

1 Muon ($g - 2$) Conceptual Design Report

2 E989 Collaboration

3 Tuesday 7th May, 2013

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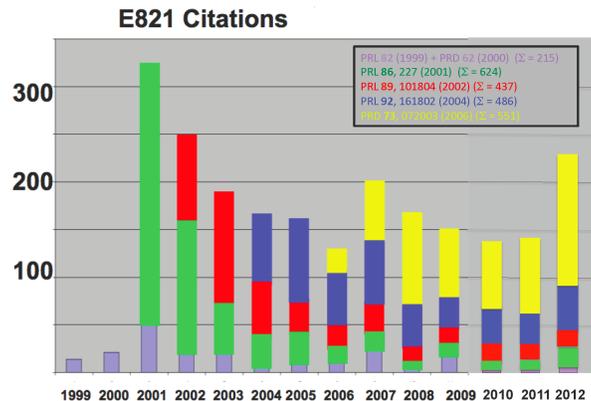
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Executive Summary

18 This Conceptual Design Report details a new experiment for Fermilab to measure the
 19 muon anomalous magnetic dipole moment, or anomaly, at least a factor of four more precisely
 20 than the E821 collaboration did at the Brookhaven AGS. The muon anomaly a_μ is a low-
 21 energy observable, which can be both measured and computed to high precision, with both
 22 theory and experiment having reached the sub-part-per-million (ppm) level of precision.
 23 For many years, a_μ has played an important role in constraining models of “New Physics”
 24 beyond the standard model, and will continue to do so in the LHC era. The Standard-Model
 25 value has contributions from quantum electrodynamics (QED), the weak interaction, and
 26 from strongly interacting particles in vacuum polarization and “light-by-light” scattering
 27 diagrams.

28 The present experimental value appears to be larger than the expected Standard-Model
 29 value by greater than three standard deviations, which could be a harbinger of New Physics,
 30 and strongly motivates the new experiment. In addition to the expected experimental im-
 31 provement of a factor of four, the uncertainty on the Standard-Model value will also be
 32 improved. One very important recent theoretical development is that lattice calculations are
 33 becoming relevant in the determination of the strong-interaction contributions.

34 BNL E821 has been a very high-impact experiment, with over 2000 citations to their four
 35 major papers, and over 2200 citations to all of those reporting physics results.



36

37 The experiment will also be optimised to improve significantly on the CP-forbidden electric
 38 dipole moment (EDM) of the muon. This presents a unique opportunity to search for an
 39 EDM of a second-generation particle. With proper design, the EDM sensitivity could reach
 40 two orders of magnitude beyond the present limit of $d_\mu < 1.8 \times 10^{-18}$ ecm obtained by BNL
 41 E821.

42 A number of major components from E821 will be relocated to Fermilab and reused. The
 43 precision 700 T superconducting storage ring magnet built at Brookhaven will be relocated
 44 to Fermilab and installed in a new building on the Muon Campus. An 8 GeV proton beam
 45 from the Booster Accelerator will be injected into the recycler ring, rebunched, and one
 46 bunch at a time will be extracted to a new pion production target at the location of the
 47 former antiproton production target. The resulting pion beam will be transported to the
 48 repurposed antiproton debuncher ring, now called the Delivery Ring, which will be used as

49 a 1,900 m decay line. The resulting muon beam will be extracted from the Delivery Ring
50 and brought to the new MC1 building and injected into the muon storage ring. The MC1
51 building will be a general purpose building, suitable for the $(g - 2)$ experiment, as well as
52 for future experiments on the muon campus.

53 While the storage ring magnet, power supply, and vacuum chambers are being reused,
54 the fast muon kicker, the electrostatic quadrupole system, the field monitoring and control
55 system, the detectors, electronics, data acquisition system will all be upgraded.

56 ...

57 (includes intro, precision goal, scope, capabilities, cost and schedule)

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436 Chapter 1

437 Project Overview

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440 1.1.2 Storage Ring

441 1.1.3 Precision Magnetic Field

442 1.1.4 Detectors

443 1.2 $(g - 2)$ and the Muon Campus

444 1.3 Conventional Facilities

445 1.4 Organization

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447 1.4.2 WBS

448 1.4.3 Controls

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451 1.4.6 Configuration Management

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453 1.4.8 Cost and Schedule

454 1.5 References

Chapter 2

Introduction and Physics Motivation

2.1 Introduction

This chapter gives the physics context of magnetic moment measurements, the Standard Model expectations, along with the reach of such experiments to identify and constrain physics beyond the Standard Model. Except for a broad-brush mention of the experimental technique, the details are left for later chapters. Chapter 3 gives an overview of the experimental method, and the subsequent chapters give the details. We attempt to follow the WBS structure in those later chapters.

2.2 Magnetic and Electric Dipole Moments

The study of magnetic moments of subatomic particles grew up with the development of quantum mechanics. For fermions the magnetic dipole moment (MDM) is related to the spin by

$$\vec{\mu} = g \frac{Qe}{2m} \vec{s}. \quad (2.1)$$

where $Q = \pm 1$ and $e > 0$. Our modern interpretation of the Stern-Gerlach experiments [1] is that their observation that: “to within 10% the magnetic moment of the silver atom is one Bohr magneton” was telling us that the g -factor of the un-paired electron is equal to 2. However, reaching this conclusion required the discovery of spin [3], quantum mechanics [4] along with with Thomas’ relativistic correction [5]. Phipps and Taylor [6] repeated the Stern-Gerlach experiment in hydrogen, and mentioned the electron spin explicitly. One of the great successes of Dirac’s relativistic theory [7] was the prediction that $g \equiv 2$.

For some years, the experimental situation remained the same. The electron had $g = 2$, and the Dirac equation seemed to describe nature. Then a surprising and completely unexpected result was obtained. In 1933, against the advice of Pauli who believed that the proton was a pure Dirac particle [8], Stern and his collaborators [9] showed that the g -factor of the proton was ~ 5.5 , not the expected value of 2. Even more surprising was the discovery in 1940 by Alvarez and Bloch [10] that the neutron had a large magnetic moment.

In 1947, motivated by measurements of the hyperfine structure in hydrogen that obtained splittings larger than expected from the Dirac theory [11, 12, 13], Schwinger [14] showed that

483 from a theoretical viewpoint these “discrepancies can be accounted for by a small additional
 484 electron spin magnetic moment” that arises from the lowest-order radiative correction to the
 485 Dirac moment¹,

$$\frac{\delta\mu}{\mu} = \frac{1}{2\pi} \frac{e^2}{\hbar c} = 0.001162. \quad (2.2)$$

486 It is useful to break the magnetic moment into two terms:

$$\mu = (1 + a) \frac{e\hbar}{2m}, \quad \text{where } a = \frac{(g - 2)}{2}. \quad (2.3)$$

487 The first term is the Dirac moment, 1 in units of the appropriate magneton $e\hbar/2m$. The
 488 second term is the anomalous (Pauli) moment [15], where the dimensionless quantity a
 489 (Schwinger’s $\delta\mu/\mu$) is sometimes referred to as the *anomaly*.

490 2.2.1 The Muon

491 The muon was first observed in a Wilson cloud chamber by Kunze[16] in 1933, where it was
 492 reported to be “a particle of uncertain nature.” In 1936 Anderson and Neddermeyer[17]
 493 reported the presence of “particles less massive than protons but more penetrating than
 494 electrons” in cosmic rays, which was confirmed in 1937 by Street and Stevenson[18], Nishina,
 495 Tekeuchi and Ichimiya[19], and by Crussard and Leprince-Ringuet[20]. The Yukawa theory
 496 of the nuclear force had predicted such a particle, but this “mesotron” as it was called,
 497 interacted too weakly with matter to be the carrier of the strong force. Today we understand
 498 that the muon is a second generation lepton, with a mass about 207 times the electron’s.
 499 Like the electron, the muon obeys quantum electrodynamics, and can interact with other
 500 particles through the electromagnetic and weak forces. Unlike the electron which appears
 501 to be stable, the muon decays through the weak force predominantly by $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$. The
 502 muon’s long lifetime of $\simeq 2.2 \mu\text{s}$ permits precision measurements of its mass, lifetime, and
 503 magnetic moment.

504 2.2.2 The Muon Magnetic Moment

505 The magnetic moment of the muon played an important role in the discovery of the generation
 506 structure of the Standard Model (SM). The pioneering muon spin rotation experiment at
 507 the Nevis cyclotron observed parity violation in muon decay [21], and also showed that g_μ
 508 was consistent with 2. Subsequent experiments at Nevis [24] and CERN [25] showed that
 509 $a_\mu \simeq \alpha/(2\pi)$, implying that in a magnetic field, the muon behaves like a heavy electron. Two
 510 additional experiments at CERN required that contributions from higher-order QED [26],
 511 and then from virtual hadrons [1] be included into the theory in order to reach agreement
 512 with experiment.

513 2.2.3 The Muon Electric Dipole Moment

514 Dirac [7] discovered an electric dipole moment (EDM) term in his relativistic electron theory.
 515 Like the magnetic dipole moment, the electric dipole moment must be along the spin. We

¹A misprint in the original paper has been corrected here.

516 can write an EDM expression similar to Eq. (2.1),

$$\vec{d} = \eta \left(\frac{Qe}{2mc} \right) \vec{s}, \quad (2.4)$$

517 where η is a dimensionless constant that is analogous to g in Eq. (2.1). While magnetic
518 dipole moments (MDMs) are a natural property of charged particles with spin, electric
519 dipole moments (EDMs) are forbidden both by parity and by time reversal symmetry.

520 The search for an EDM dates back to the suggestion of Purcell and Ramsey [28] in 1950,
521 well in advance of the paper by Lee and Yang [29], that a measurement of the neutron EDM
522 would be a good way to search for parity violation in the nuclear force. An experiment
523 was mounted at Oak Ridge [30] soon thereafter that placed a limit on the neutron EDM of
524 $d_n < 5 \times 10^{-20}$ e-cm, although the result was not published until after the discovery of parity
525 violation.

526 Once parity violation was established, Landau [31] and Ramsey [32] pointed out that
527 an EDM would violate both P and T symmetries. This can be seen by examining the
528 Hamiltonian for a spin one-half particle in the presence of both an electric and magnetic
529 field,

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}. \quad (2.5)$$

530 The transformation properties of \vec{E} , \vec{B} , $\vec{\mu}$ and \vec{d} are given in Table 2.2.3, and we see that
531 while $\vec{\mu} \cdot \vec{B}$ is even under all three symmetries, $\vec{d} \cdot \vec{E}$ is odd under both P and T . Thus the
532 existence of an EDM implies that both P and T are not good symmetries of the interaction
533 Hamiltonian, Eq. (2.5). The EDM is a CP -odd quantity, and if observed, would be the
534 manifestation of a new source of CP violation. The search for a muon EDM provides a
535 unique opportunity to search for an EDM of a second-generation particle.

Table 2.1: Transformation properties of the magnetic and electric fields and dipole moments.

	\vec{E}	\vec{B}	$\vec{\mu}$ or \vec{d}
P	-	+	+
C	-	-	-
T	+	-	-

536 Concerning these symmetries, Ramsey states [32]:

537 “However, it should be emphasized that while such arguments are appealing
538 from the point of view of symmetry, they are not necessarily valid. Ultimately
539 the validity of all such symmetry arguments must rest on experiment.”

540 Fortunately this advice has been followed by many experimental investigators during the
541 intervening 50 years. Since the Standard Model CP violation observed in the neutral kaon
542 and B-meson systems is inadequate to explain the predominance of matter over antimatter in
543 the universe, the search for new sources of CP violation beyond that embodied in the CKM
544 formalism takes on a certain urgency. Searches for a permanent electric dipole moment of

545 the electron, neutron, and of an atomic nucleus have become an important part of the search
 546 for physics beyond the Standard Model. The present limits on subatomic EDMs is given in
 547 Table 2.2.3.

Table 2.2: EDM Limits for various systems

Particle	EDM Limit (e-cm)	SM value (e-cm)
p [33]	7.9×10^{-25}	
n [34]	2.9×10^{-26}	$\simeq 10^{-32}$
^{199}Hg [33]	3.1×10^{-29}	$\simeq 10^{-32}$
e^- [35]	1.05×10^{-27}	$< 10^{-41}$
μ [36]	1.8×10^{-19}	$< 10^{-38}$

548 2.3 Quick Summary of the Experimental Technique

549 Polarized muons are produced (see Chapter 7) and injected into the storage ring (see Chap-
 550 ter 12). The magnetic field is a dipole field, shimmed to ppm level uniformity. Vertical
 551 focusing is provided by electrostatic quadrupoles (see Chapter 13).

552 Two frequencies are measured experimentally: The rate at which the muon polarization
 553 turns relative to the momentum, called ω_a , and the value of the magnetic field, normalized
 554 in terms normalized to the Larmor frequency of a free proton, ω_p .

555 The rate at which the spin² turns relative to the momentum, $\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$, where S and
 556 C stand for spin and cyclotron. These two frequencies are given by

$$\omega_S = -g \frac{Qe}{2m} B - (1 - \gamma) \frac{Qe}{\gamma m} B; \quad (2.6)$$

$$\omega_C = -\frac{Qe}{m\gamma} B; \quad (2.7)$$

$$\omega_a = \omega_S - \omega_C = -\left(\frac{g-2}{2}\right) \frac{Qe}{m} B = -a \frac{Qe}{m} B \quad (2.8)$$

557 (where $e > 0$ and $Q = \pm 1$). There are two important features of ω_a : (i) It only depends on
 558 the anomaly rather than on the full magnetic moment; (ii) It depends linearly on the applied
 559 magnetic field. In the presence of an electric field ω_a is modified

$$\vec{\omega}_a = -\frac{Qe}{m} \left[a_\mu \vec{B} + \left(a_\mu - \left(\frac{m}{p} \right)^2 \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] - \eta \frac{Qe}{2m} \quad (2.9)$$

560 If operated at the ‘magic’ momentum $p_{magic} = m/\sqrt{a_\mu} \simeq 3.09$ GeV/c the electric field
 561 contribution cancels in first order, and requires a small correction in second order.

²The term ‘spin’ is often used in place of the more accurate term ‘polarization’

562 The magnetic field is weighted by the muon distribution, and also averaged over the
 563 running time weighed by the number of stored muons to determine the value of ω_p which
 564 is combined with the average ω_a to determine a_μ . The reason for the use of these two
 565 frequencies, rather than B measured in tesla can be understood from Eq. 2.9. To obtain a_μ
 566 from this relationship requires precise knowledge of the muon charge to mass ratio.

567 To determine a_μ from the two frequencies ω_a and ω_p , we use the relationship

$$a_\mu = \frac{\omega_a/\omega_p}{\lambda_+ - \omega_a/\omega_p} = \frac{\mathcal{R}}{\lambda_+ - \mathcal{R}}, \quad (2.10)$$

568 where the ratio $\lambda_+ = \mu_{\mu^+}/\mu_p = 3.183\,345\,137(85)$ is the muon-to-proton magnetic moment
 569 ratio [41] measured from muonium (the μ^+e^- atom) hyperfine structure[43]. Of course, to use
 570 λ_+ to determine a_{μ^-} requires the assumption of *CPT* invariance, *viz.* ($a_{\mu^+} = a_{\mu^-}$; $\lambda_+ = \lambda_-$).
 571 The comparison of \mathcal{R}_{μ^+} with \mathcal{R}_{μ^-} provides a *CPT* test. In E821

$$\Delta\mathcal{R} = \mathcal{R}_{\mu^-} - \mathcal{R}_{\mu^+} = (3.6 \pm 3.7) \times 10^{-9} \quad (2.11)$$

572 2.4 Results from E821

573 2.4.1 Measurement of a_μ

574 The E821 Collaboration working at the Brookhaven Laboratory AGS used an electric quadrupole
 575 field to provide vertical focusing in the storage ring, and shimmed the magnetic field to ± 1
 576 ppm uniformity on average. The storage ring was operated at the “magic” momentum,
 577 $p_{magic} = 3.094$ GeV/c, ($\gamma_{magic} = 29.3$), such that $a_\mu = (m/p)^2$ and the electric field did not
 578 contribute to ω_a .³ The result is [38, 39]

$$a_\mu^{E821} = 116\,592\,089(54)_{stat}(33)_{syst}(63)_{tot} \times 10^{-11} \quad (\pm 0.54 \text{ ppm}). \quad (2.12)$$

579 The results from E821 are shown in Fig. 2.1 along with the Standard-Model value which is
 580 discussed below in Section 2.5

581 2.4.2 Measurement of the Muon EDM: d_μ

582 If the muon has an electric dipole moment (EDM) then the dominant effect in the spin
 583 motion is the motional electric field proportional to $\vec{\beta} \times \vec{B}$. This motional electric field
 584 produces a torque on the EDM $\vec{d} \times \vec{\beta} \times \vec{B}$ that is perpendicular to \vec{B} and $\vec{\beta}$. The result is is
 585 an up-down oscillation of the spin out of phase with ω_a , as discussed below in Section 3.7.
 586 No evidence for an up-down oscillation was seen, and the result is[36]

$$d_\mu = (0.1 \pm 0.9) \times 10^{-19} e\text{-cm}; \quad |d_\mu| < 1.9 \times 10^{-19} e\text{-cm} \quad (95\% \text{ C.L.}), \quad (2.13)$$

587 a factor of five smaller than the previous limit.

³The magic momentum was first employed by the third CERN collaboration [1].

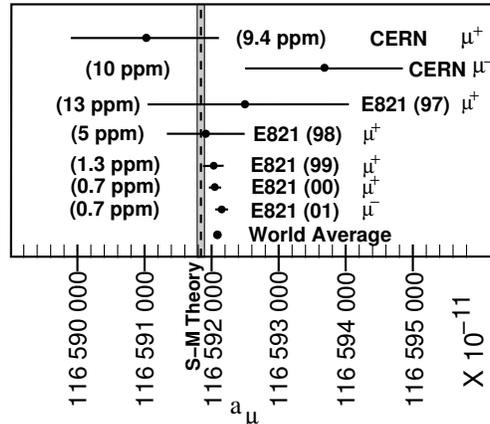


Figure 2.1: Measurements of a_μ from CERN and BNL E821. The vertical band is the SM value using the hadronic contribution from Ref. [47] (see Table 2.3).

2.5 The Standard-Model Value of a_μ

588

589 In this section we present the standard model (SM) theory of the muon anomalous magnetic
 590 moment (anomaly). In the following section we discuss physics beyond the standard model
 591 (BSM) that could contribute to the anomaly at a measurable level. The conclusion is that
 592 muon ($g - 2$) will play a powerful role in the interpretation of new phenomena that might
 593 be discovered at the LHC. If new phenomena are not discovered there, then muon ($g - 2$)
 594 becomes even more important, since it would provide one of the few remaining ways to search
 595 for new physics at the TeV scale.

2.5.1 Introduction

596

597 The magnetic moment of the muon (or electron), which is aligned with its spin, is given by

$$\vec{\mu} = g \frac{Qe}{2m_{\mu,e}} \vec{s}, \quad \underbrace{g = 2(1 + a_\mu)}_{\text{Dirac}}; \quad (2.14)$$

598 where the quantity g is exactly 2 in the Dirac theory, $Q = \pm 1$ with e a positive number.
 599 The small number a , the anomaly, arises from quantum fluctuations, with the largest con-
 600 tribution coming from the single loop diagram in Fig. 2.2(a). This contribution was first
 601 calculated by Schwinger [14], who obtained $a = (\alpha/2\pi) = 0.00116 \dots$. These calculations
 602 have been extended to higher powers in α/π , with the fourth- $(\alpha/\pi)^2$ and sixth-order $(\alpha/\pi)^3$
 603 contributions having been carried out analytically.

604 The electron anomaly is relatively insensitive to heavier physics, so in principle the
 605 0.03 ppb measurement of the electron anomaly [67] should provide a test of QED, but
 606 the few ppb precision of the *independent* measurements of α prevents this comparison. Al-
 607 ternately, one can accept that QED is valid and use the electron anomaly to determine the
 608 most precise measurement of α [68].

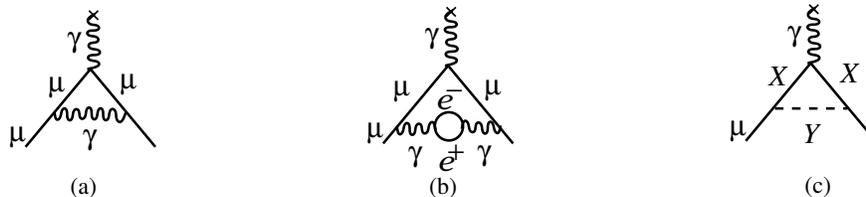


Figure 2.2: The Feynman graphs for: (a) The lowest-order (Schwinger) contribution to the lepton anomaly ; (b) The vacuum polarization contribution, which is one of five fourth-order, $(\alpha/\pi)^2$, terms; (c) The schematic contribution of new particles X and Y that couple to the muon. **The \times indicates the virtual photon from the magnetic field.**

609 The muon anomaly is an entirely different case. The relative contribution to the muon
 610 anomaly of heavier virtual particles goes as $(m_\mu/m_e)^2 \simeq 43000$, so with much less precision
 611 when compared with the electron, the muon anomaly is sensitive to mass scales in the
 612 several hundred GeV region. This not only includes the expected contribution of the W and
 613 Z bosons, but perhaps contributions from new, as yet undiscovered, particles such as the
 614 supersymmetric partners of the electro-weak gauge bosons (see Fig. 2.2(c)).

615 The standard-model value of a_μ has three contributions from radiative processes: QED
 616 loops containing leptons (e, μ, τ) and photons; loops containing hadrons in vacuum polariza-
 617 tion loops where the e^+e^- pair in Fig 2.2(b) is replaced by hadrons; and weak loops involving
 618 the weak gauge bosons W, Z , and Higgs such as is shown in Fig. 2.2(c) where $X = W$ and
 619 $Y = \nu$, or $X = \mu$ and $Y = Z$. Thus

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{hadronic}} + a_\mu^{\text{weak}}. \quad (2.15)$$

620 The QED and weak contributions to the muon anomaly are now well understood at the level
 621 needed for the comparison of Standard-Model theory with experiment.

622 The hadronic contribution must be determined from a dispersion relation using experimental
 623 data, namely the cross sections for electron-positron annihilation to hadrons. The determi-
 624 nation of this contribution represents a worldwide effort which was driven primarily by the
 625 existence of BNL experiment E821. The possibility of a new Fermilab experiment has al-
 626 ready stimulated further work that will certainly continue unabated if P989 turns into an
 627 approved and funded experiment.

628 2.5.2 QED Contribution

629 The QED and electroweak contributions to a_μ are well understood. Recently the four-loop
 630 contribution has been updated and the full five-loop contribution has been calculated [66].

631 We take the numerical values from the review by Miller, et al, [75] with the QED con-
 632 tribution updated to the Höcker and Marciano [70]. The QED contribution to a_μ has been
 633 calculated through tenth order (five loops) [66]. The present value is

$$a_\mu^{\text{QED}} = 116\,584\,718.951 (0.009)(0.019)(0.007)(.077) \times 10^{-11} \quad (2.16)$$

634 where the uncertainties are from the lepton mass ratios, the eight-order term, the tenth-
 635 order term, and the value of α taken from the ^{87}Rb atom $\alpha^{-1}(\text{Rb}) = 137.035\,999\,049(90)$
 636 $[0.66 \text{ ppb}]$. [69].

637 2.5.3 Weak contributions

638 The electroweak contribution (shown in Fig. 2.3) is now calculated through two loops [50,
 639 51, 52, 53, 56]. The single loop result

$$\begin{aligned}
 a_{\mu}^{\text{EW}(1)} &= \frac{G_F m_{\mu}^2}{\sqrt{2} 8\pi^2} \left\{ \underbrace{\frac{10}{3}}_W + \underbrace{\frac{1}{3}(1-4\sin^2\theta_W)^2 - \frac{5}{3}}_Z \right. \\
 &+ \left. \mathcal{O}\left(\frac{m_{\mu}^2}{M_Z^2} \log \frac{M_Z^2}{m_{\mu}^2}\right) + \frac{m_{\mu}^2}{M_H^2} \int_0^1 dx \frac{2x^2(2-x)}{1-x + \frac{m_{\mu}^2}{M_H^2} x^2} \right\} \\
 &= 194.8 \times 10^{-11}, \tag{2.17}
 \end{aligned}$$

640 was calculated by five separate groups shortly after the Glashow-Salam-Weinberg theory was
 641 shown by 't Hooft to be renormalizable. With the present limit on the Higgs boson mass,
 642 only the W and Z contribute to the lowest-order electroweak at a measurable level.

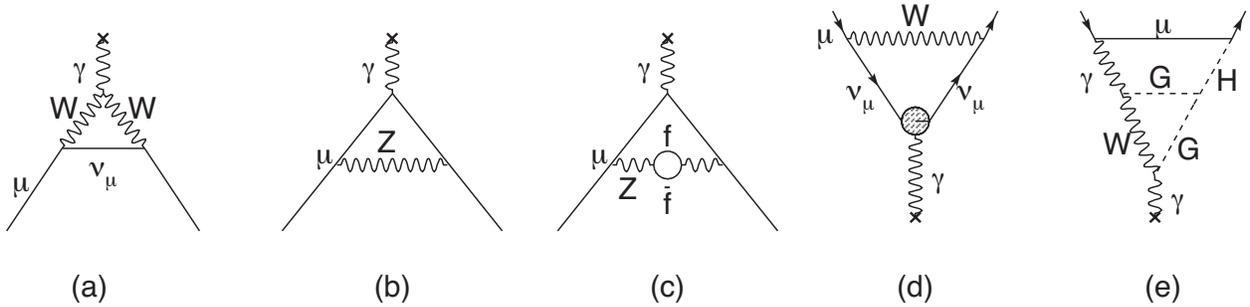


Figure 2.3: Weak contributions to the muon anomalous magnetic moment. Single-loop contributions from (a) virtual W and (b) virtual Z gauge bosons. These two contributions enter with opposite sign, and there is a partial cancellation. The two-loop contributions fall into three categories: (c) fermionic loops which involve the coupling of the gauge bosons to quarks, (d) bosonic loops which appear as corrections to the one-loop diagrams, and (e) a new class of diagrams involving the Higgs where G is the longitudinal component of the gauge bosons. See Ref. [54] for details. The \times indicates the virtual photon from the magnetic field.

643 The two-loop weak contribution, (see Figs. 2.3(c-e) for examples) is negative, and the
 644 total electroweak contribution is [75]

$$a_{\mu}^{\text{EW}} = 154(1) \times 10^{-11} \tag{2.18}$$

645 where the error comes from hadronic effects in the second-order electroweak diagrams with
 646 quark triangle loops. and the latter comes from the uncertainty on the Higgs mass [52, 51,

50, 17, 55]. The leading logs for the next-order term have been shown to be small [56]. The weak contribution is about 1.3 ppm of the anomaly, so the experimental uncertainty on a_μ of ± 0.54 ppm now probes the weak scale of the standard model.

Hadronic contribution

The hadronic contribution to a_μ is about 60 ppm of the total value. The lowest-order diagram shown in Fig. 2.4(a) dominates this contribution and its error, but the hadronic light-by-light contribution Fig. 2.4(e) is also important. We discuss both of these contributions below.

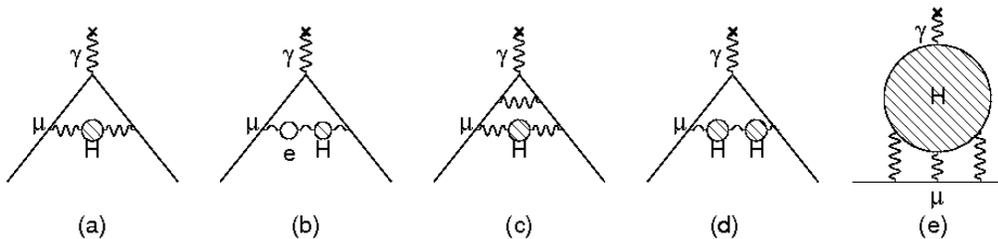


Figure 2.4: The hadronic contribution to the muon anomaly, where the dominant contribution comes from the lowest-order diagram (a). The hadronic light-by-light contribution is shown in (e).

The energy scale for the virtual hadrons is of order $m_\mu c^2$, well below the perturbative region of QCD. Thus it must be calculated from the dispersion relation shown pictorially in Fig. 2.5,

$$a_\mu^{\text{had;LO}} = \left(\frac{\alpha m_\mu}{3\pi} \right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s), \quad \text{where} \quad R \equiv \frac{\sigma_{\text{tot}}(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}, \quad (2.19)$$

using the measured cross sections for $e^+e^- \rightarrow \text{hadrons}$ as input, where $K(s)$ is a kinematic factor ranging from **0.63** at $s = 4m_\pi^2$ to 1 at $s = \infty$. This dispersion relation relates the bare cross section for e^+e^- annihilation into hadrons to the hadronic vacuum polarization contribution to a_μ . Because the integrand contains a factor of s^{-2} , the values of $R(s)$ at low energies (the ρ resonance) dominate the determination of $a_\mu^{\text{had;LO}}$, however at the level of precision needed, the data up to 2 GeV are very important. This is shown in Fig. 2.6, where the left-hand chart gives the relative contribution to the integral for the different energy regions, and the right-hand gives the contribution to the error squared on the integral. The contribution is dominated by the two-pion final state, but other low-energy multi-hadron cross sections are also important.

These data for e^+e^- annihilation to hadrons are also important as input into the determination of $\alpha_s(M_Z)$ and other electroweak precision measurements, including the limit on the Higgs mass [71].

In the 1980s when E821 was being proposed at Brookhaven, the hadronic contribution was known to about 10 ppm. It now is known to about 0.4 ppm. This improvement has come from the hard work of many experimental and theoretical physicists. The low energy e^+e^- data of the 80s have been replaced by very precise data from the CMD2 and SND collaborations

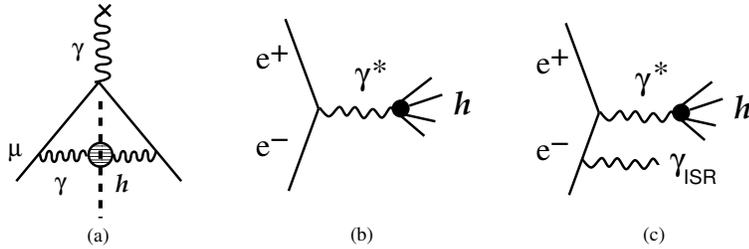


Figure 2.5: (a) The “cut” hadronic vacuum polarization diagram; (b) The e^+e^- annihilation into hadrons; (c) Initial state radiation accompanied by the production of hadrons.

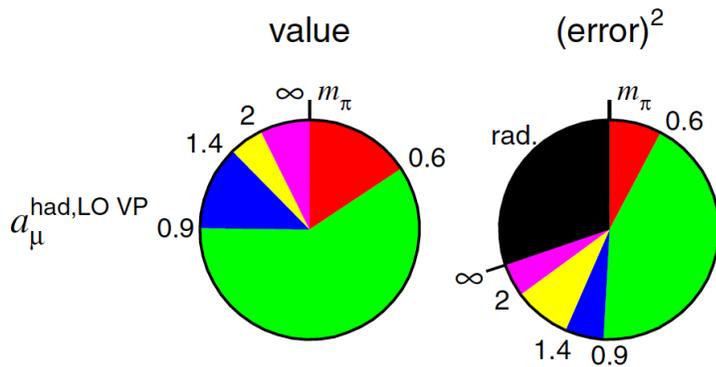


Figure 2.6: Contributions to the dispersion integral, and to the error on the dispersion integral. Taken from Hagirawa, et al., [48]

674 in Novosibirsk, the KLOE collaboration at Frascati, and the BaBar collaboration at SLAC.
 675 The new VEPP-2000 collider in Novosibirsk has been operational for several years, with two
 676 upgraded detectors, CMD-3 and SND-2000. This new facility will permit both energy scans,
 677 and the use of initial-state radiation to measure cross sections up to 2.0 GeV. Additional
 678 data on multi-hadron final states are expected from the Belle detector at KEK and **BES-III**
 679 **at BEPC**.

680 In addition to the collider experiments, significant theoretical work has been carried out
 681 in generating the radiator functions used in the initial-state radiation (ISR) experiments, as
 682 KLOE and BaBar [81, 82], as well as on the hadronic light-by-light contribution shown in
 683 Fig. 2.4(e).

684 The worldwide effort to improve our knowledge of the hadronic contribution continues
 685 to this day [90, 91]. The most recent $\pi\pi$ -final state measurements were reported by the
 686 BaBar [83] and KLOE [86, 87] collaborations. An independent analysis of KLOE data
 687 using the direct measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, which agreed well with
 688 their previous analysis using the luminosity measurement and QED calculations, **has been**
 689 **recently published** [92].

690 Muon ($g-2$), and the determination of the hadronic contribution continues to feature
 691 prominently in the international workshops Tau [84] and PHIPSI [85], where sessions were
 692 devoted to all issues around muon ($g-2$). We emphasize that while this is a difficult subject,

693 progress will continue to be made, provided that a new experiment does indeed go forward
694 at Fermilab.

695 **Lowest- and next-lowest-order hadronic contribution**

696 The cross sections at low energies dominate the dispersion relation, and until recently the
697 low-energy electron-positron storage rings in Novosibirsk and Frascati provided the bulk of
698 the new measurements. The Novosibirsk experiments CMD2 (cryogenic magnetic detector)
699 and SND (spherical neutral detector) collected data **up to 1.4 GeV** using the traditional
700 e^+e^- energy scan. The KLOE experiment ran at a fixed energy around 1 GeV, either on
701 the ϕ -resonance or just below it, using initial-state radiation to lower the collision energy
702 and provide the full energy range in a single measurement (see Fig. 2.5(c)). The BaBar
703 experiment also used the ISR technique, but operated at a much higher energy at or near
704 the $\Upsilon(4s)$, which easily permitted observation of the ISR photon. At Tau2012 the Belle
705 experiment reported new results on the $\pi^+\pi^-\pi^0$ final state [89] using ISR data. The ISR
706 (sometimes called “radiative return”) technique is possible because of the development of
707 the necessary theory [81, 82], which provides the effective virtual photon spectrum, called
708 the “radiator function.”

709 While the KLOE experiment was limited to the $\pi\pi\gamma$ channel, the higher energy of the
710 PEP-2 collider permitted BaBar to detect the ISR photon and to measure many multiple
711 hadron final states along with the $\pi\pi\gamma$ final state, thus providing important data from
712 channels which were either very imprecise, or simply not available before. The first $\pi^+\pi^-$
713 data from BaBar were released in August 2009 [83], and covered the energy range from
714 threshold to 3 GeV. Unlike the other experiments that used a calculated $\mu\mu$ cross section for
715 the denominator in Eq. (2.19), the BaBar experiment measured the $\mu\mu$ production directly
716 and took the ratio of experimental numbers to determine $R(s)$ directly. This had the benefit
717 of canceling a number of systematic errors, and significantly lowered the uncertainty on the
718 cross section. **I suggest to drop - If BaBar had used the calculated $\mu\mu$ cross section,**
719 **the cross section errors would have been at the $\sim 5\%$ level, much too large to be**
720 **useful in the determination of a_μ^{had} .**

721 Published cross sections from the BaBar, KLOE, CMD2 and SND experiments are shown
722 in Fig. 2.7. The KLOE re-analysis of their small-angle data using the ratio of the $\pi\pi$ $\mu\mu$
723 cross sections, compared large-angle data[87], and are displayed in Fig. 2.8 as the pion form
724 factor $|F_\pi|^2$, which is related to the cross section by

$$\sigma_{e^+e^- \rightarrow \pi^+\pi^-} = \frac{\pi\alpha^2}{3s} \beta_\pi^3 |F_\pi|^2. \quad (2.20)$$

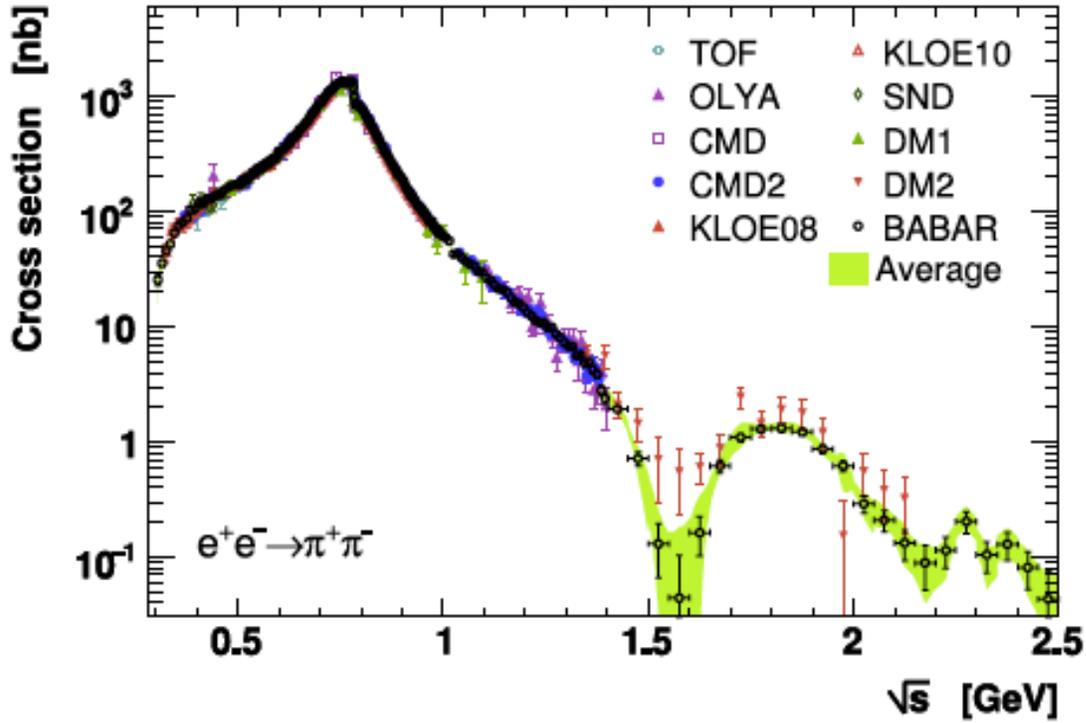
725 They were analyzed by a different group of collaborators who worked independently from
726 those involved in the the KLOE08 [86] analysis.

727 Two recent analyses [47, 48] of the e^+e^- hadroproduction data obtained:

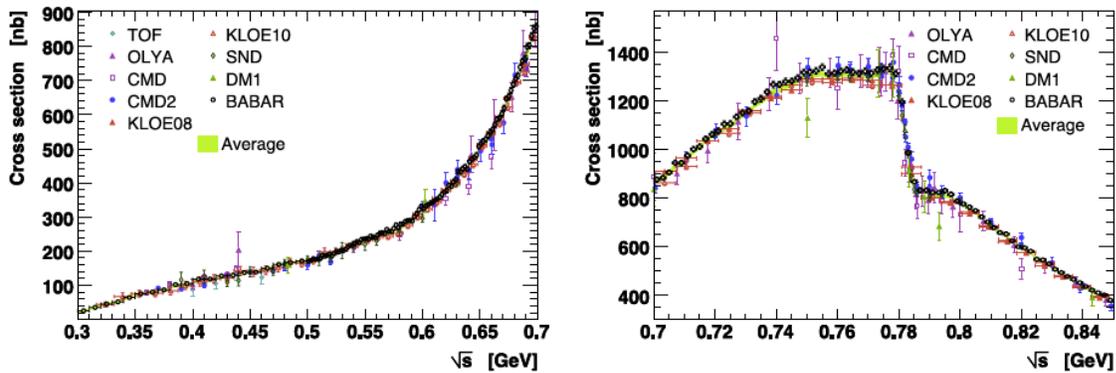
$$a_\mu^{\text{had;LO}} = 6\,923 \pm 42 \times 10^{-11}. \quad (2.21)$$

$$a_\mu^{\text{had;LO}} = 6\,949 \pm 43 \times 10^{-11}. \quad (2.22)$$

728 Important earlier global analyses include those of HMNT [72], Davier, et al., [73], Jegerlehner [74].



(a)



(b)

Figure 2.7: The $\pi\pi$ cross section from BaBar, CMD2, KLOE and SND. The lower left-hand figure shows the threshold region, the right-hand figure shows a blowup of the ρ resonance region. The sharp cusp comes from $\rho - \omega$ interference.

729

The most recent evaluation of the next-order hadronic contribution shown in Fig. 2.4(b-d) can also be determined from a dispersion relation, and the result is [48]

730

$$a_{\mu}^{\text{had:NLO}} = (-98.4 \pm 0.6_{\text{exp}} \pm 0.4_{\text{rad}}) \times 10^{-11}. \quad (2.23)$$

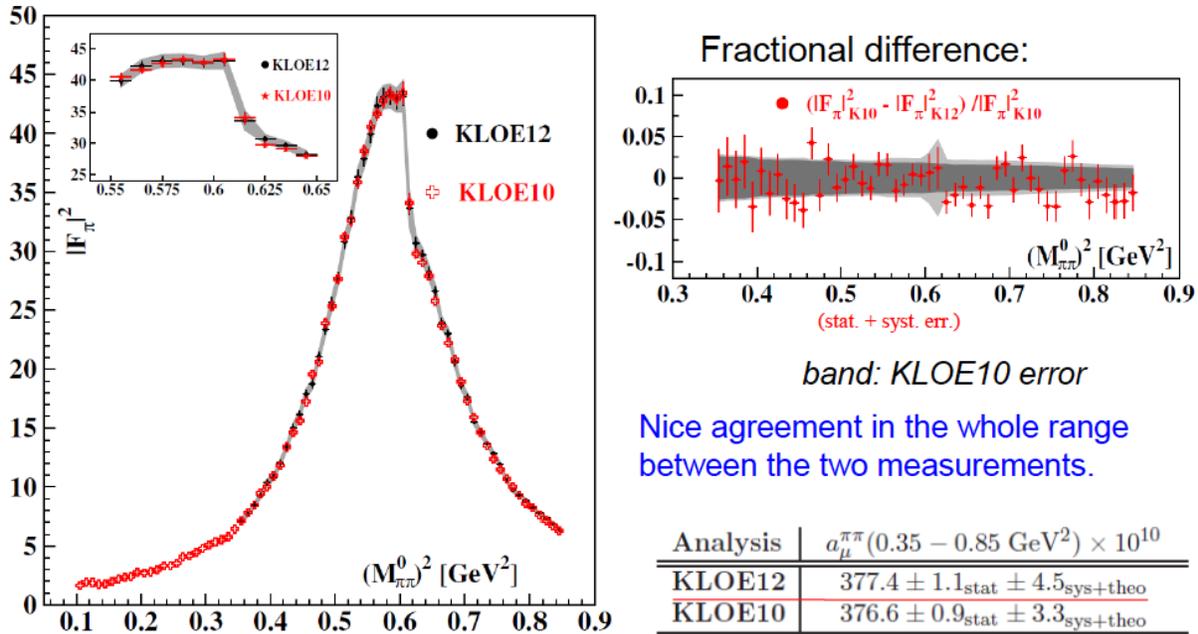


Figure 2.8: The pion form factor $|F_\pi|^2$ from KLOE2010 [87] and the re-analysis of the 2008 data [86] using the cross-section ratio described above [88]. The right-hand side shows the fractional difference between the two analyses.

731 $a_\mu^{\text{had};\text{LO}}$ from hadronic τ decay

732 The value of $a_\mu^{\text{had};\text{LO}}$ from threshold up to m_τ could in principle be obtained from hadronic τ^-
 733 decays (See Fig. 2.4)?????, provided that the necessary isospin corrections are known. This
 734 was first demonstrated by Almany, Davier and Höcker [76]. In the absence of second-class
 735 currents, hadronic τ decays to an *even* number of pions such as $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ goes through
 736 the vector part of the weak current, and can be related to e^+e^- annihilation into $\pi^+\pi^-$
 737 through the CVC hypothesis and isospin conservation (see Fig. 2.5.3????) [76, 80]. The τ -data
 738 only contain an isovector piece, and the isoscalar piece present in e^+e^- annihilation has to be
 739 put in “by hand” to evaluate $a_\mu^{\text{had};\text{LO}}$. Until recently there were 3.5 to 4.5 standard deviation
 740 differences when e^+e^- data and the CVC hypothesis were used to determine the $\tau^- \rightarrow \nu_\tau \pi^- \pi^0$
 741 or $\tau^- \rightarrow \nu_\tau 2\pi^- \pi^+ \pi^0$ branching fractions, when compared with the experimental values. Thus
 742 until recently most authors [48, 75, 74] concluded that there are unresolved issues, most likely
 743 incorrect isospin breaking corrections, that make it difficult to use the τ data on an equal

744 footing with the e^+e^- data. New isospin corrections reduced the disagreement between the
 745 two methods [47]. However, none of the analyses using tau data have tried to combine
 746 the CVC determined part with that obtained from e^+e^- data. Were this to be done, the
 747 addition of the e^+e^- data would decrease the overall tau-based evaluation of to a_μ^{had} . Even
 748 so, the tau-based evaluation has to use e^+e^- data to determine the isoscalar part, so that
 749 the tau-based evaluation by Davier, et al., [47] can never be completely independent of the
 750 e^+e^- data.

751 More recently, Jegerlehner and Szafron [77] appear to have resolved this problem by
 752 calculating the correction from $\rho - \gamma$ mixing, which had not been included correctly in the
 753 previous evaluations. A subsequent hidden local symmetry calculation [78, 79] further refines
 754 these ideas and includes the τ -data in a combined analysis. They conclude that their analysis
 755 yields a 4.7 to 4.9 σ difference with the Standard Model.

756 We should note that the theoretical uncertainties on the dispersion relation in Eq. (2.19),
 757 which assumes analyticity and the optical theorem, are negligible. The cross section that
 758 enters in Eq. (2.19) is the bare cross section, and some of the early experiments were not so
 759 careful in their reporting the data and being clear on what, if any radiative corrections were
 760 applied. All of the modern experiments are well aware of these issues, and their reported
 761 errors include any uncertainties introduced in determining the bare cross section.

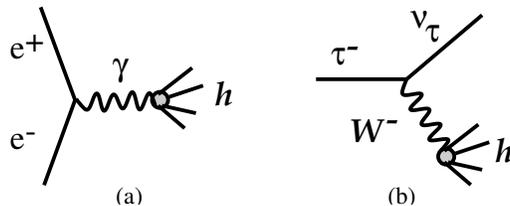


Figure 2.9: e^+e^- annihilation into hadrons (a), and hadronic τ decay (b).

762 Hadronic light-by-light contribution

763 The hadronic light-by-light contribution, (Fig. 2.4(e)) cannot at present be determined from
 764 data, but rather must be calculated using hadronic models that correctly reproduce the
 765 properties of QCD. A number of authors have calculated portions of this contribution, and
 766 recently a synthesis of all contributions has become available from Prades, de Rafael and
 767 Vainshtein [58]⁴, which has been agreed to by authors from each of the leading groups working
 768 in this field. They obtain

$$a_\mu^{\text{HLbL}} = (105 \pm 26) \times 10^{-11}. \quad (2.24)$$

769 Additional work on this contribution is underway on a number of fronts, including on the
 770 lattice. A workshop was held in March 2011 at the Institute for Nuclear Theory in Seattle [59]
 771 which brought together almost all of the interested experts.

772 One important point should be made here. The main physics of the hadronic light-by-
 773 light scattering contribution is well understood. In fact, but for the sign error unraveled

⁴This compilation is generally referred to as the ‘‘Glasgow Consensus’’ since it grew out of a workshop in Glasgow in 2007.

774 in 2002, the theoretical predictions for a_μ^{HLbL} have been relatively stable for more than ten
 775 years. We summarize with a quote from Eduardo de Rafael [61]:

776 “For the time being, concerning the issue of errors, and after the work in PdeRV,
 777 I personally think that a 25% error on the HLbL is quite a generous one. One of
 778 my reasons is the fact that in the comparable HVP contribution—assuming that
 779 we did not have data from ee -annihilations nor tau-decays—I claim that from
 780 the underlying physics which we know, and using the same techniques as in the
 781 HLbL calculation, we are presently able to make there an estimate which, when
 782 compared to the one with data, turns out to be quite good: at the 10% to 15%
 783 level.”

784 There is one calculation which used a Dyson-Schwinger approach, that appeared to
 785 strongly disagree with all of the other model calculations of the hadronic-light-by-light con-
 786 tribution [63]. However, recently these authors found several sign mistakes that change their
 787 result, moving it closer to other calculations [64].

788 At Tau2012, Blum reported that the lattice calculation of the hadronic-light-by-light
 789 contribution had started to see a signal [65]. “Signal may be emerging in the model ballpark”.
 790 Blum also had encouraging words about the precision that the lattice might reach on the
 791 lowest-order hadronic contribution.

792 In addition to the theoretical work on the HLbL, a new facility is being commissioned
 793 at DAΦNE which will provide tagged virtual photons for $\gamma^*\gamma^*$ physics. Both high- and
 794 low-energy taggers are being constructed on both sides of the interaction region to detect
 795 and measure the scattered electron and positron. Thus a coincidence between the scat-
 796 tered electrons and a π^0 would provide information on $\gamma^*\gamma^* \rightarrow \pi^0$, etc. [62], and will pro-
 797 vide experimental constraints on the models used to calculate the hadronic light-by-light
 798 contribution[93].

799 2.5.4 Summary of the Standard-Model Value and Comparison 800 with Experiment

801 We determine the SM value using the new QED calculation from Aoyama [66]; the elec-
 802 troweak from Ref. [75], the hadronic light-by-light contribution from the “Glasgow Consen-
 803 sus” [58]; and lowest-order hadronic contribution from Davier, et al., [47], or Hagawara et
 804 al., [48], and the higher-order hadronic from Ref. [48] A summary of these values is given in
 805 Table 2.3.

806 This SM value is to be compared with the combined a_μ^+ and a_μ^- values from E821 [2]
 807 corrected for the revised value of λ as mentioned above:

$$a_\mu^{\text{E821}} = (116\,592\,089 \pm 63) \times 10^{-11} \quad (0.54 \text{ ppm}), \quad (2.25)$$

808 which give a difference of

$$\Delta a_\mu(\text{E821} - \text{SM}) = (286 \pm 80) \times 10^{-11} \quad [47] \quad (2.26)$$

$$= (260 \pm 80) \times 10^{-11} \quad [48] \quad (2.27)$$

Table 2.3: Summary of the Standard-Model contributions to the muon anomaly. Two values are quoted because of the two recent evaluations of the lowest-order hadronic vacuum polarization.

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [47]	$6\,923 \pm 42$
HVP(lo) [48]	$6\,949 \pm 43$
HVP(ho) [48]	-98.4 ± 0.7
HLbL	105 ± 26
EW	$153 \pm 1 \pm 1$
Total SM [47]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}} (\pm 49_{\text{tot}})$
Total SM [48]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}} (\pm 50_{\text{tot}})$

809 depending on which evaluation of the lowest-order hadronic contribution that is used [47, 48].
 810 This comparison between the experimental values and the present Standard-Model value is
 811 shown graphically in Fig. 2.1.

812 This difference of **3.3** to 3.6 standard deviations is tantalizing, but we emphasize that
 813 whatever the final agreement between the measured and SM value turns out to be, it will
 814 have significant implications on the interpretation of new phenomena that might be found
 815 at the LHC and elsewhere. This point is discussed in detail below.

816 The present theoretical error is dominated by the uncertainty on the lowest-order hadronic
 817 contribution and uncertainty on the hadronic light-by-light contribution (see Table 2.3). The
 818 lowest-order hadronic contribution could be reduced to 25×10^{-11} based on the analysis of
 819 existing data and on the data sets expected from future efforts, e.g. VEPP-2000 in Novosi-
 820 birsk, BES-III **and a possible upgrade in energy of DAΦNE** [91]. When combined
 821 with future theoretical progress on the hadronic light-by-light contribution, the total SM
 822 error could reach 30×10^{-11} .

823 With the proposed experimental error of $\pm 16 \times 10^{-11}$, the combined uncertainty for the
 824 difference between theory and experiment could be as small as $\pm 34 \times 10^{-11}$, which is to be
 825 compared with the $\pm 81 \times 10^{-11}$ in Eq. (2.27).

826 2.5.5 Expected Improvements in the Standard-Model Value

827 Much experimental and theoretical work is going on worldwide to refine the hadronic contri-
 828 bution. The theory of $(g - 2)$, relevant experiments to determine the hadronic contribution,
 829 including work on the lattice, have featured prominently in the series of tau-lepton workshops
 830 and PHIPSI workshops which are held in alternate years.

831 Over the development period of our new experiment, we expect further improvements in
 832 the SM-theory evaluation. This projection is based on the following developments and facts:

- 833 • **Novosibirsk:** The VEPP2M machine has been upgraded to VEPP-2000. The max-
 834 imum energy has been increased from $\sqrt{s} = 1.4$ GeV to 2.0 GeV. Additionally, the

835 SND detector has been upgraded and the CMD2 detector was replaced by the much-
 836 improved CMD3 detector. The cross section will be measured from threshold to
 837 2.0 GeV using an energy scan, filling in the energy region between 1.4 GeV, where
 838 the previous scan ended, up to 2.0 GeV, the lowest energy point reached by the BES
 839 collaboration in their measurements. See Fig. 2.6 for the present contribution to the
 840 overall error from this region. Engineering runs began in 2009, and data collection
 841 started in 2011. So far two independent energy scans between 1.0 and 2.0 GeV were
 842 performed in 2011 and 2012. The peak luminosity of $3 \times 10^{31} \text{cm}^{-2} \text{s}^{-1}$ was achieved,
 843 which is limited by the positron production rate. The new injection facility, sched-
 844 uled to be commissioned during the 2013-2014 upgrade, should permit the luminosity
 845 to reach $10^{32} \text{cm}^{-2} \text{s}^{-1}$. Data collection **had resumed** by the end of 2012 with new
 846 energy scan at energies below 1.0 GeV. The goal of experiments at VEPP-2000 is to
 847 achieve a systematic error 0.3-0.5% in $\pi^+\pi^-$ channel with negligible statistical error
 848 in the integral. The high statistics, expected at VEPP-2000, should allow a detailed
 849 comparison of the measured cross-sections with ISR results at BaBar and DAΦNE.
 850 After the upgrade, experiments at VEPP-2000 plan to take a large amount of data at
 851 1.8-2 GeV, around $N\bar{N}$ threshold. This will permit ISR data with the beam energy
 852 of 2 GeV, which is between the PEP2 energy at the $\Upsilon(4s)$ and the 1 GeV ϕ energy
 853 at the DAΦNE facility in Frascati. The dual ISR and scan approach will provide an
 854 important cross check on the two central methods to determine HVP.

- 855 • **KLOE:** The KLOE collaboration has just reported the analysis of their 2008 data set
 856 using the experimental ratio $\pi\pi/\mu\mu$ final states, rather than the luminosity to get the
 857 cross sections [92]. In the future, they will begin the program of two-photon physics which
 858 will be ramping up, which will provide experimental input to the hadronic light-by-light
 859 theory.
- 860 • **BaBar:** A significant amount of new data exists from BaBar, which can be used to
 861 provide another ISR measurement from threshold to 3 GeV. It is not at all clear that
 862 the Collaboration will be able to take on the analysis challenge.
- 863 • **Belle:** Some work on ISR measurements of $R(s)$ is going on in multi-hadron channels.
 864 These studies will complement those completed at BaBar and provide an important
 865 check.
- 866 • **BES-III: BES-III can perform a direct measurement of R above 2 GeV with**
 867 **an energy scan. It can use ISR to access the region below it.**
- 868 • **Calculations on the Lattice for Lowest-Order HVP:** With the increased com-
 869 puter power available for lattice calculations, it may be possible for lattice calculations
 870 to contribute to our knowledge of the lowest-order hadronic contribution. Blum and his
 871 collaborators are continuing to work on the lowest-order contribution. Several groups,
 872 UKQCD (Edinburg), DESY-Zeuthen (Renner and Jansen), and the LSD (lattice strong
 873 dynamics) group in the US are all working on the lowest-order contribution.
- 874 • **Calculations on the Lattice of Hadronic Light-by-Light:** The hadronic light-

875 by-light contribution has a magnitude of $(105 \pm 26) \times 10^{-11}$, ~ 1 ppm of a_μ . A modest
 876 calculation on the lattice would have a large impact. Blum and his collaborators at
 877 BNL, RIKEN and Nagoya are working on HLbL, and are beginning to see a signal.

878 2.6 Physics Beyond the Standard Model

879 For many years, the muon anomaly has played an important role in constraining physics
 880 beyond the SM [45, 46, 98, 99, 100]. The more than 2000 citations to the major E821
 881 papers [2, 5, 22, 21], demonstrates that this role continues. The citations are shown as a
 882 function of year in Fig. 2.10. It is apparent that with the LHC results available in 2012,
 883 interest in the BNL results has risen significantly. As discussed in the previous section, the
 884 present SM value is smaller than the experimental value by $\Delta a_\mu(\text{E821} - \text{SM})$. The discrep-
 885 ancy depends on the SM evaluation, but it is generally in the $> 3\sigma$ region; a representative
 886 value is $(286 \pm 80) \times 10^{-11}$, see Eq. (2.27).

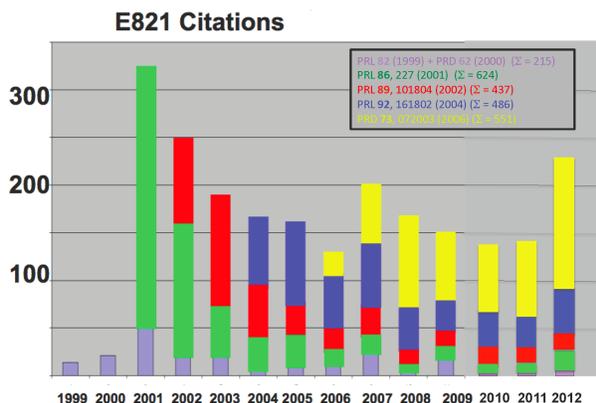


Figure 2.10: Citations by year to the E821 papers reporting physics results as of July 2012: light blue [19] plus [20]; green [21]; red [22]; blue [5]; and yellow the Physical Review article [2].

887 In this section, we discuss how the muon anomaly provides a unique window to search
 888 for physics beyond the standard model. If such new physics is discovered elsewhere, e.g.
 889 at the LHC, then a_μ will play an important role in sorting out the interpretation of those
 890 discoveries. We discuss examples of constraints placed on various models that have been
 891 proposed as extensions of the standard model. Perhaps the ultimate value of an improved
 892 limit on a_μ will come from its ability to constrain the models that have not yet been invented.

893 Varieties of physics beyond the Standard Model

894 The LHC era has had its first spectacular success in summer 2012 with the discovery of a
 895 new particle compatible with the standard model Higgs boson. With more data, the LHC
 896 experiments will continue to shed more light on the nature of electroweak symmetry breaking
 897 (EWSB). It is very likely that EWSB is related to new particles, new interactions, or maybe

898 to new concepts such as supersymmetry, extra dimensions, or compositeness. Further open
 899 questions in particle physics, related e.g. to the nature of dark matter, the origin of flavor or
 900 grand unification, indicate that at or even below the TeV scale there could be rich physics
 901 beyond the standard model.

902 Unravelling the existence and the properties of such new physics requires experimen-
 903 tal information complementary to the LHC. The muon ($g-2$), together with searches for
 904 charged lepton flavor violation, electric dipole moments, and rare decays, belongs to a class
 905 of complementary low-energy experiments.

906 In fact, the muon magnetic moment has a special role because it is sensitive to a large
 907 class of models related and unrelated to EWSB and because it combines several properties
 908 in a unique way: it is a flavour- and CP-conserving, chirality-flipping and loop-induced
 909 quantity. In contrast, many high-energy collider observables at the LHC and a future linear
 910 collider are chirality-conserving, and many other low-energy precision observables are CP-
 911 or flavour-violating. These unique properties might be the reason why the muon ($g-2$)
 912 is the only among the mentioned observables which shows a significant deviation between
 913 the experimental value and the SM prediction, see Eq. (2.27). Furthermore, while $g-2$ is
 914 sensitive to leptonic couplings, b - or K -physics more naturally probe the hadronic couplings
 915 of new physics. If charged lepton-flavor violation exists, observables such as $\mu \rightarrow e$ conversion
 916 can only determine a combination of the strength of lepton-flavor violation and the mass
 917 scale of new physics. In that case, $g-2$ can help to disentangle the nature of the new physics.

918 The role of $g-2$ as a discriminator between very different standard model extensions is
 919 well illustrated by a relation stressed by Czarnecki and Marciano [46]. It holds in a wide
 920 range of models as a result of the chirality-flipping nature of both $g-2$ and the muon mass:
 921 If a new physics model with a mass scale Λ contributes to the muon mass $\delta m_\mu(\text{N.P.})$, it also
 922 contributes to a_μ , and the two contributions are related as

$$a_\mu(\text{N.P.}) = \mathcal{O}(1) \times \left(\frac{m_\mu}{\Lambda}\right)^2 \times \left(\frac{\delta m_\mu(\text{N.P.})}{m_\mu}\right). \quad (2.28)$$

923 The ratio $C(\text{N.P.}) \equiv \delta m_\mu(\text{N.P.})/m_\mu$ cannot be larger than unity unless there is fine-
 924 tuning in the muon mass. Hence a first consequence of this relation is that new physics can
 925 explain the currently observed deviation (2.27) only if Λ is at the few-TeV scale or smaller.

926 In many models, the ratio C arises from one- or even two-loop diagrams, and is then
 927 suppressed by factors like $\alpha/4\pi$ or $(\alpha/4\pi)^2$. Hence, even for a given Λ , the contributions to
 928 a_μ are highly model dependent.

929 It is instructive to classify new physics models as follows:

- 930 • Models with $C(\text{N.P.}) \simeq 1$: Such models are of interest since the muon mass is essen-
 931 tially generated by radiative effects at some scale Λ . A variety of such models have
 932 been discussed in [46], including extended technicolor or generic models with naturally
 933 vanishing bare muon mass. For examples of radiative muon mass generation within
 934 supersymmetry, see e.g. [101, 102]. In these models the new physics contribution to a_μ
 935 can be very large,

$$a_\mu(\Lambda) \simeq \frac{m_\mu^2}{\Lambda^2} \simeq 1100 \times 10^{-11} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2. \quad (2.29)$$

and the difference Eq. (2.27) can be used to place a lower limit on the new physics mass scale, which is in the few TeV range [103, 102].

- Models with $C(\text{N.P.}) = \mathcal{O}(\alpha/4\pi)$: Such a loop suppression happens in many models with new weakly interacting particles like Z' or W' , little Higgs or certain extra dimension models. As examples, the contributions to a_μ in a model with $\delta = 1$ (or 2) universal extra dimensions (UED) [104] and the Littlest Higgs model with T-parity (LHT) [105] are given by

$$a_\mu(\text{UED}) \simeq -5.8 \times 10^{-11} (1 + 1.2\delta) S_{\text{KK}}, \quad (2.30)$$

$$a_\mu(\text{LHT}) < 12 \times 10^{-11} \quad (2.31)$$

with $|S_{\text{KK}}| \lesssim 1$ [104]. A difference as large as Eq. (2.27) is very hard to accommodate unless the mass scale is very small, of the order of M_Z , which however is often excluded e.g. by LEP measurements. So typically these models predict very small contributions to a_μ and will be disfavored if the current deviation will be confirmed by the new a_μ measurement.

Exceptions are provided by models where new particles interact with muons but are otherwise hidden from searches. An example is the model with a new gauge boson associated to a gauged lepton number $L_\mu - L_\tau$ [106], where a gauge boson mass of $\mathcal{O}(100 \text{ GeV})$ and large a_μ are viable.

- Models with intermediate values for $C(\text{N.P.})$ and mass scales around the weak scale: In such models, contributions to a_μ could be as large as Eq. (2.27) or even larger, or smaller, depending on the details of the model. This implies that a more precise a_μ -measurement will have significant impact on such models and can even be used to measure model parameters. Supersymmetric (SUSY) models are the best known examples, so muon $g-2$ would have substantial sensitivity to SUSY particles. Compared to generic perturbative models, supersymmetry provides an enhancement to $C(\text{SUSY}) = \mathcal{O}(\tan\beta \times \alpha/4\pi)$ and to $a_\mu(\text{SUSY})$ by a factor $\tan\beta$ (the ratio of the vacuum expectation values of the two Higgs fields). Typical SUSY diagrams for the magnetic dipole moment, the electric dipole moment, and the lepton-number violating conversion process $\mu \rightarrow e$ in the field of a nucleus are shown pictorially in Fig. 2.11. The shown diagrams contain the SUSY partners of the muon, electron and the SM $U(1)_Y$ gauge boson, $\tilde{\mu}$, \tilde{e} , \tilde{B} . The full SUSY contributions involve also the SUSY partners to the neutrinos and all SM gauge and Higgs bosons. In a model with SUSY masses equal to Λ the SUSY contribution to a_μ is given by [46]

$$a_\mu(\text{SUSY}) \simeq \text{sgn}(\mu) 130 \times 10^{-11} \tan\beta \left(\frac{100 \text{ GeV}}{\Lambda} \right)^2 \quad (2.32)$$

which indicates the dependence on $\tan\beta$, and the SUSY mass scale, as well as the sign of the SUSY μ -parameter. The formula still approximately applies even if only the smuon and chargino masses are of the order Λ but e.g. squarks and gluinos are much heavier. However the SUSY contributions to a_μ depend strongly on the details of mass splittings between the weakly interacting SUSY particles. Thus muon $g-2$ is sensitive

to SUSY models with SUSY masses in the few hundred GeV range, and it will help to measure SUSY parameters.

There are also non-supersymmetric models with similar enhancements. For instance, lepton flavor mixing can help. An example is provided in Ref. [107] by a model with two Higgs doublets and four generations, which can accommodate large Δa_μ without violating constraints on lepton flavor violation. In variants of Randall-Sundrum models [108, 109, 110] and large extra dimension models [111], large contributions to a_μ might be possible from exchange of Kaluza-Klein gravitons, but the theoretical evaluation is difficult because of cutoff dependences. A recent evaluation of the non-graviton contributions in Randall-Sundrum models, however, obtained a very small result [112].

Further examples include scenarios of unparticle physics [113, 114] (here a more precise a_μ -measurement would constrain the unparticle scale dimension and effective couplings), generic models with a hidden sector at the weak scale [115] or a model with the discrete flavor symmetry group T' and Higgs triplets [116] (here a more precise a_μ -measurement would constrain hidden sector/Higgs triplet masses and couplings), or the model proposed in Ref. [117], which implements the idea that neutrino masses, leptogenesis and the deviation in a_μ all originate from dark matter particles. In the latter model, new leptons and scalar particles are predicted, and a_μ provides significant constraints on the masses and Yukawa couplings of the new particles.

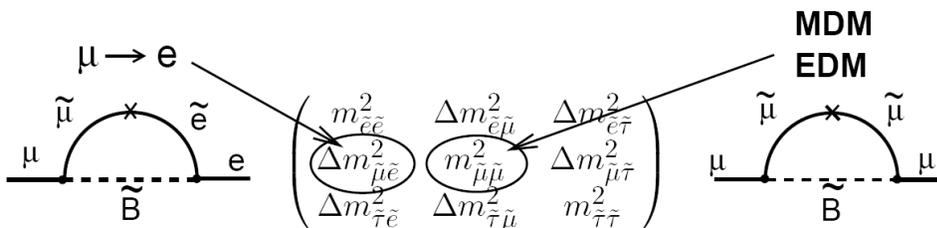


Figure 2.11: The SUSY contributions to the anomaly, and to $\mu \rightarrow e$ conversion, showing the relevant slepton mixing matrix elements. The MDM and EDM give the real and imaginary parts of the matrix element, respectively. The \times indicates a chirality flip.

The following types of new physics scenarios are quite different from the ones above:

- Models with extended Higgs sector but without the $\tan \beta$ -enhancement of SUSY models. Among these models are the usual two-Higgs-doublet models. The one-loop contribution of the extra Higgs states to a_μ is suppressed by two additional powers of the muon Yukawa coupling, corresponding to $a_\mu(\text{N.P.}) \propto m_\mu^4/\Lambda^4$ at the one-loop level. Two-loop effects from Barr-Zee diagrams can be larger [118], but typically the contributions to a_μ are negligible in these models.
- Models with additional light particles with masses below the GeV-scale, generically called dark sector models: Examples are provided by the models of Refs. [119, 120], where additional light neutral gauge bosons can affect electromagnetic interactions. Such models are intriguing since they completely decouple $g-2$ from the physics of

1002 EWSB, and since they are hidden from collider searches at LEP or LHC (see however
 1003 Refs. [121, 122] for studies of possible effects at dedicated low-energy colliders and in
 1004 Higgs decays at the LHC). They can lead to contributions to a_μ which are of the same
 1005 order as the deviation in Eq. (2.27). Hence the new $g-2$ measurement will provide an
 1006 important test of such models.

1007 To summarize: many well-motivated models can accommodate larger contributions to a_μ
 1008 — if any of these are realized $g-2$ can be used to constrain model parameters; many well-
 1009 motivated new physics models give tiny contributions to a_μ and would be disfavored if the
 1010 more precise $g-2$ measurement confirms the deviation in Eq. (2.27). There are also examples
 1011 of models which lead to similar LHC signatures but which can be distinguished using $g-2$.

1012 In the following it is discussed in more detail how a_μ will be useful in understanding
 1013 TeV-scale physics in the event that the LHC established the existence of physics beyond the
 1014 standard model [99].

1015 a_μ and supersymmetry

1016 We first focus on the case of supersymmetry, which provides a particularly well-defined and
 1017 calculable framework. We illustrate the sensitivity of $g-2$ to the SUSY parameters and the
 1018 complementarity to LHC measurements.

1019 As discussed above, supersymmetry with $\tan\beta$ up to 50 and masses in the 100–700 GeV
 1020 range can easily explain the currently observed deviation (2.27). Now the SUSY contributions
 1021 are discussed in more detail. At the one-loop level, the diagrams of the minimal supersym-
 1022 metric standard model (MSSM) involve the SUSY partners the gauge and Higgs bosons and
 1023 the muon-neutrino and the muon, the so-called charginos, neutralinos and sneutrinos and
 1024 smuons. The relevant parameters are thus the SUSY breaking mass parameters for the 2nd
 1025 generation sleptons, the bino and wino masses M_2 , M_1 , and the Higgsino mass parameter μ .
 1026 Strongly interacting particles, squarks and gluinos, and their masses are irrelevant on this
 1027 level.

1028 If all the relevant mass parameters are equal, the approximation (2.32) is valid, and the
 1029 dominant contribution is from the chargino–sneutrino diagrams. If μ is very large, the bino-
 1030 like neutralino contribution of Fig. 2.11 is approximately linear in μ and can dominate. If
 1031 there is a large mass splitting between the left- and right-handed smuon, even the sign can
 1032 be opposite to Eq. (2.32), see the discussions in [123, 124].

1033 As a result, $a_\mu(\text{SUSY})$ depends not only on the overall SUSY masses but on the indi-
 1034 vidual values of the parameters M_1 , M_2 , and μ . Exchanging these parameters can leave the
 1035 spectrum of SUSY particle masses unchanged but will have an effect on a_μ^{SUSY} . It is shown
 1036 later that this will help to disentangle different possible interpretations of LHC data.

1037 On the two-loop level, further contributions exist which are typically subleading but can
 1038 become important in regions of parameter space. For instance, there are diagrams without
 1039 smuons or sneutrinos but with e.g. a pure chargino or stop loop [125]. Such diagrams can
 1040 even be dominant if first and second generation sfermions are very heavy, a scenario called
 1041 effective SUSY [126].

1042 To date, the LHC experiments have not found indications for SUSY particles but only
 1043 for a Higgs-like particle with mass around 126 GeV. This leads to the following conclusions:

- 1044 • If supersymmetry is the origin of the deviation in a_μ , at least some SUSY particles
1045 cannot be much heavier than around 700 GeV (for $\tan\beta = 50$), most favorably the
1046 smuons and charginos/neutralinos.

- 1047 • The negative results of the LHC searches for SUSY particles imply lower limits of
1048 around 1 TeV, in particular on squark and gluino masses. The bounds are not model-
1049 independent but valid in scenarios with particular squark and gluino decay patterns.

- 1050 • The constraint that a SM-like Higgs boson mass is around 126 GeV requires either very
1051 large loop corrections from large logarithms or non-minimal tree-level contributions
1052 from additional non-minimal particle content.

- 1053 • The requirement of small fine-tuning between supersymmetry-breaking parameters and
1054 the Z-boson mass prefers certain particles, in particular stops, gluinos and Higgsinos
1055 to be rather light.

1056 A tension between these constraints seems to be building up, but the constraints act on
1057 different aspects of SUSY models. Hence it is in principle no problem to accommodate
1058 all the experimental data in the general minimal supersymmetric standard model, for most
1059 recent analyses see Refs. [127, 128].

1060 However, strongly restricted models, such as the Constrained MSSM (CMSSM) cannot
1061 anymore simultaneously explain all data. For a long time, many analyses have used a_μ as
1062 a central observable to constrain the CMSSM parameters, see e.g. [129]. The most recent
1063 analyses show that the LHC determination of the Higgs boson mass turns out to be incom-
1064 patible with an explanation of the current Δa_μ within the CMSSM [130, 131, 132]. Hence,
1065 the CMSSM is already disfavored now, and it will be excluded if the future a_μ measurement
1066 confirms the current Δa_μ .

1067 The issue of fine-tuning has led to many proposals for SUSY models in which some or all
1068 of the experimental constraints are satisfied in a technically natural way. For instance, the
1069 model of Ref. [133] is based on gauge-mediated SUSY breaking and extra vector-like matter,
1070 and it is naturally in agreement with FCNC constraints and the Higgs boson mass value. But
1071 if the SUSY particles are light enough to explain $g-2$, it is on the verge of being excluded by
1072 LHC data. Conversely, the so-called natural SUSY scenarios (see e.g. [134, 135]), where the
1073 spectrum is such that fine-tuning is minimized while squarks and gluinos evade LHC bounds,
1074 can explain the Higgs boson mass but completely fail to explain $g-2$. Similarly so-called
1075 compressed supersymmetry [136] can be a natural explanation of the Higgs mass and the
1076 negative LHC SUSY searches but, at least in the version of Ref. [137] fails to accommodate
1077 a large Δa_μ .

1078 These considerations show that a definitive knowledge of a_μ^{SUSY} will be very beneficial for
1079 the interpretation of LHC data in terms of SUSY.

1080 In the general model classification of the previous subsection the possibility of radiative
1081 muon mass generation was mentioned. This idea can be realized within supersymmetry, and
1082 it leads to SUSY scenarios quite different from the ones discussed so far. Since the muon mass
1083 at tree level is given by the product of a Yukawa coupling and the vacuum expectation value
1084 of the Higgs doublet H_d , there are two kinds of such scenarios. First, one can postulate that

1085 the muon Yukawa coupling is zero but chiral invariance is broken by soft supersymmetry-
 1086 breaking A -terms. Then, the muon mass, and a_μ^{SUSY} , arise at the one-loop level and there is
 1087 no relative loop suppression of a_μ^{SUSY} [101, 102]. Second, one can postulate that the vacuum
 1088 expectation value $\langle H_d \rangle$ is very small or zero [138, 139]. Then, the muon mass and a_μ^{SUSY}
 1089 arise at the one-loop level from loop-induced couplings to the other Higgs doublet. Both
 1090 scenarios could accommodate large a_μ^{SUSY} and TeV-scale SUSY particle masses.

1091 a_μ and model selection and parameter measurement

1092 The LHC is sensitive to virtually all proposed weak-scale extensions of the standard model,
 1093 ranging from supersymmetry, extra dimensions and technicolor to little Higgs models, un-
 1094 particle physics, hidden sector models and others. However, even if the existence of physics
 1095 beyond the standard model is established, it will be far from easy for the LHC alone to
 1096 identify which of these — or not yet thought of — alternatives is realized. Typically LHC
 1097 data will be consistent with several alternative models.

1098 For example, a situation is possible where the LHC finds many new heavy particles
 1099 which are compatible with supersymmetry. Since spin measurements are difficult, these
 1100 new states might allow alternative interpretations in terms of other models. In particular
 1101 universal-extra-dimension models (UED) [140], or the Littlest Higgs model with T-parity
 1102 (LHT) [141, 142] have been called “bosonic SUSY” since they can mimick SUSY but the
 1103 partner particles have the opposite spin as the SUSY particles, see e.g. [143]. The muon $g-2$
 1104 would especially aid in the selection since UED or Littlest Higgs models predict a tiny effect
 1105 to a_μ [104, 105], while SUSY effects are usually much larger.

1106 On the other hand, a situation where the LHC finds no physics beyond the standard model
 1107 but the a_μ measurement establishes a deviation, might be a signal for dark sector models
 1108 such as the secluded U(1) model [119], with new very weakly interacting light particles which
 1109 are hard to identify at the LHC [121, 120, 122].

1110 Next, if new physics is realized in the form of a non-renormalizable theory, a_μ might not
 1111 be fully computable but depend on the ultraviolet cutoff. Randall-Sundrum or universal
 1112 extra dimension models are examples of this situation. In such a case, the a_μ measurement
 1113 will not only help to constrain model parameters but it will also help to get information on
 1114 the ultraviolet completion of the theory.

1115 Within the framework of SUSY there are many different well-motivated scenarios that
 1116 are not always easy to distinguish at the LHC. Fig. 2.12 illustrates this.

1117 The left plot in Fig. 2.12 shows the values for the so-called SPS benchmark points [147].
 1118 These span a wide range and can be positive or negative, due to the factor $\text{sign}(\mu)$ in
 1119 Eq. (2.32). The discriminating power of the current (yellow band) and an improved (blue
 1120 band) measurement is evident from Fig. 2.12(a).

1121 One might think that if SUSY exists, the LHC-experiments will find it and measure its
 1122 parameters. Above it has been mentioned that SUSY can be mimicked by “bosonic SUSY”
 1123 models. The green points illustrate that even within SUSY, certain SUSY parameter points
 1124 can be mimicked by others. The green points correspond to “degenerate solutions” of Ref.
 1125 [144] — different SUSY parameter points which cannot be distinguished at the LHC alone
 1126 (see also Ref. [145] for the LHC inverse problem). They have very different a_μ predictions,
 1127 and hence a_μ can resolve such LHC degeneracies.

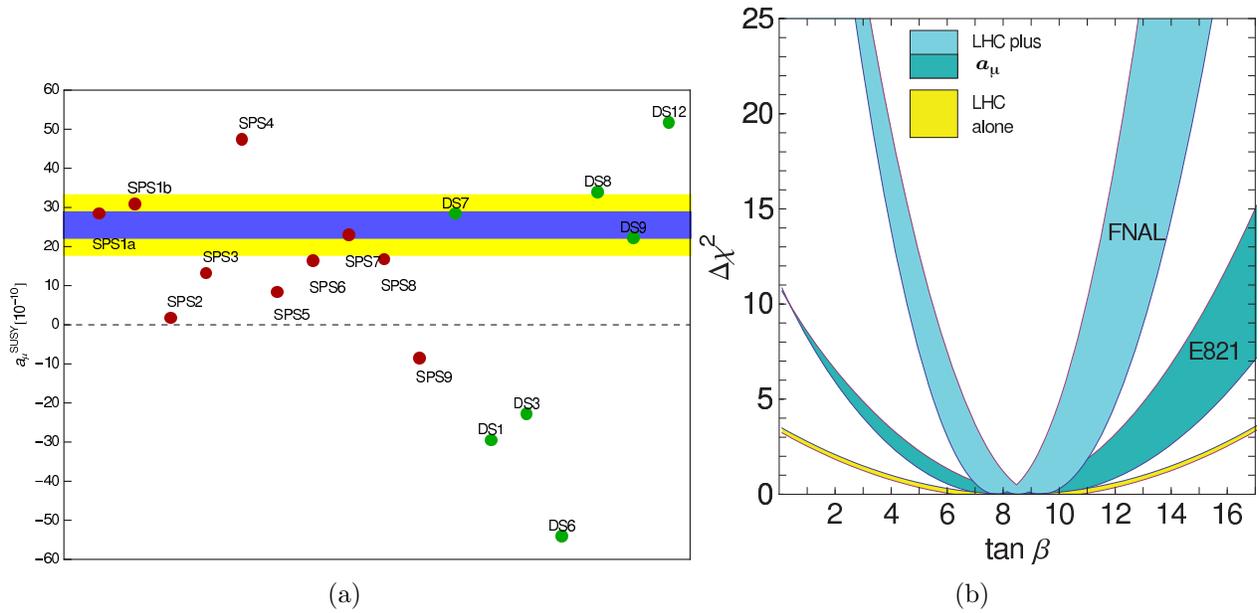


Figure 2.12: (a) SUSY contributions to a_μ for the SPS benchmark points (red), and for the “degenerate solutions” from Ref. [144]. The yellow band is the $\pm 1\sigma$ error from E821, the blue is the projected sensitivity of E989. (b) Possible future $\tan\beta$ determination assuming that a slightly modified MSSM point SPS1a (see text) is realized. The bands show the $\Delta\chi^2$ parabolas from LHC-data alone (yellow) [146], including the a_μ with current precision (dark blue) and with prospective precision (light blue). The width of the blue curves results from the expected LHC-uncertainty of the parameters (mainly smuon and chargino masses) [146].

1128 In a similar spirit, Ref. [148] discussed “supersymmetry without prejudice.” First a large
 1129 set of supersymmetry parameter points (“models”) in a 19-dimensional parameter space
 1130 was identified, which was in agreement with many important existing experimental and
 1131 theoretical constraints. Then the implications for observables such as $g-2$ were studied.
 1132 The result for $g-2$ was rather similar to Fig. 2.12(a), although the context was far more
 1133 general: the entire range $a_\mu^{\text{SUSY}} \sim (-100 \dots + 300) \times 10^{-11}$ was populated by a reasonable
 1134 number of “models.” Therefore, a precise measurement of $g-2$ to $\pm 16 \times 10^{-11}$ will be a
 1135 crucial way to rule out a large fraction of models and thus determine SUSY parameters.

1136 The right plot of Fig. 2.12 illustrates that the SUSY parameter $\tan\beta$ can be measured
 1137 more precisely by combining LHC-data with a_μ . It is based on the assumption that SUSY
 1138 is realized, found at the LHC and the origin of the observed a_μ deviation (2.27). To fix
 1139 an example, we use a slightly modified SPS1a benchmark point with $\tan\beta$ scaled down to
 1140 $\tan\beta = 8.5$ such that a_μ^{SUSY} is equal to an assumed deviation $\Delta a_\mu = 255 \times 10^{-11}$.⁵ Ref.
 1141 [146] has shown that then mass measurements at the LHC alone are sufficient to determine
 1142 $\tan\beta$ to a precision of ± 4.5 only. The corresponding $\Delta\chi^2$ parabola is shown in yellow in the
 1143 plot. In such a situation one can study the SUSY prediction for a_μ as a function of $\tan\beta$
 1144 (all other parameters are known from the global fit to LHC data) and compare it to the
 1145 measured value, in particular after an improved measurement. The plot compares the LHC
 1146 $\Delta\chi^2$ parabola with the ones obtained from including a_μ , $\Delta\chi^2 = [(a_\mu^{\text{SUSY}}(\tan\beta) - \Delta a_\mu)/\delta a_\mu]^2$
 1147 with the errors $\delta a_\mu = 80 \times 10^{-11}$ (dark blue) and 34×10^{-11} (light blue). As can be seen
 1148 from the Figure, using today’s precision for a_μ would already improve the determination of
 1149 $\tan\beta$, but the improvement will be even more impressive after the future a_μ measurement.

1150 One should note that even if better ways to determine $\tan\beta$ at the LHC alone might
 1151 be found, an independent determination using a_μ will still be highly valuable, as $\tan\beta$ is
 1152 one of the central MSSM parameters; it appears in all sectors and in almost all observables.
 1153 In non-minimal SUSY models the relation between $\tan\beta$ and different observables can be
 1154 modified. Therefore, measuring $\tan\beta$ in different ways, e.g. using certain Higgs- or b -decays
 1155 at the LHC or at b -factories and using a_μ , would constitute a non-trivial and indispensable
 1156 test of the universality of $\tan\beta$ and thus of the structure of the MSSM.

1157 The anomalous magnetic moment of the muon is sensitive to contributions from a wide
 1158 range of physics beyond the standard model. It will continue to place stringent restrictions
 1159 on all of the models, both present and yet to be written down. If physics beyond the standard
 1160 model is discovered at the LHC or other experiments, a_μ will constitute an indispensable
 1161 tool to discriminate between very different types of new physics, especially since it is highly
 1162 sensitive to parameters which are difficult to measure at the LHC. If no new phenomena
 1163 are found elsewhere, then it represents one of the few ways to probe physics beyond the
 1164 standard model. In either case, it will play an essential and complementary role in the quest
 1165 to understand physics beyond the standard model at the TeV scale.

⁵The actual SPS1a point is ruled out by LHC, however for our purposes only the weakly interacting particles are relevant, and these are not excluded. The following conclusions are neither very sensitive to the actual $\tan\beta$ value nor to the actual value of the deviation Δa_μ .

References

- 1166
- 1167 [1] O. Stern, Z. Phys. **7**, 249 (1921);
- 1168 [2] W. Gerlach and O. Stern, Z. Phys. **8**, 110 (1922); Z. Phys. **9** and 349(1922), Z. Phys.
1169 **9**, 353 (1924); W. Gerlach and O. Stern, Ann. Phys. **74**, 673 (1924).
- 1170 [3] G.E. Uhlenbeck and S. Goudsmit, Naturwissenschaften **47**, 953 (1925); G.E. Uhlenbeck
1171 and S. Goudsmit, Nature **117** (1926) 264.
- 1172 [4] E. Schrödinger, Ann. Phys. **79** (1926) 361.
- 1173 [5] L.H. Thomas, Nature **117**, (1926) 514 and Phil. Mag. **3** (1927) 1.
- 1174 [6] T.E. Phipps and J.B. Taylor, Phys. Rev. **29**, 309 (1927).
- 1175 [7] P.A.M. Dirac, Proc. R. Soc. (London) **A117**, 610 (1928), and **A118**, 351 (1928). See
1176 also, P.A.M. Dirac, *The Principles of Quantum Mechanics*, 4th edition, Oxford Univer-
1177 sity Press, London, 1958.
- 1178 [8] Sin-itiro Tomonaga, *The Story of Spin*, translated by Takeshi Oka, U. Chicago Press,
1179 1997.
- 1180 [9] R. Frisch and O. Stern, Z. Phys. **85**, 4 (1933), and I. Estermann and O. Stern, Z. Phys.
1181 **85**, 17 (1933).
- 1182 [10] Luis W. Alvarez and F. Bloch, Phys. Rev. **57**, 111 (1940).
- 1183 [11] J.E. Nafe, E.B. Nelson and I.I. Rabi Phys. Rev. **71**, 914(1947).
- 1184 [12] D.E. Nagel, R.S. Julian and J.R. Zacharias, Phys. Rev. **72**, 971 (1947).
- 1185 [13] P. Kusch and H.M Foley, Phys. Rev **72**, 1256 (1947).
- 1186 [14] J. Schwinger, Phys. Rev. **73**, 416L (1948), and Phys. Rev. **76** 790 (1949). The former
1187 paper contains a misprint in the expression for a_e that is corrected in the longer paper.
- 1188 [15] Hans A. Bethe and Edwin E. Salpeter, *Quantum Mechanics of One- and Two-Electron*
1189 *Atoms*, Springer-Verlag, (1957), p. 51.
- 1190 [16] See Figure 5 in Paul Kunze, Z. Phys. **83**, 1 (1933).

- 1191 [17] Carl D. Anderson and Seth H. Neddermeyer, Phys. Rev. **50** (1936) 263, and Seth H.
1192 Neddermeyer and Carl D. Anderson, Phys. Rev. **51** (1937) 844.
- 1193 [18] J.C. Street, E.C. Stevenson, Phys. Rev. **52** (1937) 1003.
- 1194 [19] Y. Nishina, M. Tekeuchi and T. Ichimiya, Phys. Rev. **52** (1937) 1198.
- 1195 [20] M.M. Jean Crussard and L. Leprince-Ringuet, Compt. Rend. **204** (1937) 240.
- 1196 [21] Garwin RL, Lederman LM, Weinrich M, Phys. Rev. 105:1415 (1957)
- 1197 [22] J.I. Friedman and V.L. Telegdi, Phys. Rev. **105**, 1681 (1957).
- 1198 [23] E.J. Konopinski, Ann. Rev. Nucl. Sci. **9** 99, (1959).
- 1199 [24] Garwin RL, Hutchinson DP, Penman S, Shapiro G, Phys. Rev. 118:271 (1960)
- 1200 [25] Charpak G, et al. Phys. Rev. Lett. 6:28 (1961), Nuovo Cimento. 22:1043 (1961), Phys.
1201 Lett. 1:16 (1962), Nuovo Cimento. 37:1241 (1965) and Charpak G. et al. Phys. Lett.
1202 1:16 (1962)
- 1203 [26] Bailey J, et al. Phys. Lett. 28B:287 (1968). Additional details can be found in Bailey J,
1204 et al. Nuovo Cimento. A9:369 (1972) and references therein.
- 1205 [27] Bailey J, et al. Nucl. Phys. B150:1 (1979)
- 1206 [28] E.M. Purcell and N.F. Ramsey, Phys. Rev. **78**, 807 (1950).
- 1207 [29] T.D. Lee and C.N. Yang, Phys. Rev. **104** (1956) 254.
- 1208 [30] J.H. Smith, E.M. Purcell and N.F. Ramsey, Phys. Rev. **108**, 120 (1957).
- 1209 [31] L. Landau, Nucl. Phys. **3**, 127 (1957).
- 1210 [32] N.F. Ramsey Phys. Rev. **109**, 225 (1958).
- 1211 [33] W.C. Griffith, et al., Phys. Rev. Lett. **102**, 101601 (2009).
- 1212 [34] C.A. Baker, et al., Phys. Rev. Lett. **97**, 131801 (2006).
- 1213 [35] J.J. Hudson, et al., Nature **473**, 493 (2011).
- 1214 [36] G.W. Bennett, et al., Phys. Rev. **D 80**, 052008 (2009).
- 1215 [37] Bargmann V, Michel L, Telegdi VL, Phys. Rev. Lett. 2:435 (1959)
- 1216 [38] Bennett GW, et al. (The $g - 2$ Collab.) Phys. Rev. Lett. 92:161802 (2004)
- 1217 [39] Bennett GW, et al.(The $g - 2$ Collab.) Phys. Rev. D, 73:072003 (2006)
- 1218 [40] C.S. Wu, E. Ambler, R.W. Hayward, D.D. Hoppes, R.P. Hudson, Phys. Rev. **105**, 1413
1219 (1957).

- 1220 [41] Mohr PJ, Taylor BN, Newell DB, (CODATA recommended values). *Rev. Mod. Phys.*
1221 80:633 (2008)
- 1222 [42] R. Prigl, *et al.*, Nucl. Inst. Methods Phys. Res. **A374** 118 (1996).
- 1223 [43] W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999).
- 1224 [44] Topical Workshop on The Muon Magnetic Dipole Moment; Oct. 2007
1225 School of Physics and Astronomy, The University of Glasgow. See:
1226 www.ippp.dur.ac.uk/old/MuonMDM/.
- 1227 [45] T. Kinoshita and W.J. Marciano in *Quantum Electrodynamics* (Directions in High En-
1228 ergy Physics, Vol. 7), ed. T. Kinoshita, (World Scientific, Singapore, 1990), p. 419.
- 1229 [46] Andrzej Czarnecki and William J. Marciano, Phys. Rev. **D64** 013014 (2001).
- 1230 [47] Davier M, *et al.* M. Davier¹, A. Hoecker^{2,a}, B. Malaescu^{1,b}, Z. Zhang¹ Eur. Phys. J. C
1231 71:1515 (2011), erratum Eur. Phys. J. C 72:1874 (2012).
- 1232 [48] Koru Hagiwara, Ruofan Liao, Alan D. Martin, Daisuke Nomura and Thomas Teubner,
1233 J. Phys. **G38**, 085003 (2011).
- 1234 [49] Xu Feng, Karl Jansen, Marcus Perschlies and Dru B. Renner, Phys. Rev. Lett. 107
1235 081802 (2011).
- 1236 [50] A. Czarnecki, B. Krause and W.J. Marciano, Phys. Rev. Lett. **76** (1996) 3267.
- 1237 [51] S. Peris, M. Perrottet and E. de Rafael, Phys. Lett. **B355** (1995) 523.
- 1238 [52] A. Czarnecki, B. Krause and W. Marciano, Phys. Rev. **D52** (1995) R2619.
- 1239 [53] A. Czarnecki, W.J. Marciano and A. Vainshtein, Phys. Rev. **D67** (2003) 073006.
1240 A. Czarnecki, W.J. Marciano and A. Vainshtein, Phys. Rev. **D67** (2003) 073006.
- 1241 [54] James P. Miller, Eduardo de Rafael and B. Lee Roberts, Rept. Prog. Phys. **70**, 795-881,
1242 2007.
- 1243 [55] W.J. Marciano pointed out at the Intensity Frontier Workshop, Argonne, Nat. Lab.
1244 April 2013, that the Higgs' mass measurement from CERN increased the weak contri-
1245 bution by 1×10^{-11} . <https://indico.fnal.gov/conferenceDisplay.py?confId=6248>
- 1246 [56] Andrzej Czarnecki and William J. Marciano in *Lepton Dipole Moments*, ed. B. Lee
1247 Roberts and William J. Marciano, Advanced Series on Directions in High Energy
1248 Physics, Vol. 20, World Scientific, 2010 p. 11 and references therein.
- 1249 [57] Miller JP, Roberts BL, Jungmann K. *Lepton Dipole Moments*, ed Roberts BL, Marciano
1250 WJ, p.333. World Scientific (2010)
- 1251 [58] Prades J, Rafael E. de, Vainshtein A. *Lepton Dipole Moments*, ed Roberts BL, Marciano
1252 WJ, World Scientific (2010), p.303; and arXiv:0901.0306v1 [hep-ph].

- 1253 [59] <http://www.int.washington.edu/PROGRAMS/11-47w/>
- 1254 [60] Stöckinger D. *Lepton Dipole Moments*, ed Roberts BL, Marciano WJ, p.393. World
1255 Scientific (2010)
- 1256 *J. Phys. G* **34**:R45 (2007)
- 1257 [61] Eduardo de Rafael, private communication.
- 1258 [62] G. Amelino-Camelia, et al., (KLOE-2 Collaboration) arXiv:1003.3868v1 [hep-ex] March
1259 2010.
- 1260 [63] Tobias Goecke, Christian S. Fischer, Richard Williams Phys. Rev. **D83**, 094006 (2011).
- 1261 [64] C. Fischer, private communication, October 2012.
- 1262 [65] . Tom Blum, The 12th International Workshop on Tau Lepton Physics, 17-21 September
1263 2012, Nagoya University.
- 1264 [66] Tatsumi Aoyama, Masashi Hayakawa, Toichiro Kinoshita, Makiko Nio. May 2012. May
1265 2012, arXiv:1205.5370 [hep-ph], Phys. Rev. Lett. **109**, 111808 (2012).
- 1266 [67] D. Hanneke, S. Fogwell and G. Gabrielse, Phys. Rev. Lett. **100**, 120801 (2008).
- 1267 [68] rTatsumi Aoyama, Masashi Hayakawa, Toichiro Kinoshita, Makiko Nio. May 2012, e-
1268 Print: arXiv:1205.5368 [hep-ph], Phys. Rev. Lett. **109**, 111807 (2012).
- 1269 [69] R. Bouchendir, P. Clade, S. Guellati-Khelifa, F. Nez, and F. Biraben, Phys. Rev. Lett.
1270 **106**, 080801 (2011).
- 1271 [70] A. Höcker and W.J. Marciano, Particle Data Group, Review *THE MUON ANOMA-*
1272 *LOUS MAGNETIC MOMENT* Updated July 2009, <http://pdg.lbl.gov/>
- 1273 [71] M. Passera, W.J. Marciano and A. Sirlin, Phys. Rev. **D 78**, 013009 (2008).
- 1274 [72] K. Hagiwara, A.D. Martin, D. Nomura and T. Teubner, Phys. Lett. **B649** 173 (2007).
- 1275 [73] M. Davier, hep-ph/0701163v2, Jan. 2007.
- 1276 [74] Fred Jegerlehner and Andreas Nyffeler, Phys.Rept. **477** 1 ((2009)
- 1277 [75] James P. Miller, Eduardo de Rafael, B. Lee Roberts and Dominik Stöckinger, Ann. Rev.
1278 Nucl. Part. Sci. **62**, 237 (2012).
- 1279 [76] R. Alemany, M. Davier and A. Höcker, Eur.Phys.J. **C2** 123 (1998).
- 1280 [77] Fred Jegerlehner, Robert Szafron, Eur.Phys.J. **C71** (2011) 1632.
- 1281 [78] M. Benayoun, P. David, L. DelBuono, F. Jegerlehner, Eur. Phys. J. **C72** (2012) 1848.
- 1282 [79] M. Benayoun, P. David, L. DelBuono, F. Jegerlehner, arXiv:1210.7184v2 [hep-ph] 9 Nov
1283 2012.

- 1284 [80] M. Davier and A. Höcker, Phys. Lett. **B435**, 427 (1998).
- 1285 [81] S. Binner, J.H. Kühn and K. Melnikov, Phys. Lett. **B 459**, 279 (1999).
- 1286 [82] S. Actis, et al., (Working Group on Radiative Corrections and Monte Carlo Generators
1287 for Low Energies), arXiv0912.0749, Dec. 2009, submitted to Eur. Phys. J. **C**.
- 1288 [83] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 103:231801 (2009).
- 1289 [84] <http://tau08.inp.nsk.su/> ; <http://www.hep.manchester.ac.uk/TAU2010> ;
1290 <http://tau2012.hepl.phys.nagoya-u.ac.jp/>
- 1291 [85] <http://phipsi11.inp.nsk.su/>
- 1292 [86] F. Ambrosino et al., (KLOE Collaboration), Phys. Lett. **B 670**, 285 (2009).
- 1293 [87] F. Ambrosino et al., (KLOE Collaboration), Phys. Lett. **B 700**, 102 (2011).
- 1294 [88] Giuseppe Mandaglio, The 12th International Workshop on Tau Lepton Physics, 17-21
1295 September 2012, Nagoya University.
- 1296 [89] Jason Crnkovic, The 12th International Workshop on Tau Lepton Physics, 17-21
1297 September 2012, Nagoya University.
- 1298 [90] G. Venanzoni, Frascati Phys. Ser. **54** (2012) 52 [arXiv:1203.1501 [hep-ex]].
- 1299 [91] D. Babusci, C. Bini, F. Bossi, G. Isidori, D. Moricciani, F. Nguyen, P. Raimondi and
1300 G. Venanzoni *et al.*, collider upgraded in energy,” arXiv:1007.5219 [hep-ex].
- 1301 [92] D. Babusci *et al.* [KLOE Collaboration], Phys. Lett. **B 720** (2013) 336.
- 1302 [93] D. Babusci, H. Czyz, F. Gonnella, S. Ivashyn, M. Mascolo, R. Messi, D. Moricciani
1303 and A. Nyffeler *et al.*, width and the $\gamma^* \gamma_{to} \pi^0$ transition form factor with the KLOE-2
1304 experiment,” Eur. Phys. J. **C 72** (2012) 1917.
- 1305 [94] T. Blum, Phys. Rev. Lett. **91**, 052001-1 (2003).
- 1306 [95] T. Blum, Nucl. Phys. Proc. Suppl. **129**, 904-906, 2004, and arXiv hep-lat/0310064,
- 1307 [96] T. Blum, private communication, February 2012.
- 1308 [97] M. Davier and W.J. Marciano, Ann. Rev. Nucl. Part. Phys. **54**, 115 (2004).
- 1309 [98] J. P. Miller, E. de Rafael, B. L. Roberts, and D. Stöckinger, Ann. Rev. Nucl. Part.
1310 Science **62** (2012) 237-264.
- 1311 [99] D. W. Hertzog, J. P. Miller, E. de Rafael, B. Lee Roberts and D. Stöckinger,
1312 arXiv:0705.4617 [hep-ph].
- 1313 [100] The articles listed in the SPIRES citations to Ref. [21] contain many different models
1314 beyond the standard model.

- 1315 [101] F. Borzumati, G. R. Farrar, N. Polonsky and S. D. Thomas, Nucl. Phys. B **555** (1999)
1316 53 [hep-ph/9902443].
- 1317 [102] A. Crivellin, J. Girrbach and U. Nierste, Phys. Rev. D **83** (2011) 055009
1318 [arXiv:1010.4485 [hep-ph]].
- 1319 [103] E. Eichten, et al., Phys. Rev. Lett. **45**, 225 (1980); K. Lane, arXiv [hep-ph/0102131].
- 1320 [104] T. Appelquist and B. A. Dobrescu, Phys. Lett. B **516** (2001) 85 [arXiv:hep-
1321 ph/0106140].
- 1322 [105] M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP **0705**
1323 (2007) 013 [arXiv:hep-ph/0702136].
- 1324 [106] S. Baek, N. G. Deshpande, X. G. He and P. Ko, Phys. Rev. D **64**, 055006 (2001)
1325 [hep-ph/0104141]; E. Ma, D. P. Roy and S. Roy, Phys. Lett. B **525** (2002) 101
1326 [hep-ph/0110146]; J. Heeck and W. Rodejohann, Phys. Rev. D **84** (2011) 075007
1327 [arXiv:1107.5238 [hep-ph]].
- 1328 [107] S. Bar-Shalom, S. Nandi and A. Soni, Phys. Lett. B **709**, 207 (2012) [arXiv:1112.3661
1329 [hep-ph]].
- 1330 [108] H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Lett. B **493** (2000) 135 [arXiv:hep-
1331 ph/0006097].
- 1332 [109] S. C. Park and H. S. Song, Phys. Lett. B **506** (2001) 99 [arXiv:hep-ph/0103072].
- 1333 [110] C. S. Kim, J. D. Kim and J. H. Song, Phys. Lett. B **511** (2001) 251 [arXiv:hep-
1334 ph/0103127].
- 1335 [111] M. L. Graesser, Phys. Rev. D **61** (2000) 074019 [arXiv:hep-ph/9902310].
- 1336 [112] M. Beneke, P. Dey and J. Rohrwild, arXiv:1209.5897 [hep-ph].
- 1337 [113] K. Cheung, W. Y. Keung and T. C. Yuan, Phys. Rev. Lett. **99** (2007) 051803
1338 [arXiv:0704.2588 [hep-ph]].
- 1339 [114] J. A. Conley and J. S. Gainer, arXiv:0811.4168 [hep-ph].
- 1340 [115] D. McKeen, arXiv:0912.1076 [hep-ph].
- 1341 [116] C. M. Ho and T. W. Kephart, Phys. Lett. B **687**, 201 (2010) [arXiv:1001.3696 [hep-
1342 ph]].
- 1343 [117] T. Hambye, K. Kannike, E. Ma and M. Raidal, Phys. Rev. D **75** (2007) 095003
1344 [arXiv:hep-ph/0609228].
- 1345 [118] M. Krawczyk, Acta Phys. Polon. B **33**, 2621 (2002) [hep-ph/0208076].
- 1346 [119] M. Pospelov, Phys. Rev. D **80** (2009) 095002 [arXiv:0811.1030 [hep-ph]].

- 1347 [120] H. Davoudiasl, H. -S. Lee and W. J. Marciano, Phys. Rev. Lett. **109**, 031802 (2012)
1348 [arXiv:1205.2709 [hep-ph]].
- 1349 [121] R. Essig, P. Schuster and N. Toro, Phys. Rev. D **80** (2009) 015003 [arXiv:0903.3941
1350 [hep-ph]].
- 1351 [122] H. Davoudiasl, H. -S. Lee and W. J. Marciano, Phys. Rev. D **86**, 095009 (2012)
1352 [arXiv:1208.2973 [hep-ph]].
- 1353 [123] T. Moroi, Phys. Rev. D **53** (1996) 6565 [Erratum-ibid. **56** (1997) 4424].
- 1354 [124] D. Stöckinger, J. Phys. G **34** (2007) R45 [arXiv:hep-ph/0609168].
- 1355 [125] S. Heinemeyer, D. Stöckinger and G. Weiglein, Nucl. Phys. B **690** (2004) 62 [arXiv:hep-
1356 ph/0312264]; S. Heinemeyer, D. Stöckinger and G. Weiglein, Nucl. Phys. B **699** (2004)
1357 103 [arXiv:hep-ph/0405255].
- 1358 [126] A. Arhrib and S. Baek, Phys. Rev. D **65**, 075002 (2002) [hep-ph/0104225].
- 1359 [127] R. Benbrik, M. Gomez Bock, S. Heinemeyer, O. Stal, G. Weiglein and L. Zeune, Eur.
1360 Phys. J. C **72**, 2171 (2012) [arXiv:1207.1096 [hep-ph]].
- 1361 [128] A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, JHEP **1209**, 107 (2012)
1362 [arXiv:1207.1348 [hep-ph]].
- 1363 [129] R. Ruiz de Austri, R. Trotta and L. Roszkowski, JHEP **0605** (2006) 002 [arXiv:hep-
1364 ph/0602028]; JHEP **0704** (2007) 084 [arXiv:hep-ph/0611173]; JHEP **0707** (2007) 075
1365 [arXiv:0705.2012]; B. C. Allanach, C. G. Lester and A. M. Weber, JHEP **0612** (2006)
1366 065; B. C. Allanach, K. Cranmer, C. G. Lester and A. M. Weber, JHEP **0708**, 023
1367 (2007); J. R. Ellis, S. Heinemeyer, K. A. Olive, A. M. Weber and G. Weiglein, JHEP
1368 **0708** (2007) 083; S. Heinemeyer, X. Miao, S. Su and G. Weiglein, JHEP **0808**, 087
1369 (2008).
- 1370 [130] P. Bechtle, T. Bringmann, K. Desch, H. Dreiner, M. Hamer, C. Hensel, M. Kramer
1371 and N. Nguyen *et al.*, JHEP **1206**, 098 (2012) [arXiv:1204.4199 [hep-ph]].
- 1372 [131] C. Balazs, A. Buckley, D. Carter, B. Farmer and M. White, arXiv:1205.1568 [hep-ph].
- 1373 [132] O. Buchmueller, R. Cavanaugh, M. Citron, A. De Roeck, M. J. Dolan, J. R. Ellis,
1374 H. Flacher and S. Heinemeyer *et al.*, Eur. Phys. J. C **72**, 2243 (2012) [arXiv:1207.7315
1375 [hep-ph]].
- 1376 [133] M. Endo, K. Hamaguchi, S. Iwamoto, K. Nakayama and N. Yokozaki, Phys. Rev. D
1377 **85** (2012) 095006 [arXiv:1112.6412 [hep-ph]].
- 1378 [134] H. Baer, V. Barger, P. Huang and X. Tata, JHEP **1205** (2012) 109 [arXiv:1203.5539
1379 [hep-ph]].
- 1380 [135] M. Papucci, J. T. Ruderman and A. Weiler, JHEP **1209**, 035 (2012) [arXiv:1110.6926
1381 [hep-ph]].

- 1382 [136] T. J. LeCompte and S. P. Martin, Phys. Rev. D **85**, 035023 (2012) [arXiv:1111.6897
1383 [hep-ph]].
- 1384 [137] H. Murayama, Y. Nomura, S. Shirai and K. Tobioka, Phys. Rev. D **86**, 115014 (2012)
1385 [arXiv:1206.4993 [hep-ph]].
- 1386 [138] B. A. Dobrescu and P. J. Fox, Eur. Phys. J. C **70** (2010) 263 [arXiv:1001.3147 [hep-ph]].
- 1387 [139] W. Altmannshofer and D. M. Straub, JHEP **1009** (2010) 078 [arXiv:1004.1993 [hep-
1388 ph]].
- 1389 [140] T. Appelquist, H. -C. Cheng and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001)
1390 [hep-ph/0012100].
- 1391 [141] I. Low, JHEP **0410**, 067 (2004) [hep-ph/0409025].
- 1392 [142] J. Hubisz and P. Meade, Phys. Rev. D **71**, 035016 (2005) [hep-ph/0411264].
- 1393 [143] J. M. Smillie and B. R. Webber, JHEP **0510** (2005) 069 [arXiv:hep-ph/0507170].
- 1394 [144] Adam C, Kneur J -L, Lafaye R, Plehn T, Rauch M, Zerwas D. *Eur. Phys. J. C* 71:1520
1395 (2011) [arXiv:1007.2190 [hep-ph]]
- 1396 [145] N. Arkani-Hamed, G. L. Kane, J. Thaler and L. T. Wang, JHEP **0608**, 070 (2006)
1397 [arXiv:hep-ph/0512190].
- 1398 [146] M. Alexander, S. Kreiss, R. Lafaye, T. Plehn, M. Rauch, and D. Zerwas, Chap-
1399 ter 9 in M. M. Nojiri *et al.*, *Physics Beyond the Standard Model: Supersymmetry*,
1400 arXiv:0802.3672 [hep-ph].
- 1401 [147] B. C. Allanach *et al.*, *Proc. of the APS/DPF/DPB Summer Study on the Future of*
1402 *Particle Physics (Snowmass 2001)* ed. N. Graf, Eur. Phys. J. C **25** (2002) 113 [eConf
1403 **C010630** (2001) P125].
- 1404 [148] C. F. Berger, J. S. Gainer, J. L. Hewett and T. G. Rizzo, JHEP **0902**, 023 (2009)
1405 [arXiv:0812.0980 [hep-ph]].

Chapter 3

Overview of the Experimental Technique

In this chapter we give an overview of how the experiment is done. This is followed by a number of chapters that give the details of the specific hardware being developed for E989. The order of those chapters follows the WBS as closely as possible.

The experiment consists of the following steps:

1. Production of an appropriate pulsed proton beam by an accelerator complex.
2. Production of pions using the proton beam that has been prepared.
3. Collection of polarized muons from pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$
4. Transporting the muon beam to the $(g - 2)$ storage ring.
5. Injection of the muon beam into the storage ring.
6. Kicking the muon beam onto stored orbits.
7. Measuring the arrival time and energy of positrons from the decay $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$

Central to the determination of a_μ is the spin equation¹

$$\vec{\omega}_a = -\frac{Qe}{m} \left[a_\mu \vec{B} + \left(a_\mu - \left(\frac{m}{p} \right)^2 \right) \frac{\vec{\beta} \times \vec{E}}{c} \right], \quad (3.1)$$

that gives the rate at which the spin turns relative the the momentum vector, which turns with the cyclotron frequency. The electric field term is there since we use electrostatic vertical focusing in the ring. At the magic momentum, $p_m = 3.09$ GeV/c, the effect of the motional magnetic field (the $\vec{\beta} \times \vec{E}$ term) vanishes.

Measurement of a_μ requires the determination of the muon spin frequency ω_a and the magnetic field averaged over the muon distribution.

¹See Section 3.3 for the details.

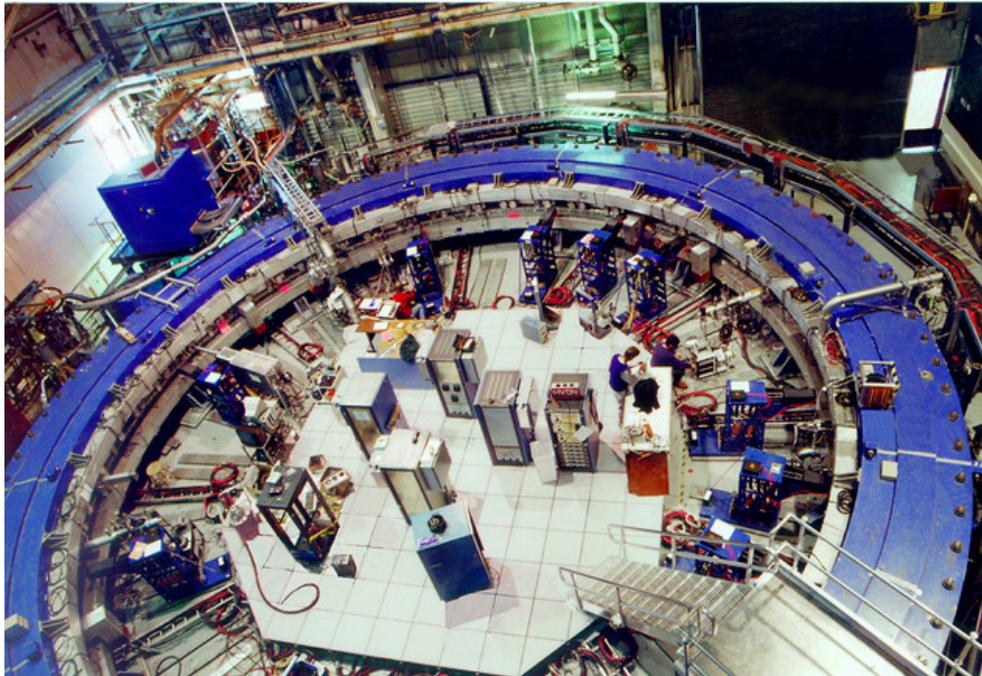


Figure 3.1: The E821 storage-ring magnet at Brookhaven Lab.

1427 3.1 Production and Preparation of the Muon Beam

1428 E989 will bring a bunched beam from the 8 GeV Booster to a pion production target located
 1429 where the antiproton production target was in the Tevatron collider program (see Chapter 7).
 1430 Pions of $3.11 \text{ GeV}/c \pm 5\%$ will be collected and sent into a large-acceptance beamline. Muons
 1431 are produced in the weak pion decay

$$\pi^\mp \rightarrow \mu^\mp + \bar{\nu}_\mu(\nu_\mu). \quad (3.2)$$

1432 Since the antineutrino (neutrino) is right-handed (left-handed) the μ^- (μ^+) is left-handed
 1433 (right-handed). A beam of polarized muons can be obtained from a beam of pions by select-
 1434 ing the highest-energy muons (a “forward beam”) or by selecting the lowest-energy muons
 1435 (a “backward beam”), where forward or backward refers to whether the decay is forward
 1436 of backward in the center-of-mass frame relative to the pion momentum. Polarizations sig-
 1437 nificantly greater than 90% are easily obtained in such beams. The pions and daughter
 1438 muons will be injected into the Delivery Ring (the re-purposed \bar{p} debuncher ring), where
 1439 after several turns the remaining pions decay. The surviving muon beam will be extracted
 1440 and brought to the muon storage ring built for E821 at Brookhaven.

1441 3.2 Injection into the Storage Ring

1442 A photograph of the E821 magnet is shown in Figure 3.1. It is clear from the photo that this
 1443 “storage ring” is very different from the usual one that consists of lumped elements. The

1444 storage ring magnet is energized by three superconducting coils shown in Fig 3.2(b). The
 1445 continuous “C” magnet yoke is built from twelve 30° segments of iron that was designed
 1446 to eliminate the end effects present in lumped magnets. This construction eliminates the
 1447 large gradients that would make the determination of average magnetic field, $\langle B \rangle$, very
 1448 difficult. Furthermore, a small perturbation in the yoke can effect the field halfway around
 1449 the ring at the ppm level. Thus every effort is made to minimize holes in the yoke, and
 1450 other perturbations. The only penetrations through the yoke are to permit the muon beam
 1451 to enter the magnet as shown in Fig 3.2(a), and to connect cryogenic services and power to
 1452 the inflector magnet and to the outer radius coil (see Fig. 3.2(b)). Where a hole in the yoke
 1453 is necessary, extra steel was placed around the hole on the outside of the yoke to compensate
 1454 for the missing material.

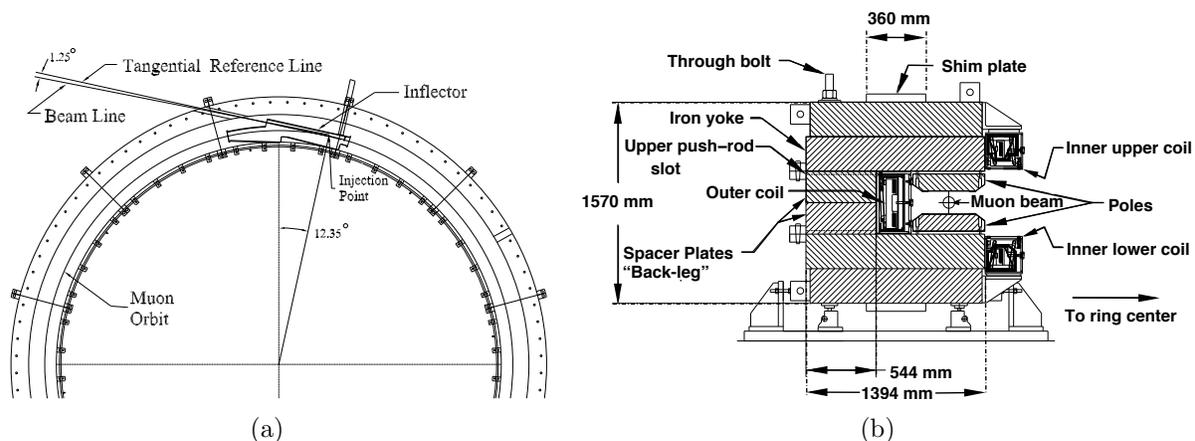


Figure 3.2: (a) Plan view of the beam entering the storage ring. (b) Elevation view of the storage-ring magnet cross section.

1455 The beam enters through a hole in the “back-leg” of the magnet and then crosses into the
 1456 inflector magnet, which provides an almost field free region, delivering the beam to the edge
 1457 of the storage region. The geometry is rather constrained, as can be seen in Fig. 3.3(a). The
 1458 injection geometry is sketched in Fig. 3.3(b). The kick required to put magic momentum
 1459 muons onto a stable orbit centered at magic radius is on the order of 10 mrad.

1460 The requirements on the muon kicker are rather severe:

- 1461 1. Since the magnet is continuous, any kicker device has to be inside of the precision
 1462 magnetic field region.
- 1463 2. The kicker hardware cannot contain magnetic elements such as ferrites, because they
 1464 will spoil the uniform magnetic field.
- 1465 3. Any eddy currents produced in the vacuum chamber, or in the kicker electrodes by the
 1466 kicker pulse must be negligible by 10 to 20 μs after injection, or must be well known
 1467 and corrected for in the measurement.
- 1468 4. Any kicker hardware must fit within the real estate occupied by the E821 kicker, which
 1469 employed three 1.7 m long devices.

1470

5. The kicker pulse should be shorter than the cyclotron period of 149 ns.

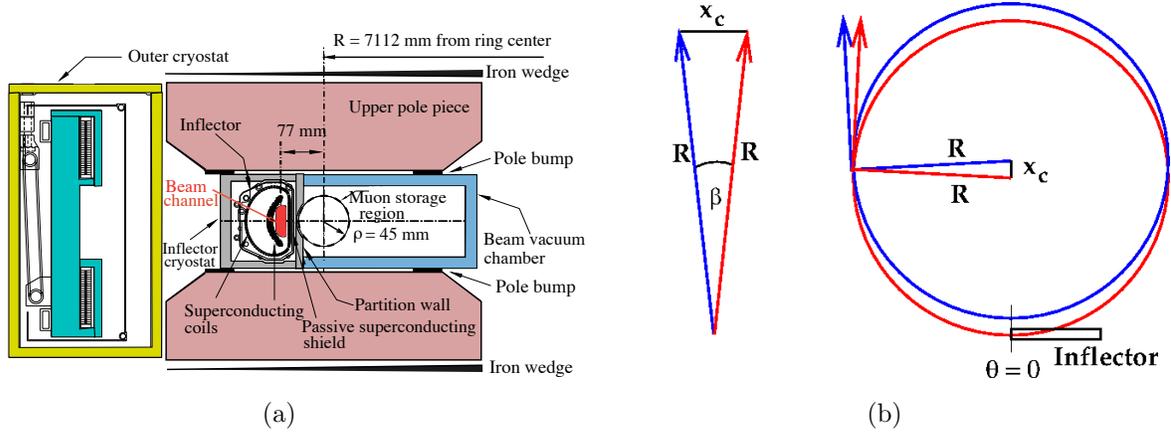


Figure 3.3: (a) The inflector exit showing the incident beam center 77 mm from the center of the storage region. The incident muon beam channel is highlighted in red. (b) The geometry of the necessary kick. The incident beam is the red circle, and the kick effectively moves the red circle over to the blue one.

1471

I would remove this since we cover the Quads in much more detail later

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The layout of the ring is shown in Fig. 3.4. The Quadrupoles cover 43% of the circumference, leaving space for the kicker and other devices. Each of the three kicker modules are 1.7 m long.

1475

3.3 The Spin Equations

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1477

Measurements of magnetic and electric dipole moments make use of the torque on a dipole in an external field:

$$\vec{\tau} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}, \quad (3.3)$$

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where we include the possibility of an electric dipole moment (\vec{d}). Except for the original Nevis spin rotation experiment, the muon magnetic dipole moment experiments inject a beam of polarized muons into a magnetic field and measure the rate at which the spin turns relative to the momentum, $\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$, where S and C stand for spin and cyclotron, respectively. These two frequencies, in the absence of any other external fields, are given by

$$\omega_S = -g \frac{Qe}{2m} B - (1 - \gamma) \frac{Qe}{\gamma m} B; \quad (3.4)$$

$$\omega_C = -\frac{Qe}{m\gamma} B; \quad (3.5)$$

$$\omega_a = \omega_S - \omega_C = -\left(\frac{g-2}{2}\right) \frac{Qe}{m} B = -a_\mu \frac{Qe}{m} B \quad (3.6)$$

1483 (where $e > 0$ and $Q = \pm 1$). There are two important features of ω_a : (i) It only depends on
 1484 the anomaly rather than on the full magnetic moment; (ii) It depends linearly on the applied
 1485 magnetic field.

1486 To measure the anomaly, it is necessary to measure ω_a , and to determine the magnetic
 1487 field B . The relevant quantity is $\langle B \rangle$, which is the magnetic field convolved with the muon
 1488 beam distribution, M defined as

$$\langle B \rangle = \int M(r, \theta) B(r, \theta) r dr d\theta, \quad (3.7)$$

1489 where the magnetic field $B(r, \theta)$ is expressed as the multipole expansion

$$B(r, \theta) = \sum_{n=0}^{\infty} r^n [c_n \cos n\theta + s_n \sin n\theta], \quad (3.8)$$

1490 and the muon distribution is expressed in terms of moments

$$M(r, \theta) = \sum_{m=0}^{\infty} [\xi_m(r) \cos m\theta + \sigma_m(r) \sin m\theta]. \quad (3.9)$$

1491 Because the harmonics $\sin n\theta \sin m\theta$, etc., orthogonal when integrated over one period,
 1492 non-vanishing integrals come from products of the same moment/multipole, in the expression
 1493 for $\langle B \rangle$. To determine $\langle B \rangle$ to sub-part-per-million (ppm) precision, one either needs excellent
 1494 knowledge of the multipole and moment distributions for B and M ; or care must be taken
 1495 to minimize the number of terms, with only the leading term being large, so that only the
 1496 first few multipoles are important. This was achieved in the most recent experiment [2] by
 1497 using a circular beam aperture, and making a very uniform dipole magnetic field.

1498 However there is one important issue to be solved: How can the muon beam be confined
 1499 to a storage ring if significant magnetic gradients cannot be used to provide vertical focusing?
 1500 The answer to this question was discovered by the third CERN collaboration [1], which used
 1501 an electric quadrupole field to provide vertical focusing. Of course, a relativistic particle
 1502 feels a motional magnetic field proportional to $\vec{\beta} \times \vec{E}$, but the full relativistic spin equation
 1503 contains a cancellation as can be seen below. Assuming that the velocity is transverse to the
 1504 magnetic field ($\vec{\beta} \cdot \vec{B} = 0$), one obtains [2, 3]

$$\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta = -\frac{Qe}{m} \left[a_\mu \vec{B} + \left(a_\mu - \left(\frac{m}{p} \right)^2 \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] - \eta \frac{Qe}{2m} \left[\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right]. \quad (3.10)$$

1505 There are both motional magnetic and electric fields in this equation – the terms which
 1506 are proportional to $\vec{\beta} \times \vec{E}$ and $\vec{\beta} \times \vec{B}$, respectively.

1507 The expression for ω_a is

$$\vec{\omega}_a = -\frac{Qe}{m} \left[a_\mu \vec{B} + \left(a_\mu - \left(\frac{m}{p} \right)^2 \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]. \quad (3.11)$$

1508 For the “magic” momentum $p_{\text{magic}} = m/\sqrt{a} \simeq 3.09 \text{ GeV}/c$ ($\gamma_{\text{magic}} = 29.3$), the second
 1509 term vanishes, and the electric field does not contribute to the spin motion relative to the

1510 momentum.² Note that if $g = 2$, then $a = 0$ and the spin would follow the momentum,
 1511 turning at the cyclotron frequency.

1512 3.4 Vertical Focusing with Electrostatic Quadrupoles

1513 The storage ring acts as a weak-focusing betatron, with the vertical focusing provided by
 1514 electrostatic quadrupoles. The ring is operated at the magic momentum, so that the electric
 1515 field does not contribute to the spin precession. However there is a second-order correction
 1516 to the spin frequency from the radial electric field, which is discussed below. There is also a
 1517 correction from the vertical betatron motion, since the spin equations in the previous section
 1518 were derived with the assumption that $\vec{\beta} \cdot \vec{B} = 0$.

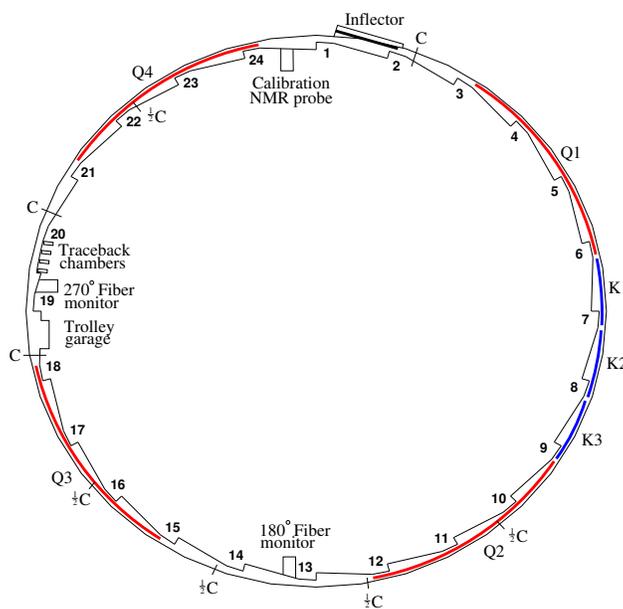


Figure 3.4: The layout of the storage ring, as seen from above, showing the location of the inflector, the kicker sections (labeled K1-K3), and the quadrupoles (labeled Q1-Q4). The beam circulates in a clockwise direction. Also shown are the collimators, which are labeled “C”, or “ $\frac{1}{2}C$ ” indicating whether the Cu collimator covers the full aperture, or half the aperture. The collimators are rings with inner radius: 45 mm, outer radius: 55 mm, thickness: 3 mm. The scalloped vacuum chamber consists of 12 sections joined by bellows. The chambers containing the inflector, the NMR trolley garage, and the trolley drive mechanism are special chambers. The other chambers are standard, with either quadrupole or kicker assemblies installed inside. An electron calorimeter is placed behind each of the radial windows, at the position indicated by the calorimeter number.

²Small corrections to the measured frequency must be applied since $\vec{\beta} \cdot \vec{B} \simeq 0$ and not all muons are at the magic momentum. These are discussed in Chapter ??.

3.5 Muon Decay

The dominant muon decay is

$$\mu^\mp \rightarrow e^\mp + \nu_\mu(\bar{\nu}_\mu) + \bar{\nu}_e(\nu_e) \quad (3.12)$$

which also violates parity.

Since the kinematics of muon decay are central to the measurements of a_μ , we discuss the general features in this section. Additional details are given in Ref. [17]. From a beam of pions traversing a straight beam-channel consisting of focusing and defocusing elements (FODO), a beam of polarized, high energy muons can be produced by selecting the "forward" or "backward" decays. The forward muons are those produced, in the pion rest frame, nearly parallel to the pion laboratory momentum and are the decay muons with the highest laboratory momenta. The backward muons are those produced nearly anti-parallel to the pion momentum and have the lowest laboratory momenta. The forward μ^- (μ^+) are polarized along (opposite) their lab momenta respectively; the polarization reverses for backward muons. The E821 experiment used forward muons, as will E989, the difference being the length of the pion decay line, which in E989 will be 1,900 m.

The pure $(V - A)$ three-body weak decay of the muon, $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$ or $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$, is "self-analyzing", that is, the parity-violating correlation between the directions in the muon rest frame (MRF) of the decay electron and the muon spin can provide information on the muon spin orientation at the time of the decay. When the decay electron has the maximum allowed energy in the MRF, $E'_{\max} \approx (m_\mu c^2)/2 = 53$ MeV. The neutrino and anti-neutrino are directed parallel to each other and at 180° relative to the electron direction. The $\nu\bar{\nu}$ pair carry zero total angular momentum; the electron carries the muon's angular momentum of $1/2$. The electron, being a lepton, is preferentially emitted left-handed in a weak decay, and thus has a larger probability to be emitted with its momentum *anti-parallel* rather than parallel to the μ^- spin. Similarly, in μ^+ decay, the highest-energy positrons are emitted *parallel* to the muon spin in the MRF.

In the other extreme, when the electron kinetic energy is zero in the MRF, the neutrino and anti-neutrino are emitted back-to-back and carry a total angular momentum of one. In this case, the electron spin is directed opposite to the muon spin in order to conserve angular momentum. Again, the electron is preferentially emitted with helicity -1, however in this case its momentum will be preferentially directed *parallel* to the μ^- spin. The positron, in μ^+ decay, is preferentially emitted with helicity +1, and therefore its momentum will be preferentially directed *anti-parallel* to the μ^+ spin.

With the approximation that the energy of the decay electron $E' \gg m_e c^2$, the differential decay distribution in the muon rest frame is given by[23],

$$dP(y', \theta') \propto n'(y') [1 \pm \mathcal{A}(y') \cos \theta'] dy' d\Omega' \quad (3.13)$$

where y' is the momentum fraction of the electron, $y' = p'_e/p'_{e \max}$, $d\Omega'$ is the solid angle, $\theta' = \cos^{-1}(\hat{p}'_e \cdot \hat{s})$ is the angle between the muon spin and \hat{p}'_e , $p'_{e \max} c \approx E'_{\max}$, and the $(-)$ sign is for negative muon decay. The number distribution $n(y')$ and the decay asymmetry $\mathcal{A}(y')$ are given by

$$n(y') = 2y'^2(3 - 2y') \quad \text{and} \quad \mathcal{A}(y') = \frac{2y' - 1}{3 - 2y'}. \quad (3.14)$$

1557 Note that both the number and asymmetry reach their maxima at $y' = 1$, and the asymmetry
 1558 changes sign at $y' = \frac{1}{2}$, as shown in Figure 3.5(a).

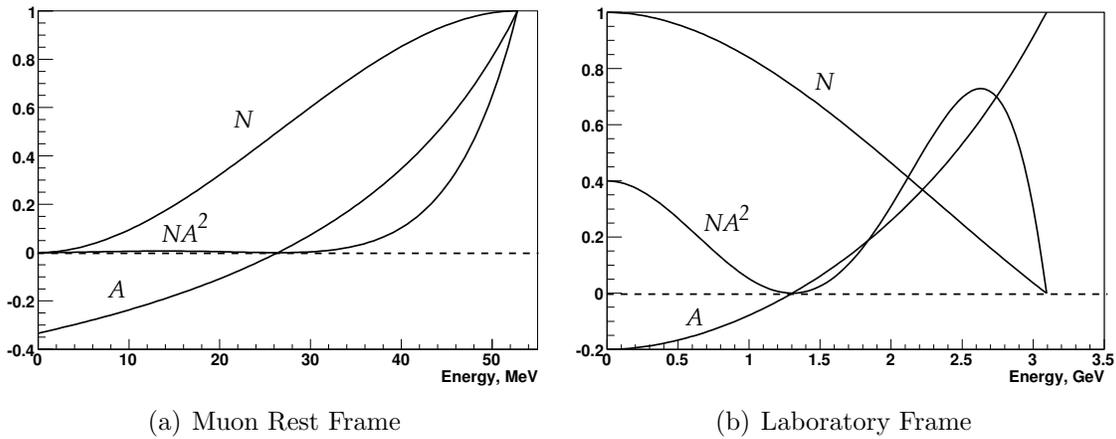


Figure 3.5: Number of decay electrons per unit energy, N (arbitrary units), value of the asymmetry A , and relative figure of merit NA^2 (arbitrary units) as a function of electron energy. Detector acceptance has not been incorporated, and the polarization is unity. For the third CERN experiment and E821, $E_{max} \approx 3.1$ GeV ($p_\mu = 3.094$ GeV/c) in the laboratory frame.

1559 The CERN and Brookhaven based muon ($g - 2$) experiments stored relativistic muons of
 1560 the magic momentum in a uniform magnetic field, which resulted in the muon spin precessing
 1561 with constant frequency $\vec{\omega}_a$, while the muons traveled in circular orbits. If *all* decay electrons
 1562 were counted, the number detected as a function of time would be a pure exponential;
 1563 therefore we seek cuts on the laboratory observable to select subsets of decay electrons
 1564 whose numbers oscillate at the precession frequency. The number of decay electrons in
 1565 the MRF varies with the angle between the electron and spin directions, the electrons in
 1566 the subset should have a preferred direction in the MRF when weighted according to their
 1567 asymmetry as given in Equation 3.13. At $p_\mu \approx 3.094$ GeV/c the directions of the electrons
 1568 resulting from muon decay in the laboratory frame are very nearly parallel to the muon
 1569 momentum regardless of their energy or direction in the MRF. The only practical remaining
 1570 cut is on the electron's laboratory energy. An energy subset will have the desired property:
 1571 there will be a net component of electron MRF momentum either parallel or antiparallel
 1572 to the laboratory muon direction. For example, suppose that we only count electrons with
 1573 the highest laboratory energy, around 3.1 GeV. Let \hat{z} indicate the direction of the muon
 1574 laboratory momentum. The highest-energy electrons in the laboratory are those near the
 1575 maximum MRF energy of 53 MeV, and with MRF directions nearly parallel to \hat{z} . There are
 1576 more of these high-energy electrons when the μ^- spins are in the direction opposite to \hat{z} than
 1577 when the spins are parallel to \hat{z} . Thus the number of decay electrons reaches a maximum
 1578 when the muon spin direction is opposite to \hat{z} , and a minimum when they are parallel. As
 1579 the spin precesses the number of high-energy electrons will oscillate with frequency ω_a . More
 1580 generally, at laboratory energies above ~ 1.2 GeV, the electrons have a preferred average
 1581 MRF direction parallel to \hat{z} (see Figure 3.5). In this discussion, it is assumed that the

1582 spin precession vector, $\vec{\omega}_a$, is independent of time, and therefore the angle between the spin
 1583 component in the orbit plane and the muon momentum direction is given by $\omega_a t + \phi$, where
 1584 ϕ is a constant.

1585 Equations 3.13 and 3.14 can be transformed to the laboratory frame to give the electron
 1586 number oscillation with time as a function of electron energy,

$$N_d(t, E) = N_{d0}(E)e^{-t/\gamma\tau}[1 + A_d(E) \cos(\omega_a t + \phi_d(E))], \quad (3.15)$$

1587 or, taking all electrons above threshold energy E_{th} ,

$$N(t, E_{th}) = N_0(E_{th})e^{-t/\gamma\tau}[1 + A(E_{th}) \cos(\omega_a t + \phi(E_{th}))]. \quad (3.16)$$

1588 In Equation 3.15 the differential quantities are,

$$A_d(E) = \mathcal{P} \frac{-8y^2 + y + 1}{4y^2 - 5y - 5}, \quad N_{d0}(E) \propto (y - 1)(4y^2 - 5y - 5), \quad (3.17)$$

1589 and in Equation 3.16,

$$N(E_{th}) \propto (y_{th} - 1)^2(-y_{th}^2 + y_{th} + 3), \quad A(E_{th}) = \mathcal{P} \frac{y_{th}(2y_{th} + 1)}{-y_{th}^2 + y_{th} + 3}. \quad (3.18)$$

1590 In the above equations, $y = E/E_{max}$, $y_{th} = E_{th}/E_{max}$, \mathcal{P} is the polarization of the muon
 1591 beam, and E , E_{th} , and $E_{max} = 3.1$ GeV are the electron laboratory energy, threshold energy,
 1592 and maximum energy, respectively.

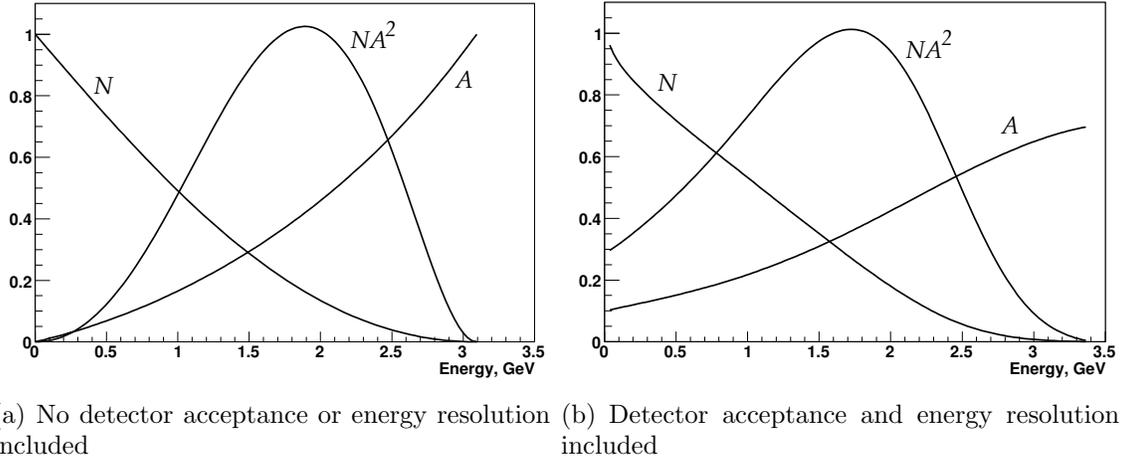


Figure 3.6: The integral N , A , and NA^2 (arbitrary units) for a single energy-threshold as a function of the threshold energy; (a) in the laboratory frame, not including and (b) including the effects of detector acceptance and energy resolution for the E821 calorimeters discussed below. For the third CERN experiment and E821, $E_{max} \approx 3.1$ GeV ($p_\mu = 3.094$ GeV/c) in the laboratory frame.

1593 The fractional statistical error on the precession frequency, when fitting data collected
 1594 over many muon lifetimes to the five-parameter function (Equation 3.16), is given by

$$\delta\epsilon = \frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu N^{\frac{1}{2}} A}. \quad (3.19)$$

1595 where N is the total number of electrons, and A is the asymmetry, in the given data sample.
 1596 For a fixed magnetic field and muon momentum, the statistical figure of merit is NA^2 , the
 1597 quantity to be maximized in order to minimize the statistical uncertainty.

1598 The energy dependencies of the numbers and asymmetries used in Equations 3.15 and
 1599 3.16, along with the figures of merit NA^2 , are plotted in Figures 3.5 and 3.6 for the case
 1600 of E821. The statistical power is greatest for electrons at 2.6 GeV (Figure 3.5). When a fit
 1601 is made to all electrons above some energy threshold, the optimal threshold energy is about
 1602 1.7-1.8 GeV (Figure 3.6).

1603 The resulting arrival-time spectrum of electrons with energy greater than 1.8 GeV from
 1604 the final E821 data run is shown in Fig. 3.7. While this plot clearly exhibits the expected
 1605 features of the five-parameter function, a least-square fit to these 3.6 billion events gives
 1606 an unacceptably large chi-square. A number of small effects must be taken into account to
 1607 obtain a reasonable fit, which will be discussed in detail in the section on systematic errors.

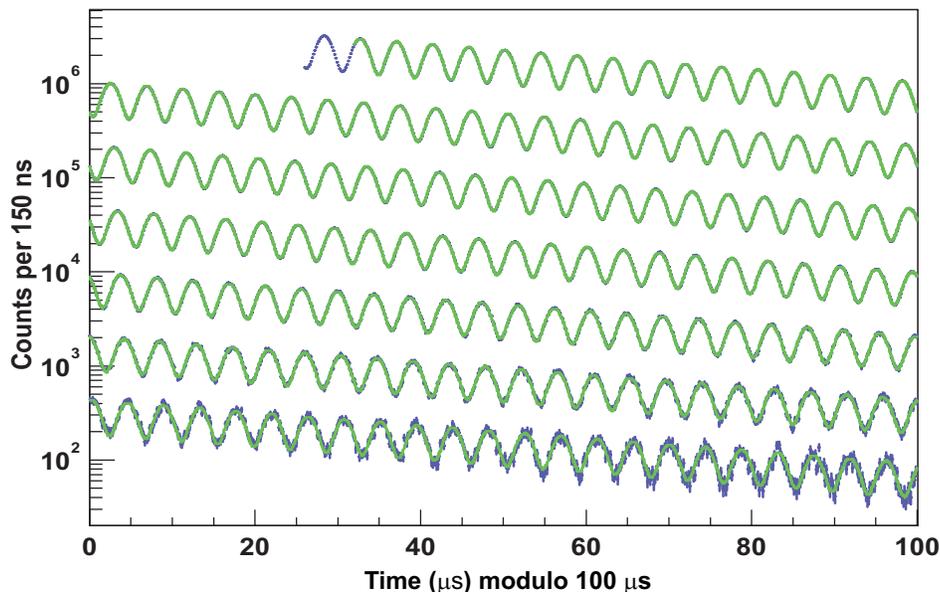


Figure 3.7: Histogram, modulo $100 \mu s$, of the number of detected electrons above 1.8 GeV for the 2001 data set as a function of time, summed over detectors, with a least-squares fit to the spectrum superimposed. Total number of electrons is 3.6×10^9 . The data are in blue, the fit in green.

3.6 The Magnetic Field

The rate at which the muon spin turns relative to its momentum (Eq. 3.11) depends on the anomaly a_μ and on the average magnetic field given by Eq. 3.7. Thus the determination of a_μ to sub-tenths of a ppm requires that both ω_a and $\langle B \rangle$ be determined to this level. The muon beam is confined to a cylindrical region of 9 cm diameter, which is 44.7 m in length. The volume of this region is $\simeq 1.14 \text{ m}^3$ or $\simeq 40 \text{ ft}^3$, which sets the scale for the magnetic field measurement and control. The E989 goal is to know the magnetic field averaged over the muon distribution to an uncertainty of ± 70 parts per billion (ppb).

The problem breaks into several pieces:

1. Producing as uniform magnetic field as possible by shimming the magnet.
2. Stabilizing B in time at the sub-ppm level by feedback, with mechanical and thermal stability.
3. Monitoring B to the 20 ppb level around the storage ring during data collection.
4. Periodically mapping the field throughout the storage region and correlating the field map to the monitoring information without turning off the magnet between data collection and field mapping. It is essential that the magnet not be powered off unless absolutely necessary.
5. Obtaining an absolute calibration of the B -field relative to the Larmor frequency of the free proton.

The only magnetic field measurement technique with the sensitivity needed to measure and control the B -field to the tens of ppb is nuclear magnetic resonance (NMR). Pulsed NMR was used, where a $\pi/2$ RF pulse rotated the spins and the resulting free-induction decay (FID) was detected by a pickup coil around the sample. The E821 baseline design used the NMR of protons in a water sample with a CuSO_4 additive that shortened the relaxation time, with the probes tuned to operate in a 1.45 T field. When the water evaporated from a few of the probes, the water was replaced with petroleum jelly, which the added features of a smaller sensitivity to temperature changes and no evaporation.

Special nuclear magnetic resonance (NMR) probes [42, 2] were used in E821 to measure and monitor the magnetic field during the experimental data collection.³ Three types of probes were used: a spherical water probe that provided the absolute calibration to the free proton; cylindrical probes that were used monitor the field during data collection and in an NMR trolley to map the field; and a smaller spherical probe which could be plunged into the muon storage region by means of a bellows system to transfer the absolute calibration to the trolley probes. A collection of 378 cylindrical probes placed in symmetrically machined grooves on the top and bottom of the muon beam vacuum chamber gave a point to point measure of the magnetic field while beam was in the storage ring. Probes at the same azimuthal location but different radii gave information on changes to the quadrupole component of the field at that location.

³The probes are described in Chapter 15

1646 The field mapping trolley contained 17 cylindrical probes arranged in concentric circles
 1647 as shown in Figure 3.8. At several-day intervals during the running periods, the beam
 1648 was turned off, and the field mapping trolley was driven around inside of the evacuated
 1649 beam chamber measuring the magnetic field with each of the 17 trolley probes at 6,000
 1650 locations around the ring. One of the resulting field maps, averaged over azimuth, is shown
 1651 in Figure 3.8(b).

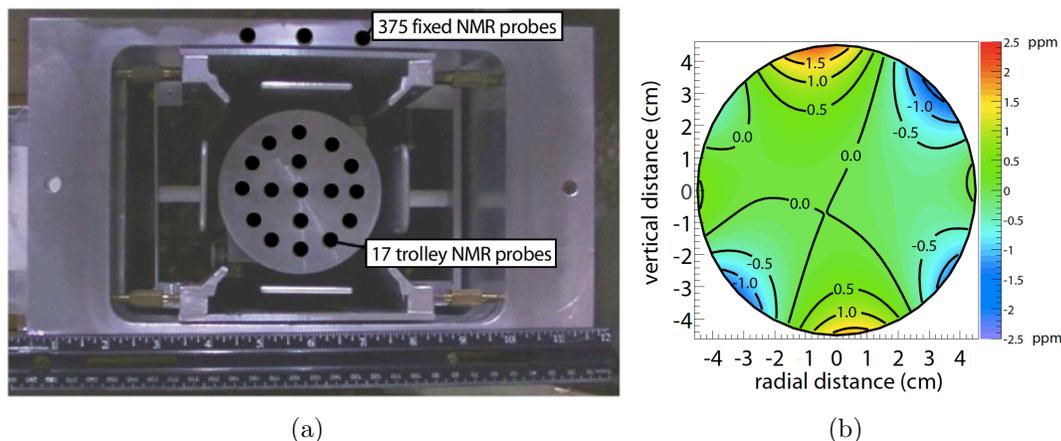


Figure 3.8: (a) The electrostatic quadrupole assembly inside a vacuum chamber showing the NMR trolley sitting on the rails of the cage assembly. Seventeen NMR probes are located just behind the front face in the places indicated by the black circles. The inner (outer) circle of probes has a diameter of 3.5 cm (7 cm) at the probe centers. The storage region has a diameter of 9 cm. The vertical location of three of the 180 upper fixed probes is also shown. An additional 180 probes are located symmetrically below the vacuum chamber. (Reprinted with permission from [2]. Copyright 2006 by the American Physical Society.) (b) A contour plot of the magnetic field averaged over azimuth, 0.5 ppm intervals.

1652 The absolute calibration utilizes a probe with a spherical water sample [7]. The Larmor
 1653 frequency of a proton in a spherical water sample is related to that of the free proton through
 1654 $f_L(\text{sph} - \text{H}_2\text{O}, T) = [1 - \sigma(\text{H}_2\text{O}, T)] f_L(\text{free})$, [8, 9] where $\sigma(\text{H}_2\text{O}, T) = 25.790(14) \times 10^{-6}$ is
 1655 from the diamagnetic shielding of the proton in the water molecule, determined from [10]

$$\sigma(\text{H}_2\text{O}, 34.7^\circ\text{C}) = 1 - \frac{g_p(\text{H}_2\text{O}, 34.7^\circ\text{C})}{g_J(H)} \frac{g_J(H)}{g_p(H)} \frac{g_p(H)}{g_p(\text{free})}. \quad (3.20)$$

1656 The terms are: the ratio of the g -factors of the proton in a spherical water sample to
 1657 that of the electron in the hydrogen ground state ($g_J(H)$) [10]; the ratio of electron to
 1658 proton g -factors in hydrogen [11]; the bound-state correction relating the g -factor of the
 1659 proton bound in hydrogen to the free proton [12, 13]. The temperature dependence is from
 1660 Reference [14]. An alternate absolute calibration would be to use an optically pumped ^3He
 1661 NMR probe [15]. This has several advantages: the sensitivity to the probe shape is negligible,
 1662 and the temperature dependence is also negligible. This option is being explored for E989.

1663 The calibration procedure used above permits the magnetic field to be expressed in terms
 1664 of the Larmor frequency of a free proton, ω_p . The magnetic field is weighted by the muon

1665 distribution, and also averaged over the running time weighed by the number of stored
 1666 muons to determine the value of ω_p which is combined with the average ω_a to determine
 1667 a_μ . The reason for the use of these two frequencies, rather than B measured in tesla can be
 1668 understood from Eq. 3.11. To obtain a_μ from this relationship requires precise knowledge of
 1669 the muon charge to mass ratio.

1670 To determine a_μ from the two frequencies ω_a and ω_p , we use the relationship

$$a_\mu = \frac{\omega_a/\omega_p}{\lambda_+ - \omega_a/\omega_p} = \frac{\mathcal{R}}{\lambda_+ - \mathcal{R}}, \quad (3.21)$$

1671 where the ratio

$$\lambda_+ = \mu_{\mu^+}/\mu_p = 3.183\,345\,137\,(85) \quad (3.22)$$

1672 is the muon-to-proton magnetic moment ratio [16] measured from muonium (the μ^+e^- atom)
 1673 hyperfine structure[18]. Of course, to use λ_+ to determine a_{μ^-} requires the assumption of
 1674 CPT invariance, *viz.* ($a_{\mu^+} = a_{\mu^-}$; $\lambda_+ = \lambda_-$). The comparison of \mathcal{R}_{μ^+} with \mathcal{R}_{μ^-} provides a
 1675 CPT test. In E821

$$\Delta\mathcal{R} = \mathcal{R}_{\mu^-} - \mathcal{R}_{\mu^+} = (3.6 \pm 3.7) \times 10^{-9} \quad (3.23)$$

1676 3.7 Measuring the Muon EDM: d_μ

1677 If an EDM is present, the measured frequency is the vector sum of two terms: the spin
 1678 motion from the torques $\vec{\mu} \times \vec{B}$ and from $\vec{d} \times \vec{E}$, as shown in Eq. 3.10; $\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta$. The
 1679 first term comes from the anomalous magnetic moment, a , and the second from the electric
 1680 dipole moment. The motional electric field is much larger than any electric field in the
 1681 lab, so the observed frequency $\vec{\omega}$ is (essentially) the vector sum of two orthogonal angular
 1682 frequencies, $\vec{\omega}_a$ and $\vec{\omega}_\eta$. These two frequencies are shown in Fig. 3.9, where the EDM related
 1683 frequency ω_η is greatly exaggerated.

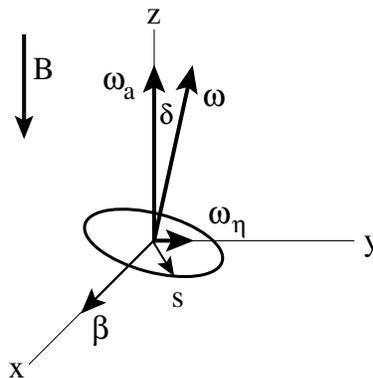


Figure 3.9: The two frequencies present if the muon has both a magnetic and electric dipole moment (not to scale). Note that the EDM ω_η is much smaller than ω_a . The muon spin precession plane is tilted by an angle proportional to the particle's EDM value.

1684 Thus there are *two* effects due to an electric dipole moment:

- 1685 1. The observed frequency is the vector sum of ω_a and ω_η so the magnitude of the observed
 1686 frequency is increased from ω_a to

$$\omega_{a\eta} \simeq \sqrt{\omega_a^2 + \omega_\eta^2} = \omega_a \sqrt{1 + \left(\frac{\eta\beta}{2a}\right)^2} \quad (3.24)$$

- 1687 2. The spin precession plane is tilted (everywhere around the ring) by a (very small) angle

$$\delta = \tan^{-1} \frac{\omega_\eta}{\omega_a} = \tan^{-1} \left(\frac{\eta\beta}{2a}\right) \quad (3.25)$$

1688 as shown in Fig. 3.9

1689 The tilting of the spin precession plane everywhere around the ring, is very much like
 1690 there is a net radial magnetic field which when integrated around the ring is not zero. In a
 1691 ring with a purely magnetic field, the average radial B -field for a stored particle is zero, since
 1692 the particle adjusts its vertical position in the focusing system to ensure this. However, in the
 1693 presence of other forces, like vertical E -fields, gravity, etc., this is not strictly true and must
 1694 be taken into account for systematic error estimation. A major tool against these types
 1695 of systematic errors, which is only possible in a dedicated EDM storage ring experiment,
 1696 would be the ability to inject into the storage ring both in a clockwise (CW) and counter-
 1697 clockwise (CCW) sense, where the non-magnetic forces are kept the same while the EDM
 1698 signal changes sign.

1699 The tipping of the plane of precession around the ring has an important implication for
 1700 the resulting decay positrons. As the muon spin turns with the frequency ω_a , following the
 1701 circle shown in Fig. 3.9, the EDM causes an up-down oscillation of the muon spin which is
 1702 out of phase by $\pi/2$ with the $(g-2)$ precession. Thus the trajectories of the decay positrons
 1703 (electrons) will oscillate between upward-going to downward-going with the frequency ω_a out
 1704 of phase with ω_a . It was this effect which was searched for in the third $(g-2)$ experiment
 1705 at CERN, and in E821 at Brookhaven. At CERN one detector station was outfitted with
 1706 two scintillators, one just above the mid-plane, one just below.

1707 Assuming the gain and acceptance of the upper and lower detectors are equal and the
 1708 storage ring and vertical detector mid-plane are identical, the number of electrons above (+)
 1709 or below (-) the mid-plane is given by[4]

$$N^\pm(t) \propto [1 \mp A_\eta \sin(\omega t + \phi) + A_\mu \cos(\omega t + \phi)] \quad (3.26)$$

1710 where A_η is proportional to d_μ . A major source of systematic error arises if there is an offset
 1711 between the average vertical position of the beam and the position of the boundary between
 1712 the upper and lower detectors.

1713 3.7.1 Search for d_μ in E821

1714 In E821, three separate methods were used to search for the up-down oscillations[4]. Five-
 1715 element hodoscopes were placed in front of about half of the 24 electron calorimeters, and
 1716 the vertical centroid of the decay electron distribution was fit as a function of time. Five

1717 calorimeter stations had finer-grained hodoscopes which also provided the vertical electron
1718 distribution of decay electrons as a function of time. One of the stations was equipped with
1719 a straw tube array that gave both x and y information, so that the electron tracks could be
1720 fit to search for the oscillation in upward- and downward-going tracks. These “traceback”
1721 chambers were primarily designed to provide information on the muon distribution in the
1722 storage ring[4], but turned out to be a powerful tool to search for the EDM signal. No
1723 evidence for an up-down oscillation was seen, and the result is[4]

$$d_\mu = (0.1 \pm 0.9) \times 10^{-19} e\text{-cm}; \quad |d_\mu| < 1.9 \times 10^{-19} e\text{-cm} \quad (95\% \text{ C.L.}), \quad (3.27)$$

1724 a factor of five smaller than the previous limit.

1725 3.7.2 Search for d_μ at Fermilab

1726 Only the tracking detector in E821 had manageable systematic errors that could be reduced
1727 significantly in a new experiment.

References

- 1728
- 1729 [1] J. Bailey, et al., Nucl. Phys. **B150**, 1 (1979).
- 1730 [2] L.H. Thomas, Nature **117**, (1926) 514 and Phil. Mag. **3** (1927) 1.
- 1731 [3] Bargmann V, Michel L, Telegdi VL, Phys. Rev. Lett. 2:435 (1959)
- 1732 [4] G.W. Bennett, et al., Phys. Rev. **D 80**, 052008 (2009).
- 1733 [5] Bennett GW, et al. (The $g - 2$ Collab.) Phys. Rev. Lett. 92:161802 (2004)
- 1734 [6] Bennett GW, et al.(The $g - 2$ Collab.) Phys. Rev. D, 73:072003 (2006)
- 1735 [7] Fei X, Hughes V, Prigl R, *Nucl. Inst. Methods Phys. Res.* A394:349 (1997)
- 1736 [8] Abragam A. In *Principles of Nuclear Magnetism*, p. 173-178. Oxford U. Press, (1961)
- 1737 [9] Mohr PJ, Taylor BH, *Rev. Mod. Phys.* 77:1 (2005)
- 1738 [10] Phillips WD, et al. *Metrologia* 13:179 (1979)
- 1739 [11] Winkler PF, Kleppner D, Myint T, Walther FG, *Phys. Rev.* A5:83 (1972)
- 1740 [12] Lamb Jr. WE. *Phys. Rev.* 60:817 (1941)
- 1741 [13] Grotch H, Hegstrom RA. *Phys. Rev.* A4:59 (1971)
- 1742 [14] B.W. Petley et al. *Metrologia*.**20**, 81 (1984)
- 1743 [15] J.L. Flowers, B.W. Petley and M.G. Richards, *Metrologia* **30**, 75 (1993).
- 1744 [16] Mohr PJ, Taylor BN, Newell DB, (CODATA recommended values). *Rev. Mod. Phys.*
1745 80:633 (2008)
- 1746 [17] James P. Miller, Eduardo de Rafael and B. Lee Roberts, Rept. Prog. Phys. **70**, 795-881,
1747 2007.
- 1748 [18] W. Liu et al., Phys. Rev. Lett. **82**, 711 (1999).
- 1749 [19] The $g - 2$ Collaboration: R.M. Carey et al., Phys. Rev. Lett. **82**, 1632 (1999).
- 1750 [20] The $g - 2$ Collaboration: H.N. Brown et al., Phys. Rev. D **62**, 091101 (2000).

- 1751 [21] The $g - 2$ Collaboration: H.N. Brown et al., Phys. Rev. Lett. **86**, 2227 (2001).
- 1752 [22] The $g - 2$ Collaboration: G.W. Bennett et al., Phys. Rev. Lett. **89**, 101804 (2002);
1753 Erratum-ibid. **89**, 129903 (2002).

Chapter 4

The Physics of Muon Storage

In this chapter we discuss the behavior of a beam in a weak-focusing betatron, and the features of the injection of a bunched beam that are important in the determination of ω_a . We also discuss the corrections to the measured frequency ω_a that come from the the vertical betatron motion, and the fact that not all muons are at the magic momentum (central radius) in the storage ring. The final section of this chapter discusses the systematic errors that come from the pion and muon beamlines.

The behavior of the beam in the $(g - 2)$ storage ring directly affects the measurement of a_μ . Since the detector acceptance for decay electrons depends on the radial coordinate of the muon at the point where it decays, coherent radial motion of the stored beam can produce an amplitude modulation in the observed electron time spectrum. Resonances in the storage ring can cause particle losses, thus distorting the observed time spectrum, and must be avoided when choosing the operating parameters of the ring. Care is taken in setting the frequency of coherent radial beam motion, the “coherent betatron oscillation” (CBO) frequency, which lies close to the second harmonic of $f_a = \omega_a/(2\pi)$. If f_{CBO} is too close to $2f_a$, the beat frequency, $f_- = f_{CBO} - f_a$, complicates the extraction of f_a from the data, and can introduce a significant systematic error.

A pure quadrupole electric field provides a linear restoring force in the vertical direction, and the combination of the (defocusing) electric field and the central magnetic field provides a linear restoring force in the radial direction. The $(g - 2)$ ring is a weak focusing ring[1, 2, 3] with the field index

$$n = \frac{\kappa R_0}{\beta B_0}, \quad (4.1)$$

where κ is the electric quadrupole gradient, B_0 is the magnetic field strength, R_0 is the magic radius $\equiv 7112$ mm, and β is the relativistic velocity of the muon beam. For a ring with a uniform vertical dipole magnetic field and a uniform quadrupole field that provides vertical focusing covering the full azimuth, the stored particles undergo simple harmonic motion called betatron oscillations, in both the radial and vertical dimensions.

The horizontal and vertical motion are given by

$$x = x_e + A_x \cos(\nu_x \frac{s}{R_0} + \delta_x) \quad \text{and} \quad y = A_y \cos(\nu_y \frac{s}{R_0} + \delta_y), \quad (4.2)$$

where s is the arc length along the trajectory. The horizontal and vertical tunes are given by $\nu_x = \sqrt{1 - n}$ and $\nu_y = \sqrt{n}$. Several n - values were used in E821 for data acquisition:

1784 $n = 0.137$, 0.142 and 0.122 . The horizontal and vertical betatron frequencies are given by

$$f_x = f_C \sqrt{1-n} \simeq 0.929 f_C \quad \text{and} \quad f_y = f_C \sqrt{n} \simeq 0.37 f_C, \quad (4.3)$$

1785 where f_C is the cyclotron frequency and the numerical values assume that $n = 0.137$. The
 1786 corresponding betatron wavelengths are $\lambda_{\beta_x} = 1.08(2\pi R_0)$ and $\lambda_{\beta_y} = 2.7(2\pi R_0)$. It is
 1787 important that the betatron wavelengths are not simple multiples of the circumference,
 1788 as this minimizes the ability of ring imperfections and higher multipoles to drive resonances
 1789 that would result in particle losses from the ring.

1790 The field index also determines the angular acceptance of the ring. The maximum hori-
 1791 zontal and vertical angles of the muon momentum are given by

$$\theta_{\max}^x = \frac{x_{\max} \sqrt{1-n}}{R_0}, \quad \text{and} \quad \theta_{\max}^y = \frac{y_{\max} \sqrt{n}}{R_0}, \quad (4.4)$$

1792 where $x_{\max}, y_{\max} = 45$ mm is the radius of the storage aperture. For a betatron amplitude
 1793 A_x or A_y less than 45 mm, the maximum angle is reduced, as can be seen from the above
 1794 equations.

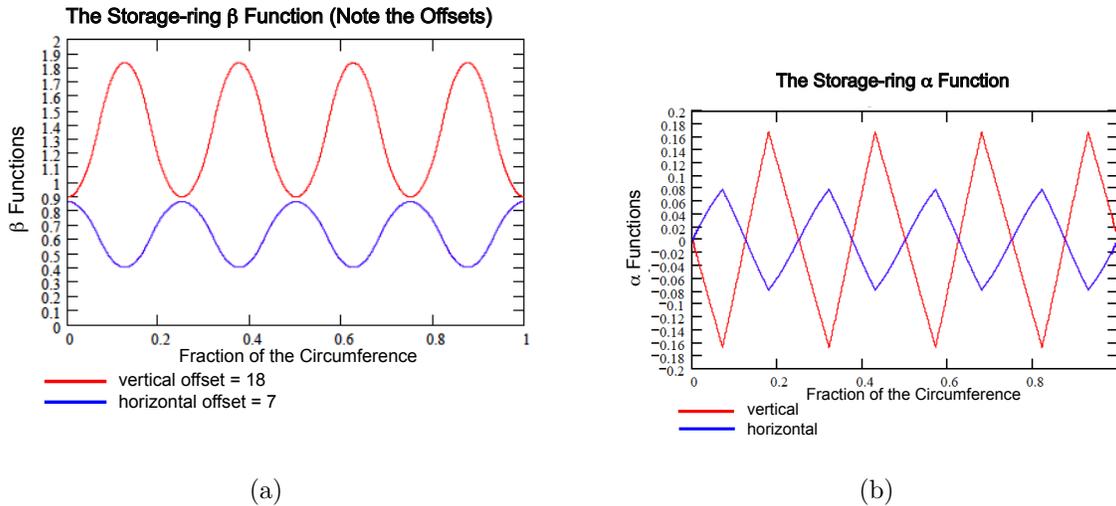


Figure 4.1: (a) The horizontal (radial) and vertical beta functions for the E821 lattice. Note the scale offset. (b) The horizontal (radial) and vertical alpha functions for the E821 lattice. The n -value is 0.134 for both. (From Ref. [8])

1795 For a ring with discrete quadrupoles, the focusing strength changes as a function of
 1796 azimuth, and the equation of motion looks like an oscillator whose spring constant changes
 1797 as a function of azimuth s . The motion is described by

$$x(s) = x_e + A\sqrt{\beta(s)} \cos(\psi(s) + \delta), \quad (4.5)$$

1798 where $\beta(s)$ is one of the three Courant-Snyder parameters.[2]

1799 The layout of the storage ring is shown in Figure 3.4. The four-fold symmetry of the
 1800 quadrupoles was chosen because it provided quadrupole-free regions for the kicker, traceback

1801 chambers, fiber monitors, and trolley garage; but the most important benefit of four-fold
 1802 symmetry is to reduce the peak-to-peak betatron oscillation amplitudes, with $\sqrt{\beta_{\max}/\beta_{\min}} =$
 1803 1.03. The beta and alpha functions for the $(g - 2)$ storage ring [8] are shown in Fig. 4.1.

1804 **fix this part**

1805 average magnetic field weighted by the muon distribution that appears in the ω_a equation

$$\vec{\omega}_a = -\frac{Qe}{m} \left[a_\mu \vec{B} + \left(a_\mu - \left(\frac{m}{p} \right)^2 \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]. \quad (4.6)$$

1806 Resonances in the storage ring will occur if $L\nu_x + M\nu_y = N$, where L , M and N are
 1807 integers, which must be avoided in choosing the operating value of the field index. These
 1808 resonances form straight lines on the tune plane shown in Figure 4.2, which shows resonance
 1809 lines up to fifth order. The operating point lies on the circle $\nu_x^2 + \nu_y^2 = 1$.

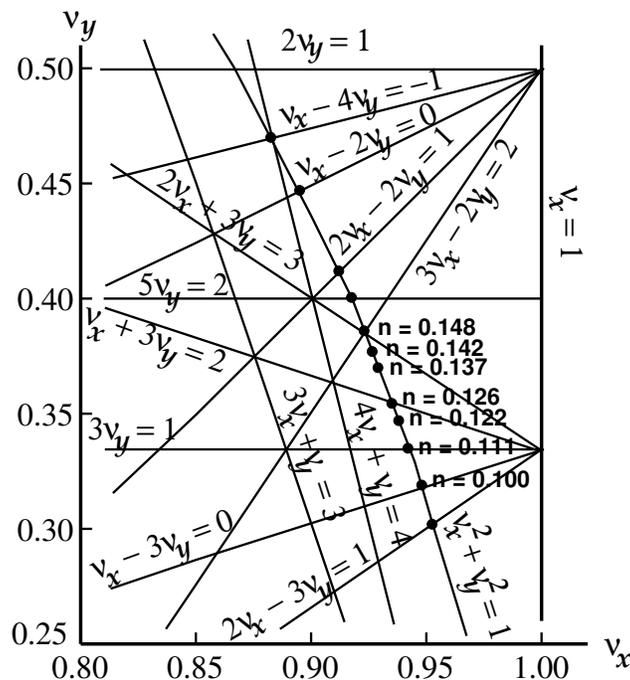


Figure 4.2: The tune plane, showing the three operating points used during our three years of running.

1810 The detector acceptance depends on the radial position of the muon when it decays, so
 1811 that any *coherent* radial beam motion will amplitude modulate the decay e^\pm distribution.
 1812 This can be understood by examining Fig. 4.3. A narrow bunch of muons starts its radial
 1813 betatron oscillation at the point $s = 0$. The circumference of the ring is $2\pi\rho$ so the x -axis
 1814 shows successive revolutions around the ring. The radial betatron wavelength is longer than
 1815 the circumference $2\pi\rho$. The rate at which the muon bunch moves toward and then away
 1816 from the detector is given by $f_{CBO} = f_c - f_x$. The CBO wavelength is slightly over 14
 1817 revolutions of the ring.

1818 **I would probably remove this paragraph since it only provides historical con-**
 1819 **text to the CBO and the previous section already describes its effects.**

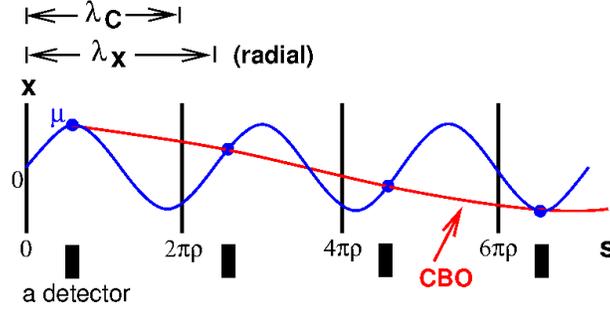


Figure 4.3: A cartoon of the coherent betatron motion (CBO). The radial CBO oscillation is shown in blue for 3 successive betatron wavelengths, the cyclotron wavelength (the circumference) is marked by the black vertical lines. One detector location is shown. Since the radial betatron wavelength is larger than the circumference, the detector sees the bunched beam slowly move closer and then further away. The frequency that the beam appears to move in and out is f_{CBO} .

1820 The presence of the CBO was first discovered in E821 from a plot that showed an azimuthal
 1821 variation in the value of a_μ shown in Fig. 4.4(a). When the CBO is included, this
 1822 azimuthal dependence disappears. Because the CBO wavelength is only slightly greater than
 1823 the circumference, its effect washes out when all detectors are added together. Adding all
 1824 detectors together was one of the techniques used in E821 to eliminate CBO effect. Since
 1825 some detectors saw more injection flash than others, this meant that data at times earlier
 1826 than around 40 μ s was discarded in those analyses. Other analyzers included the CBO and
 1827 were able to use data from the “quiet” detectors at earlier times.

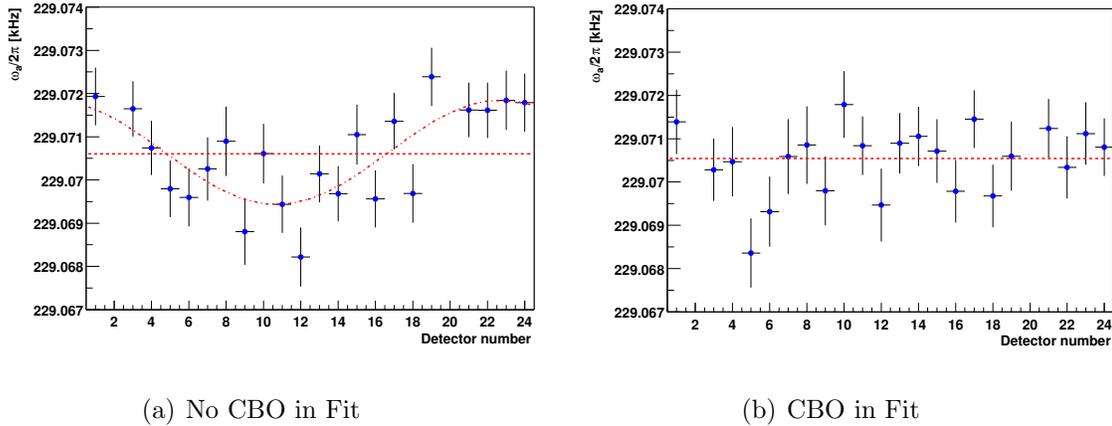


Figure 4.4: The dependence of the extracted value of a_μ vs. detector number. (a) With no CBO in the fit function. (b) With CBO included in the fit function.

1828 The principal frequency will be the “Coherent Betatron Frequency,”

$$f_{CBO} = f_C - f_x = (1 - \sqrt{1 - n})f_C \simeq 470 \text{ kHz}, \quad (4.7)$$

1829 which is the frequency at which a single fixed detector sees the beam coherently moving

1830 back and forth radially. This CBO frequency is close to the second harmonic of the ($g - 2$)
 1831 frequency, $f_a = \omega_a/2\pi \simeq 228$ Hz.

1832 An alternative way of thinking about the CBO motion is to view the ring as a spec-
 1833 trometer where the inflector exit is imaged at each successive betatron wavelength, λ_{β_x} . In
 1834 principle, an inverted image appears at half a betatron wavelength; but the radial image is
 1835 spoiled by the $\pm 0.3\%$ momentum dispersion of the ring. A given detector will see the beam
 1836 move radially with the CBO frequency, which is also the frequency at which the horizontal
 1837 waist precesses around the ring. Since there is no dispersion in the vertical dimension, the
 1838 vertical waist (VW) is reformed every half wavelength $\lambda_{\beta_y}/2$. A number of frequencies in
 the ring are tabulated in Table 4.1

Table 4.1: Frequencies in the ($g - 2$) storage ring, assuming that the quadrupole field is uniform in azimuth and that $n = 0.137$.

Quantity	Expression	Frequency [MHz]	Period [μ s]
f_a	$\frac{e}{2\pi mc} a_\mu B$	0.228	4.37
f_C	$\frac{v}{2\pi R_0}$	6.7	0.149
f_x	$\sqrt{1 - n} f_c$	6.23	0.160
f_y	$\sqrt{n} f_c$	2.48	0.402
f_{CBO}	$f_c - f_x$	0.477	2.10
f_{VW}	$f_c - 2f_y$	1.74	0.574

1839 The CBO frequency and its sidebands are clearly visible in the Fourier transform to the
 1840 residuals from a fit to the five-parameter fitting function Equation 3.16, and are shown in
 1841 Figure 4.5. The vertical waist frequency is barely visible. In 2000, the quadrupole voltage
 1842 was set such that the CBO frequency was uncomfortably close to the second harmonic of
 1843 f_a , thus placing the difference frequency $f_- = f_{CBO} - f_a$ next to f_a . This nearby sideband
 1844 forced us to work very hard to understand the CBO and how its related phenomena affect
 1845 the value of ω_a obtained from fits to the data. In 2001, we carefully set f_{CBO} at two different
 1846 values, one well above, the other well below $2f_a$, which greatly reduced this problem.
 1847

1848 4.0.3 Monitoring the Beam Profile

1849 Two tools are available to us to monitor the muon distribution. Study of the beam de-
 1850 bunching after injection yields information on the distribution of equilibrium radii in the
 1851 storage ring. The traceback chambers will provide information on the vertical centroid along
 1852 with the vertical distribution of the beam.

1853 The beam bunch that enters the storage ring is expected to have a time spread with of
 1854 around $\simeq 100$ ns, while the cyclotron period is 149 ns. The momentum distribution of stored
 1855 muons produces a corresponding distribution in radii of curvature. The distributions depend
 1856 on the phase-space acceptance of the ring, the phase space of the beam at the injection point,
 1857 and the kick given to the beam at injection.

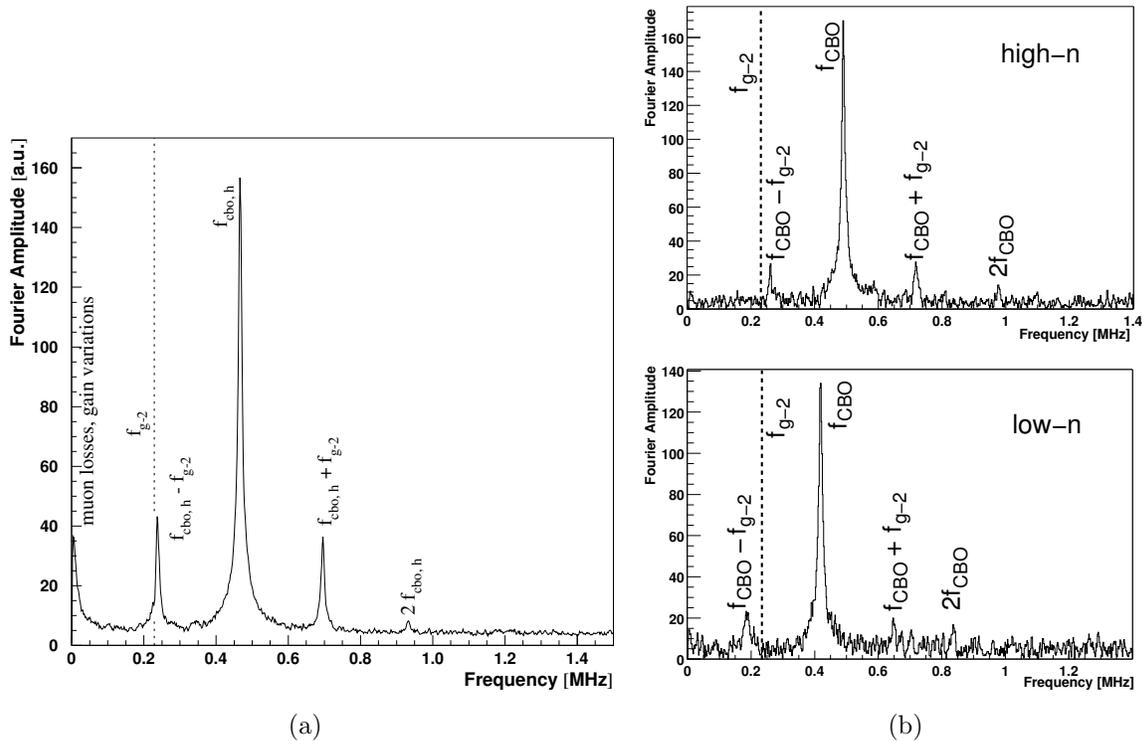


Figure 4.5: The Fourier transform to the residuals from a fit to the five-parameter function, showing clearly the coherent beam frequencies. (a) is from 2000, when the CBO frequency was close to $2\omega_a$, and (b) shows the Fourier transform for the two n -values used in the 2001 run period.

1858 **There are too many time constants in this paragraph, 23 ns, 60 μ s , 36 μ s ,**
 1859 **149 ns. I would probably unify the 36 and 60 μ s numbers somehow to avoid**
 1860 **confusion.**

1861 With the E821 inflector magnet, the narrow horizontal dimension of the beam at the
 1862 injection point, about 18 mm, restricts the stored momentum distribution to about $\pm 0.3\%$.
 1863 As the muons circle the ring, the muons at smaller radius (lower momentum) eventually
 1864 pass those at larger radius repeatedly after multiple transits around the ring, and the bunch
 1865 structure largely disappears after 60 μ s . This de-bunching can be seen in the E821 data
 1866 ($\sigma \simeq 23$ ns) in Figure 4.6 where the signal from a single detector is shown at two different
 1867 times following injection. The bunched beam is seen very clearly in the left figure, with
 1868 the 149 ns cyclotron period being obvious. The slow amplitude modulation comes from the
 1869 ($g - 2$) precession. By 36 μ s the beam has largely de-bunched.

1870 Only muons with orbits centered at the central radius have the “magic” momentum,
 1871 so knowledge of the momentum distribution, or equivalently the distribution of equilibrium
 1872 radii, is important in determining the correction to ω_a caused by the radial electric field used
 1873 for vertical focusing. Two methods of obtaining the distribution of equilibrium radii from
 1874 the beam debunching are employed in E821. One method uses a model of the time evolution

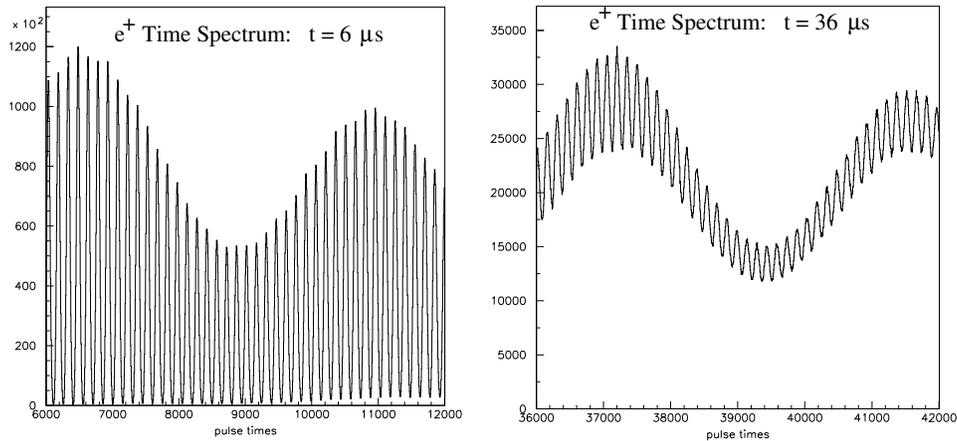


Figure 4.6: The time spectrum of a single calorimeter soon after injection. The spikes are separated by the cyclotron period of 149 ns.

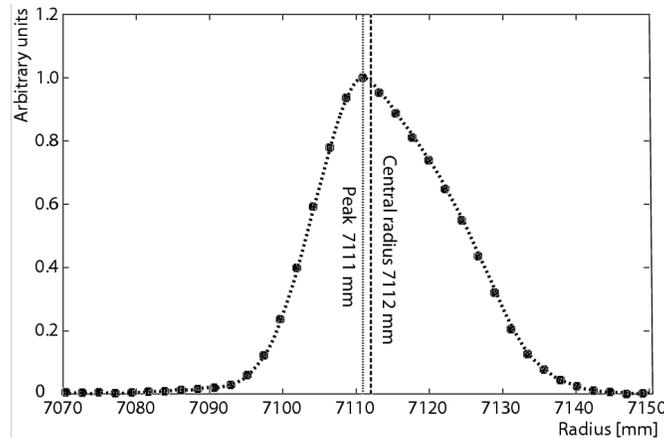


Figure 4.7: The distribution of equilibrium radii obtained from the beam de-bunching. The solid circles are from a de-bunching model fit to the data, and the dotted curve is obtained from a modified Fourier analysis.

1875 of the bunch structure. A second, alternative procedure uses modified Fourier techniques[7].
 1876 The results from these analyses are shown in Figure 4.7. The discrete points were obtained
 1877 using the model, and the dotted curve was obtained with the modified Fourier analysis.
 1878 The two analyses agree. The measured distribution is used both in determining the average
 1879 magnetic field seen by the muons and the radial electric field correction discussed below.

1880 The scintillating-fiber monitors show clearly the vertical and horizontal tunes as expected.
 1881 In Figure 4.8, the horizontal beam centroid motion is shown, with the quadrupoles powered
 1882 asymmetrically during scraping, and then symmetrically after scraping. A Fourier transform
 1883 of the latter signal shows the expected frequencies, including the cyclotron frequency of
 1884 protons stored in the ring. The traceback system also sees the CBO motion.

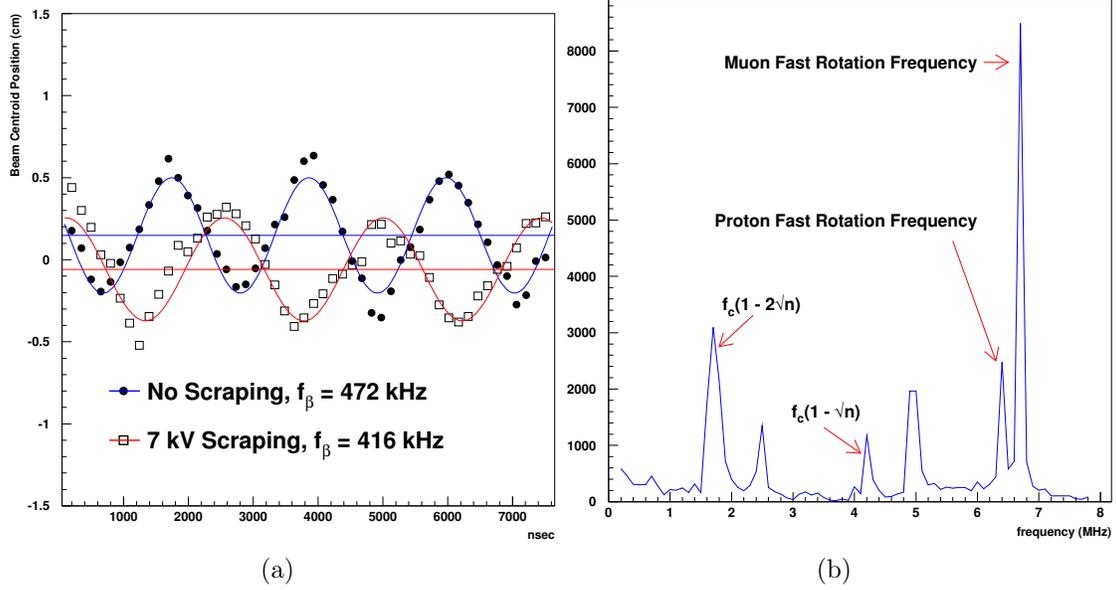


Figure 4.8: (a) The horizontal beam centroid motion with beam scraping and without, using data from the scintillating fiber hodoscopes; note the tune change between the two. (b) A Fourier transform of the pulse from a single horizontal fiber, which shows clearly the vertical waist motion, as well as the vertical tune. The presence of stored protons is clearly seen in this frequency spectrum.

1885 4.0.4 Corrections to ω_a : Pitch and Radial Electric Field

1886 In the simplest case, the rate at which the spin turns relative to the momentum is given by

$$1887 \omega_a = \omega_S - \omega_C = - \left(\frac{g-2}{2} \right) \frac{Qe}{m} B = -a \frac{Qe}{m} B \quad (4.8)$$

1887 The spin equation modified by the presence of an electric field was introduced earlier, with
 1888 the assumption that the velocity is transverse to the magnetic field, and that all muons are
 1889 at γ_{magic} . Neither of these assumptions are valid, since the vertical betatron motion must be
 1890 included, and the momentum acceptance of $\pm 0.5\%$ means the muon ensemble has a range
 1891 of momenta. Corrections for these two effects were the only corrections made to the data
 1892 In E821. In the 2001 data set, the electric field correction for the low n -value data set was
 1893 $+0.47 \pm 0.05$. The pitch correction was $+0.27 \pm 0.04$. These are the only corrections made
 1894 to the ω_a data.

1895 We sketch the derivation for E821 and E989 below[4]. For a general derivation the reader
 1896 is referred to References [5, 6].

1897 Without the assumption that $\vec{\beta} \cdot \vec{B} = 0$ the cyclotron and spin rotation frequencies
 1898 become:

$$1899 \vec{\omega}_C = -\frac{q}{m} \left[\frac{\vec{B}}{\gamma} - \frac{\gamma}{\gamma^2 - 1} \left(\frac{\vec{\beta} \times \vec{E}}{c} \right) \right], \quad (4.9)$$

1899 and the spin precession frequency becomes[?]

$$\vec{\omega}_S = -\frac{q}{m} \left[\left(\frac{g}{2} - 1 + \frac{1}{\gamma} \right) \vec{B} - \left(\frac{g}{2} - 1 \right) \frac{\gamma}{\gamma + 1} (\vec{\beta} \cdot \vec{B}) \vec{\beta} - \left(\frac{g}{2} - \frac{\gamma}{\gamma + 1} \right) \left(\frac{\vec{\beta} \times \vec{E}}{c} \right) \right]. \quad (4.10)$$

1900 Substituting for $a_\mu = (g_\mu - 2)/2$, we find that the spin difference frequency is

$$\vec{\omega}_a = -\frac{q}{m} \left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma + 1} \right) (\vec{\beta} \cdot \vec{B}) \vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]. \quad (4.11)$$

1901 If $\vec{\beta} \cdot \vec{B} = 0$, this reduces to

$$\vec{\omega}_a = -\frac{q}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]. \quad (4.12)$$

1902 For $\gamma_{\text{magic}} = 29.3$ ($p_\mu = 3.09 \text{ GeV}/c$), the second term vanishes; and the electric field does
 1903 not contribute to the spin precession relative to the momentum. The spin precession is
 1904 independent of muon momentum; *all* muons precess at the same rate. Because of the high
 1905 uniformity of the B-field, a precision knowledge of the stored beam trajectories in the storage
 1906 region is not required.

1907 First we calculate the effect of the electric field, for the moment neglecting the $\vec{\beta} \cdot \vec{B}$ term.
 1908 If the muon momentum is different from the magic momentum, the precession frequency is
 1909 given by

$$\omega'_a = \omega_a \left[1 - \beta \frac{E_r}{B_y} \left(1 - \frac{1}{a_\mu \beta^2 \gamma^2} \right) \right]. \quad (4.13)$$

1910 Using $p = \beta\gamma m = (p_m + \Delta p)$, after some algebra one finds

$$\frac{\omega'_a - \omega_a}{\omega_a} = \frac{\Delta\omega_a}{\omega_a} = -2 \frac{\beta E_r}{B_y} \left(\frac{\Delta p}{p_m} \right). \quad (4.14)$$

1911 Thus the effect of the radial electric field reduces the observed frequency from the simple
 1912 frequency ω_a given in Equation ???. Now

$$\frac{\Delta p}{p_m} = (1 - n) \frac{\Delta R}{R_0} = (1 - n) \frac{x_e}{R_0}, \quad (4.15)$$

1913 where x_e is the muon's equilibrium radius of curvature relative to the central orbit. The
 1914 electric quadrupole field is

$$E = \kappa x = \frac{n\beta B_y}{R_0} x. \quad (4.16)$$

1915 We obtain

$$\frac{\Delta\omega}{\omega} = -2n(1 - n)\beta^2 \frac{xx_e}{R_0^2 B_y}, \quad (4.17)$$

1916 so clearly the effect of muons not at the magic momentum is to lower the observed frequency.
 1917 For a quadrupole focusing field plus a uniform magnetic field, the time average of x is just
 1918 x_e , so the electric field correction is given by

$$C_E = \frac{\Delta\omega}{\omega} = -2n(1 - n)\beta^2 \frac{\langle x_e^2 \rangle}{R_0^2 B_y}, \quad (4.18)$$

1919 where $\langle x_e^2 \rangle$ is determined from the fast-rotation analysis (see Figure 4.6). The uncertainty
 1920 on $\langle x_e^2 \rangle$ is added in quadrature with the uncertainty in the placement of the quadrupoles of
 1921 $\delta R = \pm 0.5$ mm (± 0.01 ppm), and with the uncertainty in the mean vertical position of the
 1922 beam, ± 1 mm (± 0.02 ppm). For the low- n 2001 sub-period, $C_E = 0.47 \pm 0.054$ ppm.

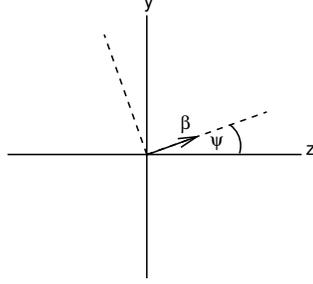


Figure 4.9: The coordinate system of the pitching muon. The angle ψ varies harmonically. The vertical direction is \hat{y} and \hat{z} is the azimuthal (beam) direction.

1923 The vertical betatron oscillations of the stored muons lead to $\vec{\beta} \cdot \vec{B} \neq 0$. Since the $\vec{\beta} \cdot \vec{B}$
 1924 term in Equation 4.10 is quadratic in the components of $\vec{\beta}$, its contribution to ω_a will not
 1925 generally average to zero. Thus the spin precession frequency has a small dependence on the
 1926 betatron motion of the beam. It turns out that the only significant correction comes from the
 1927 vertical betatron oscillation; therefore it is called the pitch correction (see Equation ??). As
 1928 the muons undergo vertical betatron oscillations, the “pitch” angle between the momentum
 1929 and the horizontal (see Figure 4.9) varies harmonically as $\psi = \psi_0 \cos \omega_y t$, where ω_y is the
 1930 vertical betatron frequency $\omega_y = 2\pi f_y$, given in Equation 4.3. In the approximation that all
 1931 muons are at the magic γ , we set $a_\mu - 1/(\gamma^2 - 1) = 0$ in Equation ?? and obtain

$$\vec{\omega}'_a = -\frac{q}{m} \left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma + 1} \right) (\vec{\beta} \cdot \vec{B}) \vec{\beta} \right], \quad (4.19)$$

1932 where the prime indicates the modified frequency as it did in the discussion of the radial
 1933 electric field given above, and $\vec{\omega}'_a = -(q/m)a_\mu \vec{B}$. We adopt the (rotating) coordinate system
 1934 shown in Figure 4.9, where $\vec{\beta}$ lies in the zy -plane, z being the direction of propagation, and y
 1935 being vertical in the storage ring. Assuming $\vec{B} = \hat{y}B_y$, $\vec{\beta} = \hat{z}\beta_z + \hat{y}\beta_y = \hat{z}\beta \cos \psi + \hat{y}\beta \sin \psi$,
 1936 we find

$$\vec{\omega}'_a = -\frac{q}{m} [a_\mu \hat{y}B_y - a_\mu \left(\frac{\gamma}{\gamma + 1} \right) \beta_y B_y (\hat{z}\beta_z + \hat{y}\beta_y)]. \quad (4.20)$$

1937 The small-angle approximation $\cos \psi \simeq 1$ and $\sin \psi \simeq \psi$ gives the component equations

$$\omega'_{ay} = \omega_a \left[1 - \left(\frac{\gamma - 1}{\gamma} \right) \psi^2 \right] \quad (4.21)$$

1938 and

$$\omega'_{az} = -\omega_a \left(\frac{\gamma - 1}{\gamma} \right) \psi. \quad (4.22)$$

1939 Rather than use the components given above, we can resolve ω'_a into components along
 1940 the coordinate system defined by $\vec{\beta}$ (see Figure 4.9) using the standard rotation formula.
 1941 The transverse component of ω' is given by

$$\omega_{\perp} = \omega'_{ay} \cos \psi - \omega'_{az} \sin \psi. \quad (4.23)$$

1942 Using the small-angle expansion for $\cos \psi \simeq 1 - \psi^2/2$, we find

$$\omega_{\perp} \simeq \omega_a \left[1 - \frac{\psi^2}{2} \right]. \quad (4.24)$$

1943 As can be seen from Table 4.1, the pitching frequency ω_y is an order of magnitude larger
 1944 than the frequency ω_a , so that in one $g-2$ period ω_{\parallel} oscillates more than ten times, thus
 1945 averaging out its effect on ω'_a so $\omega'_a \simeq \omega_{\perp}$. Thus

$$\omega_a \simeq -\frac{q}{m} a_{\mu} B_y \left(1 - \frac{\psi^2}{2} \right) = -\frac{q}{m} a_{\mu} B_y \left(1 - \frac{\psi_0^2 \cos^2 \omega_y t}{2} \right). \quad (4.25)$$

1946 Taking the time average yields a pitch correction

$$C_p = -\frac{\langle \psi^2 \rangle}{2} = -\frac{\langle \psi_0^2 \rangle}{4} = -\frac{n \langle y^2 \rangle}{4 R_0^2}, \quad (4.26)$$

1947 where we have used Equation 4.4 $\langle \psi_0^2 \rangle = n \langle y^2 \rangle / R_0^2$. The quantity $\langle y_0^2 \rangle$ was both determined
 1948 experimentally and from simulations. For the 2001 period, $C_p = 0.27 \pm 0.036$ ppm, the
 1949 amount the precession frequency is lowered from that given in Equation 4.6 because $\vec{\beta} \cdot \vec{B} \neq 0$.

1950 We see that both the radial electric field and the vertical pitching motion *lower* the
 1951 observed frequency from the simple difference frequency $\omega_a = (e/m) a_{\mu} B$, which enters into
 1952 our determination of a_{μ} using Equation 3.21. Therefore our observed frequency must be
 1953 *increased* by these corrections to obtain the measured value of the anomaly. Note that if
 1954 $\omega_y \simeq \omega_a$ the situation is more complicated, with a resonance behavior that is discussed in
 1955 References [5, 6].

References

1956

- 1957 [1] H. Wiedemann, *Particle Accelerator Physics* Vol. 1, Springer-Verlag, (1993) p. 54.
- 1958 [2] D.A. Edwards and M.J. Syphers, *An Introduction to the Physics of High Energy Accel-*
1959 *erators*, John Wiley & Sons, (1993) p. 75.
- 1960 [3] F. Combley and E. Picasso, *Phys. Rept.* **14**, 1 (1974).
- 1961 [4] We follow the approach given by J.M. Paley, Ph.D. Dissertation, Boston University,
1962 2004.
- 1963 [5] F.J.M. Farley and E. Picasso, in *Quantum Electrodynamics*, Adv. Series on Dir. in
1964 H.E.P., V7, T. Kinoshita, ed., World Scientific, 479, (1990).
- 1965 [6] F.J.M. Farley, *Phys.Lett.* **B 42**, 66 (1972), and J.H. Field, and G. Fiorentini, *Nuovo*
1966 *Cimento*, **21 A**, 297 (1974).
- 1967 [7] Y. Orlov, et al., *Nucl. Instrum. Meth.* **A482**, 767 (2002).
- 1968 [8] P. Debevec, Ringbeta, DocDB document #762.

Chapter 5

Statistical and Systematic Errors for E989

E989 must obtain twenty-one times the amount of data collected for E821. Using the T method to evaluate the uncertainty, 1.8×10^{11} events are required in the final fitted histogram to realize a 0.10 ppm statistical uncertainty. The systematic errors on the anomalous precession frequency ω_a , and on the magnetic field normalized to the proton Larmor frequency ω_p , must be reduced by a factor of three, down to the ± 0.07 ppm level. E989 will have three main categories of uncertainties:

- **Statistical.** The least-squares or maximum likelihood fits to the histograms describing decay electron events vs. time in the fill will determine ω_a , the anomalous precession frequency. The uncertainty $\delta\omega_a$ from the fits will be purely statistical (assuming a good fit). A discussion of the fitting sensitivity using various weighting schemes is given in Chapter 16, Section 16.2. The final uncertainty depends on the size of the data set used in the fit, which in turn depends on the data accumulation *rate* and the *running time*. These topics are discussed here.
- **ω_a Systematics.** Additional systematic uncertainties that will affect $\delta\omega_a$ might be anything that can will cause the extracted value of ω_a from the fit to differ from the true value, beyond statistical fluctuations. Categories of concern include the detection system (e.g., gain stability and pileup immunity), the incoming beamline (lost muons, spin tracking), and the stored beam (coherent betatron oscillations, differential decay, E and pitch correction uncertainties). These topics are discussed in Chapter ??.
- **ω_p Systematics.** The magnetic field is determined from proton NMR in a procedure described in Chapter 15. The uncertainties are related to how well known are the individual steps from absolute calibration to the many stages of relative calibration and time-dependent monitoring. The “statistical” component to these measurements is negligible.

The purpose of this chapter is twofold. First, we summarize the event-rate calculation from initial proton flux to fitted events in the final histograms in order to determine the running time required to meet the statistical goals of the experiment. We also gather the

1999 results of many systematic uncertainty discussions that are described in various chapters
 2000 throughout this document and roll up the expected systematic uncertainty tables for E989.

2001 5.1 Event Rate Calculation Methodologies

2002 The E989 Proposal [1] event rate estimate was made by making a **relative comparison**
 2003 **approach** using like terms with respect to the known situation for rates in the E821 BNL
 2004 experiment. Many factors allow for trivial adjustments (proton fills per second, kinematics
 2005 of the decay line length, kinematics of the decay line capture), while others rely on expected
 2006 improvements in specific hardware components (optimized storage ring kicker pulse shape
 2007 and magnitude, open-ended inflector, thinner Q1 outer plate and standoffs). In E821, the
 2008 transmission through the inflector, passage through the Q1 outer plates and the kick onto
 2009 the orbit all multiply to give the storage ring efficiency, but individually the contribution
 2010 from each is not known as well as the product. However, we can deduce the realized stored
 2011 muon fraction compared to the incoming muon beam intensity. For the new experiment,
 2012 each of these beam-storage elements is being optimized and we can make good estimates of
 2013 the expected improvement.

2014 We are also developing a stand-alone **bottom up** approach in which each factor is
 2015 individually studied or measured to obtain the final event rate. While not complete at this
 2016 time, this approach is converging with several factor represented by a range, owing to ongoing
 2017 design development. We present our progress on this approach in the section that follow the
 2018 Relative Comparison discussion.

2019 5.1.1 Event Rate by a Relative Comparison to E821

2020 Table 5.1 contains a sequential list of factors that affect the event rate from proton on target
 2021 to events in the final histogram. It is modified, where appropriate, compared to the 2010
 2022 Proposal based on new information and studies to date.

2023 A pion production calculation using MARS was made to estimate the number of 3.1 GeV/ c
 2024 pions emitted into the accepted phase space of the AP2 line. From this point, a conserva-
 2025 tive approach was to compare known factors between the muon capture and transmission
 2026 at Fermilab to those same factors at BNL. Many of the factors are relatively trivial to com-
 2027 pute, while others rely on our detailed Decay Turtle simulations of the BNL lattice and
 2028 modifications of this lattice for Fermilab. We are in the process of a complete end-to-end
 2029 calculation of the beamline, but this work will take additional time. In the comparison to
 2030 BNL approach, we find the important increase of stored muons per incident proton of 11.5,
 2031 assuming an improved kicker and an open-ended inflector. We require a factor of at least
 2032 6 for an experiment that can be done in less than 2 years. We use the factor of 6 in our
 2033 beam estimates, thus introducing a “beam-time contingency” factor of nearly 100% from
 2034 the beginning. Experience from E821 suggests that 1 month of setup time with beam will
 2035 be required before “good” data are obtained and an integrated second month devoted to
 2036 systematic studies will be distributed throughout the data collection period. We assume
 2037 a possibly aggressive 75% factor the the efficiency of data taking during normal running.
 2038 The down time includes the accelerator complex inefficiency (unknown to us for this new

operation) and the time to be spent mapping the magnet with the trolley (mapping will take place whenever the accelerator is down or will interrupt data taking periodically if the uninterrupted machine uptime exceeds, for example, 2 days. Mapping will take approximately 3 hours. The origin of each factor in Table 5.1, is explained in a series of notes following the Table. Notes explaining entries in Table 5.1 and comparison remarks to what was assumed

Table 5.1: Event rate calculation using known factors and a comparison to the realized stored muon fraction at BNL. This table has been updated compared to the 2010 E989 Proposal.

Item	Value	Rates	Note
Booster cycle (BC) - 15 Hz operation	1.33 s/BC	0.75 BC/s	1
Proton Batches to $g-2$	4/BC	3 batch/s	2
Proton Bunches \rightarrow fill	4/batch	12 fill/s	3
Protons on target	10^{12} p/bunch	1.2×10^{13} p/s	4
BNL realized stored μ/p efficiency	1×10^{-9} μ/p		5
FNAL estimated μ/p improvement factor	6	6000 μ /fill	6
Positrons accepted with $E > 1.8$ GeV	0.15	720 e^+ /fill	7
Positrons with $t > 30$ μ s	0.63	567 e^+ /fill	8
Number of fills for 1.8×10^{11} events	3.17×10^8 fills		9
DAQ and experiment production uptime	0.75		10
Time (months) to collect statistics	14 months		11
Commissioning time for new setup	2 months		12
Systematic studies (data not included in final fits)	2 month	s	13
Net data taking time	18 months		14

in the E989 Proposal.

1. 15 Hz Booster operation remains a valid assumption.
2. Neutrino program uses 12 out of 20 batches; 8 out of 20 are in principle available, but preparation of the 4 separated bunches of proton in the Recycler requires two Booster cycles. Therefore, only 4 of the 8 can be used. This is a change compared to the Proposal, which assumed 6/8 were useable.
3. Subdivision in Recycler of each batch into 4 “bunches” with roughly equal intensity of $\approx 1 \times 10^{12}$ p/bunch. Each is extracted separately with ~ 12 ms spacing and each initiates a storage ring “fill.”
4. Expected proton intensity per Bunch, or per fill, striking target.
5. Measured stored muon fraction per 24-GeV proton on target at BNL per 10^{12} p (Tp). This number rolls up individual factors including the FODO line length, the non-forward muon acceptance used to minimize the hadronic flash, the transmission through the closed-ended inflector, the losses in the outer Q1 quadrupole plate and standoffs, and the sub-optimal storage ring kicker efficiency

- 2059 6. The improvement factor was estimated by comparing to the known situation at BNL.
2060 We arrive at the following factors: $\times 0.4$ for the reduced pion yield; $\times 1.8$ for the AP2
2061 line with smaller beta function; $\times 2$ for the longer decay channel; $\times 3$ for the forward
2062 decay optimal muon tune; $\times 1.33$ for opening up the pion momentum acceptance; $\times 2$
2063 for the open inflector and improved kicker = 11.5. We use a factor of 6 to be very
2064 conservative. The factors here are most important at this Conceptual Design phase.
- 2065 7. Monte Carlo acceptance of 15% for events with energy above 1.8 GeV and striking the
2066 front face of one of the 24 calorimeter stations.
- 2067 8. Assume fit can be started at 30 μs , this factor represents those muons that have not
2068 yet decayed.
- 2069 9. Given the accepted fraction of events per fill listed in row above, this row gives the
2070 required number of fills to obtain the full statistical precision (not systematic studies
2071 or startup).
- 2072 10. Estimate of the uptime for the experiment and accelerator complex during steady-state
2073 data production running. Downtime will occur from accelerator issues related to the
2074 new operational modes and to routine maintenance and servicing; time required by the
2075 experiment to run trolley field mapping program (typically 3 h / 2 days), and ordinary
2076 DAQ and experimental issues requiring intervention. This is a slight aggressive number.
- 2077 11. Estimate of 2 months to commission the new experiment and machine operation se-
2078 quence. This is based, in part, on past experience at BNL, and new configuration at
2079 FNAL.
- 2080 12. Estimate of periodic dedicated systematic study weeks during data taking periods.
2081 These are crucial to establish uncertainties, but this data typically will not be included
2082 in the final statistics.
- 2083 13. Net data taking in months.

5.1.2 Bottom-Up Event Rate Calculation

Table 5.2 contains a sequential list of factors that affect the event rate based on a bottom-up approach. We include a column here, where appropriate, with an uncertainty factor if it is large enough to significantly affect the outcome. As in the previous section, the last column points to a list of Notes that explain the individual entries. Notes explaining entries in

Table 5.2: Event rate calculation using a bottom-up approach.

Item	Estimate	CDR Reference	Note
Protons per fill on target	10^{12} p	7.3	1
Positive-charged secondaries with $dp/p = \pm 2\%$???	7.4.1	2
π^+ fraction of secondaries	0.45 ???	7.4.1	2
π^+ flux entering FODO decay line	$> 2 \times 10^7$	7.4.1	2
Pion decay to muons in 220 m of M2/M3 line	0.72		3
Muons captured fraction with $dp/p < \pm 2.0\%$	0.0036	DocDB 895	4
Muon survival to storage ring	0.90	–	5
Muons arriving at front of inflector per fill	4.7×10^4	–	
Transmission and Storage Simulation	0.10 ± 0.04	10.5.1	6
Stored muons per fill	$(4.7 \pm 1.9) \times 10^3$	–	6
Positrons accepted per fill (factors 0.15 x 0.65)	450 ± 180	See Table 5.1	–
Number of fills for 1.8×10^{11} events	$(1.4 \pm 0.4) \times 10^8$ fills	–	
Time (months) to collect statistics	(13 ± 5) months		
Commissioning time for new setup	2 months		
Systematic studies (data not included in final fits)	2 months		
Net data taking time	17 ± 5 months		

Table 5.2.

1. Same starting point as in Table 5.1.
2. MARS calculation, backed up with 2012 measurement. Assumes improved proton spot size on target to 0.15 mm, which increases the yield by 40 – 60% compared to the measured rates at 0.5 mm spot size. Assumes 40-mm-mr emittance. Measurement verifies yield of positive particles. Simulation shows that 45% of them are pions. The target yield could increase by 14 – 22% if the target geometry were further optimized; see Fig. 7.10 and the text in that section.
3. Pion decay length = 173 m. M2 line = 115.6 m; M3 = 96.7 m; use 220 m total.
4. Preliminary fraction based on a phase Space simulations assuming pion emittance = beam admittance = 40 mm mrad both in x and y ; pions fill the phase space uniformly; muon momentum: $p_{magic} \pm 0.5\%$; These studies are being repeated using full Monte Carlo with G4Beamline. See Tishchenko and Morse, DocDB 895.
5. Transmission to storage ring; survive 1800 m; $(c\beta\gamma\tau)_\mu = 19280m$.

2103 6. Average results from studies of transmission through the inflector, through the outer
2104 Q1 quadrupole and standoffs, and then kicked onto orbit and stored. The kicker is
2105 assumed to be perfect and that its kick width covers the entire incoming pulse train
2106 (to be determined). The inflector is modeled as having either closed ends, as in the
2107 present E821 inflector that will be used initially, or as open-ended, meaning a material
2108 free version of the same device. Additional studies look at not only an open inflector,
2109 but also a large one. We do not include that here. The Q1 and standoff intercept the
2110 incoming beam. If they were massless, a greater fraction of muons is stored. Plans
2111 are in place to reduce mass and move the standoffs. The transmission fraction for a
2112 0.5% dp/p muon beam ranges from 6.5% to 14.5% depending on mass options used
2113 for inflector and Q1. We take a central value of 10% here and propagate the range
2114 of uncertainty, which depends on what will be built. The simulation is described in
2115 10.5.1.

2116 **I have to finish these comments but something feels wrong in the rate ... too**
2117 **high now**

Table 5.3: The largest systematic uncertainties for the final E821 ω_a analysis and proposed upgrade actions and projected future uncertainties for data analyzed using the T method. The relevant Chapters and Sections are given where specific topics are discussed in detail.

E821 Error	Size [ppm]	Plans for E989 Improvements	Goal [ppm]	Chapter & Section
Gain changes	0.12	Better laser calibration low-energy threshold	0.02	??
Pileup	0.08	Low-energy samples recorded calorimeter segmentation	0.04	??
Lost muons	0.09	Better collimation in ring	0.02	
CBO	0.07	Higher n value (frequency)		
E and pitch	0.05	Better match of beamline to ring Improved traceback Precise storage ring simulations	< 0.03 0.03	
Total	0.18	Quadrature sum	0.07	

2118 5.2 ω_a systematic uncertainty summary

2119 Our plan of data taking and hardware changes address the largest systematic uncertainties
 2120 and aims to keep the total combined uncertainty below 0.07 ppm. Experience shows that
 2121 many of the “known” systematic uncertainties can be addressed in advance and minimized,
 2122 while other more subtle uncertainties appear only when the data is being analyzed. Because
 2123 we have devised a method to take more complete and complementary data sets, we anticipate
 2124 the availability of more tools to diagnose such mysteries should they arise. Table 16.1
 2125 summarizes this section.

Table 5.4: Systematic uncertainties estimates for the magnetic field, ω_p , measurement. The final E821 values are given for reference and the proposed upgrade actions are projected. Note, several items involve ongoing R&D, while others have dependencies on the uniformity of the final shimmed field, which cannot be known accurately at this time. The relevant Chapters and Sections are given where specific topics are discussed in detail.

E821 Error	Size [ppm]	Plans for E989 Improvements	Goal [ppm]	Chapter & Section
Some Item	0.0X	Improved blah blah blah	0.02*	15
Some Item	0.0X	Depends on field uniformity	0.03**	15
Total	0.18	Quadrature sum (see notes below)	0.085	

*We have an R&D plan here to try to lower this systematic uncertainty

**We can better assess this systematic error only after the Field has been mapped

2126 **5.3 ω_p systematic uncertainty summary**

2127 The magnetic field is mapped by use of NMR probes. A detailed discussion is found in
 2128 Chapter 15. Here we produce a summary Table of the expected systematic uncertainties.

2129 References

- 2130 [1] R. M. Carey, K. R. Lynch, J. P. Miller, B. L. Roberts, W. M. Morse, Y. K. Semertzides,
2131 V. P. Druzhinin and B. I. Khazin *et al.*, “The New (g-2) Experiment: A proposal to
2132 measure the muon anomalous magnetic moment to ± 0.14 ppm precision,” FERMILAB-
2133 PROPOSAL-0989.
- 2134 [2] Bennett GW, et al.(The $g - 2$ Collab.) Phys. Rev. D, 73:072003 (2006)
- 2135 [3] B. Morse, Phase Space Calculations of Muon Injection, Brookhaven National Labora-
2136 tory, 1998, (g-2) note #303, 1998.
- 2137 [4] V. Tishchenko and W.M. Morse, Phase-Space Calculations of the Muon Acceptance by
2138 the Straight Section of the Fermilab Beamline, Brookhaven National Laboratory, docdb
2139 #487, 2012.

Chapter 6

Civil Construction Off-Project

The experimental hall is funded as a General Plant Project (GPP), as part of the Muon Campus Program. The beamline and tunnel from the delivery ring to the hall are separate GPP and Accelerator Improvement Projects (AIP). The locations of the buildings on the muon campus is shown in Fig. 6.1.

6.1 The MC1 Building

The muon storage ring will be located in the MC-1 Building on the Muon Campus, which is shown in Fig. 6.2. While it is a general purpose building, the design and features are extremely important to the success of E989. The principal design considerations are a very stable floor, and good temperature stability in the experimental hall. Both of these features were absent at Brookhaven, and presented difficulties to the measurement of the precision field. This design will serve E989, and subsequent experiments well. One portion of the MC1 building will house beamline power supplies and cryo facilities for the two initial experiments on the muon campus: ($g - 2$) and Mu2e.

The floor in the experimental area will be reinforced concrete 2' 9" (84 cm) thick. The floor is 12' below grade. Core samples show that the soil at the location is very compacted, the floor settling is expected to be about 0.25" fully loaded.

This floor will be significantly better than the floor in Building 919 at Brookhaven, where the ring was housed for E821. That floor consisted of three separate pieces: a concrete spine down the middle of the room, with a concrete pad on each side of the spine. Thus the foundation of the ring will be much more mechanically stable than it was at BNL.

Even more important is the temperature stability available in MC-1. The HVAC system will hold the temperature steady to $\pm 2^\circ$ F during magnet operation and data collection. This stability, combined with thermal insulation around the magnet will minimize the changes in the field due to temperature changes in the experimental hall.

A floor plan of MC-1 is shown in Fig. 6.3. The experimental hall is 80' \times 80' with a 30 ton overhead crane. The loading dock in the lower left-hand corner is accessed through the roll-up door labeled in Fig. 6.2 . Unlike in BNL 919, the crane coverage is significantly larger than the storage-ring diameter, simplifying many tasks in assembling the ring.

A detailed MC-1 document is available from FESS, titled "MC-1 Building", dated March



Figure 6.1: The layout of the Muon Campus, which lies between the former Antiproton Rings and the Booster Accelerator. The locations of the $(g - 2)$ and Mu2e experiments are labeled.



Figure 6.2: A rendering of the MC1 building.

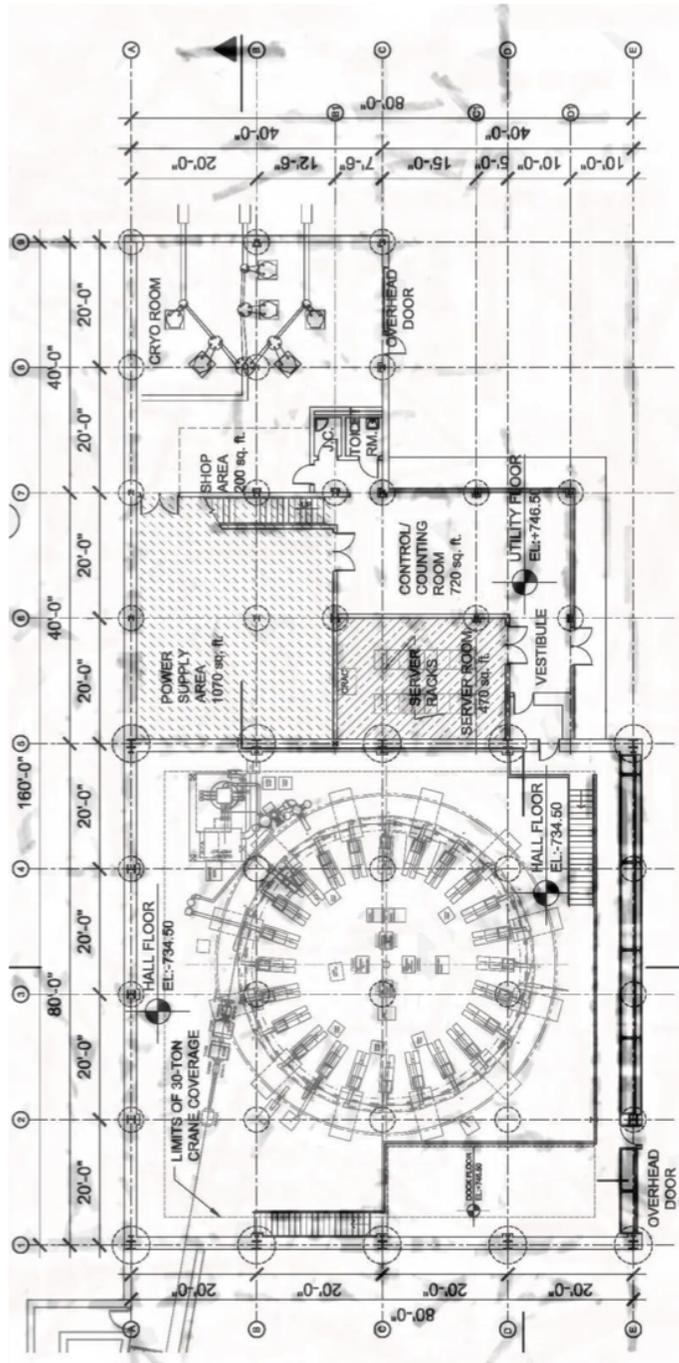


Figure 6.3: The first-floor layout of the MC1 building.

Chapter 7

Accelerator and Muon Delivery

In order to achieve a statistical uncertainty of 0.1 ppm, the total $(g-2)$ data set must contain at least 1.8×10^{11} detected positrons with energy greater than 1.8 GeV, and arrival time greater than $30 \mu\text{s}$ after injection into the storage ring. This is expected to require 4×10^{20} protons on target including commissioning time and systematic studies. For optimal detector performance, the number of protons in a single pulse to the target should be no more than 10^{12} and the number of secondary protons transported into the muon storage ring should be as small as possible. Data acquisition limits the time between pulses to be at least 10 ms. The revolution time of muons around the storage ring is 149 ns, and therefore the experiment requires the bunch length to be no more than ~ 100 ns. Systematic effects on muon polarization limit the momentum spread dp/p of the secondary beam. Requirements and general accelerator parameters are given in Table 7.1.

Parameter	Design Value	Requirement	Unit
Total protons on target	$2.3 \times 10^{20}/\text{year}$	4×10^{20}	protons
Interval between beam pulses	10	≥ 10	ms
Max bunch length (full width)	120 (95%)	< 149	ns
Intensity of single pulse on target	10^{12}	10^{12}	protons
Max Pulse to Pulse intensity variation	± 10	± 50	%
$ dp/p $ of pions accepted in decay line	2-5	2	%
Momentum of muon beam	3.094	3.094	GeV/c
Muons to ring per 10^{12} protons on target	$(0.5 - 1.0) \times 10^5$	≥ 6000 stored	muons

Table 7.1: General beam requirements and design parameters.

7.1 Overall Strategy

The $(g-2)$ experiment at Fermilab is designed to take advantage of the infrastructure of the former Antiproton Source, as well as improvements to the Proton Source and the conversion of the Recycler to a proton-delivery machine. It is also designed to share as much infrastructure as possible with the Mu2e experiment in order to keep overall costs low.

2190 The Antiproton Accumulator will no longer be in use, and many of its components will be
 2191 reused for the new and redesigned Muon beamlines. Stochastic cooling components and other
 2192 infrastructure no longer needed in the Debuncher ring will be removed in order to improve the
 2193 aperture, proton abort functionality will be added, and the ring will be renamed the Delivery
 2194 Ring (DR). The former AP1, AP2, and AP3 beamlines will be modified and renamed M1,
 2195 M2, and M3. The DR Accelerator Improvement Project (AIP) will provide upgrades to the
 2196 Delivery Ring. The Beam Transport AIP will provide aperture improvements to the P1, P2,
 2197 and M1 lines needed for future muon experiments using 8 GeV protons, including ($g - 2$).
 The layout of the beamlines is shown in Fig. 7.1.

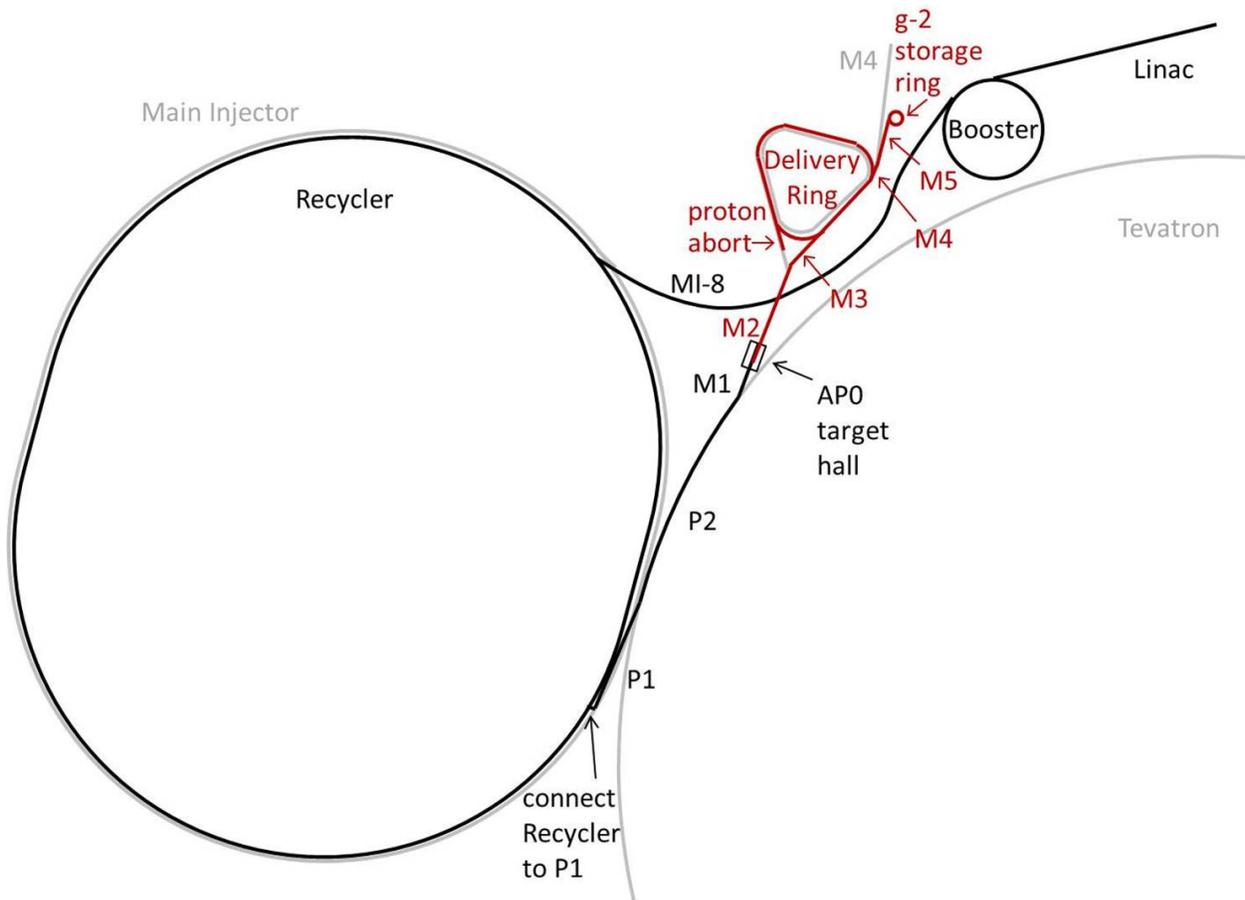


Figure 7.1: Path of the beam to ($g - 2$). Protons (black) are accelerated in the Linac and Booster, are re-bunched in the Recycler, and then travel through the P1, P2, and M1 lines to the AP0 target hall. Secondary beam (red) then travels through the M2 and M3 lines, around the Delivery Ring, and then through the M4 and M5 lines to the muon storage ring.

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The Proton Improvement Plan [1], currently underway, will allow the Booster to run at 15 Hz, at intensities of 4×10^{12} protons per Booster batch. Following the completion of the Accelerator and NuMI Upgrades (ANU) subproject at Fermilab to prepare for the $\text{NO}\nu\text{A}$ experiment [2], the Main Injector (MI) will run with a 1.333 s cycle time for its neutrino program, with twelve batches of beam from the Booster being accumulated in the Recycler

2204 and single-turn injected into the MI at the beginning of the cycle. While the NO ν A beam is
 2205 being accelerated in the MI, eight Booster batches will be available for experimental programs
 2206 such as $(g - 2)$ which use 8 GeV protons. The ANU subproject will also enable injection from
 2207 the Booster into the Recycler. Extraction from the Recycler to the P1 beamline, required
 2208 for $(g - 2)$, will be implemented in the Beam Transport AIP.

2209 Protons from the Booster with 8 GeV kinetic energy will be re-bunched into four smaller
 2210 bunches in the Recycler and transported through the P1, P2, and M1 beamlines to a target
 2211 at AP0. Secondary beam from the target will be collected using a focusing device, and
 2212 positively-charged particles with a momentum of 3.11 GeV/c ($\pm \sim 5\%$) will be selected
 2213 using a bending magnet. Secondary beam leaving the target station will travel through the
 2214 M2 and M3 lines which are designed to capture as many muons with momentum 3.094 GeV/c
 2215 from pion decay as possible. The beam will then be injected into the Delivery Ring. After
 2216 several revolutions around the DR, essentially all of the pions will have decayed into muons,
 2217 and the muons will have separated in time from the heavier protons. A kicker will then be
 2218 used to abort the protons, and the muon beam will be extracted into the new M4 line, and
 2219 finally into the new M5 beamline which leads to the $(g - 2)$ storage ring. Note that the M3
 2220 line, Delivery Ring, and M4 line are also designed to be used for 8 GeV proton transport by
 2221 the Mu2e experiment.

2222 The expected number of muons transported to the storage ring, based on target-yield
 2223 simulations using the antiproton-production target and simple acceptance assumptions, is
 2224 $(0.5 - 1.0) \times 10^5$. Beam tests were conducted using the existing Antiproton-Source config-
 2225 uration with total charged-particle intensities measured at various points in the beamline
 2226 leading to the Debuncher, which confirmed the predicted yields to within a factor of two [3].
 2227 More details are given in Sec. 7.4.1.

2228 7.2 Protons from Booster

2229 During the period when $(g - 2)$ will take data, the Booster is expected to run with present
 2230 intensities of 4×10^{12} protons per batch, and with a repetition rate of 15 Hz. In a 1.333 s
 2231 Main-Injector super cycle, twelve Booster batches are slip-stacked in the Recycler and then
 2232 accelerated in the MI and sent to NO ν A. While the Main Injector is ramping, a time corre-
 2233 sponding to eight Booster cycles, the Recycler is free to send 8 GeV (kinetic energy) protons
 2234 to $(g - 2)$. The RF manipulations of beam for $(g - 2)$ in the Recycler (Sec. 7.3.1) allow
 2235 $(g - 2)$ to take four of the eight available Booster batches. Figure 7.2 shows a possible time
 2236 structure of beam pulses to $(g - 2)$.

2237 The following section describes improvements needed to run the proton source reliably
 2238 at 15 Hz.

2239 7.2.1 Proton Improvement Plan

2240 The Fermilab Accelerator Division has undertaken a Proton Improvement Plan (PIP) [1]
 2241 with the goals of maintaining viable and reliable operation of the Linac and Booster through
 2242 2025, increasing the Booster RF pulse repetition rate, and doubling the proton flux without
 2243 increasing residual activation levels.

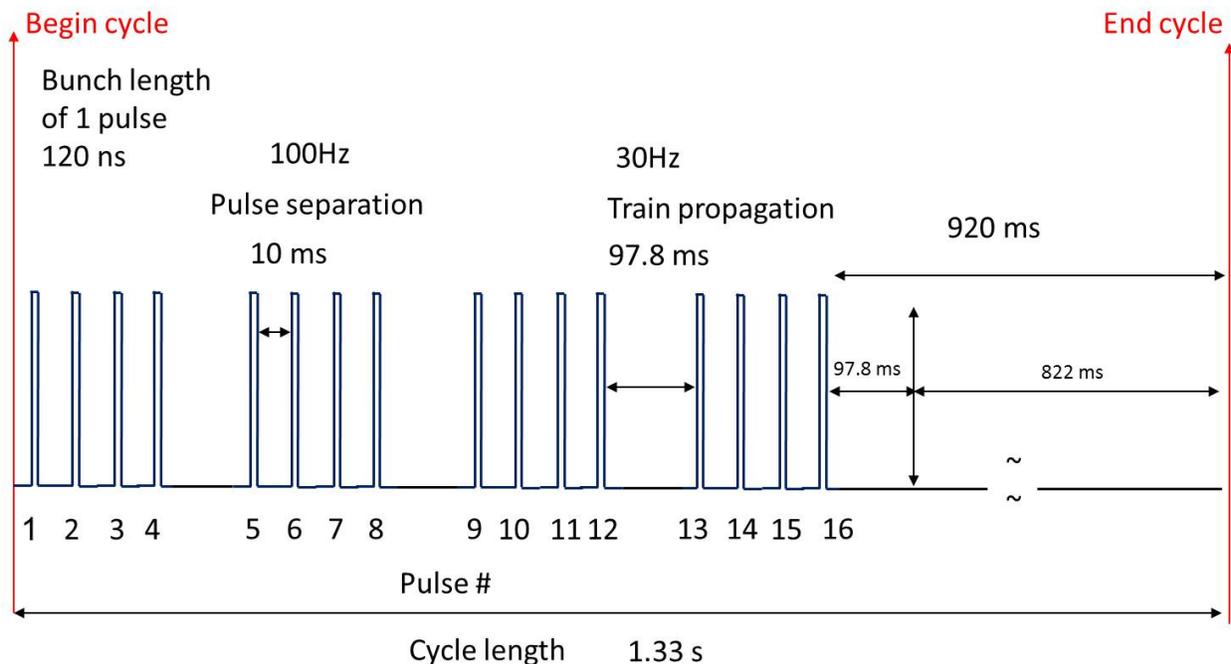


Figure 7.2: Time structure of beam pulses to $(g - 2)$.

2244 The replacement of the Cockroft-Walton pre-accelerator with a radio-frequency quadrupole
 2245 (RFQ) during the 2012 shutdown is expected to increase reliability of the pre-accelerator and
 2246 to improve beam quality.

2247 The Booster RF solid-state upgrade is necessary for reliable 15 Hz RF operations. This
 2248 involves the replacement of 40-year-old electronics that are either obsolete, difficult to find, or
 2249 unable to run at the required higher cycle-rate of 15 Hz, and will allow for easier maintenance,
 2250 shorter repair times, and less radiation exposure to personnel. The solid-state upgrade will
 2251 be completed in 2013.

2252 Refurbishment of the Booster RF cavities and tuners, in particular, cooling, is also nec-
 2253 essary in order to operate at a repetition rate of 15 Hz.

2254 Other upgrades, replacements, and infrastructure improvements are needed for viable
 2255 and reliable operation. Efforts to reduce beam loss and thereby lower radiation activation
 2256 include improved methods for existing processes, and beam studies, e.g., aimed at finding
 2257 and correcting aperture restrictions due to misalignment of components.

2258 The proton flux through the Booster over the past two decades and projected into 2016
 2259 based on expected PIP improvements is shown in Fig. 7.3.

2260 The new PIP flux goal will double recent achievements and needs to be completed within
 2261 five years. Figure 7.4 shows both the increase in flux as well as planned users. The goal
 2262 of doubling the proton flux will be achieved by increasing the number of cycles with beam.
 2263 The intensity per cycle is not planned to increase.

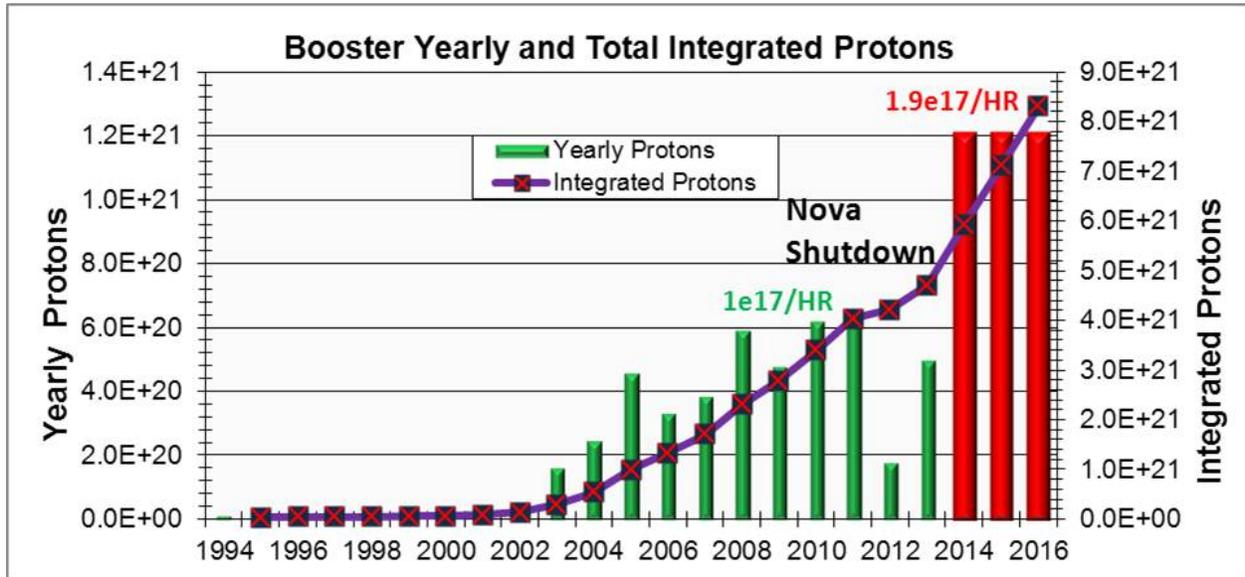


Figure 7.3: Yearly and integrated proton flux (including PIP planned flux increase).

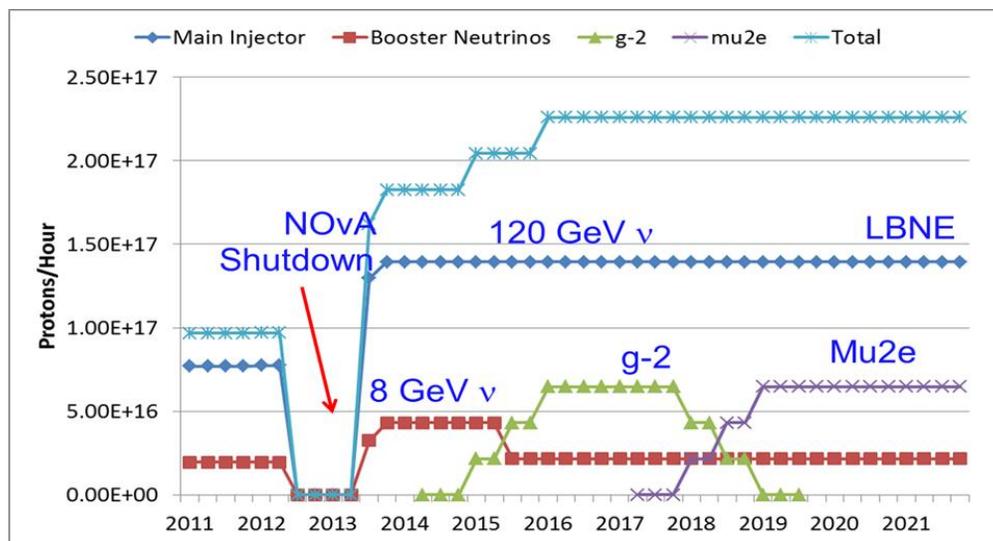


Figure 7.4: Expectations for increases in the proton flux from the Proton Source needed for future experiments.

2264 7.3 Recycler

2265 The $(g - 2)$ experiment requires a low number of decay positrons in a given segment of
 2266 the detector, and therefore requires that the full-intensity (4×10^{12} protons) bunches be
 2267 redistributed into four bunches of 1×10^{12} protons. These bunches should be spaced no
 2268 closer than 10 ns to allow for muon decay and data acquisition in the detector. Because
 2269 the revolution time of muons in the $(g - 2)$ ring is 149 ns, the longitudinal extent of the
 2270 bunches should be no more than 120 ns. The Recycler modifications needed to achieve these
 2271 requirements will be made under the Recycler AIP, and are described below.

2272 7.3.1 Recycler RF

2273 The proposed scheme for $(g - 2)$ bunch formation [4] uses one RF system, 80 kV of 2.5 MHz
 2274 RF. The design of the RF cavities will be based on that of existing 2.5 MHz cavities which
 2275 were used in collider running, but utilizing active ferrite cooling. The ferrites of the old
 2276 cavities and the old power amplifiers will be reused in the new system.

2277 In order to avoid bunch rotations in a mismatched bucket, the 2.5 MHz is ramped “adi-
 2278 abatically” from 3 to 80 kV in 90 ms. Initially the bunches are injected from the Booster
 2279 into matched 53 MHz buckets (80 kV of 53 MHz RF), then the 53 MHz voltage is turned off
 2280 and the 2.5 MHz is turned on at 3 kV and then ramped to 80 kV. The first 2.5 MHz bunch
 2281 is then extracted and the remaining three bunches are extracted sequentially in 10 ms inter-
 2282 vals. The formation and extraction of all four bunches takes two Booster ticks or 133 ms.
 2283 This limits the $(g - 2)$ experiment to using four of the available eight Booster ticks in every
 2284 Main-Injector super cycle.

2285 Simulated 2.5 MHz bunch profiles are shown in Fig. 7.5. The 53 MHz voltage was ramped
 2286 down from 80 to 0 kV in 10 ms and then turned off. The 2.5 MHz voltage was snapped to
 2287 3 kV and then adiabatically raised to 80 kV in 90 ms. The maximum momentum spread is
 2288 $dp/p = \pm 0.28\%$. The overall efficiency is 95%, and 95% of the beam captured is contained
 2289 within 120 ns. Roughly 75% of the beam is contained in the central 90 ns and 60% in 50 ns.

2290 Although the Recycler is not yet configured to do such RF manipulations, by using the
 2291 2.5 MHz coalescing cavities in the Main Injector, the proposed bunch-formation scheme was
 2292 tested with beam. In general, the agreement between simulations and data is very good.
 2293 For illustration, the comparison between the beam measurements and the simulations for
 2294 the case in which the 2.5 MHz voltage is ramped adiabatically from 3 to 70 kV in 90 ms is
 2295 shown in Fig. 7.6.

2296 Extraction from the Recycler and primary proton beam transport will be described in
 2297 the beamline section, Sec. 7.5.

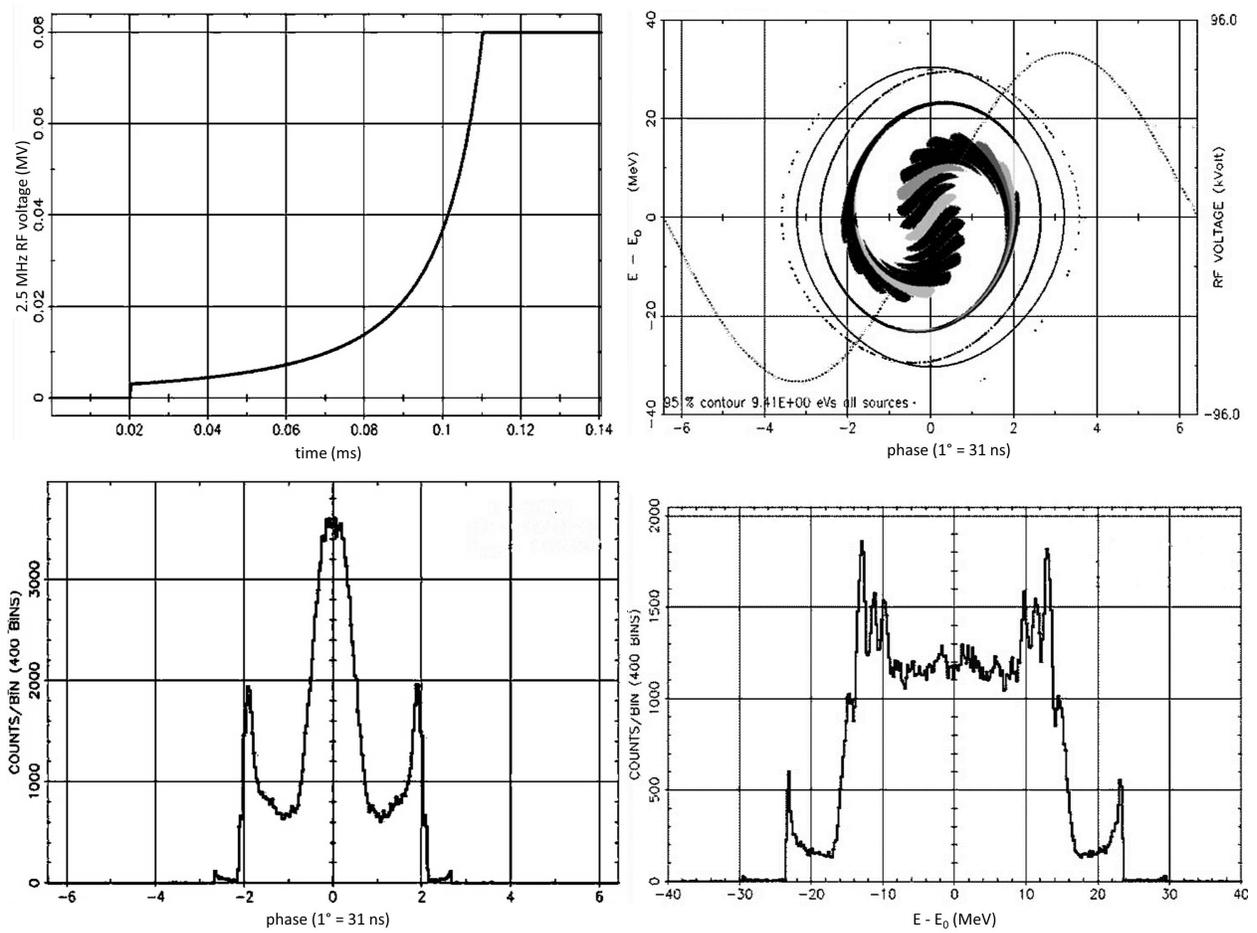


Figure 7.5: Results of RF simulations: 2.5 MHz voltage curve (upper left), phase space distribution (upper right), phase projection (lower left) and momentum projection (lower right).

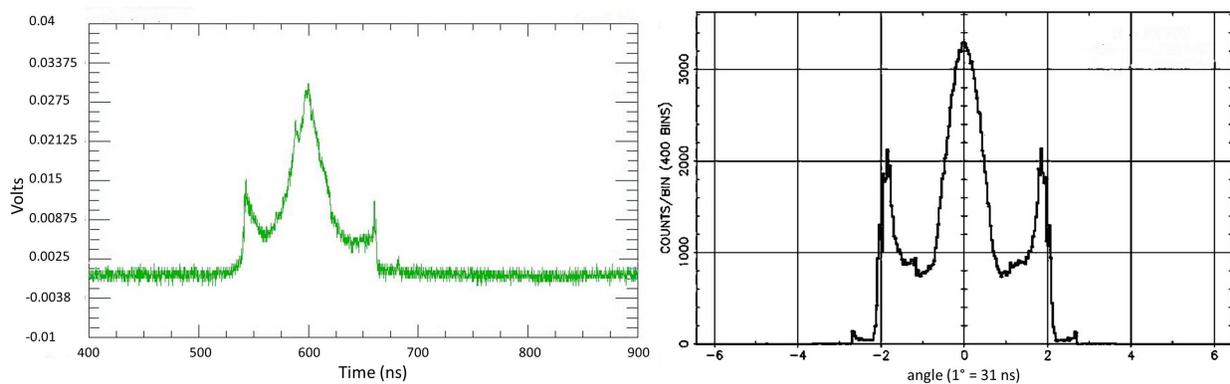


Figure 7.6: Comparison of beam profile (left) with simulation (right) for the case in which the 2.5 MHz voltage is ramped “adiabatically” from 3-70 kV in 90 ms. In both profiles, 95% of the particles captured are contained within 120 ns.

7.4 Target station

The ($g - 2$) production target station will reuse the existing target station that has been in operation for antiproton production for the Tevatron Collider for 23 years, while incorporating certain modifications. The ($g - 2$) target station will be optimized for maximum π^+ production per proton on target (POT) since the experiment will utilize muons from pion decay. Repurposing the antiproton target station to a pion production target station takes full advantage of a preexisting tunnel enclosure and service building with no need for civil construction. Also included are target vault water cooling and air ventilation systems, target systems controls, remote handling features with sound working procedures and a module test area. Figure 7.7 shows the current target-station (vault) layout. The overall layout of the target-vault modules will be unchanged from that used for antiproton production. The major differences in design will include different primary and secondary beam energies, polarity of the selected particles and pulse rate. Upgrades to pulsed power supplies, target design, pulsed-magnet design and the target dump are all considered.

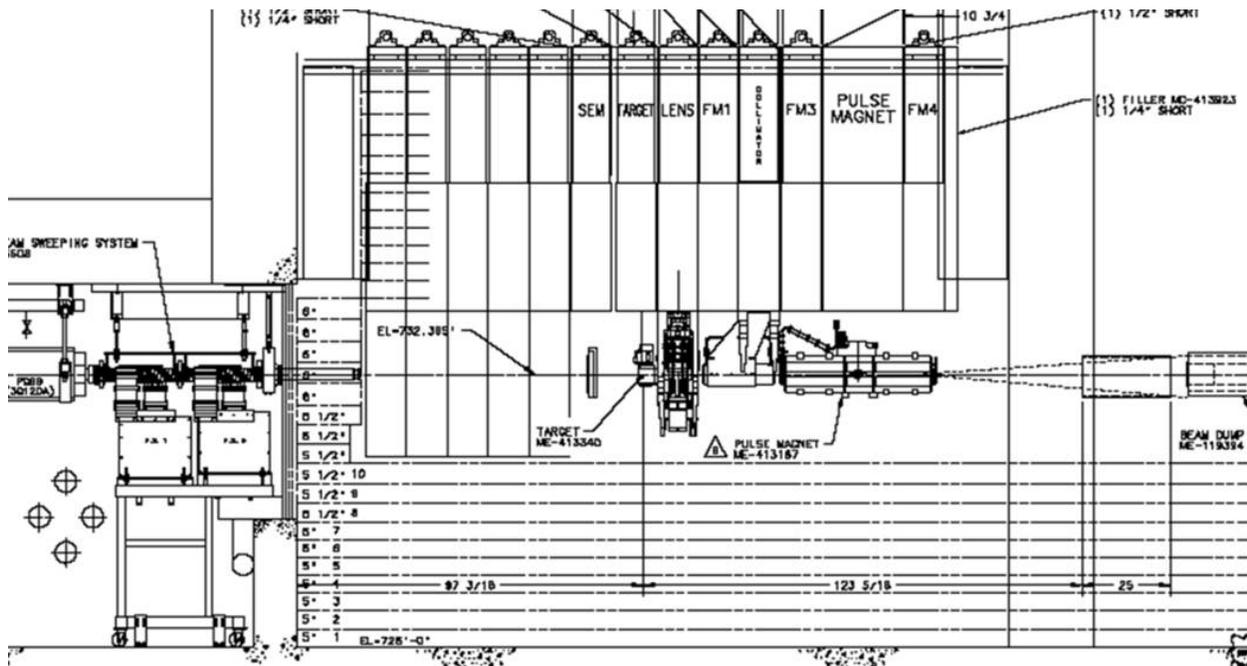


Figure 7.7: Layout of the ($g - 2$) target station.

The production target station consists of five main devices: the pion production target, the lithium lens, a collimator, a pulsed magnet, and a beam dump. Once the primary beam impinges on the target, secondaries from the proton-target interaction are focused by the lithium lens and then momentum-selected, centered around a momentum of 3.11 GeV/c, by a pulsed dipole magnet (PMAG). This momentum is slightly above the magic momentum needed to measure the muon anomalous magnetic moment in the downstream muon ring. The momentum-selected particles are bent 3° into a channel that begins the M2 beamline. Particles that are not momentum-selected will continue forward and are absorbed into the target-vault dump. An overview of some of the required beam design parameters for the

2321 ($g - 2$) target system can be found in Table 7.2.

Parameter	FNAL ($g - 2$) 12 Hz
Intensity per pulse	10^{12} p
Total POT per cycle	16×10^{12} p
Number of pulses per cycle	16
Cycle length	1.33 s
Primary energy	8.89 GeV
Secondary energy	3.1 GeV
Beam power at target	17.2 kW
Beam size σ at target	0.15-0.30 mm
Selected particle	π^+
$ dp/p $ (PMAG selection)	5%

Table 7.2: Beam parameters for the target station.

2322 One significant difference the ($g - 2$) production target station will have from the an-
 2323 tiproton production target station is the pulse rate at which beam will be delivered to the
 2324 target station. The ($g - 2$) production rate will need to accommodate 16 pulses in 1.33 s
 2325 with a beam pulse-width of 120 ns. This is an average pulse rate of 12 Hz. The antiproton
 2326 production pulse rate routinely operated at 1 pulse in 2.2 s or 0.45 Hz. This will be a chal-
 2327 lenging factor that can drive the cost of the design since the lithium lens and pulsed magnet
 2328 will need to pulse at a significantly higher rate. Figure 7.2 shows a possible ($g - 2$) pulse
 2329 scenario for pulsed devices and timing for proton beam impinging on the target.

2330 7.4.1 The ($g - 2$) production target and optimization of production

2331
 2332 The current default target to be used for the ($g - 2$) experiment is the antiproton production
 2333 target used at the end of the Tevatron Collider Run II. This target should be able to produce
 2334 a suitable yield of approximately 10^{-5} π^+ /POT within $|dp/p| < 2\%$. This target design has
 2335 a long history of improvements for optimization and performance during the collider run.
 2336 The target is constructed of a solid Inconel 600 core and has a radius of 5.715 cm with a
 2337 typical chord length of 8.37 cm. The center of the target is bored out to allow for pressurized
 2338 air to pass from top to bottom of the target to provide internal cooling to the Inconel core.
 2339 It also has a cylindrical beryllium outer cover to keep Inconel from being sputtered onto
 2340 the lithium lens from the impinging protons. The target has a motion control system that
 2341 provides three-dimensional positioning with rotational motion capable of 1 turn in 45 s. This
 2342 target and the target motion system need no modifications or enhancements to run for the
 2343 ($g - 2$) experiment. Figure 7.8 shows a drawing and a photo of the current target.

2344 Beam tests were performed to measure the yield from this target in 2012 [3]. The in-
 2345 strumentation measured total number of charged particles and did not differentiate between
 2346 particle species. Plans are in place to repeat the test in 2013 using a Cherenkov counter to
 2347 measure the particle composition of the beam. The yield of positive 3.1-GeV secondaries

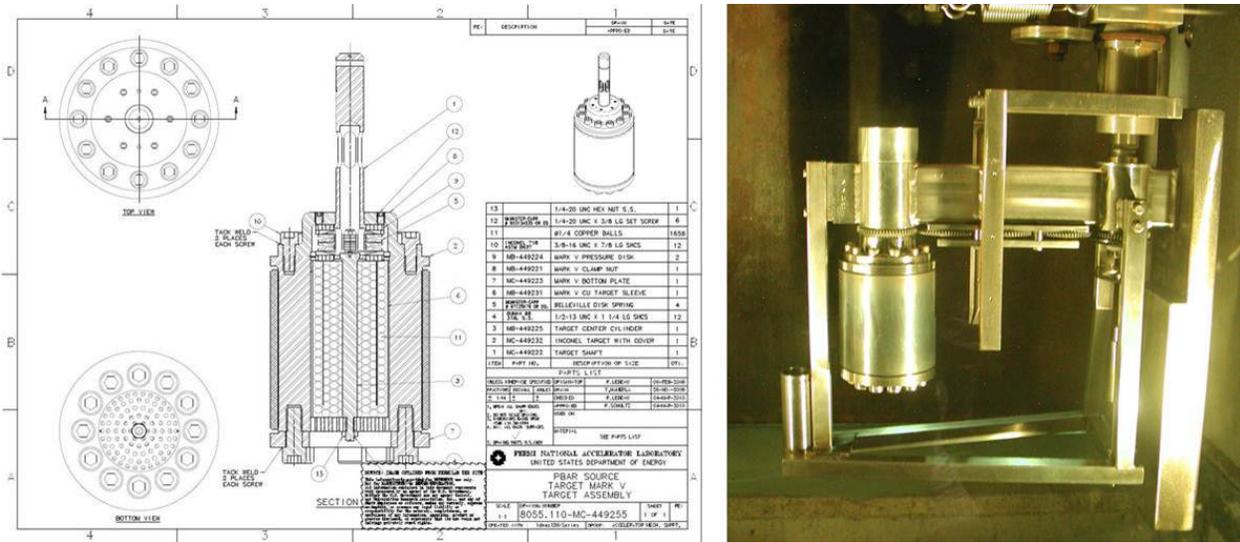


Figure 7.8: Current default target to be used for the $(g - 2)$ target station.

2348 from 10^{12} 8-GeV protons on target measured in the beam test was almost a factor of four
 2349 higher than the 2.2×10^8 particles with $|dp/p| < 10\%$ and 40π mm mr emittance predicted by
 2350 MARS [6] simulations at the beginning of the AP2 line, and was about 60-80% of the number
 2351 predicted at the end of the AP2 line with $|dp/p| < 2\%$ and 35π mm mr. Extrapolated back
 2352 to the start of the AP2 line, that prediction is 4.8×10^7 positive secondaries. The spot size
 2353 of the beam on target was $\sigma_x = \sigma_y = 0.5$ mm. As discussed later in this section and in the
 2354 beamlines section, we plan to reduce the spot size to 0.15 mm, which is expected to increase
 2355 the yield of particles with $|dp/p| < 2\%$ by 40-60%. The expected yield of positive 3.1-GeV
 2356 secondaries with $|dp/p| < 2\%$ exiting the target station will then be at least 4×10^8 , with
 2357 the simulation predicting 48% or 2×10^7 of these to be π^+ 's.

2358 Even though this target is thus expected to produce a reasonable yield of more than 10^{-5}
 2359 π^+/POT for the $(g - 2)$ experiment, considerable effort has been put into investigating a
 2360 cost-effective, practical target design optimized for 3.11 GeV pion production. Simulations
 2361 have been conducted using MARS to determine the optimal parameters, including impinging
 2362 proton spot size at the target, target material, target length and thickness, and target orien-
 2363 tation [7]. A graphical representation of the target system as implemented in the MARS15
 2364 code is shown in Fig. 7.9.

2365 The spot size of the beam on the target is an important parameter in determining the
 2366 pion yield. Initial values for the spot size were simply scaled from the $\sigma_x = \sigma_y = 0.15$ mm
 2367 size of the beam for 120 GeV antiproton production to $\sigma_x = \sigma_y = 0.55$ mm for 8.9 GeV.
 2368 Optimized results from the MARS simulations for the impinging-proton spot size can be seen
 2369 in Fig. 7.10. This plot shows the dependence of pion yield per POT on the beta function β
 2370 at half distance into the target for the current default target. A reasonable range of expected
 2371 β 's which can be achieved is from 2.5 to 3.5 cm. The simulation result demonstrates that
 2372 if the spot size is reduced from the original 0.55 mm to 0.15 mm, a 40-60% increase in pion
 2373 production can be achieved [8] depending on β . These modifications are not directly made
 2374 to the target station or target components but to the beamline just upstream of the target.

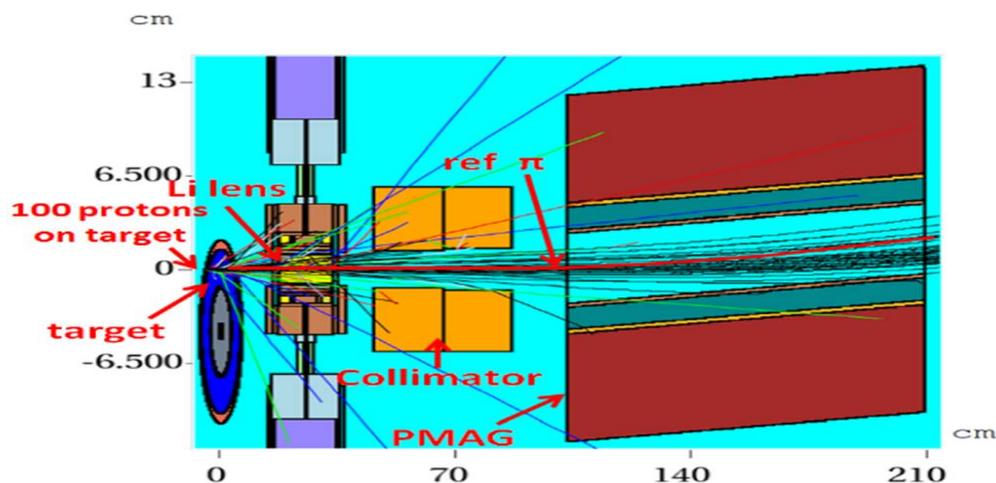


Figure 7.9: Graphical representation of target system used in MARS for simulated yield results.

2375 Details of the beamline optics incorporating this optimization for pion yield can be found in
 2376 Sec 7.5.4.

2377 Also, optimizations concerning parameters for the target material, target length, and
 2378 target width were also considered. First considered were optimizations to the target material.
 2379 Three materials were simulated: Inconel, tantalum and carbon. Figure 7.11 illustrates the
 2380 dependence of yield vs. β at the target for different materials with optimized lengths. Inconel
 2381 and carbon are shown to have higher yields than tantalum. These results, combined with
 2382 Fermilab's long history of building antiproton targets with Inconel, make Inconel the favored
 2383 target material.

2384 Next considering the dimensions of the target, Fig. 7.12a illustrates that a longer target
 2385 will produce higher yields, while Fig. 7.12b demonstrates a weak dependence on the target
 2386 thickness or radius. Therefore, the optimal pion production target may be a cylindrical rod
 2387 with a length of 89 mm and a radius of 0.6 mm. However, to favor a more practical target
 2388 design that will be able to be incorporated into the existing target mechanical and cooling
 2389 systems, horizontal slabs made of Inconel of various heights were simulated. The output of
 2390 the MARS simulation was then placed into G4beamline [9] in order to propagate particles
 2391 through the first four quadrupoles in the M2 beamline. Particles yields were tallied at the
 2392 end of these quadrupoles with appropriate acceptance cuts for the elements. Figure 7.13
 2393 shows the pion yield for two optimized horizontal slab targets one of height 0.60 mm and
 2394 the second of 0.75 mm. They are both approximately 107 mm long. Simulations for these
 2395 slab targets predict that a 22% and 14% gain in pion yield from optimized horizontal slabs
 2396 could be obtained, respectively.

2397 The actual details for the design of the alternate target are currently being worked out.
 2398 However, it is preferred that the simulated horizontal slabs transition into target discs that
 2399 could be mounted on a stacked-disc style target incorporating the simulated dimensions. In
 2400 order to provide cooling to the target material, the target discs would be separated by discs
 2401 of low Z material like beryllium or aluminum. Figure 7.14 is a picture of a proposed design
 2402 of a target incorporating stacked target and cooling discs. The blue material represents discs

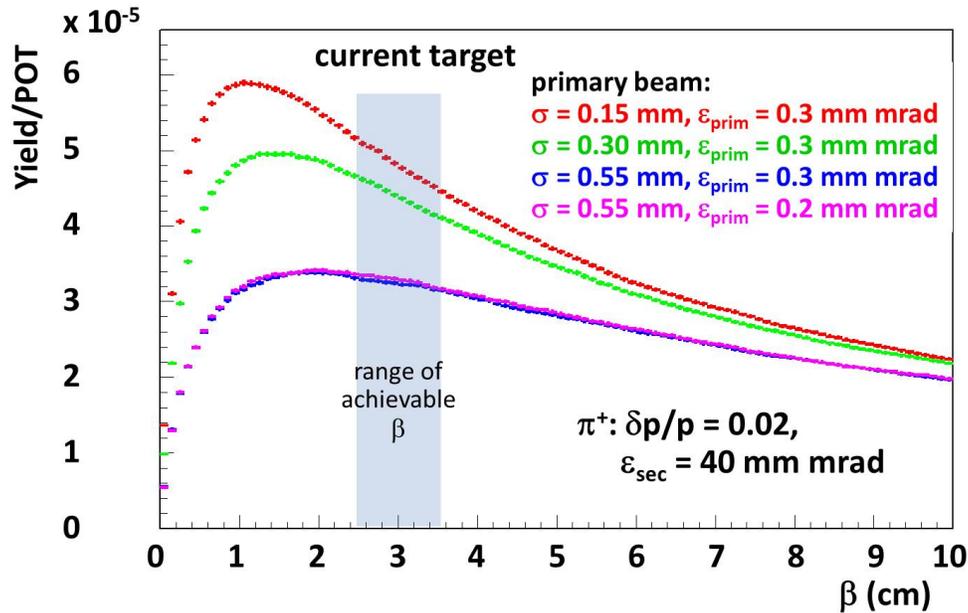


Figure 7.10: MARS simulation result for dependence of pion yield on β for different target spot sizes for a proton beam of emittance $\varepsilon_{\text{prim}}$ and secondary beam momentum spread $|dp/p| = 0.02$ and emittance $\varepsilon_{\text{sec}} = 40 \text{ mm mr}$.

2403 of Inconel separated by the grey shaded areas which would be beryllium. One consideration
 2404 for operating with the stacked discs that are very thin, approximately 0.6 mm, is the need for
 2405 beam stability on the target. This may require improvements in upstream trim power sup-
 2406 plies to achieve appropriate stability. A prototype stacked-disc target could be constructed
 2407 and tested with beam to narrow and confirm the design of the alternate target if the default
 2408 target is determined to be inadequate.

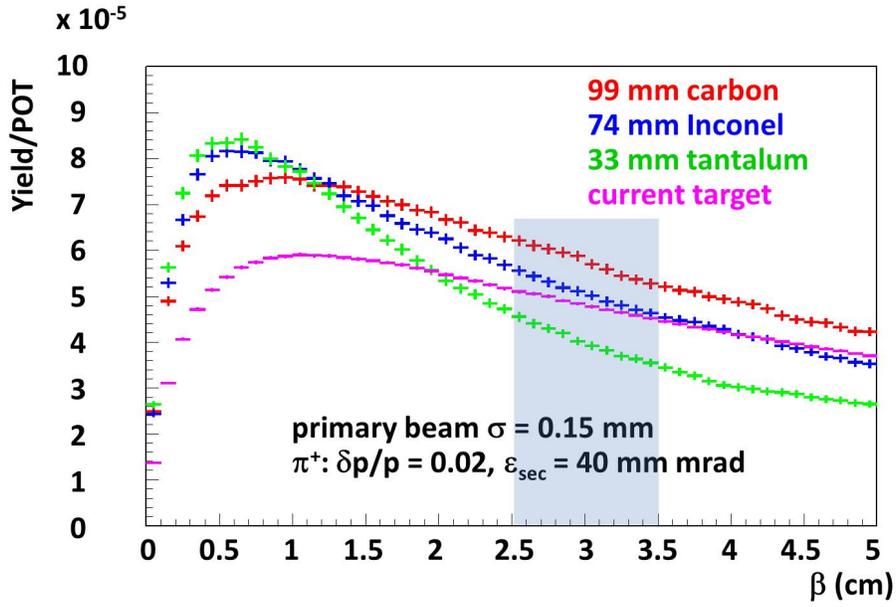


Figure 7.11: MARS simulation result for dependence of pion yield on β for different target materials. The length of the target is proportional to the interaction length of the material.

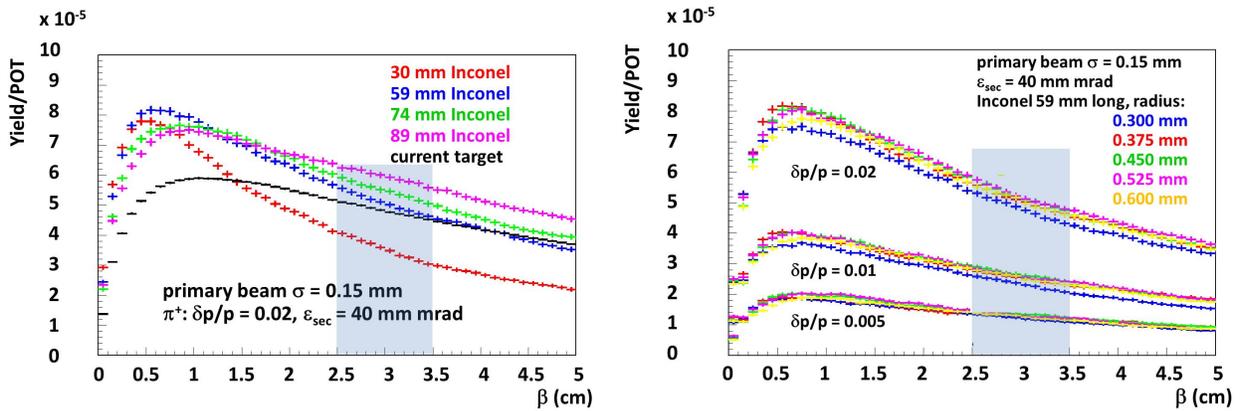


Figure 7.12: MARS simulation result for dependence of pion yield on β for different target lengths (a) and thicknesses (b).

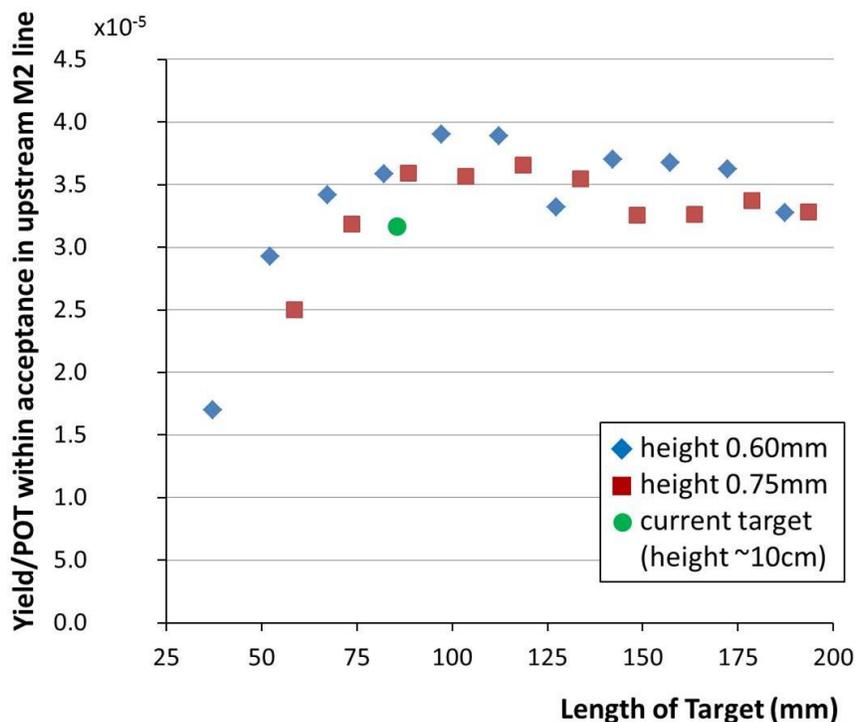


Figure 7.13: MARS/G4beamline predictions for number of pion secondaries from an Inconel target making it to the upstream M2 line as a function of target slab length for a slab of height 0.60 mm (with the upstream end of the target 56 mm from the lens focal point), a slab of height 0.75 mm (with the upstream end of the target 67 mm from the lens focal point), and the current target (assuming a chord length of 75 mm). The location of the target for a given height slab was optimized to give maximum yield. The spot size of beam on the target is taken to be 15 mm and the acceptance 40 mm mr. A thin target of length 107 mm is predicted to give an increase in yield of 14-22% over the existing target.

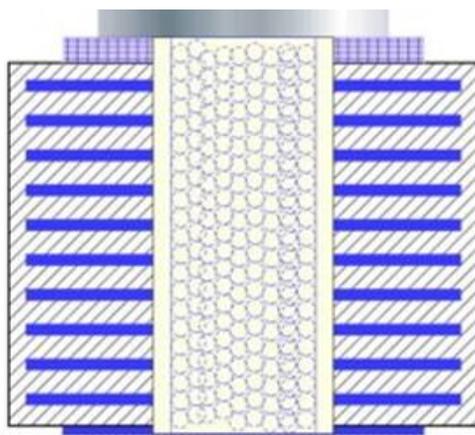


Figure 7.14: Proposal for new ($g - 2$) target design utilizing stacked thin slabs of Inconel (blue) separated by Beryllium (hashed grey). Target material air cooling channels are in the middle of the target.

2409 7.4.2 Focusing of secondaries from the target

2410 The lithium collection lens is a 1 cm radius cylinder of lithium that is 15 cm long and
 2411 carries a large current pulse that provides a strong isotropically focusing effect to divergent
 2412 incoming secondaries after the initial interaction of impinging particles with the target [10].
 2413 The lithium lens cylinder is contained within a toroidal transformer, and both lens and
 2414 transformer are water cooled. Figure 7.15 is a drawing of the lithium lens depicting (a) the
 2415 transformer and lens body, and (b) details of the lithium cylinder.

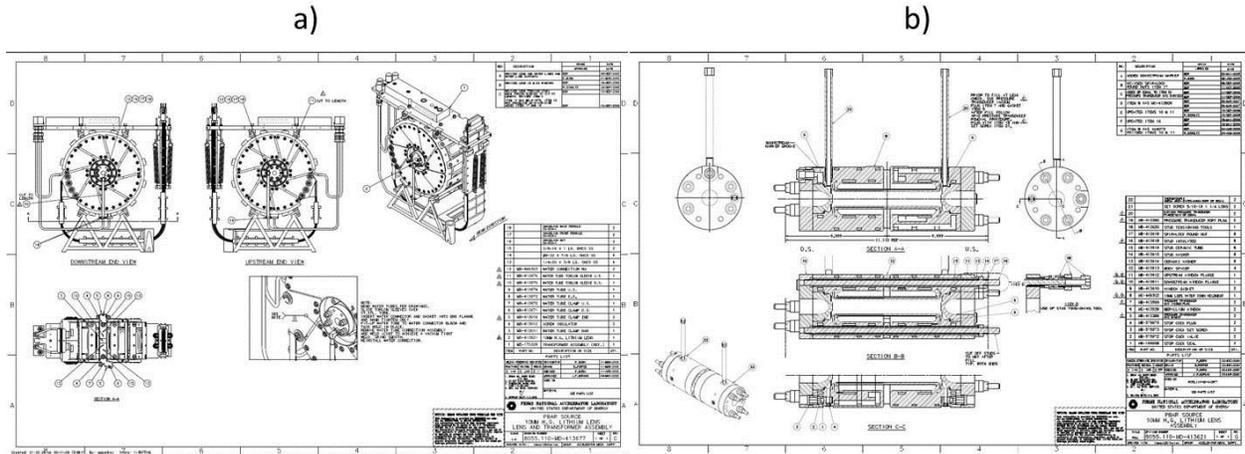


Figure 7.15: Drawing of the lithium lens and transformer (a) and the lithium cylinder body (b).

2416 During antiproton production for the Collider Run II, the lens pulsed at a peak current
 2417 of 62 kA, which is equivalent to a gradient of 670 T/m at 8.9 GeV/c with a base pulse
 2418 width of 400 μs . Scaling the lens gradient for use at 3.11 GeV/c for $(g - 2)$ and in order
 2419 to accommodate a similar range of focal lengths from the target to the lens of roughly
 2420 28 cm, the gradient required will be 230 T/m at a pulsed peak current of 22 kA with the
 2421 same 400 μs pulse width. Table 7.3 provides an overview of required operating parameters.
 2422 Accommodating the $(g - 2)$ 12 Hz average pulse rate for the lithium lens is one of the
 2423 biggest challenges and concerns for repurposing the antiproton target station for $(g - 2)$.
 2424 Even though peak current and gradient will be reduced by a factor of about 3, the pulse
 2425 rate will increase by a factor of 24 compared to the operation for antiproton production.
 2426 Resistive and beam heating loads, cooling capacity, and mechanical fatigue are all concerns
 2427 that are warranted for running the lithium lens at the $(g - 2)$ repetition rate.

Lens operation	Pulse width (μs)	Peak current (kA)	Gradient (T/m)	Pulses per day
Antiproton production	400	62.0	670	38,880
$(g - 2)$ pion production	400	22.6	230	1,036,800

Table 7.3: Lithium lens operation parameters.

2428 Therefore, in order to gain confidence that the lens will be able to run under these
 2429 conditions, a preliminary ANSYS [11] analysis has been conducted. This analysis simulated

2430 thermal and mechanical fatigue for the lens based on the pulse timing scenario in Fig 7.2
 2431 and at a gradient of 230 T/m. These results were compared to results from a similar analysis
 2432 for the lens operating under the antiproton-production mode of a gradient of 670 T/m at a
 2433 pulse rate of 0.5 Hz [12]. Figure 7.16 (left) shows the ANSYS output thermal profile of a
 2434 cutaway of the lens operating at 12 Hz. The lithium body corner is a temperature-sensitive
 2435 location and should avoid lithium melting temperatures of 453.75 K. The corner temperature
 2436 reaches a maximum temperature of 376 K. The plot on the right of Fig. 7.16 is the increase in
 2437 maximum temperature of the lithium over the 16 pulses, depicting a change in temperature
 2438 of 22 K when the operating temperature has come to equilibrium. We conclude from this
 2439 analysis that the lithium lens is adequately cooled to operate at the nominal ($g - 2$) pulse
 2440 rate.

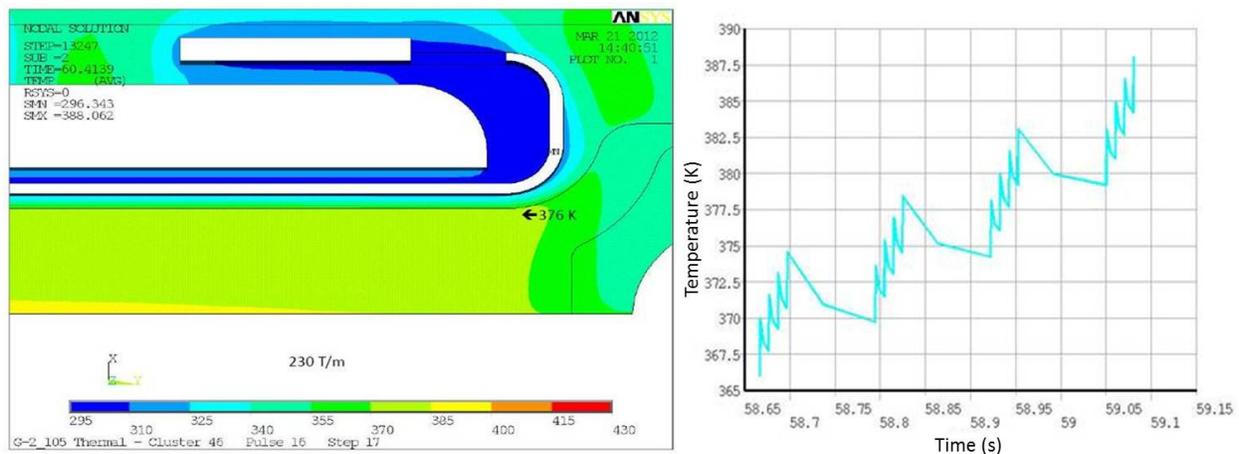


Figure 7.16: Simulated thermal profile from ANSYS for the lens operating at an average pulse rate of 12 Hz (left) depicting little beam heating and a corner temperature of 376 K. (Right) Plots showing lens temperature increase over the 16 pulses.

2441 Mechanical fatigue was also assessed for the lithium lens. Figure 7.17 depicts a constant
 2442 life fatigue plot developed for the lens from the ANSYS analysis. The two red lines represent
 2443 upper and lower estimates of fatigue limits for the lens material. The red data points
 2444 represent fatigues for gradients of 1000 T/m, 670 T/m, and two points at 230 T/m for a
 2445 preload pressure of 3800 and 2200 psi, respectively. For the lens operating in the antiproton
 2446 production conditions of 670 T/m, the mechanical fatigue was a large concern in the lens
 2447 design. It appears that for the ($g - 2$) case, the mechanical fatigue will be a comparatively
 2448 small concern.

2449 This initial assessment of the lithium lens suggests that it should be able to operate at
 2450 the ($g - 2$) repetition rate. However, since the operation of the lithium lens at the average
 2451 12 Hz rate is crucial, testing of the lens at 12 Hz is needed. The lens has been pulsed in a
 2452 test station at a 12 Hz rate in order to confirm that 1M pulses per day can be achieved and
 2453 sustained over many months. The lens has been pulsed 70 million times without problems,
 2454 and data from these tests were used to confirm predictions of the ANSYS model.

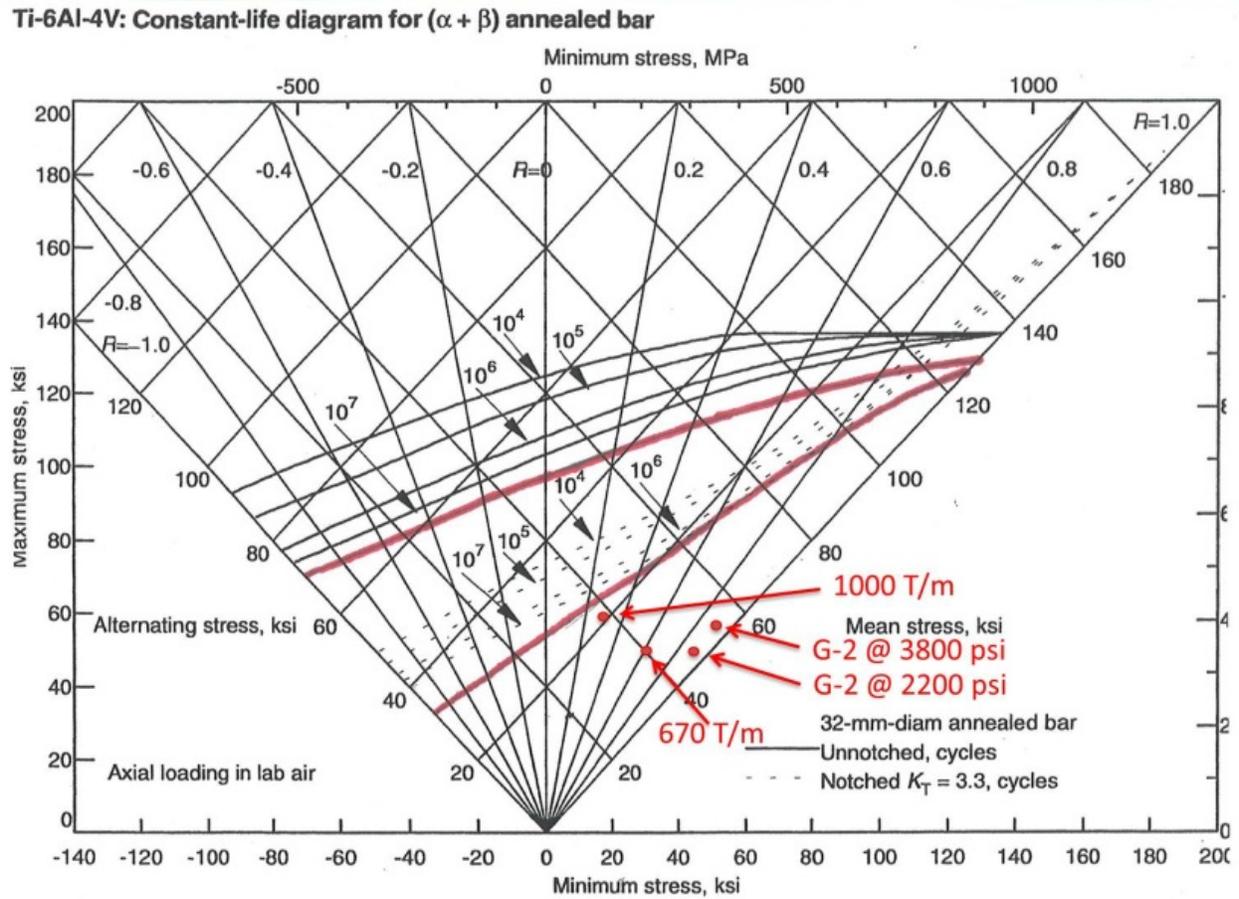


Figure 7.17: Constant-life fatigue plot of the lithium lens for antiproton and ($g - 2$) modes showing that mechanical fatigue for the ($g - 2$) pulse rate is a small concern.

2455 7.4.3 Pulsed magnet (PMAG) and collimator

2456 The pulsed magnet, shown in Fig. 7.18, selects 3.115 GeV/c positive particles and bends
 2457 them 3° into the channel that begins the M2 beamline. The magnet will operate with a
 2458 field of 0.53 T and is a 1.07 m long magnet with an aperture of 5.1 cm horizontally and
 2459 3.5 cm vertically. It is a single-turn magnet that has incorporated radiation-hard hardware
 2460 such as ceramic insulation between the magnet steel and the single conductor bars, as well
 2461 as Torlon-insulated bolts [10]. The pulsed magnet has a typical pulse width of $350 \mu\text{s}$ and
 2462 similarly to the lithium lens, will need to accommodate the $(g - 2)$ pulse rate shown in
 2463 Fig. 7.2. The pulsed magnet is water cooled. In addition to the magnet currently in the
 2464 target vault, there are three spares.

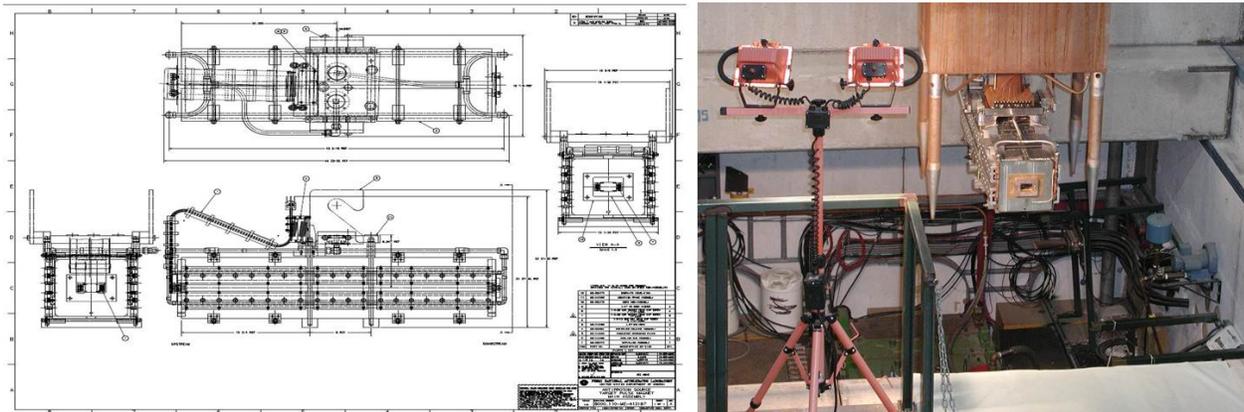


Figure 7.18: Pulsed magnet (PMAG) used for momentum-selection of pions.

2465 One initial concern regarding the pulsed magnet was that while operating in the polarity
 2466 needed to collect positive secondaries, the magnet would have an increase in energy deposited
 2467 in the downstream end of the magnet compared to antiproton production where negative
 2468 secondaries were collected. An increase in energy deposition could potentially lead to magnet
 2469 failures, and therefore running with positive polarity might require a redesign of the magnet.
 2470 A MARS simulation was conducted to look at the energy deposition across the entire pulsed
 2471 magnet compared to the antiproton production case. The simulated magnet was segmented
 2472 in order to highlight sensitive areas. The simulation concluded that although the map of
 2473 energy deposition for the positive particle polarity with 8-GeV protons on target was different
 2474 than for the antiproton production case (120-GeV protons on target), there were no locations
 2475 where the deposited energy was higher, and the total was an order of magnitude lower [13].
 2476 The negative particle polarity case was more than two times lower for 8-GeV primary beam
 2477 than for 120-GeV. Therefore a new pulsed magnet design will not be needed and the default
 2478 plan is to use the device currently installed.

2479 In order to accommodate the $(g - 2)$ pulse rate, the pulsed magnet power supply will
 2480 also need to be modified or replaced with one similar to the new supply for the lithium lens
 2481 with improved charging capability.

2482 The collimator is located directly upstream of the pulsed magnet. The purpose of the
 2483 collimator is to provide radiation shielding to the pulsed magnet to improve its longevity. It
 2484 is a water-cooled copper cylinder 12.7 cm in diameter and 50.8 cm long. The hole through

2485 the center of the cylinder is 2.54 cm diameter at the upstream end, widening to a diameter
 2486 of 2.86 cm at the downstream end. The existing collimator is currently planned to be used
 2487 without modification.

2488 7.4.4 Target station beam dump

2489 The target-station beam dump absorbs particles which are not momentum-selected by the
 2490 pulsed dipole magnet and continue straight ahead. The location of the beam dump can be
 2491 seen in Fig. 7.19. The current beam dump has a graphite and aluminum core which is water
 2492 cooled, surrounded by an outer steel box. The graphite core is 16 cm in diameter and 2 m
 2493 in length, and is designed to handle a beam power of 80 kW [14]. The existing dump has
 2494 a known water leak that developed at the end of the collider run. Therefore, consideration
 2495 for replacing the beam dump will need to be made. The current plan is to replace the beam
 2496 dump with an updated copy of the 80 kW beam dump. The maximum beam energy load
 2497 for $(g - 2)$ would occur if $(g - 2)$ takes advantage of extra cycles, for example if the $\text{NO}\nu\text{A}$
 2498 experiment were not able to run. At a rate of 18 Hz, the beam energy load would be 25 kW,
 2499 which is easily accommodated with the current dump design.

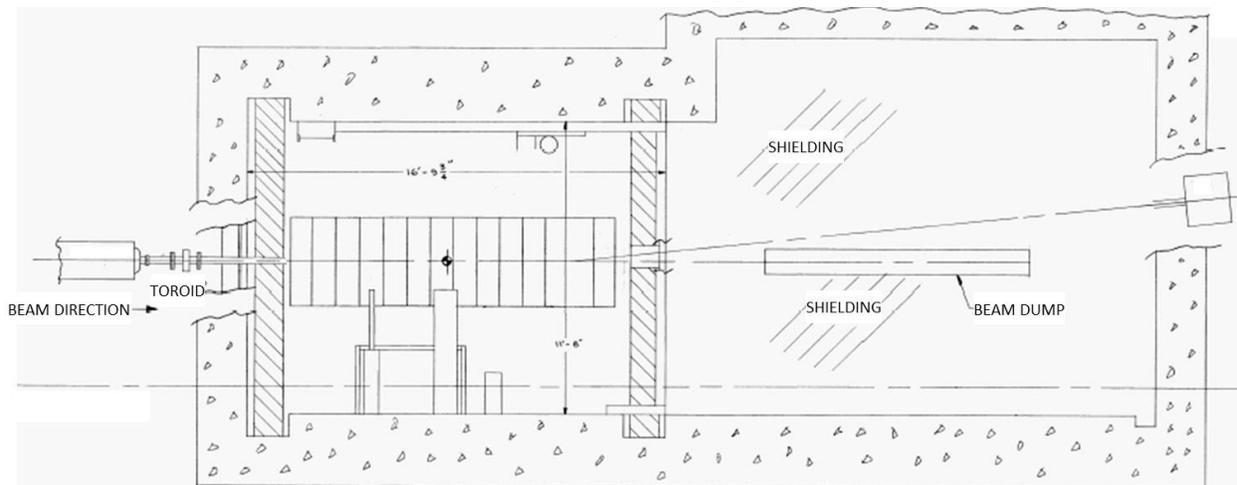


Figure 7.19: Layout of the target-station beam dump.

2500 An alternative, shorter dump was also considered and designed at an operating capacity
 2501 of 25 kW. This design resulted in a copper cylinder 2 ft long and 6 in in diameter, with
 2502 copper cooling tubes vacuum-brazed around the outside of the cylinder. The cost was found
 2503 to be similar to that of replacing the dump with a copy of the current 80-kW one.

2504 7.5 Beam Transport Lines

2505 7.5.1 Overview of $(g - 2)$ beamlines

2506 The existing tunnel enclosures and beamlines connecting the Recycler Ring to the Delivery
 2507 Ring will be largely reused for $(g - 2)$ operation. However, there are fundamental differences
 2508 between the way the Rings and beamlines were operated for Collider Operation and how
 2509 they will be used to support the Muon Campus. A high-intensity, 8 GeV kinetic energy
 2510 proton beam will be transported to the AP0 Target Station in $(g - 2)$ operation and to the
 2511 Delivery Ring for the Mu2e experiment. The increase in intensity from Collider Operation in
 2512 conjunction with the beam size of the 8 GeV beam will present challenges for efficient beam
 2513 transfer. The beamlines downstream of the AP0 Target Station will need to be reconfigured
 2514 to connect to the D30 straight section of the Delivery Ring. New extraction lines will
 2515 be constructed to transport beam from the D30 straight section to the $(g - 2)$ and Mu2e
 2516 experiments. Careful planning is required for the D30 straight section of the Delivery Ring
 2517 due to the presence of both the injection and extraction points. The extraction line will also
 2518 need to support both single-turn extraction for $(g - 2)$ and resonant extraction for Mu2e.

2519 7.5.2 Beamline Changes from Collider Operation

2520 During Pbar operation in Collider Run II, the P1 line connected to the Main Injector at
 2521 the MI 52 location. The P1 line supported operation with three different beam energies,
 2522 150 GeV for protons to the Tevatron, 120 GeV for Pbar production and SY120 operation,
 2523 and 8 GeV for protons and antiprotons to and from the Antiproton Source. (SY120 refers
 2524 to the “Switchyard” of beamlines used for the 120-GeV fixed-target program.) The junction
 2525 between the P1 and P2 lines occurs at F0 in the Tevatron enclosure. The P2 line ran at
 2526 two different beam energies, 120 GeV for antiproton production and SY120 operation and
 2527 8 GeV for protons and antiprotons to and from the Antiproton Source. The P2, P3 (for
 2528 SY120 operation), and AP1 lines join at the F17 location in the Tevatron enclosure. The
 2529 AP1 line also operated at 120 GeV and 8 GeV, but is not used for SY120 operation. The
 2530 AP3 line only runs at a kinetic energy of 8 GeV. The AP3 line connects with the AP1 line
 2531 in the Pre-Vault beam enclosure near the Target Vault and terminates at the Accumulator.

2532 After the conversion from collider to $\text{NO}\nu\text{A}$ and $(g - 2)$ operation, the Recycler will
 2533 become part of the proton transport chain and will connect directly with the Booster. There
 2534 will be a new beamline connection between the Recycler Ring and the P1 line. The P1 line
 2535 will become a dual energy line, with no further need to deliver 150 GeV protons with the
 2536 decommissioning of the Tevatron. The P2 line will continue to operate at both 8 GeV for
 2537 the Muon experiments and 120 GeV for SY120 operation. The AP2 and AP3 lines will need
 2538 to be almost completely dismantled and reconfigured to support both the transport of muon
 2539 secondaries via the Target Station for $(g - 2)$ and protons via the target bypass for Mu2e.
 2540 The $(g - 2)$ 3.1 GeV secondary beamline emanating from the Target Station and the Mu2e
 2541 8 GeV primary beamline bypassing the Target Station will merge and follow a single line
 2542 to the Delivery Ring. The new injection line will connect to the Delivery Ring in the D30
 2543 straight section. The extraction line also originates in the D30 straight section and has to
 2544 be capable of supporting both resonant and single-turn extraction.

2545 The beamlines that made up the Antiproton Source, those that have an “AP” prefix,
 2546 will be modified, reconfigured and renamed prior to $(g - 2)$ operation. The AP1 line will
 2547 only operate at an energy of 8 GeV and will be renamed M1. The AP1 line will be largely
 2548 unchanged, with the exception of the replacement of some magnets to improve aperture. The
 2549 AP2 line will become two separate beamlines and no longer be continuous. The upstream
 2550 end of the line is needed as a pion decay channel for the $(g - 2)$ experiment and will be
 2551 renamed M2. It will provide a connection from the Pbar AP0 Target Station to the M3
 2552 line. The downstream section of AP2 will become the abort and proton removal line from
 2553 the Delivery Ring. The old AP3 line will be required to transport both 8 GeV beam for the
 2554 Mu2e experiment and also a 3.1 GeV secondary beam for the $(g - 2)$ experiment and will be
 2555 renamed M3. The 18.5° right bend will be changed from a two to a three dipole configuration
 2556 in order to avoid higher beta functions in this region. The M3 line will also be modified
 2557 to connect to the Delivery Ring (formerly Debuncher) instead of the Accumulator. The
 2558 extraction line connecting the Delivery Ring to the experiments will be called M4. The M5
 2559 line will branch from the M4 line to the $(g - 2)$ storage ring in the MC-1 Building in the
 2560 “Left Bend” area. Figure 7.20 compares the Pbar beamline configuration with that proposed
 2561 for $(g - 2)$ and Mu2e operation. In general, the AP1, AP2 and AP3 lines will refer to the
 2562 old Pbar beamline configuration and M1, M2, M3, M4 and M5 will refer to the beamline
 2563 configuration for $(g - 2)$ operation.

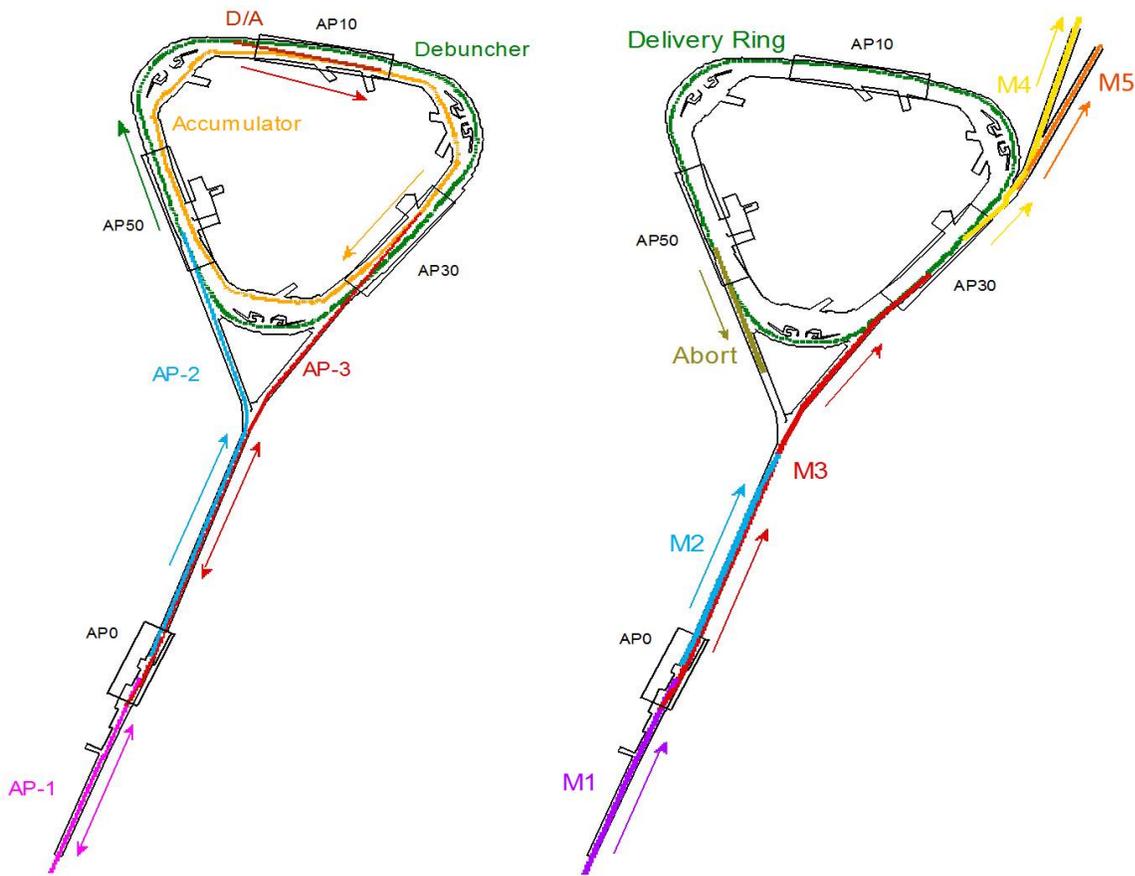


Figure 7.20: Layout of the Antiproton Source beamlines (left) and the reconfigured beamlines for $(g - 2)$ operation (right).

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Figure 7.21 shows another view of the Muon Campus beamlines and experimental halls.

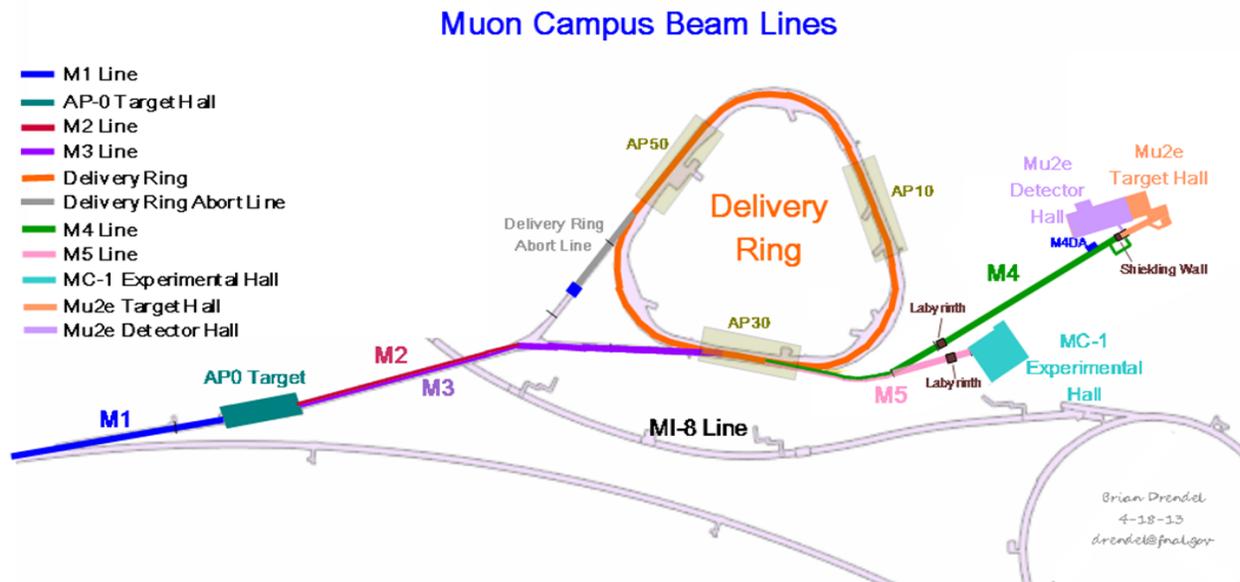


Figure 7.21: The Muon Campus beamlines and experimental halls.

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Most of the common improvements to the beamlines and Delivery Ring that benefit Mu2e, $(g - 2)$, and future experiments will be incorporated into several Accelerator Improvement Projects (AIPs). They are the Recycler RF AIP, Cryo AIP, Beam Transport AIP, and Delivery Ring AIP. The Cryo AIP provides cryogenics for the $(g - 2)$ storage ring and to the Mu2e solenoids. Table 7.4 summarizes which improvements are contained in the various AIPs, as well as those that will be managed as part of the Mu2e and $(g - 2)$ projects. Project Managers for the various projects will work closely together to ensure they interface properly. Virtually all of the work that is incorporated into the AIPs must be completed prior to beam operation to $(g - 2)$.

Description	Project	Comment
Cryogenics	CR AIP	
Recycler RF upgrade	RR AIP	
Recycler extraction/P1 stub line	BT AIP	
P1,P2 and M1 aperture upgrade	BT AIP	M1 final focus quadrupoles on $(g - 2)$
Reconfigure AP2 and AP3	$(g - 2)$	New lines are called M2 and M3
Final focus to AP0 Target Station	$(g - 2)$	
AP0 Target Station upgrades	$(g - 2)$	
Beam transport instrumentation	BT AIP	
Beam transport infrastructure	BT AIP	
Delivery Ring injection	DR AIP	
D30 straight section preparation	$(g - 2)$	
Delivery Ring modification	DR AIP	
DR abort/proton removal	DR AIP	
<i>Delivery Ring RF system</i>	<i>Mu2e</i>	
Delivery Ring controls	DR AIP	
Delivery Ring instrumentation	DR AIP	<i>DCCT and Tune measure are Mu2e</i>
<i>Resonant extraction from DR</i>	<i>Mu2e</i>	
Fast extraction from DR	$(g - 2)$	
Delivery Ring infrastructure	DR AIP	
Extraction line to split	$(g - 2)$	Upstream M4 line
<i>Extraction line from split to Mu2e</i>	<i>Mu2e</i>	<i>Downstream M4, including extinction</i>
Extraction line from split to $(g - 2)$	$(g - 2)$	Beamline to MC-1 building

Table 7.4: Beamline, Delivery-Ring, and other upgrades and associated project: $(g - 2)$ project, Mu2e project, Delivery Ring Accelerator Improvement Project (DR AIP), Beam Transport (BT) AIP, Recycler RF (RR) AIP, and Cryo (CR) AIP.

2574 7.5.3 Proton Beam Transport to the Target Station

2575 Beam transport of the 8 GeV primary beam from the Recycler Ring (RR) to the Target
 2576 Station closely resembles the scheme used to transport 120 GeV protons for antiproton
 2577 production in Collider operation. The most notable differences are the change in beam
 2578 energy and the switch from the Main Injector to the RR as the point of origin for the
 2579 P1 line. The beamlines will be modified to 1) provide a connection between the RR and
 2580 P1 line, 2) improve aperture to accommodate the larger beam size and intensity, and 3)
 2581 reconfigure the final focus region in order to reach the desired spot size on the production
 2582 target. Table 7.5 lists the beamlines connecting the RR with the Target Station and their
 2583 respective lengths.

Beam Line	Length (m)
RR to P1	43
P1	182
P2	212
AP1 (M1)	144
RR to Target Total	581

Table 7.5: Recycler Ring to Target beamline lengths.

2584 Recycler Ring to P1 line stub

2585 Operation of ($g - 2$) and Mu2e requires the transport of protons from the RR rather than
 2586 the Main Injector. A new transfer line from the RR to the P1 beamline will be constructed
 2587 to facilitate proton beam transport from the RR to the Delivery Ring. This new beamline
 2588 provides a way to deliver 8 GeV kinetic energy protons to the Delivery Ring, via the RR,
 2589 using existing beam transport lines and without the need for new civil construction.

2590 **Beamline Design** The P1 line is lower in elevation than the RR, thus the beam will be
 2591 extracted downward. This will be accomplished with a horizontal kicker that will displace
 2592 beam into the field region of a Lambertson magnet that will bend beam down. The kickers
 2593 are located immediately downstream of the RR 520 location and the Lambertson will be just
 2594 downstream of the RR 522 location. Due to space limitations, only two vertical bend centers
 2595 made up of the Lambertson and a dipole are used in the new line. An integer multiple of
 2596 360° in betatron phase advance between the two bending centers is required to cancel the
 2597 vertical dispersion from the bends. The new beamline needs to intercept the existing P1 line
 2598 in a location that doesn't disturb the extraction trajectory from the Main Injector, which
 2599 will be retained for SY120 operation. That junction point will be located near quadrupole
 2600 Q703. The angles of both the Lambertson and the vertical bending magnet (VBEND) were
 2601 obtained by matching the site coordinates from the RR to P1 line using TRANSPORT [15]
 2602 code. Figure 7.22 shows the layout of the new line, with the existing P1 line drawn in red.

2619 the design features of the new beam line stub can be found in Ref. [16]. Figure 7.23 shows
 2620 the lattice functions for the entire RR to Target Station line.

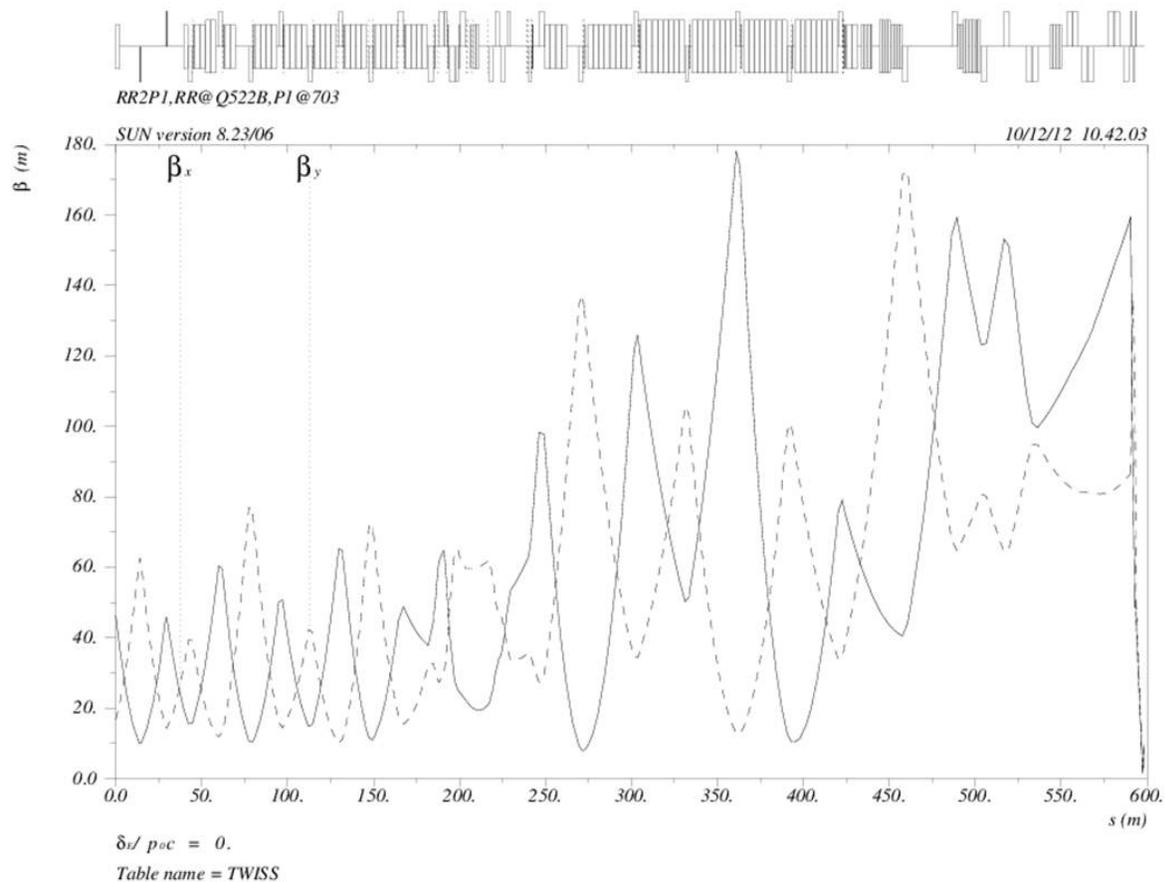


Figure 7.23: Lattice functions for primary beamlines from the Recycler to the Target Station.

2621 **Recycler orbit** The RR extraction scheme incorporates a permanent horizontal 3-bump
 2622 in the RR that displaces the circulating beam outward 25 mm at the upstream end of
 2623 the Lambertson (RLAM). Figure 7.24 shows the trajectories of the circulating and extracted
 2624 beams, including the horizontal bump at the Lambertson. The bump is created by horizontal
 2625 trim dipoles at the 524, 522 and 520 locations. The extraction kickers displace the extracted
 2626 beam inward 25 mm at the same location. This creates a separation of the RR circulating
 2627 beam and extracted beam at the front face of the Lambertson of 50 mm.

2628 **Apertures** Lambertson magnets are typically one of the limiting apertures in a beamline.
 2629 The Recycler extraction Lambertson has an adequate aperture for both the circulating and
 2630 extracted beams. Figure 7.25 shows the footprint of both beams at the Lambertson for both
 2631 a 10σ and 6σ beam size. The vertical bend magnet has a relatively small horizontal aperture,

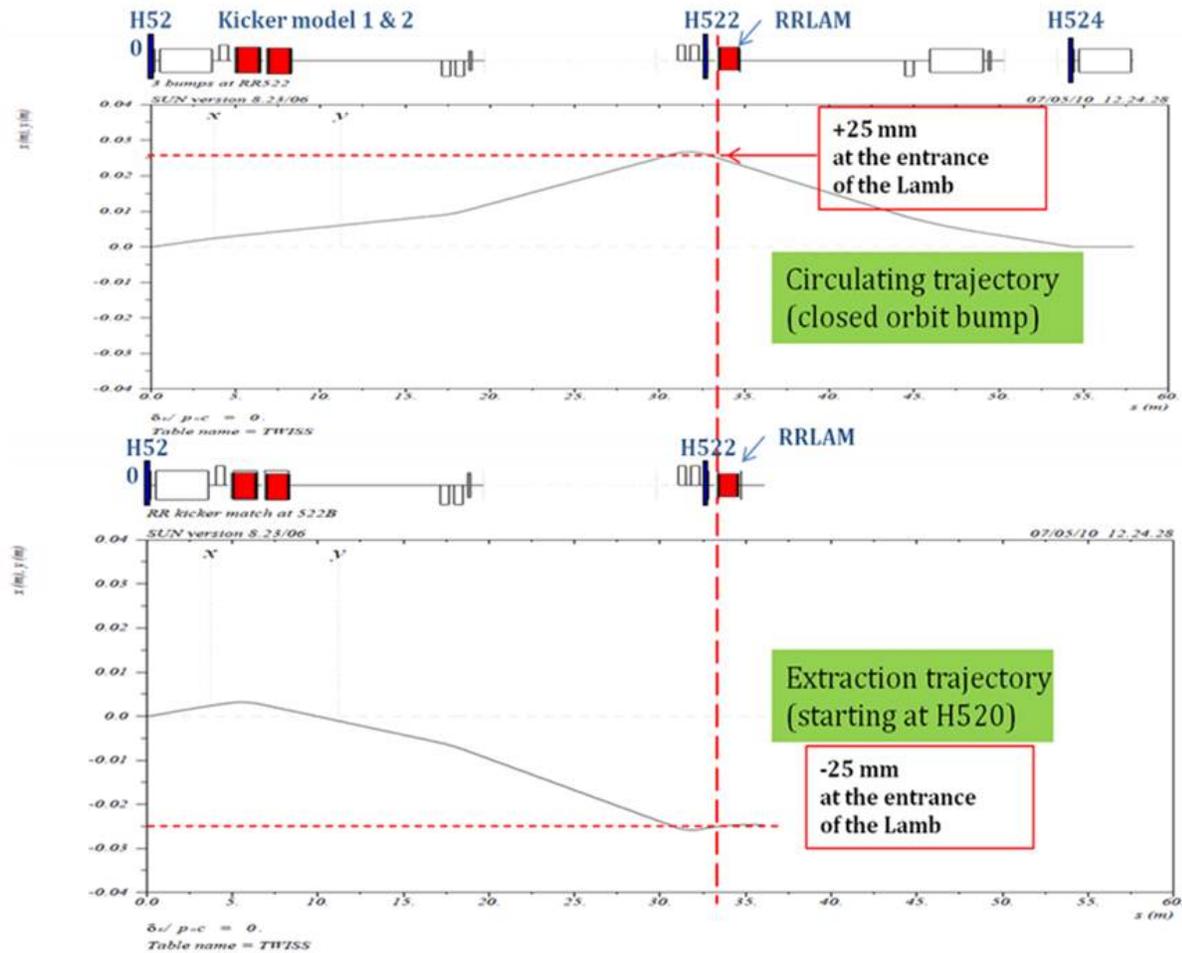


Figure 7.24: Horizontal trajectories for circulating and extracted beam from the Recycler.

2632 but is located where the horizontal beta functions are small. The horizontal acceptance of
 2633 the vertical dipole is actually larger than that of the Lambertson, despite the smaller physical
 2634 aperture. The quadrupole and trim magnets are modeled after those in the Recycler and
 2635 have good apertures.

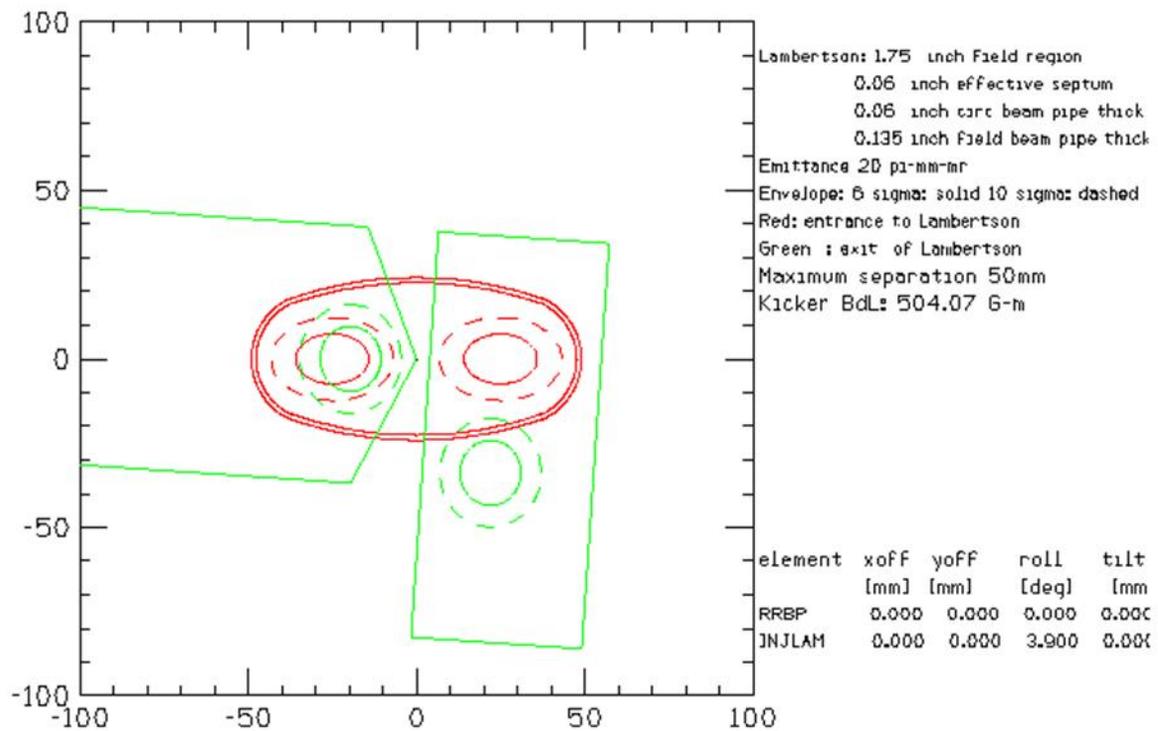


Figure 7.25: Beam sizes at the entrance (red) and exit (green) of the extraction Lambertson. The dashed outline represents 10σ and the solid outline 6σ beam for a normalized emittance of 18π -mm-mr.

2636 7.5.4 P1, P2 and AP1 Aperture Improvements

2637 The increased intensity and beam size planned for muon operation will lead to unaccept-
2638 ably high beam loss unless apertures are improved in the P1, P2 and AP1 lines. Limiting
2639 apertures were identified during Collider Run II when evaluating possible improvements,
2640 simplifying the process of identifying locations. The elimination of AP1 120 GeV opera-
2641 tion for antiproton stacking provides an opportunity to improve the aperture with weaker
2642 magnets that previously were not practical for use as replacements.

2643 The introduction of the P1-line stub has eliminated several aperture restrictions that were
2644 associated with Main Injector extraction. In particular, the vertical C-magnets that follow
2645 the MI-52 Lambertson will be avoided with the new stub line. Most of the P1 line after the
2646 P1-line stub has good aperture, until the former junction area with the Tevatron. The vertical
2647 dipole at the 714 location was installed as a C-magnet because of its proximity with the
2648 Tevatron and has a small horizontal aperture. The decommissioning of the Tevatron allows
2649 the replacement of this magnet with a conventional dipole that will increase the horizontal
2650 acceptance by more than 50%. The new magnet must also be capable of producing enough
2651 field strength to operate at 120 GeV and support SY120 operation. The four Tevatron F0
2652 Lambertsons will no longer be needed to inject protons into the Tevatron and can be removed
2653 to improve the aperture, also in the horizontal plane.

2654 In addition to the improvements to physical aperture, a new quadrupole is proposed in the
2655 region presently occupied by the Tevatron injection Lambertsons at F0. The long drift space
2656 in the P1 and P2 lines required for Tevatron injection results in large excursions in dispersion
2657 throughout the beamlines. Unless the dispersion is reduced, the increased momentum spread
2658 created by RR bunch formation will cause high beam losses. The addition of a quadrupole
2659 (or quadrupoles) in this region will provide the means to improve the optics of the transport
2660 lines.

2661 The P2 line will remain a dual-energy line supporting $(g - 2)$ and SY120 operation, so
2662 the junction between the P2, AP1, and P3 beamlines at F17 will remain. The aperture for
2663 both $(g - 2)$ and SY120 operation will substantially improve with the proposed replacement
2664 of the F17 C-magnets with a large aperture CDA magnet that both beams will pass through.
2665 The B-3 dipole at the F-17 location will remain.

2666 AP1 will only operate at 8 GeV for $(g - 2)$ operation, so the eight EPB magnets that
2667 make up the HV100 and HV102 string can be replaced with larger-aperture, weaker dipoles.
2668 The number of dipoles can be reduced from four to two in each string. The 1.5 m “modified
2669 B-1” magnets (formally known as MDC magnets) have a pole gap that is 2.25 in instead of
2670 1.5 in and provides more than a factor of two increase in acceptance. Several trims will also
2671 be replaced or relocated to complete the aperture upgrade. The final-focus region at the
2672 end of AP1 is described separately in the next section. Table 7.7 summarizes the proposed
2673 improvements to the physical apertures in the RR to Target Station lines. Reference [16]
2674 has a more detailed explanation of the devices used to improve the aperture and how the
2675 improvements will be implemented.

Location	Existing magnet	Proposed improvement
V714	C-magnet	1 B2 magnet
F0 Lambertsons	4 Lambertsons	Remove magnets
F17 (V)	B3 and two C-magnets	1 CDA (retain B3)
HV100	4 EPB dipoles	2 MDC
HV102	4 EPB dipoles	2 MDC

Table 7.7: Proposed aperture improvements for RR to Target Station beamlines.

2676 Final Focus Region

2677 The desired spot size on the production target, a proton beam σ in both planes of 0.15 mm,
 2678 is the same as what was used in antiproton production during collider operation. Because
 2679 the beam momentum is 8.89 GeV/c for ($g - 2$) operation instead of the 120 GeV/c that
 2680 was used for antiproton production, much smaller beta functions are required to achieve this
 2681 spot size (0.068 m vs. 0.878 m, respectively). The existing quadrupole configuration in AP1
 2682 cannot produce the desired spot size and will need to be reconfigured. Figure 7.26 shows
 2683 a modified version of the scheme proposed in Ref. [17], where a quadrupole triplet replaces
 2684 the last quadrupole, PQ9B, in the AP1 line. Figure 7.26 shows the optics in the final 50 m
 2685 of the AP1 line where the final focus occurs. The quadrupoles making up the triplet need to
 2686 be as short as possible while concurrently producing a very strong integrated gradient. The
 2687 PQ8A&B and PQ9A magnets are not powered and can be removed to improve aperture, if
 2688 desired. Larger aperture NDB trim magnets from surplus Pbar inventory will replace HT107
 2689 and VT108 to provide adequate aperture.

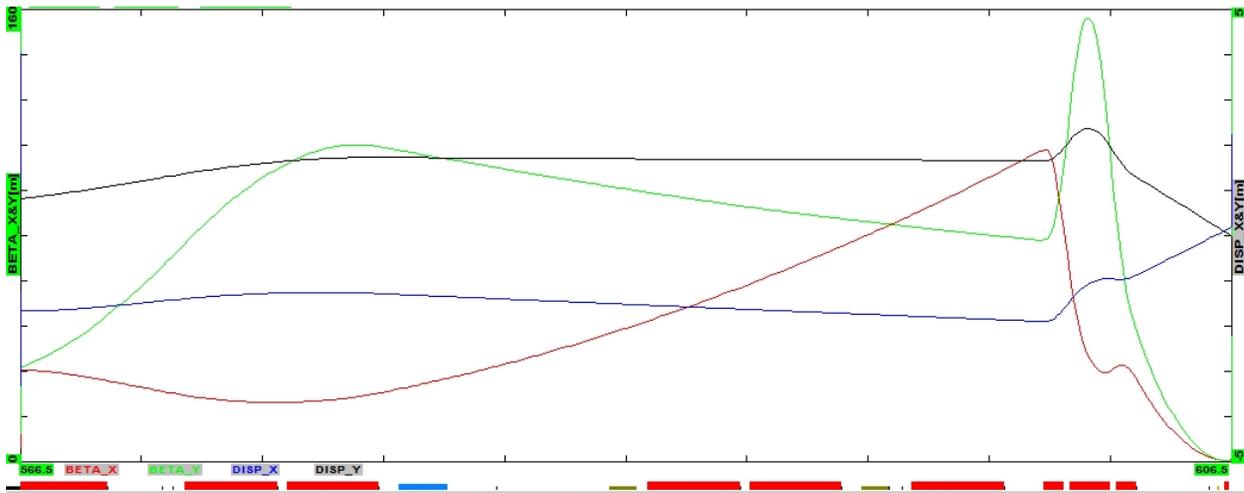


Figure 7.26: Beta functions (horizontal is red, vertical is green) and dispersion functions (horizontal is blue, vertical is black) for final focus region of AP1 line.

2690 The best compromise between maximizing integrated field, minimizing quadrupole length
 2691 and providing adequate aperture, from available magnets, is to use a triplet made of of an
 2692 SQD – SQE – SQD combination. The quadrupoles are required to run between 400 and
 2693 500 Amps in order to achieve the desired 0.15 mm spot size, which equals the highest currents

2694 these types of magnets have ever operated at. The temperature and flow of Low Conductivity
2695 Water (LCW) through these magnets will be particularly critical and may necessitate the
2696 construction of a dedicated closed-loop LCW system to prevent problems from overheating.
2697 The SQE magnet in the middle of the triplet is the strongest Pbar quadrupole available and
2698 operates at the highest current of the triplet quadrupoles (490 Amps).

2699 7.5.5 Pion to muon decay beamlines

2700 The M2 and M3 lines are designed to capture as many magic-momentum muons from pion
 2701 decay as possible. The M2 line will be rebuilt from the former AP2 line, which transports
 2702 secondary beam from the target station. The M3 line, rebuilt from the former AP3 line,
 2703 begins as a target-bypass which will be used by the Mu2e experiment to transport primary
 2704 8-GeV protons. For $(g - 2)$, the M2 line crosses over into the M3 line. Focusing of the
 2705 secondary beam within the target station is limited by available space in the target vault.
 2706 Immediately following the target station, the M2 line starts with a series of quadrupoles
 2707 which then match into a regular FODO lattice.

2708 Design layout

2709 With the exception of a few specialized insertions, the M2 and M3 lines track the trajectories
 2710 of the existing (but now defunct) AP2 and AP3 antiproton lines. The first 115.6 m of M2
 2711 downstream of the target-station lithium lens coincides with the AP2 trajectory. Pions
 2712 collected from the lens are transported to and aligned parallel with the left side of the tunnel
 2713 via the existing PMAG and IB1 dipoles, each of which bends the beam through 3° (52 mr).
 2714 From this point, the beam travels a further 96.7 m up to, and including, the existing IQ713
 2715 AP2 quadrupole.

2716 Through a two-step horizontal translation, the beam crosses the tunnel to merge with
 2717 the incoming upstream M3 line (used by the Mu2e experiment). Each of the four horizontal
 2718 bend centers in this insertion contributes 104 mr. The relatively large bends involved at
 2719 each stage of this transition are driven by:

- 2720 • Maintaining tight focusing quad spacing in M2 for $(g - 2)$ to capture as many magic-
 2721 momentum decay muons as possible;
- 2722 • Minimizing the distance in which hardware would interfere with transportation / travel
 2723 down the middle of the tunnel;
- 2724 • Minimizing the impact of the insertion on maintaining continuous, controlled optical
 2725 properties, and;
- 2726 • Providing the flexibility to convert between $(g - 2)$ and Mu2e operations without
 2727 downtime to reconfigure hardware.

2728 The last two magnets in the transition insertion act as a switch between $(g - 2)$ and Mu2e
 2729 running. A large-aperture quadrupole, Q733, followed by a modified B1 dipole are both
 2730 aligned with the M3 trajectory. During $(g - 2)$ operation, the beam enters the quadrupole
 2731 off-axis and receives a 25 mr dipole kick. The B1 dipole provides an additional 43.6 mr to
 2732 complete the merger with the M3 line. (For Mu2e operation the beam will enter the quad
 2733 on-axis, and the B1 dipole is turned off).

2734 Immediately following the transition across the aisle, a specialized insertion created by
 2735 two SDB dipoles bends the trajectory through 18.5° (323 mr) to the right, aligning with the
 2736 existing AP3 path in the tunnel. The beam continues for 63.0 m to the beginning of the
 2737 geometric and optical matching section between the M3 line and the Delivery Ring (DR)
 2738 injection point in the D30 straight section.

2739 This final injection section satisfies multiple, interleaved design constraints:

- 2740 • Providing the optical match between the lattice functions of the M3 line and those of
2741 the DR;
- 2742 • A 86 mr horizontal right bend to align with the D30 straight section, and;
- 2743 • An overall 4-ft elevation drop from M3 to the DR, performed in two steps.

2744 The first step of the drop in elevation uses two SDC dipoles bending through 85 mr. The
2745 second down-bend is provided by a SDD dipole bending down at 102.7 mr.

2746 Embedded in the level beamline section between the first and second elevation step-
2747 changes, two modified B1 dipoles bend horizontally, each through 43.1 mr to align the
2748 trajectory with the D30 straight section.

2749 The final stages of injection occur entirely in the vertical plane, with the final up-bend
2750 produced by a combination of a C-magnet in the beamline, followed by a large-aperture
2751 focusing quadrupole Q303 and a DC septum in the DR. The C-magnet bends in the upward
2752 direction by 32.2 mr, and steers the beam 11.6-cm high off-axis through Q303, generating
2753 another 29.9 mr of vertical kick. The septum adds 45.0 mr of bend up. Three kicker modules
2754 upstream of quad Q202 close the trajectory onto the orbit of the Delivery Ring.

2755 Total beamline length from the face of the target-station lithium lens to mid-quad Q202
2756 in the Delivery Ring is 296 m. Parameters of the main magnets are listed in Table 7.8.

2757 Optics

2758 Optical properties of the $(g - 2)$ beamline are defined by 65 quadrupoles of the proven
2759 Fermilab SQx and LQx types, and the 4Qx series from Brookhaven. The $(g - 2)$ beamline
2760 design is comprised of distinct optical modules, as illustrated in Fig. 7.27.

- 2761 • A matching section between the lithium lens and the main body of the upstream M2
2762 lattice;
- 2763 • A periodic series of thirteen FODO cells (115.6 m);
- 2764 • An achromatic 18.5° right bend formed using a quadrupole triplet;
- 2765 • A series of six FODO cells in the M3 line, and;
- 2766 • A matching section between the M3 FODO cells and the Delivery Ring in the D30
2767 straight section.

2768 The extreme upstream end of the M2 line is unchanged from the existing AP2 magnet
2769 configuration. Pions from the production target are optically focused by the lithium lens and
2770 the existing Q701 - Q704 quadrupole triplet. The magnet series of PMAG, quad triplet, and
2771 IB1 form a horizontal achromat. The subsequent four quadrupoles are powered individually
2772 in order to perform the optical match to lattice functions of a long section of FODO cells.

2773 In the M2 line, the FODO cells are characterized by their 90° of betatron phase advance
2774 and half-cell length of 4.444 m. The half-cell length is chosen to triple the existing quadrupole

Name (#)	Type	L [m]	B [T]	tilt	G [T/m]
M2 match from lithium lens to FODO section					
	PMAG	1.029	0.05283		
Q701	SQC	0.66675			-5.5725
Q701	SQC	0.66675			+4.7126
Q702	SQC	0.66675			+4.7126
Q704	SQC	0.66675			-5.6254
	MOD B1	1.5065	0.3579		
Q705	SQC	0.66675			+6.5782
Q706	SQC	0.66675			-9.6317
Q707	SQC	0.66675			+5.3884
Q708	SQC	0.4064			+3.3203
90° FODO straight section cells Q709-Q727					
QBNL (13)	4Q24	0.6096			±5.5037
QSQC (6)	SQC	0.66675			±5.1562
M2/M3 merge and 90° FODO cells Q728-Q734					
	SDE	2.500	0.4294		
Q728	4Q24	0.6096			+5.5037
	SDC	1.524	0.3812		
Q729	4Q24	0.6096			-5.5037
	SDC	1.524	0.3232		
Q730	SQC	0.66675			+5.1562
Q731	4Q24	0.6096			-5.5037
	SDE	2.500	0.4294		
Q732	4Q24	0.6096			+5.5037
	CMAG	1.524	0.2393		
Q733	LQC	0.66675			-5.1562
	MOD B1	1.5065	0.2989		
Q734	SQC	0.66675			+5.1562
Q735	SQC	0.66675			-4.4177
Q736	SQC	0.66675			+5.1562
Q737	SQC	0.66675			-3.9445
18.5° triplet achromat					
	SDB	3.048	0.548		
Q738	SQE	1.27635			+3.3814
Q739	SQE	1.27635			-3.1351
Q740	SQE	1.27635			+3.3814
	SDB	3.048	0.548		
M3 72° FODO cells					
Q741-752 (12)	SQC	0.66675			±3.3784
match to Delivery Ring Q202					
Q753	SQC	0.66675			-3.3127
	SDC	1.524	0.576	+90°	
Q754	SQC	0.66675			+3.4055
	SDC	1.524	0.576	-90°	
Q755	SQC	0.66675			-3.2048
	MOD B1	1.5065	0.2952		
Q756	SQE	1.27635			+4.3374
Q757	SQD	0.86995			-3.8292
Q758	SQD	0.86995			-3.8292
Q759	SQE	1.27635			+4.3374
	MOD B1	1.5065	0.2952		
Q760	SQC	0.66675			-3.2856
Q761	SQC	0.66675			+4.0158
	SDD	1.6605	0.638	+90°	
Q762	4Q16	0.4064			-3.3150
Q763	4Q16	0.4064			-3.3150
	CMAG	1.524	0.218	-90°	
Delivery Ring					
Q303	LQD	0.86995			+3.0580
	SEPTUM	1.8796	0.247	-90°	
Q302	SQC	0.66675			-3.9850
Q301	SQC	0.66675			+4.0224
(3)	KICKER	1.0012	0.021	-90°	
Q202	SQC	0.66675			-3.9658

Table 7.8: Main magnet parameters of the M2 and M3 beamlines for $(g - 2)$ operation at 3.094 GeV/c.

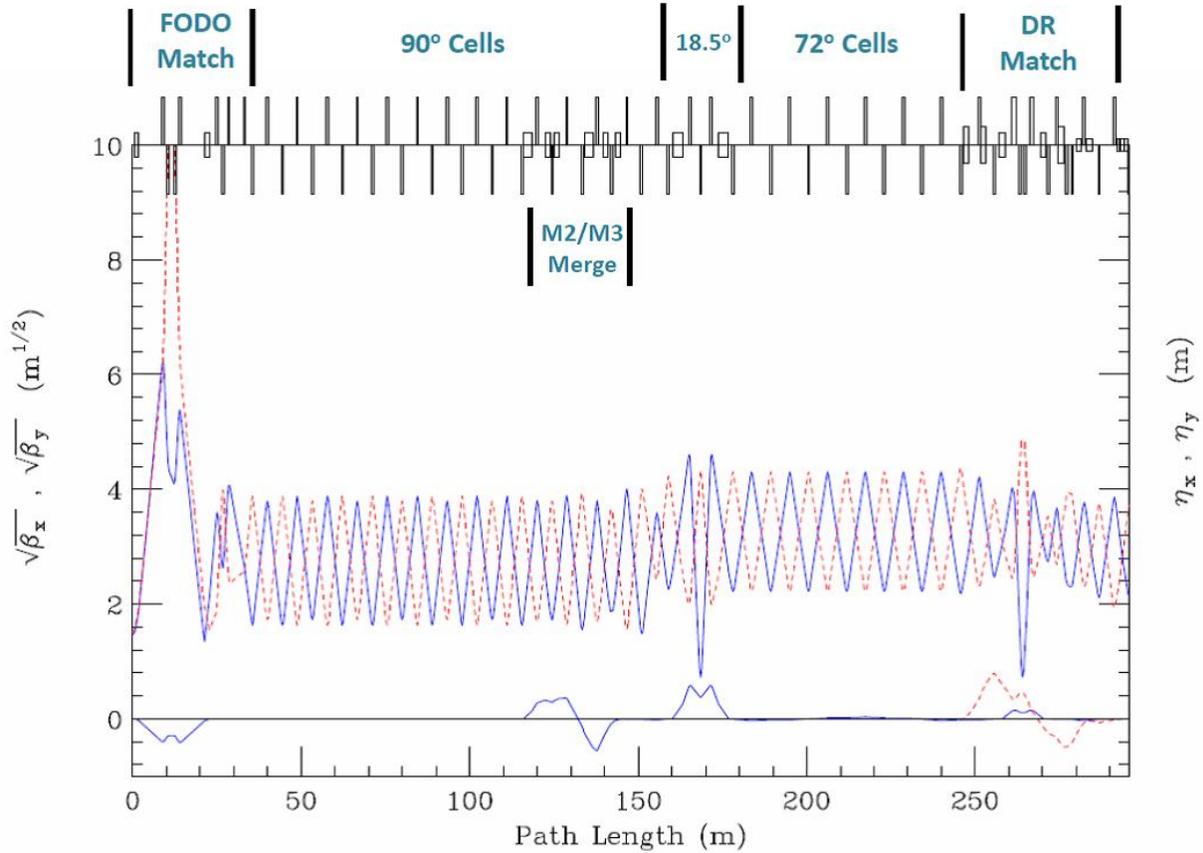


Figure 7.27: Horizontal (solid blue) and vertical (dashed red) lattice functions of the $(g - 2)$ transfer line from the face of the lithium lens to mid quad Q202 in the Delivery Ring. Boxes centered along the top axis indicate dipole locations, while boxes extending up and down are focusing and defocusing quadrupoles.

2775 density in the regularly spaced upstream portion of the M2 line. Embedded in the last four
 2776 of these cells is the two-step horizontal achromat that transitions the M2 line across the
 2777 tunnel to merge onto the M3 line trajectory (Fig. 7.28).

2778 The 18.5° horizontal bend has the two bend centers separated by a quadrupole triplet of
 2779 SQC.s to generate the 180° of betatron phase advance needed to kill the dispersion locally.

2780 M3-line FODO cells are characterized by 72° of phase advance and a half-cell length of
 2781 5.613 m. These parameters are chosen to accommodate Mu2e operation at 8.889 GeV/c.
 2782 The $\sim 25\%$ longer cell length and slightly weaker focusing than in the M2-line FODO section
 2783 relative to M3 allow the SQC quads to operate at approximately their design gradient of
 2784 9.8 T/m.

2785 The final nine quadrupoles in the line perform the optical match between the 72° FODO
 2786 cells and the Delivery Ring. This section contains an achromatic horizontal bend embedded
 2787 in an achromatic vertical descent from the M3 elevation to that of the DR. Lattice functions
 2788 and bend directions are shown in Fig. 7.29.

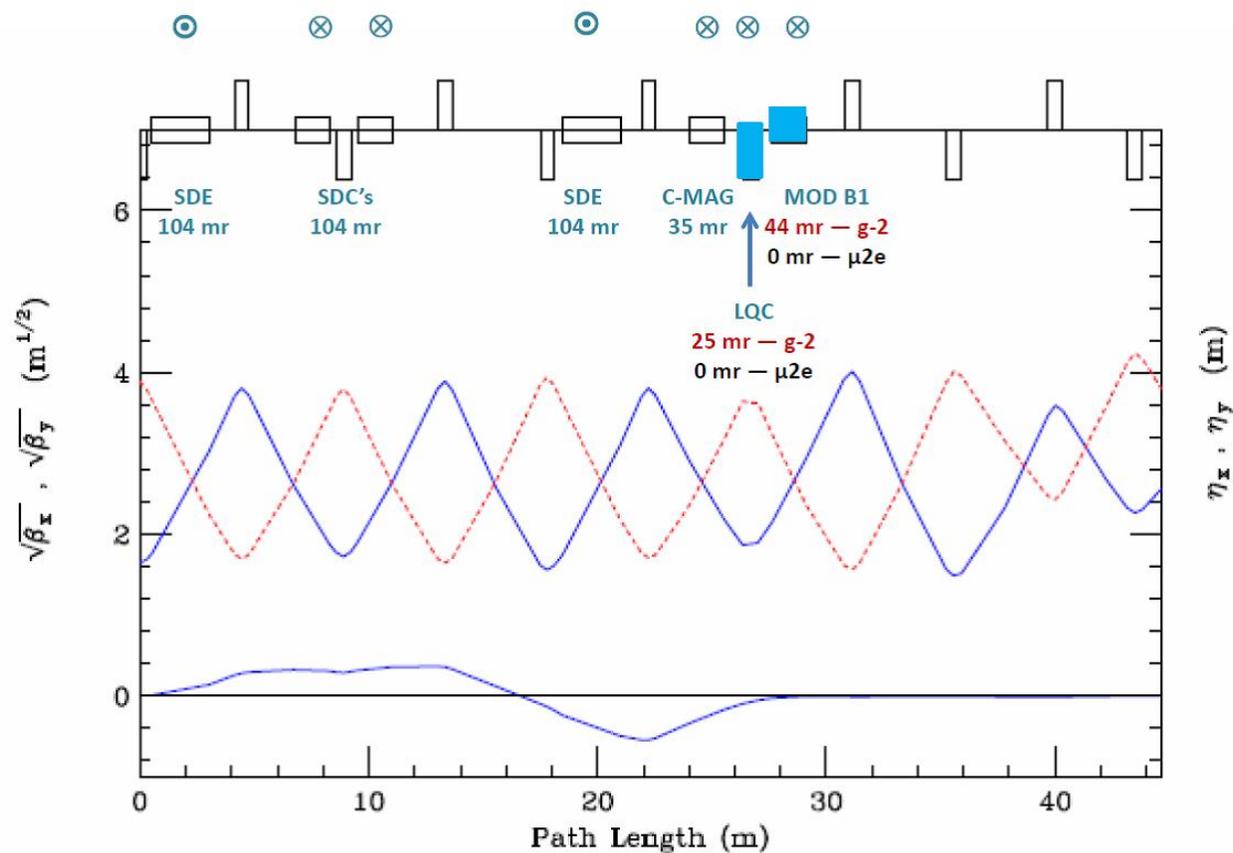


Figure 7.28: Horizontal (solid blue) and vertical (dashed red) lattice functions through the horizontal transition from the M2 line across the tunnel to merge with the M3 line. Circles shown above the upper axis indicate bend directions – those with a cross are bends left, and those with a dot are bends right. The final two (highlighted) magnets create a dipole switch between $(g - 2)$ and Mu2e operations.

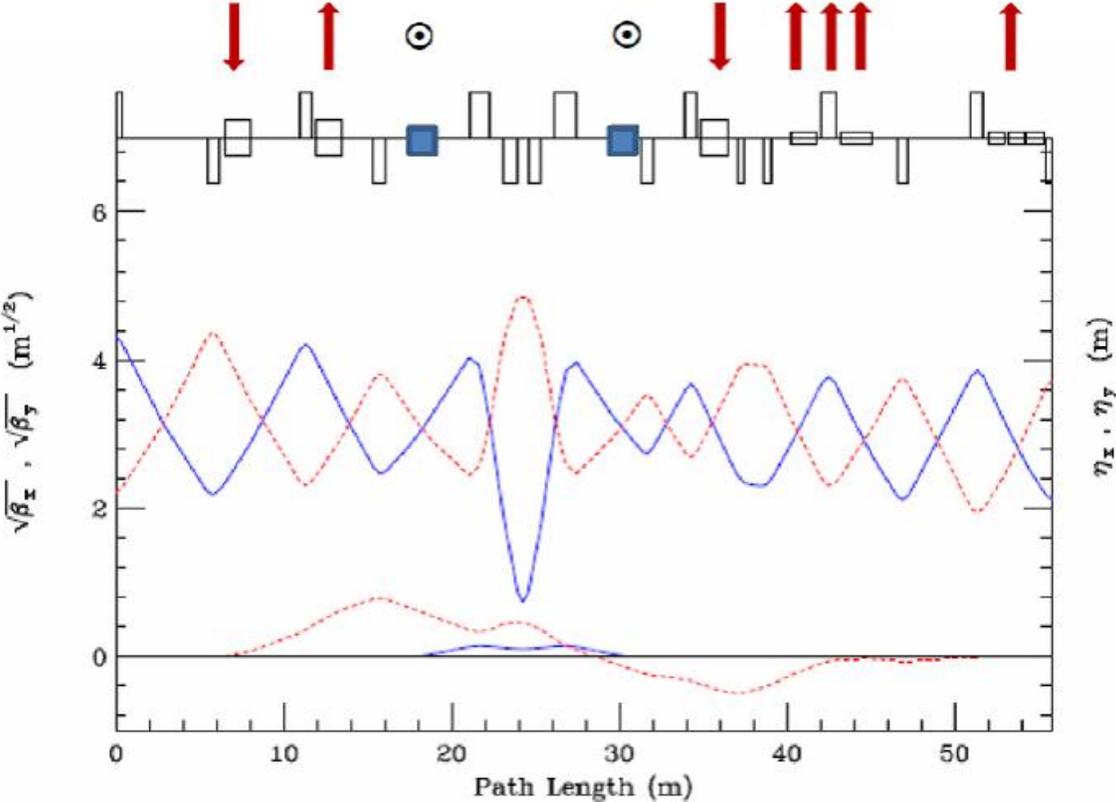


Figure 7.29: Horizontal (solid blue) and vertical (dashed red) lattice functions through the matching section from the M3 FODO cells into the DR straight. Arrows indicate the vertical bend direction in the two steps of the 4-ft drop in elevation.

7.5.6 Delivery Ring

The Pbar Debuncher ring will largely remain intact for $(g-2)$ operation and will be renamed the Delivery Ring for its new role in providing muons to the experiment. A considerable amount of equipment left over from Pbar operation will need to be removed from the Debuncher. Most of the equipment targeted for removal was used for stochastically cooling the antiproton beam during collider operation and is not needed for $(g-2)$. Some of these devices also have small apertures, so the ring acceptance will be improved with their removal. The cooling tanks in the D30 straight section also need to be removed to provide room for the new injection and extraction devices.

The Pbar Accumulator ring will not be needed for $(g-2)$ and Mu2e operation and will become a source of magnets, power supplies and other components for use in the reconfigured beamlines. In particular, the M4 (extraction) line will be largely made up of former Accumulator components. Some larger-aperture magnets will also be needed in the injection and extraction regions and will come from the Accumulator or other surplus sources.

Rings Lattice and Acceptance

The original design lattice for the Debuncher will be used for the Delivery Ring with few modifications. The lattice has a 3-fold symmetry with additional mirror symmetry in each of the three periods, with three zero-dispersion straight sections: D10, D30 and D50. The original lattice parameters were largely dictated by the requirements for Pbar stochastic cooling and the RF systems. The Debuncher was designed with a large transverse and longitudinal momentum acceptance in order to efficiently RF-debunch and stochastically cool antiprotons from the production target. This lattice design is also well suited for $(g-2)$ operation. During Collider Run II, the original lattice was distorted somewhat in order to reduce the beam size in the stochastic cooling tanks that had limiting apertures. Since these tanks will be removed, the lattice that will be used for the $(g-2)$ conceptual-design work will revert back to the original Debuncher design lattice. Figure 7.30 shows the lattice functions for one period of the Debuncher.

It should be noted that the design acceptance of the Debuncher was 20π -mm-mr. During the 25 years of Pbar operation, numerous aperture improvements were undertaken to boost the acceptance of the Debuncher. After the final Collider Run II aperture improvements were put in place in 2007, the measured acceptance of the Debuncher was as high as 33π -mm-mr in both transverse planes. The $(g-2)$ design goal of a 40π -mm-mr acceptance for the Delivery Ring, while reusing as much of the original equipment as possible, presents a difficult challenge.

The transverse acceptances of the Debuncher dipole, quadrupole, sextupole, and trim magnets are quite large. The smallest magnet acceptance is in the vertical plane of the dipoles and is approximately 54π -mm-mr on one end, growing to 79π -mm-mr on the other end. The dipoles have a 90π -mm-mr or larger horizontal acceptance (90π -mm-mr for the $\pm 2\%$ momentum spread and locations with the largest dispersion) and the other magnets have a 100π -mm-mr or larger acceptance in both planes. Since the original Debuncher lattice will not be significantly changed for $(g-2)$ operation, the main Delivery-Ring magnets will not be limiting apertures. In general, devices with a physical aperture of 50 mm or greater

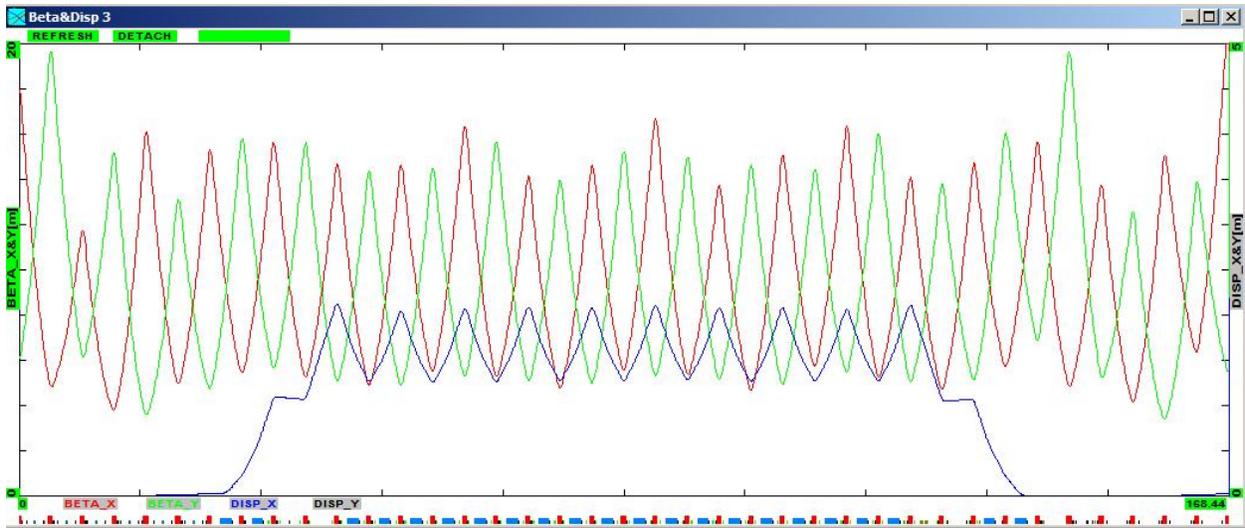


Figure 7.30: Debuncher/Delivery Ring lattice functions through 1/3 of the ring. β_x is in red, β_y in green, and horizontal dispersion in blue.

2831 provide an acceptance of over 40π -mm-mr in the Debuncher, and select locations can provide
 2832 that acceptance for devices that have an aperture of 40 mm, as long as they are relatively
 2833 short.

2834 During Collider operation, the smallest physical apertures in the Debuncher came from
 2835 stochastic cooling tanks, RF cavities, instrumentation, and devices used for injecting and
 2836 extracting beam. Many of these devices will be removed as part of the repurposing of the
 2837 Debuncher for the muon experiments. Some of these devices, most notably the kickers,
 2838 will be retained in the interest of economy and/or complexity and lead-time of manufacture.
 2839 Other devices, such as the injection septa, will be new devices with necessarily small physical
 2840 apertures in order to provide enough bend strength.

2841 During Collider Run II, the Band-4 stochastic cooling tanks were the limiting aperture
 2842 in both planes of the Debuncher. The Band-4 tanks had a 38 mm physical aperture in the
 2843 cooling plane, and there were both horizontal and vertical pick-up and kicker tanks in the
 2844 D10 and D30 straights respectively. All of the stochastic cooling tanks will be removed prior
 2845 to $(g - 2)$ operation.

2846 There is only one RF cavity planned for the Delivery Ring, which is needed to support
 2847 Mu2e operation and will have an aperture similar to the Debuncher rotator cavities. Since
 2848 the rotator cavities had an acceptance that was greater than 100π -mm-mr, the new cavity
 2849 will have ample aperture and need not be removed when switching from operating Mu2e
 2850 to $(g - 2)$. All RF cavities used for antiproton production will be removed prior to $(g - 2)$
 2851 operation.

2852 Many of the beam detectors used during Pbar operation had small physical apertures in
 2853 order to improve sensitivity. Since the beam intensities when running $(g - 2)$ are expected
 2854 to be even smaller than those seen during Pbar operation, designers will need to be mindful
 2855 of the aperture needs of the $(g - 2)$ experiment. Similarly, when instrumentation is being
 2856 considered for reuse in the Delivery Ring, the physical aperture and proposed tunnel location
 2857 should be analyzed for adequate acceptance.

2858 The transverse Schottky detectors used in the Debuncher had apertures that were only
 2859 slightly larger than the Band-4 stochastic cooling pick-up. They were removed from the
 2860 Debuncher during Run II, but have been reinstalled for use during ($g - 2$) and Mu2e studies.
 2861 Although these Schottkys are slated for removal prior to ($g - 2$) operation, the Mu2e exper-
 2862 iment may need a new device to monitor tunes during resonant extraction. If a new device
 2863 is made, it will need to have adequate aperture for ($g - 2$) or will have to be removed when
 2864 switching between the two experiments. The DCCT beam-intensity monitor will also be used
 2865 by the Mu2e experiment. It is expected to have adequate aperture as long as it is located
 2866 in the middle of a straight section half-cell, where the beam has a circular cross-section.

2867 Both injection from the M3 line and extraction to the M4 line take place in the D30
 2868 straight section. Injection will be located in the upstream half of the straight section, and
 2869 the pulsed magnetic septum and kicker magnets will have small apertures in order to provide
 2870 adequate bending strength. The septum has a small aperture in both planes, while the kicker
 2871 is primarily limited in the horizontal plane. The septum is a modified Booster-style (BSE)
 2872 magnetic septum magnet. The septum modifications involve increasing the pole gap from
 2873 28 mm to 42 mm in order to greatly improve the horizontal acceptance, and reducing the
 2874 septum thickness from 14 mm to 9 mm to increase the vertical acceptance. The injection
 2875 kicker system will be made up of two surplus Pbar AP4 injection kicker magnets. The
 2876 horizontal aperture is only 41 mm and will likely be one of the limiting apertures of the
 2877 Delivery Ring. The extraction kicker system will be made up of two Pbar extraction kicker
 2878 magnets. They have a vertical aperture of 41 mm and will also be one of the limiting
 2879 apertures of the Delivery Ring.

2880 Kickers and Septa

2881 The kickers and septa required for ($g - 2$) operation will need to operate at a much higher
 2882 frequency than that used for antiproton production, with peak rates increasing as much
 2883 as a factor of 30. In an effort to make the new kicker systems more economical, existing
 2884 kicker magnets will be reused. Kickers will be required for injection and extraction from
 2885 the Delivery Ring as well as for proton removal. Table 7.9 compares kicker parameters
 2886 for existing Pbar systems to the specifications for the ($g - 2$) injection and proton-removal
 2887 kickers. The rise and fall time specifications for ($g - 2$) are generally less strict than what
 2888 was needed for antiproton production, due to the short bunch length of the muons (and
 2889 protons). Decreasing the rise time of the proton removal kicker, however, will reduce the
 2890 number of turns required in the Delivery Ring to adequately separate the protons from the
 2891 muons. Although the Pbar kicker magnets are suitable for reuse, new power supplies will be
 2892 needed to operate at the increased rate. Resistive loads for the kickers will need to be cooled
 2893 with Fluorinert. A single Fluorinert distribution system is planned, with piping bridging the
 2894 distance between the load resistors from kickers in the D30 and D50 straight sections.

2895 The septa and pulsed power supplies used during Pbar operation are not suitable for
 2896 rapid cycling and cannot be used for ($g - 2$). The septa have no internal cooling to handle
 2897 the increased heat load from the planned high duty cycle, and the power supplies are not able
 2898 to charge quickly enough. The Booster-style septum magnets can be modified to have the
 2899 necessary size and field strength required for use in the injection and proton removal systems,
 2900 and therefore are the preferred choice. The power supplies used in the Booster to power the

Kicker (modules)	Integrated Field (kG-m)	Kick Angle (mr)	Rise Time 95%/5% (ns)	Fall Time 95%/5% (ns)	Flat Top Time (ns)
Debuncher Extraction (3)	1.34	4.6	150	150	1500
Debuncher Injection (3)	1.81	6.1	185	185	1500
Delivery-Ring Injection (2)	0.64	6.2	n/a	800	300
Delivery-Ring Extraction (2)	0.83	7.0	450	n/a	200
Delivery-Ring Proton Removal (3)	0.64	6.2	180	n/a	270

Table 7.9: Existing Pbar (top) and future ($g - 2$) (bottom) kicker strength and waveform specifications.

2901 septum magnets also appear to be a good fit. Although they are designed to operate at
 2902 a lower frequency (15 Hz) than the peak needed for ($g - 2$), the lower operating current
 2903 (for 3.1 GeV/c versus 8.89 GeV/c momentum) should more than compensate for changes to
 2904 the heat load and mechanical stresses due to the increased pulse rate. The Booster septum
 2905 magnets are slightly shorter than their Pbar counterparts, so the new septa can comfortably
 2906 fit between quadrupoles in the injection and proton removal regions.

2907 Delivery Ring D30 straight section

2908 The Delivery-Ring injection and extraction regions will both be located in the D30 straight
 2909 section. In both cases, the tight quadrupole spacing in the Delivery Ring creates physical
 2910 conflicts with existing utilities and ring devices in the areas of elevation change to and
 2911 from ring level. The existing cable trays on the Debuncher side of the ring will need to
 2912 be completely dismantled and relocated towards the middle of the tunnel so that the new
 2913 beamlines can be hung from the ceiling. The extraction line will closely follow the trajectory
 2914 of the decommissioned AP4 (Booster to Debuncher) line. The tunnel in this region has an
 2915 existing stub region that the extraction line will pass through, eliminating the need for civil
 2916 construction to widen and strengthen the tunnel. Figure 7.31 shows the layout of injection
 2917 and extraction devices in the D30 straight section.



Figure 7.31: D30 straight section, injection on right, extraction on left.

2918 Injection

2919 The M3 line runs above the Delivery Ring in the upstream end of the D30 straight section
 2920 and ends with a vertical translation into the ring. M3 injection will be achieved with a
 2921 combination of a C-magnet, magnetic septum, D3Q3 quadrupole, and kicker magnets, which
 2922 will all provide vertical bends. The septum and C-magnet are both based on existing designs,
 2923 which reduces overall costs, but modified to improve the aperture. Both magnet designs
 2924 required modifications in order to attain the ($g - 2$) acceptance goal of 40π -mm-mr.

2925 The magnetic septum is a modified Booster-style (BSE) magnet, with an increased pole
 2926 gap and a thinner septum to improve aperture. The BSE magnet has a 1.1-in pole gap, which
 2927 will be increased to 1.65 in for the new septum. Similarly, the C-magnet is a larger aperture
 2928 (2.1 in instead of 1.6 in) and shorter (2.0 m instead of 3.0 m) version of the Main-Injector
 2929 ICA magnet. An identical C-magnet is used in the extraction region. The descending beam
 2930 in M3 will pass through the C-magnet first and will be bent upward by 38 mr. The beam
 2931 will continue well above the center of the D3Q3 quadrupole and receive a 30-mr upward
 2932 kick. Since the beam is up to 140 mm above the centerline of the quadrupole, a large-bore
 2933 quadrupole magnet is required in order to provide adequate aperture. The large quadrupole
 2934 at D3Q3 will be the LQE magnet from the D2Q5 location, which will be replaced by an
 2935 8-in quadrupole, as described below. The LQx magnets were designed to have a substantial
 2936 good-field region that extends between the poles. Similar arrangements with LQ magnets
 2937 can be found in Pbar at D4Q5 (former AP2 injection, planned proton removal) and D6Q6
 2938 (former Debuncher extraction). The injected beam then passes through the field region of the
 2939 septum magnet and receives a 37-mr upward bend as required for the necessary trajectory
 2940 entering the injection kicker magnets. The kicker magnets provide a final 6.2-mr vertical
 2941 bend to place the injected beam on the closed orbit of the Delivery Ring.

2942 The two-module kicker system is located between the D30Q and D2Q2 magnets. To min-
 2943 imize the horizontal β function and maximize acceptance, the kickers will be located as close
 2944 to the D2Q2 quadrupole as possible. Spare Pbar injection kicker magnets will be refurbished
 2945 and reused for muon injection. The magnets are already designed to be oriented vertically,
 2946 so little additional effort will be required to convert them to their new application. Kicker
 2947 rise and fall time specifications and power supply information was provided in Table 7.9 and
 2948 the accompanying text. Figure 7.32 shows the injection devices and their location in the
 2949 Delivery Ring, along with their bend angles. Due to the large vertical excursion through the
 2950 top of the D3Q2 magnet, a vertical bump across the injection region will be incorporated
 2951 to lower the beam and improve the aperture. The quadrupole magnets at D2Q2, D30Q and
 2952 D3Q4 will be displaced to create the bump by generating steering due to the beam passing
 2953 off-center through the magnets. To create a 15-mm downward displacement at D3Q2, the
 2954 magnets will be lowered by 8.1, 11.0, and 4.2 mm respectively. It would be beneficial, but
 2955 not necessary for 40 π -mm-mr acceptance, to install an existing “extended star chamber”
 2956 quadrupole at the D3Q2 location. SQD-312, in magnet storage, was previously located at
 2957 D4Q4 in the Pbar AP2 injection area and has an extended top lobe in its star chamber.

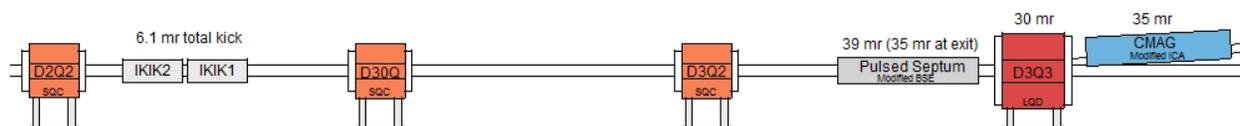


Figure 7.32: Delivery-Ring injection devices.

2958 **Extraction**

2959 Extraction from the Delivery Ring takes place in the downstream half of the D30 straight
 2960 section. The extraction channel and the first 30 m of the M4 line will be used for both
 2961 Mu2e resonant extraction and $(g - 2)$ single-turn extraction. This arrangement avoids the
 2962 complexity and additional expense of dual extraction lines in the limited available space.
 2963 It also eliminates the need to remove potentially highly radioactive objects from the ring
 2964 when switching between experiments. The ideal extraction configuration will provide enough
 2965 aperture for both the Mu2e resonantly-extracted proton beam and the $(g - 2)$ muon beam
 2966 to be transported efficiently through the M4 line.

2967 A Lambertson and C-magnet pair will be used, in conjunction with the intervening D2Q5
 2968 quadrupole, to bend the beam upward out of the Delivery Ring. In the interest of compati-
 2969 bility between $(g - 2)$, Mu2e, and future muon experiments, a Lambertson magnet is required
 2970 for extraction. The resonant-extraction process used for Mu2e is very restrictive on the size,
 2971 strength, and location of the electrostatic septa that are required to split the extracted beam.
 2972 The electrostatic septa must be located on either side of the D2Q3 quadrupole, and are ex-
 2973 pected to be about 1.5 m in length. In order to achieve the goal of a combined extraction
 2974 channel and beamline, the $(g - 2)$ extraction kickers must be located in a lattice location that
 2975 is $\sim n\pi/4$ radians from the Lambertson, where n is an integer, and in an area not already
 2976 occupied by injection or extraction devices.

2977 The $(g - 2)$ extraction kickers will be located between the D2Q2 and D2Q3 quadrupoles.
 2978 There will be two kicker modules of approximately 0.85 m length each. During the dedicated
 2979 period of $(g - 2)$ operation, the kickers will be located as close to the D2Q3 quadrupole as
 2980 possible in order to minimize the vertical β function and maximize acceptance. The kicker
 2981 magnets will be repurposed Pbar extraction kicker magnets that have a vertical aperture of
 2982 41 mm. The kicker magnets will be powered in series from a single power supply. There is also
 2983 an alternative layout planned that would allow $(g - 2)$ to operate after the Mu2e electrostatic
 2984 septa are installed. There is only room for a single kicker near the D2Q2 quadrupole in this
 2985 arrangement, so the kicker magnet would need to be modified in order to provide enough
 2986 bending strength. The relocation of the kicker would also reduce aperture unless the β
 2987 functions in this region could be suppressed by about 20%. Figure 7.33 shows the layout of
 2988 the extraction devices for dedicated $(g - 2)$ operation and 40 π -mm-mr acceptance.

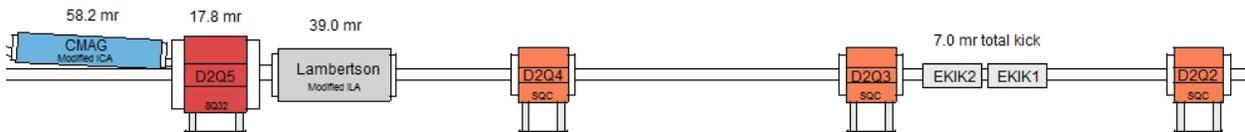


Figure 7.33: Delivery-Ring extraction devices.

2989 **Proton Removal (Abort) System**

2990 The proton removal system is an example of both repurposing an otherwise unneeded part
 2991 of the Antiproton Source and implementing a dual function system that can be used by both

2992 ($g - 2$) and Mu2e. During Mu2e operation, an abort is needed to minimize uncontrolled
 2993 proton beam loss and to “clean up” beam left at the end of resonant extraction. The proton
 2994 beam must be removed quickly, by means of kicker magnets, in order to minimize losses in
 2995 the ring. The ($g - 2$) experiment can benefit from the removal of protons before they reach
 2996 the storage ring. The abort system can serve this purpose, as long as the protons sufficiently
 2997 slip in time to create a gap for the kickers to rise through.

2998 The old Debuncher injection point from the AP2 line in the D50 straight section will
 2999 be used for the abort and proton removal systems. Recall that most of the AP2 line will
 3000 be removed and replaced with the new M2 line that will merge with the M3 line upstream
 3001 of the right bend. The downstream end of AP2, where antiprotons were formerly injected
 3002 into the Debuncher, can now be used to extract protons from the Delivery Ring. This is
 3003 made possible by the change in beam direction (as viewed from above) from clockwise to
 3004 counterclockwise. The existing Pbar injection kicker magnets can be reused, although a new
 3005 power supply will be needed to operate at the frequency needed to support Mu2e and ($g - 2$).
 3006 The septum magnet and power supply will also need to be upgraded for the same reason.
 3007 The new larger-aperture septum magnet will be identical to what was previously described
 3008 for injection into the Delivery Ring. The section of the AP2 beamline being repurposed will
 3009 require the addition of a vertical bending magnet to steer beam into the abort dump located
 3010 in the middle of the Transport tunnel. Figure 7.34 shows the layout of the abort line.

Vertical Profile of the Delivery Ring Abort Line

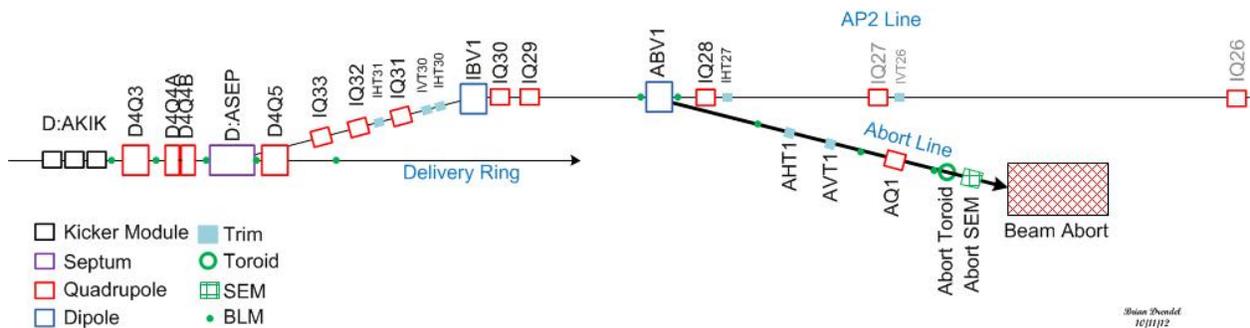


Figure 7.34: Side view of the Delivery Ring Abort/Proton Removal line.

3011 The most economical plan is to only power the first kicker magnet, which provides the
 3012 shortest rise time, a (barely) strong enough kick and requires only a single power supply.
 3013 The rise time of the kickers with this configuration is about 180 ns. The kickers will be
 3014 reconfigured for Mu2e operation, because all three kicker magnets are required to provide
 3015 enough strength due to the higher beam momentum for Mu2e. Mu2e will also need a longer
 3016 flattop to cover the entire proton revolution period of 1695 ns. For ($g - 2$) proton removal,
 3017 the 180-ns rise time requires several revolutions around the Delivery Ring to provide enough
 3018 gap between the muons and protons for the kicker to rise through. Table 7.10 lists the
 3019 separation between the beams and the gap size for different numbers of turns. Four turns
 3020 around the Delivery Ring would be required to cleanly remove all of the protons without
 3021 disturbing the muons. All of the protons could be removed in three turns, but some of the

3022 muons would also be deflected. The table is based on the assumptions already stated: that
 3023 the kicker rise time is 180 ns, the proton and muon bunch lengths are 120 ns and that the
 3024 kicker should not disturb any of the muons.

	Muon vs. Proton		Impact of proton removal kickers
	Centroid time difference (ns)	Gap size (ns)	
Injection	40	None	Unable to kick protons only
1 st turn at Abort	91	None	Unable to kick protons only
2 nd turn at Abort	161	41	25% of protons removed
3 rd turn at Abort	231	111	85% of protons removed
4 th turn at Abort	301	181	Protons cleanly removed
5 th turn at Abort	371	251	Protons cleanly removed

Table 7.10: Efficiency of proton-removal system for different number of turns in the Delivery Ring, based on a 120-ns bunch length and 180-ns kicker rise time.

3025 As the kicker magnets “fill” during the rising current waveform, the kicker magnetic
 3026 field and bending strength increase proportionally. Protons are completely removed from
 3027 the Delivery Ring when the kicker strength is about 85% of what is needed to center beam
 3028 in the abort channel. Between 85% and 100% of the nominal kicker strength, some of the
 3029 protons will be lost on the Abort Septum instead of traveling to the abort. As the kicker
 3030 strength drops below 85%, an increasing number of protons remain in the Delivery Ring. In
 3031 addition to separating the beams to improve removal efficiency, the percentage of protons
 3032 removed can also be increased by firing the kicker earlier and disturbing part of the muons.

3033 A side benefit of the muons taking multiple turns around the Delivery Ring is that
 3034 virtually all of the pions will have decayed before the muons reach the storage ring. The
 3035 primary potential problem with this proton removal concept is due to differential decay
 3036 systematic errors caused by the different muon path lengths as they travel through the
 3037 Delivery Ring. Although a preliminary analysis indicates that this will not be a significant
 3038 problem [18], a more thorough analysis is needed.

3039 Vacuum Systems

3040 The existing vacuum systems in the rings and transport lines have performed very well
 3041 during Pbar operation. Typical vacuum readings in the Debuncher and transport lines were
 3042 approximately 1×10^{-8} Torr. The Debuncher has good ion-pump coverage that should
 3043 generally be adequate for ($g - 2$) operation. Stochastic cooling tanks, kickers and septa that
 3044 will be removed during the conversion have built-in ion pumps, so some of these pumps may
 3045 need to be installed in the vacated spaces. Injection and extraction devices should have ion
 3046 pumps integrated into the design, or there should also be additional pumping capacity added
 3047 to the surrounding area. Vacuum components from the AP2 and AP3 lines should provide
 3048 most of the needs for the reconfigured M2 and M3 lines. The Accumulator has enough
 3049 surplus ion pumps and vacuum pipe available to cover part of the needs for the extraction
 3050 beamlines.

3051 **Infrastructure Improvements**

3052 Electrical power for the Antiproton Source is provided by Feeder 24, which operated with
 3053 a power level of about 4.4 MW during Pbar operation. Although the $(g - 2)$ power load
 3054 is expected to be considerably less than what was used in Pbar by virtue of the reduced
 3055 beam momentum, the Mu2e experiment must also be able to operate the same magnets
 3056 at 8.89 GeV/c. For Mu2e, most service buildings are expected to use approximately the
 3057 same amount of power as they did in Pbar operation. The exception is the AP-30 service
 3058 building, where there will be an increase in power load from the injection- and extraction-
 3059 line power supplies. A new transformer may be needed at AP-30 to provide the additional
 3060 power. A power test was performed on the individual service building transformers to aid
 3061 in predicting the power needs for Mu2e [19]. Also, since the Accumulator will no longer be
 3062 used, approximately 1.4 MW will be available for new loads.

3063 Presently, Pbar magnets and power supplies receive their cooling water from the Pbar 95°
 3064 Low Conductivity Water (LCW) system. The cooling requirements for $(g - 2)$ are expected
 3065 to be lower than for Pbar operation. However, Mu2e will operate at 8.89 GeV/c and create
 3066 a substantially larger heat load than $(g - 2)$. Fortunately, the removal of the heat load from
 3067 decommissioning the Accumulator and the AP2 line should be enough to offset the increase
 3068 from the extraction line and other new loads. The extraction beamlines (M4 and $(g - 2)$ lines)
 3069 will have an LCW stub line connecting to the Debuncher header in the D30 straight section.
 3070 If necessary, it is also possible to design smaller closed-loop systems that heat-exchange with
 3071 the Chilled Water system. The Chilled Water system has adequate capacity and is already
 3072 distributed to the Pbar service buildings.

3073 **7.5.7 Muon transport to storage ring**

3074 **Considerations**

3075 The $(g - 2)$ 3-GeV muon beam and the Mu2e 8-GeV proton beam must utilize common
 3076 D30 extraction magnetic components to complete separation from the Delivery Ring, and
 3077 extraction must occur vertically in order to accommodate the existing DR enclosure. The
 3078 large differences in beam size and energy place difficult, sometimes conflicting, demands on
 3079 the common extraction optics, especially the extraction Lambertson and vertical-bending
 3080 dipoles. The civil constraints of the local geography further complicate execution of the two
 3081 external beamlines.

3082 The civil constraints of the local geography for what is termed the muon campus can be
 3083 deduced from Fig. 7.35. The physical separation from the Delivery Ring through an achro-
 3084 matic vertical bend section (which separates and delivers beam into the external beamlines)
 3085 must be followed by strong horizontal bends to direct beam to the two experiments. The
 3086 length of the Mu2e beamline is limited by wetland avoidance and the much reduced $(g - 2)$
 3087 beamline length by the storage ring enclosure location. The $(g - 2)$ storage ring location
 3088 is required to avoid stray magnetic fields from Mu2e components on the west and utility
 3089 corridors on the east. The short distance from the common extraction Lambertson to the
 3090 $(g - 2)$ ring mandates efficient, space-conserving separation of the two external lines. Sepa-
 3091 ration must first occur vertically component-wise and then final separation utilizing a large
 3092 difference in the strengths of the left horizontal bends in the M4 and M5 lines which are now

3093 vertically independent. With no space available for a second vertical translation (and the
 3094 required achromatic conditions) the first vertical section must take the $(g - 2)$ beamline to
 3095 the required elevation for injection into the $(g - 2)$ storage ring.

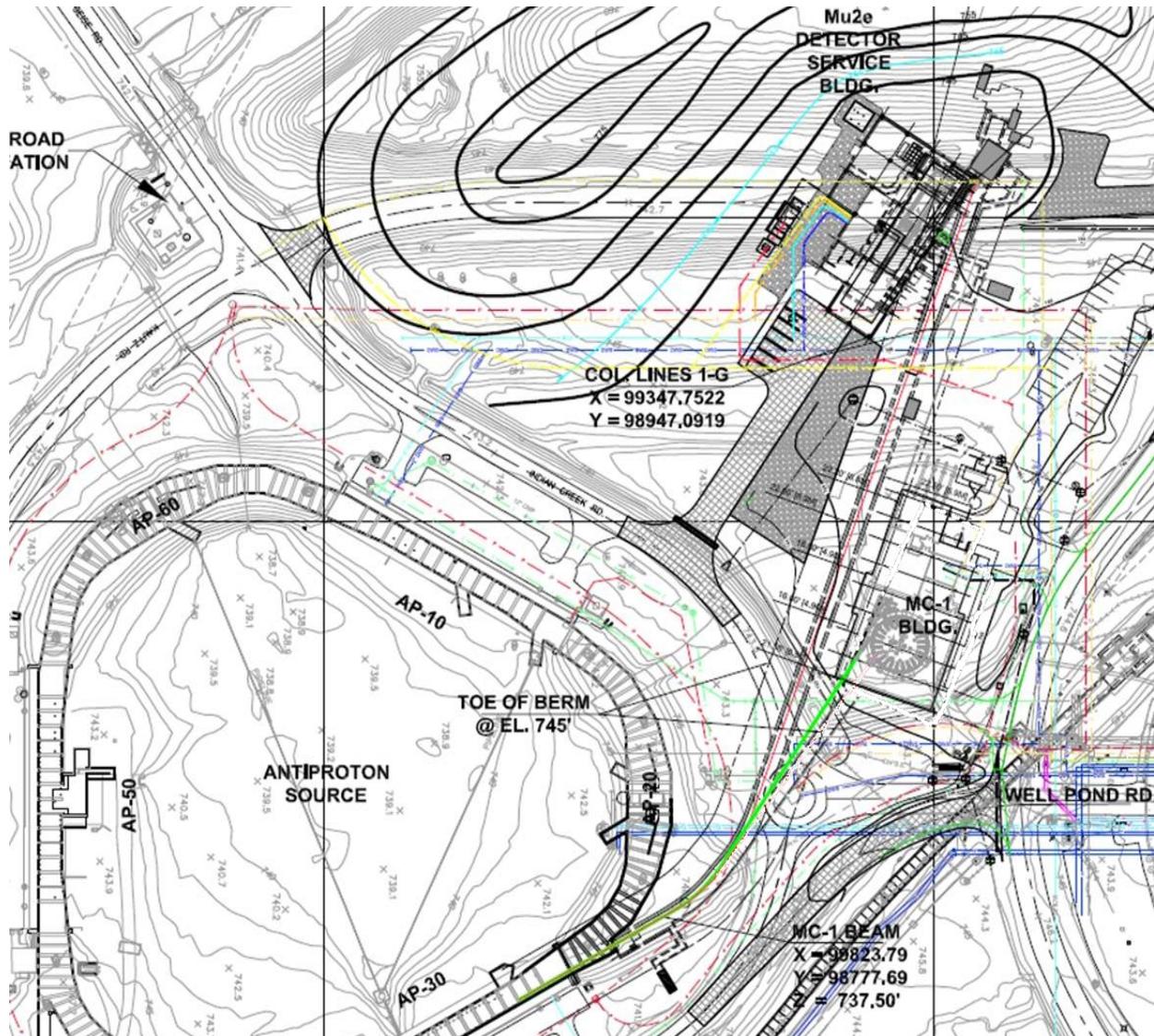


Figure 7.35: Layout of the muon campus showing the M4 and M5 external beamlines and Mu2e and $(g - 2)$ experimental halls.

3096 To appreciate the complexities of the two beamlines and $(g - 2)$ beam conditions, the
 3097 following criteria that must be addressed are listed under the criteria that dominate the line
 3098 design.

3099 Civil Layout

- 3100 • Horizontal extraction via a kicker in the D30 straight

- 3101 • Vertical separation from the Delivery Ring magnetic components (section common to
3102 Mu2e/ $(g - 2)$) and takes advantage of existing civil construction)
- 3103 • Vertical separation from Mu2e through a reversed vertical dipole. This section cleanly
3104 derives a separate beamline for $(g - 2)$ by changing the bend strength of a single dipole
3105 between $(g - 2)$ and Mu2e operation. Another dipole is added to the M5 line to level
3106 the beamline off at the storage ring elevation
- 3107 • The final elevation is 50" above projected civil elevation of $(g - 2)$ ring enclosure floor
3108 (@734.5' above sea level) or 225.1460 m and 6.3' above the Mu2e line in this region
3109 (@223.2243 m) and 10.3' above the Delivery Ring elevation (@222.005097 m)
- 3110 • A 27° horizontal bend string fixes the direction of the beamline from the D30 straight
3111 towards the geographic location chosen for the $(g - 2)$ storage ring. (Mu2e has a
3112 40.5° bend). The change in bend eventually separates the two experimental beamline
3113 enclosures.
- 3114 • Tunable dispersion in the horizontal bend string (0-4 m)
- 3115 • A FODO cell periodic section to propagate dispersion to the ring
- 3116 • A final focus section to tune beam through the inflector to injection

3117 Beam Properties

- 3118 • Requested geometric acceptance of 40π mm-mr
- 3119 • Limits the beam size or beta functions to ~ 40 m through most of the line
- 3120 • Injection matching into $(g - 2)$ storage ring is strongly influenced by the inflector
3121 aperture

3122 Beam Optics

- 3123 • An achromat is required to suppress vertical dispersion from the D30 vertical extrac-
3124 tion to the final beamline elevation. Dispersion must be suppressed upstream of the
3125 horizontal bend string to avoid coupling between the two planes. The M5 vertical
3126 achromat is a complicated 5-bend achromat (if one includes beam passing off-center
3127 through the D2Q5 quadrupole which contributes to vertical dispersion).
- 3128 • An adjustable horizontal dispersion module is required for the 27° horizontal directional
3129 bend string. The dispersion can be adjusted to propagate a value between 0 and 4 m
3130 to the injection point of the $(g - 2)$ storage ring.
- 3131 • A periodic FODO structure is utilized to propagate either zero dispersion or a dis-
3132 persion wave to the injection point at the ring. Dispersion cannot be matched at the
3133 ring as the line cannot sustain 8 m of dispersion aperture wise. If a new inflector is
3134 built, 4 m is possible. With the existing inflector, however, zero dispersion is the only
3135 solution.

- 3136 • If a new inflector with a significant non-zero field is constructed then the line must
3137 move to the opposite side of the tunnel enclosure to match into the new injection
3138 trajectory. Another dipole would be required to aim correctly to injection.
- 3139 • At this time, momentum collimation would be difficult to incorporate in the external
3140 beamline.

3141 Civil and geographical constraints (avoidance of wetlands, for example) dictate a $\sim 27^\circ$
3142 bend after extraction from D30 to satisfy the location of experimental hall. Only ~ 80 m are
3143 available for the M5 beamline after accomplishing the vertical elevation change.

3144 7.5.8 Beam Line Sections

3145 As stated above, the M5 beam line is best described in terms of its modular functionality.
3146 Correspondingly, the following descriptions detail the important sections, and discuss the
3147 rationale and justify the design approach for each section.

3148 **Extraction from the Delivery Ring** Incorporation of $(g - 2)$ and Mu2e extraction
3149 systems into the D30 straight has been carefully designed. The extraction part of the straight
3150 is considered to start at the center of D30Q (the center of the D30 straight). All quadrupoles
3151 have been carefully and relatively aligned in the optics input deck using the alignment data
3152 provided in Table 7.11. (This alignment data is considered so critical it has been included
3153 for future reference.) A number of kicker and septa locations were studied and the final
3154 location was previously described in Sec. 7.5.6.

3155 The pulsed magnetic kicker provides a $+6.1$ mr easterly horizontal kick (to the right
3156 looking downstream). The downstream defocusing quadrupole – D2Q4 – enhances the effect
3157 of the kicker and maximizes the beam separation at the entrance to a Lambertson. This
3158 kicked beam is then tracked in coordinate space through the Lambertson and D2Q5 with an
3159 offset relative to the Delivery Ring central reference orbit. At the entrance to the Lambert-
3160 son, the horizontal offset generated from circulating Delivery Ring beam is ~ 49 mm. The
3161 Lambertson is specified to be 1.5 m in length with a 0.8 T maximum field for Mu2e beam,
3162 and is located just upstream of D2Q5 (0.4 m). It is adjusted to deliver a 40 mr upward bend
3163 for both Mu2e and $(g - 2)$.

3164 The net bend up requires additional vertical bending which comes from two more sources.
3165 The next focusing quadrupole (D2Q5) in the Delivery Ring acts like a combined-function
3166 magnet and adds to the upstream Lambertson kick. (Since D2Q5 is a horizontally focusing
3167 quadrupole, the offset of the beam vertically generates an upward kick – a kick critical to
3168 efficient separation of the extracted beam from the Delivery Ring, adding approximately
3169 17 mr.) Just downstream of D2Q5 a 2 m-long C-magnet with a 58 mr bend angle is planned
3170 because a Lambertson-type magnet becomes difficult, but there is still insufficient separation
3171 to insert a full dipole. The combined effect of all three vertical bends (111.3 mr) allows beam
3172 to clear the next magnet – the last horizontally defocusing quadrupole in the D30 straight
3173 (D2Q6). Beampipe in the extraction line clears D2Q6 by a few inches and is 0.524 m, center
3174 to center at the upstream end. An SQA quadrupole located just downstream of D2Q6
3175 represents the first independent quadrupole in the M4 line.

SpatialAnalyzer SA 2012.07.09			
Points Relative to Coordinate Frame 'A::WORLD:FSCS_XYZ'			
location	x (m)	y (m)	z (m)
D2Q2_CT	30454.057473	30059.297097	222.005099
D2Q2_DN	30454.224153	30059.008397	222.005110
D2Q2_UP	30453.890802	30059.585847	222.005090
D2Q3_CT	30451.839361	30063.137949	222.005506
D2Q3_DN	30452.005882	30062.849149	222.005440
D2Q3_UP	30451.672881	30063.426769	222.005623
D2Q4_CT	30449.625500	30066.971251	222.004893
D2Q4_DN	30449.792071	30066.682481	222.004852
D2Q4_UP	30449.458900	30067.260031	222.004857
D2Q5_CT	30447.409089	30070.809692	222.005368
D2Q5_DN	30447.599539	30070.479722	222.005427
D2Q5_UP	30447.218599	30071.139693	222.005331
D2Q6_CT	30445.185298	30074.661744	222.006067
D2Q6_DN	30445.383758	30074.318054	222.006104
D2Q6_UP	30444.986868	30075.005454	222.006060
D3Q2_CT	30458.488435	30051.624184	222.004533
D3Q2_DN	30458.655185	30051.335484	222.004517
D3Q2_UP	30458.321735	30051.912884	222.004549
D3Q3_CT	30460.706756	30047.782592	222.004346
D3Q3_DN	30460.873366	30047.493822	222.004355
D3Q3_UP	30460.540176	30048.071372	222.004286
D3Q4_CT	30462.920737	30043.948321	222.004030
D3Q4_DN	30463.087337	30043.659580	222.003936
D3Q4_UP	30462.754087	30044.237071	222.004097
D3Q5_CT	30465.137738	30040.108389	222.004650
D3Q5_DN	30465.336018	30039.764599	222.004633
D3Q5_UP	30464.939388	30040.452149	222.004695
D3Q6_CT	30467.357589	30036.264157	222.004381
D3Q6_DN	30467.555989	30035.920447	222.004360
D30Q_CT	30456.274864	30055.456706	222.005097
D30Q_DN	30456.441694	30055.168035	222.004878
D30Q_UP	30456.108074	30055.745346	222.005317
D2Q7_CT	30442.972467	30078.493776	222.005572
D2Q7_DN	30443.139067	30078.205036	222.005532
D2Q7_UP	30442.805817	30078.782526	222.005637
D2Q8_CT	30440.580506	30082.215658	222.004713
D2Q8_DN	30440.774006	30081.944157	222.004801
D2Q8_UP	30440.387026	30082.487128	222.004573

Table 7.11: Alignment coordinates for the D30 straight provided by the Fermilab metrology group.

Device	Magnet Type (Status)	Strength	Field	Pitch
D30q	SQC (existing)	0.385 m^{-2}	3.98 T/m	0 mr
Kicker	(to be built)	4 mr	0.028 T	0 mr
d2q2	SQC (existing)	-0.388 m^{-2}	4.01 T/m	0 mr
d2q3	SQC (existing)	0.378 m^{-2}	3.91 T/m	0 mr
d2q4	SQC (existing)	-0.370 m^{-2}	3.82 T/m	0 mr
Lambertson	(to be built)	40 mr	0.28 T (0.79 T / Mu2e)	40 mr
d2q5	8Q32 (replaces SQD)	0.258 m^{-2} (13.3 mr)	2.67 T/m	53.3 mr

Table 7.12: Extraction components and parameters common to the Delivery Ring.

3176 Once the beam clears the Delivery-Ring components, it can be steered onto a centered
3177 midplane trajectory in the combined Mu2e/ $(g - 2)$ section (M4) of the external beamline.
3178 Steering magnets will be strategically placed to correct for differences between the $(g -$
3179 $2)/\text{Mu2e}$ and kicker/septa forms of extraction. The exact extraction orbit depends sensitively
3180 on the D30 quadrupole strengths and these depend on the Delivery-Ring tunes established for
3181 resonant extraction or muon beam delivery for Mu2e and $(g - 2)$, respectively. It is unlikely
3182 these will be identical, however for the purposes here, a third integer resonant extraction
3183 tune was assumed for Mu2e and a lattice similar to the original Pbar design for $(g - 2)$.
3184 The relevant quadrupole strength values used are given in Table 7.12 and translated into
3185 gradients for the $(g - 2)$ 3.1-GeV/ c beam.

3186 The initial bend upwards is so strong in order to clear the Delivery Ring, it must be
3187 leveled before the final elevation is achieved for Mu2e or $(g - 2)$; otherwise it is not pos-
3188 sible to implement a vertical achromat, which requires significant phase advance generated
3189 by quadrupoles. Sufficient space must be allocated for a series of quadrupoles. There-
3190 fore, an EDWA dipole is installed after the first quadrupole in the subsequent D30 straight
3191 with a bend equal and opposite to the combined bends of the Lambertsons and focusing
3192 quadrupole. Leveling the line at $\sim 32''$ above the Delivery Ring centerline provides a long
3193 elevated “straight” (again extracted-beam center to DR-beam center) allowing an indepen-
3194 dent common extraction beamline to be installed without conflicts with the Delivery Ring
3195 line below. The only conflicts are with the extended saddle coils of the DR dipoles and
3196 these must be avoided. However, now an achromat can be formed using 4 quadrupoles.
3197 This straight section is followed by two MDC dipoles for Mu2e beam with reverse bends
3198 (up/down) that elevate the Mu2e extracted beam to a final elevation of 1.22 m (4') above
3199 the Delivery Ring. For $(g - 2)$, three dipoles are required – the last Mu2e vertical dipole is
3200 reversed, sending the beam steeply upward to achieve rapid separation of the M5 line from
3201 the M4 line. This rapid separation proves critical in order to position the strong horizontal
3202 bend section; otherwise the ring location would move eastward into a utility corridor. The
3203 final elevation of the Mu2e line is 225.1460 m (738.6') which is 6.3' above the Mu2e beamline,
3204 10.2' above the M4 beamline enclosure floor and 1.9' from the enclosure ceiling (@740.5' and
3205 3.9' below the experimental hall ceiling).

3206 Figure 7.36 displays the achromatic optics of Delivery Ring extraction from the center
3207 of the first quadrupole upstream of the Lambertsons to the end of the achromat. These
3208 optical functions are predicated on an assumed matched beam distribution extracted from
3209 the Delivery Ring. This is not likely to be the case, and extracted beam properties will

3210 differ significantly between $(g - 2)$ and Mu2e. Therefore it is important that the two vertical
 3211 achromats have been separated between the M5 line and the M4 line and can be independently
 3212 tuned.

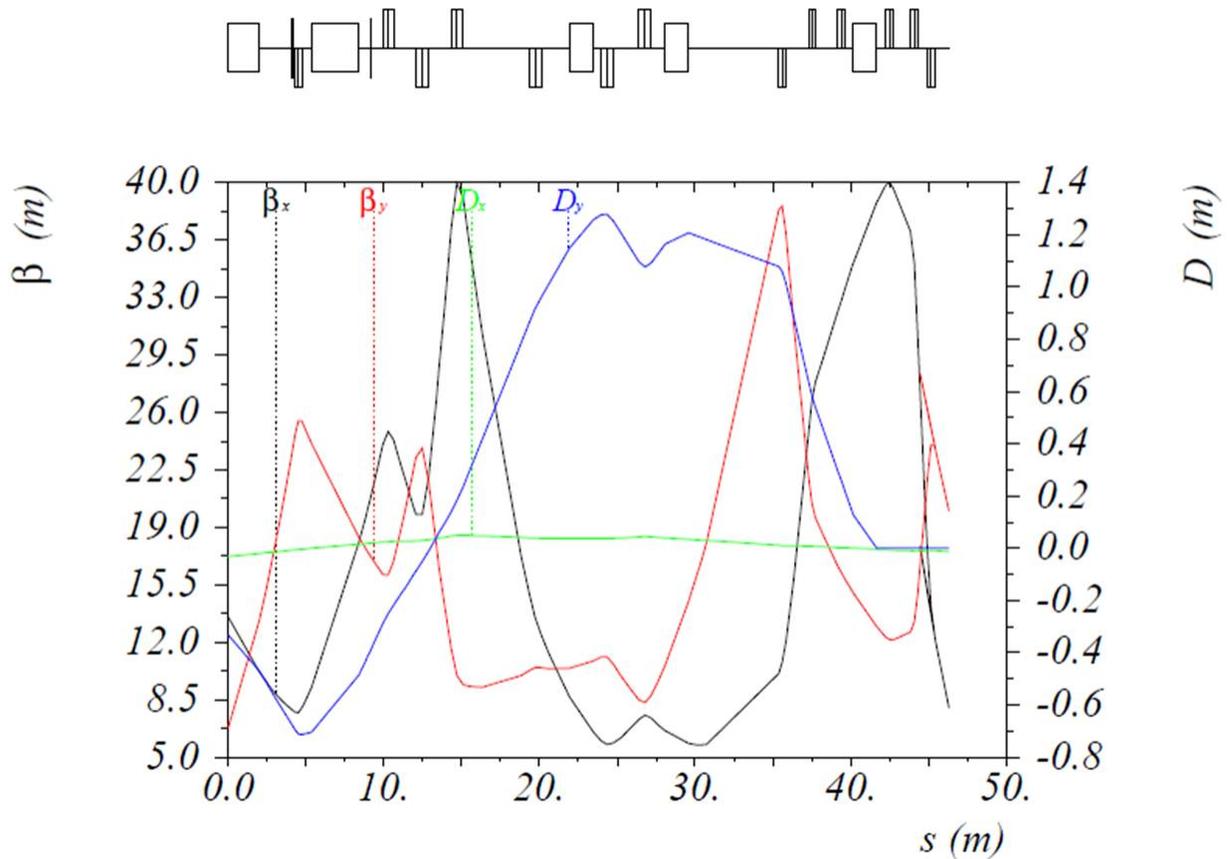


Figure 7.36: The extraction optics showing the two Lambertsons followed by an opposite-sign vertical bend, quadrupoles to form the achromat and a final bend up and then level again to the elevation of the beamline (all EDWA dipoles).

3213 A three-dimensional drawing of Delivery-Ring injection and extraction and the M4 and
 3214 M5 lines to the $(g - 2)$ storage ring is shown in Fig. 7.37.

Device	Magnet Type (Status)	Strength	Field	Pitch
C-magnet	(to be built)	58 mr	0.3T (0.86 T / Mu2e)	111.3 mr
Q1	4Q24	-0.244 m ⁻²	-2.52 T/m	111.3
D1	EDWA (to be built)	-111.3 mr	0.377 T (1.08 T / Mu2e)	0 mr
Q2	SQC	0.234 m ⁻²	2.42 T/m	0 mr
Q3	SQD	-0.357 m ⁻²	-3.69 T/m	0 mr
Q4	SQD	0.311 m ⁻²	3.21 T/m	0 mr
Q5	SQD	-0.062 m ⁻²	0.64 T/m	0 mr
D2	MDC (available)	65.5 mr	0.44 T (1.27 T / Mu2e)	65.5 mr
Q6	SQD	-0.132 m ⁻²	-1.36 T/m	65.5 mr
Q7	SQD	0.205 m ⁻²	2.12 T/m	65.5 mr
D3	MDC (available)	94.7 mr	0.64T (-1.27 T / Mu2e)	160.2 mr

Table 7.13: Extraction components and parameters in the vertical translation section common to ($g - 2$) and Mu2e in the M4 line. Quadrupole strengths are given for ($g - 2$) only.

Device	Magnet Type (Status)	Strength	Field	Pitch
gQ1	4Q24	-0.339 m ⁻²	-3.51 T/m	111.3 mr
gQ2	4Q24	0.229 m ⁻²	2.37 T/m	0 mr
gQ3	4Q24	0.01 m ⁻²	0.087 T/m	0 mr
gD1	MDC	160.2 mr	1.09 T	0 mr
gQ4	4Q24	0.082 m ⁻²	0.84 T/m	0 mr
gQ5	SQA	0.073 m ⁻²	0.75 T/m	0 mr
gQ6	4Q24	0.056 m ⁻²	0.58 T/m	0 mr

Table 7.14: Components and parameters in the independent ($g - 2$) vertical translation section in the M5 line including matching quads to the horizontal bend string.

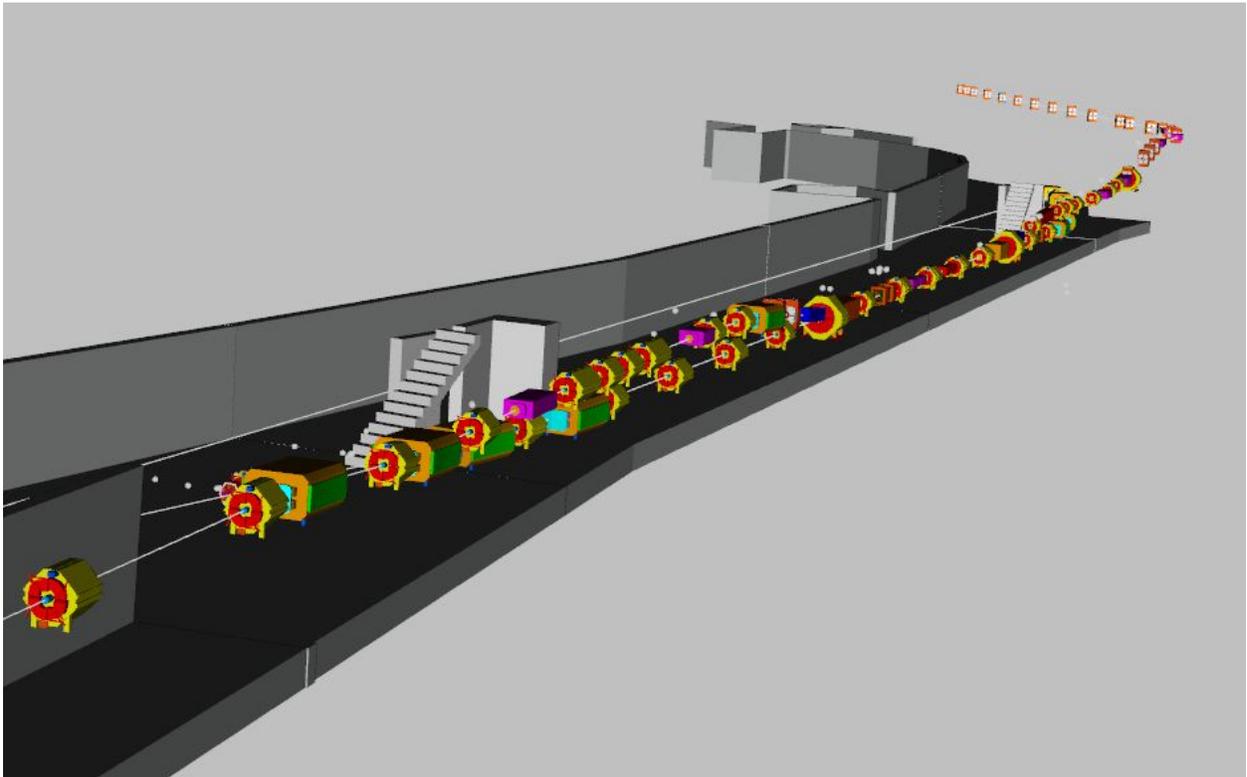


Figure 7.37: Three-dimensional view of Delivery-Ring injection and extraction and the M4 and M5 lines to the $(g - 2)$ storage ring.

7.6 Controls and beam monitoring

7.6.1 Accelerator controls

A well-established controls system allows devices in the former Antiproton-Source (“Pbar”), now Muon, service buildings and tunnel enclosures to receive information such as synchronization signals and to communicate back to other accelerator systems. A map of the service buildings, labeled “AP” for former Antiproton-Source buildings, and “F” for buildings which are part of the F-sector of the Tevatron, is shown in Fig. 7.38. Devices in the new extraction beamlines and MC-1 building will also need to be connected to the controls system.

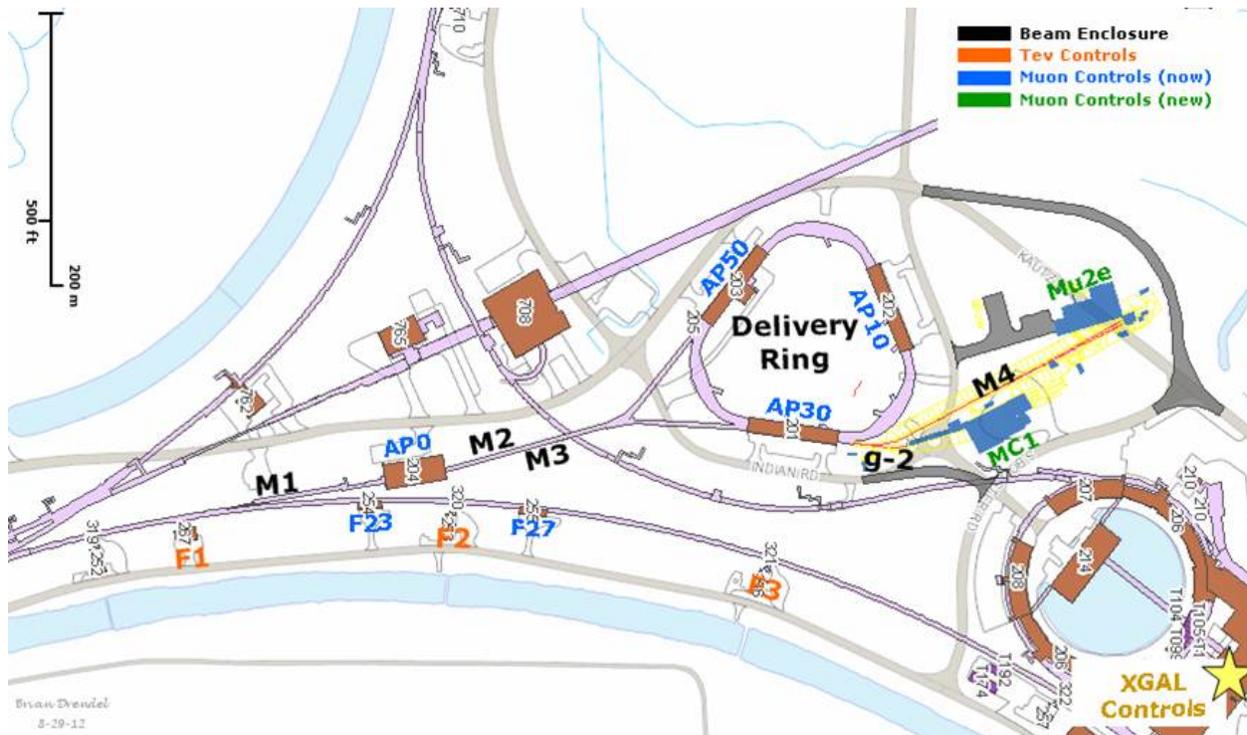


Figure 7.38: Muon Campus service buildings.

3223 CAMAC and links

3224 The existing accelerator service buildings will continue to use the legacy controls infras-
 3225 tructure that is currently in place. These service buildings include all of the Main Injector
 3226 service buildings, as well as F0, F1, F2, F23, F27, AP0, AP10, AP30 and AP50. Future
 3227 Muon Campus service buildings, including MC-1 and Mu2e, will be upgraded to a more
 3228 modern controls infrastructure which will be discussed later in this document. Migration of
 3229 the existing buildings to the more current controls standard is preferred and is being consid-
 3230 ered; however, sufficient funding is not available to start the upgrade path and it is believed
 3231 that the existing infrastructure will be adequate for $(g - 2)$ operations.

3232 Computer Automated Measurement and Control (CAMAC) crates exist in each service
 3233 building and communicate with the control system through a VME-style front-end computer

3234 over a 10 MHz serial link as shown in Fig. 7.39. Both digital and analog status and control of
 3235 many accelerator devices occur through the CAMAC front ends. There should be no need to
 3236 install additional CAMAC crates, as there is excess capacity in most of the existing crates.
 3237 An inventory of existing CAMAC crates in the Muon service buildings shows that about 25%
 3238 of the slots are unoccupied and could be used for additional CAMAC cards [20]. In addition,
 3239 further slots have become available that were used to interface devices that became obsolete
 3240 with the retirement of Collider Run II operations. It is anticipated that there will be ample
 3241 CAMAC-crate coverage for $(g - 2)$ operation in the existing Muon service buildings, and
 3242 very few crates will need to be added or moved.

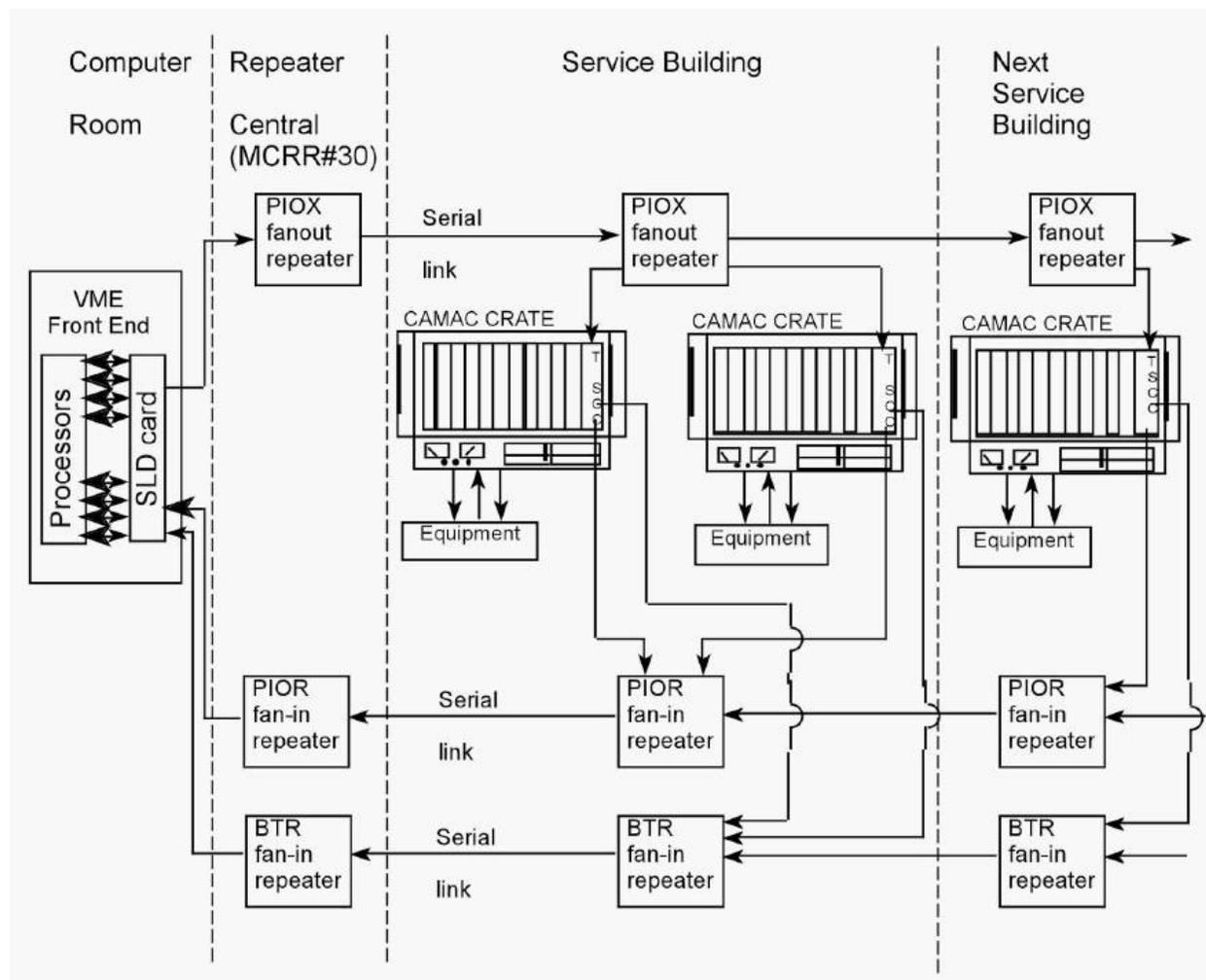


Figure 7.39: Legacy CAMAC crates interfacing VME front ends via serial links provide both analog and digital status and control of accelerator devices, and will continue to be used in existing Muon service buildings.

3243 There are serial links that are distributed through and between the service buildings, via
 3244 the accelerator enclosures, that provide the necessary communications paths for CAMAC
 3245 as well as other necessary signals such as clock signals, the beam permit loop, and the Fire
 3246 and Utilities System (FIRUS). Controls serial links can be run over multimode fiber-optic

3247 cable or copper Heliac cable. Most Muon links that run through accelerator enclosures are
3248 run over Heliac, which should function normally in the radiation environment expected for
3249 ($g - 2$) operations.

3250 Accelerator device timing that does not require synchronization to the RF buckets will
3251 remain on the existing 10 MHz Tevatron Clock (TCLK) system. The existing TCLK in-
3252 frastructure will remain in existing service buildings and new TCLK link feeds will be run
3253 via multimode fiber optic cable from the Mac Room to the new MC-1 and Mu2e service
3254 buildings.

3255 Accelerator device timing for devices that require synchronization to the RF buckets
3256 will continue to be handled through the Beam Synch Clocks; however, a few changes will
3257 be required to maintain functionality. The F0, F1 and F2 service buildings will need both
3258 53 MHz Main Injector beam synch (MIBS) for SY120 operations and 2.5 MHz Recycler
3259 beam synch (RRBS) for ($g - 2$) and Mu2e operations. These buildings already support
3260 multiple beam synch clocks, so the addition of RRBS will require minimal effort. An obsolete
3261 53 MHz Tevatron beam synch (TVBS) feed in the MI60 control room will be replaced with
3262 a 2.5 MHz RRBS feed in order to provide the necessary functionality. The remaining Muon
3263 service buildings currently use 53 MHz MIBS, but will require 2.5 MHz RRBS for ($g - 2$)
3264 and Mu2e operations. This functionality can be obtained by replacing the MIBS feed at F0
3265 with RRBS and using the existing infrastructure. Further upgrades and cable pulls will only
3266 be required if it is later determined that both MIBS and RRBS are required in these service
3267 buildings. New beam synch feeds to the ($g - 2$) and Mu2e service building will be run via
3268 multimode fiber-optic cable from the Mac Room.

3269 The Delivery-Ring permit loop provides a means of inhibiting incoming beam when there
3270 is a problem with the beam delivery system. The Pbar beam permit infrastructure will be
3271 used in the existing buildings. The CAMAC 201 and 479 cards, which provide the 50 MHz
3272 abort loop signal and monitor timing, will need to be moved from the Mac Room to AP50
3273 to accommodate the addition of the abort kicker at AP50. Existing CAMAC 200 modules
3274 in each CAMAC crate can accommodate up to eight abort inputs each. If additional abort
3275 inputs are required, spare CAMAC 200 modules will be repurposed from the Tevatron and
3276 will only require an EPROM or PAL change. The permit loop will be extended to the MC-1
3277 and Mu2e service buildings via multimode fiber-optic cable from the Mac Room. Abort
3278 inputs for these buildings will plug into a Hot-Link Rack Monitor abort card as will be
3279 mentioned below.

3280 Operational and permit scenarios are under development. The capability of running
3281 beam to the Delivery-Ring dump when Mu2e and ($g - 2$) are down will be needed, as well
3282 as the ability to run to either experiment while the other is down.

3283 **Hot-Link Rack Monitor**

3284 New controls installations will use Hot-Link Rack Monitors (HRMs) in place of CAMAC. A
3285 HRM runs on a VME platform that communicates with the control system over Ethernet
3286 as shown in Fig. 7.40. Unlike CAMAC, no external serial link is required, minimizing the
3287 need for cable pulls between buildings. Each HRM installation provides 64 analog input
3288 channels, 8 analog output channels, 8 TCLK timer channels, and 8 bytes of digital I/O.
3289 This incorporates the features of multiple CAMAC cards into a single, compact chassis.

3290 Like CAMAC, when additional functionality or controls channels are needed, additional
 3291 units can be added. As an example, a HRM version of the CAMAC 200 module will be
 3292 constructed to provide inputs into the Delivery-Ring permit system. One or two HRMs
 3293 will be installed in both the MC-1 and Mu2e buildings and should provide ample controls
 3294 coverage for both accelerator and experimental devices.



Figure 7.40: A Hot-Link Rack Monitor is a flexible data acquisition system composed of a remote unit and a PCI Mezzanine card that resides in a VME crate. Each HRM provides sixty four 16 bit analog input channels, 8 analog output channels, 8 TCLK timer channels and 8 bytes of digital I/O. HRM.s will eventually replace all of the functionality of CAMAC [21].

3295 HRMs are expected to eventually replace legacy CAMAC systems in the existing build-
 3296 ings. This migration will start by replacing existing 12-bit MADCs and CAMAC 190 cards
 3297 for analog readings with 16-bit HRM channels. This option was considered for $(g - 2)$ op-
 3298 eration, but was determined to be impractical considering expected funding, limited legacy
 3299 Ethernet connectivity in three of the Muon service buildings, and the determination that
 3300 the existing CAMAC would likely provide adequate performance for $(g - 2)$ operations.

3301 Ethernet

3302 Many modern devices have some form of Ethernet user-interface. In addition, many devices
 3303 and remote front-ends use Ethernet to interface with the control system, instead of using
 3304 the traditional CAMAC. The results are an increasing demand on the Controls Ethernet.
 3305 Figure 7.41 is a map of the Muon Controls network. All of the current Muon Ring service
 3306 buildings have Gigabit fiber-optic connections from the Cross-Gallery computer room to
 3307 Cisco network switches centrally located in each service building. These will provide ample
 3308 network bandwidth and connections after the reconfiguration for $(g - 2)$ and Mu2e. A central
 3309 Ethernet switch that fans out to the other Muon Department buildings is currently located
 3310 in AP10, but will need to be moved to AP30, as will be discussed later in this document.

3311 Ethernet connects between the Muon-Ring service buildings via multimode fiber-optic
 3312 cable paths that traverse the Rings enclosure on the Accumulator side. The multimode fiber
 3313 currently in place will remain functional during $(g - 2)$ operations. However, in the higher-
 3314 radiation environments expected during Mu2e operations, these fiber-optic cables will need

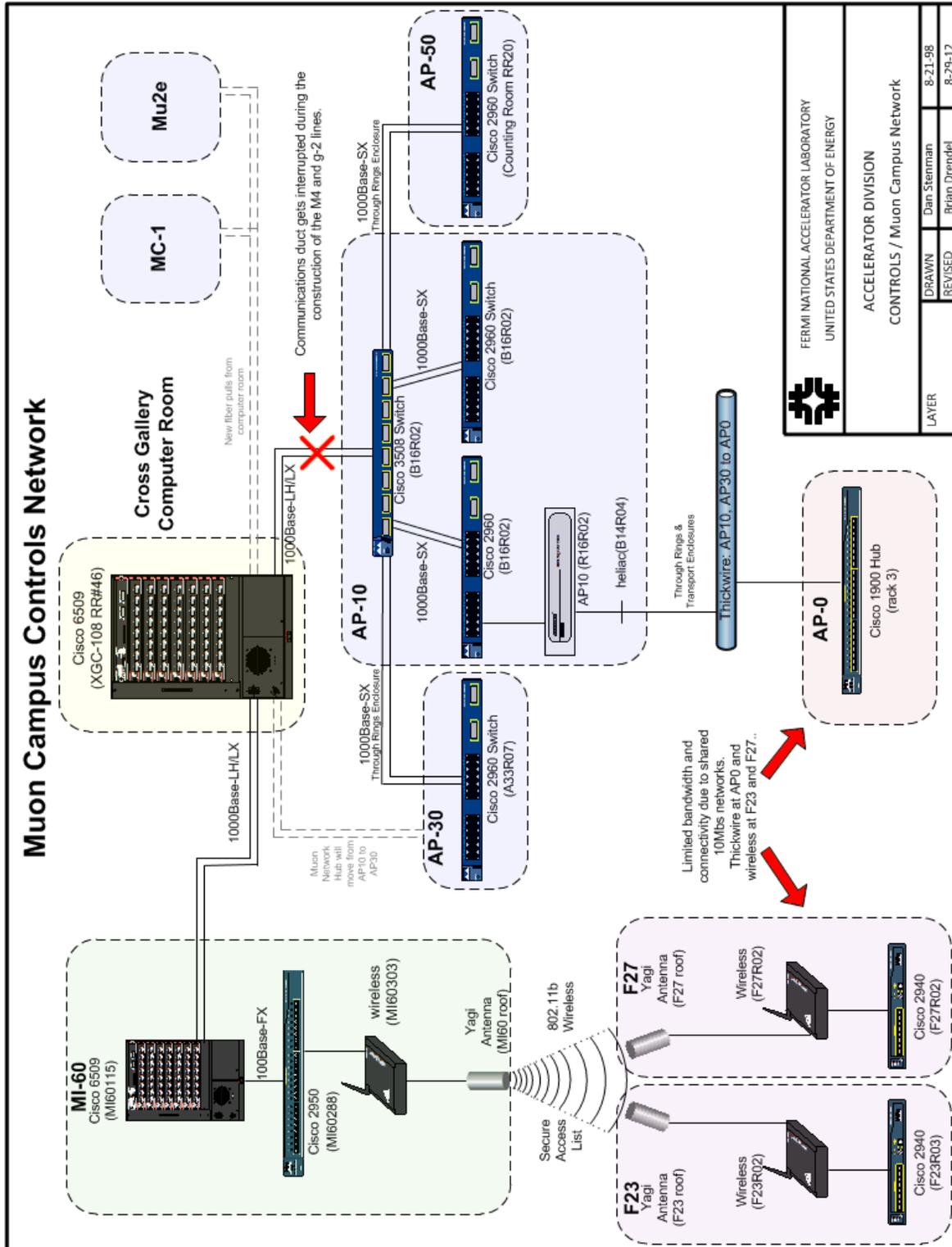


Figure 7.41: Controls Ethernet to the Muon Department service buildings is expected to be adequate for $(g - 2)$ operations. The central switch at AP10 will be moved to AP30. Legacy networks at AP0, F23, and F27 have limited bandwidth and connectivity.

3315 to be upgraded to single-mode fiber at a minimum, or to the more costly radiation-hard fiber
3316 if radiation rates are too high.

3317 Most beamline service buildings have gigabit fiber connected to centrally located network
3318 switches that provide ample network bandwidth and connections. AP0, F23, and F27 are
3319 the only three buildings that do not have this functionality. AP0 runs off a 10 Mbps hub
3320 that connects to 10Base5 “Thicknet” that runs through the Transport and Rings enclosures
3321 back to AP10, while F23 and F27 run off 802.11b wireless from MI60. Both are 10 Mbps
3322 shared networks with limited bandwidth and connectivity. It is anticipated that the network
3323 in these three buildings may be sufficient for $(g - 2)$ operations; however, network upgrade
3324 options are being considered, as will be discussed below.

3325 **Controls connectivity**

3326 Civil construction of the M4 and M5 beamline enclosures will result in the removal of the
3327 underground controls communication duct that provides the connectivity between the Ac-
3328 celerator Controls NETwork (ACNET) and the Muon Campus [22]. Included in this com-
3329 munication duct is the fiber-optic cable that provides Ethernet connectivity, as well as 18
3330 Heliac cables that provide the controls serial links and other signals including FIRUS. These
3331 cables currently connect from this communications duct to the center of the 20 location in
3332 the Rings enclosure, and travel through cable trays on the Delivery Ring side to the AP10
3333 service building. After removal of the communications duct, FESS will construct new com-
3334 munications ducts from the existing manholes. These communications ducts will go directly
3335 to AP30, MC-1 and Mu2e service buildings without going through accelerator enclosures.
3336 See Fig. 7.42 for drawings of the current and future controls connectivity paths.

3337 **Restoring connectivity** When the Heliac and fiber-optic cables are cut during the re-
3338 moval of the above-mentioned communications duct, controls connectivity will be lost. The
3339 base plan for restoring both Ethernet and controls-link connectivity is to pull new fiber optic
3340 cable from the cross gallery, through the MI-8 line communications ducts to AP30. As a
3341 result of the new fiber pull, the Ethernet and controls links will fan out from AP30 instead of
3342 AP10. This will require some additional controls hardware configuration and labor. Efforts
3343 will be made to minimize the disruption by pulling the fiber and staging the new hardware at
3344 AP30 before the communication duct is cut. This is especially important for FIRUS which
3345 is necessary for monitoring building protection.

3346 More details regarding the base plan and several alternatives, including cutting and splic-
3347 ing the Heliac cable or attempting to keep the fiber and Heliac intact during construction,
3348 can be found in Ref. [23].

3349 **Establish connectivity to MC-1** New fiber-optic cable will be pulled from the Mac
3350 Room to the MC-1 service building. Single-mode fiber is needed for Ethernet and FIRUS,
3351 and multimode fiber is needed for the timing links and the abort-permit loop. A bundle of
3352 96 count single-mode and a bundle of 36 count multimode fiber optic cable will be pulled to
3353 MC-1. The fiber bundles will share a common path with the fiber bundles headed toward
3354 Mu2e from the Cross Gallery to the manhole by Booster West Tower. All three fiber bundles
3355 will travel through a single inner duct to the manhole. The Mu2e and MC-1 fiber bundles

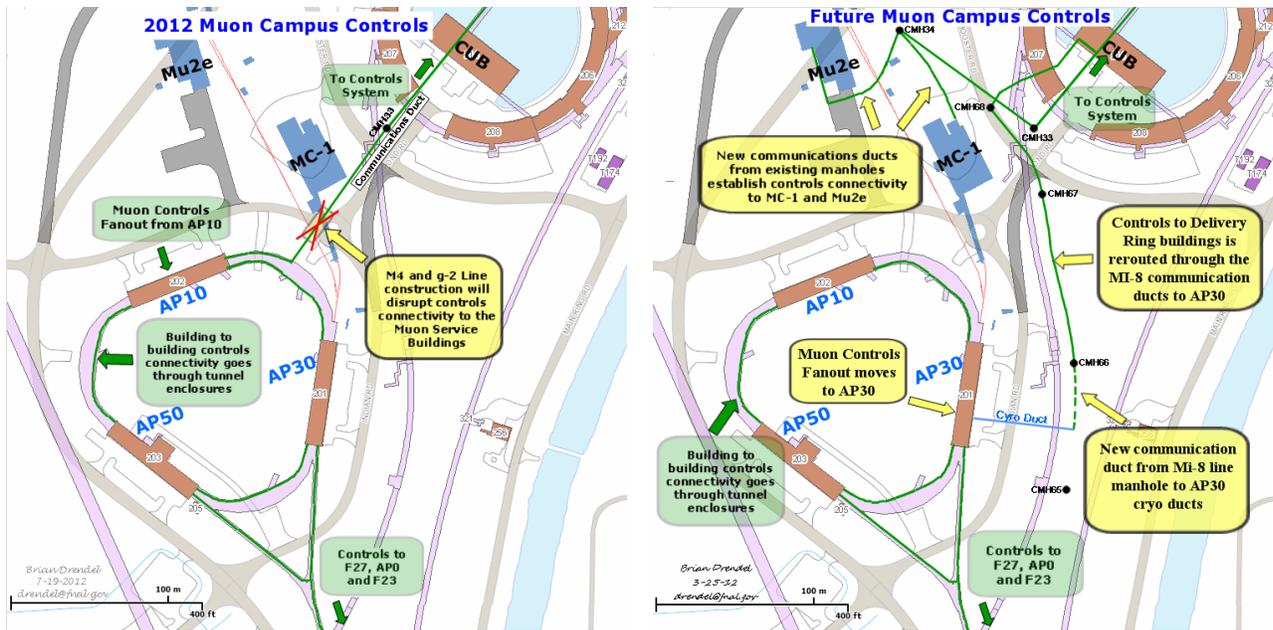


Figure 7.42: Muon campus controls paths. During construction of the M4 and $(g - 2)$ beamlines, the communications duct that provides controls connectivity to the Muon Campus will be interrupted. A new communications duct will be built to restore controls connectivity to the Muon service buildings. New controls will need to be established at the MC-1 and Mu2e buildings.

3356 will then branch off to a second manhole inside a common inner duct, and then separate
 3357 into the new communication ducts to the Mu2e and MC-1 service buildings. The fiber pulls
 3358 will provide ample connectivity for all Ethernet and controls signals for both the accelerator
 3359 and experiment. The $(g - 2)$ experiment anticipates requiring network rates approaching
 3360 100 MB/sec during production data taking which can be handled easily with the proposed
 3361 infrastructure.

3362 One alternate solution considered was to pull the new fiber along the existing communi-
 3363 cations duct until it intersected the extraction-lines enclosure. From there, the fiber could
 3364 be directed along tunnel-enclosure cable trays to the MC-1 service buildings. Though this
 3365 option would provide MC-1 cable-pull lengths of approximately the same length as the base
 3366 option, it was eliminated due to the extra complications of pulling fiber through the tunnel
 3367 enclosures to both Mu2e and AP-30. In both cases, the expected radiation environment
 3368 would require a more expensive radiation-hard single-mode fiber. In addition, the CAMAC
 3369 fiber links only run on multimode fiber, so link and clock repeaters would have to be re-
 3370 designed to run on single-mode fiber, adding additional expense to the project.

3371 **Possible upgrades for legacy networks** If the legacy Ethernet networks at AP0, F23,
 3372 and F27 prove to provide insufficient connectivity or bandwidth for $(g - 2)$ operations, they
 3373 can be most cost-effectively upgraded by replacing the current 10Base5 “Thicknet” with
 3374 single-mode fiber-optic cable. The path would be from the AP30 service building to the
 3375 Rings enclosure, along the cable trays toward the M3 beamline, and down the Transport

enclosure. From the Transport enclosure, the fiber-optic cable runs can go to F27 and AP0. An additional fiber-optic cable pull from AP0 through the PreVault enclosure provides a path to F23. The largest issue with this upgrade is that the single-mode fiber-optic cable is susceptible to radiation. If the radiation environment in the accelerator enclosures does not allow for single-mode fiber-optic cable, then radiation-hard fiber-optic cable can be pulled, but at a higher cost. Standard 96-count single-mode fiber costs approximately \$1.50/foot, whereas 96-count radiation-hard fiber costs approximately \$22/foot. Upgrading to the radiation-hard cable would add approximately \$50K to the cost of the cable pull. Other fiber-optic cable path options have been considered, but prove to be more costly to implement.

7.6.2 Accelerator instrumentation

Beam types

Beam monitoring can be divided into distinct zones: primary protons, mixed secondaries, proton secondaries, and muon “secondaries” (actually the dominant source of muons should be from the decay of the pion secondaries, so are technically “tertiary”). The locations of each of these areas are shown in Fig. 7.43. The expected beam properties in each of these areas are shown in Table 7.15.

Beam Type	Particle Species	Beam Momentum (GeV/c)	Number of Particles	RF Bucket (MHz)	Bunch Length (ns)	Transverse Emittance (mm-mr)
Primary protons	p	8.9	10^{12}	2.515	120	18π
Mixed secondaries	μ^+ , π^+ , p, e^+	3.1	10^7 to 2×10^8	2.515	120	40π
Proton secondaries	p	3.1	10^7	2.515	120	40π
Muons	μ^+	3.1	$< 10^5$	2.515	120	40π

Table 7.15: Expected properties of primary proton beam, secondary beam off the target, and muon beam from pion decay relevant to instrumentation designed to measure beam. Transverse emittances are 95% normalized.

Primary proton beam Primary proton beam will traverse the Recycler, P1 stub, P1, P2 and M1 lines. Much of the instrumentation needed to measure the primary proton beam during ($g - 2$) operation already exists, but needs to be modified for use with the faster cycle times and 2.5 MHz RF beam structure. The overall beam intensity is similar to that seen in Pbar stacking operations, and in many cases requires only small calibration changes be made to the instrumentation. Toroids will be used to monitor beam intensity and will be used in conjunction with Beam Loss Monitors (BLMs) to maintain good transmission efficiency in the beamlines. Multiwires and Secondary Emission Monitors (SEMs) will provide beam profiles in both transverse planes. Beam Position Monitors (BPMs) will provide real-time orbit information and will be used by auto-steering software to maintain desired beam positions in the beamlines.

Toroids are beam transformers that produce a signal that is proportional to the beam intensity. There are two toroids in the P1 line, one in the P2 line and two in the M1 line.

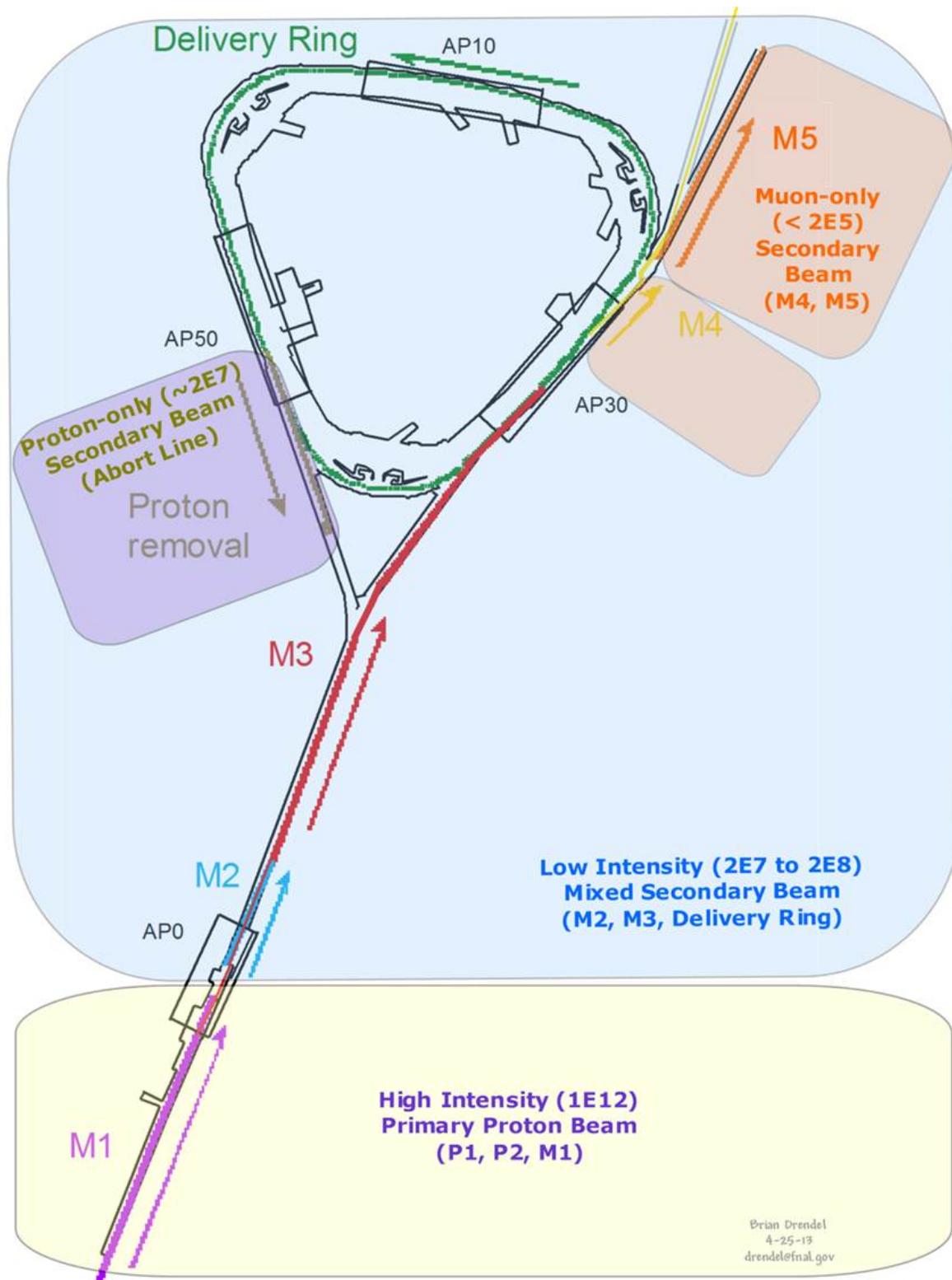


Figure 7.43: Beam monitoring can be divided into four different zones, each with different instrumentation schemes. High-intensity proton beam will be monitored with Toroids, BPMs and BLMs. Low-intensity secondary and proton-only secondary beam will be monitored with Ion Chambers, BPMs and SEMs. Muon-only secondary beam will be monitored with Ion Chambers and SWICs.

3406 They will continue to be used in ($g - 2$) operation to measure the primary proton beam.
 3407 The electronics for these toroids are comprised of legacy analog processing inside of NIM
 3408 crates. The base plan, due to funding limitations, is to continue to use the legacy electronics.
 3409 If funding becomes available, the electronics would instead be upgraded to a VME-based
 3410 processing environment, repurposing electronics from Collider Run II in order to provide
 3411 cost savings. The existing toroids provide the majority of the required coverage, though the
 3412 addition of a second toroid in the P2 line and a toroid in the P1 stub is desirable. The present
 3413 toroid installation locations will be reviewed and modified as needed to provide adequate
 3414 coverage. One possible change would be to move the upstream P1-line toroid downstream
 3415 of the P1 line and P1 stub merge so that it could measure the beam injected into the P1
 3416 line from the stub. Filters, chokes, and preamps will be added for analog conditioning.
 3417 Electronics will be modified, where necessary, to calibrate the toroids for ($g - 2$) operations.

3418 Beamline BPMs provide single-pass orbit-position information with sub-millimeter res-
 3419 olution, and will continue to be the primary beam-position devices in the P1, P2 and M1
 3420 lines. All BPMs share the Echotek style of electronics which was built as part of the Rapid
 3421 Transfers Run II upgrade [24], and is the current standard for beamline BPMs. A functional
 3422 diagram of the BPM hardware is shown in Fig. 7.44. These BPMs were designed to detect 7
 3423 to 84 consecutive 53 MHz proton bunches and four 2.5 MHz antiproton bunches for Collider
 3424 Run II operations. Minimal electronics modifications will be required to measure the single
 3425 2.5 MHz bunches of 10^{12} particles expected during ($g - 2$) operations. Two additional BPMs
 3426 will be installed in the P1 stub.

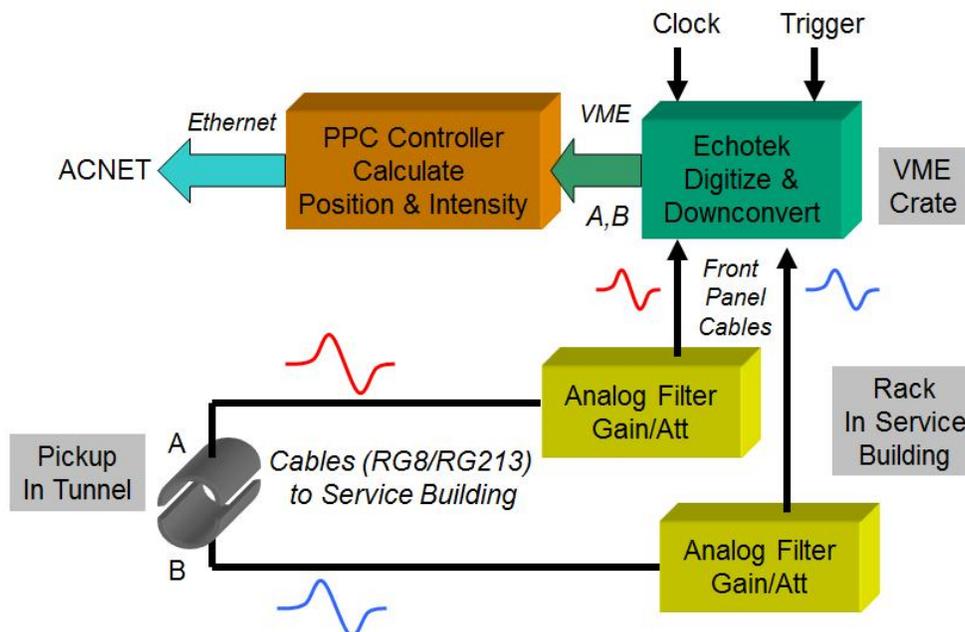


Figure 7.44: BPMs with Echotek processing electronics will be used to measure the transverse beam position of the 2.5MHz primary proton beam in the P1, P2 and M1 lines for ($g - 2$) operations. The BPMs are not sensitive enough to see the low intensity secondary beams downstream of the AP0 target [24].

3427 Beam Loss Monitors are already in place in the P1, P2, and M1 beamlines. Existing ion-
3428 chamber detectors will be utilized for Mu2e operation. BLMs will be upgraded to modern
3429 BLM log monitor electronics, repurposing unused components from the Tevatron in order to
3430 minimize cost. An optional upgrade is being considered that would add snapshot capability
3431 to the BLMs. This feature would allow the loss monitors to distinguish losses from individual
3432 15 Hz pulses of beam. However, this option adds significant cost to the BLM system. Two
3433 additional BLMs will be installed in the P1 stub.

3434 There are two types of beam profile monitors in the beamlines: multiwires in the P1
3435 and P2 lines, and SEMs in the other beamlines. The profile monitors will primarily be used
3436 for commissioning, studies, and documentation of the beamlines. General maintenance will
3437 be performed on the hardware and electronics to ensure proper functionality. The current
3438 location and wire spacing of the monitors will be reviewed and modified accordingly. Two
3439 additional multiwires will be installed in the P1 stub.

3440 **Mixed secondaries** Mixed-secondary beam will traverse the M2 and M3 lines, as well
3441 as the Delivery Ring. Changes to existing instrumentation are required in these areas as a
3442 result of the secondary beam being approximately two orders of magnitude lower in intensity
3443 than that during the former Antiproton stacking operations. In addition, 2.515 MHz bunch
3444 structure and a faster pulse rate must be taken into consideration. Mu2e beam will have
3445 beam intensities four to five orders of magnitude higher than $(g - 2)$ operations in the
3446 M3 line and Delivery Ring, so design upgrades must take into account the vastly different
3447 beam intensities required for both experiments. Beam studies have been conducted in order
3448 to help determine what instrumentation best suits the low-intensity secondaries of $(g - 2)$
3449 operations [3].

3450 Four toroids are available for use in the secondary beamlines and were the primary
3451 intensity-measurement device in these lines during Antiproton operations. These will be
3452 used for Mu2e operations; however, beam studies show that even with high gain and careful
3453 filtering, we were only able to measure beam intensities at levels one order of magnitude
3454 higher than $(g - 2)$ operational beam [3], as demonstrated in Fig. 7.45. As a result, toroids
3455 will likely not be used during normal $(g - 2)$ operations, but may still be used with higher-
3456 intensity beams during commissioning and studies periods.

3457 A Direct-Current Current Transformer (DCCT) has been used in the Delivery Ring to
3458 measure beam intensity. This device will not function at $(g - 2)$ operational intensities and
3459 cycle time.

3460 Ion chambers will become the primary beam-intensity measurement device for mixed-
3461 secondary beam. They are relatively inexpensive devices that can measure beam intensities
3462 with an accuracy of $\pm 5\%$ with as little as 10^5 particles. Ion chambers were used in the AP2
3463 line in the past, and work was done during beam studies to recommission the ion chamber
3464 that used to be operational near the end of the AP2 line [3]. For $(g - 2)$ operations, one
3465 or two ion chambers will be implemented in the M2 line. Ion chambers are also being
3466 considered for the M3 line and the Delivery Ring; however, these would need to be installed
3467 in a vacuum can with motor controls to allow them to be pulled out of the beam during the
3468 higher-intensity Mu2e operations. Figure 7.46 shows an ion chamber installation in the AP2
3469 line.

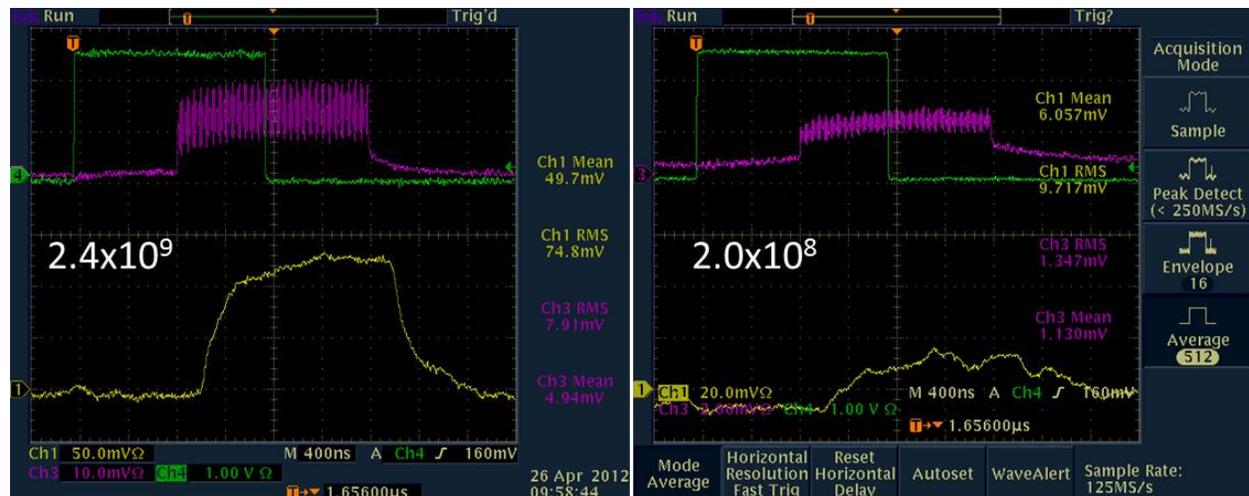


Figure 7.45: The yellow trace on both plots is a calibration test pulse on Toroid 724 in the AP2 line with high-gain preamps and special filtering to look for low-intensity beam. At beam intensities in the low 10^9 's, there is an easily-measurable beam signal. However, when the beam intensities are lowered to the level of 10^7 - 10^8 , the $(g - 2)$ expected secondary beam intensity range, beam intensities can not be measured.

3470 Wall Current Monitors (WCMs) are an alternative intensity-measurement device being
 3471 considered for mixed-secondary beam. These devices have the advantage of being completely
 3472 passive, and not requiring a break in the vacuum, which may make them a better fit in the
 3473 M3 line where we need to stay compatible with the higher intensities of Mu2e operations,
 3474 and the Delivery Ring where beam circulates for approximately 56 ms in Mu2e operations.
 3475 New WCM designs are being considered that would provide accurate intensity measurements
 3476 for secondary beam during $(g - 2)$ operations. The design is based on that of a WCM for
 3477 Mu2e extraction. Each slice of the slow-spilled Mu2e beam is approximately 2×10^7 , which is
 3478 consistent with the intensity that we would expect in the M3 line and Delivery Ring during
 3479 $(g - 2)$ operations.

3480 BPMs were a key diagnostic in Antiproton-Source operation providing sub-millimeter
 3481 orbit information in the beamlines and Delivery Ring. BPMs are located at each quadrupole,
 3482 providing ample coverage. There are 34 BPMs in the AP2 line, 28 BPMs in the AP3 line
 3483 and 120 BPMs in the Delivery Ring; however, it is believed that the BPMs in these areas
 3484 will not be able to see the low-intensity 2.515 MHz $(g - 2)$ secondary beam.

3485 SEMs will be used to measure beam profiles in the M2 and M3 lines, as well as the
 3486 Delivery Ring. There are eight SEMs in the AP2 line, seven SEMs in the AP3 line, three
 3487 SEMs in the D/A line, two in the Debuncher, one in the Accumulator and three spares from
 3488 the former AP4 line to draw from. SEM tunnel hardware will require some maintenance, and
 3489 locations where SEMs are moved will require new cable pulls. Beam studies showed that
 3490 special high-gain preamps will be required to measure the low-intensity secondary beam
 3491 during $(g - 2)$ operations [3]. There are only two working high-gain preamps, so additional
 3492 preamps will need to be designed and fabricated. Additional SEMs will need to be added
 3493 to the Delivery Ring from the pool of unused SEMs and spares. A photo of a SEM and its



Figure 7.46: Fixed-position ion chamber in the AP2 line. The ion chamber is separated from the beam pipe by a vacuum window on each side. Fixed-position ion chambers will only be used in the M2 line. In locations like the M3 line and Delivery Ring that will also see Mu2e beam, the ion chambers will be put inside of vacuum cans and made retractable.

3494 profile display are shown in Fig. 7.47.

3495 BLMs (Fig. 7.48) will be used to help maintain good transmission efficiency through the
 3496 lines. Both Delivery-Ring and AP3 loss monitors will use the existing hardware and elec-
 3497 tronics for $(g - 2)$ operations, but will be replaced for the higher-intensity Mu2e operations.
 3498 Care will need to be taken to make a BLM plan that allows for switching back and forth
 3499 between the two separate BLM systems.

3500 **Proton Secondaries** Proton secondaries will be extracted to the Delivery Ring abort line and
 3501 will have a similar beam intensity to that of the Delivery Ring. Existing instrumentation from
 3502 the downstream AP2 line will be used. A toroid will be used to measure beam intensity for
 3503 Mu2e operations, but will be out of its operational range for $(g - 2)$. If intensity measurement
 3504 is needed, a retractable ion chamber will be added to the line. Ion chambers, SEMs and
 3505 BLMs will be used in the same way they are for the mixed secondary lines.

3506 **Muon Secondaries** Muon secondaries will traverse the upstream portion of the M4 line
 3507 and the M5 line. The largest technical challenge will be measuring muon secondary beam,
 3508 which models show should be on the order of 10^5 muons per pulse. This is two or three
 3509 orders of magnitude smaller than the upstream mixed-secondary beam. Most diagnostics
 3510 will not work at these beam intensities.

3511 Beam intensity will be measured with ion chambers that are designed with three signal
 3512 foils and four bias foils to increase the signal amplification. This design will allow beam

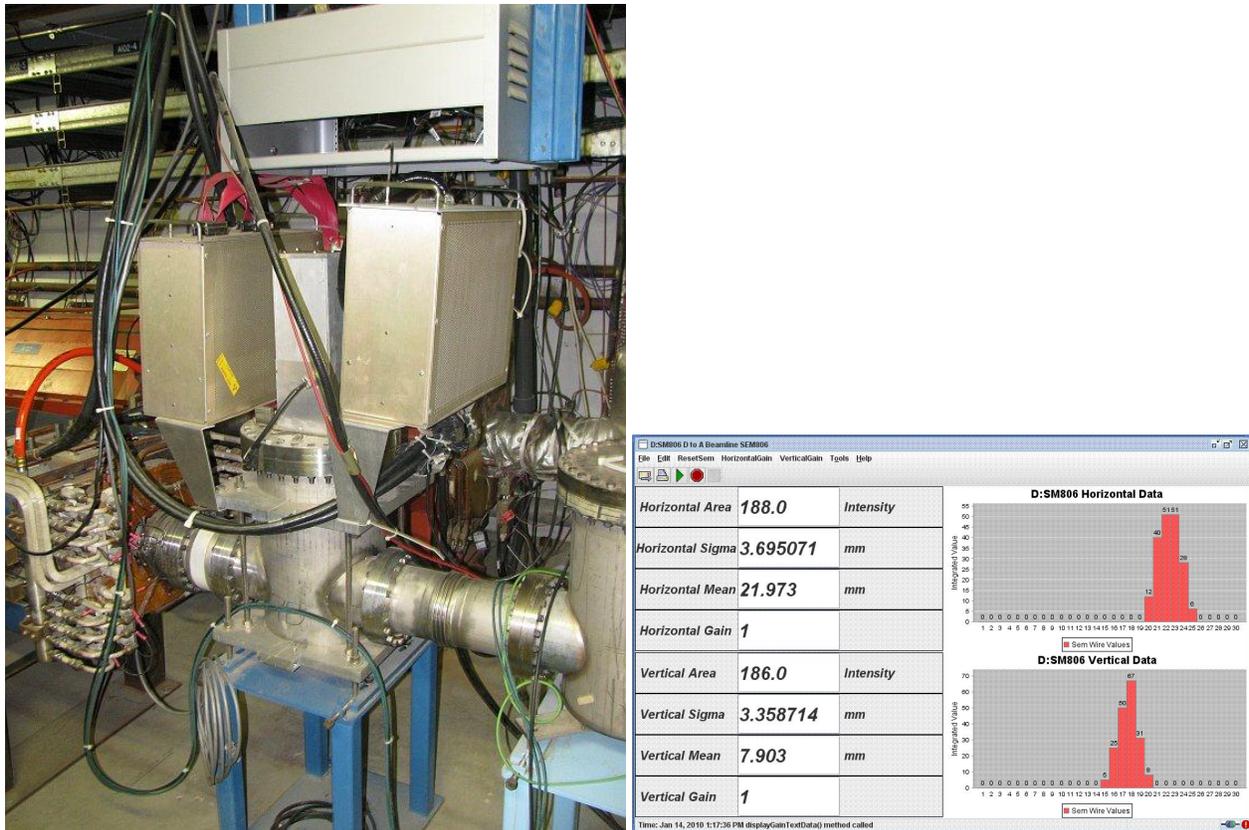


Figure 7.47: SEMs will be used to measure mixed secondary beam profiles. SEM tunnel hardware (left) is pictured. Preamp boxes are mounted next to the vacuum can. The SEM wires can be pulled out of the beam when not in use. SEMs can be used with to measure beam profiles, positions and intensities (right).

3513 intensity measurements down to 10^5 particles. The ion chamber in the M4 line will need to be
 3514 retractable in order to be compatible with Mu2e operations, while the M5-line ion chambers
 3515 can be permanently in the beam path. New ion chambers will be designed and built for
 3516 the M4 line because there is not a pool of available spares to populate these beamlines.
 3517 Ion chambers for the M5 line will be provided by the repurposed BNL SWICs as will be
 3518 discussed below. A Wall Current Monitor is another option being considered for beam-
 3519 intensity measurement in the upstream M4 line. Though this device may be able to measure
 3520 the Mu2e slow-spill beam intensity, it is not clear if one could be designed that is sensitive
 3521 enough to see the lower-intensity muon beam expected for $(g - 2)$ operations.

3522 The base plan for measuring beam profiles in the upstream M4 and M5 lines are to
 3523 use Segmented Wire Ion Chambers (SWICs), which are very similar to Multiwires with the
 3524 exception that the beam goes through ArCO_2 gas, which is ionized by the charged-particle
 3525 beams, creating an amplification that allows measurements of beam intensities down to
 3526 the 10^4 particle range. This is an order of magnitude lower than the expected $(g - 2)$
 3527 operational beam. In addition, SWICs are robust enough to handle particle beams several
 3528 orders of magnitude higher in intensity than are expected during $(g - 2)$ operations. This
 3529 will provide the flexibility of running higher-intensity protons through the M4 and M5 lines

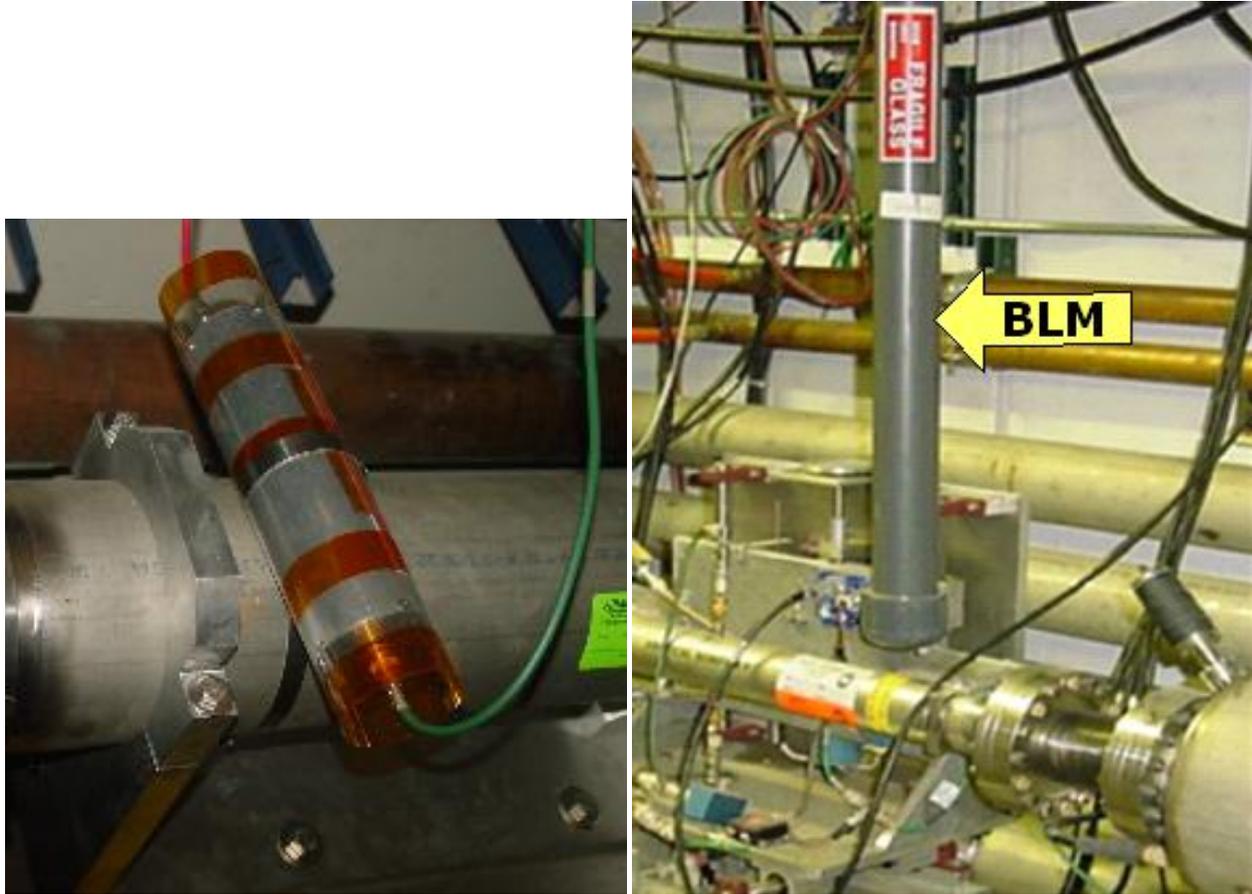


Figure 7.48: Two styles of BLMs will be used. Tevatron-style ion chamber loss monitors (left) will be used in areas of primary beam, and also in the Delivery Ring for Mu2e operations. The Pbar-style ion chamber, which consists of a plastic scintillator and a long light guide connected to a photomultiplier tube shielded from light in PVC, will be used in the Delivery Ring during $(g - 2)$ operations.

3530 for commissioning and beam studies. The SWICs in the upstream M4 line will need to be
 3531 retractable since they are a destructive measurement device. Some vacuum cans can be
 3532 acquired from other systems to minimize the cost; however, the inventory of spare vacuum
 3533 cans is not sufficient enough to cover all of the SWICs. The SWICs in the M5 line will
 3534 combination SWIC and Ion Chamber units repurposed from BNL. These devices allow have
 3535 both wires for measuring beam profiles as well as foils for measuring beam intensities, but
 3536 are not retractable and require vacuum windows on both sides of the device.

3537 While maintenance is being performed on the BNL SWICs and interfaces to the FNAL
 3538 control system are being designed for these devices, three alternate options are being con-
 3539 sidered for beam profile measurement in the M5 line. The first option is to design and build
 3540 new SWICs. This would give us the flexibility of making them retractable and not require
 3541 additional vacuum breaks; however, it would also require us to design and build new Ion
 3542 Chambers for the line. Similar to the BNL SWICs, newly designed SWICs would measure
 3543 beam down to the the 10^4 particle range.

3544 A second option that was considered is the Proportional Wire Chamber (PWC). The
 3545 advantage of the PWC is that it can measure beam down to 10^3 particles, and the wire
 3546 planes are modular. The major disadvantage is that the wires are easily damaged by higher-
 3547 intensity pulses, limiting the ability to run higher intensity study beam.

3548 The third option that was considered is to design Scintillator Fiber Profile Monitors
 3549 (SFPMs), which can measure down to 100 particles. These devices are similar to SWICs or
 3550 PWCs, but the wires are replaced with scintillating fiber. They have been used in the SY120
 3551 test-beam lines, and the fibers have been shown to survive long periods of beam operation.
 3552 The largest disadvantage is that SFPMs cost significantly more than SWICs.

3553 The upstream M4 line will be made compatible with both Mu2e and $(g - 2)$ operations.
 3554 Beam in the M4 line for $(g - 2)$ will be at least two orders of magnitude smaller than the
 3555 individual slices of slow-spilled beam that the line will see in Mu2e operations.

3556 Intensity and profile information will also need to be collected just before and after
 3557 the inflector, which will likely be achieved with ion chambers and some combination of
 3558 the profile-measurement devices mentioned above. The two primary factors limiting the
 3559 instrumentation after the inflector are a much smaller available physical space and potentially
 3560 lower-intensity beam.

3561 If muon beam profile information cannot be accurately measured with the proposed
 3562 diagnostics, one option being considered is to develop a tune-up mode. In this mode, protons
 3563 in the Delivery Ring would not be sent to the abort, but extracted toward $(g - 2)$ with the
 3564 muon beam. This would result in 10^7 particles per pulse in the extraction lines, which is
 3565 easily measured by ion chambers and SWICs.

3566 Accelerator instrumentation summary

3567 A summary of instrumentation devices which will potentially be used for $(g - 2)$ is shown in
 3568 Table 7.16.

Beamline	Beam type	Intensity	Position	Profile	Loss
Primary protons	P1, P2, M1	toroids	BPMs	multiwires, SEMs	BLMs
Mixed secondaries	M2, M3, DR	ion chambers, WCMs	SEM	SEM	BLM
Proton secondaries	DR abort	ion chambers, WCMs	SEM	SEM	BLM
Muons	M4, $(g - 2)$	ion chambers, WCMs	SWICs, PWCs, SFPMs		

Table 7.16: Potential instrumentation to be used in the beamlines for $(g - 2)$ operations.

3569 **7.7 ES&H, Quality Assurance, Value Management**

3570 **7.7.1 ES&H**

3571 The Accelerator Division ES&H Department has the responsibility for providing Environ-
3572 mental, Safety, and Health coordination and oversight of ES&H throughout the project. As
3573 with all Fermilab projects, attention to ES&H concerns will be part of the project man-
3574 agement, and Integrated Safety Management will be incorporated into all processes. Line
3575 management responsibility for ES&H will be maintained on this project. Safe coordination of
3576 installation activities will be accomplished through the Project Management team, Project
3577 ES&H Coordinator, Project Engineer, and Task Manager. During installation, the Subcon-
3578 tractors, T&M Crafts, and all Fermilab personnel will utilize Project Hazard Analyzes to
3579 plan all work and to mitigate hazards. The Project Manager and Project ES&H Coordinator
3580 will audit compliance with all applicable ES&H requirements.

3581 The handling and installation of magnets, vacuum systems, power supplies, and other
3582 accelerator components are common tasks within the Accelerator Division, and standard
3583 safety practices will be used. If any work falls outside of common practices, job hazard
3584 analyses will be conducted in order to ensure that the tasks are performed safely. Detailed
3585 procedures exist for handling components in the radioactive target vault, and the activation
3586 will be lower after years of not running beam than it was during antiproton production.

3587 **7.7.2 Quality Assurance**

3588 All aspects of the accelerator work will be periodically reviewed with regard to Quality
3589 Assurance issues from Conceptual Design through completion. The following elements will be
3590 included in the design and construction effort: an identification of staff assigned to each task
3591 with clear definition of responsibility levels and limit of authority as well as delineated lines
3592 of communication for exchange of information; requirements for control of design criteria and
3593 criteria changes and recording of standards and codes used in the development of the criteria;
3594 periodic review of the design process, drawings, and specifications to insure compliance with
3595 accepted design criteria.

3596 **7.7.3 Value Management**

3597 Significant cost savings have been incorporated into the $(g-2)$ accelerator design by utilizing
3598 the existing infrastructure from the Antiproton Source. Existing target station components
3599 will be reused: target, lens, collimator, and momentum-selection magnet, as well as main-
3600 taining the same target-vault layout. A new target-station dump to replace the current one
3601 which has an internal water leak will be constructed using the existing design. As many ex-
3602 isting components as possible will be reused for the beamlines, including beamline magnets
3603 from the previous $(g-2)$ experiment at BNL. New magnets will be based on existing designs,
3604 where practical. Much of the beamline instrumentation will also be recycled, with upgraded
3605 readout electronics where necessary in order to see the low-intensity $(g-2)$ secondary and
3606 tertiary beam.

References

- 3607
- 3608 [1] W. Pellico *et al.*, “Proton Source Task Force Report”, Beams Doc. 3660 (2010); F. G.
3609 Garcia *et al.*, “Fermilab Proton Improvement Plan Design Handbook”, Beams Doc 4053
3610 (2012).
- 3611 [2] D.S. Ayres *et al.*, “NO ν A Technical Design Report”, NO ν A Doc 2678 (2007).
- 3612 [3] D. Still *et al.*, “ $g - 2$ Yield Beam Study Results – April 2012”, $g - 2$ Doc 430 (2012).
- 3613 [4] I. Kourbanis, “Bunch Formation for $g - 2$ experiment”, $g - 2$ Doc 335 (2012).
- 3614 [5] M. Xiao, “Transport from the Recycler Ring to the Antiproton Source Beamlines”, Beams
3615 Doc 4085 (2012).
- 3616 [6] N. Mokhov, <http://www-ap.fnal.gov/MARS>.
- 3617 [7] C. Yoshikawa *et al.*, “Optimization of the Target Subsystem for the New $g - 2$ Experi-
3618 ment”, IPAC2012.
- 3619 [8] S. Striganov, “Optimization of $g - 2$ Target Parameters”, Fermilab Doc GM2-doc-197.
- 3620 [9] Muons, Inc., <http://www.muonsinc.com/muons3/G4beamline>.
- 3621 [10] B. Drendel *et al.*, “Antiproton Source Rookie Book”, Beams-doc-2872, June 2010.
- 3622 [11] ANSYS®, <http://www.ansys.com>.
- 3623 [12] R. Shultz, “ANSYS Mechanical Simulation for Lithium Lens”, Fermilab Doc GM2-doc-
3624 362.
- 3625 [13] T. Leveling, “An Estimation of Antiproton Source Target Station Performance for Muon
3626 $g - 2$ ”, $g - 2$ Doc 536.
- 3627 [14] C. Hojvat *et al.*, “The Fermilab Tevatron I Project Target Station For Antiproton
3628 Production”, Fermilab TM-1175 (March 1983).
- 3629 [15] D.C. Carey, K.L. Brown, F. Rothacker, FERMILAB-Pub-98/310 (1998).
- 3630 [16] $g - 2$ Doc 484 (2012).
- 3631 [17] V. Lebedev, $g - 2$ Doc 171 (2012).

- 3632 [18] $g - 2$ Doc 252 (2012).
- 3633 [19] J.P. Morgan, “Power tests for Pbar service buildings”, Mu2e Doc 2117 (2012).
- 3634 [20] B. Drendel *et al.*, “Pbar Controls Reference Material”, Mu2e-doc-1161, May 2012.
- 3635 [21] A. R. Franck *et al.*, “HOTLink Rack Monitor”, FERMILAB-Conf-01/342/E.
- 3636 [22] B. Drendel *et al.*, “Controls to Mu2e/g-2/Muon and Communications Duct Issues”,
3637 Mu2e-doc-2069, February, 2012.
- 3638 [23] communications duct details and alternative plans
- 3639 [24] N. Eddy and E. Harms, “Beamline BPM Upgrade”, Beams-doc-1279, September 2004.

Chapter 8

Relocation of the E821 Storage Ring Magnet

The muon storage ring magnet consists of superconducting coils inside their cryostats and the steel yoke and pole pieces. The steel is easily disassembled and shipped by truck, i.e., the time reversal of the process we used twenty years ago. However, the 15m diameter coils were wound in Brookhaven Building 919. In order to maintain the exceptional magnetic field the coils may not be disassembled to the degree that would allow conventional trucking. Special transportation for the very large load is required. Transporting the coils in their horizontal orientation is highly desired in order to prevent extraordinary forces and stresses on the coils.

The largest portion of the coil transport will occur by barge from Long Island, New York to Illinois via the Mississippi River system to the Illinois Waterway. Along the eastern seaboard the barge will travel through the Intracoastal Waterway keeping the barge near ports and in calm waters as compared to open sea travel. An ocean tug will be used from Long Island to New Orleans. A river tug will be used for the remainder of the trip to Lemont, Illinois. A back up plan could route the barge north via the St. Lawrence Seaway and Great Lakes to the Illinois Waterway.

A feasibility study in 2012 studied the best mode of transportation over land for both Long Island and Illinois. The result of the study indicated that the use of a specialized truck and trailer is the best option. Some vendors in the heavy haul industry are capable of performing the work required with a specialized truck/trailer suitable for moving the g-2 coils. A transportation review based on the feasibility study was held at FNAL in September, 2012. One of the recommendations from this review was to be sure that we document the coil/cryostat system before the move. The documentation is given in Fermilab g-2 doc-db references [1], [2], [3], and [4].

A Request for Proposal (RFP) was written at Fermilab and a meeting for the coil/cryostat transportation was held at BNL in November, 2012. Four companies replied to the RFP and attended the meeting; three of these submitted proposals. Emmert International was chosen to perform the work and the contract was signed.

The present plan is to truck the coil/cryostat from Brookhaven National Laboratory to Smith Point Marina in Suffolk County, Long Island. From this port the barge will travel to the Ozinga port on the Illinois Waterway. From the port in Lemont, the coils will travel via

3673 specialized truck/trailer to FNAL this summer.

3674 An analysis has been performed by Emmert International to determine the deflection of
3675 the shipping fixture arms while supporting the coils. This has been determined for various
3676 support conditions that the fixture will undergo during the phases of the shipment. The
3677 results of the Emmert calculations have been verified at Fermilab. The expected forces and
3678 deflections have also been imposed on the coils in a Finite Element Analysis at Fermilab.
3679 The stresses imposed on the coils are seen to be low on the order of a few hundred psi. The
3680 coils and other internal components of the cryostats are not expected to be damaged as a
3681 result.

3682 The shipment of the coils will be performed using a quality assurance plan. The plan
3683 will provide a means of assuring that the coils will not see stresses above those that we plan
3684 for. Severe storms will be avoided. Distant storms that cause higher than normal wave
3685 motion will be monitored. The shipment will be monitored with accelerometers capable of
3686 transmitting a signal. For wave motion approaching our limits, the barge will be called to safe
3687 harbor. A safe harbor plan will be a part of this quality assurance plan. The accelerometer
3688 readings will be recorded for later analysis as well.

3689 8.1 Preparations for Shipping

3690 Figure 8.1 shows a recent picture of the cryostats and the mostly disassembled steel. In this
3691 photo the upper yoke plates have been removed as well as much of the spacer plates. The
3692 coils will be removed for shipment before most of the lower yoke and the remaining spacer
3693 plates will be moved.

3694 The following are the important activities occurring (or in process of occurring) in prepa-
3695 ration for the move:

- 3696 • Replacing all the G10 radial stops with Aluminum stops. The G10 stops do not touch
3697 the mandrel when warm, only when cold. The Aluminum stops are longer and are
3698 designed to touch the mandrel. This prevents the coil from moving sided-to-side.
- 3699 • For the outer coil, vertical bolts at the hangar locations will be inserted through the
3700 cryostat's top surface, and engage the mandrel. This is additional protection to prevent
3701 the mandrel from moving side-to-side. FEA simulations of this item and of the first
3702 item, show that these safeguards are sufficient for handling the worse case of 0.7g side
3703 load.
- 3704 • The exposed (unpainted) surfaces of the yoke steel was coated with Cosmoline to
3705 prevent rusting.
- 3706 • A structure has been designed to support the interconnect and the hardware outside
3707 the outer cryostat (see reference [5]). This is to minimize the stress on both the coils
3708 and cryostat walls.
- 3709 • A shrink wrap will cover the cryostats during the move.
- 3710 • During the move, dry nitrogen will be flowing through the cryostat to keep it dry.



Figure 8.1: Coils/Cryostats at BNL.

3711 8.2 The Coil Shipping Fixture and Transportation

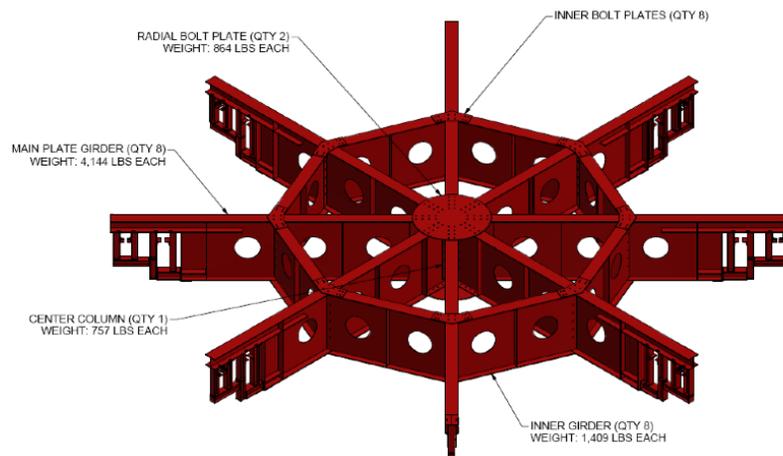


Figure 8.2: The shipping fixture.

3712 Figure 8.2 shows the shipping fixture as specified by Fermilab and designed and built
 3713 by Emmert International per the criteria to carry the coils. The coils will remain very flat
 3714 during the shipment to limit the stress imposed onto the coils.

3715 Figure 8.3 shows an engineering drawing of the mover and support fixture. Overall length
 3716 of this rig is in excess of 117 feet. The trailer has three hydraulic zones to keep the load
 3717 level and to distribute the weight to the wheels evenly. The truck will move slowly over the
 3718 roadways ranging from walking speed to a maximum of 10 mph depending on the terrain
 3719 and the proximity of obstacles along the path. The shipment will move over public roadways
 3720 during night time hours to limit disruption to public traffic.

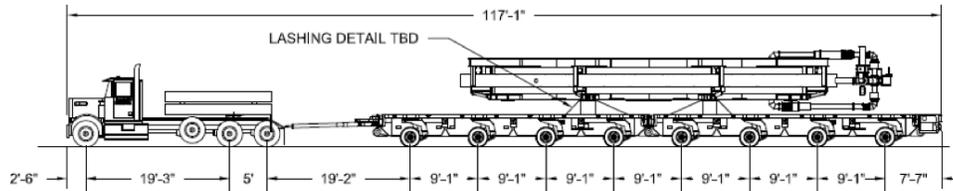


Figure 8.3: Specialized Truck and Trailer for Coil Shipment.



Figure 8.4: Scaled model showing the specialized truck and trailer holding the coils.

3721 Figure 8.4 shows a model of the mover and support fixture. The 50 foot diameter coils
 3722 require roughly the width of four traffic lanes to traverse the roadways in Long Island and
 3723 Illinois.

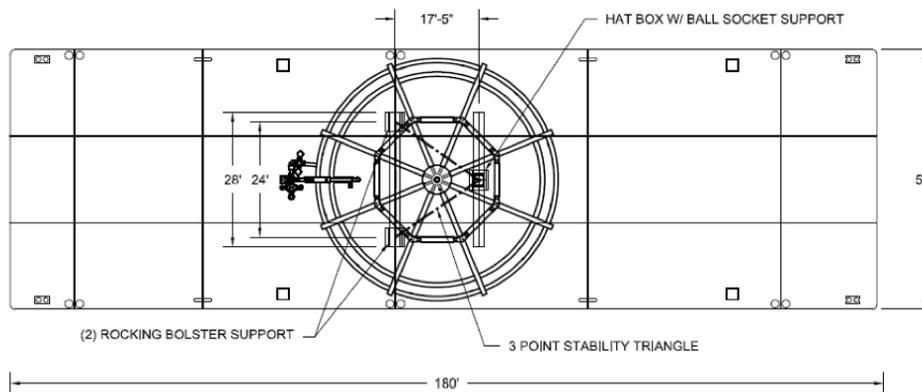


Figure 8.5: Shipping fixture with coils shown secured to the barge.

3724 Figure 8.5 shows a drawing of the shipping fixture with coils secured to the barge. The

3725 barge that we plan to utilize has a 54 foot width by 180 foot length. This barge size is chosen
3726 to limit the maximum roll, pitch, and heave the coils will experience over the water.

3727 **References**

- 3728 [1] E821 Muon Storage Ring Coil Resistance Benchmark. g-2 DocDB note 499-v1.
- 3729 [2] Coil Resistance to Ground Measurements. g-2 DocDB note 352-v1.
- 3730 [3] Cryostat Vacuum System Documentation. g-2 DocDB note 314-v1.
- 3731 [4] E821 Interconnects. g-2 DocDB note 302-v1.
- 3732 [5] Erik Voirin, g-2 Cryostat Interconnect Support for Transportation. g-2 DocDB note
3733 979-v1.

Chapter 9

The Muon Storage Ring Magnet

9.1 Introduction

As emphasized in Chapter 2, the determination of the muon anomaly a_μ requires a precise measurement of the muon spin frequency in a magnetic field ω_a , and an equally precise measurement of the average magnetic field felt by the ensemble of precessing muons, $\langle B \rangle$. We repeat the spin equation given in Eq. 3.11, since it is central to the design of the storage-ring magnet.

$$\vec{\omega}_a = -\frac{Qe}{m} \left[a_\mu \vec{B} + \left(a_\mu - \left(\frac{m}{p} \right)^2 \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]. \quad (9.1)$$

As explained in Chapter 2, the need for vertical focusing and exquisite precision on $\langle B \rangle$ requires that: either the muon trajectories be understood at the tens of parts per billion level, and the magnetic field everywhere be known to the same precision; or the field be as uniform as possible and well-measured, along with “reasonable knowledge” of the muon trajectories. This latter solution was first employed at CERN [1] and significantly improved by E821 at Brookhaven [2]. The uniformity goal at BNL was ± 1 ppm when averaged over azimuth, with local variations limited to ≤ 100 ppm.

Fermilab E989 will use the storage-ring magnet designed and built for Brookhaven E821, with additional shimming to further decrease the local variations in the magnetic field. This requires the relocation of the ring from BNL to Fermilab, which is described in detail in the following chapter. While the magnet steel comes apart and can be moved by conventional trucks, the 14.5 m diameter superconducting coils will need to be moved as a package, on a custom designed fixture that can be pulled by a truck to travel by road, and put on a barge to travel by sea, and then again by road to get it to the Fermilab site.

The storage ring is built as one continuous superferric magnet, an iron magnet excited by superconducting coils. A cross-section of the magnet is shown in Fig. 9.1. The magnet is C-shaped as dictated by the experiment requirement that decay electrons be observed inside the ring. The field, and hence its homogeneity and stability, are determined dominantly by the geometry, characteristics, and construction tolerances of the iron. Although both copper and superconducting coils were considered, the use of superconducting coils offered the following advantages: thermal stability once cold; relatively low power requirements; low voltage, and hence use of a low-voltage power supply; high L/R time constant value

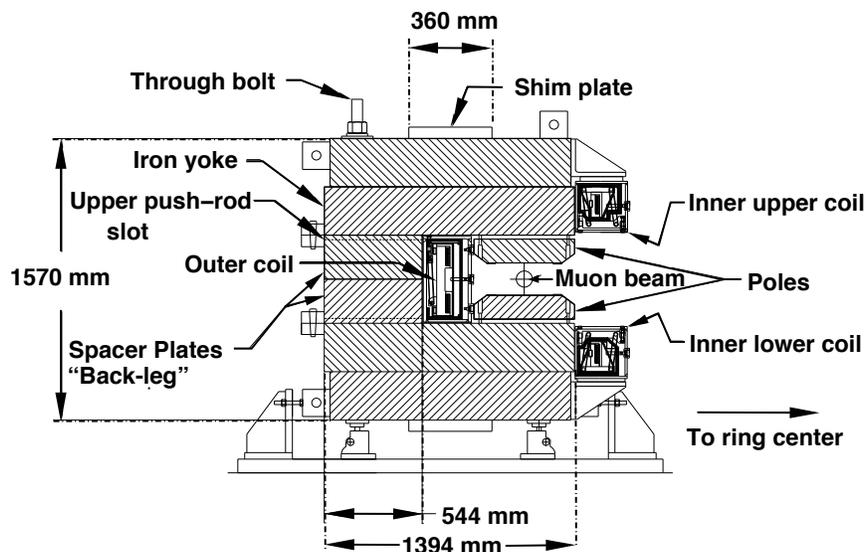


Figure 9.1: Cross section of the E821 storage-ring magnet. The yoke is made up of 12 azimuthal sections, each of which consists of six layers of high quality magnet steel provided by Lukins Steel Corporation. The pole pieces were provided by Nippon Steel Corporation.

3764 and hence low ripple currents; and thermal independence of the coils and the iron. The
 3765 main disadvantage was that the coils would have a much larger diameter and smaller height
 3766 than any previously built superconducting magnet. However, since the E821 magnet team
 3767 could not identify any fundamental problems other than sheer size, they decided to build
 3768 superconducting coils.

3769 To obtain the required precision in such a large diameter magnet with an economical
 3770 design is an enormous challenge. The magnet had to be a mechanical assembly from sub-
 3771 pieces because of its size. With practical tolerances on these pieces, variations up to several
 3772 thousand ppm in the magnetic field could be expected from the assembled magnet. To
 3773 improve this result by two to three orders of magnitude required a design which was a
 3774 “shimable kit”.

3775 Because of the dominant cost of the yoke iron, it was an economic necessity to minimize
 3776 the total flux and the yoke cross-section. This led to a narrow pole, which in turn conflicts
 3777 with producing an ultra-uniform field over the 9 cm good field aperture containing the muon
 3778 beam.

3779 A simple tapered pole shape was chosen which minimized variations in the iron perme-
 3780 ability and field throughout the pole. The ratio of pole tip width to gap aperture is only
 3781 2/1. This results in a large dependence of the field shape with the field value B . However,
 3782 since the storage ring is to be used at only one field, $B = 1.45$ T, this is acceptable. Because
 3783 of dimensional and material property tolerance variation, the compact pole piece increases
 3784 the necessity for a simple method of shimming.

3785 Experience with computer codes, in particular with POISSON [4], had demonstrated
 3786 that, with careful use, agreement with experiment could be expected at a level of 10^{-4}
 3787 accuracy. POISSON is a two-dimensional (2D) or cylindrically symmetric code, appropriate

3788 for the essentially continuous ring magnet chosen for the ($g - 2$) experiment. Computational
 3789 limitations, finite boundary conditions, and material property variations are all possible
 3790 limitations on the accuracy of “paper” designs.

3791 We will briefly discuss the design features that are relevant to E989, especially to moving
 3792 the ring, but not repeat all the details given in Danby et al. [3], and in the E821 Design
 3793 Report [5]. The parameters of the magnet are given in Table 9.1

Table 9.1: Magnet parameters

Design magnetic field	1.451 T
Design current	5200 A
Equilibrium orbit radius	7112 mm
Muon storage region diameter	90 mm
Inner coil radius - cold	6677 mm
Inner coil radius - warm	6705 mm
Outer coil radius - cold	7512 mm
Outer coil radius - warm	7543 mm
Number of turns	48
Cold mass	6.2 metric tons
Magnet self inductance	0.48 H
Stored energy	6.1 MJ
Helium-cooled lead resistance	$6 \mu\Omega$
Warm lead resistance	0.1 m Ω
Yoke height	157 cm
Yoke width	139 cm
Pole width	56 cm
Iron mass	682 metric tons
Nominal gap between poles	18 cm

3794 9.2 Yoke Steel

3795 E989 will reuse the yoke steel manufactured for the E821 experiment. The yoke pieces have
 3796 been surveyed and disassembled at Brookhaven and are in the process of being shipped to
 3797 Fermilab. The design and construction of the magnet has been documented and published
 3798 in NIM [3] as well as the final report in Phys. Rev. D [2]. We summarize the main design
 3799 features and issues here, with a discussion of potential improvements in Section 9.4.

3800 Ideally, the $g - 2$ magnet would be azimuthally symmetric. To ease the fabrication and
 3801 assembly processes, the magnet was built with twelve 30° sectors. Each sector consists of
 3802 an upper and lower yoke separated by a spacer plate as shown in Fig. 9.1. Due to the large
 3803 thickness of the yoke (54 cm), the individual plates were fabricated separately and welded
 3804 together after machining. The spacer plate is also split at the midplane to allow for the
 3805 installation of beam pipes and other services after the lower section is in place but prior to

3806 the installation of the upper yoke. The yoke plates and spacers in each sector are all fastened
3807 together with eight long high-strength steel bolts that cover the full 1.57 m tall yoke. The
3808 total sector mass is $\approx 57,000$ kg, which results in a total magnet mass of $\approx 680,000$ kg.

3809 Significant quality control efforts were taken during the manufacturing process to ensure
3810 that the magnet had sufficiently uniform permeability and the appropriate geometric shape.
3811 Both of these parameters have strong effects on the uniformity of the magnetic field in the
3812 storage region.

3813 High-quality plates were manufactured by hot-rolling AISI 1006 iron to minimize mag-
3814 netic voids in the material. These plates were manufactured with $< 0.08\%$ of carbon and
3815 other impurities. The finished plates were inspected ultrasonically to detect voids and in-
3816 clusions, and analyzed chemically to understand the composition.

3817 Although the yoke steel is partially magnetically isolated from the storage region by an
3818 air gap near the pole pieces, strict machining specifications are required to minimize non-
3819 uniformities in the storage region field. The surfaces of the yoke plates closest to the storage
3820 region were milled flat within $130\ \mu\text{m}$ and $1.6\ \mu\text{m}$ finish. Similarly, the spacer plate surfaces
3821 were milled flat within $\pm 130\ \mu\text{m}$, with a thickness accurate to $\pm 130\ \mu\text{m}$. These surfaces are
3822 parallel within $180\ \mu\text{m}$. The radial tolerance for each yoke plate and the spacer plates was
3823 $\pm 130\ \mu\text{m}$. When constructed, the vertical yoke gap had an rms deviation of $\pm 90\ \mu\text{m}$, or
3824 500 ppm of the total air gap of 20 cm, and a full-width spread of $\pm 200\ \mu\text{m}$.

3825 Each of the 12 sectors need to be connected smoothly to achieve azimuthal symmetry. To
3826 achieve azimuthal continuity, each sector end has four radial projections for bolts to fasten
3827 adjacent sector ends to each other. When the sectors are fitted to each other, shimmed, and
3828 the bolts tightened, relative motion of adjacent sectors is minimized. The average azimuthal
3829 gap between sectors was 0.8 mm, with an rms deviation of ± 0.2 mm.

3830 When we begin to reconstruct the storage ring, we will clean the yoke steel and remove
3831 any rust that has developed. It will be important to do this in a non-destructive manner
3832 that maintains the high-level of precision achieved during manufacturing.

3833 9.3 Poles and Wedges

3834 E989 will reuse the pole pieces and wedge shims that were manufactured for the E821 exper-
3835 iment. The pole pieces and wedges have been removed from the storage ring at Brookhaven
3836 and have already been shipped to Fermilab where they are awaiting reassembly.

3837 9.3.1 Poles

3838 More stringent quality requirements are placed on the machining of the pole pieces than
3839 the yoke steel. The air gap between the yoke and pole pieces decouples the field region
3840 from non-uniformities in the yoke. Thus, irregularities in the pole pieces dominate the field
3841 aberrations. Ultra-pure continuous vacuum cast steel with $< 0.004\%$ carbon impurities is
3842 used for the pole pieces. The fabrication process greatly minimizes impurities such as ferritic
3843 inclusions or air bubbles.

3844 A dimensioned view of the pole pieces is shown in Figure 9.2. Each 30° yoke sector
3845 contains three pole pieces (azimuthally). The pole pieces are 56 cm wide (radially), with

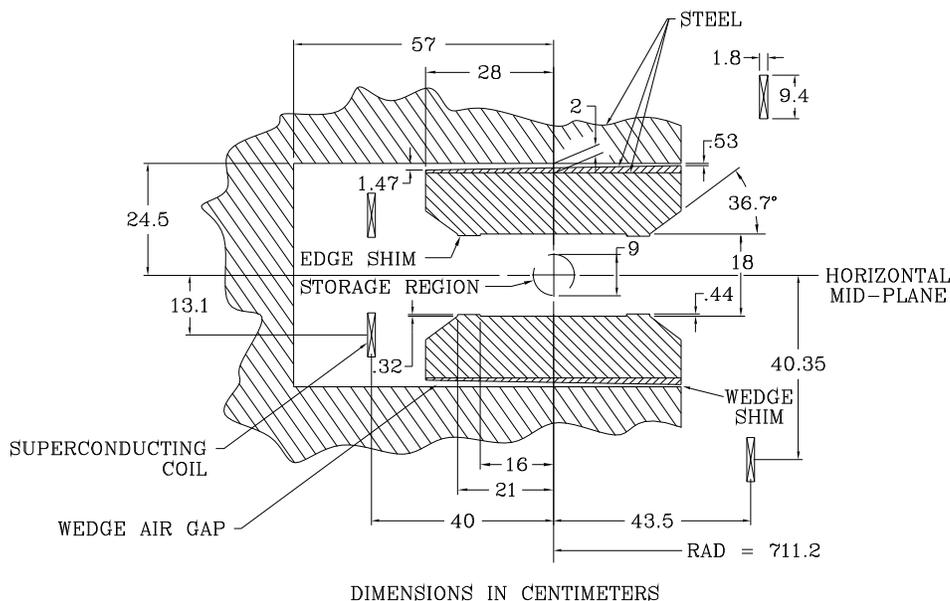


Figure 9.2: Cross section view of the magnet gap region.

3846 a tolerance of $50 \mu\text{m}$. The thickness (vertical) of each piece is 13.3cm with a tolerance of
 3847 $40 \mu\text{m}$. The pole faces which define the storage ring gap have tight machining tolerances.
 3848 Each face has a flatness tolerance of $25\mu\text{m}$, leading to upper and lower faces being parallel
 3849 within a $50 \mu\text{m}$ tolerance. The surface finish is $0.8 \mu\text{m}$. These machining tolerances are
 3850 so stringent due to the large quadrupole moment introduced by non-parallel surfaces. An
 3851 OPERA-2D simulation of the magnet has determined that a $100 \mu\text{m}$ tilt of the pole piece
 3852 over its width corresponds to $> 100 \text{ ppm}$. This is in good agreement with the 2D POISSON
 3853 calculations performed for the E989 simulations.

3854 Each yoke sector contains three pole pieces. Vertically, the pole pieces are mounted to
 3855 the yoke plates with steel bolts. The outer two pieces are each machined radially, parallel
 3856 to the yoke sector. The middle pole piece in each sector is interlocking, with an angle of
 3857 7° with respect to the radial direction. The pole pieces were isolated azimuthally by $80 \mu\text{m}$
 3858 kapton shims, which served two purposes. First, the kapton shims helped position the pole
 3859 pieces at the correct azimuth. Second, the kapton electrically isolated the poles from each
 3860 other. If the poles were all in contact with each other, large eddy currents would develop
 3861 around the entire circumference of the ring during field ramping leading to distortions of the
 3862 magnetic field

3863 The pole gap distance was measured using a capacitive sensor, as described in Section
 3864 15.4.2. The gap was 18 cm with an rms variation of $\pm 23 \mu\text{m}$, and a full range of $130 \mu\text{m}$.
 3865 As the magnet is powered, the induced torque causes the open side of the C-magnet (inner

3866 radius) to close slightly. Thus, during the installation, the poles were aligned with an opening
3867 angle of $80 \mu\text{rad}$. A precise bubble level was used to achieve $50 \mu\text{m}$ precision over the length
3868 of the pole piece. Pole realignment will be part of the shimming process described in Section
3869 15.4.2.

3870 9.3.2 Wedges

3871 The gaps between the yoke and poles isolate the yoke steel from the poles and provide a
3872 region where shims can be inserted to fine-tune the magnetic field. Steel wedges that are
3873 sloped radially (see Fig 9.2) are inserted to compensate for the intrinsic quadrupole moment
3874 produced by the C-magnet. There are 72 wedges in each 30° yoke sector. The induced
3875 quadrupole term depends on the slope of the wedge, which was calculated to be 1.1 cm over
3876 the 53 cm width for E821. This wedge angle was verified empirically, and no additional
3877 grinding was needed. The radial position of the wedges can be adjusted to change the total
3878 material in the gap, affecting only the dipole moment (see Section 15.4.3).

3879 During the ramping of the main coil current, the thick end of the wedge attracts more
3880 field lines, leading to a torque. To prevent the wedges from deflecting vertically, an aluminum
3881 “anti-wedge” is used to fill the air gap between the wedge and the pole piece.

3882 E989 will reuse the wedge-spacer combination as is. Fine tuning of the quadrupole
3883 moment can be achieved with active current shims, as discussed in Section 15.4.3.

3884 9.4 Thermal Effects

3885 Temperature variations in the experimental hall are expected to be controlled within $\pm 1^\circ\text{C}$
3886 during the course of data taking. This will change the shape of the magnet, which will in
3887 turn change the magnetic field. We produced thermal simulations with ANSYS to quantify
3888 the geometric distortions, which are then input into the OPERA-2D model of the storage
3889 ring.

3890 E821 used 3.5” of fiber glass insulation around the bulk of the yoke and 3/8” foam
3891 rubber insulation near the poles pieces, as shown in Figure 9.3 (a). Reasonable thermal
3892 film coefficients in the range of $5\text{-}25 \text{ W/m}^2\text{C}$ were used at the surfaces of the magnet.
3893 Thermal oscillations based on day-night temperature cycles are imposed on the $g-2$ magnet
3894 system and modeled with ANSYS. The air temperature is assumed to be spatially uniform
3895 throughout the hall. The model indicates that this will lead to thermal fluctuations at the
3896 yoke and pole pieces of a few tenths of a degree, as shown in Figure 9.3 (b). The pole pieces
3897 are constrained mechanically to prevent sliding, thus, in response to the thermal variations,
3898 they bend.

3899 Figure 9.4 shows the response of the magnet under the 1°C hall fluctuations. The
3900 contours show the maximum extent of the deflection for the both radial shifts (Figure 9.4
3901 (a)) and vertical shifts (Figure 9.4 (b)). The deflections are on the order of $1 \mu\text{m}$ per degree
3902 C change in the hall temperature. The parallelism of the pole faces is known to affect the
3903 higher-order multipole components of the magnetic field. Figure 9.5 plots the relative change
3904 in the pole gap as a function of radius for the thermal changes described above.

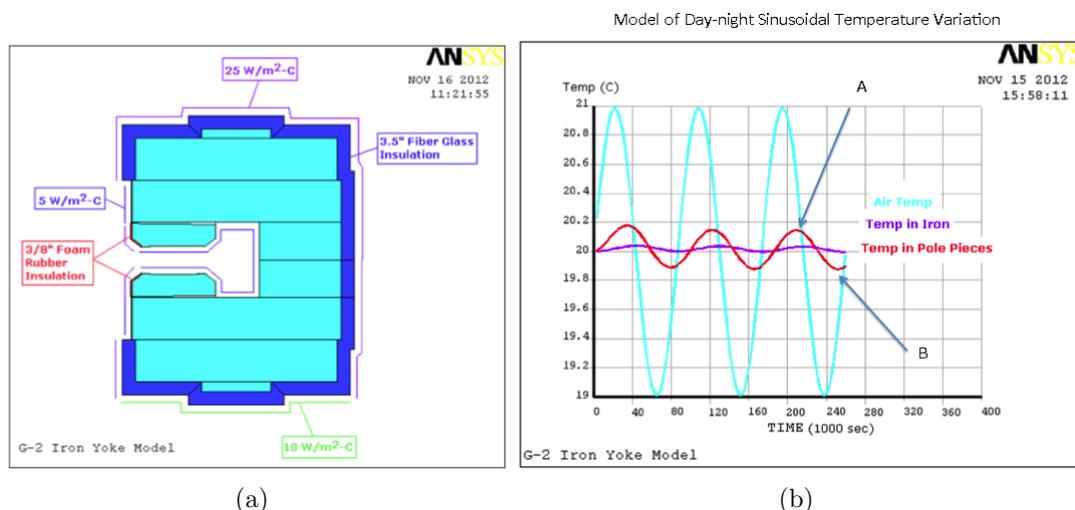


Figure 9.3: (a) An ANSYS model of the $g - 2$ storage ring includes the thermal insulation used in E821. (b) Thermal oscillations based on day-night temperature cycles are imposed on the $g - 2$ magnet system assuming a $\pm 1^\circ\text{C}$. The temperature variations of the the yoke (purple) and pole (red) are overlaid.

3905 Two different thermal contact resistances of the pole foam rubber insulation were mod-
 3906 eled. In both cases, the gap distortion leads to a change of about $1 \mu\text{m}$. The pole gap
 3907 distortions were input into the OPERA-2D magnetic field simulation. Distortions on there
 3908 order of a few tenths of a ppm were observed in the sextupole and octupole moment with
 3909 a change of $1 \mu\text{m}$ in the pole gap. Because the monitoring of the higher order multipole
 3910 moments is done primarily with the trolley runs, extrapolation of the field map from the
 3911 fixed probes during the main data collection will rely on stable magnet geometry.

3912 The ANSYS and OPERA tools nicely complement each other and allow us to understand
 3913 the effects of magnet deflections in E989. We plan to repeat these studies with varied
 3914 insulation thickness and with additional insulation around the inner superconducting coils.
 3915 With a high quality temperature control system stabilizing the experimental hall and better
 3916 thermal isolation of the steel, E989 will have significantly smaller time-dependent magnet
 3917 distortions than E821. This will lead to more stable multipole components.

3918 9.5 WBS 476.03.02.03 The Superconducting Coil Sys- 3919 tem

3920 9.5.1 Overview

3921 The coil design was based on the TOPAZ solenoid at KEK [6]. TOPAZ conductor was used,
 3922 with pure aluminum stabilizer and niobium-titanium superconductor in a copper matrix.
 3923 Conductor characteristics are given in Table 9.5.1. At full field the critical temperature of
 3924 the outer coil is 6.0 K. The magnet typically operates at 5.0 K. This represents 76% of

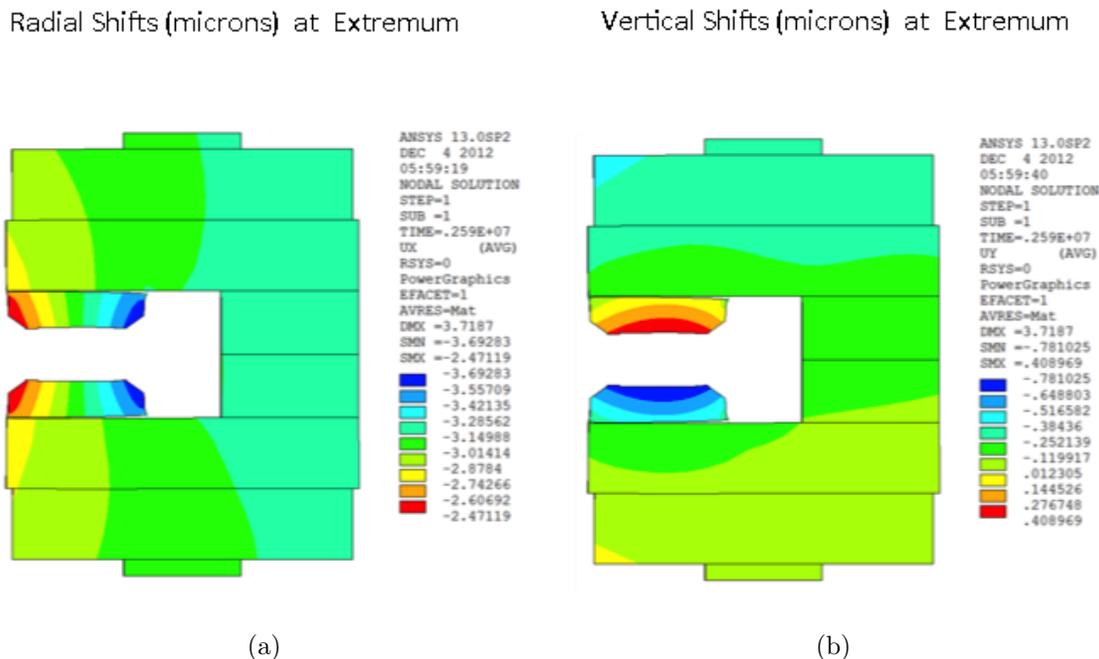


Figure 9.4: The thermal fluctuations depicted in Figure 9.3 are imposed on the magnet, causing distortion of the magnet, as modeled in ANSYS. The deflections are decomposed in (a) the radial and (b) the vertical dimensions for the worst-case scenario.

3925 the superconductor limit. Each coil block is effectively a very short solenoid with 24 turns,
 3926 and one layer. The coils are wound from the inside of the ring so that, when powered,
 3927 the coils push out radially against a massive aluminum mandrel. Cooling is indirect with
 3928 helium pipes attached to the mandrels. The coil turns, coil stack and insulation are epoxied
 3929 together, forming a monolithic block. The coils hang from the cryostat with low heat load
 3930 straps, and the shrinkage and expansion of the coils is taken by the straps. The coils are
 3931 located using radial stops on the inner radius. For the outer coil the stops transfer the force
 3932 from the coil to the cryostat box, and push rods from the iron yoke transfer the force from
 3933 the box to the iron (see Fig. 9.7). For the inner coils, pins replace the pushrods.

3934 When the coils are cooled, they contract down onto the radial stops into a scalloped
 3935 shape. When powered, the Lorentz force pushes the coils outward, increasing the force
 3936 against the mandrel, which provides cooling. This feature, the result of winding on the
 3937 inside of the mandrel, reduces the risk of cooling problems even if the coil were to separate
 3938 from the mandrel during transport citeyamamoto-pc.

3939 A ground plane insulation band of 0.3 mm thickness was built from a sandwich of three
 3940 layers of 50 μm kapton, epoxy coated, between two layers of epoxy-filled fiberglass. The
 3941 insulation assembly was fully cured and placed into the mandrel. A 0.1 mm layer of B-stage
 3942 epoxy film was placed between the mandrel and kapton laminate, and between the kapton
 3943 laminate and the conductor block after winding. A 4.8 mm thick G-10 piece was placed on
 3944 the winding ledge, and on top and on the inner radius of the completed coil block. The
 3945 insulation protected against a local failure in an insulation layer and against creep failure

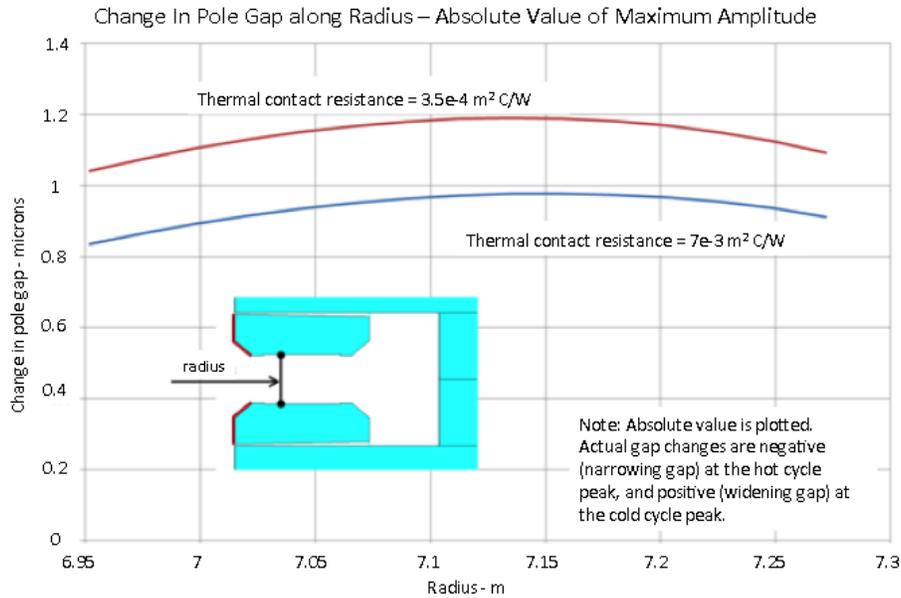


Figure 9.5: The deflections of the pole pieces under thermal variations are quantified in ANSYS simulations as a function of the radial coordinate. Typical fluctuations of 1°C will produce micron scale distortions. Two different thermal contact resistances are shown.

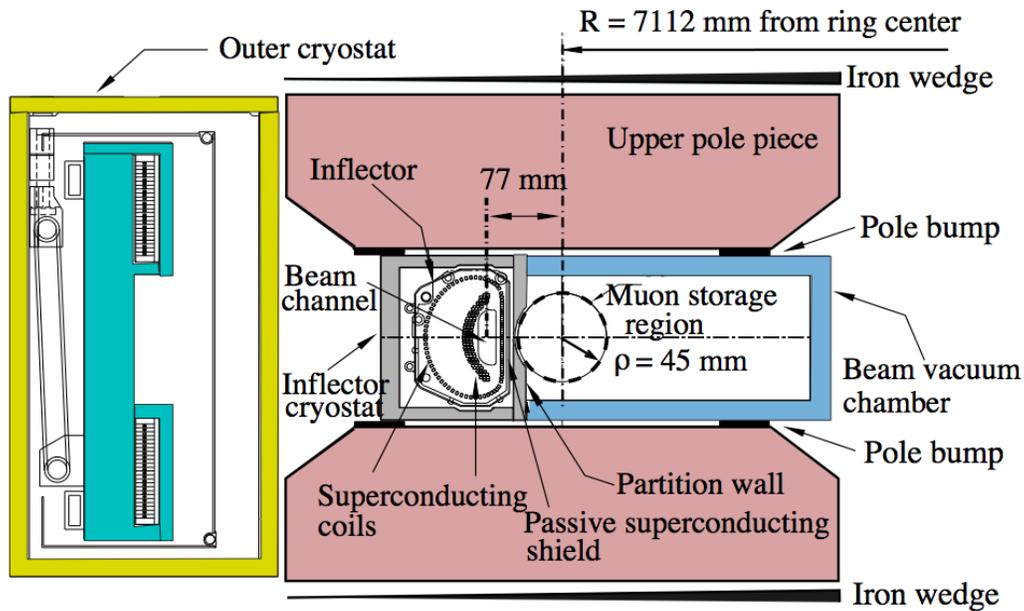


Figure 9.6: The arrangement of the pole pieces, shimming wedges and the inflector cryostat, showing the downstream end of the inflector where the beam exits. The beam is going into the page, and the ring center is to the right.

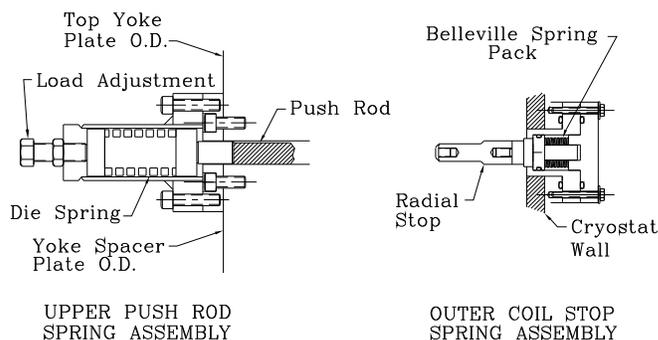


Figure 9.7: The spring-loaded radial stop and push rod. The stops are attached to the cryostat inner wall. The push rods preload the outer cryostat, attaching to the yoke at the outer radius, passing through a radial slot in the yoke to the outer cryostat.

3946 along a surface. The epoxy-filled fiberglass in the ground plane insulation sandwich improved
 3947 heat transfer between coil and mandrel.

Table 9.2: Superconductor parameters

Superconductor type	NbTi/Cu
Nominal dimensions	1.8 mm \times 3.3 mm
NbTi/Cu ratio	1:1
Filament 50 μ m	
Number of filaments	1400
Twist pitch	27 mm
Aluminum stabilizer type	Al extrusion
Ni/Ti composite dimensions	3.6 mm \times 18 mm
Al/(NbTi + Cu) ratio	10
RRR (Al)	2000-2500
RRR (Cu)	120-140
I_c	8100 A (2.7 T, 4.2 K)

3948 The coil was then wound using a machine that wrapped the superconductor with three
 3949 overlapping layers of 25 μ m of kapton and fiberglass filled with B-stage epoxy, 19 mm in
 3950 width, laying the conductor into the mandrel with a compressive load as described in Ref. [3].
 3951 The wrap was tested at 2000 V DC during the wind. Aluminum covers were added after the
 3952 coil was wound, and the entire assembly heated to 125° C to cure the epoxy. See Fig. 9.8.

3953 The outer coil contains two penetrations, one to permit the beam to enter the ring, and
 3954 one which which could have permitted high voltage to be fed to a proposed electrostatic

3955 muon kicker. It was decided at the time to make this “kicker penetration” in the outer coil,
 3956 but not to make a hole through the magnet yoke until it was shown that this kicker could
 3957 be built (which was not demonstrated).

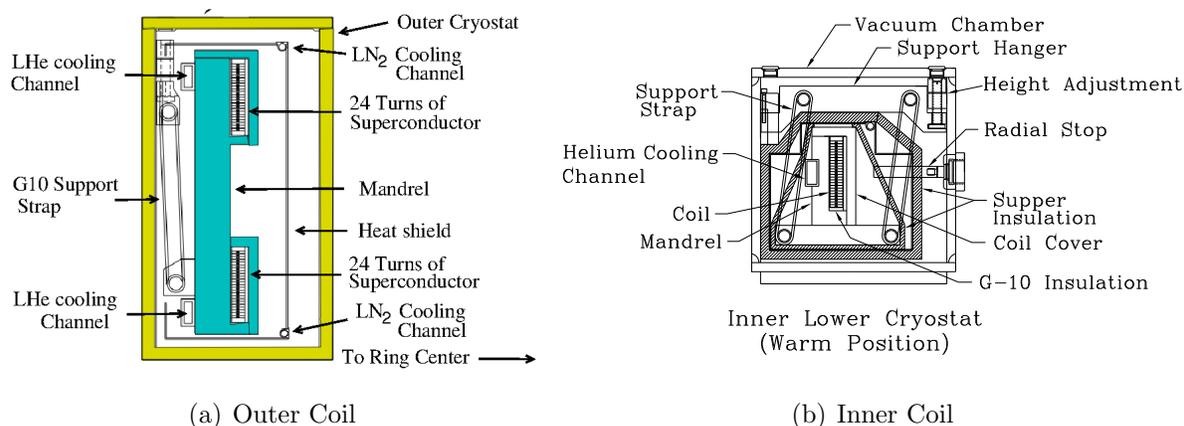


Figure 9.8: The outer and inner coil structures. Both are shown in their warm configuration.

3958 The coils are indirectly cooled with two-phase He flowing through channels attached to
 3959 the mandrel, as shown in Fig. 9.8. The two-phase helium cooling avoids the increase in
 3960 temperature that would occur in a circuit cooled with single-phase helium. The operating
 3961 temperature of the coils is within 0.2 K of the coldest temperature in the cooling circuit.
 3962 The advantages of two-phase cooling are: (1) the helium flows in well-defined flow circuits;
 3963 (2) the total amount of helium that can be flashed off during a quench is limited to the mass
 3964 of helium in the magnet cooling tubes; and (3) the location of the helium input and output
 3965 from the cryostat and the location and orientation of the gas cooled leads are not affected
 3966 by the cooling system [8].

3967 The key to the operation of a two-phase helium cooling circuit is a helium dewar (the
 3968 control dewar) that contains a heat exchanger. This heat exchanger sub-cools the helium
 3969 from the J-T circuit before it enters the magnet cooling circuits. This isobaric cooling
 3970 provides a higher ratio of liquid to gas with a higher pressure and lower temperature than
 3971 the refrigerator J-T circuit alone would provide. This feature is important for the long
 3972 cooling channels in the magnet cooling circuits. The use of a heat exchanger in the control
 3973 dewar reduces the helium flow circuit pressure drop by a factor of two or more. The control
 3974 dewar and heat exchanger also have the effect of damping out the oscillations often found in
 3975 two-phase flow circuits. The helium in the control dewar acts as a buffer providing additional
 3976 cooling during times when the heat load exceeds the capacity of the refrigerator.

3977 The $(g-2)$ cooling system was originally designed to have three separate cooling circuits:
 3978 a 218 m long cooling circuit that cools all three mandrels in series, the lead and coil inter-
 3979 connect circuits that are 32 m long (the gas-cooled leads are fed off of this circuit), and a
 3980 14 m long cooling circuit for the inflector magnet. Later the cooling system was modified to
 3981 permit each of the mandrels to be cooled separately. Ultimately, the $(g-2)$ cooling system
 3982 operates with parallel cooling circuits for the coils, inflector, and lead cooling. Electrically,
 3983 the three coils are connected in series so that the two inner coils are in opposition to the

3984 outer coil to produce a dipole field between the inner and outer coils. The magnet is powered
 3985 through a pair of tubular gas-cooled leads developed for this application. Each lead consists
 3986 of a bundle of five tubes. Each tube in the bundle consists of three nested copper tubes with
 3987 helium flow between the tubes. The copper tubes used in the leads are made from an alloy
 3988 with a residual resistance ratio of about 64. The lead length is 500 mm. A typical cool down
 3989 from 300 to 4.9 K takes about 10 d. Once the control dewar starts to accumulate liquid
 3990 helium, it takes another day to fill the 1000 l dewar. In operation, the pressure drop across
 3991 the magnet system is about 0.02 MPa (3.0 psi). We initiated several test quenches and had
 3992 one unintentional quench when the cooling water was shut off to the compressors. The peak
 3993 measured pressure during a 5200 A quench was 0.82 MPa (105 psig). Other places in the
 3994 cooling circuit could have a pressure that is 40% higher. The quench pressure peak occurs
 3995 11 s after the start of the quench. The quench pressure pulse is about 12 s long compared
 3996 to current discharge time constant at 5200 A of 31 s. The outer coil mandrel temperature
 3997 reaches 38 K after the quench is over. Re-cooling of the magnet can commence within 5 min
 3998 of the start of the quench. After a full current quench, it takes about 2 h for the outer coil
 3999 to become completely superconducting. The inner coils recover more quickly.

Table 9.3: Estimates of cryogenic heat leaks

		4.9 K load	80 K load
		(W)	(W)
Magnet system heat load	Outer coil cryostat	52	72
	Two inner coils	108	77
	Inflector	8	5
	Interconnects	11	46
	Magnet subtotal	179	200
Distribution	Helium piping	19	
	Control dewar	5	
	Interconnects/valves	33	32
	Nitrogen piping		34
	Distribution subtotal	57	66
Lead gas (1.1 g/s)	Equivalent refrigeration	114	
Total refrigeration		351	266
Contingency		70	51
Cryogenic design	Operating point	421	308

4000 Both persistent mode and power supply excitation were considered. The total flux,
 4001 $\int \vec{B} \cdot d\vec{s}$, is conserved in persistent mode. However, room temperature changes would result
 4002 in changes in the effective area. Thus although the flux, is conserved, the magnetic field in
 4003 the muon storage region is not. Persistent mode would also require a high-current super-
 4004 conducting switch. Power supply excitation with NMR feedback was chosen, although no
 4005 feedback was used for the 1997 run. This method gives excellent control of the magnetic
 4006 field and allows the magnet to be turned off and on easily. The power supply parameters
 4007 are shown in Table 9.5.1.

Table 9.4: Power supply parameters

Rating	5 V, 6500 A	
Rectifier	480 VAC input, 12 pulse (Two $\pm 15^\circ$, 6 pulse units in parallel)	
Output filter	0.4 F	
Regulator	Low-level system	0.1 ppm stability with 17 bit resolution
	Power section	Series regulator with 504 pass transistors
Cooling	Closed loop water system with temperature regulation	
Regulation	Current-internal DCCT	± 0.3 ppm over minutes to several hours
	Field-NMR feedback (current vernier)	± 0.1 ppm (limited by the electronics noise floor)
Manufacturer	Bruker, Germany	

4008 Both persistent mode and power supply excitation were considered. The total flux,
4009 $\int \vec{B} \cdot d\vec{s}$, is conserved in persistent mode. However, room temperature changes would result
4010 in changes in the effective area. Thus although the flux, is conserved, the magnetic field in
4011 the muon storage region is not. Persistent mode would also require a high-current super-
4012 conducting switch. Power supply excitation with NMR feedback was chosen, although no
4013 feedback was used for the 1997 run. This method gives excellent control of the magnetic
4014 field and allows the magnet to be turned off and on easily. The power supply parameters
4015 are shown in Table 9.5.1.

4016 The quench protection design parameters were determined by the requirements of mag-
4017 netic field stability and protection of the magnet system in case of a quench. When the
4018 energy is extracted, eddy currents are set up in the iron which oppose the collapse of the
4019 field. This can cause a permanent change in the magnetic field distribution [9]. This is
4020 sometimes called the ‘umbrella effect, since the shape of the change over a pole resembles an
4021 umbrella. The eddy currents are minimized if the energy is extracted slowly. There will also
4022 be eddy currents in the aluminum mandrels supporting the coils. Electrically, this can be
4023 represented by a one turn shorted transformer. These eddy currents will heat the mandrels
4024 and can cause the entire coil to become normal. This is called quench-back. This has several
4025 beneficial effects. The part of the stored energy that is deposited in the coil is deposited uni-
4026 formly over the entire coil and mandrel assembly. Also, once quench-back occurs, the energy
4027 extraction process is dominated by the quenchback and not by the specifics of where the
4028 quench occurred. Therefore, the effects of a quench on the reproducibility of the magnetic
4029 field should be minimal.

4030 The energy extraction system consists of a switch, resistor, and quench detection elec-
4031 tronics. An energy extraction resistor of 8 m) was chosen. Including the resistor leads,

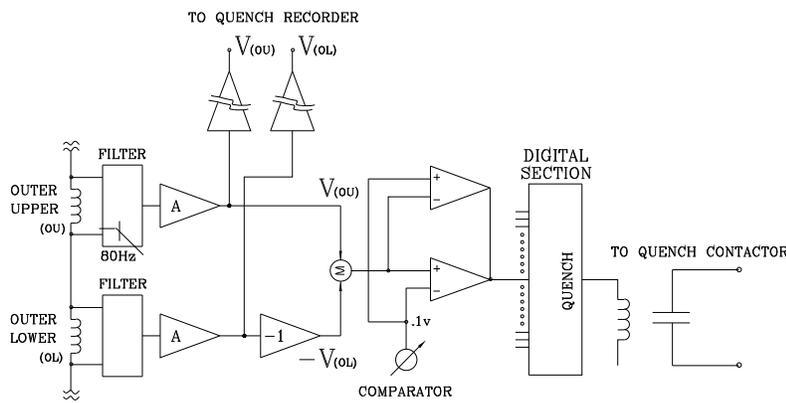


Figure 9.9: Diagram of the quench protection circuit.

4032 the room temperature resistance is 8.8 m). This gives an L/R time constant of 1 min. The
 4033 actual time constant varies due to the temperature increase of the coil and dump resistor
 4034 and the effect of eddy currents in the mandrels during the energy extraction (see below).
 4035 This resistance value was calculated to cause quenchback in the outer mandrel within 2 s
 4036 at full current. The quench protection circuit is shown in Fig. 9.9. The energy extraction
 4037 trigger for a quench which originates in one of the coils is the voltage difference between
 4038 matching coils; for example, $V(\text{outer} - \text{upper}) - V(\text{outer} - \text{lower})$. Since the inductance is
 4039 effectively the same, the voltages should be equal even while charging the magnet, unless a
 4040 quench develops in one coil. This quench threshold is set at 0.1 V. However, the coil inter-
 4041 connects are thermally coupled together with the helium tubes. It is possible that a quench
 4042 in an interconnect could propagate to both coils almost simultaneously. Therefore, a voltage
 4043 threshold of 10 mV was chosen for each interconnect. The outer upper to lower interconnect
 4044 is only 1 m long. This threshold was set to 5 mV. The thresholds were determined by the
 4045 requirement that the quench be detected within 0.2 s. The gas-cooled leads develop a voltage
 4046 of typically 15 mV at full current. If the lead voltage exceeds 30 mV, the energy is extracted.

4047 9.5.2 Preparations Prior to Transportation

4048 No significant changes will be made to the design, and nearly all components are reused
 4049 from E821. The WBS sections below describe the steps to reassemble and recommission the
 4050 items above. We will not need to fabricate any parts, other than to replace old components
 4051 or to build spares.

4052 Prior to the coil transportation, room temperature tests were performed to verify as much
4053 as possible the working state of the system. These were:

- 4054 • Electrical verification of the instruments connected to the coil and/or mandrel. These
4055 refer to the temperature probes, voltage taps for quench detection, and strain gauges.
4056 The instruments connected to the cryostat consists of thermometers, voltage taps, and
4057 strain gauges. There are as indicated in figures 9.10 and 9.11. The strain gauges are
4058 attached to the straps, which counteract the Lorentz forces, and the radial stops, which
counteract the shrinking of the radial stops due to cooling.

Outer Cryostat Thermometer and Strain Gauge Locations

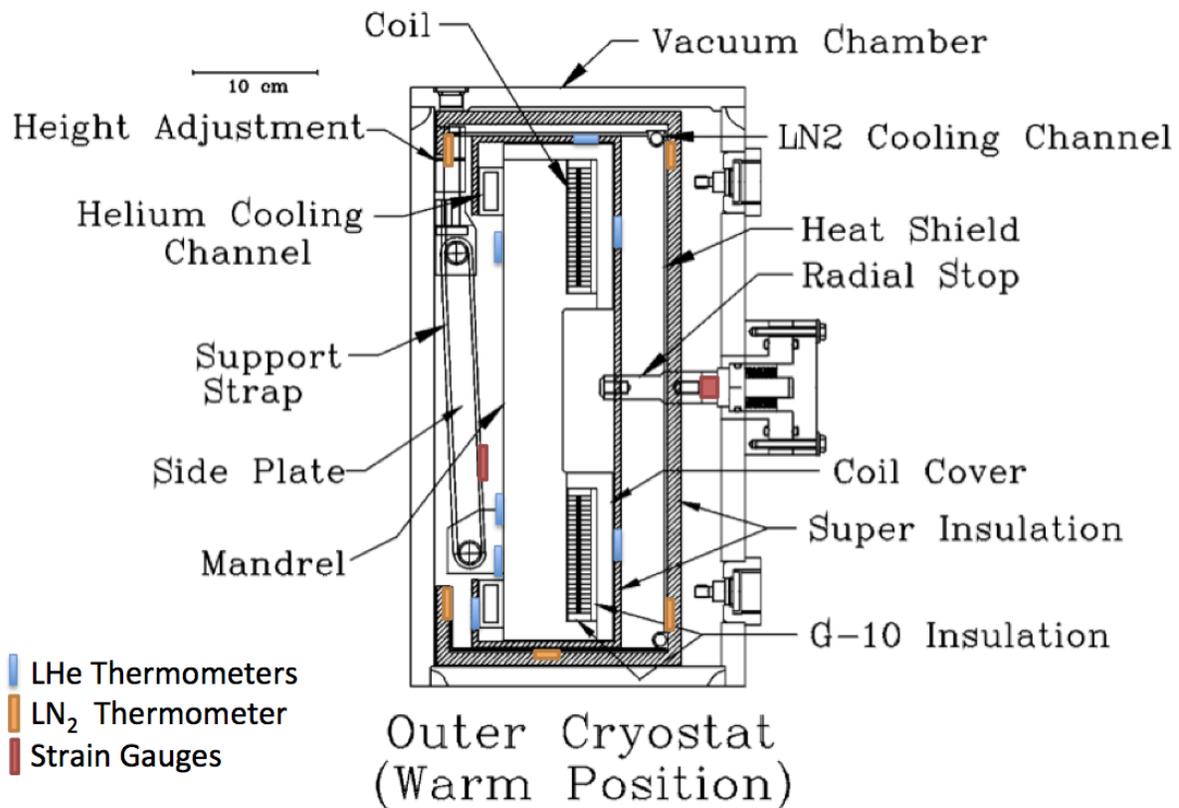


Figure 9.10: Location of outer coil instrumentation, showing the LHe LN₂ thermometers, and strain gauges. For the thermometers, there are typically 8 locations in azimuth at each locations indicated.

4059

- 4060 • Resistance measurements of the coil at room temperature, which agree with measure-
4061 ments performed in 1995 (see table 9.5).

- 4062 • The resistance between the coil leads and ground was measured to be a few kohms,
4063 where as an open resistance was expected. Further tests showed the 'short-to-ground'
4064 occurring at the connection between the inner lower coil and the power supply (see

Inner Cryostat Thermometer and Strain Gauge Locations

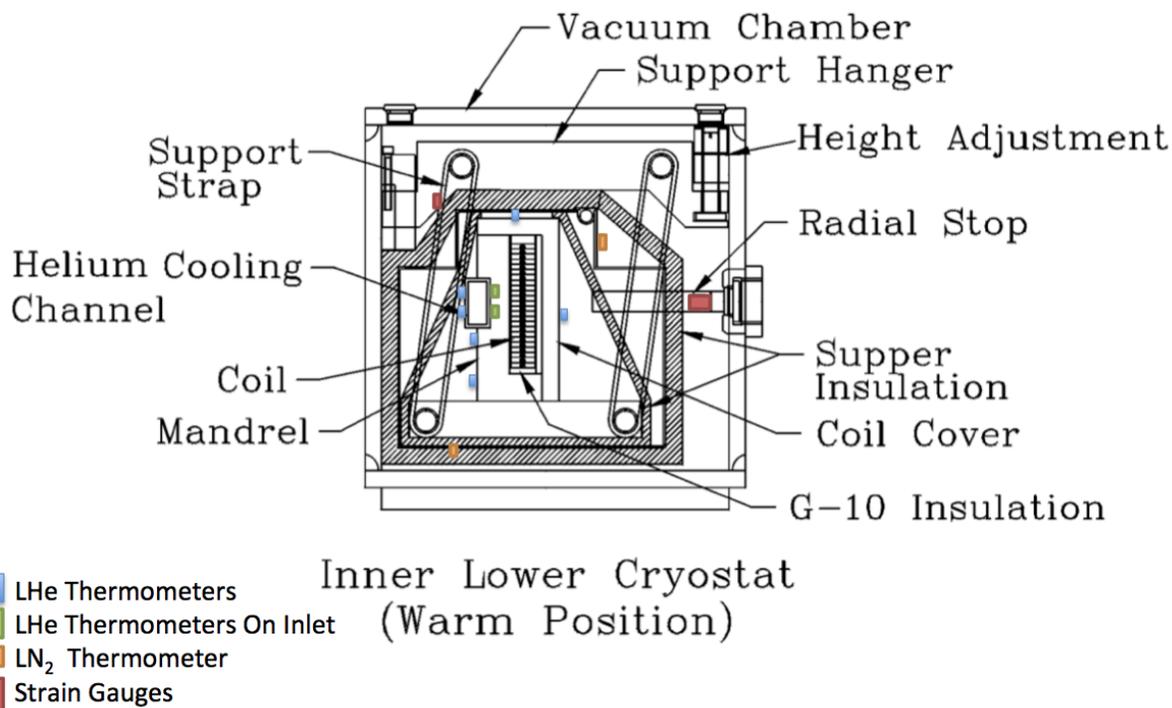


Figure 9.11: Location of the lower inner coil instrumentation, showing the LHe and LN₂ thermometers, and strain gauges. The instrument locations are symmetrically placed for the upper coil instruments. For the thermometers, there are typically 8 locations in azimuth at each locations indicated.

4065 figure 9.15), and is a straight-forward repair. There is no short within the coils them-
 4066 selves. This short was likely present during E821 running, and would have contributed
 4067 a 0.01 mA current-to-ground, out of a total of 5200 amps. This is 2 ppb effect and
 4068 would not have been seen in E821 (see references [11] and [12]).

4069 Following this verification, the interconnections between the three coils (see figure 9.12)
 4070 were separated by a grinding wheel. The temperature was monitored and kept well below
 4071 100°C during the process to minimize degradation to the Aluminum resistance and the NbTi
 4072 current-carrying capacity. Figures 9.13 and 9.14 shows the detail of the welds that were cut
 4073 in this region.

4074 9.5.3 WBS 476.03.02.03.01 Cryostat Vacuum Chambers

4075 This WBS consists of the vacuum chambers that provide the thermal insulation for the coils.
 4076 After the interconnects have been rewelded (see section 9.5.7), the vacuum flanges enclosing
 4077 that region will be reconnected.

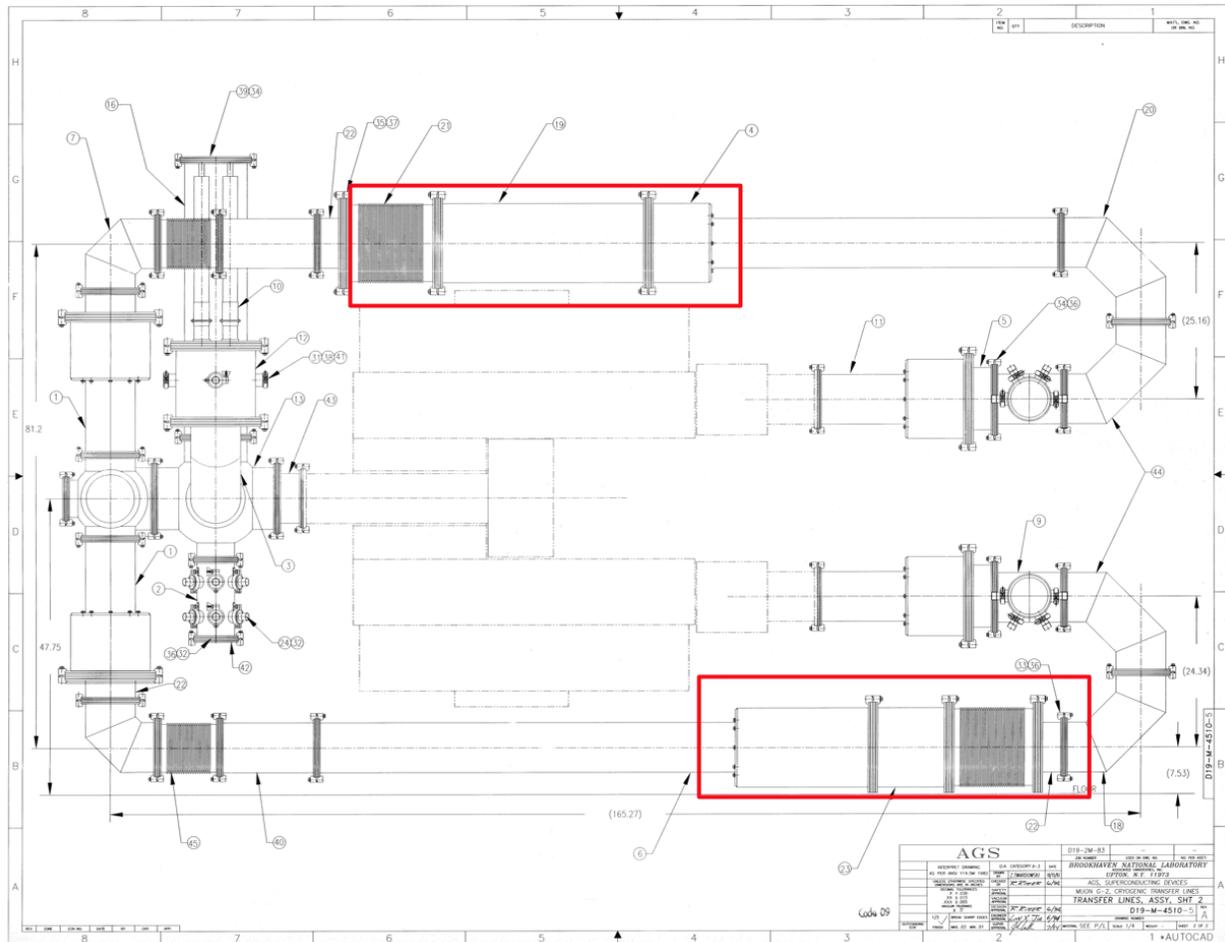


Figure 9.12: The connection between the three coils are indicated. The upper(lower) red box is the connection between the outer-upper (outer-lower) coil and the inner-upper (inner-lower) coil.

4078 For transportation, a vacuum port connected to the outer cryostat will be cut in order
 4079 to gain clearance. Therefore, this pipe will be rewelded upon reassembly at Fermilab.

4080 9.5.4 WBS 476.03.02.03.02 Vacuum Pumps

4081 New or refurbished 'dry' vacuum pumps will used to pump down the cryostat vacuum cham-
 4082 bers. The pumps must remain a few meters away from the storage beam region in order
 4083 to not perturb the precision magnetic field. The vacuum quality needed is about 10^{-4} Torr
 4084 (check with Del).

4085 E821 implemented a mechanism described below to deal with a potential failure mode
 4086 called the 'cold cryostat problem'. In the event of loss of cryostat vacuum while the coils are
 4087 cold, the cryostat walls will also become cold and therefore will shrink. Such could happen
 4088 if the cryogenic lines leaked cryogenes into the vacuum. However, the cryostat positions are
 4089 firmly attached to the yoke steel in order to have a well-defined coil position. Therefore,
 4090 the cryostat wall at the attachment point would experience stresses exceeding the allowable

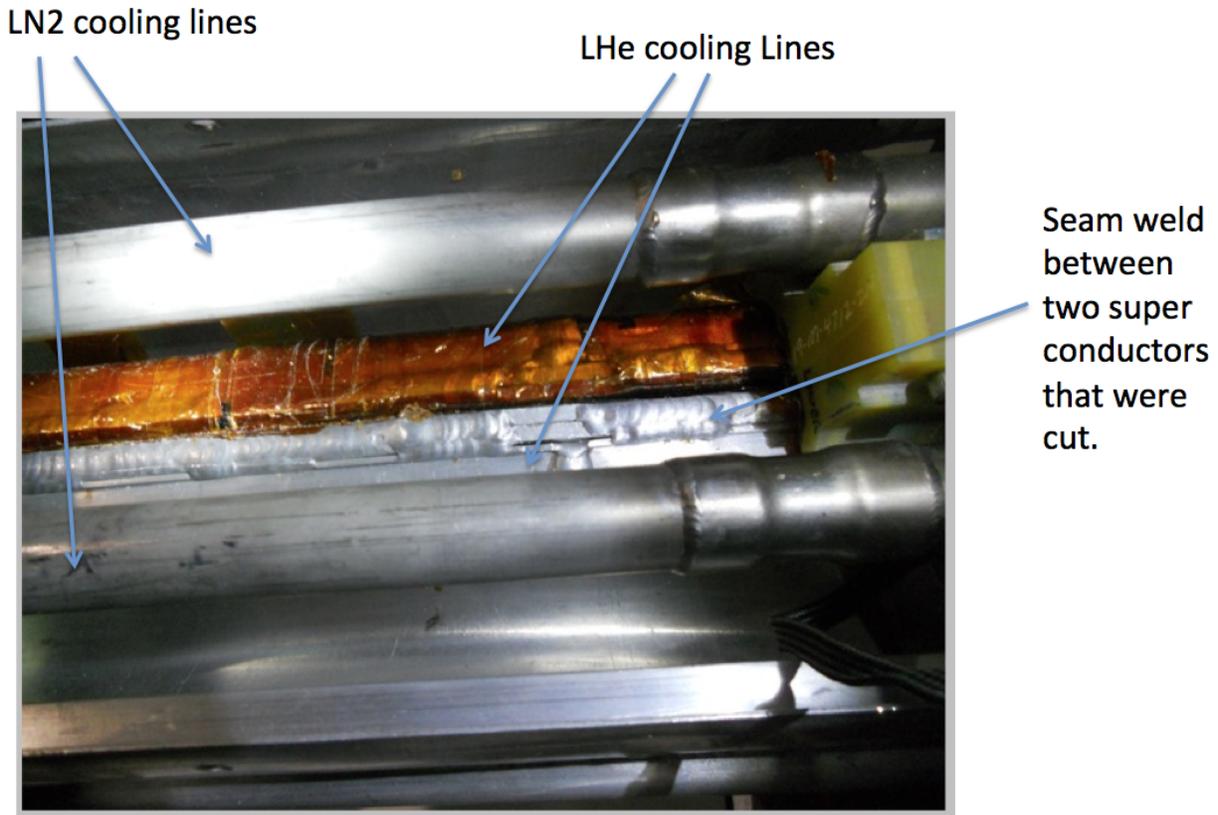


Figure 9.13: Photograph of the region of the interconnection, indicating welds and cooling lines.

4091 value for Aluminum.

4092 For this potential failure scenario, E821 implemented a scheme to trigger a large Roots
4093 blower vacuum pump to rapidly evacuate the vacuum chamber.

4094 **9.5.5 WBS 476.03.02.03.03 Power Supply and Quench Protection**

4095 The power supply for the main ring will be the same unit use in E821 and as described
4096 in reference [3]. Therefore the design and specifications will be the same. Once moved to
4097 Fermilab, the power supply will be refurbished, tested, and then commissioned for installation
4098 and use. A similar process will be used for the quench protection circuitry and components.
4099 The voltage taps and quench detection circuitry are located as shown in figures 9.15 and
4100 9.16.

4101 Once the hardware examination and the necessary replacement procedures have been
4102 completed, the power supply unit will be tested in stages. This testing process will be done
4103 in a staging area and not connected to any other component:

- 4104 • Stage 1: AC power will be applied to the separate modules of the unit. This is to first
4105 check out operation of readout and controls.

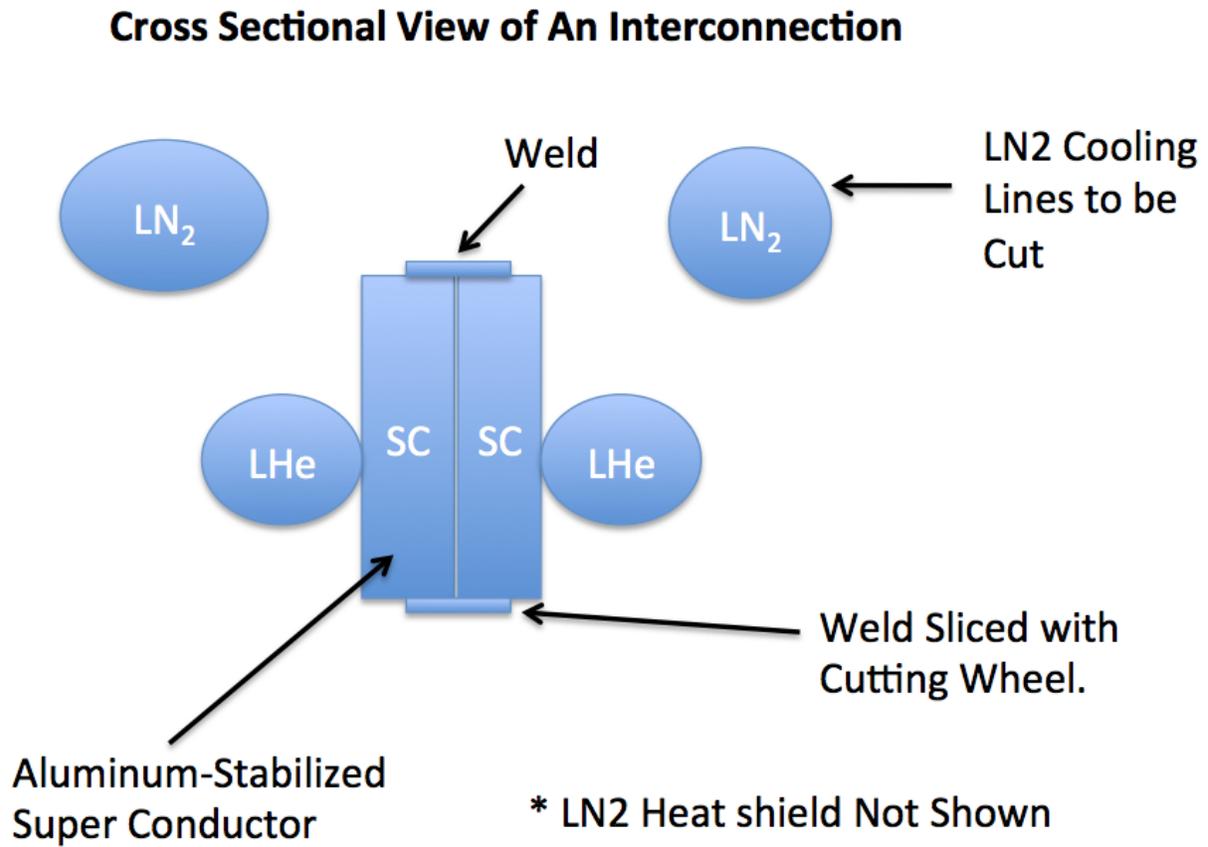


Figure 9.14: Diagram of the region of the interconnection, indicating welds and cooling lines that were cut, in order to facilitate the transportation.

- 4106 • Stage 2: AC power will then be applied to the complete unit with no DC load con-
- 4107 nected. This is designed to observe and check out the initial operation and to exercise
- 4108 the controls.
- 4109 • Stage 3: Once the controls operation is verified, a partial DC load (10-20%) will be
- 4110 applied to exercise the output and to check for stability.
- 4111 • Stage 4: Add parallel DC loads to the output to slowly bring up the power supply to
- 4112 full power. Once the initial checkout is done, this step will be repeated.

4113 The quench detection voltage threshold used for E821 was 100 mV across the coils, and 10

4114 mV across each interconnect between the outer and inner coils, and 5 mV across the outer

4115 upper and outer lower coils. The thresholds were determined by the requirement that the

4116 quench be detected within 0.2 s. The gas-cooled leads develop a voltage of typically 15 mV

4117 at full current. If the lead voltage exceeds 30 mV, the energy is extracted.

4118 In a similar manner to that used for the power supply, the quench protection circuitry

4119 will be examined and refurbished to its original operational state. Testing will also be in

4120 stages until the completed unit, along with the transfer switch and dump resistor, operates

Coil	Resistance (ohms) Sept-1995	Resistance (ohms) Dec-2011
Inner Upper	0.429	0.430
Inner Lower	0.426	0.430
Outer Upper	-	0.483
Outer Lower	-	0.476
Outer Upper + Lower	0.952	0.958

Table 9.5: Room temperature coil resistance (ohms) measurements, showing consistency between Sept-1995 and Dec-2011.

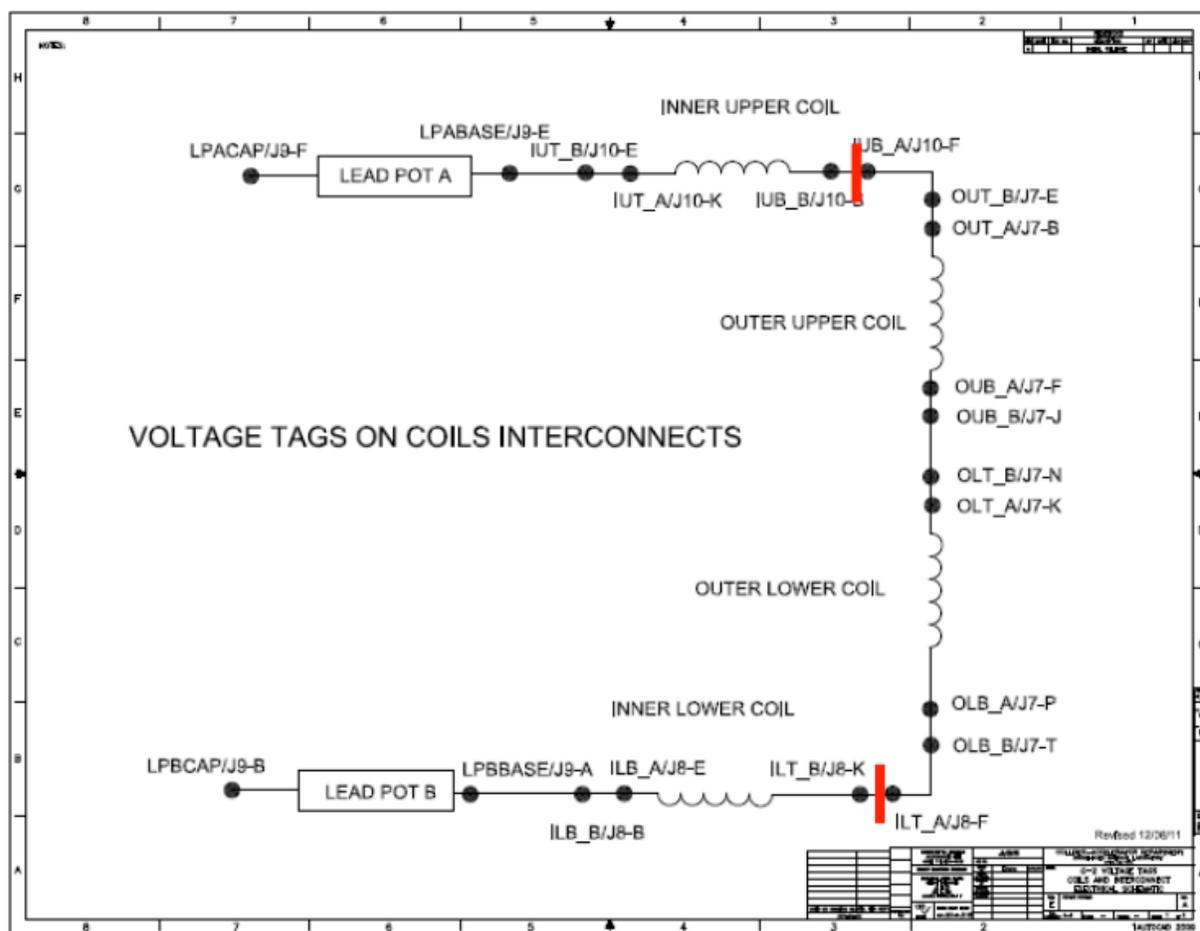


Figure 9.15: Voltage tap locations for quench detection. The red bars indicate the location of the cuts needed for transportation.

4121 as originally designed. This testing will also be in stages and not connected to any ring
 4122 components.

4123 Similar to E821, the dump resistor will be located outdoors. During energy extraction,
 4124 approximately 6 MJoules of energy will be dissipated into the dump resistor. If the dump
 4125 resistor was located indoors, it would raise the air temperature by approximately 2°C. While

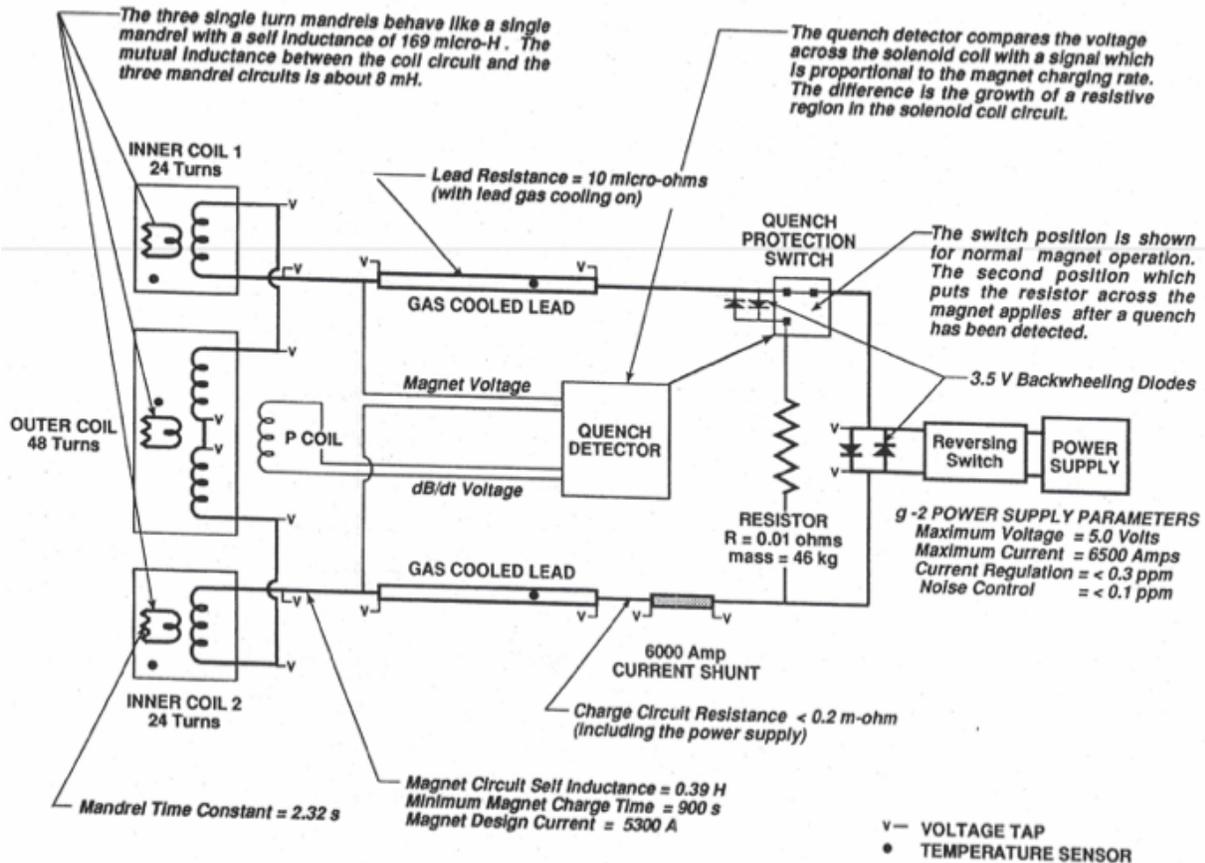


Figure 9.16: Quench detection and power supply diagram.

4126 that can be handled by the building HVAC, it would produce unwanted temperature non-
4127 uniformity in the hall.

4128 Once the four main components, power supply, quench protection unit, transfer switch,
4129 and dump resistor have been tested individually, reconnection of these components will be
4130 done in the staging area. At this time, specific procedures will be developed for reconnection.
4131 These procedures will be fully tested and reviewed prior to connection to the main ring coils.
4132 A simulated load will be used to mimic operation of the ring coils. At first, this load will be
4133 resistive or active linear loads. A desired, but not necessary next step would be to use an
4134 existing magnet coil to test all operation.

4135 After these tests are completed satisfactorily, the components will then be moved to the
4136 g-2 hall for final assembly and commissioning. The commissioning process will be dependent
4137 on the assembly of the main ring. Again, this process should be done in stages of operation
4138 (low to medium power, warm to cold coil operation) but these stages need to be defined once
4139 the risk to the main ring connections can be identified and reasonably mitigated.

4140 9.5.6 WBS 476.03.02.04 Cryogenics

4141 This WBS refers to the cryogenics (LHe and LN₂) required to cool the coils to 4.9K, the
 4142 cooling lines, the heat shields cooled to LN₂ temperatures, and the flow control valves. The
 4143 E821 will be reused as much as possible, especially the 1000 liter dewar. The E821 cryogenic
 flow diagram is shown in figure 9.17.

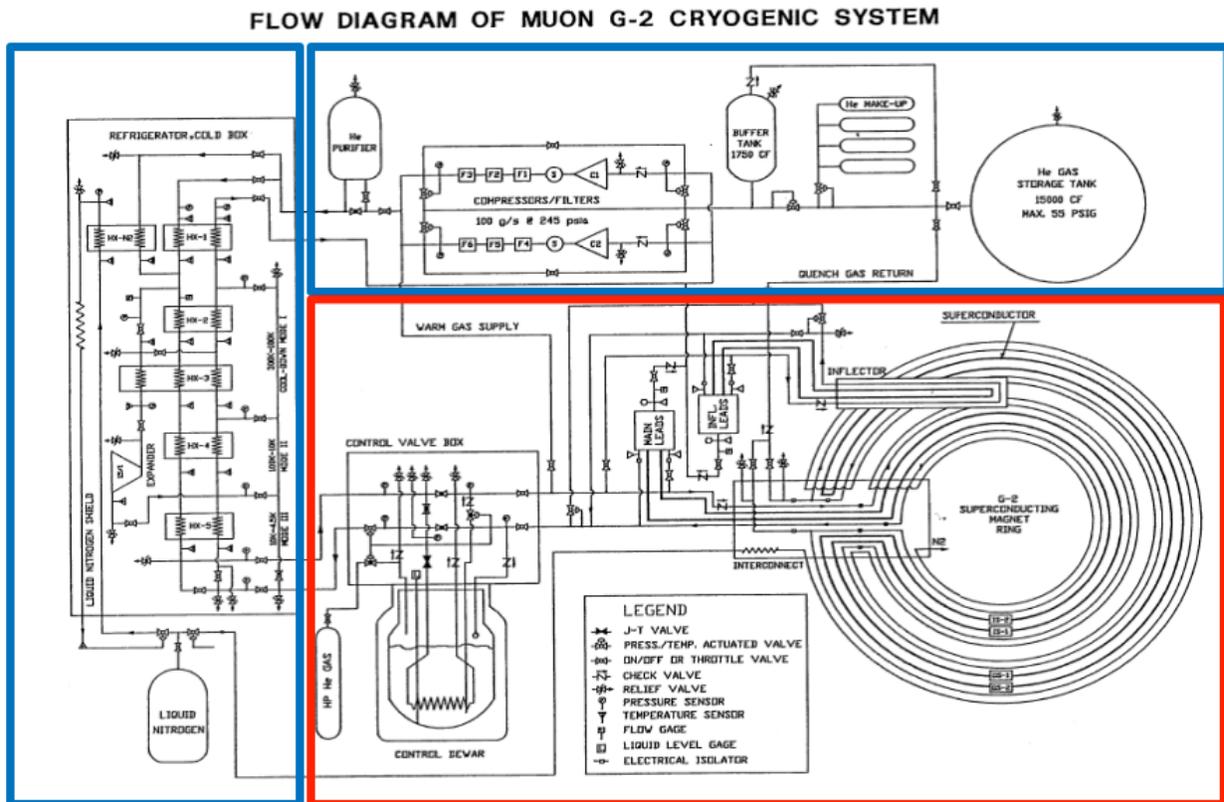


Figure 9.17: The cryogenic plant and its connection with E821 (G-2). The red box outlines the flow within building 919 at BNL. The upper (left) blue box outlines the LHe (LN₂) cryogenic plant.

4144

4145 While no design changes will be made, this WBS requires considerable verification, reanal-
 4146 ysis, and documentation due to the significant hazard and stored energy, and the potential
 4147 for the ‘cold cryostat’ problem as described in the section above.

4148 The documentation were generated for E821, and will be reaccessed for E989. Attention
 4149 will be given to:

- 4150 • Heat load of the system. There will be a slight increase due to the rewelding of the
 4151 coils at the interconnection (see section 9.5.7) and a slightly longer run between the
 4152 cryogenic plant and the LHe dewar.
- 4153 • Flow diagram, pressure drops, and flow rates. These are specified to be identical to
 4154 that of E821.
- 4155 • Cool-down and warm-up procedure.

- 4156 • Connection to the Controls and Instrumentation WBS.

4157 The Fermilab Accelerator Division (AD) will provide two dedicated refrigeration system for
4158 E989. An important difference between E821 and E989 is that the latter will share aspects
4159 of the cryogenic plant with the Mu2e experiment[13]. Mu2e and g-2 helium gasses are mixed
4160 together, and therefore share a common compressor. The AD design includes a cryo adsorber
4161 to trap contamination.

4162 9.5.7 WBS 476.03.02.05 Super Conducting Coils

4163 After the steel yoke pieces and coils have been reinstalled into the correct position, the
4164 recommissioning activities can begin. The key recommissioning activities for this WBS
4165 consists of:

- 4166 • Performing electrical continuity tests of the instruments such as thermometers and
4167 strain gauges.
- 4168 • Performing electrical continuity tests on the coils. This also verifies unwanted thermal
4169 shorts.
- 4170 • Rewelding the coil interconnects using pure Aluminum filler using the TiG (Tungsten
4171 inert Gas) welding technique.
- 4172 • Rewelding the LHe and LN₂ cooling lines in the interconnection region.

4173 During the interconnect cutting and the TiG rewelding process, a small amount of degra-
4174 dation to the pure Aluminum stabilizer is to be expected due to work hardening. Work
4175 hardening will cause a resistance increase of the Aluminum, therefore adding to the heat
4176 load at 4.9K and a small local heating at the interconnection region.

4177 It also reduces the critical current capacity (I_c) before the superconductors become nor-
4178 mal. For the welding that took place during the E821 construction, the SC coil heating due
4179 to welding was modeled. The maximum temperature seen by the SC coils due to welding is
4180 350°C[3]. Degradation of NbTi critical current of < 5% was measured for a 2T field for an
4181 annealing time of 10s at 400°C[9].

4182 For E821, the coil current and temperature were approximately 5200 amps and 4.9K
4183 respectively. The magnetic field at the coil was approximately 2T. The critical temperature
4184 was estimated to be 6.2K, giving a safety margin of 1.2K[10]. However, the magnetic field
4185 at the interconnect is estimated to be < 1T, and so the safety margin at the interconnect is
4186 even greater.

4187 E821 also welded a test overlap joint, and measured a cold resistance of $16 \cdot 10^{-9}$ ohms
4188 at 2T. At the current of 5200 Amps, the heat load is 0.43 Watts at 4.9K, as compared to
4189 the heat load of 351W at 4.9K (see table 5 of reference [3]).

4190 In summary, the coils were designed with a rather large safety margin. No quenches were
4191 observed to have taken place at the interconnects. To be conservative, we will measure the
4192 resistance properties of an overlap weld, cut it and reweld, and remeasure the resistance
4193 properties. Finally, work hardening of the Aluminum is strongly anti-correlated with yield
4194 strength[14]. Therefore, room temperature tests can be performed to gauge the level of work
4195 hardening.

4196 9.6 ES&H, Quality Assurance, Value Management, Risks

4197 9.6.1 Yoke, Pole, and Shims

4198 The hazards will be in the stored mechanical energy of these very heavy items during the
4199 use of the crane during installation. While the magnet is powered, the super bolts will be
4200 stressed (stretched) to counteract the magnetic forces' tendency to close the pole gaps. The
4201 stored electro-mechanical energy is approximately 6 MJoules. The storage region magnetic
4202 field of 1.45T is also a hazard.

4203 Mitigation would be to train the collaboration in proper procedures, controlling access to
4204 the area, and implementing a mechanism for detecting high magnetic susceptibility materials
4205 so that they are kept away from the high field area.

4206 Quality assurance, value management, and risks concerns are minimal since these items
4207 have been built and worked to specifications for E821. They are also passive material and
4208 have high mechanical strength. Since considerable E989 machinery has already developed
4209 to model the magnetic field, temperature, we can simulate all alignment requirements.

4210 9.6.2 Power Supply and Quench Protection System

4211 Hazards

4212 The hazards during the testing processes will be primarily electrical. There will be an arc-
4213 flash hazard based on the incoming 480 VAC power feed and at 60-amperes. A complete hazard
4214 analysis can be made once the units are received and initially examined. The mitigations
4215 for these hazards are:

- 4216 • In the staging area, a safety disconnect switch will be used to provide emergency shut-
4217 off of power to the power supply.
- 4218 • No operation of any component will be done unattended. There will always be 2
4219 persons minimum present during any operation and testing.
- 4220 • Only properly trained persons, Electrical NFPA-70E and LOTO II at a minimum, will
4221 be allowed to work on the equipment.
- 4222 • Proper PPE and distances will be observed during operation and testing, especially
4223 during initial power up and during full-load operation. The level of PPE will be
4224 determined once the staging area is set up.

4225 Risks

4226 Risks to the successful completion of the tasks:

- 4227 • Use of Obsolete Components: Level-Medium. This risk involves the use of relatively
4228 old electronics. Therefore, component failure probability (based on hours of previous
4229 operation and power cycles, will need to be assessed for critical components of the
4230 power supply. Mitigation, at a minimum, will be to list these components and acquire

4231 spares in case of failure. To minimize the effect this risk will have on the schedule, the
4232 component list will be generated in parallel with the other operations. Initial costs will
4233 be incurred to acquire these spare components.

4234 • Catastrophic Failure During Testing: Level-Low to Medium. The units have operated
4235 before and they operated as initially designed. Therefore, testing of the components
4236 and of the units in stages should provide early indications of failure and allow replace-
4237 ment before the start of connection and commissioning.

4238 • Difficulty in Acquiring the Proper Testing Equipment: Level-Low. At this time, most
4239 equipment needed for testing, is, or should be, readily available on site. Therefore,
4240 purchases of new equipment will be at a minimum.

4241 • Catastrophic Failure During Commissioning: Level-Low. The risk here would be the
4242 most critical since failure of any component while connected to the ring coils would also
4243 present risk to the coils themselves. Mitigation here would be the exhaustive testing of
4244 components prior to connection to the ring and the powering up of the ring in stages
4245 of load and cooling. In addition, specific procedures for connection to the rings leads
4246 will be repeatedly and continuously reviewed.

4247 **Quality Assurance**

4248 The assurances that the units will operate as required are two-fold: First, the design is
4249 already done. Redesign should be at a minimum. Second, there will be exhaustive testing of
4250 each component prior to re-assembly. These testing procedures will be continuously reviewed
4251 during and after each stage of testing. Again, the primary process for all this is the initial
4252 examination followed by testing in stages as opposed to a one-time, massive final test. The
4253 staged testing allows deficiencies or problem areas to be identified at the earliest possible
4254 point in the task schedule. This again stresses the importance of the initial examination for
4255 the results of this will determine, in large part, the testing schedule.

4256 **Value Management**

4257 As much reuse of components will be implemented throughout these processes. Also, prelim-
4258 inary examination will serve to spot questionable components. Overall, the refurbishment
4259 process is used to minimize the need to purchase or redesign components and systems. Since
4260 the design is already done and it did operated as designed, the risk and extra effort in
4261 developing a new design can be kept to a minimum.

4262 **9.6.3 The Cryogenic and Related Systems**

4263 The hazards are related to the use of LHe and LN₂ cryogenics: thermal energy and ODH.
4264 As described above, if the cooling lines in the vacuum cryostat leak, there is potential for
4265 the ‘cold-cryostat’ scenario (see above). These can be mitigated in the same fashion as
4266 E821. The cooling lines and vacuum chambers can be pressure tested at room temperature,
4267 following delivery from BNL and prior to use.

4268 Quality assurance, value management are minimal since these items have been built and
4269 worked to specifications for E821. Should the items fail during recommissioning, they can
4270 be easily replaced since they are commercially available items of reasonable cost. These
4271 are vacuum parts and cryogenic lines. The only outstanding technical skills required are
4272 Aluminum welding and vacuum leak-testing.

4273 There are inherent risks in nearly all cryogenic systems since these are usually very com-
4274 plex and have long time scales. Even though E821 operated a successful system, significant
4275 engineering is required for recertification. A mitigating factor is that similar systems have
4276 been built at Fermilab, and is inline with the expertise of the project mechanical engineer.

4277 9.6.4 The Superconducting Coil System

4278 The coils system do not present a significant health hazard. Quality assurance and value
4279 management concerns are minimal since these items have been built and worked to specifi-
4280 cations for E821.

4281 The risks are not considerable. The risk of damage to the coils, straps, heat shields, glue
4282 joints are minimal since the stresses expected during transportation is at least 4x smaller than
4283 the maximum allowable stress. The expected stresses and deflections due to transportation
4284 have been simulated by FEA.

4285 However, we itemize them here since the replacement cost of the coils is beyond the scope
4286 of the project:

- 4287 • The coil windings are on the inside radial surface of the mandrel, rather than on the
4288 outside. During power up, the coils push against the mandrel, thereby enhancing the
4289 thermal cooling. Therefore, the system can tolerate failures of the glued interface,
4290 which is designed to enhance thermal conductivity.
- 4291 • Failure of the straps, though unexpected, can be detected as we slowly energize the
4292 coils. If a strap fails, it can be detected as a shift in the coil vertical position. It can
4293 be repaired by cutting an access hole in the vacuum cryostat. The downtime would be
4294 of order 2 weeks.
- 4295 • Failure in the heat shield can be detected as the system taking too long for cool down.
4296 Failure of the cooling lines can be detected as loss of vacuum. These are repaired via
4297 cutting access holes into the vacuum cryostat. However, it will be difficult to locate
4298 the point of failure.
- 4299 • There is a very slight risk of the Aluminum resistance at the interconnection becomes
4300 too high during the reweld. We will prototype the rewelding process and study the
4301 correlation of resistance with yield strength. We can anneal the interconnection to
4302 improve the resistance.

References

4303

- 4304 [1] Bailey J, et al. Nucl. Phys. B150:1 (1979).
- 4305 [2] Bennett GW, et al.(The Muon ($g - 2$) Collaboration) Phys. Rev. D, 73:072003 (2006).
- 4306 [3] G.T. Danby, et al., Nucl. Inst and Meth. **A 457**, 151 (2001).
- 4307 [4] Reference Manual for teh POISSON/SUPERFISH group of codes, LANL, LA-UR-87-
4308 126.
- 4309 [5] Design Report, BNL E821, A New Precision Measurement of the Muon ($g - 2$) Value at
4310 the level of 0.35 ppm. 3rd edition, D.H. Brown et al. B.L. Roberts Editor, March 1995.
- 4311 [6] A. Yamamoto, H. Inoue, H. Hirabayashi, J. Phys. 45 (1984) C1-337.
- 4312 [7] A. Yamamoto, private communication.
- 4313 [8] M.A. Green et al., Operation of a two-phase cooling system on a large superconduct-
4314 ing magnet, Proceeding of the Eighth International Cryogenic Engineering Conference,
4315 Genoa, Italy, June 1980, IPC Science and Technology Press, 1980, p. 72.
- 4316 [9] Th. Schneider and P. Turowski, Thirteenth International Conference on Magnet Tech-
4317 nology, Victoria, Canada, September 1993, Paper R-J-07.
- 4318 [10] Bill Morse, Characteristic of the E821 Interconnects, GM2-doc-302-v1.
- 4319 [11] Bill Morse, Coil Resistance to Ground Measurements, GM2-doc-352-v1.
- 4320 [12] Bill Morse, Coil Resistance to Ground Measurements, GM2-doc-976-v1.
- 4321 [13] Del Allspach, Vacuum and Cryogenics Presentation at g-2 December 2012 Collaboration
4322 Meeting, GM2-doc-615-v1.
- 4323 [14] T. Tonogi et. al., Aluminum Stabilized Superconductor for the Atlas Central Solenoid
4324 Magnet, Hitachi Cable Review No. 18, V87.

Chapter 10

The Superconducting Inflector Magnet

In this chapter we first introduce the E821 inflector magnet, which is our baseline starting option. We then describe the shortcomings of this magnet, as well as the characteristics and the benefits that an improved inflector would have. Any new design will require significant R&D and opera simulations to arrive at a new inflector design.

10.1 Introduction to the Inflection Challenges

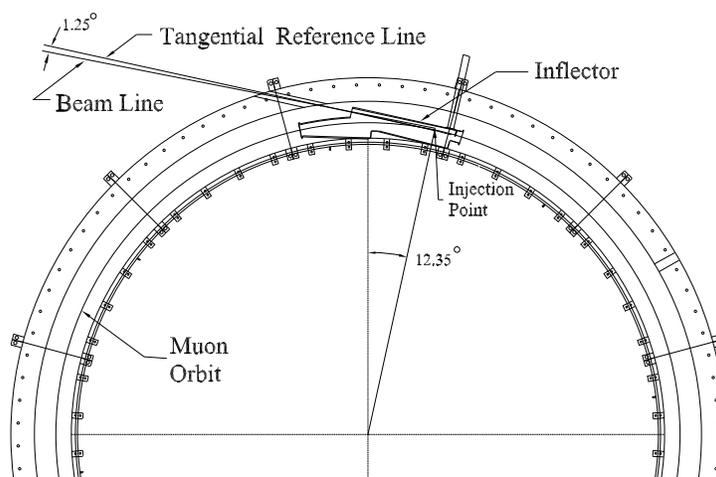


Figure 10.1: Plan view of the beam entering the storage ring.

The usual storage ring is composed of lumped beamline elements such as dipoles, quadrupoles, sextapoles, etc., which leaves space for injection, extraction, and other beam manipulation devices. For the measurement of a_μ , the requirement of ± 1 ppm uniformity on the magnetic field, which in E821 must be known to $\leq \pm 0.07$ ppm, prohibits this usual design. Instead, as described in Chapter 9 the $(g - 2)$ storage ring is designed as a monolithic magnet with

no end effects. The “C”-magnet construction shown in Fig 9.1 presents several obstacles to transporting a beam into the storage ring: There must be holes through the back-leg of the magnet and through the outer coil cryostat and mandrel for the beam to enter the experiment. These holes must come through at an angle, rather than radially, which complicates the design, especially of the outer-coil cryostat.

A plan view of the beam path entering the storage ring is given in Fig. 10.1. Since the beam enters through the fringe field of the magnet, and then into the main 1.5 T field, it will be strongly deflected unless some magnetic device is present that cancels this field. This device is called the inflector magnet.

The injection beam line is set to a 1.25° angle from the tangential reference line (Fig. 10.1). The inflector is aligned along this reference line and its downstream end is positioned at the injection point. The point where the reference line is tangent to the storage ring circumference is 77 mm radially from the muon central orbit. The main magnet fringe field, upstream of the inflector, bends the incoming beam by about 1.25° , so that the beam enters the inflector nearly parallel to the inflector axis.

The requirements on the inflector magnet are very restrictive:

1. To a good approximation it should null the storage ring field such that the muons are not deflected by the main 1.5 T field.
2. It should be a static device *to prevent time-varying magnetic fields correlated with injection*, which could affect $\int \vec{B} \cdot d\vec{\ell}$ seen by the stored muons and produce an “early to late” systematic effect.
3. It cannot “leak” magnetic flux into the precision shimmed storage-ring field that affects $\int \vec{B} \cdot d\vec{\ell}$ at the sub-ppm level.
4. It cannot contain any ferromagnetic material, which would distort the uniform magnetic field.
5. The inflector angle in the cryostat should be variable over the full range permitted by the constraints of the space available.

10.2 The E821 Inflector Design and Operation

Three possible solutions were considered in E821: A pulsed inflector, a superconducting flux exclusion tube, and a modified double $\cos\theta$ magnet. The pulsed inflector proved to be technically impossible at the repetition rate necessary at BNL. Furthermore it violates item 2 above. Naively one could imagine that a superconducting flux exclusion tube would work for this application. However, an examination of Fig. 10.2 shows that in the vicinity of the tube, the magnetic field is perturbed on the order of 10%, or 100,000 ppm [1], an unacceptable level. Attempts to figure out how to mitigate this problem were unsuccessful. This is because the large eddy currents needed to shield the 1.45 T field are large enough to affect the uniformity of the field seen by the muons contained in the red semicircle. However, this principle will re-appear in the discussion of how to shield the 200 G (20 mT) residual magnetic field from the truncated double $\cos\theta$ design employed in the E821 inflector. The properties of the E821 Inflector are summarized in Table 10.1

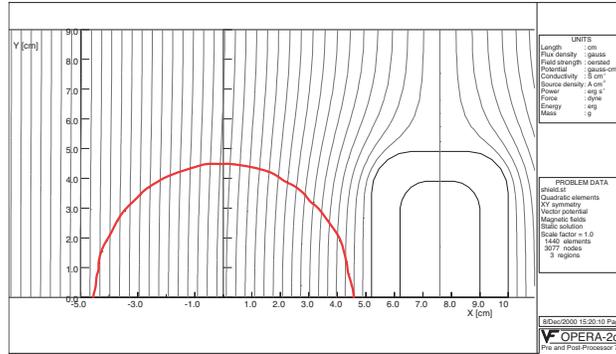


Figure 10.2: The calculated magnetic field outside of a superconducting flux exclusion tube placed in a 1.45 T magnetic field. The red circle is the muon beam storage region. (From Ref. [1])

Table 10.1: Properties of the inflector superconductor.

Overall dimension	110(W)× 150(W)×2025(L) mm ³
Magnetic length	1700 mm
Beam aperture	18 mm (W) × 56 mm (H)
Design current	2850 A (with 1.45 T main field)
Number of turns	88
Channel field	1.5 T (without main field)
Peak field	3.5 T (at design current, with main dipole field)
Inductance	2.0 mH
Resistance	1.4 Ω (at 300 K)
Cold mass	60 kg
Stored energy	9 kJ (at design current)

Table 10.2: Properties of the inflector superconductor.

Configuration (NbTi:Cu:Al)	1:0.9:3.7
Stabilizer	Al (99.997% RRR = 750)
Process	Co-extrusion
NbTi/Cu composite	Diameter 1.6 mm monolith
NbTi filament	Diameter 0.02 mm
Number of filaments	3050
Twist pitch	31 mm
Conductor dimension	2 × 3 mm ²
Insulated conductor dimension	2.3 × 3.3 mm ²

4378 10.2.1 Magnetic Design of the E821 Inflector

4379 Only the double $\cos\theta$ design[2] satisfied the three criteria listed above. The double $\cos\theta$
 4380 design has two concentric $\cos\theta$ magnets with equal and opposite currents, which outside has
 4381 negligible field from Ampère’s law. A double $\cos\theta$ design provides a 1.5 T field close to the
 4382 storage region, and traps its own fringe field, with a small residual fringe field remaining.
 4383 However, what is needed for the $(g - 2)$ beam channel is a septum magnet. This is achieved
 4384 by truncating the two $\cos\theta$ distributions along a line of constant vector potential A [2]. The
 4385 truncation method is shown in Fig. 10.3, taken from Ref. [2], which should be consulted for
 4386 additional details.

4387 Aluminum-stabilized superconductor was chosen for the BNL $(g - 2)$ inflector: (a) to
 4388 minimize the interactions of the incoming pion/muon beam at both upstream and down-
 4389 stream ends of the coil with no open apertures for the beam, and (b) to make the coils and
 4390 cryostat design compact, so that the conductive cooling (without liquid helium containers
 4391 surrounding the coils) can be achieved effectively. An existing Al-stabilized superconductor
 4392 was supplied by Japan KEK (fabricated by Furukawa Co.). This conductor was developed
 4393 for ASTROMAG (Particle Astrophysics Magnet Facility) [3, 4]. Fig. 10.4 shows the cross-

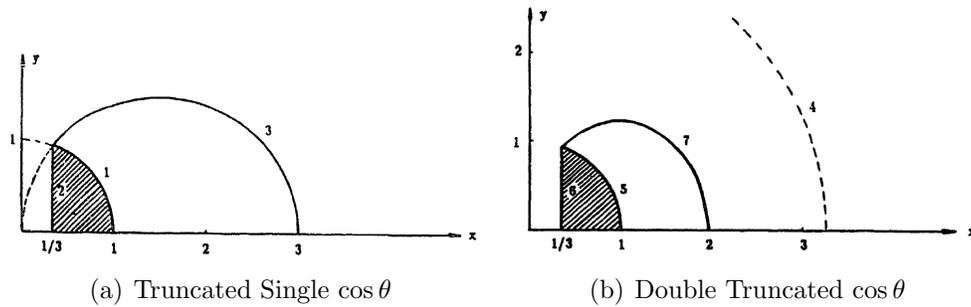
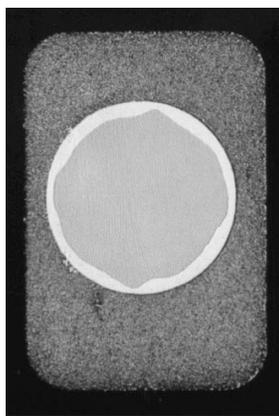
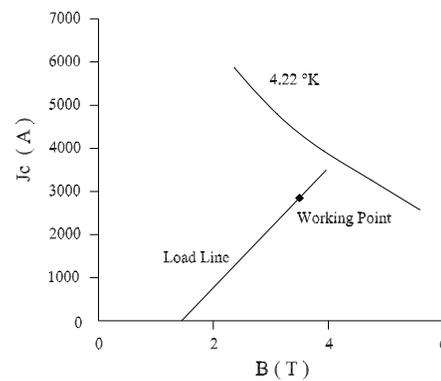


Figure 10.3: (a) The principle of the truncated single $\cos \theta$ magnet. (b) The principle of the truncated double $\cos \theta$ magnet.



(a) SC cross-section



(b) Inflector Load Line

Figure 10.4: (a) The inflector superconductor cross-section. (b) Superconductor characteristics and the inflector load line in the environment of 1.45 T magnetic field.

4394 section of this conductor. The basic parameters are listed in Table 10.2. From computer
 4395 calculations, the peak field seen by the by the inflector conductor filaments reaches 3.5 T; if
 4396 the self-field effect [5] is taken into account. This is due to the superposition of the return
 4397 flux and the main field. Short sample tests showed that the critical current of this super-
 4398 conductor is about 3890 A at 4.6 K and 3.5 T. In the ($g - 2$) storage ring, the inflector sees
 4399 1.45 T field (from the main magnet) even at zero operating current. From the conductor
 4400 characteristics, the inflector operates at around 73% of the full load (at 4.6 K). The short
 4401 sample test data and the inflector load line (in the storage ring field environment) are shown
 4402 in Fig. 10.4(b).

4403 The result is a magnet with conductors arranged as shown in Fig. 10.5(a). The conductors
 4404 are connected in series, with an equal number with current into and out of the page. In
 4405 Fig. 10.5(a) the current is flowing out of the page in the backward “D” shaped pattern of
 4406 conductors, and into the page in the “C” shaped arrangement of conductors. The field from

4407 the inflector magnet is vertical up in the beam channel and downward in the return area,
 4408 as shown in Fig 10.5(a). With the main storage ring field vertical, there is no field in the
 4409 beam channel and $\simeq 3$ T field in the return area. With this design and the ASTROMAG
 4410 conductor, it is difficult to open up the beam channel very much because moving the “C”
 4411 arrangement of conductors to the left would quickly exceed their critical current.

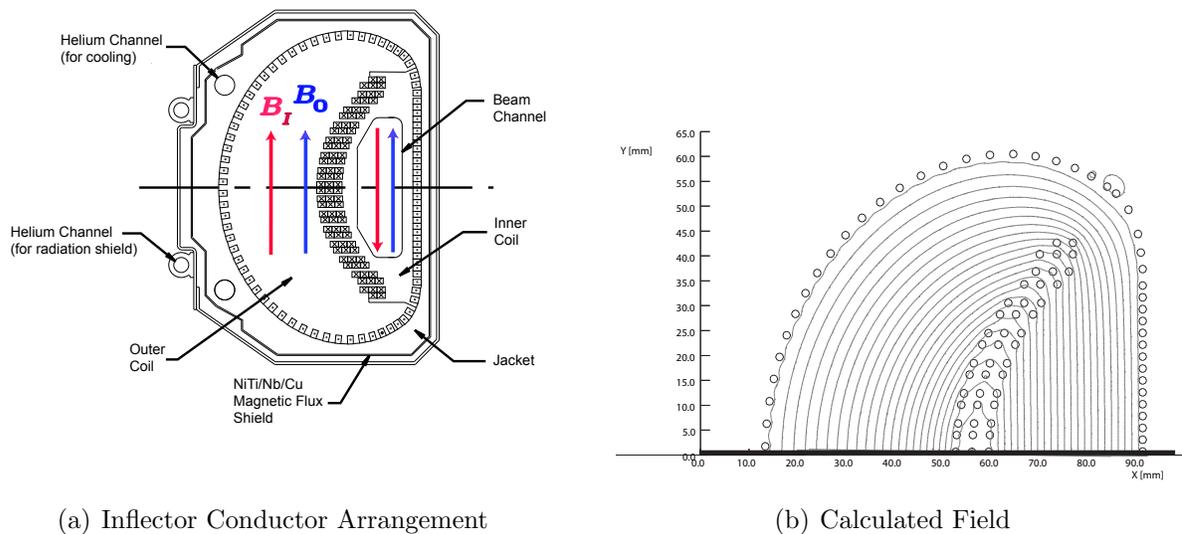


Figure 10.5: (a) The arrangement of conductors in the inflector magnet, showing the direction of the inflector field B_I and the main field B_0 for a beam of positive muons going into the page. The current in the inner “C” is into the page and is out of the page in the backward “D”. (b) The magnetic field generated by this arrangement of conductors. The beam aperture is $18 \times 56 \text{ mm}^2$.

4412 There are two sources of magnetic flux that from the inflector that can leak into the
 4413 storage region. Because the field is produced by discrete conductors, rather than a contin-
 4414 uous current distribution, some flux does leak out of this arrangement of conductors, see
 4415 Fig. 10.5(b). The inflector lead configuration is also important, and when it was necessary
 4416 to produce a second inflector, the lead configuration was changed to reduce this effect.

4417 The coil was wound in two different pieces indicated by “inner” and “outer” coils in
 4418 Fig. 10.5(a). One end of the coil is shown in Fig. 10.6(a) The choice was made to wind the
 4419 coil over the beam channel, because this configuration would have less flux leakage, and was
 4420 thought to be more stable from quenches. However, a 0.5 m prototype was constructed with
 4421 one open and one closed end, which are shown in Fig. 10.6. This prototype inflector was
 4422 operated in the earth’s field, and then in an external 1.45 T field without incident.

4423 The inner coil and the outer coil are connected in series. The joint is located inside the
 4424 downstream end of the coils; and is made by soldering the superconductors without removing
 4425 the aluminum stabilizer. The joined leads were placed inside a U-shaped groove, as shown
 4426 in Fig. 10, attached to the coil end structure. Cooling tubes run through the extender

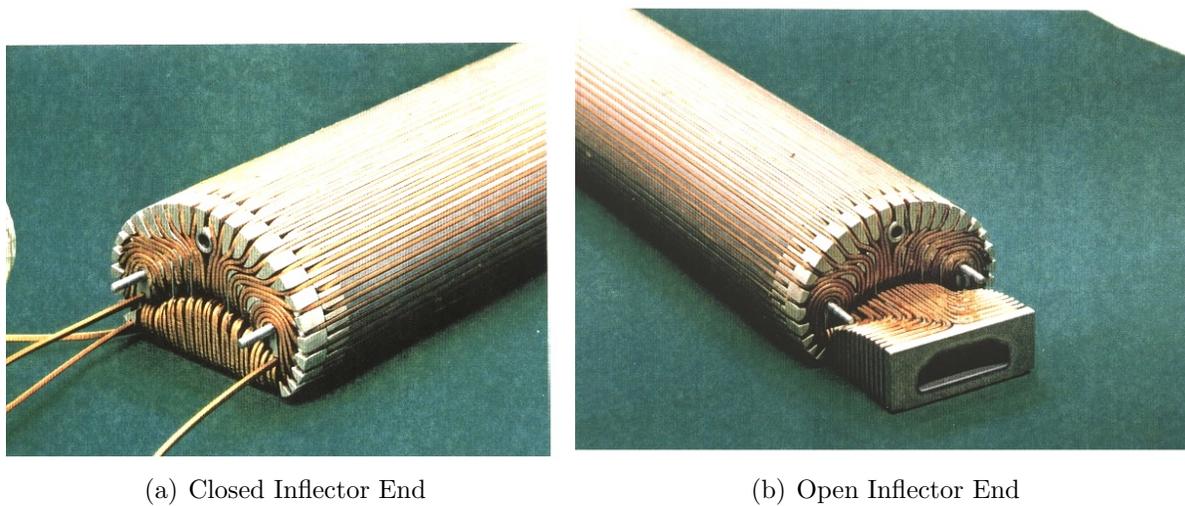


Figure 10.6: (a) The prototype closed inflector end. (b) The prototype open inflector end.

4427 (aluminum block). One temperature sensor was mounted near the joint to monitor the local
4428 ohmic heating.

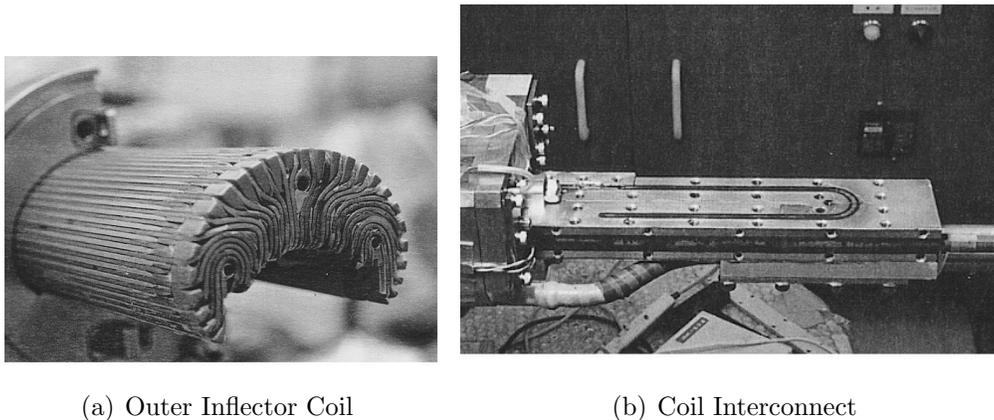


Figure 10.7: (a) The arrangement of conductors in the inflector magnet. (b) The joint and lead holder for the interconnect.

4429 The geometry of the inflector cryostat is complicated by the proximity of the outer-coil
4430 cryostat, the pole pieces and the muon beam. A sketch of the beam path through the outer
4431 coil is shown in Fig. 10.8(a). The complicated arrangement where the inflector entrance
4432 nests into the concave wall of the inflector cryostat is shown in Fig. 10.8(b). Fig. 10.9 shows
4433 the combined inflector cryostat and beam vacuum chamber. The cryostat region and beam
4434 region have different vacuums, so the inflector can be cooled, independent of whether the
4435 beam vacuum chamber is evacuated or not.

4436 The exit of the inflector magnet is shown in Fig. 10.10, which clearly indicates the accel-
4437 erator physics issue. The incident beam is contained in the red 18 mm \times 56 mm “D”-shaped

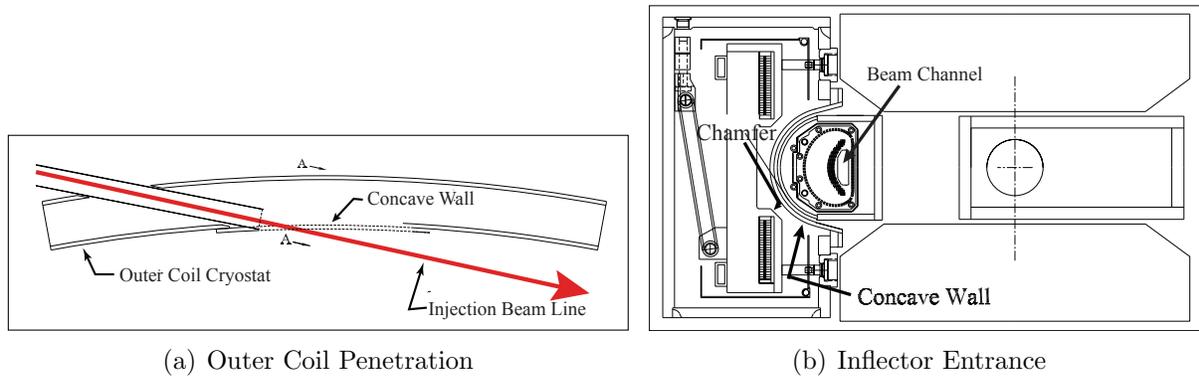


Figure 10.8: (a) A plan view of the beam penetration through the outer coil and cryostat. (b) An elevation view of the inflector entrance showing the concave wall of the outer-coil cryostat where the beam exits the outer coil-cryostat.

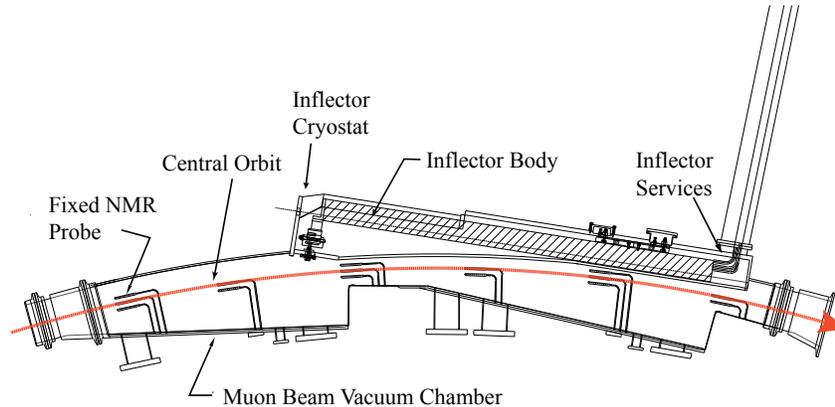


Figure 10.9: Plan view of the combined inflector cryostat-beam vacuum chamber arrangement. The inflector services (power, LHe and sensor wires) go through a radial hole in the back-leg outside of the storage-ring magnet. The NMR fixed probes are in grooves on the outside of the vacuum chambers, above and below the storage region. The red arrow shows the muon beam central orbit.

4438 channel, while the stored beam is confined to a 45 mm diameter circular aperture. Thus it
 4439 it impossible to match the β or α functions between the ring and the muon beamline. The
 4440 the result is a “ β wave” that causes muon losses after the beam is injected.

4441 10.2.2 Shielding the residual fringe field

4442 At the design current, the maximal fringe field within the muon storage region was calculated
 4443 to be about 200 G (1.4%) near the outer edge. The fringe field behaves in such a way that
 4444 it is a rapidly varying function along the transverse direction, i.e. the radial direction of the

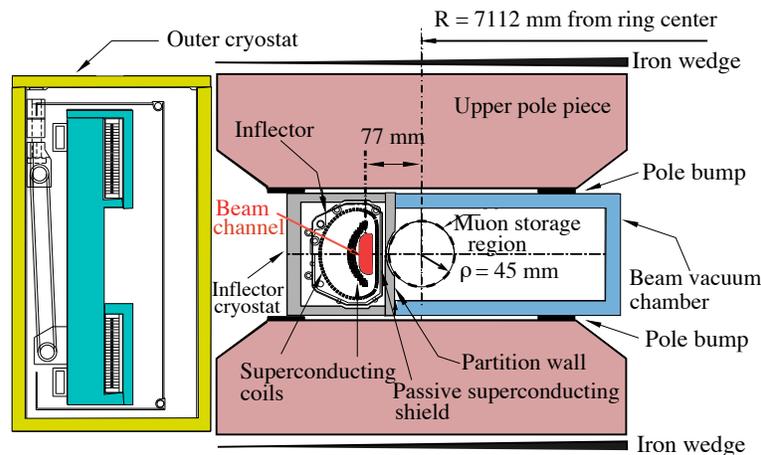


Figure 10.10: The inflector exit showing the incident beam center 77 mm from the center of the storage region. The incident muon beam channel is highlighted in red. (Modified from Fig. 9.6)

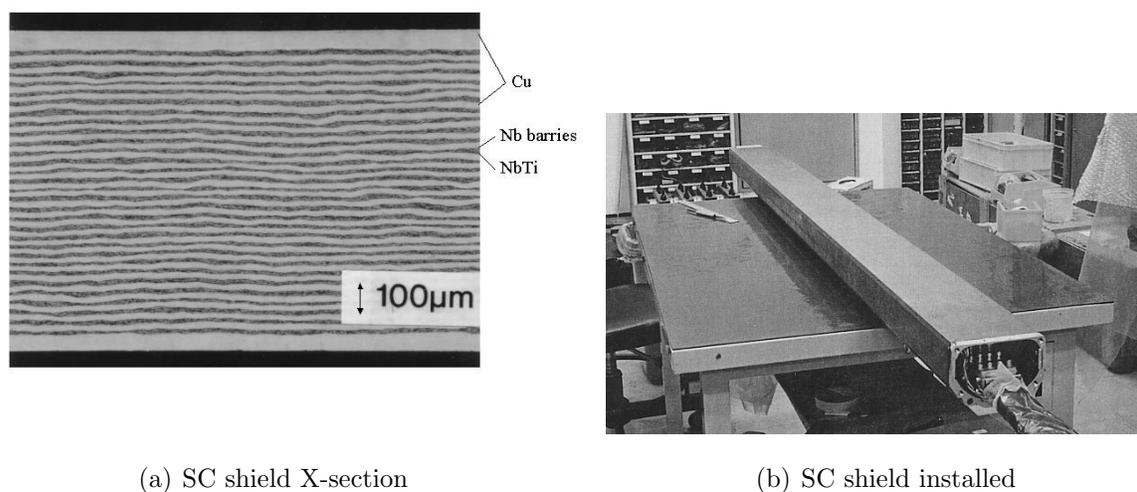
4445 storage ring, and essentially gives a negative disturbance. The fringe field of the inflector
 4446 is opposite to the main field at the outer radius of the storage ring, and changes sign while
 4447 crossing the central orbit.

4448 The consequence of such a fringe field is severe. The high gradient of the field would be
 4449 beyond the working range of the NMR probes, so that the magnetic field map of the storage
 4450 region would be incomplete, directly impacting the error of the measurement precision of
 4451 the muon magnetic moment.

4452 Conventional magneto-static shimming studies to reduce this fringe field using computer
 4453 simulations were carried out. The iron compensation must be located outside the muon
 4454 storage region. Its contribution to the central field will be a slowly varying function in this
 4455 space, which is not able to cancel the larger gradient fringe field to an acceptable level [10].
 4456 The best way to eliminate a multipole fringe field is to create an opposite multipole current
 4457 source with the same magnitude. The best such current source is the super-current generated
 4458 inside a superconducting material due to the variation of the surrounding field. A method
 4459 of using SC material to shield the inflector residual fringe field was studied and developed.
 4460 The fringe field specification was then satisfied.

4461 A test sheet of a superconducting shield was developed that contained 30 layers NbTi, 60
 4462 layers Nb, and 31 layers Cu. The Cu layers greatly improved the dynamic stability against
 4463 flux jumping [7]. The Nb layers act as barriers, which prevent the diffusion of Ti into Cu. The
 4464 diffusion could form hard inter-metallic layers and create difficulties for the rolling process.
 4465 Fig. 10.11 shows the typical cross section of the sheet. Based on successful tests, Nippon
 4466 Steel Corp. developed large, thin pieces of sheet especially for the $(g - 2)$ inflector, to cover
 4467 its $2 \times 0.5 \text{ m}^2$ surface and to fit into the limited space between the storage region and main
 4468 magnet coil. The shielding result was extremely satisfactory.

4469 The steps in using the shield are as follows:



(a) SC shield X-section

(b) SC shield installed

Figure 10.11: (a) Cross section of the multi-layer superconducting shield sheet. (b) The superconducting shield installed around the body of the inflector.

- 4470 1. With the inflector warm (~ 20 K) the storage ring magnet is powered and allowed to
4471 reach equilibrium.
- 4472 2. The inflector is then cooled to superconducting. The shield material is a Type-II super
4473 conductor, where $H_{C1} = 0.009$ T for NbTi is the maximum field for the Meissner effect
4474 to occur. Therefore, as it is cooled down to the superconducting state, the shield is
4475 not able to expel the external field. Rather, the external field will fully penetrate the
4476 shield. and the shield traps the main field
- 4477 3. The inflector is then powered. In this superconducting state, the shield will exhibit
4478 perfect diamagnetism, and will resist any change in the flux penetration through its
4479 surface.

4480 10.2.3 Performance of the E821 Inflector

4481 Two full-size inflectors were produced. To emphasize the importance of the superconducting
4482 shield, we relate what happened when the shield on the first inflector was damaged. In
4483 the testing of the first inflector, an accident occurred, where the interconnect shown in
4484 Fig. 10.7(b) was melted, leaving a few centimeters of undamaged cable outside of the inflector
4485 body. In order to repair it, the superconducting shield was cut to give access to the damaged
4486 superconductor. After the repair, an attempt was made to apply a patch to the shield.
4487 Unfortunately this attempt was not completely successful. The resulting fringe field reduced
4488 the storage-ring field by 600 ppm (8.7 G) over a 1° azimuthal angle, resulting in unacceptable
4489 magnetic-field gradients for the NMR trolley probes closest to the inflector body. It was also
4490 realized that a significant fringe field came from the inflector leads. An average field map
4491 from the 1999 run using the damaged inflector, and from the 2001 run using the new inflector

4492 are shown in Fig. 10.12. The field in the region with large gradients had to be mapped by
 4493 a special procedure following data taking. This large fringe field introduced an additional
 4494 uncertainty into the average field of ± 0.20 ppm in the result [12]. While this additional
 4495 error in the 1999 result, which had a 1.3 ppm total error, it would have been completely
 4496 unacceptable for the subsequent runs.

4497 The damaged inflector was replaced in mid 1999, well before the 2000 running period.
 4498 Two modifications were made to the new inflector design: The superconducting shield was
 4499 extended further beyond the downstream end; The lead geometry was changed to reduce
 4500 the fringe field due to the inflector leads. Both of these improvements were essential to the
 4501 excellent shielding obtained from the second inflector. For both the 2000 and 2001 running
 4502 periods, the fringe field of the inflector was immeasurably small [15, 16].

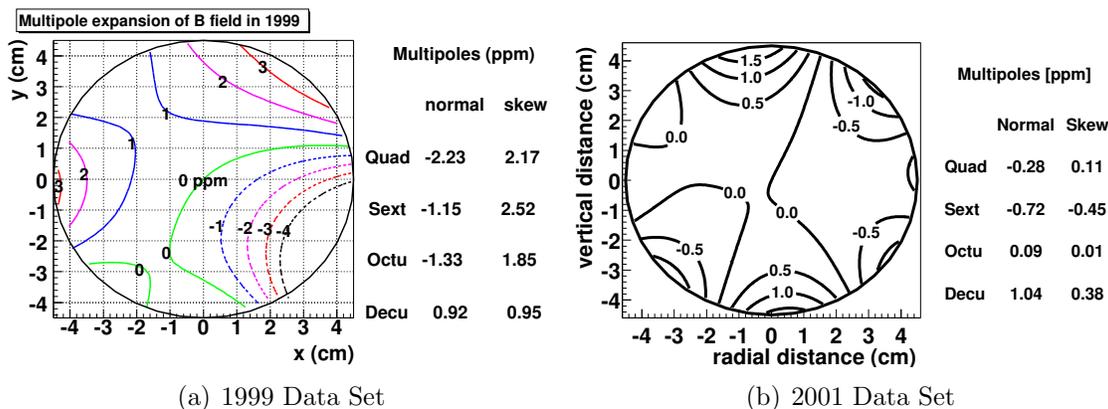


Figure 10.12: The average magnetic field $\langle B \rangle_{azimuth}$ (a) with the damaged inflector (1 ppm contours) (b) and with the second inflector (0.5 ppm contours). Note that the large disturbance in the average field was from a 600 ppm disturbance in the field over 1° in azimuth.

4503 10.3 Lessons for E989 from the E821 Inflector

4504 The most important single lesson from the E821 inflector came from the flux leakage from
 4505 the damaged inflector, and the realization that the first design of the inflector leads also con-
 4506 tributed to this problem (see Fig.10.12). The ± 0.2 ppm systematic error from this problem
 4507 is three times the E989 magnetic field error budget of ± 0.07 ppm. The highly localized 600
 4508 ppm perturbation at the location of the “repaired” superconducting shield simply could not
 4509 be shimmed away. The second issue that must be addressed is the mismatch in the E821
 4510 inflector aperture and the storage ring’s. The third issue is to open the ends, and to open
 4511 the size of the beam channel.

4512 The guiding principles going forward are:

- 4513 • *The flux inside of the inflector must be confined inside of the inflector and not permitted*
 4514 *to leak into the storage region.*

- 4515 • *Any new inflector design must have a horizontal (radial) aperture significantly larger*
4516 *than 18 mm; as close to 40 mm as possible.*
- 4517 • *The ends of the inflector need to be open, rather than have coil windings across them.*

4518 The latter two conditions could increase the number of stored muons by almost a factor of
4519 four.

4520 The muon injection efficiency achieved in E821 was around 2%. Early simulations pre-
4521 dicted that it should be 5 - 7%. Opening the ends of the inflector would have doubled the
4522 number of stored muons. So it becomes clear that a new open-ended inflector with a larger
4523 aperture, perhaps as large as 30 to 40 mm diameter, is desirable and possible. Given the
4524 time that will be needed to develop a new inflector, it is impractical to have a new inflector
4525 ready by mid-2015 when the shimming program would be ready to install vacuum chambers
4526 and the inflector.

4527 Going forward, we need: (i) To open both ends of the inflector; (i) A larger aperture than
4528 the E821 inflector; Careful lead design to minimize stray field; A passive superconducting
4529 shield that prevents flux leaking from the inflector into the precision magnetic field.

4530 10.4 A New Inflector

4531 Several concepts have been considered to replace the existing inflector. Any new design is
4532 constrained by the injection geometry shown in Figs. 10.1, 10.8 10.9 and 10.10. A passive
4533 superconducting shield to remove any leakage flux from the new inflector will be essential.

4534 The small aperture of the E821 inflector, and the coil windings over the beam channel
4535 make matching the beamline to the storage ring impossible. While it worked well enough in
4536 E821 to reach ± 0.54 ppm, and there would have been no issues in reaching the ± 0.35 ppm
4537 goal, had the running at BNL not been terminated. Since E989 plans to accumulate 21 times
4538 the data of E821, it is necessary to revisit the inflector aperture issue. Opening the radial
4539 aperture to a 3 - 4 cm would come close to matching with the incoming beam, and permit
4540 many more muons to be stored. The trade-off is as the aperture gets larger, a larger kick will
4541 be needed to place the beam on orbit. Shielding a large open end will also be challenging.

4542 In E989 the knowledge of the average magnetic field needs to be improved by a factor of
4543 three over E821. While the plan to improve the magnetic field measurement and control is
4544 discussed in Chapter 15, this plan is meaningless if any device in the experiment spoils the
4545 field by introducing extraneous magnetic flux into the storage region. The damaged inflector
4546 in E821 demonstrated how a 0.2 ppm problem can easily be introduced.

4547 Two possible suggestions have been proposed for a new inflector:

- 4548 • A double coil structure that is either the double-cosine θ design, or another double
4549 magnet that cancels the storage ring field.
- 4550 • An elliptical double dipole magnet

4551 Any of the powered magnet solutions would need a passive superconducting shield that
4552 traps whatever flux might leak from the magnets, preventing this leakage flux from changing
4553 the magnetic field seen by the muons while they are stored in the ring.

4554 10.4.1 A New Double Cosine Theta Magnet

4555 This option needs study. The truncated double cosine theta design encased in a multi-layer
 4556 superconducting shield worked well in E821, albeit with the limitations discussed above.
 4557 Certainly any new design must have open ends, since the multiple scattering makes it im-
 4558 possible to correctly match the incoming beam to the ring. The open ends will certainly
 4559 produce issues for shielding the fringe field, which are common to the other wound magnets
 4560 discussed below.

4561 Fortunately our UK colleagues at the Rutherford-Appleton Laboratory (RAL) have sug-
 4562 gested studying how to make such a double-cosine theta magnet using modern supercon-
 4563 ductor, with an increased aperture. A target would be going from the $18 \times 56 \text{ mm}^2$ E821
 4564 aperture to $40 \times 56 \text{ mm}^2$.

4565 10.4.2 Double magnet, using the serpentine winding technique

4566 Brett Parker at Brookhaven has developed a new technique to wind superconducting mag-
 4567 nets, using CNC techniques [17], which permits multi-layer coils of rather complicated current
 4568 distributions to be fabricated. An example of a quadrupole magnet is shown in Fig. 10.13.
 4569 A visit to his lab at BNL was very informative, and he has confirmed that he could wind
 4570 elliptical dipoles, as well as circular ones.



Figure 10.13: Coil for a superconducting quadrupole

4571 An examination of Fig. 10.10 shows the problems. A circular cross section moves the
 4572 beam center further away from the center of the storage region, thus requiring a much
 4573 stronger kick. An elliptical cross section would significantly open the beam aperture, permit
 4574 a larger vertical aperture, while reducing the extra kick needed to store the beam. the cross
 4575 section of such a coil is shown in Fig. 10.14. Parker says that to achieve the fields needed in
 4576 E989, it would be necessary to have four layers. There would also have to be the canceling
 4577 magnet outside, and a superconducting shield to remove any residual flux.

4578 10.4.3 Inflector Superconducting Passive Shield

4579 While the exact fringe field will be modeled by computer simulations, and made as small
 4580 as practically possible, our baseline goal for the shield is that it should be able to cancel a
 4581 fringe field $< 1 \text{ kG}$ ($H_{MAX} = 1000 \text{ Oersted}$).

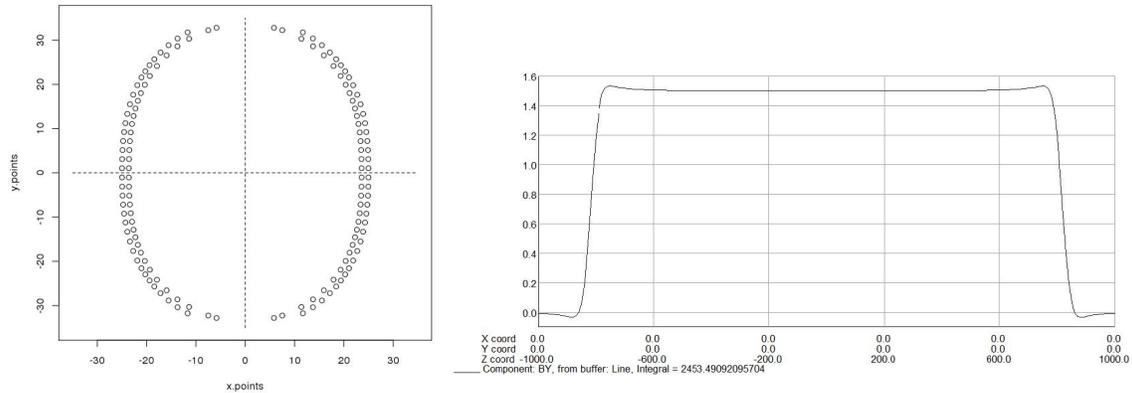


Figure 10.14: (a) An elliptical coil arrangement. (b) The calculated longitudinal magnetic field from this coil arrangement.

4582 The shield will surround the inflector coils. The shield should be as large and as long
 4583 as possible, while still fitting within the inflector cryostat. The open end of a new inflector
 4584 will present additional challenges for the shield, and will need to be studied in simulations.
 4585 From this constraint, the shield diameter will be approximately 12 cm. It extends 26 cm
 4586 downstream of the inflector coils. Upstream, it is flush with the coils due to space limitations.

4587 We have several options for shield material supply: (1) reuse the shield from existing
 4588 working shield, (2) reuse the shield from spare (but broken) inflector, and (3) contact industry
 4589 to fabricate a new shield.

4590 Option (1) is not preferred, since we need to preserve a working inflector. Option (2) is
 4591 possibility. The shield was epoxied to the inflector mandrel. We should be able to melt the
 4592 epoxy to remove the shield.

4593 For option (3), we have contacted and are in discussion with MTI Metal Technology[20]
 4594 and ATI Wah Chang[21]. We have not been able to contact Nippon Steel, the original maker
 4595 of the shield.

4596 In principle, a shield can be fabricated from smaller overlapping pieces. However, care
 4597 must be taken to provide sufficient cooling. We should prototype, test, and verify that the
 4598 overlapping region functions properly as a shield. Given the issues with the attempt to repair
 4599 the damaged shield on the original inflector, overlapping shields, rather than one continuous
 4600 one, is by no means a viable option.

4601 10.5 Muon Storage Simulations Using a New Inflector

4602 Several aspects of a new superconducting inflector magnet are simulated to study their
 4603 impact on the fraction of muons transmitted into the storage region. The options studied
 4604 are the following with the E821 setting shown in parentheses: *a*) open-end vs closed-end
 4605 (E821) geometry, *b*) 30 or 40 mm vs 18 mm (E821) horizontal aperture, *c*) sensitivity to
 4606 beam phase-space matching. Results of the simulation are presented as improvement factors
 4607 defined as the fraction of stored muons with the new inflector divided by the baseline E281

4608 inflector. The baseline E821 storage rate is also presented. Assuming all improvements add
 4609 coherently, a new open-ended inflector with a 40 mm horizontal aperture is expected to
 4610 increase the fraction of stored muons by **X.Y** compared to the E821 inflector.

4611 10.5.1 E821 Inflector Simulation

4612 The E821 inflector magnet is simulated using a GEANT4-based software, which allows parti-
 4613 cle tracking beginning at the inflector and into the storage region. Within this framework, the
 4614 closed ends of the inflector are constructed using distinct volumes of aluminum (1.58 mm),
 4615 copper (0.39 mm), and niobium-titanium (0.43 mm). An additional 4 mm of aluminum is
 4616 added to each end to model the window, flange, and cryostat. Between the end-caps, a
 4617 “D”-shaped vacuum beam channel is constructed to approximate the double cosine theta
 4618 geometry. The magnetic field within the beam channel is the vector sum of the main magnet
 4619 fringe field and the 1.45 T field ($\int \vec{B} \cdot d\vec{\ell} = 2.55 \text{ Tm}$) produced by the inflector magnet leading
 4620 to a net cancellation of the impulse caused by the main magnetic field.

4621 The E821 muon beam is simulated by uniformly populated a phase space ellipse bounded
 4622 such that the area defined as $A = \varepsilon \times \pi = 40\pi$, where ε is the beam emittance. The phase
 4623 space axes are determined by the beam TWISS parameters, α and β in both horizontal (x)
 4624 and vertical (y) directions. The nominal TWISS parameters are determined by maximizing
 4625 the transmission rate through the inflector and shown in Table 10.3 when the beam is
 4626 localized at the “downstream”-end of the inflector (*i.e.* nearest to the ring). The beam
 4627 momentum, $|P|$, is generated by sampling a Gaussian distribution with mean equal to the
 4628 magic momentum P_m and width $\delta P/P = 0.5\%$. The longitudinal width of the beam, or
 4629 equivalently, the width in time is 25 ns. The orientation of the inflector angle with respect
 4630 to the ring tangent was set to -3 mrad to optimize transmission. These settings approximate
 4631 those of the 1997 E821 run at BNL.

Table 10.3: Nominal muon beam Twiss parameters.

Direction	Emittance (ε)	α	β
Horizontal (x)	40	-0.544	2.03
Vertical (y)	40	-0.0434	19.6

4632 All muons passing into the storage region are given a “perfect kick” to place them onto
 4633 a stable orbit. This kick is modeled by applying a 220 Gauss magnetic field throughout the
 4634 kicker volume for the first revolution. Finally, the storage rate is defined as the fraction of
 4635 muons surviving 100 revolutions around the storage ring. No muons are allowed to decay in
 4636 this simulation.

4637 10.5.2 Open-ended vs. Closed-ended Inflector Geometry

4638 The E821 inflector magnet was constructed with a closed end (*i.e.* the superconducting coils
 4639 wrapped around the end of the magnet) because this greatly reduced magnetic flux leakage

4640 into the muon storage region. The impact of the closed end on the horizontal and vertical
 4641 emittance was studied analytically and with the **GEANT** tracking software. In the analytic
 4642 approach, the fraction of muons traversing the inflector ends is studied by comparing the
 4643 horizontal and vertical beam widths (σ_x, σ_y) after multiple scattering in the material. In
 4644 this study, a beam filling the horizontal aperture of 18 mm grows to a size of ≈ 35 mm,
 4645 suggesting that approximately half ($18/35 = 51\%$) of the beam will fail to exit the inflector
 4646 aperture. Of course, with two closed ends the net effect is to lose between 50 – 75% of the
 4647 incoming beam.

4648 The tracking simulation approach removes the end coils, flange, and window from the
 4649 **GEANT** inflector material without altering the magnetic fields. Table 10.4 summarizes the
 4650 muon storage rates assuming an open and a closed inflector magnet. The beam parameters
 4651 and inflector aperture are identical in both simulations. Values within parentheses show the
 4652 results of an incoming beam with a momentum spread of 2% instead of the nominal 0.5%.

Table 10.4: Summary of E821 Inflector Simulations.

Inflector Geometry (Upstream-Downstream)	Muons Generated	Muons Surviving	Storage Fraction
Open-Open	5000 (20000)	664 (691)	13.2±0.3 (3.4±0.1)
Closed-Open	5000 (20000)	522 (593)	10.4±0.3 (2.8±0.1)
Closed-Closed	5000 (20000)	323 (395)	6.5±0.3 (1.9±0.1)
Improvement Factor \equiv Open-Open/Closed-Closed			
	5000 (20000)	-	2.1× (1.7×)
Improvement Factor \equiv Closed-Open/Closed-Closed			
	5000 (20000)	-	1.6× (1.5×)

4653 10.5.3 Sensitivity to Beam Phase-space Matching

4654 A consequence of the limited inflector aperture is gross phase space mismatching into the
 4655 storage region. This is seen by studying the amplitude of the muon beam (A), which is defined
 4656 as $A = \sqrt{\beta\varepsilon}$. The maximum horizontal size of a beam clearing the inflector is ± 9 mm, thus,
 4657 a beam with $\varepsilon = 40$ mm-mrad must have $\beta_x < 2.5$ m and $\beta_y < 19.6$ m. As this beam
 4658 propagates into the storage region the horizontal β -function subsequently undergoes large
 4659 oscillations with $\beta^{\max} = 28$ m and $\beta^{\min} = 2.5$ m. This corresponds to a modulation of the
 4660 horizontal beam amplitude (A) of $r = \sqrt{\frac{\beta^{\max}}{\beta^{\min}}} = 3.4$.

4661 An alternative to these large oscillations is to perfectly match the β -functions into the
 4662 storage ring. Assuming a drift space within the inflector ($\vec{B} = 0$), then the β -function at
 4663 the inflector is defined as $\beta^{\text{inf}} = \beta^{\text{ring}} + s^2/\beta^{\text{ring}}$. The resulting β -functions ($\beta_x^{\text{inf}} = 7.6$ m
 4664 and $\beta_y^{\text{inf}} = 19.2$ m) requires the incoming beam to be 2.38 times larger than the inflector
 4665 aperture. Thus, only $1/2.38 = 42\%$ of the beam will clear the inflector. This conclusion
 4666 follows the **GEANT**-based tracking result, which shows 53% of the beam clearing the inflector
 4667 aperture.

10.5.4 Increased Horizontal Aperture

The E821 inflector was constructed with a ± 9 mm horizontal aperture in part due to the double cosine theta magnet geometry and the limited space between the outer main magnet cryostat and the muon storage region. The horizontal aperture also constricts the available phase space in the muon storage region, whose aperture is ± 45 mm.

An augmented inflector “D”-shaped aperture of $\pm 20 \times \pm 28$ mm² is modeled in the GEANT tracking software. In this study, the main magnet fringe field is assumed to be identically canceled within the inflector beam channel for simplicity. The horizontal beam size is increased allowing for ideal matching to the storage ring β -function, corresponding to $\beta_x = 7.6$ m. The horizontal and vertical α Twiss parameters are set to zero in this scenario.

Table 10.5 summarizes the muon storage rate for the two apertures (18 vs 40 mm) and the two end coil inflector geometries (open vs closed) ¹.

Table 10.5: Summary of E821 Inflector Simulations. The “D”-shaped aperture shown in Fig. 10.5(a) was used. The vertical aperture was 56 mm, the horizontal (radial) aperture was 18 mm, or 40 mm.

Inflector Aperture (Open or Closed ends)	Muons Generated	Muons Surviving	Storage Rate
18 mm Aperture ($A_{\pm 9}$)			
(open ends)	120000	11444	9.5±0.1
(closed ends)	120000	5117	4.2±0.1
40 mm Aperture ($A_{\pm 20}$)			
(open ends)	120000	19161	15.9±0.1
(closed ends)	120000	8706	7.2±0.1
<hr/>			
Improvement Factor $\equiv A_{\pm 20}/A_{\pm 9}$			
(open ends)	-	-	1.7×
(closed ends)	-	-	1.7×
Improvement Factor $\equiv A^{\text{Open}}/A^{\text{Closed}}$			
(18 mm Aperture)	-	-	2.2×
(40 mm Aperture)	-	-	2.2×
Improvement Factor $\equiv A_{\pm 20}^{\text{Open}}/A_{\pm 9}^{\text{Closed}}$			
	-	-	3.8×

10.6 ES&H

The superconducting inflector is in a cryostat that includes one section of muon beam tube. The cryostat vacuum is separate from the beam vacuum chamber, so that the inflector can be operated independently of whether the muon beam chamber is evacuated. The

¹Note that these storage rates are computed with a different muon beam and therefore can not be compared directly to the rates in the previous sections.

4684 cryogenic system, and its operation will follow all Fermilab safety standards for cryogenic
4685 and vacuum system operations. This includes, but is not limited to Extreme Cold Hazard,
4686 Oxygen Deficiency Hazards. The cryogenics involved are liquid helium and liquid nitrogen.
4687 No flammable liquids or gases will be employed. The existing E821 inflector was operated
4688 at Brookhaven National Laboratory where similar safety requirements were in place.

4689 **10.7 Risks**

4690 **10.7.1 Relocation Risk**

4691 There is a small risk that in the de-installation at Brookhaven and shipping to Fermilab of the
4692 E821 Inflector that some problem is introduced that compromises the inflector performance.
4693 We will seek to minimize this risk by careful disassembly and shipping. As soon as cryogenic
4694 capability is available in MC-1, we would set up a test stand in the experimental area outside
4695 of the ring to cool and power the inflector.

4696 **10.7.2 Other Risks**

4697 There is the possibility that some mechanical aspect of the E821 inflector has deteriorated
4698 in the 12 years since it was operational, causing the magnet to quench repeatedly before
4699 reaching full current. This risk is probably small, since it was tested at KEK, shipped to
4700 BNL, installed, and was brought to full current with only a few training quenches. It was
4701 very robust in subsequent operation at BNL. The plan to test it as soon as possible at
4702 Fermilab will clarify this risk.

4703 A helium leak in the valve box or lead-pot will need to be located and repaired. There is
4704 a small risk that the leak was in the magnet itself, but this is viewed as extremely unlikely
4705 by Akira Yamamoto, who supervised the engineering design and construction, and Wuzheng
4706 Meng, who did the magnetic design and was responsible for its operation at BNL.

4707 The most sensitive part of the re-installation is reconnecting the inflector leads. Our
4708 technician Kelly Hardin was involved in the disassembly at BNL, and understands the issues
4709 involved in the reconnection very well.

4710 **10.8 Quality Assurance**

4711 Proper quality assurance is essential in the transport and reassembly of the inflector magnet.
4712 The mechanical aspects, heat shield, etc. will be carefully examined for issues, once the
4713 inflector arrive at Fermilab. It will be determined as quickly as possible whether the inflector
4714 meets the Muon g-2 requirements for performance and reliable operation. Quality Assurance
4715 will be integrated into all phases of the transport and reassembly work. including design,
4716 procurement, fabrication, and installation.

4717 10.9 Value Engineering

4718 The baseline is to begin the experiment by re-using the existing E821 Inflector. A new
4719 inflector with a much larger horizontal aperture could permit three to four times as many
4720 muons to be stored. A gain of this factor would significantly improve the statistical reach of
4721 the experiment, and permit more beam time to be used for systematic studies. This presents
4722 a significant opportunity to improve the experiment and to use running time more effectively.
4723 At present we plan that our UK collaborators at the Rutherford-Appleton Laboratory will
4724 produce a new inflector. If they are unable to obtain funding, we will explore the possibility
4725 that a larger-aperture inflector can be produced in collaboration with Brett Parker at BNL.

References

- 4726
- 4727 [1] A. Yamamoto, et al., Nucl. Inst. Meth. **A 491**, 23 (2002).
- 4728 [2] Frank Krienen, Dinesh Loomba and Wuzheng Meng, Nucl. Inst. Meth. **A238**, 5 (1989).
- 4729 [3] A. Yamamoto, Nucl. Instr. and Meth. A 453 (2000) 445.
- 4730 [4] Y. Makida, et al., IEEE Trans. Magn. 27(2) (1991) 1944.
- 4731 [5] M. Garber, A. Ghosh, W. Samson, IEEE Trans. Magn. 25 (2) (1989) 1940.
- 4732 [6] Y. Saito, et al., Development of beam inflection superconducting magnet evaluation of
4733 prototype, Tokin Technical Review, No. 20.
- 4734 [7] M.N. Wilson, Superconducting Magnets, Oxford Science Publications, Oxford, 1983.
- 4735 [8] A. Yamamoto, Status of the inflector, Internal Meeting Minutes, 1992; W. Meng, K.
4736 Woodle, Superconducting shield test on ($g - 2$) inflector magnet, ($g - 2$) Note, No. 210,
4737 1994.
- 4738 [9] M.A. Green, W. Meng, IEEE Trans. Appl. Supercond. 5 (2) (1995) 667.
- 4739 [10] G.T. Danby, W. Meng, W. Sampson, K. Woodle, IEEE Trans. Magn. 30 (4) (1994)
4740 1766.
- 4741 [11] I. Itoh, T. Sasaki, IEEE Trans. Appl. Supercond. 3 (1993) 177.
- 4742 [12] H.N. Brown, et al, Phys. Rev. Lett. **86** 2227 (2001).
- 4743 [13] F. Krienen, et al., IEEE Trans. Appl. Supercond. **5** (2) (1995) 671.
- 4744 [14] W. Meng, K. Woodle, Superconducting shield test on g-2 inflector prototype, g-2 Note,
4745 No. 210, 1994.
- 4746 [15] The $g - 2$ Collaboration: G.W. Bennett et al., Phys. Rev. Lett. **89**, 101804 (2002);
4747 Erratum-ibid. **89**, 129903 (2002).
- 4748 [16] Bennett GW, et al. (The $g - 2$ Collab.) Phys. Rev. Lett. 92:161802 (2004)
- 4749 [17] <http://www.bnl.gov/magnets/Staff/Parker/>
- 4750 [18] Brett Parker, private communication, March 2013.

- 4751 [19] Lance Cooley, Fermilab. Private Communication.
- 4752 [20] Steve Smith at MTI Metal Technology. <http://www.mtialbany.com/>
- 4753 [21] Tony Nelson at ATI Wah Chang. <http://www.atimetals.com/>

Chapter 11

WBS 476.03.04 Beam Vacuum Chambers

The muon storage volume, which lies within the 1.45T magnetic field, is evacuated in order to minimize multiple scattering of muons and positrons. This is accomplished by a set of aluminum vacuum chambers, which also provides mechanical support for:

- the beam manipulation systems: the electrostatic plates of the quadrupole system, the collimators, and plates of the magnetic kicker system.
- the positron detection systems: the trace-back straw trackers and auxiliary detectors such as the fiber harp.
- the magnetic field measurement systems: 400 fixed NMR probes surrounding the storage volume, a set of rails for the trolley NMR system, and the plunge probe system.

The chambers from BNL E821 will be reused for E989, and we will make changes as described in the section below. The chamber design is detailed in the BNL E821 design report[1], and so only a brief discussion is given here. Figure 11 shows the layout. The systems comprises mainly of 12 large vacuum chambers, separated by 12 short bellows adapter sections.

A simplified FEA model of a large vacuum chamber is shown in figure 11.2, showing the 15 grooves for mounting the NMR probes. The 15 grooves on the bottom and flange ports are not shown. The FEA model predicts that the top and bottom surfaces deflect by 0.453 mm under vacuum load[2]. This is agreement with the measurement of 0.45 mm[3]. The FEA model reconfirms that the chamber has reasonable factors against buckling, and the wall stresses are below 12000 psi, as required by the ASME Pressure Vessel Code for pressure vessels for Aluminum 6061-T6.

The 12 vacuum chambers and 12 bellow adapter sections are bolted together and placed in between the upper and lower pole pieces. The average radius of this structure is mechanically fixed and cannot be adjusted. There are thin dielectric sheets in between vacuum sections to prevent low frequency eddy currents from traveling in between the sections. Finally, all chamber materials including bolting hardware are non-magnetic.

Figure 11.3 and 11.4 shows the cage system and how it resides inside a vacuum chamber. The cage system holds the quadrupole plates, kicker plates, and the rails used by the trolley.

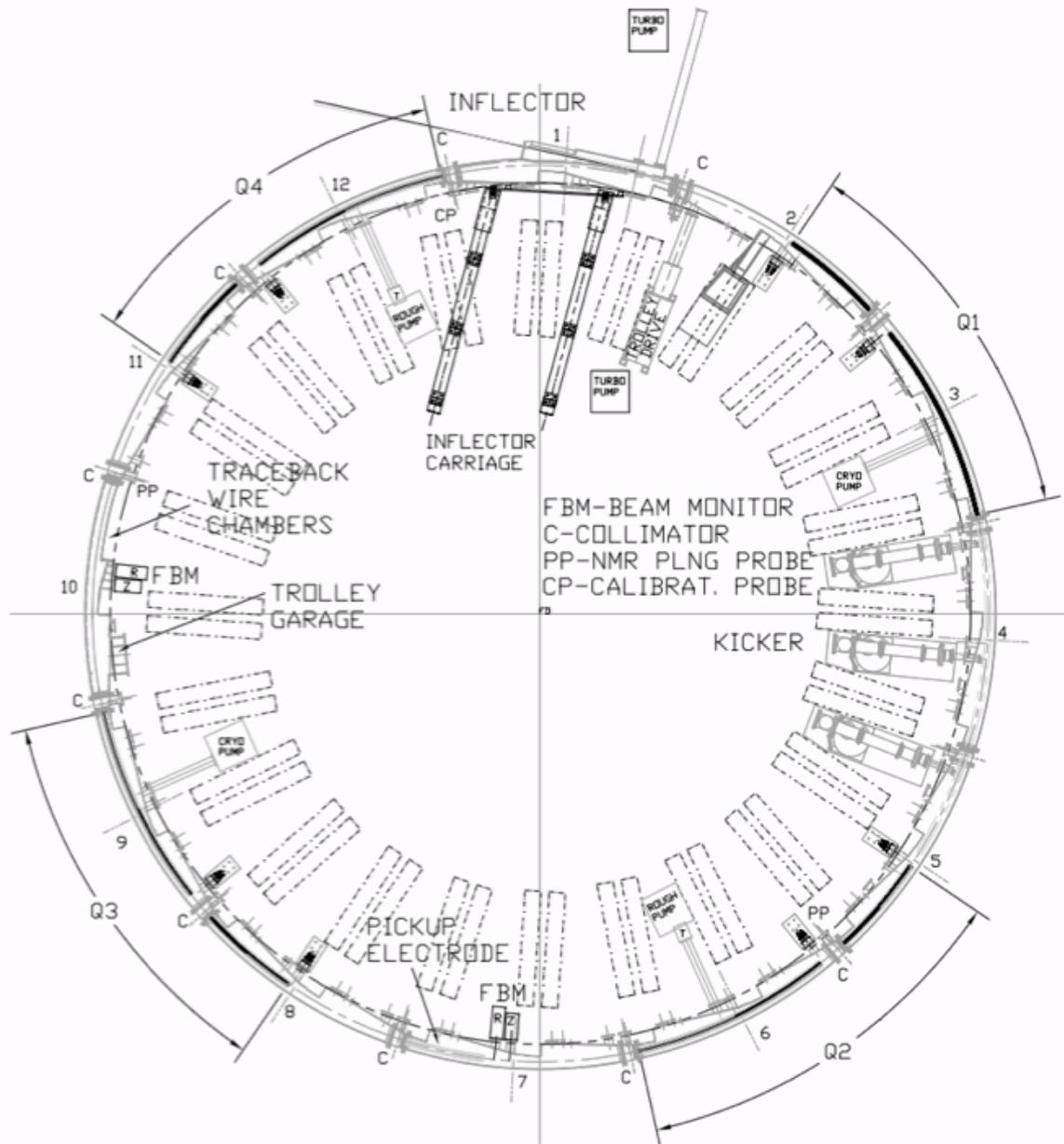


Figure 11.1: Layout of the BNL E821 beam vacuum chamber system.

4784 Screws allow for adjusting the position of the cage within the vacuum chamber system. The
 4785 position of the cage system plays an important role, and has the following requirements. (1)
 4786 The rail system from neighboring vacuum sections must line up to allow smooth motion of
 4787 the trolley as it travels between sections. And (2), since the quadrupole plates and kicker
 4788 plates positions define the beam storage region, these devices should place the beam in the
 4789 most uniform portion of the magnetic field. The beam center should be at the geometrical
 4790 center between upper and lower pole faces. A critical period occurs after installing the
 4791 chambers and before vacuum pump down. During this time, the vacuum flanges are open

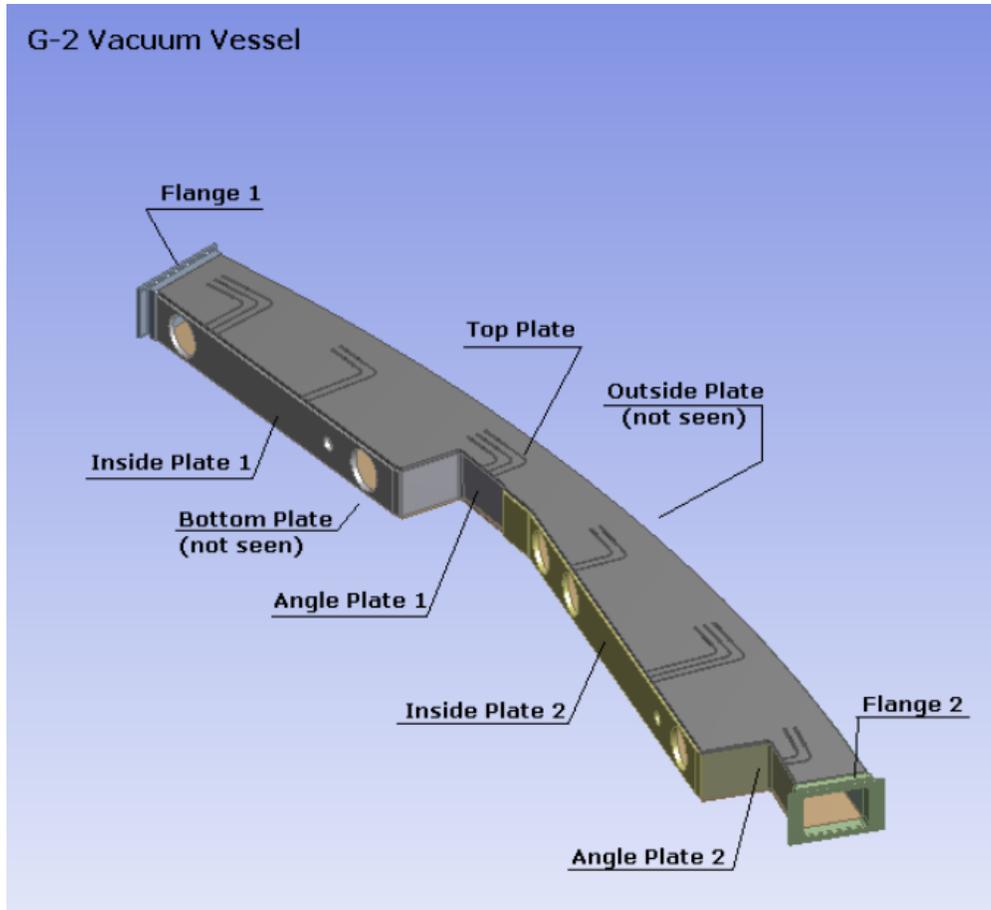


Figure 11.2: Simplified mechanical model for stress and strain analysis.

4792 and so will allow access to the adjustment screws.

4793 11.1 Changes to the E821 Design

4794 For E989, we are proposing to make the following changes. We will add fixed NMR probes
 4795 to the mid plane ('mid plane probes') of the beam storage region. A concept is shown in
 4796 figures 11.6 and 11.7, showing the probes mounted to the cage system. The mid plane probes
 4797 will have the long axis aligned in azimuth, and should lie as close as possible to the edge of
 4798 the beam region. But they must remain sufficiently far from the quadrupole and kicker
 4799 plates in order to prevent sparking and signal pickup. The probes will be in vacuum, and the
 4800 probe coax cables attach to commercially-available vacuum SMA electrical feed throughs.
 4801 As shown from simulations, the magnetic field values should be within the mid plane probe
 4802 operating range.

4803 For E821, a small fraction of the upper and lower fixed probes were too close (in azimuth)
 4804 to the boundary between two pole pieces. In this region, the magnetic field gradient is
 4805 generally larger due to gaps and steps (of order < 25 microns) between two pole pieces, and
 4806 therefore degrades the probe's S/N. Simulations show that maintaining a distance of $O(5$

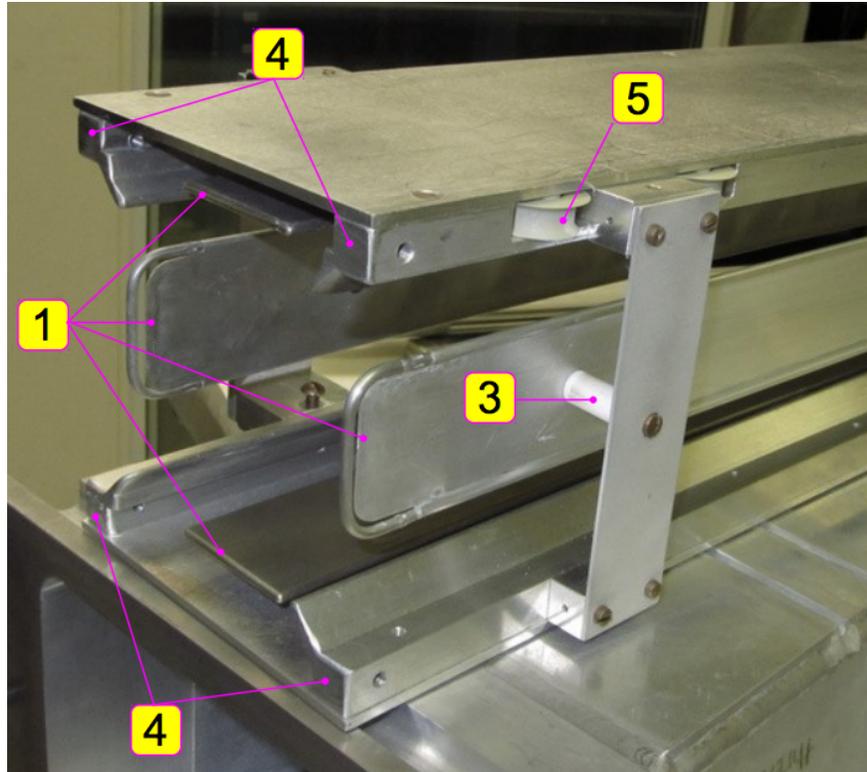


Figure 11.3: Picture of a cage system showing the (1) quadrupole plates, (3) macor (insulator) supports, (4) trolley rails, and (5) a wheel for guiding the cable that pulls the trolley

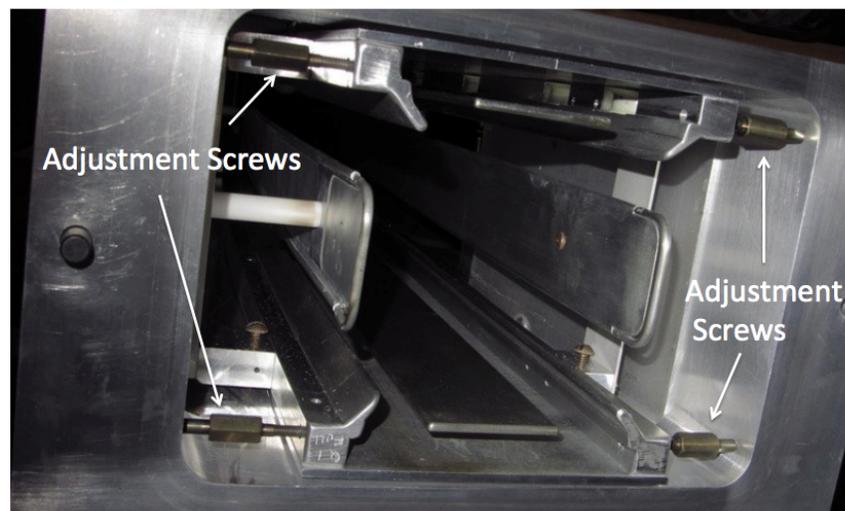


Figure 11.4: Picture of a cage system inside a vacuum chamber showing the adjustment screws to center the quadrupole plates to the geometrical center of the pole pieces.

4807 cm) (*check this*) will recover the required S/N. For E989, we will either lengthen or cut new
 4808 grooves to optimize probe placement.

4809 In E821, the trace back system operated in air and was located in vacuum chamber sector

4810 10, which was modified to be without a ‘scallop’. For E989, the straw trace back system
 4811 will be in vacuum, and vacuum chamber sector 10 will have its scallop shape reinstalled.
 4812 A second straw station will be placed in sector 8. The inner radius vertical side walls of
 4813 sectors 8 and 10 will be modified to accept the straw chamber flange. Figure 11.8 shows the
 4814 locations of the proposed changes.

4815 The kicker occupies chamber sectors 4 and 5. The magnetic kicker firing will cause eddy
 4816 currents, which compromises physics data at beginning of injection and reduces the kicker
 4817 field strength. Opera simulations are being done to see whether the top and bottom surface
 4818 of the vacuum chamber can be redesigned to reduced eddy currents. A concept for this
 modification is shown in figure 11.5.

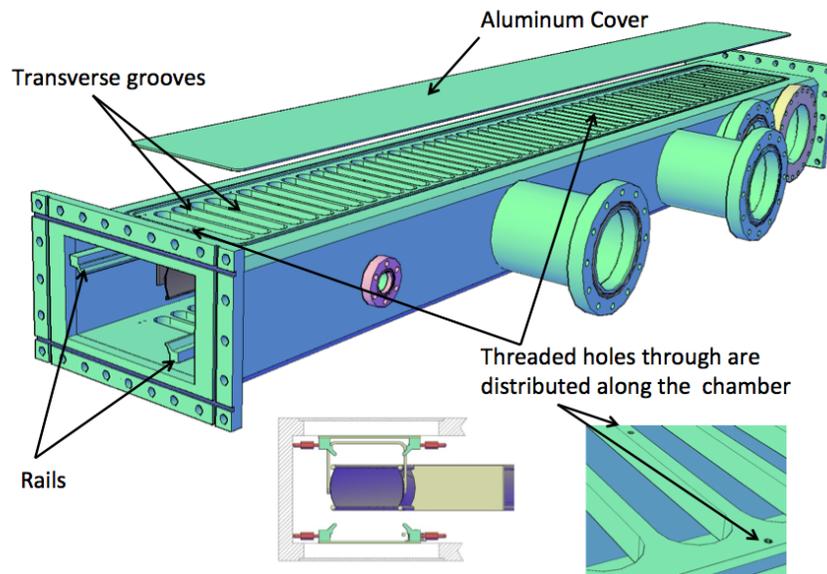


Figure 11.5: Concept for modifying chamber sectors 4 and 5 to reduce eddy currents induced by the kicker system.

4819

4820 Finally, the vertical inner radius surface of the vacuum chamber will be lined with insu-
 4821 lation. This will improve the thermal stability of the magnet iron.

4822 11.2 WBS 476.03.04.02 Vacuum Chambers

4823 This WBS refers to the actual chambers, the small bellows, the piping to the pumps, and
 4824 the bolting hardware. We are exploring major modifications to sectors 8, 10, 4, and 5. This
 4825 WBS also covers the reassembly labor effort.

4826 Chamber sectors 10 and 8 would be re-machined to accept the new in-vacuum straw trace
 4827 back chambers. For sector 10, the ‘scallop’ portion must be reinstalled. Chamber sectors 4
 4828 and 5 would have the top and bottom plates modified to install transverse grooves to reduce
 4829 eddy currents.

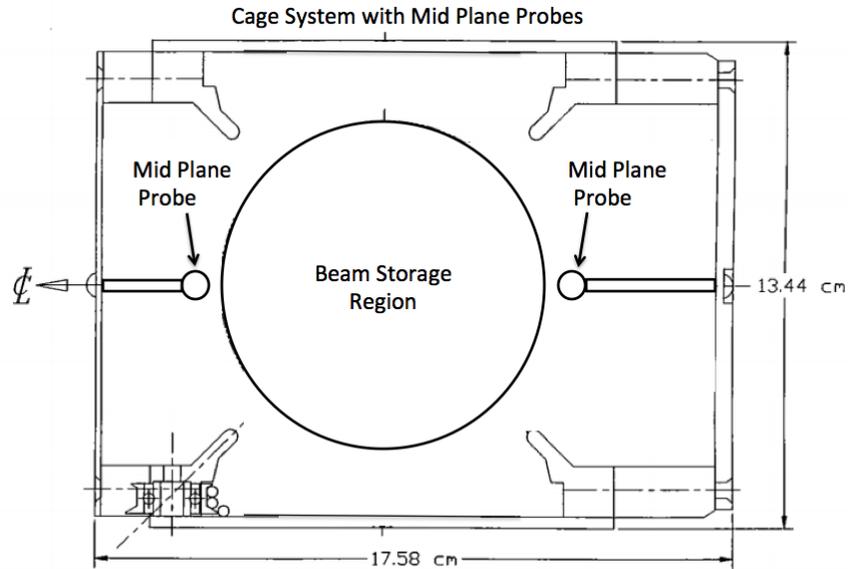


Figure 11.6: Concept for placement and attachment of mid plane probes within the cage systems that do not contain quadrupole and kicker plates. Signal coax cables attach to commercially available vacuum SMA electrical feed throughs.

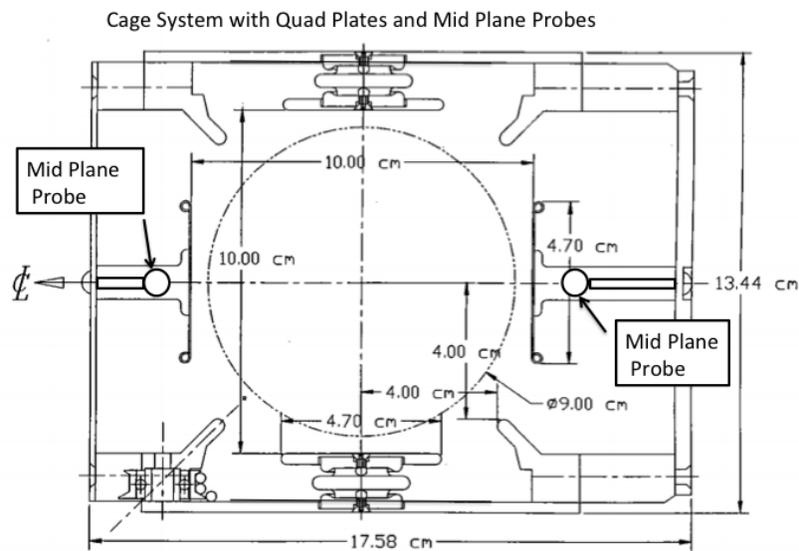


Figure 11.7: Concept for placement and attachment of mid plane probes within the cage system in the quadrupole plate region. The mid plane probes are farther from the beam center. They are offset and do not interfere with the macor quadrupole plate support stands. Signal coax cables attach to commercially available vacuum SMA electrical feed throughs.

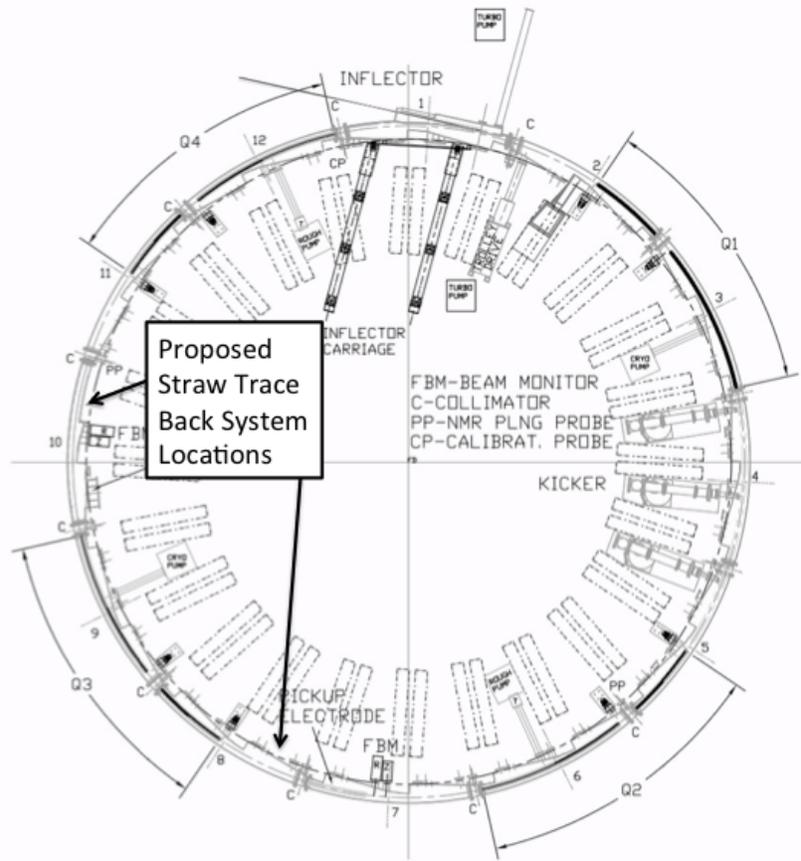


Figure 11.8: Proposed locations for in-vacuum straw trace back chambers.

11.3 WBS 476.03.04.03 Vacuum Pumps

4830

4831 The vacuum level must be less than 10^{-6} Torr in the region of the quadrupoles. This is
 4832 to minimize the trapping of ionized electrons due to the residual gas. However, there is a
 4833 vacuum load of < 100 liters/sec at 10^{-6} Torr from each of the two straw tracker trace back
 4834 system (*Check with Mandy and Brendan Casey*).

4835

4836 From this requirement alone, the minimum pumping speed is 100 liters/sec at 10^{-6} Torr.
 4837 However, each pump is attached to the vacuum chamber through a large pipe. As the
 4838 pumps will likely contain ferromagnetic material and generate transients that would affect
 4839 the magnetic field uniformity, they must remain sufficiently far from the vacuum volume.
 4840 For E821, this distance was 1-2 meters. Therefore, extra piping will increase slightly the
 4841 pumping speed requirement. The exact minimum pumping speed will be determined by
 4842 engineering calculations. For E821, the pumping speed was 2000 liters/sec at 10^{-6} Torr,
 accomplished by 3 pumps spaced uniformly over the ring.

4843

4844 Finally, the vacuum chamber system should remain clean, as the quadrupole and kicker
 4845 plates carry high voltage and the high current, respectively. We will ensure this by utilizing
 dry (oil-free) roughing and turbo pumps.

4846 11.4 WBS 476.03.04.04 Mechanical Interface

4847 As mentioned above, the vacuum chambers must provide the mechanical interface for several
4848 systems. This WBS covers the following activities needed for the NMR system:

- 4849 • Modifications to the upper and lower grooves to improve the S/N of fixed probes near
4850 the boundary between pole pieces.
- 4851 • Adding additional commercially available vacuum SMA connections to readout the in-
4852 vacuum mid plane probes. The exact number and location will be estimated by Opera
4853 simulations.
- 4854 • Calibration of the trolley position in absolute space: for a given motor or position
4855 encoder reading, what is the actual position of fiducial marks on the trolley in absolute
4856 space.
- 4857 • Calibration and operation of the positions of the plunge probe motors. Calibration
4858 refers to converting a given motor encoder reading to an actual position (in absolute
4859 space) of the probe head.

4860 The mechanism to move the plunge probe is shown in figure 11.9. This mechanism bolts to
4861 vacuum flanges at positions shown in figure 11. The probe itself is in air. There is a vacuum
4862 bellows in which the probe is inserted. The probe is moved radially by piezo electric motors.
4863 We expect no changes are needed for the plunge probe mechanism, other than connection
to a different computer.

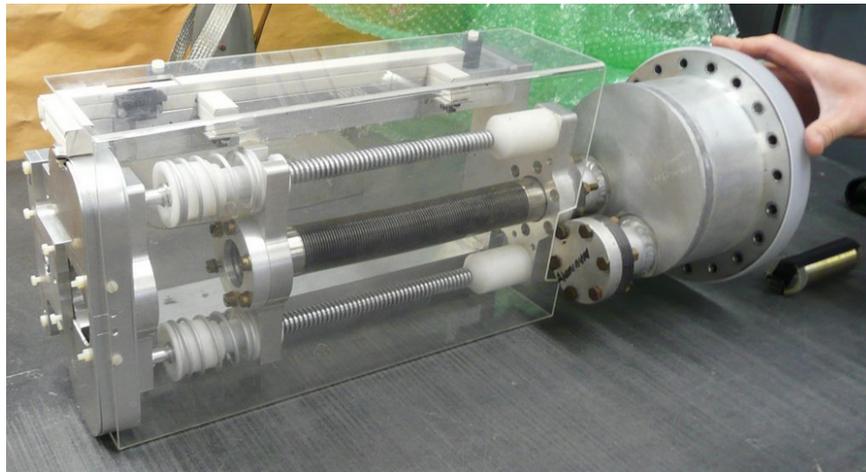


Figure 11.9: The plunge probe mechanism.

4865 **References**

4866 [1] BNL E821 Design Report

4867 [2] GM2 Doc-417-V1

4868 [3] BNL E821 Muon G-2 Note 248

Chapter 12

The Fast Muon Kicker

Injected muons exit the downstream end of the inflector magnet, and enter the good field region of the main dipole. The trajectory of the muons exiting the inflector is a circle displaced 77 mm radially outward the closed orbit of the storage ring. The path of the muons that emerge without having been scattered in the coil end of the inflector will be tangential to that displaced circle. On exiting the inflector, muons are within the full 1.41 T field of the ring dipole. The muons cross the closed orbit of the storage ring, that is the orbit at the magic radius, about 90° azimuthally around the ring from the end of the inflector. The circular trajectory of the muons intersects that closed orbit at an angle of $\theta_0 = 10.8\text{mrad}$. Indeed the minimum crossing angle, namely $\theta_0 = 10.8\text{mrad}$ obtains for trajectories that are tangential at the inflector exit. Any angle, positive or negative, with respect to the tangent line results in crossing angle greater than the minimum. Therefore muons that scatter in the inflector coil end will necessarily cross the closed orbit with a larger angle. The crossing angle is related to the scattering angle α according to

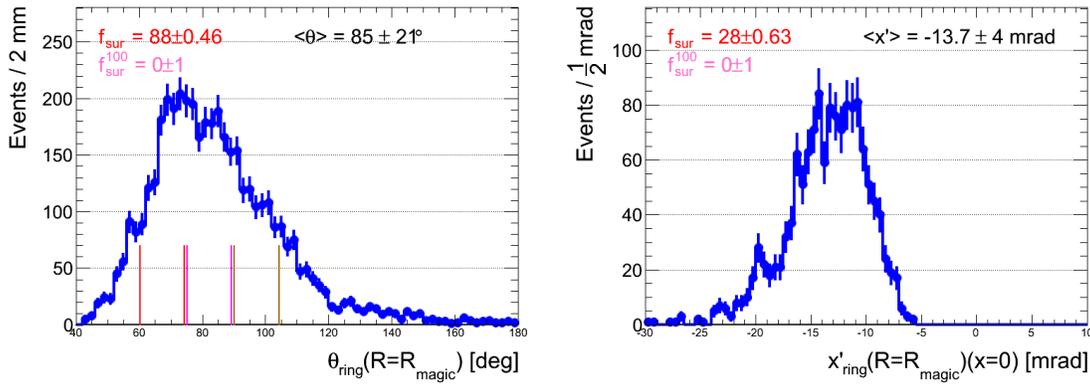
$$\theta \sim (\theta_0^2 + \alpha^2).$$

The contribution to beam divergence angle due to multiple scattering in the coil end is estimated to be about 4.6 mrad. Divergence due to the finite emittance of 40 mm-mrad is about 4 mrad. The result is that the mean angle at which muons cross the closed orbit is $\theta \sim 12.4$ mrad. Simulation that includes energy spread of the injected muons and scattering in the quadrupole plate indicates that the mean angle is nearly 14 mrad. Our specification for the system is a 14 mrad kick.

The azimuthal angle at which the muons cross the closed orbit, and the crossing angle are computed using a **GEANT4** simulation of the E821 experiment. This result, however, assumes three properties of the muon beam which are not realized in the experiment. First, the beam must have zero emittance (i.e., $|p| = p_z$), momentum localized around the magic momentum (i.e., $\delta p/p \ll 1$), and no multiple scattering as it traverses the outer quadrupole plates and standoffs. Varying each of these properties changes the azimuthal position and the crossing angle as seen in Table 12.1. Assuming a realistic beam with 40π emittance, $\delta p/p = 0.5\%$, and allowing for multiple scattering through the quadrupoles plates, the required kick increases from 10.8 mrad to 13.7 ± 3.9 mrad. Distributions of the azimuthal crossing point and crossing angle θ under these assumptions are shown in Fig. 12.1.

Table 12.1: Summary of Kicker Requirements for Different Beam and Ring Properties.

Beam $\delta p/p$ (%)	Emittance [mm · mrad]	Multiple Scattering	Azimuthal Crossing Point [degrees]	Crossing Angle [mrad]
0	0	OFF	89 ± 0	10.8 ± 0
0.5	0	OFF	88 ± 17	12.4 ± 2.7
0	40	OFF	86 ± 10	11.3 ± 3.3
0	0	ON	76 ± 7.8	15.1 ± 1.8
0.5	40	ON	85 ± 21	13.7 ± 3.9

Figure 12.1: (a) Azimuthal crossing angle in degrees (b) Required kick x' in milliradians.

4887 The fast kicker is a pulsed magnet with vertical field that directs the muons, onto the
 4888 ideal orbit by compensating the crossing angle. Ideally, the centroid of the injected bunch,
 4889 on exiting the field of the kicker plates will coincide with the closed orbit of the storage
 4890 ring, thus ensuring maximal capture efficiency and minimum residual coherent betatron
 4891 oscillation. The 10-14 mrad kick requires an integrated vertical field of 1.1 - 1.4 kG-m.
 4892 The kicker is comprised of three independent 1.7m long magnets, each with dedicated pulse
 4893 forming network. Muons are delivered to the storage ring in pulses with transverse emittance
 4894 near 40π mm-mrad, pulse length of about 120ns and at a repetition rate of up to 100Hz. The
 4895 ideal kicker field maintains a flat top at about 220-280 Gauss, for the full 120ns, and then
 4896 returns to zero before the lead muons complete a single revolution and re-enter the kicker
 4897 aperture 149ns later.

4898 The injection of muons into the storage ring is complicated by several requirements:

- 4899 1. Since the magnet is continuous, any kicker device has to be inside of the precision
 4900 magnetic field region.
- 4901 2. The kicker hardware cannot contain magnetic elements such as ferrites, since they will
 4902 spoil the uniform magnetic field.
- 4903 3. Any eddy currents produced in the vacuum chamber, or in the kicker electrodes, must

4904 be negligible by 10 to 20 μs after injection, or must be well known and corrected for
 4905 in the measurement.

4906 4. Any kicker hardware must fit within the real estate occupied by the E821 kicker, which
 4907 employed three 1.7 m long devices.

4908 5. The kicker pulse should be shorter than the cyclotron period of 149 ns

4909 12.1 Requirements for the E989 Kicker

4910 The need for a fast muon kicker was introduced in Section 3.2. Direct muon injection was
 4911 the key factor that enabled E821 to accumulate 200 times the data as the preceding CERN
 4912 experiment. Since E989 needs more than twenty times as much data as E821, it is critical
 4913 that the limitations of the E821 kicker be eliminated. The layout of the E821 storage ring is
 4914 repeated in Fig 12.2. The three kickers magnets are located approximately 1/4 of a betatron
 4915 wavelength around from the inflector exit.

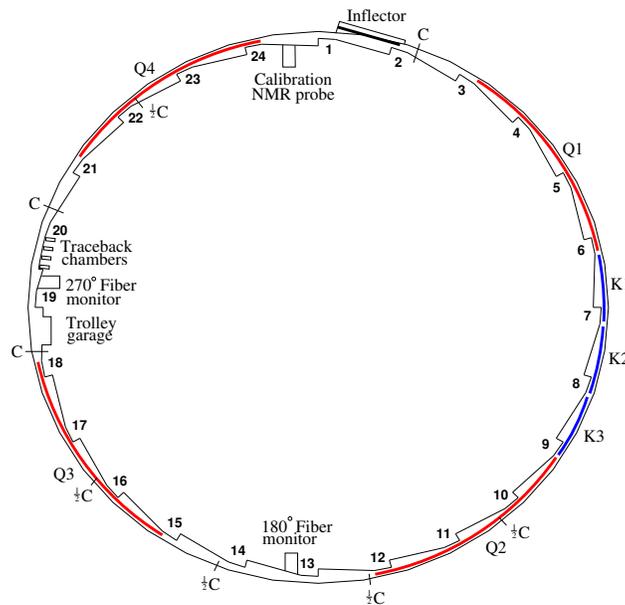


Figure 12.2: The layout of the storage ring, as seen from above, showing the location of the inflector, the kicker sections (labeled K1-K3), and the quadrupoles (labeled Q1-Q4) (Fig. reffg:ring repeated here for convenience).

4916 12.1.1 The E821 Kicker and its Limitations

4917 The E821 kicker [1] consisted of three identical sectors with 1.7 m long parallel plates carrying
 4918 current in opposite directions, located as shown in Fig. 12.2. Each section was powered by a
 4919 pulse forming network where a HV capacitor was resonantly charged to $\simeq 95$ kV, and then
 4920 shorted to ground by a deuterium thyratron, giving a characteristic damped LCR oscillating

4921 current and magnetic field. The resulting LCR pulse is shown in Fig. 12.3. Unfortunately
 4922 the LCR pulse was much wider than the beam width, in fact significantly longer than the
 4923 cyclotron period of 149 ns. This is emphasized by the series of red gaussians which are
 4924 separated by the 149 ns revolution period. Thus the beam is kicked several times before the
 4925 LCR pulse dies away.

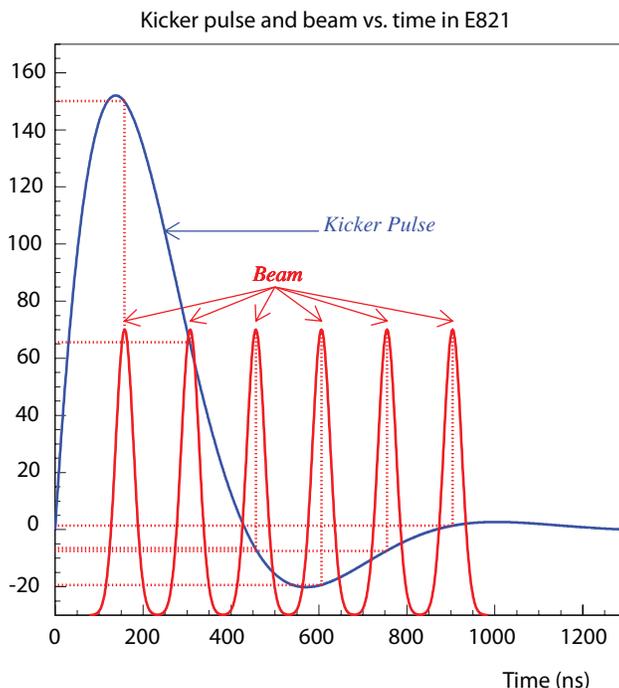


Figure 12.3: The E821 kicker LCR waveform (blue). The red pulses represent the injected beam, which has a cyclotron period of 149 ns.

4926 The kicker units began sparking around 95 kV, and each section had a different volt-
 4927 age defined as 100%. The number of muons stored vs. kicker high voltage is shown in
 4928 Fig. fg:stored-v-HV. Unfortunately, at the maximum voltage possible, the number of stored
 4929 muons did not turn over. It is not clear how many muons might have been stored if it
 4930 had been possible to increase the voltage until the maximum number of stored muons was
 4931 reached.

4932 12.2 New Kicker Design

4933 The design of the kicker for E989 attempts to address the shortcomings of the E821 kicker,
 4934 specifically, the pulse shape and pulse amplitude. We are developing a pulse forming network
 4935 based on a Blumlein triaxial transmission line as an alternative to the E821 LCR PFN. The
 4936 kicker plates are redesigned to yield a spatially more uniform field and with somewhat higher
 4937 efficiency in terms of gauss per unit current through the plates. The kickers consist of 1.7m
 4938 long plates as shown in Figure 12.5

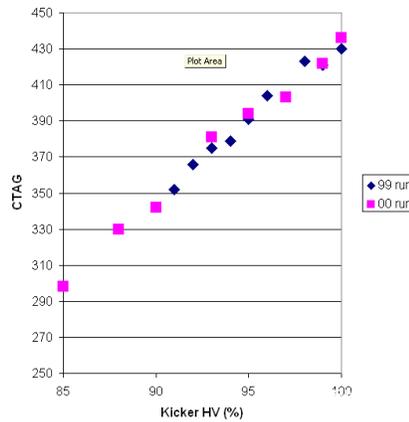


Figure 12.4: The number of stored muons versus kicker high voltage (arbitrary units).

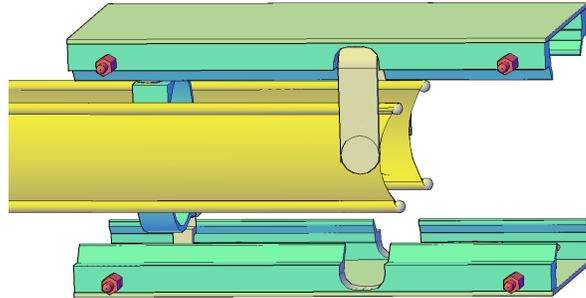


Figure 12.5: The kicker plates for E989. The current pulse is fed to the 1.7m long plates at the far end to the left of the plot. A jumper connecting the plates at the near end that closes the circuit is shown.

4939 The proposed implementation is a variation on a transmission line PFN driving a matched
 4940 load. We consider each 1.7 m long pair of kicker plates a load (each pair of plates is a
 4941 transmission line in its own right) with impedance Z_L , and imagine, at least conceptually,
 4942 that each kicker is terminated with a resistive load $R = Z_L$. If the impedance of the PFN
 4943 transmission line matches the impedance of kicker plates and load, then we anticipate
 4944 a rectangular current pulse with width $\tau = 2L/c$ where L and c are the length and group
 4945 velocity of the PFN, and current $I = V/Z$, where V and Z are the peak charging voltage
 4946 and the impedance of the line respectively. With such a configuration we expect that the
 4947 rise and fall time of the pulse will be limited by the turn on/off time of the thyatron switch
 4948 of about 20-30ns.

4949 We estimate the impedance of the kicker plates to be nearly 600Ω . The current required
 4950 to achieve the requisite ~ 250 G field is about 3kA corresponding to the impractically high
 4951 charging voltage of 1.8MV if the impedance of the PFN is matched to the impedance of
 4952 the kicker plates. Furthermore it would be awkward to terminate the kicker plates with

4953 a resistor. We propose alternatively to place a load resistor with resistance of only 25 Ω .
 4954 between the pulse forming network and the kicker plates. The PFN transmission line is then
 4955 matched to the load resistor. The reflections that will inevitably arise from the imperfect
 4956 match at the junction of load resistor and kicker plates, will be confined to the plates, and
 4957 dissipated on the timescale of the plate transit time of about 6ns. We thus deliver the
 4958 desired current with $\sim 87\text{kV}$ charging voltage. At the transition through the load resistor to
 the kicker, the transmission line is tapered to mitigate the mismatch.

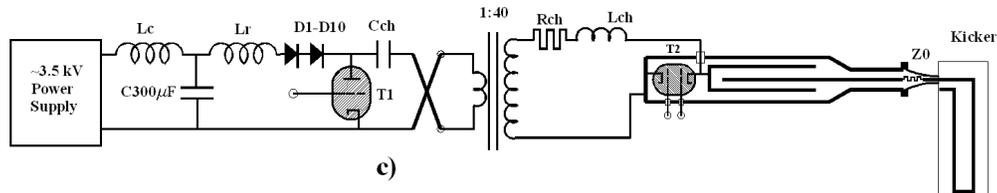


Figure 12.6: Schematic of the kicker, pulse forming network and charging circuit. The Blumlein, resistive load (Z_0) and kicker are in series to the right of the figure. In the final installation the load resistor is mounted near the vacuum chamber coupling directly to the kicker plates. The blumlein connects to the resistor via high voltage coax.

4959

4960 12.3 New Pulseforming Network

4961 The pulse forming network that we are developing for the kicker is a Blumlein triaxial
 4962 transmission line. The Blumlein is shown schematically in Figure 12.7. The LCR circuit
 4963 used in E821, and a coaxial transmission line are included in the Figure for comparison. The
 4964 equivalent circuit for a Blumlein is a pair of series bi-axial lines with a shared conductor and
 4965 it is so rendered blumlein in Figure 12.8.

The width of the pulse

$$\tau = \frac{2L}{v} = 2L \frac{\sqrt{\mu\epsilon}}{c}.$$

4966 For the bi-axial line the voltage at a matched load is half the charging voltage. For the
 4967 Blumlein, output voltage and charging voltage are one and the same[2]. Another advantage
 4968 of the Blumlein as compared to a bi-axial transmission line is that the base of the thyatron
 4969 can be fixed at ground potential. A bi-axial pulse forming network would require that the
 4970 base of the tube float to high voltage when the thyatron is switched. The Blumlein
 4971 PFN under development at Cornell is shown in cross section in Figure 12.9. The middle
 4972 conductor is connected through a large resistance and inductance to the high voltage power
 4973 supply. Current flows through the load Z_L off of the central conductor during the charging
 4974 cycle. The thyatron (T) shorts the middle conductor to the outer conductor and after a
 4975 delay of $T/2$, where T is the width of the current pulse generated by the line, the current
 4976 flows through the resistive load and into the kicker.

4977 Some details of our implementation of the Blumlein are shown in Figure 12.10. The
 4978 left and right drawings correspond to configurations with characteristic impedance of 25 Ω

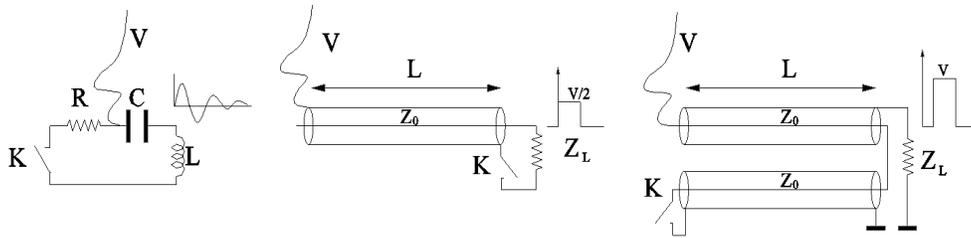


Figure 12.7: The overdamped LCR circuit at left was use in E821. The line labeled “V” indicates the charging voltage and K the thyatron switch. At center is a coaxial transmission line PFN. The Blumlein equivalent circuit is at the right. The corresponding pulse shape is shown for each of the configurations. Note that for both coaxial and triaxial lines, pulse width is proportional to twice the line length. Voltage across a matched load for the blumlein is twice that of the coax. The Blumlein pulse is delayed by half of the pulse width.

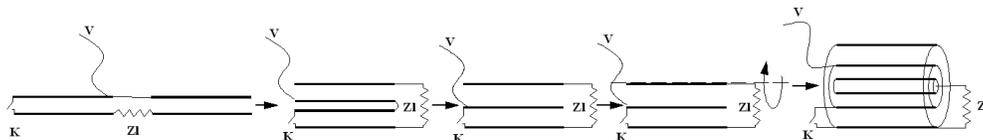


Figure 12.8: Topological modification of series coaxial lines into a tri-axial blumlein transmission line. (One can choose the rotation axis coinciding with the lower plate).

4979 and 12.5Ω respectively, (assuming 561 silicon oil with $\epsilon = 2.7$). We have modeled the
 4980 basic electrical properties of the pulser with an equivalent circuit using SPICE. Each of the
 4981 two series coaxial lines are modeled with discrete elements as shown in Figure 12.11. The
 4982 kicker load is represented with characteristic capacitance and inductance. The current pulse
 4983 through the kicker when the switch is closed, as computed with SPICE, is shown in Figure
 4984 12.12.

4985 The impedance of the triaxial line is equivalent to the sum of the impedances of the
 4986 series bi-axial lines. The middle conductor in Figure 12.9 that is charged to high voltage
 4987 serves as the inner conductor for one bi-axial line and the outer conductor for the other. The
 4988 impedance of each of these bi-axial components is 12.5Ω . The output of the PFN is coupled
 4989 to the load with a pair of parallel 50Ω high voltage coaxial cables, with combined impedance
 4990 of 25Ω . The transition hardware is shown in Figures 12.13 and in an exploded view in 12.14.

4991

4992 A schematic of the Blumlein pulser connected via high voltage coax to the kicker inside
 4993 the muon ring vacuum chamber is shown in Figure 12.15. Also shown is the electronics rack
 4994 with 1500 V power supply, thyatron driver, and thyatron trigger pulser. The cylindrical
 4995 container sitting on the floor beside the rack is the oil tank with high voltage transformer.
 4996 The single high voltage transformer will charge the three Blumleins for each of the three
 4997 kickers. Figure 12.16 is a rendering of the 5m long Blumlein with coupling to charging
 4998 transformer at the right and transition to a pair of coaxial cables at the left. The thyatron

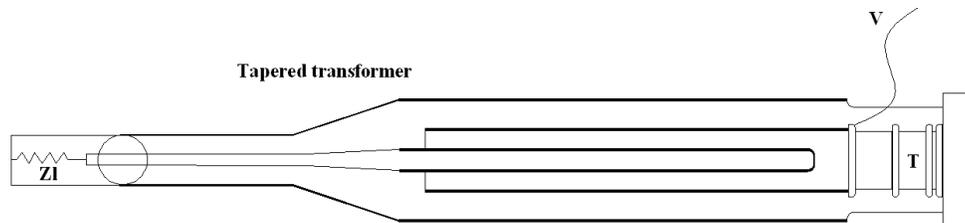


Figure 12.9: Middle conductor is charged to high voltage via the line labeled “V”. The centermost conductor is coupled via a high voltage coaxial cable to the resistive load that is mounted directly to the input of the kicker. (The kicker is not shown here.) The thyatron (T) shorts the middle conductor to ground. The volumes between conductors, around the thyatron and load are all filled with transformer oil.

4999 is housed in the section at the extreme right.

5000 12.4 New Kicker Plate Design

5001 The geometry of the kicker plates will be optimized for better uniformity over the storage
 5002 volume and higher efficiency. We show the field profile for the proposed plate geometry in
 5003 Figure 12.17(Left) as compared to the E821 geometry in Figure 12.17(Right). A proper
 5004 calculation of the magnetic field generated by the time dependent current pulse has not yet
 5005 been completed. But in the limit of steady state current and neglecting the effect of eddy
 5006 current in the vacuum chamber and plates themselves, the new plate geometry provides at
 5007 least 33% more magnetic field per unit current than the old design. Distancing the kicker
 5008 plates from the vacuum chamber also mitigates the effect of induced field in the aluminum.
 5009 We estimate that a current of 3500A will be required to achieve a 14mrad kick, corresponding
 5010 to a charging voltage of 87.5 kV, (~ 10 kV below the breakdown voltage of the E821 kicker
 5011 system).

5012 Whereas in the E821 configuration, the kicker plates served as rails for the NMR trolley,
 5013 those functions will be separated in the new implementation as can be seen in Figure 12.18.
 5014 The kicker plates will be suspended from the top of the vacuum chamber as shown in Figure
 5015 12.19. Care must be taken to ensure the stability of the plates with respect to the time
 5016 dependent forces associated with the current pulse. At the same time it is desirable to
 5017 minimize the thickness of the plates and scattering of decay electrons.

5018 12.5 Kicker R&D at Cornell

5019 A laboratory has been outfitted at Cornell to build and test a prototype Blumlein pulse
 5020 forming network and fast kicker magnet. The electronics that has been recovered from the
 5021 E821 experiment and re-assembled includes: high voltage power supply, high voltage charging
 5022 transformer, thyatron driver, trigger pulser and thyatron. We have fabricated a prototype
 5023 5 meter Blumlein and tests with a resistive load are in progress. Figure 12.20 shows two

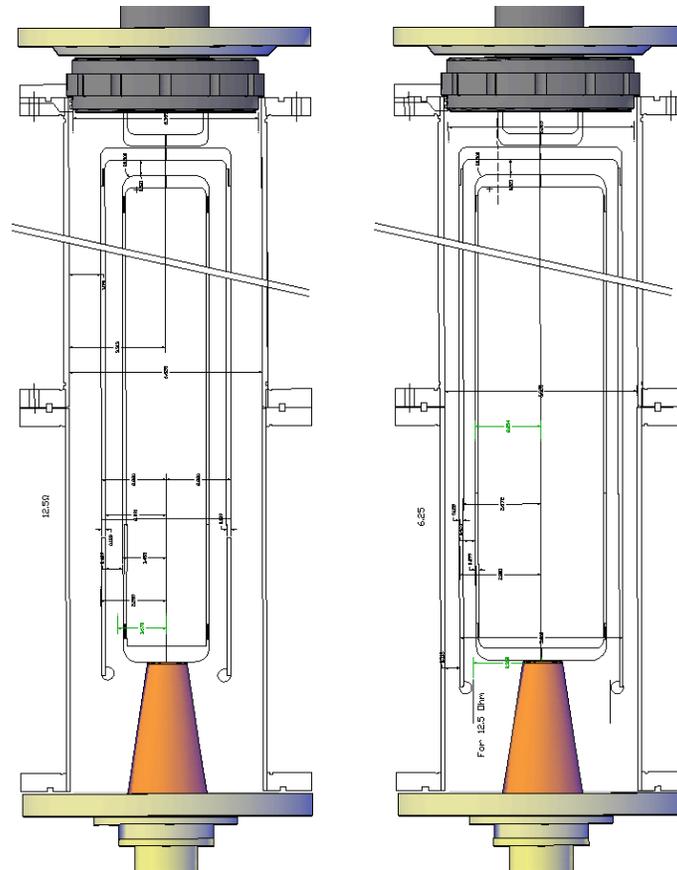


Figure 12.10: Cross section of 25Ω (left) and 12.5Ω (right) Blumlein. The central conductor couples through the orange transition at the bottom of the figure to the load resistor and kicker. The middle conductor connects through the U bracket near to the top to the klystron (not shown). The penetration of the high voltage charging line through the outer conductor to the middle conductor is not shown.

5024 views of the prototype Blumlein. The downstream, business end of the Blumlein is shown
 5025 in Figure 12.21. For the test in progress, the line is terminated in a 25Ω resistive load. The
 5026 Figure also shows the current pulse through the load as measured with both E-field antenna
 5027 and B-field current monitor. The rise and fall time of the E-field pulse is dominated by the
 5028 thyratron turn on and off time. The limited bandwidth of the B-field further degrades the
 5029 apparent rise time. The base width of the E-field pulse is about 100 ns and the rise time is
 5030 30ns, not atypical for a 10 year old, 4-gap tube. (We plan to experiment with other 4-gap
 5031 thyratron and are investigating the possibility of a 2-gap tube. The required standoff voltage
 5032 is somewhat less than 100kV, and we have identified a two-gap tube that at least according
 5033 to its specifications is a viable alternative.

5034 The prototype vacuum chamber is shown in Figure 12.22. Ports have been added to the
 5035 top and bottom of the chamber to provide a path for the laser light for the Faraday effect
 5036 field measurement. Macor high voltage standoffs are mounted to the ceiling of the chamber.
 5037 The new plates will hang from the standoffs. (The laser light ports and macor standoffs are

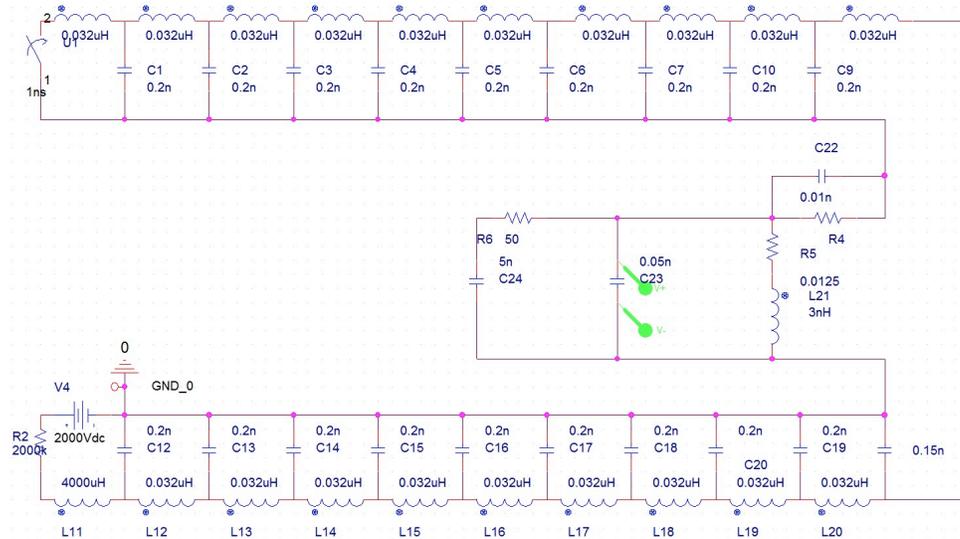


Figure 12.11: Discrete circuit element of the Blumlein that is shown as the right hand schematic in 12.7. Each of the two transmission lines is assembled with lumped inductance and capacitance. The kicker load is represented as inductance with small capacitance.

5038 not visible in the Figure)

5039 The coaxial coupling of the Blumlein to the prototyp vacuum chamber is shown in Figure
5040 ??.

5041 The kicker lab is equipped to test and modify and test again the PFN and the kicker
5042 plate assembly as required to meet the design specifications.

5043 12.6 Kicker Field Measurement

5044 Measurement of the time dependent field of the kicker will ultimately determine the effec-
5045 tiveness of the design choices. Furthermore, it is essential to measure, and ideally eliminate,
5046 fields due to the eddy currents in the vacuum chamber and kicker plates, that are generated
5047 by the kicker pulse. If the eddy currents have a long decay time, any persistent field will
5048 introduce a systematic shift in a_μ .

5049 We plan to implement a Faraday rotator to measure the time dependence of the kicker
5050 field and associated persistent fields modeled on the device used in E821. We have machined
5051 ports into the prototype vacuum chamber for transmitting polarized laser light through a
5052 birefringent crystal that will be mounted between the plates in the laboratory. It is desirable
5053 to repeat field measurements in-situ during the course of the experiment and we are exploring
5054 the possibility of implementing a Faraday rotator for that purpose.

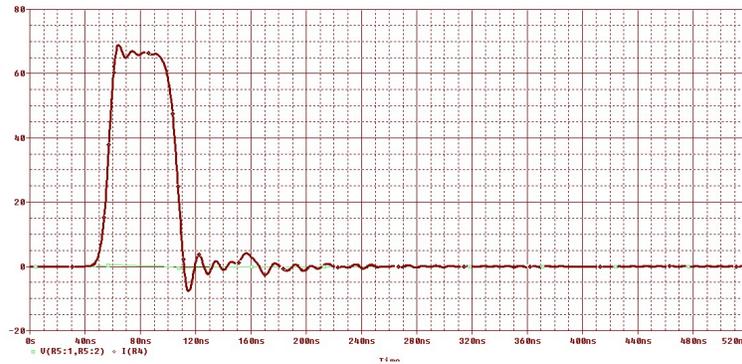


Figure 12.12: Pulse generated by blumlein equivalent circuit in Figure 12.11. Width of the “flat” top is about 70 ns. (Major ticmarks (solid lines) along time axis are every 50 ns.)

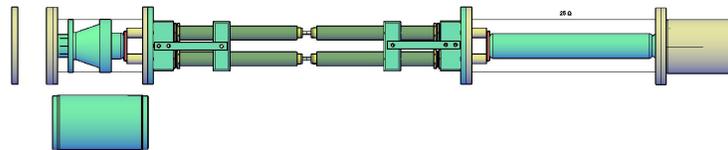


Figure 12.13: Transition from Blumlein to load. The green cylinder at the right couples to the centermost conductor of the Blumlein. With the outer conductor in place (not shown in this view), this short coax will have an impedance of 25Ω . The 25Ω coax couples to a pair of 50Ω high voltage coax cables. At the load end of the cables, there is a transition back to a single 25Ω coax and to the load resistor through the exponential impedance transformer.

12.7 Risks

12.7.1 Performance Risk

The kicker system will be designed to provide an integrated field of 1447 G-m for the duration of the length of the injected muon pulse (~ 120 ns), and then drop to zero field, 149ns after the first muons entered the ring. Failure to achieve the specified field value will result in reduced muon capture efficiency and increased coherent betatron oscillation of the muons that are captured. Failure to turn off after 149 ns will likewise compromise capture efficiency and contribute to coherent betatron motion. The risk of less than optimal system performance are increase in statistical error (fewer muons) and additional systematic error (increased coherent betatron motion). The risk will be mitigated by extensive system testing and optimization prior to installation.

A failure of the thyatron tube, a breakdown internal to the Blumlein-PFN, or a break-



Figure 12.14: Exploded view of the impedance transformer in Figure 12.13 is shown at left. Two possible implementations of the load resistor, that is located on the axis of the transformer, are shown at right.

5067 down of the plates inside the vacuum chamber would have more catastrophic consequences,
 5068 as very few muons will store without an operational kicker. We plan to operate the system
 5069 continuously at the design repetition rate before installation into the muon ring to establish
 5070 reliability. We note that the system is designed to operate at 87 kV, approximately 10 kV
 5071 below the level at which the E821 system was limited by breakdown.

5072 There is some risk that the kicker will excite a long lived eddy current in the vacuum
 5073 chamber that will in turn generate a lingering magnetic field that will alter the muon pre-
 5074 cession frequency. We plan to calculate and more importantly measure the parasitic fields
 5075 generated by the kicker pulse and if we are unable to eliminate them entirely, to account for
 5076 them in the analysis. We are developing instrumentation for an in-situ monitor of the long
 5077 lived field.

5078 12.8 Quality Assurance

5079 The quality of the kicker system will be assured by extensive testing in advance of installation
 5080 into the ring.

5081 12.9 ES& H

5082 The kicker system will operate at high voltage ~ 90 kV, however there will be no exposed
 5083 high voltage. All external surfaces of the Blumlein will be fixed at ground potential. As
 5084 there are no diodes in the charging circuit, the time constant for dissipation of stored charge

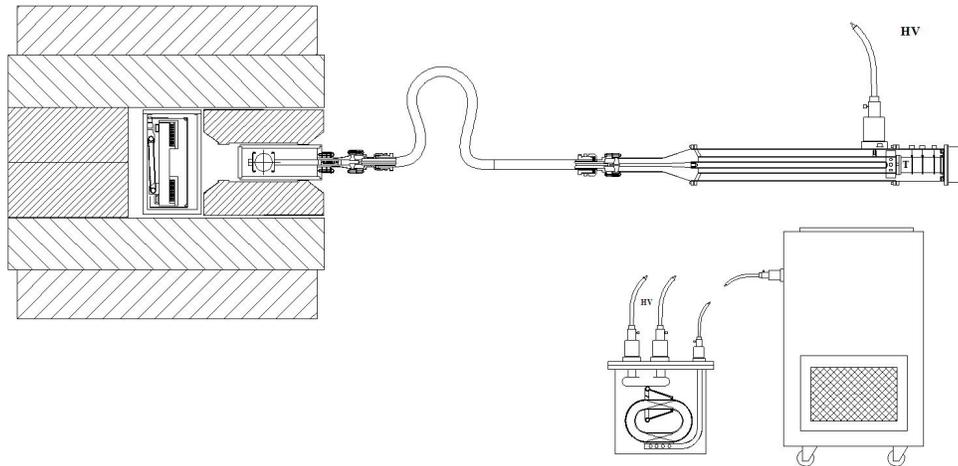


Figure 12.15: Blumlein is coupled through a pair of 25Ω high voltage coaxial cables to the kicker magnet inside the ring vacuum chamber. (Only a single coax is shown). High voltage power supply and thyatron driver are in the electronics rack at right. The 1:84 high voltage transformer that provides charging voltage to the PFN is in the oil tank to the left of the electronics rack.

5085 is a few seconds. A procedure for de-energizing in the event that disassembly is required will
 5086 be established. Each of the three Blumlein tri-axial lines will be filled with non-flammable
 5087 and nontoxic 561 silicon transformer oil. While there is the danger of a spill, (75 liters/line),
 5088 the oil itself is not hazardous.

5089 12.10 Value management

5090 We are reusing as much as possible, components from E821, in particular, the thyatron
 5091 tubes.

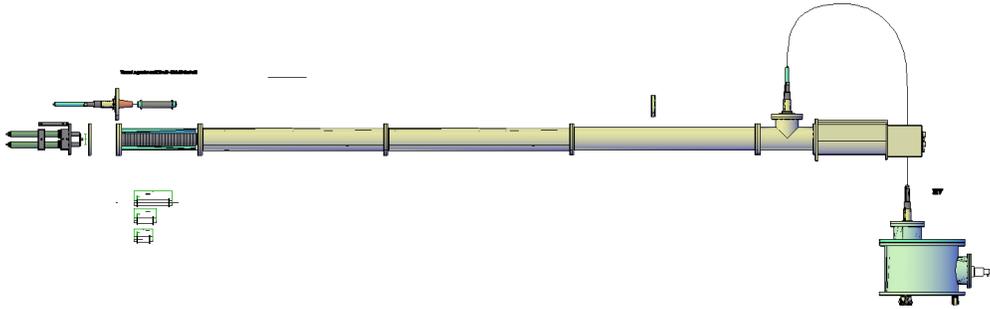


Figure 12.16: Blumlein connected to high high voltage charging transformer. Transition to dual coaxial lines is at the left.

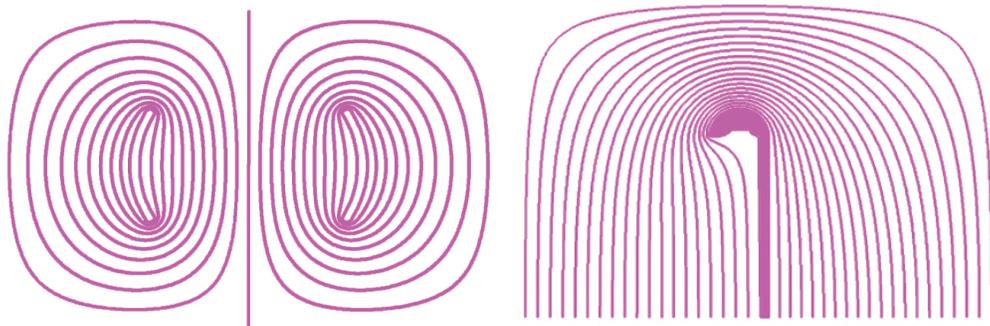


Figure 12.17: (Left) Proposed kicker plate geometry and magnetic field lines computed with MERMAID. (Right) One quadrant of the E821 kicker plate geometry and field lines. The boundary condition at the vacuum chamber surface is set to mimic effect of induced currents due to fast rise time. Note high density of field lines at the edge of the plate that also serves as the trolley rail.

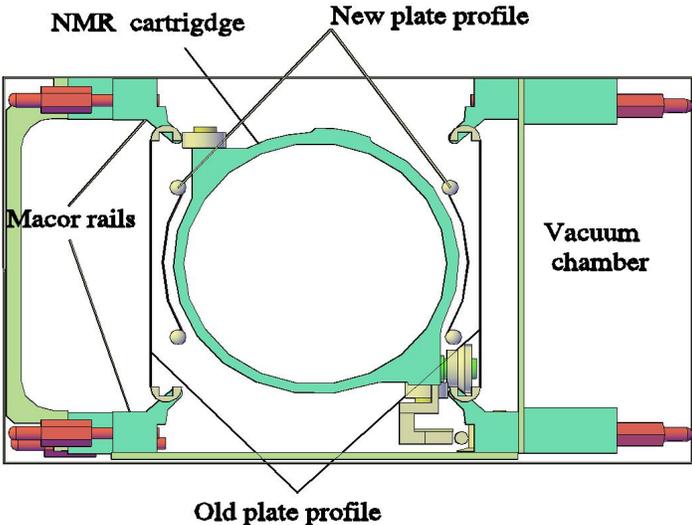


Figure 12.18: E821 kicker plates, new plates, NMR trolley, and new rails are shown in the vacuum.

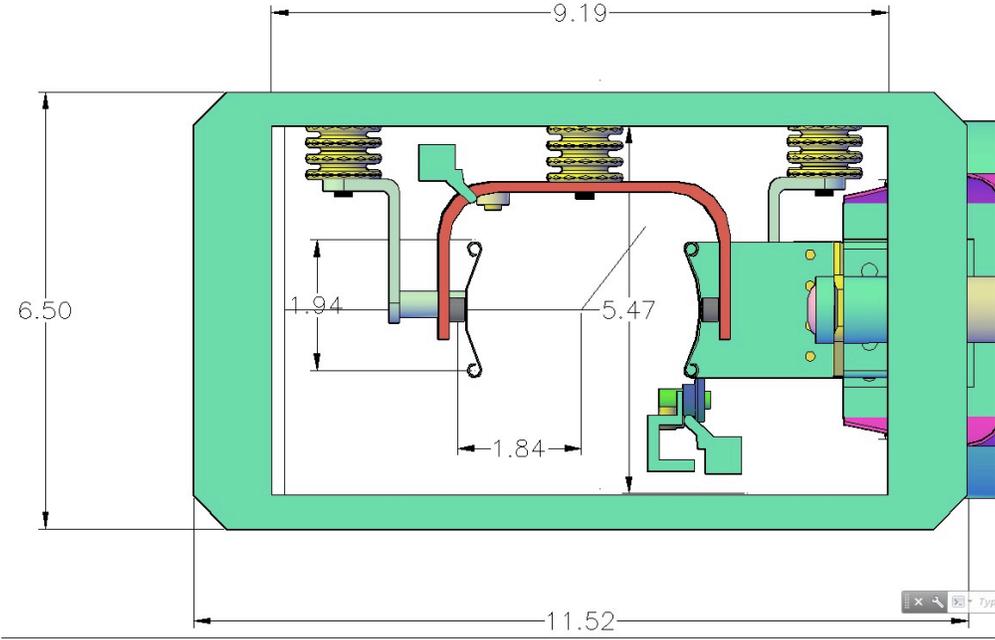


Figure 12.19: The new kicker plates hang from macor standoffs mounted on the top of the vacuum chamber. The crossover from inner to outer plate at the far end of the kicker is also shown.



Figure 12.20: (Left) Upstream end of Blumlein. The black cable attached at the top of the transition delivers the charging current. The thyatron is mounted horizontally in the far right module with the red High Voltage warning label. The space between the conductors of the Blumlein and the volume around the thyatron is filled with transformer oil. (Right) Looking from the business end of the Blumlein upstream towards the thyatron.

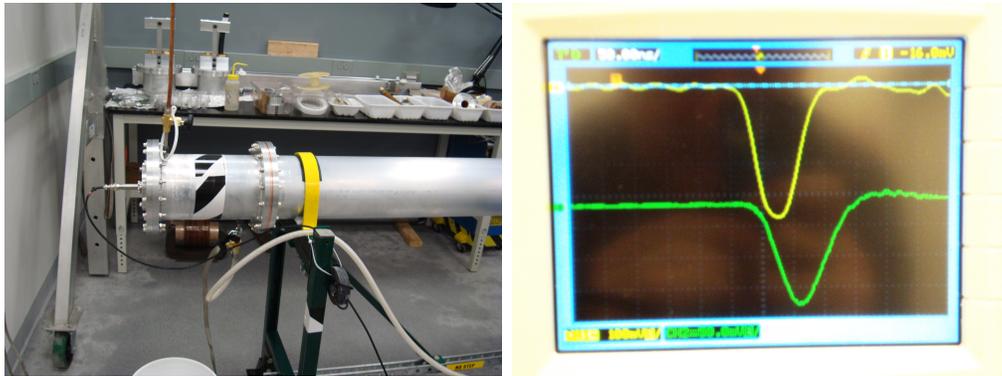


Figure 12.21: (Right) Pulse generated with Blumlein, discharged through a resistive load that is in the end section of the Blumlein (Left). The horizontal scale (hard to see) is 50 ns/division. The base of the yellow pulse is about 100 ns and the rise time 30ns. The nominal pulse width, for the 5m line and ideal switch is 50ns. The width of this pulse is dominated by the thyatron switching time. The yellow signal is from an antenna probe and the green from a somewhat slower current monitor. With 561 oil, $\epsilon = 2.7$ the pulse width ~ 50 nsec, with Castor oil, $\epsilon = 4.7$, the pulse width ~ 66 nsec. and with addition of Ferrofluid, $\mu_{eff} \sim 3$, the pulse width ~ 112 nsec.

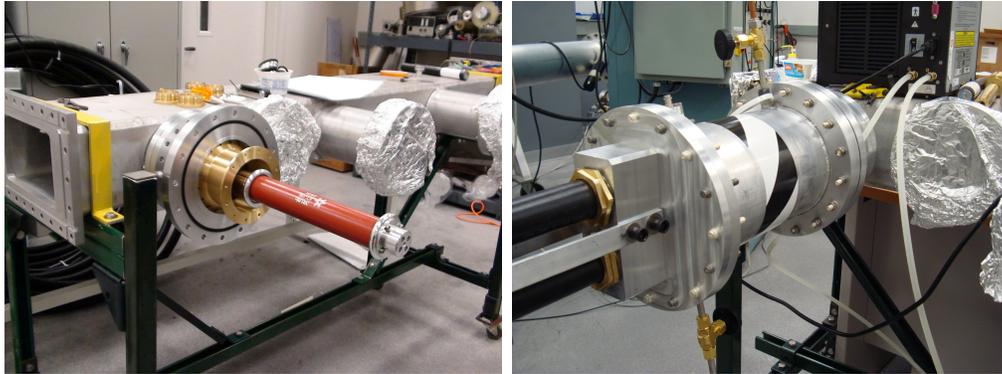


Figure 12.22: (Left) Load resistor at vacuum chamber port. (Right) The pair of coaxial cables links the Blumlein output to the load resistor (located inside the chamber with the black and white tape) and then to the kicker plates inside the vacuum chamber.



Figure 12.23: A pair of 50Ω coaxial cables couples Blumlein (background) to input to vacuum chamber (foreground)

5092 **References**

- 5093 [1] Efstathiadis E, et al. *Nucl. Inst. and Methods Phys. Res.* A496:8-25 (2002)
- 5094 [2] A.D. Blumlein, Apparatus for Generating Electrical Impulses, U.S. Patent No. 2,496,979
- 5095 Feb 7(1950).

Chapter 13

The Electrostatic Quadrupoles

13.1 Introduction

One of the ways to be able to store a significant number of muons in the storage ring is to use electric focusing quadrupoles (ESQ) and muons at their magic momentum of about 3.09 GeV/c. At that momentum the radial E -field precesses the muon momentum and the muon spin vectors at exactly the same rate and thus it does not influence the $(g - 2)$ precession frequency. The method was first used in the last muon $(g - 2)$ experiment at CERN [1], and in E821, the muon $(g - 2)$ experiment at BNL [2]. We have also decided to use it for E989, the FNAL experiment, after we have carefully considered alternatives, e.g., weak magnetic focusing, and alternating skew electrostatic quad focusing. However, we found the present scheme, used in E821, to be preferable.

The principal characteristics of the design are similar to the E821 ESQ described in [3]. In the present document we are going to describe them and include the main points that aim to improve the muon ring acceptance and reduce muon losses as well as certain systematic errors associated with the coherent betatron oscillation frequencies. Fig. 13.1 shows a schematic of the top view of the muon $(g - 2)$ ring and the vacuum chambers indicating the azimuthal coverage of the quadrupoles in E821. The total azimuthal coverage is kept at 43%, keeping a four-fold symmetry with segment names of Q1, Q2, Q3, and Q4. Each quad segment consists of a “short” quad of 13° and a long one of 26° , see Fig. 13.2, for two reasons: 1) to make every quadrupole chamber independent of others, facilitating their development, testing, etc., and 2) to reduce the extend of low energy electron trapping. Therefore there are two high voltage vacuum-to-air interfaces for each segment.

The maximum voltage we used during the muon runs on the ESQ of E821 was 25.4 kV resulting to a field focusing index of 0.144. We now plan to raise the maximum voltage to 32 kV for a field focusing index of $n = 0.18$. At 0.18 the following things we expect to happen:

1. Increase the ring admittance and most likely the muon storage efficiency.
2. Reduce the muon losses during storage.
3. Reduce the coherent betatron oscillation (CBO) systematic error.

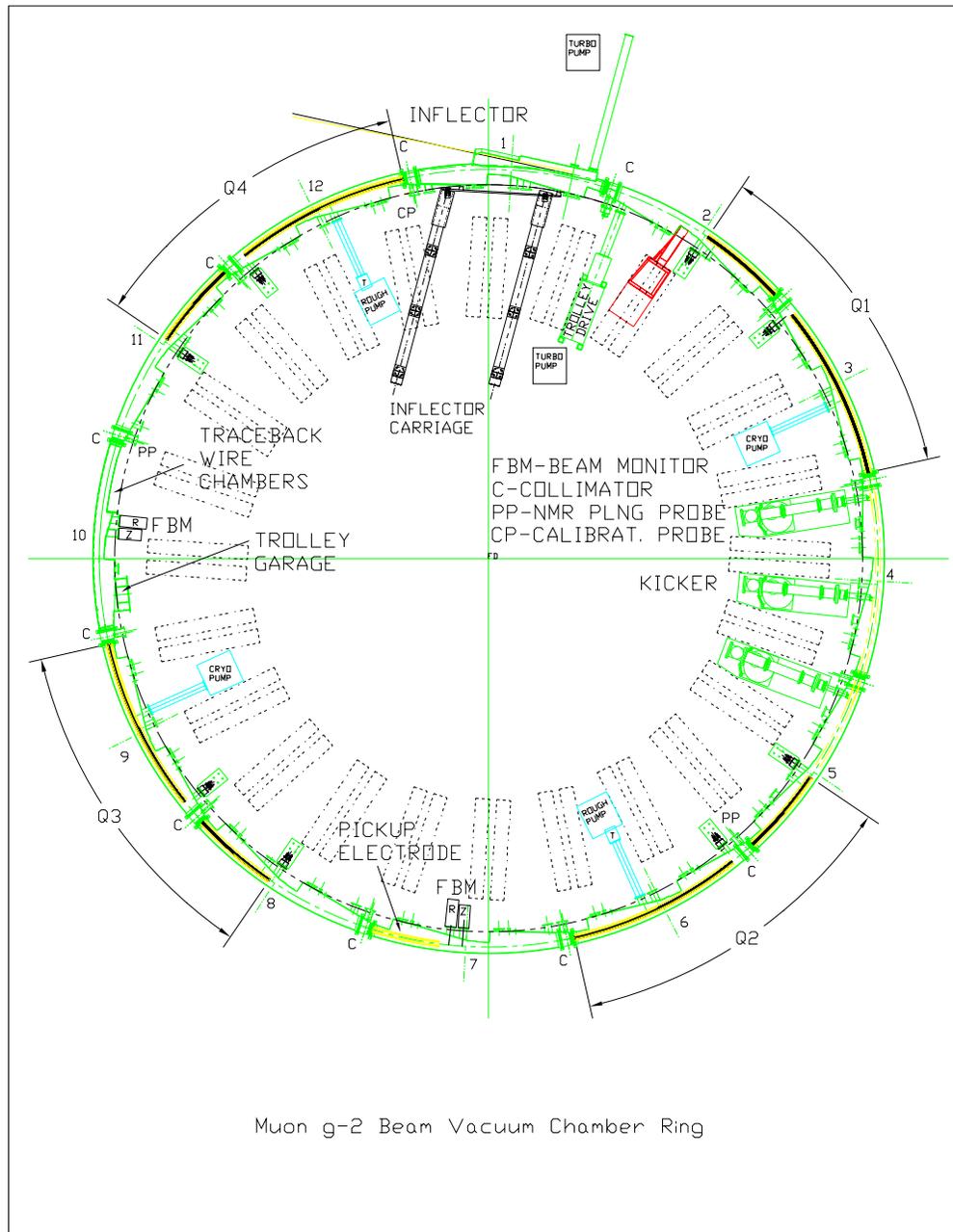


Figure 13.1: A schematic of the muon ($g-2$) ring as well as the location of Q1, Q2, Q3, and Q4, the four-fold symmetric electrostatic focusing system.

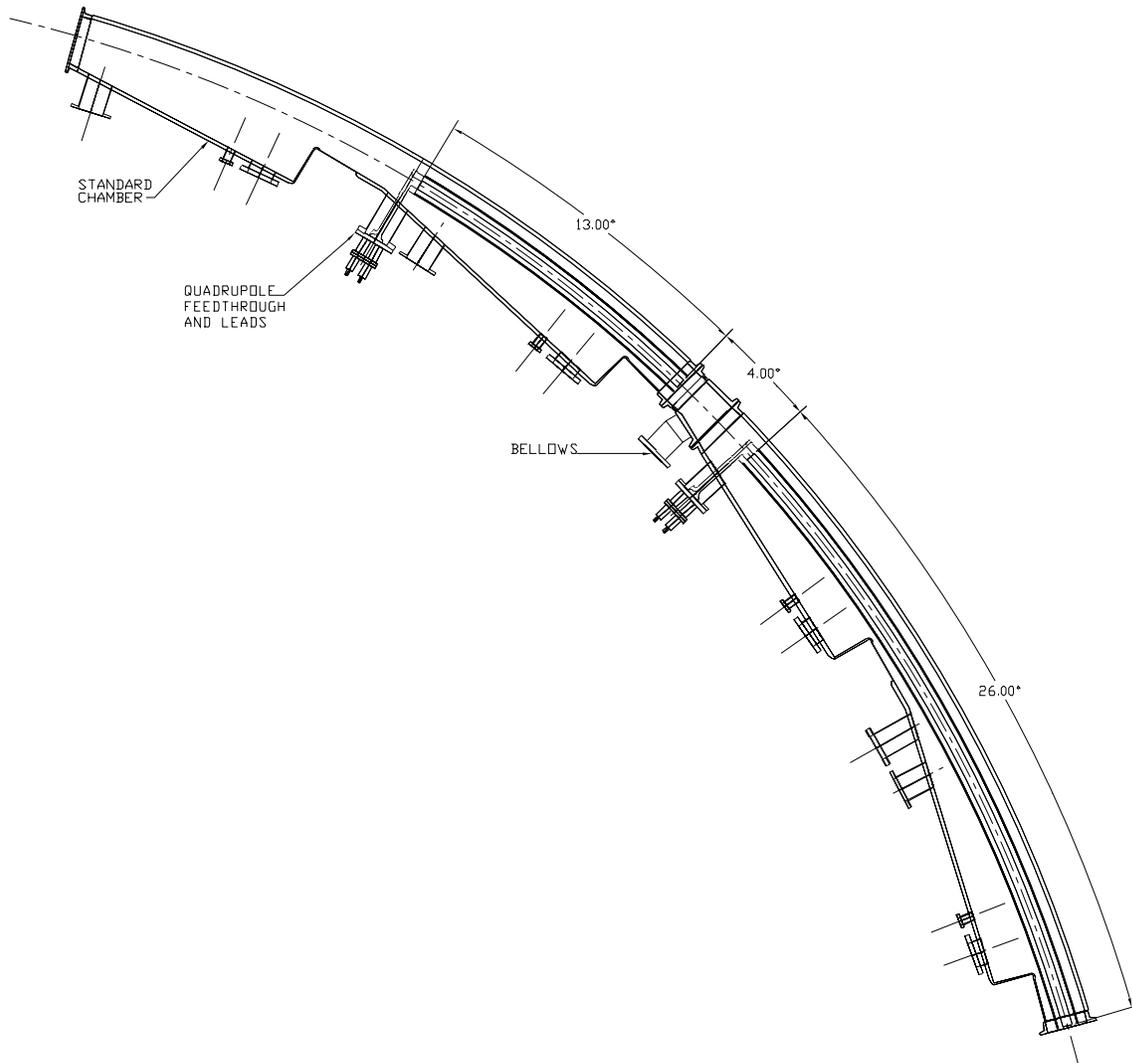
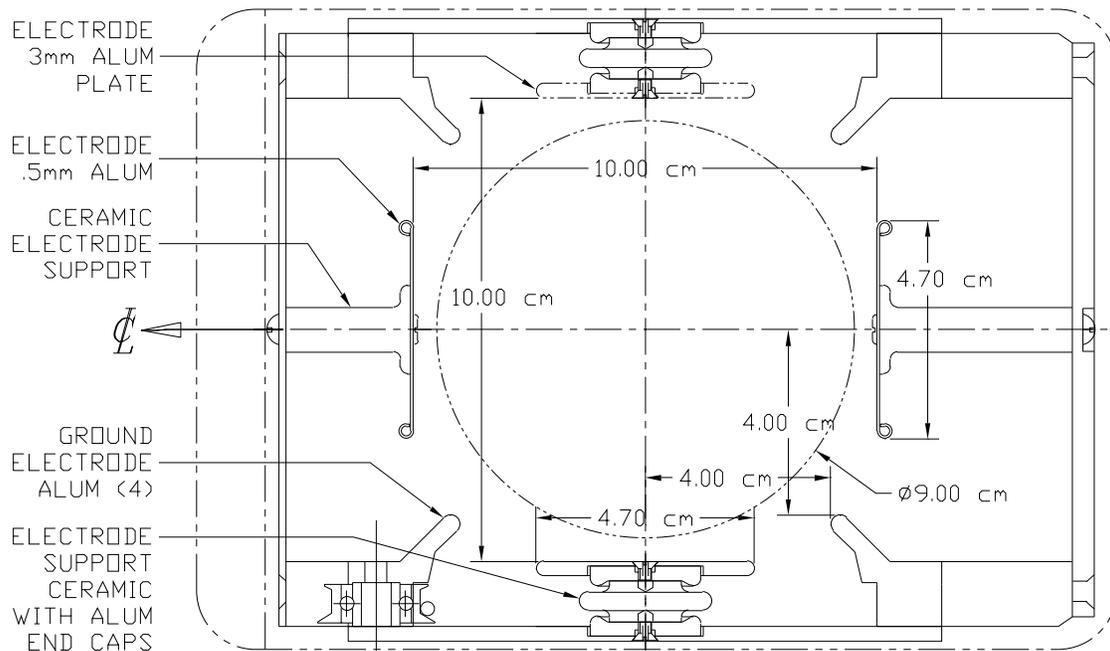


Figure 13.2: A schematic of a short quad of 13° , and the adjacent long one of 26° is shown here. The high voltage feeding leads break the quad symmetry at the upstream end of the plates to quench the low energy electron trapping and guide them outside the magnetic field region, where they can be released. Some of the bellows were equipped with collimators where the muon beam was scrapped immediately after injection.

5126 We will test the quads up to 35 kV, about 10% higher voltage than the anticipated
 5127 nominal voltage level, in order to substantially reduce the required number of pulses to be
 5128 applied for a successful testing. A large number of improvements will be implemented to
 5129 the new system based on the experience we accumulated running the quadrupole system for
 5130 E821. They are discussed later on in this chapter.

5131 13.2 E821 Design and Limitations

5132 The cross-section of the quadrupoles is shown in Fig. 13.3 with the various dimensions
 5133 indicated in the figure. The ESQ consist of four aluminium plates symmetrically placed
 5134 around the muon storage region. The placement accuracy was 0.5 mm for the horizontal
 5135 (top/bottom) quad plates, and 0.75 mm for the vertical (side) quad electrodes. When
 5136 measured by the surveyors they were found to be well within those values.



ELECTRODE AND SUPPORT FRAME - END VIEW

Figure 13.3: A schematic of the quadrupole cross-section. The rails in the corners are kept at ground potential. Most of the support insulators are replaced with uniform diameter insulators of 0.5 cm.

5137 Fig. 13.4 shows a picture of the quadrupoles at the downstream end of one chamber.
 5138 The main issue in E821 was to be able to hold the high voltage without sparking for about

5139 1 ms. This is a very demanding task, especially for storing negative polarity muons, due
5140 to low energy electron trapping in the quad region. We were able to achieve this task by
5141 designing the HV feeding leads in a way to quench the low energy electron trapping, see
5142 Figs. 13.5, 13.6, 13.7.

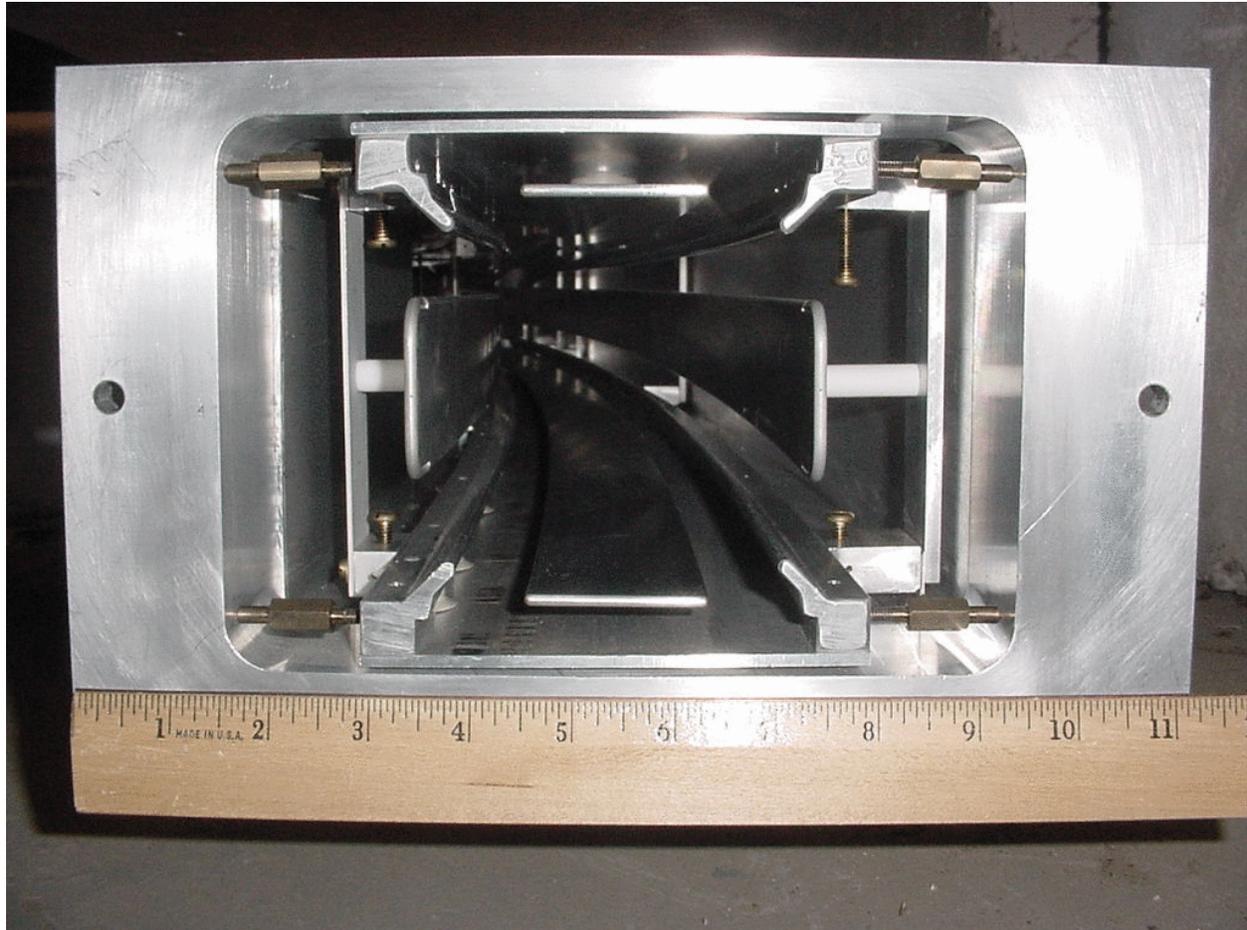


Figure 13.4: A photograph of the downstream end of a vacuum chamber with the cage and quads showing.

5143 Fig. 13.8 shows the schematic of the HV pulsing system. Two of the quadrupoles were
5144 used to scrape the injected beam horizontally, by moving the beam sideways [3], while all the
5145 quadrupoles were used to scrape the beam vertically [3]. The HV monitor location is also
5146 indicated. Fig. 13.9 shows the (home-made) HV monitors output waveforms as recorded by
5147 an oscilloscope.

5148 The great success of the quadrupole system is based on the fact that it allowed the storage
5149 of positive and negative muons for more than 0.75 ms in the storage ring, even though
5150 the azimuthal quad coverage was almost half that of the last muon ($g - 2$) experiment at
5151 CERN. The vacuum requirements were in the low 10^{-6} Torr for the positive muons and
5152 low 10^{-7} Torr for the negative muons. Higher vacuum pressures were tolerated for limited
5153 operation periods. Those requirements allowed a speedy recovery after any unavoidable
5154 opening up of the vacuum chambers during the initial stages of the runs, related mostly to

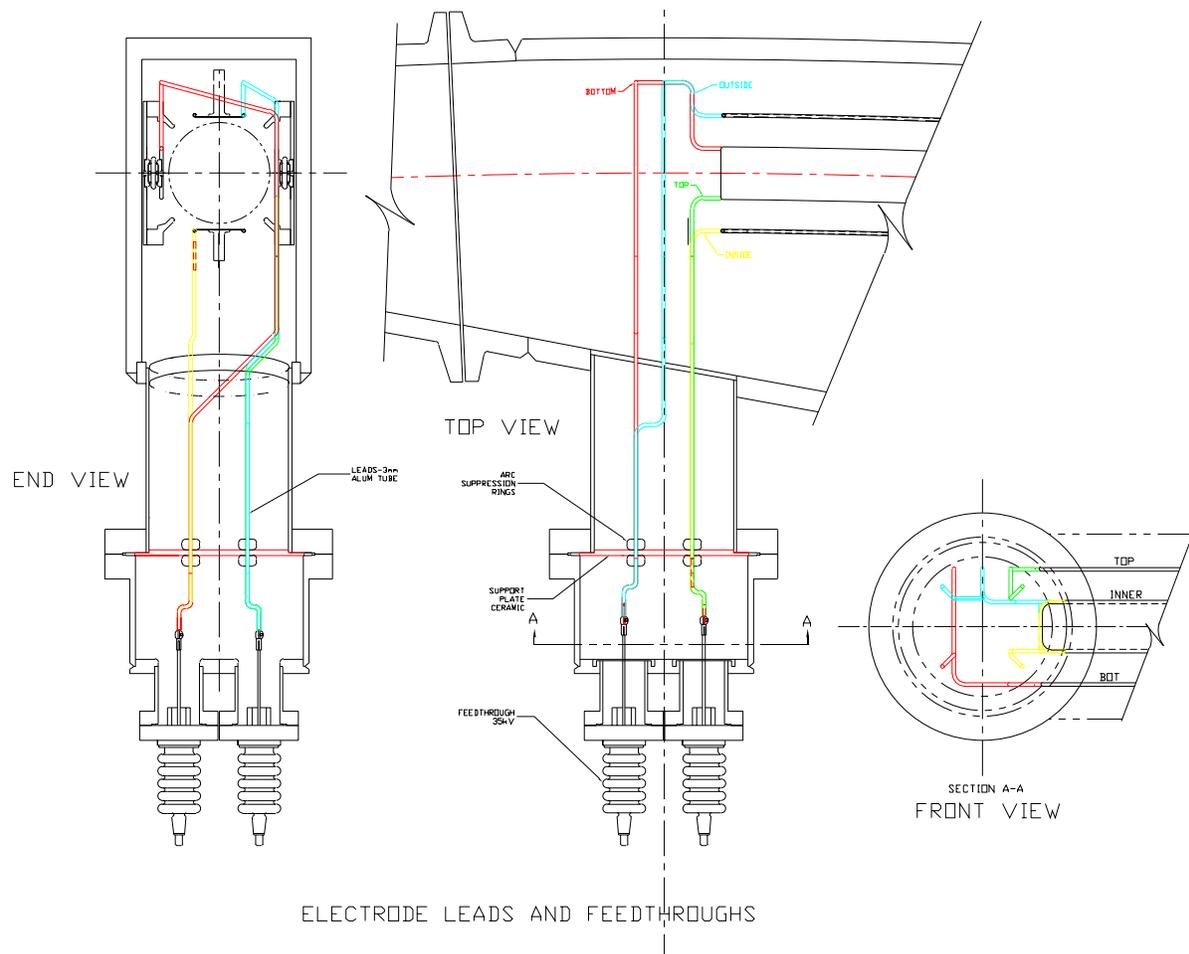


Figure 13.5: Various aspects of the quadrupole high voltage feeding lead geometry, designed to minimize low energy electron trapping.

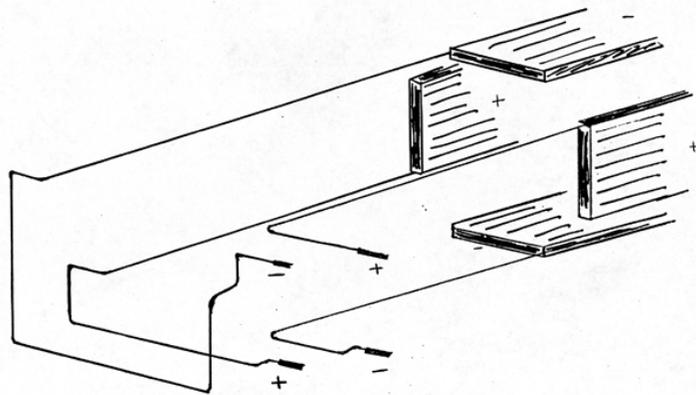


Figure 13.6: Early stages of a hand drawing indicating the high voltage feeding lead geometry.

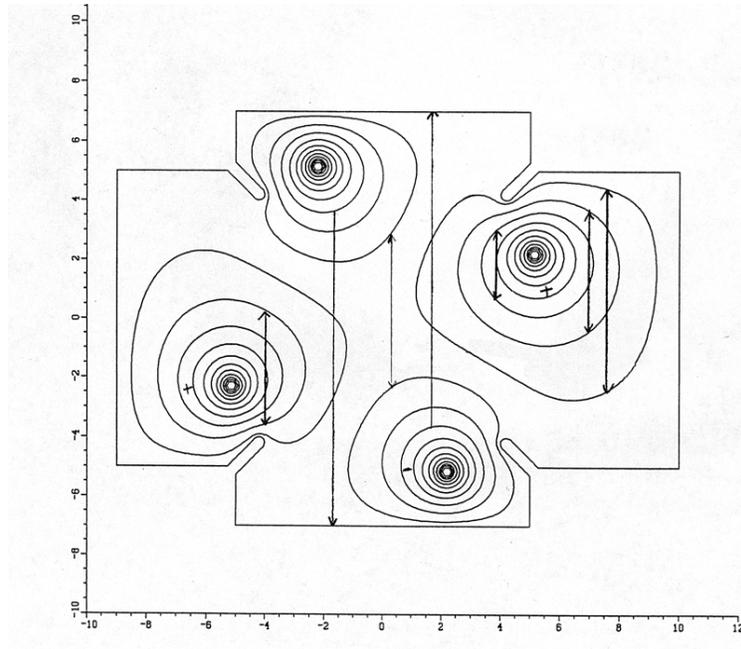


Figure 13.7: A cross section of the lead geometry (vertical [cm] vs. horizontal [cm]). The schematic showing the equipotential lines as well as the low energy electron trapping regions. The lead-geometry was designed to optimize the quenching of the electron trapping for the negative muon storage polarity.

5155 issues other than the quadrupole operations.

5156 For E989 we focus on positive muon storage only, due to the following advantages:

- 5157 • It allows us to improve the E -field quality by restoring the normal quadrupole field in
5158 the lead region. The plan is now to connect the leads at the center of the plates, expose
5159 the E -field from the leads for a couple of centimeters, and then hide them behind a
5160 ground shield. The aim is to shield the muon storage region from the E -field generated
5161 by the leads. Space is very tight at this location, so we will work very carefully to
5162 avoid sparking.
- 5163 • We will be able to raise the high voltage and keep it there for longer times, which
5164 may have an impact on the muon lifetime measurement or other systematic error
5165 measurements.
- 5166 • For E821 the quadrupoles required a lengthy conditioning period (a couple of hours,
5167 depending on pressure) after every trolley run. For positive muon storage plus an au-
5168 tomated conditioning system we expect to minimize this recovery time by a factor of
5169 two to three. Quadrupole conditioning is much more straight forward in the positive
5170 polarity than in the negative polarity. The main reason is that in the negative polarity
5171 the support insulators are intercepting the low energy trapped electrons, which, de-
5172 pending on the trapping rate, could cause sparking. The conditioning process in the
5173 negative polarity was very delicate and lengthy. One of the possible models why it even

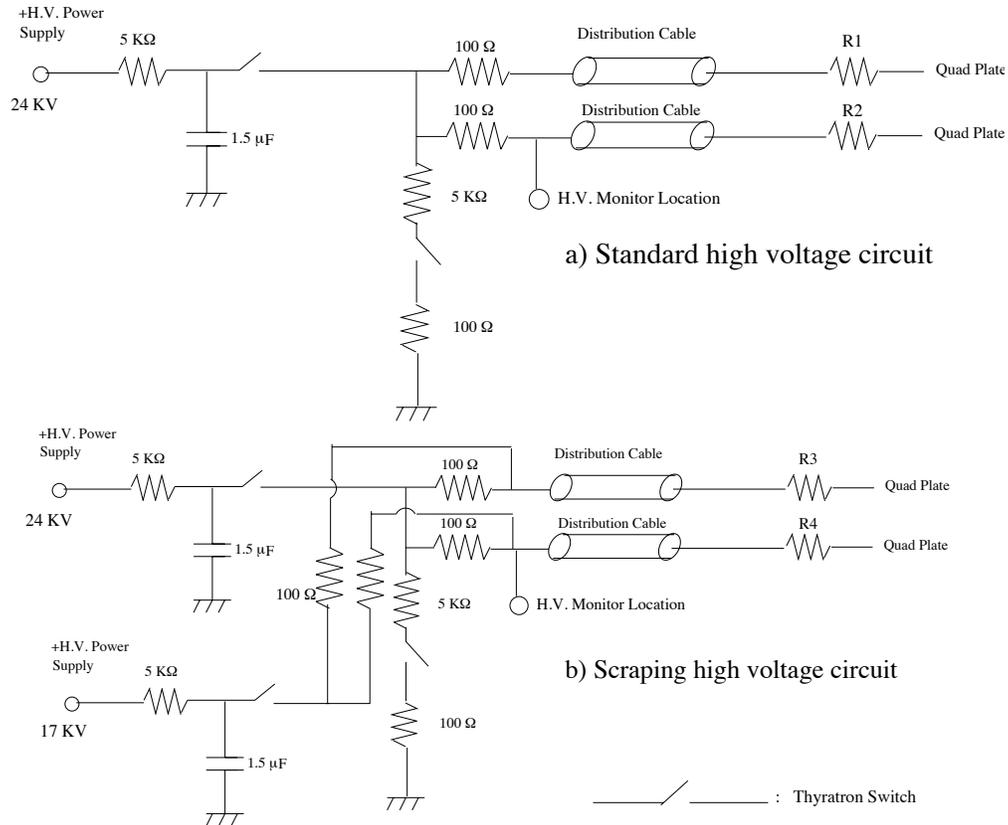


Figure 13.8: A schematic of the scraping and normal HV pulsing systems. The Thyatron switch model used in E821 was the CX1585A from eeV, good to 40 kV.

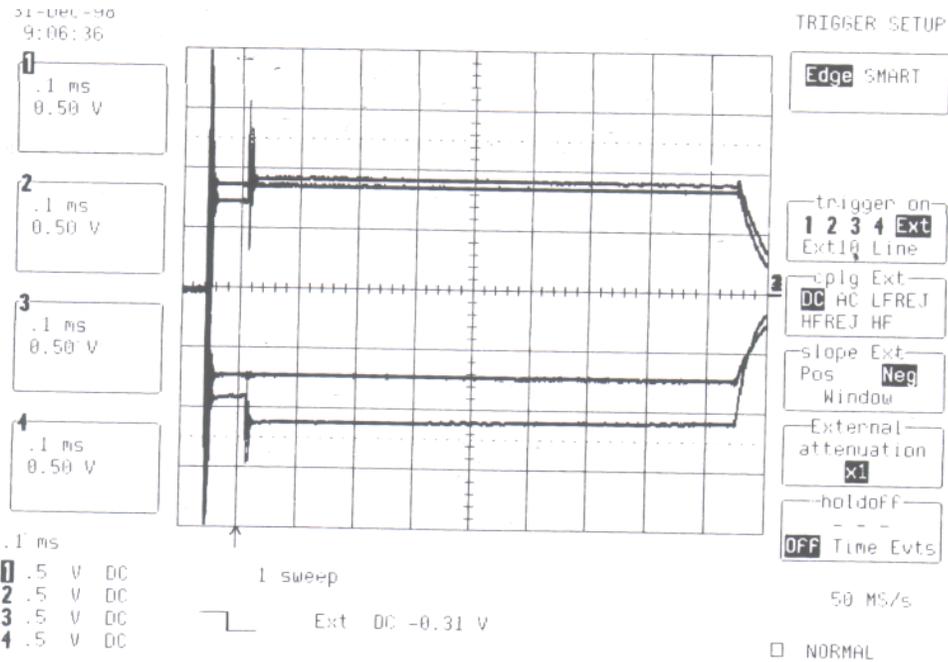


Figure 13.9: The output of the HV monitors as recorded by the oscilloscope.

worked was that the slow conditioning creates a thin conducting layer on the insulator surface, allowing them to slowly move and thus avoid accumulating a critical level. For the positive polarity there are no insulators in the way of the trapped electrons. We will write a computer software program that will be able to condition the quadrupoles taking into account the vacuum pressures and sparking history.

- For positive muon storage we expect the voltage on the plates to be more stable as a function of time and from pulse to pulse.

Table 13.1: Comparison of high- n and very high- n values.

Parameter	$n=0.142$	$n=0.18$
ν_x	0.926	0.906
ν_y	0.377	0.425
f_{CBO}	495 kHz	634 kHz
f_{CBO}/f_a	2.15	2.76
$1/(f_{\text{CBO}} - 2f_a)$	$27\mu\text{s}$	$5.7\mu\text{s}$
HV	25 kV	32 kV

For E989 we require improvements in a number of areas:

1. Operate the quadrupoles at a higher n -value to primarily change the horizontal coherent betatron oscillations (CBO) frequency away from near twice the muon ($g - 2$) frequency. The CBO frequency, being very close to twice the ($g - 2$) frequency, see Table 13.1, pulled the ($g - 2$) phase and was a significant systematic error that required special attention during data analysis. We target to operate at $n = 0.18$ to reduce it by more than a factor of three. Other improvements, e.g., properly matching the beam-line to the storage ring (requiring a proper inflector channel) is expected to reduce it by at least another factor of three. Overall the CBO systematic error can be reduced to a level required by E989.
2. Reduce the muon losses by more than an order of magnitude to reduce the muon losses systematic error. We will achieve this goal by moving the operating point to $n = 0.18$, beam scraping by 2 mm in the horizontal and vertical directions after injection, and by keeping the radial B -field below 50 ppm (this level of radial B -field displaces the average vertical position by about 2 mm). The region around $n = 0.18$ is more resonance free than the previous n -values we ran with, see Fig. 13.10. We will refine the quadrupole operating mode by running precision beam dynamics tracking simulations to more accurately predict the muon population phase-space after scraping.
3. Shield the muon storage region from the modified quadrupole field due to the HV feeding lead geometry. This region is less than 5% of the good quad coverage around the ring, but it can still influence the muon loss rate.
4. The quadrupole voltage monitors were home-made with limited success in achieving an adequate frequency compensation. We now plan to equip every quad plate (32 in

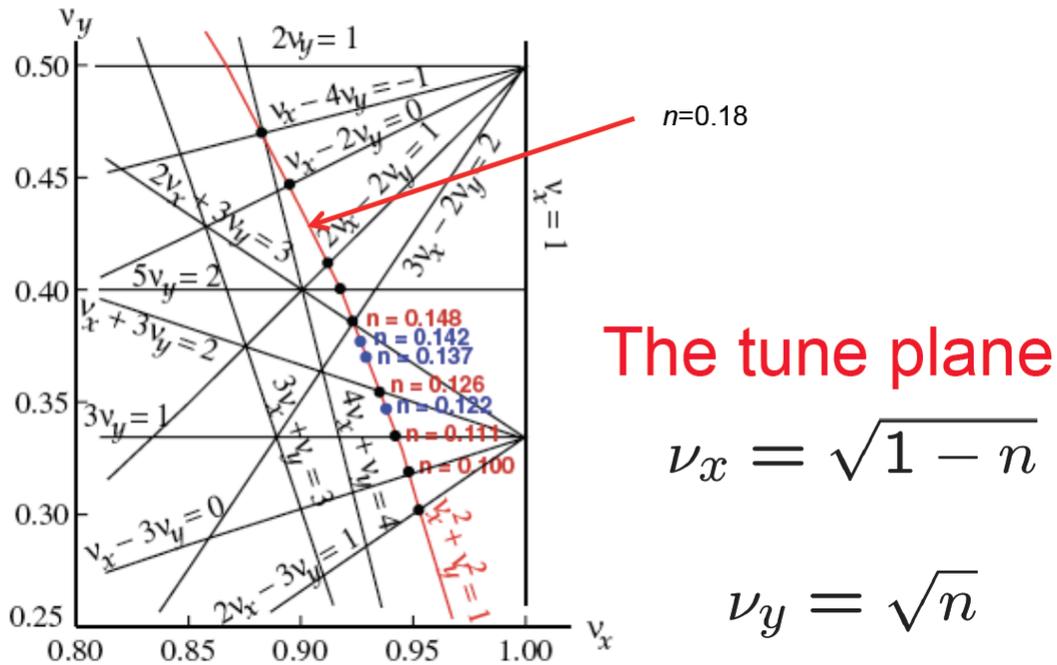


Figure 13.10: The vertical vs. horizontal tune plane together with a number of potential resonance points. The value $n = 0.18$ is on the red line and in the middle between the resonance lines $\nu_x - 2\nu_y = 0$ and $2\nu_x - 2\nu_y = 1$.

5204 total) with a commercially available frequency compensated HV monitor. This will
 5205 improve the voltage stability readout by an order of magnitude. In addition, we will
 5206 cross-calibrate the frequency compensation of each monitor with the electric field in
 5207 the quad region measured using the Kerr effect.

5208 5. Improve the reliability of the HV-vacuum interface regions with a goal of reducing
 5209 sparking by at least an order of magnitude. The base design is to cover the interface
 5210 in oil capable of holding high electric fields. Alternative design calls for increasing the
 5211 spacing between positive and negative leads in the air side of the interface.

5212 6. The outer Q1 plate and support insulators are estimated to have reduced the stored
 5213 muon population by about 40%. We now plan to address the muon loss issue by a
 5214 number of alternative modifications. Currently the baseline is to relocate the outer Q1
 5215 from $x = -5$ cm to $x = -7$ cm to allow for the uninhibited injection of the muon beam.
 5216 Fig. 13.11 shows the OPERA model of the quadrupole plates in a quadrupole cage. The
 5217 plate width is adjusted so that only the normal quadrupole field is dominant, and the
 5218 20-pole is kept at the 2% level. Every other multipole is below 0.1%, including the
 5219 sextupole, octupole, etc. Fig. 13.12 shows the current plan for providing a “massless”
 5220 outer Q1 plate, by placing it outside the muon path. In order to restore an acceptable
 5221 field quality, the plate voltage also needs to be raised by about a factor of two, see
 5222 Fig. 13.13. Another parameter we can use to improve the field quality is to work with
 5223 the plate geometry (width, shape, etc.). The requirement of increasing the voltage by

5224
5225

a factor of about two we believe we can achieve in the positive muon polarity and we will test it with the setup planned at BNL.

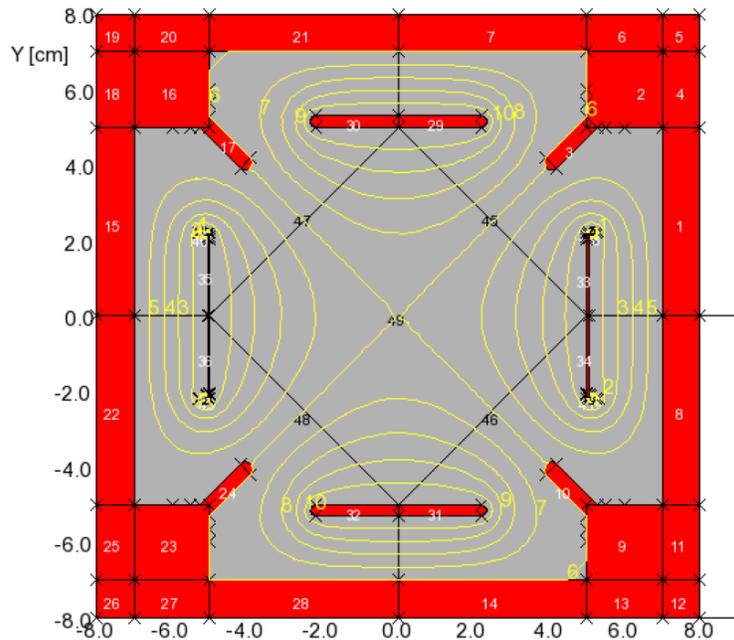


Figure 13.11: An OPERA model of the (normal: Q2, Q3, and Q4) electrostatic quadrupole plates. The top/bottom plates are at a positive voltage and the side electrodes are at (the same) negative voltage. The yellow curves represent the equipotential lines.

5226

7. Measure the plate vibration during pulsing and stiffen the plate support as needed.

5227

13.3 Improvements that Permit Higher n -Value Operation

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5229

Quad upgrade and testing with the aim to produce an ESQ focusing system that maximizes muon statistics and minimizes potential systematic errors. Fig. 13.14 shows one segment of the muon ($g - 2$) electrostatic quadrupoles at BNL outside its vacuum chamber.

5232

Vladimir Tishchenko is the L3 manager for the ESQ system and Yannis Semertzidis was the former L3 manager for the same system. The ESQ system currently consists of 8-chambers, 4-pulsers systems, 6-HV-power supplies, and a HV monitoring system:

5234

5235

- Refurbish the H.V. pulsers to operate at a maximum voltage of ± 35 kV, from the present ± 25 kV used in E821. The side insulators are all varnished during the negative muon operation at BNL, see Fig. 13.15. The insulators will be either cleaned or will be replaced by new ones.

5236

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- Utilize a C-magnet at BNL to imitate the conditions of running the ESQ in the muon ($g - 2$) magnet as closely as possible. For practical reasons we can only test the half-scale

5240

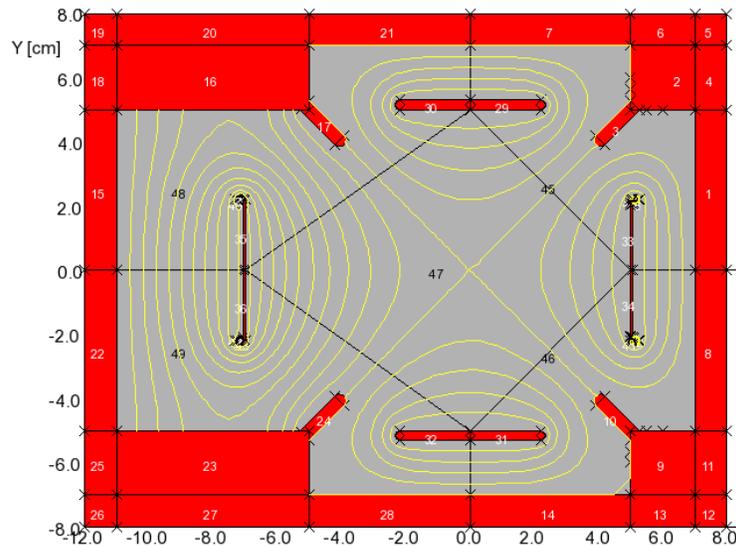


Figure 13.12: An OPERA model of the electrostatic quadrupole plates for Q1. The left plate is displaced to the outside by 2 cm to allow the muons to enter the storage region without having to cross the plates or the support insulators. In order to restore a good field quality (indicated by the symmetric equipotential lines in the center region), the voltage on the left plate is about twice that on the right plate.

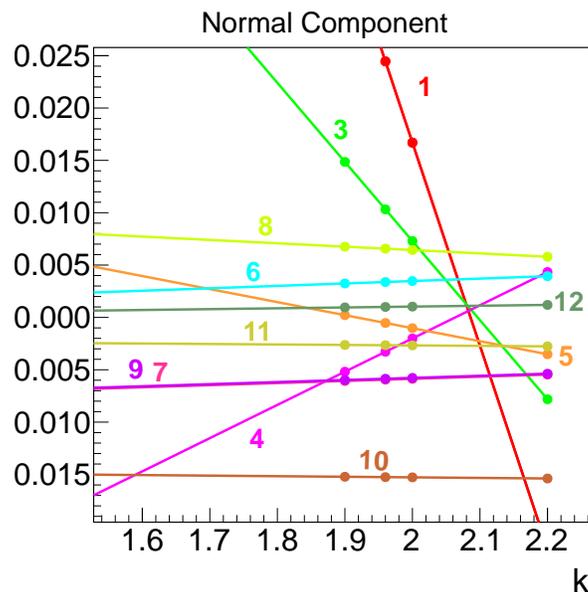


Figure 13.13: Results from OPERA as a function of the voltage multiplication factor for the displaced (outer Q1) plate. Most of the multipoles are below 0.5% but not all. Next we will study the effect of the plate shape on the multipoles.



Figure 13.14: One cage (placed here up-side-down) that holds the plates of the electrostatic quadrupoles of the muon ($g - 2$) experiment.

- 5241 quadrupoles, as the (straight) C-magnet under consideration could not accommodate
5242 the full scale quads, see Fig. 13.16. We will be able, however, to extrapolate to the full
5243 quads by placing stricter requirements on the vacuum pressure.
- 5244 • Optimize the ESQ for positive polarity muon storage. The leads will be re-configured
5245 to quench the low energy electron trapping more efficiently aiming to achieve higher
5246 electric field gradient by 30% compared to E821. Achieving this goal will help eliminate
5247 the CBO systematic error as well as substantially reduce muon losses.
 - 5248 • Expand the H.V. vacuum chamber/air interface tube aiming to significantly reduce the
5249 sparking in the vacuum side of the leads.
 - 5250 • Modify the geometry of the H.V. -vacuum interface to reduce sparking in the air side
5251 of the H.V. lead system or immerse it in oil that can withstand the E -field strength.
5252 The later is applied routinely in H.V. applications but it is harder to gain access to it.
5253 The sparking rate in the positive polarity in E821 was dominated by sparks at those
5254 locations (approximately one spark per 0.5-1 million pulses).
 - 5255 • Shield the electric field generated by the leads from the muon storage region.
 - 5256 • Measure or place strict limits on the magnetic field generated by the trapped electrons.

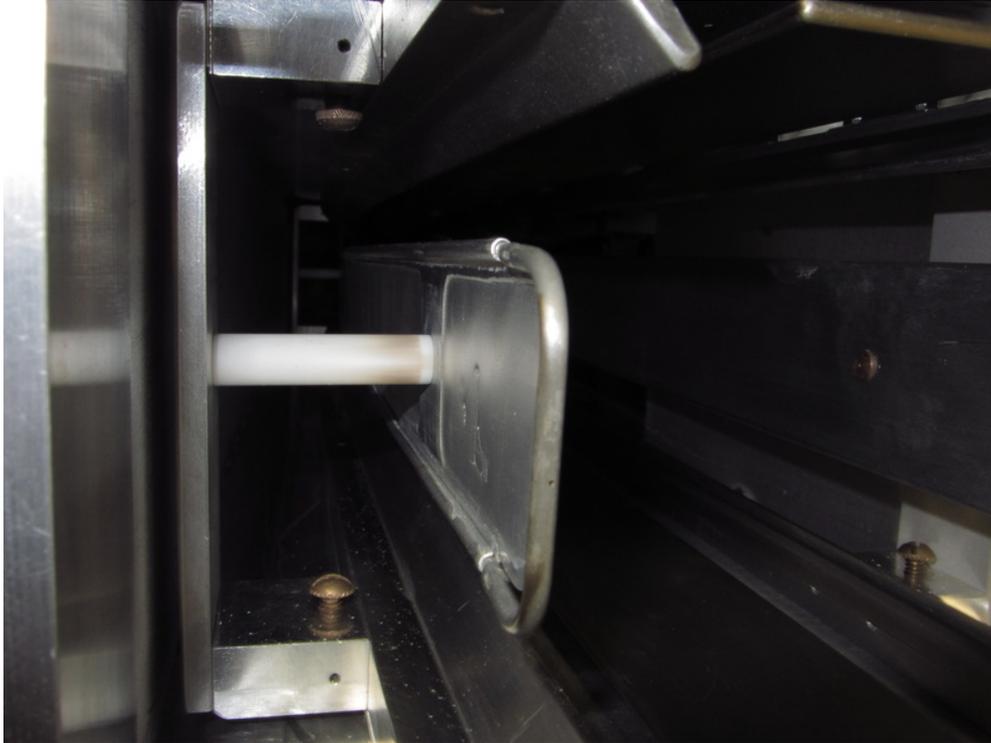


Figure 13.15: The side support insulators are varnished due to trapped electron obstruction during negative muon operations at BNL.

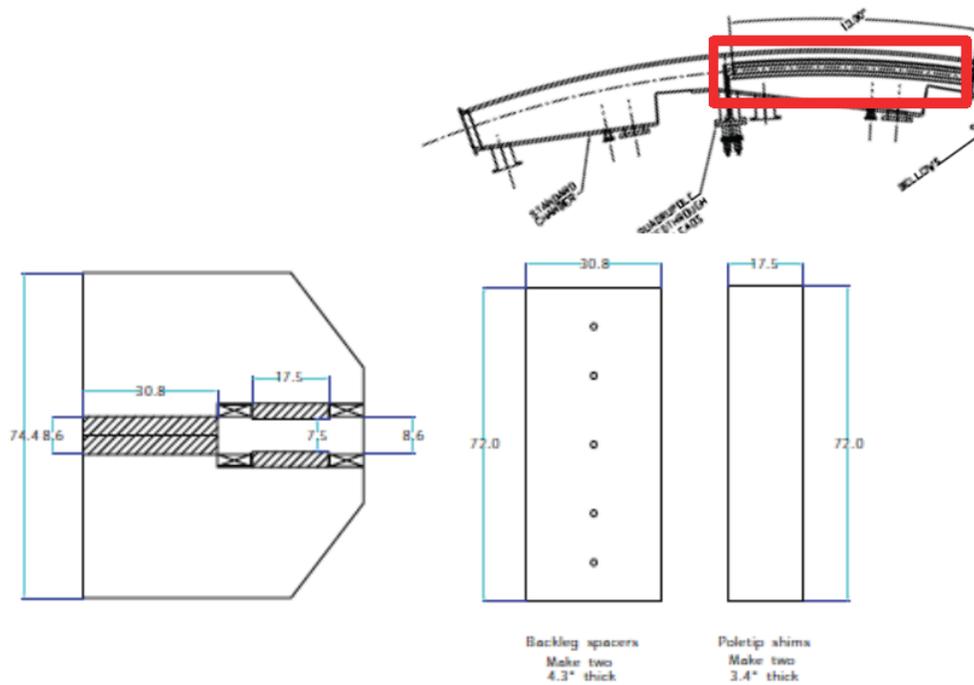


Figure 13.16: A C-magnet is being prepared at BNL for testing the quad upgrades. The magnet can fit the short quads but it requires shortening the plates by about 20 cm (for testing purposes only).

- 5257 • Calibrate the pulse shape output of the commercial H.V. monitors by measuring the
5258 electric field generated by the plates using the Kerr effect. The bandwidth (BW) of
5259 the Kerr effect measurement is in the GHz range and therefore it is not limited by
5260 the level of frequency compensation due to the large capacitance of the components
5261 involved.

- 5262 • Measure the vibration parameters of the quadrupole plates when pulsed using a laser
5263 light and a split diode detector. The quad plates can flex under the electromagnetic
5264 forces when pulsed. This flexing is (crudely) estimated that it can be of order of 10 mm
5265 if the pulse duration is of order 1 s. However, for 1 ms the plates can only move by
5266 about 10 μm , much below our specs. We will setup a laser system to measure the plate
5267 motion due to the impulse of the electrostatic pulse.

5268 13.3.1 Coherent Betatron Oscillations

5269 The average position and width of the stored beam can vary as a function of time as the
5270 beam alternately focuses and defocuses in the ring. This is the result of a mismatched
5271 injection from the beam-line into the $(g - 2)$ ring via a narrow line, the so-called inflector
5272 magnet. This imposes an additional time structure on the decay time spectrum because the
5273 acceptance of the detectors depends on the position and width of the stored muon ensemble.

5274 The CBO frequency in E821 was close to the second harmonic of ω_a , so the difference
5275 frequency $\omega_{\text{CBO}} - \omega_a$ was quite close to ω_a , causing interference with the data fitting procedure
5276 and thereby causing a significant systematic error. This was recognized in analyzing the E821
5277 data set from 2000. In the 2001 running period the electrostatic focusing field index was
5278 adjusted to minimize this problem. This greatly reduced the CBO systematic uncertainty.
5279 We will follow this strategy again but this time we will increase the quad voltage by another
5280 30% to decrease the CBO systematic error by more than a factor of three, see Fig. 13.17.

5281 In addition, the anticipated new kicker pulse shape will better center the beam on orbit.
5282 On the detector side, we plan to increase the vertical size of the detectors compared to E821
5283 (from 14 to 15 cm). This reduces the fraction of lost electrons passing above or below the
5284 detector, and therefore the sensitivity of the detector acceptance to beam position and width.

5285 In an ideal world, where the detector resolution is uniform around the ring, the CBO
5286 systematic error averages to zero when all the detected positron pulses are summed up.
5287 However, for E821 the kicker plate geometry broke significantly the detector resolution sym-
5288 metry around the ring resulting to a non-zero average. With the new design we expect to
5289 significantly restore this symmetry.

5290 The combined efforts should reduce the CBO uncertainty by at least a factor of 4 to well
5291 below 0.02 ppm. If a new, more appropriate inflector with wider horizontal aperture is used,
5292 then it is feasible to eliminate the CBO systematic error to well below our sensitivity level.

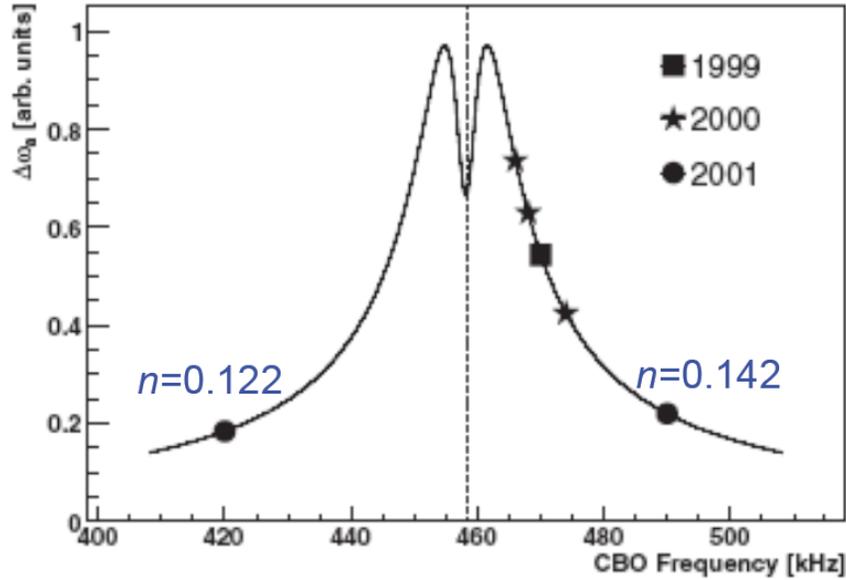


Figure 13.17: The CBO systematic raw error (arbitrary units) as a function of CBO frequency. The year notation indicates the frequencies ran with in E821. For E989 we plan to use much higher field focusing index (see quad section) with a projected CBO frequency of 634 kHz. This frequency will significantly reduce the CBO systematic error.

13.3.2 Electric Field and Pitch Correction

5293

5294 With a vertical magnetic field B_y and radial electric field E_r , the precession frequency is
5295 given by

$$\omega_a = -\frac{q}{m} \left[a_\mu B - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \beta E_r \right]. \quad (13.1)$$

If B_y and E_r vary with position, the time averages $\langle B_y \rangle$ and $\langle E_r \rangle$ should be used. At exactly the magic momentum the effect from E_r is zero. Muons of slightly higher momentum δp have an equilibrium orbit

$$x_e = \frac{R_o}{1 - n} \cdot \frac{\delta p}{p}.$$

5296

5297 As they oscillate about this equilibrium orbit they experience a mean electric field $\langle E_r \rangle =$
5298 $n(\beta B_y / R_o) x_e$ and their deviation from the magic momentum is proportional to x_e . This
5299 leads to a correction to ω_a proportional to x_e^2 . In this experiment n is measured from the
5300 observed horizontal betatron frequency, and the distribution of muons with respect to x_e is
5301 found from the modulation of counting rate by the rotation frequency of the muon bunch.
5302 The observed value of $\langle x_e^2 \rangle$ was confirmed by simulation. The correction is +0.46 ppm.

5303

5304 With electric focusing, the plane in which the muon spin is precessing oscillates vertically,
5305 exactly following the oscillation of the muon momentum. When the orbit is inclined at angle
5306 ψ to the horizontal, ω_a is reduced by the factor $(1 - \frac{1}{2}\psi^2)$. If ψ_m is the angular amplitude
5307 of the vertical oscillation, the average over the ensemble of muons is $(1 - \frac{1}{4}\langle \psi_m^2 \rangle)$ where the
brackets indicate an average over the muon population, $\langle \psi_m^2 \rangle = n \langle y_m^2 \rangle / r_o^2$ where y_m is the
amplitude of the vertical oscillation.

Information on $\langle \psi^2 \rangle$ is obtained by simulation in which a representative set of muons is tracked around the ring from the inflector exit, via the kicker magnet, for many turns. The discrete quadrupole structure and aperture defining collimators are included as well as the calculated deviations from a pure quadrupole field. The pitch correction is +0.29 ppm.

A combined (correlated) electric field and pitch correction uncertainty of 0.05 ppm was used in E821. We expect to improve on our knowledge of the electric field and pitch corrections by use of a new muon traceback system that can better image the beam motion versus time at a number of azimuthal positions around the ring. Furthermore, our simulation effort has improved, which is essential to some of these corrections. It is expected to reduce the uncertainty on these important corrections and we estimate a final combined error of less than 0.03 ppm.

13.4 Collimators and Lost Muon Systematic Error

The E821 lost muon systematic error was 0.09 ppm. In this section we discuss how we will decrease the lost muon rate with an improved storage ring/collimator system. The distortions of the vertical and horizontal closed orbits due to radial and vertical magnetic field distortions are:

$$\Delta y_{\text{CO}} = \sum_{N=0}^{\infty} \frac{R_0}{B_0} \frac{B_{RN} \cos(N\Theta + \phi_{yN})}{N^2 - Q_y^2} \quad (13.2)$$

$$\Delta x_{\text{CO}} = \sum_{N=0}^{\infty} \frac{R_0}{B_0} \frac{B_{yN} \cos(N\Theta + \phi_{xN})}{N^2 - Q_x^2} \quad (13.3)$$

For E821, B_{R0}/B_0 drifted by typically 40 ppm per month, which was correlated with temperature changes. About once a month B_{R0} was adjusted with the current shims to maximize the number of stored muons, i.e., centering the beam vertically in the collimators. From equ. (13.2) $B_{R0}/B_0 = 40$ ppm changes the vertical closed orbit by 2 mm. At FNAL we plan much better temperature control compared to E821. B_{y1}/B_0 was shimmed to < 20 ppm, which distorted the horizontal closed orbit by < 1 mm. For the FNAL experiment, we want both of these components < 10 ppm. Other components are less important since $Q_y^2 \approx 0.18$ and $Q_x^2 \approx 0.82$ are closest to the integers 0 and 1, respectively (see Table 13.2). For E821 we used $Q_y^2 \approx 0.13$ and $Q_x^2 \approx 0.87$.

The E821 collimators were circular with radius 45 mm. The E821 beta functions vs. ring azimuth are shown in Fig. 13.18. The FNAL experiment collimators will be oval with the x and y axes modulated by the square root of the beta functions, i.e., ± 0.8 mm in x and ± 0.7 mm in y .

Fig. 13.19 shows the E821 collimator ring placement. Since the E821 kick extended over many turns, we needed "half" collimators just after the kicker and at π radial betatron phase advance, so that the muons would survive enough turns to get the full kick. The FNAL kicker is being designed to give the full kick on the first turn. Thus we can go from 3 full collimators and 5 half-collimators to eight full collimators.

We purposely distorted the vertical and horizontal closed orbits by 2.6 mm during scraping for the first 10^2 turns, but 2.6 mm was not large compared to the above effects. Indeed,

Table 13.2: Distortion of the closed orbits for E821 (FNAL) tune values and B_{RN}/B_0 and $B_{yN}/B_0 = 10$ ppm.

N	y_{CO} (mm)	x_{CO} (mm)
0	0.53 (0.40)	0.08 (0.09)
1	0.08 (0.09)	0.53 (0.40)
2	0.02 (0.02)	0.02 (0.02)
3	0.01 (0.01)	0.01 (0.01)

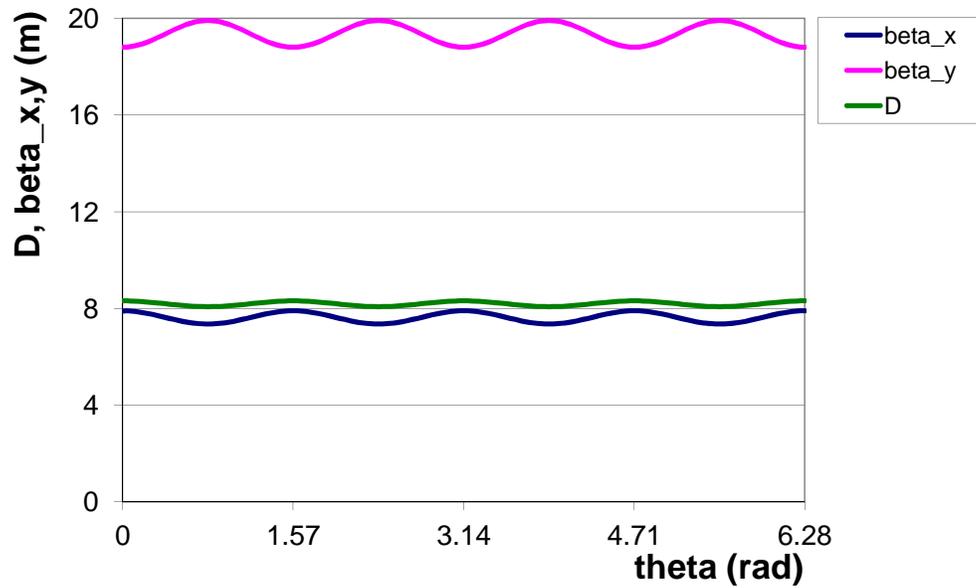


Figure 13.18: E821 horizontal and vertical beta functions.

5344 when there were large temperature variations, we sometimes observed that the lost muon
 5345 rate went *up* after scraping ended! With better control over the horizontal and vertical orbit
 5346 distortions due to B_{R0} and B_{y1} , oval collimators to match the ring beta functions, and eight
 5347 full collimators, we anticipate a lost muon rate at FNAL which will be about ten times lower
 5348 than E821. The exact lost muon rates will be calculated with tracking simulation. The
 5349 collimators should be surveyed to better than 0.2 mm. The coefficient of expansion of steel
 5350 is $1.3 \times 10^{-5}/\text{C}$; multiplying times the radius of 7.1 m gives 0.1 mm/C.

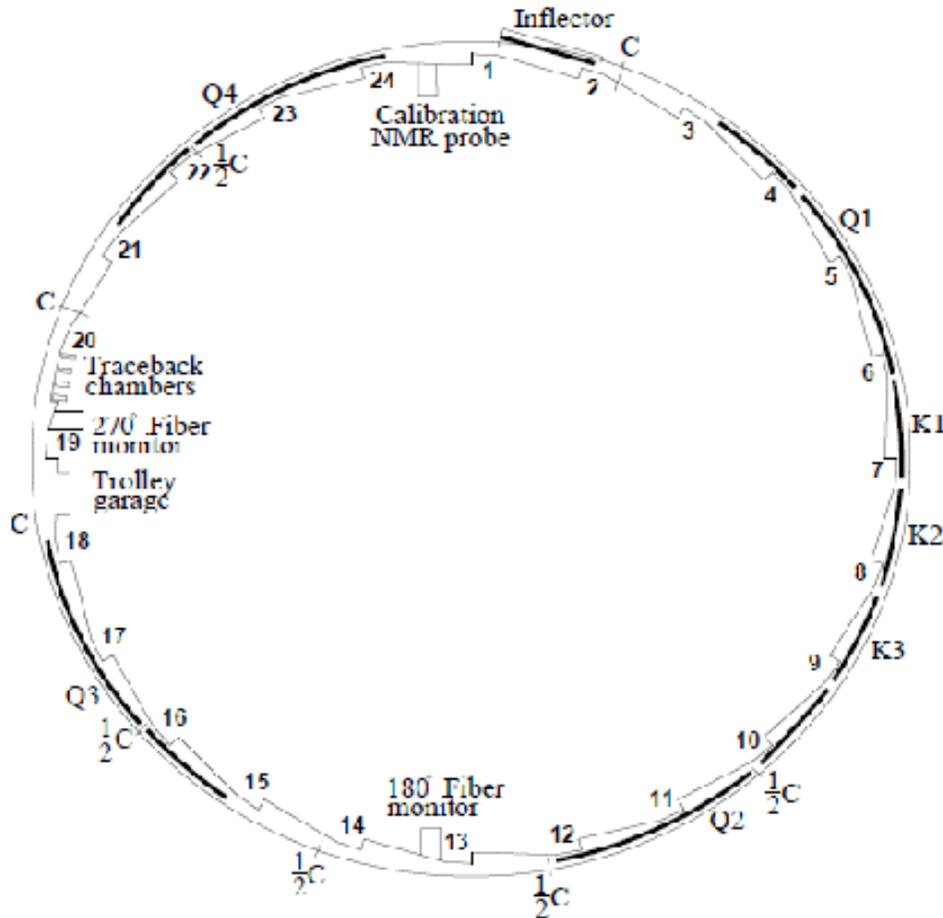


Figure 13.19: Schematic diagram of the E821 ring showing the location of the half and full collimators. For the FNAL experiment, there will only be full collimators.

5351 13.5 ES&H

5352 Potential hazards of the ESQ system are power system and X-rays.

5353 The system contains both low voltage, high voltage (up to 75 kV) and high current
 5354 circuits. There are no exposed electrical terminals. All electrical connections are bolted

5355 and enclosed. Cables will either be run along the floor in cable tray or in double-grounded
5356 conduit. The power supplies and the thyratrons are fused. We will use lock out/tag out
5357 when servicing the unit. When the power supplies are disabled, the storage capacitors will
5358 also be shorted to ground with a safety relay. We do not anticipate that we will need to work
5359 on the unit hot. There are no requirements for emergency power. There will be a remote
5360 control unit in the control room. The operation of ESQ will be limited to system experts
5361 and trained personnel.

5362 Soft X -rays can be produced in the system in spark discharges. Even though the ESQ
5363 system is designed to have no sparks during normal running conditions, sparks are most
5364 likely to occur during conditioning of the system. The ESQ plates are enclosed in 1-cm-thick
5365 Al vacuum chambers, which will provide shielding against X -rays emission. Safety expert at
5366 BNL will conduct calculations of the effect for the Test Stand which will be used at BNL
5367 for R&D studies and development. The equipment will be checked for the production of
5368 X -rays during a discharge. The results will be applicable to the $(g - 2)$ experiment. It
5369 is unlikely that X -rays will be a serious hazard in the experiment, but depending on the
5370 recommendation of the safety expert additional safety measures may follow. Irrespective of
5371 the outcome, all personnel will be required to wear TLD badges in the experimental hall.

5372 One of the alternative designs of the outer plate of Q1 quadrupole includes beryllium foil.
5373 Beryllium is ideal material for such purpose due to its mechanical, electrical and magnetic
5374 characteristics. Most importantly, muon scattering in beryllium will be significantly reduced
5375 in comparison with aluminum plate due to lower Z of beryllium. However, beryllium is
5376 a significant health hazard. We are not planning to machine beryllium. The foil will be
5377 produced and, presumably, assembled by a certified commercial company. During running
5378 the beryllium plate will be enclosed in vacuum chamber inaccessible to regular personnel.
5379 Only certified persons will be allowed to perform work on ESQ Q1.

5380 13.6 Risks

5381 The baseline design is to displace the Q1 outer plate by about 2 cm (the needed displacement
5382 will be determined more accurately by R&D studies). If the baseline design cannot be
5383 achieved for various reasons, we will consider the following alternatives for Q1 outer plate, *i*)
5384 a plate made from a thin beryllium foil, *ii*) a plate made from a thin wire mesh, *iii*) a plate
5385 made from a thinner aluminum foil, *iv*) a plate from other alternative materials (e.g. fiber
5386 carbon). This will lead to the following consequences to the Project

- 5387 • More effort will be needed for R&D studies of alternatives.
- 5388 • Muon scattering in any material will reduce the fraction of stored muons and hence
5389 increase the time required to reach the statistical goal of the experiment. The preferable
5390 material is beryllium.
- 5391 • Beryllium foil will increase the cost of the Project. The cost of the beryllium material
5392 for the plate is about \$16 k per meter. Thus, to cover a 5-m-long quadrupole plate at
5393 least \$90 k in addition will be required not including the manufacturing and assembling
5394 expenses.

- 5395 • Beryllium is a hazardous material. Special handling requirements will complicate ESQ
5396 plate installation and adjustment procedure.

5397 The baseline design is to increase the operating voltage of ESQ to ± 35 kV. The CBO
5398 systematic error will be more challenging to address if this goal is not reached. This will
5399 also increase muon losses.

5400 The ESQ system requires good vacuum to operate properly (10^{-6} Torr or better). Bad
5401 vacuum conditions may lead to inability of ESQ to operate at nominal voltage. One potential
5402 source of vacuum leak is the tracker system. Two to four additional vacuum pumps may
5403 be needed to pump the vacuum chambers equipped by the tracker system. If high vacuum
5404 conditions are not met with installation of additional vacuum pumps, we may consider taking
5405 production data without tracker system and taking special runs with the tracker system to
5406 measure the distribution of muons in the storage ring. The disadvantage of such a mode of
5407 operation is that the tracker runs will be excluded from the production dataset.

5408 **References**

- 5409 [1] Bailey J, et al. Nucl. Phys. B150:1 (1979)
- 5410 [2] Bennett G.W., et al., Phys. Rev. D 73, 072003 (2006)
- 5411 [3] Y. K. Semertzidis et al., Nucl. Instr. Meth. Phys. Res., A 503 (2003) 458-484

Chapter 14

WBS 476.03.07 Ring Instrumentation and Controls

This chapter gives a preliminary description of the g-2 cryogenic and vacuum control system. This control system will be a copy of the typical Siemens S7-400 PLC (Programmable Logic Controller) control system as deployed by the Fermilab mechanical department.

The g-2 cryogenic and vacuum system will be located on the Muon campus in the MC1 building, Muon g-2 experimental hall. This area is classified as ODH class 0 area and has several large cryogenic and gas components. Cryogenics include liquid Helium and Liquid Nitrogen.

This cryogenic system has approximately 300 electronic input sensing devices and 50 output devices. Input devices include temperature sensors, pressure transmitters, vacuum gages, level probes, and strain gages. Output devices include solenoid valves, control valves, and vacuum valves and pumps.

All electronic and electrical control system equipment is air cooled and does not require any forced air cooling or water cooling. Cabinet air vents are provided for certain devices where appropriate.

The control system equipment components are all commercially available products which are UL listed. The cryogenic control system has been designed and will be built following all the required rules and standards such as the NEC and NFPA 70E. All premises wiring is to be installed by Fermi Electrical contractors and licensed electricians.

14.0.1 Cryogenic/Vacuum Control System

Programmable Logic Controller

The g-2 cryogenic/vacuum system will be controlled by a Siemens S7-400 PLC with S7-300 associated I/O modules (or equivalent industrial controls system) networked on a Profibus network. This PLC system will be programmed using the Siemens S7 engineering programming software (or equivalent software meeting IEC 61131-3 standard). Siemens S7-400 PLC systems are currently in use at several Fermilab projects: LAPD, LBNE 35 Ton, Super CDMS, and NML/CMTF. A diagram of the typical PLC in use at Fermilab is given in figure 14.1

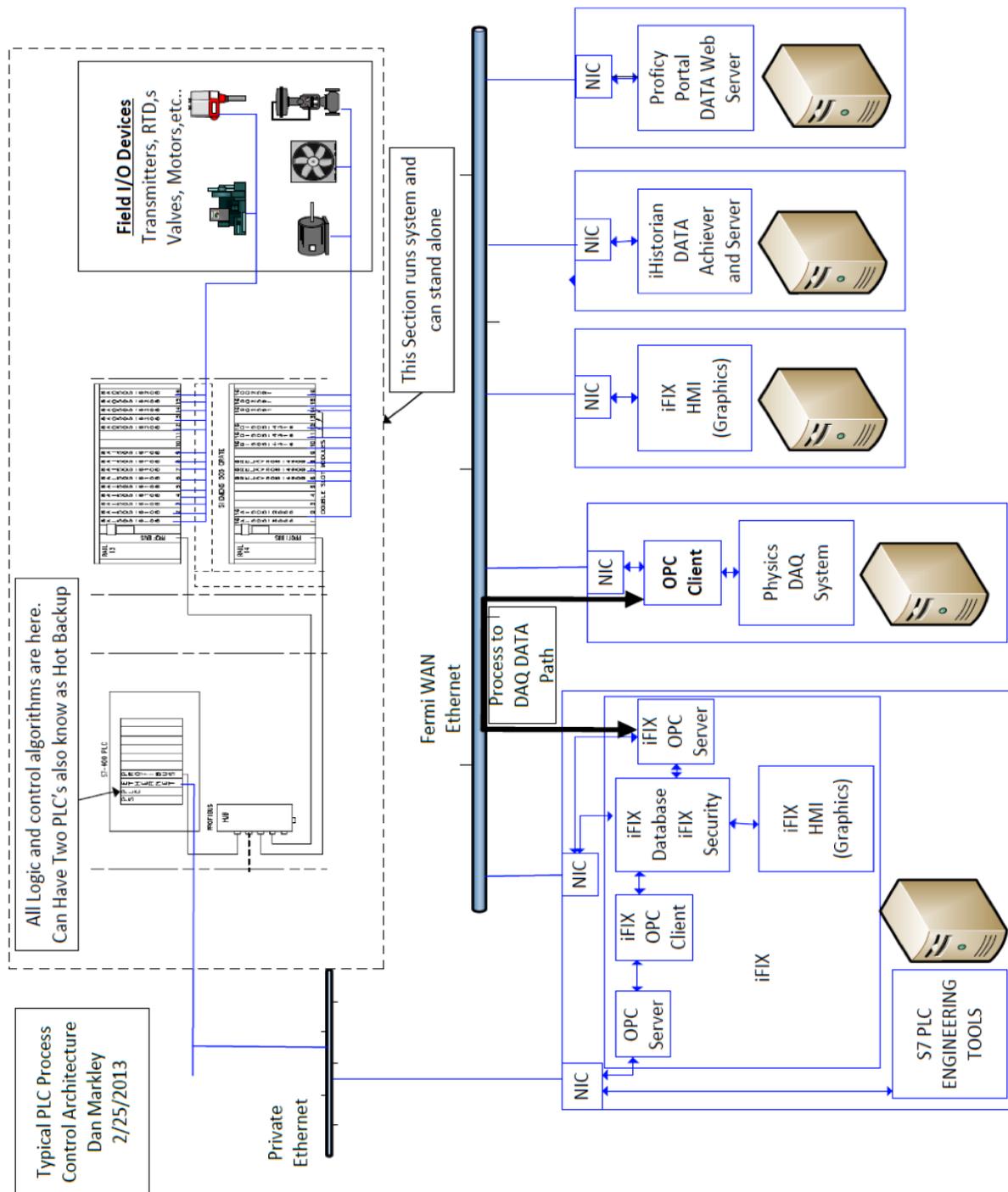


Figure 14.1: Diagram of a typical PLC in use at Fermilab.

5442 **Human Machine Interface**

5443 Human Machine Interface (HMI) controls will be provided through GEFANUCs iFIX soft-
 5444 ware. iFIX connects to the S7-400 through Private Ethernet using an OPC driver purchased

5445 from Kepware. iFIX will handle all operator security, computer alarming, and remote op-
 5446 erator controls via the PPD-iFIX server. iFIX will also provide historical data through the
 5447 PPD-iFIX historian. This historical data will be viewable in iFIX picture displays or on the
 5448 web through the iFIX Proficy portal server. An example of a HMI for the LAPD experiment
 5449 is shown in figure 14.2.

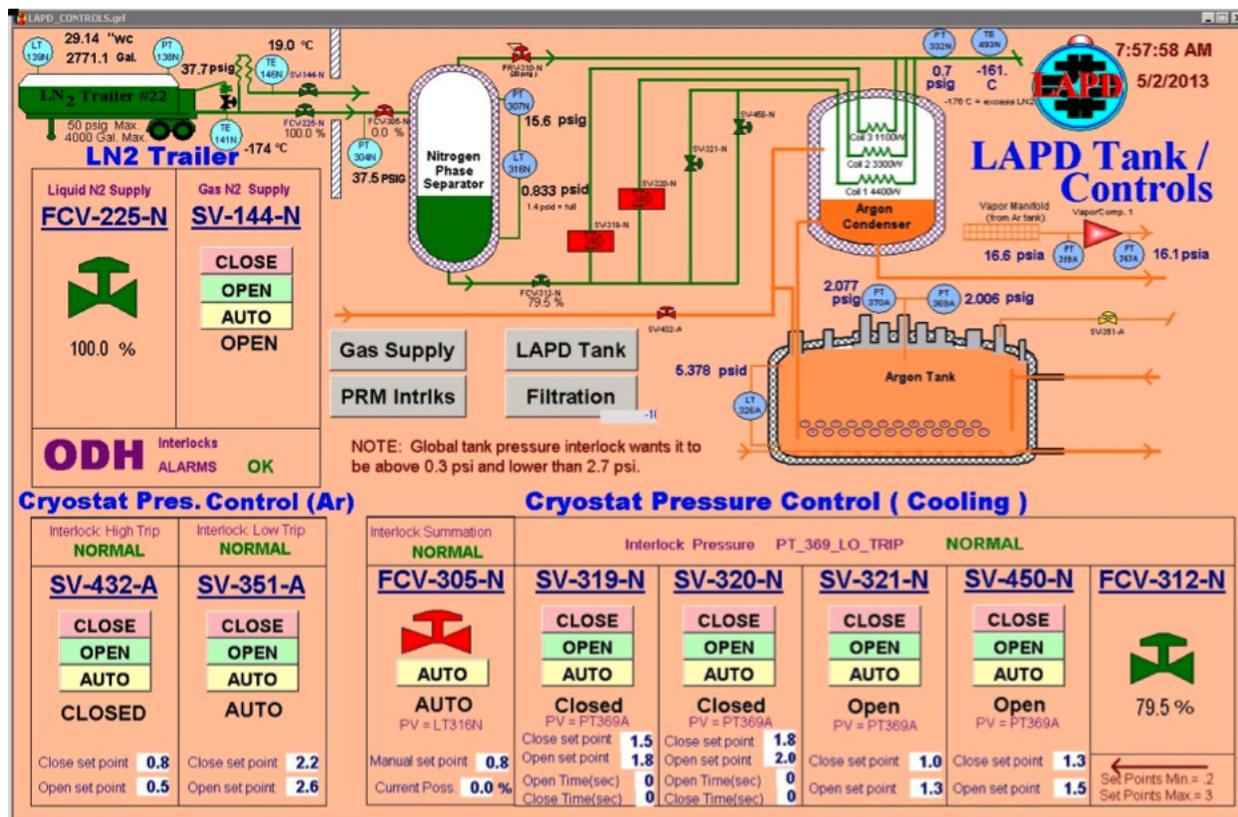


Figure 14.2: Human Machine Interface for the LAPD experiment.

14.0.2 Life Safety and System Reliability

ODH Control System

5452 The ODH system will utilize four MSA O2 heads. Two O2 heads will be located near the
 5453 ceiling of the g-2 experimental hall, with another two O2 sensors located near the floor of
 5454 the hall. There will be an ODH warning horn and strobe lamp. These will be centrally
 5455 located in the hall. There will be two ventilation fans used to maintain the ODH risk class
 5456 zero status in the g-2 hall. One fan will exhaust air out of the g-2 hall at the ceiling venting
 5457 it outside. The second fan will supply fresh air to the building near the floor outside of the
 5458 rings. These fans are controlled by the S7 PLC and can also be run locally using a switch
 5459 mounted at the fan controls. The ODH system is hardwired to both fans such that during
 5460 an ODH alarm both fans run.

5461 The O2 Sensors are MSA model A-UltimaX-PL-A-14-03D2-0000-100 and have a span of
 5462 0-25%. Each O2 sensor is to be wired to an MSA electronic controller which provides an

5463 analog output signal wired to the S7 PLC. This MSA electronic unit also provides relays
5464 which have three O2 level alarms thresholds, 18.5%, 18%, and 17.5%. The relay output
5465 that is set at 18.5% is wired directly to the ODH warning horns and strobe lamps located
5466 in MC1 and FIRUS. The MSA electronic unit also provides a trouble relay output which is
5467 also wired to the PLC and FIRUS. The trouble output is wired in a failsafe manner, such
5468 that loss of power or blown fuse to the ODH controls will generate a trouble alarm.

5469 The MSA equipment is wired directly to its own self-contained control circuitry in its
5470 own enclosure. This self contained enclosure has its own power supply which is independent
5471 of the PLC control system, allowing the ODH system to function independently of the PLC
5472 control system. The power for this ODH system comes from a U.P.S.

5473 **Uninterruptible Power Supply (U.P.S.)**

5474 The control system U.P.S. is to be a commercial unit such as those manufactured by Best
5475 power. The U.P.S. input power is fed from a premises powered outlet using the U.P.S. input
5476 line cord. This U.P.S. system will be diesel generator backed. The diesel generator will be
5477 auto start with auto switchover on commercial power loss. There may be other loads on this
5478 generator as well.

5479 The U.P.S. has standard outlets located on the rear of the cabinet. An APC surge
5480 protector is located on the U.P.S. and its input power cord is plugged into the U.P.S output
5481 outlets. All relevant control system loads are plugged into the APC surge protector output
5482 outlets.

5483 **PLC Reliability and Redundancy**

5484 Siemens SIMATIC (S7 PLC and ET200M I/O modules) components meet all relevant in-
5485 ternational standards and are certified accordingly. Temperature and shock resistance are
5486 defined in the SIMATIC quality guidelines, as are vibration resistance or electromagnetic
5487 compatibility. The Siemens S7 PLC system equipment can be redundant at many different
5488 levels, from the PLC CPU (Hot Backup) to the module and instrument level. The level of
5489 redundancy, if any, has not yet been determined for the g-2 control system.

5490 **References**

- 5491 [1] Electrical Design Standards for Electronics to be used in Experiment Apparatus at
5492 Fermilab.
- 5493 [2] EED/Infrastructure Doc. No:H011228A.

Chapter 15

The Precision Magnetic Field: ω_p

In this chapter we present the requirements on the storage ring magnetic field and field measurement, with a conceptual design for fulfilling these requirements. We first consider the field measurement requirements and the recommended design. The requirements on the storage ring magnetic field and recommended design are then discussed.

15.1 Precision Magnetic Field Measurement

15.1.1 Relation between a_μ and ω_p

In an idealized experiment, the anomaly a_μ could be extracted by measuring the difference frequency ω_a between the muon spin ω_s and cyclotron frequencies ω_c for a muon in a storage ring with a perfectly homogeneous magnetic field \vec{B} with no focusing (see Eqn. ??):

$$\vec{\omega}_a = -\frac{Qe}{m_\mu} a_\mu \vec{B}. \quad (15.1)$$

The magnetic flux density $|\vec{B}|$ could be determined in Tesla through proton nuclear magnetic resonance (NMR) measurements via $\omega_p = \gamma_p |\vec{B}|$, where ω_p is the free proton precession frequency and $|\vec{B}|$ is the lab-frame magnetic field which governs muon motion in the storage ring. The free proton gyromagnetic moment ratio γ_p is currently known to 24 ppb [1]. The muon charge to mass ratio appearing in Eq. 15.1 can be expressed in terms of (m_e/m_μ) known to 25 ppb and (e/m_e) known to 22 ppb [1]. Even with measurements of ω_a and ω_p at the ppb level of precision, a_μ could only be extracted to 41 ppb due to uncertainties on these auxiliary ratios. Fortunately it is not necessary to determine the field in Tesla. The anomaly a_μ is dimensionless and can instead be extracted from the same measurements in terms of a ratio of frequencies and a dimensionless ratio of magnetic moments :

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_{\mu^+}/\mu_p - \omega_a/\omega_p}. \quad (15.2)$$

This is derived from Eq. 15.1 based on relations between fundamental constants, with the requirement that ω_p refers to the free proton precession frequency in the same flux

5517 density \vec{B} seen by the muons. The additional input, $\mu_{\mu^+}/\mu_p = 3.183\,345\,24(37)$ (120
 5518 ppb) is determined from the E1054 LAMPF measurement of Zeeman ground state hyperfine
 5519 transitions in muonium (Mu) [2, 1]. The result is based solely on measured quantities, the
 5520 validity of the Breit-Rabi Hamiltonian to describe the experiment, and a small (17.6 ppm)
 5521 bound-state QED correction to the g factor for a muon in muonium (where the uncertainty
 5522 on the correction is sub-ppb).

5523 Alternatively, the same experiment measured the ground state hyperfine interval in muo-
 5524 nium, $\Delta\nu_{\text{Mu}}(\text{E1054}) = 4\,463\,302\,765(53)$ Hz (12 ppb), where the theoretical prediction is
 5525 given by [1]:

$$\Delta\nu_{\text{Mu}}(\text{Th}) = \frac{16}{3}cR_\infty\alpha^2\frac{m_e}{m_\mu}\left(1 + \frac{m_e}{m_\mu}\right)^{-3} + \text{higher order terms} \quad (15.3)$$

$$= 4\,4634\,302\,891(272) \text{ Hz (61 ppb)}. \quad (15.4)$$

5526 The theory uncertainty has a 101 Hz contribution from uncertainty/incompleteness in the
 5527 theory calculation, but is dominated by the uncertainty in the mass ratio m_e/m_μ which
 5528 appears as a parameter in the prediction.

5529 The hyperfine interval is dominated by QED contributions, but there is a weak contribu-
 5530 tion $\Delta\nu_{\text{Weak}} = -65$ Hz from Z^0 exchange, a hadronic contribution $\Delta\nu_{\text{Had}} = 236(4)$ Hz, and
 5531 a hadronic light-by-light contribution of 0.0065 Hz (see references in [1]).

5532 Setting $\Delta\nu_{\text{Mu}}(\text{E1054}) = \Delta\nu_{\text{Mu}}(\text{Th})$ can determine the mass ratio (m_μ/m_e) to 25 ppb,
 5533 which in turn can determine $\mu_\mu/\mu_p = 3.183\,345\,107(84)$ to 26 ppb since

$$\frac{m_\mu}{m_e} = \frac{\mu_e}{\mu_p} \frac{\mu_p}{\mu_\mu} \frac{g_\mu}{g_e}, \quad (15.5)$$

5534 where the uncertainty on μ_e/μ_p is 8.1 ppb and the uncertainty on g_μ/g_e is less than 1 ppb [1].
 5535 This determination, which is nearly 5 times more precise than μ_μ/μ_p extracted directly from
 5536 measurement, requires that the Standard Model fully describes $\Delta\nu_{\text{Mu}}$. However, theories
 5537 predicting new contributions to the muon anomaly might also lead to new contributions to
 5538 $\Delta\nu$ that should be considered.

5539 Given that the difference between a_μ^{E821} and a_μ^{SM} is roughly twice the weak contribution
 5540 to a_μ , a comparable contribution to $\Delta\nu$ would imply the current theory uncertainty might be
 5541 underestimated, as would be the 26 ppb uncertainty on μ_μ/μ_p . A more precise, independent
 5542 measurement of μ_μ/μ_p , planned at J-PARC, would be very helpful. Note however, that even
 5543 in the absence of a new measurement, any BSM theory can be tested against E989 at the
 5544 0.14 ppm level as long the BSM contributions to $\Delta\nu$ are considered simultaneously and the
 5545 uncertainties are at the level of 25 ppb or less.

5546 15.1.2 Physics Requirements on ω_p

5547 Based on the above approach for a_μ , our requirement for the total uncertainty on ω_p in
 5548 E989 is $\delta\omega_p \leq 0.07$ ppm, roughly a factor of three smaller than was achieved in E821. Here
 5549 $\tilde{\omega}_p$ refers to the free proton precession frequency weighted by the muon distribution in the
 5550 storage ring.

15.2 Recommended Design

E989 will largely use the principles and hardware originally developed at Universität Heidelberg and Yale, that were employed successfully in E821 (and E1054 at LANL). The E821 field measurement electronics and the underlying physics are described in [3]. The calibration of the field measurements in terms of the equivalent free proton precession frequency using an absolute calibration probe is described in [4]. Details of the E821 field analysis, systematics, and of the hardware are described in the final E821 paper [5], and in several theses [6, 7, 8].

While E821 achieved an uncertainty $\delta\tilde{\omega}_p \approx 0.17$ ppm, E989 will have to implement specific changes to the hardware and techniques to reduce the systematic errors to a final goal of $\delta\tilde{\omega}_p \approx 0.07$ ppm. The recommended E989 hardware, techniques, and changes from E821 will be discussed in the rest of this chapter. A table of estimated contributions to the systematic uncertainty on ω_p is presented at the end of the chapter.

15.2.1 Overview of field measurement using NMR

Nuclear magnetic resonance (NMR) is at the heart of the magnetic field shimming, measurement, and control, since it can measure magnetic fields to absolute accuracies of tens of parts per billion (ppb).

The pulsed NMR hardware developed for E821, which produced and detected the free induction decay (FID) signals from protons in water, has already demonstrated single shot accuracy at the level of 10 ppb [3], and absolute calibration in terms of the free proton precession frequency at the level of 35 ppb [4]. The challenge of the field measurement is to effectively transfer this absolute calibration to the many NMR probes required to monitor the field in the large volume and over long periods in which muons are stored.

There are four major tasks required from the NMR system: (1) Monitoring the field when muon data are being collected; (2) Providing feedback to the storage ring power supply when muon data are collected; (3) Mapping the storage ring field when the beam is off; (4) Providing an absolute calibration relating field measurements to the Larmor frequency of a free proton.

15.2.2 The Fixed Probe NMR system

The fixed probe system consist of the fixed NMR probes and the accompanying VME system, DAQ, pulser, mixer, multiplexers, and digitizers. Its purpose it to accomplish the first task of monitoring the field continuously while muon data are being collected. A block diagram of the recommended system is shown in Fig. 15.1.

The recommended design consists of a set of 378 NMR probes at 72 locations in azimuth around the ring. The number of probes at each azimuthal position alternates between two probes at radii of 7112 and 7142 mm, or three probes at radial positions of 7082, 7112, and 7142 mm, where the probes are placed in grooves on the upper surface of the storage ring vacuum chambers. In addition, probes matching in azimuth and radius are placed in grooves on the lower surfaces of the vacuum chambers. From this geometry the fixed probes provide

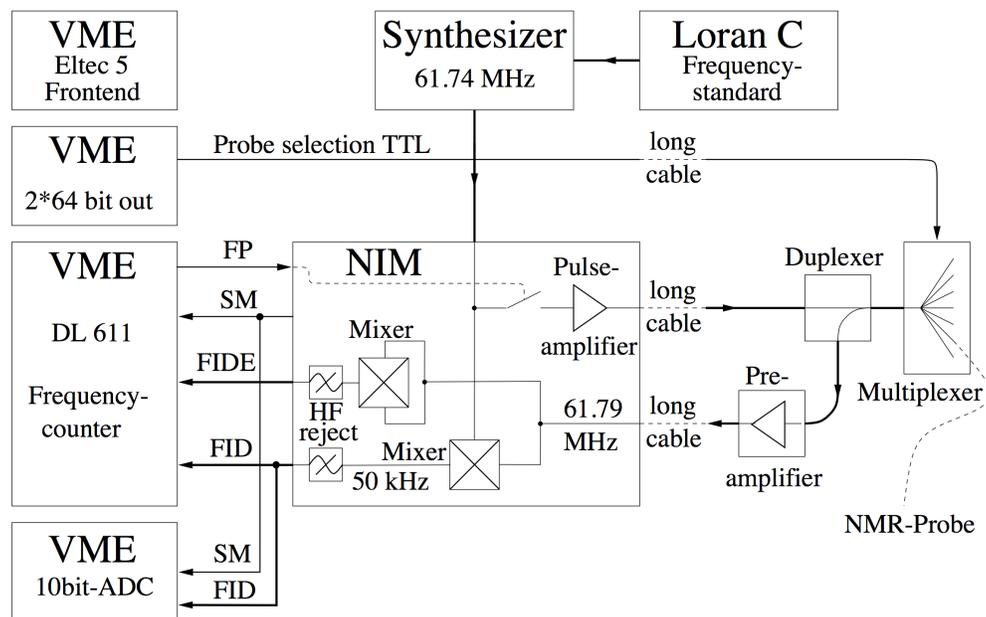


Figure 15.1: A schematic of the fixed probe system. The system consists of a set of NMR probes close to the muon storage volume connected to multiplexer boxes that sit on the storage ring magnet. The multiplexers are connected to NIM modules and a VME system and DAQ that sit in the counting house. The functions of each element are described in the text.

5590 a good monitor of the dipole field around the ring, with some sensitivity to changes in the
 5591 skew and normal quadrupole components.

5592 In E821, roughly half of these fixed probes were used to monitor the storage ring field.
 5593 Of the remainder, some probes were noisy, and a significant number of fixed probes were
 5594 located in regions near the pole-piece boundaries where the local magnetic field gradients
 5595 were sufficiently large to reduce the free induction decay time in the probe. This limited the
 5596 precision of the frequency measurement. In E989 several steps will be taken to increase the
 5597 number of useful probes.

5598 First, finite element analysis of the vacuum chambers indicates that the grooves contain-
 5599 ing the probes can be extended without significantly increasing the deflection of the chambers
 5600 under vacuum. This will allow probes to be moved farther from pole boundaries, increasing
 5601 the number of useful probes. Second, in E821 the majority of the NMR samples in the fixed
 5602 probes were cylinders of water. Over the course of the experiment, the water samples could
 5603 evaporate. In E989, the possibility of replacing the water samples with petrolatum (CAS
 5604 8009-03-8) will be explored. Petroleum jelly was observed in E821 to have several advantages
 5605 over water: low evaporation, a proton NMR signal comparable in magnitude and frequency
 5606 to water, and a temperature coefficient smaller than that of water, which is better for our
 5607 experiment. In addition, it has favorable relaxation times; preliminary measurements at U.
 5608 Michigan indicate T_2 of order 40 ms. Third, during the refurbishment of the probes for
 5609 E821 (see below), any intermittent electrical contacts will be improved. Finally, the NMR

5610 electronics of E821 which extracted precession frequencies by counting zero-crossings of FIDs
5611 mixed down to the 50 kHz range, will be supplemented with a high-performance set of digi-
5612 tizers. The 16 bit (13 bits effective), 20 MS/sec digitizers (Struck SIS 3302) will allow useful
5613 information to be extracted from probes with short signals. In addition, higher resolution is
5614 possible by interpolating the positions of zero-crossings, and fitting the signals around zero
5615 crossings can help when dealing with probes with poor signal to noise. Digitizers will allow
5616 the lineshape (and changes in the lineshape) to be extracted from the Fourier transform
5617 of the signals. This may allow a more robust extraction of the average field compared to
5618 counting zero crossing when the digitization noise is comparable or less than the signal to
5619 noise of the FID, since the zero-crossing rate itself is time-dependent when the lineshape is
5620 asymmetric.

5621 15.2.3 Fixed Probes for E989

5622 The same basic probe design from E821 is recommended for E989, and is shown in Fig-
5623 ure 15.2. Materials used to construct the probes, mostly aluminum and PTFE, have low
5624 susceptibility and the coax cable has copper conductors instead of the more common copper
5625 plated steel. The probe's outer aluminum shell has a diameter of 8 mm which fits in grooves
5626 machined into the outside surface of the top and bottom plates of the vacuum chamber. The
5627 probe's outer shell and the inner body form the capacitor C_s , which in series with L_s makes
5628 a resonant circuit. C_s is adjusted by moving a PTFE sleeve in and out to tune the circuit to
5629 the frequency ω_p . The circuit quality factor $Q \approx 30$ corresponds to a bandwidth of 3% which
5630 is the range over which the magnetic field can be measured without retuning the probes.
5631 A coil in parallel, L_p , allows for tuning the impedance of the probe to 50 Ω 's for optimal
5632 transmission.

5633 Resurrecting the existing E821 measurement system requires a complete working set of
5634 probes provided either by refurbishing existing ones or constructing new ones.

5635 **Refurbishing existing probes:** In E821 the sample volume was filled with water with
5636 CuSO_4 added to decrease the relaxation time and allow for shorter measurement times.
5637 In some of the probes the water has leaked and corroded part of the probe. These
5638 probes need to be rebuilt. Tests on about 40 fixed probes from E821 indicate that
5639 about 1/4 are in this category. The coil wire and coax cable shield are bonded to the
5640 aluminum parts with low temperature solder. These connections require inspection
5641 and all broken connections require re-soldering. All the other probes will be refilled
5642 with petroleum jelly, tuned and checked for correct functioning.

5643 An existing dipole magnet at University of Washington (UW) has been re-purposed
5644 to provide the 1.45 Tesla field required for testing the probes. Its field is uniform to
5645 1000 ppm/cm but will be shimmed to 100 ppm uniformity over the active volume of
5646 the probe to increase the duration of the NMR signal. A Metrolab PT 2025 Teslameter
5647 with 10 ppm accuracy is used to independently map the field in the magnet. A test
5648 facility to provide the $\pi/2$ pulse, send/receive duplexer switch and preamplifier that
5649 does not require the E821 electronics has been set up at UW.

5650 **Constructing new probes:** Any new probes constructed must meet the above geometry

5651 and materials requirements including any solders used to bond the wires. The probes
 5652 will be reverse engineered and CAD drawings produced. In consideration of the quan-
 5653 tity, new parts will be produced using numerically controlled machines at the UW
 5654 machine shop. Metric sized aluminum tubing 8 mm x 0.5 mm and 7 mm PTFE rods
 5655 are available in the European market. After the parts are completed the coils will be
 5656 wound and the same procedure as for refurbishing will be followed.

5657 **Testing the probes:** For each probe, the resonant circuits are tuned to 61.79 MHz and
 5658 50Ω impedance using a vector impedance meter. The resonance is then excited in the
 5659 probe and if the free induction decay FID is observed with sufficient signal to noise
 5660 ratio SNR, the probe passes the test. In the E821 system the SNR at the beginning of
 5661 the decay was $\approx 300:1$.

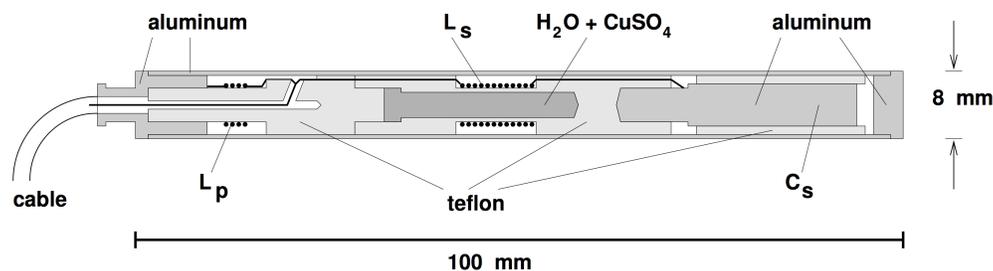


Figure 15.2: NMR fixed probe containing a cylindrical water sample. The resonant circuit is formed by the two coils with inductance L_s and L_p and a capacitance C_s made by the Al-housing and a metal electrode. The active water volume has a diameter of 2.5 mm and a length determined by the coil L_s of 15 mm.

5662 15.2.4 Multiplexers

5663 Groups of up to 20 fixed probes are connected to a single multiplexer located a few meters
 5664 away in the experimental hall. The multiplexer is a self-contained electronic module that
 5665 selects one of 20 NMR probes based on the bit pattern of 5 TTL-levels which are set in the
 5666 counting house, and which arrive on a DB-9 connector. The TTL signals control PIN diodes
 5667 in the multiplexer and direct an RF $\pi/2$ pulse, from NIM modules in the counting house
 5668 and used to tip the spins, to the single selected NMR probe. To improve the isolation of
 5669 open switches effective- $\lambda/4$ lines are incorporated. A duplexer (basically a transmit/receive
 5670 switch) in the multiplexer steers the output of the RF pulse towards the NMR probe. The
 5671 same duplexer steers the pulse away from the sensitive low-noise preamplifier, but sends the
 5672 low-level precession signal to a low noise preamplifier after the pulse, with an overall gain
 5673 of 60 dB. The module requires an external source of power, +15 Volts at 0.3 Amperes. The
 5674 switches, duplexer, and TTL integrated circuits are realized with discrete surface mount
 5675 components and replacements are readily available. The preamplifier uses two RF amplifier
 5676 modules UTO-101 and GPD-201. The multiplexer design is described in [3, 6].

5677 The preamps for E821 were made by Avantek, a company no longer in existence. An
5678 important characteristic of these amplifiers is their rapid recovery from an overload condition
5679 as experienced when the probe is excited. While some Avantek products are still sourced
5680 at Teledyne-Cougar (www.teledyne-cougar.com), future supplies are not guaranteed. For
5681 existing modules we will procure spare Avantek products if available. In constructing new
5682 multiplexer modules for E989, a new preamplifier design will be considered.

5683 15.2.5 Pulser and Mixer

5684 Each of the 20 multiplexers is connected to a single width NIM module located in the counting
5685 house. These function as the receiver and transmitter (pulse generator) for the NMR fixed
5686 probes. The pulse generator creates the $4\mu\text{s}$ $\pi/2$ pulse of $\omega_{ref} = 61.74$ MHz and sends it
5687 through a custom made 10-watt class C amplifier to the multiplexer. In the receiver part of
5688 the module, the amplified NMR signal at the Larmor frequency ω_L from the multiplexer is
5689 mixed with the frequency synthesizer output; a signal of well defined frequency ω_{ref} close to
5690 the NMR frequency $\omega_L \approx 61.79$ MHz. From the mixing products the difference frequency
5691 $\omega_L - \omega_{ref}$ is selected by a low pass filter and further amplified. This signal (at roughly 50
5692 kHz) is referred to as the FID (free induction decay) of the NMR probe. In a second branch
5693 of the receiver the envelope of the NMR signal, called FIDE, is constructed by multiplying
5694 the preamplifier output by itself and discarding the $2\omega_L$ component. A TTL SM (signal
5695 measure) pulse is generated in the NIM module roughly $10\mu\text{s}$ after the end of the RF pulse.
5696 This pulse goes to the custom Heidelberg DL611 frequency counter module in the NMR
5697 VME crate (discussed below) to start the zero crossing counter. The delay accommodates
5698 deadtime in the multiplexer preamplifier, and transients such as from ringdown of the L_s
5699 coil and decay of the transient response in the low-pass filter.

5700 The inputs to the NIM module are the TTL FP (fire pulse) which starts the RF pulse
5701 generator. The FP signal is generated in the DL611 frequency counter modules in the VME
5702 crate. A second input is the synthesizer reference at 61.74 MHz, and the NMR probe
5703 signal from the multiplexer preamplifier. The outputs are the $\frac{\pi}{2}$ pulse, a TTL signal whose
5704 width is the dead time of the receiver (the SM signal), the FIDE and two channels of the
5705 FID (one for the zero-crossing counter in the VME crate, one for a digitizer in the crate).

5706 For the most part this module contains surface mount and integrated circuit components
5707 and replacements are readily available. The exceptions are 5 amplifiers GPD-201, GPD-202,
5708 and 3 GPD-462 made by Avantek, which no longer exists. The most likely point of failure
5709 in the 10 watt class C amplifier is a DU2820S MOSFET that is still available and could
5710 be replaced if necessary with little difficulty. Replacement amplifiers exist but they tend to
5711 be wide band class A amplifiers which are less efficient. In constructing new pulser/mixer
5712 modules, using a class A or class AB amplifier would require that it be mounted external
5713 to the NIM module to dissipate the additional heat. Modular high performance commercial
5714 RF amplifiers are available from Amplifier Research and other vendors.

15.2.6 NMR VME System and DAQ : Requirements and Recommended Design

The fixed probe NMR system will be controlled by a VME crate in the counting house, performing similar functions as in E821 but with updated hardware for E989.

The NMR VME system is required to (1) send a bit pattern to each multiplexer that encodes which NMR fixed probe to use (2) Send FP (fire pulse) signals to the NIM modules in an adjacent crate, (which send the RF $\pi/2$ pulses to the fixed probes) (3) Count zero crossings of the FIDs from the NIM modules (4) Send the zero crossing data and a timestamp to a PC to be recorded.

The Eltec 9 VME crate controller used in E821, which ran the realtime operating system OS9, no longer works and must be replaced. The original E821 NMR VME crate, which was customized with the addition of -5V power supply to run the Heidelberg DL611 frequency counter modules, is still operational.

For E989 the recommended design replaces the Eltec controller with a Struck SIS1100 VME crate controller which connects via a fiber optic cable to a Struck SIS3104 PCIe card on a PC running Scientific Linux. The new controller is compatible with the VMEbus IEEE-1014 standard E821 crate, and with the faster 2eVME bus cycles of VME64x systems.

To accomplish task (1) above, a 5-bit pattern using TTL levels must be set in each of the 20 multiplexers, and is used to select which of the 20 fixed NMR probes is to be used. In E821 these levels were set by two custom VME modules made at Heidelberg (module number DL620). These modules still work, but a commercial solution will be sought as replacement in the case of failure and to allow more multiplexers to be added easily. Possible solutions include an Acromag AVME9660 VME carrier card for up to 4 IP-EP201 FPGA Digital I/O modules with 48 TTL lines each. FPGA I/O modules using high-speed USB or PCIe interfaces are also possible but a VME-based solution is preferred. The latter is more portable (modules reside in a single crate) and flexible (allows the VME crate to be placed in the experimental hall and controlled by the PC over a single fiber optic cable), and the software should be easier with just a single interface to deal with.

To accomplish task (2), the fire pulse (FP) TTL signal can be issued by the Heidelberg DL611 frequency counter modules. There are 5 DL611 modules, and each one can issue 4 independent FPs, allowing 20 NIM modules to be controlled. These DL611 modules still function and will be used as is in E989. New modules acting as spares based on the DL611 design will be made at the Center for Experimental Nuclear Physics and Astrophysics (CENPA) at the University of Washington. These additional modules will allow more multiplexers to be controlled if more fixed probes are added. Note that the new digital I/O cards could also be used to issue the FP signals.

Task (3) which involves counting the FID zero crossings will be accomplished with the existing DL611 modules and with the spares that are constructed. The DL611 modules, which are described in [3], count the zero crossings, k , of the FID till the FID signal falls below an adjustable threshold or until a maximum time has elapsed. Over the same interval the ticks, N , of an external clock at $\nu_{\text{clock}}=20$ MHz are counted. This 20 MHz clock signal is an input on the front panel of each DL611, and comes from a stabilized frequency synthesizer. For both counters the start and stop coincide with a positive zero crossing of the FID. The frequency of the FID is $\nu_{\text{FID}} = k \times \nu_{\text{clock}}/N$. For FID signals exceeding 1 ms, the uncertainty

5759 on the frequency due to the discretization of the clock counts is roughly 8 ppb or less. The
5760 uncertainty on the frequency due the finite signal-to-noise of the FID (typically $S/N \approx 100$
5761 when FIDE falls below threshold) is roughly the signal linewidth/ (S/N) . This is typically
5762 of order 25 ppb on a single NMR FID above threshold for a ms or more [3]. Any new
5763 design for the multiplexer preamps, NIM module electronics, and DL611 modules will need
5764 to meet or exceed this specification which is achieved by the existing hardware. The option of
5765 performing the frequency determination with fast, high-accuracy digitizers will be explored
5766 (see next section).

5767 Recording the results of the frequency measurement, task (4), is accomplished by reading
5768 the contents of the DL611 VME addresses containing the zero-crossing and clock counts, and
5769 writing them to disk on the DAQ PC. In E821, roughly 100 fixed NMR probes were read per
5770 second, and data rates were much less than 100 kB/second. Another custom VME module
5771 from Heidelberg provided a timestamp to be recorded with the measurements. For E989
5772 the preliminary design replaces the Heidelberg timestamp module with a Hytec 2092 VME
5773 module. This module has an antenna input to receive GPS timing signals and provides a
5774 timestamp with an absolute accuracy better than 100 ns with respect to UTC (Co-ordinated
5775 Universal Time). This is more than adequate for NMR signals which are typically 1 ms
5776 in length or longer. The advantage of this scheme is that potential external influences on
5777 the storage ring field from booster operations at 15 Hz, pickup at 60 Hz and harmonics,
5778 coordination with muon fills of the storage ring (which are typically asynchronous with the
5779 NMR readings) and other external events can be investigated when all NMR signals have a
5780 reliable, high-resolution absolute time stamp. Finally, the Hytec module produces a GPS-
5781 derived 1 pps TTL output which will be used to stabilize a Rb frequency reference producing
5782 a 10 MHz reference for the NMR and ω_a frequency synthesizers. There is other hardware
5783 for obtaining GPS-derived 1 pps references and reliable computer timestamps - the Hytec
5784 module is recommended as part of the conceptual design since it accomplishes several goals
5785 in a single module.

5786 Finally we note that low level software for the Struck controller has been developed to
5787 control the original Heidelberg clock, DL620 probe selector, and DL611 frequency counter
5788 modules. It can be recommended for use in E989 over alternative controllers because it has
5789 already been shown to work.

5790 15.2.7 Digitizer

5791 Struck SIS3302.

5792 15.2.8 Frequency Reference

5793 The $(g-2)$ experiment is essentially a measurement of the ratio ω_a/ω_p . Its goal is to achieve
5794 relative uncertainties of 0.07 ppm for both of these frequencies. Frequency references are
5795 necessary for both of these measurements, and the contribution to the uncertainty budget
5796 from uncertainties in the reference should be made negligible.

5797 The NMR system requires a frequency synthesizer at 61.74 MHz which is amplified and
5798 pulsed for manipulating the proton spins in the NMR probes. The FID at the Larmor
5799 frequency (typically 61.79 MHz) is mixed down by subtracting the 61.74 MHz reference,

5800 and the frequency of the resulting 50 kHz signal is determined by counting zero crossings
 5801 with respect to a 20 MHz clock (for the fixed probe) or the 61.74 MHz reference clock (for
 5802 the probes in the trolley) from a digitizer. The accuracy goal for the ω_p determination
 5803 requires that the 61.74 MHz and 20 MHz clocks be accurate at the ppb level. Since the
 5804 NMR clocks and the clock used by the waveform digitizers to determine the muon spin
 5805 precession frequency are phase-locked to the same master clock, the variations in the master
 5806 clock frequency drop out to first order, and the ppb-level accuracy requirement is reduced
 5807 to be less than about 10^{-5} . Nevertheless, to simplify the study of systematic uncertainties
 5808 in the magnetic field in the ring, our goal is to have relative uncertainties in the reference
 5809 clock frequencies to be less than 1 ppb.

5810 This uncertainty is required to be achieved short-term, that is, for a single NMR mea-
 5811 surement that takes about a few ms where phase noise is the limiting factor. It is also a
 5812 limitation on the long-time drift over the course of the experiment, that is, several years.

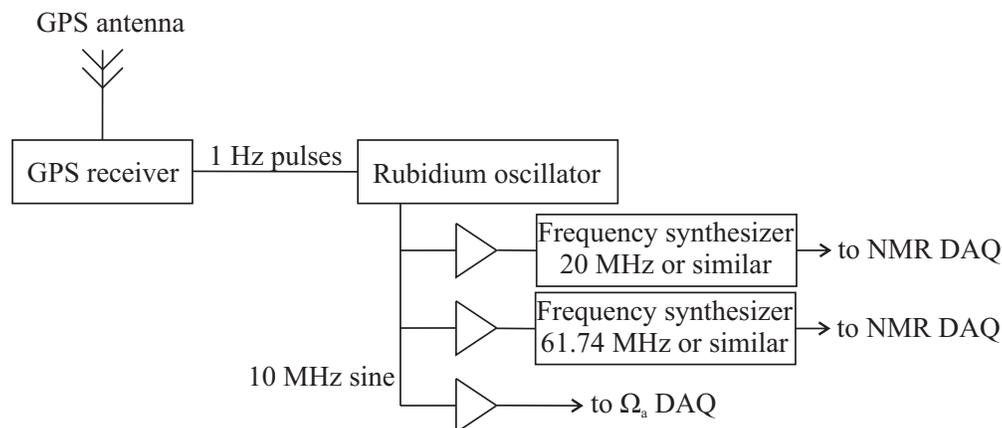


Figure 15.3: Scheme for common master-clock.

5813 Figure 15.3 shows how the reference frequencies are generated. The master clock is
 5814 planned to be an atomic rubidium oscillator that is disciplined by GPS for better long-
 5815 term stability. It generates a master frequency that is a sine wave, usually at 10 MHz.
 5816 The master frequency is distributed to the data acquisition system for ω_a , where frequency
 5817 synthesizers are used to transfer the master clock frequency to the clock frequency needed
 5818 by the waveform digitizers. It is also used as input for the frequency synthesizer responsible
 5819 for the reference frequency ω_{ref} , and for another synthesizer responsible for the fixed 20 MHz
 5820 frequency signal. Frequency synthesizers in both systems should have resolutions of about
 5821 1 ppb, to allow for some variability in the frequency that can be used for blinding schemes
 5822 and for tests of systematics. It is the synthesized frequencies that have to fulfill the accuracy
 5823 requirement discussed above. Master clock and synthesizers that fulfill the requirements
 5824 given above are available from vendors like Precision Test Systems, Symmetricon, Agilent,
 5825 and Stanford Research Systems. Amplifiers from vendors like Stanford Research Systems
 5826 and Mini-Circuits can distribute master clock and the needed reference frequencies to the
 5827 places where they are needed. There is experience in the collaboration from the BNL- $(g-2)$
 5828 experiment and, more recently, from the clock system used for the MuLan experiment at

5829 PSI in Switzerland in the specification and use of these systems.

5830 **15.3 Trolley**

5831 The in-vacuum NMR trolley system shown in Fig. 15.8(a) has the purpose of precisely
5832 mapping the magnetic field distribution over the muon storage aperture around the ring.
5833 From this distribution, the multipole composition of the field averaged over the ring azimuth
5834 is extracted in order to subsequently fold it with the multipole expansion of the measured
5835 stored muon beam profile. Because the trolley measurements prohibit the injection of muons,
5836 the mapping of the field around the entire storage ring happens intermittently with the spin
5837 precession frequency measurement. During these typically 2 hour runs with the trolley, a
5838 cross-calibration of the field observed by the fixed probes to the field measured by the trolley
5839 probes is performed. This is an important ingredient due to the fact that the magnetic field
5840 encountered by the stored muons can only be inferred from the fixed probes.

5841 In the following sections, we will first specify the requirements for E989 and then discuss
5842 the conceptual design of future upgrades and efforts related to the trolley system.

5843 **15.3.1 General requirements**

5844 As can be seen from Table 15.2, trolley related systematic errors in the BNL E821 experiment
5845 were of sizeable amount and require significant improvement to meet the physics goals in
5846 E989. The two main sources of uncertainty stem from the calibration procedure of the trolley
5847 probes to the plunging probe (0.09 ppm) and errors related to position uncertainties during
5848 the actual trolley runs (0.05 ppm). Additional smaller effects (like temperature or voltage
5849 drifts) were grouped into one systematic error (Others) together with non-trolley related
5850 systematics in the field measurement. For the new E989 experiment, the trolley system will
5851 be used in a very similar fashion as in E821. Given the required improvements in the overall
5852 systematic errors for the field measurement, we will need some changes for the new system.

5853 The requirements for the actual measurement during a single trolley run remain the same.
5854 An individual NMR frequency measurement will have a precision at least as good as 20 ppb
5855 as was achieved in E821. The field will be measured at 6000 points around the ring for each
5856 probe. A single trolley run should be accomplished in at most two hours. While about 1
5857 hour is required for the mapping of the 6000 data points for each probe, the return trip
5858 can be sped up to reduce the interruption of the spin frequency measurement. Trolley runs
5859 should be repeated more frequently than in E821 where an interval of 2-3 days was typical.
5860 Increased frequency of trolley measurements will reduce the error associated with the fixed
5861 probe interpolation and allow for a complete mapping over all temperature changes in the
5862 storage ring.

5863 As mentioned above, transverse and longitudinal position uncertainties coupled with field
5864 gradient are a major systematic error category in the measurement. While we plan on having
5865 improved overall shimming in E989 and hence reduced gradients, we will also put effort into
5866 reducing the position uncertainties. The longitudinal position knowledge during the trolley
5867 field mapping was inferred from a combination of the measurement of the cable unwinding
5868 by means of optical rotary encoders in the drums and by the observed change in the NMR

5869 frequency in the fixed probes due to the small but measurable changes in the magnetic field
5870 induced by the trolley (maximally in the vicinity of the onboard electronic). The overall
5871 longitudinal position knowledge was estimated to be on the order of 1 cm corresponding to a
5872 50 ppb systematic error. Together with the better shimming in the azimuthal direction (see
5873 section 15.4), we aim to reduce the position uncertainty to 5 mm to significantly improve on
5874 this error contribution.

5875 During its movement the trolley rides on two rails which determine the transverse posi-
5876 tion of the trolley with respect to the center of the muon distribution. The requirements on
5877 the precision alignment of the trolley rails remain the same as in E821. A maximal deviation
5878 from their circular, ideal position of ± 0.5 mm will keep the associated systematic error below
5879 10 ppb. The rails were not continuous at the vacuum chamber interjoints. Slight misalign-
5880 ment of neighboring rails at these gaps led to possible transverse deviations of the trolley's
5881 center introducing an estimated systematic error of 10 ppb. In E989, we will reduce these
5882 misalignments and precisely verify the deviation of the rails from their nominal position
5883 around the full azimuth. Here, we will employ two methods, namely i) optical survey with
5884 laser systems or other precision metrology observation equipment and ii) the introduction
5885 of known, transverse gradients by means of the pole surface coils during dedicated special
5886 trolley runs.

5887 During the calibration with the plunging probe in a specially shimmed region in the
5888 storage ring, relative position uncertainties between the plunging and trolley probes added
5889 contributions to the overall systematic error. In E821, the transverse reproducibility was
5890 estimated to be 1 mm whereas the relative position uncertainty in azimuth was determined
5891 to 3 mm. This resulted in contributions of 20 ppb and 30 ppb, respectively. For E989, we
5892 aim to cut these contributions in half (at least in the azimuthal direction) by a more precise
5893 alignment of the probes in a repeatable way. For this, we plan to introduce a mechanical
5894 stop for the trolley in the calibration region, by allowing a positioning of the plunging probe
5895 in all three directions and by testing the calibration transfer carefully in a homogeneous
5896 solenoid test magnet before data taking.

5897 Other effects contributed to the E821 result with a summed contribution of 50 ppb. These
5898 included the temperature and voltage dependence of the NMR measurement and an estimate
5899 of the influence of higher multipoles. The dependence of the supply voltage of the trolley
5900 was derived to be 0.27 ppm/V and a voltage stability of 50 mV was achieved. In the new
5901 experiment, a modern power supply will significantly reduce the voltage drift and make this
5902 contribution totally negligible. We will reduce the effects of a temperature change on the
5903 extracted NMR frequency. One possibility is to use petroleum jelly instead of water for the
5904 NMR probes due to the reduced temperature coefficient of the jelly. In addition, an increase
5905 in the heat dissipation of the trolley would reduce the change of its temperature during the
5906 measurement. Overall, the effect should be negligible in the E989 experiment and we can
5907 carefully study it in the solenoid test magnet under controlled temperature conditions. The
5908 30 ppb systematic error in E821 stemming from the folding of higher multipoles with the
5909 muon distribution can be improved by a modification of the current trolley probe arrange-
5910 ment shown in figure 15.8(b). There is room to further move the probes to an outer position
5911 closer to the 4.5 cm aperture of the muon storage region. In addition, a reconfiguration of
5912 the overall probe distribution can help to get a better handle on the measurement of the
5913 sextupoles and higher multipoles.

5914 It should be noted that any additional modifications should respect the strict requirement
5915 that the field at the NMR probes is disturbed as minimally as possible. The maximal
5916 distortion of the field by the trolley electronics in E821 was about 2 ppm and future changes
5917 cannot introduce any major additional magnetic contribution compared to this level.

5918 In the following sections, we will detail our specific conceptual design for future up-
5919 grades and activities that are aimed to meet the above outlined requirements for the E989
5920 experiment.

5921 15.3.2 Garage

5922 The trolley garage shown in Fig. 15.4 serves the purpose of storing the trolley inside the
5923 vacuum outside the muon storage aperture during the main periods of spin precession mea-
5924 surement. A set of three rods driven by a non-magnetic piezo motor provides the mechanism
5925 to move cut-outs of the rails into the muon storage region and retract them. The in-vacuum
5926 requirements and a lack of motion stops have possibly put stress on these mechanics over
5927 the course of the E821 operation. The overall integrity of the system will need inspection to
5928 understand if the system is suited for the extended operation over the two years of data tak-
5929 ing in E989. Future improvements might include the replacement of the rods, the addition
5930 of non-magnetic limit switches to smoothly stop the rail movement when in place, or even a
5931 re-design of the garage with a switchyard solution. While ideally the garage could be oper-
5932 ated as is in E989, the exact measures to improve will be decided after detailed inspection
5933 in the near future at Brookhaven and later at Argonne.

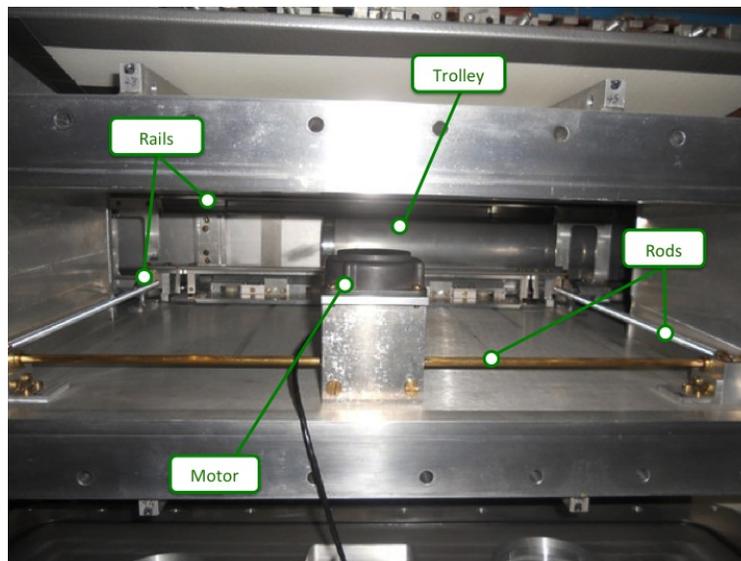


Figure 15.4: Trolley garage with the piezo motor, the driving rods, the rails and the trolley partially in the parking position where it can be retracted from the storage region.

5934 As can be seen in Figure 3.4, the trolley garage is attached to one of the 12 vacuum
5935 chambers. Since the general upgrades to other systems (like the alignment of the trolley

5936 rails) will require collaborators to work on the vacuum chambers, the upgrade activities
5937 with respect to the garage will be coordinated over the course of the next two years.

5938 15.3.3 Drive

5939 The trolley drive mechanism shown in Figure 15.5 is located about 120° degree away from
5940 the garage. It is connected to one of the vacuum chambers and sits on the inner side of
5941 the storage ring (see the 1 o'clock position in Fig. 11. The cable drums together with the
5942 driving piezo motors are outside the vacuum. Two 1.5 m-long tubes guide the two cables
5943 from the drive to the vacuum chamber and provide the vacuum feedthrough. Two cables are
5944 required to pull the trolley a full 360 degrees in each direction during its NMR measurement
5945 and its return trip. Since the cables remain attached to the trolley during the storage in the
5946 garage, one of the two cables runs through the kicker region. To prevent any damage to the
5947 onboard electronics from electronic pickup on the cable from the kicker pulses, this cable is
5948 a non-conducting fishing line. The other cable is an all-copper double-shielded cable with an
5949 outer coating suitable for in-vacuum operation. This cable allows the feeding of the power
5950 and reference frequency signal as well as the communication with the trolley microcontroller.

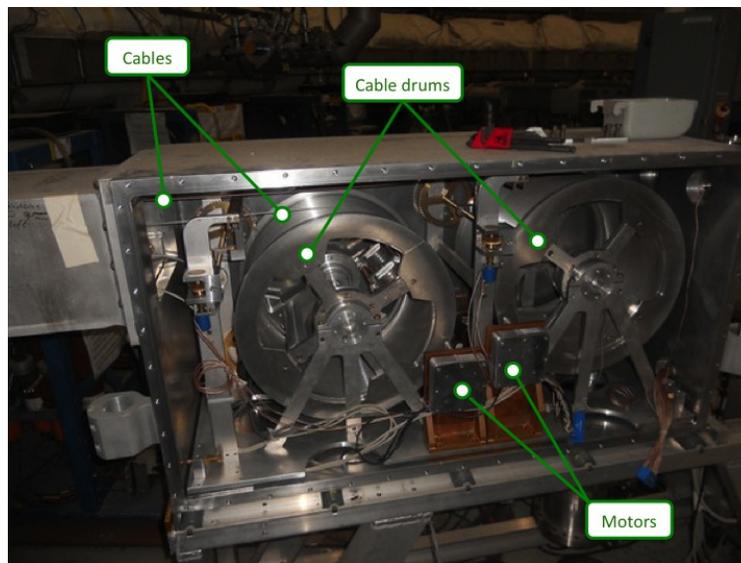


Figure 15.5: Trolley drive with the cable drums, motors and cables.

5951 The cable drive mechanism will need refurbishment and inspection of its functional in-
5952 tegrity. In general, we expect it to be used mainly as is since the overall wear in E821 was
5953 small and the mechanical parts should survive another 2 years of operation during the E989
5954 experiment. In order to speed up the return trip of the trolley to minimize interruption of the
5955 spin precession frequency measurement, an upgrade of one of the motors is anticipated. We
5956 also plan to relocate two optical rotary encoders that monitor the unwinding of the cables
5957 to minimize some non-linearities in their readback values with respect to the actual cable
5958 unwinding length. For full operation of the drive, the motor controller needs to be brought
5959 back into operation. Its central component is an Infineon SAB80C535 microcontroller that

5960 facilitates the communication with the remote DAQ. Its refurbishment should mainly require
5961 compilation and uploading of the Pascal software code which is available to us.

5962 **15.3.4 Position Measurement**

5963 The measurements of the trolley's position in both the longitudinal and transverse directions
5964 relative to its motion plays an important role in the evaluation of several systematic error
5965 sources. Uncertainties in the trolley's position convoluted with the local field gradients give
5966 rise to a shift in the measured B fields during both the relative calibration with the plunging
5967 probe and the mapping of the field around the full azimuth.

5968 As stated in the requirements section 15.3.1 above, some improvements in the determina-
5969 tion of the trolley's position compared to the E821 experiment are necessary. Together with
5970 the better shimming of the magnet (c.f. section 15.4) and hence reduced field gradients, this
5971 will give the overall reduction of the position related systematic errors required for E989.

5972 During the calibration procedure of the trolley probes in a specially shimmed region in
5973 the ring, the plunging probe and the trolley probes need to be positioned repeatedly at the
5974 same position. The uncertainty in E821 for the relative azimuthal alignment was estimated
5975 to be 3 mm. As the trolley was positioned visually, we foresee improvements by means of
5976 a well-defined stop mechanism or an external laser beam on a fine positioning grid through
5977 the viewing port. The plunging probe currently has only limited directional movement and
5978 addition of its azimuthal adjustment inside the vacuum should also help in reducing this
5979 position uncertainty.

5980 While the trolley moves on the rails around the ring, the transversal position of the 17
5981 NMR probes relative to the central muon orbit is mainly defined by the precision alignment of
5982 the rails. An average radial and vertical deviation of the rails of less than ± 0.5 mm would be
5983 sufficient to keep the associated systematic error negligible. While mechanical improvements
5984 of the rail fixture, curvature, and positioning inside the vacuum chambers will be performed
5985 in conjunction with other work on the cages, a precise verification of this stringent alignment
5986 requirement needs to follow. We anticipate a combination of two measurements to have a
5987 consistent cross-check of the trolley's transversal movement. The first verification will be
5988 based on optical (or other suitable) survey techniques with the trolley riding on the rails.
5989 This technique should work on individual vacuum chambers in air. Once all chambers are
5990 mounted in the storage ring and evacuated, optical inspection of the trolley's movement could
5991 only happen via ports on the radial inner side of the chambers (see figure 3.4). However, the
5992 sole inspection of the trolley's movement inside a non-evacuated chamber might be sufficient
5993 since FEA modeling and measurements show that the deflection of the chamber walls is
5994 small. A second technique will make usage of imposing radial and vertical gradients using
5995 the surface coils to observe the changes in the NMR probe readings around the ring.

5996 The longitudinal position measurement of the trolley was achieved by a combination of
5997 optical rotary encoders and potentiometers monitoring the cable unwinding as well as the
5998 response spikes in the NMR frequency of the fixed probes due to the passing electronics of the
5999 trolley. The overall estimate of the longitudinal uncertainty was on the order of a centimeter.
6000 We aim to reduce this uncertainty to 5 mm or better by refurbishing an onboard barcode
6001 reader that was mostly unused in E821 due to its overheating in the vacuum environment. As
6002 can be seen in Figure 15.6, the vacuum chambers are equipped with marks around the ring.

6003 The continuously spaced marks have a spacing of 2.5 mm while the larger spaced irregular
6004 codes serve as absolute reference marks. A reduction of the power consumption by usage
6005 of more efficient LEDs and light sensitive detectors or by increasing the heat dissipation
6006 capabilities of the reader head would then give a direct longitudinal measurement of the
6007 trolley at the required precision level.

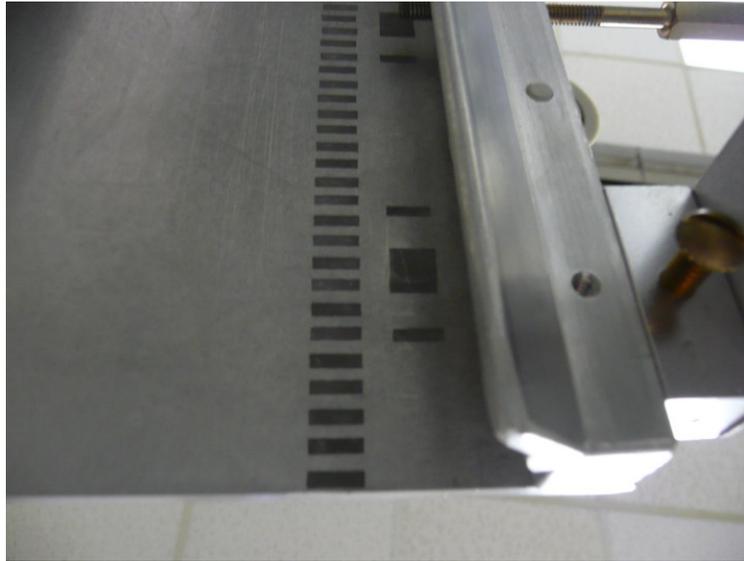


Figure 15.6: Trolley bar code marks on vacuum chamber plate

6008 15.3.5 Probes

6009 The 17 trolley NMR probes (c.f. Figure 15.9(b)) are identical to the fixed probes. No major
6010 work should be necessary for future usage in E989 except for a standard refurbishment pro-
6011 cedure performed by collaborators from the University of Washington. These activities will
6012 include the refilling with the NMR substance (either water or petroleum jelly), resoldering
6013 of broken wire connections, tuning of the probes Q-value and impedance matching to the
6014 $50\ \Omega$ cable as well as testing of a normal NMR response at 1.45 T. Replacement of parts of
6015 the probe would also be handled in these steps.

6016 As can be seen in the Figure 15.8(b), the outermost radius covered by the trolley probes
6017 is 3.5 cm. The folding of the muon distribution with the magnetic field multipole expansion
6018 is performed over the entire muon storage aperture with radius 4.5 cm. In E821, the esti-
6019 mate of the contribution from the sextupole and higher multipoles were obtained from data
6020 with a special shimming trolley in 1998 and amounted to a systematic error contribution of
6021 0.03 ppm. Since a different arrangement of the 17 NMR probes, especially moving towards
6022 outer radii, could be beneficial to reduce this contribution, we will study the gains. The
6023 implementation would require two new teflon holder plates inside the trolley with a new hole
6024 configuration for the probe placement.

6025 15.3.6 Frequency Measurement

6026 The NMR frequency measurement for the 17 NMR trolley probes is currently all integrated
 6027 into the onboard electronics. At its heart sits the Motorola 68332 μ C microcontroller with
 6028 a multitude of functionality. Power, RS232 communication, and the NMR reference fre-
 6029 quency are brought in over a single double-shielded cable. The remaining NMR components
 6030 (RF pulse amplifier, multi- and duplexer, signal preamplifier and frequency counter) are all
 6031 integrated into the trolley housing. Additional temperature and pressure sensors and the
 6032 barcode reader are also available. The development of this minimally magnetic, low power
 6033 and noise system was a major effort in E821. As future changes to the internal electronics
 6034 come at the risk of a failure and could cause the need of significant engineering resources,
 6035 we will avoid such activities as much as possible.

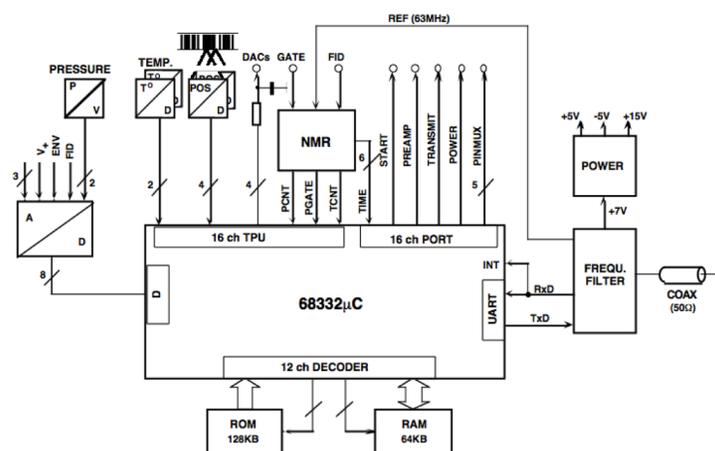


Figure 15.7: Schematics of central electronics on board of the trolley.

6036 Even the low electric power of less than 1 W leads to changes in the temperature of the
 6037 trolley electronics and the probes of a few degrees $^{\circ}\text{C}$ over the course of a trolley run. As
 6038 the measured NMR frequency is temperature dependent, minimization of the temperature
 6039 changes will help to reduce the associated systematic error. While we will also study the
 6040 temperature dependence carefully in a test solenoid, we will investigate whether the heat
 6041 dissipation via radiation to the vacuum chamber walls could be increased by increasing the
 6042 surface emissivity of the trolley's aluminum shell or if an additional heat sink could stabilize
 6043 the temperature sufficiently long enough.

6044 15.3.7 DAQ

6045 The communication with the onboard microcontroller happens via the pulling cable over
 6046 the RS232 communication protocol. A new standard DAQ computer will be established to
 6047 perform this functionality in the future E989 experiment and to provide all necessary user
 6048 interfaces to execute commands on the trolley microcontroller. The same DAQ infrastruc-
 6049 ture will be used to communicate with the trolley drive which is similarly interfaced via a

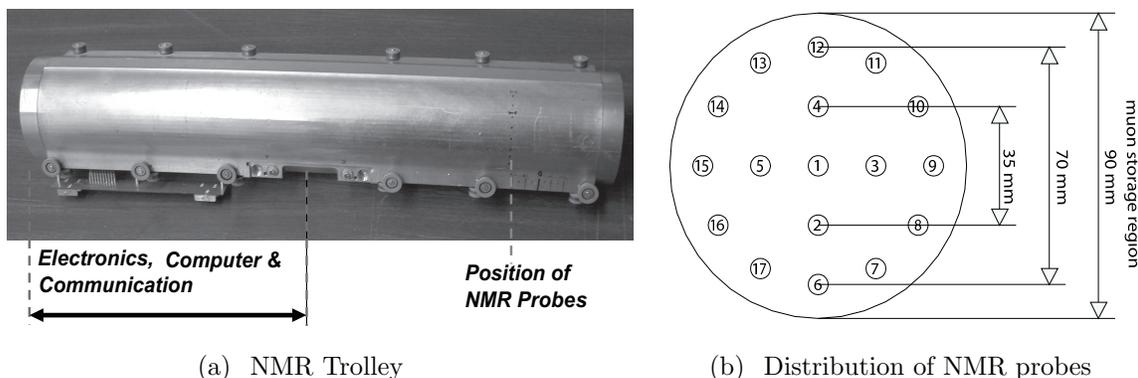


Figure 15.8: (a) Photograph of the NMR trolley, which measures the magnetic field in the storage ring. The array of 17 NMR probes, which are located inside the trolley housing, 82(1) mm behind the front of the trolley. Electronics occupies the back part of the device. At the location of the probes, the field perturbation by these materials is less than 2 ppm and is accounted for by the calibration method. (b) The probe numbers and placement are given by the schematic.

6050 microcontroller. The plunging probe mechanism shares the same microcontroller concept
 6051 and could be operated from this computer, too. If possible, we will also operate the garage
 6052 retraction mechanism from here.

6053 To map the storage ring magnetic field when the beam is off we will use a beam-tube
 6054 trolley.

6055 A central element of the system is a field-mapping trolley, shown in Fig. 15.8(a) that
 6056 mapped the field at several thousand points around the ring. This trolley contains 17 NMR
 6057 probes arranged in concentric circles as shown in Fig. 15.8(b).

6058 The magnetic field is measured and monitored by pulsed Nuclear Magnetic Resonance
 6059 of protons in water samples [3]. The free induction decay (FID) is picked up by the coil
 6060 L_S in Fig. 15.9 after a pulsed excitation rotates the proton spin in the sample by 90° to
 6061 the magnetic field. The proton response signal at frequency f_{NMR} is measured by counting
 6062 its zero crossings within a well-measured time period the length of which is automatically
 6063 adjusted to approximately the decay time ($1/e$) of the FID. It is mixed with a stable reference
 6064 frequency and filtered to arrive at the difference frequency f_{FID} chosen to be typically in the
 6065 50 kHz region. The reference frequency of $f_{\text{ref}} = 61.74$ MHz is obtained from a frequency
 6066 synthesizer, which is phase locked to a LORAN C secondary frequency standard [?], and it
 6067 is chosen such that always $f_{\text{ref}} < f_{\text{NMR}}$. The very same LORAN C device also provides the
 6068 time base for the ω_a measurement. The relationship between the actual field B_{real} and the
 6069 field corresponding to the reference frequency is given by

$$B_{\text{real}} = B_{\text{ref}} \left(1 + \frac{f_{\text{FID}}}{f_{\text{ref}}} \right). \quad (15.6)$$

6070 The field measurement process has three aspects: calibration, monitoring the field during
 6071 data collection, and mapping the field. The probes used for these purposes are shown in

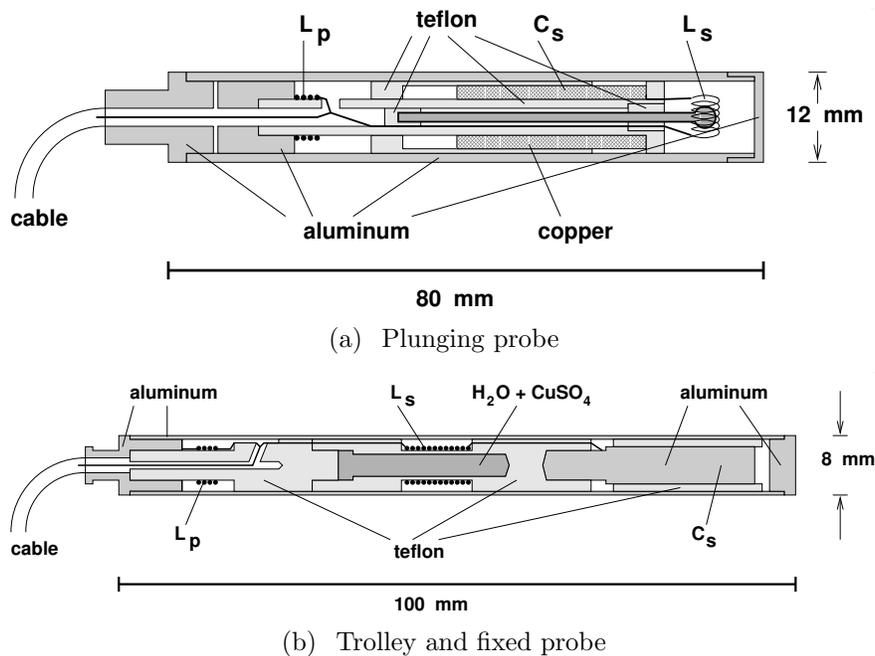


Figure 15.9: (a) Plunging probe, which can be inserted into the vacuum at a specially shimmed region of the storage ring to transfer the calibration to the trolley probes. (b) The standard probes used in the trolley and as fixed probes. The resonant circuit is formed by the two coils with inductances L_s and L_p and a capacitance C_s made by the Al-housing and a metal electrode.

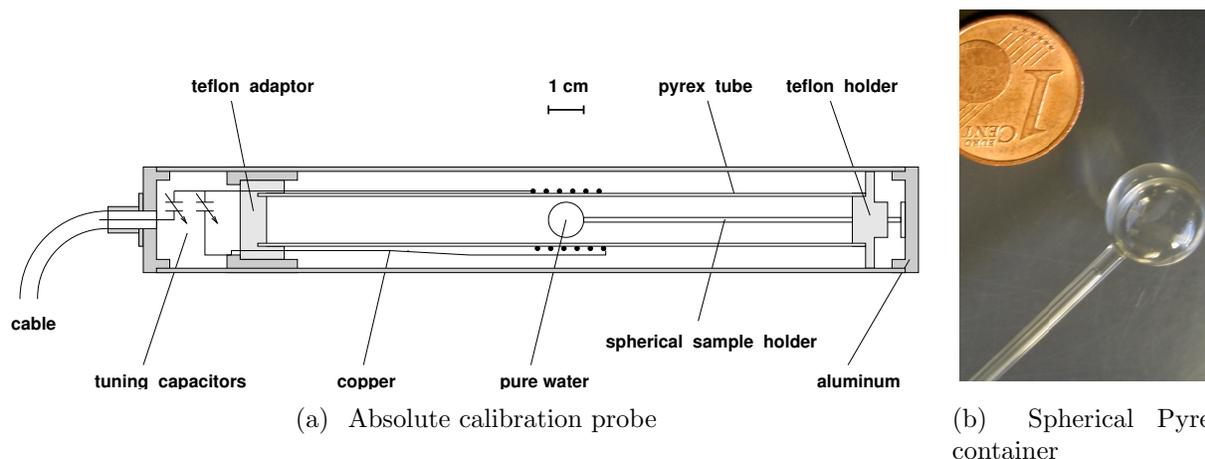


Figure 15.10: The different NMR probes. (a) Absolute probe featuring a spherical sample of water. This probe and all its driving and readout electronics are the very same devices employed in reference [16] to determine λ , the muon-to-proton magnetic-moment ratio. (b) The spherical Pyrex container for the absolute probe.

6072 Fig. 15.9 To map the field, an NMR trolley [7] was built with an array of 17 NMR probes
6073 arranged in concentric circles, as shown in Fig. 3.8. While it would be preferable to have
6074 information over the full 90-mm aperture, space limitations inside the vacuum chamber,
6075 which can be understood by examining Figs. 3.8, prevent a larger diameter trolley.

6076 The trolley is built from non-magnetic materials and has a fully functional CPU on-
6077 board which controls a full FID excitation and zero crossing counting spectrometer. It is
6078 pulled around the storage ring by two cables, one in each direction circling the ring. One of
6079 these cables is a thin co-axial cable with only copper conductors and Teflon dielectric and
6080 outside protective coating (Suhner 2232-08). It carries simultaneously the dc supply voltage,
6081 the reference frequency f_{ref} and two-way communication with the spectrometer via RS232
6082 standard. The other cable is non-conducting nylon (fishing line) to eliminate pickup from
6083 the pulsed high voltage on the kicker electrodes.

6084 During muon decay data-collection periods, the trolley is parked in a garage (see Fig. 3.4)
6085 in a special vacuum chamber. Every few days, at *random times*, the field is mapped using
6086 the trolley. During mapping, the trolley is moved into the storage region and over the course
6087 of 2 hours is pulled around the vacuum chamber, measuring the field at some 100,000 points
6088 by continuously cycling through the 17 probes while moving. Data were recorded in both
6089 possible directions of movement. During the approximately three-month data-collection
6090 runs, the storage-ring magnet remains powered continuously for periods lasting from five
6091 to twenty days; thus the conditions during mapping are identical to those during the data
6092 collection.

6093 To cross calibrate the trolley probes, a two-axis non-magnetic manipulator made from
6094 aluminum and titanium only, including titanium bellows, and driven by non-magnetic piezo
6095 motors was developed. It was placed at one location in the ring and it permits a special NMR
6096 plunging probe, or an absolute calibration probe with a spherical water sample [4], to plunge
6097 into the vacuum chamber. In this way the trolley probes can be calibrated by transferring
6098 the absolute calibration from the calibration probe shown in Fig. 15.9 to individual probes
6099 in the trolley. These measurements of the field at the same spatial point with the plunging,
6100 calibration and trolley probes provide both relative and absolute calibration of the trolley
6101 probes. During the calibration measurements before, after and occasionally randomly during
6102 each running period, the spherical water probe is used to calibrate the plunging probe, and
6103 with this then the trolley probes. The absolute calibration probe provides the calibration to
6104 the Larmor frequency of the free proton [10], which is called ω_p below.

6105 The magnetic field data consist of three separate sets of measurements: The calibration
6106 data taken before, after, and occasionally during each running period; maps of the magnetic
6107 field obtained with the NMR trolley at intervals of a few days at random hours; and the field
6108 measured by each of the fixed NMR probes located in the vacuum chamber walls. For the
6109 latter measurements groups of 20 probes were connected via one of 20 analog multiplexers
6110 to one of 20 readout channels, each consisting of a frequency mixer and a custom-designed
6111 FID zero crossing counting device [3]. The plunging probe and the calibration probe [4] were
6112 also connected to one of the multiplexer inputs. The probes of each group were sequentially
6113 excited and their FID was read in full cycles repeated approximately every 5 seconds all
6114 throughout the experimental periods and whenever the magnet was energized. The data
6115 taken concurrent with the muon spin-precession data were tied to the field mapped by the
6116 trolley, which were used to determine the average magnetic field in the storage ring, and

6117 subsequently the value of ω_p to be used in Eq. (3.21).

6118 Calibration of the trolley probes

6119 The errors arising from the cross-calibration of the trolley probes with the plunging probes
 6120 are caused both by the uncertainty in the relative positioning of the trolley probe and the
 6121 plunging probe, and by the local field inhomogeneity. At this point in azimuth, trolley
 6122 probes are fixed with respect to the frame that holds them, and to the rail system on
 6123 which the trolley rides. The vertical and radial positions of the trolley probes with respect
 6124 to the plunging probe are determined by applying a sextupole field and comparing the
 6125 change of field measured by the two probes. The field shimming at the calibration location
 6126 minimizes the error caused by the relative-position uncertainty, which in the vertical and
 6127 radial directions has an inhomogeneity less than 0.2 ppm/cm, as shown in Fig. 15.11(b). The
 6128 full multipole components at the calibration position are given in Table 15.3.7, along with
 6129 the multipole content of the full magnetic field averaged over azimuth. For the estimated rms
 6130 1 mm-position uncertainty, the uncertainty on the relative calibration is less than 0.02 ppm.

6131 The absolute calibration utilizes a probe with a spherical water sample (see Figs. 15.9(a),
 6132 15.9(b)) [4]. The Larmor frequency of a proton in a spherical water sample is related to that
 6133 of the free proton through [8, 11]

$$f_L(\text{sph} - \text{H}_2\text{O}, T) = [1 - \sigma(\text{H}_2\text{O}, T)] f_L(\text{free}), \quad (15.7)$$

6134 where $\sigma(\text{H}_2\text{O}, T)$ is from the diamagnetic shielding of the proton in the water molecule,
 6135 determined from [10]

$$\sigma(\text{H}_2\text{O}, 34.7^\circ\text{C}) = 1 - \frac{g_p(\text{H}_2\text{O}, 34.7^\circ\text{C})}{g_J(H)} \frac{g_J(H)}{g_p(H)} \frac{g_p(H)}{g_p(\text{free})} \quad (15.8)$$

$$= 25.790(14) \times 10^{-6}. \quad (15.9)$$

6136 The g -factor ratio of the proton in a spherical water sample to the electron in the hydrogen
 6137 ground state ($g_J(H)$) is measured to 10 parts per billion (ppb) [10]. The ratio of electron to
 6138 proton g -factors in hydrogen is known to 9 ppb [12]. The bound-state correction relating the
 6139 g -factor of the proton bound in hydrogen to the free proton are calculated in References [13,
 6140 14]. The temperature dependence of σ is corrected for using $d\sigma(\text{H}_2\text{O}, T)/dT = 10.36(30) \times$
 6141 $10^{-9}/^\circ\text{C}$ [15]. The free proton frequency is determined to an accuracy of 0.05 ppm.

6142 The fundamental constant $\lambda_+ = \mu_{\mu^+}/\mu_p$ (see Eq.(3.21)) can be computed from the hy-
 6143 perfine structure of muonium (the μ^+e^- atom) [11], or from the Zeeman splitting in muo-
 6144 nium [16]. The latter experiment used the very same calibration probe as well as the essential
 6145 NMR field monitoring and mapping devices and techniques, including all the driving and
 6146 readout electronics, as we used in our ($g - 2$) experiment. The magnetic environments of
 6147 the two experiments were slightly different, so that perturbations of the probe materials on
 6148 the surrounding magnetic field differed by a few ppb between the two experiments, which
 6149 can be neglected at our level of accuracy. We have therefore a direct robust link of our
 6150 magnetic field to the muon magneton (proton NMR has only the role of a fly wheel), which
 6151 is independent of possible future changes in fundamental constants in the regular adjustment
 6152 procedures [11], unless the muon magneton will be remeasured experimentally.

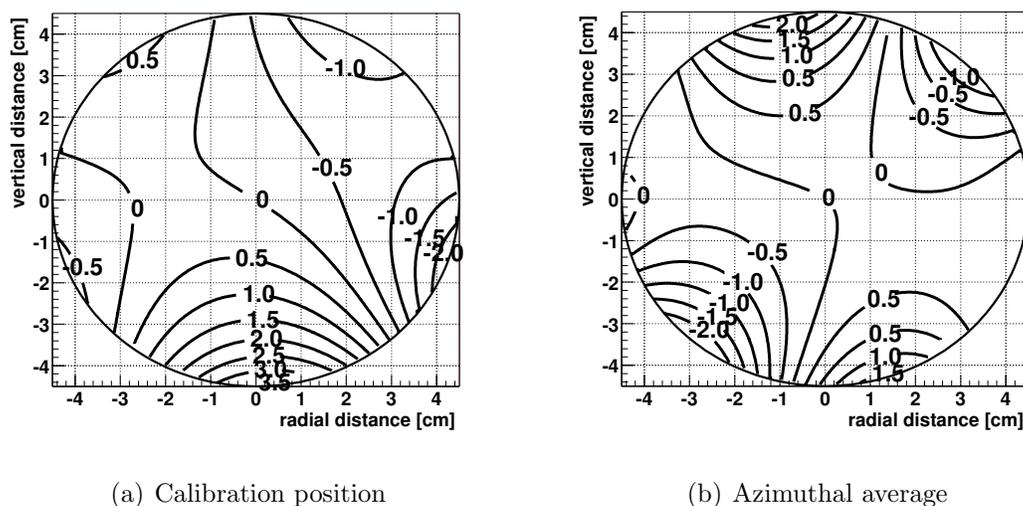


Figure 15.11: Homogeneity of the field (a) at the calibration position and (b) for the azimuthal average for one trolley run during the 2000 period. In both figures, the contours correspond to 0.5 ppm field differences between adjacent lines.

6153 The errors in the calibration procedure result both from the uncertainties on the positions
 6154 of the water samples inside the trolley and the calibration probe, and from magnetic field
 6155 inhomogeneities. The precise location of the trolley in azimuth, and the location of the
 6156 probes within the trolley, are not known better than a few mm. The uncertainties in the
 6157 relative calibration resulting from position uncertainties are 0.03 ppm. Temperature and
 6158 power-supply voltage dependences contribute 0.05 ppm, and the paramagnetism of the O_2
 6159 molecules in the air-filled trolley causes an experimentally verified 0.037 ppm shift in the
 6160 field.

Table 15.1: Multipoles at the outer edge of the storage volume (radius = 4.5 cm). The left-hand set are for the plunging station where the plunging probe and the calibration are inserted. The right-hand set are the multipoles obtained by averaging over azimuth for a representative trolley run during the 2000 period.

Multipole [ppm]	Calibration		Azimuthal Averaged	
	Normal	Skew	Normal	Skew
Quadrupole	-0.71	-1.04	0.24	0.29
Sextupole	-1.24	-0.29	-0.53	-1.06
Octupole	-0.03	1.06	-0.10	-0.15
Decupole	0.27	0.40	0.82	0.54

6161 **Mapping the magnetic field**

6162 During a trolley run, the value of B is measured by each probe at approximately 6000
 6163 locations in azimuth around the ring. The magnitude of the field measured by the central
 6164 probe is shown as a function of azimuth in Fig. 15.12 for one of the trolley runs. The insert
 6165 shows that the fluctuations in this map that appear quite sharp are in fact quite smooth,
 6166 and are not noise. The field maps from the trolley are used to construct the field profile
 6167 averaged over azimuth. This contour plot for one of the field maps is shown in Fig. 15.11(b).
 6168 Since the storage ring has weak focusing, the average over azimuth is the important quantity
 6169 in the analysis. Because the recorded NMR frequency is only sensitive to the magnitude of
 6170 B and not to its direction, the multipole distributions must be determined from azimuthal
 6171 magnetic field averages, where the field can be written as

$$B(r, \theta) = \sum_{n=0}^{n=\infty} r^n (c_n \cos n\theta + s_n \sin n\theta), \quad (15.10)$$

6172 where in practice the series is limited to 5 terms.

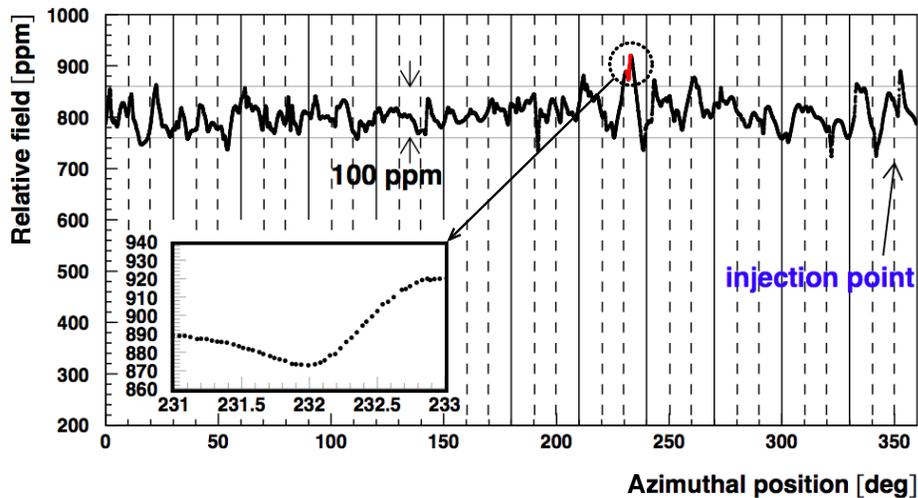


Figure 15.12: The magnetic field measured at the center of the storage region vs. azimuthal position. Note that while the sharp fluctuations appear to be noise, when the scale is expanded the variations are quite smooth and represent true variations in the field.

6173 **Tracking the magnetic field in time**

6174 During data-collection periods the field is monitored with the fixed probes. To determine
 6175 how well the fixed probes permitted us to monitor the field felt by the muons, the measured
 6176 field, and that predicted by the fixed probes is compared for each trolley run. The results
 6177 of this analysis for the 2001 running period is shown in Fig. 15.13. The rms distribution of
 6178 these differences is 0.10 ppm.

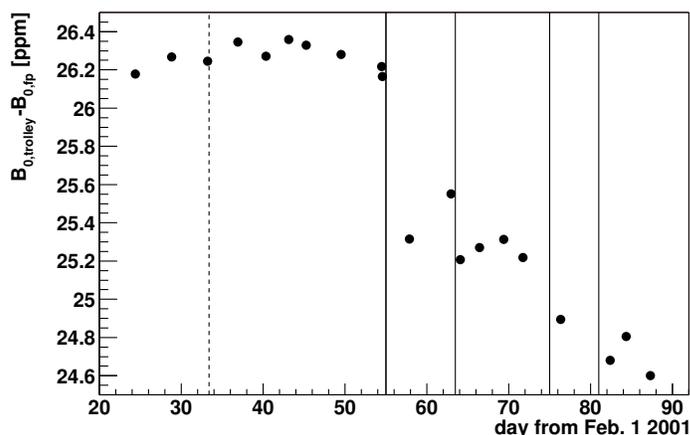


Figure 15.13: The difference between the average magnetic field measured by the trolley and that inferred from tracking the magnetic field with the fixed probes between trolley maps. The vertical lines show when the magnet was powered down and then back up. After each powering of the magnet, the field does not exactly come back to its previous value, so that only trolley runs taken between magnet powerings can be compared directly.

6179 Determination of the average magnetic field: ω_p

6180 The value of ω_p entering into the determination of a_μ is the field profile weighted by the muon
6181 distribution. The multipoles of the field, Eq. (15.10), are folded with the muon distribution,

$$M(r, \theta) = \sum [\gamma_m(r) \cos m\theta + \sigma_m(r) \sin m\theta], \quad (15.11)$$

6182 to produce the average field,

$$\langle B \rangle_{\mu\text{-dist}} = \int M(r, \theta) B(r, \theta) r dr d\theta, \quad (15.12)$$

6183 where the moments in the muon distribution couple moment-by-moment to the multipoles
6184 of \vec{B} . Computing $\langle B \rangle$ is greatly simplified if the field is quite uniform (with small higher
6185 multipoles), and the muons are stored in a circular aperture, thus reducing the higher mo-
6186 ments of $M(r, \theta)$. This worked quite well in E821, and the uncertainty on $\langle B \rangle$ weighted by
6187 the muon distribution was ± 0.03 ppm.

6188 The weighted average was determined both by a tracking calculation that used a field
6189 map and calculated the field seen by each muon, and also by using the quadrupole component
6190 of the field and the beam center determined from a fast-rotation analysis to determine the
6191 average field. These two agreed extremely well, vindicating the choice of a circular aperture
6192 and the ± 1 ppm specification on the field uniformity, that were set in the design stage of
6193 the experiment. [5]

6194 Summary of the magnetic field analysis

6195 The limitations on our knowledge of the magnetic field come from measurement issues, i.e.
6196 systematics and not statistics, so in E821 the systematic errors from each of these sources
6197 had to be evaluated and understood. The results and errors are summarized in Table 15.2.

6198 15.3.8 ^3He Magnetometry

6199 A second absolute calibration probe being considered will contain polarized ^3He . Such a
6200 probe has the advantage that the NMR frequency does not depend on the shape of the ^3He
6201 volume, unlike the water sample which has to be spherical, and depends on a number of
6202 external quantities discussed above.

6203 NMR with hyperpolarized ^3He produced by laser optical pumping is practical because
6204 the NMR signal per atom is of order 10^5 times larger than protons at 1.5 T, compensating
6205 for the much lower concentration in the gas phase. There are several potential advantages to
6206 using hyperpolarized ^3He in place of distilled water in the calibration/field-mapping probes
6207 leading to reduced systematic uncertainties. From equation ??, the diamagnetic shielding
6208 factor $\sigma_{^3\text{He}} = 50.924(2) \times 10^{-6}$, though larger than for H_2 and H_2O , has about $100\times$ smaller
6209 temperature coefficient for gases [?]. Additionally, motional narrowing eliminates line-shape
6210 distortion and the FID produces a Lorentzian line shape whose center is well defined. For
6211 H_2O the line shape must be analyzed in the same way as reference [?] in order to accurately
6212 transfer the calibration. Our experience with hyperpolarized xenon suggests that that signal-
6213 to-noise is comparable to the E821 H_2O calibration sample. Additionally, the samples can be
6214 made smaller, e.g. 5 mm diameter and thus average over a smaller volume, though cell-shape
6215 effects, discussed in the next paragraph, are more difficult to deal with in smaller cells.

6216 Hyperpolarized ^3He can be provided from a spin-exchange (SEOP)[?, ?] or metastability-
6217 exchange (MEOP)[?, ?] set up. We have extensive experience with SEOP and have worked
6218 closely with MEOP systems and will cooperate with expert groups at Ecole Normal Su-
6219 perieur and Simon Fraser to develop an effective system. The MEOP approach has ad-
6220 vantages for the calibration because it can be applied at room temperature and therefore
6221 in-situ in the probe. In the MEOP scenario, a turnkey 1083 nm laser light from a fiber
6222 laser (e.g. <http://www.keopsys.com/index.php/en/products-n-services/cw-laser/cyfl/cyfl-giga-series.html>)
6223 is distributed to each of the probe cells by a fiber. A discharge is struck
6224 in the cell to produce the excited state. Polarization of 10% or more is expected in a few
6225 minutes. A second option is hyperpolarized ^3He produced in a separate cell and transferred
6226 to the calibration cells through PFE tubing similar to the polarizers we have used for medical
6227 imaging work [?]. In either scenario, the dominant corrections will arise due to cell-shape
6228 effects (δ_b in equation ??), i.e non-sphericity of the cell, but more importantly the polarized
6229 gas in any tubing or pull off used in cell filling.

6230 High-field hyperpolarization magnetometry using the MEOP technique will be developed
6231 at Michigan working with long-term collaborators from our EDM [?] and medical-imaging
6232 work [?]. One of the challenges is effecting high magnetization at high field (signal-to-noise is
6233 proportional to magnetization, i.e. the product of polarization and gas density). High-field
6234 MEOP polarization of ^3He has been recently studied by the ENS group [?, ?], who show
6235 that, due to higher polarization rates, nuclear polarization, of 80% at 1.33 mbar and 25%

at 67 mbar, have been achieved. The magnetization at 67 mbar is essentially identical to protons in H_2O at 1.5 T, though the signals may be slightly smaller due to the difference of gyromagnetic ratios (32.4 MHz/T for ^3He and 42.6 MHz/T for protons).

The development work at Michigan will make use of our 1.5 T field and will enable probe development, polarization and studies of temperature dependence similar to those planned for petrolatum. SEOP polarized samples are also under consideration, and we have significant experience in these techniques and equipment.

As a basis for discussion, the systematic errors from E821 are listed below in Table 15.2.

Table 15.2: Systematic errors for the magnetic field for the different run periods. [†]Higher multipoles, trolley temperature and its power supply voltage response, and eddy currents from the kicker.

Source of errors	R99 [ppm]	R00 [ppm]	R01 [ppm]
Absolute calibration of standard probe	0.05	0.05	0.05
Calibration of trolley probes	0.20	0.15	0.09
Trolley measurements of B_0	0.10	0.10	0.05
Interpolation with fixed probes	0.15	0.10	0.07
Uncertainty from muon distribution	0.12	0.03	0.03
Inflector fringe field uncertainty	0.20	–	–
Others [†]	0.15	0.10	0.10
Total systematic error on ω_p	0.4	0.24	0.17
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400

15.4 Magnet Shimming

15.4.1 Overview

The main technical objective of the $g - 2$ storage ring shimming is to produce a field that is extremely uniform when averaged over azimuth. Both the muon distribution and the average field can be described by multipole expansions (see Sec 15.1). Care should be taken to minimize higher-order multipoles in the field. Improved field uniformity at any local azimuthal position is also desirable since the performance of the NMR probes relies on keeping the field gradients as small as possible in order to optimize the measurement of the free induction decay (FID) signal (see Sec ??). Furthermore, small field gradients reduce the uncertainty contribution from the position uncertainty of the probes. Since the probes sample the field over a non-negligible volume, the requirements on knowledge of the position are relaxed if the field gradients are minimized.

Before shimming, the magnet was designed to produce a field uniformity in the muon storage region of better than a few parts in 10^4 . This was achieved by using high-quality steel for the magnet yoke, and ultra-low carbon steel (ULCS) for the pole pieces. Upon assembly, the field uniformity is improved by more than two orders of magnitude through

6260 a shimming sequence. The general shimming strategy implemented in E821 was two-fold:
6261 passive shimming via precision alignment of ferromagnetic materials and active shimming
6262 utilizing current distributions. We will base our general shimming procedure on that of
6263 E821 and the experience gained therein. The $g - 2$ superconducting coils, yoke, pole pieces,
6264 and shims has been simulated with OPERA-2D as well as OPERA-3D. The results of these
6265 simulations are compared both with the POISSON simulations and results obtained during
6266 the development of E821 [17, 18, 19, 20, 21, 22, 23]. One critical aspect of the simulation
6267 is the use of realistic B-H magnetization curves. Although the steel is not fully saturated
6268 at 1.45 T, the response is not perfectly linear. This non-linearity is partially responsible
6269 for generating higher-order multipole moments in the shimming simulations, and must be
6270 recognized during the actual shimming procedure. Our OPERA simulations will allow for a
6271 sophisticated shimming plan that improves the overall uniformity of the field in E989.

6272 15.4.2 Passive Shims

6273 Passive shimming refers to the set of mechanical adjustments that are performed during the
6274 assembly of the ring and remain fixed during a long running period. The general strategy is
6275 to begin with adjustments far from the muon storage region and work towards it with finer
6276 and finer adjustments. The principle passive shimming controls consist of the following:

- 6277 1. Iron pieces on the yoke
- 6278 2. Alignment of the pole faces
- 6279 3. Wedge shims in the air gap between the pole piece and yoke
- 6280 4. Edge shims in the gap between upper and lower pole faces
- 6281 5. Iron pieces in the azimuthal gaps between adjacent pole faces

6282 Throughout the physics measurement, the NMR trolley described in Section 15.3 will
6283 travel around the ring to map out the magnetic field. However, prior to the installation of
6284 the vacuum chambers, more space is available between the pole pieces and a larger trolley
6285 can be used. This shimming trolley (see Figure 15.14) consists of 25 NMR probes; one is
6286 at the center of the muon storage region, eight are at a radius of 2.25 cm, and 16 are at
6287 a radius of 4.5 cm. This allows a mapping that extends to the outer radius of the muon
6288 storage region. The shimming trolley was positioned on the end of a ≈ 7 meter turntable
6289 arm positioned about the center of the storage ring. Rotating the turntable allowed the
6290 shimming trolley to map the field at various azimuthal positions.

6291 The platform on which the shimming trolley rests also allows for a precision measurement
6292 of the vertical gap between the upper and lower pole faces. Plastic rods with capacitive
6293 sensors (model Capacitec HPB-150A-A-L2-10-B-D) on each end allowed for a determination
6294 of the relative parallelism between the poles [23]. By rotating the assembly by 180° about
6295 the vertical axis, any systematic error due to the relative length of the rods was eliminated.
6296 The analysis of the data from the shimming trolley provided feedback during each stage of
6297 the shimming procedure.

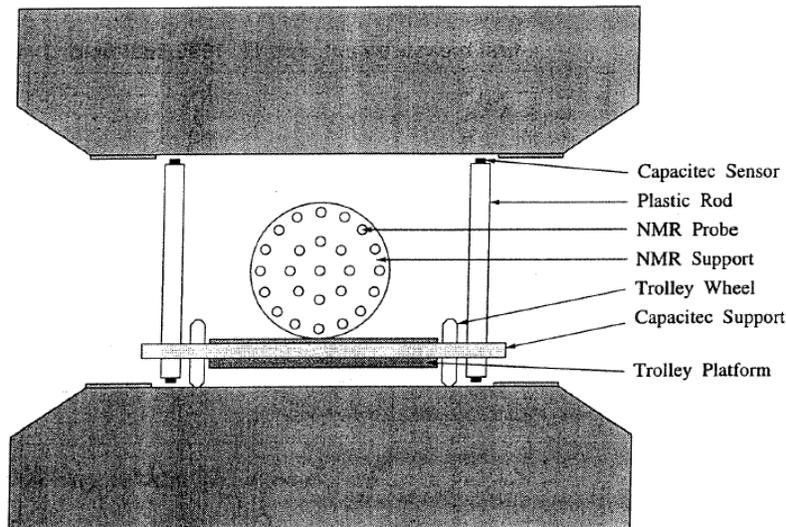


Figure 15.14: Schematic depiction of the NMR shimming trolley situated on a platform. Capacitive sensors on plastic rods help measure the pole piece alignment.

6298 Procedure

6299 A two-dimensional slice of the $g - 2$ magnet simulated in OPERA-2D is shown in Figure
6300 15.15.

6301 **Yoke Iron** The yoke is subdivided into twelve 30° sectors, as described in Section 9.2.
6302 Long wavelength azimuthal variations in the field uniformity can be addressed by adjusting
6303 the positioning of pieces of iron on the outer surface of the yoke. In particular, an increase
6304 in the air gap between the top piece of steel (labeled 7 in figure 15.15) and the upper yoke
6305 plate (labeled 5) leads to an increase the overall reluctance of the magnetic circuit. In this
6306 manner, rough adjustments to the dipole field can be achieved on a sector by sector basis.
6307 In other regions of the ring, steel shims will be added to the outside of the yoke in order to
6308 compensate for holes that are required for items like vacuum feedthroughs, the inflector, etc.

6309 **Pole Piece Alignment** The Capacitec sensors mounted to the shimming trolley apparatus
6310 will be able to measure the gap to a precision of $< 0.25 \mu\text{m}$. An increase in the gap size
6311 of $25 \mu\text{m}$ corresponds to a 100 ppm decrease of the dipole field. A $50 \mu\text{m}$ tilt over the
6312 length of the pole corresponds to a change in the quadrupole moment of 120 ppm . Thus the
6313 information from the shimming trolley will be used to properly align the pole pieces.

6314 **Wedge Shims** Wedge shims are inserted into the 2-cm air gap between the pole piece
6315 and the yoke, as depicted in Figure 15.16. The gap is designed to isolate the high-quality
6316 precision pole pieces from the yoke steel, which contains some magnetic inhomogeneities.
6317 Each 30° sector contains 72 wedge shims, which are 9.86 cm wide (azimuthally) and 53 cm-
6318 long (radially)[3]. This is shorter than the 56 cm-long pole pieces (radially), to accommodate

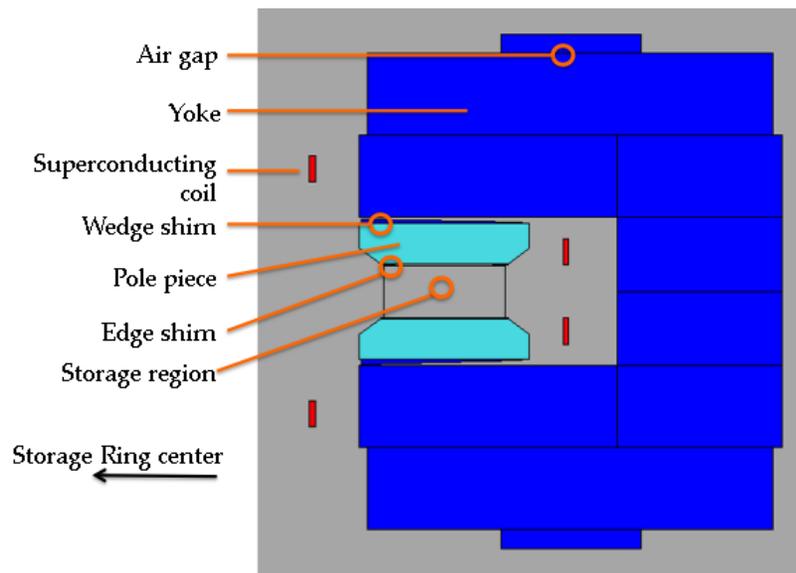


Figure 15.15: OPERA-2D model of the $g - 2$ magnet. The yoke and wedge shims are steel and shown in blue. The yoke (cyan) is made from ultra-low carbon steel (ULCS). The current in the superconductor coils is into the page for the inner coils and out of the page for outer coils.

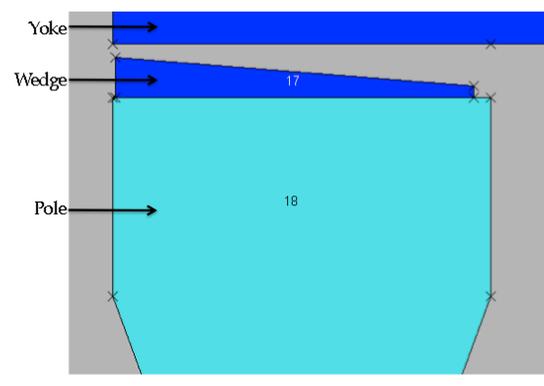


Figure 15.16: OPERA-2D model of the $g - 2$ magnet, zoomed in on the air gap between the yoke and pole pieces. The wedge shims are radially adjustable.

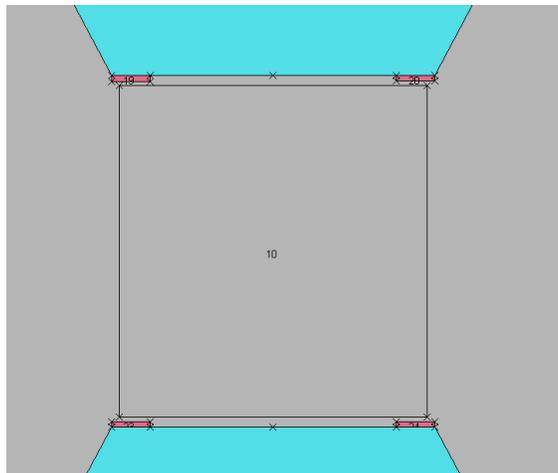


Figure 15.17: OPERA-2D model of the $g - 2$ magnet, zoomed in on the storage region. Edge shims are mounted on the pole pieces. “Inner” refers the shim at smaller radius (closest to the center of the ring), while “outer” refers to the shim at the larger radius (closest to the return yoke).

6319 radial adjustments. At the inner radius, the wedge shims are 1.65 cm thick, while at the
 6320 outer radius, they are 0.5 cm thick. Viewed from above, each wedge shim is rectangular.
 6321 Thus the space between adjacent wedge shims increases as the radial coordinate increases.

6322 The angle of the wedge shims was calculated to be 20 milliradian in order compensate for
 6323 the intrinsic quadrupole moment produced by the C-shaped magnet. Due to the asymmetry
 6324 in the C-magnet, the field lines would tend to concentrate in the gap near the return yoke.
 6325 The dipole field is determined by the average thickness in the air gap above the storage
 6326 region. The average wedge thickness is adjusted by translating the radial position of the
 6327 wedge shims. Because of the shallow angle of 20 mrad, a radial movement by $50 \mu\text{m}$ changes
 6328 the gap by $1 \mu\text{m}$, allowing fine control for the dipole field. OPERA-2D simulations show that
 6329 inserting the wedges into the air gap (towards the return yoke) radially by $50 \mu\text{m}$ produces
 6330 a 5.4 ppm increase in the dipole field. The quadrupole and higher-order multipoles are each
 6331 affected by less than 0.1 ppm for this adjustment.

6332 **Edge Shims** Each of the 36 pole pieces has four removable edge shims mounted on the
 6333 surface closest to the muon storage region, as shown in Figure 15.17. Each shim is 5 cm wide
 6334 (radially), spans one pole piece (10° azimuthally), and is positioned at either the inner or
 6335 outer edge of the pole faces. Variation of the thickness of the edge shims can produce (and
 6336 thus counteract) predictable multipole moments.

6337 In E821, the shims were ordered oversized (3.2 mm for the outer shims and 4.4 mm for
 6338 the inner shims) and then ground down to tune the quadrupole through octupole moments.
 6339 A first pass was performed to uniformly grind the shims as a function of azimuth. A final
 6340 pass optimized the thickness of the edge shims pole piece by pole piece.

6341 We have studied the effect of systematic shim thickness variations in OPERA-2D. Since
 6342 the model assumes vertical symmetry, the upper and lower edge shims are always adjusted

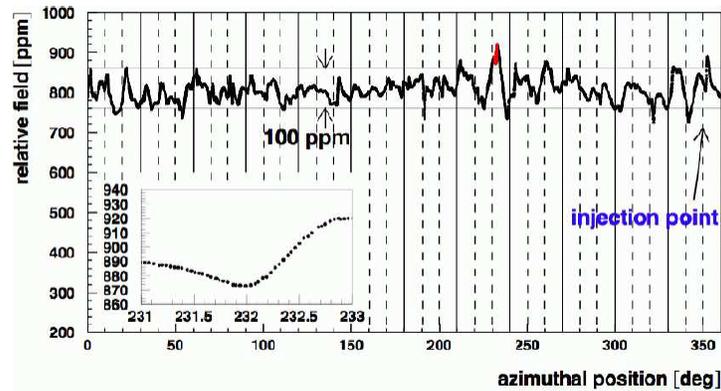


Figure 15.18: The magnetic field determined by the center NMR trolley probe versus azimuthal position in the storage ring during one trolley pass (reproduced from Ref [?]). The solid vertical lines denote boundaries between the 12 yoke sectors. The dashed vertical lines denote the pole piece boundaries.

6343 simultaneously. Symmetrically increasing the thickness of both the inner and outer edge
 6344 shims affects primarily the sextupole moment. We found that a $100\mu\text{m}$ increase in the edge
 6345 shim thickness in all four corners increases the sextupole moment by 10.8 ppm . Asymmetric
 6346 thickness adjustment leaves the sextupole moment unchanged and allows fine tuning of the
 6347 quadrupole and octupole moments. Increasing the outer edge shim thickness by $100\mu\text{m}$ while
 6348 decreasing the inner edge shim thickness by the same amount increases the quadrupole and
 6349 octupole moments by 13.2 ppm and 5.6 ppm , respectively. Although the simulation utilized
 6350 vertical symmetry, this model can be extended to up-down and diagonal (skew) asymmetries.

6351 We plan to use a similar shimming strategy in E989. We will order oversized edge shims,
 6352 map the field, grind, and repeat. Based on the experience of E821 and the extensive OPERA
 6353 simulations, we believe this phase of the shimming will require only two iterations.

6354 **Gap shims** Azimuthally, significant variations in the magnetic field occur at the bound-
 6355 aries between adjacent pole pieces, as shown in figure 15.18. The effect is even more pro-
 6356 nounced at the pole piece surface than in the storage region, jeopardizing the effectiveness
 6357 of the fixed probes located near the inter pole piece gaps. In E989, we plan to reduce the az-
 6358 imuthal variations in the field by shimming the gaps with thin iron plates. The basic concept
 6359 would be to span the surface of adjacent pole pieces with high quality steel plates varying
 6360 from 10 to $100\mu\text{m}$. Simulations show that a local change of $10\mu\text{m}$ in the air gap between
 6361 the pole pieces results in a 40 ppm shift in the dipole field. This should be a fairly short
 6362 wavelength affect that will reduce the local field gradients and improve the performance of
 6363 the fixed NMR probes mounted in the vacuum chambers.

6364 Radial Field

6365 An auxiliary measurement of the radial component of the magnetic field was performed
 6366 during the passive shimming phase prior to the installation of the vacuum chambers. In the

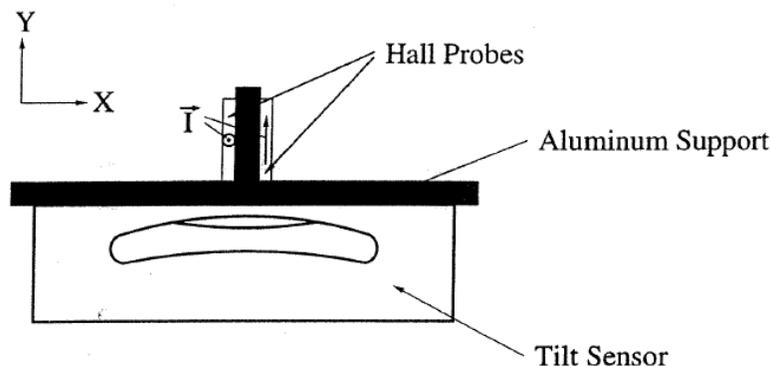


Figure 15.19: (a) A schematic representation of the radial field measurement configuration. Two Hall probes are mounted to measure the radial component of the field (x) with Hall currents oriented in the z and y directions. The rigid configuration is equipped with a tilt sensor. Rotating the entire setup 180° about the y -axis isolates the radial component.

6367 storage region, the direction of magnetic field is principally vertical. The presence of a radial
 6368 field component has a significant impact on the muon storage beam dynamics, affecting
 6369 both the mean vertical position and the vertical betatron oscillations. Quantitatively, the
 6370 radial field component needs to be measured to ≈ 10 ppm. However, the NMR probes
 6371 only measure the total magnitude of the magnetic field without providing information about
 6372 the separate vertical and radial components. In E821 an auxiliary measurement using Hall
 6373 probes was implemented to quantify the radial component of the field. We plan to reproduce
 6374 this procedure.

6375 Figure 15.19 shows a schematic representation of the setup used to measure the radial
 6376 field. Two Hall probes (BH-206, F.W. Bell) were vertically aligned to measure the radial
 6377 magnetic field, with the Hall currents running in the z and y directions. To ensure align-
 6378 ment of the setup with respect to the gravitational vertical direction, electrolytic tilt sensors
 6379 (RG33A, Spectron Systems Technology, Inc.) were mounted to the support structure. Fi-
 6380 nally to account for potential misalignment of the Hall probes with respect to the support
 6381 structure, the measurements were repeated after rotating the entire structure by 180° about
 6382 the vertical axis and taking the difference of the Hall voltages.

6383 Figure 15.20 shows the data from the Hall probes overlaid on the expected radial field
 6384 as calculated from the multipole expansion of the absolute field measurement. The overall
 6385 precision of the radial field measurement was significantly better than the required 10 ppm.
 6386 Figure 15.21 shows the radial field measurement (dots) from the Hall probe as a function
 6387 of the azimuthal position around the ring. The line in this plot represents the measured
 6388 pole tilt derived from the capacitive sensor data described above. The tracking of these two
 6389 curves demonstrates the qualitative dependence of the radial field on the pole alignment.

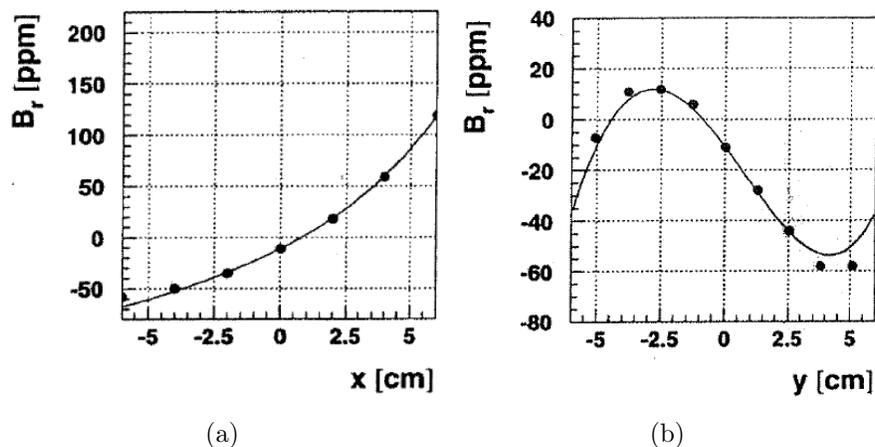


Figure 15.20: Radial component of the magnetic field in ppm as a function of (a) radial position x and (b) vertical position y . The dots show the data from the Hall probe, while the solid lines represent the field variation expected from the multipole coefficients calculated from the absolute field measurement.

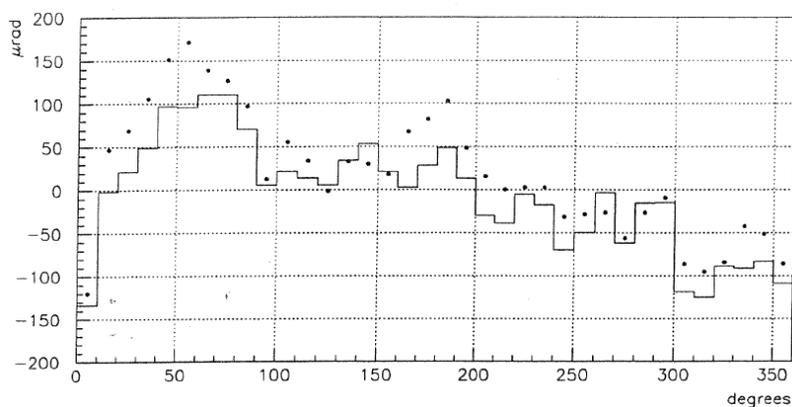


Figure 15.21: (a) The radial field measurement (dots) from the Hall probe and the average pole tilt (line) from the tilt sensor are shown as a function of the azimuthal position around the ring.

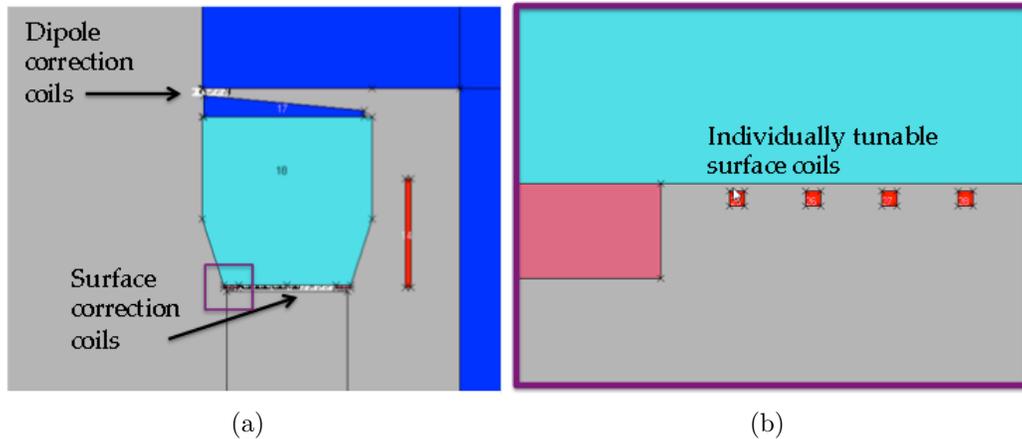


Figure 15.22: An OPERA-2D depiction of the dipole correction coils and the surface correction coils. (a) Schematic overview showing the positions of the current traces on the printed circuit boards. The purple box is zoomed in and displayed in panel (b). Individual traces are adjusted to tune various multipole contributions.

15.4.3 Active Shims

Active shimming refers to the adjustment of current distributions to eliminate any residual field non-uniformities that remain after the passive shimming is complete.

The principle active shimming controls consist of the following:

1. Control of the main superconductor current
2. Surface correction coils on printed circuit boards between the pole face and the vacuum chamber
3. Dipole correction loops in the gap between the wedge shim and the yoke
4. Gap correction loops in the azimuthal gaps between adjacent pole faces

Main Current

NOTE: DO WE WANT THIS TO BE IN THIS SECTION AT ALL? IT IS A DIPOLE SHIMMING PARAMETER IN A SENSE BUT IS PROBABLY BEST COVERED ELSEWHERE The central value of the dipole field is determined primarily by the current in the main superconducting coils. The nominal current is 5200 Amp per turn. OPERA simulations show that an increase of 1 A increases the field in the storage region by about XX *ppm*. During beam-on data collection periods, the field is monitored by the fixed NMR probes. The shape of the magnet gets distorted due to temperature variations, so a feedback loop is utilized to stable the dipole field.

6408 **Surface Correction coils**

6409 Correcting coils on the surface of the poles permit ultimate fine control of static, and slowly
 6410 varying errors. The surface coils can be used to correct lowest multipoles to tens of ppm, thus
 6411 providing significant overlap between the iron shimming and the dynamic shimming. These
 6412 coils have been constructed to generate moments over the entire 360° azimuth. The coils were
 6413 designed with printed circuit boards, with 120 wires running azimuthally around the ring on
 6414 the top and bottom pole surfaces facing the storage ring gap, and spaced radially 2.5 mm
 6415 apart, to avoid lumpy effects which generate higher multipoles. The boards must be thin
 6416 enough to fit between the pole faces and the vacuum chamber. We have studied the surface
 6417 correction coils in OPERA-2D (see Figure 15.22) and verified that the various multipole
 6418 contributions can be compensated for with the appropriately applied current distributions.
 6419 A summary of the principle current distributions is shown in Table 15.4.3. E821 used these
 6420 coils successfully to shim out the final few ppm for the higher order multipoles.

Table 15.3: Current distributions needed to correct for various multipole components, and the maximum range that can be corrected with less than 1 Amp. The currents are calculated at the fixed vertical position of the boards ($y=a=9$ cm).

Multipole	$K(x)$ ($y=a$)	Maximum range (ppm)
Quadrupole	a	20
Sextupole	$2ax$	10
Octupole	$3ax^2 - a^3$	8
Decupole	$4ax(x^2 - a^2)$	6
Duodecupole	$5a(x^4 - 2x^2a^2 + a^4/5)$	4
Quattuordecupole	$2ax(3x^4 - 10x^2a^2 + 3a^4)$	2

6421 For E989, we plan to fabricate 12 new printed circuit boards at Fermilab that extend over
 6422 each sector. Because these coils extend azimuthally around the entire ring, interconnects
 6423 between adjacent boards must be designed. We will study the trace spacing and radial
 6424 range to ensure our solution provides fine enough tuning without drawing too much power.
 6425 Currents are expected to be limited to about 1 Amp. Finally, we will explore the option of
 6426 using the bottom of the boards for active current shims in the gaps between pole pieces.

6427 **Dipole correction loops**

6428 The “continuous” ring was built with 10° pole sections, 36 of which form an almost continuous
 6429 ring. Dipole correction coils are located in the air gaps for each 10° pole, as depicted in
 6430 Figure 15.22 (a). These coils are a pancake design with 50 turns of copper wire wound in
 6431 a rectangular shape. The dipole correction coils will be capable of tuning each pole section
 6432 independently. E821 used active NMR feedback loops to stabilize the field by adjust the
 6433 main superconductor current. It is possible that the field could be stabled in each pole piece
 6434 separately by using the local NMR feedback to adjust the dipole correction currents. This
 6435 would be particularly useful if temperature gradients over the 14 m diameter ring lead to
 6436 different field distortions in different locations.

6437 **Gap correction loops**

6438 We want to minimize the azimuthal variation of the magnetic field, as explained in Section
 6439 15.4.2. Thus, E989 will use OPERA-3D to study the possibility of adding small loops to
 6440 the bottom of the surface correction coil boards at the azimuthal positions between adjacent
 6441 poles. We would primarily have control over the dipole moment, with limited ability to
 6442 modify the higher order multipoles.

6443 **15.4.4 E821 results**

6444 E821 successfully implemented many of the passive and active shimming techniques described
 6445 above. Table 15.4.4 shows the historical progression of the uniformity of the field as a
 6446 function of time during the commissioning phase of the experiment. As they worked towards
 6447 the storage region, the higher order became more controlled. The final column shows the
 6448 principle changes that were implemented at that step. We plan to use this experience to
 compress the shimming schedule for E989.

Table 15.4: If time permits, convert this to a plot that shows the evolution of these moments vs time. Quadrupole (Q), Sextupole (S), Octupole (O), and Decupole (D) multipoles, broken down into normal(n) and skew(s) components, in *ppm*, evaluated at the storage radius ($r = 4.5$ cm).

Date	Q_n	S_n	O_n	D_n	Q_s	S_s	O_s	D_s	Action
Jun 1996	-169.12	112.03	-34.16	23.71	27.06	5.82	3.12	0.46	Initial configuration
Nov 1996	5.52	3.19	-1.11	1.95	9.13	5.32	0.85	0.45	Edge shims ground uniformly
Jul 1997	5.26	2.94	-1.03	1.45	12.26	2.78	0.36	0.25	Edge shims ground in each pole piece+ pole alignment
Aug 1998	7.73	-5.29	-2.79	0.38	-2.07	-0.02	-0.25	0.71	Final passive shimming
Sep 1998	-2.54	-1.25	-2.70	0.34	-2.39	-0.18	-0.28	0.42	Active shimming commissioned
PRD	0.24	-0.53	-0.10	0.82	0.29	-1.06	-0.15	0.54	something

6449

6450 **15.5 Alternatives**

6451 The determination a_μ in terms of $\omega_a/\tilde{\omega}_p$ and μ_μ/μ_P requires the storage ring magnetic field be
 6452 measured in terms of the muon distribution weighted free proton precession frequency, $\tilde{\omega}_P$. In
 6453 principle this could be done by injecting a 3.1 GeV/c polarized proton beam into the storage

6454 ring with a proton spin analyzer (polarimeter) in the ring based on the spin dependence of
6455 p -carbon elastic scattering. The anomalous precession frequency would be close to 40 MHz,
6456 and the phase space of the protons and muons would have to be matched or measured to mm
6457 precision. Proton beam measurements of the field distribution would have to alternate with
6458 muon injection. Developing a polarized proton source, 3.1 GeV/ c accelerator, polarimeter,
6459 proton beam position monitoring hardware etc. would add significant cost and technical
6460 challenge to the experiment, and it's not clear that the field determination could be made
6461 to 70 ppb. Further, during periods of muon injection, an NMR-based system of fixed probes
6462 outside the storage volume would still be required to monitor the field and provide feedback
6463 to the power supply to stabilize the field. A similar NMR system would be required to shim
6464 the magnet.

6465 Other field measurement technologies such as Hall probes have been considered. One
6466 advantage is that a 3-axis device could make measurements of B_x , B_y , B_z . However, Hall
6467 probes have a significant temperature dependence ($\leq 20\text{ppm}/^\circ\text{C}$), resolutions at the 1 ppm
6468 level (versus 20 ppb for NMR), and fluctuating offsets. Commercial technology is currently
6469 inadequate for the level of accuracy sought in E989. Further, they would require frequent
6470 calibration in terms of an equivalent free proton precession frequency, so an NMR-based
6471 absolute calibration probe would still have to be developed and tested.

6472 Finally we note that pulsed NMR is preferred over CW techniques since the latter typ-
6473 ically requires a small field modulation coil that perturbs the local field, introduces image
6474 fields in the iron poles and yokes, and is potentially difficult to calibrate at the precision
6475 sought in E989. In addition, the lineshape analysis required in CW techniques to achieve
6476 ppb levels of precision is substantially more difficult than the analysis methods required for
6477 analyzing pulsed NMR FIDs.

6478 15.6 ES&H

6479 15.7 Quality Assurance

6480 It is necessary to test the NMR hardware before shimming and installation in the g-2 stor-
6481 age ring. This requires the development of independent test-stands that include a set of
6482 NMR probes, NMR electronics, DAQ, and a magnet. We have located at least 4 magnets
6483 suitable for these purposes, where the requirements on the magnet depend on the hardware
6484 component being tested.

6485 To test the fixed probes requires a vector impedance meter or network analyzer and a
6486 magnet at 1.45 T with field gradients less than 20 ppm/cm. The latter is sufficient to ensure
6487 an FID of ms duration, sufficient to confirm the probe works. An electromagnet suitable for
6488 testing fixed probes and basic functioning of the NMR hardware is being prepared spring
6489 2013 at the University of Washington.

6490 Precision tests of the NMR hardware - such as single shot frequency resolution, temper-
6491 ature dependence of NMR signals, reference frequency dependence of the electronics, aging
6492 effects, measurements of T_2 , etc. require magnets with stability of 0.01-0.1 ppm per hour
6493 and field gradients of <0.2 ppm/cm. Such a magnet is available to the group at Univ. of
6494 Michigan (with access to a large bore persistent mode MRI magnet). The Univ. of Mas-

6495 sachusetts group has unrestricted access for several years to a small bore (89 mm) persistent
6496 mode superconducting magnet from Cryomagnetics, with better than 0.01 ppm/hr stability
6497 and a shim set to achieve sub-ppm/cm homogeneity over an 8 cm³ volume. The small bore
6498 cannot accomodate the E989 NMR probes (it can only accomodate the plunging probe),
6499 but many sensitive tests of the NMR electronics and behavior of the NMR probe samples
6500 (temperature effects etc.) can be measured at the 10 ppb level using custom probes.

6501 Finally, we require a large bore superconducting persistent mode magnet at Fermilab for
6502 local tests of the hardware. The LANL Biological and Quantum Physics group agreed to
6503 transfer to FNAL the Oxford Magnet Technology Unistat 41443 MRI solenoid used by E1054
6504 at Los Alamos. This solenoid has measured stability of better than 0.1 ppm/hour, a shim
6505 set for ppm-level homogeneity over a 10 cm diameter volume, and a 910 mm bore diameter,
6506 essential for extensive performance tests of the NMR trolley in advance of installation in
6507 the g-2 storage ring. This will also be essential for determining the magnet influence of the
6508 calorimeter and tracker hardware on the storage ring field. (Early tests of basic performance
6509 of the trolley will be made with a large gap electromagnet at BNL).

6510 Extensive early testing of the NMR hardware should allow identification of problems
6511 and the implementation of solutions in advance of installation in the g-2 ring. By having
6512 several absolute calibration probes, repeated calibration of the trolley probes, and extensive
6513 investigations of potential systematics, we intend to produce a robust result on ω_p .

6514 15.8 Value Management

References

- 6515
- 6516 [1] P. J. Mohr, B. N. Taylor, and D. B. Newell, Rev. Mod. Phys. **84**(4), 1527 (2012).
- 6517 [2] W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999).
- 6518 [3] R. Prigl, *et al.*, Nucl. Inst. Methods Phys. Res. **A374** 118 (1996).
- 6519 [4] X. Fei, V. Hughes and R. Prigl, Nucl. Inst. Methods Phys. Res. **A394**, 349 (1997).
- 6520 [5] G. Bennett, *et al.*, (Muon ($g - 2$) Collaboration), Phys. Rev. **D73**, 072003 (2006).
- 6521 [6] Ralf Prigl, doctoral thesis, Universität Heidelberg (1994)
- 6522 [7] Alex Grossmann, doctoral thesis, Universität Heidelberg (1998)
- 6523 [8] Huaizhang Deng, doctoral thesis, Yale University (2002)
- 6524 [9] see A. Abragam, “Principles of Nuclear Magnetism”, Oxford U. Press, (1961), pps.
6525 173-178.
- 6526 [10] W.D. Phillips *et al.*, Metrologia **13**, 179 (1979).
- 6527 [11] P.J. Mohr and B.H. Taylor, Rev. Mod. Phys. **77**, 1 (2005).
- 6528 [12] P.F. Winkler, D. Kleppner, T. Myint, and F.G. Walther, Phys. Rev. **A5**, 83 (1972).
- 6529 [13] W.E. Lamb Jr., Phys. Rev. **60**, 817 (1941).
- 6530 [14] H. Grotch and R.A. Hegstrom, Phys. Rev. **A4**, 59 (1971).
- 6531 [15] B.W. Petley *et al.*, Metrologia **20**, 81 (1984).
- 6532 [16] W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999); D.E. Groom, *et al.* (Particle Data
6533 Group), Eur. Phys. J. **C15**, 1 (2000).
- 6534 [17] G.T. Danby and J.W. Jackson, E821 Muon $g - 2$ Internal Note No.1, 1(1987).
- 6535 [18] K. Woodle, E821 Muon $g - 2$ Internal Note No.44, 1(1990).
- 6536 [19] S. Redin, E821 Muon $g - 2$ Internal Note No.51, 1(1990).
- 6537 [20] X. Fei and V.W. Hughes, E821 Muon $g - 2$ Internal Note No. 86 (R), 1(1991).

- 6538 [21] M.J. Fischer, E821 Muon $g - 2$ Internal Note No. 114, 1(1992).
- 6539 [22] G.T. Danby and J.W. Jackson, E821 Muon $g - 2$ Internal Note No.180, 1(1993).
- 6540 [23] R. Prigl, Internal Note.

Chapter 16

The ω_a Measurement

The anomalous spin precession frequency ω_a is one of the two observables required to obtain the muon anomalous magnetic moment, a_μ . In order to reach the experiment's proposed goal of 0.14 ppm precision in a_μ , the targeted error budget allows for a 0.1 ppm statistical uncertainty combined with equal 0.07 ppm systematic uncertainties from the ω_a and ω_p analyses. This chapter summarizes the procedure for the ω_a measurement, with subsequent Chapters 17-22 elaborating upon the design of each subsystem. First the decay kinematics are reviewed and the encoding of the muon spin information into the data set is explained (Section 16.1). From that basis several complementary methods are explained (16.1.2). Then a review of uncertainties is presented, first the statistical (Section 16.2) and then the systematic uncertainties intrinsic to the detector (Section 16.3). Finally the detector system organization is explained and broken down into subsystems (Section 16.4). These subsystems include: stored muon monitoring, electron decay tracking, electron calorimeter, signal digitization, data acquisition, and slow control systems.

16.1 Measurement Overview

The anomalous precession frequency, ω_a , is the difference between the ensemble-averaged muon spin precession and the cyclotron frequency. The weak decay of the muon is parity violating, with the consequence that the emitted electron energy is correlated—on average—with the muon spin direction¹. Therefore by measuring the decay electrons and analyzing their energy a measurement of the muon spin is possible. The angle between the boost from the muon center-of-mass frame (CM) to the lab frame and the muon spin acts as an analyzer. As the spin rotates relative to the boost direction the rate observed modulates at the frequency ω_a . That modulation is observed over several boosted muon lifetimes and fit to extract ω_a .

16.1.1 Muon Decay and Boost Kinematics

The angular distribution of emitted electrons from an ensemble of polarized muons at rest is

¹The discussion which follows is extracted in part from Ref. [1].

$$dn/d\Omega = 1 - a(E) (\hat{S}_\mu \cdot \hat{P}_e). \quad (16.1)$$

6568 Where \hat{S}_μ is the muon spin direction and \hat{P}_e is the electron momentum direction. The
 6569 asymmetry a depends on electron energy (E) and is such that the higher-energy electrons
 6570 have the strongest correlation to the muon spin.

6571 The decay electron energies in the laboratory frame are related to the CM energy by

$$E_{e,lab} = \gamma(E_e^* + \beta P_e^* \cos \theta^*) \approx \gamma E_e^* (1 + \cos \theta^*). \quad (16.2)$$

6572 The starred quantities indicate CM frame, $\gamma = 29.3$, and θ^* is the angle between the rest
 6573 frame electron momentum and the boost direction. The maximum energy in the lab frame
 6574 occurs when the electron momentum is aligned with the boost direction and the decay energy
 6575 is the maximum. Therefore by applying a threshold to lab frame electron energy only the
 6576 highest energy muon rest frame decay electrons are observed. Thus capturing the important
 6577 relationship that the electron *energy* in the lab frame is correlated to the emitted *angle* and
 6578 therefore muon spin in the CM frame.

6579 16.1.2 Analysis Methods Summary

6580 The simplest analysis procedure is to identify individual decay electrons and plot the rate
 6581 of their arrival versus time using only events having a measured energy above a threshold.
 6582 This is dubbed the T (time) method; it was the dominant analysis technique used in the
 6583 Brookhaven experiment and it is fairly robust against systematic uncertainties.

6584 The rate of detected electrons above a single energy threshold E_{th} is

$$\frac{dN(t; E_{th})}{dt} = N_0 e^{-t/\gamma\tau_\mu} [1 + A \cos(\omega_a t + \phi)]. \quad (16.3)$$

6585 Here the normalization, N_0 , asymmetry, A , and initial phase, ϕ , are all dependent on the
 6586 threshold energy. The time spectrum of detected electrons from a portion of the data from
 6587 Brookhaven E821 is shown in Figure 16.1. This is the type of distribution from which the
 6588 anomalous precession frequency will be extracted.

6589 While the T Method is sufficient to reach the experimental goal, additional analysis
 6590 techniques can also be used. Weighting the events by their average asymmetry or by their
 6591 energy increases the statistical power for the same data set as the cost of more stringent
 6592 systematic requirements. As in the T method, the data stream from the calorimeters must
 6593 be first deconstructed into individual events, which are then processed into histograms akin
 6594 to what was shown in Figure 16.1. The uncertainties here are largely based on the stability
 6595 of the deconstruction process vs. time in the storage ring fill.

6596 There is an additional experimental method that involves identical hardware to the T
 6597 Method but a different data acquisition philosophy. The Q method, does not require event
 6598 by event reconstruction. Instead simply integrates the detector current (energy for a linear
 6599 device) vs. time in fill.

- 6600 • **T Method:** Events are individually identified and sorted. The events vs. Time-in-Fill
 6601 histogram is built from all events with reconstructed energy about a threshold. All

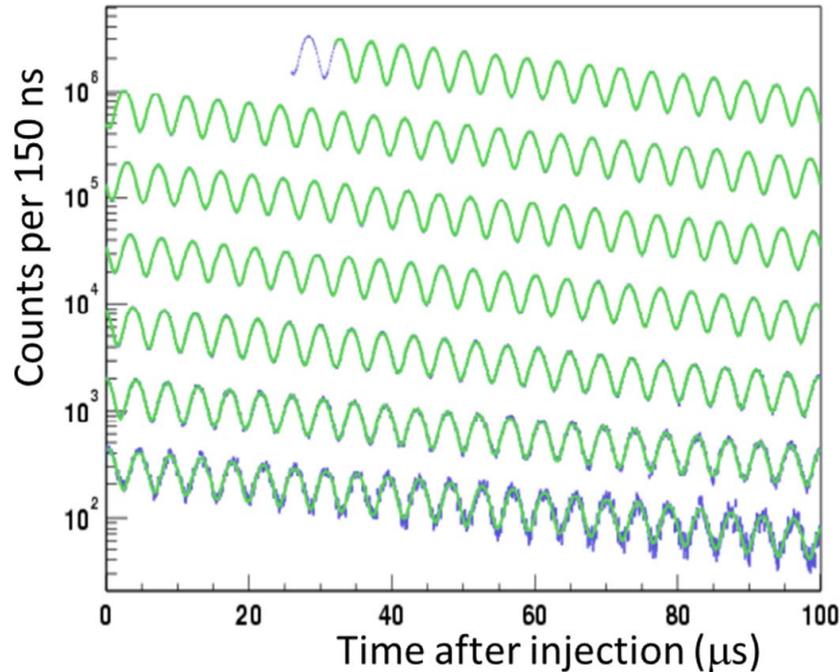


Figure 16.1: Example precession frequency data (blue) and fit (green) from Brookhaven E821. The calorimeter data must be analyzed to determine the energy and time for each event. The plotted time is modulo $100 \mu s$.

6602 events in the histogram are given equal weight. The acceptance-modified figure-of-
 6603 merit (FOM, defined to be equal to 1.0 here) is optimized at $y \approx 0.6$, corresponding
 6604 to an electron energy of 1.8 GeV. The quantity ω_a is obtained from a fit to a pileup-
 6605 subtracted histogram. This is the standard method used in E821 and the benchmark
 6606 for determining the statistical and systematic requirements for the E989 experiment.

6607 • ***E*-Weighted Method:** Identical to the *T* method except that the histogram is built
 6608 by incrementing a time bin with the value of the energy of an event, not by each count,
 6609 therefore producing the Energy vs. Time-in-Fill histogram. The bin weight in the fit
 6610 varies over one full $g - 2$ cycle and it can be determined reliably by an analysis of
 6611 late-time events that are not plagued by pileup effects. The FOM maximum is realized
 6612 at a slightly lower threshold than the *T* Method. This method will be more vulnerable
 6613 to gain- or energy-scale variations compared to the *T* method.

6614 • ***A*-Weighted Method:** Identical to the *T* method except that the histogram is built
 6615 by incrementing a time bin with the value of the asymmetry for that electron energy.
 6616 The weight for each bin must be determined separately. This is potentially a powerful
 6617 method, but the systematics are unknown. Further study is warranted.

6618 • ***Q* Method:** Events are *not* individually identified. Energy vs. Time-in-Fill histograms
 6619 are built by summing the energy of a all digitized waveform samples vs. time for a

6620 calorimeter station. The application of appropriate zero-suppression will have to be
 6621 introduced to minimized the noise contribution. No attempt to correct for pileup is
 6622 necessary in the fit; only a low-threshold makes sense here. The acceptance-corrected
 6623 FOM is nearly identical to the standard T method.

6624 16.2 Statistical Uncertainty

6625 The T , energy-weighted, asymmetry-weighted, and Q methods of analysis all lead to his-
 6626 tograms similar to what is shown in Figure 16.1, albeit with different bin weights and asym-
 6627 metries. A fit is then performed using Equation 16.3 and the relevant parameter ω_a is
 6628 obtained. The optimization of the experimental system follows from minimizing the uncer-
 6629 tainty on that parameter, namely $\delta\omega_a$. A detailed study of the statistical methods used in
 6630 the E821 experiment that gives guidance to the statistical power of any data set built using
 6631 various weighting methods was published in Ref. [2]. That publication parameterizes the
 6632 uncertainty on ω_a as

$$\delta\omega_a = \sqrt{\frac{2}{N(\gamma\tau_\mu)^2} \cdot \frac{\langle p^2 \rangle_y}{\langle pA \rangle_y^2}}, \quad (16.4)$$

6633 where N is the integrated number of decay electrons in the analysis, p is the weight function
 6634 and therefore is method dependant, and $\langle f \rangle_y$ is the value of f averaged over all detected
 6635 electron energies above threshold. The parameter y is the fractional decay electron energy
 6636 with respect to a maximum value; therefore y ranges from 0 to 1, where $y = 1$ corresponding
 6637 to approximately 3.1 GeV.

6638 In the following, care must be paid to whether distributions shown vs. y are differential or
 6639 whether they represent the integrated value from threshold y . For example, Fig. 16.2 shows
 6640 *differential* plots of N , A and NA^2 vs. energy for a uniform acceptance detector. The plots
 6641 illustrate the importance of the higher-energy electrons that have the greatest asymmetry.
 6642 he asymmetry is negative for lower-energy electrons; thus, a single low threshold can be
 6643 expected to dilute the average asymmetry. If, on the other hand, data are sorted by energy
 6644 bin and then fit (using possible weighting schemes by energy or asymmetry), the overall
 6645 statistical power of the data set can be improved. Importantly, the modification of the ideal
 6646 curves owing to finite detector acceptance is non-negligible as the detector placement greatly
 6647 favors the higher-energy events because low energy electrons can curl between detectors and
 6648 be missed. The acceptance impacts the values of N and A , which are functions of the energy-
 6649 dependent detector acceptance, and modified significantly the idealized curves of Fig. 16.2.
 6650 In the T method each event carries the same weight ($p = 1$) and the uncertainty $\delta\omega_a$ following
 6651 Eq. 16.4 reduces to

$$\delta\omega_a = \frac{1}{\gamma\tau_\mu} \sqrt{\frac{2}{NA^2}}. \quad (16.5)$$

6652 The boost factor $\gamma = 29.3$ is fixed by the magic momentum requirement. The figure of
 6653 merit (FOM) that should be maximized to minimize $\delta\omega_a$ is NA^2 . The value of the threshold
 6654 that maximizes the FOM corresponds to $A \approx 0.4$ and an energy of 1.8 GeV. Therefore the

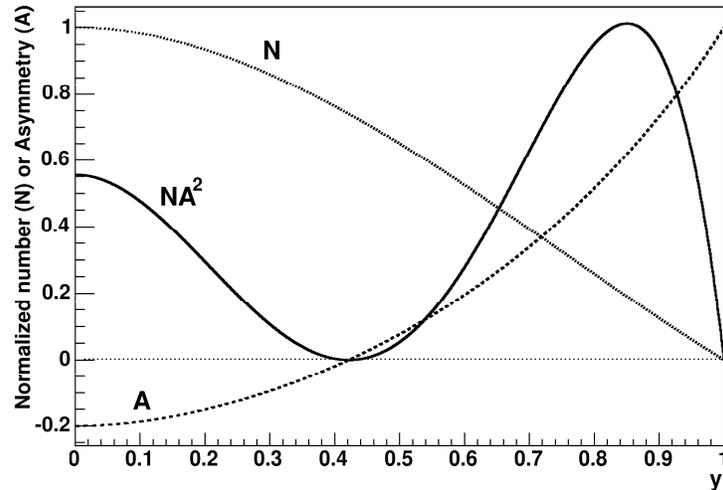


Figure 16.2: The differential distributions: normalized number of events (N/N_{total}), asymmetry (A), and the figure of merit (NA^2). Note, this plot assumes uniform detector acceptance across the full energy spectrum.

6655 relative uncertainty in ω_a is

$$\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a} \cdot \frac{\sqrt{2}}{\gamma\tau_\mu A} \cdot \frac{1}{\sqrt{N}} \approx \frac{0.0385}{\sqrt{N}}. \quad (16.6)$$

6656 For a statistical uncertainty on $\delta\omega_a/\omega_a$ of 0.10 ppm, $N = 1.5 \cdot 10^{11}$ fitted events would be
 6657 required, stemming from a 100% polarized stored muon beam.

6658 For the energy-weighted ($p = y$) and asymmetry-weighted ($p = A(y)$) analysis methods
 6659 the computation of $\langle p^2 \rangle_y / \langle pA \rangle_y^2$ in Eq. 16.4 is non-trivial. Figure 16.3 (left panel) shows the
 6660 figure of merit for different analysis technique assuming a uniform detector acceptance [2].
 6661 The gain from performing a weighted analysis is potentially as high as 10% for the energy-
 6662 weighted and 20% for asymmetry-weighted analyses. We conducted a simulation that in-
 6663 cluded the finite detector acceptance to determine the FOM for the T and energy-weighted
 6664 techniques. The right panel of Fig. 16.3 is to be compared to the uniform acceptance case.
 6665 Notice that the FOM for the energy method does not fall as fast at low threshold because
 6666 the detector preferentially selects events having higher energy.

6667 A tacit assumption in the methods described is that each event can be treated as if
 6668 it is identified accurately for energy and time of arrival at the detector. The events are
 6669 then sorted and placed into histograms with appropriate weights. When the rate is high
 6670 events can overlap in time and space such that some fraction of them cannot be resolved
 6671 into individual occurrences. High-rate, asymmetry-based experiments (e.g, parity-violating
 6672 electron scattering) encounter this problem regularly and solve it by simply integrating the
 6673 current on a detector as a function of time (or beam burst). Here, the same concept can
 6674 be employed. By integrating the light yield from the calorimeters as a function of time,
 6675 one obtains an unresolved “energy” method, or charge method, we call Q . The method
 6676 makes no effort to record anything other than a histogram of energy in the detector vs.
 6677 time. As shown in Fig. 16.3, this corresponds to the “weighted method” plotted for the

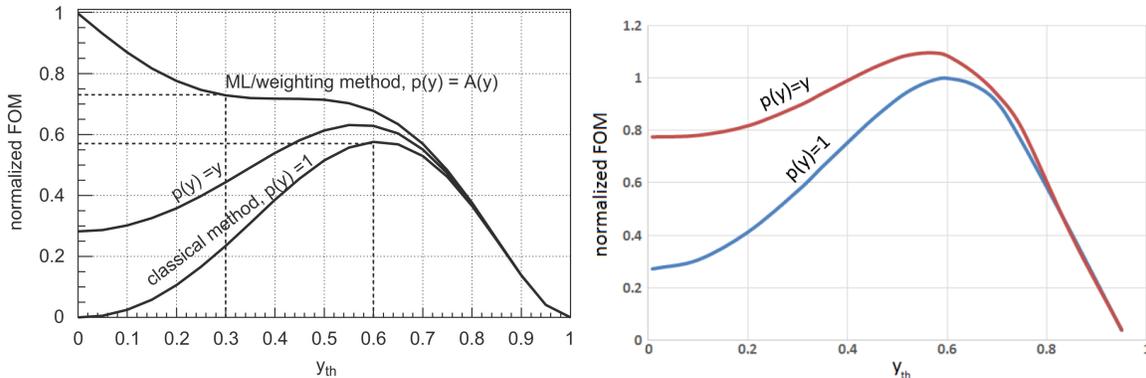


Figure 16.3: Left: Figure of merit as a function of energy threshold. These curves were calculated analytically [2] with uniform acceptance in energy space assumed. What is labeled “classical” method is the T method; the $p(y) = y$ is the energy-weighted method, and the $p(y) = A(y)$ is the asymmetry method. The right hand panel shows the T and energy-weighted distributions produced as the output of a detailed analysis using simulated data and finite detector acceptance. Of particular interest is the low-threshold behavior of the energy-weighted method, which remains high in the real model.

6678 finite acceptance simulation with a threshold approaching $y = 0$. The method provides a
 6679 statistical power approximately equivalent to the T method and it does not involve pileup
 6680 subtraction. We have studied this method using Monte Carlo simulations to determine the
 6681 proper weighting to place on the bins in the fit; they vary over the $g-2$ cycle, but can be easily
 6682 determined using a sample of late-time data that can be evaluated using individual events
 6683 to build a pseudo- Q -method histogram in the absence of pileup. We plan to incorporate this
 6684 alternative data-taking and analysis method in the new experiment. Figure 16.4 shows a
 6685 fit to Monte Carlo data generated with the full ring simulation in terms of muon spin and
 6686 time dependence and the finite acceptance of the detectors. Here, the beam polarization is
 6687 assumed to be unity and an event is accepted at its defined energy if the the electron hit
 6688 anywhere on the front face of the calorimeters. The ω_a value represented by R is 116 in the
 6689 truth and the units of R are ppm. Both T and Q methods give similar statistical precision.

6690 It was not possible in E821 owing to the high energy threshold and lack of memory in the
 6691 digitizers. These technical limitations are easily overcome with today’s large memories in
 6692 such devices). We are also actively exploring the types of systematic uncertainties associated
 6693 with the Q method. Note that the data sets in the T and Q method are not identical, but
 6694 substantial overlap exists. For example, in the T method, all events below ~ 1.8 GeV do
 6695 not contribute and all events above are weighted with $p = 1$. The Q includes all events that
 6696 strike the detector and weights each by its energy, $p = y$. Therefore, a combination of the
 6697 results of the two methods will enable an overall reduction in the final uncertainty of ω_a ; but
 6698 more importantly, the two methods will serve as important cross checks that systematics are
 6699 under control.

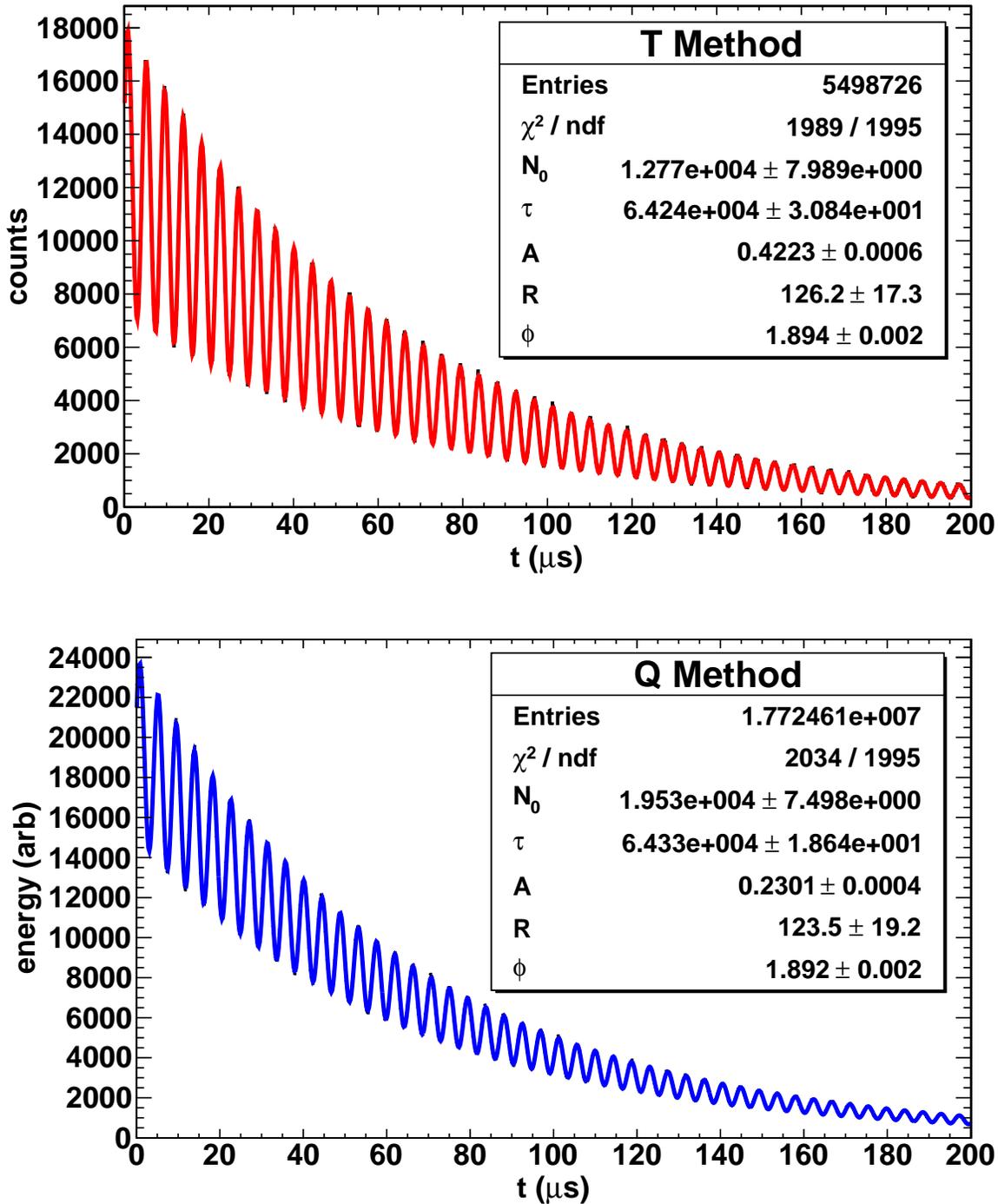


Figure 16.4: Top: Monte Carlo data analyzed using the T method with a threshold cut at $y = 0.6$. Bottom: Same data analyzed using the Q method. Detector acceptance is included. The asymmetry A is much higher for the T method, however the Q method has many more events (N). The ω_a central value is listed as R in the fit table with $R = 116$ in ppm the truth. Both methods give similar statistical uncertainty.

Table 16.1: Detector-specific systematic uncertainties in E821 and proposed upgrade actions and projected future uncertainties for E989.

E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques	0.04

16.3 Detector-related Systematic Uncertainties

In this section we discuss the systematic error issues related to the Detectors, Electronics, DAQ and the Offline Analysis. Table 16.1 lists the Gain and Pileup uncertainties and projections for improvements in the new $g-2$ experiment. The traditional T method analysis is assumed because uncertainties can be reliably projected based on our considerable experience in these analysis efforts. Since the Q method is new, we have not included its positive and partially independent impact on the final statistical result, nor are we presently able to fully project associated systematics. This topic is an active study in the collaboration. One key attractive feature of the Q method is pileup immunity; there is no correction necessary so that systematic uncertainty is absent. Comparing the analysis results using both T and Q methods will provide a valuable confirmation that systematic errors are understood.

16.3.1 Gain Changes and Energy-Scale Stability

The hardware gains of the E821 detectors [1] were determined to be stable to $\approx 0.15\%$ from early-to-late times within a storage ring fill. This limit was established by plotting the average energy for each $(g-2)$ period versus time after the PMTs were switched on. The gating circuitry in the tube base that allowed the PMTs to be turned off to avoid the initial burst of pions entering the ring, also resulted in a small variation in the gain. For gain variations like this one, where the time constant is long compared to the $(g-2)$ oscillation period, the coupling to the ω_a frequency is small and, after correction, the residual systematic error is less than 0.02 ppm.

Several aspects of the current plan will be different. The first is that we will use silicon photo-multipliers (SiPMs), which can be saturated from a light burst and then recover with the same time constant as they might do for a low-light pulse. Each pixel is “on” or “off” and recovers with a common time constant. Importantly, we do not intend to switch off these devices during injection because the anticipated hadronic-based flash will be (largely) absent. The initial pion flux at the target location will be reduced the factor $\exp(-x/173)$, where 173 m is the pion decay length for 3.1 GeV/ c . The path from target to storage ring, including 4 trips around the muon Delivery Ring (DR) is approximately 2000 m; thus primary pions are reduced by a factor of 10^5 . Essentially no pions will enter the ring. Similarly, beam protons²—which travel slower than pions at the magic momentum— will be eliminated in

²positive beam will run first and protons out of the target are a large component of the beam guided by

6730 the DR using a kicker system timed to fire when the muon and proton bunches are well
6731 separated in space.

6732 If the gain oscillates at a frequency ω_a , with an amplitude that varies in time, and with
6733 a phase that differs from that of the ω_a oscillation of the electron sample, then a direct error
6734 on the measured value of ω_a is produced. The average rate at which energy is deposited
6735 into the calorimeters oscillates with frequency ω_a , and therefore any rate dependence in the
6736 gain of the detectors produces gain oscillations. We were able to demonstrate that the gain
6737 dependence on rate was small enough that its effect on ω_a was typically less than 0.03 ppm.
6738 In the new experiment, the slightly increased beam rates will be offset by increased detector
6739 segmentation and our proposed monitoring system will be greatly improved compared to
6740 that employed in the past.

6741 In E821, a UV-laser system was used to periodically pulse the scintillator in the detectors
6742 and thus monitor the complete gain and reconstruction chain during data collection against
6743 an out-of-beam reference counter. Unfortunately, the light distribution system included too
6744 many branches and only one upstream reference detector. Small fluctuations cascaded so
6745 that gain stability could be monitored to no better than a few tenths of a percent. The
6746 system being designed for E989 is based on the experience with cascaded systems having
6747 multiple monitors. This is described in Chapter 17, Section 17.2.4.

6748 The largest contribution to the gain systematic error in E821 came from artificial gain
6749 oscillations at the ω_a frequency, introduced by the data reconstruction software. Here, the
6750 “energy-scale” stability is related to software reconstruction of waveforms, not to the hard-
6751 ware. When a signal was above the waveform digitizer (WFD) hardware threshold, a pre-set
6752 minimum number of sequential samples was recorded. These data were fit offline for the peak
6753 plus linear background to deduce the energy and time of the electron. But, if the trigger
6754 pulse was followed or preceded closely by another pulse, both pulses were fit together with a
6755 common background term, and the fitting region becomes longer compared to that used for
6756 a single pulse. The fitted energy was found to depend slightly on the length of the fitting
6757 region and the fitting samples were fixed in number by hardware. Because the data rate
6758 oscillates at frequency ω_a , and is higher at early than at late decay times, it follows that the
6759 fitting region length oscillates at ω_a and is, on average, longer at early times compared to late
6760 times. This produces a small, effective gain oscillation with frequency ω_a whose amplitude
6761 decreases with time, leading to a systematic error on ω_a . Given the current capabilities in
6762 data throughput, the new electronics will record all samples in place of isolated islands, thus
6763 removing the source of this reconstruction bias. In summary, the larger of the gain system-
6764 atic pieces will be eliminated by design and the smaller contribution will be monitored more
6765 precisely.

6766 16.3.2 Pileup

6767 The unresolved pileup fraction scales linearly with rate in each segment of the detectors.
6768 The effective size of the segment depends on the geometric extent of the shower. Our
6769 simulations demonstrate that an array of PbF₂ crystals, having 54 independent segments
6770 (see Chapter 17), and a smaller Molière radius compared to the Pb/SciFi used in E821, will

the FODO channel and into the DR.

6771 provide an effective three-fold reduction in the intrinsic pileup based on the implementation
 6772 of a very simple and robust shower separation routine and a 9-element cluster algorithm.
 6773 The simulation includes a representative stored muon ensemble in the ring and correct spin
 6774 physics in precession and decay.

6775 While the final stored muon rate increase will depend on the actual implementation of
 6776 several options discussed in earlier chapters on the Beam and Ring, we work here with the
 6777 expectation of a 50% increase compared to E821 and design for a range of up to a factor of
 6778 3 higher. We will use a factor of 3 below as it represents an upper limit of what might be
 6779 expected.

6780 With a 3-fold rate increase compared to BNL, the intrinsic pileup rate for the same
 6781 two-pulse resolution time resolution of 5 ns is expected to be largely the same as in E821.,
 6782 owing to the segmentation. What can be improved is the uncertainty associated with the
 6783 correction for unresolved pileup. We will characterize the two-pulse resolution by an applied
 6784 artificial deadtime (ADT). The ADT is the time established in the analysis software below
 6785 which two pulses are not resolved (even if they can be). The analysis proceed by sorting
 6786 data using a series of ADT values beginning with the true, device-specific minimum, and
 6787 extending to much larger values that exaggerate the pileup. The extraction of ω_a is then
 6788 done for each data set, and ω_a will be plotted as a function of ADT. The true value occurs
 6789 at the zero-ADT extrapolation point. We have spent considerable laboratory bench time
 6790 and offline pulse-reconstruction efforts to determine and optimize the minimum hardware
 6791 ADT that our detectors will permit. Our laboratory tests demonstrate that pulses separated
 6792 by 5 ns or more can easily be resolved for most pulse-amplitude ratios expected. We have
 6793 even demonstrated resolved pulses with Δt between them as low as 2.5 ns. On the analysis
 6794 procedure side, we have carried out a precision muon lifetime analysis with a pileup correction
 6795 algorithm based on this ADT extrapolation concept. The work is well documented [4].

6796 In the past, an artificial pileup spectrum was constructed from individual pulses in the
 6797 data, then subtracted from the raw spectrum. In the pileup construction, it is necessary
 6798 to use pulses with pulse heights below as well as above the hardware threshold. Because
 6799 of the relatively high hardware threshold and limited storage of the E821 WFD system,
 6800 those pulses below threshold were only found by searching during the relatively short period
 6801 of continuous WFD digitization following the trigger generated by the presence of a large
 6802 pulse above threshold. Consequently, the sample size for pileup events was limited and
 6803 somewhat biased, since they had to always ride on the tails of larger pulses. In the new
 6804 scheme, described in the following Chapters on Electronics and Data Acquisition, it will be
 6805 possible to significantly improve the pileup construction process. Continuous digitization,
 6806 with local software sorting of data streams including T -method, Pileup T -method and Q -
 6807 method datasets, is anticipated. Pulses of all heights can be searched for, independent of
 6808 whether there is a nearby large pulse that fired a hardware trigger.

6809 The contribution of pileup to the error in ω_a for E821 was divided into three components.
 6810 The first two are correlated and add linearly. The third is not correlated so it is added in
 6811 quadrature to the other two.

- 6812 1. Pileup efficiency, 0.036 ppm. This is due to an estimated 8% uncertainty in the ampli-
 6813 tude of the constructed pileup spectrum.
- 6814 2. Pileup phase, 0.038 ppm. This is the error due to the uncertainty in the phase of the

constructed pileup spectrum.

- Unseen pileup, 0.026 ppm. This is the error due to pulses so small that they cannot be reconstructed and therefore they are not included in the pileup construction.

We expect that the segmented detectors, better laser calibration, more complete waveform record storage, and the use of our more modern extrapolation algorithms will lead to a comprehensive pileup correction with minimal uncertainty. We assign up to 0.04 ppm here to account for any difficulties in the anticipated analysis. As mentioned earlier, the Q method is complementary to the traditional T method and has different sources of systematic errors. The most significant difference is the effect of pileup—it will be greatly reduced for the Q method.

16.4 Detector Systems Overview

Three principle detector systems are central to the ω_a measurement: Calorimeter, Electronics, Data Acquisition. They each have their own chapter in this report. The Tracker System and Auxiliary detectors contribute to systematic uncertainty determination. Figure 16.5 illustrates the various subsystems within the direct ω_a measurement framework, organized to illustrate how we define our work plans and distributed effort.

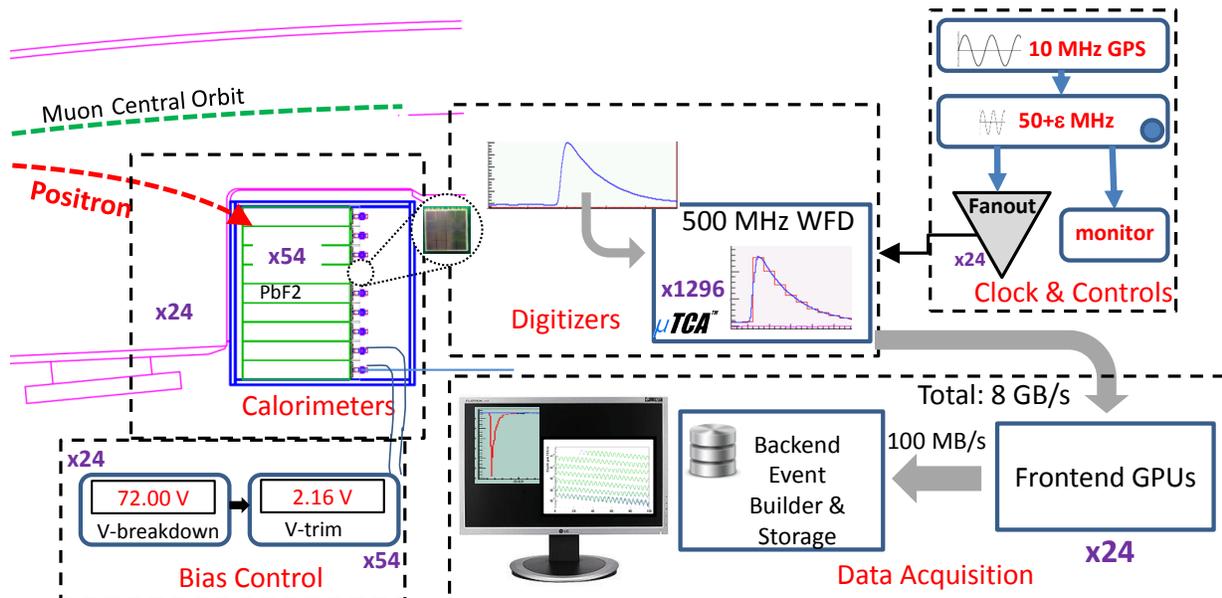


Figure 16.5: Schematic of the ω_a instrumentation organized by dedicated systems.

16.4.1 Calorimeter Subsystem Considerations

The decay electrons have momenta below the muon storage momentum and therefore they curl to the inside of the ring through the opening in the C -shaped magnet. Electromagnetic

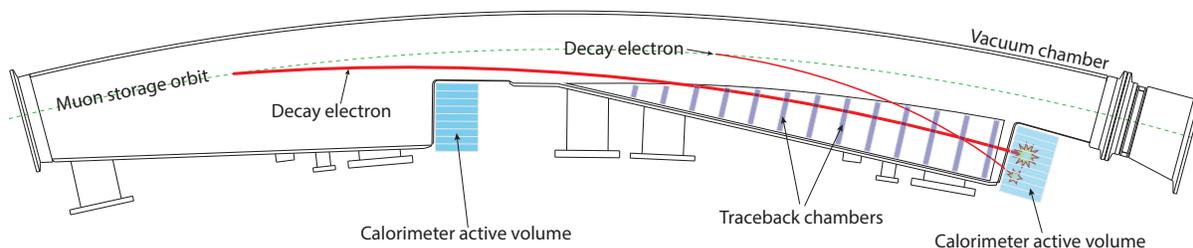


Figure 16.6: Scalloped vacuum chamber with positions of calorimeters indicated. A high-(low-) energy decay electron trajectory is shown by the thick (thin) red line, which impinges on the front face of the calorimeter array.

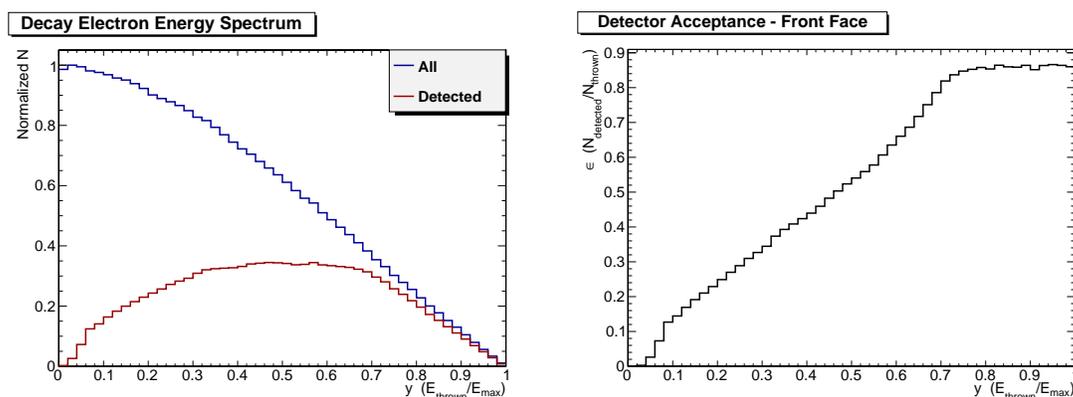


Figure 16.7: Left panel: Number of decay events vs. y in the laboratory frame (upper curve) and those that intercept the front face of a calorimeter (lower curve). Simulation uses full geometry, including pre-showering effects. Right panel: The differential acceptance of the 24 calorimeters vs. energy (the ratio of the two curves in the left panel). This is the fractional acceptance of events that hit the front face of the calorimeter array only.

6834 calorimeters are used to intercept the electrons and provide a measurement of energy and
 6835 time of detection. The time of flight is different depending on their energy, see Fig.16.6.

6836 The calorimeters will be placed adjacent to the storage ring vacuum chambers, and
 6837 located at 15 degree intervals around the ring. The 24 stations and their locations are
 6838 constrained by the plan to reuse the E821 vacuum chambers, see Fig. 16.6. These parameters
 6839 were optimized in a study preceding E821 construction and the conclusions remain valid for
 6840 E989.

6841 The number of emitted decay electrons vs. fractional energy is shown in the left panel
 6842 of Fig. 16.7. The upper curve is all decay electrons. The lower curve are only the electrons
 6843 that that strike the front face of one of the calorimeters. The right panel shows the ratio
 6844 of detected to thrown electrons vs. fractional energy. The geometry is designed to favor
 6845 the high-energy electrons that carry the maximum spin correlation information. Low-energy
 6846 electrons will often curl in between calorimeter stations and be lost. The design of the
 6847 new calorimeters is constrained by the unusual experimental demands. It is important to
 6848 emphasize that the relevant time scale for most systematic uncertainties is one 700 μ s long

6849 measuring period. The instantaneous event rate of several MHz drops by almost five orders
 6850 of magnitude during the 700 μs measuring period; thus, any rate-dependent detector or
 6851 readout response changes must be accurately known. The overall measurement system must
 6852 be extraordinarily stable for each short-term storage ring fill; however, long time scale drifts
 6853 can generally be tolerated. As an example, consider a gain function G that varies from the
 6854 beginning of a fill to the end of a fill; that is, $G \rightarrow G(t)$. When coupled to a fixed energy
 6855 threshold, the population of accepted events will then vary throughout the fill. Because the
 6856 asymmetry A and phase ϕ are functions of energy, the extracted ω_a will vary throughout the
 6857 fill. If this occurs systematically during each fill (as it might if the gain change is coupled
 6858 to rate), and is unaccounted for, then ω_a might be incorrectly determined. Similarly, a
 6859 time shift Δt owing to the clocking system or other influence can also change the fitted
 6860 frequency. Our experience in E821 established that the stability conditions that ensure less
 6861 than a 0.05 ppm shift to ω_a can be characterized by the requirement that $\Delta G < 0.1\%$ and
 6862 $\Delta t < 10$ ps over a 200 μs interval.

6863 Two low-energy electrons, arriving close together in time, can be interpreted as one equiv-
 6864 alent high-energy electron, a type of “pileup” event. Because the low-energy electrons have
 6865 a shorter flight path to the detector compared to higher-energy electrons, they correspond to
 6866 muons having a slightly greater muon phase advance. Therefore, if such incorrect interpre-
 6867 tations of high-energy electrons are made more often early vs. late in a storage ring fill, the
 6868 ensemble average phase will shift, which is equivalent in the fit to a shift in ω_a . Unaccounted
 6869 for, pileup will produce this effect, since the rate of fake high-energy electrons coming from
 6870 coincident low-energy electrons has a $\sim e^{-2t/\gamma\tau}$ time dependence. This means the pileup
 6871 rate falls twice as fast as the muon population decays. To minimize pileup, the calorimeter
 6872 response must be fast (few ns) and the readout system must record information to enable the
 6873 distinction between closely occurring pulse pairs, which strike the same detector elements.
 6874 This information should also provide a mechanism to correct the data, on average, by re-
 6875 moving the pileup events. Furthermore, if the detector segmentation is optimized, many
 6876 simultaneous lower-energy electrons will be recorded in independent area of a calorimeter
 6877 station and thus will not be interpreted as a pileup event. The goal in the detector design is
 6878 to reliably resolve same-element pulses separated by 5 ns or more, to segment the detector
 6879 to minimize pileup, and to accurately subtract unresolved pileup.

6880 The calorimeter resolution must be moderately good near 1.8 GeV to provide adequate
 6881 energy discrimination. However, it also must be compact to avoid a preponderance of elec-
 6882 trons that strike the inside face of the detector. Usually higher density materials imply
 6883 lower resolution, so an optimization must be made. For E989, we are aiming for improved
 6884 resolution compared to E821 at BNL by a factor of 2. This will aid in the pileup analysis,
 6885 but is not particularly critical to the simple T method threshold analysis in the absence of
 6886 pileup.

6887 16.4.2 Electronics and Data Acquisition Subsystems Considera- 6888 tions

6889 To guarantee deadtime-free calorimetry readout, the signal from each of the 1296 active
 6890 calorimeter channels will be continuously digitized for every 700 μs muon fill. Those wave-

6891 forms are then transferred to the DAQ system for data reduction – isolation of the time
6892 windows containing electromagnetic showers – and storage. The DAQ must apply an energy
6893 threshold to identify showers within a station, so the 54 waveforms from that station must
6894 be summed to keep the threshold independent of the incident electron position in a crystal.
6895 All 54 WFD waveforms must therefore be transferred to the same frontend DAQ system,
6896 which will use the waveform sum to perform data reduction on the digitization stream:
6897 identification of time islands with activity (T -method) and time rebinning of the waveform
6898 (Q -method).

6899 The energy range of interest for an individual calorimeter element is 25 to 3100 MeV
6900 for single events. Allowing pileup, suggests pushing the upper limit close to 5000 MeV. A
6901 digitizer with 12-bit depth (4096), is ideal. It will allow good pulse definition, important for
6902 the energy resolution requirements, and it will not saturate for the highest energy events.
6903 As discussed in Chapter 17, the pulse shape risetime is approximately 2-4 ns and we are
6904 actively working to reduce it. The laboratory tests done to date suggest that a minimum of
6905 500 MHz sampling will be required to accurately fit the pulses, subject to optimizing pileup
6906 rejection. Therefore, each digitized waveform is therefore 350K 12-bit words for each muon
6907 fill.

6908 A precision oscillator (“clock”) will provide the timebase from which the ω_a frequency
6909 is measured. It must be controlled to provide negligible error compared to the anticipated
6910 0.1ppm uncertainty on ω_a . In order to achieve this, the clock must have jitter that is
6911 significantly less than the 2 ns sampling period of the waveform digitizers. It must also have
6912 very low (< 10 ps) systematic shift across the time of a single fill. This latter requirement is
6913 important because of the large variation in event rate within a fill. A systematic time-slew
6914 that is correlated with muon or positron intensity would bias the result. The clock system
6915 must also enable a convenient blinding scheme such that the actual precise clock frequency
6916 cannot be known to the data analyzers.

6917 The data acquisition system must provide a deadtimeless readout of calorimeter segments
6918 using the waveform digitizers. Onboard memories in the digitizers will buffer the raw data
6919 and allow its asynchronous readout, thus decoupling the data acquisition cycles from storage
6920 ring fills. A frontend layer of multicore CPUs/GPUs will process the digitized records of each
6921 fill from every calorimeter segment into T -method, Q -method and other derived datasets. A
6922 backend layer of multicore CPUs/GPUs will handle the assembly of event fragments from
6923 the frontend layer and transfer of assembled events to the mass storage. Each stored event
6924 will represent a complete deadtime-free history of the entire activity in the detector system
6925 for every fill cycle.

6926 **References**

- 6927 [1] D. W. Hertzog and W. M. Morse, *Ann. Rev. Nucl. Part. Sci.* **54**, 141 (2004).
- 6928 [2] G. W. Bennett *et al.* [Muon G-2 Collaboration], *Nucl. Instrum. Meth. A* **579**, 1096
6929 (2007).
- 6930 [3] Sedykh SA, et al. *Nucl. Instrum. Meth. A*455:346 (2000).
- 6931 [4] V. Tishchenko *et al.* [MuLan Collaboration], *Phys. Rev. D* 87, 052003 (2013)
6932 arXiv:1211.0960 [hep-ex].

Chapter 17

Calorimeter

This chapter illustrates the design concept for the electron calorimeter. The primary purpose of the electron calorimeter is to measure the energy and time of arrival of decay electrons from stored muon decay. First the physics goals and subsequent requirements are reviewed. Then the recommended design is presented broken down by subsystems which include: Absorber, Photodetection (SiPM), Bias Control, Laser Calibration, and mechanical. Alternative designs are also presented. The chapter ends with a discussion of: ES&H, risks, quality assurance, and value management.

17.1 Introduction

17.1.1 Physics Goals and Requirements

The energy and timing information from the electron calorimeter introduces possibly two major sources of systematic errors to ω_a :

1. Unidentified pileup events, i.e. simultaneous electron showers in the same calorimeter station that cannot be resolved.
2. Rate-dependent effects that couple to the spin precession frequency (e.g. a rate-dependent gain change).

To meet the new FNAL E989 goal, the electron calorimeter must be able to resolve two simultaneous showers by either the timing information or spatial separation. For two electron showers hitting the same calorimeter with a time separation of more than 5 ns, the new calorimeter must allow to separate these at 100% efficiency. For showers that occur closer in time than 5 ns, the new design must allow for a separation of the two shower signals for $\approx 66\%$ of these pileup events. Therefore, the new calorimeter must have improved spatial resolution compared to the former design employed at the BNL E821 experiment [1].

The requirement of stable gain G leads to the design goal of a maximally allowed gain change of $\frac{\delta G}{G} < 0.1\%$ within a 200 μs time period in a fill. In addition, the arrival of a pulse should not affect the gain for a second pulse arriving a few nanoseconds later on the same channel, unless that change is understood and can be applied to the interpretation of a following pulse in a reliable manner. The long term gain stability ($>$ seconds) is more

6962 relaxed and we aim at $\frac{\delta G}{G} < 1\%$. To verify the overall gain stability, each of the 24 stations
 6963 needs to be equipped with a calibration system that monitors the gain continually during
 6964 the muon spills with a precision of $\frac{\delta G}{G} \sim 0.03\%$.

6965 17.1.2 Evaluation Methodologies: Test Beams and Simulations

6966 The recommended design follows extensive testing and simulation efforts. Prototype detec-
 6967 tors were built. Various silicon photomultiplier (SiPM) and photomultiplier tube (PMT)
 6968 candidates were tested and several iterations of the electronics boards needed to operate the
 6969 SiPMs were built and tested. We also employ simulations to study detector performance,
 6970 sensitivity to ω_a and pulse-shape fitting. A brief summary is given next for context.

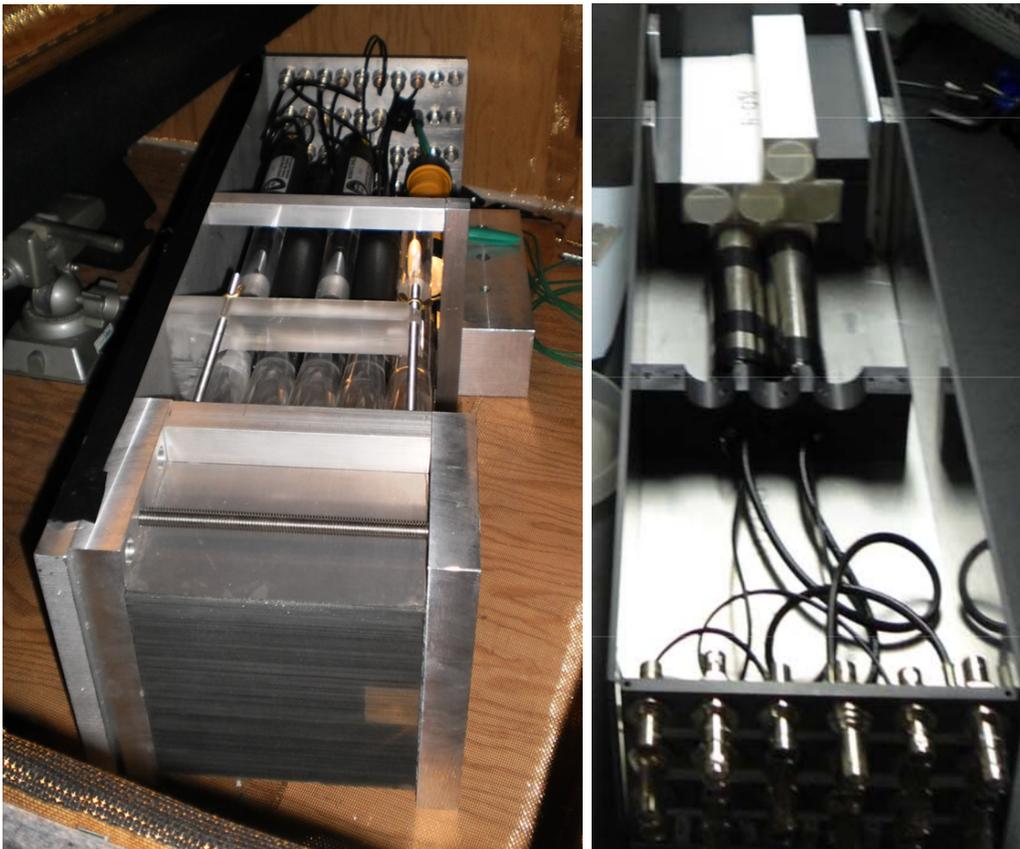


Figure 17.1: left: Monolithic block of W/SciFi having 0.5 mm thick pure tungsten plates alternated with 0.5 mm diameter ribbons of blue scintillating fiber. The readout side is divided into 25 individual elements. Tapered lightguides direct the light from a $3 \times 3 \text{ cm}^2$ area to a PMT. right: Crystals being prepared for test beam. Here, PMTs are used for the outer elements and a SiPM will be placed on the center crystal and alternatively a very fast Hamamatsu R9800 PMT for comparison.

6971 The Fermilab Test Beam Facility (FTBF) was used several times to evaluate prototype
 6972 calorimeters. In particular, our first effort with a mixture of 0.5-mm pitch tungsten plates
 6973 alternated with 0.5-mm layers of scintillating fiber resulted in a publication [2]. A larger

6974 prototype was then built and tested, see left panel of Fig. 17.1. Finally, the recommended
 6975 design based on PbF_2 crystals was tested using a $2 \times 3 \times 2$ array. The April 2012 FTBF
 6976 period was used to directly compare these crystals to the W/SciFi detector and to a custom
 6977 PbWO_4 crystal. The right panel of Fig. 17.1 shows the arrangement of PbF_2 crystals during
 6978 assembly and Fig. 17.2 displays a front view of the full test setup. Various readout methods,
 6979 wrappings and couplings were employed.

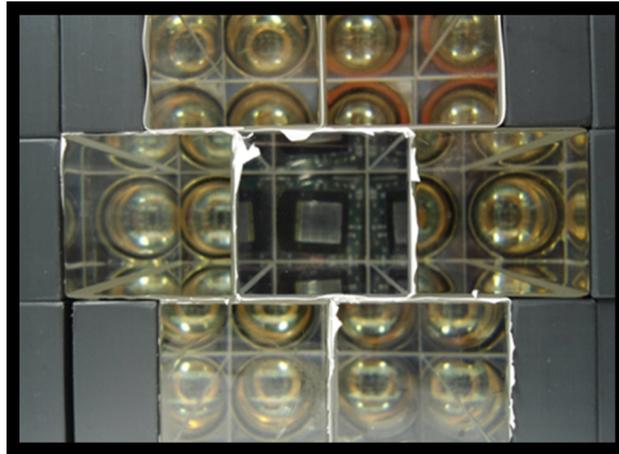


Figure 17.2: Front picture of the 7-crystal test array used in the FTBF. In this configuration, a SiPM is visible on the center channel, while PMTs are used on the remaining elements. These crystals were wrapped in white millipore paper.

6980 We also used simulation tools to evaluate performance and optimize parameters. GEANT-
 6981 4 simulations were used to study light collection in crystals and to evaluate crystals shape,
 6982 wrapping, and light yield. They were used to study array size and cluster formation. A
 6983 realistic muon storage simulation was used to produce decay events having the correct en-
 6984 ergy, spatial, and temporal distributions on the calorimeters. Finally, we developed custom
 6985 software to build pulse-shape libraries from controlled lab test and to use the libraries to fit
 6986 individual events and two-pulse events. The results of these efforts are described in line with
 6987 the design recommendation topics.

6988 17.2 Recommended Calorimeter Design

6989 The Calorimeter System includes the following subsystems: Absorber, Photodetection, Bias
 6990 Control, Calibration, and Mechanical. Over the past several years, the calorimeter design
 6991 has gone through an extensive down-select process from considered absorber and readout
 6992 technologies. Briefly, each of the 24 calorimeter stations will consist of a 6×9 array of
 6993 lead-fluoride (PbF_2) Cherenkov crystals. Each crystal will be read out by a 16-channel
 6994 Hamamatsu MPPC (Multi-Pixel Photon Counter, but more generically, these have been
 6995 dubbed “SiPMs” or silicon photomultipliers). Custom supporting electronics amplify the
 6996 summed signal and convey it to the digitizers following a hardware pole-zero correction to
 6997 shape the output. SiPM gains are very sensitive to bias and temperature. A precise and
 6998 stable bias voltage control system is being developed and a temperature-stable operating

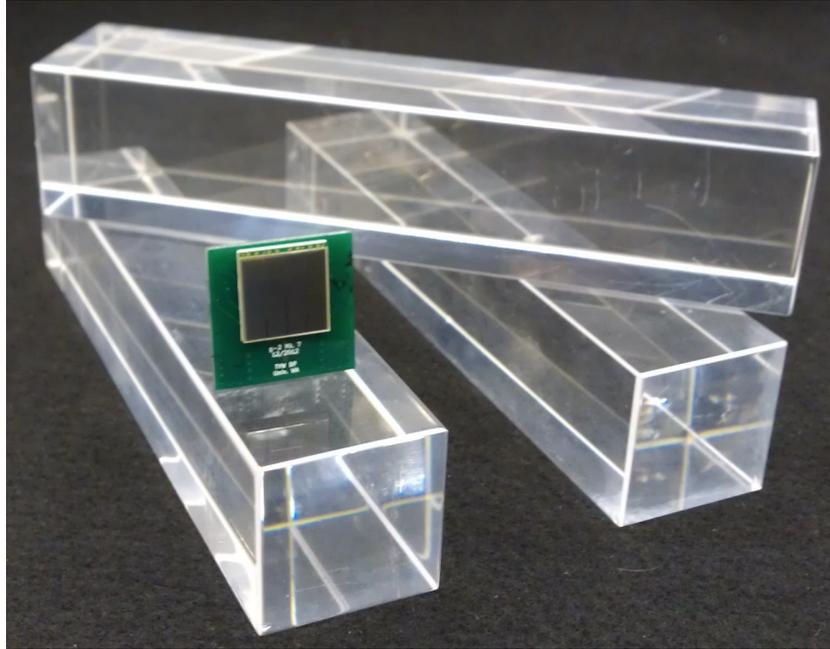


Figure 17.3: Sample $3 \times 3 \times 14 \text{ cm}^3$ PbF_2 crystals together with a 16-channel Hamamatsu SiPM mounted to our Mark VII, resistive summing, voltage amplifier board. (Note, these crystals are larger than in the conceptual design.)

6999 environment has been designed. Both systems will help to maintain high gain stability,
 7000 which addresses a leading source of systematic uncertainty. A state-of-the-art laser-based
 7001 distributed calibration system has been designed. It will permit precise monitoring of gain
 7002 vs. time-in-fill for the nearly 1300 crystals. A photo of the prototype crystals and 16-channel
 7003 surface-mount SiPM is shown in Fig. 17.3.

7004 Several factors that influenced the technology choice are:

- 7005 • Each of the 24 calorimeter stations will be located in the fringe field of the central
 7006 storage ring, directly adjacent to the muon storage volume in a cutout of a scalloped
 7007 vacuum chamber (see Fig. 16.6). The space is highly constrained vertically (17 cm)
 7008 and longitudinally (owing to vacuum interconnects and flanges). Strict limits exist on
 7009 the allowed magnetic field perturbation from the absorbers, electronics and mechanical
 7010 housings.
- 7011 • The absorber must be dense to minimize the Molière radius and radiation length. The
 7012 latter and to minimize the number of electrons entering the side of the calorimeter.
- 7013 • The intrinsic signal speed must be very fast with no residual long-term tail, thus
 7014 minimizing pileup.
- 7015 • The resolution should be good—it is used to select events—but it need not be “ex-
 7016 cellen.” A resolution of $\approx 5\%$ at 2 GeV is the required benchmark and improves upon
 7017 the E821 calorimeter system by a factor of 2.

Table 17.1: Properties of lead-fluoride crystals

Crystal cross section	$2.5 \times 2.5 \text{ cm}^2$
Crystal length	14 cm ($> 15X_0$)
Array configuration	6 rows, 9 columns
Density of material	7.77 g/cm^3
Magnetic susceptibility	$-58.1 \times 10^{-6} \text{ cm}^3/\text{mol}$
Radiation length	0.93 cm
Molière radius R_M	2.2 cm
Molière R_M (Cherenkov only)	1.8 cm
$KE_{threshold}$ for Cherenkov light	102 keV
Expected photo-electron yield* / GeV (White wrapping)	1765
Expected photo-electron yield* / GeV (Black wrapping)	685

*using 1.2 cm^2 SiPM on rear face; light integrated over several crystals to have full shower containment

7018 17.2.1 Absorber Subsystem

7019 The default material choice following an extensive comparative evaluation program (see
 7020 Sec. 17.3) is lead-fluoride crystal (PbF_2). This crystal exhibits good energy resolution and a
 7021 very fast Cherenkov signal response. It is (essentially) non-magnetic, have a radiation length
 7022 of $X_0 = 0.93 \text{ cm}$, and a Molière radius of 1.8 cm. We used a precise ($\delta P/P \sim 1\%$) Frascati
 7023 500 MeV electron beam to verify the resolution and light yield that had been documented [3]
 7024 by a Mainz Collaboration, that built a large PbF_2 array for their experiments. They found
 7025 $\sigma/E \sim 3.5\%/\sqrt{E}$ and about 1.7 p.e./MeV. A summary of the properties of the crystals is
 7026 given in Table 17.2.1.

7027 The Shanghai Institute of Ceramics (SICCAS) provided the prototype crystals and an
 7028 attractive quote for the 1350 elements required for the full system (plus spares). We own and
 7029 have used instrumentation to measure the spectral response of the crystals over the range
 7030 230 nm to 800 nm, see Fig. 17.4. We have also made AFM measurements on a crystal to
 7031 determine the surface quality that we might properly represent it in our light-propagation
 7032 simulations. The crystal procurement plan involves a 1st-stage quality control check by the
 7033 Shanghai University members of the collaboration, who are local to the vendor. Next, the
 7034 crystals will be sent to the University of Washington team for wrapping and assembly. PbF_2
 7035 crystals are relatively easy to handle; they are only slightly hydroscopic.

7036 Detailed GEANT ray-trace simulations and direct laboratory measurements have been
 7037 used to study the light collection efficiency of the crystals subject to various wrapping
 7038 schemes and couplings to the photo-sensitive readout. We have focussed on two extremes,
 7039 namely an all-black tedlar absorptive wrapping, and a diffuse reflective white millipore pa-
 7040 per wrapping. The black wrapping largely transmits only the direct Cherenkov light cone,
 7041 while the white wrapping allows light to bounce multiple times within the crystals even-
 7042 tually leading to a higher overall photon yield. Both wrappings have advantages. For the
 7043 shortest pulse occupancy time, the black wrapping excels. For the greatest light yield, the
 7044 white wrapping is better. Shorter-duration pulses improve pileup rejection; higher light yield

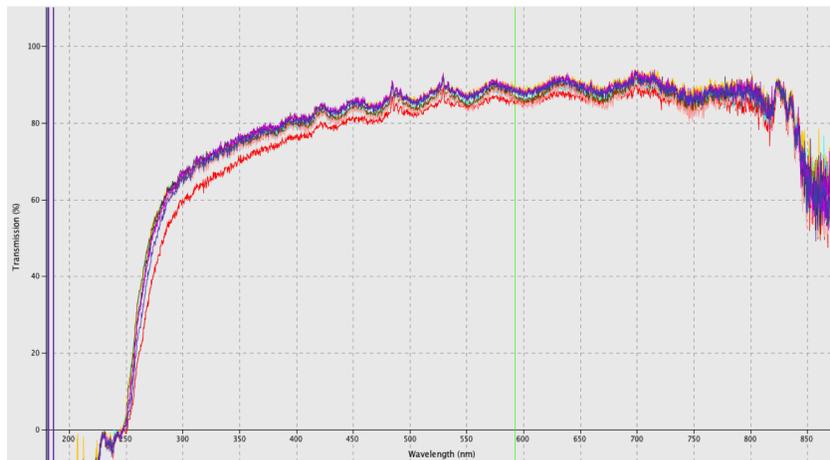


Figure 17.4: Transverse transmission efficiency vs. wavelength through a 3-cm-thick PbF_2 prototype crystal. The four curves correspond to rotations of the crystal with respect to the light source from an Ocean Optics spectrometer.

7045 improves resolution. We have tested both wrappings and an aluminum foil wrapping in a
 7046 test-beam using a standard 29-mm Photonis PMT for readout. The left panel of Fig. 17.5
 7047 shows the results with the amplitudes normalized. The tedlar wrapped FWHM is limited
 7048 here by the PMT. The right panel compares PbF_2 to alternative design options discussed
 7049 in Sec. 17.3. Here we observe the true full width of 4 ns for the PbF_2 crystal as measured
 7050 using a fast Hamamatsu R9800 PMT.

7051 Table 17.2.1 includes two entries that compare absolute light yield in photo-electrons as
 7052 would be detected by our default photo-sensitive detectors. The simulation generates the
 7053 correct Cherenkov light distribution (by wavelength) from a 2 GeV incident electron and
 7054 it uses the correct crystal dimensions and surface reflectivity parameters. Optical-grease
 7055 coupling is assumed as is the photo-detection efficiency of the readout device as a function
 7056 of wavelength. The yield of white paper wrapping is 2.5 times greater than the black paper,
 7057 which is consistent with laboratory tests we carried out with cosmic rays. The pulse duration
 7058 is also measured and largely agrees with the measurements. We intend to repeat the light
 7059 yield test in a beam with a better control of the pe/channel of the photo-sensitive readout.

7060 GEANT-4 simulations have been used to study to optimize the individual crystal size
 7061 and the array matrix configuration. A visualization of a typical 2 GeV electron shower is
 7062 shown in Fig. 17.6. A driving specification for an array of crystals is the reduction in pileup
 7063 to be realized by spatial separation. Candidate arrays of 5×7 and 6×9 (height by width)
 7064 segmentation using $3 \times 3 \text{ cm}^2$ or $2.5 \times 2.5 \text{ cm}^2$, $15X_0$ -deep crystals, respectively, will fit the
 7065 space constraints. A simulation with full showering and cluster reconstruction using a simple
 7066 and robust two-shower separation algorithm was used to choose the best arrangement. Not
 7067 surprisingly, the higher-granularity array is best. We find that it will provide at least a 3-fold
 7068 reduction in pileup compared to a monolithic design. These conclusions were arrived at from
 7069 a combination of simulation and direct measurement using the FTBF.

7070 Energy sharing among neighbor crystals is shown in Fig. 17.7 for a shower that strikes
 7071 the center of the middle crystal. The simulation is calibrated against the test-beam measure-

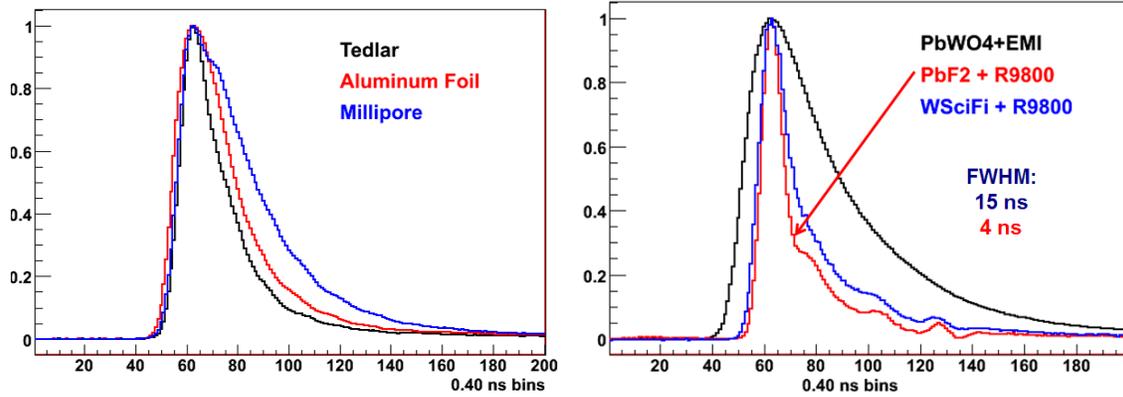


Figure 17.5: Left panel: Normalized response of PbF_2 crystal wrapped in absorptive black tedlar, reflective aluminum foil, and a bright, white millipore paper. A standard 29-mm Photonis PMT was used. Right panel: Comparison of three pulse shapes from PbF_2 , using a very fast Hamamatsu R9800 PMT, to W/SciFi using the same PMT and to PbWO_4 using an EMI PMT.

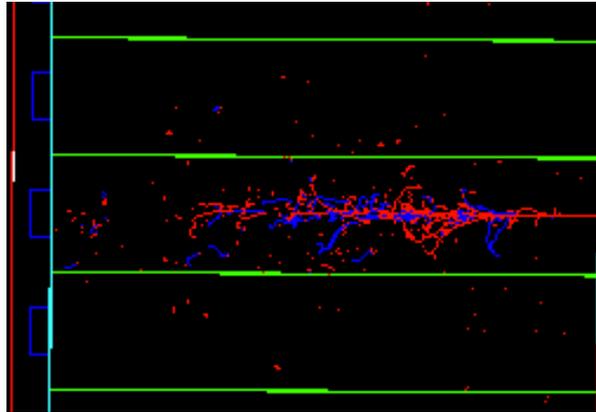


Figure 17.6: A single shower showing secondary positrons and electrons in a $2.5 \times 2.5 \text{ cm}^2$, by $15X_0$ deep PbF_2 crystal, subject to a 2 GeV incident electron.

7072 ments in which an electron beam was directed into a crystal at various known positions and
 7073 the ratio of neighboring crystal responses was recorded. Fig. 17.7 also shows a histogram
 7074 of data vs. the simulation prediction. The agreement is excellent and verifies the model
 7075 used to optimize array size and to evaluate pileup by shower separation. The simulation was
 7076 then used to study the spatial separation efficiency for two simultaneous showers. The left
 7077 panel of Fig. 17.8 shows schematically the shower deposition by color. The right panel is
 7078 a systematic study of two-shower events as distributed on the calorimeter based on the full
 7079 muon storage and decay simulation. From the simulation we see that the 6×9 configuration
 7080 will enable a reduction in pileup by a factor of $2/3$ compared to a monolithic array.

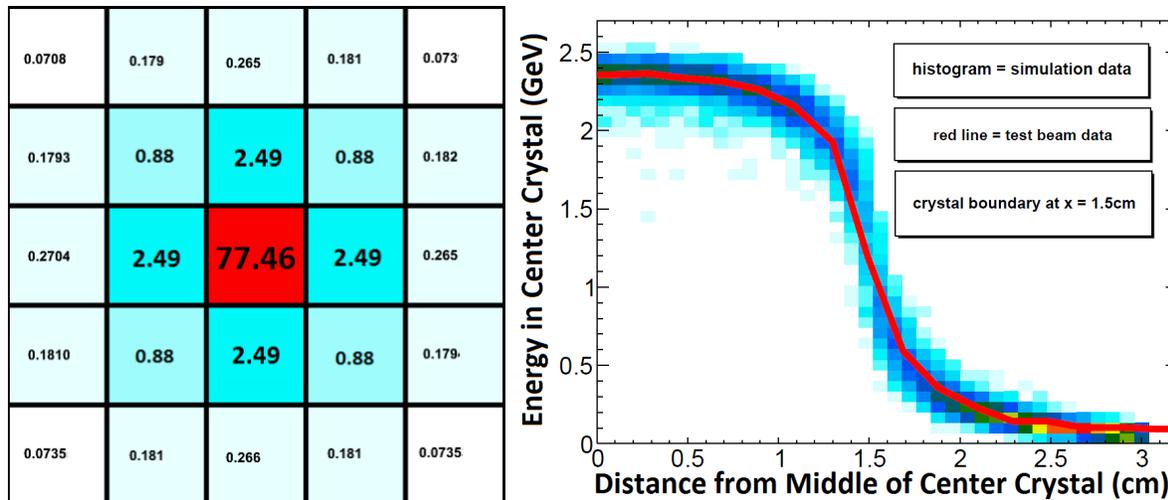


Figure 17.7: Left: Schematic representation of energy deposition in a section of the segmented electromagnetic calorimeter. Each cell is one crystal with dimensions ($2.5 \times 2.5 \times 14 \text{ cm}^3$). The numbers represent the percentage of the kinetic energy deposited in each crystal. This data was produced from a GEANT-4 simulation with an electron incident on the center of the central crystal. The results do not change for electrons in the range of 0.5 GeV to 3 GeV. Right: A comparison of test beam data and simulation data. This plot shows the shower leakage into neighboring crystals as a function of beam incidence position.

17.2.2 Photodetection - SiPM - Subsystem

7081

7082 Silicon photomultipliers (SiPMs) are assumed in the baseline design to read out the crystals.
 7083 While challenging and relative new devices, they are increasingly becoming the standard
 7084 substitute for traditional PMTs in many nuclear and particle physics applications. As such,
 7085 the body of experience in their use is growing rapidly and the variety of SiPM devices from
 7086 many manufacturers is increasing. They work as pixelated Geiger-mode counters. The
 7087 default SiPM we are considering has 57,600 $50\text{-}\mu\text{m}$ -pitch pixels on a $1.2 \times 1.2 \text{ cm}^2$ device.
 7088 When a photon strikes a pixel, it can cause an avalanche that is summed together with the
 7089 other struck pixels in a linear fashion to produce the overall response. Quenching resistors are
 7090 intrinsic to the device to arrest the avalanche and allow the device to recover with typically
 7091 10's of ns time constant. Those pixels that are not struck, meanwhile, remain ready for a
 7092 next pulse. In general, the concept is to have a pixel count that greatly exceeds the highest
 7093 photon count that would strike the device. For example, for our crystals, a working number
 7094 is 1 pe/MeV (where pe represents a converted photon). With a range of up to 3100 MeV
 7095 for single events, the occupancy fraction remains no more than about 5%, which is in a
 7096 near-linear regime and allows for a good measurement of any closely trailing second pulse.

7097 The selection of SiPMs over PMTs is pragmatic. They can be placed inside the storage
 7098 ring fringe field, thus avoiding the awkward, long lightguides that would be needed for
 7099 remote PMTs. They have high photo-detection efficiency, they will not perturb the storage
 7100 ring field, and they can be mounted directly on the rear face of the PbF_2 crystals. The cost
 7101 of large-area SiPM arrays is rapidly falling and their performance characteristics continue to
 7102 improve. We have spent the last 2 years developing lab tests to evaluate these devices. The

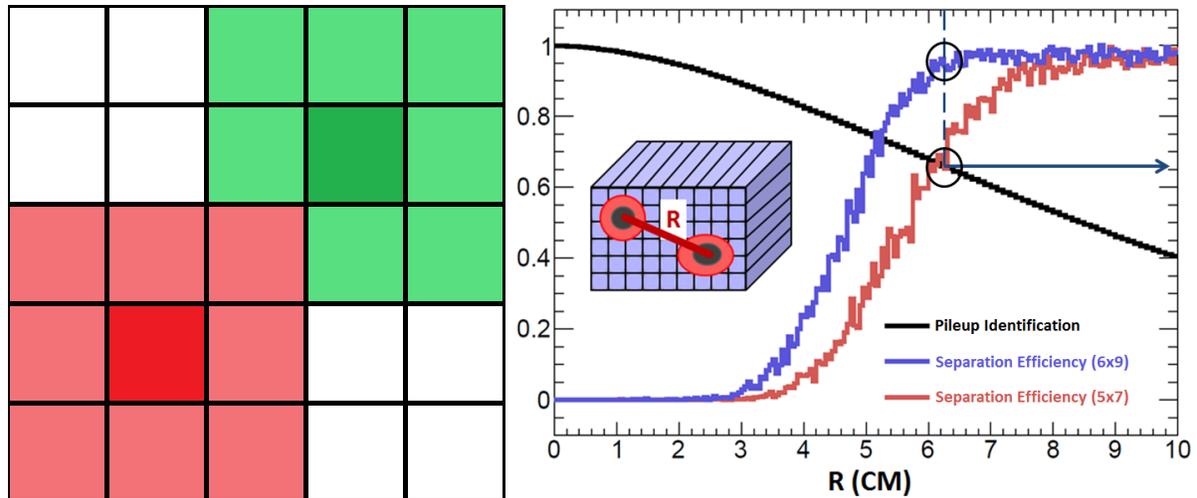


Figure 17.8: Left panel: Schematic representation of energy deposition in a section of the segmented electromagnetic calorimeter. Red represents the primary cluster reconstructed by the analysis software. Green represents the secondary cluster. The dark cells dictate the seed of each cluster. Right panel: Pileup separation efficiency curves for two different crystal segmentations, 6x9 (blue) and 5x7 (red), which correspond to 2.5 cm and 3 cm crystals, respectively. The black curve represents the amount of pileup rejected for a certain R value. The variable R is the distance between the two incident electrons and is shown graphically in the inset.

7103 collaboration has designed and built a series of custom pre-amplifier and summing amplifier
 7104 boards. The most recent version features low-power consumption and an intrinsic short pulse
 7105 when coupled to a pole-zero correction circuit that eliminates the long RC time-constant tail
 7106 of the device.

7107 Large-area SiPM devices are packaged as arrays of smaller individual channels. While
 7108 the market is constantly evolving, we are presently using a Hamamatsu surface-mount 16-
 7109 channel MPPC having 57,600 50- μm pixels in a $1.2 \times 1.2 \text{ cm}^2$ active area. It is reasonably
 7110 well-matched to the surface $2.5 \times 2.5 \text{ cm}^2$ crystal face. Figure 17.9 shows the Hamamatsu
 7111 16-channel surface-mount MPPC (SiPM). This board is based on a the concept of a passive
 sum and voltage amplifier. The output of a SiPM from a photo-electron event is a pulse

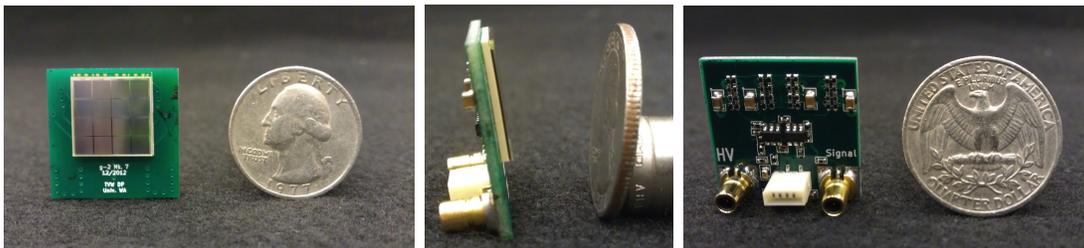


Figure 17.9: Surface-mount 16-channel MPPC. The coaxial connections represent the signal out and the common bias voltage in. The board low voltage is supplied through the white edge connector.

7113 of current, with a fast rising, sub-ns, edge and a longer tail on the order of tens of ns,
 7114 which is converted to a voltage by a load resistor. In our present design, this is followed
 7115 by two stages of voltage amplification provided by high speed op amps. We are constantly
 7116 improving our circuit and watching the field to learn about new devices and techniques.
 7117 Our development will likely cycle through 2 or more iterations prior to final purchase of
 7118 components in order to take advantage of the latest offerings. We have also begun a dialog
 7119 with University of Washington EE and Medical Physics research groups who are developing
 7120 an ASIC design having many overlapping features of common interest. Considering this
 7121 dynamic environment, the baseline conceptual design has been demonstrated to function
 7122 well enough for $g - 2$, but we are confident that improvements will be made based on
 7123 announcement of new products from the vendors and from the rapid advancement in the
 7124 electronics designs.

7125 One of the challenges of using SiPMs is their particular sensitivity to temperatures.
 7126 Figure 17.10 (left panel) shows the gain change of our SiPM device vs. temperature. The
 7127 slope of about 4%/ deg C implies that we must keep the board temperature stable during a fill
 7128 to 1 part in 40. While short-term shifts are unexpected, the overall SiPM environment must
 7129 be maintained at a fairly constant temperature in order to simplify the global calibration
 7130 of gain during the running period. The response of a SiPM is also quite sensitive to the
 7131 bias voltage stability above Geiger-mode breakdown threshold. The right panel of Fig. 17.10
 7132 shows a lab measurement of our SiPM and voltage amplifier board vs. bias voltage. Around
 7133 the working bias of 72.5 V, the slope is steep, leading to the need to have a separate bias
 control subsystem, which we describe in Subsection 17.2.3.

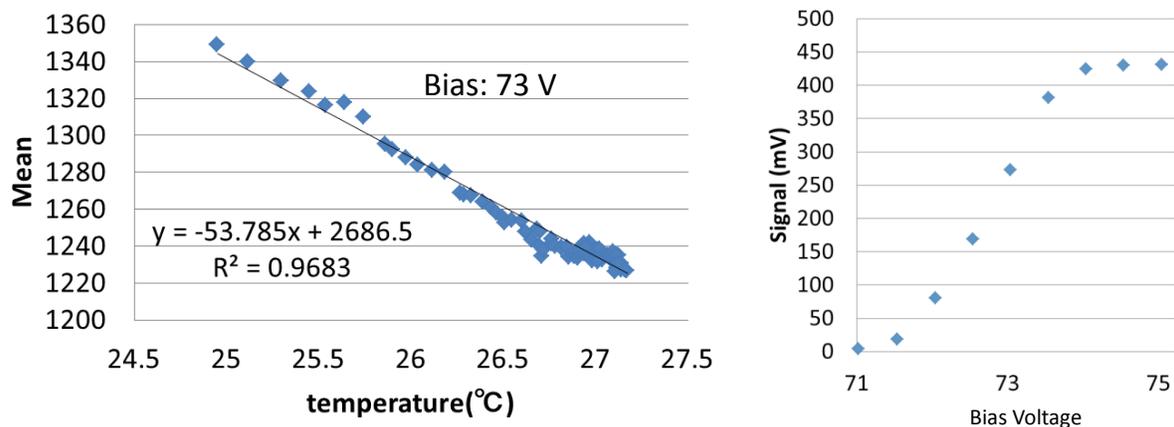


Figure 17.10: Left: Gain vs. temperature for 16-channel SiPM array. Right: Gain vs. bias voltage.

7134

7135 Given the working electronics board described above, simulations were carried out to
 7136 determine pulse-shape characteristics and, most importantly, two-pulse separation. We used
 7137 a 5 GSPS digitizer to record a series of pulses in which a SiPM was excited by a 600 ps
 7138 pulse-length N_2 laser (337 nm) light burst. The intrinsic fast risetime of a SiPM is slowed
 7139 somewhat by our circuit and the quenching resistance and internal capacitance determined
 7140 the exponential recovery time constant. Because the pulse shape is predictive, a pole-zero

7141 correction can be applied, post-amplifier, to produce the final recorded pulses. The left
 7142 panel of figure 17.11 shows the intrinsic raw SiPM pulse with its long recovery time. The
 7143 same pulse is seen with the pole-zero correction circuit applied. A series of pulses is used
 7144 to develop a pulse-shape library. The right panel then shows a representative single pulse
 7145 fit using the library template. This procedure is the basic element of our eventual analysis
 7146 protocol.

7147 The analysis of two-pulse waveforms is critical for pileup rejection. Both simulated and
 7148 measured studies were made, following many of the protocols we developed for the MuLan
 7149 1-ppm muon lifetime experiment. In that effort, unresolved pileup had to be subtracted
 7150 at the per mil level to avoid distortions to the lifetime [4]. It is less severe here, but still
 7151 important. Our two-pulse resolution software was adopted for the new $g - 2$ situation,
 7152 which has different pulse shapes and a much wider range of amplitude ratios for the two
 7153 nearby pulses. At present, we find that two pulses separated by 5 ns or more can be reliably
 7154 separated. An active area of our laboratory work is to systematically map out the two-pulse
 7155 separation function with varying pulse-to-pulse amplitude ratios and time separations. As
 7156 an example, Fig. 17.12 shows the waveform from laboratory tests in which the laser pulse
 7157 was split with one leg delayed by exactly 5 ns with respect to the second. Further details
 7158 regarding the digitization the these pulses are given in Chapter20.1. The lab setup allows
 7159 both to be measured individually and then the sum together. The figure clearly shows
 7160 resolved pulses. Tests are ongoing to map the efficiency of two-pulse resolution vs. Δt and
 7161 R_{12} , the ratio of amplitudes for pulse 1 and pulse 2. Additionally, we intend to map out
 7162 the function $G2(\Delta t, R_{12})$, which is the fidelity of the gain of the second pulse amplitude
 7163 versus the time separation and amplitude ratio. Because pixels are struck (and therefore
 7164 temporarily disabled) from the leading pulse, the trailing pulse effectively see a “smaller”
 device, but in a predictable manner.

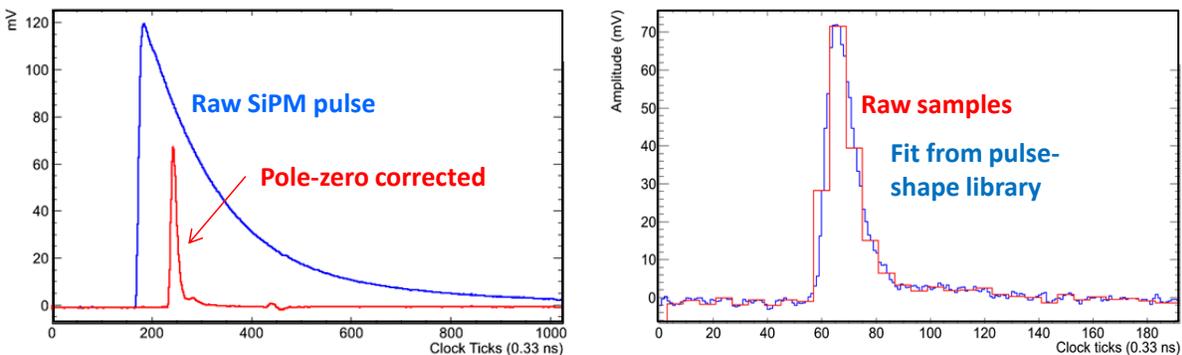


Figure 17.11: Left: Raw Laboratory measurement of raw 16-channel SiPM pulse using voltage amplifier. Same pulse with post-amplifier, pole-zero circuit included. Right: Single pulse and fit using pulse-shape template library and current pulse-finding analysis software.

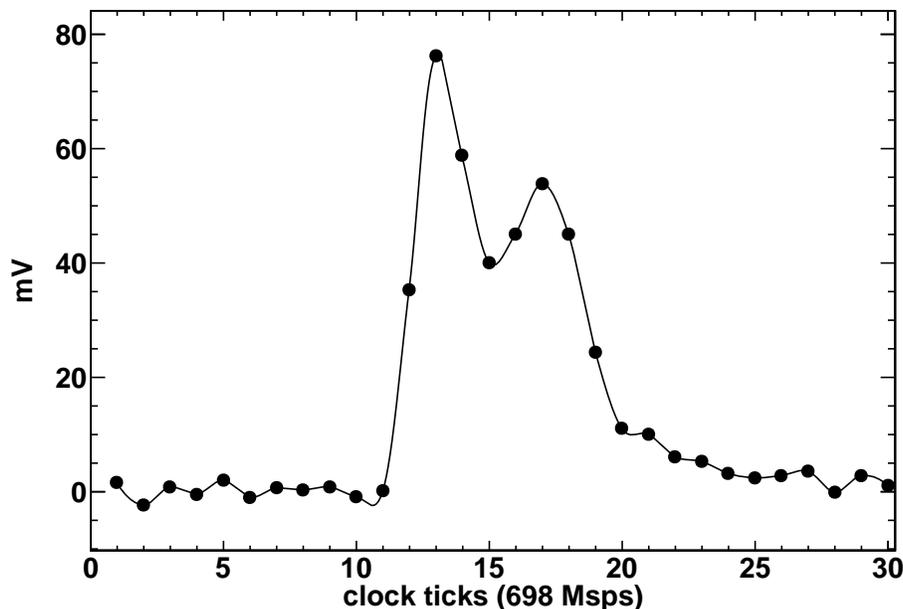


Figure 17.12: Digitized samples for a pair of pulses laser pulses striking the SiPM array 5 ns apart.

7166 17.2.3 Bias Control Subsystem

7167 The bias voltage control system will provide the operating voltage setpoint for the SiPMs.
 7168 Key design aims are that each of the 1296 installed boards must be adjustable in mV incre-
 7169 ments over a range of ± 2.5 V around the nominal HV bias of ~ 72 V, just above the Geiger
 7170 mode breakdown voltage. Further, the system must maintain a high degree of bias voltage
 7171 stability and deliver an average current of up to $50 \mu\text{A}$ per channel. These are unusually
 7172 strict benchmarks that are established to minimize any offline gain correction procedures.
 7173 At this time, no commercial device satisfies these requirements and the need for distribution
 7174 to the 24 “satellite” locations around the ring. Hence, the system will be built by the UVa
 7175 and JMU groups. It will conform to global $g - 2$ slow control protocols and provide control
 7176 and readback functions based on the new Midas Slow Control Bus (MSCB) standard. The
 7177 system will consist of a stabilized DC power supply, HV boards, readback and control (16
 7178 channels/board), 5 V DC power, shielded twisted pair ribbon HV cables, and RS485 serial
 7179 bus for the MSCB. These will be packaged together as a single unit capable of providing 64
 7180 channels of HV into a single module. Twenty five modules will be built and tested.

7181 17.2.4 Laser Calibration Subsystem

7182 A high performance calibration system is required for the on-line monitoring of the output
 7183 stability of each individual tower in all calorimeter stations. It is estimated that the detector
 7184 response must be calibrated with relative accuracy at sub-per mil level to achieve the goal
 7185 of the E989 experiment to keep systematics contributions to the accuracy on the measured
 7186 observables at 0.02 ppm level. This is a challenge for the design of the calibration system
 7187 because the desired accuracy is at least one order of magnitude higher than that of all other

7188 existing, or adopted in the past, calibration systems for calorimetry in particle physics.

7189 Almost 1,300 channels must be calibrated during data taking; the proposed solution
7190 is based on the method of sending simultaneous light calibration pulses onto the readout
7191 photo-detector through the active sections (crystals) of the calorimeter. Light pulses must
7192 be stable in intensity and timing to correct for systematic effects due to drifts in the response
7193 of the crystal readout devices. A suitable photo-detector system must be included in the
7194 calibration architecture to monitor any fluctuation in time of the light source intensity and
7195 beam pointing as well as any fluctuation of the transmitted light along the optical path of the
7196 light distribution system, which could occur due to mechanical vibrations or optics aging.

7197 Some guidelines are defined to select the light source(s) and to design the geometry of
7198 the light distribution and monitoring; the following criteria are adopted to select the light
7199 source type:

- 7200 • Light wavelength must be in the spectral range accepted by the detector and deter-
7201 mined by the convolution of the spectral density of the Cherenkov signal produced by
7202 electrons in PbF_2 crystals with the spectral transmission of the crystals, and with the
7203 spectral quantum efficiency (Q.E.) of the photo-detector; Q.E. is peaked around 420
7204 nm for SiPMs.
- 7205 • The luminous energy of the calibration pulses must be in the range of the electron
7206 deposit in the crystals, typically 1-2 GeV; this corresponds to a luminous energy on each
7207 tower of a calorimeter station of about 0.01 pJ, or to about 0.013 nJ for simultaneous
7208 excitation of all calorimeter readout channels (1300). The numbers quoted above are
7209 merely indicative of the order of magnitude and they are derived by assuming that the
7210 readout of each crystal will produce up to 2 photo-electrons per MeV with 50% P.D.E.
7211 (Particle Detection Efficiency) for SiPMs and with 40% coverage of the crystal readout
7212 face.
- 7213 • The pulse shape and time width must be suitable to infer on the readout capability
7214 in pile-up event discrimination; pulse rise/trailing time must be of the order of some
7215 hundred of picoseconds, the total pulse width should not exceed 1 ns. This implies
7216 a peak power per pulse at the source of about 1 Watt (1 nJ in a 1 ns wide pulse),
7217 assuming the conservative value $T \simeq 0.01$ for the total intensity transmission factor of
7218 the calibration system.
- 7219 • The pulse repetition rate must be of the order of 10 KHz; this value will be tuned to
7220 obtain the best compromise between the need of having enough calibration statistics in
7221 the time interval (some tens of microseconds after the muon injection in the ring) when
7222 the maximum rate is achieved in the readout devices and the need to avoid saturation
7223 of the DAQ bandwidth.

7224 A number of commercial diode lasers cope with the criteria listed above, and have been
7225 considered as a source for the calibration pulses. The final choice will be made after the
7226 completion of all tests required to qualify, in terms of light transmission and time stabil-
7227 ity, all other optical elements of the calibration system. Guidelines for designing the light
7228 distribution chain are listed below:

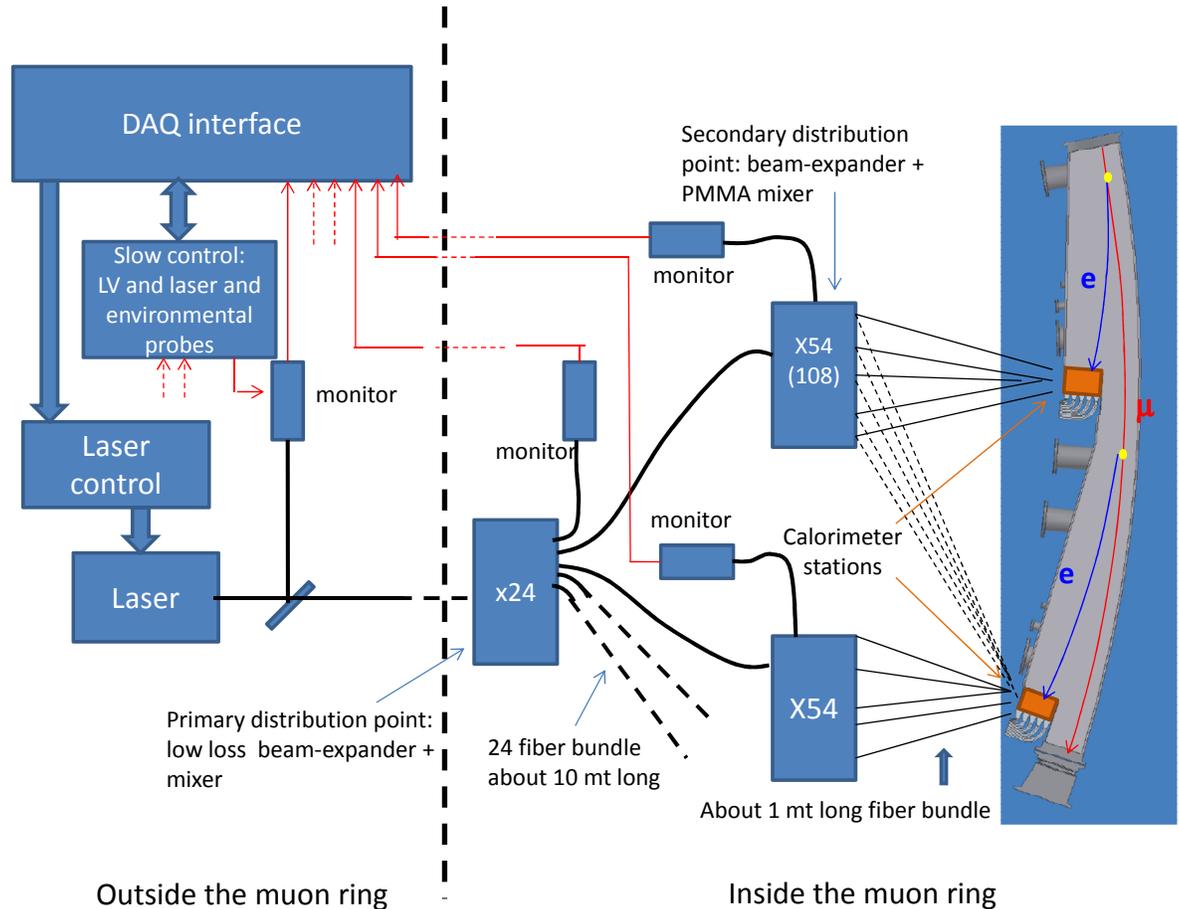


Figure 17.13: Calorimeter calibration system: sketch with the main components.

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- High sensitivity monitors of the transmitted light at the end-point of each individual section of the distribution chain must be used to ensure online control of the system stability and to have information for applying feed-back correction to the source operation parameters, if needed.
- The optical path must be minimized in order to limit the light loss due to self-absorption in the optical fibers; the number of cascade distribution points must be also minimized to reduce the unavoidable light loss in the couplers between different sections;
- The laser source and its control electronics should be located outside the muon ring in order to avoid e.m. perturbations of the local field induced by the current flow used to excite the laser. Consequently, a suitable geometry should include a primary light distribution point outside the ring, a bundle of fibers about 20 meter long and used to feed light from the primary distribution point to the secondary ones, and secondary distribution points located close to each calorimeter station; from the secondary distri-

7242 bution points, short fibers, about 1 meter long, feed the light to the individual towers
7243 of each calorimeter station.

- 7244 • Optical fiber selection: silica fibers (20 dB/Km attenuation at 400 nm) are the best
7245 solution for long path light transmission and in terms of robustness against solarization
7246 or other aging affects due to large values of transmitted light intensity. For the shorter
7247 fiber bundles, where the transmitted intensity is at least one order of magnitude lower,
7248 also PMMA clear fibers (200 dB/Km attenuation at 400 nm) can be considered to save
7249 money.

7250 A possible geometry fulfilling all the requirements set by the guidelines listed above is
7251 shown in Figure 17.13; light generated by a laser source is fed onto a primary distribution
7252 device located in the center of the muon ring; quartz fibers (about 10 meter long, one
7253 per calorimeter station plus spares for monitoring purposes) route the light to secondary
7254 distribution devices located near the calorimeter stations, each distributor serving one or
7255 two close stations. A small fraction of the light exiting the source and the light distributors
7256 is routed to monitors whose analog signal is returned to the DAQ system for on-line checking
7257 of the system stability. Interface with DAQ is also required for slow control signal recording
7258 and communication with the timing signal controls is used to trigger the electronics of the
7259 laser driver.

7260 Qualification tests of the individual components will include comparison measurements
7261 of different options; apart the fiber type, alternative approaches are considered for:

- 7262 • laser source; as an alternative to a single, powerful laser light source, the possibility to
7263 use two or four lower power, synchronized, lasers can be considered; the latter solution
7264 would have the advantage that, in case of laser failure, no calibration stops will occur
7265 during data acquisition; moreover, lower power lasers have, in general, better stability
7266 characteristics. Issue for the multi-source option is to demonstrate that the different
7267 pulses can be synchronized at the desired level, some tens of ps.
- 7268 • light distributors; baseline solution uses custom designed beam-expanders with light
7269 mixers inside; this feature is required to guarantee intensity stability of the distributed
7270 light against geometrical effects due to beam-pointing instabilities. Integrating spheres
7271 are an alternative and offer a high degree of output uniformity at the price of a higher
7272 factor in intensity loss (up to 100). Beam-splitters made with the linear circuit tech-
7273 nology could also be considered if commercial devices, nowadays widely used only in
7274 the IR range for telecommunication, will be produced for the near-UV/visible range.

7275 17.2.5 Mechanical Subsystem

7276 Each calorimeter station will comprise a number of individual crystals which are made out
7277 of dense material which is usually also brittle. In addition, the detector including the photo-
7278 sensitive device needs to be in a light tight encapsulation. A typical set of crystals and photo-
7279 detectors forming one calorimeter station weighs ≈ 40 kg. The housing must provide the light
7280 tightness, proper stability to carry the weight, feedthrough for cables, and a mechanism for
7281 easy lifting of the entire box and insertion into or out of the ring in the radial direction (e.g,
7282 rails).

7283 The locations of the 24 calorimeter experiment are fixed by the design of the scallop-
 7284 shaped vacuum chambers. Several vacuum ports, bellows and the magnet's pole gap impose
 7285 spatial limitations on the design. Specifically, the length of the calorimeter station along
 7286 the electrons trajectory cannot exceed 38 cm. The pole gap limits each station to less than
 7287 17 cm. There are no tight limiting factors in the radial dimension that we can see would
 7288 constrain the calorimeter station.

7289 For installation, maintenance and access to the vacuum chamber or the magnet, each
 7290 calorimeter station needs to be easily removable. We will determine later the degree of
 7291 alignment necessary, but a system of pins should allow for a reproducible position. The
 7292 absolute position is less critical. The calorimeter housing and retractable platform must allow
 7293 for routing of a variety of cables (detector signals, bias voltage, control signals, monitoring
 7294 signals) and service lines (e.g. water cooling pipes). The mechanical design must incorporate
 7295 space for the readout electronics crates to be placed on-board to be compatible with the
 7296 moving mechanism.

7297 A mechanical housing system was built for the test beam and a full-scale version has
 7298 been designed by CENPA engineers and costed for the experiment. It ensures a light-tight
 7299 environment, provides cooling as necessary, includes patch panels for cable runs and has a
 7300 front-end that will mate to the calibration interface plate described above. The housing has
 7301 serviceable doors that will allow easy access to the crystals and readout devices. Figure 17.14
 7302 shows three engineering drawings of the proposed system. Modifications will be made once
 7303 the decision on the signal and bias cabling is finalized. The front panel of the light-tight
 7304 housing holds the calibration plate. Figure 17.15 shows our current design in perspective.
 7305 This system will couple to the rest of the enclosure in a manner that allows easy removal for
 servicing.

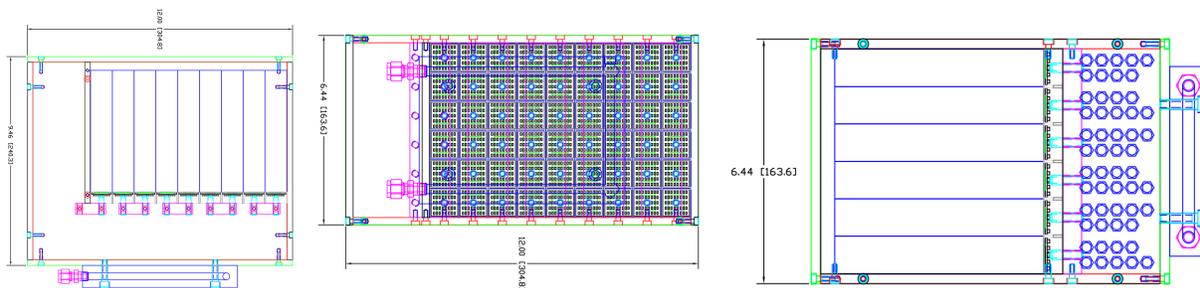


Figure 17.14: Proposed calorimeter light-tight housing. Left: Top view of 9 crystal columns. The storage ring is on the right. The extra space on the left side is used for panels, cooling, servicing. The rear part of the box includes a cooling channel. The front accommodates the calibration plate (not shown here). Mid: Side view of 6 rows of crystals. The conceptual plan for the signal feedthroughs is indicated. Right: Rear view showing the 54 SiPM pre-amplifier / amplifier summing boards.

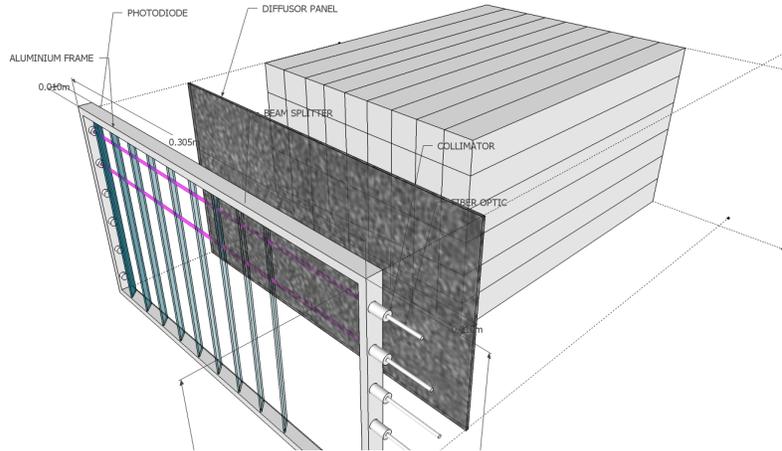


Figure 17.15: Proposed front calibration plate. Six optical fibers penetrate from the inner radial direction. The light is split using a series of beam splitter plates. A diffusor panel spread the light across the crystal front faces. This system is being prototyped.

17.3 Alternative Design Considerations

7307

7308 Two alternative calorimeter material options and one alternative readout option were tested
 7309 using the Fermilab test beam facility. These included a home-built tungsten-scintillating
 7310 fiber sampling calorimeter, which is dense ($X_0 = 0.7$ cm), and has a fast-scintillator signal
 7311 response [2]. Unfortunately, it did not exhibit acceptable resolution in the as-built W:SciFi
 7312 50:50 ratio and necessary modifications would reduce the density. Next we tested a custom
 7313 undoped lead tungstate (PbWO_4) crystal. The idea was to reap the benefits of the higher
 7314 light yield of PbWO_4 , but to avoid the slow scintillator light component that is prohibitive
 7315 long for our application. Although its resolution was excellent, the intrinsic pulse FWHM
 7316 of 15 ns greatly exceeds the 4 ns width measured for PbF_2 . There were no benefits of this
 7317 crystal from cost or other perspectives. A comparison of the pulse shapes from W/SciFi and
 7318 PbWO_4 to our default design of PbF_2 is shown in the right panel of Fig. 17.5.

7319 We also evaluated fast photomultiplier tubes as alternatives to SiPMs. The Hamamatsu
 7320 9800 is an excellent PMT, having a fairly compact footprint and intrinsic fast response. We
 7321 are using it regularly to benchmark the intrinsic light output time distribution from our
 7322 crystals. Unfortunately, it is not a good choice for full implementation in the experiment
 7323 owing to the need to place these PMTs at least 1.5 m from the calorimeter arrays. Because
 7324 of the rear-face readout from the geometry, the guides would require a rapid 90-degree bend
 7325 toward the radial direction and then a second bend to put the PMTs out of plane. The
 7326 high cost of the PMTs (about 5 times higher than the SiPMs) and the awkward lightguide
 7327 constraint were deemed to be major issues compared to the development of SiPMs that can
 7328 be located onboard the crystals.

7329 We are also actively evaluating SiPMs made by different companies, including the latest
 7330 blue sensitive SiPMs from SensL, STMicroelectronics and other vendors. Hamamatsu has
 7331 also announced new devices with attractive features such as silicon vias and lower quench
 7332 resistance. One option to increase the fractional readout area on the rear face of the crystals
 7333 (presently $144 \text{ mm}^2 / 625 \text{ mm}^2$ for the 16-ch MPPC) is to use larger area arrays of tileable

7334 SMT packaged SiPMs on custom-designed PCBs. For example, an ideal 5×5 array of 3 mm^2
7335 can be made using devices, which are competitively priced, from STMicroelectronics. Larger
7336 area coverage would allow the use of smaller, thus faster pixels, while maintaining sufficient
7337 overall photon detection efficiency. We are exploring these options prior to freezing the final
7338 design.

7339 **17.4 ES&H**

7340 The 1300 SiPMs all receive a low-current $\sim 70 \text{ V}$ bias voltage, which is delivered to the
7341 enclosed housing through coax cables from a custom-built bias control system. A laser
7342 system will be used to distribute calibration pulses. Apart from the laser hut, the light will
7343 be entirely contained in optical fibers, with no possibility of escaping under normal use. The
7344 laser hut will be upstairs in the main MC-1 building and appropriate safety requirements
7345 will have to be developed to isolate the room and limit access to trained experts. The
7346 mechanical weight of the calorimeters is only 40 kg each and they will be supported on
7347 railed housings. There is no vacuum insertion, but these detectors will be placed near the
7348 storage ring magnetic field and, as such, care must be taken when servicing them to ensure
7349 that no magnetic tools are used (a general requirement for any access to the storage ring
7350 area).

7351 **17.5 Risks**

7352 **17.5.1 Performance Risks**

7353 If the gain stability of the system in actual use fails to meet the specifications, other anal-
7354 ysis techniques will have to substitute. This situation happened in E821, where the laser
7355 system did not meet the performance goals. Instead, the stability of the gain was able to be
7356 determined from the data itself. It is not ideal, but did mitigate the risk.

7357 **17.5.2 Schedule Risks**

7358 An NSF Major Research Instrumentation proposal was submitted in February, 2013. This
7359 proposal would fund the costs of the detector, electronics and data acquisition systems. A
7360 substantial matching component was arranged from the domestic and international universi-
7361 ties involved. Separately, the Italian groups await approval from INFN for their production
7362 of the calibration subsystem. If either of these proposal fail, a greater burden on the Project
7363 budget will follow, with possible delays in the schedule.

7364 The production of large numbers of crystals and the procurement of SiPMs and the design
7365 and assembly of the bias control system all could encounter vendor or design delays. We
7366 do not anticipate this, given the quoted 18-month production time for the longest lead-time
7367 item (crystals), but any delay in funding, coupled with a slower production rate could impact
7368 the schedule. The demanding performance parameters applied to the bias control and laser
7369 gain monitoring system could require revision cycles that impact the schedule. We will try
7370 to get ahead of this curve with an aggressive R&D program.

7371 **17.6 Quality Assurance**

7372 Our local Shanghai University collaborators will inspect the crystals at the factory before
7373 acceptance of the products. The crystals will then be shipped to the University of Washington
7374 where a sample of them will be tested for transmission efficiency. The crystals will then be
7375 wrapped. The SiPM boards will be build and tested using a custom light scanner that
7376 can calibrate each device. Finally, the assembly of complete crystal-SiPM blocks will be
7377 assembled into an array and tested with a calibrated laser front panel plate. We have a
7378 SiPM test laboratory to evaluate the production SiPM boards and will prepare a program
7379 using undergraduate students to evaluate each piece in the assembly line.

7380 **17.7 Value Management**

7381 Competitive quotes have been obtained in order to prepare the MRI Proposal. Local fab-
7382 rication at universities with largely overhead-free labor will keep costs in check. We are
7383 continuing an aggressive program of SiPM vendor evaluations and board designs to obtain
7384 a higher fractional readout coverage at competitive cost.

7385 **17.8 R&D**

7386 We have used test beam opportunities repeatedly as necessary. We intend to use the new
7387 SLAC electron test beam to make final measurement of the light yield of crystals with two
7388 wrappings and the final SiPM device. In 2013, the Detector Team intends to build a 25-
7389 element array (5 x 5) and take it to the test beam for a full evaluation with all systems
7390 operational, including prototype digitizers and data acquisition.

7391 We continue to use our local laboratory tools to evaluate SiPM performance and have
7392 several student projects ongoing to map out gain functions and other performance charac-
7393 teristics.

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References

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[1] Sedykh SA, et al. *Nucl. Instrum. Meth. A* **445**:346 (2000).

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[2] R. McNabb, *et al.*, *Nucl. Instrum. Meth. A* **602**, 396 (2009) [arXiv:0910.0818 [physics.ins-det]].

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[3] P. Achenbach, *et al.*, *Nucl. Instrum. Meth. A* **465**, 318 (2001).

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[4] V. Tishchenko *et al.* [MuLan Collaboration], *Phys. Rev. D* **87**, 052003 (2013) arXiv:1211.0960 [hep-ex].

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Chapter 18

Tracking Detectors

18.1 Physics Goals

The primary physics goal of the tracking detectors is to measure the muon beam profile at multiple locations around the ring as a function of time throughout the muon fill. This information will be used to determine several parameters associated with the dynamics of the stored muon beam [1]. This is required for the following reasons:

- Momentum spread and betatron motion of the beam lead to ppm level corrections to the muon precession frequency associated with the fraction of muons off the magic momentum and the fraction of time muons are not perpendicular to the storage ring field.
- Betatron motion of the beam causes acceptance changes in the calorimeters that must be included in the fitting functions used to extract the precession frequency.

Uncertainty	E821 value (ppm)	E989 goal (ppm)	role of tracking
Magnetic field seen by muons	0.03	0.01	Measure beam profile on a fill by fill basis ensuring proper alignment
Beam dynamics corrections	0.05	0.03	Measure beam oscillation parameters as a function of time in the fill
Pileup correction	0.08	0.04	Isolate an event library with more than one positron hitting the calorimeter
Calorimeter gain stability	0.12	0.02	Better tracking resolution and E/p measuerments

Table 18.1: Systematic uncertainty goals for the Muon g-2 experiment. Information from the tracking detectors will be used to constrain these in several ways as indicated in the final column. For the first two rows, the tracker plays a primary role. For the last two, the tracker plays a supporting role.

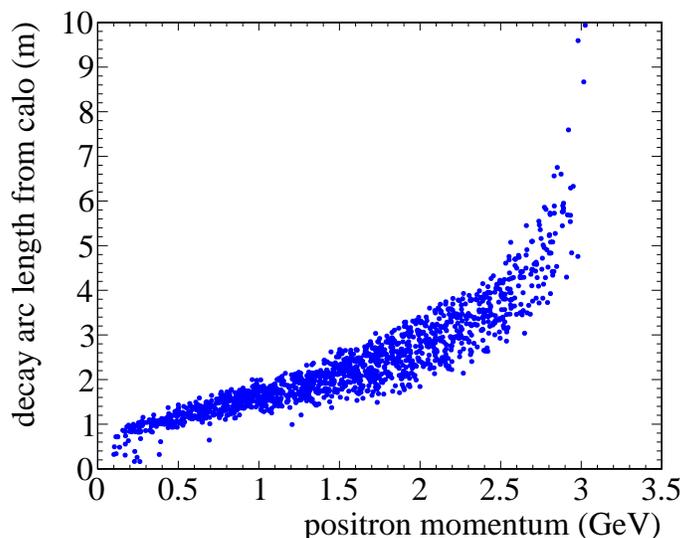


Figure 18.1: Arc length between the calorimeter and the muon decay point as a function of positron momentum.

- 7414 • The muon spatial distribution must be convoluted with the measured magnetic field
7415 map in the storage region to determine the effective field seen by the muon beam.

7416 The tracking detectors also play an important roll in understanding systematic uncertain-
7417 ties associated with the muon precession frequency measurement derived from calorimeter
7418 data. In particular, the tracking system will provide a library of time windows that have
7419 multiple positrons hitting the calorimeter within a short time period and will provide an
7420 independent measurement of the momentum of the incident particle. This will allow an
7421 independent validation of techniques used to determine systematic uncertainties associated
7422 with calorimeter pileup, calorimeter gain, and muon loss based solely on calorimeter data.
7423 The goal for the systematic uncertainties that can be directly determined or partially con-
7424 strained using tracking information are listed in Table 18.1.

7425 The tracking detectors will also play a leading role in the search for a permanent electric
7426 dipole moment (EDM) of the muon. A muon EDM causes the precession plane to tilt out of
7427 the horizontal plane. This leads to a time dependent asymmetry in the positron angle that
7428 can best be measured using a tracking detector [2].

7429 18.2 Requirements

7430 Requirements for the tracking detectors have been documented elsewhere [3] and are sum-
7431 marized here. The DC nature of the muon beam requires that the tracker perform well over
7432 a large momentum range and for muon decay points up to 10 meters in front of the first
7433 tracking plane. The arc length between the calorimeter and the muon decay point as a func-
7434 tion of positron momentum is shown in Fig. 18.1. The tacker must measure the vertical and

radial profile of the muon beam to much better than a centimeter leading to requirements of below $100 \mu\text{m}$ resolution per measurement. The long extrapolation from the tracking detector to the muon decay point requires that multiple scattering be minimized and that the material associated with each tracking plane be below 0.1% radiation length.

The trackers are required to reside in vacuum chambers in a vacuum of approximately 10^{-6} Torr and have either a vacuum load on the system below 5×10^{-5} Torr l/s or include a local increase in pumping speed near the tracker. The readout electronics must also be in the vacuum chamber to minimize the need for excessive feedthroughs. The tracker must be located as close to the stored muon beam as possible without interfering with the NMR trolley.

Any perturbations to the magnetic field due to material or DC currents must be below 10 ppm at the center of the storage region over an azimuthal extent of greater than 2° . Any perturbations due to transient currents on time scales below 1 ms must be below 0.01 ppm since these cannot be detected or monitored with NMR [4]. The requirements are summarized in Table 18.2.

18.3 Recommended Design

The recommended design is an array of straw tubes in UV configurations with alternating planes oriented 7.5° from the vertical direction. The DC nature of the beam requires a tracker with multiple planes spread out over as long a lever arm as possible. The required number of planes, along with the need to minimize multiple scattering lead to the choice of a gas based detector. The requirement to place the detectors in the vacuum leads to the choice of straws since the circular geometry can hold the differential pressure with minimal wall thickness.

Parameter	value	comments
Impact parameter resolution	$\ll 1 \text{ cm}$	set by RMS of the beam
Vertical angular resolution	$\ll 10 \text{ mrad}$	set by angular spread in the beam
Momentum resolution	$\ll 3.5\%$ at 1 GeV	set by calorimeter resolution
Vacuum load	5×10^{-5} Torr l/s	assumes 10^{-6} Torr vacuum and E821 pumping speed
instantaneous rate	10 kHz/cm ²	Extrapolated from E821
Ideal coverage	$16 \times 20 \text{ cm}$	Front face of calorimeter
number of stations	≥ 2	required to constrain beam parameters
Time independent field perturbation	$< 10 \text{ ppm}$	extrapolation from E821
Transient ($< 1 \text{ ms}$) field perturbation	$< 0.01 \text{ ppm}$	invisible to NMR

Table 18.2: Summary of the major requirements and environmental considerations for the tracking detectors.

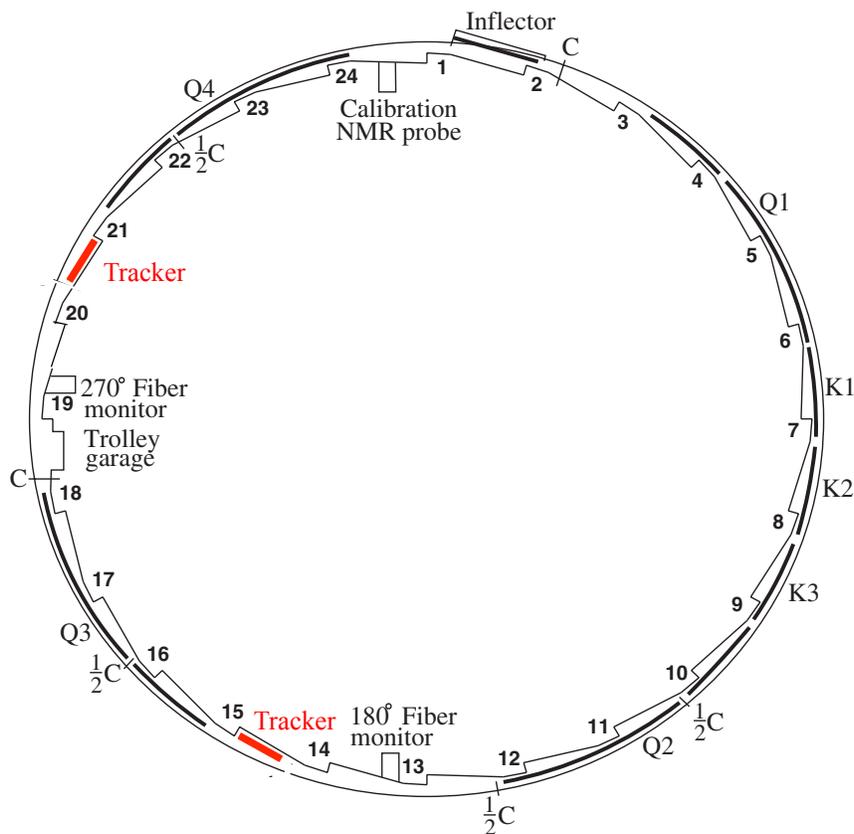


Figure 18.2: Placement of the tracking detectors in the muon storage ring. The detectors can be seen in front of calorimeter stations 15 and 21.

7458 18.3.1 Mechanical Design

7459 The design is to have two tracking detectors placed at approximately 180 and 270 degrees
7460 from the injection point as shown in Fig. 18.2. These locations have a clear line of sight to

Material	Aluminized Mylar
Thickness	15 μm
Wire length	25 μm gold plated tungsten 12 cm
sterio angle	$\pm 7.5^\circ$ from vertical
gas	80:20 Argon:CO ₂
pressure	1 Atm
Operating voltage	1400 V

Table 18.3: Summary of the properties of the tracking detectors.

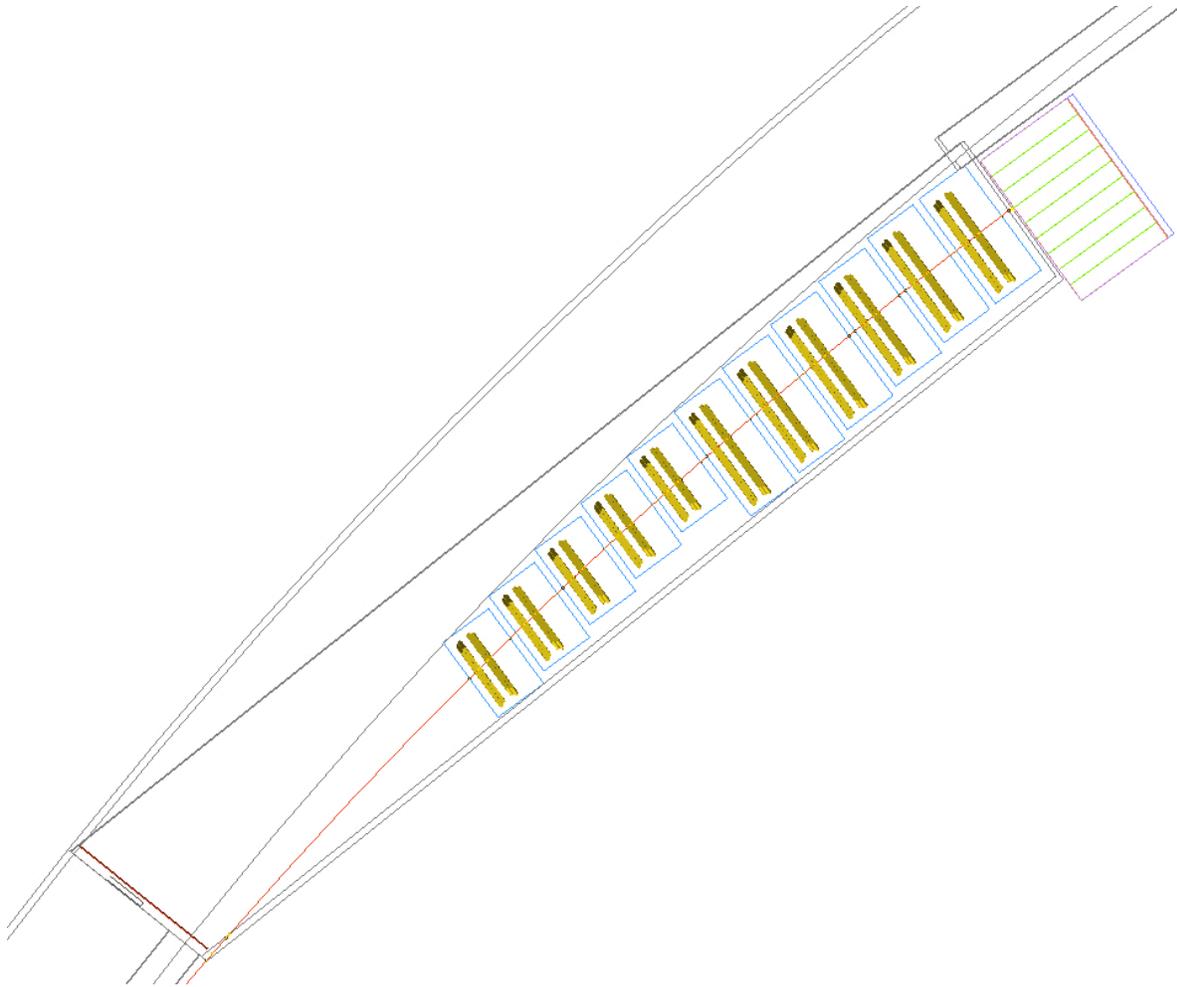


Figure 18.3: Placement of the straw tracking stations in the scalp region of the vacuum chamber.

7461 the muon beam. The vacuum chambers in these locations will be modified to contain large
7462 flanges that allow for installation and servicing of the tracking detectors.

7463 Each tracking detector consisting of 11 tracking stations as shown in Fig. 18.3. Each
7464 tracking station station has two planes of straws. The planes are in a UV configuration
7465 oriented $\pm 7.5^\circ$ from the vertical direction. Each plane consists of a closed pack doublet of
7466 straws.

7467 There are two types of station to account for the decreasing area in the scalloped region of
7468 the vacuum chamber. The first station is 10 cm wide and contains 64 channels. The second
7469 type is 14 cm wide and contains 96 channels. The total channel count including prototypes
7470 and spares is listed in

7471 A diagram of the largest station is shown in Fig. 18.4. The active height of each station
7472 is 10 cm. A 2.5 cm high gas manifold sits above and below the the straws and houses the
7473 readout electronics. The stations are self supporting and sit on the bottom of the vacuum
7474 chamber on a thin aluminum plate that locks the stations in place controlling the station

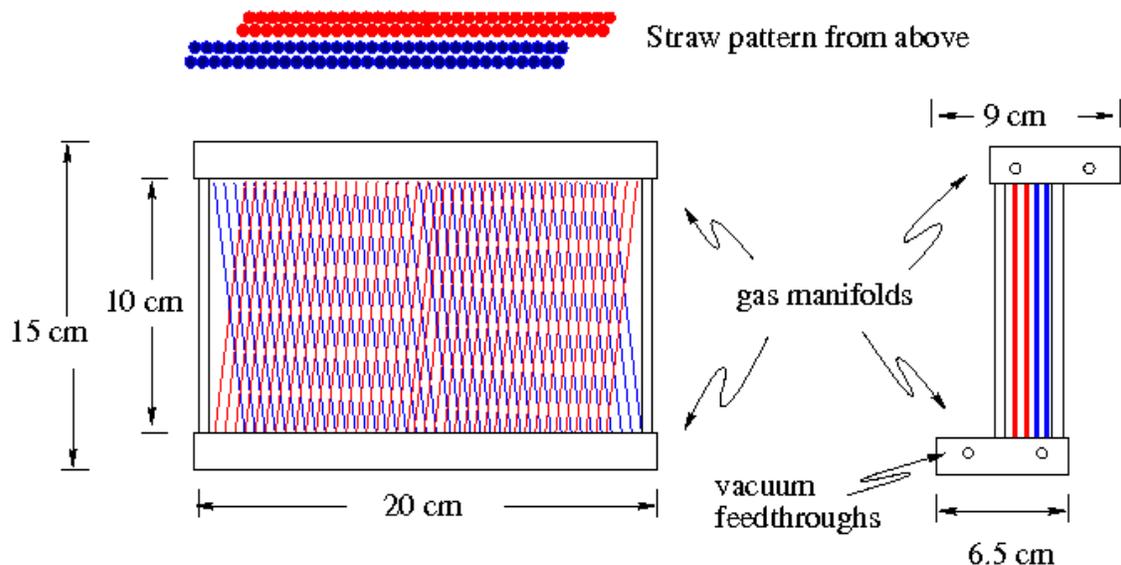


Figure 18.4: Diagram of the largest tracking station. The station is 32 straws wide. The figure on the left is the vertical-radial view. The figure on the right is the vertical azimuthal view. Needs to be updated to a 24 station

7475 alignment.

7476 add table for straw count

7477 We have chosen a system based on Mu2e straws [5]. Each straw is 5 mm diameter and
 7478 12 cm long. The straw wall is made of two layers of 6 μm Mylar, spiral wound, with a 3 μm
 7479 layer of adhesive between layers. The total thickness of the straw wall is 15 μm . The inner
 7480 surface has 500 \AA of aluminum overlaid with 200 \AA of gold as the cathode layer. The outer
 7481 surface has 500 \AA of aluminum to act as additional electrostatic shielding and improves
 7482 the leak rate. The straws are attached to the manifolds at the ends and tensioned to 50
 7483 grams to compensate for expansion under vacuum. The straw parameters are summarized
 7484 in Table 18.3.

7485 Add paragraph and table for material budget.

7486 The sense wire is 25 μm gold plated tungsten centered on the straw. The wire is tensioned
 7487 to 10 grams and supported on the ends. The wire will be held at a voltage of 1400 V. The
 7488 drift gas is 80 : 20 Argon:CO₂. The requirements of the best position resolution and the
 7489 relatively low rates per straw allow us to not require a fast, flammable gas.

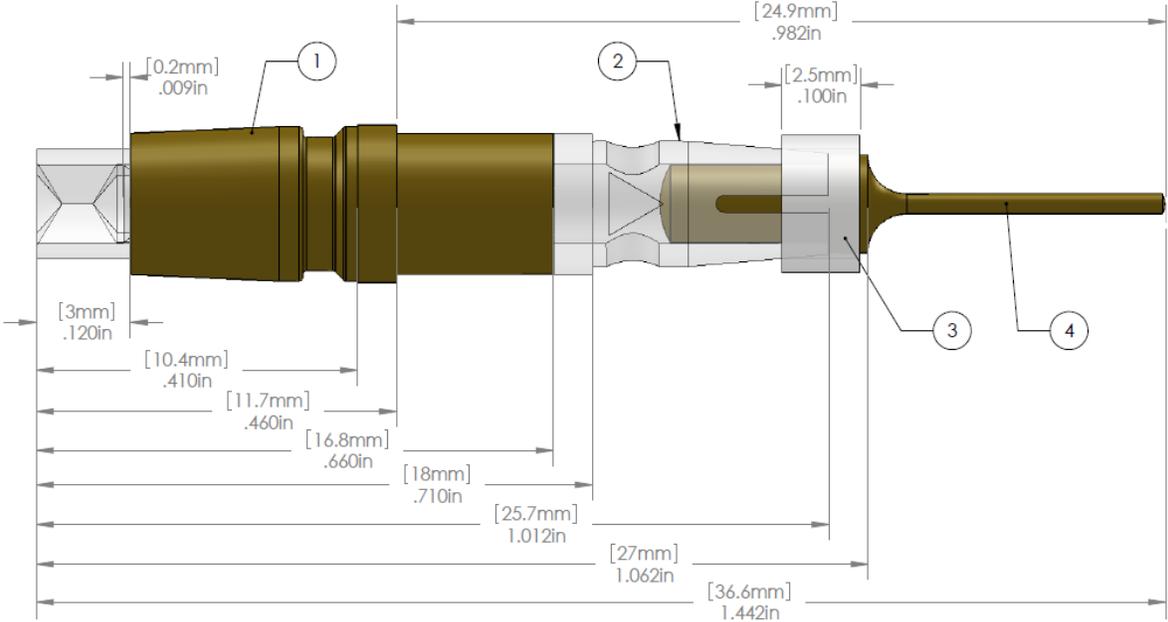


Figure 18.5: Straw terminations.

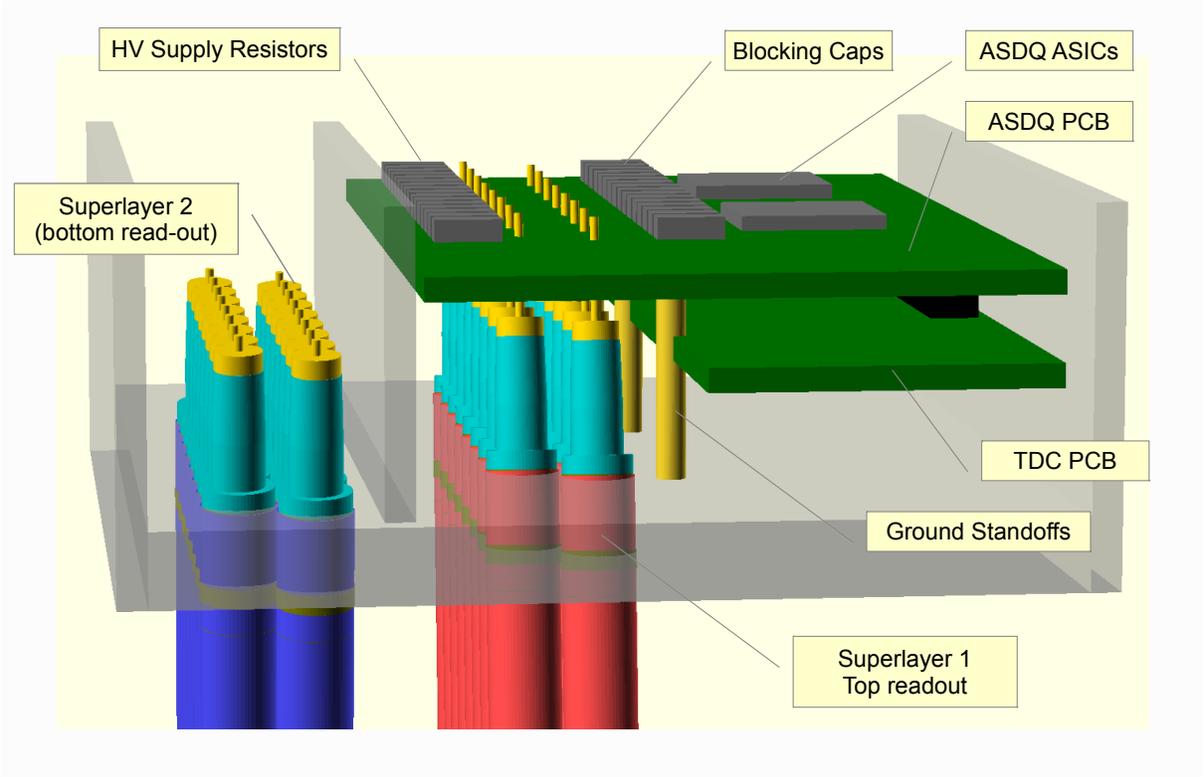


Figure 18.6: Gas manifold and electronics housing for the straws.

7490 The straw terminations are shown in Fig. 18.5 are an iteration of the terminations suc-
 7491 cessfully deployed by the Brookhaven E781 experiment [6] and consist of an aluminum collar
 7492 with an injection molded ULTEM insulator. The insulator contains a V groove to position
 7493 the wire and an aluminum pin crimps the wire in place and holds the wire tension.

7494 The straw is attached to the collar with a bead of silver epoxy to provide the electrical
 7495 connection and a bead of standard epoxy to provide mechanical strength. A similar blend
 7496 is used to connect the straw terminations to the manifolds.

7497 The gas manifolds for the straws are shown in Fig. 18.6. They are approximately 2.5 cm
 7498 high and contains separate gas paths for the U and V straws. The gas is brought into the
 7499 manifold through a vacuum penetration through the flange and the manifold. The gas flows
 7500 through the straws and then over the readout electronics. The gas is required to dissipate
 7501 approximately 5 Watts from the readout electronics. The gas then flows out a wide 5/8 in
 7502 tube that also carries 2 twisted pair cables that carry low voltage, high voltage and control
 7503 signals to the readout electronics and carry the digitized signals out of the straws.

7504 18.3.2 Readout Electronics

Channels per readout board	32 or 48
Gas Gain	4×10^4
Number of Primary Electrons (P.E.) for a typical track	41 pe
Signal amplitude for a typical track	256 fC
Operating threshold in P.E.	10 pe
Operating threshold	32 fC
Capacitance	1 pF

Table 18.4: Tracker Readout parameters

7505 The basic instrumentation parameters which drive the design of the readout are given in
 7506 Table 18.4. The readout electronics for a stereo layer pair consists of two stacked PC boards,
 7507 a readout board and a TDC board. The readout board contains two or more ASDQ ASICs[7]
 7508 which provide amplification, shaping, discriminator and charge measurement for eight straws.
 7509 The ASDQ outputs are digitized by a TDC implemented in a field-programmable gate array
 7510 (FPGA).

7511 The tracker wire connection diagram is shown in Figure 18.8. The HV terminal provides
 7512 high voltage (1400V nom.) to each tube through a 100k current limit resistor. HV is blocked
 7513 by a 2kV SMT capacitor (value *t.b.d.*). A protection circuit consisting of four Schottky diodes
 7514 in a 2x2mm DFN package provide bipolar protection for both the primary and inverting
 7515 ASDQ inputs. A 10 ohm series resistor limits peak current.

7516 The ASDQ provides eight channels of full analog signal processing between the chamber
 7517 and the TDC. Though developed for the CDF Central Outer Tracker, it provides a good
 7518 match to the muon g-2 tracking detector requirements. It provides fast charge collection
 7519 (≈ 7 ns), good double pulse resolution of ≈ 30 ns, low power (≈ 40 mW/ch) and low opera-
 7520 tional threshold (≈ 2 fC). Baseline restoration and ion tail compensation using the pole-zero
 7521 cancellation technique are provided. The output of the ASDQ is eight digital differential

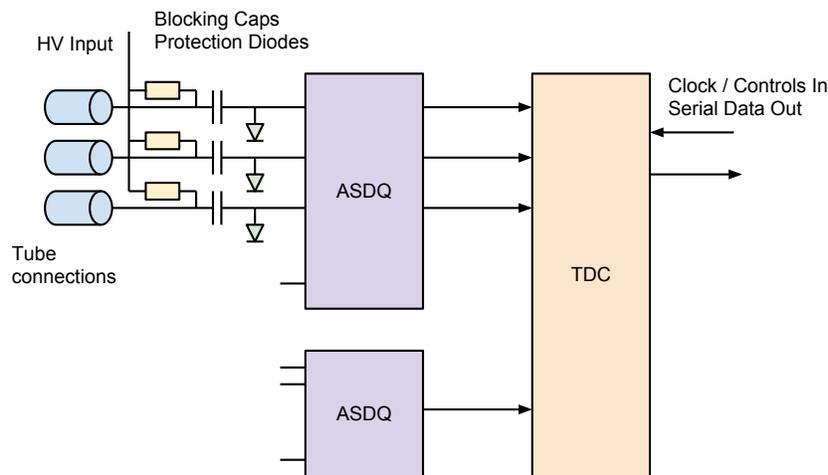


Figure 18.7: On-Chamber Electronics Overview

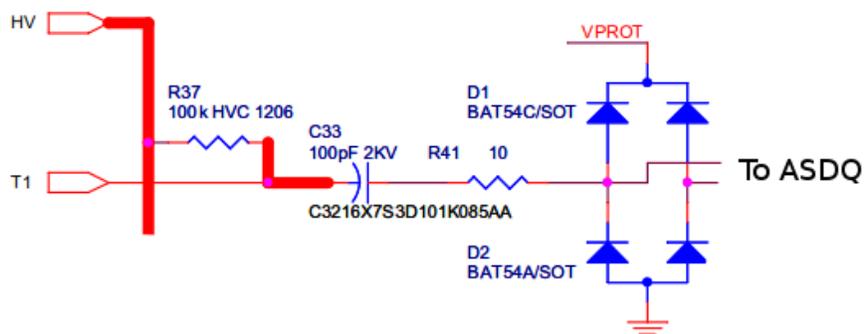


Figure 18.8: Input Schematic Detail

7522 signals, with leading edge representing the threshold crossing time and the pulse width pro-
 7523 portional to input charge.

7524 A 16-channel TDC with 625 ps LSB is implemented in an Altera EP3C5F256C6 FPGA,
 7525 with the initial design using about 50% of the FPGA logic resources. A reference clock
 7526 of 10 MHz is provided externally on an LVDS signal pair with multiplexed trigger and
 7527 control signals. The clock is multiplied internally to a four-phase 400 MHz clock for time
 7528 measurement and internal operation. Up to 2k TDC hits are stored on-chip and read out
 7529 over a single serial link at 25 MHz.

7530 Power, clock, control and readout for each chamber is provided by a tracker readout
 7531 module (TRM), implemented as an advanced mezzanine card[8] (AMC) and mounted in a
 7532 MicroTCA[9] crate. A block diagram is shown in Figure 18.10. An FPGA in the TRM
 7533 receives clock and control signals from the MicroTCA crate controller via the MicroTCA
 7534 backplane and distributes them to each station. DAQ data is received from the chambers
 7535 and decoded and buffered in the FPGA, which also provides a gigabit Ethernet interface via

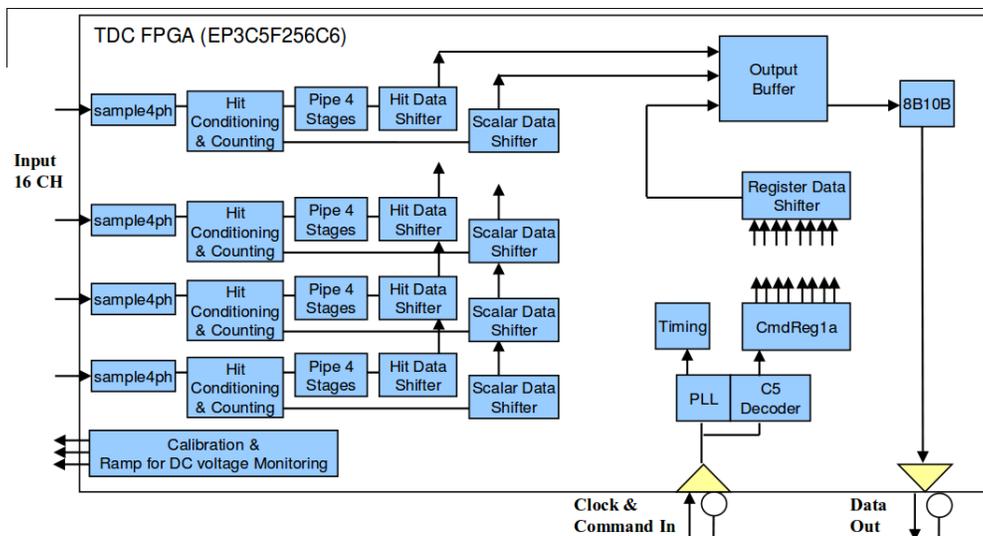


Figure 18.9: TDC Block Diagram

7536 the MicroTCA hub controller. Cables carry DC power from the TRM to the top and bottom
 7537 of each chamber’s readout electronics, along with clock, control and readout signals. Power
 7538 for the on-chamber electronics is switched and current-limited on the TRM.

7539 Up to 12 TRM modules are mounted in a MicroTCA crate, as shown in Figure 18.11.
 7540 Control and configuration commands are provided to all modules by a commercial MicroTCA
 7541 hub controller (MCH) module via switched gigabit Ethernet and intelligent platform man-
 7542 agement bus (IPMB)[10] interfaces. A custom AMC13 module[11] developed for the CMS
 7543 experiment distributes clock and timing signals and reads out data from the TRMs.

7544 18.4 Performance

7545 The expected performance of the tracker conceptual design is determined by a simulation.
 7546 The performance of a single straw is determined using GARFIELD [12]. This program simu-
 7547 lates the propagation of electrons and ions in a gas in the presence of electric and magnetic
 7548 fields. The geometry of the system is determined using a full GEANT4 [13] model of the
 7549 g-2 storage ring that includes the proper physics model to simulate muon storage, preces-
 7550 sion, and decay. The performance of the tracker is determined using a fast tracking software
 7551 package that takes the positron hit positions from the GEANT4 simulation, applies resolution
 7552 from GARFIELD and multiple scattering corrections, determines the positron trajectory, and
 7553 extrapolates back to the point of tangency to determine the muon decay position.

7554 The $x - t$ relation and single straw resolution determined from GARFIELD are shown in
 7555 Fig. 18.12. The average resolution is found to be approximately $100 \mu\text{m}$. The efficiency to
 7556 reconstruct at least 5 hits as a function of momentum and as a function the muon decay
 7557 distance is shown in Fig. 18.13. There is sufficient coverage at all momenta that can be used
 7558 to determine beam parameters. The loss of efficiency at lower momenta is due to the fact that
 7559 the lowest momentum positrons originate very close to the calorimeter and it is difficult to fit

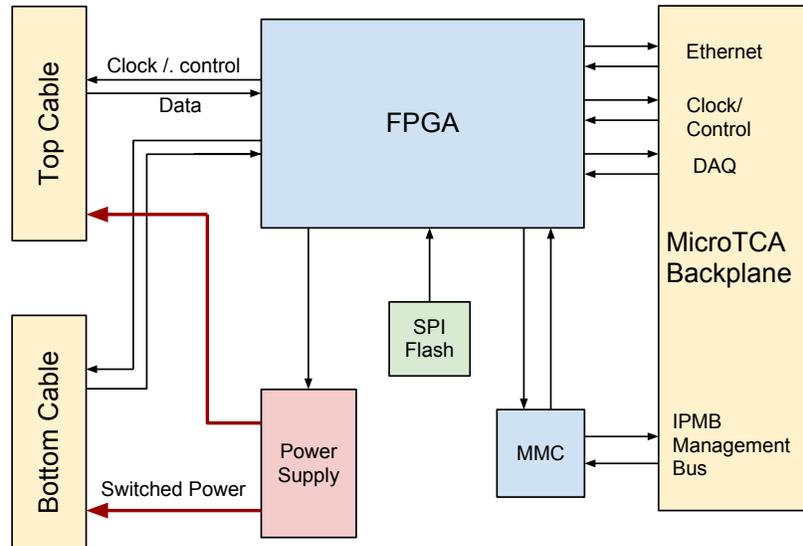


Figure 18.10: Tracker Readout Module Block Diagram

7560 enough tracking stations close enough together. The distance between stations is currently
 7561 dominated by the area necessary for the readout PCBs. In the final design iteration we will
 7562 investigate different geometries that could increase this efficiency.

7563 The momentum resolution, muon decay position, and positron vertical angle resolution
 7564 are shown in Figs. 18.14,18.15,18.16, and 18.17. The muon decay position resolution is
 7565 roughly 3 mm in the radial direction and 2 mm in the vertical direction. Both resolutions
 7566 become significantly worse above 2.6 GeV. In this region, the muons are decaying between
 7567 5 and 10 meters from the first tracking plane and the large lever arm makes a more precise
 7568 determination impractical. The momentum resolution is lower than for a typical gas based
 7569 system but is well below the resolution of the calorimeter which satisfies the requirements.
 7570 The vertical angle resolution is also well below the requirements.

7571 A single straw prototype has been constructed to verify key features of the GARFIELD
 7572 simulation and to gain experience with the assembly procedure. The straw is read out using
 7573 an ASDQ chip that has an analog output after directly before the discriminator. The straw
 7574 is illuminated with an Fe^{55} source with produces on average 230 primary electrons in our
 7575 gas mixture. The signal peak after amplification and shaping is shown in Fig 18.18. The
 7576 turn-over in the plot is due to clipping in the readout electronics. From this we expect that a
 7577 typical positron depositing 41 primary electrons will correspond to a signal peaking at about
 7578 16 mV at an operating voltage of 1400 V which should be well above noise.

7579 The mechanical integrity of the design is modeled using ANSYS. Particular attention
 7580 was given to the grounding plate in the manifold. The plate should be as thin as possible to
 7581 maximize the vertical acceptance of the detectors and the straw pitch should be as close to
 7582 the straw diameter as possible to avoid large gaps. However, the plate must be thick enough
 7583 to hold the straw tension and the 1 ATM pressure differential.

7584 The final conceptual design calls for a x mm plate thickness and a 5.5 mm straw pitch.

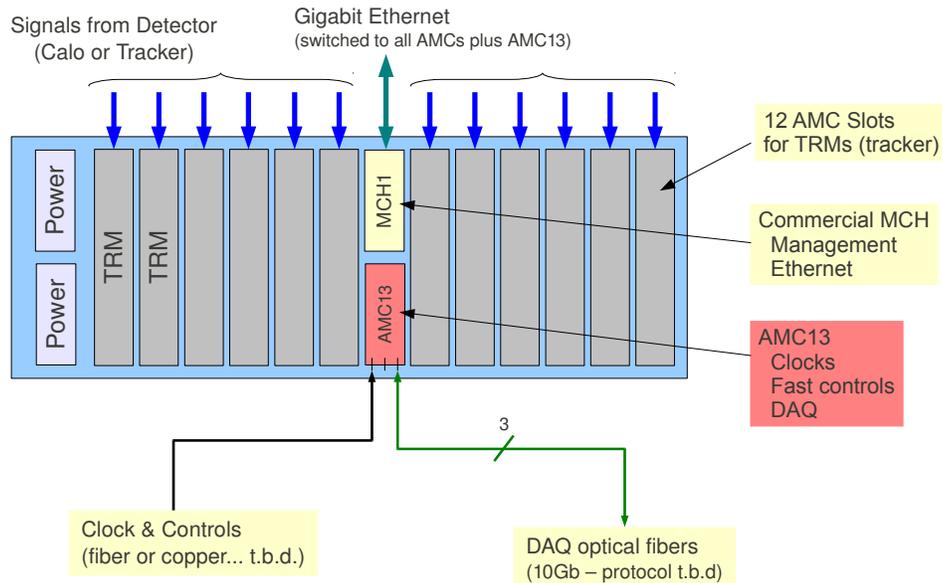


Figure 18.11: MicroTCA Crate

7585 The stresses on the manifold are shown in Fig. 18.19. The model indicates that the manifold
 7586 can safely hold the stresses but the current deflection gradient needs to be reduced. This
 7587 will most likely be accomplished in the next design iteration by adding a rib structure to the
 7588 inside of the large manifold.

7589 The front end electronics are based on the ASDQ chip which has been used in several
 7590 experiments and the performance is well documented. A first version of the TDC code exists
 7591 and an LSB of 0.6 ns has been achieved. The specifications for data size and transfer rates
 7592 are well below the limits of the micro-TCA crate specifications.

7593 Add EDM paragraph here.

7594 18.5 Alternatives

7595 The two leading alternatives to a straw based system for the tracker are both Silicon based.
 7596 The first would use 300 μm Hamamatsu single sided strip sensors. These sensors were
 7597 purchased for the Dzero Run Iib detector upgrade but never used. Sufficient sensors are in
 7598 hand to build the g-2 tracker. The readout would be based on the FSSRII chip originally
 7599 designed for BTeV and now being used for instrumentation upgrades for the JLab 12 GeV
 7600 program. Tracking stations could be made with two sensors at a small stereo angle for a
 7601 total material budget of 0.5% X_0 per station.

7602 The second alternative would use the 50 μm thick Mimosa 26 pixel sensor that has been
 7603 developed with ILC R&D funding. There is about 25% dead space on the chip which would

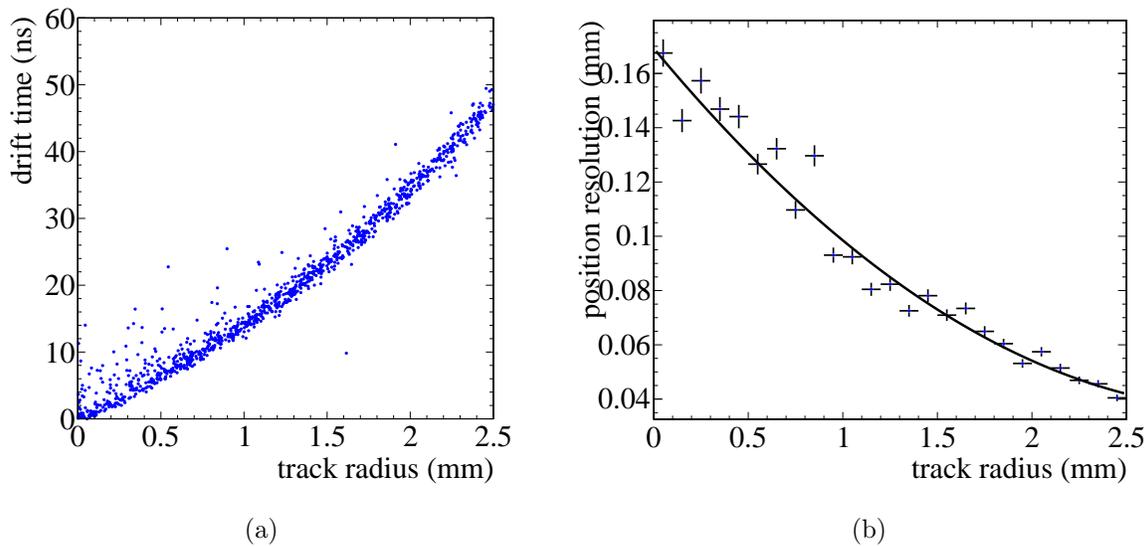


Figure 18.12: (a): Time versus distance relation in a single straw predicted by GARFIELD. (b): The position resolution determined from GARFIELD for a single straw using the derived x - t relation.

7604 require a doublet structure. Material is also needed in the active region for cooling and for
 7605 flex cables. A thermal model of the device indicates that heat can be adequately dissipated
 7606 if the two layers are mounted on blocks of 2.5 mm thick Si foam. After the Si foam and flex
 7607 cables are added, the material budget is also close to 0.5% X_0 per station.

7608 If we had a well defined interaction point and could build something like a 4 layer detector,
 7609 either of these two alternatives would be preferable to straws. However, the DC nature of the
 7610 beam requires us to have a multi layer device to sufficiently cover the momentum spectrum of
 7611 the positrons. Building this out of the Silicon options above would add far too much material
 7612 and the effects of multiple scattering would severely compromise our ability to extrapolate
 7613 the positron trajectories all the way back to the muon decay position.

7614 For the amplifier, besides the ASDQ chip, we explored using discrete components or
 7615 building an ASIC. Discrete components were ruled out due to space considerations and also
 7616 due to power consumption. An ASIC is an expensive alternative particularly since the ASDQ
 7617 chips are free, but it has the advantage that we could control all material used in the chip to
 7618 avoid magnetic components such as tin. However we brought the ASDQ and FPGA chips
 7619 to a 1.5 T test magnet at the Fermilab Technical division and determined that these chips
 7620 have magnetic properties well below our specifications.

7621 For the TDC, we considered commercially available products such as the 128 channel
 7622 CAEN 767 or 1190 model multi hit TDCs. This would require bringing all signals out of the
 7623 vacuum through some sort of feedthrough system. We investigated the feedthroughs being
 7624 designed for liquid Argon but these would have difficulty operating at the g-2 vacuum of 10^{-6}
 7625 Torr. The current design of an FPGA based TDC is much more simple and cost effective.

7626 For the station geometry, we considered a more closed packed system that could be
 7627 constructed using existing vacuum ports without requiring modifications to the existing

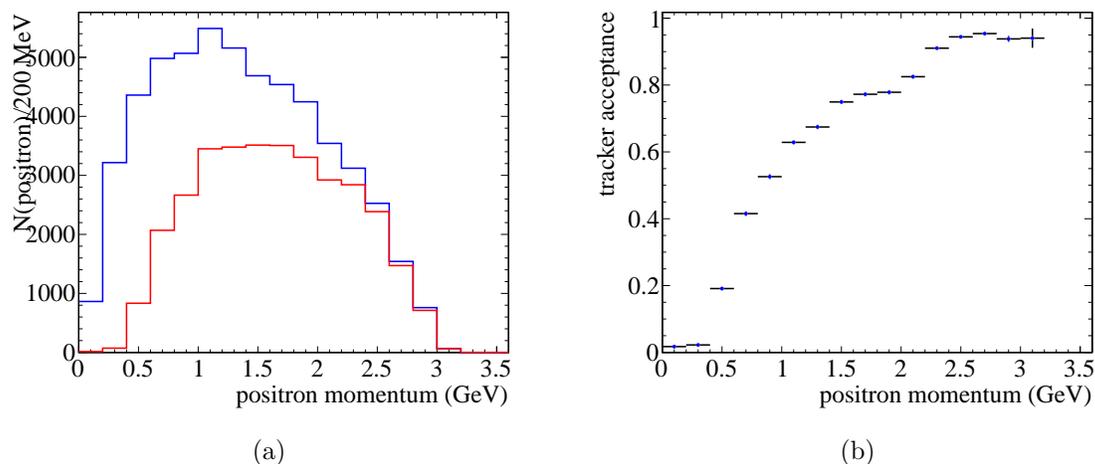


Figure 18.13: (a): The positron momentum spectrum for positrons incident on the front face of the calorimeter (blue) and also with sufficient hits in the tracking detector to form a track (red). (b): The ratio of the two distributions giving the relative efficiency between the tracker and the calorimeter as a function of positron momentum.

7628 vacuum chambers. A working solution was found for a detector that would have a total
 7629 length of 0.5 meters. However, simulation indicates that the 1 meter lever length we have
 7630 now is required to gain useful information on the higher momentum tracks that have the
 7631 longest extrapolation back to the muon decay point.

7632 There are two alternatives still under consideration. The conceptual design calls for a
 7633 closed packed doublet geometry with each layer offset by half a straw diameter. Once the
 7634 required gap between straws is considered and the fact that the resolution is worst at the
 7635 center of the straw, we would like to consider alternative offsets between layers. One option
 7636 we will consider is having the two layers offset by 1/3 a straw diameter.

7637 The tracking simulation studies indicate that we have better resolution on the vertical
 7638 parameters of the beam than the radial parameters. In general, the radial parameters have a
 7639 greater effect on the g-2 systematic uncertainties since they directly effect the acceptance of
 7640 the calorimeters. The original stereo angle was chosen based on calculations of the error on
 7641 parameters by hand. The full tracking simulation indicates that we may be able to reduce
 7642 the stereo angle and improve the vertical resolution without adversely effecting the horizontal
 7643 resolution.

7644 18.6 ES&H

7645 The g-2 tracker is similar to other gas-based detectors that are commonly used at Fermilab
 7646 and are identical in many cases to the Mu2e system. Potential hazards include power systems
 7647 and compressed gas. The gas will permeate at a small level inside the g-2 vacuum and come
 7648 in contact with the quadrupole high voltage. Any gas leak in the experimental hall with also
 7649 bring the gas in contact with the high voltage stand-offs and feed-throughs of the kicker and

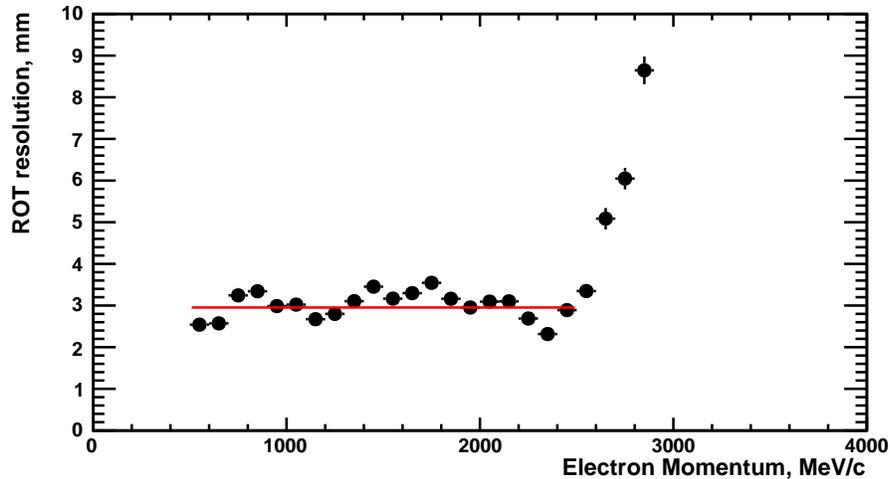


Figure 18.14: Resolution on the radius of the positron at the point of tangency to the central muon orbit as a function of positron momentum. The red line is a fit to the points in the region below 2.5 GeV.

7650 quadrupoles. Because of this, and because using non-flammable gas appears to work, we are
 7651 precluding the use of flammable gas. These and all other hazards have been identified and
 7652 documented in the Muon g-2 Preliminary Hazard Analysis.

7653 The detector requires both low voltage, high current and high voltage, low current power
 7654 systems. During normal operation, the tracker will be inaccessible inside the storage ring.
 7655 Power will be distributed to the tracker through shielded cables and connectors that comply
 7656 with Fermilab policies. Fermilab will review the installation prior to operation.

7657 Gas that will be used for the tracker will be kept in DOT cylinders in quantities limited
 7658 to the minimum required for efficient operation. The cylinders will be stored in a dedicated
 7659 location appropriate to the type of gas being used. The storage area will be equipped with
 7660 fire detection and suppression system. The installation, including all associated piping and
 7661 valves, will be documented and reviewed by the Fermilab Mechanical Safety Subcommittee.

7662 The detector itself does not have any radioactive sources. However, Fe^{55} sources will be
 7663 used to measure the gain of the straws before installation. Usage of radioactive sources will
 7664 be reviewed to ensure adherence to Fermilab safety policy. In particular, the sources will be
 7665 monitored and stored and we see no opportunity for producing mixed waste.

7666 Solvents such as ethanol will be used to clean components before assembly and epoxy
 7667 resins will be used in the assembly process. All chemicals will be clearly labeled and stored
 7668 in approved, locked storage cabinets and will adhere to the Fermilab safety policy.

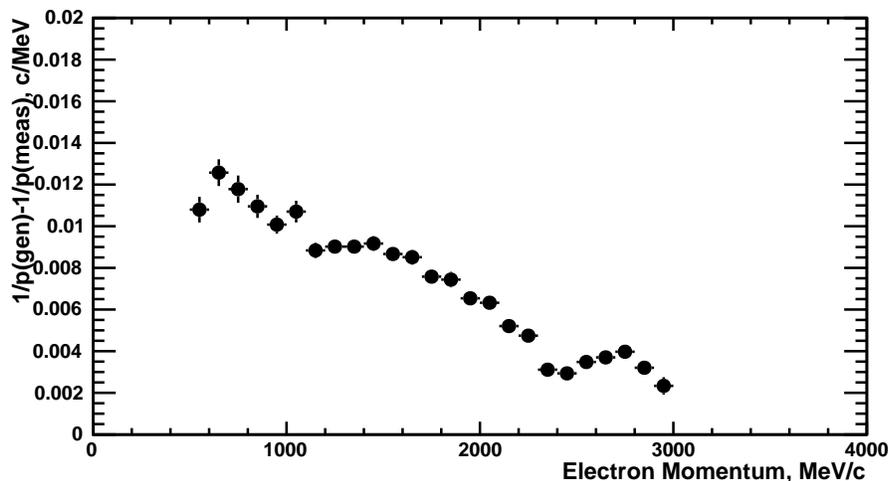


Figure 18.15: Resolution on the radius of the track curvature as a function of positron momentum.

18.7 Risks

18.7.1 Performance Risk

The performance of the system relies on the single straw resolution. Simulation indicates that the resolution is adequate to meet the goals of the experiment however the final performance will be a factor of many variables, particularly how well the system is assembled. This risk is being mitigated by perfuming cosmic tests of prototypes and a beam test of a full station prototype in Fall 2013. This will give a very good indication of the single straw resolution in a real system and will give us sufficient opportunities to make adjustments to the design before the project is baselined. Several quality control procedures will be put in place such as x-raying the detectors to determine proper positioning of the wires to insure that the resolution is not compromised during assembly.

The detector will require precise alignment with respect to the central muon orbit. Poor alignment could easily become the dominant source of error in the tracking measurement. The alignment can be determined in-situ using positrons but this can take a long time and can not be used to monitor alignment in real time. This risk will be mitigated by taking complete trackers to a beam test before final installation to determine the relative alignment between stations. Dedicated muon fills will also be taken on a regular basis where the muon losses are intentionally increased. These muons are essentially straight when they go through the tracker and can be used to verify the inter-station alignment as well as determine the alignment of the system with respect to the beam. We are also investigating adding 3-D Hall probes inside the gas manifolds for the tracking stations. The precision field is known well enough so that any change in the Hall probe readout would constitute a change in the tracking station position.

The tracker has been designed assuming a max instantaneous rate of 10 hKz/cm². This value is extrapolated from measurements at the Brookhaven experiment. The Brookhaven

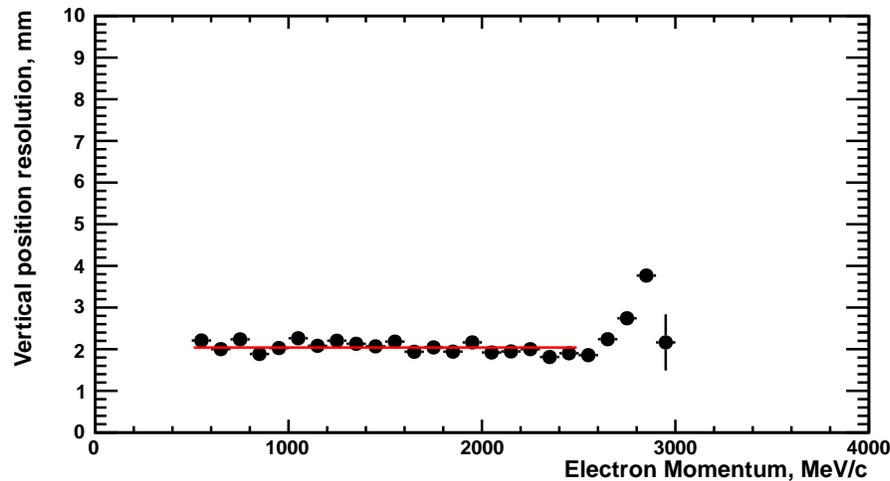


Figure 18.16: Resolution in the vertical muon decay position as a function of positron momentum. The red line is a fit to the distribution below 2.5 GeV.

7694 experiment had significant contamination from pions that lead to a large hadronic flash
 7695 at the beginning of the fill. This pion contamination has been removed from the Fermilab
 7696 experiment but there is still a possibility that there will be some unaccounted for background
 7697 that leads to unacceptable rates. The straws have been designed to operate with CF_4 so a
 7698 after gas could be used to deal with this. We are also investigating using a circuit to reduce
 7699 the gain of the straws during injection. This is complicated and would require electrical
 7700 engineering resources to design if we are required to go down that path.

7701 The system of collimators used to scrape the muon beam after injection is partially in
 7702 the line of sight of the tracking detectors. This would limit the acceptance of the tracker and
 7703 potentially cause high backgrounds early in the fill. To mitigate this risk, we are perfuming
 7704 studies to determine alternative locations for the collimators and working closely with the
 7705 groups associated with the collimator system.

7706 18.7.2 Technical and Operational Risk

7707 The greatest technical risk is that the tracking system will in some way effect the precision
 7708 magnetic field of the storage ring. This risk is being mitigated in several ways:

- 7709 • All scientists, engineers, technicians, students, and vendors involved in the design and
 7710 construction of the system are educated on the importance of the magnetic properties
 7711 of the system.
- 7712 • The specifications are clearly stated in terms of the static and dynamic effects on the
 7713 field. These have been documented and agreed on by the collaboration.
- 7714 • Individual components are taken to an existing 1.5 T test magnet and their static
 7715 magnetic properties are verified to be within specifications.

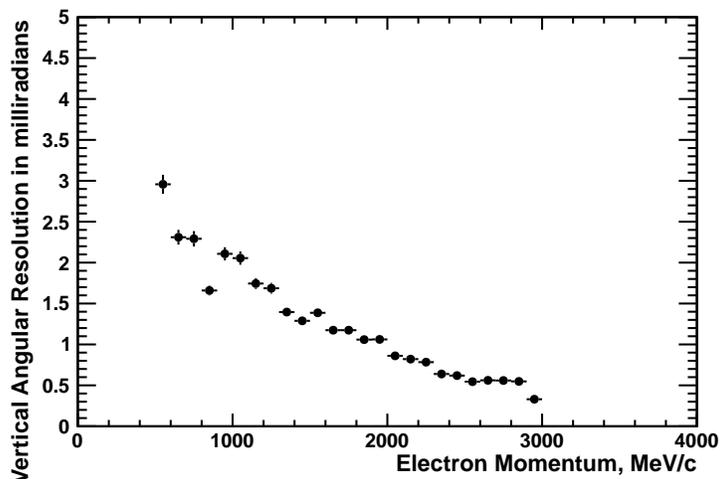


Figure 18.17: Resolution on the vertical positron angle as a function of positron momentum.

- 7716 • Full magnetic simulation of the detector using OPERA is added to the existing storage
7717 ring OPERA simulation to verify that any static effects can be shimmed out of the
7718 field using the existing shimming kit.
- 7719 • The full detector will be tested in a test solenoid that is being shipped from LANL to
7720 Fermilab specifically for this purpose.
- 7721 • A fast coil will be designed to measure the size and time structure of any transient
7722 magnetic fields being produced by the electronics.

7723 The vacuum specifications for the g-2 storage ring are set by the electrostatic quadrupoles
7724 inside the storage ring. The combination of the electric field from the quads and the mag-
7725 netic field from the g-2 magnet leads to regions where photoelectrons can be captured in
7726 Penning traps. These electrons can eventually interact with residual gas molecules leading
7727 to avalanche and sparking. This is the number one factor influencing the lifetime of the
7728 quadrupole plates.

7729 For μ^+ operation, a vacuum of 10^{-6} Torr is required. If μ^- running is required or if the
7730 quadrupoles are operated at a greater HV to move to a different tune point, the vacuum may
7731 need to be decreased to 10^{-7} Torr. The leak rate of the straws has been measured by Mu2e
7732 and indicates that 10^{-6} Torr can be achieved. To mitigate the risk of needing to operate at
7733 a higher vacuum we are designing the ability to add higher capacity to the pumping speed
7734 near the tracking detectors.

7735 Contaminated gas is a serious risk for any drift chamber. This risk is mitigated in several
7736 ways. First, Ar:CO₂ is one of the least prone gasses to harmful contaminants. Second, by
7737 performing a detailed analysis on each batch of gas. Finally, monitoring chambers will be
7738 included in the system and will be illuminated with radioactive sources to give early warning
7739 of problems.

7740 A broken wire will cause an entire plane of a station to be inoperable. A broken straw will
7741 cause an entire station to be inoperable. To mitigate this risk, the system is being designed

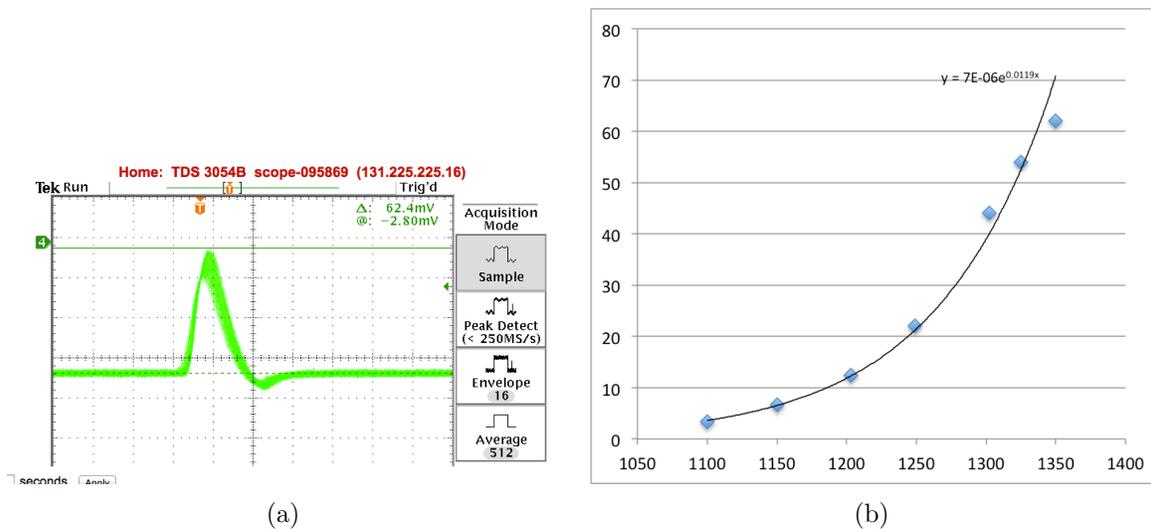


Figure 18.18: (a): The signal from a Fe^{55} source after amplification and shaping corresponding to 230 primary electrons at an operating voltage of 1400 V. (b) The peak voltage of the Fe^{55} signal as a function of applied voltage.

7742 in a way so that a damaged station can be easily removed and replaced with a spare with
 7743 approximately 1 day lost to reestablishing the vacuum. We anticipate breaking vacuum at
 7744 least once every several months to service the NMR trolley so as long as the frequency of
 7745 problems is much less than this, there is no risk to the run schedule.

7746 18.8 Quality Assurance

7747 Proper quality assurance is essential to construct a tracking detector that meets the Muon
 7748 g-2 requirements for performance and reliable operation. Quality Assurance will be inte-
 7749 grated into all phases of the tracker work including design, procurement, fabrication, and
 7750 installation.

7751 Individual straws must be leak tight, straight, and have the proper wire tension. The
 7752 straws will be leak tested before being installed. The straws will be connected to a clean gas
 7753 system and over-pressured. The leak rate will be measured over an appropriate time interval
 7754 by measuring the pressure drop. After the assembly of a station, the entire station will be
 7755 leak tested again.

7756 The straws must maintain their shape and be mounted at the proper stereo angle to op-
 7757 erate efficiently and to maintain an appropriate distance between the wire and the grounded
 7758 Mylar surface to avoid breakdown. Straws will be visually inspected for roundness and
 7759 straightness before assembly. Flawed straws that escape detection during visual inspection
 7760 can be identified by non-uniform gas gain and resolution. This will be done as part of the
 7761 wire position measurement.

7762 The appropriate tension must be applied and maintained in a straw for efficient, stable
 7763 operation. Tension is applied through calibrated mechanical force but can be lost through

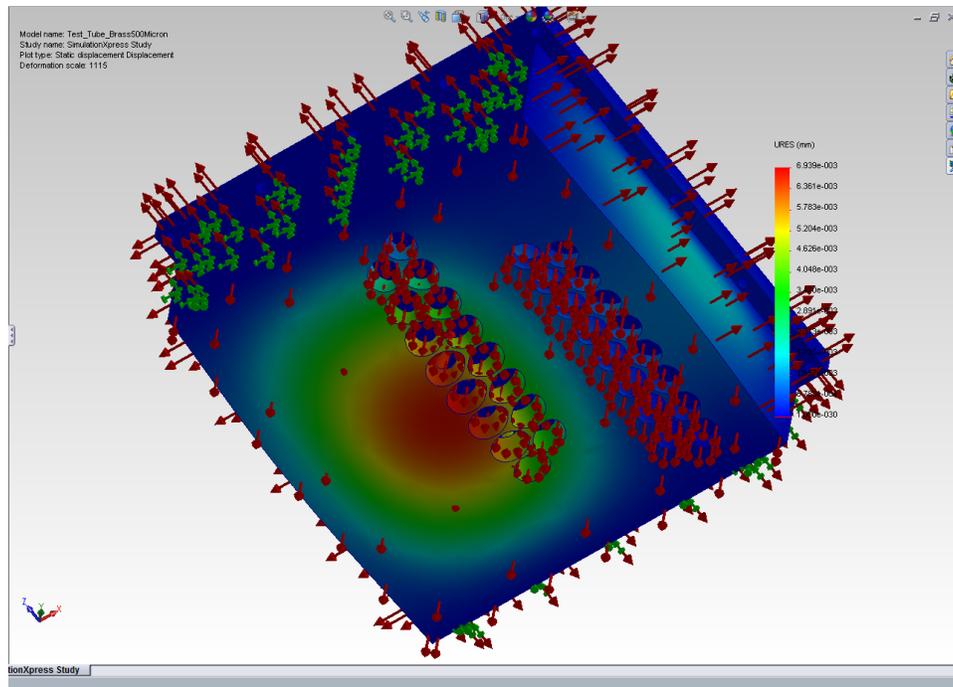


Figure 18.19: ANSYS model of the stresses in the gas manifold due to the straw and wire tension and the 1 ATM differential pressure.

7764 relaxation mechanisms. Both wire and straw tension will be measured after assembly using
 7765 vibrational resonance techniques appropriate to our short straws.

7766 All electronics components will be tested prior to installation on the tracking stations
 7767 including a suitable burn-in period. The high voltage circuits will be tested for leakage
 7768 current. The threshold characteristics of each channel will be tested with a threshold scan.
 7769 A noise scan will be performed for various threshold settings to identify channels with large
 7770 noise fractions. The FPGA TDCs will be validated by comparing their output to commercial
 7771 TDC devices with higher resolution.

7772 18.9 Value Management

7773 The tracker technology for Muon g-2 is well established and has been implemented in other
 7774 high energy and nuclear physics experiments. Value management principles have been ap-
 7775 plied over time during the development of the technology. Value management moving forward
 7776 is mainly related to labor costs since the straw tracker assembly will be labor intensive. We
 7777 have identified collaborating institutions with students who can perform a large fraction of
 7778 the assembly work at minimal cost. This requires more work up front in engineering to
 7779 design parts that do not require highly skilled technicians for assembly but this is in any
 7780 case part of best practice engineering.

7781 We are subcontracting engineering to university engineering departments and using Fer-
 7782 milab engineering resources to perform independent design reviews before production or

7783 procurement. This keeps the overall engineering costs low while maintainig the standards of
7784 Fermilab engineering.

7785 We are also in the process of performing a full analysis of determining the beam parame-
7786 ters from the tracking system. While the default configuration calls for two tracking stations
7787 around the ring separated by 90 degrees, this study may indicate we need more than two
7788 stations or that the information from one station is sufficient.

7789 The back-end readout electronics and data acquisition for the tracker are equivalent to
7790 those used for the calorimeters. This simplifies the design and operation of the system.
7791 However, once the final specifications are known, we will investigate possible cost savings by
7792 using different system components. Current FPGA technology is sufficient to meet the needs
7793 of the tracker electronics. These will be purchased once they are no longer the most current
7794 devices which should lead to significant cost savings. Sufficient spares will be purchased to
7795 ensure the stock for the lifetime of the experiment.

7796 The straw terminations require injection molded pieces. The cost of these pieces is almost
7797 entirely driven by the cost of the mold and so design iterations are costly. To mitigate this,
7798 we intend to first produce all injection molded pieces with a 3-D printer and construct straws
7799 with the printed pieces to validate the design before the molds are procured.

7800 **18.10 R&D**

7801 Work is well underway on straw termination, tensioning, and alignment procedures. Three,
7802 4 to 8 channel prototypes have been constructed to gain experience with proper handling
7803 and assembly procedures. A full type-8 station is currently under construction that will
7804 include a prototype ASDQ readout board and an FPGA evaluation board. This will be
7805 tested in-vacuo using cosmics and in a beam test scheduled for Fall 2013.

7806 References

- 7807 [1] G. W. Bennett *et. al.* (Muon $g - 2$ Collaboration) Phys. Rev. D 73, 072003 (2006).
- 7808 [2] G. W. Bennett *et. al.* (Muon $g - 2$ Collaboration) Phys. Rev. D 80, 052008 (2009).
- 7809 [3] B.C.K. Casey, GM2-doc-512-v1.
- 7810 [4] B.C.K. Casey, D. Kawall *et. al.* GM2-doc-xxx-vy.
- 7811 [5] R.E.Ray, Mu2e-doc-1169-v21
- 7812 [6] S. Graessle *et. al.*, Nucl. Inst. Meth. A 367, 138 (1995).
- 7813 [7] T. Affolder *et. al.*, Nucl. Inst. Meth. A 526, 249 (2004).
- 7814 [8] “AdvancedMCTMMezzanine Module” AMC.0 Rev 2.0, PICMG.
- 7815 [9] “MicroTCA[®]” Rev MTCA.0 Rev 1.0, PICMG.
- 7816 [10] Intelligent Platform Management Interface.
- 7817 [11] Evolving design.
- 7818 [12] The appropriate reference for Garfield.
- 7819 [13] S. Agostinelli *et. al.* Nucl. Inst. Meth. A 506, 250 (2003).

Chapter 19

Auxiliary detectors

19.1 Fiber harps

19.1.1 Purpose

The fiber beam monitor (FBM) system is designed to serve two primary purposes:

- As a commissioning instrument, to determine the radius and angle of the beam in its first turns, and
- To observe and directly characterize periodic beam motion, notably the modulation of beam centroid position and width by coherent betatron oscillations.

On the other hand, the FBM is not suited to a determination of the equilibrium radius of the stored beam. A GEANT4 simulation showed that energy loss in the fibers moves the average radius inward by ~ 0.1 mm/ μ s, so it will be altered before equilibrium can be established. Even an order of magnitude less energy loss would still be unacceptable for this measurement, so it is not plausible that any system that intercepts the beam would be useful for it.

19.1.2 Existing system

The FBMs were originally built for E821 by a group at KEK that is not part of the Fermilab collaboration [1, 2]. We intend to refurbish and reuse all components from the existing system that remain suitable.

Each FBM holds a “harp” of seven scintillating fibers of 0.5 mm diameter, each 90 mm long and separated from its neighbors by 13 mm, as shown in Figure 19.1(a). There are a total of four devices, and they are deployed near the 180° and 270° positions in the ring. The 180° FBM should observe an image of the beam as it was injected at the inflector, while the 270° FBM should map the inflector angle into position. At each position, one FBM has the fibers suspended vertically to measure in x , and the other arranges them horizontally to measure in y . The fibers stay inside the beam vacuum, and they can be plunged into the beam path. They can be also rotated into a horizontal plane, where all fibers see the same beam, for calibration, or upright for measurement. Because ferromagnetic material cannot

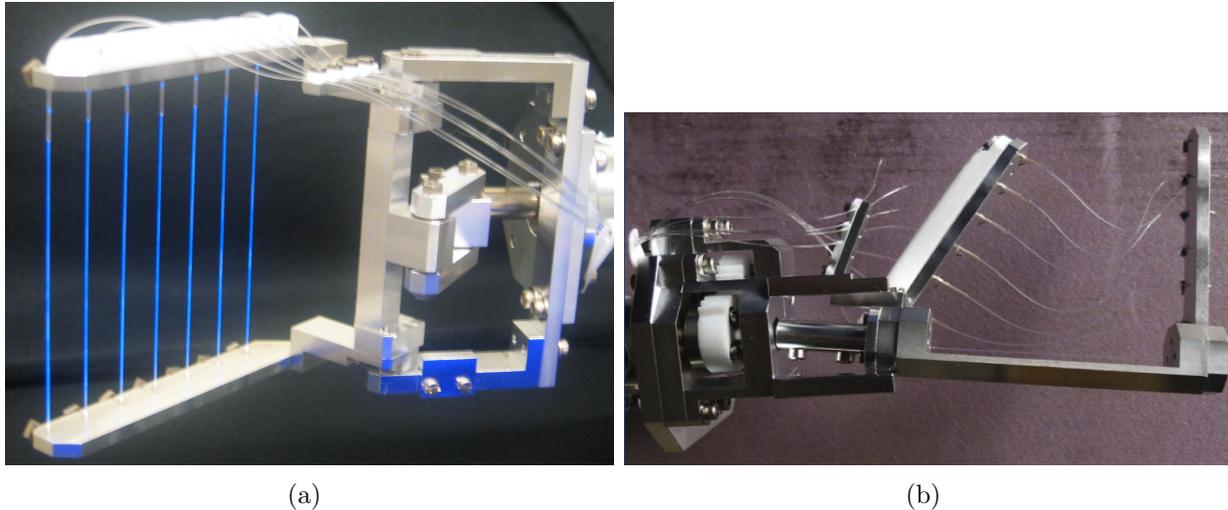


Figure 19.1: (a) The 180° x profile monitor, glowing under ultraviolet illumination in the laboratory. (b) The 270° y profile monitor, which was found to be damaged when it was removed from the Brookhaven E821 storage ring.

7848 be placed this close to the precision magnetic field, aluminum motors and actuators driven
7849 by compressed air are used for this motion.

7850 Each scintillating fiber is bonded to a standard optical fiber that connects it to a vacuum
7851 feedthrough. At that point, a ~ 3 m long fiber connected each fiber to an Amperex XP2202/B
7852 photomultiplier tube (PMT) that was located in a cable tray above the storage ring in a
7853 location where the magnetic fringe field could be shielded with mu-metal. The signals were
7854 small enough that various models of LeCroy linear amplifiers in an adjacent NIM crate were
7855 needed to drive the long cables to the counting room.

7856 19.1.3 Refurbishment and upgrade plans

7857 All of the FBMs have been dismantled from E821, and three of the four appear to be in
7858 good condition. One FBM was found to be damaged, with a snapped fiber and some bent
7859 frame components, as shown in Figure 19.1(b). The observed muon loss rate in E821 when
7860 the fiber harps were inserted suggests that this damage may have existed at that time. At
7861 a minimum, this frame will need to be straightened and realigned, and the broken fiber will
7862 need to be re-bonded.

7863 We will clean and lubricate the parts of the system that were outside the vacuum, and
7864 we will test the compressed-air driven motion control system, making any necessary repairs.
7865 Similarly, we will test and assure the vacuum integrity of the system.

7866 The PMTs and voltage divider bases that were used in E821 had already been reused
7867 from a previous project, and they are clearly aging devices that are in need of replacement.
7868 Replacement by SiPMs mounted directly on the fiber harps will allow the long fiber to a
7869 remote PMT to be eliminated. SiPMs also have higher photon detection efficiency than
7870 conventional PMTs.

7871 Initial SiPM tests have been conducted with the Hamamatsu S10362-11-050C, for which
7872 we have developed a readout board with a simple two-stage voltage preamplifier. It has a
7873 $1 \times 1 \text{ mm}^2$ area that is suitable for fiber readout applications. It also seems to be an appro-
7874 priate match to the estimated number of photoelectrons. An initial GEANT4 simulation
7875 indicated that the most probable energy deposit is 0.06 MeV in each interaction, leading
7876 to approximately 6 photons at the SiPM. This SiPM, with $\sim 65\%$ quantum efficiency and
7877 61.5% fill factor, would therefore yield 2.4 photoelectrons per interaction. Approximately
7878 1% of stored muons should interact with a typical fiber in each turn. Extrapolating from
7879 E821, we anticipate approximately 7000 stored muons in each fill, which would lead to 170
7880 photoelectrons. This is comfortably near the center of the dynamic range of 400 available
7881 pixels on the SiPM. The maximum dark count rate of 800 kcps would give one photoelectron
7882 of noise every 8 fills.

7883 We have acquired a quantity of 30 of this model of SiPM from unused spares from a
7884 previous project at Argonne National Laboratory, more than the 28 that are required. We
7885 will refine the readout board so that one printed circuit board will provide both mechanical
7886 support and preamplification for all seven SiPMs on each device.

7887 **19.2 Entrance counters**

7888 **19.2.1 Purpose**

7889 The time at which the muon bunch enters the ring must be subtracted from the time of
7890 each decay electron in order to align data from different fills properly. The relative intensity
7891 of each fill is also monitored. An entrance counter, positioned just outside the inflector, is
7892 needed to record the time and intensity of each fill.

7893 In E821, “flashlets” of beam that leaked from the AGS onto the target during the mea-
7894 suring period were a potential systematic error. The primary method of monitoring the rate
7895 of flashlets was to suppress the firing of the electrostatic quadrupoles periodically, preventing
7896 the injected muon bunch from being stored. Any signals that appeared in the calorimeters
7897 during these fills were presumed to be from flashlets. However, a dedicated flashlet counter
7898 was also deployed at times just outside the inflector.

7899 **19.2.2 Existing system**

7900 In E821, the primary entrance (“T0”) counter consisted of a 1 mm thick, 10 cm diameter
7901 volume of Lucite that produced Cerenkov light. It was coupled to a two-inch Hamamatsu
7902 R1828 photomultiplier. This existing T0 counter appears to be in good condition. It will be
7903 tested and repaired as needed. Because it will be among the only traditional photomultipliers
7904 in the experiment, a single-channel high voltage supply will need to be procured for it.

7905 The flashlet counter was a plastic scintillation detector that was only used in early runs
7906 of E821. The photomultiplier was configured to be gated off at the primary beam injection
7907 time by reversing the voltages on two dynodes. Consequently, the gain could be set to
7908 observe small amounts of beam entering at later times. This detector is also believed to be
7909 in working condition and to require only a suitable high voltage power supply.

7910 19.3 Alternatives

7911 Initially, we evaluated reusing the conventional photomultipliers that were used with the
7912 fiber beam monitors in E821. However, an initial inspection showed that they were in poor
7913 condition and unsuitable for future use. It would have been necessary to develop a new
7914 light conversion system, whether or not we moved to SiPM technology. Given the collabora-
7915 tion's familiarity with SiPMs from their extensive use in the calorimeter development, their
7916 compactness, and their comparatively low cost, there was a clear choice.

7917 We also briefly considered diagnostics that would remain continuously deployed in the
7918 storage ring. However, any detector that intercepts the muons would degrade the beam
7919 lifetime unacceptably, and the E821 experience with pickup electrodes was unsatisfactory;
7920 they were paralyzed by the pulsed high voltage devices.

7921 19.4 ES&H

7922 The most significant hazards associated with the auxiliary detectors are electrical. The bias
7923 voltages needed for the SiPM readout of the fiber beam monitors will be approximately 70 V.
7924 To mitigate this hazard, a current-limited power supply will be used, with the current limit
7925 set to the lowest value that allows the devices to operate. The photomultipliers required by
7926 the entrance counters require a voltage of approximately 2000 V. Again, an appropriately
7927 current-limited high voltage supply will be used. All electrical devices will be subject to
7928 Fermilab's standard design review and operational readiness clearance processes.

7929 The fiber beam monitors will be powered by compressed air at less than 150 psi. Require-
7930 ments for appropriate personal protective equipment, such as eye protection, when working
7931 around compressed air lines will be determined in consultation with Fermilab ES&H experts.
7932 Similarly, the fiber beam monitors interface with the ultra high vacuum system, and they
7933 are within the large fringe field of the storage ring magnet. We will work with Fermilab
7934 ES&H to establish appropriate procedures to mitigate these hazards.

7935 19.5 Risks

7936 There is a risk of hidden damage, or degradation over time, to the fiber beam monitors that
7937 might require more repair work than anticipated. This damage may not be discovered until
7938 mechanical, vacuum, and light output tests are completed. There is also a risk that, after
7939 testing, we may find that the SiPMs that we were able to acquire at no cost are not suitable
7940 for the application and that we need to procure another model.

7941 However, the only risk that would be expected to increase the project cost by \$40k or
7942 more would be the destruction or damage beyond repair of one or more of the existing fiber
7943 harp devices by an accident in shipping, storage, or testing. Because much of the original
7944 knowledge of the system has been lost, to re-create an FBM from scratch would require a
7945 significant level of unplanned engineering cost in addition to the precision machining work.

7946 Because the fiber beam monitors interface with the ultra high vacuum system, any leak
7947 could cause downtime for the experiment. The motion control system could potentially fail
7948 in a way that would not allow them to be retracted, which would also cause downtime,

7949 requiring the entire storage ring to be brought up to atmospheric pressure to remove them.
7950 We intend to minimize these risks by careful testing before installation.

7951 **19.6 Quality Assurance**

7952 We will test the motion and vacuum integrity of the fiber beam monitors with extensive
7953 exercises in a test chamber in the laboratory before they are installed in the storage ring.
7954 We will also check the output of each fiber, and therefore the functionality of each SiPM
7955 channel, with a set of light pulsers and radiation sources.

7956 **19.7 Value Management**

7957 The auxiliary detectors represent a successful application of value management principles.
7958 All components that are suitable for reuse from Brookhaven E821 will be reused. The
7959 primary upgrade to the fiber beam monitor devices will be a SiPM readout system. For that
7960 installation, suitable unused SiPM devices (spares from a previous project) were identified
7961 and made available by Argonne National Laboratory.

7962 **19.8 R&D**

7963 Extensive R&D work on the auxiliary detectors will begin in earnest in summer 2013. Sev-
7964 eral undergraduate students will have summer research projects related to the fiber beam
7965 monitors. One will develop an improved version of our SiPM readout circuit and will use it
7966 to test the light output from each fiber. Another will re-establish the motion of the devices
7967 and will set up a vacuum test stand to check for leaks. A third student will begin to define
7968 the interface between the motion controller and the MSCB-based slow control system.

7969 **References**

- 7970 [1] Y. Mizumachi and T. Sato, E821 Muon $g - 2$ Internal Note No. 192, 1(1994).
- 7971 [2] Design Report, BNL E821, A New Precision Measurement of the Muon ($g - 2$) Value at
7972 the level of 0.35 ppm. 3rd edition, D.H. Brown et al. B.L. Roberts Editor, March 1995.

Chapter 20

Anomalous Precession Frequency Measurement Backend Electronics

20.1 Backend Electronics

The backend electronics for E989 encompass the systems for the distribution of the clock and synchronization signals to the experiment, and for the digitization of the waveforms from each channel of electromagnetic calorimetry.

20.1.1 Physics Goals

The clock system must provide a frequency stabilized and blinded clock signal that provides the time basis for determination of ω_a and a second frequency-stabilized clock, tied to the same master clock, for the determination of ω_p .

The waveform digitizers (WFD) must convert the analog waveforms to digital while retaining the signal fidelity necessary to meet the calorimetry requirements on energy resolution and pileup differentiation. The system must convert the distributed clock frequency to the required sampling frequency range while maintaining the timing requirements, without allowing circumvention of the experimental frequency blinding. The digitized waveforms must be transferred without loss to the DAQ front ends for data reduction. The system must also provide the support and infrastructure to capture samples for pedestal determination, gain monitoring and correction, and for stability cross checks of the gain monitoring system.

20.1.2 Requirements

Clock and synchronization distribution

To avoid systematic biasing of ω_a , the distributed clock must be held stable against systematic phase shifts or timing drifts to under 10 ps over the 700 μ s fill. To help maintain signal fidelity, the random timing jitter should be much smaller than the ADC signal sampling window (the ADC's aperture delay), which is of order 100 – 200 ps for the required digitization rates. The frequency up-conversion within the WFDs must maintain these requirements.

7999 Synchronization signals such as start-of-fill and reset must be distributed to each front-
8000 end electronics channel. These signals must perform two distinct functions. First, to allow
8001 precise time alignment of signals from each channel within a calorimeter to allow for rapid
8002 summation on the DAQ front-end data reduction algorithms, they should be delivered to
8003 each channel within a calorimeter with a relative precision commensurate with the ADC
8004 aperture delay.

8005 Second, across the entire experiment, the the synchronization signals will flag the specific
8006 the clock cycle on which to begin data acquisition for each muon fill. This requires signal
8007 delivery to the detector stations within a time window somewhat smaller than the digitization
8008 period.

8009 **Waveform Digitization**

8010 **Signal requirements** The energy resolution budget (5% near the 1.5 GeV threshold for
8011 fitting) determines the waveform digitizer (WFD) minimum bit depth. Assuming a typical
8012 3×3 array of crystals summed to determine the energy, having 8 bits at 1.5 GeV would
8013 already contribute 1.2% to the energy resolution. This energy is about 1/2 the maximum
8014 energy range, and the system should have the overhead for complete study of the pileup
8015 energy distribution, which requires 10 effective bits. The effective number of bits is typically
8016 between 1 and 2 bits lower than the physical ADC bits. We therefore requires a digitization
8017 depth of at least 12 bits.

8018 The signal separation characteristics will be determined by a combination of the crystal
8019 wrapping, the choice of which the GEANT4 Cherenkov light simulation (section ??) shows
8020 can cause the rise time to vary from 1 to 3 ns, the SiPM and amplifier response (see Fig-
8021 ure 17.11), and the total cable and WFD bandwidth. The WFD bandwidth must be large
8022 enough to avoid significant stretching of the pulse shapes, with the rise time remaining under
8023 2 ns (if the final wrapping choice allows). The overall pileup requirement for the experiment
8024 (see section ??), that the system must be able to distinguish pulses separated by 5 ns, drives
8025 the specification for the digitization sampling rate. Laboratory tests at 700 megasamples
8026 per second (MSPS) show clear separation of pulses with this separation (see figure 17.12).
8027 Figure 20.1) shows the fits for two pulses measured in the lab with 5 and 10 ns separations
8028 at 500 MSPS sampling rate. We can clearly resolve even the 5 ns separation at 500 MSPS,
8029 but we will lose fidelity at lower sampling rates. We still have some headroom to separate
8030 pulses separated less than 5 ns, which will help ensure our pileup separation requirement,
8031 and therefore require a minimum digitization rate of 500 MSPS.

8032 **Physical requirements** The WFD crates will be located about 1 - 1.5 m from the dipole
8033 field of the storage ring, where the fringe field is of order 100 gauss. Ideally, the resulting
8034 magnetization of the materials in each WFD station would perturb the storage ring field by
8035 well under a part per million. We can make rough limit on magnetic materials assuming a
8036 magnetized sphere of material in a uniform magnetic field with static perturbations under
8037 10^{-7} . A predominantly aluminum chassis would be no problem – 15 kg would result in a
8038 perturbation under 0.1% of this limit. For ferromagnetic materials, however, the total mass
8039 must kept under about 200 g, which may require the power supplies to be located farther
8040 away. WFD prototype studies will determine whether shielding will be required to suppress
8041 dynamical field perturbations.

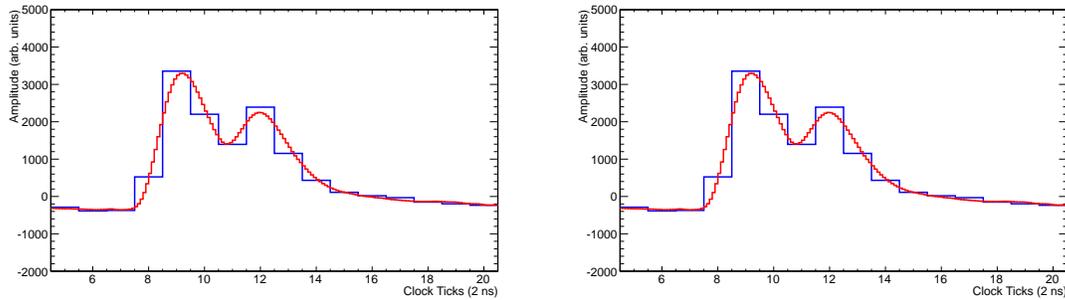


Figure 20.1: Fits to test data (see Section ??) with two pulses separated by 5 ns (left) and 10 ns (right) with a 500 MSPS sampling rate. The fits (red) clearly resolve the two peaks in the data (blue), even for the 5 ns separation.

8042 **DAQ requirements** During experimental running, muons will be stored in the storage
 8043 ring for 700 μ sec fills. The basic fill structure will be four groups of four fills, with the fills
 8044 within a group occurring at 12 msec intervals and the groups of four occurring at 132 msec
 8045 intervals. This basic structure repeats every 1.3 sec., for an average fill rate of 12 Hz.

8046 To eliminate dead-time, the 700 μ sec waveform for each calorimeter channel will be
 8047 digitized and transferred to the DAQ front-end system for data reduction. Each WFD
 8048 station must provide adequate buffering and throughput to support the average data rate,
 8049 assuming a 500 MSPS digitization rate, of 3 Gbit / s. The rates will require high speed serial
 8050 lines, which must be quiet during each fill to avoid introducing potentially rate-dependent
 8051 noise. There must therefore be a begin-of-fill synchronization signal that arrives early enough
 8052 to allow any WFD \rightarrow AMC13 block data transfers to complete before the fill starts.

8053 20.1.3 Recommended Design

8054 Clock distribution

8055 The Clock System will distribute a high-precision clock and synchronization signals to each
 8056 front-end crate. It will provide timing that is fully independent of accelerator timing to
 8057 insure that the ω_a measurement is not biased by synchronous events.

8058 The Clock System follows a similar strategy to that which was used in E821 and MuLan.
 8059 This system will primarily consist of off-the-shelf components. The primary clock signal will
 8060 be produced by a Meridian Precision GPS TimeBase, a GPS-disciplined oscillator. We have
 8061 recently purchased an initial module and are currently evaluating its properties. The Merid-
 8062 ian module will be supplemented by their "Low-Phase-Noise" output module to minimize
 8063 jitter. The GPS TimeBase will be used as the clock source for both the ω_a and ω_p measure-
 8064 ments. The utilization of the clock in the ω_p measurement is described in Sect. 15.2.8. The
 8065 GPS clock produces a 10 MHz output signal. This will be fed to a Fluke 6160B frequency
 8066 synthesizer that will shift the ω_a clock to 50 MHz plus a small offset that will be blinded.
 8067 The $50 + \epsilon$ MHz clock, where ϵ is the blinded offset that will be kept constant, will then be
 8068 distributed to the calorimeter front end crates. An AMC13 board, originally designed for

8069 the CMS μ TCA on each calorimeter μ TCA crate will receive the clock signal and put it on
 8070 the μ TCA backplane. Once received by each waveform digitizer, the clock frequency will be
 8071 shifted up to the 500 MHz sampling frequency.

8072 To minimize pickup from other sources, particularly sources that might be synchronous
 8073 with within a fill, the clock will be delivered to each front end crate on double-shielded
 8074 RG-142 cable.

8075 Monitoring of the clock system will occur at several stages. We will continuously monitor
 8076 the source and frequency synthesizer for any systematic shifts in frequency. At the receiving
 8077 end, the AMC13 will verify clock functionality with an internal counter compared to a local
 8078 oscillator. Further, direct tests on time slewing and other systematic effects will be performed
 8079 using the clock signals as seen by the waveform digitizers.

8080 The Clock System will also receive and distribute timing signals from the Fermilab ac-
 8081 celerator system. For example, the “Recycler Ring beam sync” signal will identify the time
 8082 of Recycler beam extraction. This signal, after time-alignment, will serve as the “begin
 8083 fill” signal that will synchronize all front ends (provide a common $t = 0$) and initiate data
 8084 acquisition. We will deliver accelerator synchronization signals to each calorimeter crate
 8085 differentially on shielded, twisted pair cable.

8086 In order to perform system testing at all sites participating in this proposal, we will
 8087 construct a μ TCA “Test Clock” emulator board that will deliver a realistic set of clock
 8088 and synchronization signals to the AMC13 board. The Test Clock will not have the timing
 8089 precision of the final system, but it will permit development and testing to go on at remote
 8090 sites under realistic DAQ system conditions. This increases the likelihood of a smooth
 8091 transition to full scale system assembly at Fermilab.

8092 **Waveform digitization**

8093 The proposed system draws heavily on a DAQ upgrade underway for the CMS experiment
 8094 at the Large Hadron Collider (LHC), which utilizes μ TCA technology. The WFDs for each
 8095 calorimeter station will reside in a single Vadatech VT892 μ TCA crate as a set of 5 channel
 8096 Advanced Mezzanine Cards (AMCs). The crate accommodates 12 full height AMC cards.
 8097 Eleven AMCs will instrument the 54 calorimeter channels for one calorimeter station, leaving
 8098 one channel for the pin diode signal that monitors the laser calibration intensity delivered to
 8099 the station. A twelfth WFD AMC will reside in the crate as a hot spare. The μ TCA choice
 8100 brings a robust system designed for remote operation and monitoring, with cooling, power
 8101 distribution and clock distribution capabilities already designed in.

8102 CMS has already prototyped the AMC13 as part of its hadronic calorimeter DAQ upgrade
 8103 (Figure 20.3), and Cornell has begun assembling a μ TCA test bench for the WFD AMC
 8104 development.

8105 VadaTech has previous experience in migrating other μ TCA chassis from their standard
 8106 steel-based configuration to an aluminum chassis. They will provide us with a custom alu-
 8107 minium chassis for the full order, and will send us preliminary versions of the chassis for
 8108 magnetics characterization before filling the full order. They are currently working with
 8109 us to identify and control other areas of the crate and modules that contain ferromagnetic
 8110 materials.

8111 Readout will be controlled by a CMS-designed AMC card that replaces a second (re-

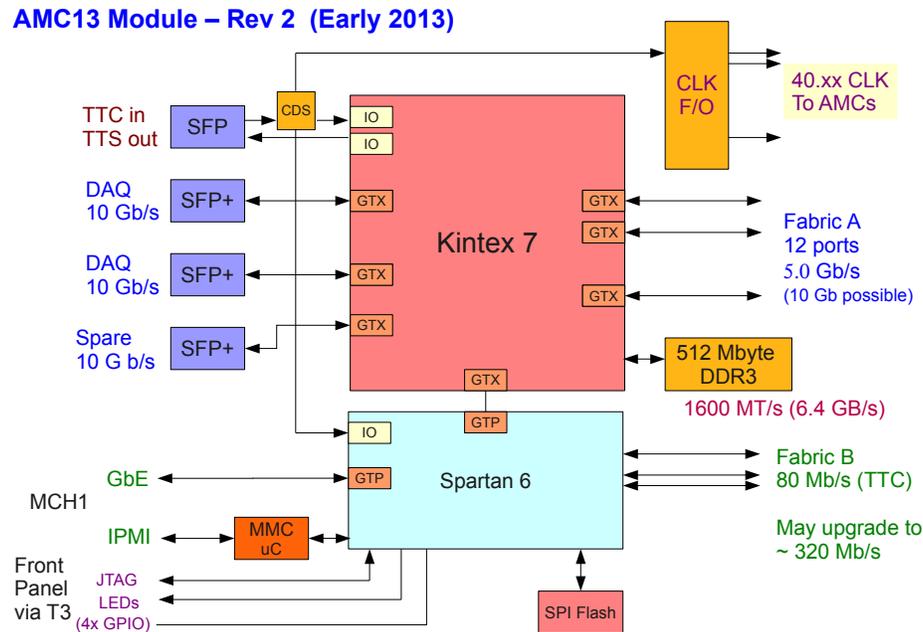


Figure 20.2: Block diagram of the CMS-designed AMC13 μ TCA card that will control the $g-2$ WFD readout.

8112 dundant) μ TCA Carrier Hub (MCH) in the μ TCA crate. This AMC13 card [1] is shown
 8113 in block diagram form in Figure 20.2. The μ TCA backplane connects each of the 12 WFD
 8114 AMC cards in a star topology (Figure 20.4). These connections, managed by the Kintex 7
 8115 FPGA, allow parallel readout of the 12 WFDs at rates up to 5 Gbit / second. The current
 8116 CMS firmware introduces overhead that maintains backwards compatibility with some of
 8117 their subdetectors, but currently limits the throughput to 2.5 Gbit / second. This overhead
 8118 will be eliminated through reprogramming of the Kintex 7, with no hardware modifications.

8119 The AMC13 itself can provide buffering of several seconds of calorimeter waveform data
 8120 on its 512 MB on board memory the AMC13 by taking advantage of lossless encoding /
 8121 decoding. This encoding can easily be accommodated by the Kintex 7 on the fly. This
 8122 buffering alone will allow the AMC13 to communicate with the external DAQ system at
 8123 the average data rate of 3 Gbit / second, though the individual WFD channels will provide
 8124 deeper buffering. The AMC13 includes 3 10 Gbit optical links for communicating with the
 8125 DAQ front-end computers, though $g-2$ needs only one of these links. We will support a
 8126 TCP/IP protocol on standard 10 Gbit ethernet, so the DAQ system will communicate with
 8127 the WFD system via a standard 10 Gbit optical NIC.

8128 The AMC13 has substantial on-board processing capability in the Kintex 7 device which
 8129 could be used to form time islands for the T method or accumulate histograms for the Q
 8130 method. This would substantially reduce the required bandwidth between the AMC13 and
 8131 the DAQ front ends, as well as relieving processing requirements on the DAQ, if needed.

8132 The baseline WFD design is centered on the TI ADS5463, a 500 MSPS 12 bit ADC with



Figure 20.3: Left: VadaTech 892 with CMS AMC13 under testing for CMS HCAL DAQ upgrade. Right: Core μ TCA equipment under setup at Cornell to begin testing for $g-2$.

8133 an input bandwidth of 300 MHz, and will be based on the successful 300 MSPS design [2]
 8134 (see Fig. 20.5) used for the CESR-TA project at the Cornell Electron Storage Ring (CESR).
 8135 The block diagram for the five-channel AMC card is also shown in Fig. 20.5. Each channel
 8136 will have a Kintex 7 FPGA to control the data flow out of the ADC and to / from an 64M
 8137 x 16 bit SDRAM memory buffer. At an average 12 Hz fill rate, this buffer can hold over 15
 8138 seconds of data.

8139 A sixth Kintex-7 FPGA provides the interface to the μ TCA fabric. The BU engineering
 8140 group, which has designed the AMC13 for CMS, will provide the FPGA firmware block that
 8141 supports the 5 Gbit/s transfer link from our WFD AMC to the AMC13 Kintex-7. This
 8142 Kintex-7 will transfer data out of the five channels sequentially, communicating with the
 8143 each channel's FGPA over a dedicated high speed serial line. For the 500 MSPS 12 bit
 8144 baseline design, the data from one fill can be transferred from the five-channel card in 4
 8145 msec over the 5 Gbit link.

8146 The AMC card must frequency lock on the distributed $50 + \varepsilon$ MHz clock and upconvert
 8147 to a near-500 MHz clock for the ADCs. The WFD cards will receive the 50 MHz clock
 8148 via the μ TCA backplane, which is distributed by the AMC13 via the FPGA-free LVDS
 8149 clock path shown in Fig. 20.6. The full clock path will need significant testing to verify
 8150 that it will have highly stable% duty cycle, slew and wander within the phase stability
 8151 specifications over a fill, and no differential nonlinearities. The engineer responsible for the
 8152 clock for operation of the Cornell Electron Storage Ring (CESR), which also has stringent
 8153 timing requirements, does not anticipate any intrinsic difficulty in meeting the $g-2$ stability
 8154 specification. On timescales of several hundred μ sec, a more important issue is typically
 8155 environmental noise. We must ensure, for example, that the clock supplied to the ADC will
 8156 be immune in particular to noise sources correlated with the fill structure, such as the firing
 8157 of the kicker. Because environmental noise is an issue, we are planning a single package clock
 8158 management, based on the TI LMK04010 or similar chip, rather than a discrete component
 8159 solution. This chip can up convert the 50 MHz input clock to the 500 MHz range, distribute
 8160 it over five output channels with a programmable delay on each line. The programmable

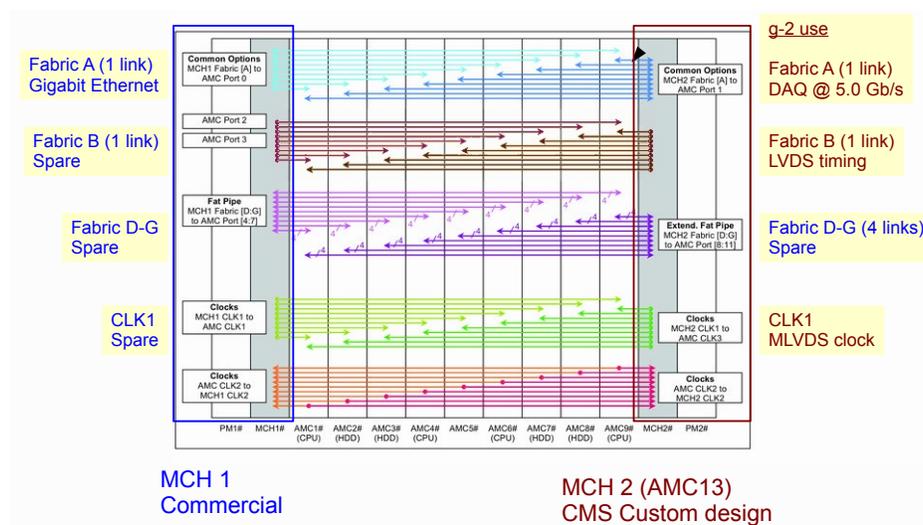


Figure 20.4: Dual-star backplane configuration for use with g-2 AMC13. High speed data transfers proceed over Fabric A. Timing and synchronization proceed via Fabric B.

8161 delay will allow correction of channel by channel timing differences in signal path lengths
 8162 from the photodetectors at the sub-clock-cycle level. The single package device will be far
 8163 less immune to external noise than a discrete component solution, and has much better
 8164 overall jitter specifications (under 200 fs) than a discrete component solution.

8165 We will operate the WFDs following the CESR-TA implementation: the ADC chips
 8166 will sample continuously, and data collection will be gated during the fill, triggered by the
 8167 synchronization signal. There will also be options for dedicated operation to collect pedestal
 8168 and gain data.

8169 Bench testing the clock distribution from the AMC13 to the ADC will be the highest
 8170 priority testing we will launch with the one-channel prototype under development. These
 8171 studies will include sensitivity to environmental noise sources. We are also considering
 8172 design options for the final system that would incorporate monitoring of the final ADC
 8173 clock. Options could include onboard comparison to a second independent stabilized clock
 8174 signal generated locally on each station's MCH.

8175 20.1.4 Performance

8176 The proposed baseline will meet the basic energy, pulse separation, readout rate and random
 8177 jitter requirements. As noted above, the level of control of systematic timing trends over the
 8178 700 μ s fill times with the expected fill structure must still be characterized, but we do not
 8179 expect a serious problem.

8180 The proposed solution also provides the experiment with significant flexibility. The sys-
 8181 tem is capable of readout of the data from a fill in the 11 msec inter fill period, even at a 1
 8182 GSPS sampling rate. Should the opportunity arise, for example, for a higher average rate of
 8183 muon fills, there is no intrinsic limitation from the μ TCA-based solution outlined here.

8184 With the TI ADC, we expect each station to consume approximately 500 W of power,



Figure 20.5: Left: A single-channel 300 MSPS ADC mezzanine card with on board buffering developed for the CESR-TA program. Right: Block diagram of the five-channel WFD AMC card.

8185 which is safely below the maximum power of the 792 W power module available for the
 8186 VadaTech crate

8187 The μ TCA solution also provides a natural platform for the tracker readout boards 18.

8188 20.1.5 Alternatives and Value Engineering

8189 We considered a PCIe-based system to host the WFD's as an alternative to μ TCA. Under this
 8190 scenario, the WFD's would become PCIe cards that plug either directly into a PCIe-based
 8191 motherboard or into a PCIe expansion chassis. We would need to engineer all of the timing,
 8192 cooling, power, mechanical and remote monitoring elements that are already engineered into
 8193 a COTS μ TCA system, escalating the risk. Data throughput rates would require a PCIe
 8194 backplane with enough 16 lane slots to accommodate all of the WFDs, which were difficult to
 8195 locate. Finally, the solution did not scale easily from the 35 channel calorimeter considered
 8196 early on to the 54 channel baseline. As our initial estimates indicated that the solution was
 8197 only about 10% less expensive, but carried significantly more risk, particularly for the 54
 8198 channel calorimeter.

8199 We also considered COTS waveform digitizers. When approaching Struck, however, the
 8200 reply we received was "For an application in the 1500 channel count I tend to assume, that
 8201 a custom card may be advised to optimize performance and cost to the application." We
 8202 continued on the path of developing our own.

8203 We considered two other 12 bit 500 MSPS ADC chips as alternatives to the TI ADS5463,
 8204 the e2v AT84AS001 and the Analog Devices AD9434-500. All chips had a similar cost /
 8205 part. The e2v AT84AS001 has a much larger footprint than the other chips, which would
 8206 complicate the layout in an already dense board, so we eliminated it from consideration. The
 8207 TI chip had slightly better noise and bandwidth specifications, while the AD chip consumed
 8208 considerably less power and space. We may have opted for the AD9434-500, all else being
 8209 equal, but TI offered to donate all 1600 ADCs needed for prototype WFD development and
 8210 final WFD production.

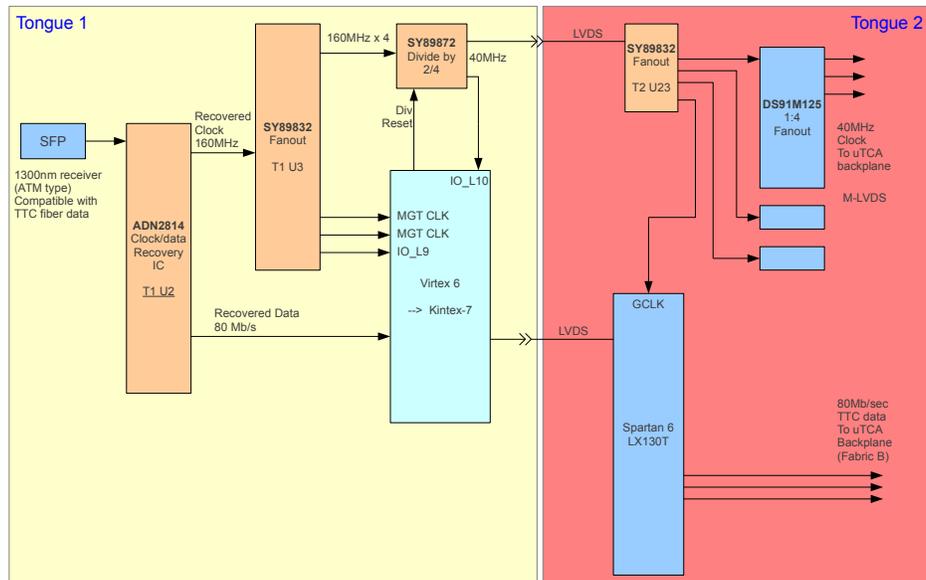


Figure 20.6: Right: Timing paths through the AMC13 for the LHC. The $g-2$ experiment will utilize the FPGA-free LVDS path, which distributes the 40 MHz clock shown for CMS, but in principle can support any frequency in the range from 10 to several hundred MHz. The $g-2$ baseline design utilizes 50 MHz.

8211 We also explored the 1 GSPS versus 500 MSPS digitization rate, but find the cost
 8212 prohibitive at this time. Currently, the price differential for native 1 GSPS ADCs alone would
 8213 double the cost of the WFD system, even before considering the additional engineering re-
 8214 quired for the increased clock stability and higher rate data movement between ADC and
 8215 buffer memory. Interleaving two 500 MSPS TI chips would also essentially double the WFD
 8216 system cost. The power requirement would almost double, and we are already near the max-
 8217 imum we would consider given the power the crate can deliver. Hence we would need two
 8218 μ TCA crates per system, as well as additional parts and FPGAs. Interleaving the AD ADCs
 8219 is feasible from a power perspective, but would forego the TI donation. The incremental
 8220 system cost would exceed \$500,000 in that scenario.

8221 We have investigated discrete component circuitry on the WFD AMC card based on the
 8222 AD9510 or another similar clock synthesizer. The design included a clock delay line for each
 8223 channel that can correct for differences in signal path lengths from the photodetectors at
 8224 the sub-clock-cycle level. Such a design would have significantly more inherent jitter, several
 8225 tens of picoseconds, and would have greater sensitivity to environmental noise.

8226 As we move forward, we will continue to evaluate performance / cost issues for emerging
 8227 μ TCA MCH options, component options for the WFD AMC cards, for power supplies for
 8228 the μ TCA crates, and elsewhere as the opportunity arises.

8229 For the Clock System, we have considered alternate clock sources. The clock for E821
 8230 was disciplined by the LORAN-C signal which is now obsolete. Undisciplined Rubidium
 8231 oscillators would likely deliver the precision necessary, however the GPS disciplined oscillator
 8232 provides long term stability as well as additional features like time-stamps which are of

8233 particular use to the field measurement. Options for the frequency synthesizer are limited
8234 by the 50 MHz signal necessary for the WFD.

8235 20.1.6 ES&H

8236 The μ TCA crate for each calorimeter station will weigh approximately 30 pounds and will be
8237 supported by the calorimeter housing (see section 17.4). Power to each crate will be supplied
8238 by a 60 – 70 V supply that connects to an in-crate power module that maintains the stable
8239 48 V on the backplane. When fully populated with the WFDs, the each station will draw
8240 approximately 500 W of power. If the magnetic field requirements allow, the power supply
8241 will be resident on the crate. If not, the supplies will be located more centrally in the ring,
8242 with a few meter cable run and the supply voltage closer to 70 V.

8243 The latter configuration in particular involves high voltage with several amps of current.
8244 We will ensure that all our equipment and installation conforms to the Operational Readiness
8245 Clearance criteria.

8246 20.1.7 Risks

8247 The largest risk in the WFD project regards the distribution of the clock signal through the
8248 AMC13 and μ TCA backplane, and in particular, whether that path will meet the frequency
8249 and phase drift requirements. To mitigate risk to the project, we will design the WFD AMC
8250 cards to allow timing and synchronization inputs via the front panel. We can then engineer a
8251 standalone distribution system to the AMC modules that meets the final specifications. This
8252 alternative would also require a modified clock fan-out and cabling scheme. Total differential
8253 cost to the experiment should be under \$40K for engineering and production. Biases in the
8254 clock translate directly into biasing of ω_a , so the clock must meet its stability requirements.

8255 20.1.8 Quality Assurance

8256 Cornell is establishing a test station to assess the performance of the μ TCA platform, of the
8257 AMC13 modules and the WFD AMCs themselves. We plan two major stages of prototyping:
8258 and initial one channel design to verify the fundamental per channel performance without
8259 facing the board density issue simultaneously. The second stage will move the one channel
8260 design to the full five channel design with the denser component layout. The plans for each
8261 stage include two versions of AMC prototype, and both versions will undergo significant
8262 testing to assure that the baseline requirements for $g-2$ are met.

8263 We will produce enough of the second five channel prototype to fully populate the μ TCA
8264 crate, as planned for the experiment, so that we can ensure the entire system under full load
8265 can meet the specifications, and that we do not encounter unanticipated cross talk or clock
8266 biasing with the full system. This system will also be deployed in the 25 channel test beam
8267 planned to stress test the entire calorimeter through DAQ design.

8268 Production of the WFD AMC modules and delivery of the μ TCA crates should complete a
8269 year in advance of the start of the experiment. Burn-in and stress-testing of the production
8270 components will continue at Cornell as we receive the components, and can continue for
8271 several months thereafter before moving the equipment to FNAL for installation.

8272 The Illinois group will test and evaluate each component of the clock system prior to
8273 installation. In addition, we will perform detailed in-situ timing for each path in the final
8274 experimental configuration. This "timing-in" is necessary to insure that the synchronization
8275 signals are delivered to each location simultaneously.

8276 **20.1.9 References**

8277 **References**

- 8278 [1] Amc13 development project, <http://www.amc13.info>.
- 8279 [2] N.T. Rider, J.P. Alexander, J.A. Dobbins, M.G. Billing, R.E. Meller, M.A. Palmer,
8280 D.P. Peterson, C.R. Strohman, *Development of an X-Ray Beam Size Monitor with*
8281 *Single Pass Measurement Capability for CESRTA*, Proceedings of the 2011 Particle
8282 Accelerator Conference (PAC 11) , 687 (2011).

Chapter 21

Data Acquisition System

21.0.10 Physics Goals

The data acquisition system must read, process, monitor and store the data produced by the various detector systems in the muon $g-2$ experiment. Most importantly, the DAQ must provide a distortion-free record of the detector signals originating from the decay positrons during the 700 μs -long spills from the muon storage ring. Additionally, the system must record all data required to perform the corrections from effects such as pulse pileup, gain instabilities and beam dynamics. Furthermore, the system must permit the monitoring needed to guarantee the overall integrity of data taking and record-keeping needed to document the experimental conditions during data taking.

21.0.11 Overall Requirements

The DAQ must handle the accelerator-defined time structure of the data readout from the detector systems. Under normal operations we anticipate a 12 Hz average rate of muon spills that comprises sequences of four consecutive 700 μs spills with 11 ms spill-separations for each booster batch received by the muon $g-2$ experiment. The procedures for reading, processing, monitoring and storing these data must introduce no time-dependent losses or time-dependent distortions of the detector signals during the muon spills.

The DAQ must handle the readout, processing, monitoring and storage of the data obtained from the 1296 channels of 500 MHz, 12-bit, waveform digitizers instrumenting the individual PbF_2 crystals of the twenty four calorimeters. For each spill the raw data will consist of 1296 channels of 700 μs -long streams of continuously-digitized ADC samples. The DAQ must process these raw data into derived datasets including: T-method data (*i.e.* individual islands of digitized pulses), Q-method data (*i.e.* accumulated histograms of calorimeter spectra), and other calibration, diagnostic and systematic data. At a 12 Hz spill rate the readout (*i.e.* raw) data rate will be about 8 GB/s and the stored (*i.e.* derived) data rate will be about 50 MB/s.

The DAQ must also handle the readout, processing, monitoring and storage of the data obtained from the two positron tracking stations. This system consists of roughly 2000 channels of straw tubes with associated amplifier-discriminator-TDC electronics. The raw data – consisting of time stamps and spill numbers from individual straw tubes – is expected

8314 to yield a roughly 2 MB/s time-averaged data rate.

8315 Additionally, the DAQ must handle the readout, processing, monitoring and storage of
8316 data from the auxiliary detector systems. These systems include the muon entrance detector,
8317 fiber harp detectors and electric quadrupole monitors and involve both instrumentation that
8318 is operated during normal data taking (the muon entrance detector) and instrumentation
8319 that is operated during dedicated data taking (the fiber harp detectors). The read out for
8320 the muon entrance detector, fiber harp detectors and electric quadrupole monitors will use
8321 an existing system of custom-built, fast-sampling, VME-based, waveform digitizers. The
8322 expected data rates from auxiliary detector systems are: (i) 17 MB/s during dedicated data
8323 taking with the fiber harp detectors and (ii) 3 MB/s during normal data taking with the
8324 muon entrance detector and the electric quadrupole monitors.

8325 The DAQ must coordinate the acquisition of data by the frontend readout processes with
8326 the accelerator-defined spill cycles. This coordination involves both readout systems where
8327 data is transferred synchronously with spill cycles (direct memory transfer from VME-based
8328 electronics) and readout electronics where data is transferred asynchronously with spill cycles
8329 (network packet transfer from micro-TCA based electronics).

8330 The DAQ must assemble the individual fragments of spill-by-spill data from networked
8331 readout processes into complete, deadtime-free, records of each muon spill. This includes
8332 assembling the data banks of T-method and other datasets from the twenty four calorime-
8333 ters stations as well as the data from the two tracker stations and the auxiliary detector
8334 systems. In total the event builder must match and assemble the fragments originating from
8335 roughly thirty frontend processes at an expected rate of about 50 MB/s. The resulting
8336 fully-assembled spill-by-spill events must be transferred to the Fermilab computing facilities.

8337 The DAQ must provide the local / remote run control for data taking as well as facilities
8338 for configuration and read-back of parameters such as high voltages, digitizer configurations,
8339 *etc.* The system must provide the monitoring of data integrity and data quality and a
8340 comprehensive database of the experimental conditions and configuration parameters during
8341 data taking. The system must additionally provide for local storage of sufficient data for
8342 online analysis tasks.

8343 **21.0.12 Recommended Design**

8344 The major challenge for the data acquisition is the combination of the high data rates with the
8345 requirement of avoiding any time-dependent losses or time-dependent distortions of detector
8346 signals during muon spills. In addition, the system must provide: the monitoring of data
8347 integrity, cataloging of experimental conditions, and flexibility for diagnostics measurements.

8348 The DAQ will acquire data in deadtime-free blocks that correspond to individual muon
8349 spills from the storage ring. Each event will represent a complete deadtime-free history of the
8350 entire activity in the detector systems for a complete spill – rather than events corresponding
8351 to individual positrons. This scheme will utilize the on-board memories in waveform digitizer
8352 and multi-hit TDCs to temporarily buffer the recorded data before its data transfer to the
8353 data acquisition. The design will be implemented as a modular, distributed computer system
8354 on a parallel, layered array of networked, commodity processors with graphical processing
8355 units (GPUs). The DAQ group have developed and operated very similar architectures [1]
8356 for the MuLan, MuCap and MuSun experiments at the Paul Scherrer Institute.

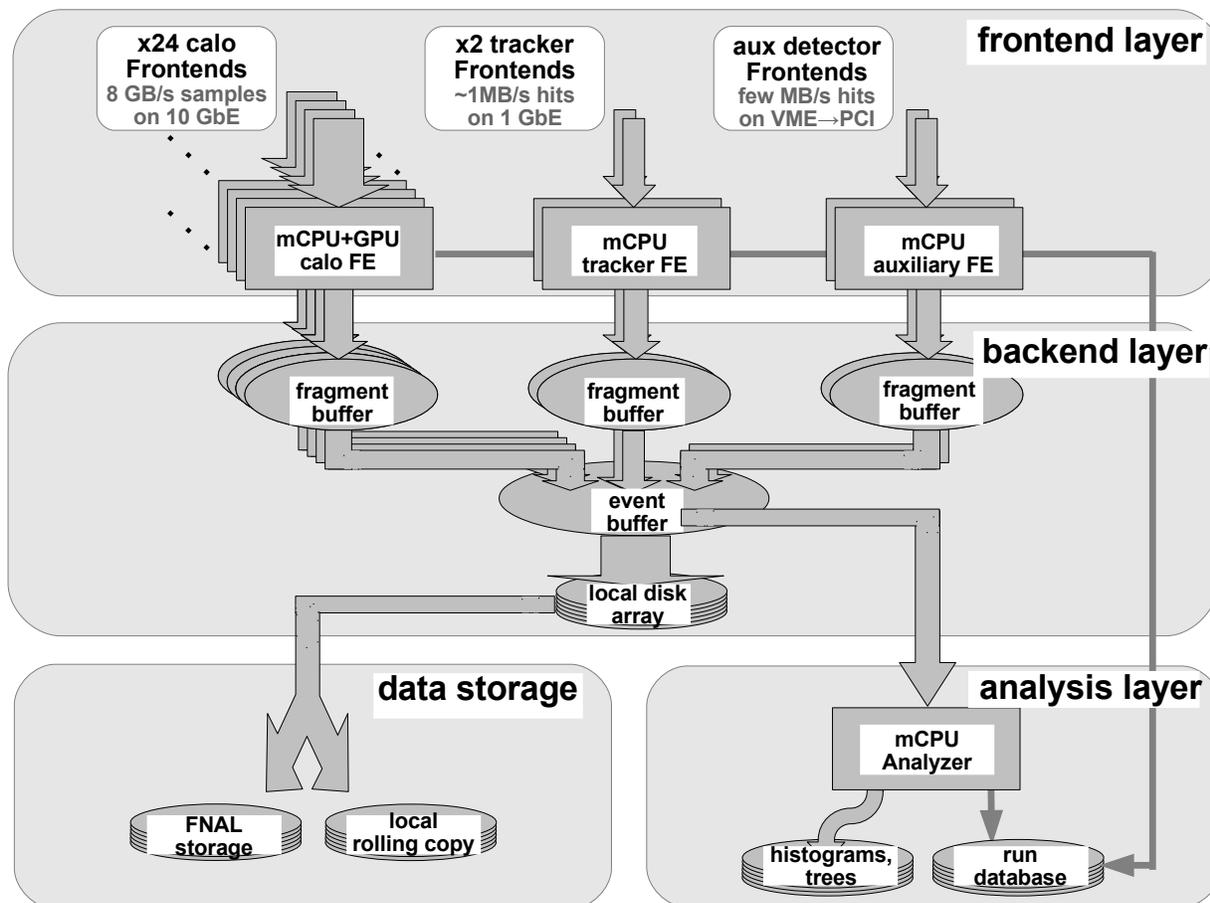


Figure 21.1: Conceptual design of the g-2 data acquisition. The figure shows: (i) the frontend layer for readout and processing of data from the calorimeter stations, tracking stations and auxiliary detector systems, (ii) the backend later for event building and data storage, (iii) the analysis layer for monitoring data quality and recording run-by-run experimental conditions, configuration parameters, *etc.*, and (iv) data storage. The layers comprise arrays of networked commodity processors.

8357 The data acquisition system is depicted schematically in Fig. 21.1. It shows a frontend
 8358 processor layer responsible for readout and processing of waveform digitizer and multihit
 8359 TDC data, a backend layer responsible for event assembly and data storage, a slow con-
 8360 trol layer responsible for control and read-back, and a data analysis layer responsible for
 8361 monitoring data integrity. The DAQ hardware will comprise a networked cluster of high
 8362 performance processors running Scientific Linux. The DAQ software will be based on the
 8363 MIDAS data acquisition package [2], ROOT data analysis package [3], and NVIDIA's par-
 8364 allel computing platform CUDA. To maximize bandwidth, one network will handle traffic
 8365 between the frontend layer and the backend layer and another network will handle traffic
 8366 between the backend layer and the analysis layer.

8367 The calorimeter readout consists of one frontend processor per calorimeter station. Each

8368 frontend processor will read out the 54 waveform digitizer channels associated with the 9×6
8369 PbF_2 crystals of a single calorimeter station. Each group of 54 waveform digitizer channels
8370 will occupy a single micro-TCA crate. The digitizers are configured via a commercial MCH
8371 controller [] with a 1 GbE link and read out via a custom AMC13 controller [] with a 10 GbE
8372 link. For each spill the raw calorimeter data will consist of $24 \times 54 = 1296$ channels of $700 \mu\text{s}$ -
8373 long streams of continuously-digitized, 500 MHz, 12-bit, ADC samples – a total of 680 MB
8374 per spill. The processors are designed to provide the necessary performance to compress the
8375 continuously-digitized ADC samples into the T-/Q-method datasets at the software level
8376 in the frontend CPU/GPUs. The T-method datasets will consist of individual “islands” of
8377 above-threshold calorimeter signals and the Q-method datasets will consist of histograms
8378 of consecutive spills of continuously-digitized samples. The algorithms for constructing the
8379 T-/Q-method datasets involve copying, masking and summing data arrays and therefore are
8380 well suited to GPU-based parallelization using standard algorithms. The scheme will offer
8381 the flexibility to implement other datasets – such as pile-up datasets (*e.g.* by summing fills
8382 before storing islands) and diagnostic datasets (*e.g.* by storing prescaled fills of fully-digitized
8383 samples) – as needed. Each calorimeter frontend processes will finally zip, pack and dispatch
8384 the various derived datasets as MIDAS-format databanks over the frontend network to the
8385 event builder.

8386 The positron tracking system consists of two tracking stations that each comprise about
8387 1000 individual channels of straw tube detectors. The raw data – derived from amplifier-
8388 discriminator-TDC electronics that instrument each straw tube detector – are transferred to
8389 custom AMC modules housed in a single micro-TCA crate for each tracking station. The
8390 AMC modules are configured and read out via a commercial MCH controller with a 1 GbE
8391 link. Each tracker frontend process will receive the raw data – *i.e.* hits defined by a time
8392 stamp and a spill index – and then zip, pack and dispatch the tracking station data as
8393 MIDAS-format databanks over the frontend network to the event builder.

8394 The auxiliary detector systems comprise the muon entrance detector, fiber harp detec-
8395 tors and electric quadrupole monitors. Their read out will be based on existing electronics of
8396 custom-built, high-speed, 8-bit, waveform digitizers [] with 512 kByte on-board FIFO mem-
8397 ories. These digitizers are configurable for different sampling rates and different triggering
8398 / gating modes and therefore suitable for the read out of the different detector systems.
8399 The digitizers are housed in 6U VME crates and readout using Struck Innovative Systeme
8400 SIS3100/1100 VME-to-PCI interfaces. The muon entrance readout will use a single digitizer
8401 channel operating at 500 MHz sampling rate to record continuous ADC samples. The fiber
8402 harp detector read out will use 28 channels of waveform digitizers operating at a 500 MHz
8403 sampling rate with an external gate signal to record continuous streams of ADC samples
8404 during the initial $100 \mu\text{s}$ of the muon spill. The electric quadrupole monitors will be read
8405 out using 32 channels of waveform digitizers operating at a 25 MHz sampling rate with an
8406 external gate signal to record continuous streams of ADC samples during the entire $700 \mu\text{s}$
8407 of the muon spill.

8408 The DAQ design incorporates a master frontend process and hardware control logic in
8409 order to synchronize the data acquisition readout cycles with the accelerator-defined spill
8410 cycles. Importantly, the master frontend and control logic must accommodate both the spill-
8411 synchronous data transfer from the VME crates via Struck SIS 3100/3300 interface modules
8412 and the spill-asynchronous data transfer from the micro-TCA crates via 1/10 GbE network

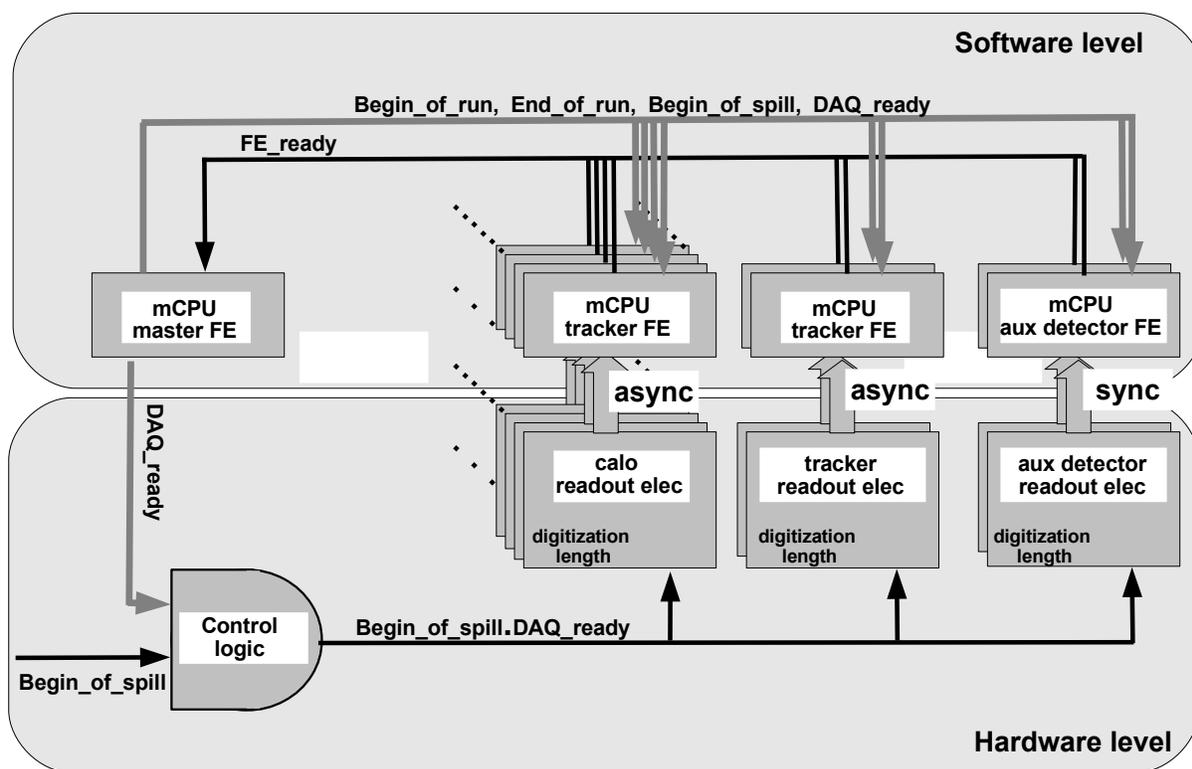


Figure 21.2: Conceptual design of the g-2 control logic. The controls signals involve a accelerator-defined `begin_of_spill` signal and a process-defined `DAQ_ready` signal. Control signals are distributed across the readout processes by remote procedure calls (the upper software level) and across the read electronics by the control logic module (the lower hardware level).

8413 links.

8414 The conceptual design of the logic to coordinate the fill cycles and readout cycles is
 8415 given in Fig. 21.2. The design involves two control signals – a `begin_of_spill` signal and
 8416 `DAQ_ready` level – that are distributed to the readout electronics via the hardware control
 8417 logic and distributed to the frontend readout processes by the master frontend process. On
 8418 run start-up, after completing their initialization, each enabled readout process will transmit
 8419 a `FE_ready` signal via a remote procedure call to the master frontend process. On receipt of all
 8420 `FE_ready` signals from all enabled readout processes the master processes sets the `DAQ_ready`
 8421 level “high” in the control logic. The next `begin_of_spill` signal then: propagates through
 8422 the control logic to initiate the digitization by readout electronics, propagates to the readout
 8423 processes to initiate any software `begin_of_spill` functions, and resets the `DAQ_ready` level
 8424 “low”. The digitization time range for each detector system is a configuration parameter

8425 set in the readout electronics by the data acquisition. Synchronous frontend processes,
8426 which require the readout of data between spills, will identify the end of digitization by a
8427 polling scheme and report the completion of read out via a FE_ready remote procedure call.
8428 Asynchronous frontend processes, that receive their data as network packets from frontend
8429 electronics, do not report the spill-by-spill completion of read out cycles. After receiving the
8430 FE_ready signals from all synchronous readout processes, the master processes again sets
8431 the DAQ_ready level “high” in the control logic – thus continuing the data taking. Note we
8432 plan to use a PCI-based GPS synchronization card [5] to GPS timestamp the digitized spills
8433 to facilitate later coordination between the detector system readout and the magnetic field
8434 readout.

8435 Each frontend readout process will transmit its spill-by-spill data fragments as MIDAS-
8436 format databanks across the frontend network to the backend processor. Initially, the data
8437 fragments from the twenty four calorimeter processes, two tracking system processes and
8438 various auxiliary detector processes, are transferred to individual shared memory segments
8439 on the backend machine. After matching the MIDAS serial numbers and muon spill indexes
8440 of event fragments the event builder process assembles all data fragments into single events
8441 representing a complete record of each spill. The spill events are then written by the event
8442 builder process to a final memory segment known as the system memory segment and are
8443 available for data storage tasks, data analysis tasks, *etc.*

8444 The backend layer will use a two step procedure to permanently store a full copy of the
8445 data on the Fermilab Computing facilities and temporarily store a rolling copy of the recent
8446 data on our analysis layer. First, the data will be transferred from the system memory
8447 segment to a temporary disk file on a local redundant disk array on the backend processor.
8448 Next, the temporary data files on the backend processor will be asynchronously migrated to
8449 both the Fermilab computing facilities for permanent storage and the DAQ analysis layer
8450 for local analysis projects. This approach will minimize any delays in data taking due to
8451 latencies associated with the permanent archiving of the experimental data and make the
8452 current data available for local analysis projects.

8453 The DAQ analysis layer will provide both integrity checking and online histogramming.
8454 The online analyzer will receive events over the network from the system memory segment on
8455 the backend layer. These events will be received “as available” in order to avoid introducing
8456 any delays into the read out or the data storage. The online analysis will utilize the MIDAS
8457 analyzer package and a modular, multistage approach to the analysis tasks. Specifically, the
8458 different analysis tasks are implemented as individual analyzer modules and switched on /
8459 off as needed. Each analysis module had access to a global structure that contains both
8460 the raw MIDAS databanks from the readout processes and any derived MIDAS databanks
8461 from the preceding analysis modules. Low-level modules will be responsible for unpacking
8462 the databanks and checking their integrity. Intermediate-level modules will be responsible
8463 for various histogramming to ensure the correct operations of detector systems. High-level
8464 modules will be responsible for online “physics” analysis such as fits to the precession signal.

8465 The data acquisition system will incorporate database support to provide a comprehen-
8466 sive run-by-run record of the experimental conditions, configuration parameters, *etc.*, during
8467 data taking. The run-by-run database will store information derived from the MIDAS online
8468 database such as run start time, run stop time, operator run-time comments, the number of
8469 events, and hardware settings including the high voltage setting, digitizer configuration pa-

rameters, multihit-TDC configuration parameters, *etc.* In addition, the database will record such quantities as detector gains, pedestals, *etc.*, fitted frequencies, lifetimes, *etc.*, that are derived from the analysis layer. These metadata are foundations for the offline data analysis.

The DAQ will be housed in the computer room in the MC-1 building. 10 GbE optical fiber links (64 cables) and 1GbE copper Ethernet (48 cables) will provide the connections between the detector sub-systems in the experimental hall and the data acquisition in the control room. The DAQ will require clean, uninterruptible power of roughly 50 kiloWatts total power with appropriate power distribution for roughly thirty rackmount computers and associated network switches, mass storage devices, *etc.* The control room will require air circulation for appropriate temperature and humidity control with temperature, humidity and air velocity sensors with digital readout. It will require a reliable, fast network connection between the MC-1 computer room and the Fermilab data storage facilities that is capable of a sustained data rate of roughly 100 MB/s.

21.0.13 Design Performance

The DAQ is designed to operate at 12 Hz average spill rate with muon spills that comprises sequences of four consecutive 700 μ s spills with 11 ms spill-separations. It must handle the readout, processing and storage of the raw data rates from the twenty four calorimeter stations, two tracking station, and the auxiliary detector systems

During normal data taking at 12 Hz spill rate, the time-averaged data rate of raw calorimeter ADC samples will be 340 MB/s per individual station and 8.2 GB/s for all twenty four stations. Overall – to achieve both manageable rates and reasonable volumes of stored data – the data processing by calorimeter frontends must achieve at least a 100-fold compression of continuously-digitized ADC samples into T-/Q- and other method datasets. During normal data taking at 12 Hz spill rate, the tracking system raw data rate is expected to be roughly 2 MB/s. and the auxiliary detector systems raw data rates are expected to be roughly 3 MB/s.

The experiment will require the Fermilab data storage facilities to handle a sustained data rate of up to 80 MB/s during the operating periods of the g -2 experiment. Based on about one year of total running time, the experiment will require a permanent data storage capacity from Fermilab data storage facilities of 1-2 Petabytes.

21.0.14 Alternatives and value engineering

The collaboration considered two alternative data acquisition frameworks: the CODA DAQ package that is used at JLab and the Art-DAQ framework that is under development at Fermilab. One advantage of using the MIDAS is that collaboration members have already developed very similar DAQ architectures with the MIDAS framework for other experiments. The g -2 DAQ can therefore profit from the software/hardware development for the earlier experiments. Another advantage of MIDAS is the availability of an extensive range of DAQ tools including an event builder, an analysis framework, a slow control system, a data alarm system, data storage and database tools, as well as large collections of device drivers for readout hardware. MIDAS has a active community of software developers and is widely used at numerous nuclear and particle laboratories.

8511 Several alternatives were considered for processing the raw calorimeter data into T-, Q-
8512 and other method datasets. In particular, the collaboration considered the possibilities of
8513 deriving the T-/Q- method datasets at either the software level in the frontend processors
8514 or the hardware level in the digitizer FPGA electronics. An advantage of the software
8515 implementation is the greater flexibility to modify or add new datasets as needed during
8516 the design, commissioning and running phases of the experiment. An advantage of the
8517 firmware implementation is the lower data rates from the readout electronics to the frontend
8518 processors.

8519 Different architectures and parallelization schemes were also considered for the calorime-
8520 ter frontend processors. In one parallelization scheme using multicore CPUs the frontends
8521 process individual spills in separate CPU threads in order to achieve the necessary data com-
8522 pression bandwidth. In another parallelization scheme using many core GPUs the frontends
8523 process individual samples in separate GPU threads in order to achieve the necessary data
8524 compression bandwidth. The GPU-based approach is better suited to paralleling the tasks
8525 involved in deriving T-/Q-method datasets and takes advantage of standard algorithms for
8526 such operations.

8527 Two different NVIDIA GPU architectures – the newer Kepler architecture and the older
8528 Fermi architecture – will be evaluated for the frontend processors. The Kepler architecture
8529 may permit faster data transfer between the CPU and the GPU and thereby improve the
8530 rate performance for data compression.

8531 In addition to T-/Q-method data compression we plan to evaluate the loss-less com-
8532 pression of digitizer data using standard libraries (*e.g.* ZLIB library [6]). For continuously-
8533 digitized ADC samples that consist of occasional pulses the loss-less algorithms should offer
8534 efficient compression.

8535 **21.0.15 ES&H**

8536 The components of the data acquisition do not involve either hazardous materials or unusual
8537 electrical / mechanical hazards. The system will comply with standards for use of power
8538 strips and will require appropriate temperature, humidity and air velocity sensors.

8539 **21.0.16 Risks**

8540 The largest risk in the data acquisition system is the corruption or the distortion of the
8541 positron time spectra (the calorimeter readout involves computation of derived T-/Q-method
8542 datasets from continuously digitized ADC samples). Another risk is delays in the software
8543 development of the data acquisition that would impact schedules for detector commissioning
8544 and data taking. A further risk is insufficient performance of the data acquisition hard-
8545 ware/software that would impact rates of data accumulation during running periods. The
8546 DAQ is assembled from commodity computing hardware so procurement and delivery is not
8547 a risk.

8548 **21.0.17 Quality Assurance**

8549 Kentucky has established a test stand for DAQ development, testing and quality assurance.
 8550 Our first stage of prototyping for calorimeter readout and event building is underway using
 8551 simulated data. A second stage of prototyping will begin this summer with the acquisition
 8552 of micro-TCA crate with MCH/AMC13 cards and continue this fall with the acquisition of
 8553 a single prototype digitizer. Other DAQ groups at UIUC and Oxford will also establish test
 8554 stands for DAQ development, testing and quality assurance for the tracker readout and the
 8555 DAQ control system.

8556 An important milestones for DAQ development is a single calorimeter test run planned
 8557 for SLAC in spring 2014 and a tracker sub-system test run planned for Fermilab in fall
 8558 2013. Stress tests and integrity tests of the DAQ components will be conducted using the
 8559 test stands at the various institutions. Software and support will be provided to other
 8560 institutions responsible for readout electronics and detector systems.

8561 **21.0.18 R&D**

8562 The collaboration has conducted a number of R&D projects to test the design components.
 8563 In particular, a number of R&D projects were conducted on the hardware / software imple-
 8564 mentation of the: (i) frontend processing of raw calorimeter ADC samples into T-/Q-method
 8565 datasets, (ii) event builder tasks of event fragment matching and event fragment assembly,
 8566 and (iii) coordination between the accelerator-controlled spill cycles and the the computer-
 8567 controlled readout cycles. In addition, a DAQ system was developed for beam tests of
 8568 calorimeter prototypes and evaluation tests of waveform digitizer systems.

8569 The MIDAS-based DAQ platform for R&D projects is shown in Figs. 21.3 and 21.4. It
 8570 comprises a network of three frontend processor and one backend processors. The backend
 8571 processor hosts the MIDAS server process MSERVER that manages inter-process commu-
 8572 nications, the MIDAS web daemon MHTTPD that provides run control, the MIDAS event
 8573 builder MEVB, as well as MIDAS data storage and analysis tools. Frontend processor FE01
 8574 comprised two quad-core Intel Xeon X5550 CPUs and a 1024-core, NVIDIA Tesla C1060
 8575 GPU. A calorimeter emulator in that enabled processor FE01 was used for development
 8576 work on GPU-based T-/Q-method processing of continuously-digitized ADC samples. A
 8577 GbE interface to two 12-bit, 500 MHz Struck SIS3350 waveform digitizer modules [4] was
 8578 used for both DAQ development work and prototype calorimeter tests. Another frontend
 8579 processor FEMB was connected to a Xilinx FPGA-based programmable pulser and used
 8580 to emulate the accelerator-defined spill cycles. Another frontend processor FEMB was used
 8581 for the synchronization between the spill cycles and the readout cycles. The platform was
 8582 arranged as a local network of disk-less, frontend processors with a backend server.

8583 Fig. 21.5 shows a typical spill of simulated data – *i.e.* 3.5×10^5 ADC samples of $700 \mu\text{s}$
 8584 continuous-digitization – that was Monte-Carlo generated by the calorimeter emulator. In
 8585 building streams of ADC samples, the decay positrons were generated with the appropriate
 8586 energy-time distributions for $3.094 \text{ GeV}/c$ decays and the calorimeter hits were generated
 8587 with appropriate x-y distributions and pulse shapes. The raw data were “read out” and
 8588 processed into T-/Q-method datasets in the DAQ frontend layer and then analyzed and
 8589 histogrammed in the DAQ analysis layer. Representative plots of T-method energy and

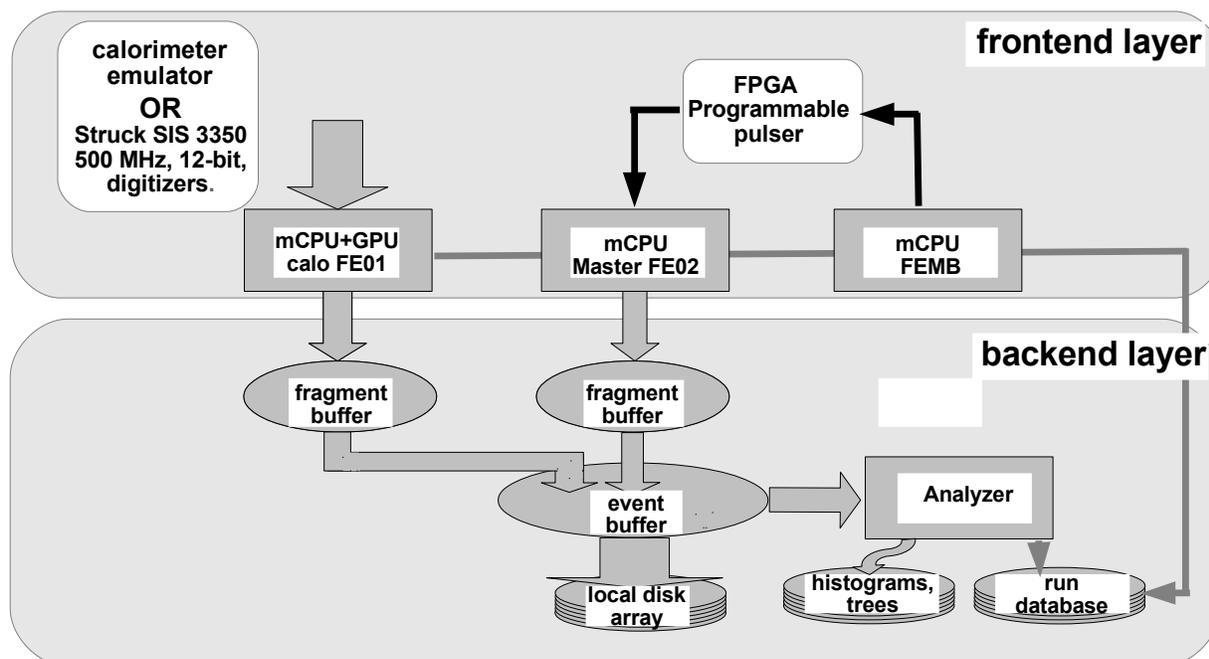


Figure 21.3: Layout of MIDAS-based DAQ-platform for R&D projects. The frontend FE01 incorporates both readout of emulated continuously-digitized ADC samples from a calorimeter simulation thread and real continuously-digitized ADC samples from a Struck SIS3350 digitizer system. The frontend FEMB emulates the Fermilab accelerator control signals and the frontend FE02 provides the software synchronization of spill-by-spill readout. The system also includes an event builder layer and data monitor layer.

8590 time distributions of decay positrons are shown in Fig. 21.6.

8591 Results from frontend timing tests of the GPU-based, T-/Q-method processing of the
 8592 simulated calorimeter data are shown in Fig. 21.7. After completing the read out of each
 8593 spill of ADC samples the raw data are transferred from the CPU memory to the GPU
 8594 memory. The GPU then initiates a sequence that involves: derivation of the segment-
 8595 summed calorimeter samples from the individual crystal segment samples, identification of
 8596 the T-method above-threshold pulses in the summed calorimeter samples, assembly islands of
 8597 the T-method above-threshold islands with pre-/post-samples, and transfer of the resulting
 8598 T-method data from the GPU memory to the CPU memory. Additionally, a Q-method
 8599 dataset was constructed by summing consecutive blocks of 32 ADC samples of digitizer data
 8600 and then copied from the GPU memory to the CPU memory. Finally, the T-/Q-method



Figure 21.4: Photograph of the DAQ test stand at the University of Kentucky,

8601 datasets are packaged into MIDAS databanks and transferred to the backend layer.

8602 Also conducted were timing tests of event building on simulated databanks in the back-
8603 end layer of the data acquisition. The tests showed the rate limitations in event building
8604 were largely governed by memory copy operations during event fragment assembly. For the
8605 backend processor in the R& platform – a six core, Intel i7 processor with 8 GBytes of
8606 high-bandwidth DDR3 memory – the DAQ was able to handle a 80 MB/s data rate of event
8607 building without introducing time delays.

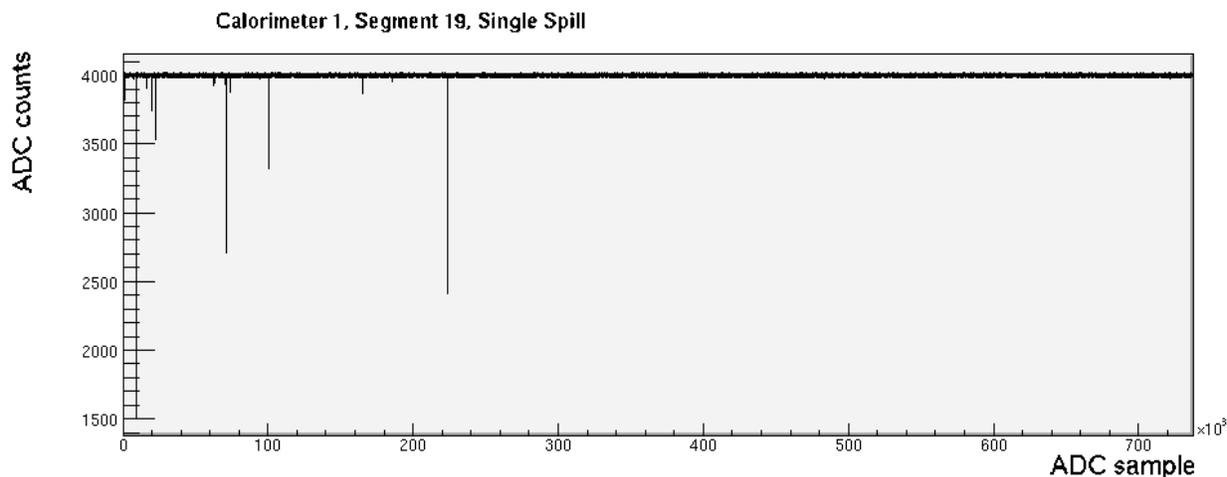


Figure 21.5: A representative single spill of simulated data generated by the calorimeter emulator. The data correspond to 3.5×10^5 ADC samples of $700 \mu\text{s}$ continuous-digitization for one segment of one calorimeter.

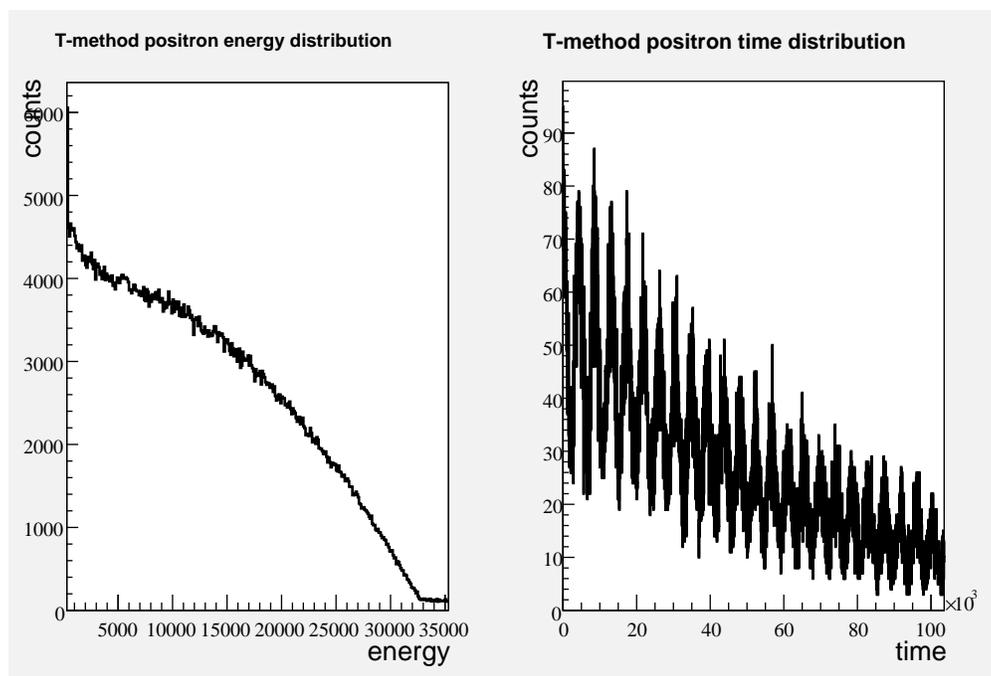


Figure 21.6: Energy distribution (lefthand plot) and time distribution (righthand plot) of energy / times of positron hits. The data were generated as continuous-digitization spills by the calorimeter emulator, were processed into T-Method datasets in the calorimeter, and histogrammed in the analysis layer. The energy distribution shows the positron endpoint energy and the time distribution shows the anomalous precession frequency.

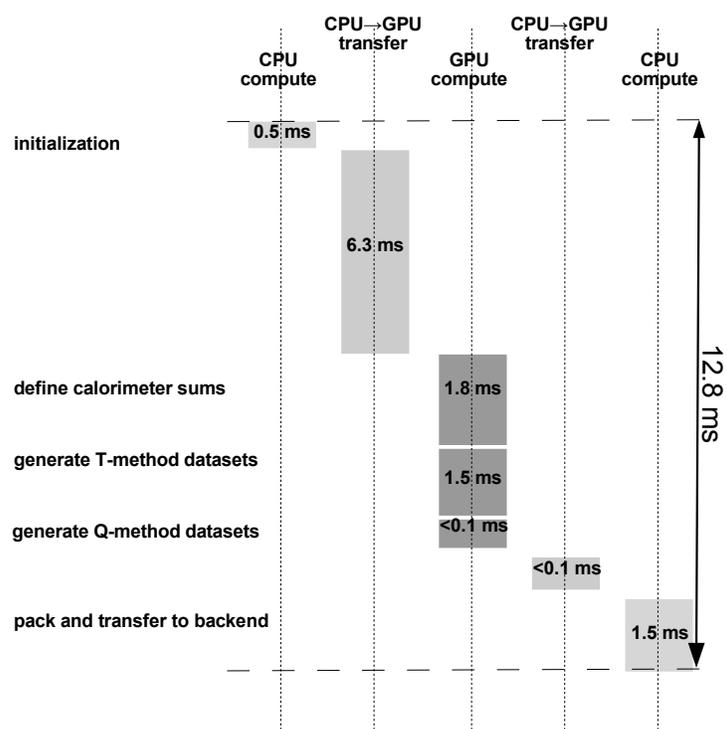


Figure 21.7: Schematic diagram of frontend processing of T-/Q-method datasets from simulated data of continuously-digitized ADC samples.

8608 References

- 8609 [1] V. Tishchenko, S. Battu, S. Cheekatmalla, D. B. Chitwood, S. Dhamija, T. P. Gor-
8610 ringe, F. Gray and K. R. Lynch *et al.*, Nucl. Instrum. Meth. A **592**, 114 (2008)
8611 [arXiv:0802.1029 [nucl-ex]].
- 8612 [2] E. Frlez *et al.*, Nucl. Instrum. Meth. **A526** (2004) 300; see also <http://midas.psi.ch/>.
- 8613 [3] Rene Brun and Fons Rademakers, Nucl. Instrum. Meth. **A389** (1997) 81; see also
8614 <http://root.cern.ch/>.
- 8615 [4] Struck Innovative System, Harksheider Str. 102A, 22399 Hamburg, Germany; see also
8616 <http://www.struck.de/>.
- 8617 [5] For example see <http://www.spectracomcorp.com/ProductsServices/TimingSynchronization>,
8618 Spectracom Corporation, 1565 Jefferson Road, Suite 460, Rochester, NY 14623.
- 8619 [6] D. A. Huffman, Proceedings of the Inst. of Radio Engineers, **40** (1952) 1098; see also
8620 <http://www.zlib.net/>.

Chapter 22

Slow Controls

22.1 Overview and general requirements

The g-2 muon storage ring experiment is a complex system that involves many subsystems for which adequate sensing and control during normal operation is required. The purpose of the slow controls and its data acquisition system is to set and monitor external parameters such as (high) voltages, currents, gas flows, temperatures etc. These tasks are essential for operation of the experiment over many months of data taking. The immediate online feedback allows to monitor the quality of the incoming data and react to changes in the running conditions. In addition, some of these variables can be extremely helpful in understanding trends in the analysis and relate shifts in the main observables to the change in running conditions. For example, unprecedented gain stability via precise control of bias voltages for the silicon photo-multiplier readout of the electron calorimeter is required to meet the systematic error budget for ω_a . While the gain stability of these photo-detectors will be monitored at the 10^{-3} level or better via a dedicated laser calibration system, immediate feedback on the two parameters (bias voltage and temperature) determining the gain of these devices is achieved via such continuous monitoring. There are plenty of other cases where such external parameters will be useful in this high precision measurement to establish a full understanding of all systematic errors.

For setting and read-back of parameters, the slow control system must provide sufficient sensors or control units which will either be directly integrated into the design of new subsystems or come as external devices. Most of these systems will connect to the slow control DAQ via the Midas Slow Control Bus (MSCB) which is a cost effective field bus developed at the Paul Scherrer Institute (PSI), Switzerland. This very mature system has been successfully employed in other similar experiments and allows for easy integration into the envisioned data acquisition framework MIDAS. The slow control DAQ will also include communication interfaces to other external systems like the main g-2 storage ring controls (iFix) and the Fermilab accelerator over ACNet to allow for the exchange of data. Other external devices like the μ TCA crates for the readout electronics of the electron calorimeter will need to be interfaced as well as to monitor their operational status.

The demand and read-back values for all parameters controlled by the slow control system need to be stored in a convenient database such as MySQL or PostgreSQL. While a local copy

8653 of the data will be available for online monitoring and analysis, the copy will be transferred
8654 to a Fermilab database server for long-term storage. For efficient usage of the read-backs
8655 during data taking, user friendly visualization tools have to be provided in order to easily
8656 access the stored database information. A web browser based framework will be developed
8657 to display the large amount of different channels monitored by the system. Such script based
8658 tools are easy to expand and offer an interface for users without the need of installation of
8659 special software tools.

8660 Critical subsystems of the detectors might require special handling in case of unsafe
8661 running conditions. A stand-alone alarm systems will provide necessary interlocks and other
8662 measures for such situations. For example, the gas flow of the straw tracker will be monitored
8663 and shutdown in case of flow read-backs that are out of a specified normal range. Other
8664 critical systems like the cryogenic and vacuum controls of the g-2 ring will be embedded
8665 in a special PLC system. In the current design, no direct communication between the two
8666 systems has been designed but it is anticipated that the two systems might be interlinked.
8667 The alarm system within the slow control system will provide all measures in case of unsafe
8668 running conditions to comply with possible regulations.

8669 **22.2 Recommended Design**

8670 **22.2.1 Software and hardware architecture**

8671 The slow control will comprise a variety of sensors and control units described in more de-
8672 tail in the following section. Some of these systems will be purchased as single units (like
8673 power supplies) and interfaced via serial or parallel standard (like RS232, GPIB). Other
8674 subsystems will be custom-built and their design requires integration of an appropriate slow
8675 control interface. The usage of field buses like CAN, Profibus and LON are not justified as
8676 their integration requires significant effort. Instead, we will employ the Midas Slow Control
8677 Bus (MSCB, <http://midas.psi.ch/mscb>) which is a field bus developed at PSI. This sys-
8678 tem was optimized for the environment of a typical physics experiment and cost-efficiency
8679 (typically \$20 per node). In addition, it conveniently integrates into the MIDAS data acqui-
8680 sition (<http://midas.psi.ch>) which is the basic design choice for the slow control computing
8681 infrastructure.

8682 The MSCB as a mature system will be the default choice for all sensors and control
8683 units that are custom built for the g-2 experiment. The MSCB is based on the RS485
8684 protocol which is similar to RS232 except for employing differential signals for superior noise
8685 immunity. RS485 is a multidrop half duplex so that many nodes can be connected to the
8686 same bus but only one can send data at a time. Hence, a single submaster can facilitate the
8687 communication between the MIDAS host computer and up to 256 individual MSCB nodes.
8688 In fact, by employing a layer of repeaters up to 65536 nodes can be operated on a single bus
8689 with up to a few km long cables. The MSCB requires two signal wires for the differential
8690 signal and a ground wire. Three additional lines provide power (+5 V, ± 12 V). The usage of
8691 a 10-wire flat ribbon cable provides four additional digital lines for application specific usage.
8692 Figure 22.1(a) shows one of the available submasters that can be purchased from PSI. Given
8693 the simple MSCB protocol, a typical node remains relatively compact like for example the

8694 SCS100 shown in Fig. 22.1(b) that contains DACs, ADCs and an integrated temperature
 8695 sensor for the on-board micro-controller. For g-2 specific applications, the development of
 8696 new nodes is a viable option which we will employ for some systems in the g-2 setup (e.g. the
 8697 bias voltage module for the electron calorimeter). The alternative is to purchase the more
 8698 integrated SCS2000 unit with appropriate MSCB daughter cards for various applications.
 8699 This possibility will be explained in more detail in the section 22.2.2 below.



(a) MSCB ethernet submaster



(b) SCS100 MSCB node with DACs, ADCs and integrated temperature sensor.

8700 The MSCB protocol is byte oriented and uses the bit 9 from RS232 for addressing pur-
 8701 poses. As this bit usually cannot be switched on and off fast enough in the UART of a PC,
 8702 simply using RS232-RS485 converters is not sufficient. This can be overcome by employing
 8703 a submaster on the computer side with a micro-controller to provide the handshake with the
 8704 PC and enough memory to avoid data loss. In this scheme, bit rates of up to 345600 baud
 8705 are sustainable.

8706 As mentioned before, the MIDAS software framework will be used for the slow control
 8707 data acquisition computer(s). Straightforward integration of MSCB based hardware is al-
 8708 ready provided by appropriate drivers integrated into the software package. The end user has
 8709 to provide an application specific frontend module to control the specific sensor or control
 8710 unit, i.e. to set and readout parameters of the hardware system. Setting of the parameters
 8711 such as detector voltages or the readout rates of sensors are handled by corresponding set-
 8712 tings in the online database (ODB) on the slow control computer. A backend main server
 8713 will handle the collection of the readout data with an adapted event builder provided in the
 8714 MIDAS software. The assembled MIDAS events from all slow control subsystems are then
 8715 handed off to a data logger module which will store the data in an SQL based database
 8716 locally as well as transfer it to the Fermilab long-term storage server.

8717 Figure 22.1 shows the basic layout of the slow control system in the g-2 experiment
 8718 indicated by the solid colored boxes. A single slow control backend host (brown box) manages
 8719 the communication with all MSCB nodes (blue boxes) via the MSCB submaster (green box).
 8720 Non-MSCB based sensor and control nodes (purple boxes) will communicate directly with the
 8721 backend server via appropriate interfaces (e.g. USB, RS232, ...). During the development

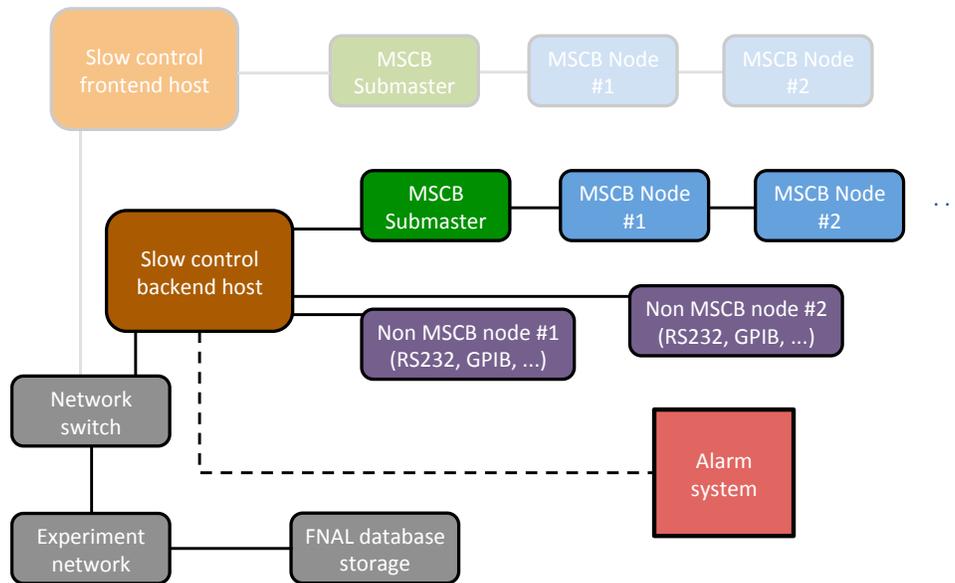


Figure 22.1: Slow control system for the g-2 experiment: The basic layout includes a backend host (brown box) which manages the communication with all MSCB nodes (blue boxes) via the MSCB submaster (green box). Non-MSCB nodes (purple boxes) directly connect to the backend via the appropriate interface (USB, RS232, ...). Lightly shaded boxes refer to possible frontend computer(s) with their own MSCB bus and nodes for dedicated applications which would communicate and exchange data with the backend server via ethernet network. The stand-alone alarm system (red box) will provide adequate measures to handle unsafe running conditions.

8722 phase of the g-2 experiment, we expect several institutions to setup their own MIDAS and
 8723 MSCB host computers for testing of individual components (e.g. the MSCB interface for the
 8724 SiPM bias voltage control). Although a single main PC and submaster would be sufficient to
 8725 handle all MSCB nodes in the g-2 experiment, these additional available host computers with
 8726 their MSCB submaster and nodes could be easily integrated into the slow control system.
 8727 Therefore, the final implementation in E989 might involve additional MSCB frontend hosts
 8728 to control special subsystems as indicated by the light shaded chain of boxes in Fig. 22.1.
 8729 Data exchange between a frontend computer and the slow control backend computer happens
 8730 via ethernet network. This scheme adds redundancy to the system in case of maintenance
 8731 or failure of one of the computers since MSCB nodes and their appropriate MIDAS software
 8732 frontend can be easily moved from one to another computer. The system is completed by a
 8733 stand-alone alarm system (red box) to provide appropriate actions in case of unsafe operating
 8734 conditions of various subsystems.

8735 In the following subsection, we will describe the sensors and control units, their require-
 8736 ments and the institutional responsibility. Thereafter, the conceptual design of the alarm
 8737 system, the backend server and the data storage are outlined.

8738 **22.2.2 Sensors and controls**

8739 The g-2 experiment will employ a variety of systems to facilitate the overall measurement
 8740 of the muon anomalous magnetic moment. Figure 22.2 displays the current required func-
 8741 tionality for a variety of systems (as depicted by the individual nodes). Solid boxes denote
 8742 systems that are currently known to have direct interfacing to the slow control whereas
 8743 lightly shaded nodes are currently interfaced by the fast calorimeter DAQ system (see 21).

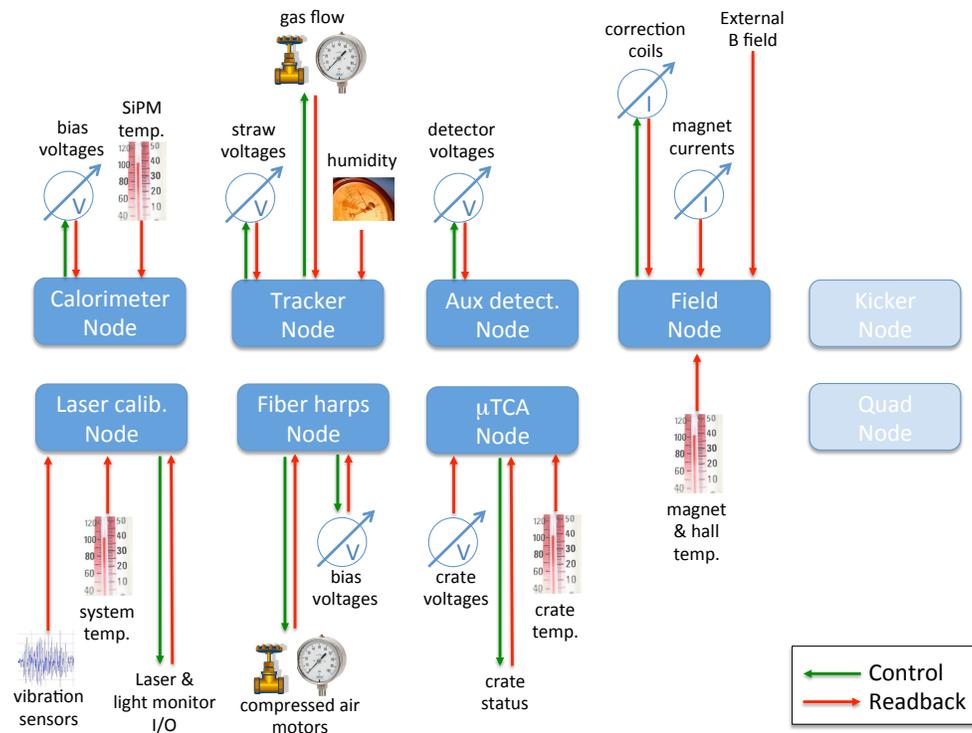


Figure 22.2: Schematic breakdown of the individual slow control nodes with individual control of parameters and sensor read-backs. More details are given in the text.

8744 The corresponding table 22.1 lists the actual parameters set and monitored via the slow
 8745 control. The read-back precision, rates and channel counts are preliminary estimates as
 8746 far as they are known today and will be subject to change with advancing design of each
 8747 system. The photo-readout of the electron calorimeter for the spin precession frequency will
 8748 be based on silicon photo-multipliers (see section 17). The design incorporates a surface
 8749 mount SiPM on a readout board integrating the bias voltage supply and an amplification
 8750 of the readout signal. Since the experiment requires high gain stability, a stabilization and
 8751 monitoring of the two external parameters that determine the SiPM gain, namely the bias
 8752 voltage and temperature, is required. While the bias voltage of each SiPM channel is set
 8753 and monitored separately for each channel, the temperature sensors will only be placed at a
 8754 few locations inside each calorimeter station. The associated laser calibration system which
 8755 monitors absolute gain changes will require a monitoring of the laser and light distribution
 8756 system's temperature at several locations. Due to the usage of diffusing spheres for the laser

8757 distribution and their sensitivity to small mechanical movement, a vibration monitor is most
 8758 likely needed during operations. It would consist of a 3-axis inclinometer and be integrated
 8759 over a second so that readout rates of the order of less than 1 Hz are required. In order to
 8760 control and enable the system, a few I/O channels will be necessary. Depending on the final
 8761 implementation of the laser system, somewhere between 2 and 48 channels for each input
 8762 and output are necessary. Finally, some of the available lasers under consideration have a
 8763 serial (USB, RS232) interface to control and read-back the laser status.

8764 The tracker system comprises two stations of in-vacuum straws located in two scallop
 8765 regions. The slow control will provide readings for ambient temperature, humidity, and
 8766 pressure at the two locations. It will also monitor the gas flow and temperature as well as
 8767 currents and high voltages for the 36 individual substations. The system will provide the
 8768 setting of the high voltage demand values as well as their read-backs. The stand-alone alarm
 8769 system (see section 22.2.4) will provide interlocks for immediate shutdown of gas and HV in
 8770 case of irregular running conditions.

Table 22.1: List of control and read-back parameters in g-2 handled by the slow control unit with anticipated read-back precision and rates, channel counts and the institutional responsibility for the implementation of the actual devices.

Parameter	Read-back precision	Read-back rate	Channel count	Responsibility
Calorimeter				
SiPM bias voltage	\sim mV	0.1 Hz	1300	UVa, JMU
preamp voltage	0.1 V	0.01 Hz	24	UVa, UW
SiPM temperature	0.1° C	0.1 Hz	\sim 75	ANL, UW
Laser calibration				
Laser temperature	$<$ 0.5° C	$<$ 1 Hz	$<$ 10	INFN, ANL
Vibration monitor		$<$ 1 Hz	\sim 10	INFN
Output signals (enable)			$<$ 48	INFN
Input signals			$<$ 48	INFN
Serial laser interface	–		$<$ 10	INFN
Tracker				
Voltage	\sim 1 V	$<$ 1 Hz	36	FNAL
Current		$<$ 1 Hz	36	FNAL
Amb. pressure		$<$ 1 Hz	2	FNAL, ANL
Amb. temperature	$<$ 0.5° C	$<$ 1 Hz	2	FNAL, ANL
Amb. humidity		$<$ 1 Hz	2	FNAL, ANL
Gas flow		$<$ 1 Hz	36	FNAL
Gas temperature		$<$ 1 Hz	36	FNAL
Fiber harps				
SiPM bias voltage	few mV	0.01 Hz	2	Regis
preamp voltage	0.1 V	0.01 Hz	2	Regis
SiPM temperature	0.1° C	0.1 Hz	4	ANL

Table 22.1 – *Continued from previous page*

Motor control	-	-	4	Regis, ANL
t_0 & flashlet counter				
PMT HV	$\sim 1V$	0.01 Hz	2	Regis
General				
Yoke temperature	$< 0.5^\circ C$	< 0.01 Hz	~ 20	ANL
Hall temperature	$< 0.5^\circ C$	< 0.01 Hz	~ 5	ANL

8771

8772 The fiber harp detectors will be equipped with high and low voltage power supplies that
 8773 have some serial interface for the communication so that remote control and readback of the
 8774 voltages is possible. As the SiPMs for the readout of the fibers are grouped in 4 rows of 7, we
 8775 anticipate monitoring the SiPM temperatures with one probe per row so that four sensors
 8776 are required. As the fiber harps are rotated into the beam by compressed air actuators, 2
 8777 control channels and readbacks of these must be available.

8778 The auxiliary detectors node in Fig. 22.2 includes all future additional counters that
 8779 might be added to the g-2 setup. At this moment, it only comprises the so-called t_0 flashlet
 8780 counter which is a scintillator paddle with standard PMT readout that requires a single
 8781 channel HV power supply with a serial interface for remote communication.

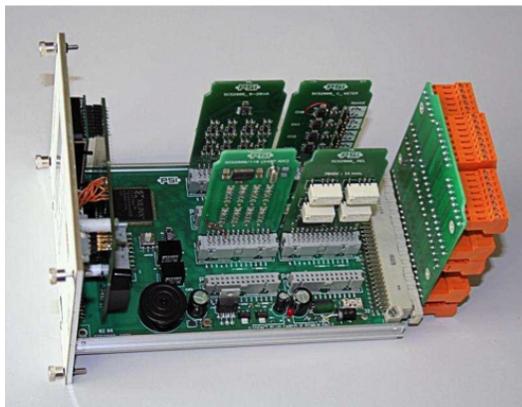
8782 The μ TCA node comprises the communication between the slow control DAQ and the
 8783 μ TCA crates via the Remote Management Control Protocol to monitor the status of each
 8784 crate. As we are mainly reading status parameters provided by the crate, most likely no
 8785 additional sensors will be required. Some more details about this communication interface
 8786 will be covered in the following section 22.2.3.

8787 The field node in Fig. 22.2 includes possible readouts of the main magnet and the
 8788 correction coil currents as well as external fluxgate monitors. While these readbacks will be
 8789 recorded, they are currently not explicitly listed in Table 22.1 since it is most likely that
 8790 these are stored by the DAQ for the fixed NMR probes.

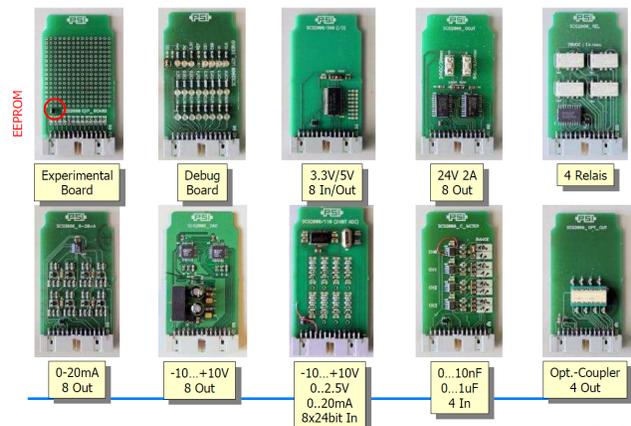
8791 Many of the systems described above include temperature readout channels. In addition,
 8792 we will monitor the ambient hall and magnet yoke temperatures at approximately 25 addi-
 8793 tional locations. Since changes in the magnet temperature are the main driver for changes
 8794 in the field homogeneity, a monitoring of the temperature will allow detection of any irreg-
 8795 ular temperature trends which could be caused by a deterioration of the magnet insulation.
 8796 Overall, we expect a total of ~ 100 temperature probes with a readback precision of at most
 8797 $0.1^\circ C$. Since we are mostly sensitive to temperature changes, the absolute accuracy is of
 8798 less importance. For the implementation of these temperature sensors, we plan to use the
 8799 available general purpose SCS2000 unit¹ shown in Fig. 22.3(a). The SCS2000 provides the
 8800 MSCB communication over Ethernet via the MSCB submaster with the PC. The unit has
 8801 an on-board programmable logic device (CLPD, Xilinx XC2C384) which handles the MSCB
 8802 protocol on one side. On the other end, there are slots for 8 independent MSCB daughter
 8803 cards which are each accessed by the CLPD via a 2-lane SPI and a parallel 8-bit bus. The
 8804 available daughter cards come with a multitude of different functions. Examples are shown in

¹At the time of the expected purchase, the successor SCS3000 will be available which provides the same functionality but adds a graphics display for direct user interaction and immediate status feedback.

8805 Fig. 22.3(b) and the complete set of these daughter cards comprises functions like standard
 8806 I/O channels, 24-bit ADCs, current sources, valve controls, and many more. This system is
 8807 successfully employed in the MEG experiment at PSI and therefore, the set of typical slow
 8808 control functionality is available. Because the MSCB protocol and communication is handled
 8809 by the central CPLD in the SCS2000, the layout of the daughter cards is pretty simple and
 8810 the whole package offers a relatively cost-efficient solution. For the above mentioned ~ 100
 8811 temperature channels, we plan on using an existing 8-channel temperature daughter card
 8812 based on the Analog Device AD590 2-terminal temperature transducer. Since each channel
 8813 senses the current in the AD590, long cables of more than 10 m can be used so that the
 8814 SCS2000 unit(s) may be located at the center of the ring. Unused card slots in the two
 8815 SCS2000 can be used for additional other functionality.



(a) SCS-2000 general purpose control unit.



(b) Examples of available SCS200 daughter cards.

8816 Figure 22.2 also shows two nodes (Kicker and Quads) in a lighter color indicating that
 8817 these are currently not foreseen to be integrated into the slow control system. Since both
 8818 systems operate at the frequency of the muon injection, the readback of these is handled by
 8819 the fast DAQ (described in section 21) which has fill-by-fill synchronization. This scheme
 8820 eliminates the need for a precise timestamp synchronization of the slow control DAQ with
 8821 the muon fills.

8822 22.2.3 Communication with external systems

8823 The slow control DAQ will not only retrieve data from the various sensors described above
 8824 but also communicate with other systems in the g-2 experiment and the Fermilab accelerator
 8825 infrastructure. As of now, there are a total of three such systems. Communication will need
 8826 to be established with the main ring control system, the Fermilab accelerator complex, and
 8827 the μ TCA crates for the readout of the electron calorimeter stations. In the following we will
 8828 shortly describe some more details about the three communication methods to the extent
 8829 relevant for the conceptual design of the slow controls.

8830 The ring control system for the cryogenics and vacuum is based on PLC interfaces which
 8831 are accessed via the human machine interface iFix. Figure 14.1 shows the schematic layout
 8832 for this complex system. As can be seen in the figure, the communication path (thick double

8833 arrow) between the iFix server (bottom left rectangle) and the slow control computer (bottom
8834 middle computer labeled “Physics DAQ system”) will be facilitated via an OLE for Process
8835 Control (OPC) server integrated into iFix. The communication on the slow control DAQ
8836 side is handled by an OPC client which is available as commercial or open-source products
8837 for the Linux based system.

8838 During the g-2 operation, some parameters of the accelerator (like magnet currents,
8839 beam intensities, status of other beam elements) will be stored in the output datastream.
8840 This information can be retrieved via a data broker from the accelerator network (ACNet).
8841 Retrieval of accelerator related parameters is already implemented at Fermilab in the larger
8842 context of a beam database for the intensity frontier experiments (IFbeam) and we will be
8843 able to benefit from this existing implementation by adapting it to our needs and software
8844 infrastructure. The data is usually stored in PostgreSQL format and can be integrated into
8845 our experimental condition database.

8846 A third system that we want to establish communication with are the μ TCA crates for
8847 the readout of the electron calorimeters and possibly other electronics in the experiment.
8848 These crates typically provide internal status parameters (e.g. temperature, fan speeds,
8849 error indicators etc.) that are useful to monitor to quickly identify hardware problems or
8850 failures. System management and monitoring is achieved by means of software solutions
8851 based on the Intelligent Platform Management Interface (IPMI), a standardized computer
8852 system interface. A variety of user interfaces can be employed such as web-based GUIs or
8853 programmatic interfaces. The latter comprise the Simple Network Management Protocol, an
8854 industry standard and the Remote Management Control Protocol (RMCP) which supports
8855 the IPMI commands over IP. For now we anticipate establishing an RMCP based client on
8856 the slow control side to establish the required monitoring and communication with these
8857 central electronics infrastructure in the g-2 experiment.

8858 **22.2.4 Alarm system**

8859 A stand-alone alarm system will serve the purpose of allowing quick and safe shutdown of
8860 certain elements of the g-2 detectors. Similar functionality via the slow control software by
8861 changing the demand values of high voltages or a valve status is typically not immediate and
8862 for some components of the experiment, the availability of hardware interrupt is preferable. It
8863 should be noted that there will be a separate PLC based system handling the more critical
8864 components like the cryogenics of the magnet as well as vacuum controls. The system
8865 described here will deal with detector components which are not critical in the sense of life
8866 threatening unsafe conditions. The interrupts provided by the alarm system are mainly
8867 for protection of the detector components and other systems. While this functionality will
8868 ideally be unused during operations, it could be beneficial of having such a system readily
8869 available in case of unforeseen changes in the experimentl conditions.

8870 At this moment, we plan to provide hardware interlocks for the high voltages and the
8871 non-flammable gas for the straw detectors which are located inside the vacuum. Scenarios
8872 necessitating shutdown of voltages and gas flow could be vacuum leaks in the ring vacuum
8873 chambers, overheating or high fluctuations in the straw current that could indicate a devel-
8874 oping problem. An interlock for the laser calibration system might be useful to protect the
8875 system in case of overheating or other abnormal parameters. Similarly, hardware interlocks

8876 for the SiPM bias voltages could be provided in the same scheme if the request for it arises.

8877 Given the experience with other similar experiments, such an alarm system typically
 8878 is expanded over time because additional useful interlocks are identified during the design,
 8879 testing and implementation of detector systems. Therefore, we will adopt a simple basic
 8880 concept using relays for the various interlock mechanisms. Figure 22.3 shows the schematic
 8881 design for the system. Components that form a group and are interlocked at the same time
 8882 will be connected to their own relay (Double Pole Double Throw type). The relay's actuator
 8883 for such a group is triggered by different sources like the backend computer or a direct
 8884 hardwired signal. For example, the straw tracker gas flow and high voltage system might be
 8885 shutdown if the vacuum exceeds a defined threshold. As the vacuum control and readback
 8886 happens in the PLC, the actuator trigger might come directly from an output channel of
 8887 the PLC system (see section 14). On the other hand, an interlock of the laser system might
 8888 only be required if the readback temperature of this system rises above a threshold. As this
 8889 presumably is a slow process and not time critical, the interlock signal can come from the
 8890 slow control computer monitoring these temperature readbacks.

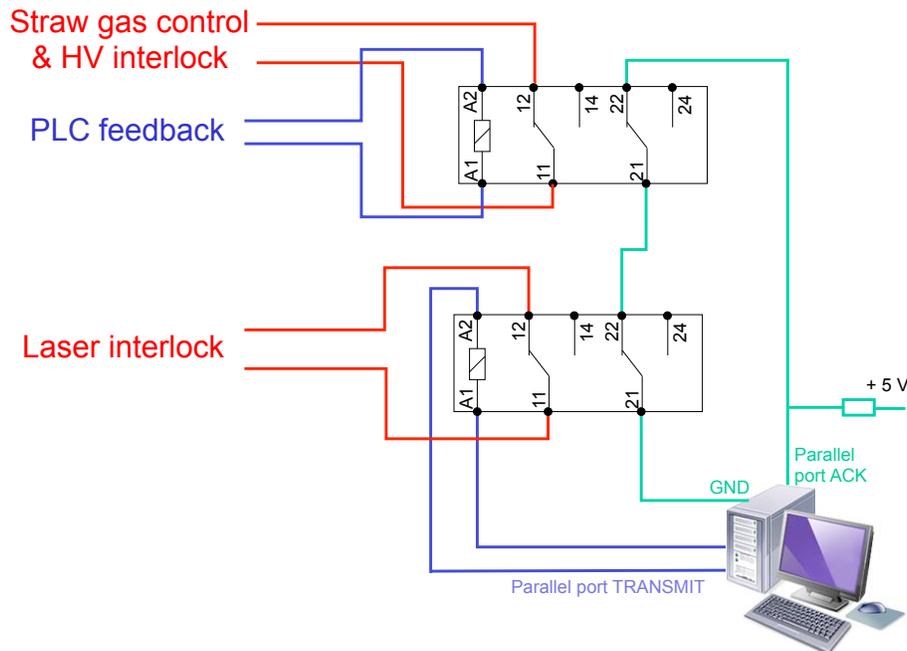


Figure 22.3: Basic conceptual design for the stand-alone slow control alarm system with two exemplary interlock groups (straw detector and laser).

8891 The interlocks for each groups are actually activated by the first internal relay switch
 8892 (contacts 11, 12, 14). The second relay switch (contacts 21, 22, 24) can be used to form a
 8893 serial loop monitored by the slow control computer's parallel port (acknowledge channel).
 8894 A triggered actuator of any of the serialized relays would then trigger an alarm on the
 8895 computers in the g-2 control room. Depending on the criticality of each system, a triggered
 8896 relay interlock might also include to set off an alarm siren and flashing light. The details
 8897 of these alarm feedbacks have to be decided for each system. If necessary, one can setup
 8898 multiple computer feedback loops by adding parallel port interfaces. The concept is very

8899 modular and easily expandable.

8900 It should be noted that the basic concept will be based on the underlying general layout
8901 that systems need positive approval (i.e. a running computer, powered PLC system etc.) in
8902 order to be functional.

8903 **22.2.5 Backend server**

8904 The backend server is the central computer in the slow control DAQ to communicate with
8905 the various control units and sensors and retrieve all readbacks. Since data rates on the
8906 slow control backend server are low (less than 1 MB/s), a standard modern Linux desktop is
8907 sufficient. It should provide enough interfaces (RS232, USB, MSCB) for the external devices.
8908 As mentioned above, we will work within the MIDAS software framework to coordinate the
8909 different tasks. The various sensors and controls can be accessed individually by independent
8910 frontend programs which run in parallel within the main MIDAS server. Each frontend has
8911 its specific functionality to set experimental parameters (like high voltages for each SiPM),
8912 readback parameters, and allow to change readback rates. For MSCB devices, the necessary
8913 hardware drivers are provided by MIDAS so that the actual implementation of the frontends
8914 is simplified. For other hardware connecting to the backend over RS232 or USB, MIDAS
8915 also includes software components that will make integration of these subsystems into the
8916 slow control easier. Such frontend code has been developed previously like for the MuLan
8917 and MuCap experiments at PSI by some of the current E989 collaborators. Therefore, the
8918 implementation of the various frontends for all sensors and controls should not pose a major
8919 effort.

8920 **22.2.6 Data storage and access tools**

8921 For the data storage of slow control parameters, we will use a SQL-based database format
8922 (MySQL or PostgreSQL). While MIDAS has already built in options for MySQL handling,
8923 Fermilab's preferred choice is PostgreSQL which is the current anticipated choice for E989.
8924 Integration of PostgreSQL capabilities into the MIDAS framework should be feasible with-
8925 out too much additional effort. The backend server will have standard ethernet network
8926 connection(s) for the communication with external systems (see section 22.2.3) and synchro-
8927 nization of the local database with the remote long term storage at Fermilab. We will employ
8928 the automated script-based mechanisms developed at Fermilab for this purpose. Overall, the
8929 database handling and storage is expected to nicely integrate into the existing infrastructure.

8930 Any data acquisition requires a well designed interface for the online monitoring and
8931 during the offline analysis. For example, a user friendly visualization interface to inspect
8932 the large number of different channels (the calorimeter alone has 1300 channels) is very
8933 essential during data taking. Based on past developments for muon precision experiments
8934 at PSI and current other Intensity Frontier experiments at Fermilab, we will have a variety
8935 of options to establish such tools. The IFbeam software tools incorporate the python based
8936 Web Server Gateway Interface and subsequent Google Charts to access and display database
8937 information in the web browser. The experiments at PSI, MuLan and MuCap, used custom
8938 developed web browser based tools to query and display the database information as well
8939 as standalone graphics displays within the ROOT framework. At this point, it is not clear

8940 which exact tools we will use for E989. In general, usage of a single tool will increase user
8941 friendliness but it could be advantageous to have optimized tools for various different data
8942 streams. However, the specific implementation will profit from extensive former experience
8943 which will guide the collaboration in making the final decisions in the future.

8944 22.3 Alternative Design Considerations

8945 The information recorded by the slow digitization DAQ is quite independent from any other
8946 DAQ system in g-2. Therefore, we have investigated the usage of alternative software pack-
8947 ages like the ORCA system. The collaboration has used this system in the ongoing SiPM
8948 tests at UW in order to gain practical experience with this system. Another option is the
8949 EPICS software which is well supported at the Advanced Photon Source at ANL and at
8950 FNAL. However a careful comparison of the three systems has revealed that MIDAS is our
8951 best choice for the software framework for the slow control DAQ. Its major advantages are
8952 the fact that several of the g-2 collaborators have many years of experience with this system.
8953 It has been used successfully by a variety of experiments at PSI and other laboratories. We
8954 also have a good relationship with the main developers of MIDAS at PSI. Last but not least,
8955 synergies with the fast detector DAQ are obvious as it is based on the same framework. The
8956 amount of maintenance and debugging reduces and collaborators on shifts will only need to
8957 familiarize themselves with the subtleties of one system.

8958 The default choice of the MSCB for hardware components is tightly connected to the
8959 decision for using the MIDAS framework as the latter has easy integration of MSCB compo-
8960 nents. In addition, the MSCB is optimized for cost efficiency. We have looked into the usage
8961 of more commercial products (e.g. National Instruments hardware with possible integration
8962 into LabVIEW) but such systems would simply increase the cost. In addition, some of our
8963 systems require custom built components (e.g. the extremely stable low voltage power sup-
8964 ply for the SiPM) and therefore, we can profit from the simplicity of the MSCB protocol.
8965 Finally, the MIDAS and MSCB framework is very open and we have good connections to one
8966 of the experts of this system at the Paul Scherrer Institute, Switzerland. We are therefore
8967 confident, that development of new modules should be feasible with limited effort. It should
8968 also be noted, that we can still rely on non-MSCB off-the-shelf components if it turns out
8969 that they are an optimal choice to control or monitor some of our subsystems. Communica-
8970 tion with such devices via typical standards of RS232 or USB is available within the MIDAS
8971 framework. Our default choice is therefore very modular and expandable but comes at a
8972 quite optimal cost.

8973 The alarm system is based on a simple relay concept. There has been good experience
8974 with this concept in the muon capture experiment MuCap at PSI where it was used to
8975 interlock critical detectors in a similar way as proposed. The stand-alone design (i.e. separate
8976 form the main PLC-based control system, see section 14) has the advantage that we can
8977 operate detector systems separately which might be very useful during beam tests before
8978 the real data taking. However, while the design of the subsystems evolves, it might turn out
8979 that this basic concept is inadequate for some of our applications. In that case, we have the
8980 alternative to integrate the monitoring and interlock functionality into the PLC based system
8981 described in section 14. This will most likely require additional hardware in form of control

8982 and sensor boards, i.e. more channels for the system. Due to the more complex nature of
8983 this system, the costs per channel are significantly higher than in the current default design
8984 and the implementation of this alternative was dismissed.

8985 22.4 ES&H

8986 The slow control system will involve sensor and control units that mainly need low voltages
8987 and currents for operations. If high voltages (like for the SiPM bias voltage or the PMT
8988 voltage) are involved, adequate protection (shielded cables, enclosed and fused electronic
8989 components) will be employed to comply with Fermilab's safety rules. The components for
8990 the slow control do not require any hazardous materials and there are no mechanical hazards
8991 since the components are typically small.

8992 The alarm system included in the design of the slow control will mainly interlock non-
8993 critical components to prevent direct damage to the hardware. It does not include any
8994 life-threatening hazards.

8995 22.5 Risks

8996 The default design of slow control relies on the mature MSCB system that has been success-
8997 fully employed in several experiments. Therefore, there is only a small risk that components
8998 will not work appropriately to the specified requirements. Certainly, the exact design and im-
8999 plementation of the stringent bias voltage system for the SiPMs in the calorimeter is crucial
9000 in succeeding to meet the gain stability. This specific risk is considered in the calorimeter
9001 section (see Sec. 17). Other sensors (like temperature, voltage, currents etc.) are read-
9002 ily available and should be sufficient to meet the requirements in the E989 experiment. If
9003 not, a design of an appropriate component would require additional resources. Since the
9004 implementation of the MSCB nodes is pretty simple, the associated cost risk is rather small.

9005 A failure in meeting the specified requirements for controlling devices and read back of
9006 performance parameters potentially causes an inability of detecting a loss in the data quality
9007 during the experiment. This could result in the necessity of dismissing data from the analysis
9008 and could result in the need of longer data taking to acquire the full statistics.

9009 During the design phase of various subsystems, it could be found that the current design
9010 of the alarm system based on a simple relays layout is inadequate. Examples for such a
9011 diagnosis could be that the systems is not reliable enough, that it is not compliant with
9012 safety rules that require a more complex system to interlock detectors, that the response is
9013 not fast enough. In that case, we might need to integrate its functionality into the more
9014 complex PLC based main control system (see section 17). The probability for this risk is
9015 very low since we already have good experience with the current scheme from the muon
9016 capture experiment at PSI. However, if realized it would certainly increase the costs as we
9017 would need additional labor resources to transfer the functionality to the different system
9018 and come up with an adequate design. In addition, we would need to purchase necessary
9019 hardware channels to control, monitor and interlock the systems appropriately.

9020 Any components installed close to the precision magnetic field (especially electronics

9021 circuits with time-varying currents) can cause a static or dynamic distortion to the homo-
9022 geneity of the field and possibly decrease the precision in its measurement. Mitigation of this
9023 risk is achieved by using non-magnetic materials close to the field region and by testing all
9024 components for their magnetic properties in a 1.45 T test magnet and with special designed
9025 pickup coils for transient fields.

9026 **22.6 Quality Assurance**

9027 The implementation of the slow control system relies on well established software in form
9028 of the MIDAS framework. In addition, we will employ the very matured MSCB hardware
9029 whenever possible or purchase commercially available systems. Quality assurance measures
9030 are therefore mainly limited to verifying that custom-built sensors and control units meet
9031 the requirements that all systems work properly and comply with all safety regulations. We
9032 will extensively test individual components and the full system in dedicated bench tests
9033 before the final installation in the experimental hall. As outlined in the risks, these tests
9034 will include the verification of the stringent magnetic requirements for components installed
9035 in the vicinity of the precision magnetic field of the storage ring.

9036 Since the slow control provides an online monitoring of the status of many systems in
9037 the g-2 experiment, care will be taken to properly design the appropriate visualization tools
9038 providing easy access to all parameters. This will be an important component in detecting
9039 any changes in the quality of the collected data during the experiment.

9040 **22.7 Value Management**

9041 The usage of freely available open-source MIDAS software and the specifically cost-optimized
9042 MSCB hardware is key in keeping the slow control systems overall cost low. Some compo-
9043 nents that cannot be readily purchased (like the SiPM bias voltage supply with its stringent
9044 requirements, see section 17.2.3) and need to be custom-built. Most of these will be designed
9045 and implemented by collaborators at universities and outside the US in order to keep the
9046 overall cost low. At the same time, the centralized integration of all components at Argonne
9047 will allow to verify the full system and detect any interference of different sensors or control
9048 units.

9049 **22.8 R&D**

9050 Necessary R&D for custom-built components that will be integrated in the slow control
9051 system is performed by some of the collaborating institutions and will be described in the
9052 appropriate sections in this document. Examples for these are the SiPM bias voltage supply
9053 (section 17.2.3) or the laser calibration system (section 17.2.4).

9054 **Chapter 23**

9055 **Simulations**

9056 **Chapter 24**

9057 **Search for the muon EDM, d_μ**

9058 **24.1 Introduction**

9059 **24.2 Straw Tube Array**

9060 **24.2.1 The chambers**

9061 **24.2.2 The readout electronics**

9062 **24.3 Sensitivity**

9063 **24.4 ES&H, etc**

9064 **Chapter 25**

9065 **Life Cycle Costs**