Muon Campus Plans

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Accelerator Division, Muon Department
1/10/13
Muon Campus layout
Looking toward the Muon Rings
View from Wilson Hall
Thanks and disclaimers

• Thanks in advance to everyone I “borrowed” content from
  – including Russ Alber, Jerry Annala, Brendan Casey, Brian Drendel, Doug Glenzinski, Arkadiy Klebaner, Ioanis Kourbanis, Tom Lackowski, Nikolai Mokov, Jim Morgan, Hogan Nguyen, Chris Polly, Ron Ray, Dean Still, Steve Werkema, ...

• I have been involved with g-2 for a little over a year, and the broader Muon Campus planning for about 2 months
  – I am not at all an expert on Mu2e
Mu2e
Mu2e

- Muons regularly decay to electrons and neutrinos: \( \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \)
- Mu2e will search for charged lepton flavor violation (\( \mu N \rightarrow e N \))
  – Neutrino flavor oscillations already observed

- Conversion rate distinguishes between different theories
Mu2e

• Generate beam of low-momentum $\mu^-$
• Stop the muons in a target
  – Aim to improve sensitivity by $10^4$ over previous experiments
  – requires $\sim 10^{18}$ stopped muons
• Stopped muons are trapped in orbit around the nucleus
  – Using Aluminum target (nucleus):
    • characteristic time $\tau_{\mu}^{\text{Al}}=864$ ns
    • conversion-electron energy 104.97 MeV
    • (maximum decay-e energy 52.8 MeV)
• Extinction system (AC dipole) to prevent prompt background from out-of-time
  protons hitting production target
Mu2e Apparatus

Production Target

Collimators

Transport Solenoid

Detector Solenoid

Stopping Target

Tracker

Calorimeter

about 75 feet end-to-end
Proton Beam delivered to the production target via the former Pbar beamlines followed by an external beamline
Mu2e Apparatus

Production Solenoid

Transport Solenoid

Detector Solenoid

Production Target

Collimators

Stopping Target

Tracker

Calorimeter
## Mu2e schedule

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g-2
The anomalous magnetic moment and $g$-2

- $g \approx 2$ but higher-order corrections
  - QED, EW, hadronic, new physics?

- Currently $\sim 3\sigma$ discrepancy between theory and experiment
- New muon $g$-2 experiment at Fermilab expected precision could yield $\sim 5\sigma$
Measuring g-2

- Polarized muons in magnetic field precess with Larmor spin precession frequency
  \[ \vec{\omega}_s = -\frac{eB}{\gamma mc} - \frac{e}{mc} a \vec{B} \quad a = \frac{g - 2}{2} \]

- Measure g-2 using cyclotron

\[ \vec{\omega}_c = -\frac{e\vec{B}}{\gamma mc} \]

\[ \vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e\vec{B}}{2mc} (g - 2) \]

- Requires precise measurements of \( \omega_a \) and of the magnetic field
Measuring $\omega_a$

- One more trick:
  - Polarized muons in storage ring with vertical focusing by electrical quadrupole field

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

- At magic momentum $p_\mu = 3.094$ GeV/c ($\gamma = 29.3$), g-2 precession frequency $\omega_a$ independent of electric field

- Distribution of decay electrons as function of time

\[
N(t) = N_0 e^{-t/\gamma\tau} \left[ 1 - A \cos(\omega_a t + \varphi) \right]
\]

Intensity at a single detector station shortly after injection

g-2 apparatus

- Reusing storage ring from BNL g-2 experiment
- New calorimeters and straw-tube tracking
Planned improvements

• Rebunch high-intensity beam into multiple bunches to lower the instantaneous rate
• Increase the detector segmentation to reduce the instantaneous rate in a given cell
• Modify secondary beamlines to store as many muons from pion decays as possible
• Remove pions and protons from muon beam to prevent hadronic flash in calorimeters
  – Allows analysis of more (earlier) decay e+
  – Longer beamline for pion decay
  – Let heavier protons separate in time from pions/muons and kick them out
• Improve beam dynamics in storage ring
• Improve storage ring field uniformity and the measurement and calibration system
g-2 schedule

- Preparing for CD1 review this spring
- MC1 building complete early FY14
- g-2 storage ring ships early FY14
- Ring reassembly starting FY14
- Cryo ready to cool ring early FY15
- Ring magnetic field shimming starting mid FY15
- Recycler and Muon beamline work FY14-15
- New beamline enclosure beneficial occupancy mid FY15
- Beam to g-2 early 2016
Beam to Mu2e

- Primary (8 GeV) proton beam resonantly-extracted from Debuncher
- Extinction of out-of-time beam
- Original plan for increased flux involved “threading” Mu2e batches between NOvA batches, stacking proton bunches in Accumulator, and rebunching / resonant-extraction in Debuncher

Beam to g-2

- Rebunch primary (8 GeV) protons so that rate in detectors is not too high, bunch length < ring revolution time of 147ns
- Create 3.1 GeV secondary pions off a target
- Beamline long enough for ~all pions to decay
- Capture 3.094 GeV (“magic momentum” muons)
  - aim for $40\pi$ acceptance
- Limit secondary pions and protons making it into g-2 storage ring (cause “hadronic flash” in calorimeters)
Original Mu2e and g-2 plans for former Pbar beamlines

- Stacked proton bunch to Debuncher
- Resonant extraction to Mu2e target
- AP3 line connects to Accumulator
- Abort
- 8 GeV protons to Accumulator
- 8 GeV protons bypass target

3.1 GeV secondaries to Debuncher (need high quad density to capture decay muons)
- New connection Debuncher to AP3
- Bring 40π beam back thru target bypass to g-2 ring
- 8 GeV protons to target (rebunched in Recycler)
g-2 near Mu2e in “Muon Campus”

- Locating g-2 experiment near Mu2e has advantages
  - Both g-2 and Mu2e circulate in same direction
    - No need to switch polarity, just energy
    - Frees some magnets in AP2 line for reuse, no conflict with Mu2e plans for primary beam abort in AP2
    - Can use Mu2e abort to remove proton contamination from g-2 secondary beam
  - New building location also much better
    - Old location jammed between road and berm
    - Utility corridor to be rerouted
    - Don’t have to pass g-2 secondary beam back through AP0
  - Can share cryo and other infrastructure
  - Time-dependent stray magnetic fields at g-2 ring smaller near Booster than near Main Injector
Mu2e Accelerator Task Force Cost Savings

- Trade Mu2e rate for run time (3 yrs running vs 1 yr)
- Elimination of Accumulator removes almost every g-2/Mu2e conflict
- Over $100M in savings in the combined program
Muon Campus beamline plan for Mu2e and g-2

- 3 GeV $p, \pi^+, \mu^+$
- After ~5 turns essentially all $\pi^+$ decayed

- 3 GeV $p, \pi^+, \mu^+$ to Delivery Ring for g-2
- 8 GeV protons to Delivery Ring for Mu2e (target station bypass)

- 3 GeV $p, \pi^+, \mu^+$ to M3 line for g-2 ("$\pi$ decay line")
- 8 GeV protons to target for g-2
- 8 GeV protons to M3 line for Mu2e

- After ~5 turns, $p$ separated in time from $\mu^+$, kick into abort
- Primary abort for Mu2e

- Extract $\mu^+$ for g-2
- Resonant extraction for Mu2e

- Proton removal

M3 line connects to Delivery Ring (Debuncher)

(where M2 line joins M3 line not yet finalized)
Shared infrastructure

• Any shared infrastructure needs to be ready in time for g-2
  – Make use of Accelerator Improvement Projects (AIPs) and General Plant Projects (GPPs)
  – MC-1 building houses cryo refrigerators and beamline power supplies in addition to g-2 storage ring / future expts (GPP)
  – Cryo work moves to AIP
  – Extraction-line tunnel moves from Mu2e to GPP
  – First part of extraction line moves from Mu2e to g-2
  – Recycler work was on g-2 project (g-2 drives specs), later moved to AIP at recommendation of Mu2e CD-1 review committee
  – Proton abort and other Delivery-Ring work moved to AIP
  – P1, P2, M1 line 8-GeV aperture improvements moved to AIP
  – Controls and common instrumentation(?) on g-2 project

• Yes, partly this makes Mu2e look less expensive, but there is also a limit on the total cost of the Muon campus program
Recent modifications to Muon Campus plan likely scope change need additional AIP to cover costs? AIP’s and GPP’s have hard cap at $10M
Packaging into AIPs/GPPs

• Actually the packaging of the work is still in flux
  – Except for MC1 building GPP which is already in progress
• DOE recommendation resulted in acceleration of Mu2e civil construction schedule, had to shuffle work between Mu2e and other Muon Campus projects
• AIPs and GPPs have a hard cap of $10M, don’t include conceptual design
  – As designs are becoming more mature and in some cases work is pushed later, cost estimates indicate that the work may not fit in the planned packages
• Internal AD review later this month to make sure nothing is missing between all these packages and to look for ways to reduce costs
• Following the review, we will propose how to package the individual pieces into AIPs and GPPs
Rough funding plan for GPPs and AIPs

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- The additional site power feeder that was part of site-prep GPP ($1M) is not included here, may be needed in 2017 or 2018

on critical path for g-2

longer lead time for RF

on critical path for g-2
Protons to the Muon Campus
Protons available

• (Mu2e and g-2 cannot run simultaneously)

Need 2 Booster cycles to manipulate g-2 beam in Recycler
Re-bunching beam in Recycler

- 53 MHz bunches (4x10^{12} protons) reformed into 4 bunches (1x10^{12} protons) at 2.5 MHz
  - Reduce pile-up in detector
  - Build new cavities for 2.5MHz system
- g-2 needs beam pulses out of Recycler not longer than ~100ns
  -Muon storage ring revolution time 147ns
  -Balance efficiency, momentum spread, and longitudinal extent
  -Achieve pulses with 95% of beam within 120ns
- Beam pulses should be separated by ~10ms for the muons to decay in the g-2 storage ring and data to be recorded
- Mu2e specs are less stringent than g-2
Recycler AIP

- Allows 8 GeV proton beam to be rebunched in the Recycler and extracted to the P1 line for transport to experimental areas
  - 2.5 MHz RF for re-bunching beam
  - Extraction kickers
  - Beamline connection from Recycler to P1 line
  - MI52 building extension for kickers (civil – move to separate FESS project?)

- RF cavity production
  - Cavities must have active cooling
  - Reuse ferrites from MI coalescing cavities
  - Labor intensive
  - 7 RF systems (cavities + PA’s) for Recycler
  - 2 cavities for Mu2e to be installed in the Delivery Ring
Simulation of rebunched beam

- 95% capture efficiency, 95% of captured beam within 120ns
• Very good agreement between simulations and beam data at low intensities
• Beam loading will be much less of an issue in Recycler
Recycler extraction kicker system

- 2 new kicker magnets of the new RKB style designed for ANU
- Re-use the beam tubes from the recently decommissioned Recycler kicker magnets
- Re-use the PFLs from the Recycler kickers
- Build two new 25 Ohm loads capable of up to 250 W average power
- Fluorinert cooling skid to cool the loads
- Extend existing building at MI-52 for kicker power supplies

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Transporting proton beam to Muon Campus

- New connection from Recycler to P1 line
MI-52 Extraction Region
Muon Campus beamlines
New Mu2e and g-2 plans for former Pbar beamlines

- After ~5 turns, p separated in time from μ+, kick into abort
- **Primary abort for Mu2e**

(53.2x32.8 cm)

- 3 GeV p,π+,μ+
- After ~5 turns, essentially all π+ decayed
- 3 GeV p,π+,μ+ to Delivery Ring for g-2
- 8 GeV protons to Delivery Ring for Mu2e (target station bypass)

- μ+ to g-2 ring
- Extract μ+ for g-2
- Resonant extraction for Mu2e

- 8 GeV protons to target for g-2
- 8 GeV protons to M3 line for Mu2e

Proton removal

M3 line connects to Delivery Ring (Debuncher)

- After ~5 turns, p separated in time from μ+, kick into abort
- **Primary abort for Mu2e**

(53.2x32.8 cm)

- 3 GeV p,π+,μ+
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- μ+ to g-2 ring
- Extract μ+ for g-2
- Resonant extraction for Mu2e

- 8 GeV protons to target for g-2
- 8 GeV protons to M3 line for Mu2e
Aperture improvements in P1, P2, M1 lines

120 GeV Pbar production
MI to Target Station

8 GeV protons
RR to Target Station

MI-52 Lam., V701 C-magnets (?)
V714 C-magnets
Tev. F0, Lambertsons
F-17 C-Magnets
HV100 dipoles
HV102 dipoles
HT105 trim

need changes to final focus for g-2
M2 and M3 lines

• M2 line
  – Secondary beamline for g-2
  – Add quadrupoles to create a regular lattice with smaller β functions to capture more muons from decays
  – Beamline magnets from BNL g-2 experiment, also from Accumulator

• M3 line (target bypass section)
  – Acceptable for Mu2e as is but must match to incoming M2 line for g-2

• M2 to M3 connection
  – Need connection that accommodates Mu2e 8 GeV proton beam down M3 while preserving small β functions for g-2
M3 line into Delivery Ring

• New connection to Delivery Ring
  – Two elevation changes and a 5° horizontal bend
  – Confined area for magnet supports in area over Delivery Ring
  – Need enough room between DR and M3 to allow use of existing pbar magnets
  – Match injection into DR and acceptance must be at least $40\pi$ for g-2
Delivery Ring Modifications

• DR aperture improvements
  – Removal of unneeded devices such as stochastic cooling tanks

• DR abort
  – Beam abort for Mu2e
  – Proton removal for g-2
    • Need a fast-rise kicker

• Electrical infrastructure improvements
Delivery-Ring injection/extraction strategy

• Keep injection and extraction regions separated (D30 straight)

• Maximum flexibility between g-2 and Mu2e at least expense
  – Reuse existing equipment
  – New devices should be based on existing designs where practical

• Work around Mu2e extraction devices
  – Resonant extraction more difficult to design
  – Requires use of Lambertson
  – Placement of extraction channel defined by resonantly extracted beam
  – Electrostatic septa added for Mu2e operation

• Maximizing acceptance for g-2 (40\pi)
  – Kicker placement
  – Large vertical(horizontal) bump across injection(extraction) region
    • Motorized quadrupoles (existing) used to create bump for g-2
  – C-magnet used in addition to magnetic septum(Lambertson)
  – Some specialized large aperture quads (existing)
g-2 operation and Mu2e commissioning

Horizontal bend (5°)

Injection kickers

Extraction kickers

Vertical bend

Extraction Lambertson and C-magnet

Injection Septum and C-magnet

Vertical bends
Dual running mode configuration

- Horizontal bend (5°)
- Injection kickers
- Injection Septum and C-magnet
- Extraction Lambertson and C-magnet
- Vertical bends
- Extraction septa (Mu2e)
- Extraction kicker (g-2)
Extraction lines

• M4 and g-2 beamline design in progress

Split between the M4 and g-2 lines

• g-2 line splits from M4 line in the middle of the left bends
• Momentum collimation will be integrated into Left Bend
• g-2 line is roughly 50 m long
• Vertical dogleg will make elevation change to g-2 storage ring
• BNL magnets and other components will populate most of the g-2 line
• Final focus and matching to Storage Ring will be designed in collaboration with Ring Team
Beamline enclosure and site plan

• Details depend on beamline lattice which is not complete yet
External beamline enclosure design

- **Main Injector type enclosure**
  - 10 feet wide x 8 feet high (typical except near MC-1 where higher ceiling will be required.
  - Painted walls and ceiling, sealed floor. Floor to have 3” cover over rebar to enable stand anchorage.
  - Channel inserts walls and ceiling @ 8’ o/c. (no inserts 5’ from floor on aisle side)

- **Shielding**
  - 16 feet of earth/concrete for M4 beamline. (w/ beamline 4’ from clg.)
  - 6 to 9 feet for g-2 beamline. Shielding needed within enclosure between MC-1 building and M4 / Delivery Ring.

- **Access for magnets** is provided directly from Ring enclosure; lift provided for magnet installation. Shielded hatch provided for magnet installation / replacement.
Beamline enclosure timeline

- Mu2e NTP: Mar. FY 14
- Mu2e Complete: April FY16
- Beamline B.O.: April FY15
- Beamline B.O. To g-2: Mar. FY15
- $3.7 M Construction Funds Issued
- $5.1 M Construction Funds Issued
- NTP Jun FY14
- Final Design
- Bid and Award

MC BEAMLINE CUMULATIVE COST CURVE
g-2 target station
g-2 target station

• Use existing Pbar target station at AP0

• Fermilab expertise, existing spares, and radioactivity of target vault make it desirable to maintain current setup as much as possible
  – Rotating, air-cooled target
  – Lithium lens for focusing
  – Pulsed magnet for momentum selection

• Simulations indicate that the current setup can deliver the desired yield of $\sim 10^{-5}$ pion/POT
  – Conducted beam tests to confirm
g-2 beam tests and simulations

Study plan
- Step from stacking to g-2 mode

<table>
<thead>
<tr>
<th>proton mom. (GeV)</th>
<th>secondary mom. (GeV)</th>
<th>charge</th>
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<tr>
<td>120</td>
<td>8.9</td>
<td>-</td>
</tr>
<tr>
<td>120</td>
<td>3.1</td>
<td>-</td>
</tr>
<tr>
<td>8.9</td>
<td>3.1</td>
<td>-</td>
</tr>
<tr>
<td>8.9</td>
<td>3.1</td>
<td>+</td>
</tr>
</tbody>
</table>

- MARS simulation of target station
  - g-2 mode: yield per POT: $\sim 10^{-5} \pi+$, $\sim 2x$ as many protons, $\sim 10^{-8} \mu+$

- G4beamline simulation of start of pion decay line (C Yoshikawa, Muons Inc)

Expected number of particles for 1x10^{12} protons on target (g-2 single pulse)

Start of AP2 line

8.89 GeV/c proton beam
Chord=7.5cm

Li lens (1-cm radial aperture)

Collimator

Momentum-selection dipole
Results of beam test

- Intensities track beam on target
- Current monitor at beginning of AP2 line shows expected scaling from 120→8-/120 → 3-
- Ion chamber at end of AP2 line shows order-of-magnitude agreement with predictions: $10^9$ particles for 120 → 3- and $10^7$ particles for 8 → 3- and 8 → 3+ per $10^{12}$ protons on target
- Beam profiles seen on Secondary Emission Monitors (SEMs)
- Existing target and lens appear to provide sufficient yield
- Smaller spot size on target will increase yield
Lithium lens in g-2 mode

- Higher pulse rate, more complicated cycle than for stacking
  - Will need new power supplies for lithium lens and pulsed magnet
Lithium lens modeling and testing

- Lens ANSYS model predicts higher temperatures and stresses for g-2 but fatigue parameters are better
  - Less difference between max and min stresses in cycle
  - Can reduce stresses by reducing pressure of lithium “preload”

- Currently pulse-testing lens in test stand at full gradient (230 T/m) and average 12 Hz repetition rate
  - Running 24hrs/day
  - Have integrated ~18M pulses
  - Pulse lens for months or until we find its limits
Cryogenics for g-2 and Mu2e experiments
Experiment Cryogenics Requirements

Cryogenic loads:

- **g-2 storage ring**
  - Liquefaction load – 1.4 [g/sec]
  - Refrigeration load – 300 [W]
  - LN2 Shield flow rate – 1.6 [g/sec]

- **Mu2e solenoids**
  - Liquefaction load – 0.8 [g/sec]
  - Refrigeration load – 350 [W]
  - LN2 Shield flow rate – 20 [g/sec]

- The Cryogenic System shall support simultaneous steady state operation of both experiments, Muon g-2 and Mu2e. It shall provide for independent operation of the two experiments, including transient modes, e.g. warm-up, cooldown, etc.

- It should be possible to connect and/or isolate Mu2e magnets from the transfer line while under cold conditions
Cryo compressor system

- A0 compressors (four skids)

- Each skid consists of the following:
  - Two-stage oil injected screw compressor
  - 300 kW motor
  - 60 g/s capacity
  - Compression from 1 atm to 20 atm
  - Slide valve for capacity control
  - 6 kW oil pump
  - Oil cooler heat exchanger
  - Aftercooler heat exchanger
  - Oil separator
  - Oil removal system
  - Entire system is contained on a single, fabricated steel base skid, oil removal on separate skid

Two-stage compound oil flooded screw compressor Mycom 2016C
Piping headers
Refrigerator room (cont)
Transfer line
Transfer line (cont)
Cryo AIP timeline

- **2013**
  - Plant and g-2

- **2014**
  - Compressors
  - Refrigerators
  - g-2 cryo distribution

- **2015**
  - Mu2e distribution

- **2016**
  - Mu2e cryo distribution

- **2017**
  - Mu2e

- **Tasks**
  - Engineering and design
  - Procurement and installation
  - Refurbishment and installation
  - Cooldown
MC-1 Building
MC-1 Building GPP

- MC-1 building designed to house g-2 and future experiments, cryo system for g-2 and Mu2e, and power supplies for some beamline components
  - 80’ x 80’ high-bay with 30 T crane
  - internal loading dock
  - floor stable, load-bearing to 700 T
  - good temperature control
  - 70’ x 70’ low-bay for staging, assembly, control room
MC-1 Building – Site Plan
MC-1 Building – Second Floor Plan
MC-1 Building – Cross Sections
MC-1 Building site prep in progress

• Construction split into two packages to expedite construction
• Goal of site prep package is to
  1) relocate all utilities out of building excavation, and
  2) perform all shutdown work during current shutdown
    – Relocate/tap into utilities
    – Relocate Well Pond Road (shutdown)
    – Install cryo line supports and under-road piping (shutdown)
Building construction will be out for bid in the next few months.
A look ahead and conclusions
Muon Campus offers many advantages

• Distinguishes between project-specific and more general upgrades, needed for g-2 and Mu2e this decade...opportunities for Stage 1 Project X
• Allows GPP/AIP pieces to move forward quickly and meet the combined specifications and timelines
• Recognized over $100M in savings in the total cost of the muon program, Mu2e run time extended to 3 years, added capability for muon g-2
Possibilities for Muon Campus experiments using Project X

- Mu2e upgrade, muon EDM experiments, ...
Conclusions

• Plans for accelerator and civil work needed to support g-2, Mu2e, and future Muon Campus experiments are maturing
• Still determining how to best package the work into Projects: g-2, Mu2e, Accelerator Improvement Projects, and General Plant Projects
• Shared infrastructure between Mu2e and g-2 as well as reuse of existing infrastructure enables us to do these projects for significantly lower cost
• Aiming for g-2 beam in early 2016, Mu2e in 2019