Accelerator Preparations for Muon g-2 Experiment at Fermilab

Mike Syphers
Michigan State University

Outline:
8 GeV Proton Economics at Fermilab
Proton Transport and Bunch Formation
Targeting and Pion Collection
Muon Transport to Storage Ring
Run II Operation

- Daily Operation
  - Set up p-pbar store in Tevatron, ...
  - Produce more antiprotons, and drive the **neutrino** program
  - time line governed by 1/15 s Booster cycle
  - 11 Booster pulses to MI every 2.2 s
    - 9 for NuMI
    - 2 for pbar production
  - Off-load pbars to Recycler ~every hour
  - Spare pulses (~4) to miniBooNE
  - 1 pulse to SY120 occasionally...
Post Run II

- Following Tevatron Run II...
  - to Minnesota: MINOS, NOvA
  - to South Dakota: LBNE
- On-going program of long baseline neutrino experiments
Post Run II

- NOvA is major program for Main Injector beam -- up to 700 kW
- MicroBooNE, also approved, will utilize existing beam line used for miniBooNE
- In addition, following Collider Operation, Antiproton Source becomes available for other uses
  - Already proposed for use in Muon-to-Electron Conversion Experiment (Mu2e)
  - Time between Run II ending and Mu2e start-up provides for early mounting of New g-2 experiment
NOvA / ANU and Proton Plan

• To meet the needs of the neutrino program utilizing the Main Injector, FNAL successfully completed the Proton Plan project and is following through with the Accelerator and NuMI Upgrades project (ANU)
• Proton Plan -- updated hardware in the Booster synchrotron to allow higher beam repetition rate -- up to 9 Hz average rate
• ANU -- upgrading Main Injector and Recycler to allow for higher beam throughput in both synchrotrons -- brings MI to 700 kW beam power
• The 8 GeV Booster magnet system operates at a 15 Hz rate; however, beam throughput presently limited to ave. of ~9.5 Hz due to RF system components; runs at ~7 Hz for reliability during Run II; continuing improvements toward full 15 Hz capability.

• For today’s Antiproton production and NuMI/MINOS neutrino experiment, only about 5 Hz required from Booster; spare cycles presently used to provide beam to miniBooNE (1-2 Hz, ave.).

• The NOvA neutrino experiment requires beam from Booster at average rate of about 9 Hz (hence, the Proton Plan upgrades).

• Thus, ~9 Hz for NOvA, and up to as much as ~6 Hz available for other programs at 8.9 GeV/c.
With present Booster running conditions, at ~4 Tp/pulse,

~ 1 Hz  \(\iff\) 4 Tp/s  \(\iff\) ~0.8 \times 10^{20} \text{ POT/yr}

Program requests are ~18 \times 10^{20} \text{ POT} over about 6-7 years,

thus, need an average rate of ~3+ Hz, beyond the 9 Hz for NOvA

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Total Beam Request</th>
</tr>
</thead>
<tbody>
<tr>
<td>MicroBooNE</td>
<td>(6.7 \times 10^{20}) POT</td>
</tr>
<tr>
<td>(g-2)</td>
<td>(4.0 \times 10^{20}) POT</td>
</tr>
<tr>
<td>Mu2e</td>
<td>(7.2 \times 10^{20}) POT</td>
</tr>
</tbody>
</table>

While a 15 Hz Booster is ultimate goal, the extra 6 Hz this would provide is twice that which is needed to meet the goals of these three requests.
Booster 8 GeV Program

- MicroBooNE takes beam directly from Booster through its own line
- New g-2 experiment uses antiproton rings as a pion decay channel, tuned to momentum of 3.1 GeV/c
- Mu2e will also use antiproton rings, tuned to 8.9 GeV/c
- These two experiments can share certain infrastructure and beam lines
- Switching between g-2 and Mu2e experiments is mutually beneficial, allowing these precision experiments to perform analysis and work on systematic errors
  - switch-time ~ 2-4 weeks, max.; maybe much less
The g-2 Baseline Proposal

- New g-2 operates “per Booster cycle” (1/15th of sec.)
  - send Booster pulse to the Recycler
  - form into 4 bunches -- takes about 30 ms to perform
  - transfer one-at-a-time to g-2 Ring, every 12 ms; all occurs within one Booster cycle (details in back-up slides)
- Note: bunches ~30 ns (rms) in length, ~ 10^{12} each
- Proposal is to deliver beam to target on 6 Booster cycles, every NOvA cycle (1.333 s)
- thus, average rate is 4.5 Hz -- could meet requested POT in 1 year, though requesting 2; thus, conservatism built in
**g-2 Proposed Operational Scenario**

- Target at AP0 target hall; use pbar rings as 1-pass “decay channel” for pions; accumulate muons in g-2 ring
FNAL Plan--Booster to Recycler

- Use same transfer into the Recycler as NOvA
- Allow beam to circulate, and form into bunches, prepare for extraction
To control rate-dependent systematics, need to re-bunch each Booster batch into 4 bunches in the Recycler, 400 ns spacing

- implies average rate of ~18 Hz into exp., compared to 4.5 Hz at BNL E821

Need to move existing 2.5 and 5.0 MHz RF systems from MI to Recycler, possibly need to increase voltage by 10-30%

Extract bunch every 12 ms

full Booster cycle
To control rate-dependent systematics, need to re-bunch each Booster batch into 4 bunches in the Recycler, 400 ns spacing

- implies average rate of ~18 Hz into exp., compared to 4.5 Hz at BNL E821

Need to move existing 2.5 and 5.0 MHz RF systems from MI to Recycler, possibly need to increase voltage by 10-30%

Extract bunch every 12 ms
FNAL Plan--Extraction to AP1

- Very similar to NOvA injection line
- Extraction hardware necessary, also, for Mu2e
- Connects Recycler to beam lines leading toward the 8 GeV storage rings
  - preliminary optics design exists, mechanical layout being drawn, tunnel interferences being checked
- Requires a kicker to eject bunch every 12 ms
  - Average rate of 18 Hz
  - Rise time 180 ns, flat top 50 ns, back down in 5 μs, ready to kick again in 12 ms
  - similar components to kicker required for Mu2e; should be able to share much of the hardware
- Remove today’s aperture restrictions to handle the 25 kW, 8 GeV beam
**FNAL Plan--APO Target Station**

- **Plan A:** Use conventional rad-hard quads
  - Solution used in BNL E821
- **Plan B:** Re-use current target & Li lens (used for pbars)
  - Have to evaluate if Li lens can operate at higher rate with reduced current
- Also looking at a multi-turn, DC PMAG design

(Huhr, Leveling, Mokhov, Morgan, Nagaslaev, Striganov, Werkama, Wolff)
Critical to the experiment is an 800 m or longer decay line ($\pi^+ \rightarrow \mu^+$)

- much longer than BNL decay line, providing much purer muon beam and much reduced pion backgrounds
- Plan to use AP2 --> Debuncher --> AP3
- New connection DEB-->AP3
- Denser quad spacing in AP2/AP3

(J. Johnstone)
FNAL Plan--New tunnel to surface building

- Need to bring beam up to surface building
- First-order solution can be achieved
  - Horizontal and vertical bends keep the dispersion controlled
  - Match final optics into ring

(J. Johnstone)
Accelerator Summary

- In NOvA era, have cycles available to run 8 GeV program from Fermilab Booster which can serve microBooNE, g-2, and Mu2e
- g-2 operates on a Booster cycle time, as does microBooNE; no physical interference, thus can run together -- Program Planning decides sharing of Booster cycles
- g-2 can start taking data 1-2 years before Mu2e; if necessary the two can operate in a “leap-frog” fashion; each takes several weeks/months of running; will take only days or weeks (<4) to switch between them (not months)
- two independent teams have analyzed the accelerator portion of the g-2 proposal, its feasibility and cost estimate -- the estimated costs agreed to within 10%
- strong accelerator team has gathered to put forth viable path for g-2 at Fermilab
proposed siting:

- New building
- New beam line from AP0 target hall
- E821 magnet, etc.
Back-Ups
NuMI/NOvA, after Run II

- NOvA project and associated accelerator upgrades anticipate using 12 Booster cycles per 1.333 s MI cycle.

- Thus, of the 20 15-Hz Booster cycles per NOvA cycle, leaves up to 8 Booster cycles for “other program(s)”.

- Both Mu2e and New g-2 propose using 6 of these cycles.

- Average pulse rate would be 4.5 Hz, at 4 Tp/pulse --> 18 Tp/s.

For NOvA, average rate of BOO:

\[\text{for NOvA, ave rate of BOO} = \frac{12}{20} \times 15 \text{ Hz} = 9 \text{ Hz}\]
Simulations*

**Broadband:**  4 kV

2.5 MHz:  80 kV

5.0 MHz:  16 kV

*C. Bhat and J. MacLachlan*
Rotate into 4 Bunches

Extraction of the 1st Bunch continues to tumble in phase space
The four maxima are at the times the bunch widths are minimum. The interval is one half of a synchrotron oscillation period, $\sim 12$ ms. The $\Delta p/p$ is about 0.8% full width. Therefore, if the effective $\epsilon_\ell$ in the Booster is much larger than the 0.07 eVs assumed, the momentum aperture of the Recycler could become a concern, but there is nearly 50% headroom with the parameters used.
The four maxima are at the times the bunch widths are minimum. The interval is one half of a synchrotron oscillation period, $\sim 12 \text{ ms}$. The $\Delta p/p$ is about 0.8% full width. Therefore, if the effective $\varepsilon_{\ell}$ in the Booster is much larger than the 0.07 eV/s assumed, the momentum aperture of the Recycler could become a concern, but there is nearly 50% headroom with the parameters used.
The four maxima are at the times the bunch widths are minimum. The interval is one half of a synchrotron oscillation period, $\sim 12$ ms. The $\Delta p/p$ is about 0.8 % full width. Therefore, if the effective $\varepsilon_\ell$ in the Booster is much larger than the 0.07 eV/s assumed, the momentum aperture of the Recycler could become a concern, but there is nearly 50 % headroom with the parameters used.
A Possible Alternative Configuration

- Direct Feed from Booster for Mu2e; g-2 still fed from Recycler
- Multiple turns in the storage rings provide long pion decay path, very high muon beam purity
- Beam for both experiments circulates in same direction in rings -- easier to switch running configuration
- Can share much of external beam line

J. Morgan, DVM, et al.
A Possible Alternative Configuration

- Direct Feed from Booster for Mu2e; g-2 still fed from Recycler
- Multiple turns in the storage rings provide long pion decay path, very high muon beam purity
- Beam for both experiments circulates in same direction in rings -- easier to switch running configuration
- Can share much of external beam line
A Possible Alternative Configuration

- Direct Feed from Booster for Mu2e; g-2 still fed from Recycler
- Multiple turns in the storage rings provide long pion decay path, very high muon beam purity
- Beam for both experiments circulates in same direction in rings -- easier to switch running configuration
- Can share much of external beam line

J. Morgan, DVM, et al.
A Possible Alternative Configuration

- Direct Feed from Booster for Mu2e; g-2 still fed from Recycler
- Multiple turns in the storage rings provide long pion decay path, very high muon beam purity
- Beam for both experiments circulates in same direction in rings -- easier to switch running configuration
- Can share much of external beam line
A Possible Alternative Configuration

- Direct Feed from Booster for Mu2e; g-2 still fed from Recycler
- Multiple turns in the storage rings provide long pion decay path, very high muon beam purity
- Beam for both experiments circulates in same direction in rings -- easier to switch running configuration
- Can share much of external beam line
Some References

• J. Reid, R. Ducar, “Booster RF Repetition Rate Limit,” Beams-doc-2883.
• M.J. Syphers, “Accelerator Preparations for Muon Physics Experiments at Fermilab,” DPF09, FERMILAB-CONF-09-509-AD.