Muon Storage Ring and g-2

W. Morse - BNL

Spin

- 1925 Goudsmit and Uhlenbeck:
- Electron has spin h/2!
- Quantum Mechanics:
- Rotate to a new coordinate system:
- $\psi_e' = \exp(-i\Theta S/h)\ \psi_e$
- For $\Theta = 360°$, $\psi_e' = -\psi_e$!
- This leads to the Pauli Exclusion Principle, Chemistry, and us.

History

- Magnetic moment $\mu = geS/2m$
- Dirac equation predicts $g = 2$ for a “point particle”.
- Electron $g = 2.00 \pm 0.02$
- Proton $g = 5.6$!
- Explained in the 1960s by the naive quark model: $\mu_p / \mu_n = -3/2 \approx -1.46$.

The Physics 1930 - 40s

- 1930s: Oppenheimer et al. tried to calculate first order correction = infinity!
- 1947: Kusch, Foley, Rabi measured electron g = 2.002!
- $a = (g-2)/2$
- Schwinger et al. calculate the right answer.
- QED ……

Muon $a = (g-2)/2$ Measurements CERN/BNL

- G. Charpak et al., Phys. Lett. 1, 16 (1962), ±0.2% accuracy.
- CERN II – storage ring with p injection.
- J. Bailey et al., Nuovo Cimento A9, 369 (1977), ±0.03% accuracy
- CERN III – pion injection at magic energy.
- J. Bailey, Nucl. Phys. B150 (1979) ±7ppm.

Spin Precession in Storage Ring

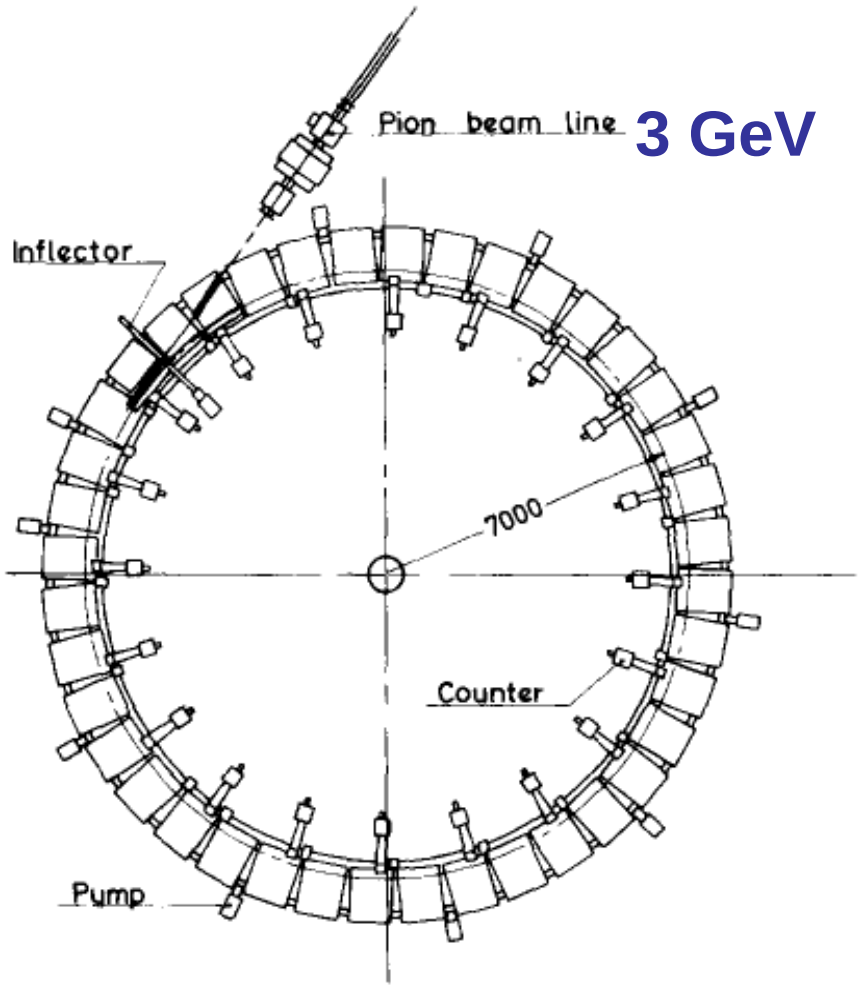
$$\vec{\mu} = \frac{ge\vec{S}}{2mc} \qquad a = \frac{g-2}{2}$$

$$\vec{\omega}_a = -\frac{e}{m}\left[\underline{a\vec{B}} + \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

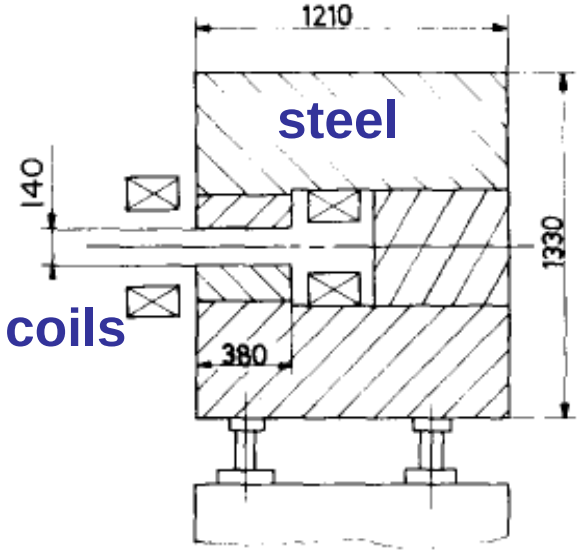
$$\left(a - \frac{1}{\gamma^2 - 1}\right) = 0$$

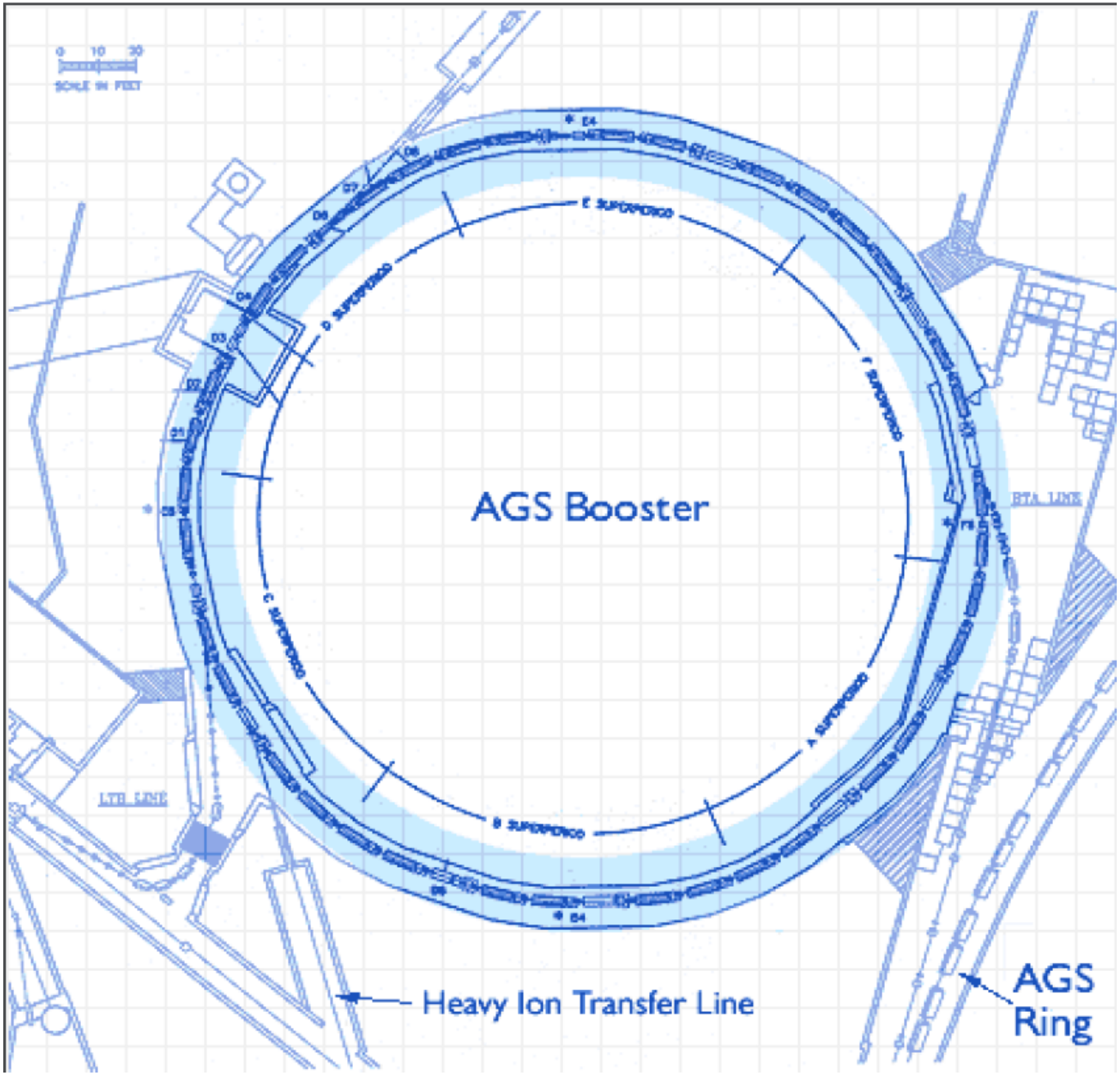
P_{magic} = 3.1 GeV/c

CERN III Muon Storage Ring



1.5T "C" Magnet




AGS Booster
Heavy Ion Transfer Line
AGS
Ring

Uniform B – Grinding Pole Faces

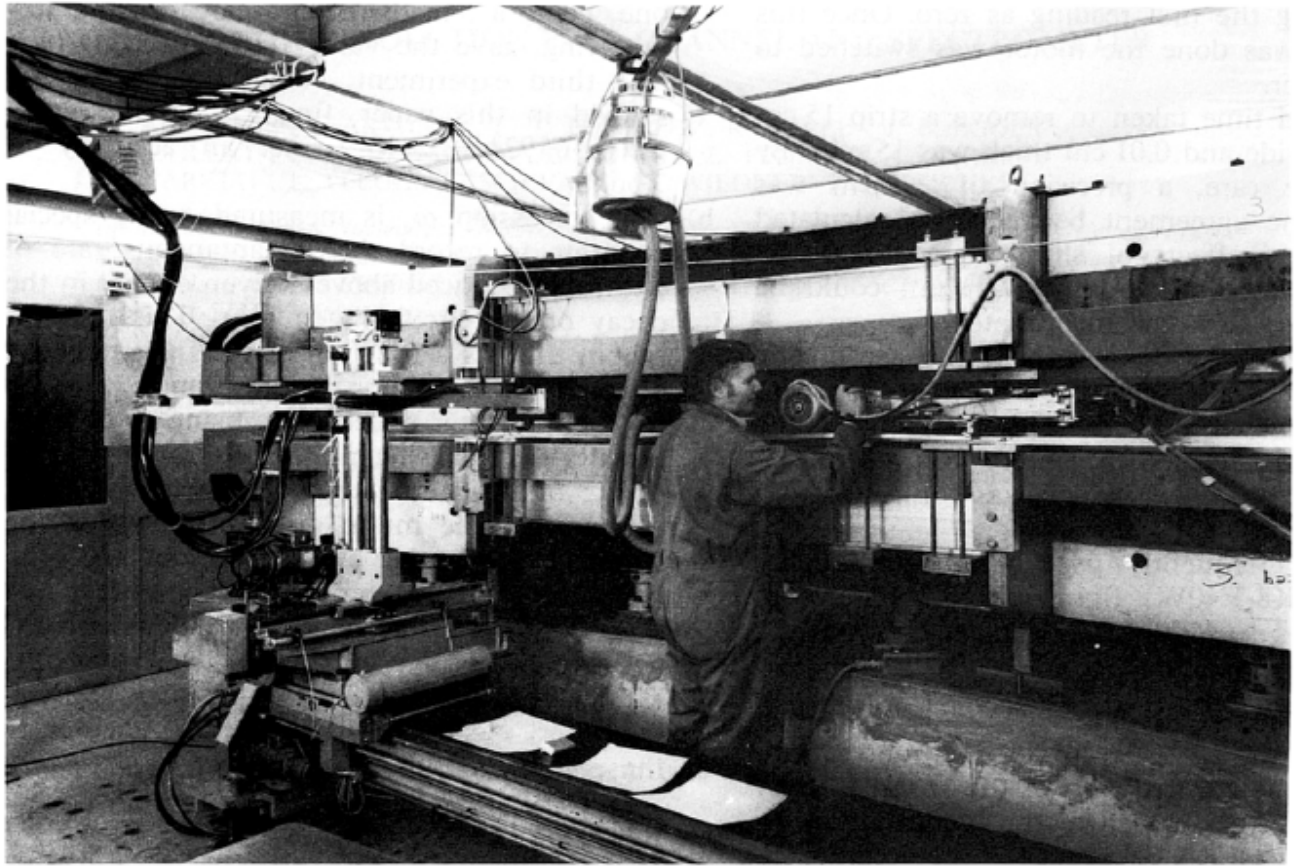
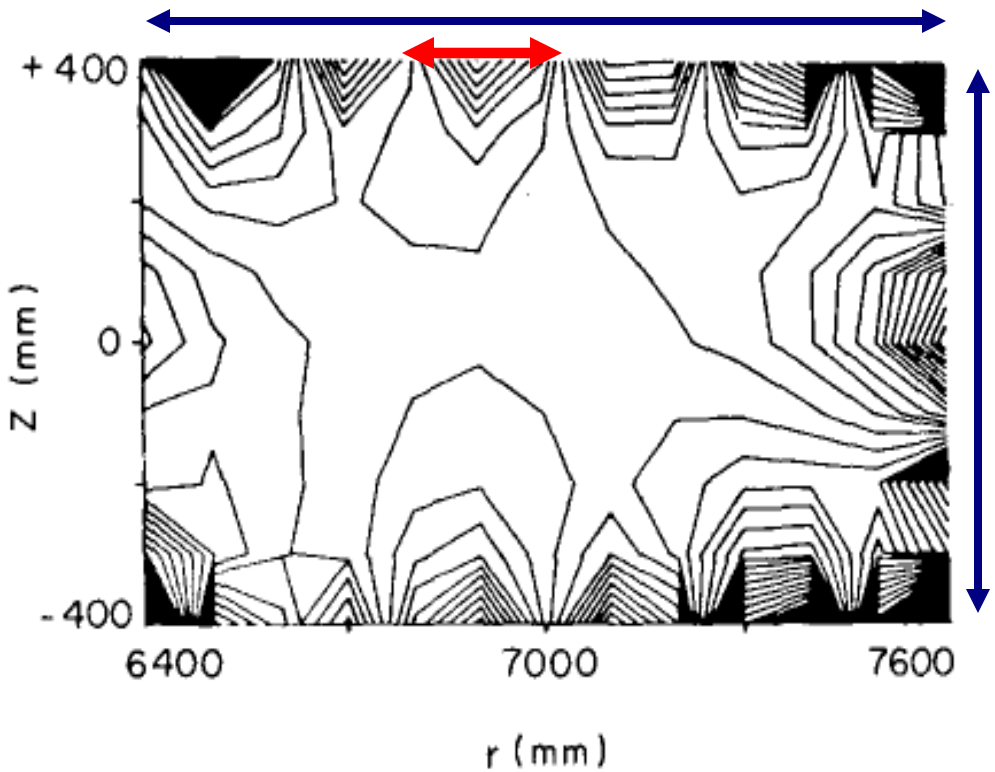


Fig. 17. The grinding tool in its working position in the four-block set-up. The numerically controlled scanner is visible in the foreground.

CERN B After Grinding

±6cm

2ppm contours

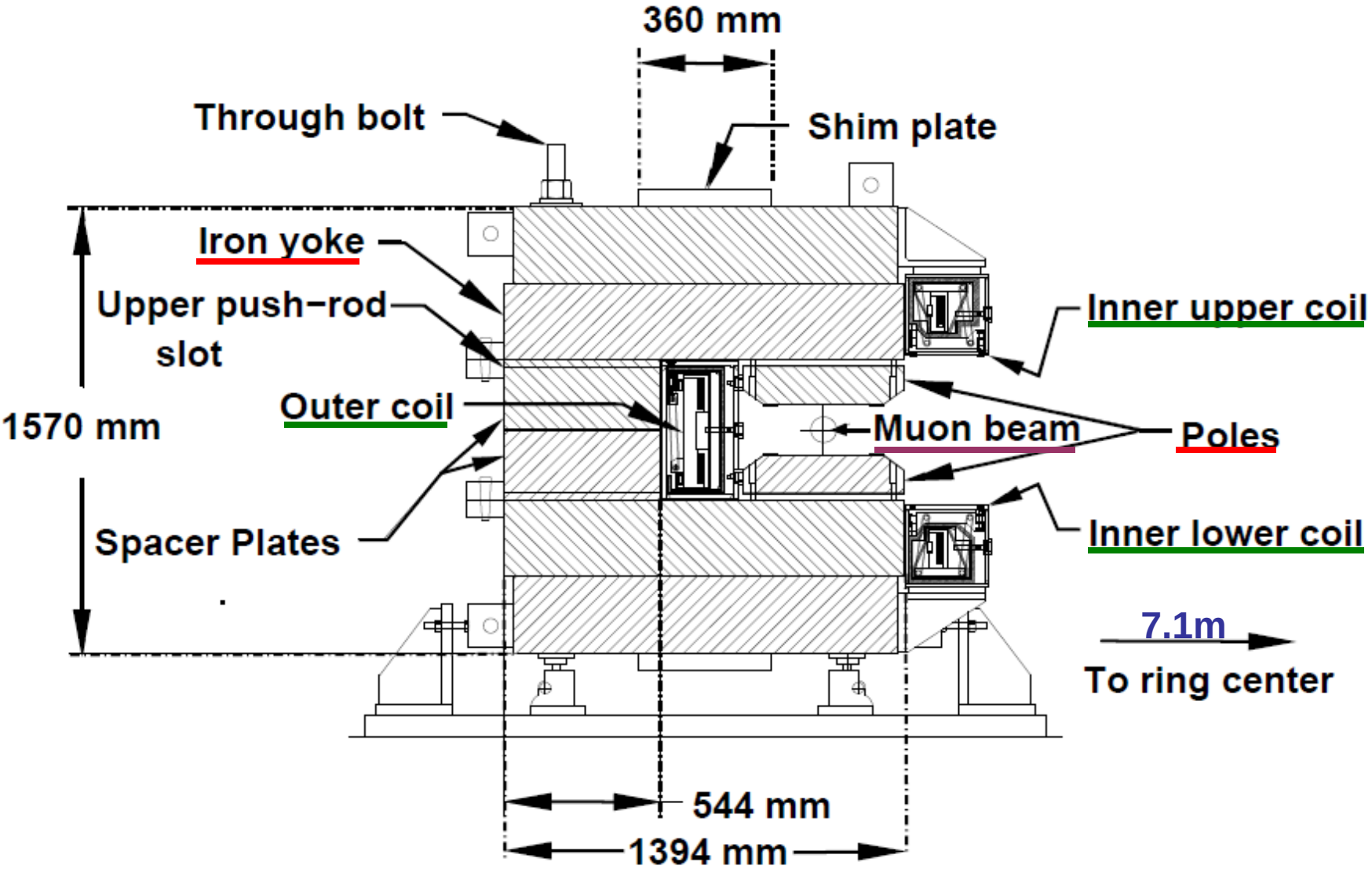


±4cm

Fig. 5. A contour line plot of the magnetic field strength in the muon storage aperture. This map is obtained by averaging a three-dimensional map in azimuth. The interval between the contours of equal field strength is 2 ppm or 3 μT.

1982 Workshop at BNL
Vernon Hughes – Rabi's Student

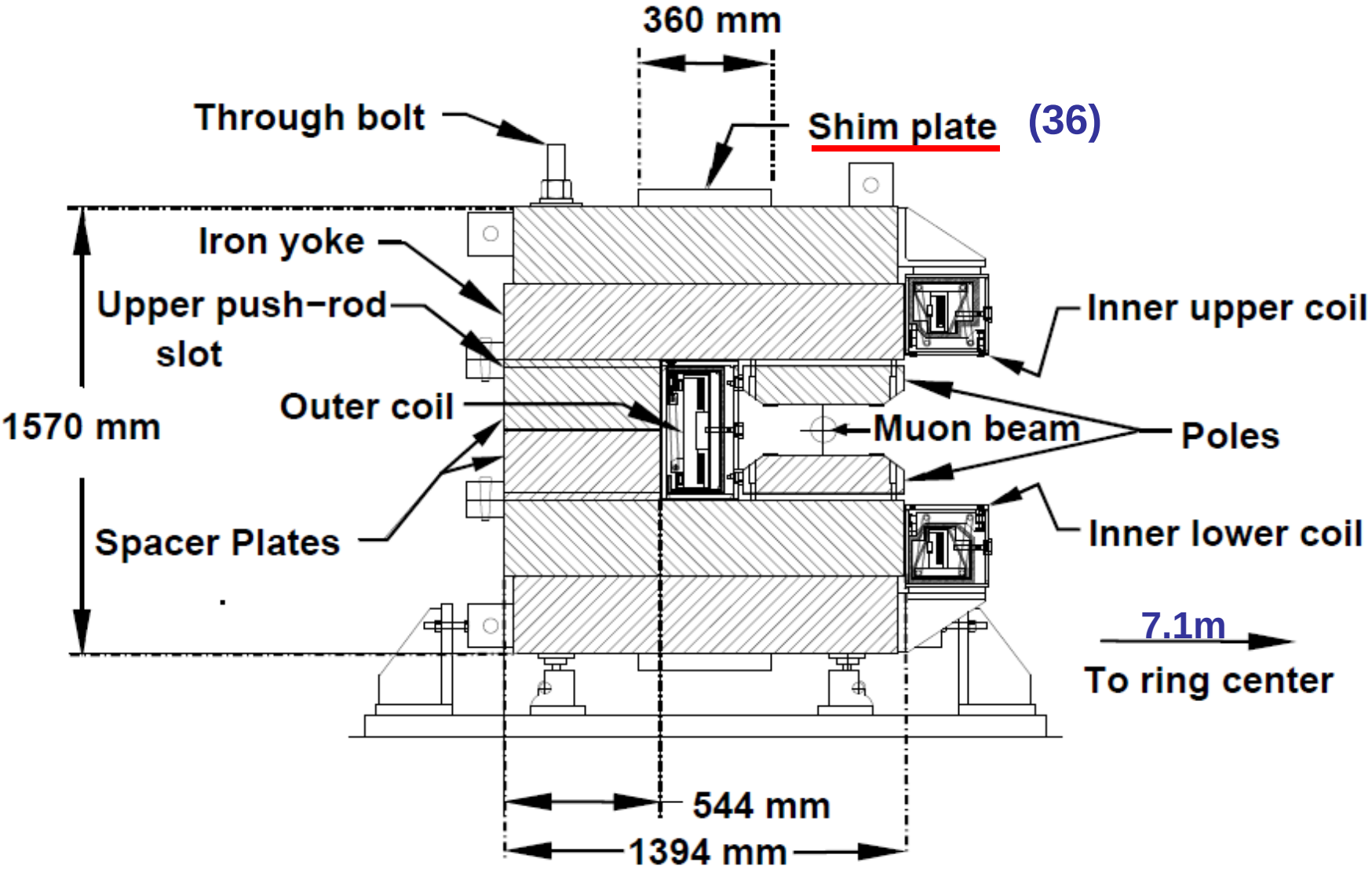
E821 Storage Ring Magnet



The Magnet Pieces

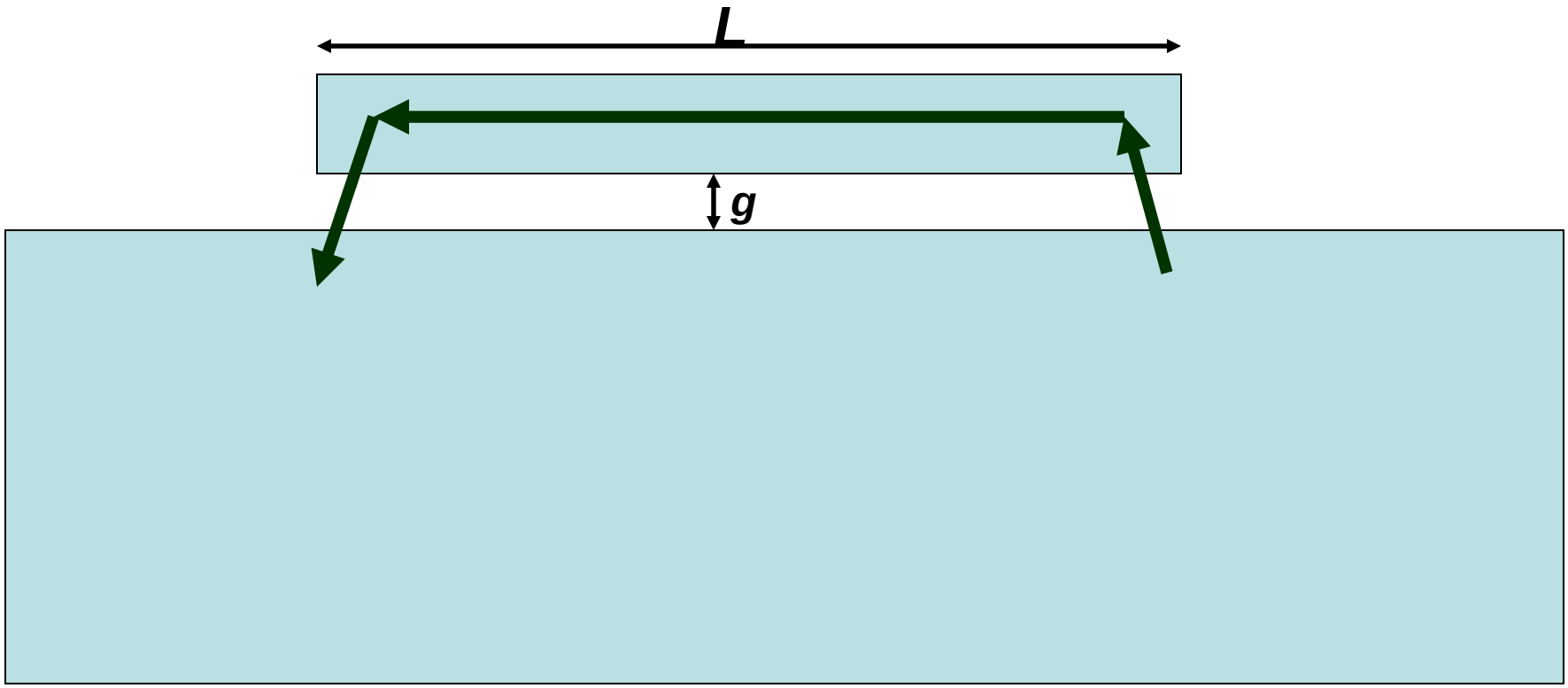
- Poles: vacuum cast very low carbon (50ppm) – KEK
- Air gap decouples yoke and pole steel, and use for shimming the magnet field uniformity.
- Yoke steel 0.05% carbon – Lukens Steel Co, PA
- 5.2KA Brucker power supply stability:
- Short term 0.2ppm.
- Long term several ppm.
- Stabilize with NMR.

Danby - Build Shimming Kit

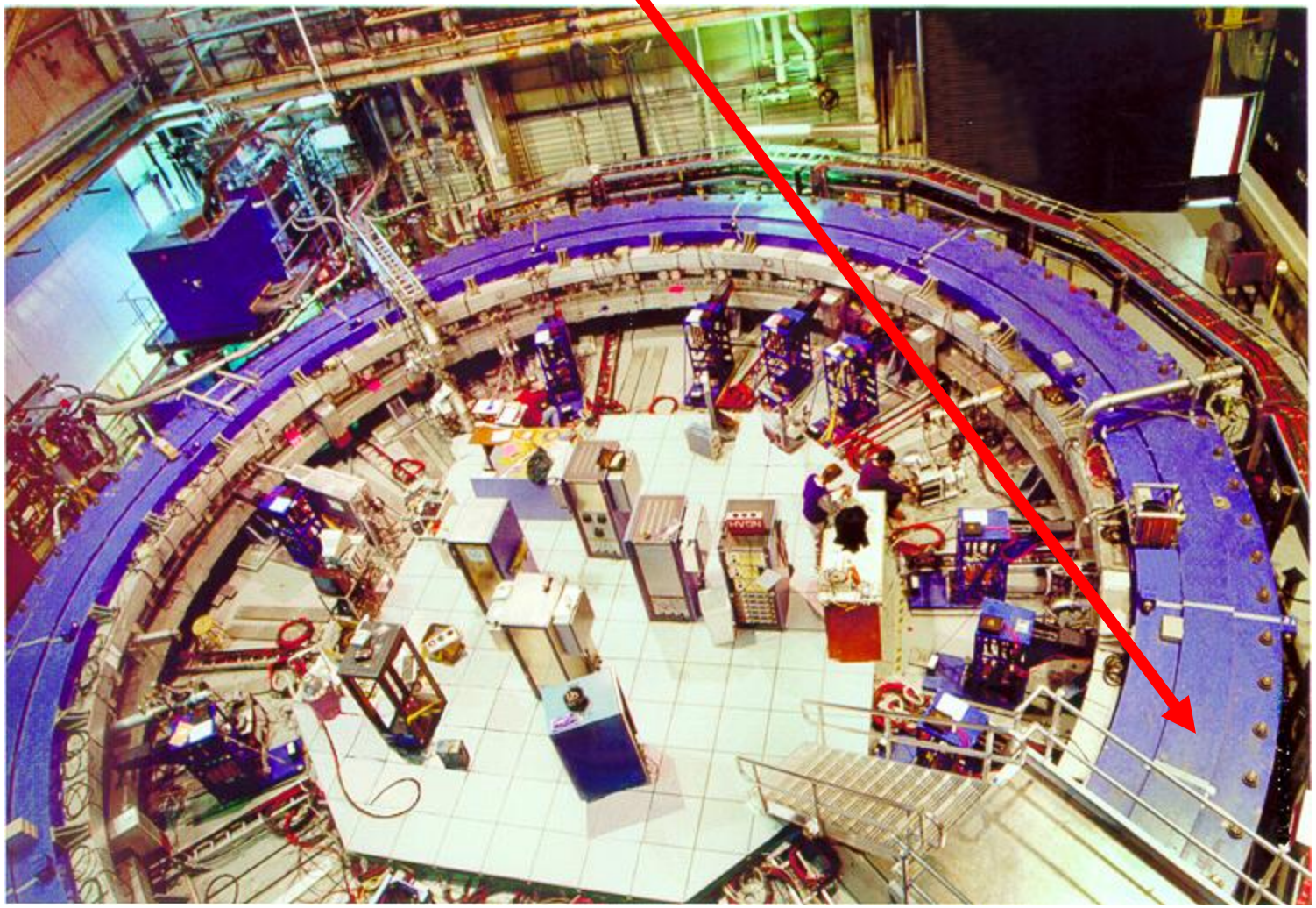


How the Shim Plate Works

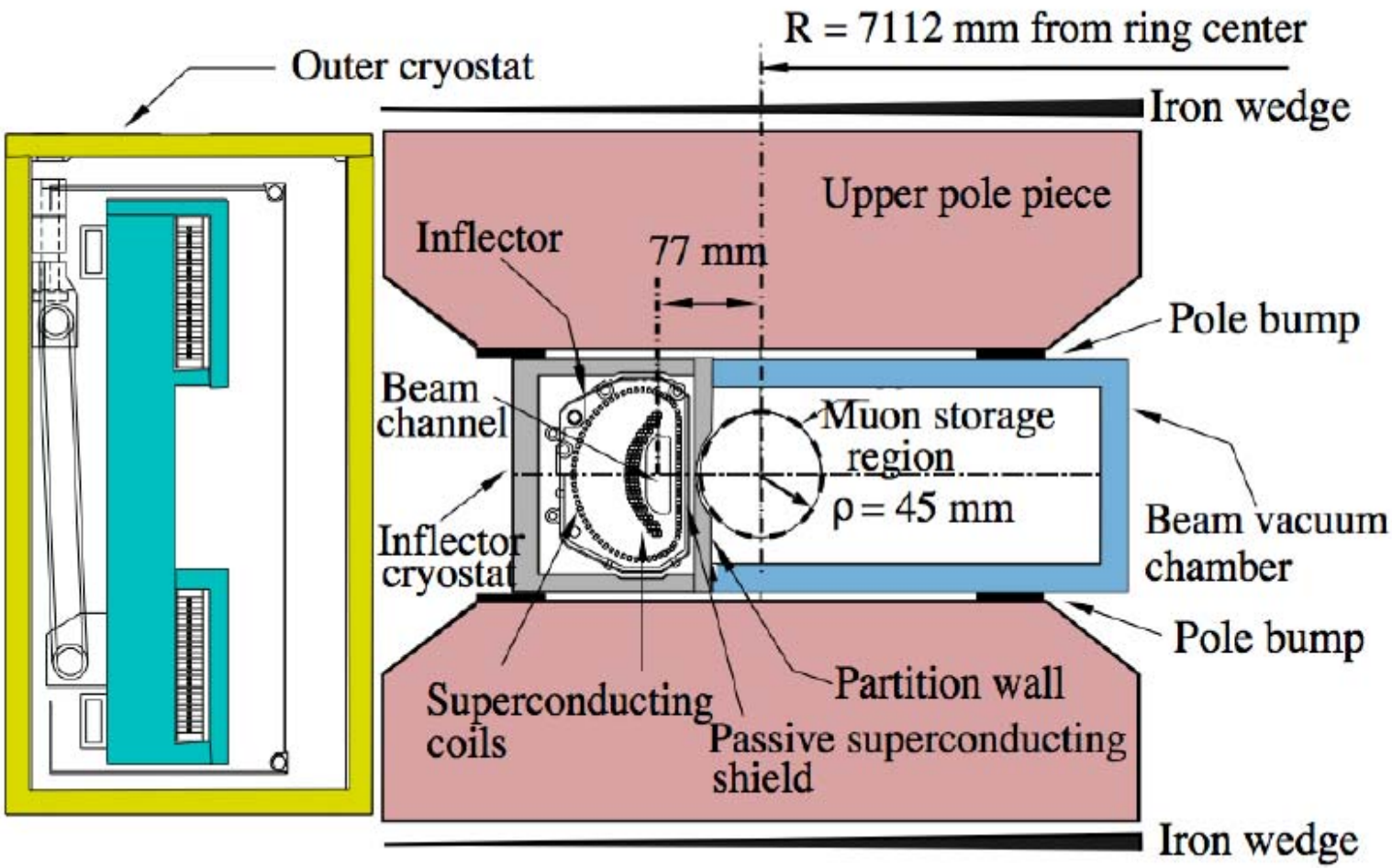
$$L_M \approx 2g + \frac{L}{\mu}$$



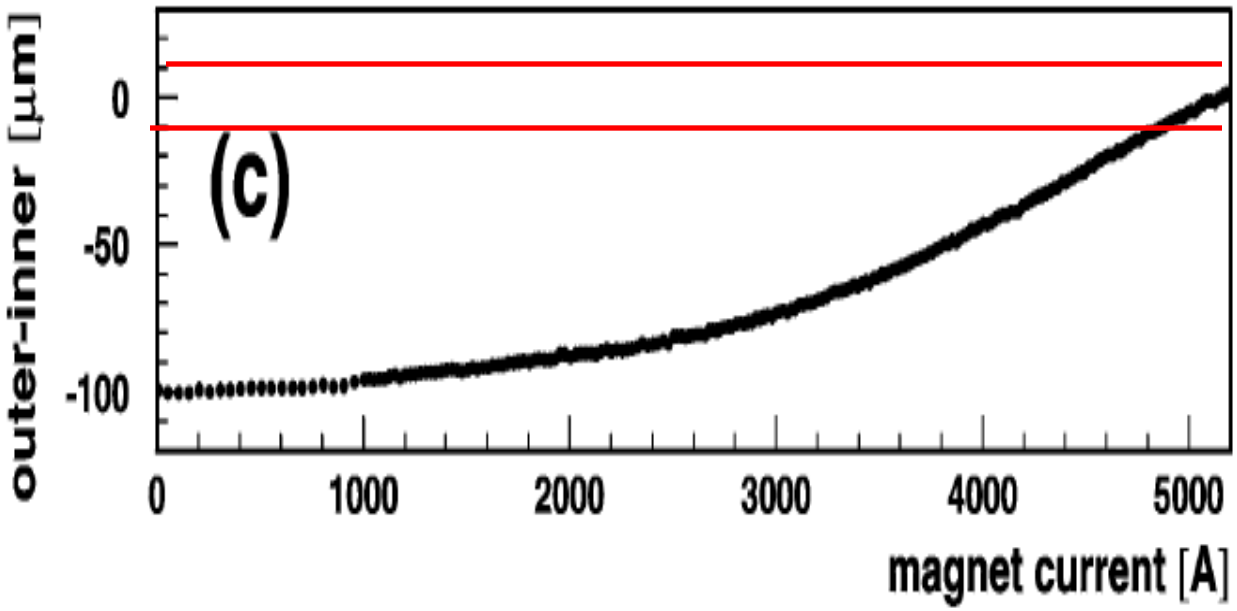
Shim Plates



Wedge, Pole Bump, Active Shims



Getting Poles Faces Parallel



Normal or Superconducting Coils

- Superconducting – much more stable!
- Largest SC coils in 1990 were several meters in diameter only!
- Topaz solenoid superconductor – KEK.
- Decided on superconducting.
- Today this would go into the risk registry!

Outer Coil Design

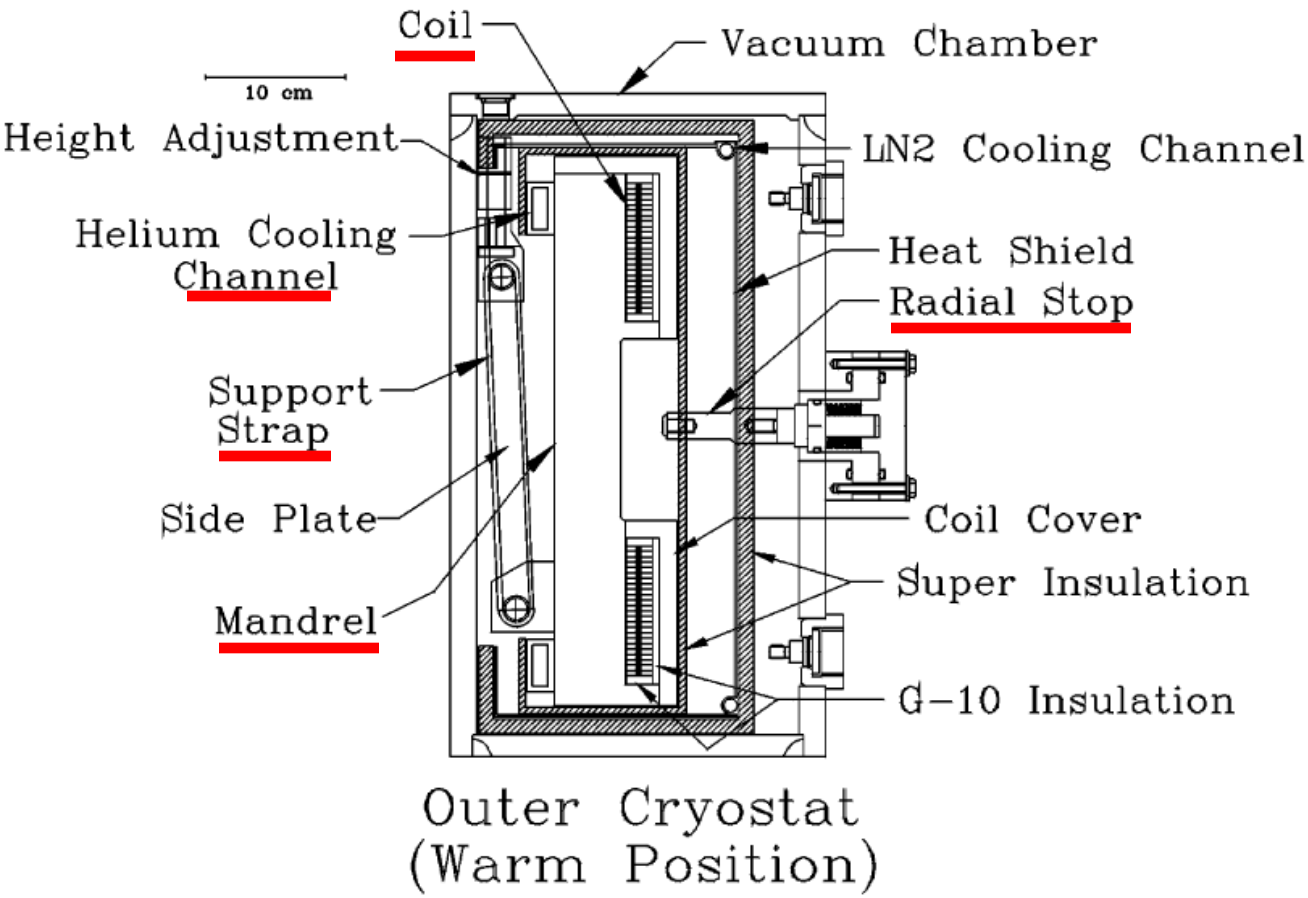


Fig. 8. A cross-section of the outer coil and cryostat assembly at the location of a radial stop.

Cooling Down the Outer Coil

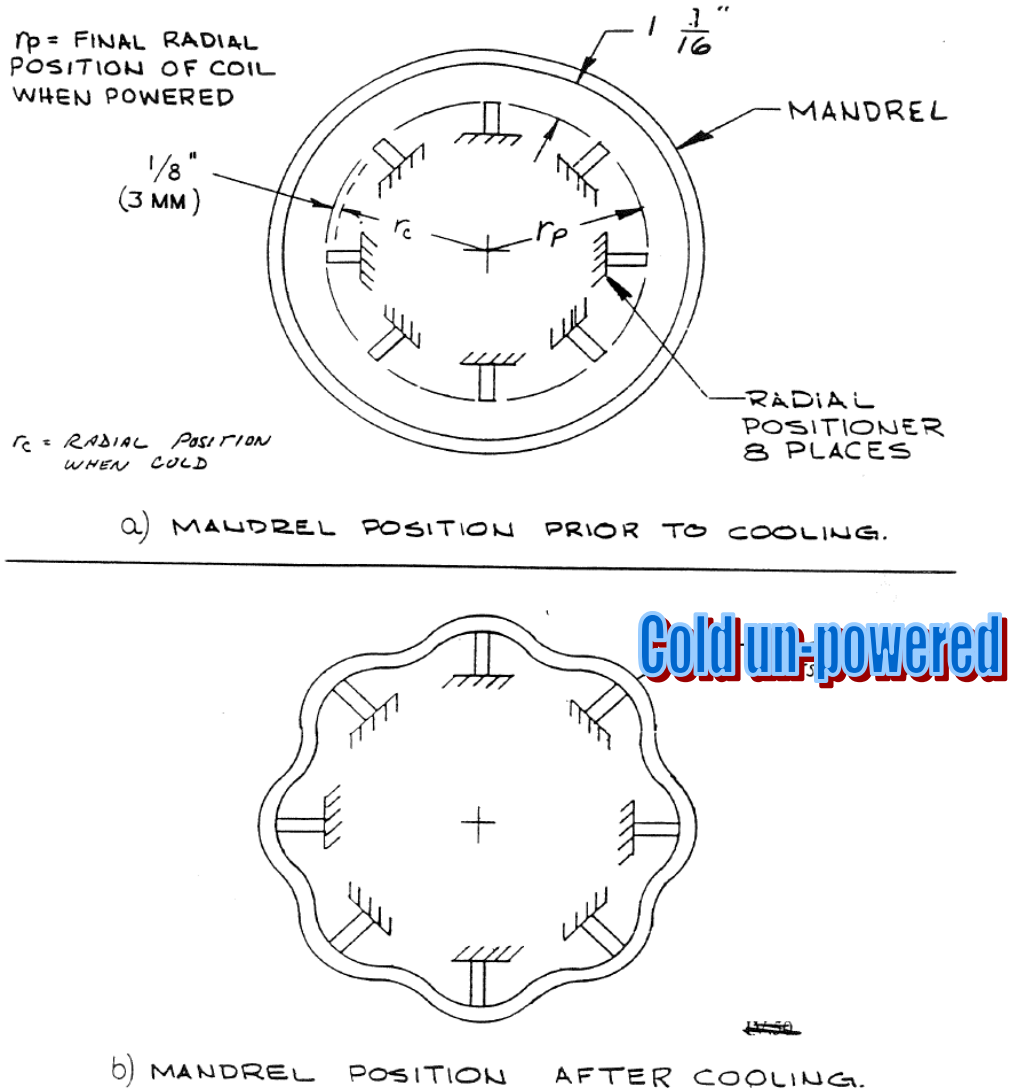
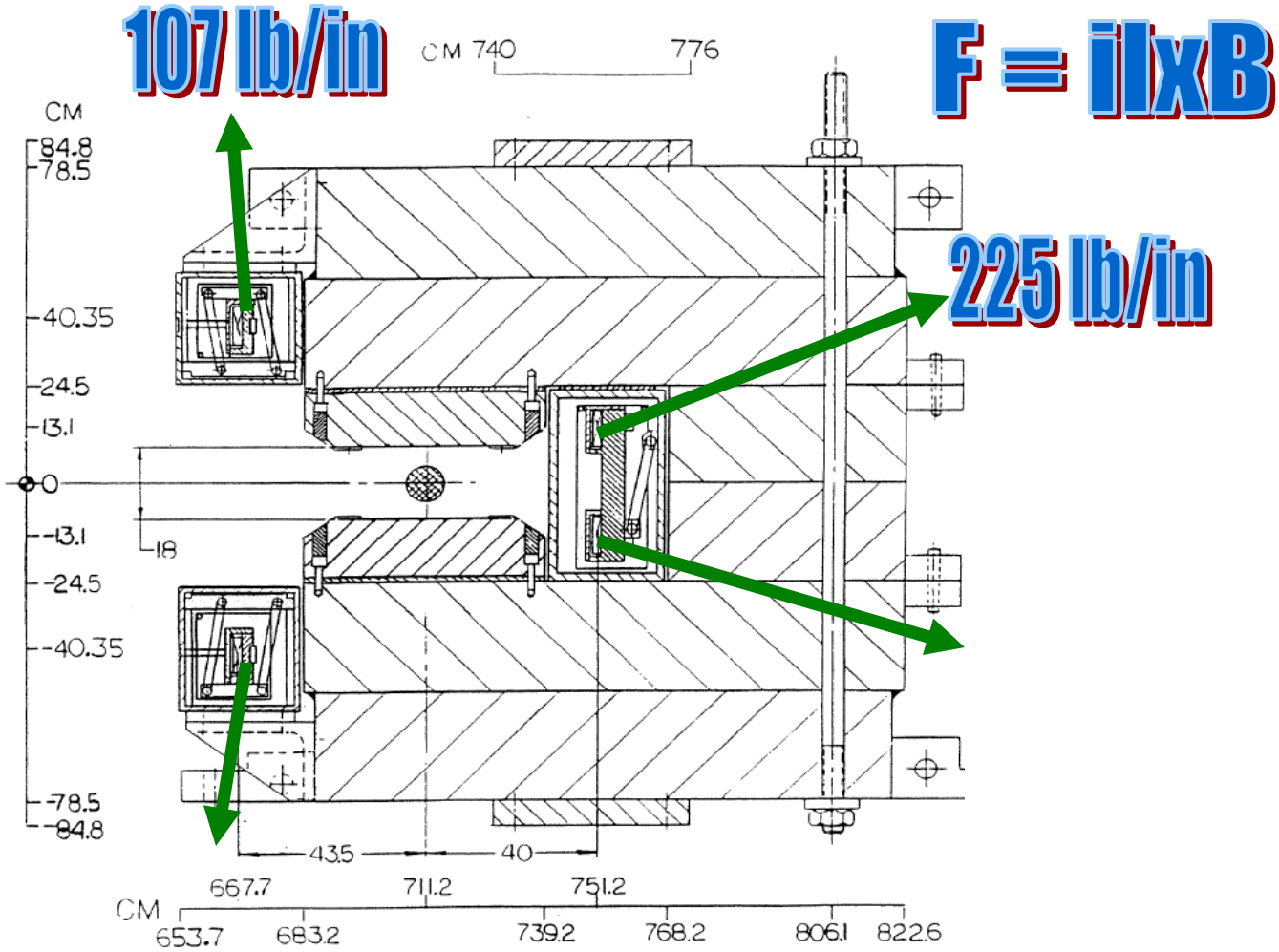
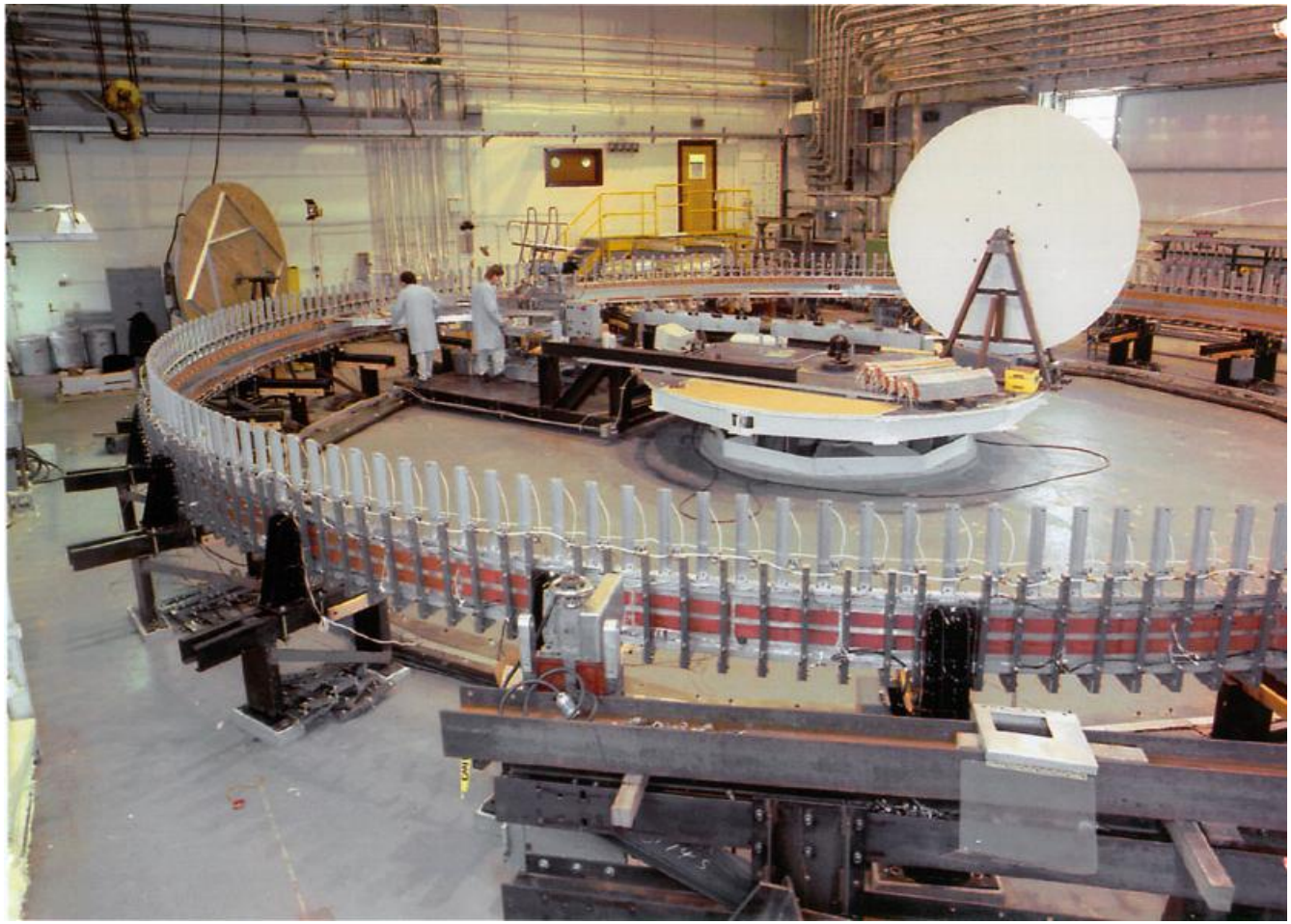


FIGURE 8.6-2 RADIAL COIL POSITIONERS

Lorentz Forces

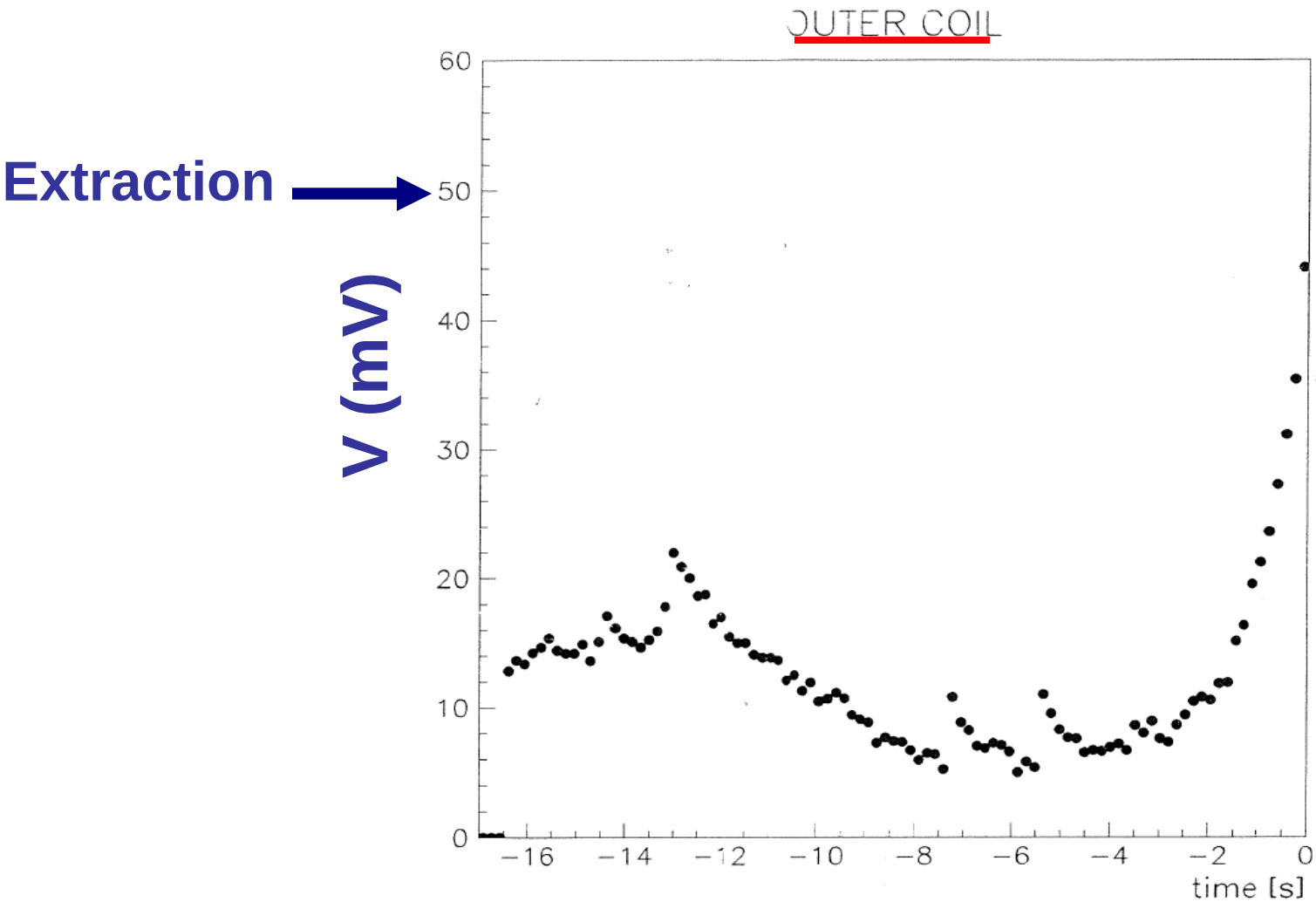


Winding the Inner Lower Coil



Coil Shuffling

Magnet Commissioning to Full Field – Problem at 70% Full Field



Measure Radial Magnetic Field in Hole in Outer Mandrel

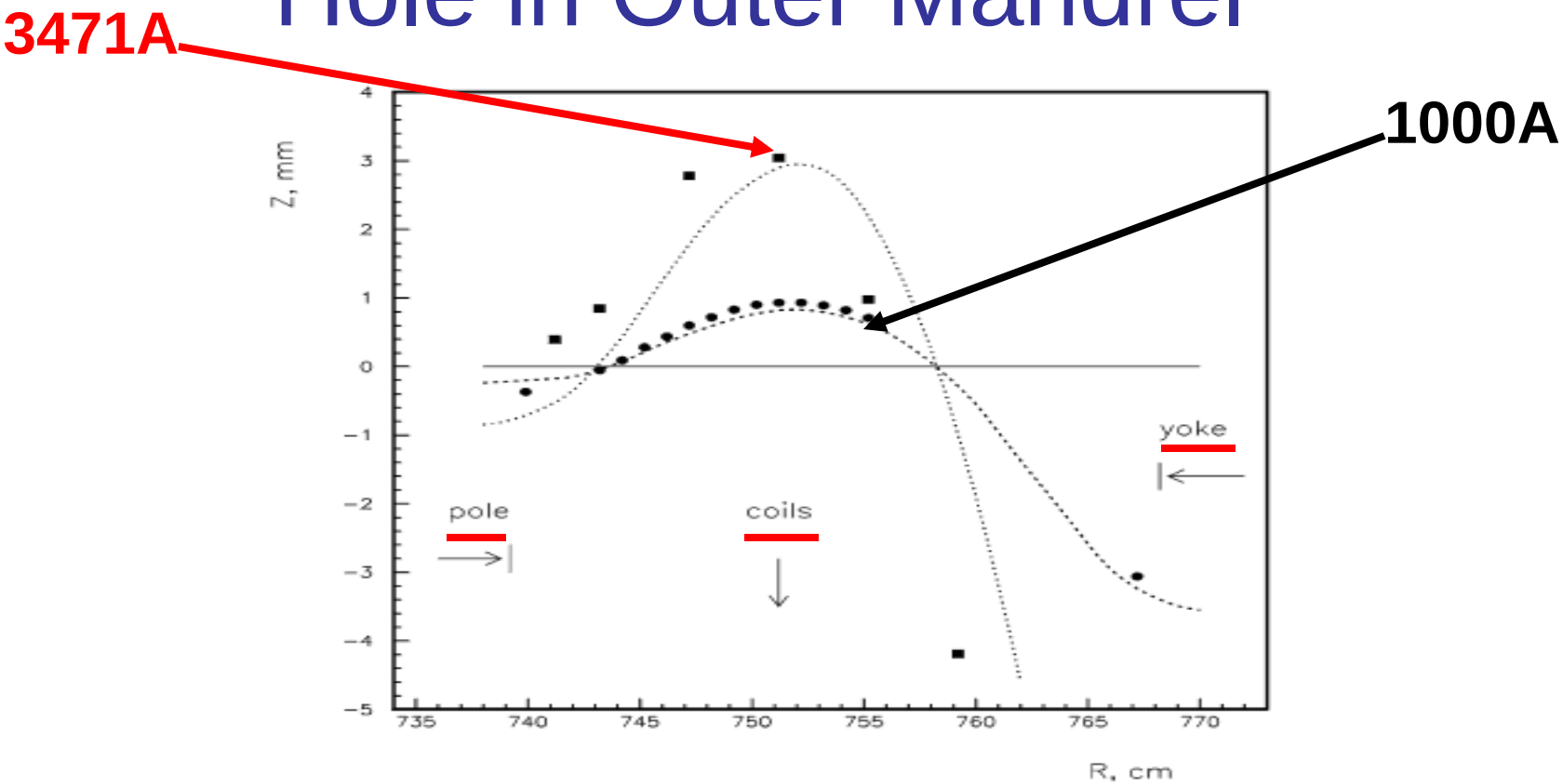
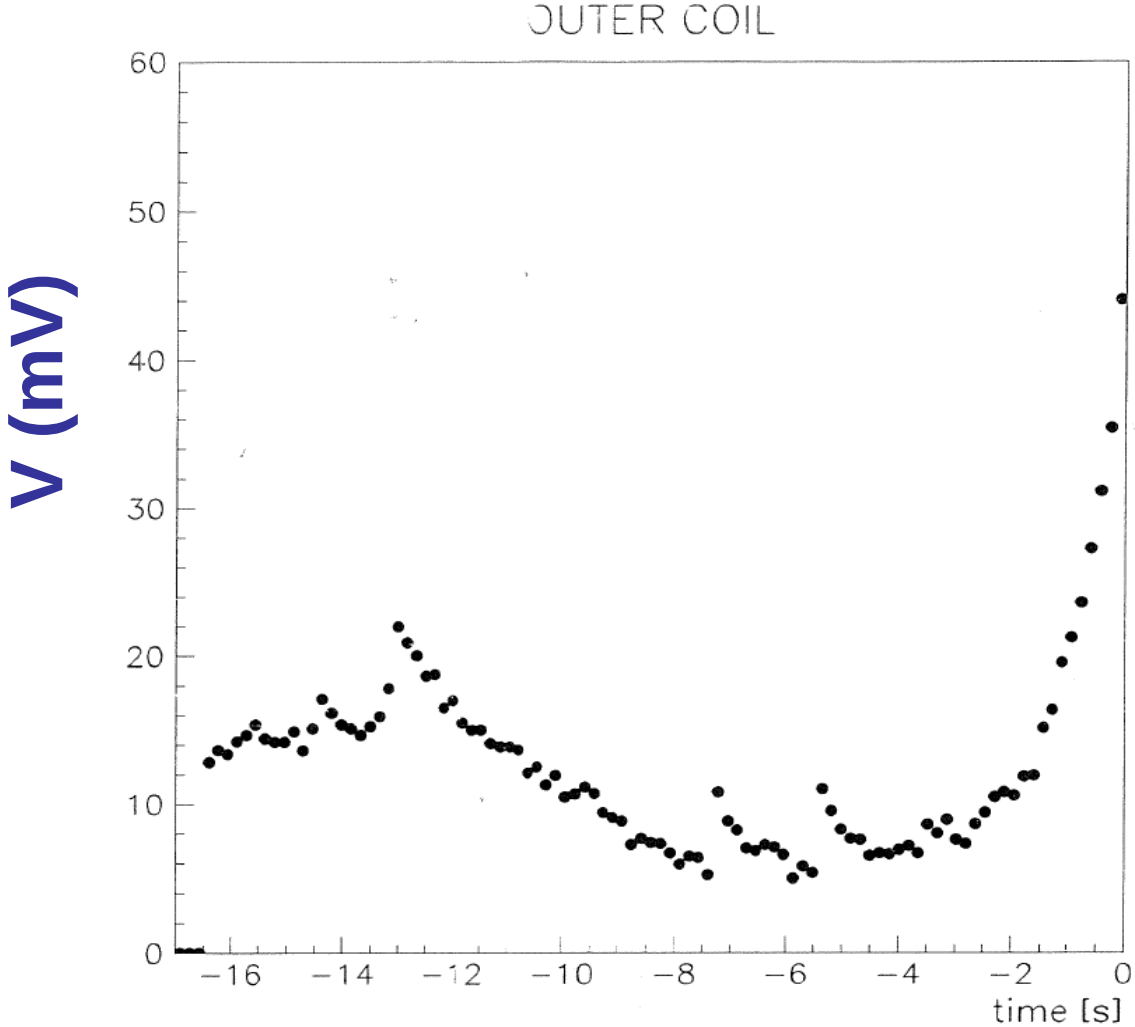


Fig. 14. Measured location of the null in the radial field versus radius R and vertical position Z, for two excitation currents, 1000 A (circles), and 3471 A (squares). The curves show the calculated null in the radial field if the coil were on the midplane (solid line), if the coil were displaced 2 mm upward and 1000 A (dashes), and if the coil were shifted up by 7 mm and 3471 A (dots).

$V = \cancel{iR + Ldi/dt} + idL/dt$

The coil distorted into a saddle shape 4mm(V) and 2cm(H)



Outer Coil Calculations

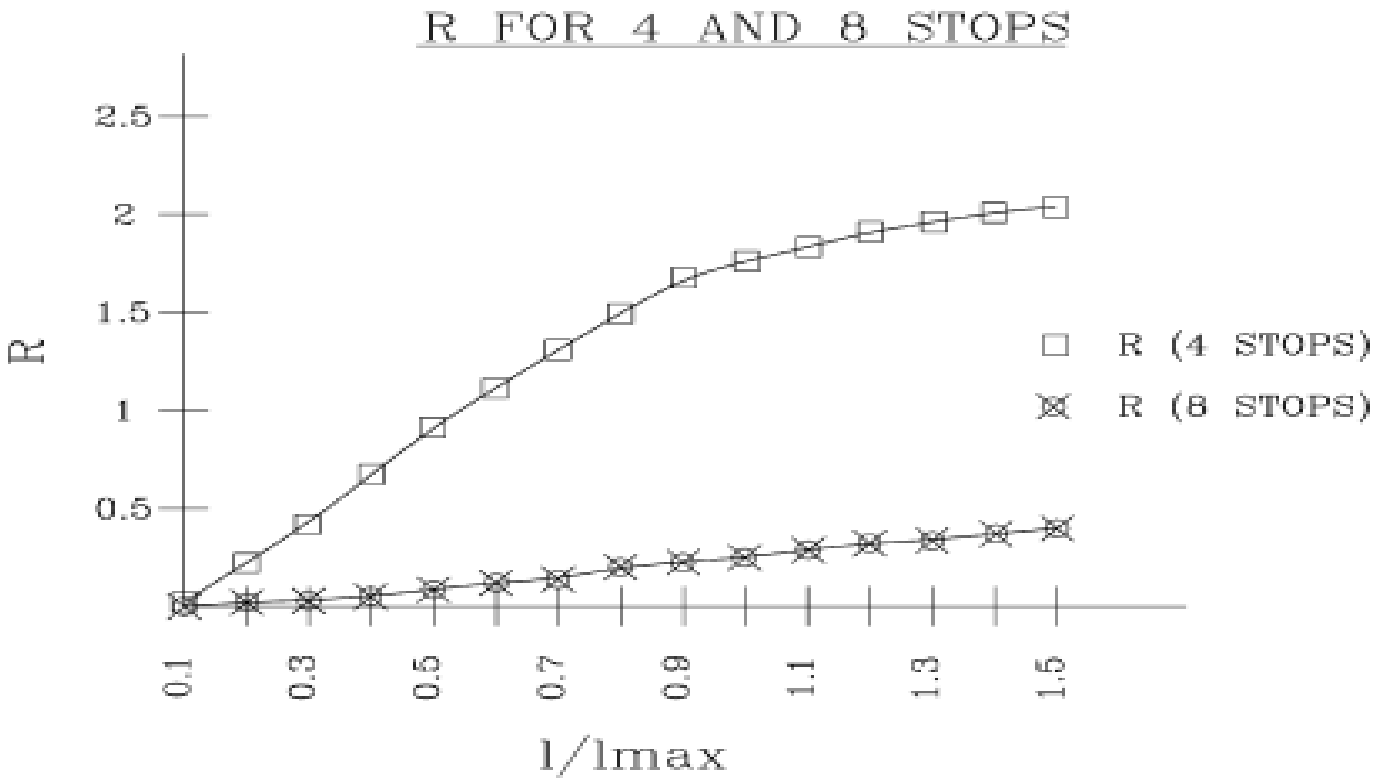
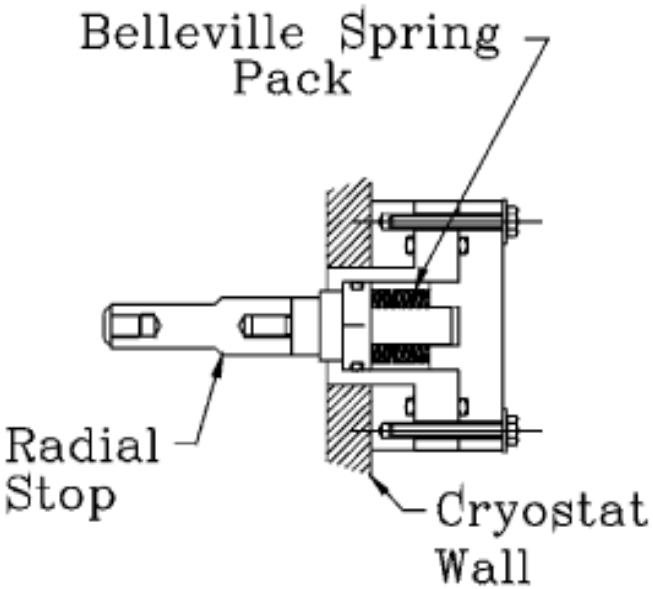


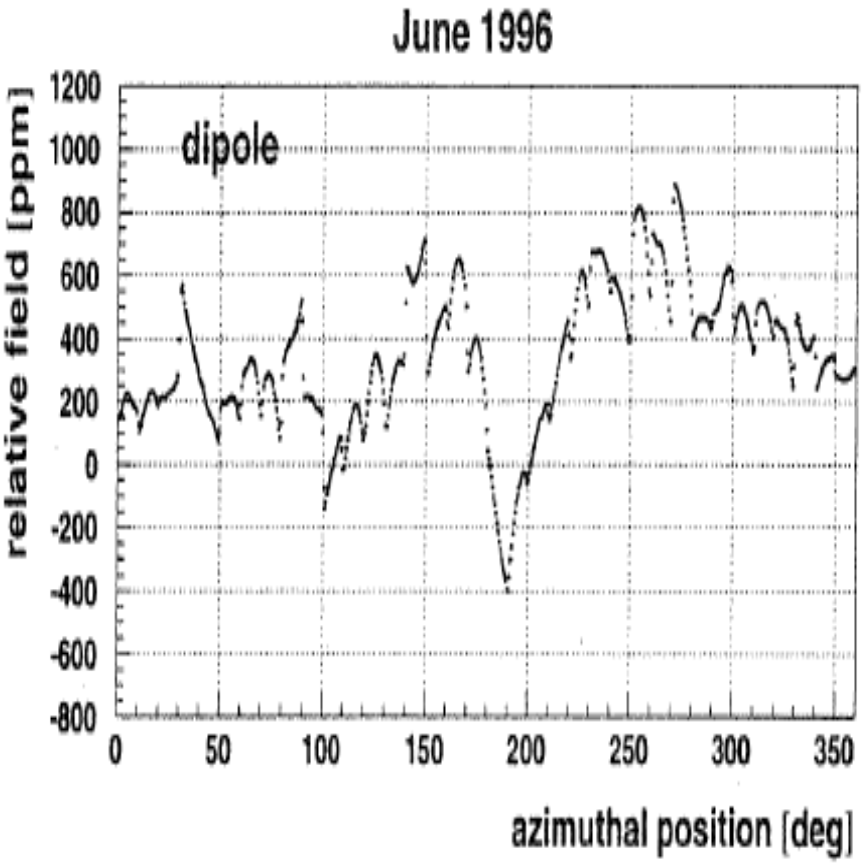
Fig. 15. Analysis showing the ratio of the destabilizing force to the restoring force, versus magnet current, shown for 4 and 8 radial stops.

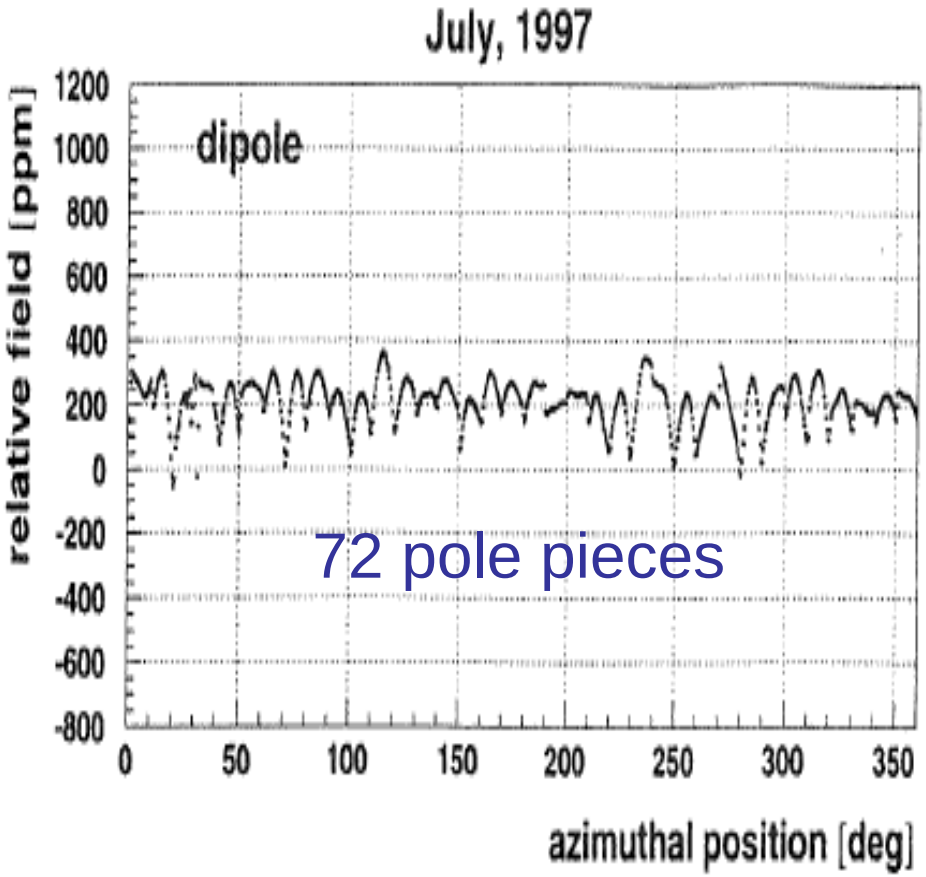
Eight Spring Loaded with Firm Stops



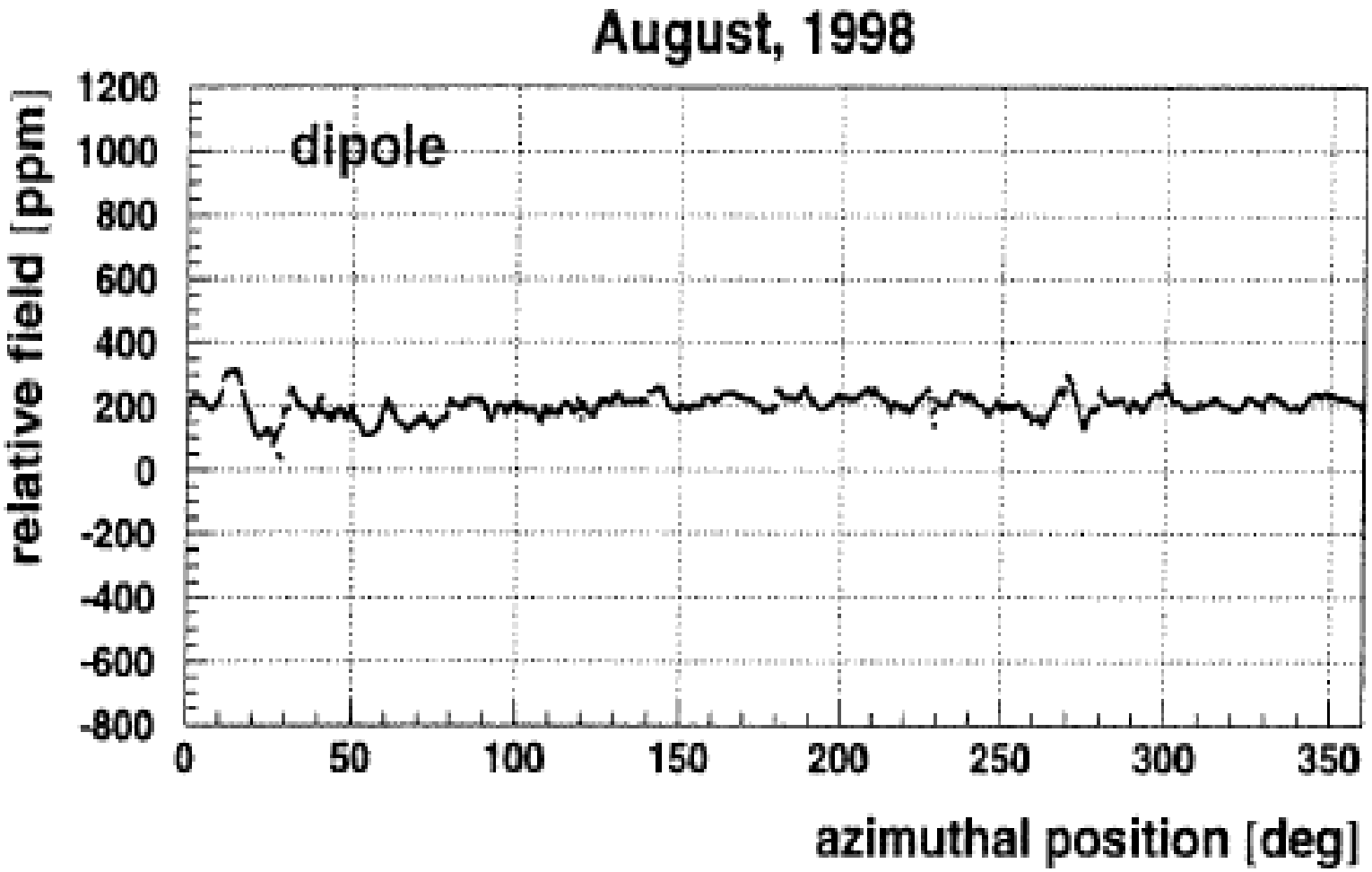
OUTER COIL STOP
SPRING ASSEMBLY

Finally Full Current! Shim B vs. Ring Azimuth





Shim Gaps Between Pole Pieces



The Magnetic Field as Seen By the Muons

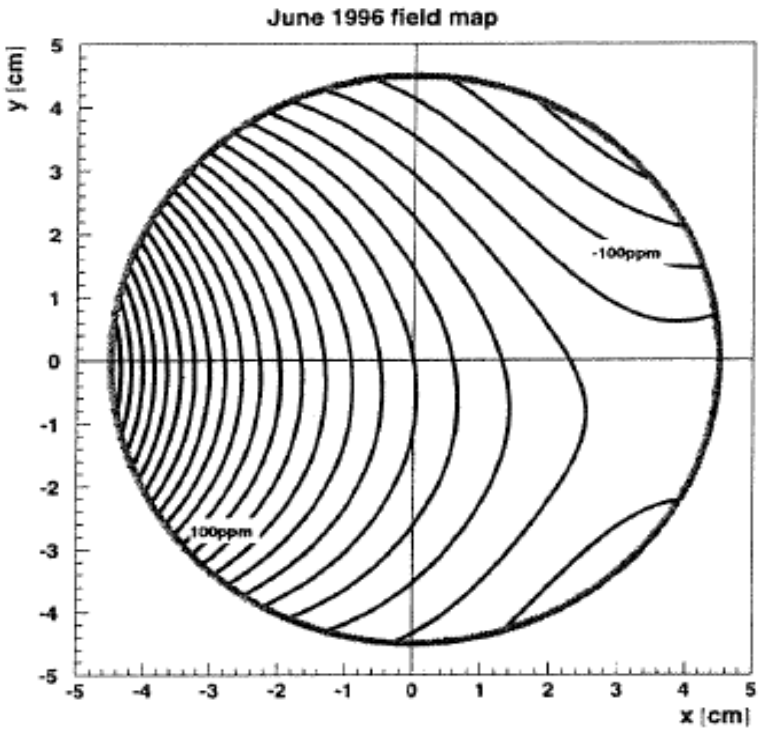


Figure 27: 20 *ppm* contour plot, June 1996.

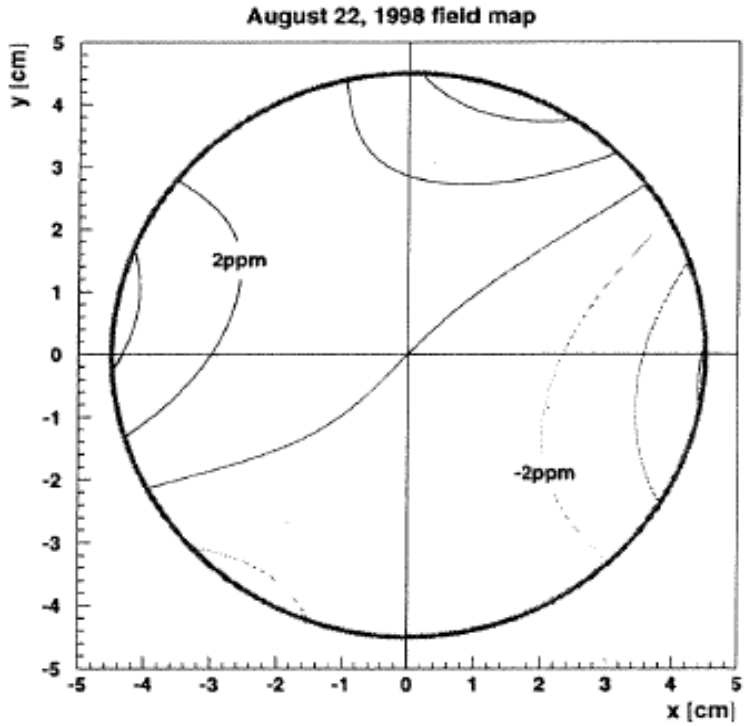


Figure 30: 2 *ppm* contour plot, August 22, 1998.

CERN Pulsed Inflector

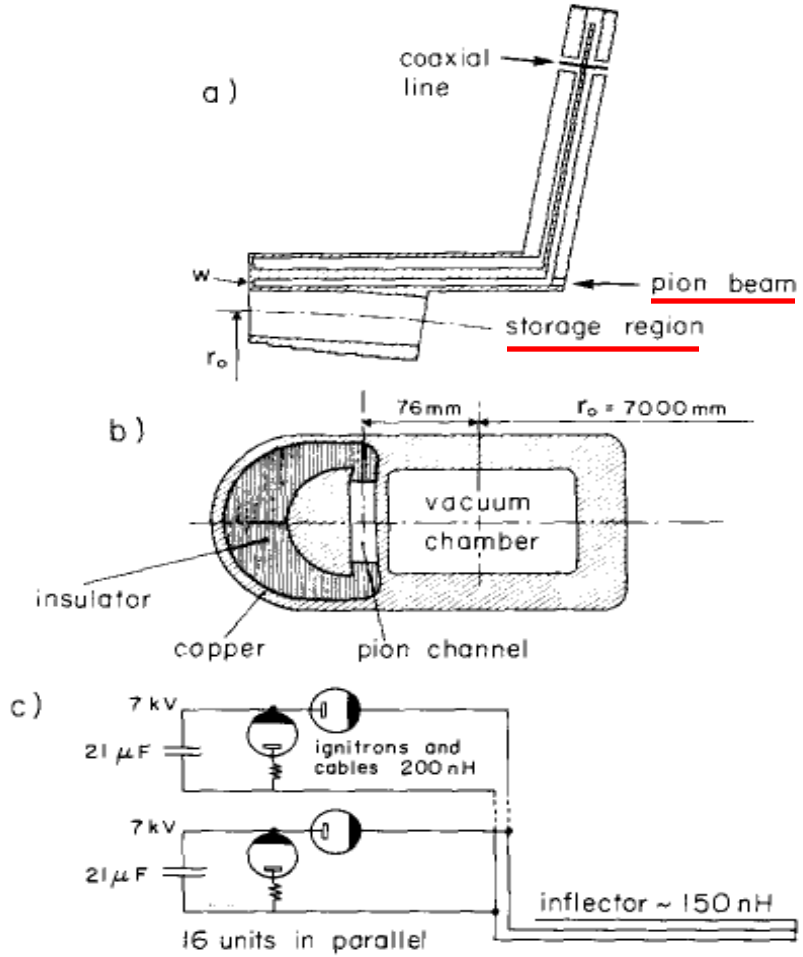
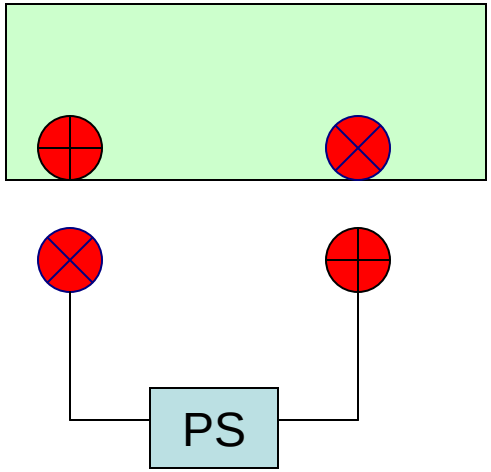
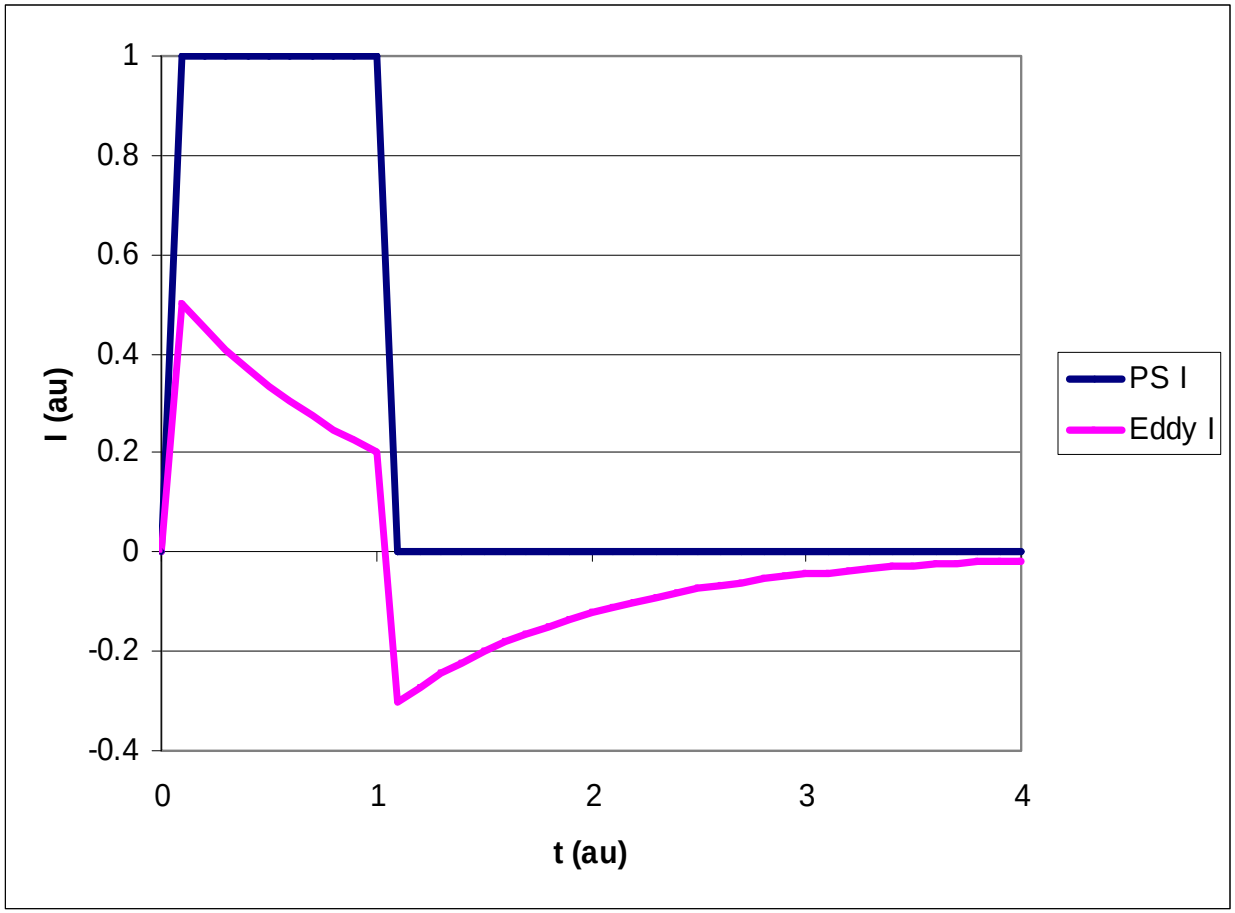


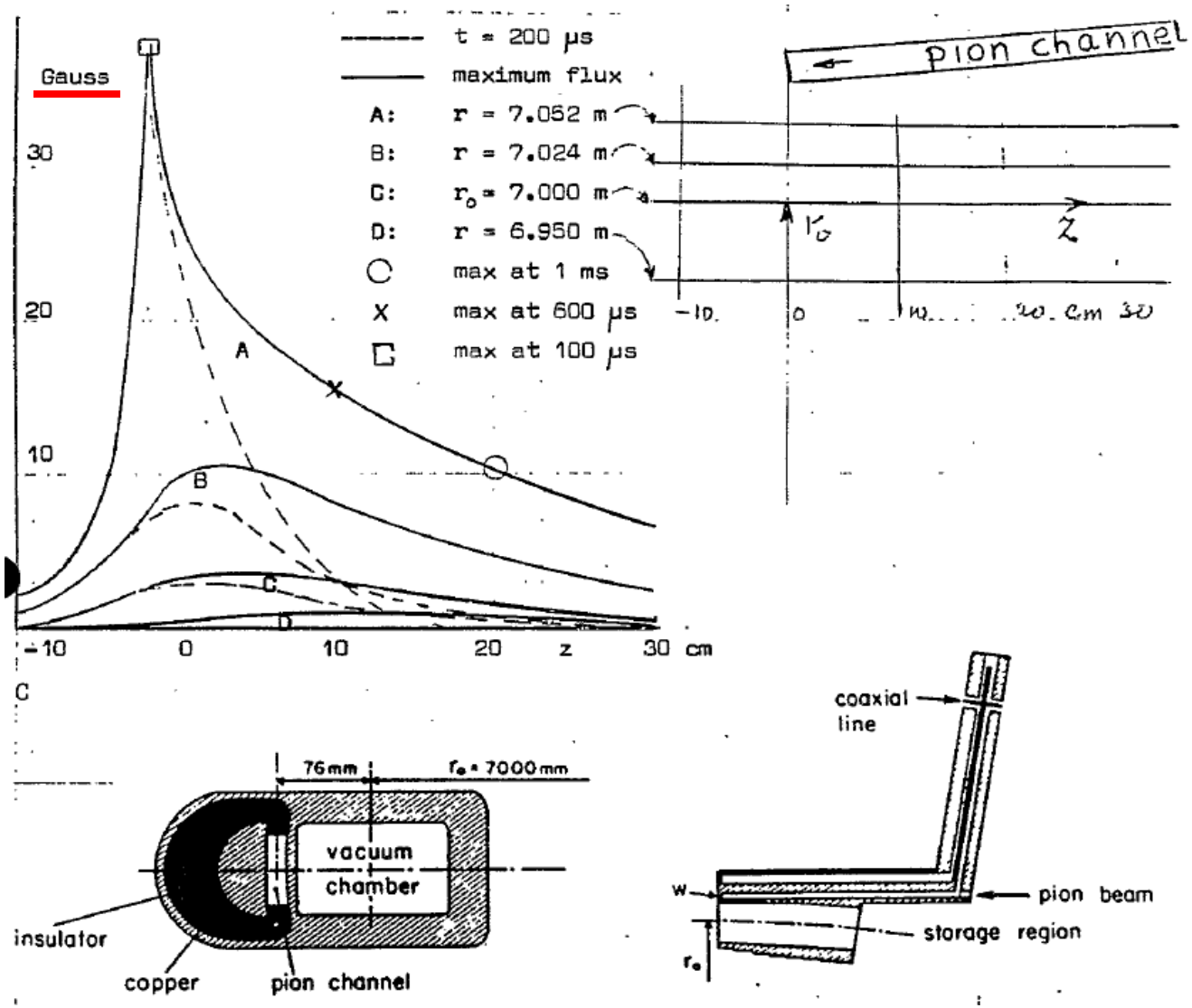
Fig. 4. (a) A horizontal section through the inflector showing the pion channel and adjacent part of the storage region. (b) A vertical section through the inflector. (c) The basis crowbar circuit used to pulse the inflector.

Eddy Currents





Eddy Current Fields Large



Frank Krienen: DC Inflector

A. Yamamoto et al. / Nuclear Instruments and Methods in Physics Research A 491 (2002) 23–40

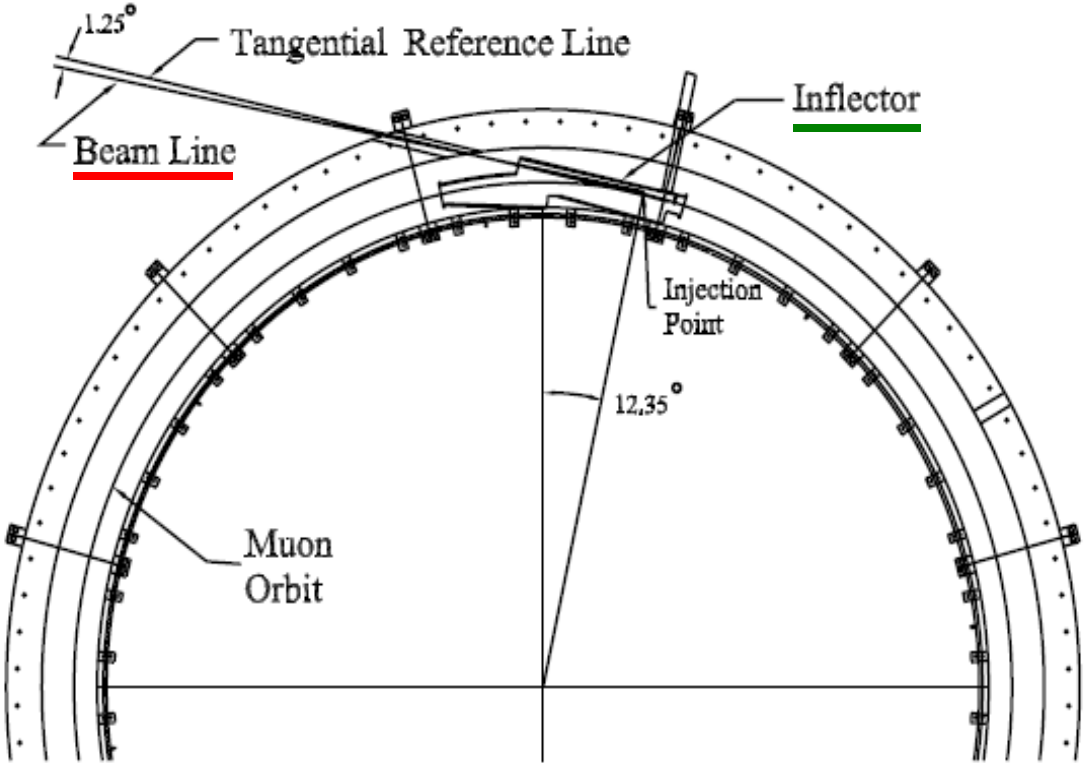


Fig. 1. Inflector in the storage ring.

SC Inflector Magnet
Cancel 1.45T Field for Injection

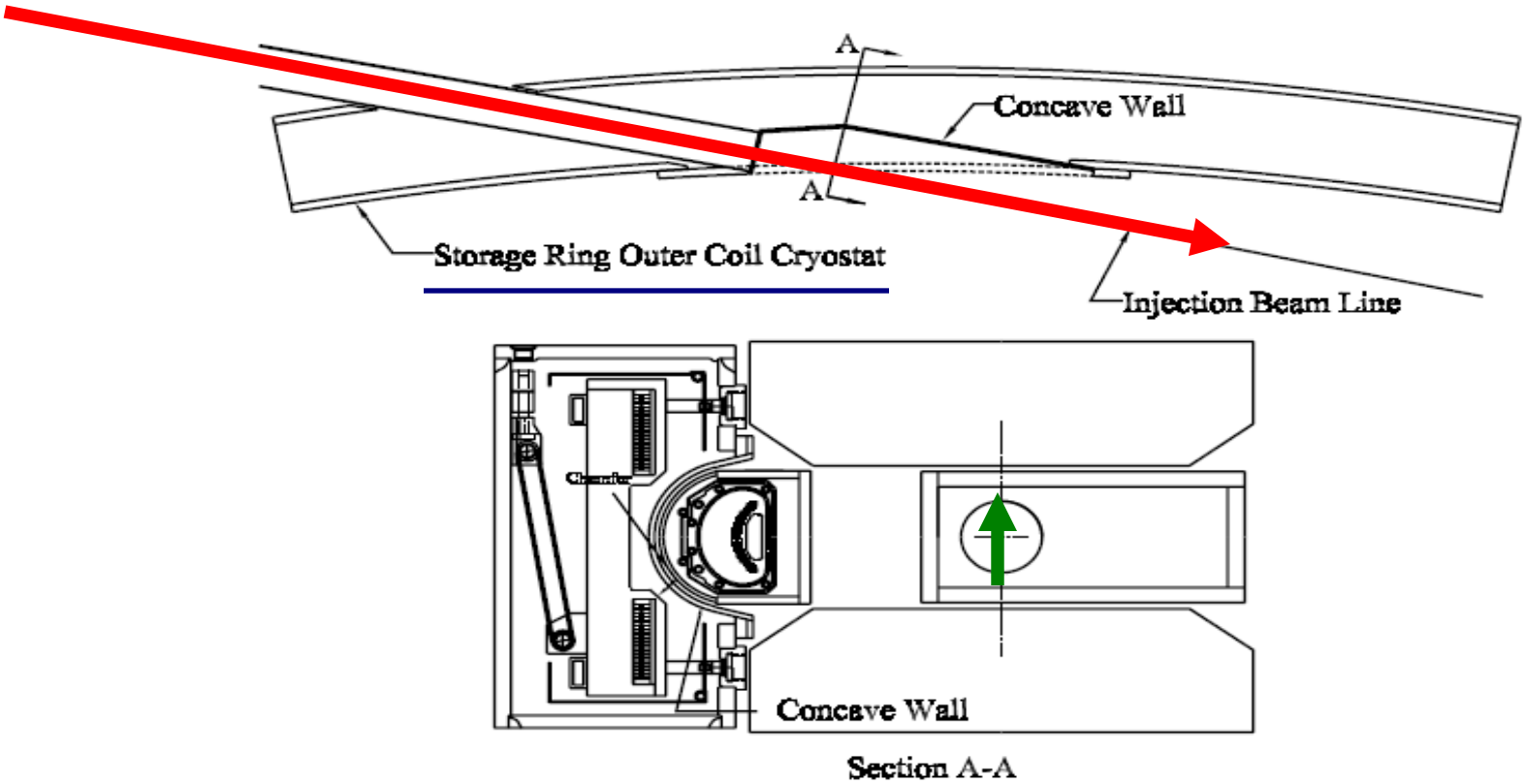
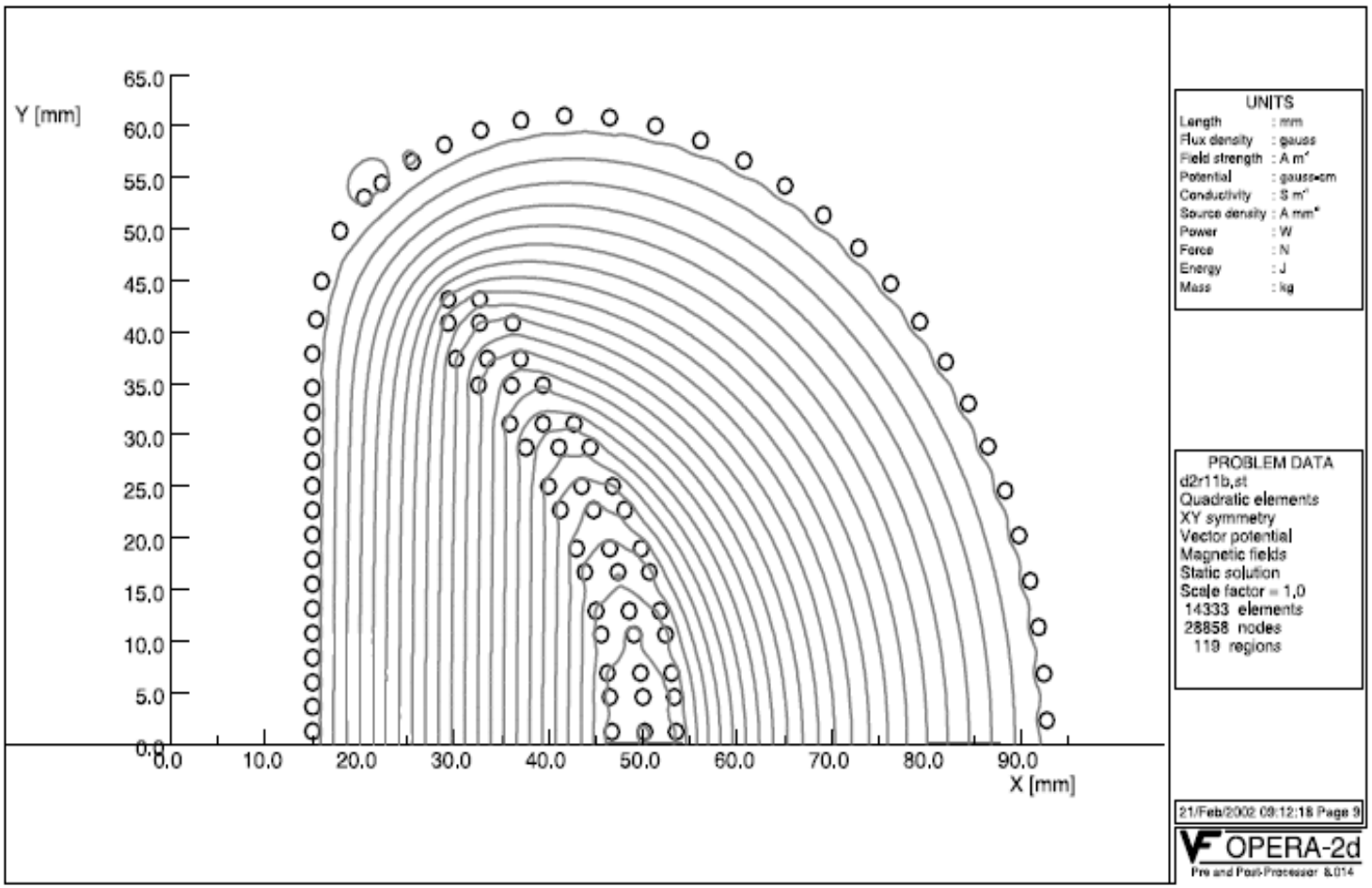


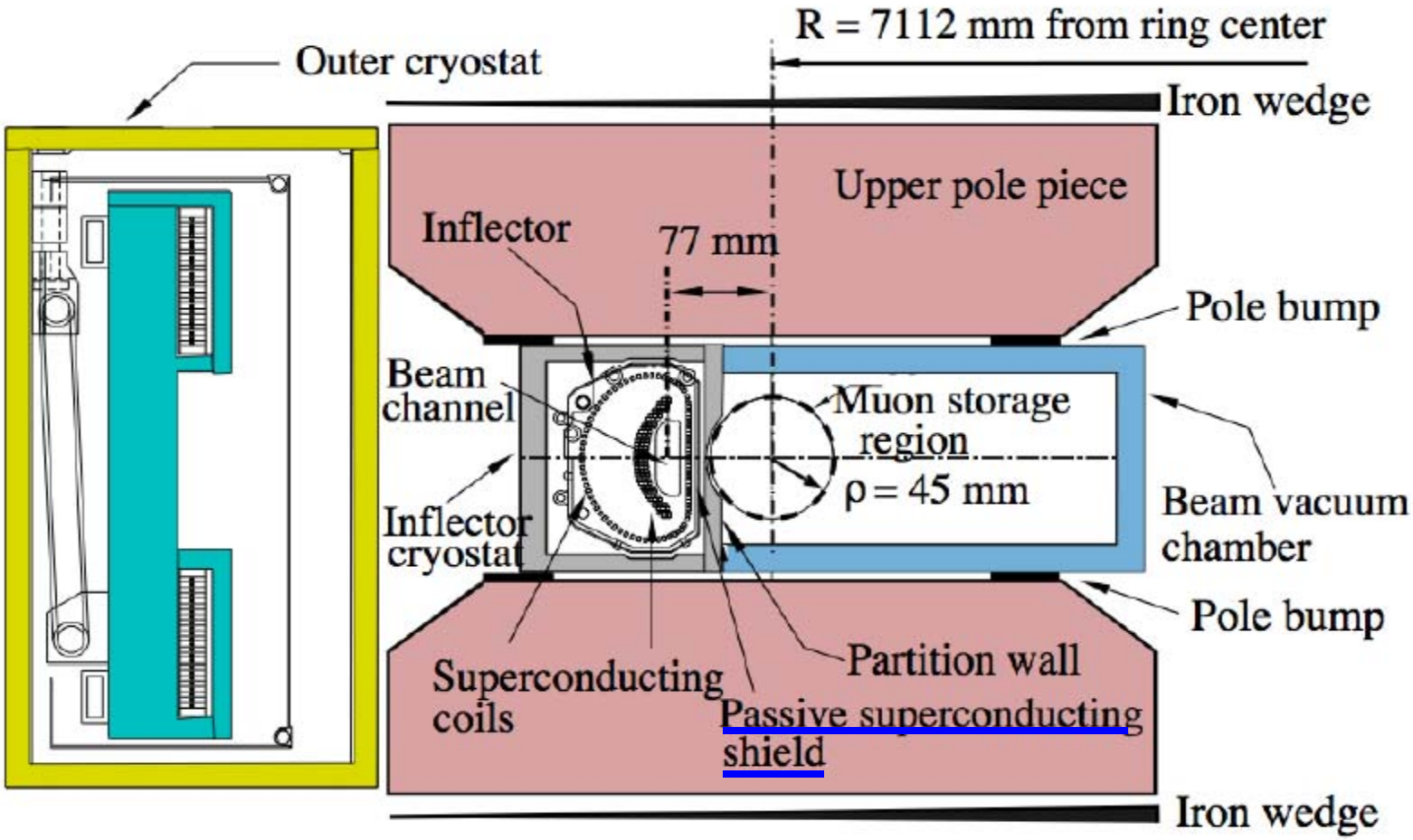
Fig. 20. Up-stream of cryostat and main magnet coils.

Superconducting Inflector Truncated Double Cosine Design

A. Yamamoto et al. / Nuclear Instruments and Methods in Physics Research A 491 (2002) 23–40



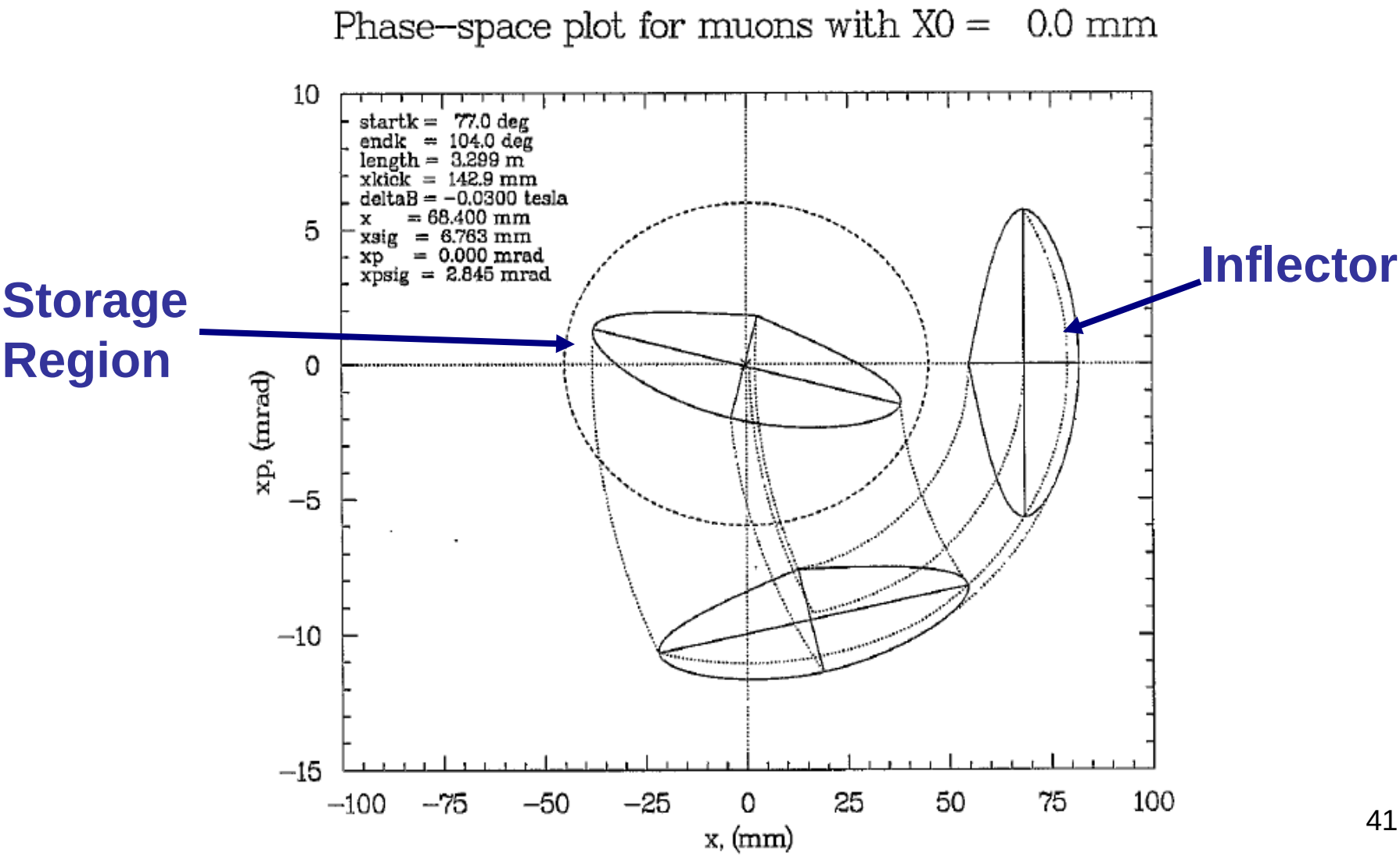
Inflector Downstream End



Pion or Muon Injection?

- E821 approved for pion injection 1989.
- R&D on fast muon injection kicker.
- What about kicker eddy currents?
- Made beamline length 1/2 pion $\beta\gamma c\tau$ so we can do both pion and muon injection.

Kicker x-x' Phase Space Plot



Kicker

- F. Krienen – electric 3MV/m – no eddy currents.
- Y.Y. Lee – magnetic 0.01T.
- What about eddy currents?
- Vernon offers bottle of wine to anyone who can measure eddy current field.
- Y. Semertzidis, thesis was axion search.

Farady Effect

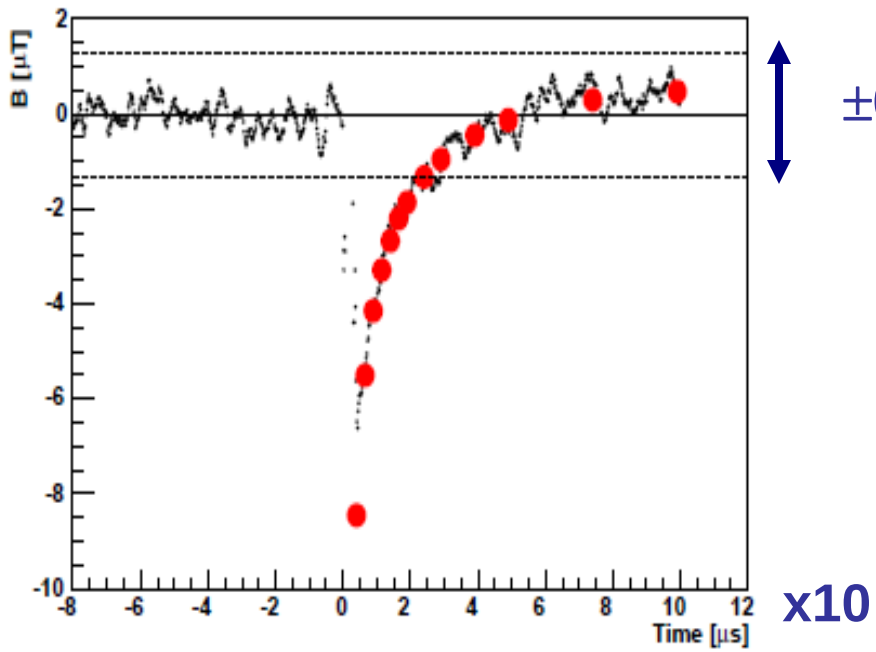
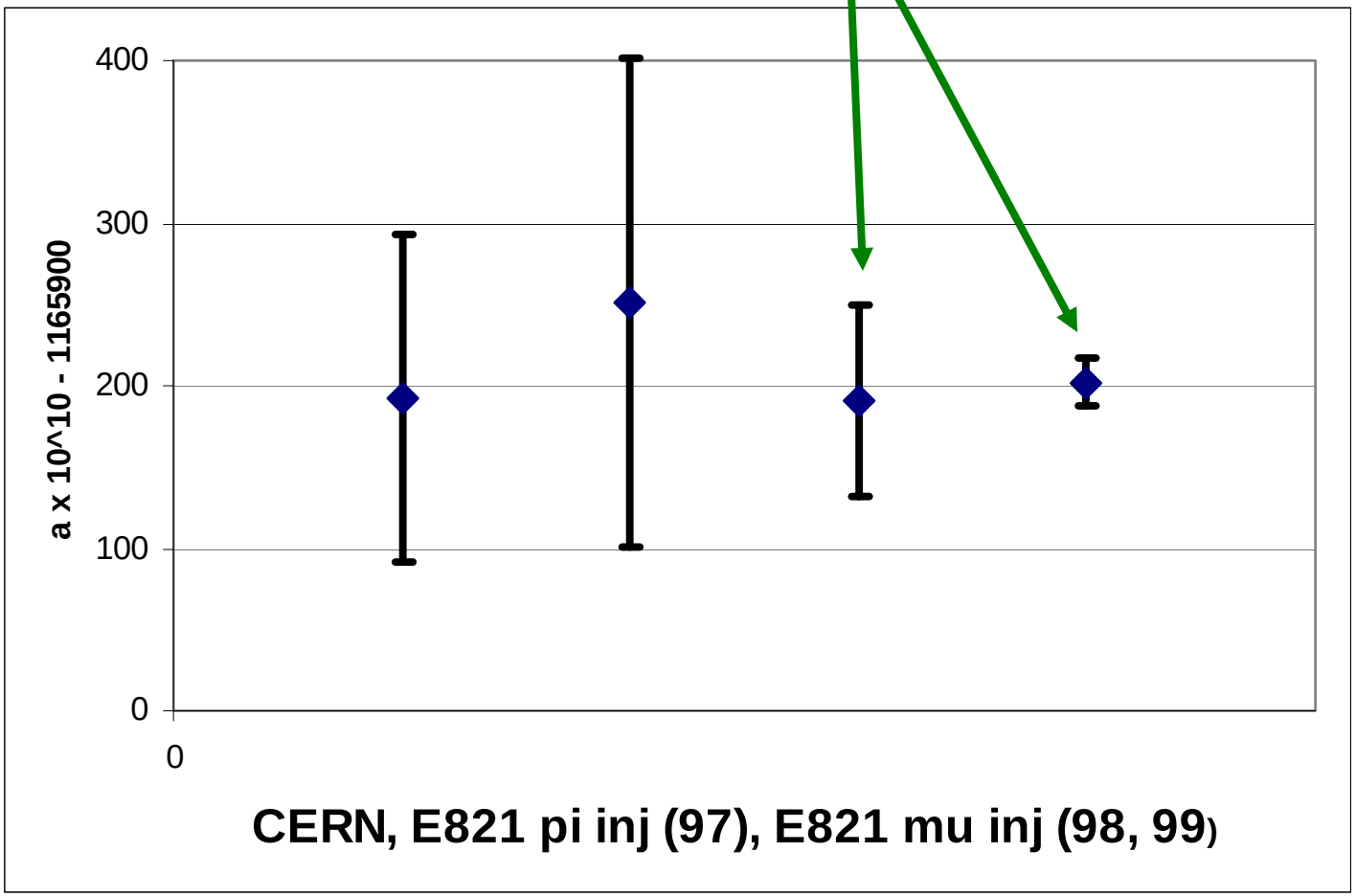


FIG. 11: The magnetic field produced mainly by eddy currents on the kicker plates as measured by an optical polarimeter with the crystal at $(x, y) = (25\ \text{mm}, 0)$ position. The kicker is fired at 95 kV, producing 4200 A at the kicker plates. The band shows the range of ± 0.1 ppm on integrated magnetic field. The large filled circles correspond to simulations with OPERA, which used the measured current pulse as the input.

Muon Injection!

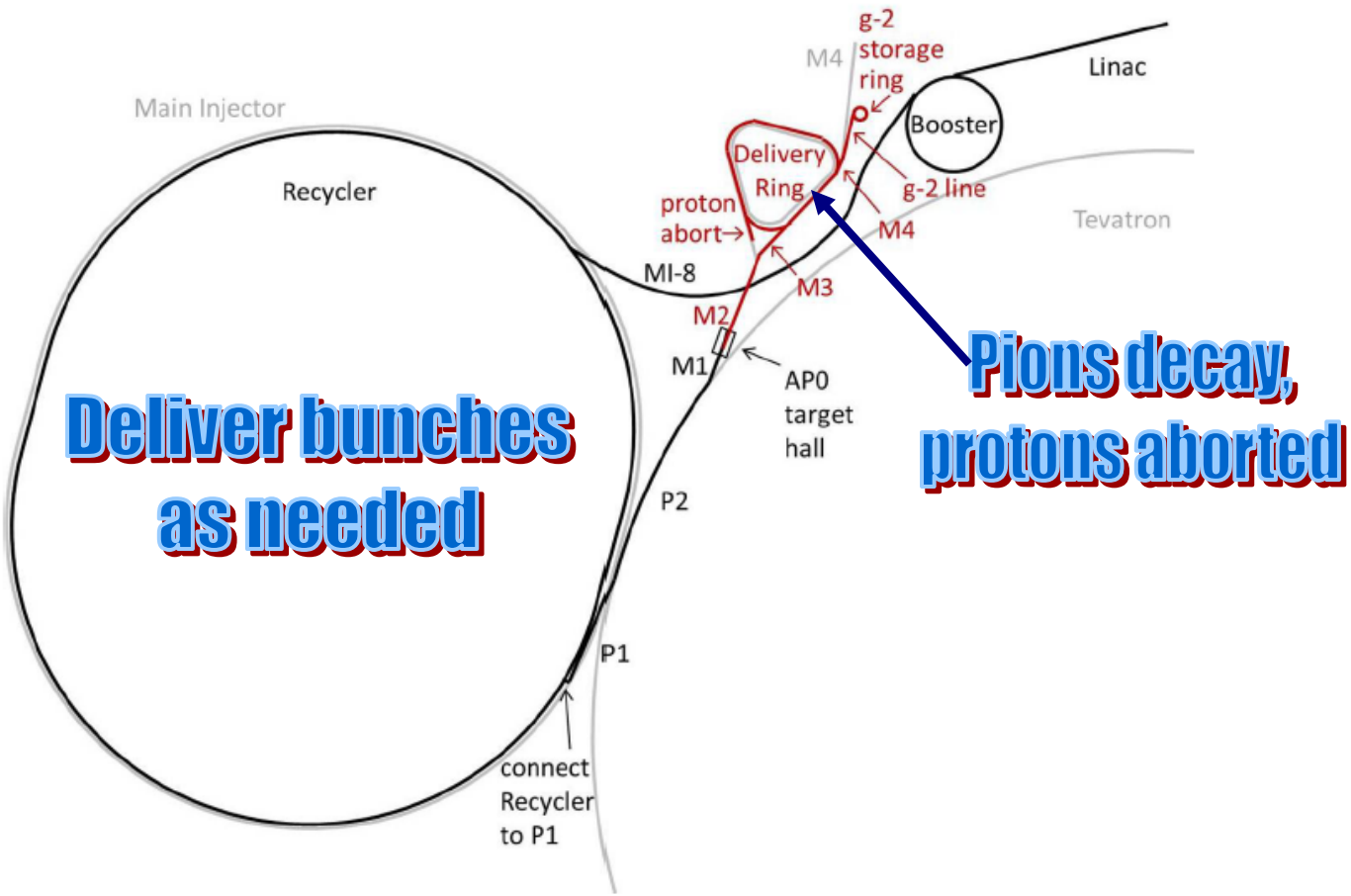


BNL E821 → FNAL E989

E989 Collaboration

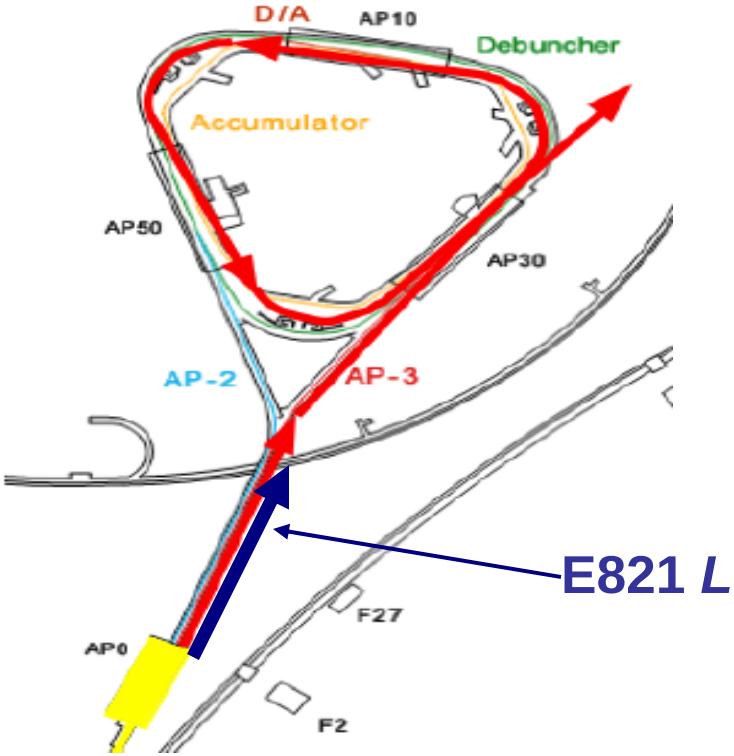
P. Winter, **ANL**, E. Barnes, R. Carey, E. Hazen, J. Miller, B. Roberts*,**Boston Univ**, W. Morse, Y. Semertzidis, V. Tishenko, **BNL**, V. Druzhinin, B. Khazin, I. Koop, I. Logashenko, Y. Shatunov, **BINP**, R. Bjorkquist, L. Gibbons, A. Mikhailichenko, Y. Orlov, D. Rubin, R. Talman, **Cornell**, D. Allspach, G. Annala, B. Casey, M. Convery, B. Drendel, D. Harding, T. Gadford, K. Hardin, C. Johnstone, J. Johnstone, A. Klebaner, K. Krempetz, I. Kourbanis, A. Leveling, A.L. Lyon, N. Mokhov, J.P. Morgan, D. Neuffer, H. Nguyen, J-F. Ostiguy, A. Para, C.C. Polly**, M. Popovic, M. Rominsky, P. Rubinov, R. Schultz, D. Still, A.K., Soha, S. Strigonov, G. Velev, **FNAL**, P. Debevec, K. Pitts, **Univ of Illinois**, K. Giovanetti, **James Madison Univ**, N. Khomutov, N. Kuchinskiy, **JINR, Dubna**, N. Saito, *KEK,* C. Crawford, R. Fatemi, T. Gorringe, W. Korsch, B. Plaster, **Univ of Kentucky**, K. Jungmann, C.J.G. Onderwater, **KVI**, M. Cordelli, S. Giovannella, F. Happacher, A. Luca, M. Martini, S. Mischetti, I. Sarra, G. Venanzoni, **Frascati**, D. Kawall, **Univ Mass**, T. Chupp, **Univ Michigan**, C. Ankenbrandt, M. Cummings, R. Johnson, C. Yoshikawa, **Muons Inc**, A. de Gouvea, H. Shellman, L. Welty-Rieger, **Northwestern**, T. Itahashi, Y. Kuno, *Osaka,* G.D. Alkhazov, V.L. Golovtsov, P. Neustroev, L. Uvarov, A. Vasilyev, A. Vorobyov, M. Zhalov, **Petersburg Nuclear Physics Inst**, F. Gray, **Regis Univ**, X. Ji, L. Li, **Shanghai Jiao Tong Univ**, D. Stockinger, **Tech Univ Dresden**, S. Baessler, M. Bychkov, E. Frlez, D. Pocanic, **Univ Virginia**, L. Alonzi, J. Crnkovic, N. Froemming, A. Garcia, D. Hertzog*, P. Kammel, B. Kiburg, M. Smith, E. Swanson, T. Zhao, **Univ Washington**, K. Lynch, **York College, CUNY**

8 GeV Protons from FNAL Booster



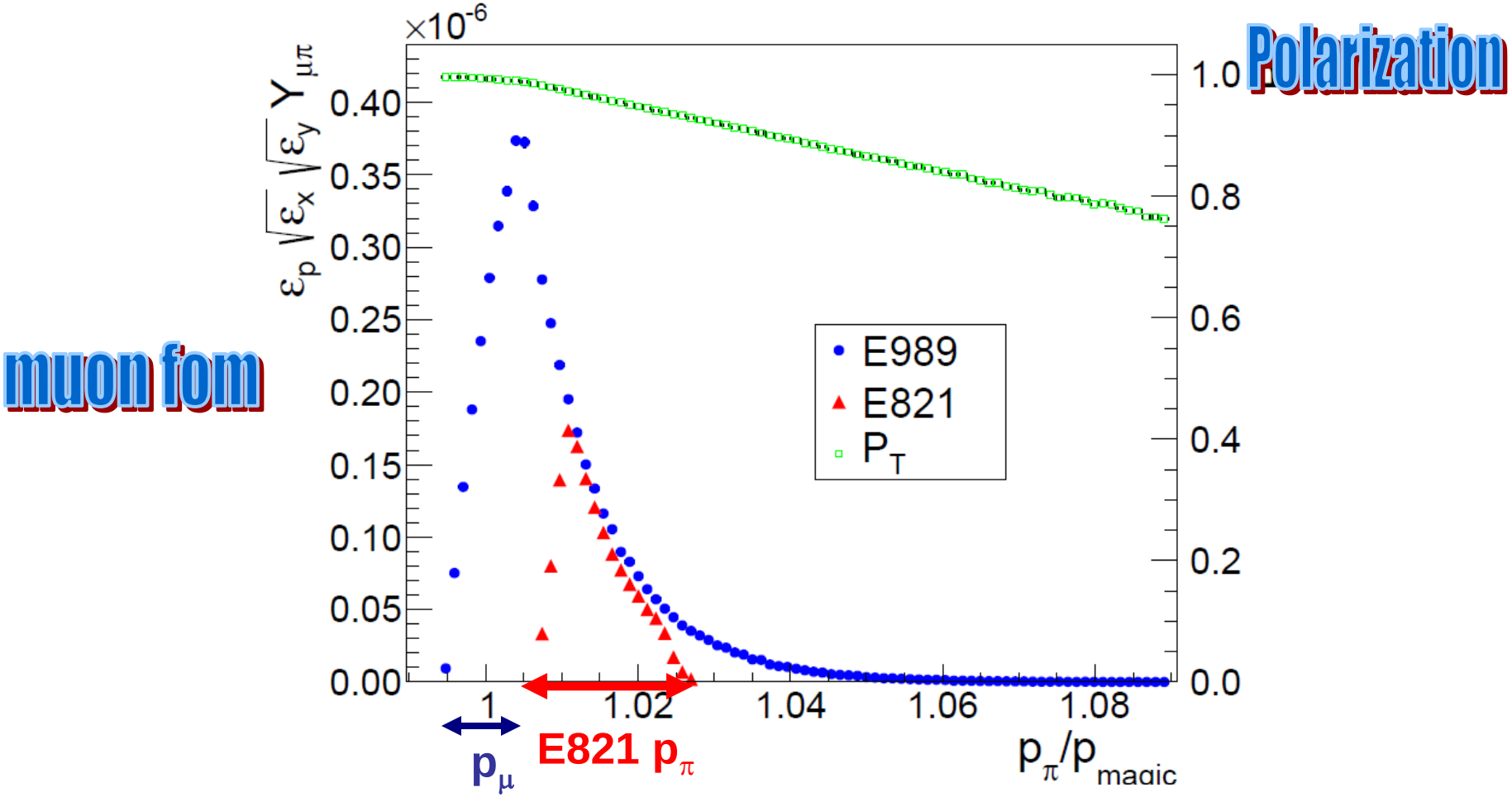
Pion Decay Length

- E821 $L/\beta\gamma c\tau \approx 0.5$
- E989 $L/\beta\gamma c\tau \approx 1.$

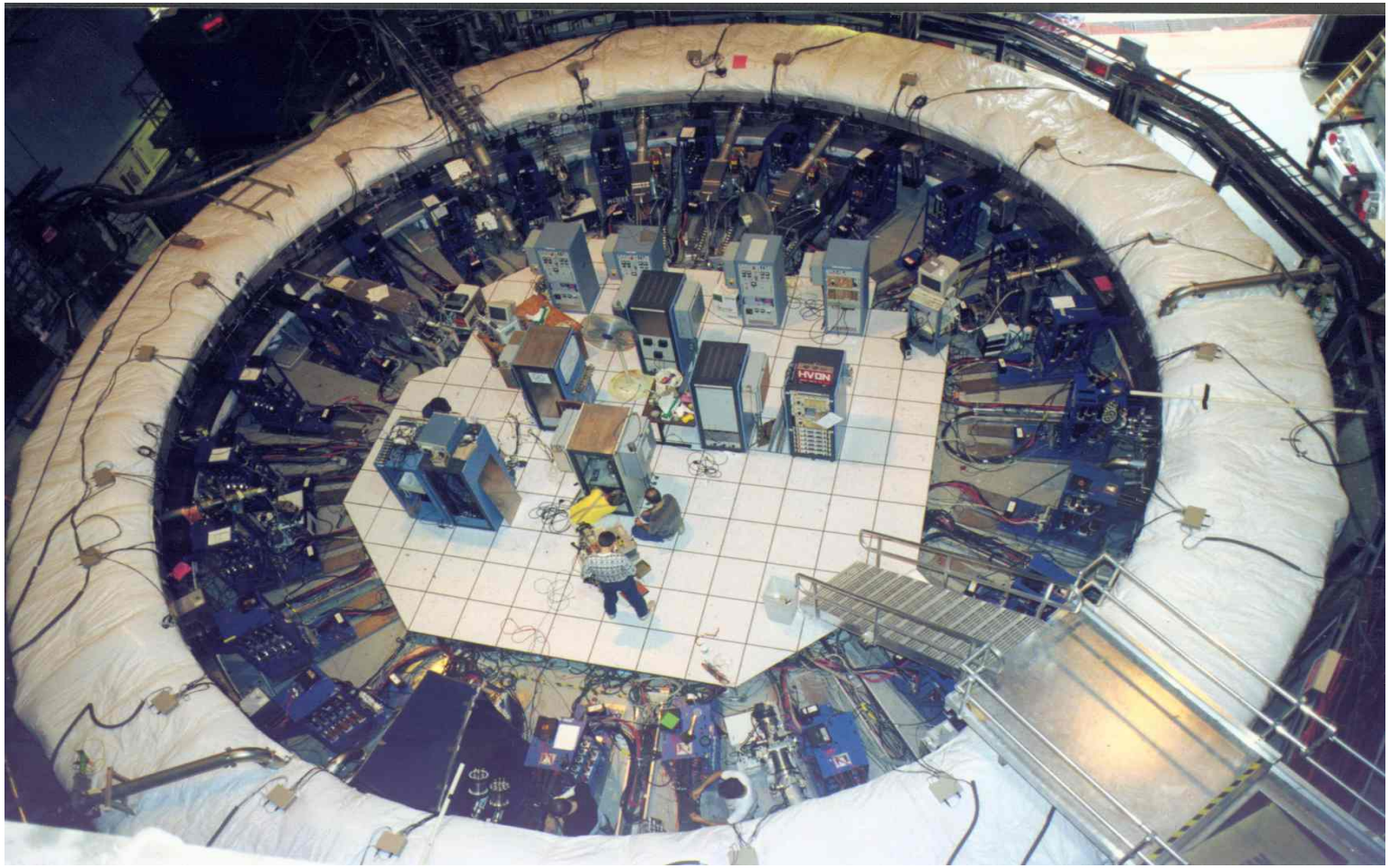


V. Tishchenkov
BNL

$\pi \rightarrow \mu\upsilon$



E821 Muon Storage Ring 1997

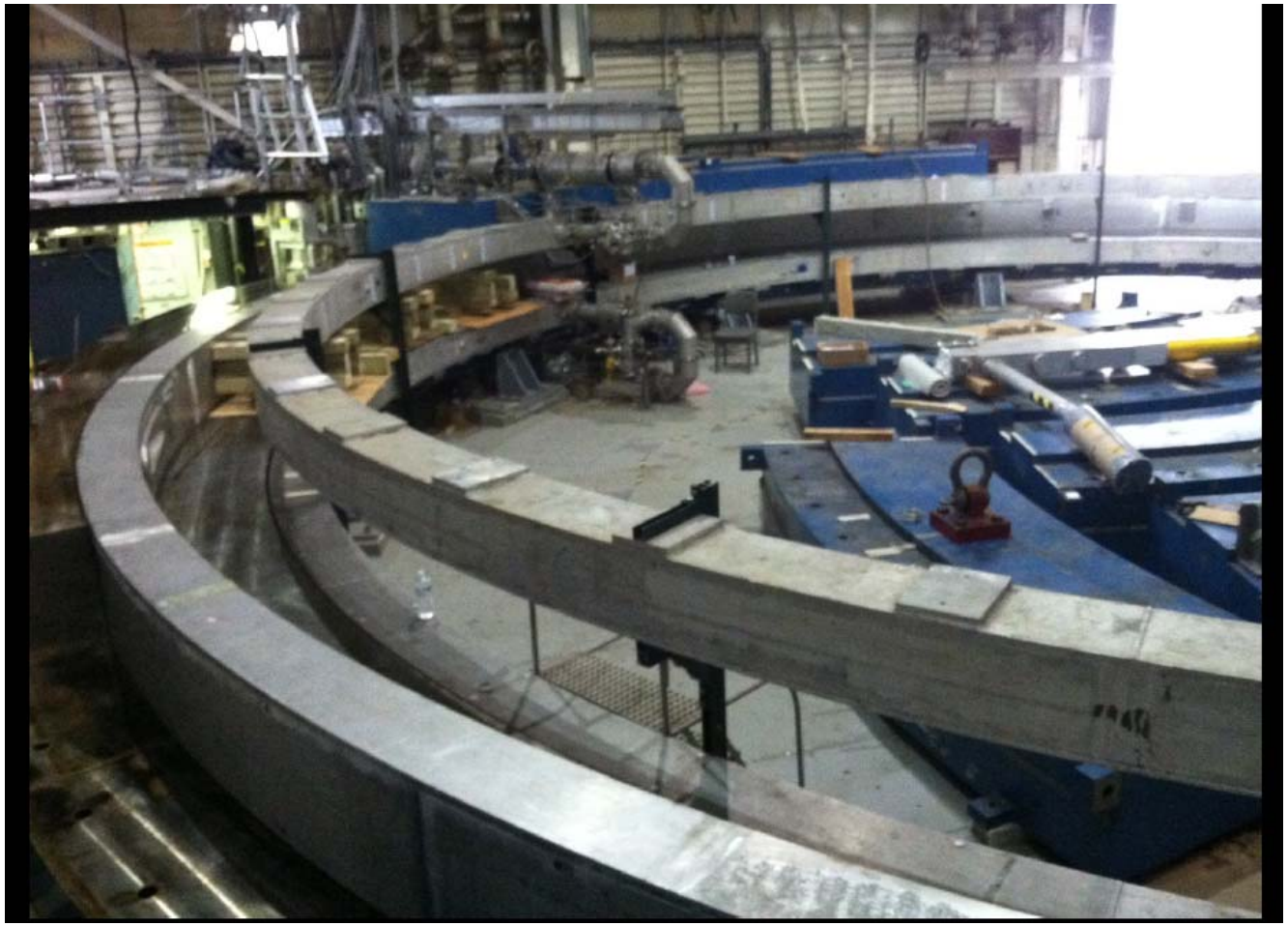


FNAL Contingent 2012

University Contingent

FNAL Warehouse

2013



Moving Coils out of the Bldg.

- Plan A
- BNL “spider”
- Plan B:
- Lift coil hydraulically

2012 Feasibility Study
Helicopter or Truck

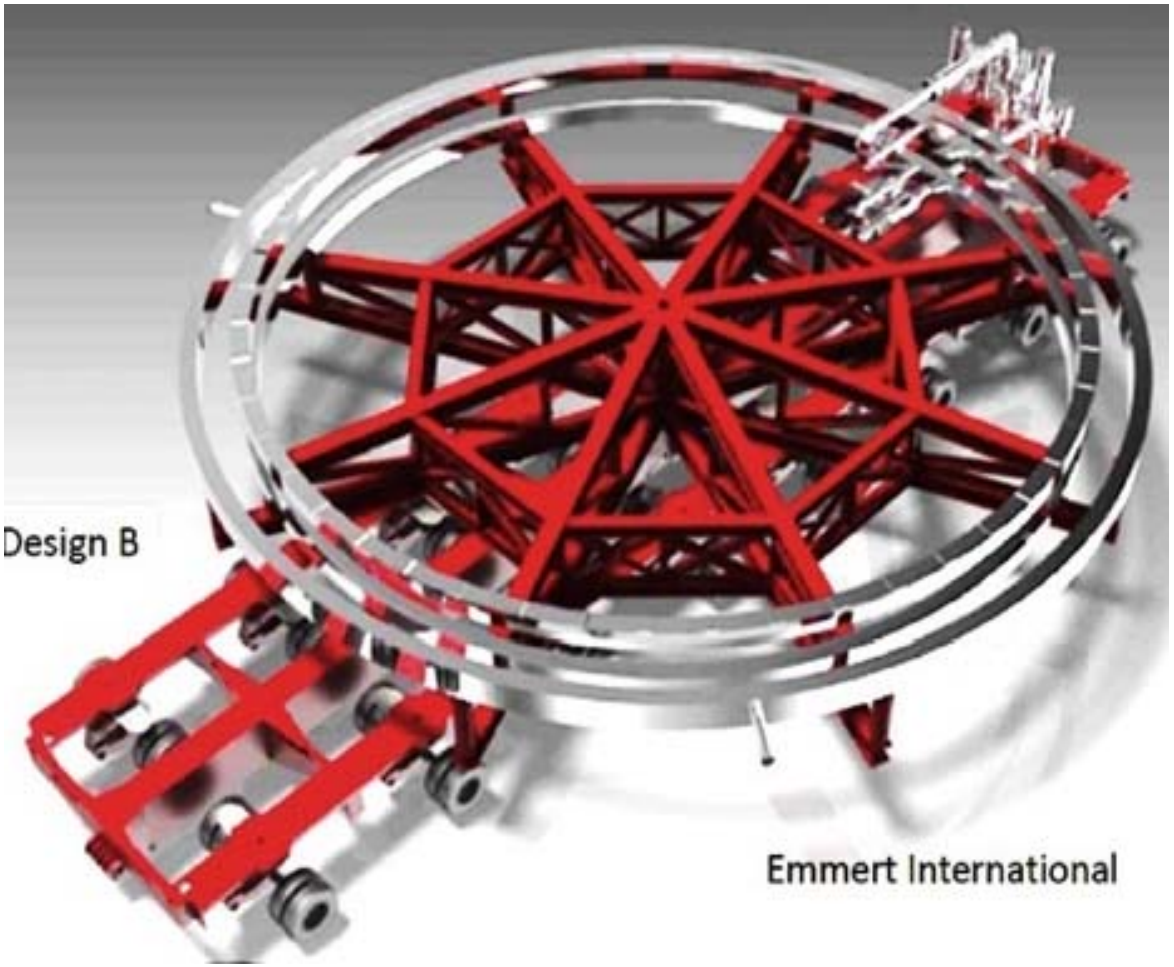
G-2 Aircraft Model S64F

6-6-2012 Allsoach

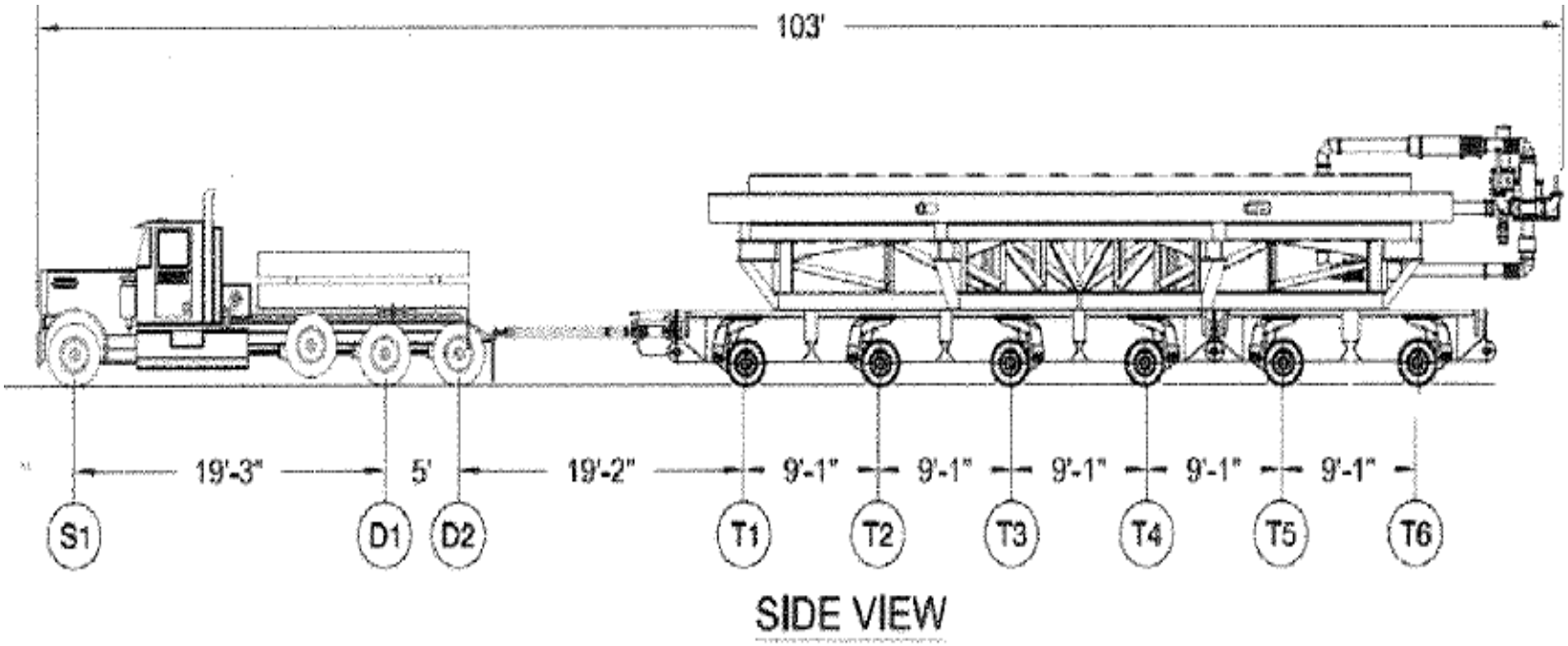
Routes

- Northern route:
- Truck: BNL/Shoreham
- Barge: St. Lawrence Seaway/ Illinois Waterway
- Truck: Illinois Waterway/FNAL
- Southern route:
- Truck: BNL/ Smith Point Marina
- Barge: Mississippi River/ Illinois River/ Illinois Waterway

Outer Coil is 15m wide

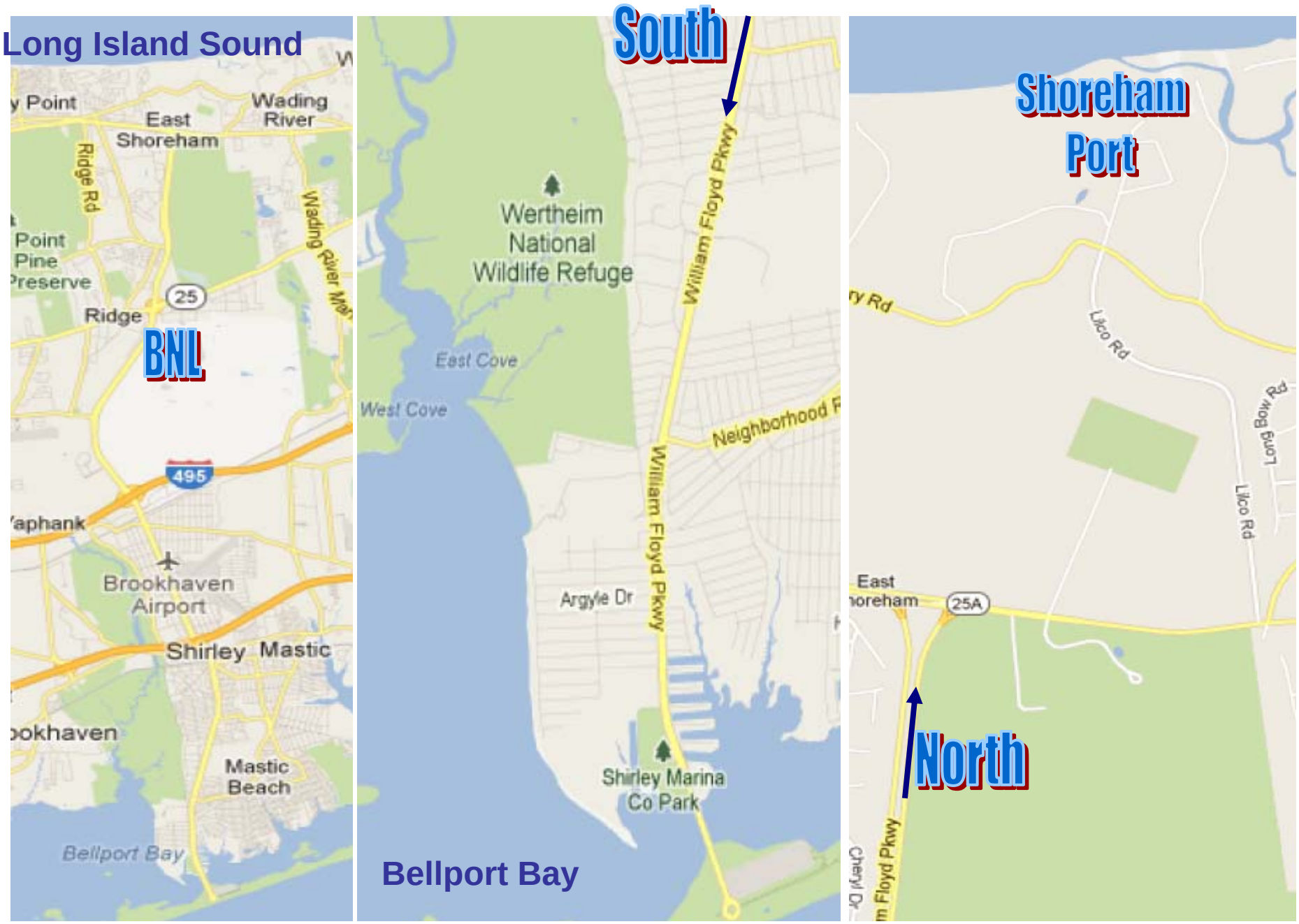


Mover

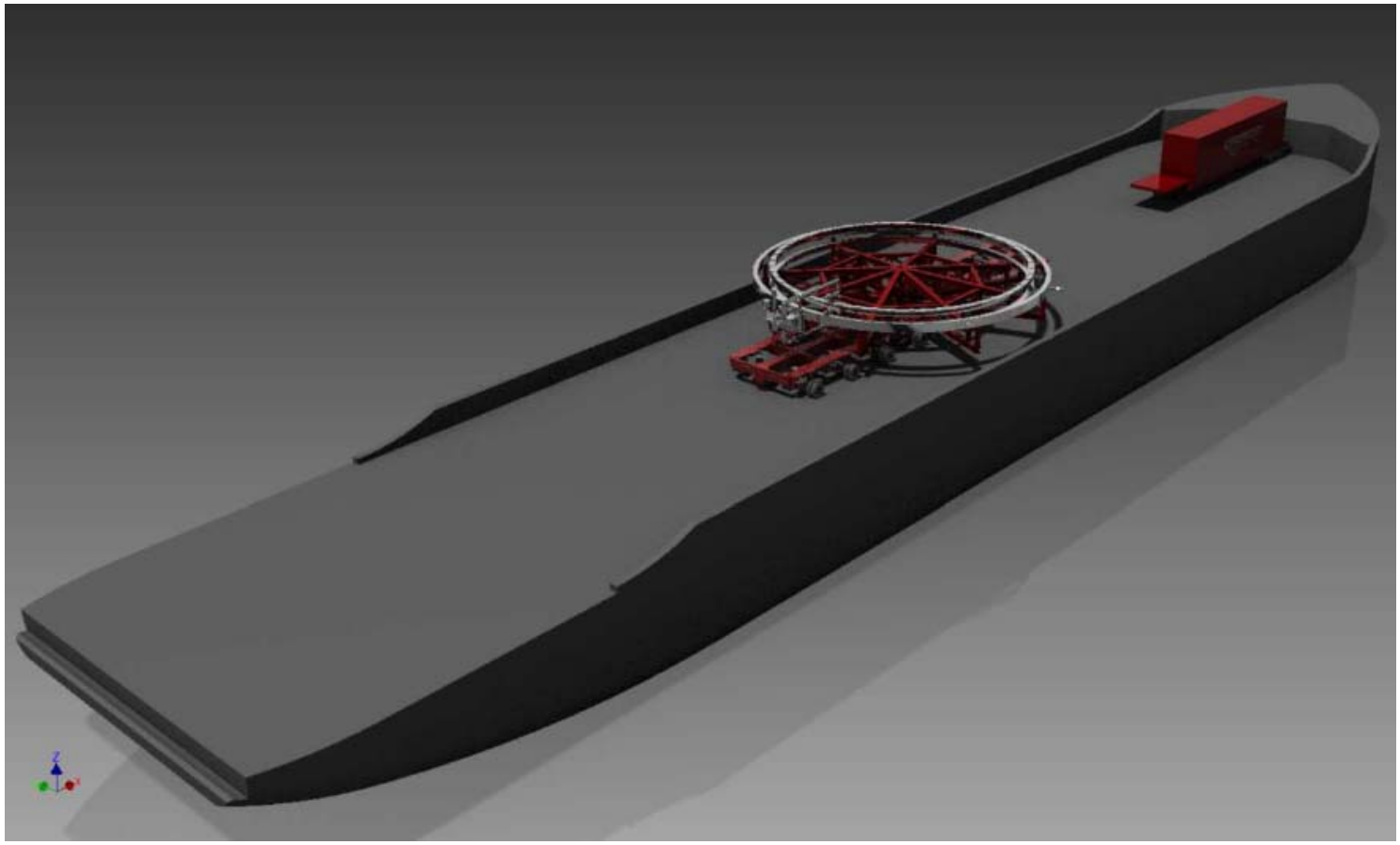


Emmert International Model

Model

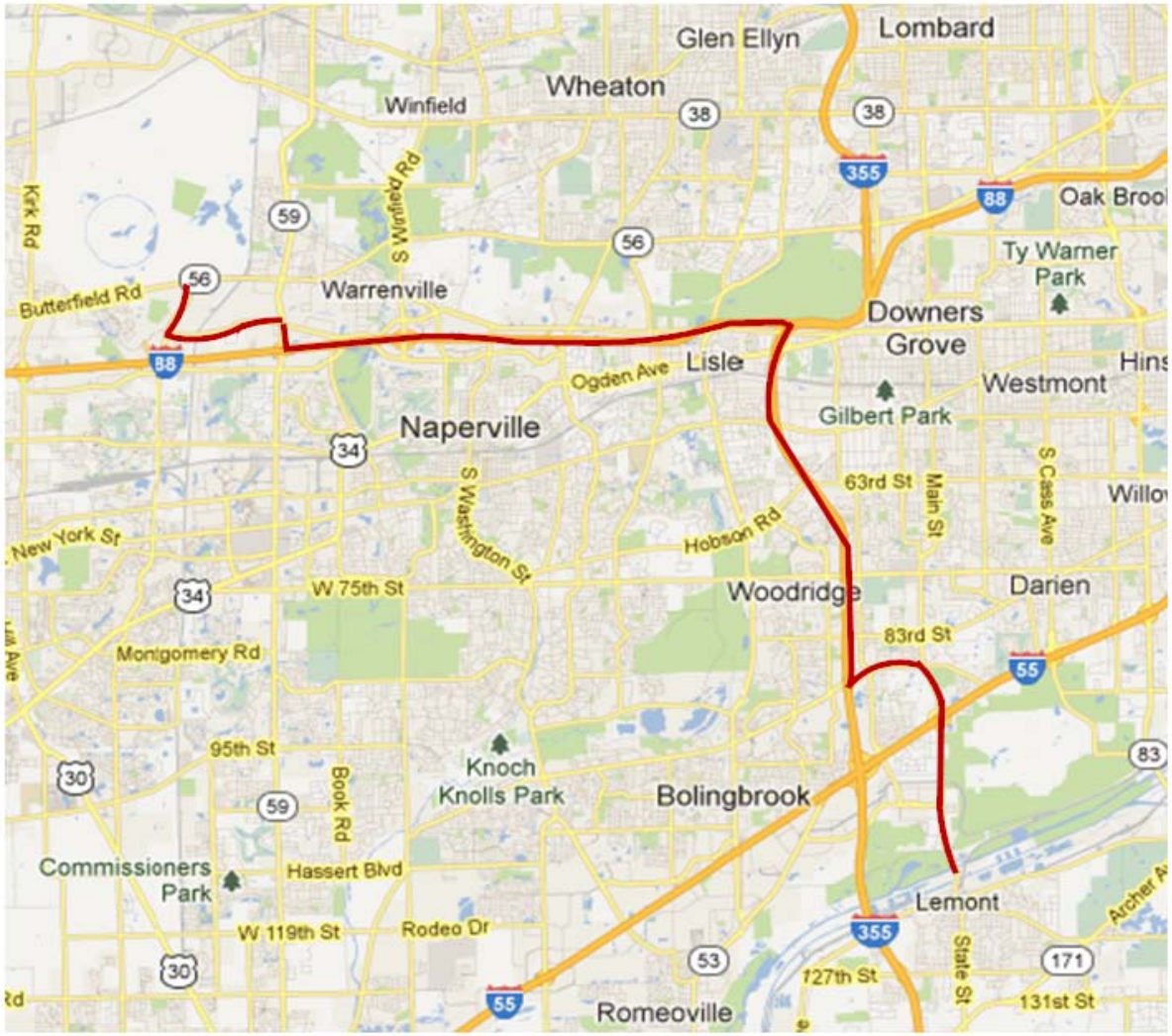

Long Island Sound
Point
Wading River
East Shoreham
Ridge Rd
Point Pine Preserve
Wading River
25
Ridge
BNL
495
Brookhaven Airport
Shirley
Mastic
Mastic Beach
Bellport Bay
South
Wertheim National Wildlife Refuge
William Floyd Pkwy
East Cove
West Cove
Neighborhood
Argyle Dr
Shirley Marina Co Park
Bellport Bay
Shoreham Port
Licco Rd
Long Bay Rd
East
25A
North

54’×180’ Barge



avoid ice
avoid hurricanes
nesota
Wisconsin
Michigan
Chicago
Iowa
Illinois
Indiana
Ohio
Toronto
Montreal
Maine
New York
Pennsylvania
New York
Massach
Rhode Islan
Connecticut
New Jersey
Delaware
Maryland
District of Columbia
Missouri
Kentucky
West Virginia
Virginia
Tennessee
North Carolina
Arkansas
Mississippi
South Carolina
Alabama
Georgia
Louisiana
Florida
Gulf of Mexico

Illinois Route: Lemont to FNAL



Route:
Illinois Waterway
Lemont Road north
87th Street west
I-355 north
I-88 west
Hwy 59 north
Ferry Road west
Eola Road north
Fermilab

Tollway

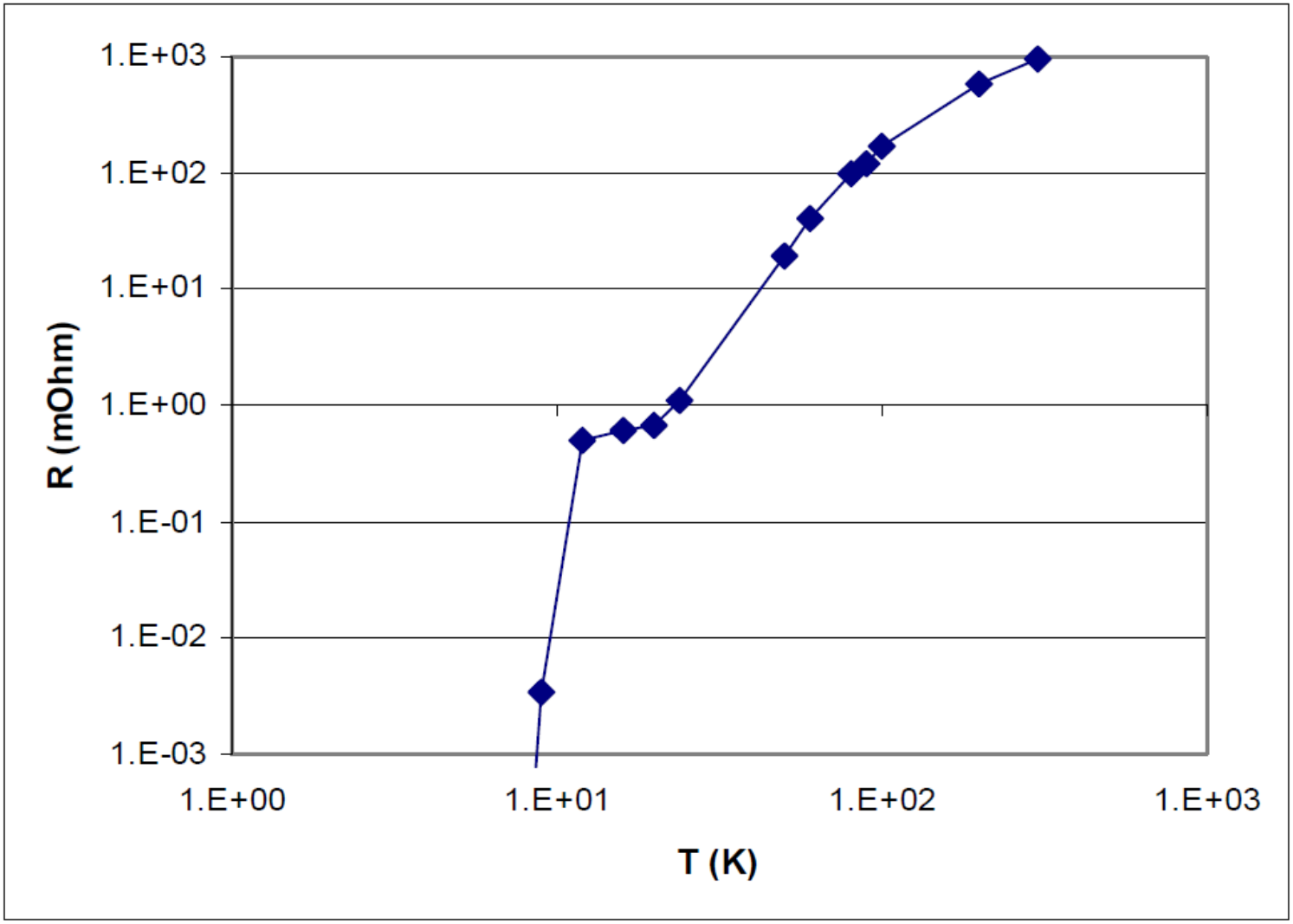
Site prep started at FNAL

Muon Campus Aerial

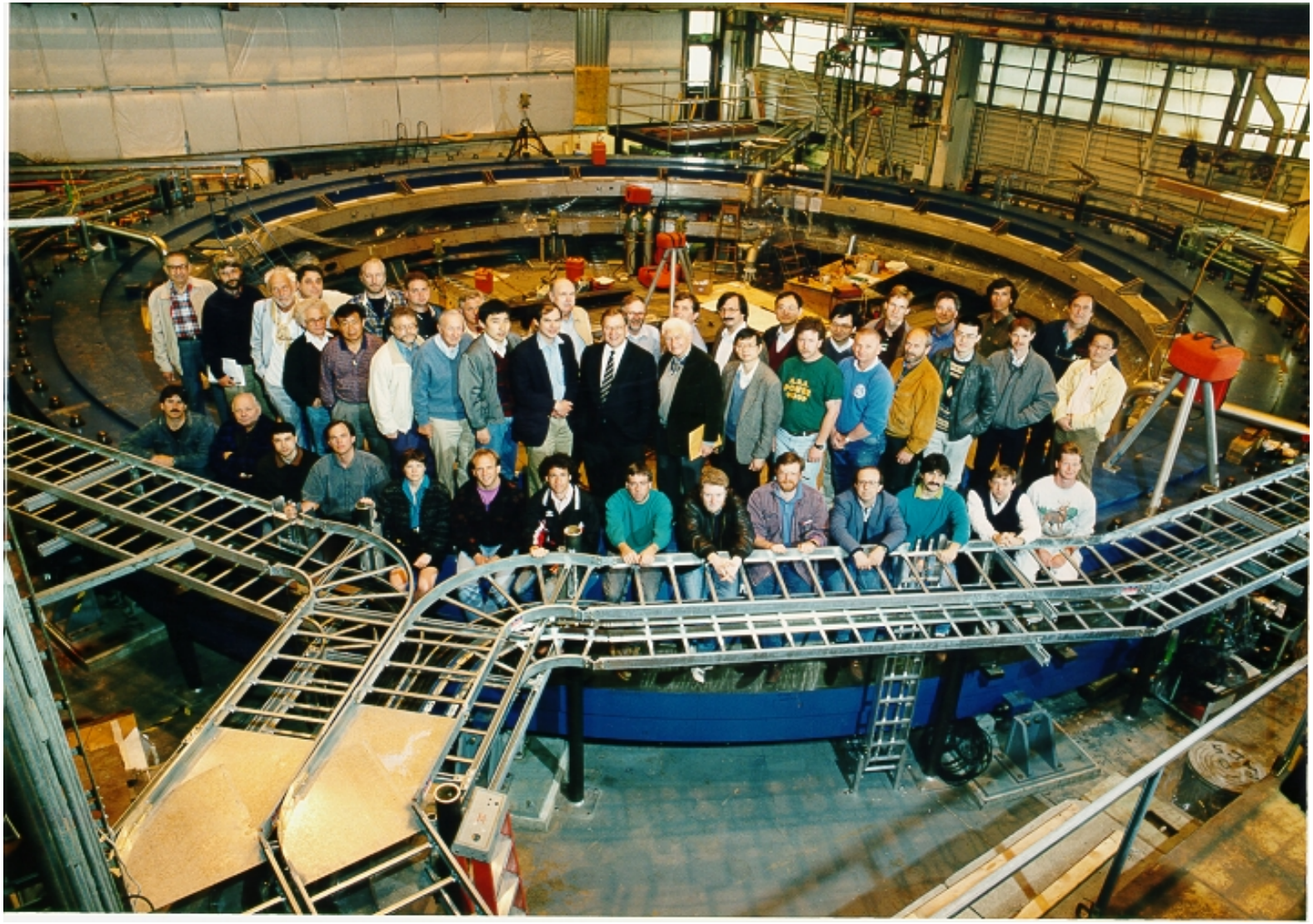
Conclusion ……..

Extras

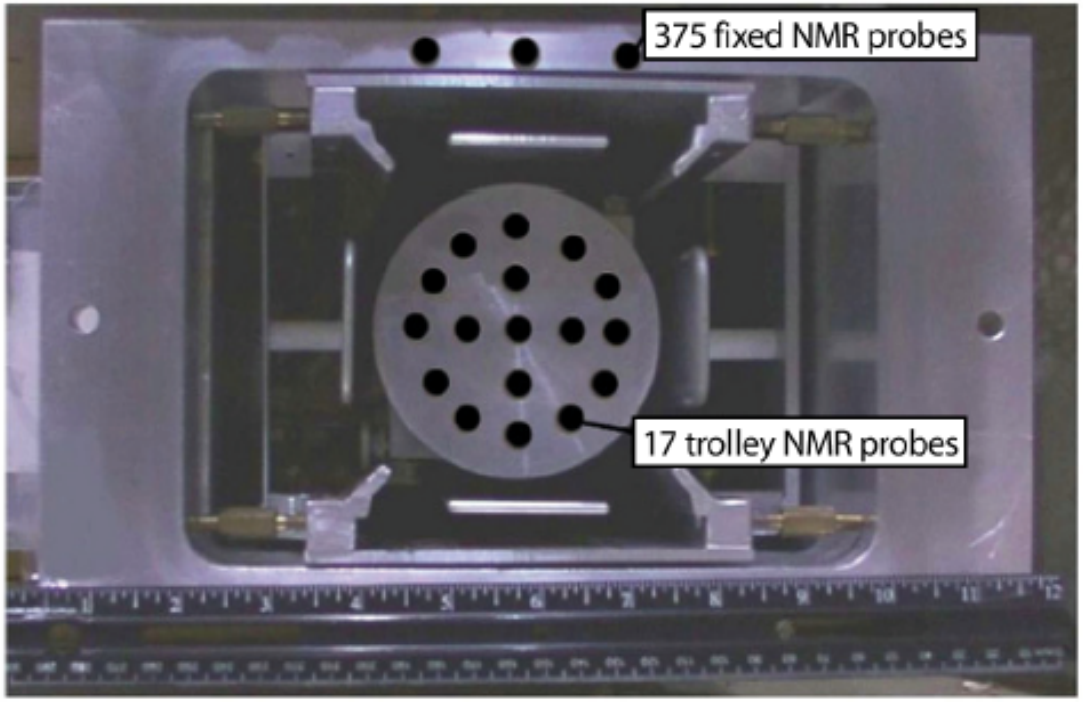
Benchmark Coil R, R to Ground, etc.



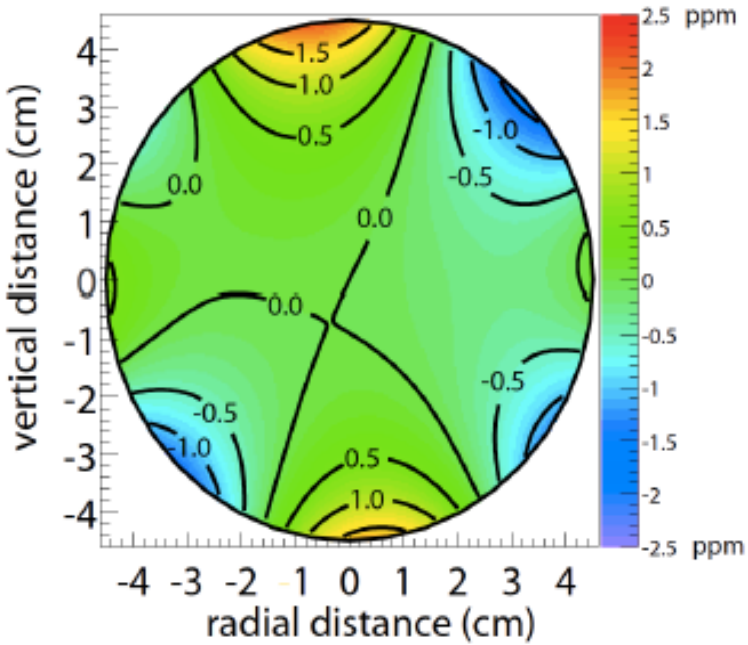
E821 Muon Storage Ring 1996



Measuring B



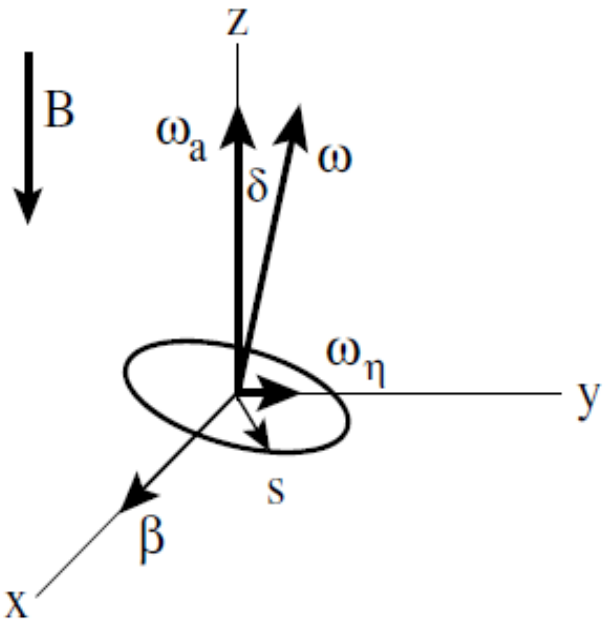
(a)



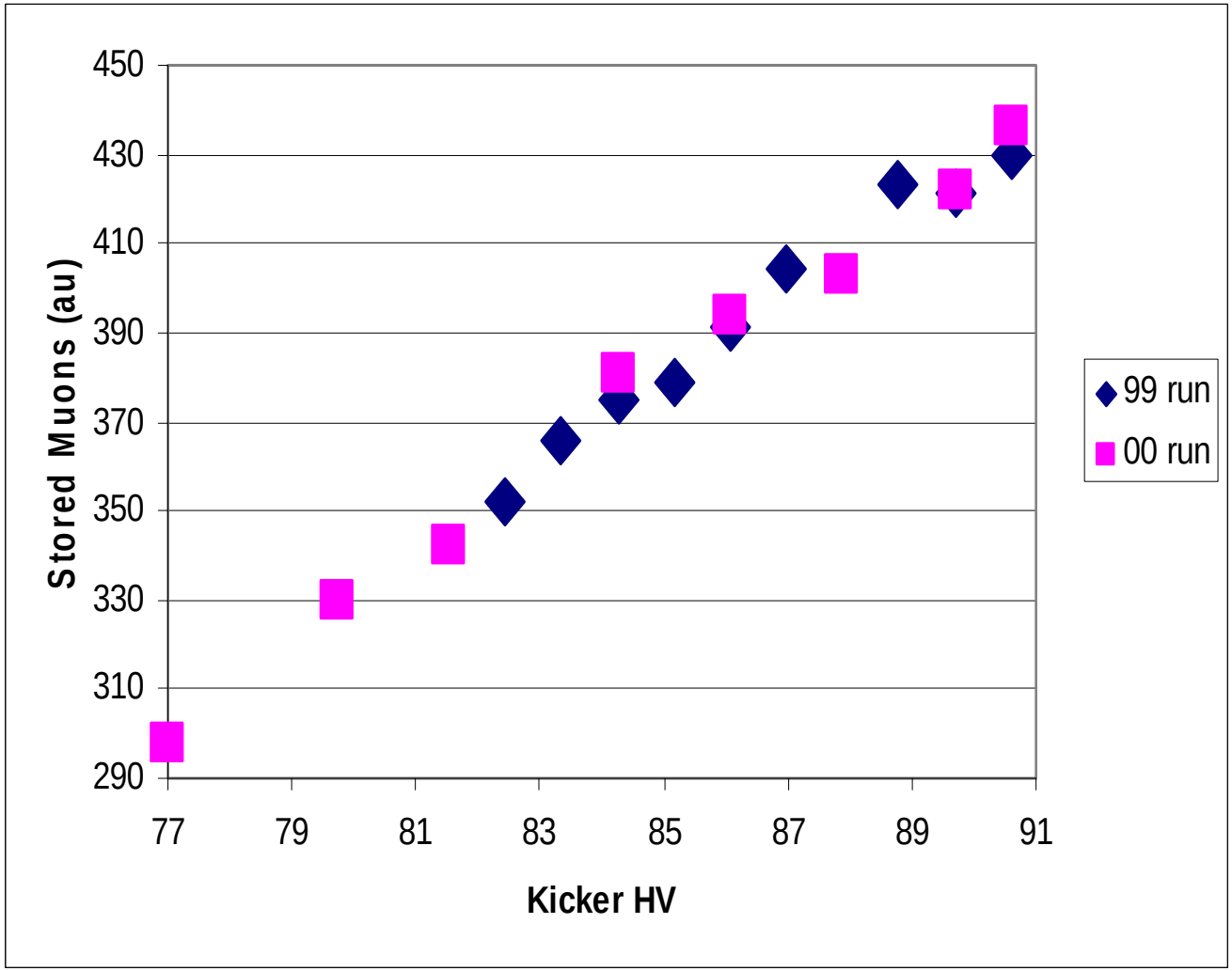
(b)

Electric Dipole Moment

- E821: $d_\mu < 1.8\times10^{-19}$ecm.
- Only edm experiment for a charged particle.
- Neutron, atoms, ….



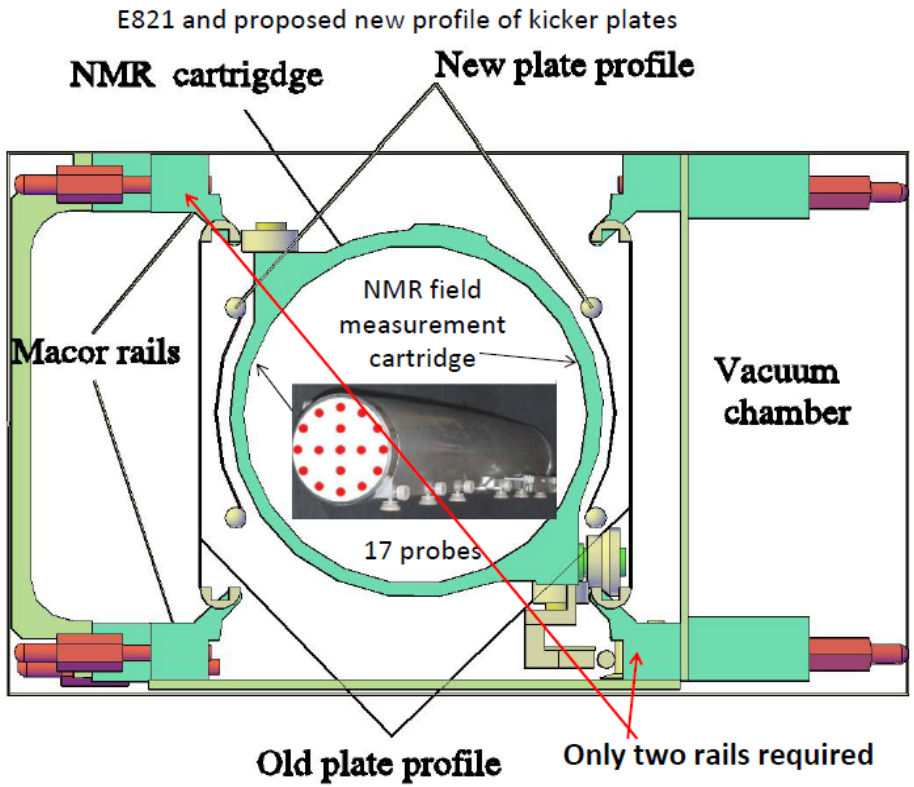
E821 Stored Muons vs. Kicker HV

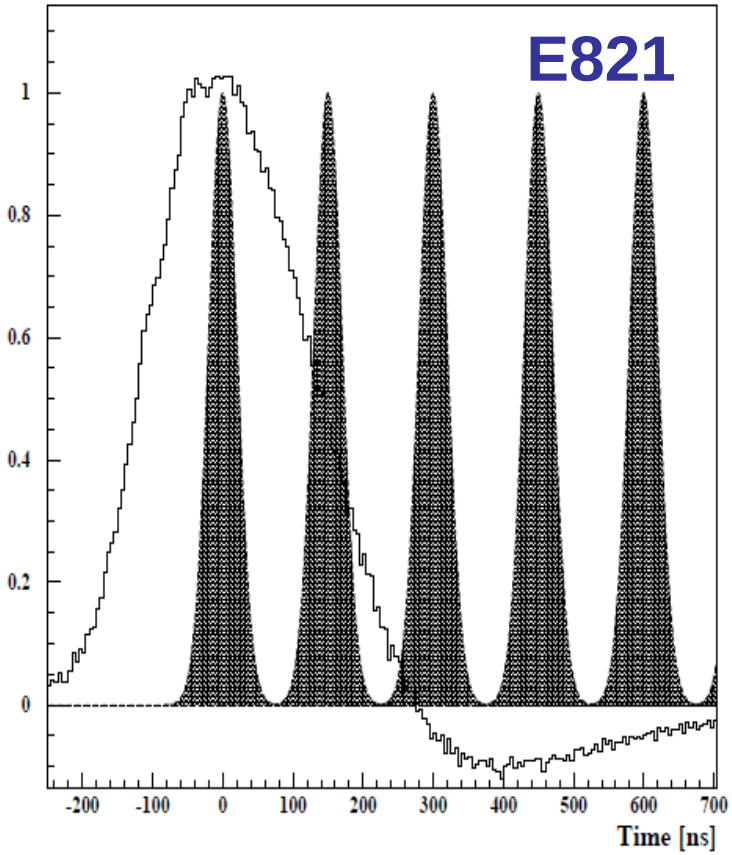


FNAL Muon g-2 Exp.

- Proposed 2010
- CD0 approval 2012
- CD1 approval 2013
- Move coils summer 2013
- Magnet assembled 2014
- Magnet powered/shimmed 2015
- First Run 2016

Kicker Upgrade - Cornell





Hadronic Vacuum Polarization

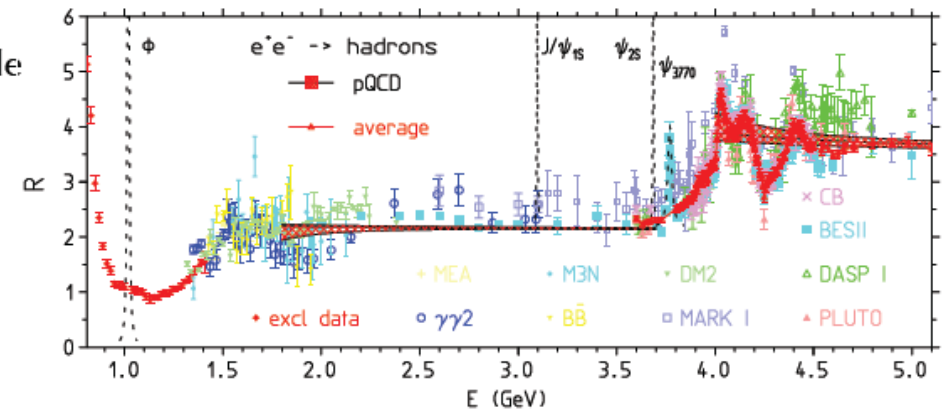
- Standard-Model value for a_μ^{HVP} obtained from experimental measurement of $\sigma_{total}(e^+e^- \to \text{hadrons})$ via optical theorem:

$$a_\mu^{\rm HVP} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} {\rm d}s \frac{R(s)K(s)}{s^2} \qquad R \equiv \frac{\sigma_{\rm total}(e^+e^- \to {\rm hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

  - (Away from quark thresholds, use four-loop pQCD)

- Includes >20 multi-particle channels with up to six final-state hadrons

- Multi-hadron channels represent a small absolute contribution to a_μ^{HVP}, but contribute a significant fraction of the total uncertainty



[Jegerlehner and Nyffeler, Phys.Rept. 477 (2009) 1-110]

BNL E821 vs. SM Theory

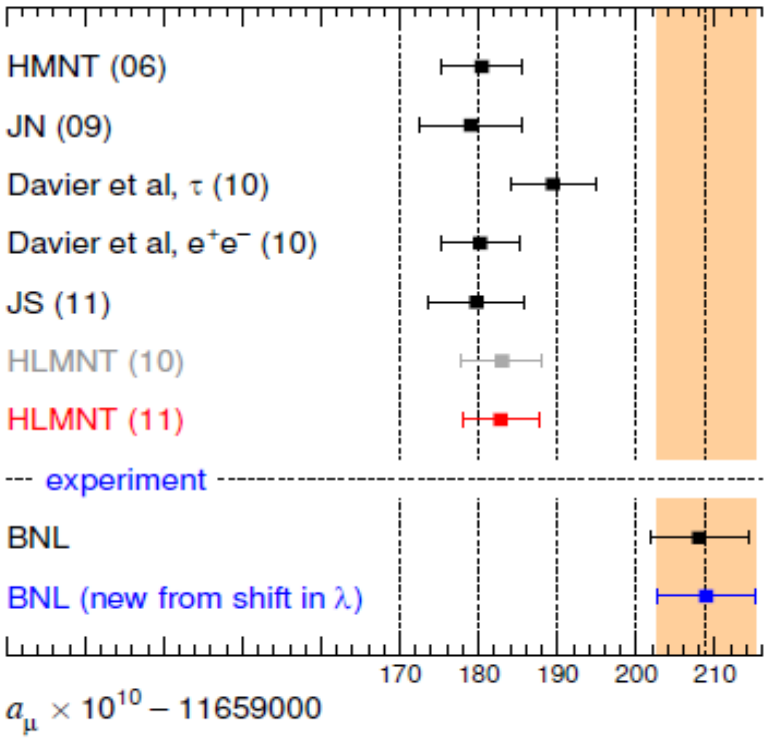
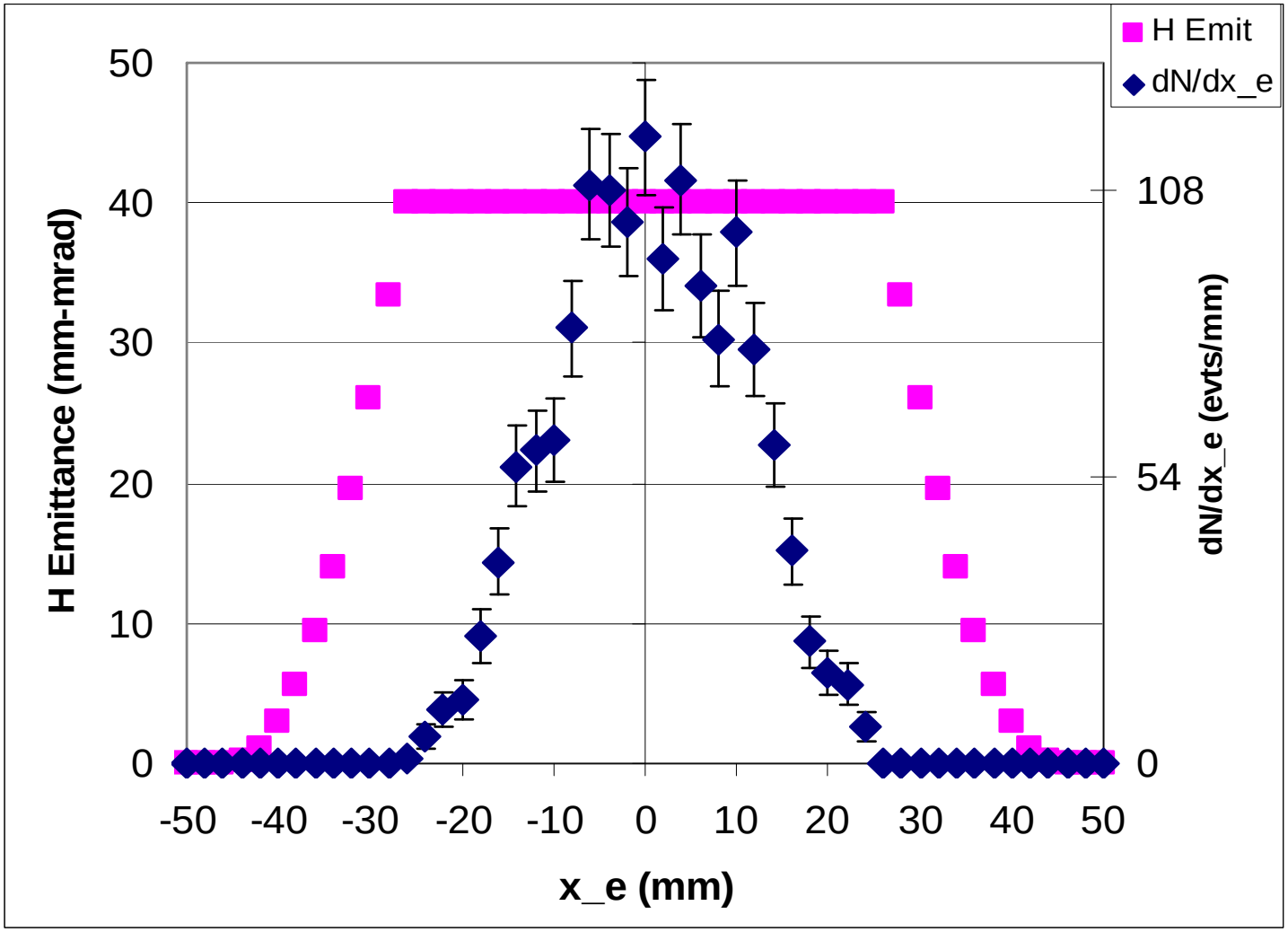


Figure 1: Standard Model predictions of a_μ by several groups compared to the measurement from BNL (from Ref. [4]).

Perfectly Matched Inflector gains factor of 2.3 more muons

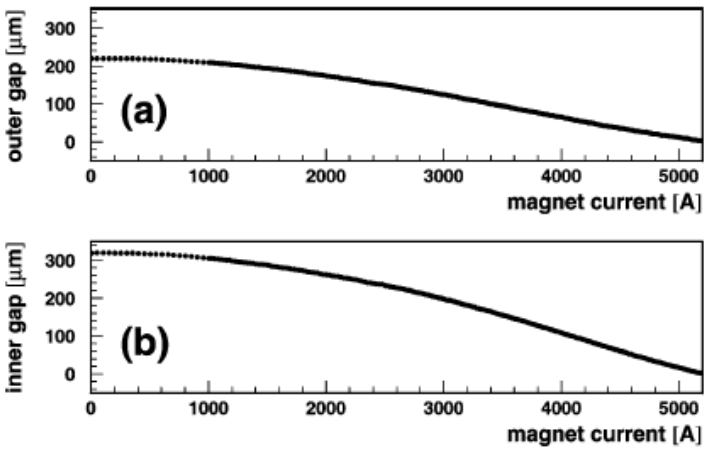
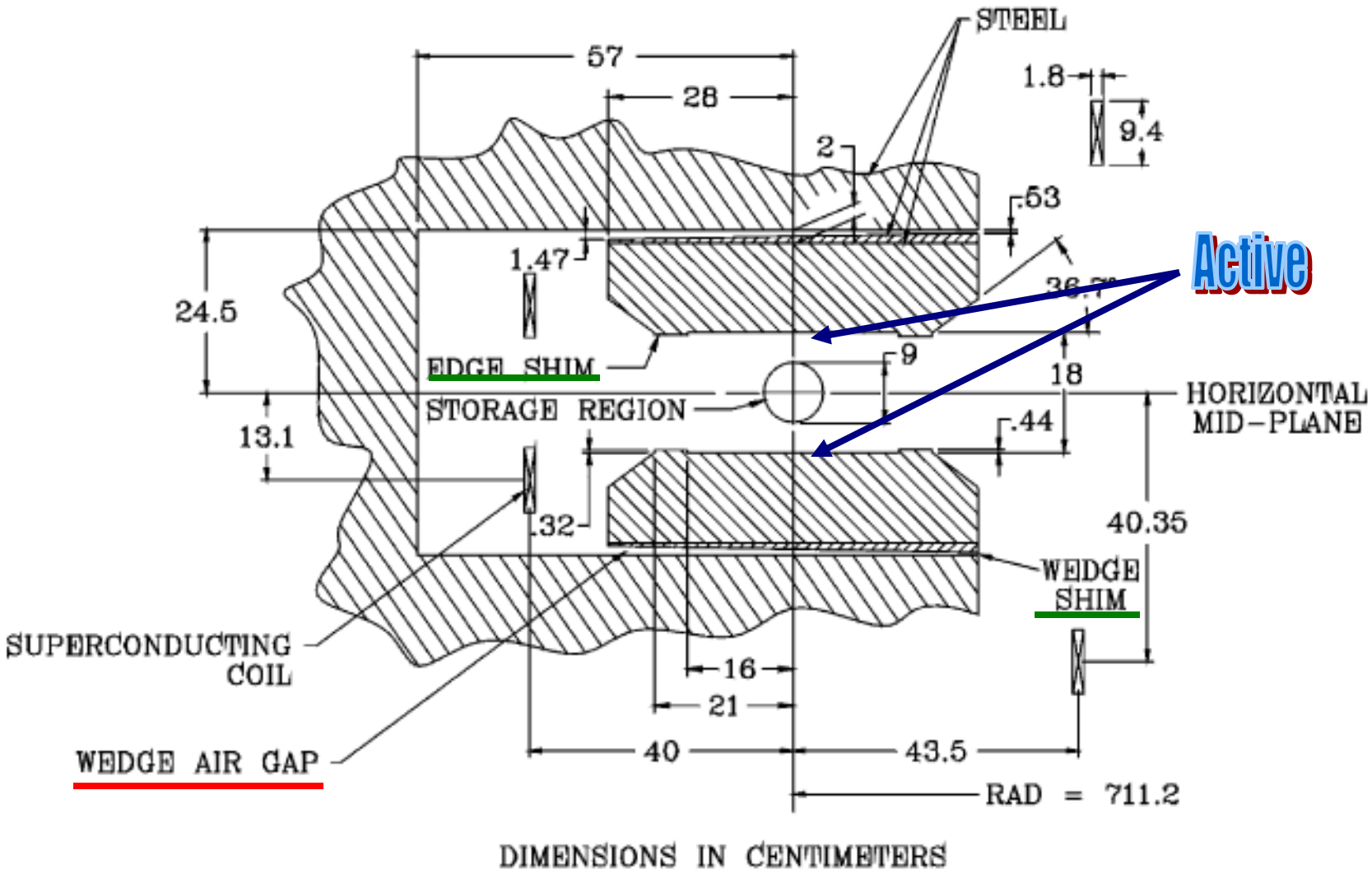


Distortion of Closed Orbit

- B_{R0}/B_{y0} = 40ppm
- dy = 2.1mm for n = 0.137
- dy = 1.6mm for n = 0.180

$$\frac{\partial^2 y}{\partial \theta^2} + ny = \sum_N \frac{R_0}{B_{y0}} B_{RN} \cos\left(N\theta + \phi_N\right)$$

$$dy = \frac{R_0}{B_{y0}} \frac{\sum B_{RN} \cos\left(N\theta + \phi_N\right)}{N^2 - n}$$


outer gap [μm]
300
200
100
0
(a)
0
1000
2000
3000
4000
5000
magnet current [A]
inner gap [μm]
300
200
100
0
(b)
0
1000
2000
3000
4000
5000
magnet current [A]

Wedge, Edge, Active Shims