Preparations for the new muon g-2 experiment

Mary Convery

Fermilab Accelerator Division
Muon Department

for the E989 collaboration:
Boston, BNL, Budker, Cornell, Fermilab, Illinois, James Madison, KEK, Kentucky, KVI Netherlands, Frascati, Massachusetts, Michigan, Muons Inc., Northwestern, Osaka, Petersburg, Regis, TU Dresden, Virginia, Washington

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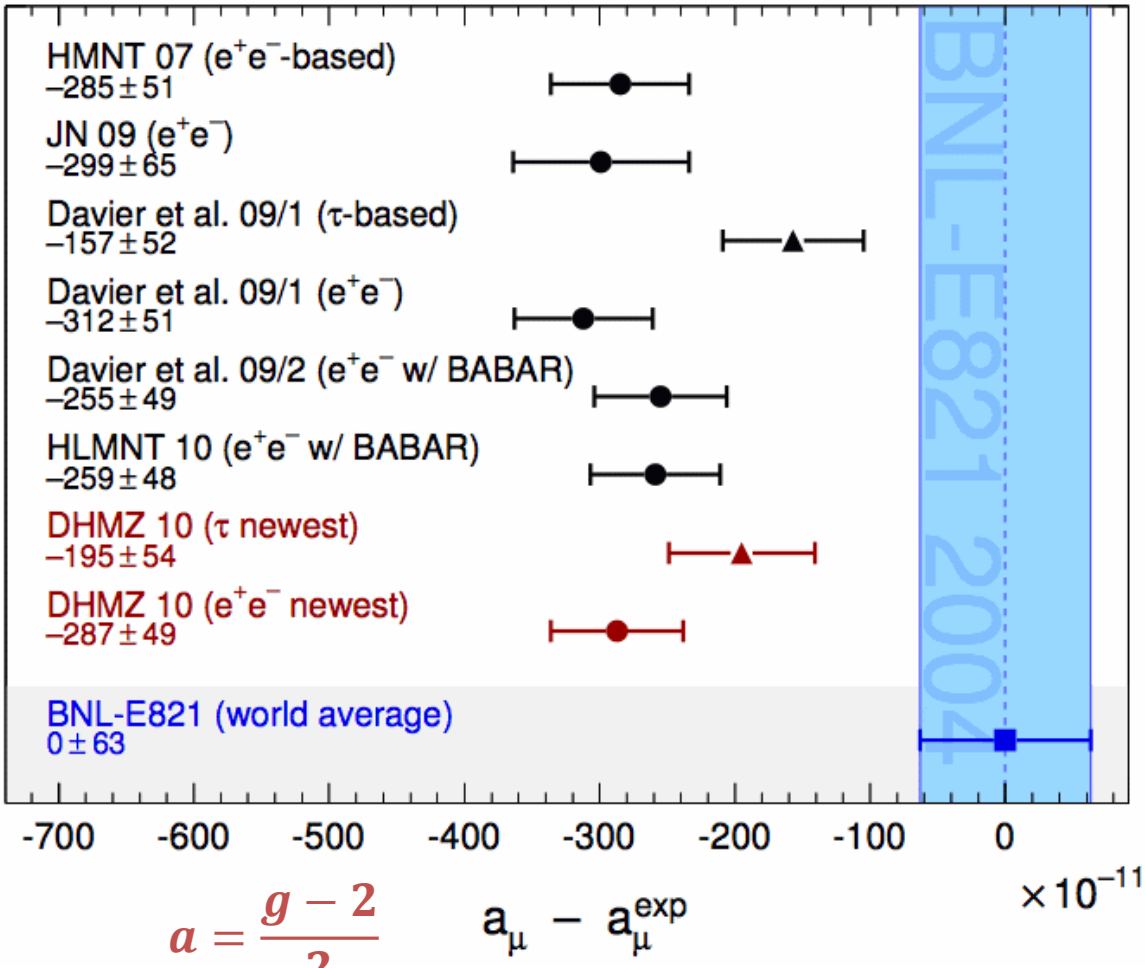
The anomolous magnetic moment and g-2

- g≈2 but higher-order corrections
  - QED, EW, hadronic, new physics?

$$\vec{\mu} = g_s \left(\frac{q}{2m} \right) \vec{s}$$



- Currently ~3σ discrepancy between theory and experiment
- New muon g-2 experiment at Fermilab expected precision could yield ~5σ

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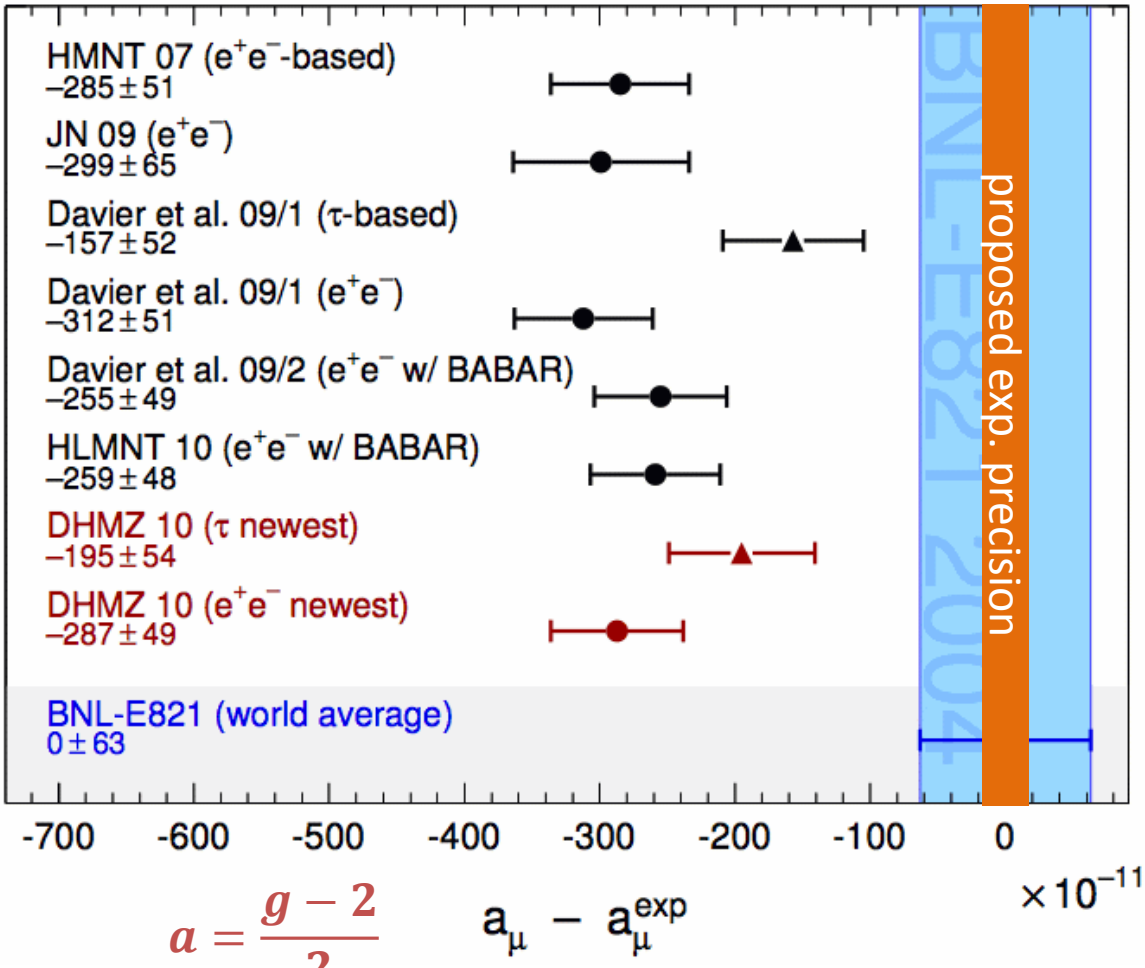

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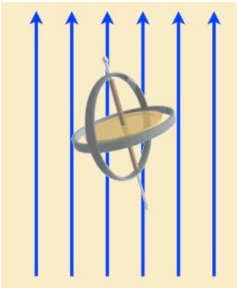
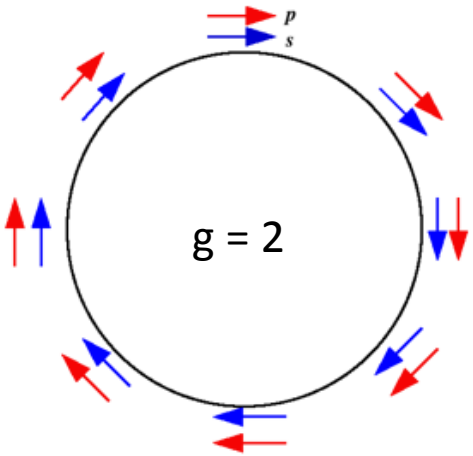
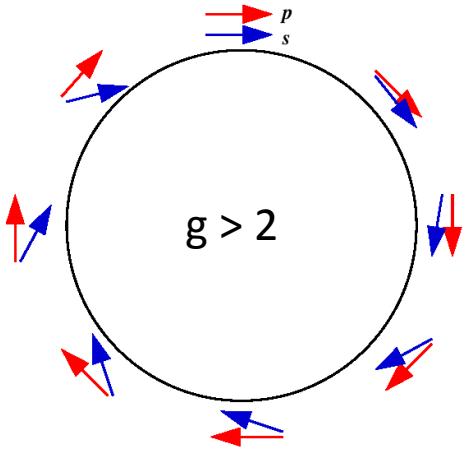
Measuring g-2

- 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





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

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

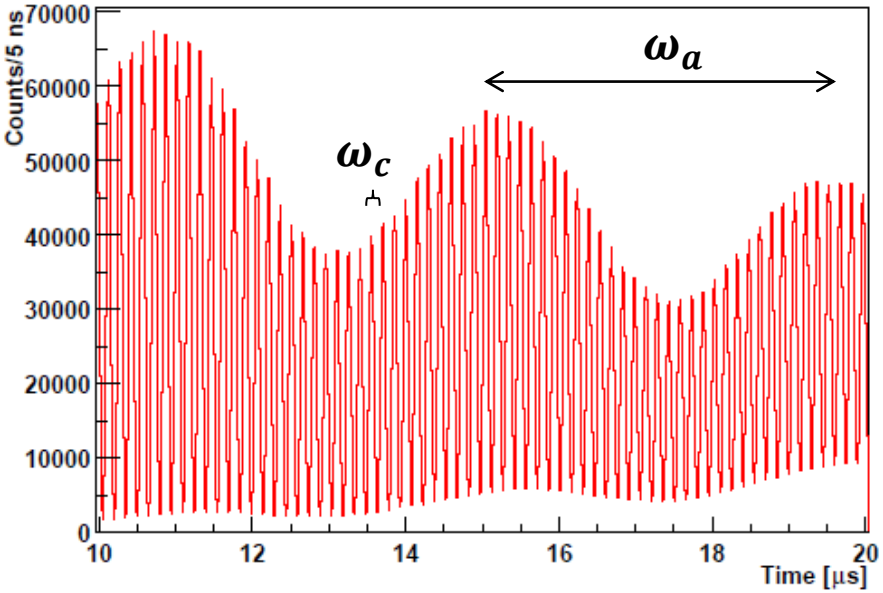
- Requires precise measurements of $\boldsymbol{\omega_a}$ and of the magnetic field

Measuring ω_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_μ = 3.094 GeV/c (γ = 29.3), g-2 precession frequency ω_a independent of electric field
- Distribution of decay electrons as function of time



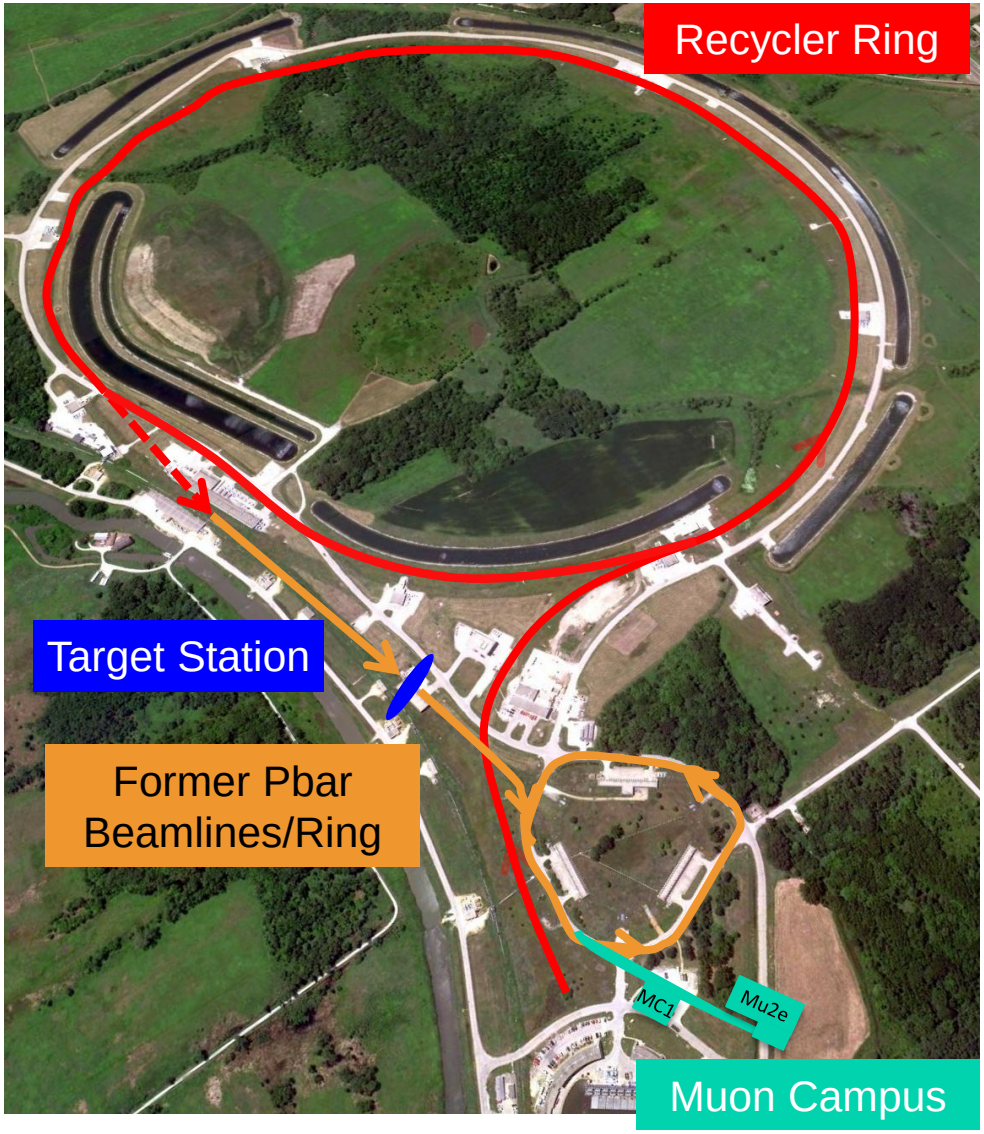
$$N(t) = N_0 e^{-t/\gamma\tau}[1 - A\cos(\omega_a t + \varphi)]$$

Intensity at a single detector station shortly after injection
Phys. Rev. D73 (2006) 072003

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
- Aperture improvements in 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

Plan for beam to g-2

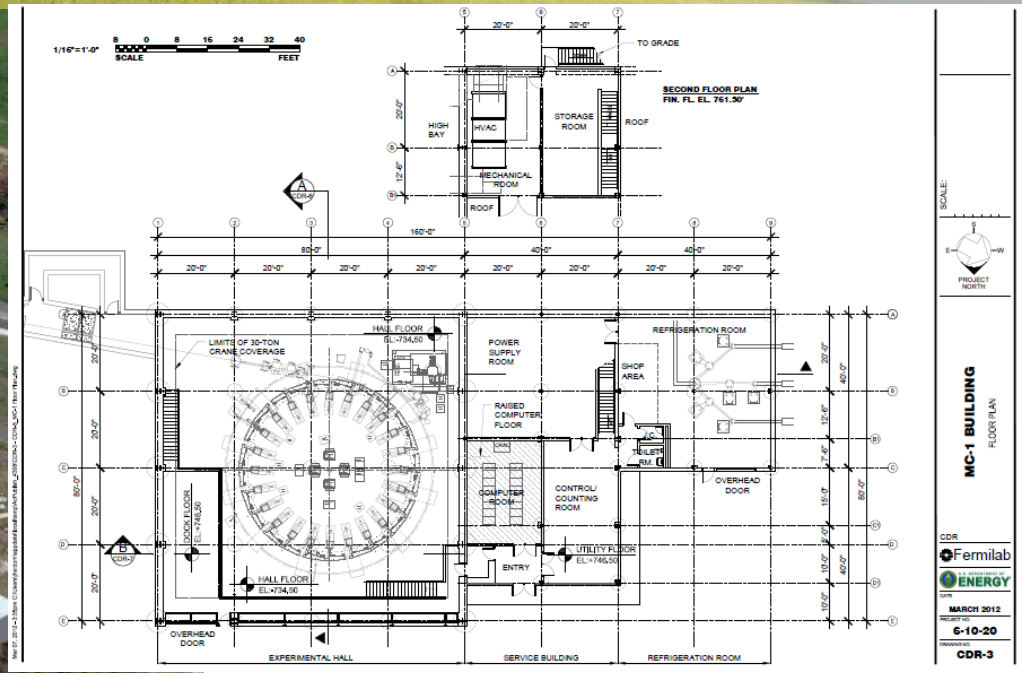


- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
- Target station
  - Target
  - Focusing (lens)
  - Momentum selection
- Beamlines
  - 8 GeV protons to target
  - 3 GeV secondary beamline
  - Muons transported to g-2 ring in new MC1 building

Muon campus and MC1 building

- MC1 building will house
  - g-2 ring, counting room and control room
  - Cryo refrigerators and power supplies for g-2 and Mu2e
- In final design stages

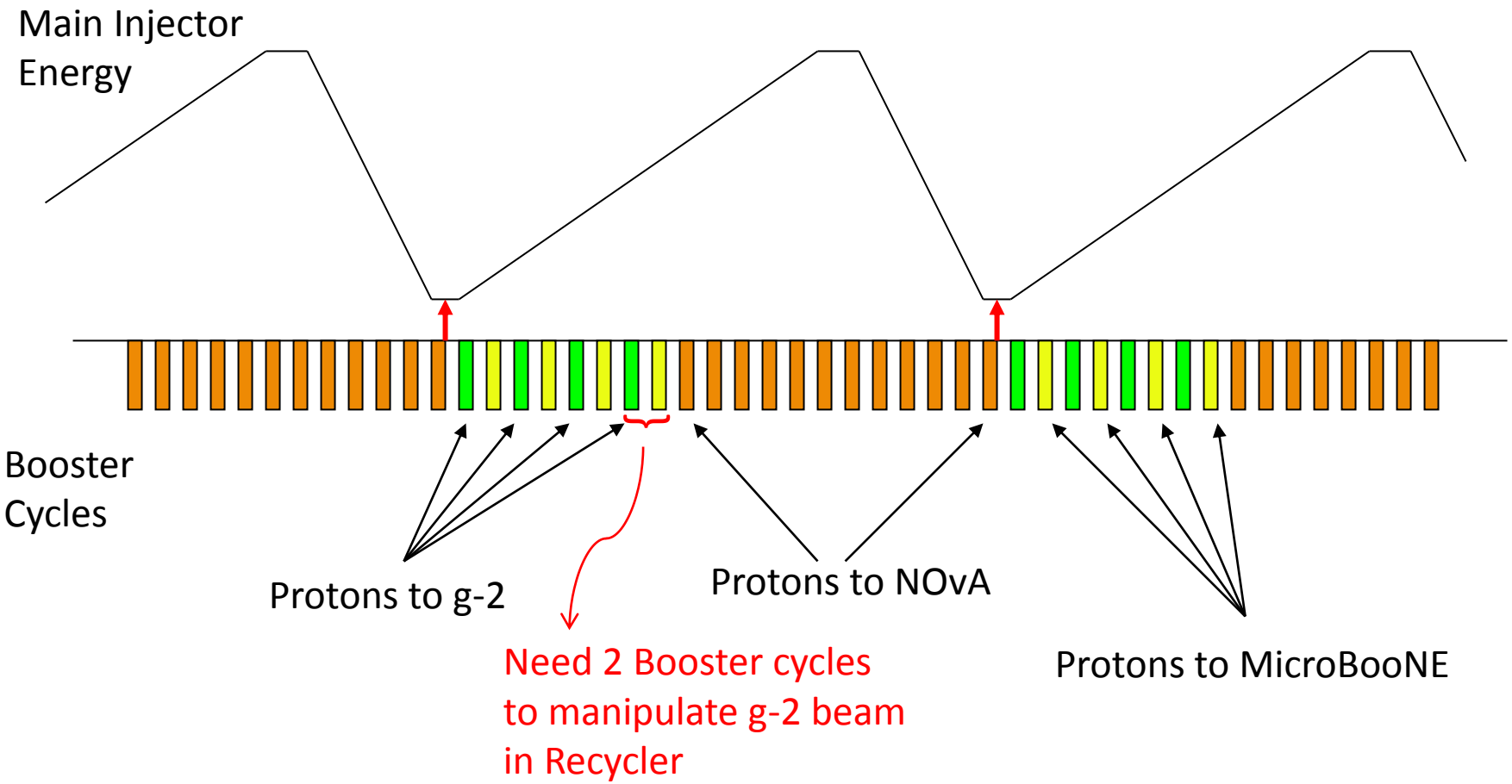
- Multipurpose building designed to use for future experiments as well



Accelerator preparations for g-2

- Determining necessary reconfiguration of accelerator in order to provide beam for g-2
- Prior to the shutdown, conducted beam studies
  - Proton rebunching for primary beam
  - Target yield

Protons available to g-2



Re-bunching beam in Recycler

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

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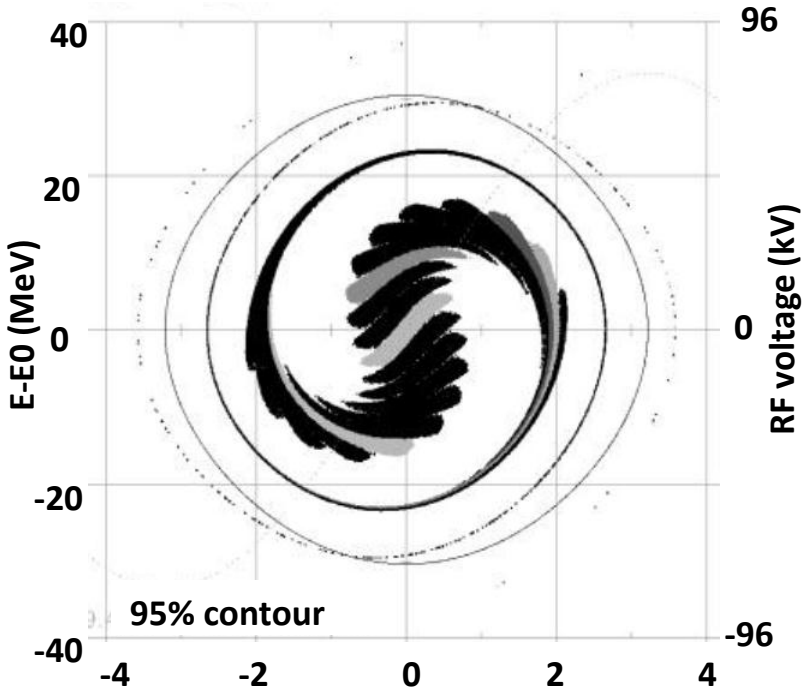
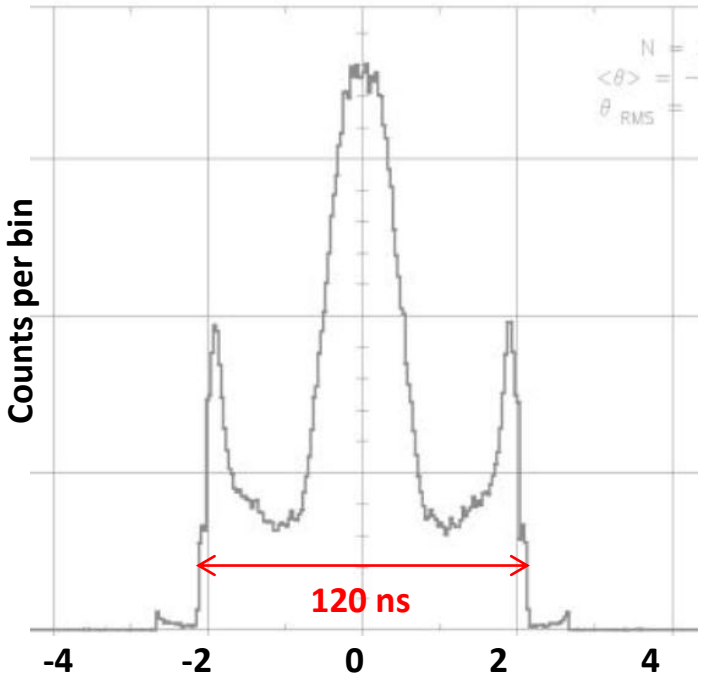
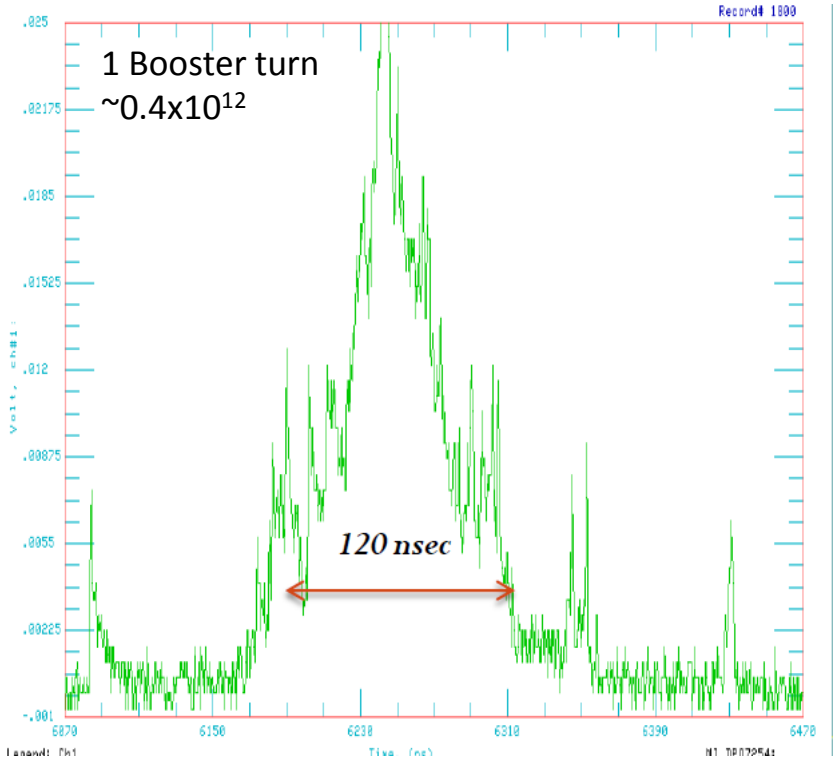
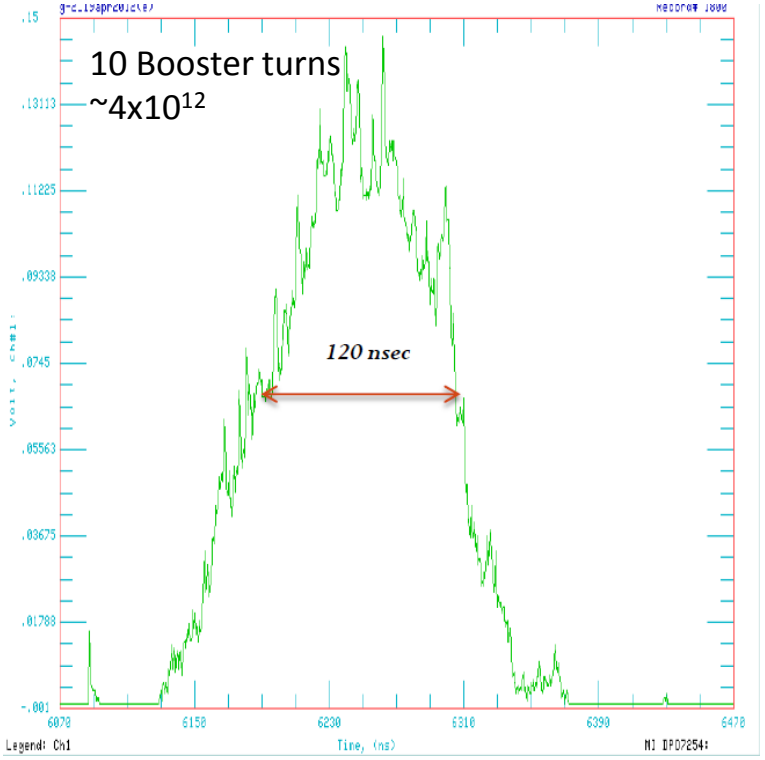
Simulation of rebunched beam





Beam distributions in Main Injector

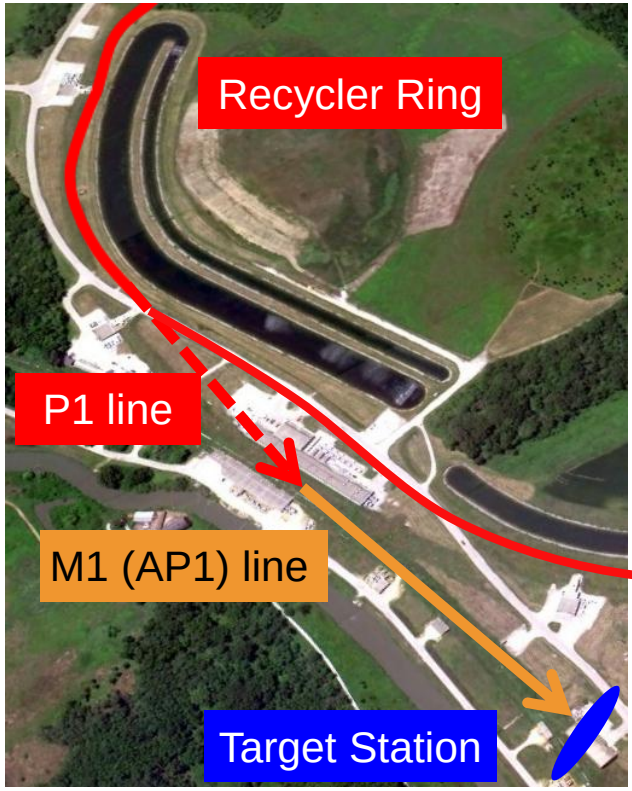




- Very good agreement between simulations and beam data at low intensities
- Beam loading will be much less of an issue in Recycler

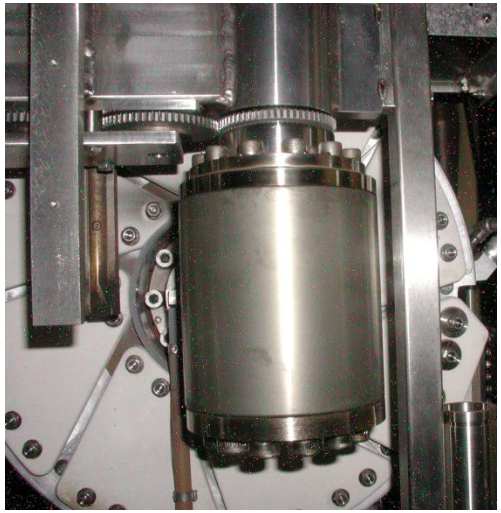
Proton beam to target

- Extraction Kicker System in Recycler
  - Use 2 of 3 existing Recycler kickers from collider program
  - New magnets, new (faster) charging power supplies, new pulser controls
  - Extend existing building at MI-52 for kicker power supplies
- New connection from Recycler to P1 line
- Minor aperture improvements in primary beamline needed for 8 GeV primary beam (vs 120 GeV beam for stacking)
  - Beneficial to both g-2 and Mu2e
- Different final-focusing magnets needed to improve aperture and reduce spot size of 8 GeV beam on target



Target station

- Use existing target enclosure used for anti-proton production
- 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



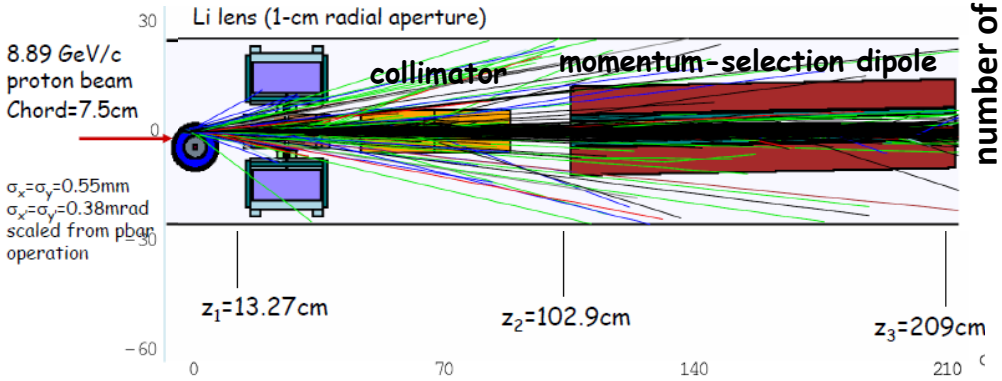
- Simulations indicate that the current setup can deliver the desired yield of ~10^{-5} pion/POT
  - Conducted beam tests to confirm

Beam tests and simulations

Study plan

- Step from stacking to g-2 mode

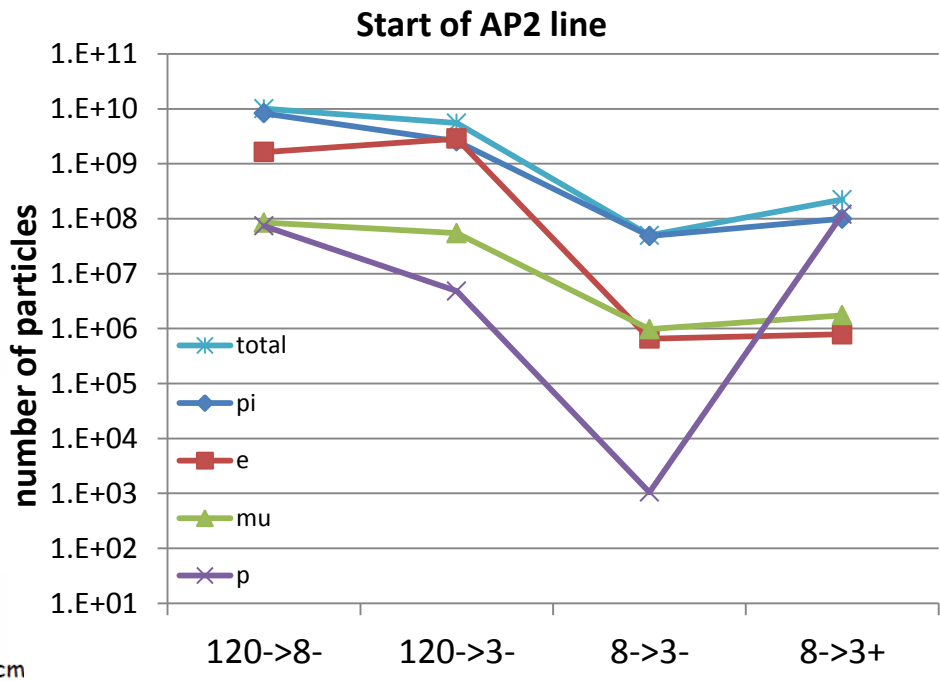
proton mom. (GeV)	secondary mom. (GeV)	charge	
120	8.9	-	Stacking mode
120	3.1	-	Change magnet strengths in secondary beamlines
8.9	3.1	-	"reverse proton" mode beam to target
8.9	3.1	+	Change polarity of lens, magnets in secondary beamline; g-2 mode



Expected number of particles

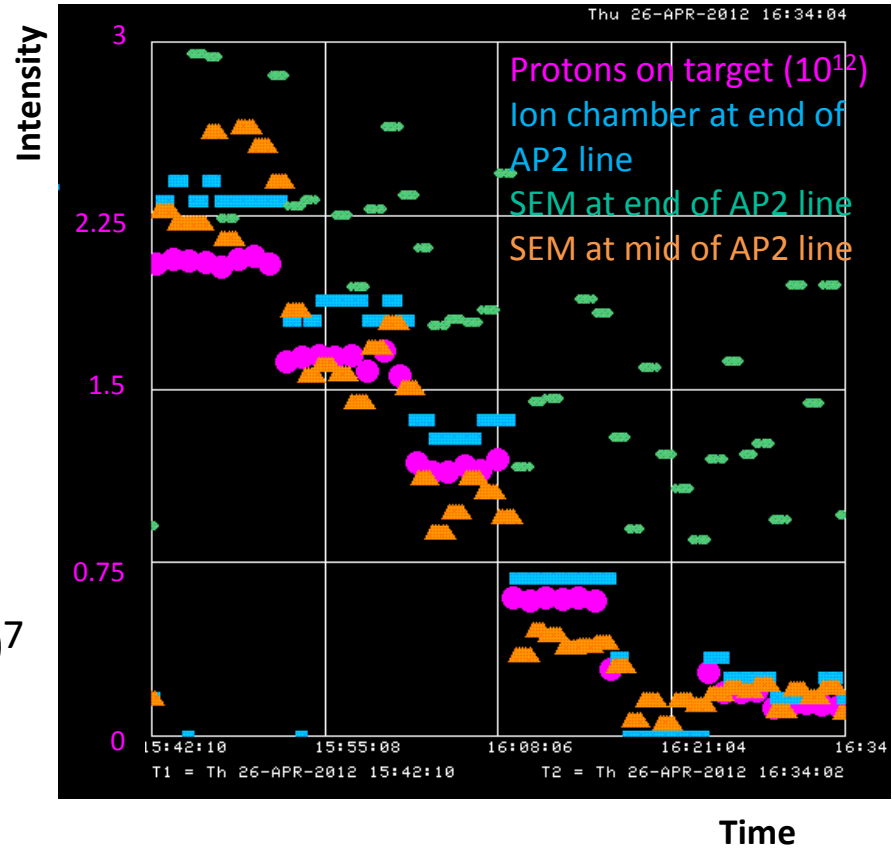
for 1x10^{12} protons on target (g-2 single pulse)

- MARS simulation of target station
  - g-2 mode: yield per POT: ~10^{-5} π+, ~2x as many protons, ~10^{-8} μ+
- G4beamline simulation of start of pion decay line



Results of beam test

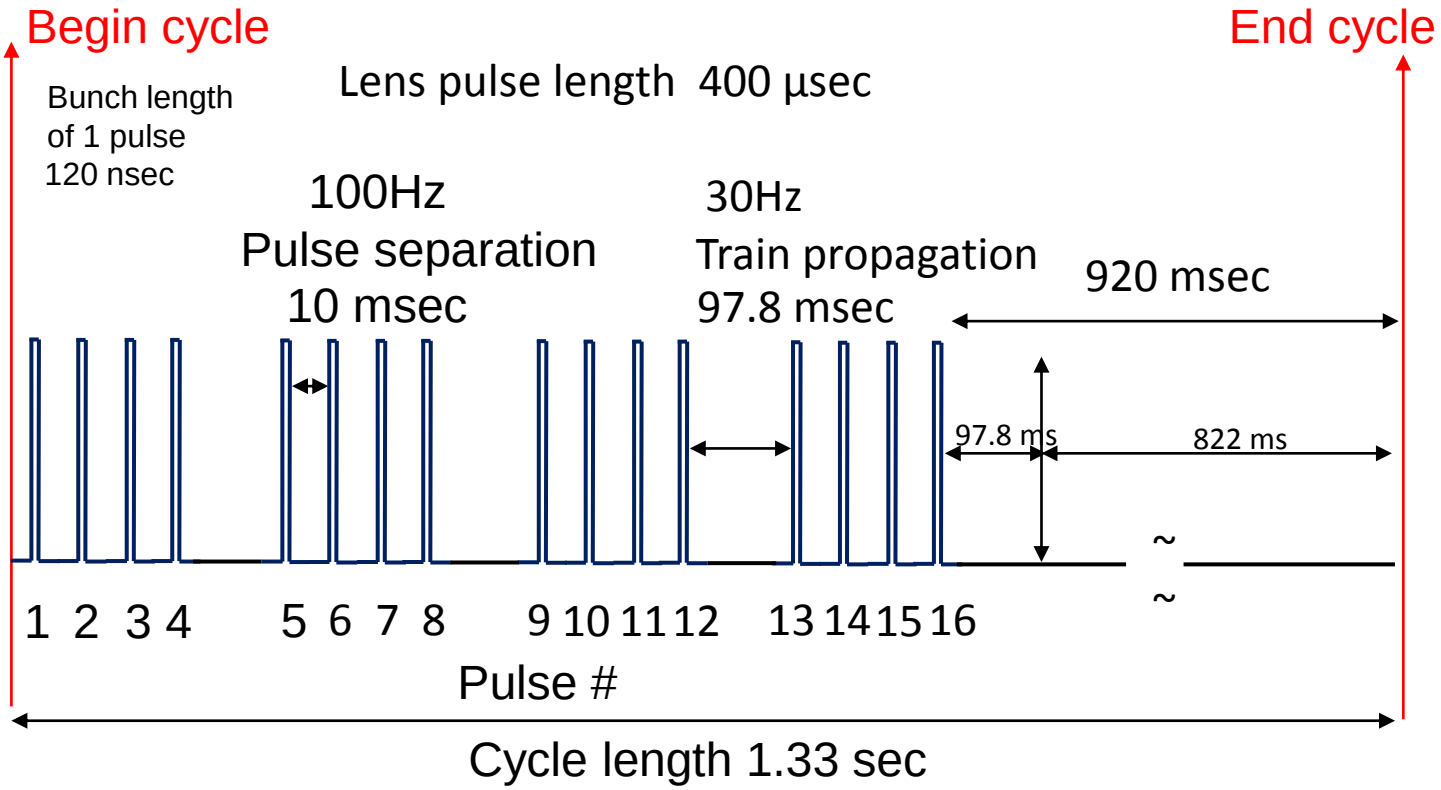
- Intensities track beam on target
- Current monitor at beginning of AP2 line shows expected scaling from 120→8-/120 → 3-
- Ion chamber at end of AP2 line shows order-of-magnitude agreement with predictions: 10^9 particles for 120 → 3- and 10^7 particles for 8 → 3- and 8 → 3+ per 10^{12} protons on target



- 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

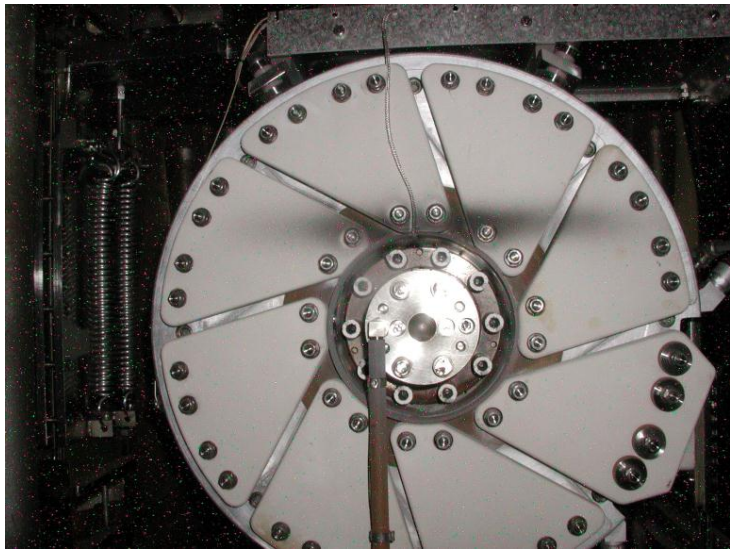
- Higher pulse rate, more complicated cycle than for stacking



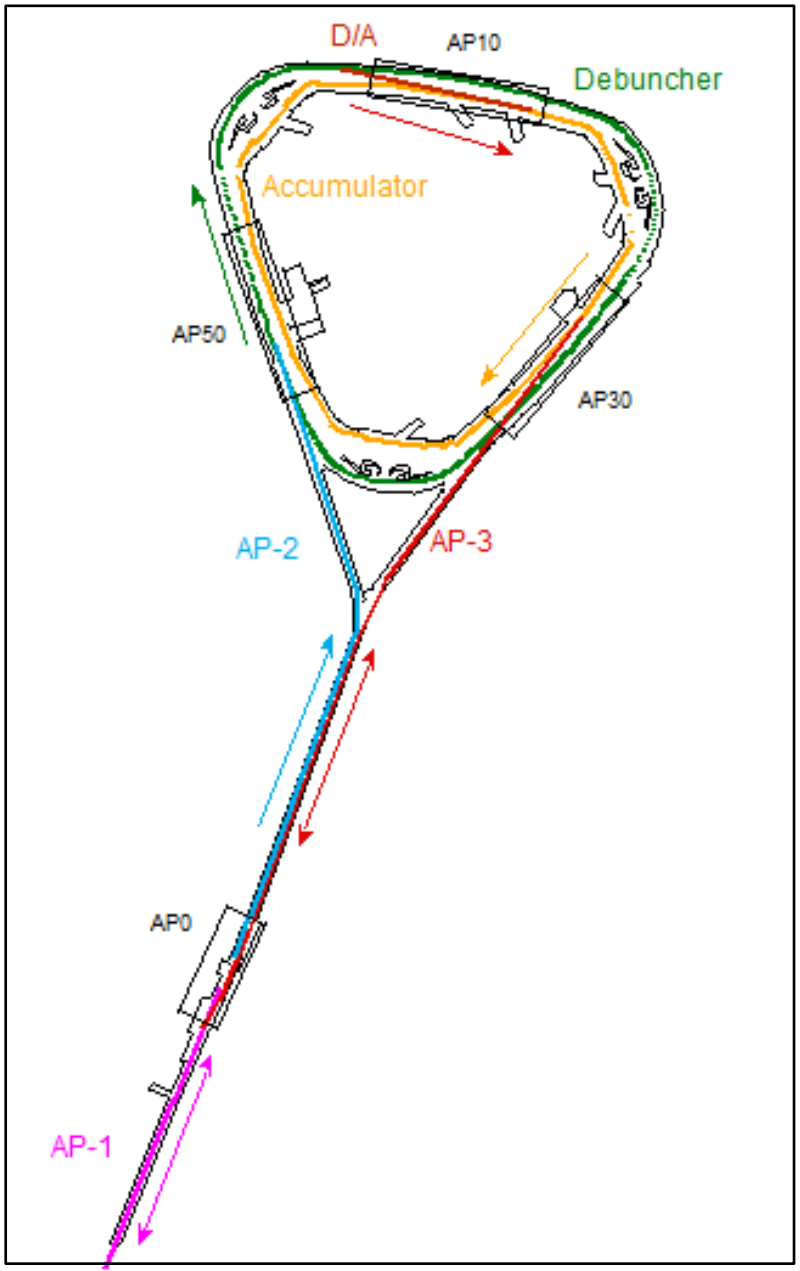
- Will need new power supplies for lithium lens and pulsed magnet
- Preparing to test-pulse lithium lens and
- Have modeled stresses

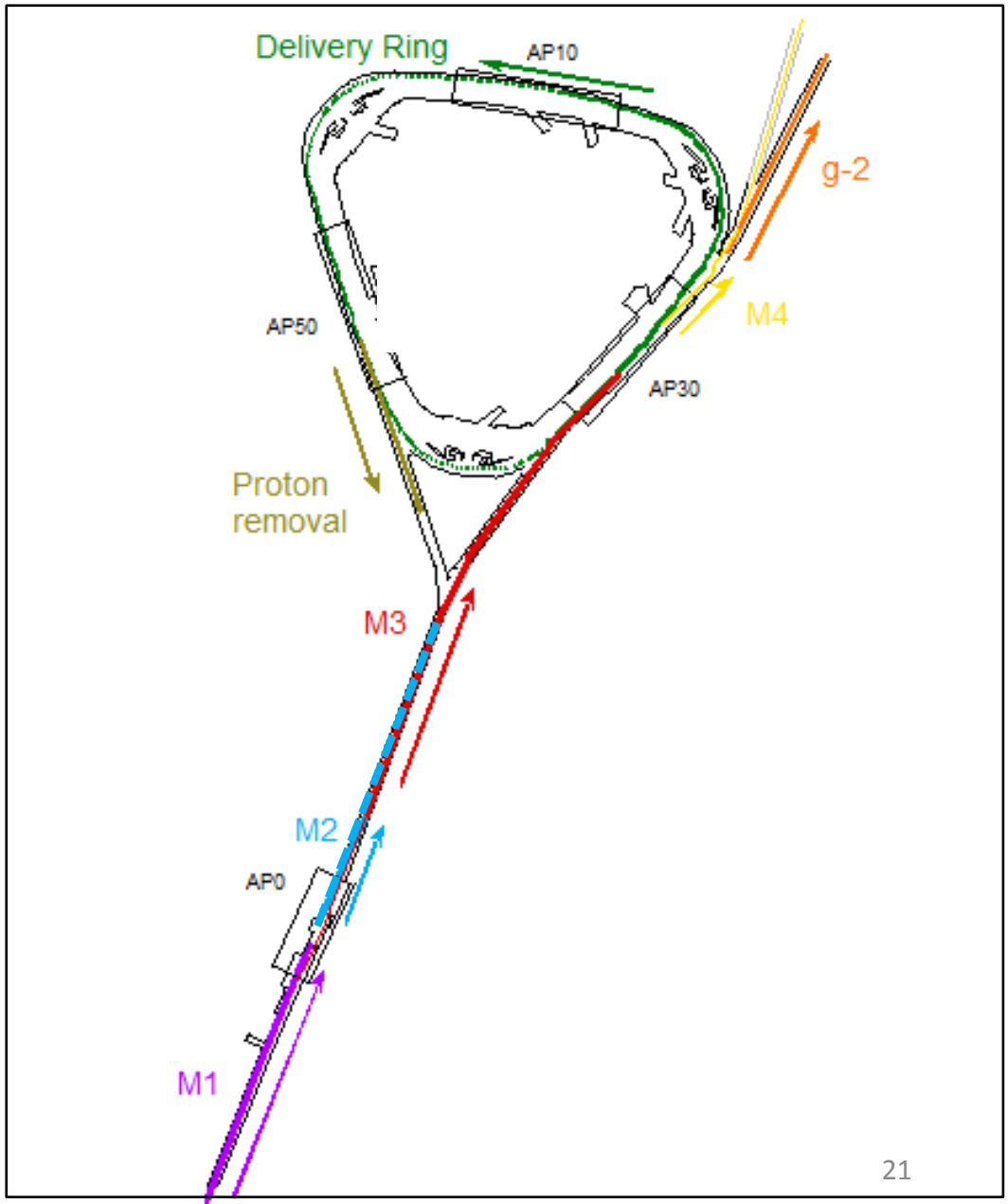
Lens ANSYS modeling

- Lens ANSYS modeling results:
  - Temperatures are higher for g-2 than for stacking
  - Stresses are also higher for g-2 than for stacking
    - Can reduce by reducing pressure of lithium “preload”
  - But Fatigue parameters are better
    - Less difference between maximum and minimum stresses in cycle
- Three ready spares (at preload used for lenses for stacking)
- New spares (4) ready to be assembled
  - Can reduce Lithium preload to lower stresses and increase fatigue life
- Should work, but a million pulses per day is a lot of pulses!
- Preparing to test-pulse spare lens



Beamlines: Pbar stacking vs g-2





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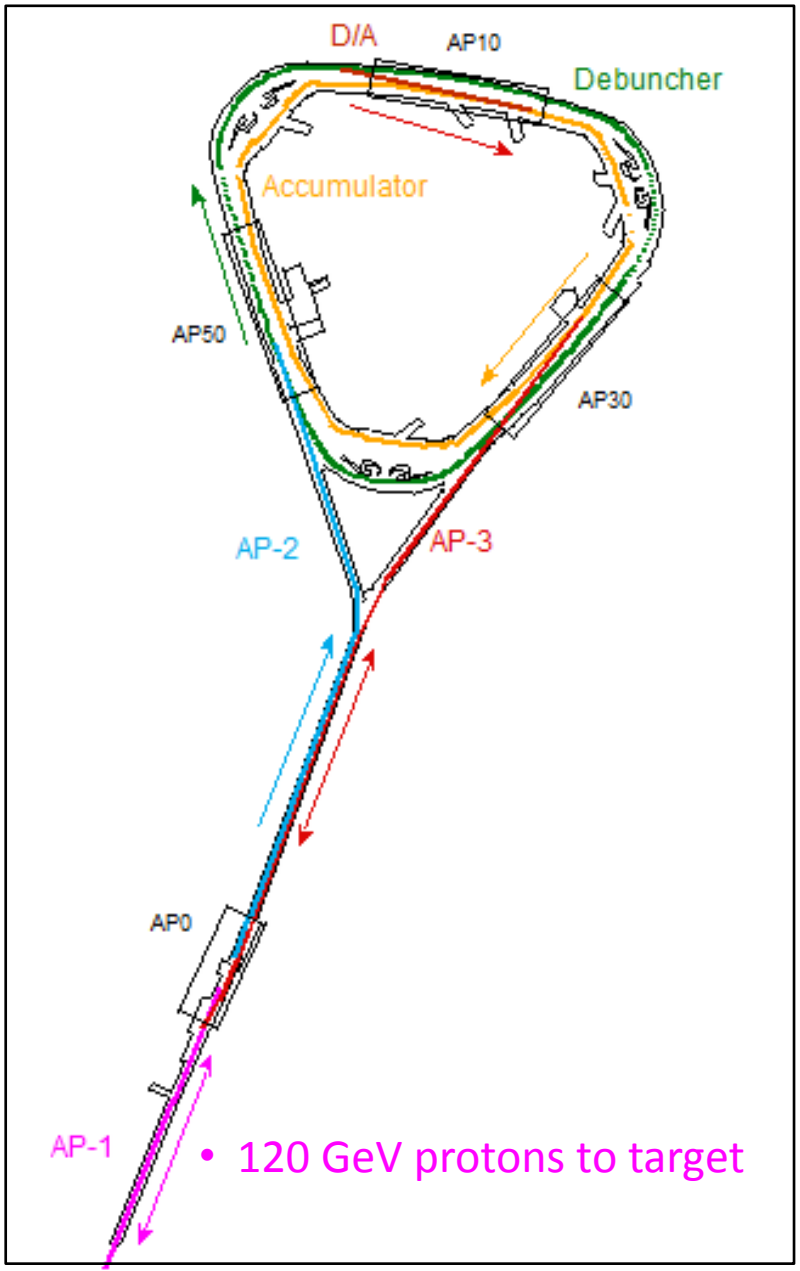

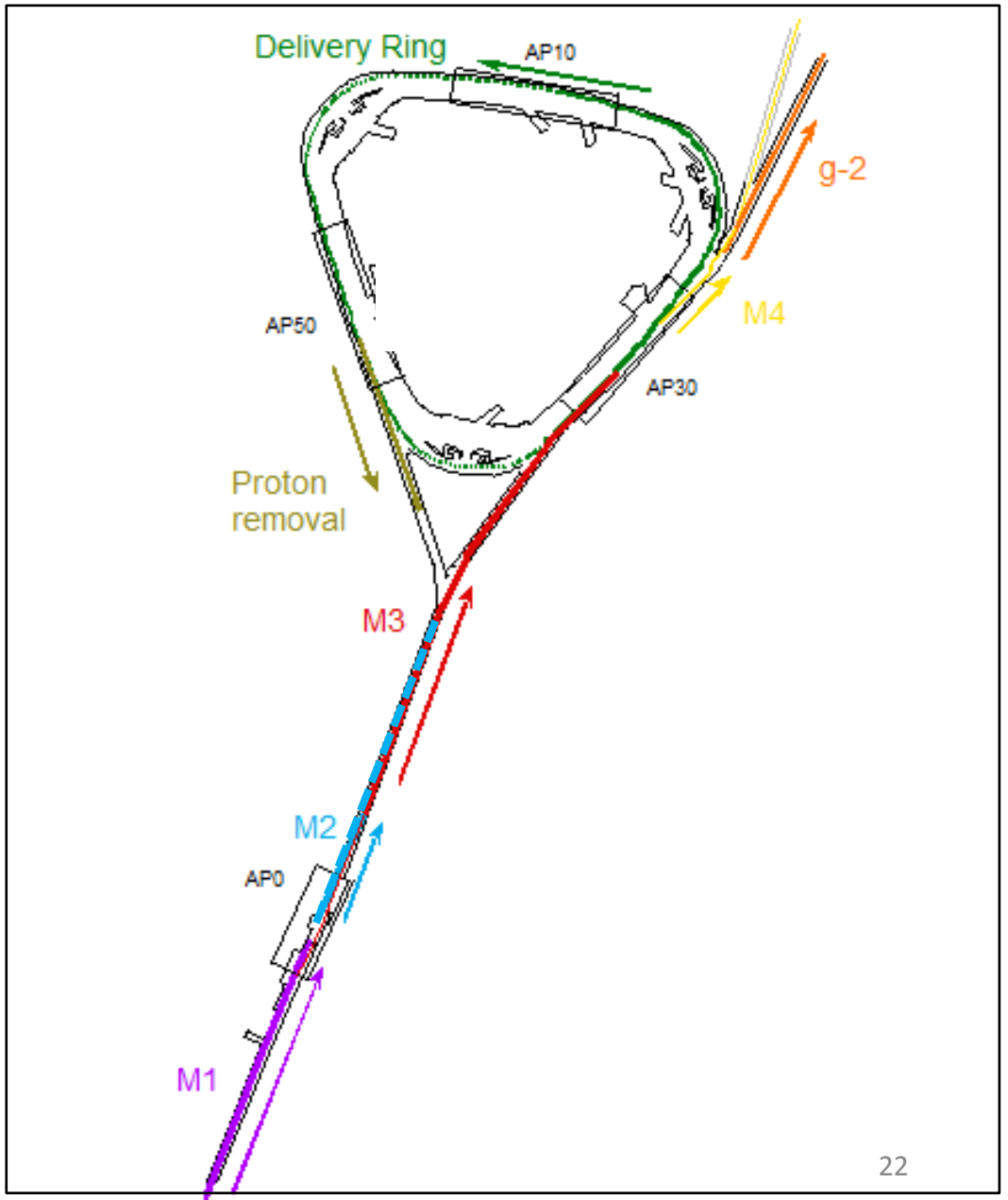

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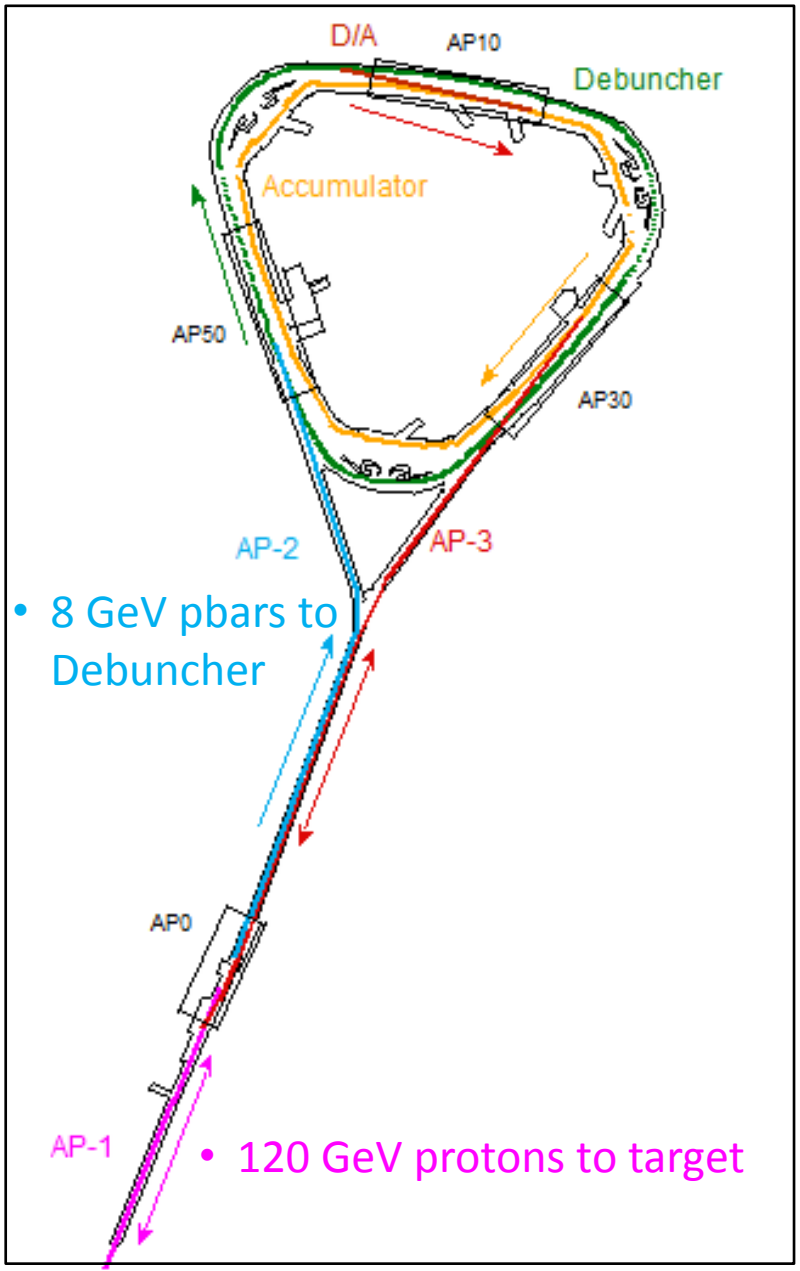
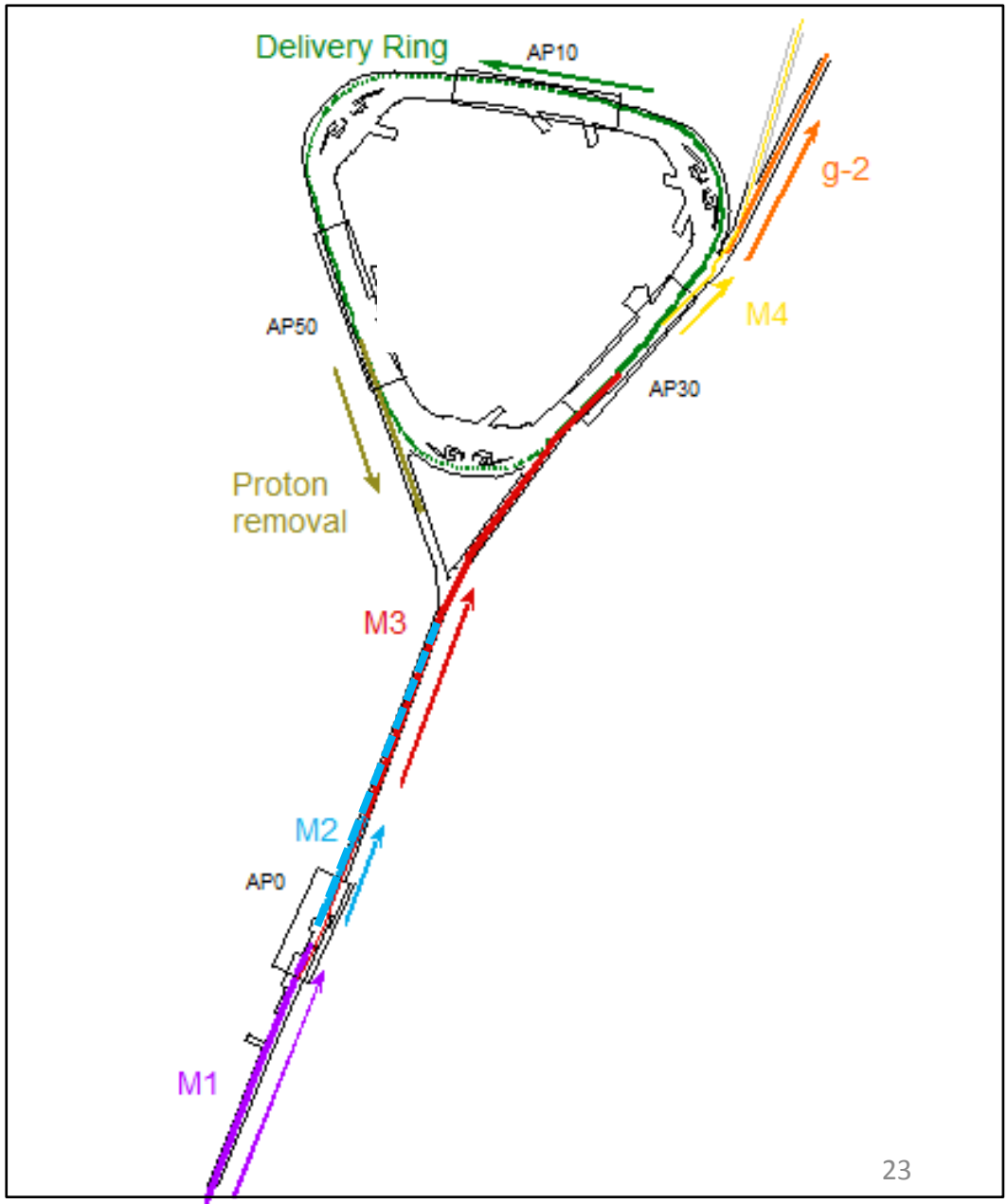


- 8 GeV pbars to Debuncher
- 120 GeV protons to target



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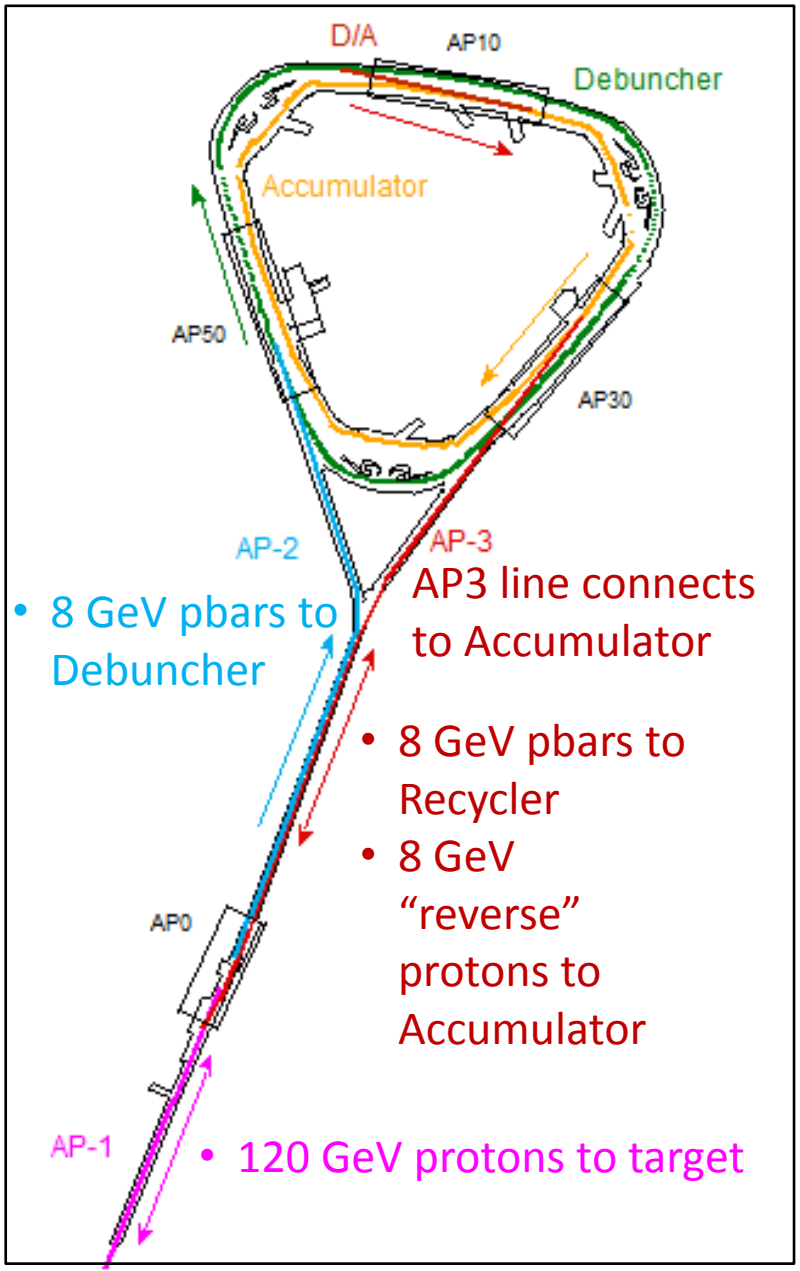

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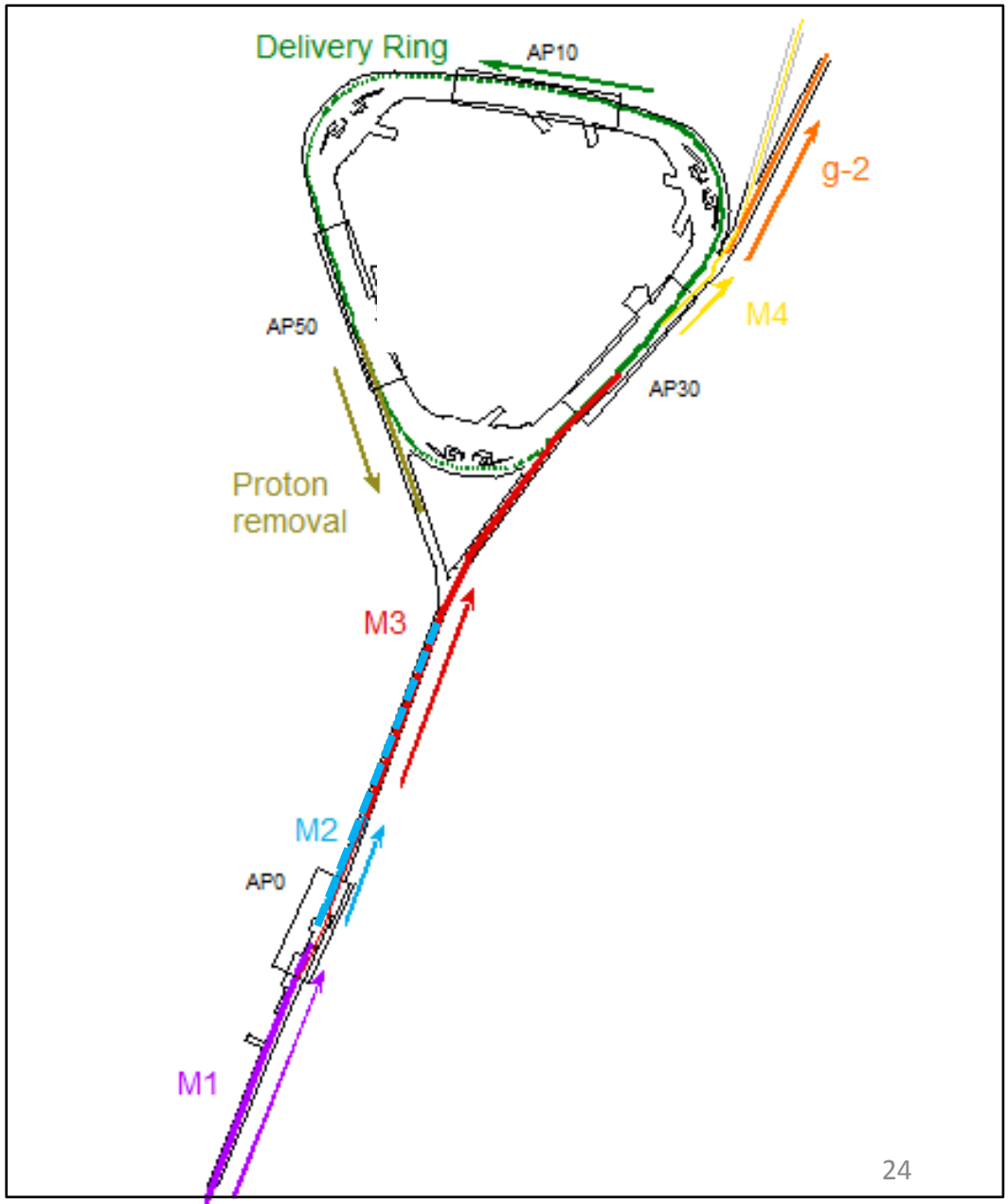
AP3 line connects to Accumulator

- 8 GeV pbars to Recycler
- 8 GeV "reverse" protons to Accumulator

- 120 GeV protons to target



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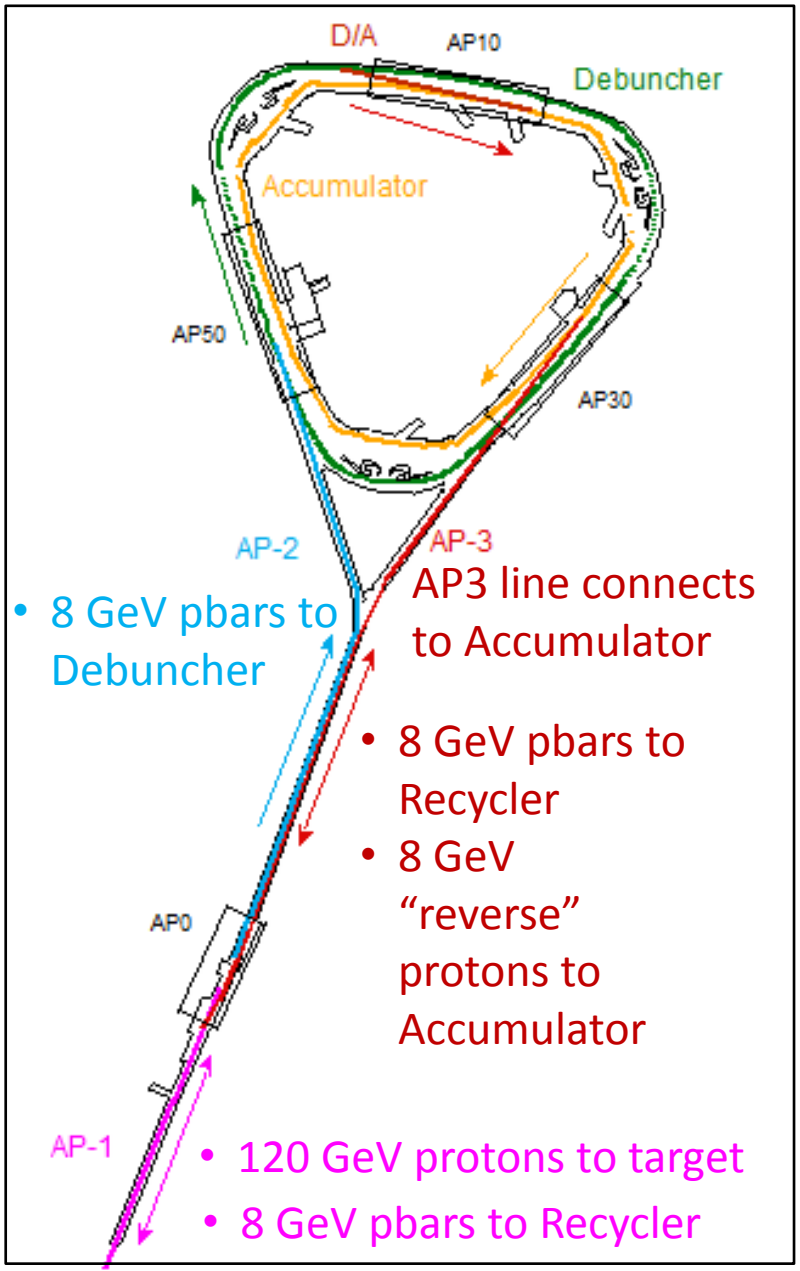

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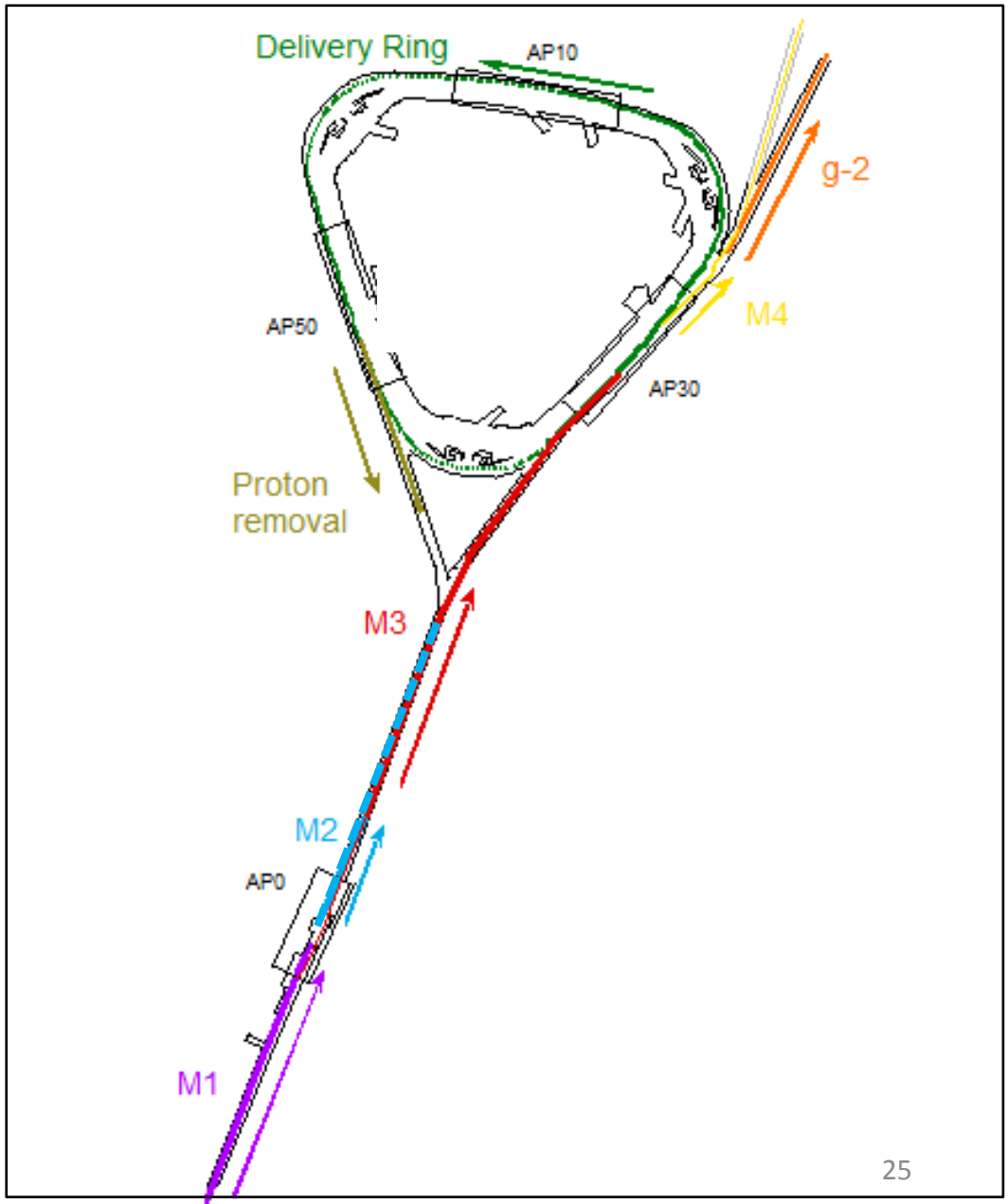

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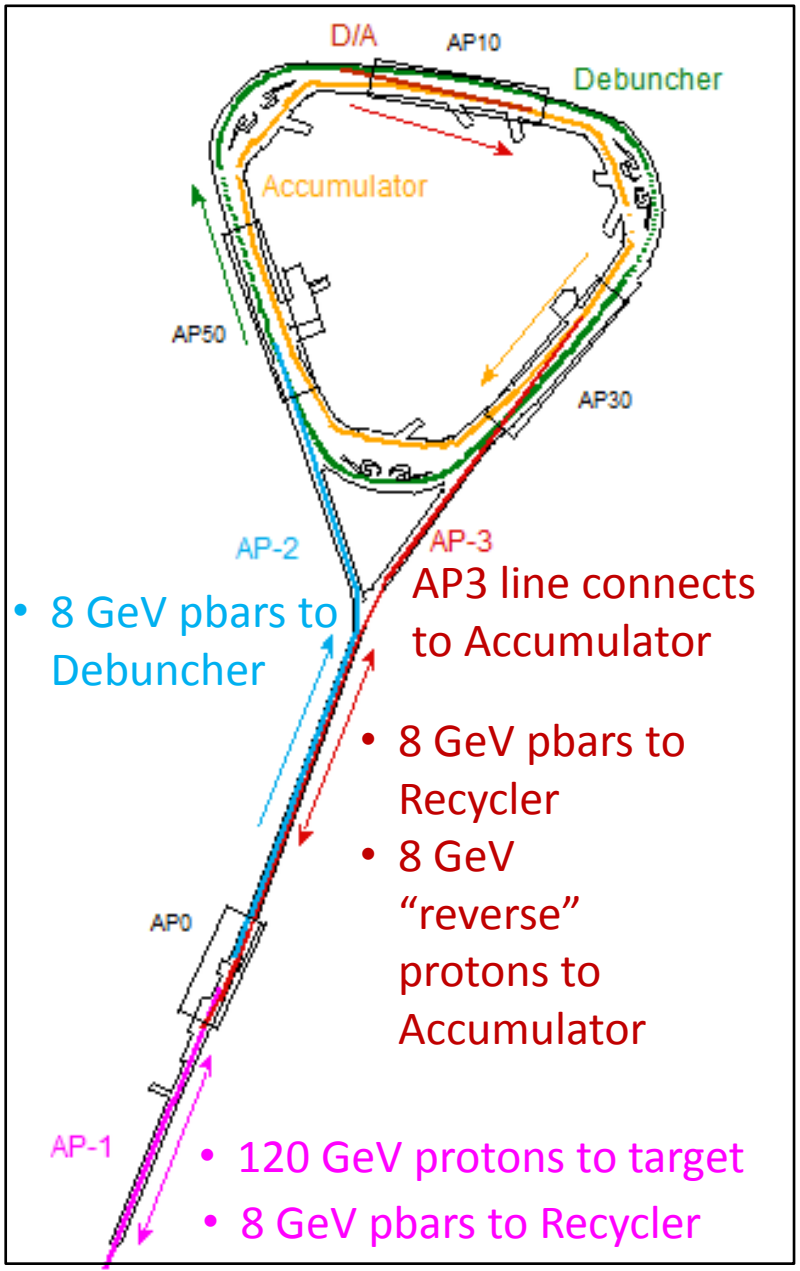

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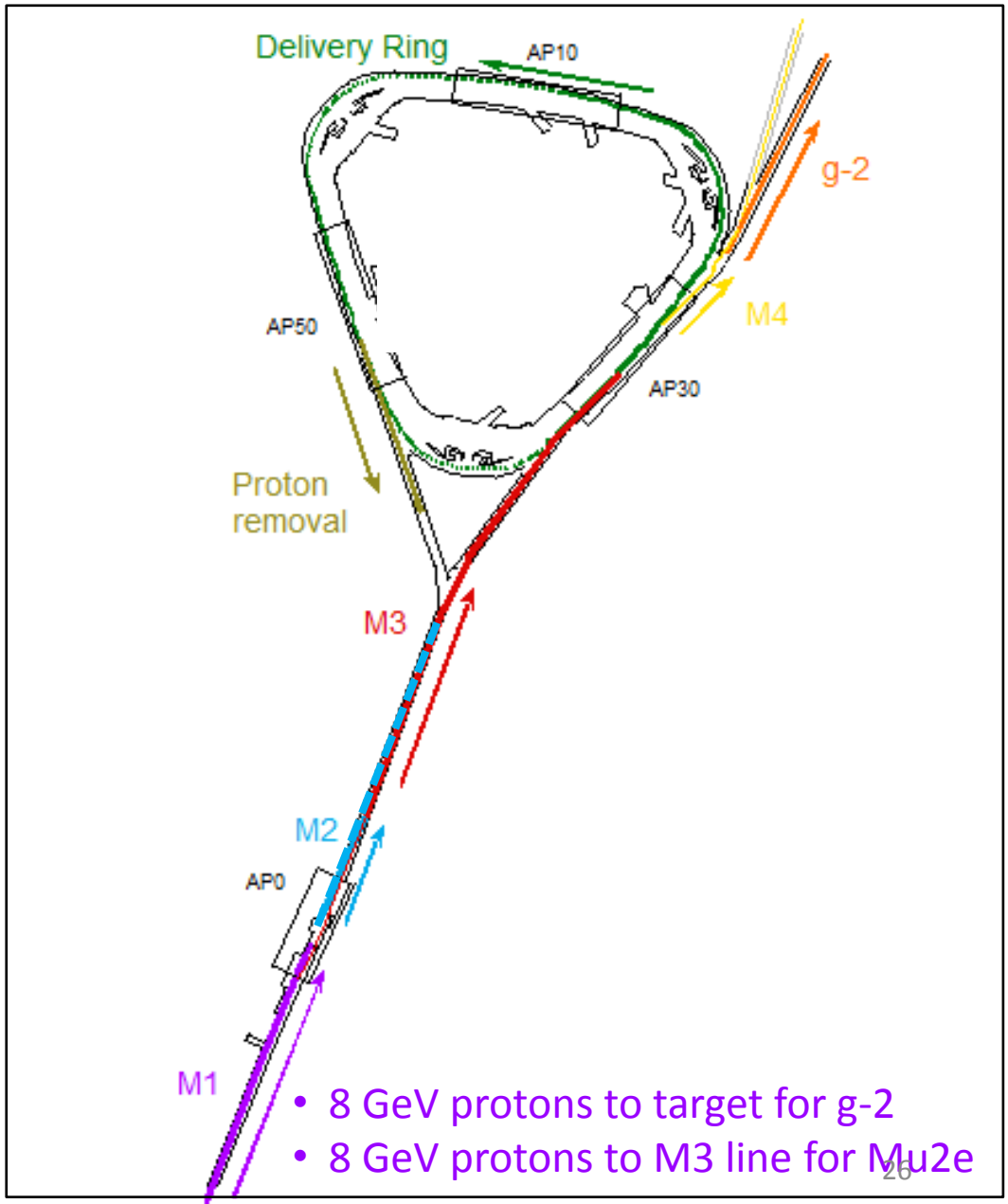
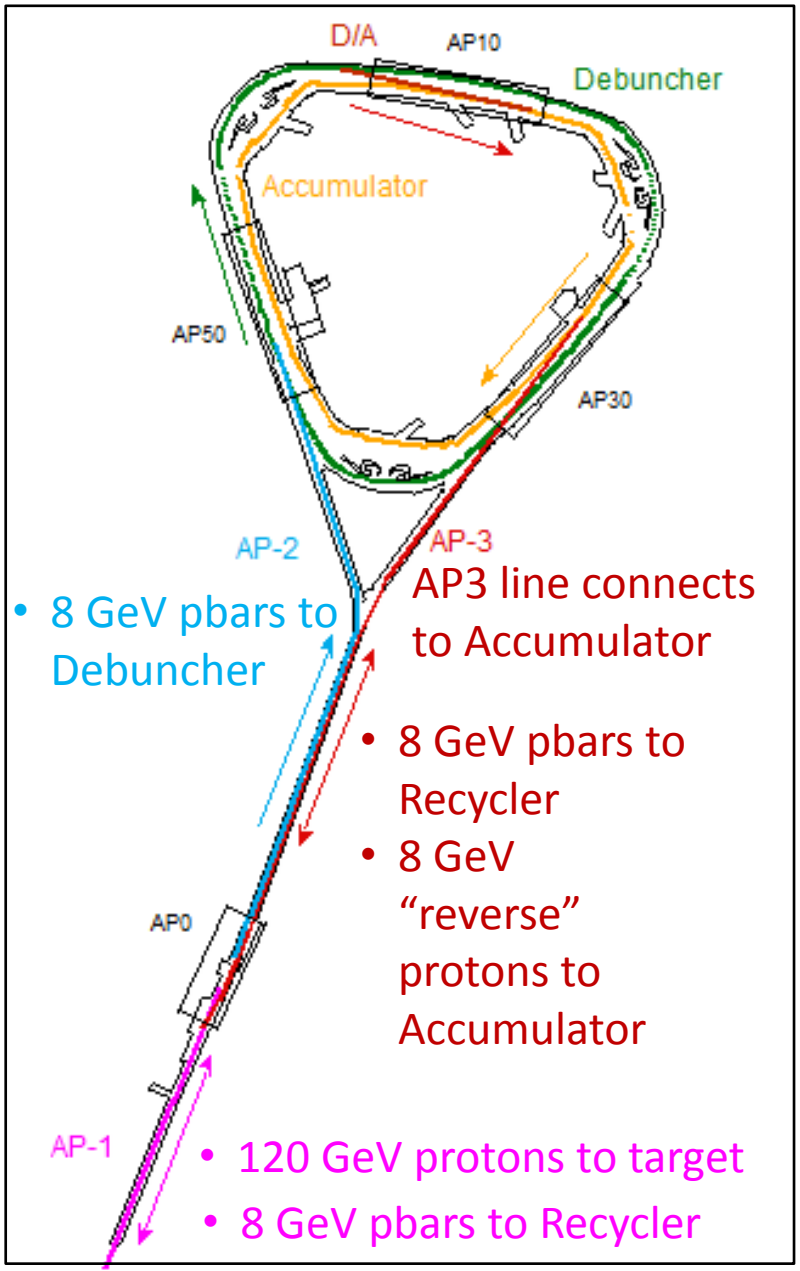


- 8 GeV protons to target for g-2
- 8 GeV protons to M3 line for Mu2e

Beamlines: Pbar stacking vs g-2



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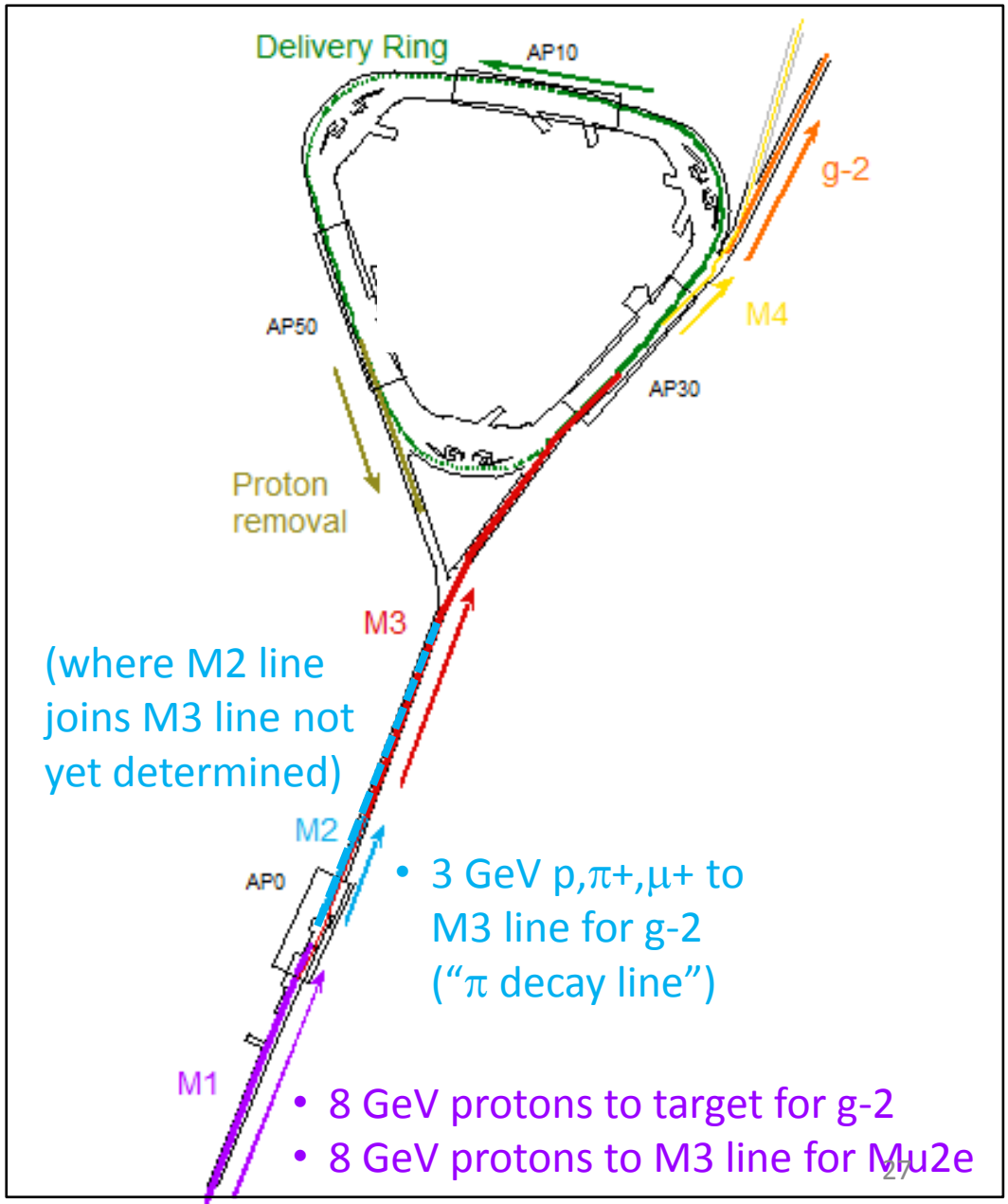

(where M2 line joins M3 line not yet determined)

- 3 GeV p,π+,μ+ to M3 line for g-2 ("π decay line")

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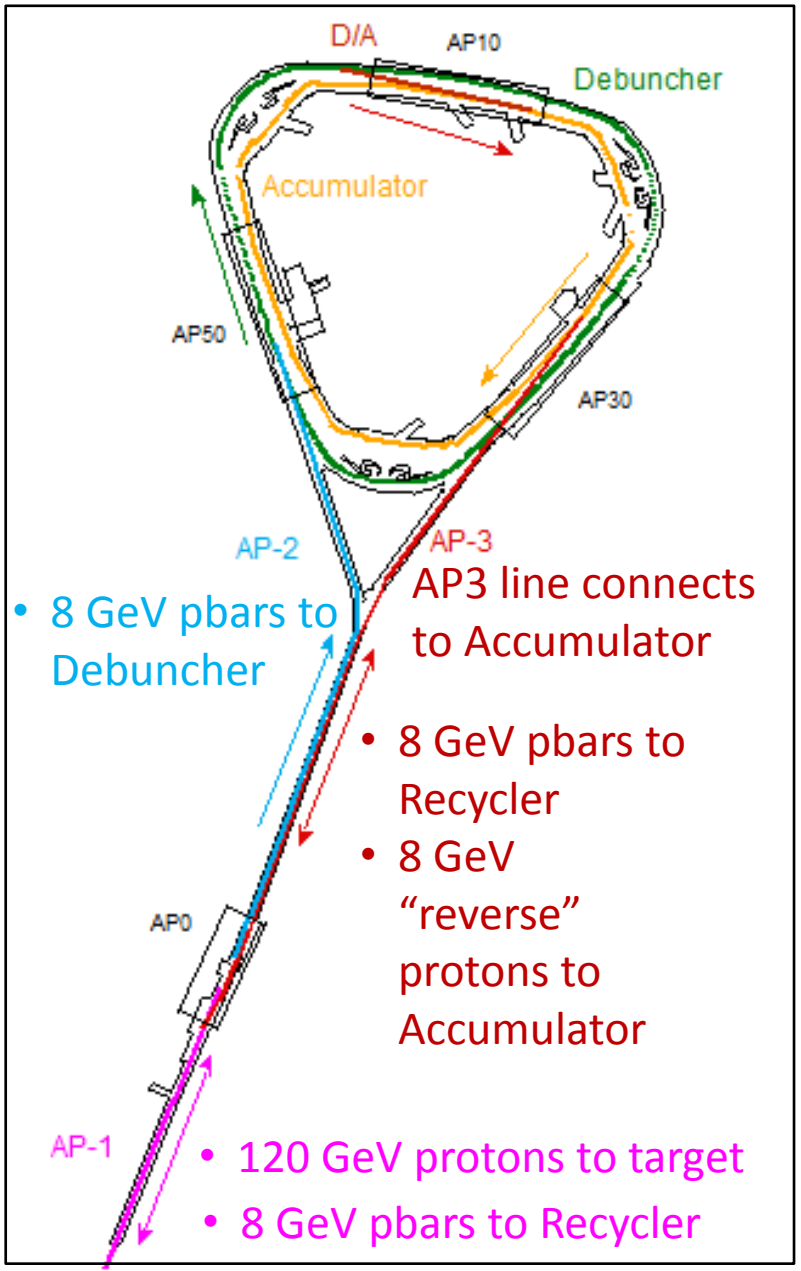
Beamlines: Pbar stacking vs g-2



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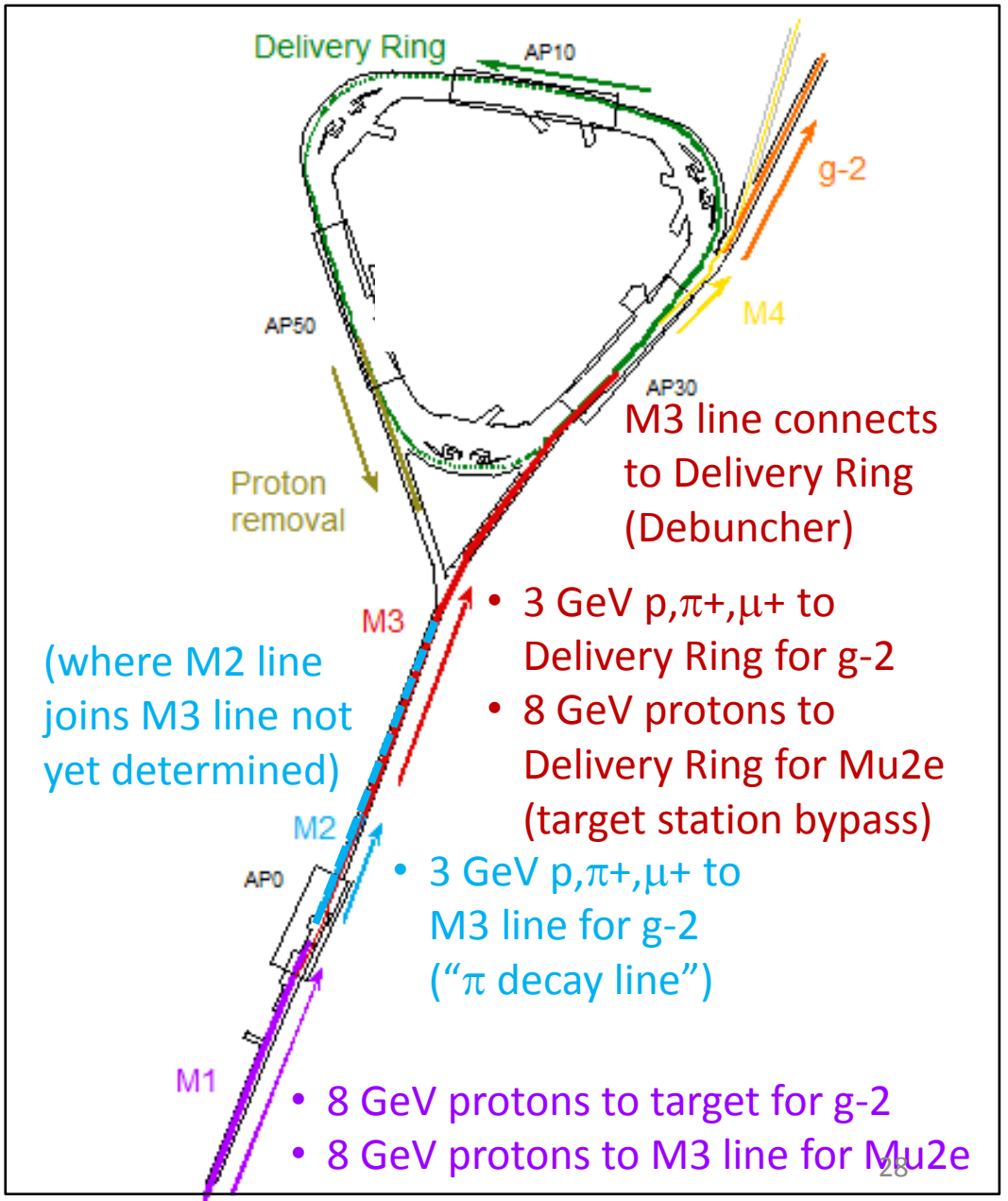

M3 line connects to Delivery Ring (Debuncher)

(where M2 line joins M3 line not yet determined)

- 3 GeV p,π+,μ+ to Delivery Ring for g-2
- 8 GeV protons to Delivery Ring for Mu2e (target station bypass)

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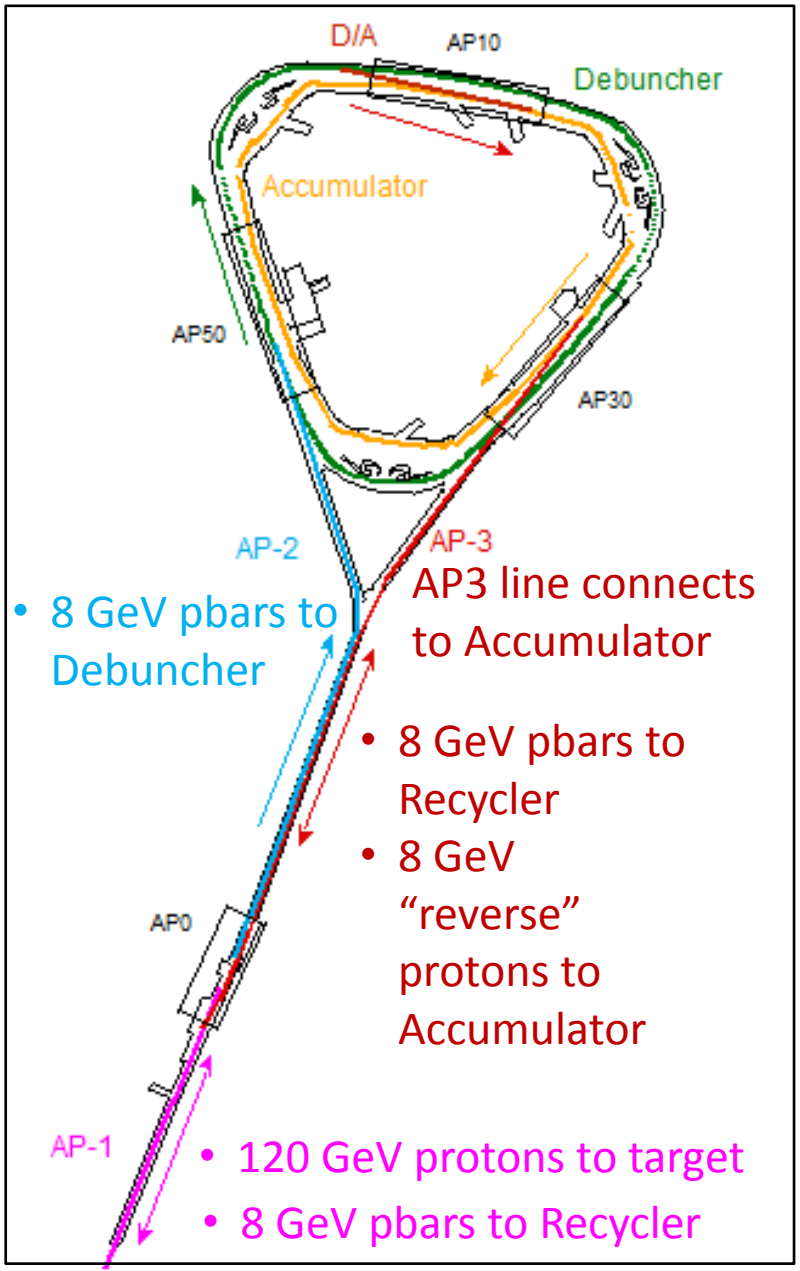

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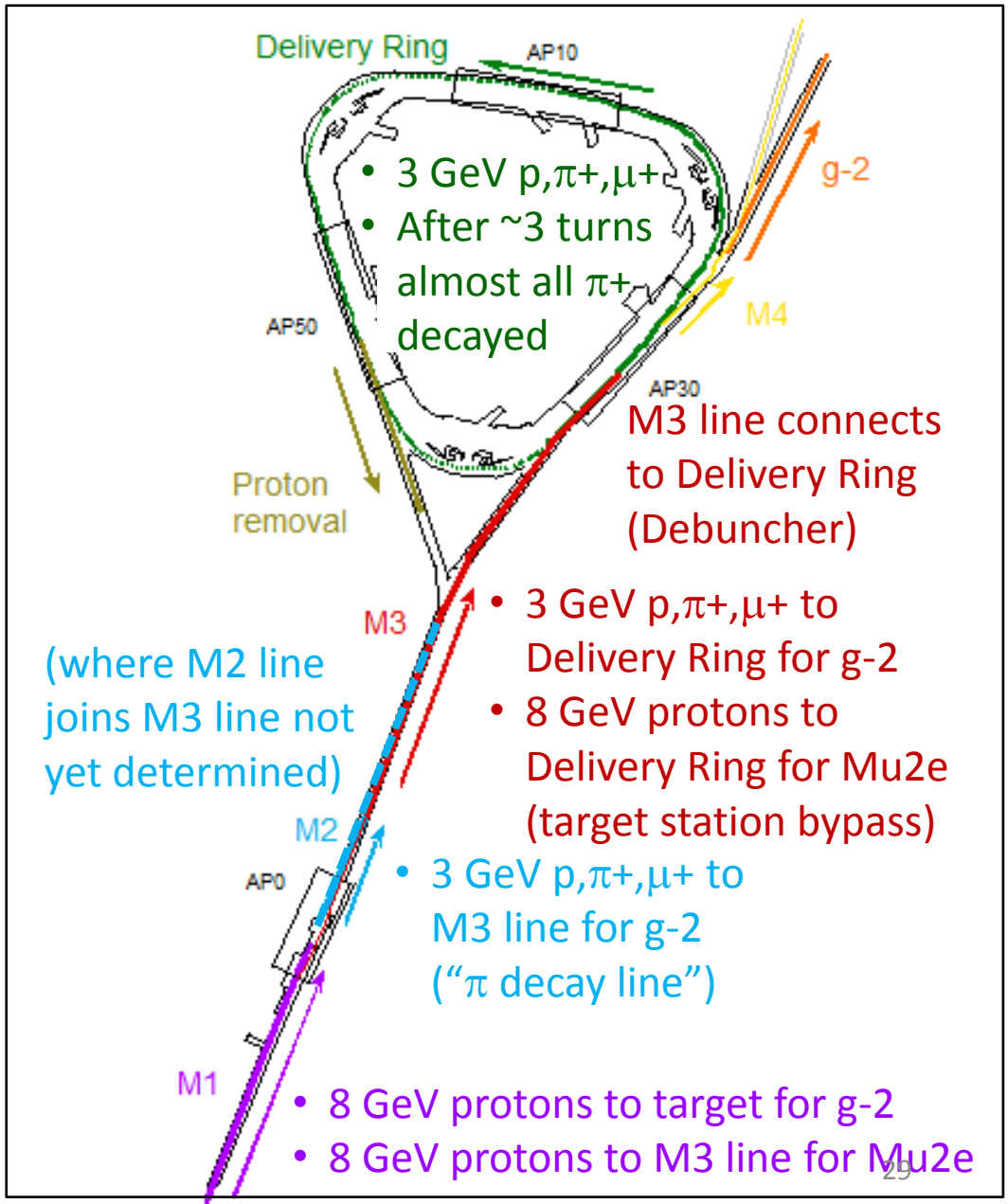

- 3 GeV p,π+,μ+
- After ~3 turns almost all π+ decayed

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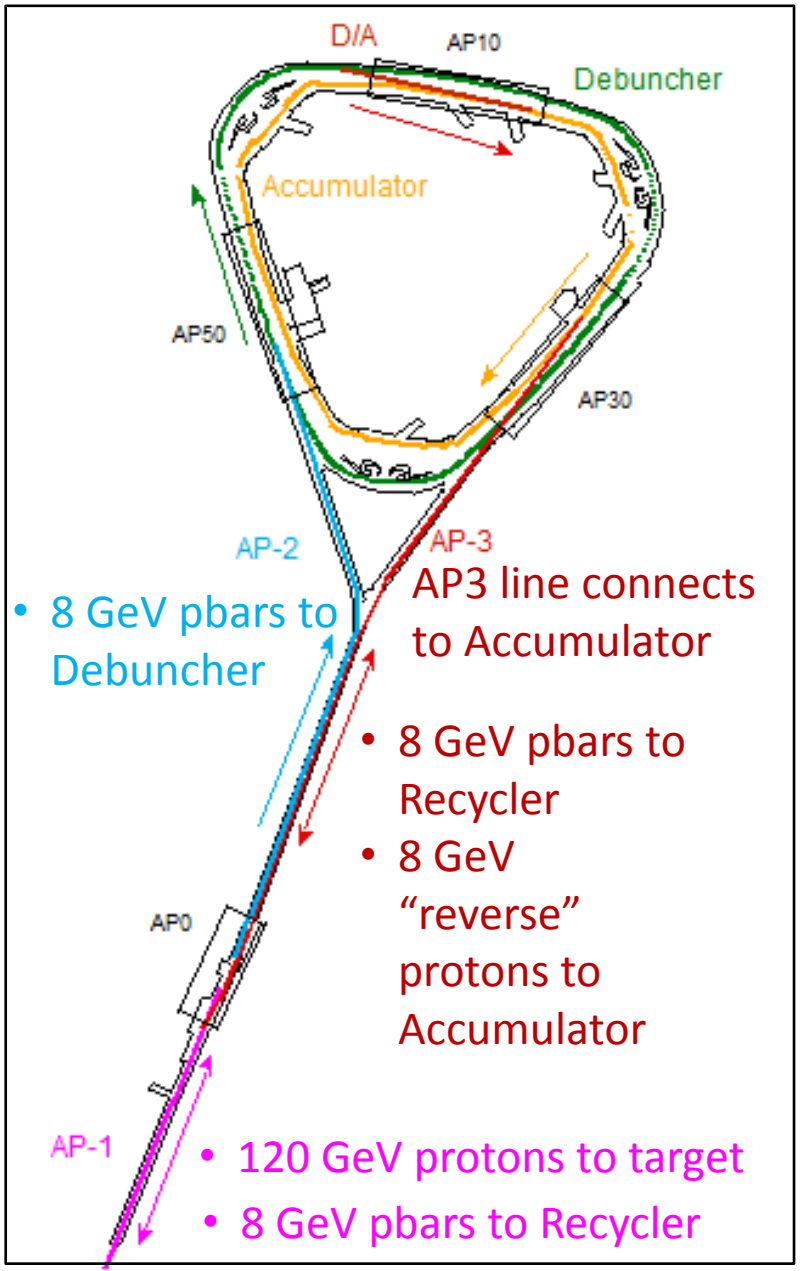

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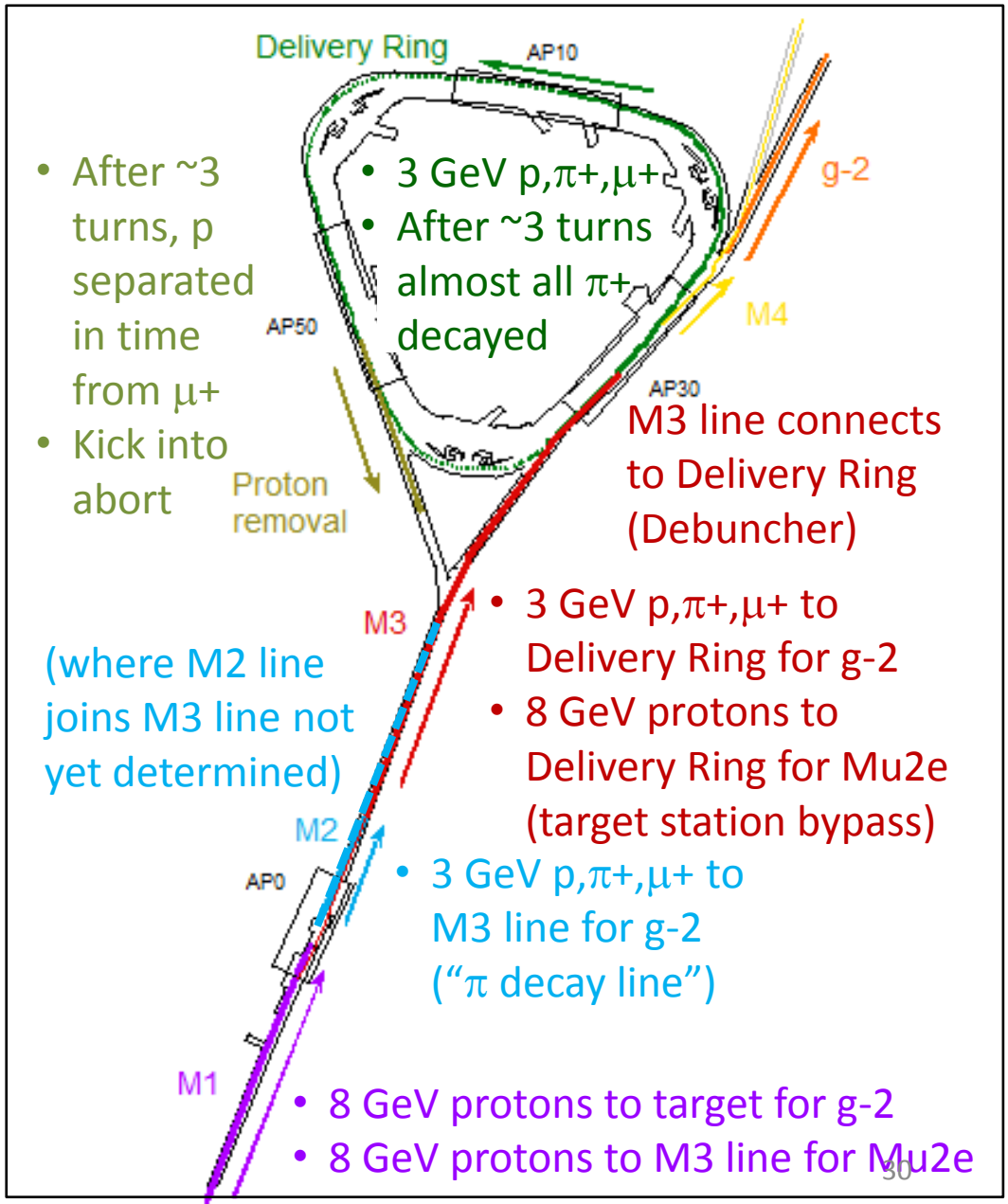
AP3 line connects to Accumulator

- 8 GeV pbars to Recycler
- 8 GeV "reverse" protons to Accumulator

- 120 GeV protons to target
- 8 GeV pbars to Recycler



- After ~3 turns, p separated in time from μ+
- Kick into abort

- 3 GeV p,π+,μ+
- After ~3 turns almost all π+ decayed

M3 line connects to Delivery Ring (Debuncher)

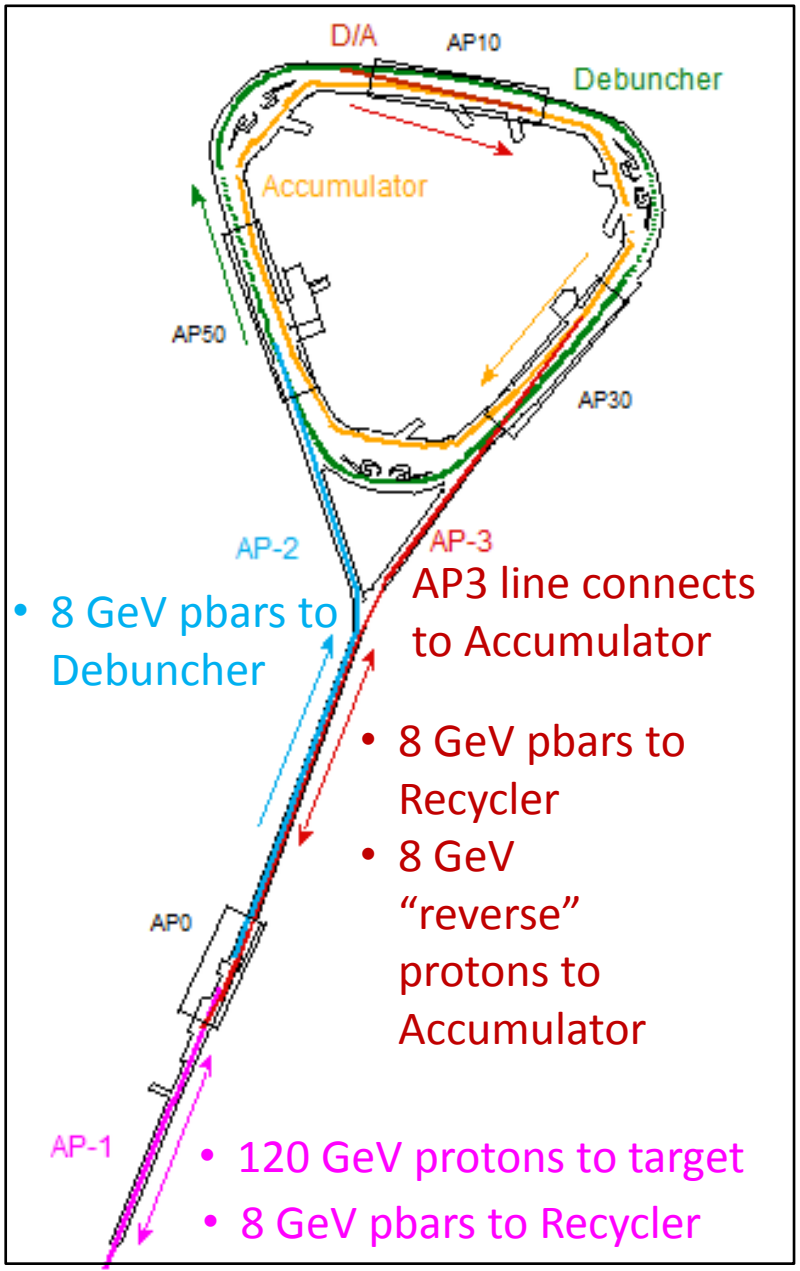
(where M2 line joins M3 line not yet determined)

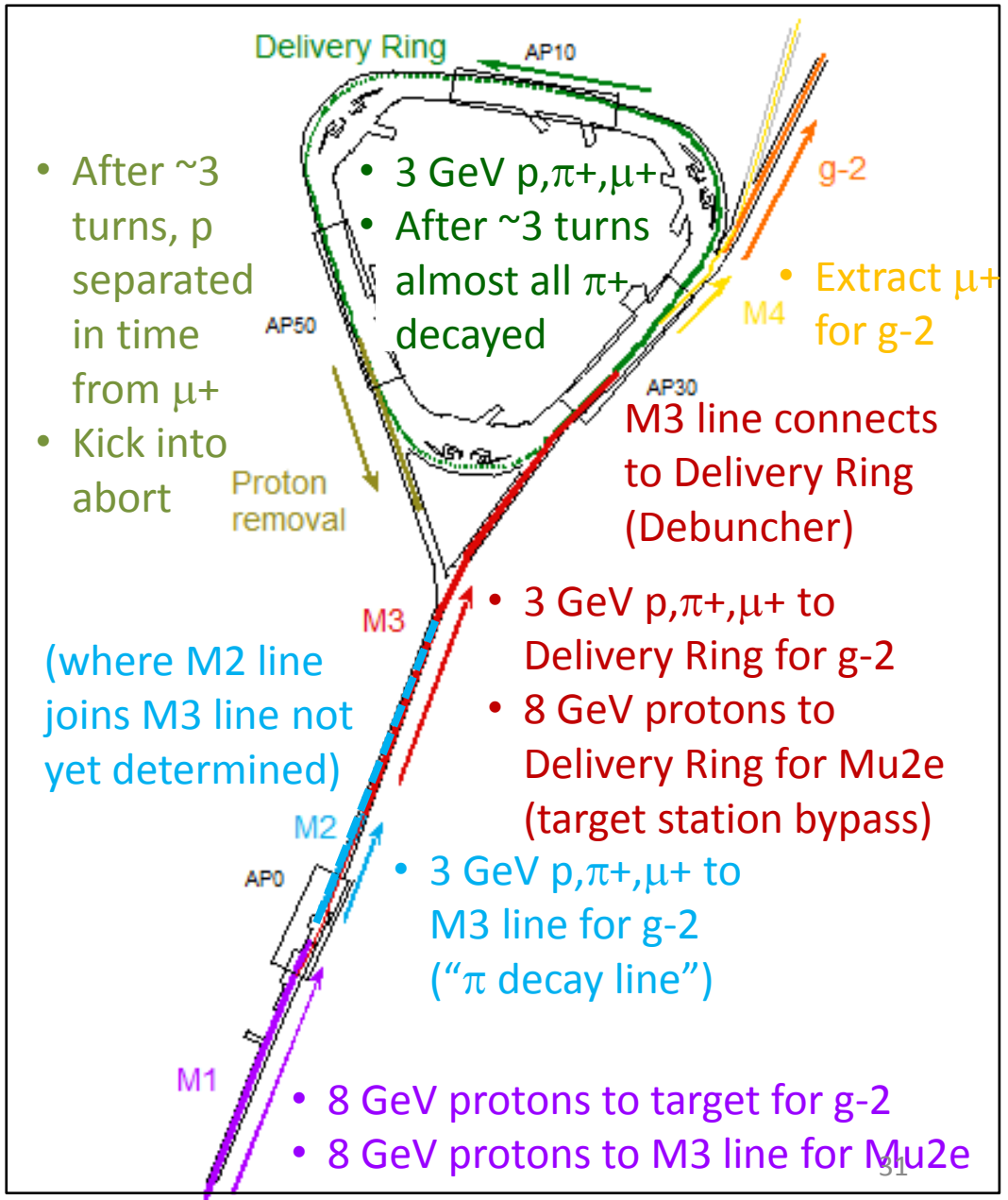
- 3 GeV p,π+,μ+ to Delivery Ring for g-2
- 8 GeV protons to Delivery Ring for Mu2e (target station bypass)

- 3 GeV p,π+,μ+ to M3 line for g-2 ("π decay line")

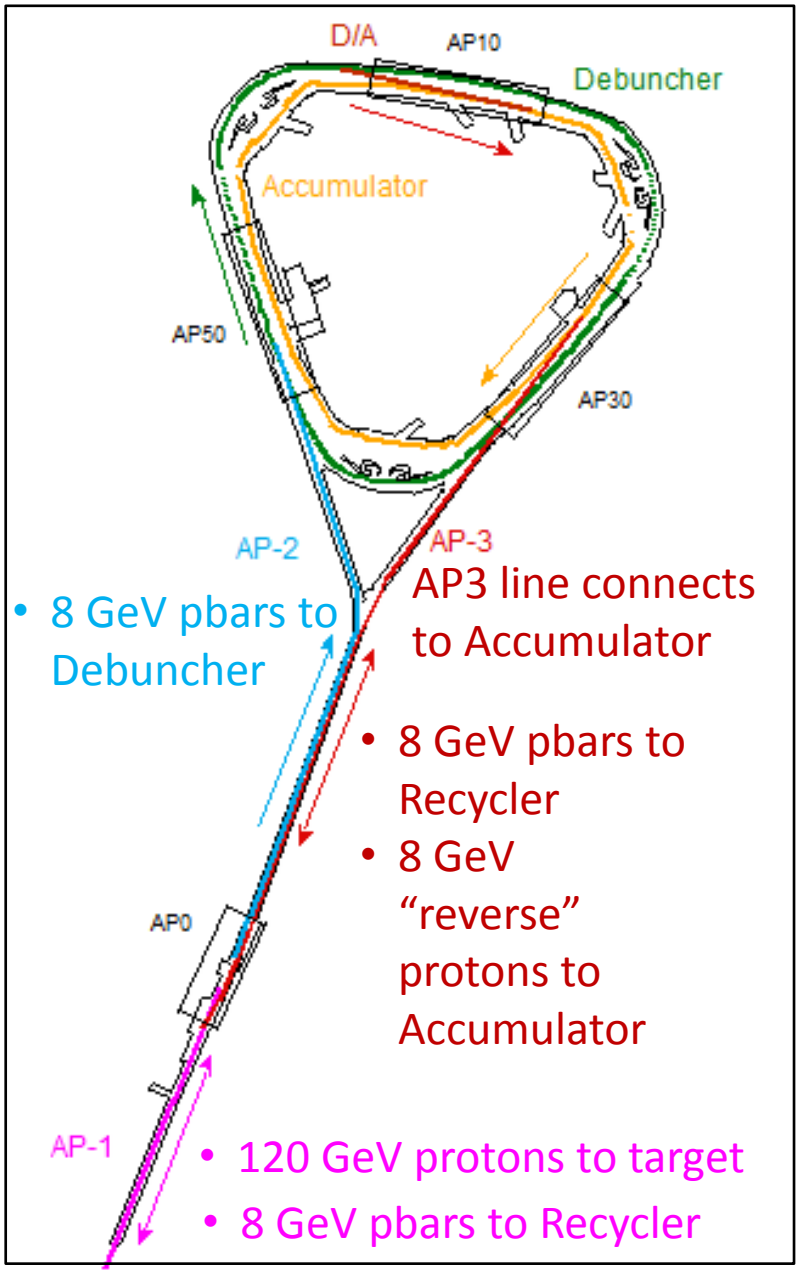
- 8 GeV protons to target for g-2
- 8 GeV protons to M3 line for Mu2e

Beamlines: Pbar stacking vs g-2





Beamlines: Pbar stacking vs g-2

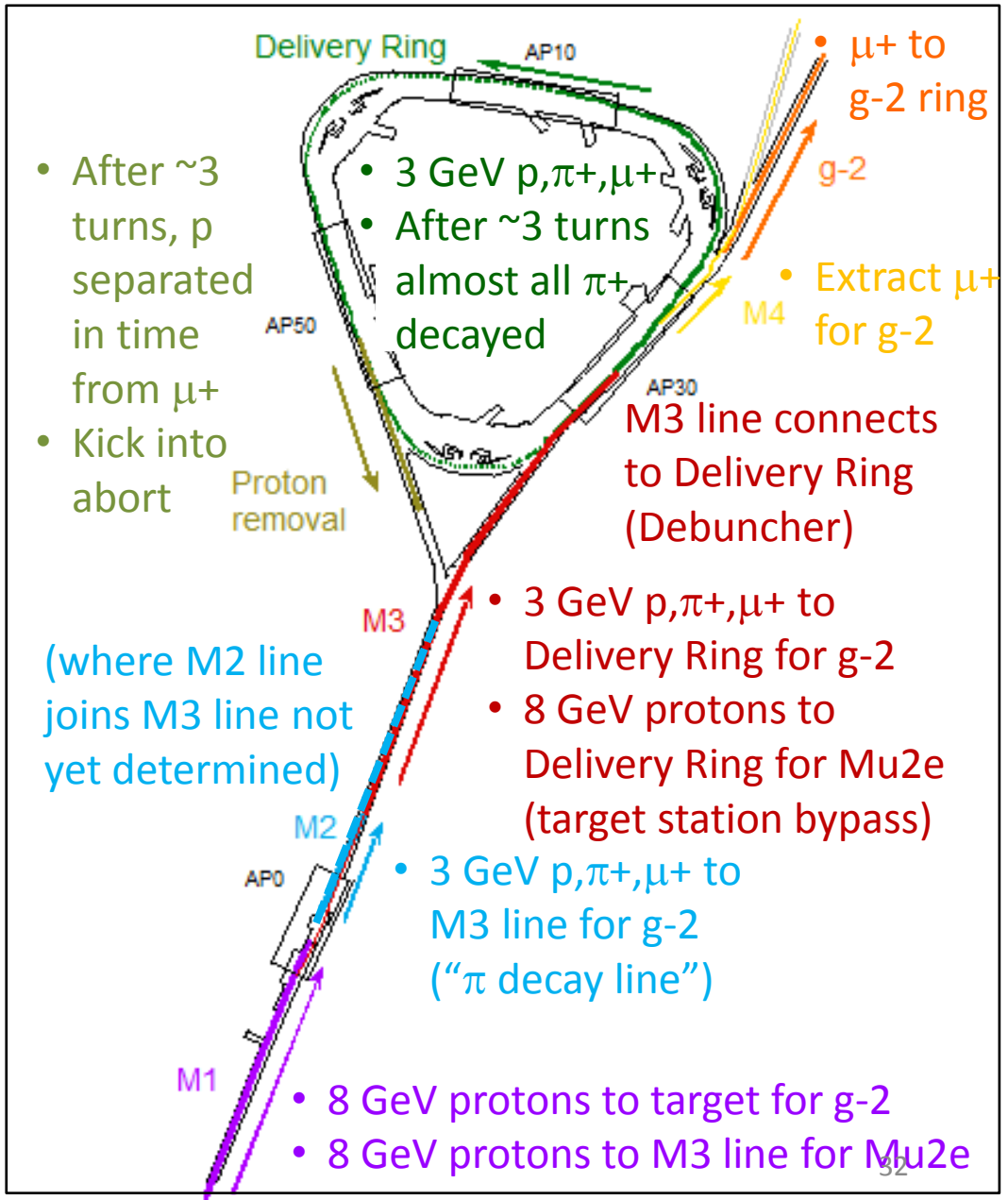


- 8 GeV pbars to Debuncher

AP3 line connects to Accumulator

- 8 GeV pbars to Recycler
- 8 GeV "reverse" protons to Accumulator

- 120 GeV protons to target
- 8 GeV pbars to Recycler



- After ~3 turns, p separated in time from μ+
- Kick into abort

- 3 GeV p,π+,μ+
- After ~3 turns almost all π+ decayed

- μ+ to g-2 ring
- Extract μ+ for g-2

M3 line connects to Delivery Ring (Debuncher)

(where M2 line joins M3 line not yet determined)

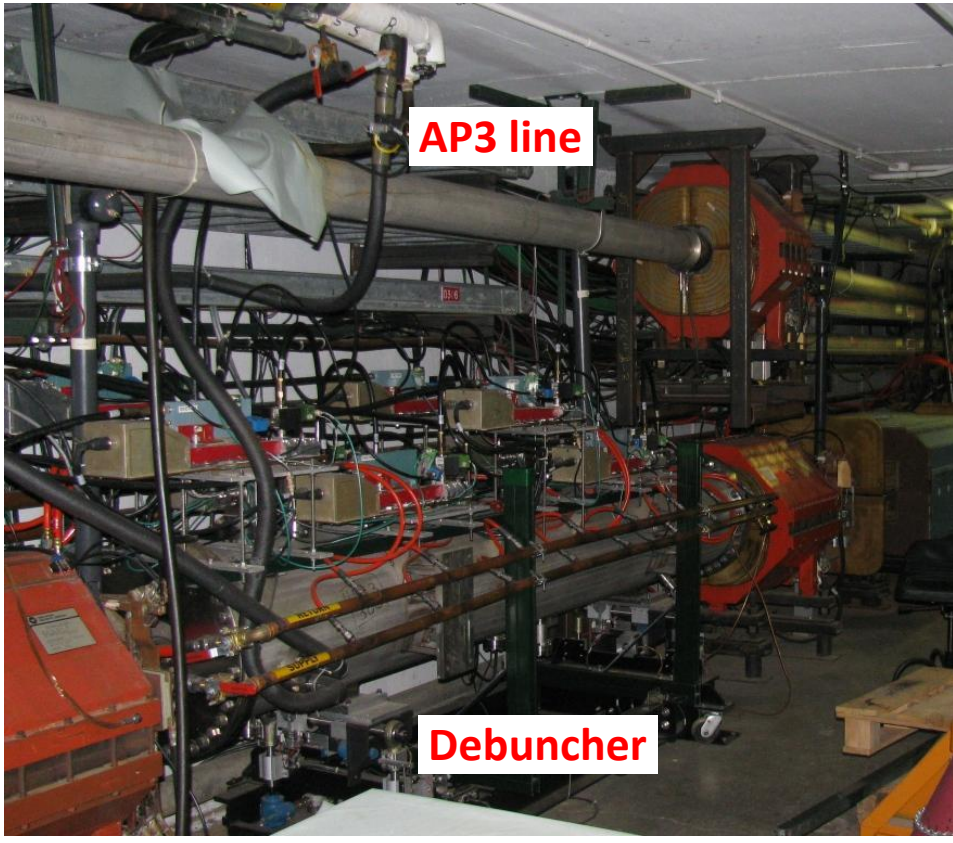
- 3 GeV p,π+,μ+ to Delivery Ring for g-2
- 8 GeV protons to Delivery Ring for Mu2e (target station bypass)

- 3 GeV p,π+,μ+ to M3 line for g-2 ("π decay line")

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

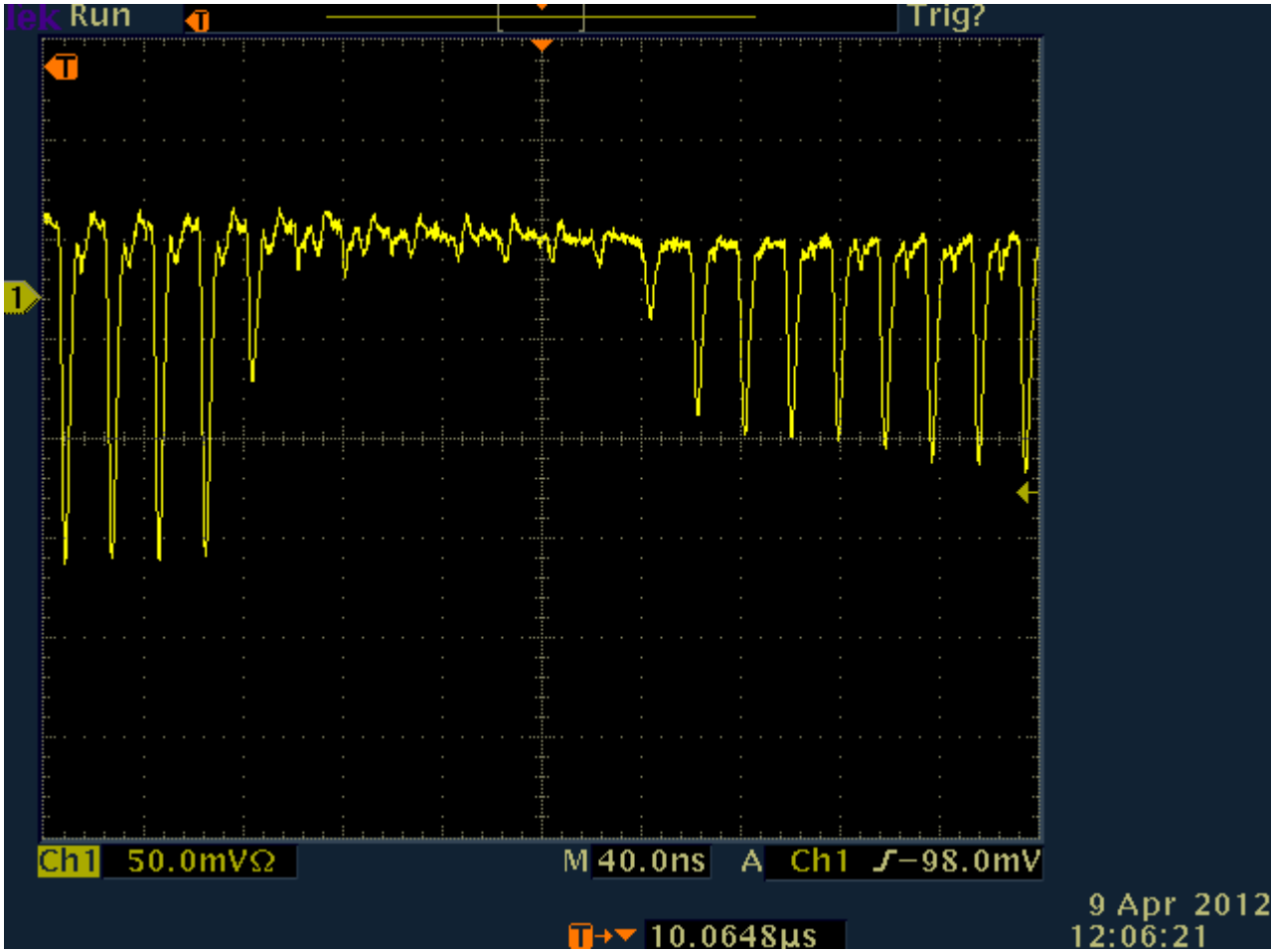
Summary of secondary-beamline upgrades

- M2/M3 lines
  - Current plan is to rebuild a significant part of the line to create a regular lattice with larger aperture to capture more muons from decays
  - Beamline magnets from BNL g-2 experiment, also from Accumulator
- New connection to Delivery Ring
  - Significant mechanical conflicts
- Abort/Proton removal line
  - Need a fast-rise kicker
  - Mu2e abort component will be used for proton removal
- Extraction from Delivery Ring
  - Extraction kicker and septum



3 GeV beam circulating in Debuncher

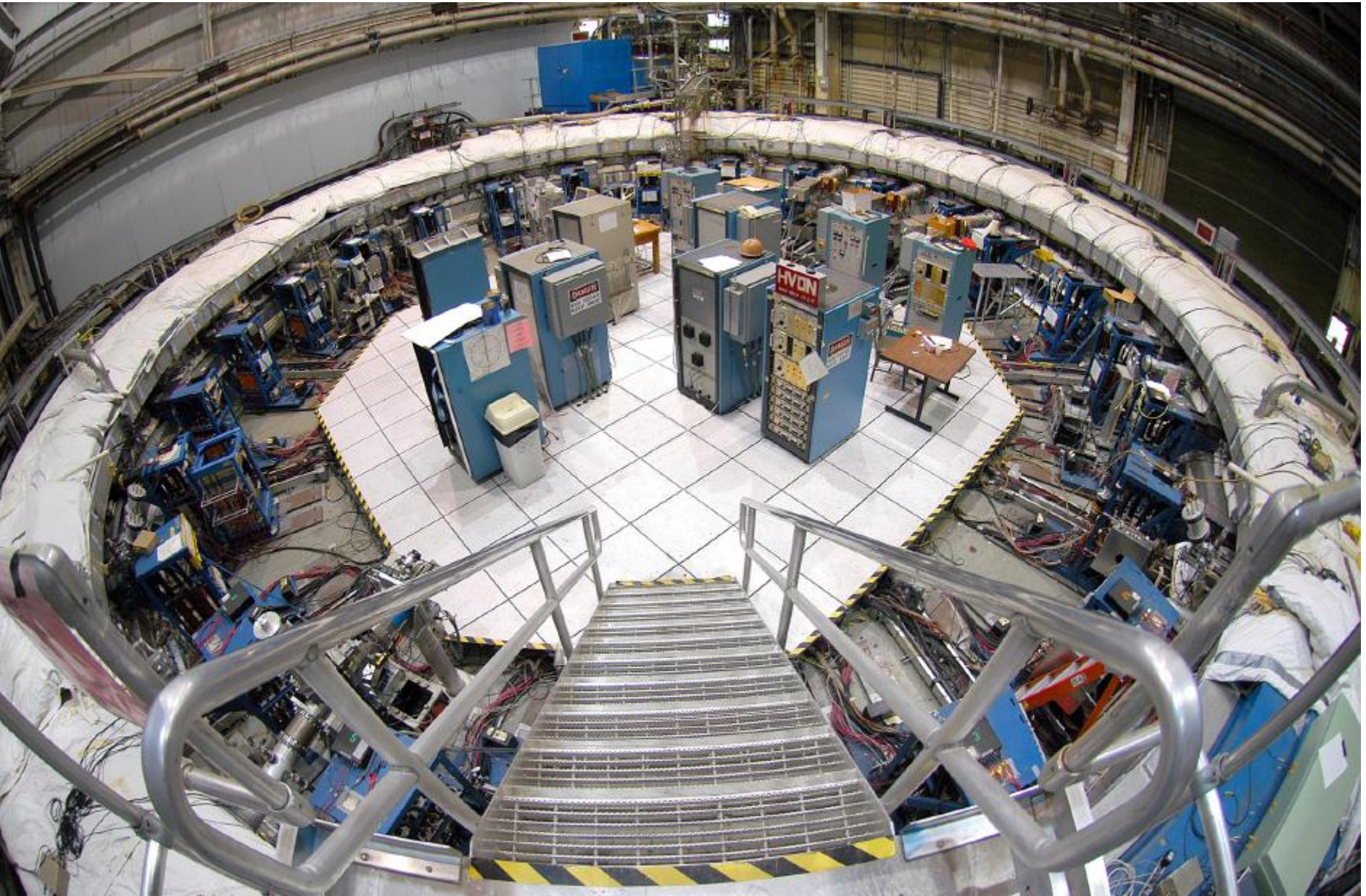
- During target yield studies, with 120 GeV protons on target, circulated 3 GeV negative particles in the Debuncher
- Can see separation of pbars from lighter particles in Debuncher
  - This plot after ~7 turns
  - This effect will be used to remove protons from the beam to g-2



g-2 storage ring and detectors

- Over the last year, work parties from Fermilab and university groups have taken part in disassembling the ring and detectors
- Many components to universities for upgrades
- Preparing to transport the ring to Fermilab

g-2 ring at BNL a year ago



During first trip for ring disassembly

Recent trip

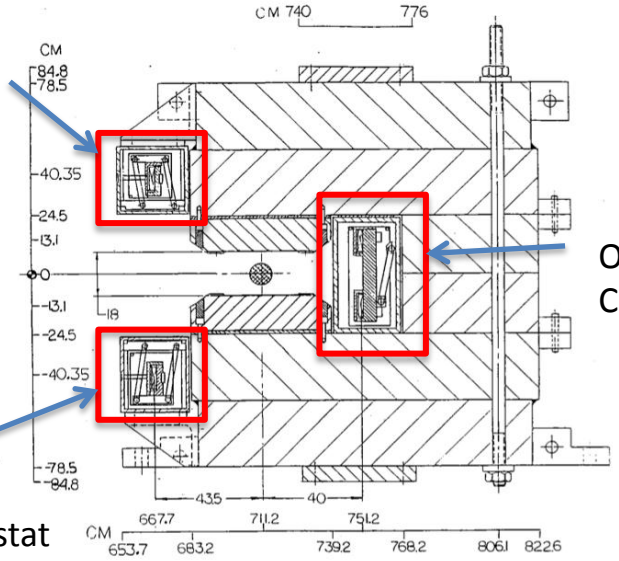
Not much left now besides the ring itself

Most equipment delivered by truck

Transporting the ring cryostats

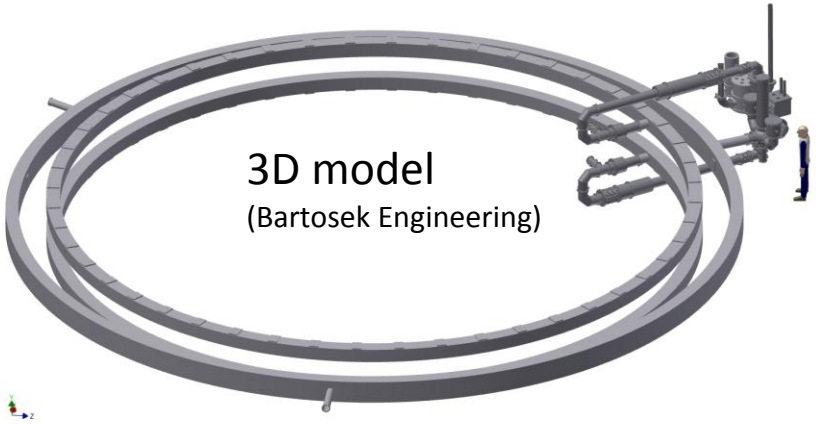
Ring cross section

Upper Inner Cryostat



Outer Cryostat

Lower Inner Cryostat



Moving the outer coil at BNL in 1992

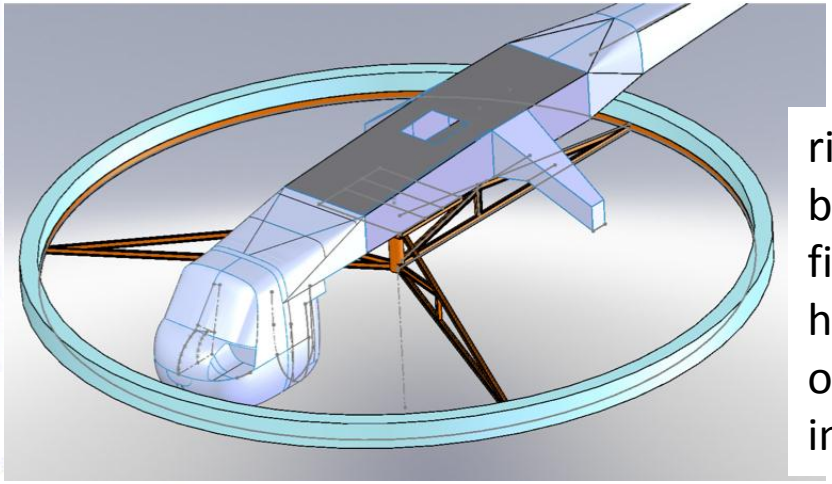
Most of the trip will be by barge

Technical feasibility studies in progress

30%-level cost estimate this month and a firm cost by August

Erickson Air Crane (helicopter)

Emmert International (truck and barge)



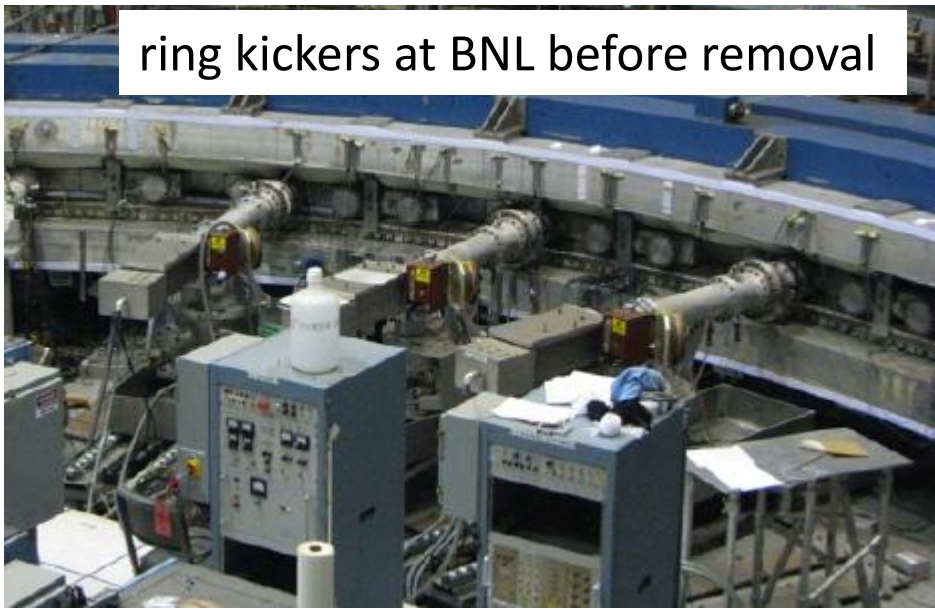
ring will have to be attached to fixture on helicopter in order to fly over inhabited areas

An Erickson Air-crane picks up a load from a semi-trailer truck on East Wacker Drive Sunday morning. The part was for a new HVAC unit on the west tower of Hyatt Regency Chicago. Photo by Mark Ulaszek.

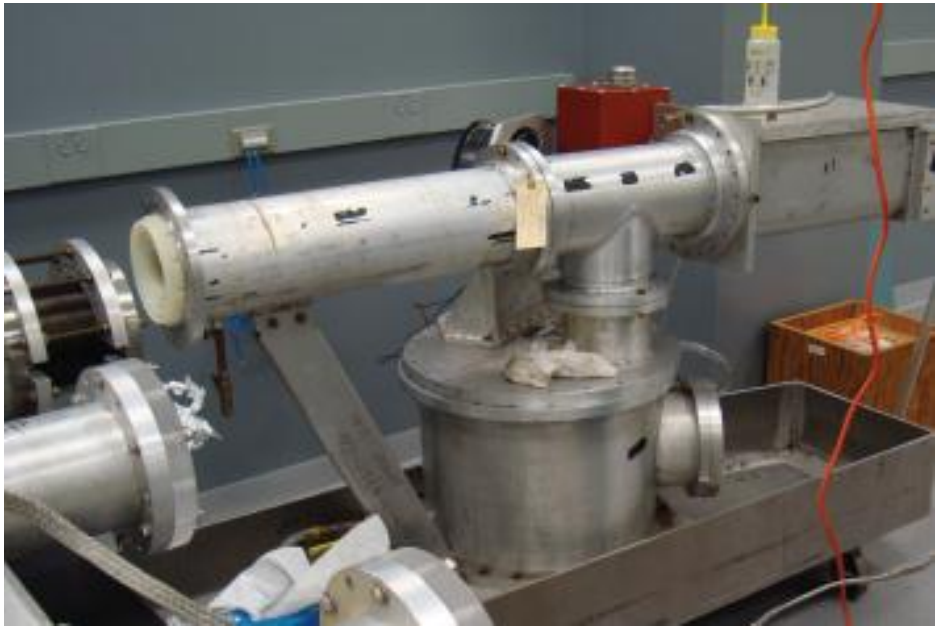
Ring kickers to Cornell

spare kicker at BNL a year ago

ring kickers at BNL before removal

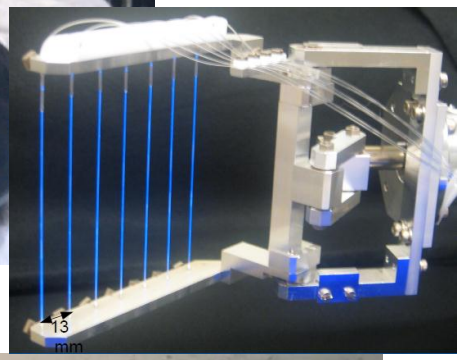


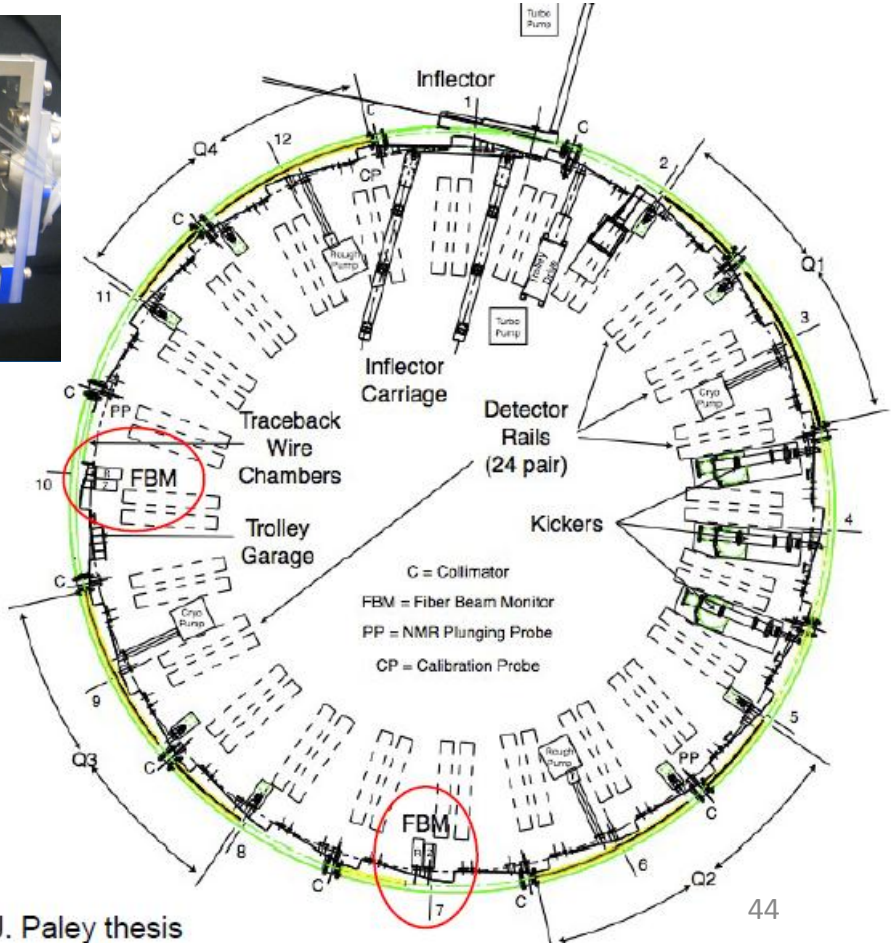
spare kicker at Cornell
as of Apr 2012



Fiber beam monitors to Regis U

- Plunge into beam for tuning, monitoring
- Use as is, reconfigure, redesign?
- SiPM vs PMT
- Motion control

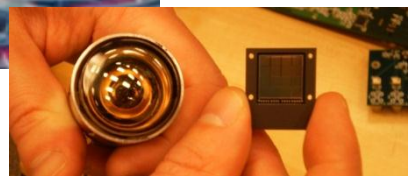




J. Paley thesis

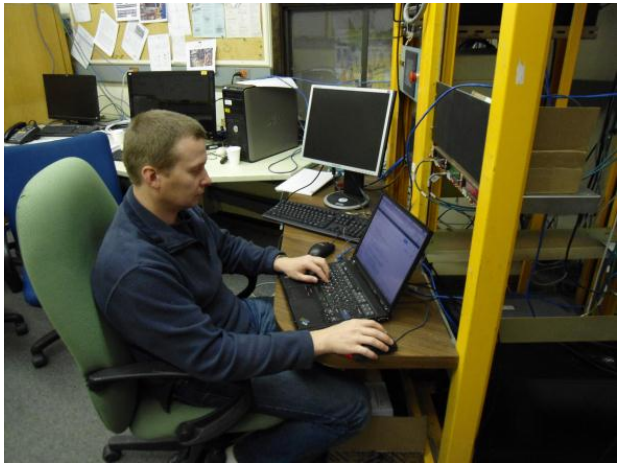
Calorimeters at U Washington

- Working on new design to better resolve pileup
- Evaluating
  - PbF_2 Cherenkov vs W/SciFi
  - SiPM vs very-fast PMT (R9800)

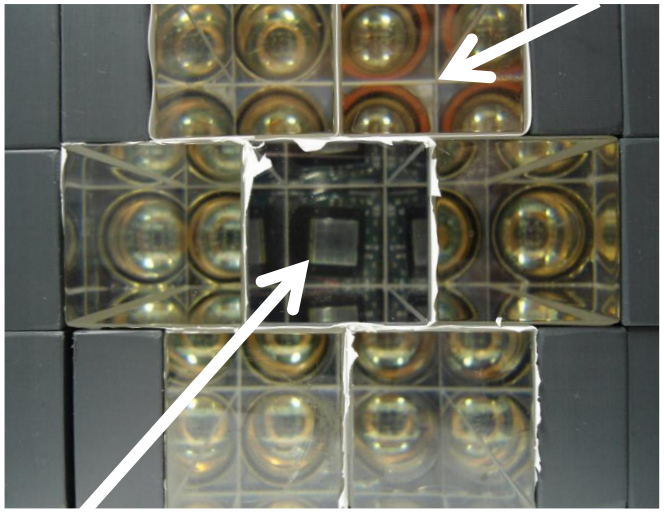


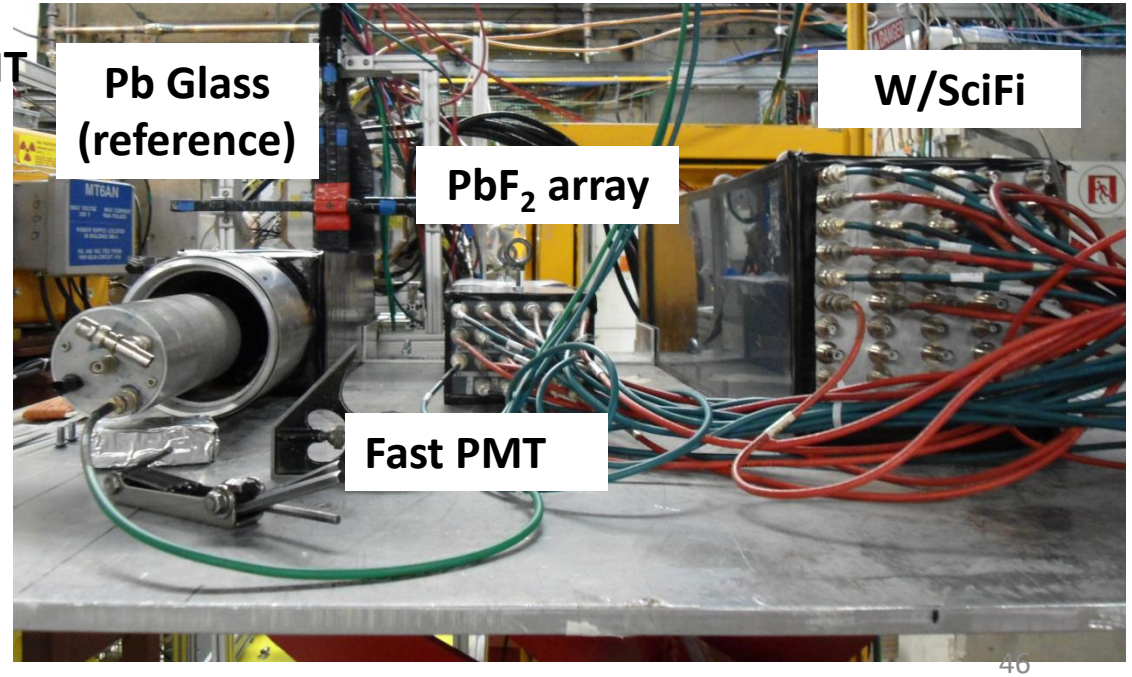
Test beam studies at Fermilab

Crystal preparation



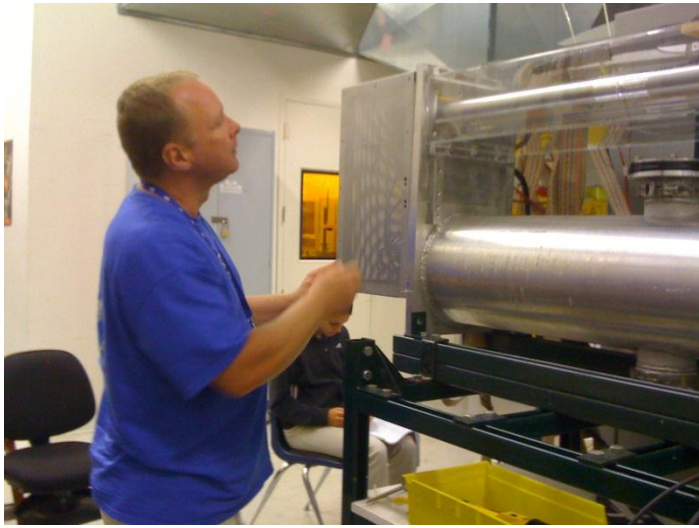
MIDAS DAQ

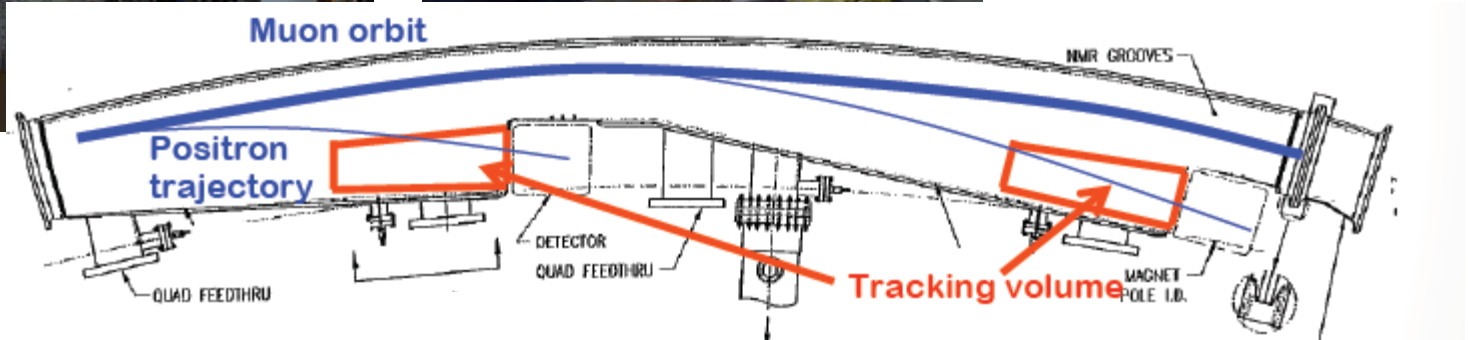




Tracker at Fermilab

- New tracker will be inside the vacuum
- Designing, building, and testing straw-tube tracker at Fermilab





Project X Physics Study

- More details on detectors in talks at Project X Physics Study June 14-23

Conclusions

- Much activity over the last year
  - Conceptual reconfiguration of accelerator to provide beam for g-2
  - Beam studies of proton delivery and target yield
  - Ring disassembly and preparation for transport from BNL to FNAL
  - Redesign of many detector components
  - Test-beam measurements of potential detector components
  - MC1 building design
- Working on Conceptual Design Report this summer
- Making good progress towards goal of taking data in 2016