Beam delivery commissioning

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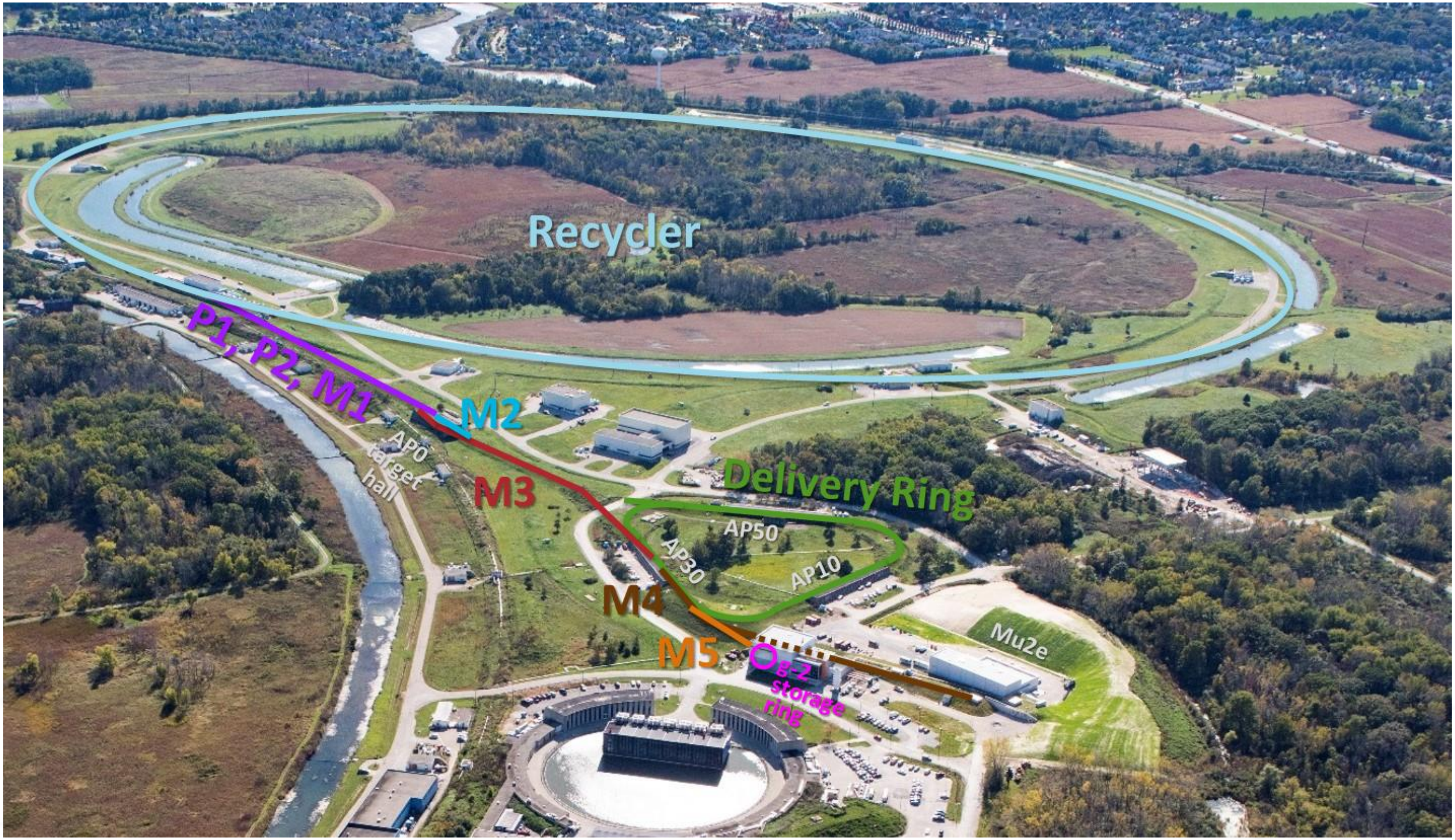
Outline

- Targeting and pion collection
- Delivery Ring commissioning
- Emittance and Twiss parameters measurements
- Beam line optics measurements
- Detection of positrons and deuterons
- Final focus tuning

The beam source: Muon Campus



Beam delivery for g-2 and Mu2e

g-2 EXPERIMENT

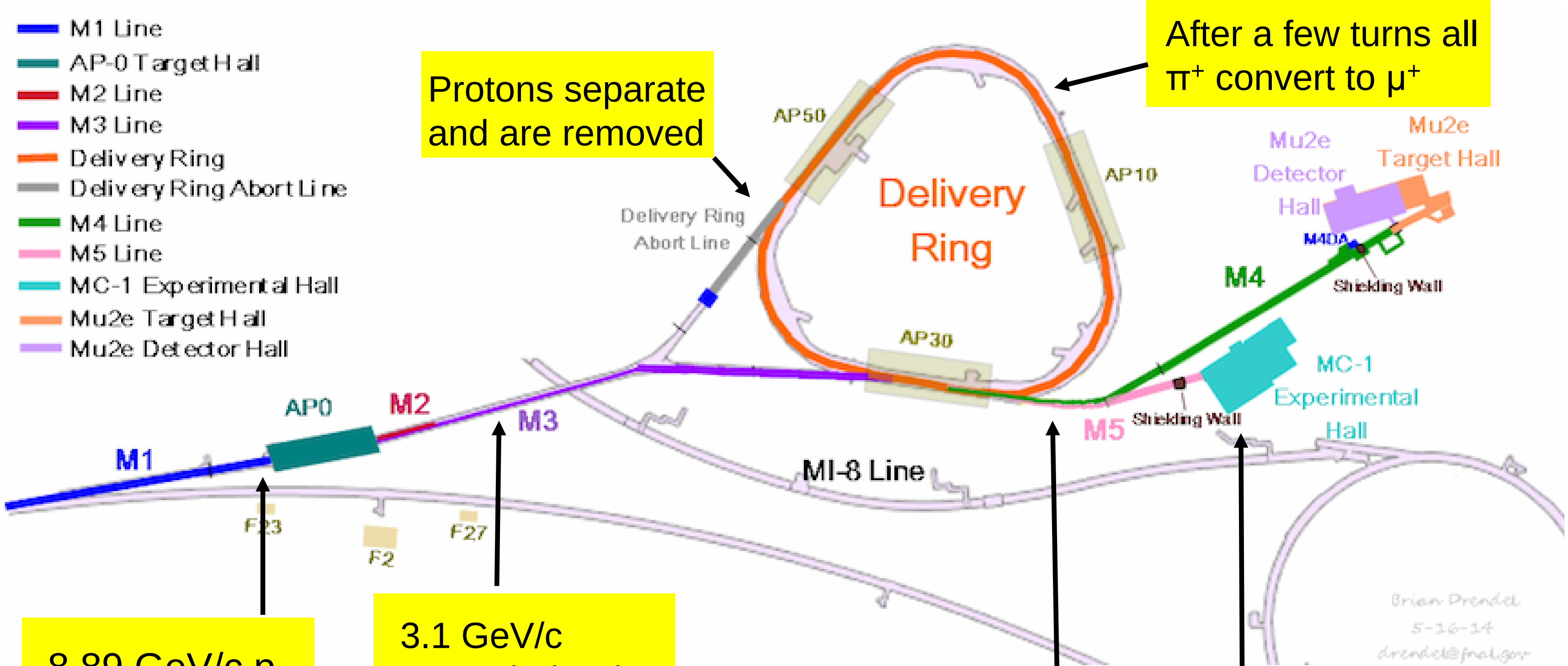
- Recycler bunches are extracted every 10 ms and directed toward the target
- Create 3.1 GeV/c pions and make beamline long enough for all pions to decay
- Capture 3.094 GeV/c muons from forward decayed pions (aim a polarization of >97%).
- Ring accepts only muons with $\Delta p/p = \pm 0.15\%$ of magic

Mu2e EXPERIMENT

- Recycle bunches are extracted every 48 ms and bypass the target
- The beam is resonantly extracted from the Delivery Ring and sent to the Mu2e target
- Eliminate out-of-time proton beam

← FOCUS OF THIS TALK

Muon Campus for g-2 operations



Protons separate and are removed

After a few turns all π^+ convert to μ^+

8.89 GeV/c p beam impacts the target

3.1 GeV/c secondaries (π^+, μ^+, p, e^+) travel along M2 & M3

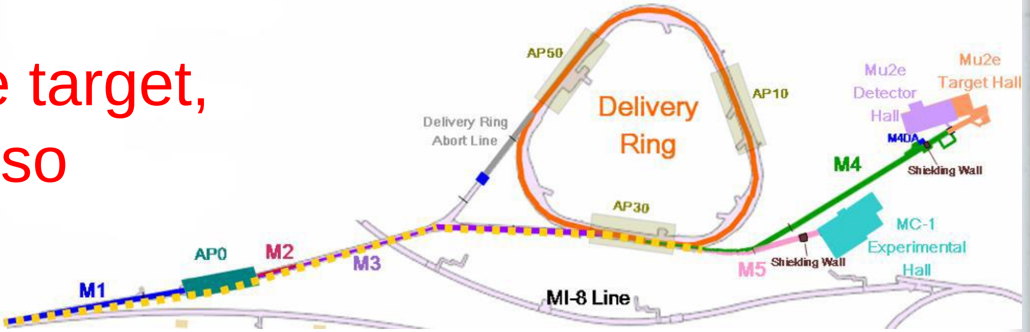
μ^+ are extracted from the ring and transferred into the storage ring via M4, M5

μ^+ enter the g-2 storage ring

Commissioning timeline

May 2017

- 8 GeV protons bypass the target, through shared M4 and also around the DR



June 2017

- 8 GeV protons to target, 3.1 GeV/c secondaries straight to the g-2 ring

December 2017

- 8 GeV protons to target, 3.1 GeV/c secondaries around the DR, proton removal, muons to the g-2 ring

Commissioning effort

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 011001 (2019)

Commissioning and first results of the Fermilab Muon Campus

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(Received 1 October 2018; published 3 January 2019)

In the following years, the Fermilab Muon Campus will deliver highly polarized muon beams to the Muon $g-2$ experiment. The Muon Campus contains a target section wherein secondaries are produced, the delivery ring which separates the muons from the rest of the beam, and a sequence of beam lines that transports them to the Muon $g-2$ storage ring. Here, we report the first results of beam measurements at the Muon Campus with an emphasis on the key achievements that have contributed to the successful beam delivery to the Muon $g-2$ experiment. These achievements include the production of an intense secondary beam from the target, its transport over 2 km, the successful monitoring of muons from the available diagnostics, and the development of techniques for measuring the transverse optics. We also present detailed comparisons between the experimental data and simulation and discuss the similarities and differences observed.

DOI: 10.1103/PhysRevAccelBeams.22.011001

Simulation effort

- Significant effort over the last two years, to accurately estimate the pion, muon and proton rates along the Muon Campus

GOAL: Verify results with at least two codes

TARGET
GEANT4
MARS

SECONDARY BEAM TRANSPORT
G4BEAMLINE
BMAD
COSY

STORAGE RING
G4BEAMLINE
BMAD
COSY
gm2ringsim

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 111003 (2017)

Accelerator performance analysis of the Fermilab Muon Campus

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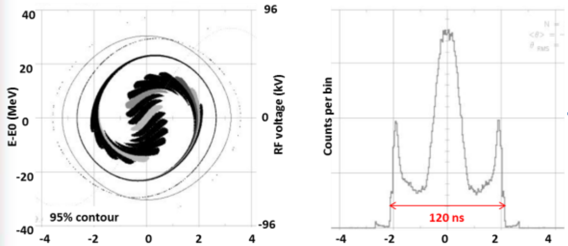
(Received 29 March 2017; published 21 November 2017)

Recycler ring & bunch formation

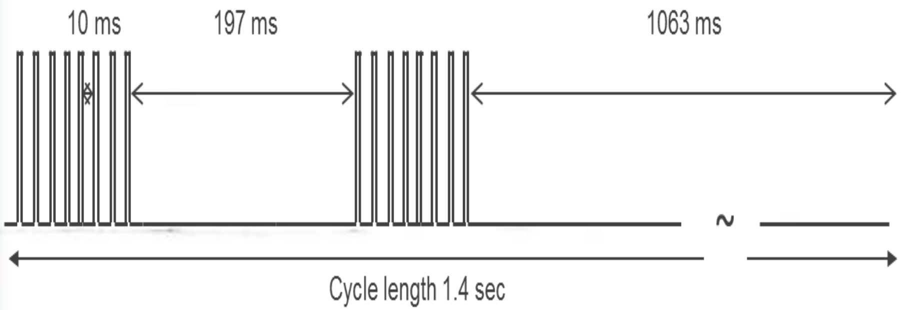
- Rebunch primary (8 GeV) protons in the RR so that rate in detectors is not too high, bunch length < 147ns ring revolution time



Simulation of rebunched beam

Recycler 2.5 MHz RF

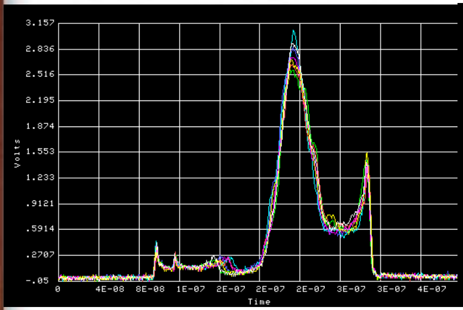
- 4 Booster batches every 1.4s rebunched into 4 bunches each



Parameter	Value
Protons on target (POT) per pulse	10^{12}
Pulse width	120 ns
Number of pulses	16
Cycle length	1.4 s
Frequency	12 Hz
Primary beam kinetic energy	8 GeV

Primary beam profile (06-2018)

9A



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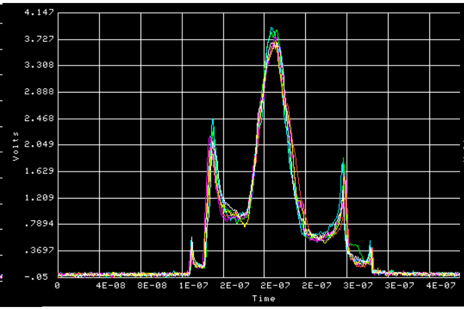

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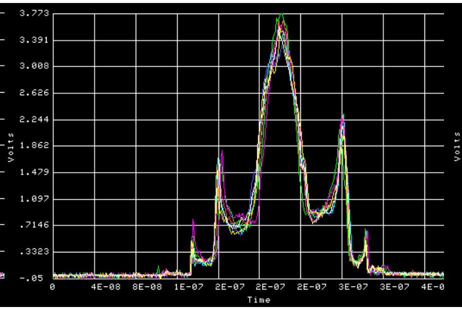

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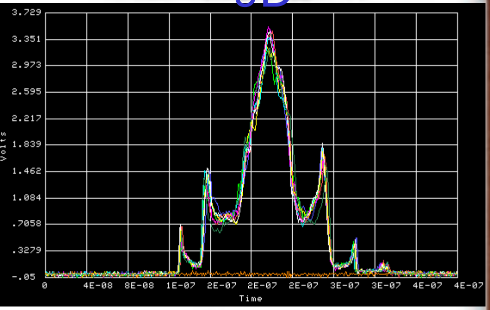

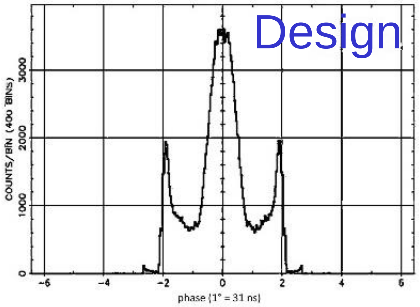

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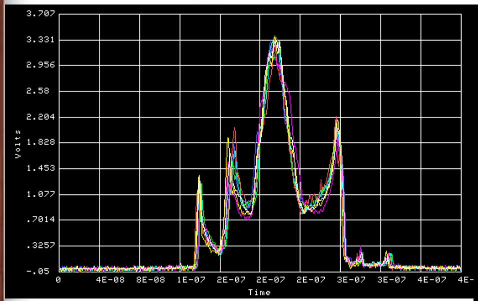

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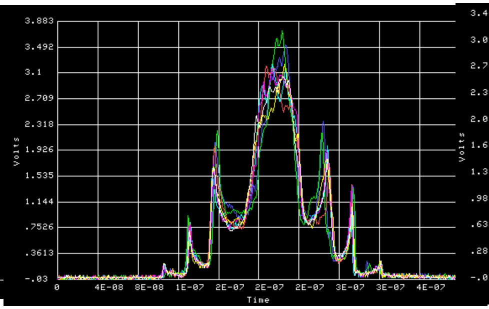

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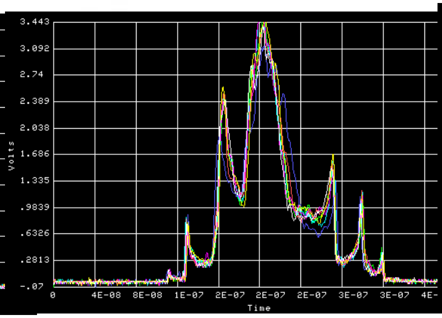

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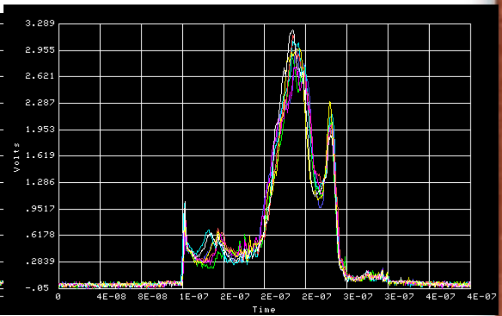
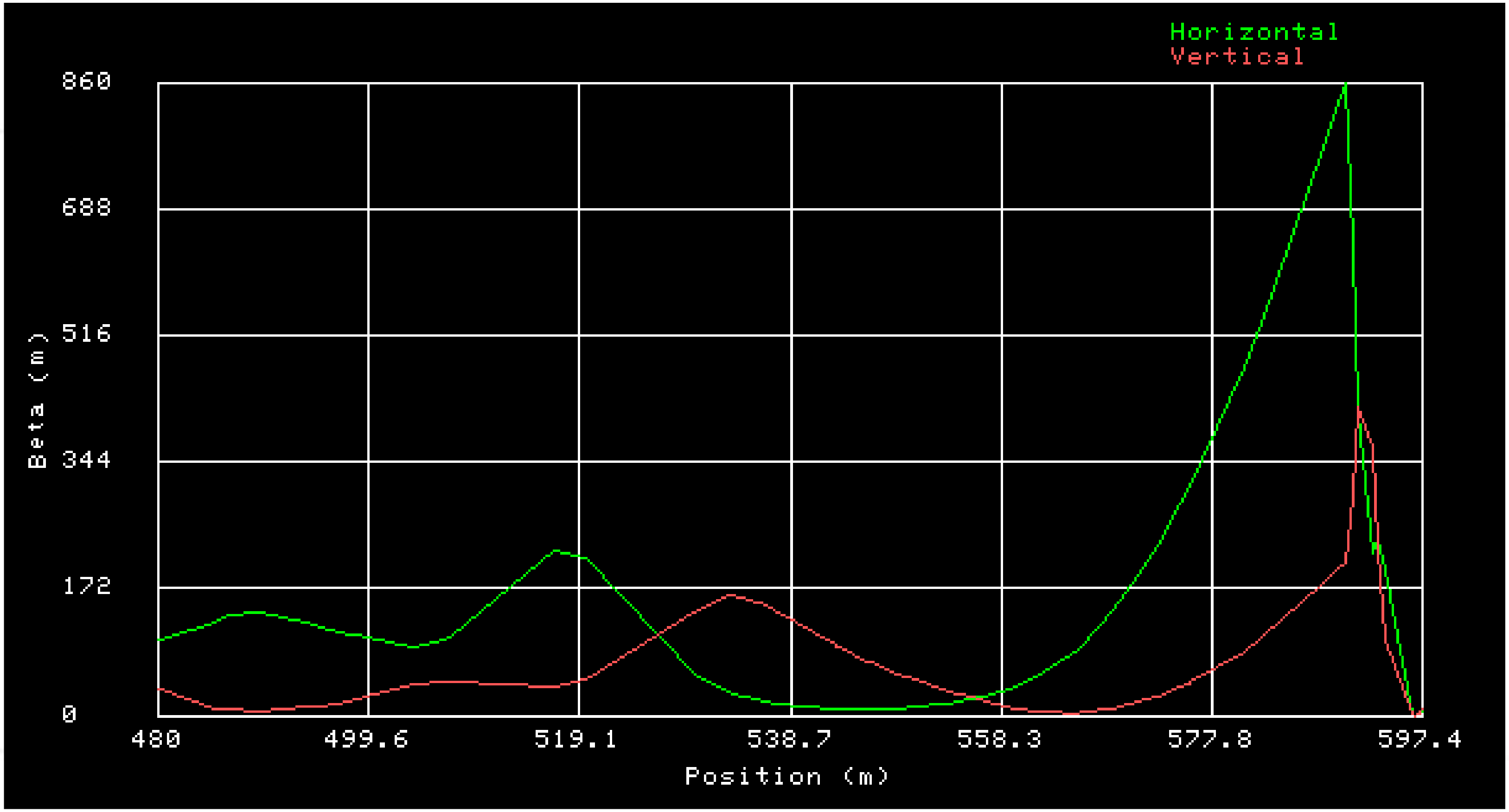
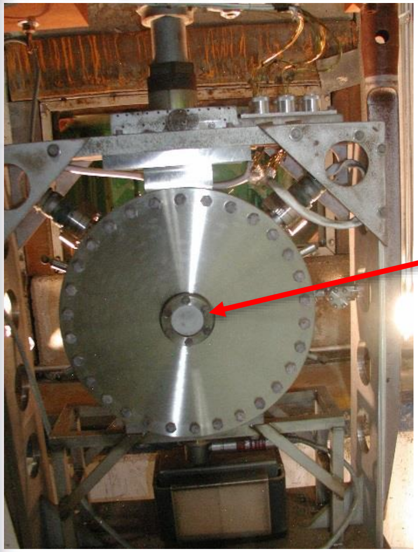


Beamline to target

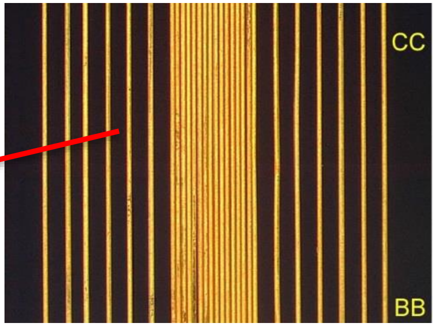


Beam at target

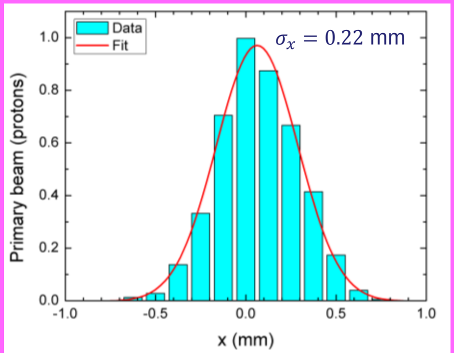
Target-SEM

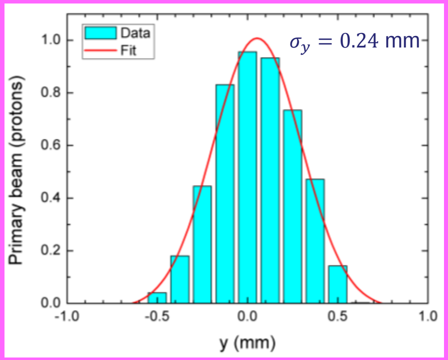


Target-SEM



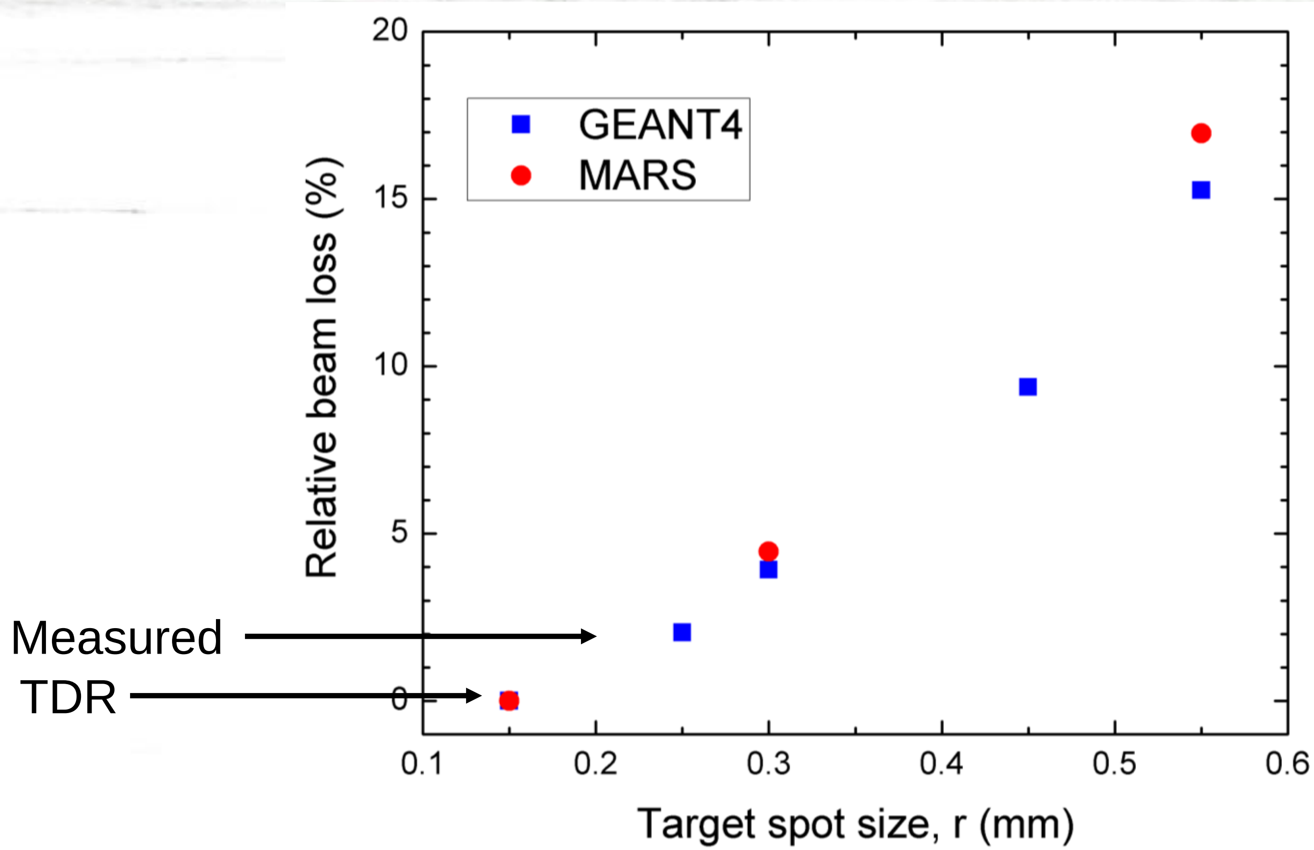
Measured spot size on target





- Beam size measured at target-SEM, about 30 cm upstream of the target
- Gaussian shaped distributions with almost equal beam sizes ($\sigma_x = 0.22$ mm and $\sigma_y = 0.24$ mm)

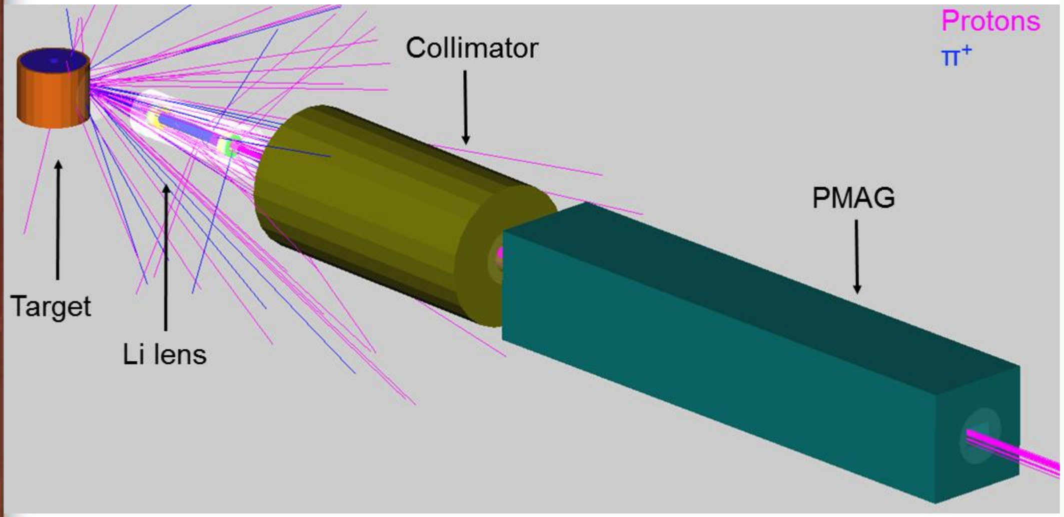
Target spot size sensitivity

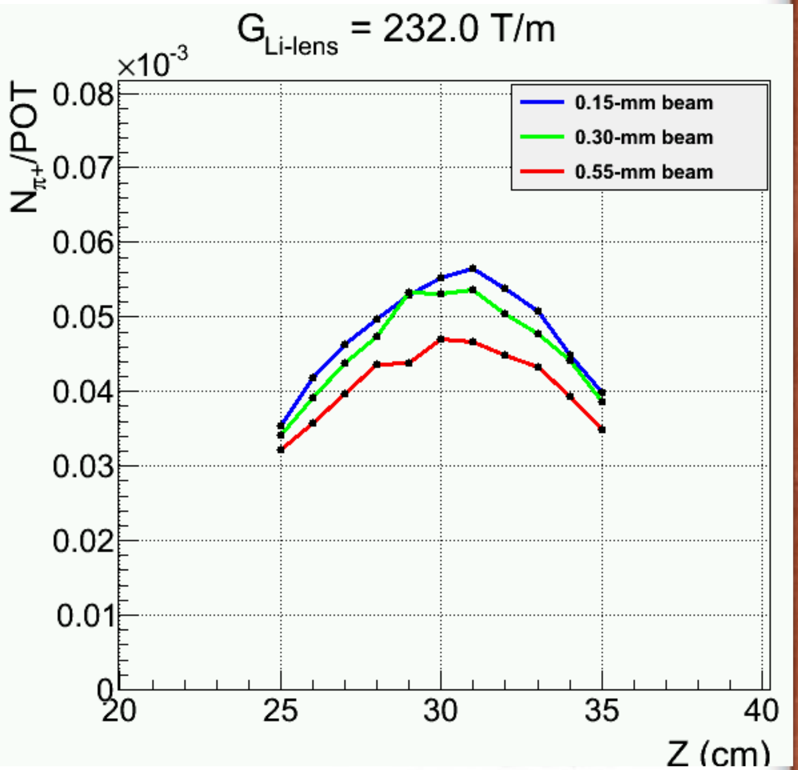


- While 0.15 mm is desired, the 0.20-0.25 mm achieved has a <5% impact in performance

Target station

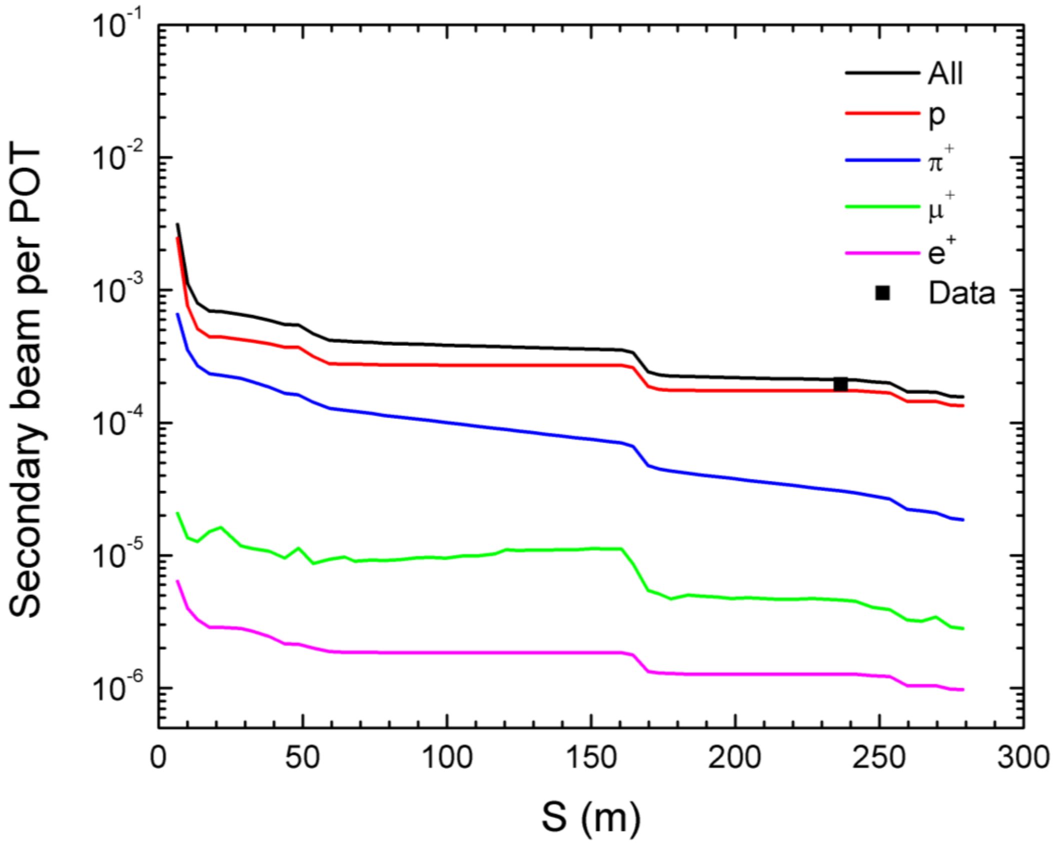
- Lithium lens has been optimized for peak performance:
  - lens strength optimization
  - distance optimization
  - target spot size optimization



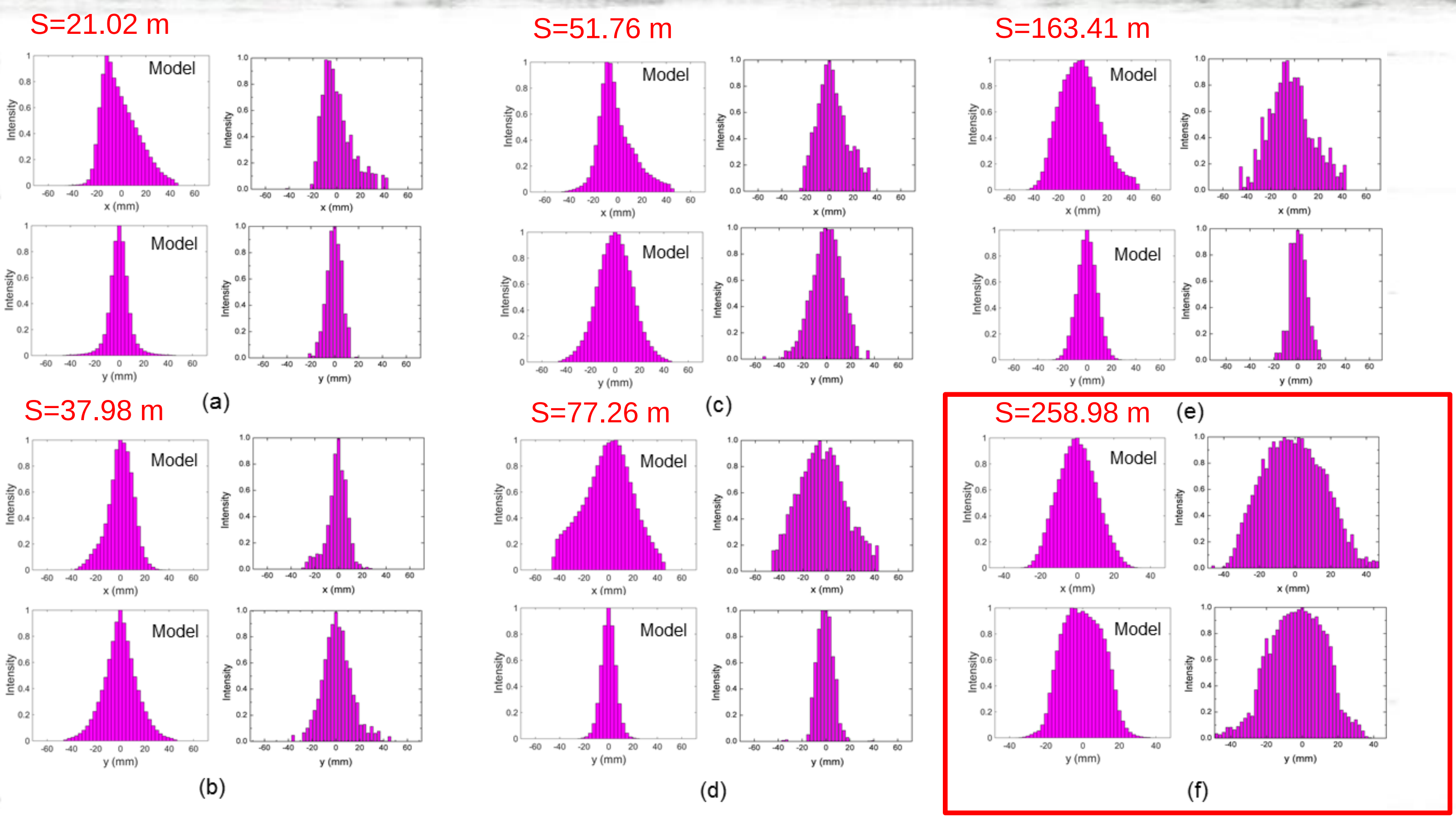


M2 & M3 beam lines

- Measured intensity matches prediction from simulation!



M2 & M3 lines: Data vs. Model

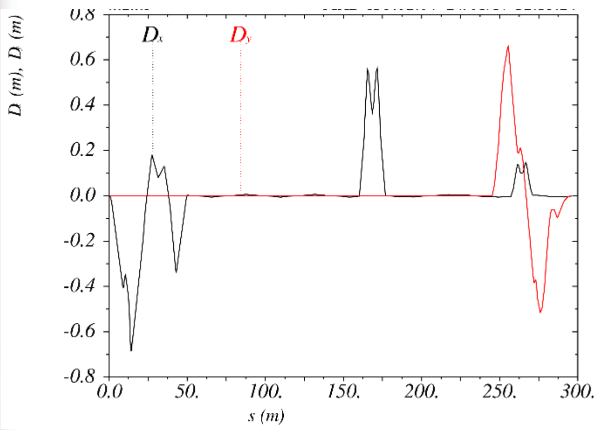


- Compared to the simulation, the beam at the end of the M3 line has a larger core and longer tails

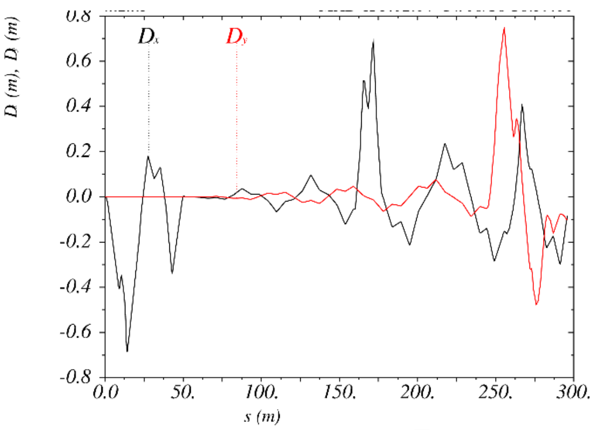
Possibility 1: Lattice instabilities

- A small positioning error can trigger a dispersion wave which becomes amplified further downstream
- Example below show what happens if quad magnet 709 (S=66.0) is misplaced in both horizontal and vertical directions

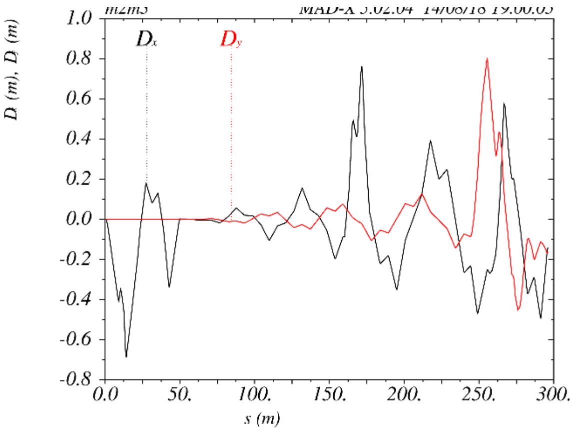
design lattice



1.5 mm

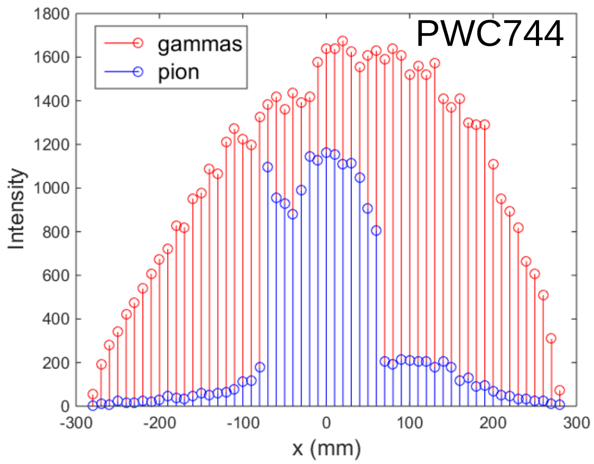


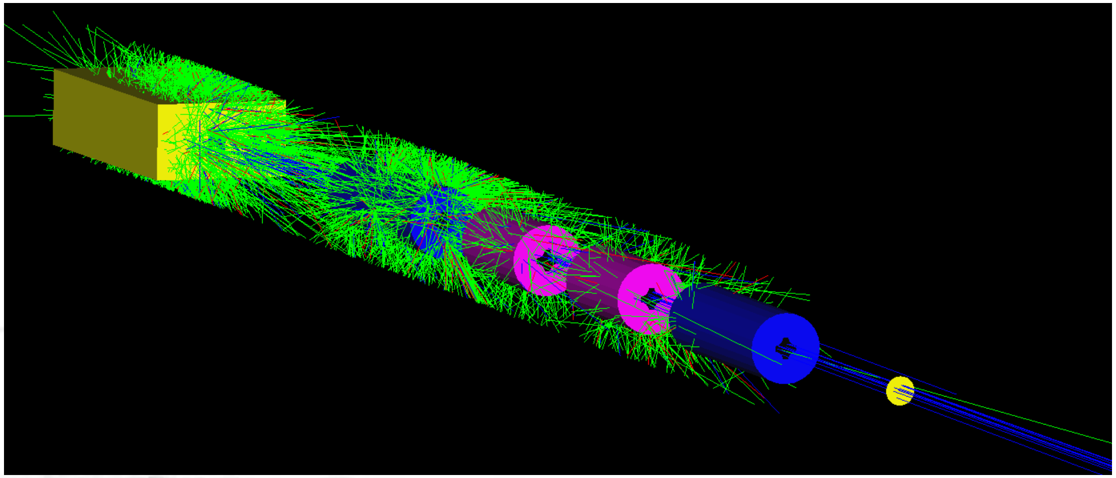
2.5 mm

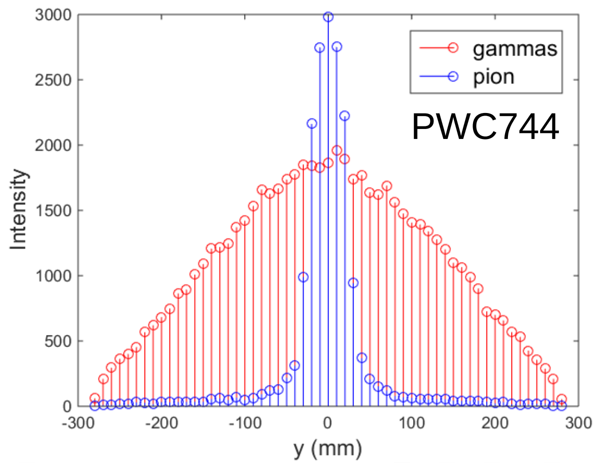


Possibility 2: Photons

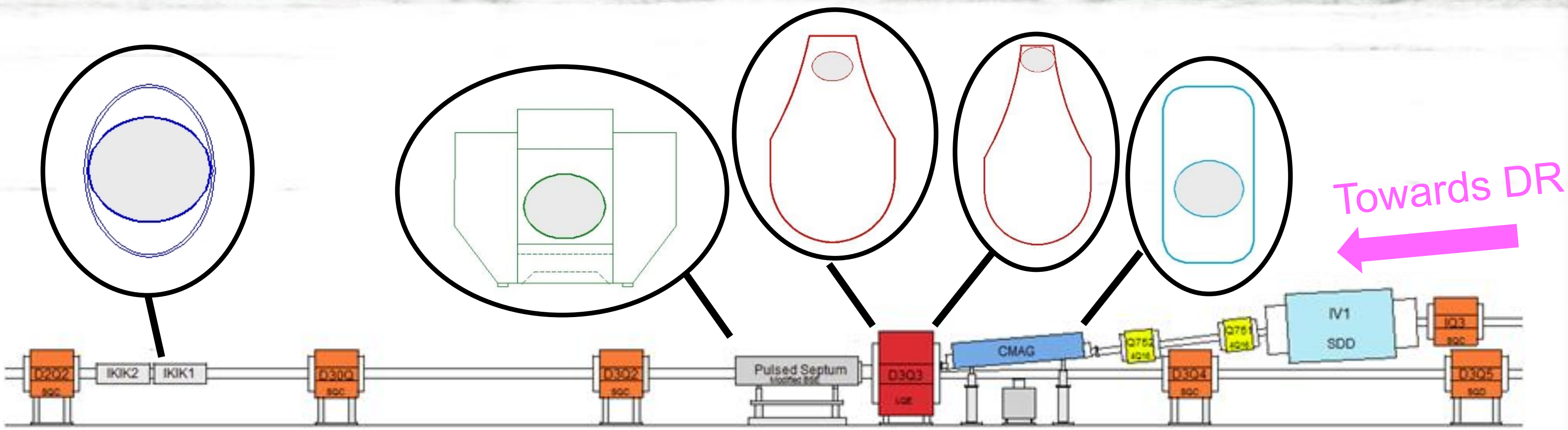
- Scattering through magnetic material can create photons
- While SEMs or ICs are not sensitive to them, PWC are!







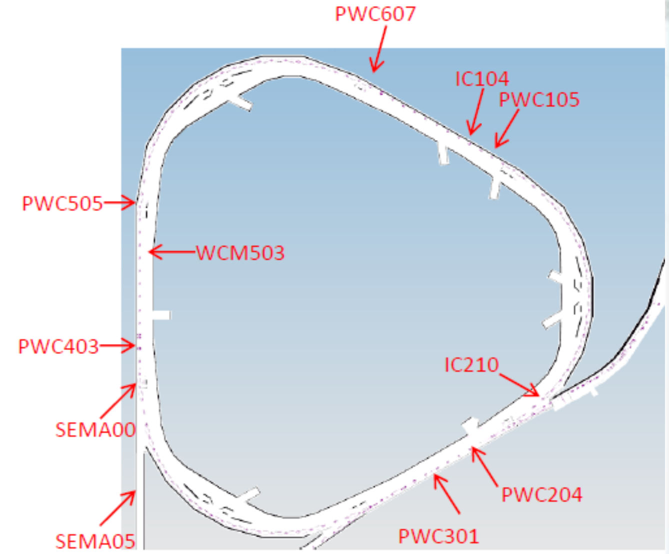
Injection to the DR

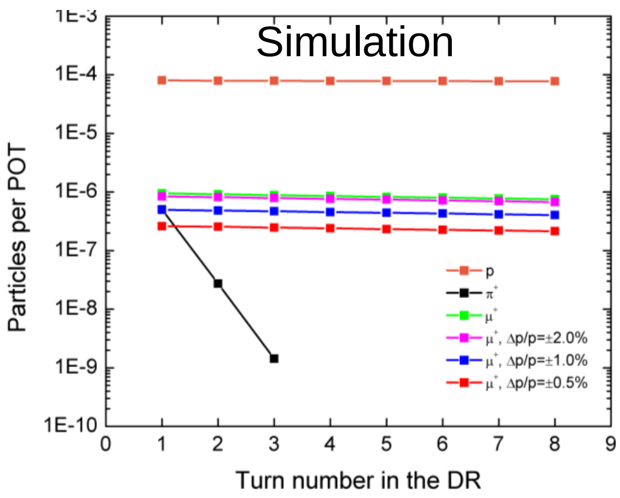


- Ideal beam barely fits through the small DR apertures and any upstream mismatches can lead to losses
- Roughly **1/3** of the beam is lost at injection
- Off-momentum particles will lost at much higher rates than magic momentum muons -> Good news for g-2

Delivery Ring (DR)

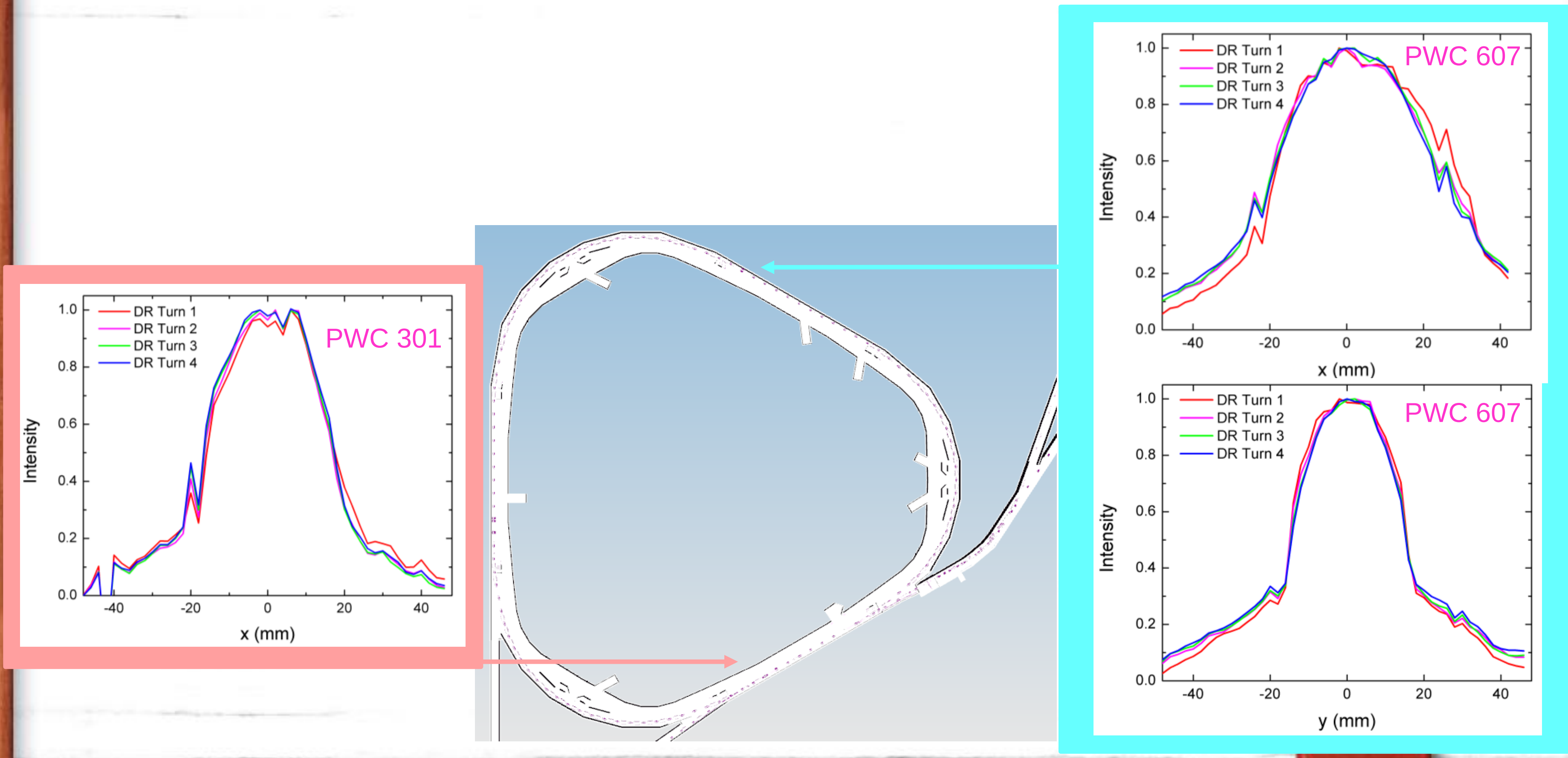
- Beam is monitored through proportional wire chambers (PWCs) and ion chambers (ICs)
- 120 BPMs can be used for higher intensity primary beam commissioning only
- Proton Removal became operational in December 2017





DR performance (Turns 0-4)

- Beam is proton dominated (all data before proton extraction)
- The beam profile is reproducible from turn to turn



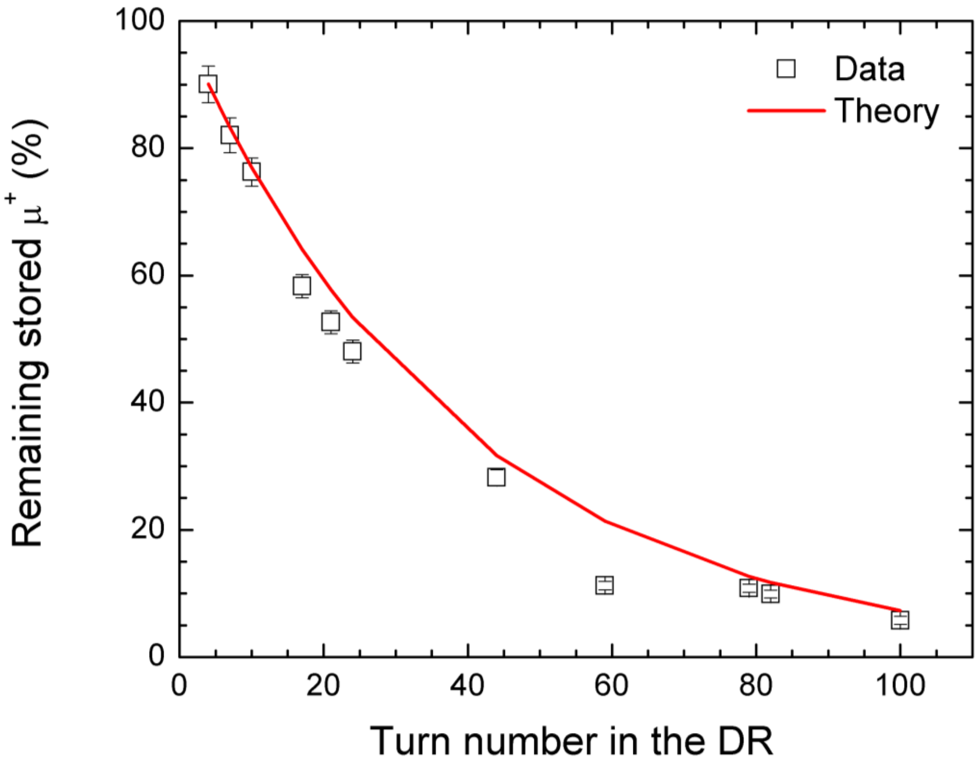
DR performance (Turns 4-100)

- Protons are extracted, beam is muon dominated and we increased the number of turns to 100. Not a typical operating point but we used it to benchmark the DR
- The goal was to measure the beam rates for several turns at two different locations

g-2 calorimeters: Is INSIDE the storage ring (measurement contains decayed e+ from stored mu+ only)
GOAL: Measure the muon rate vs. DR turn number

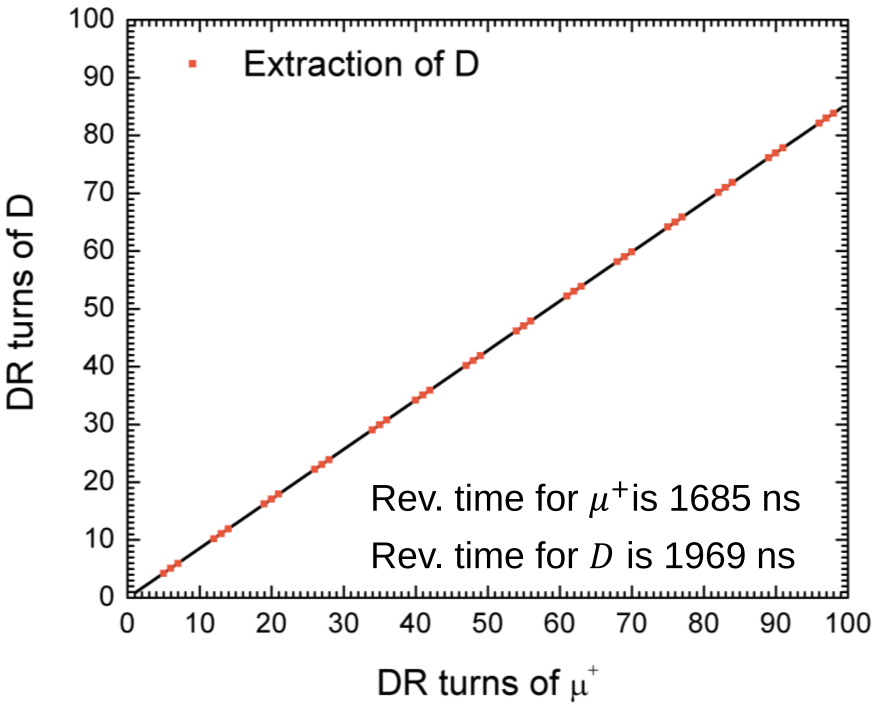
IC025: Is UPSTREAM the storage ring entrance (beam contains mu+, e+, Deuterons)
GOAL: Estimate contamination of e+ from the target

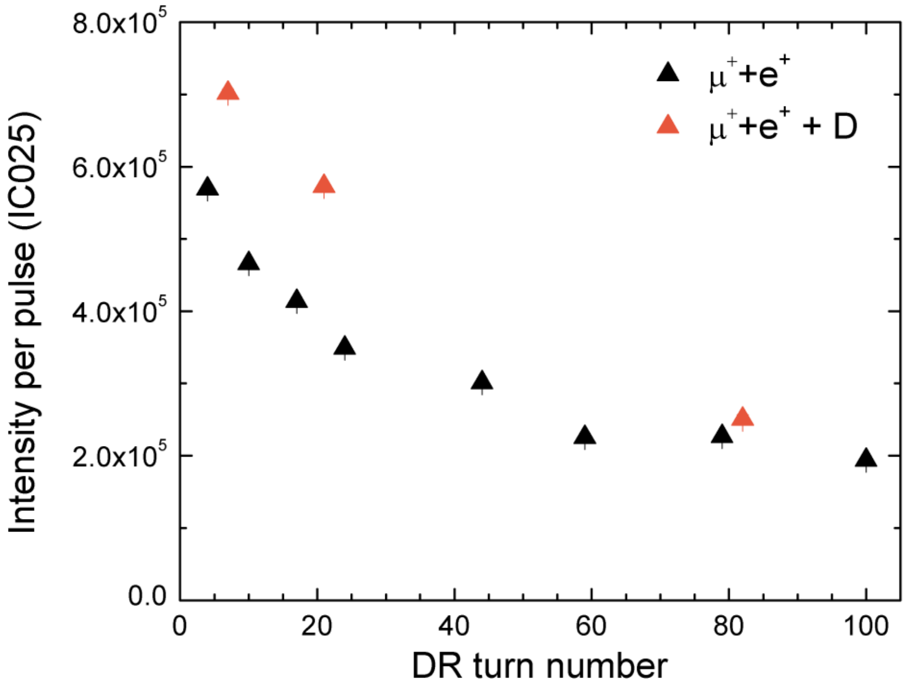
Measurement using g-2 calorimeters



- Measurement is not far from the exponential decay law
- Minimal losses from collimation

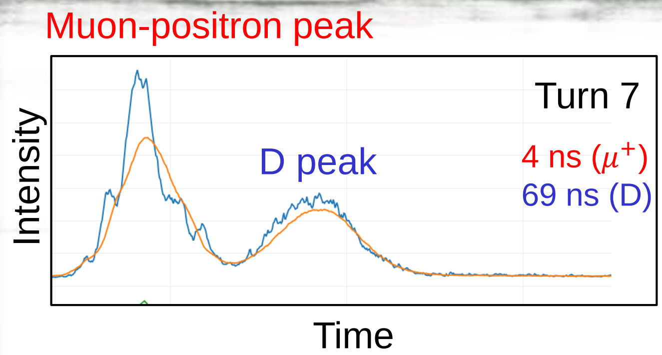
Measurement using IC025

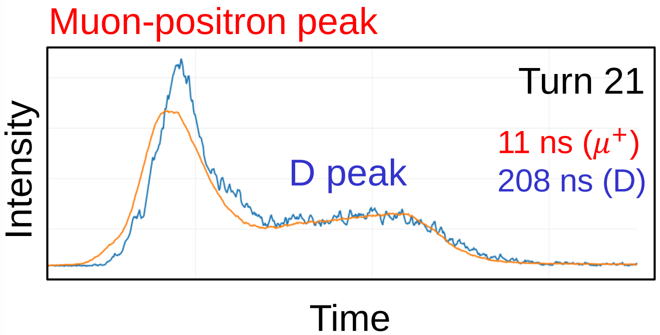


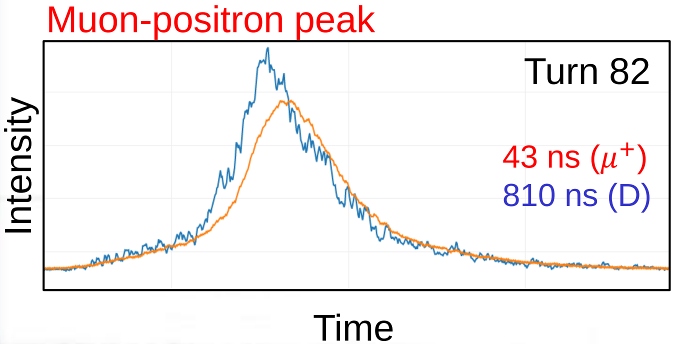


- For some discrete number of turns we noticed that the beam delivered to the storage ring was contaminated with Deuterons

Deuteron path length

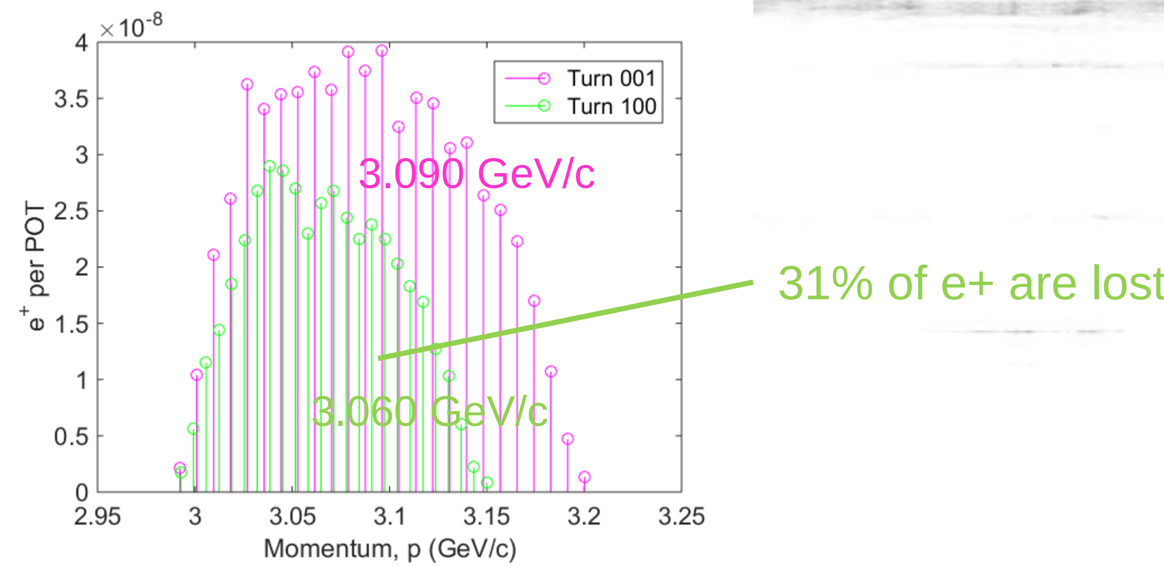






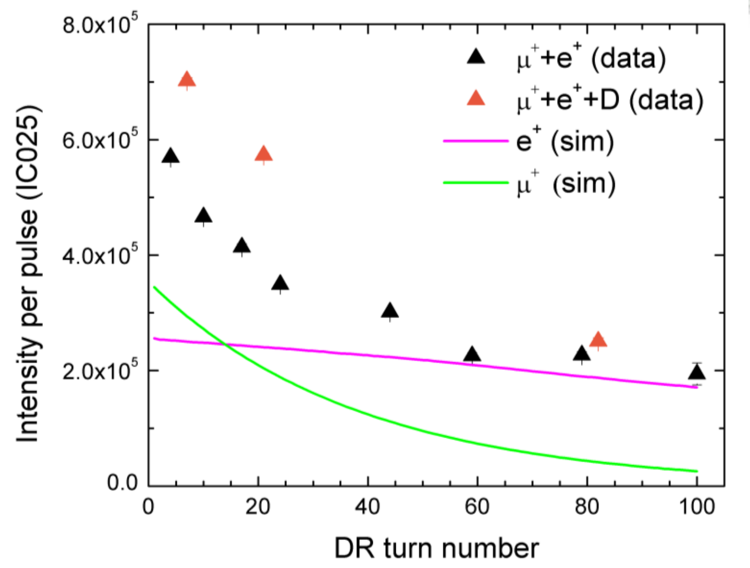
- Recall that: $\Delta\tau = \frac{L}{c\beta}\left(\alpha_c - \frac{1}{\gamma^2}\right)\frac{\Delta p}{p}$
- Relativistic factor γ is 29.3 for μ^+ and just 1.9 for D.
- For the DR, α_c is 0.017 and assuming $\Delta p/p = 2\%$ we can estimate $\Delta\tau$
- Deuterons are not detectable after 80 turns, simply because they cover half of the DR

Synchrotron radiation



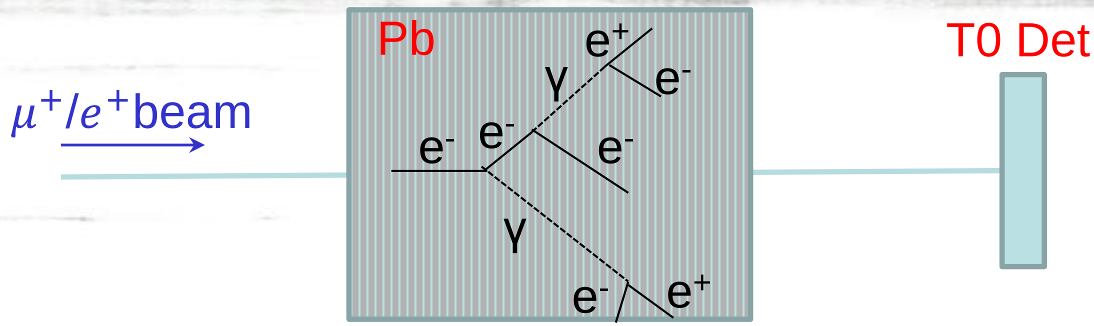
- Positrons will emit electromagnetic radiation as they move a circular orbit. Power radiated: $P = \frac{1}{6\pi\varepsilon_0}\frac{e^2 c}{\rho^2}\left(\frac{E}{mc^2}\right)^4$
- The DR has 66 dipoles at 1.67 m and therefore $\rho = 17.5$ m
  - Energy (per turn) lost for muons: 10^{-10} MeV !
  - Energy (per turn) lost for positrons: 0.31 MeV

Estimate positron contamination

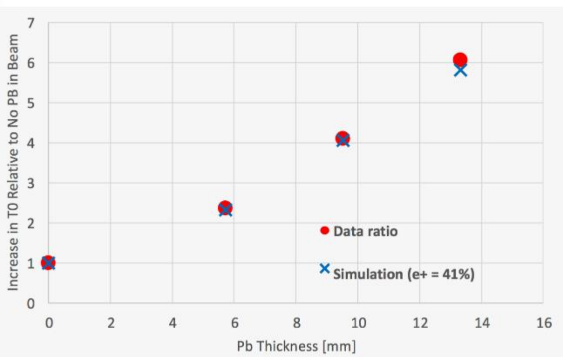


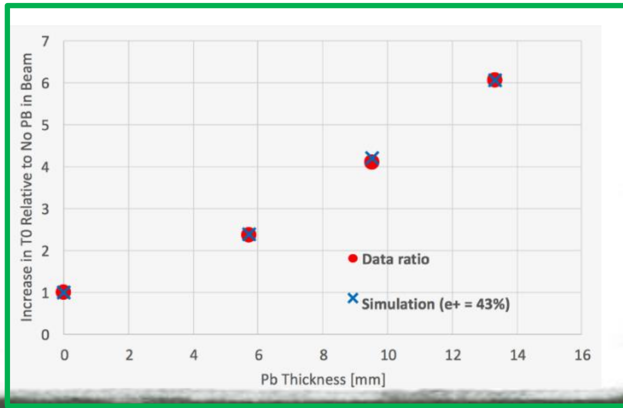
- After turn 4: $N_e + N_\mu = 5.693 \times 10^5$
- Simulation predicts that ~31% of the e^+ beam will get lost after 100 turns due synchrotron radiation.
- After turn 100: $\frac{69}{100} N_e + \frac{7}{100} N_\mu = 1.943 \times 10^5$
- We estimate that: $\mu^+ = 57\%$ and $e^+ = 43\%$

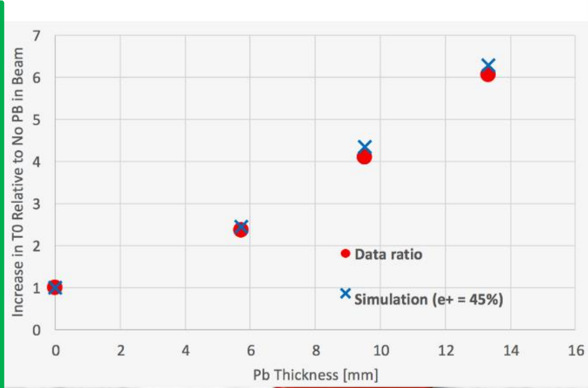
Independent positron test



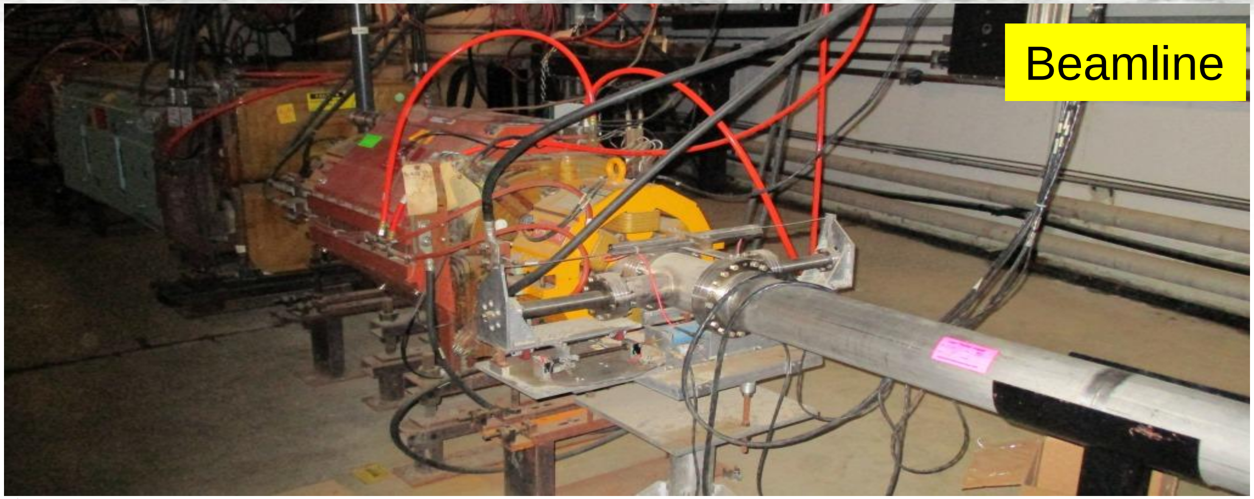
- A variable thickness Pb block was added along the beam path
- Positrons create electromagnetic showers that can be captured at the T0 detector upstream the storage ring
- Compared results with simulations

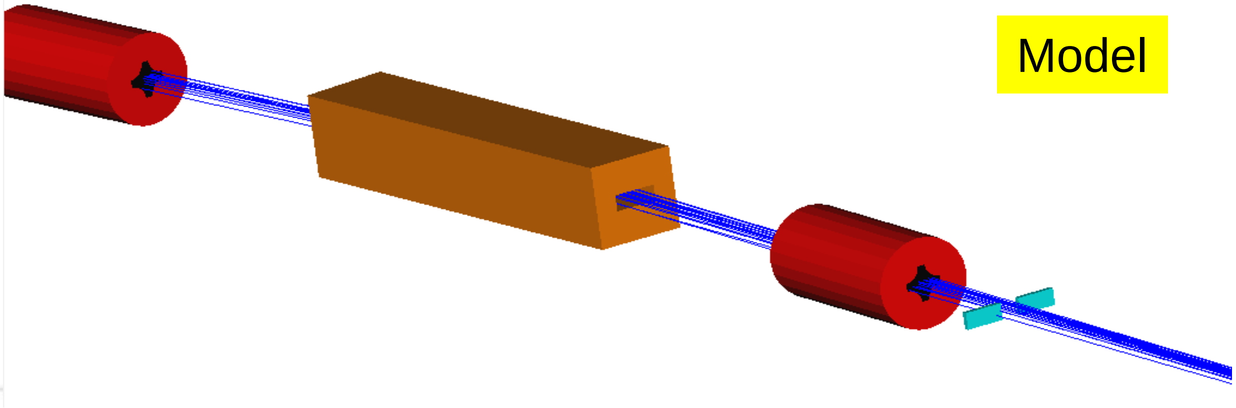






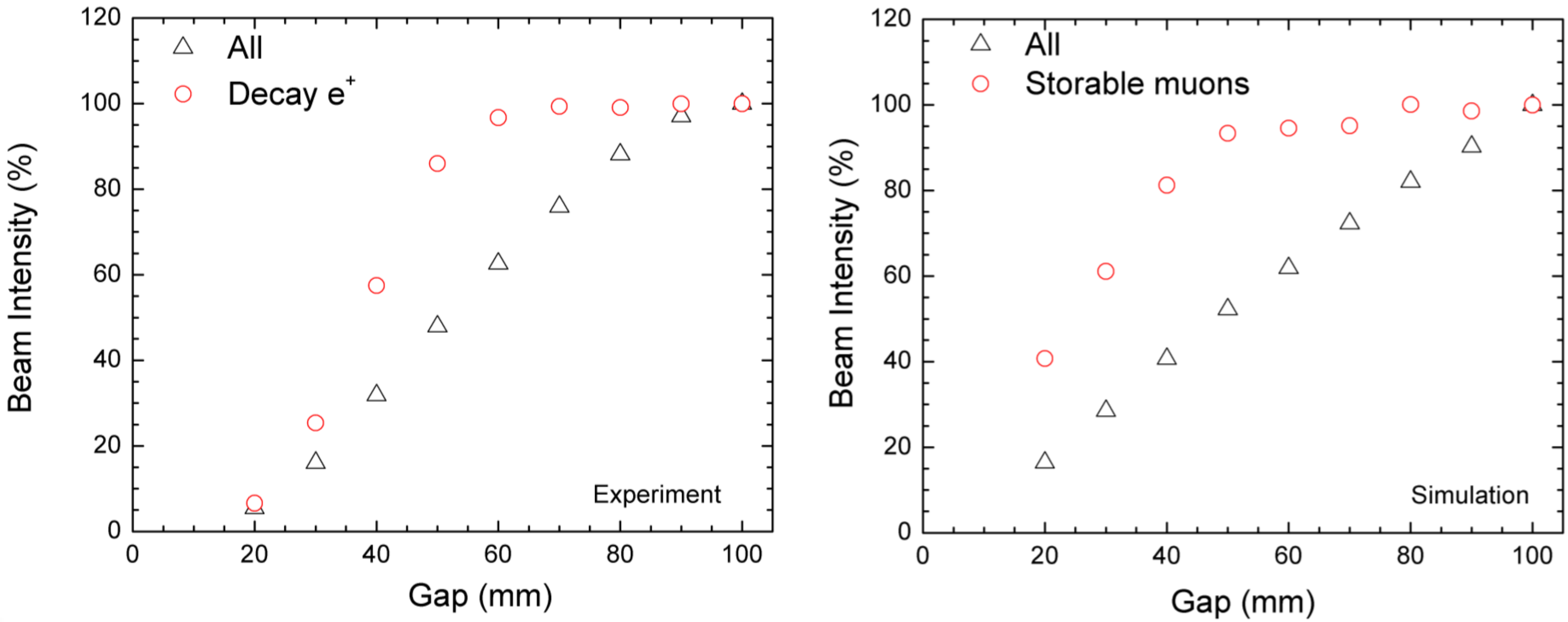
Momentum collimator commissioning





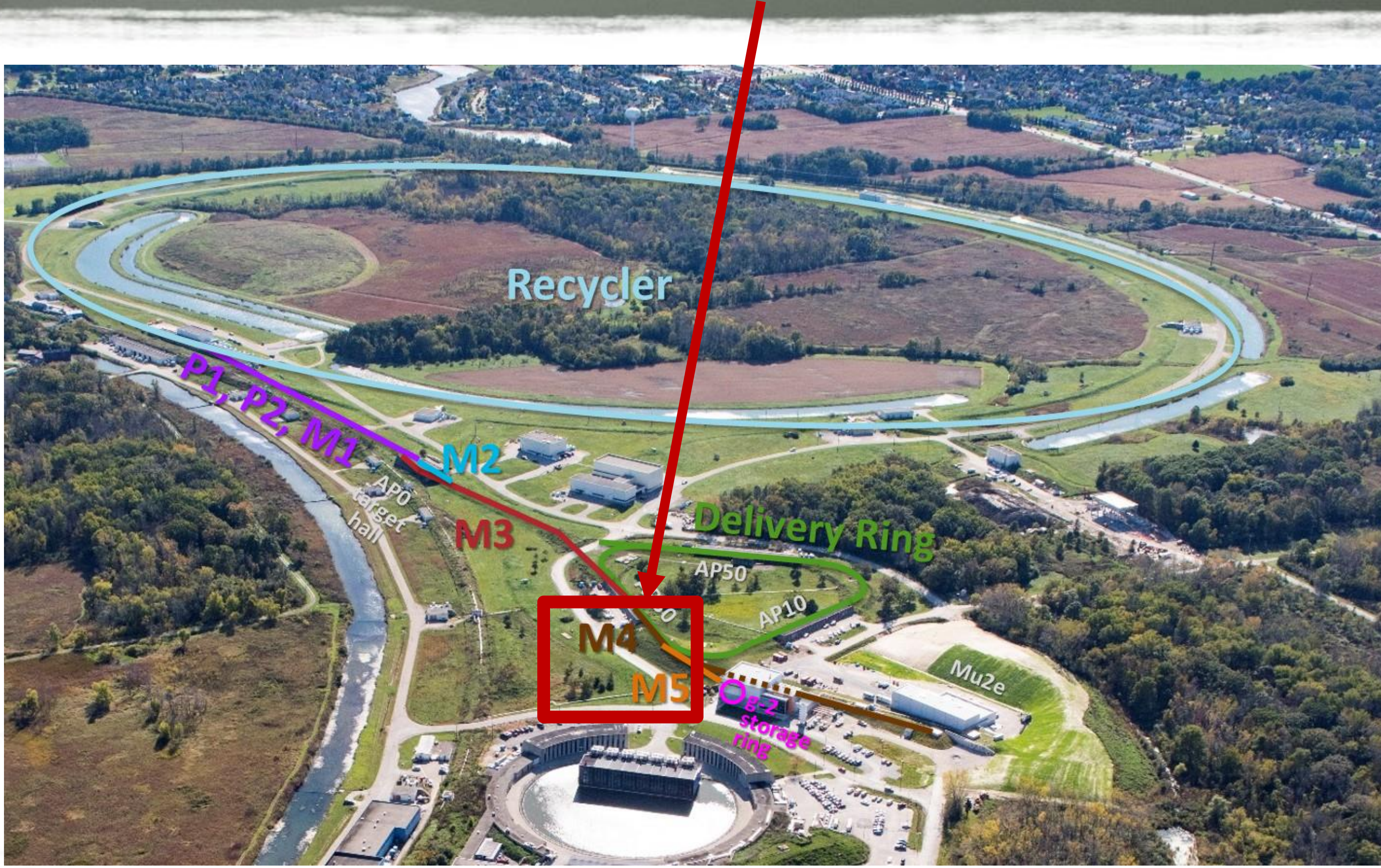
- Placed upstream of Q411 in a dispersive area ~ 1 m

Momentum collimator commissioning



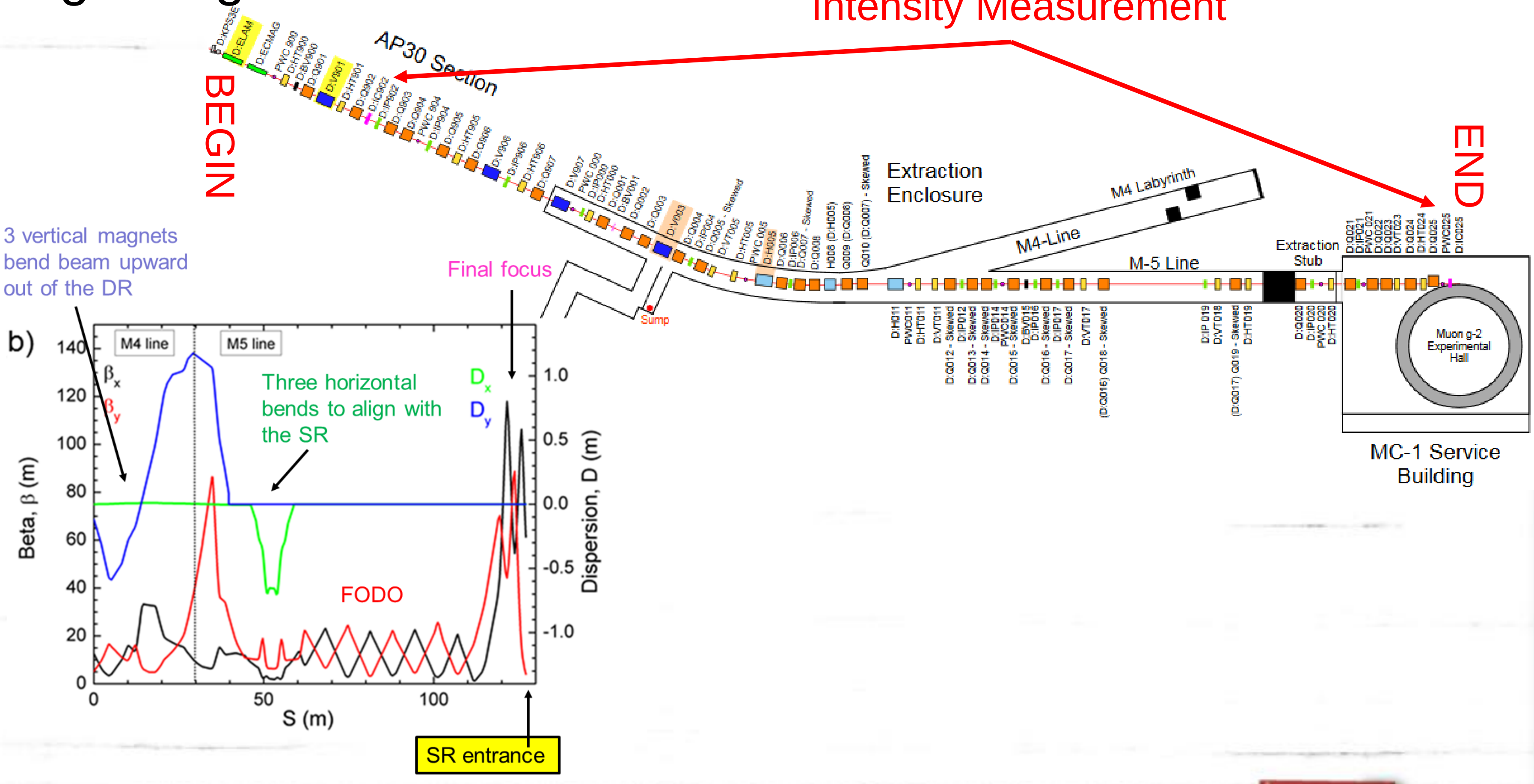
- Collimator has the potential to reduce the beam intensity by more than 40% without affecting stored muons
- This trend is confirmed by the simulation model

Beam to g-2 storage ring (M4-M5)



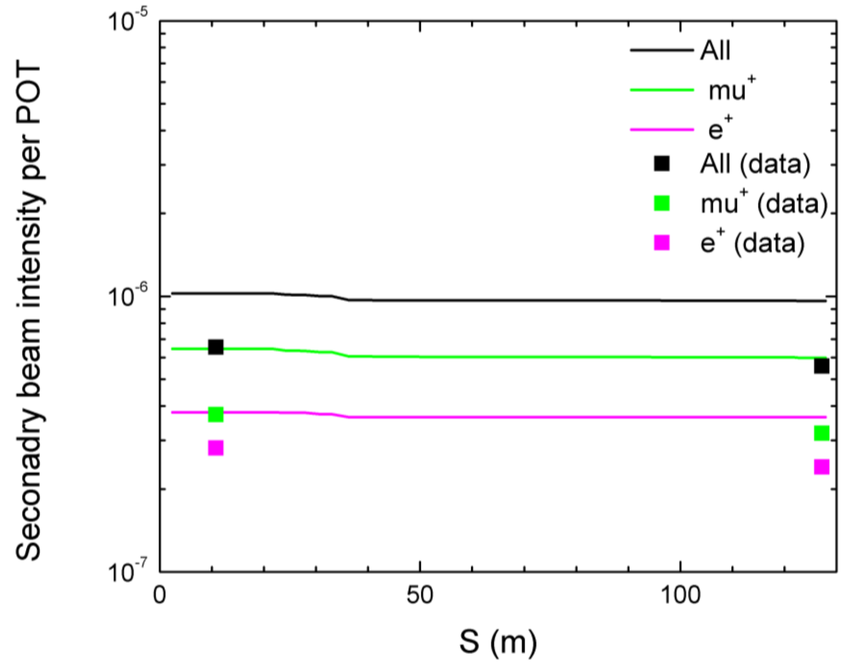
Performance within M4 & M5 lines

- 130 m long line that transports the beam from the DR to the g-2 ring



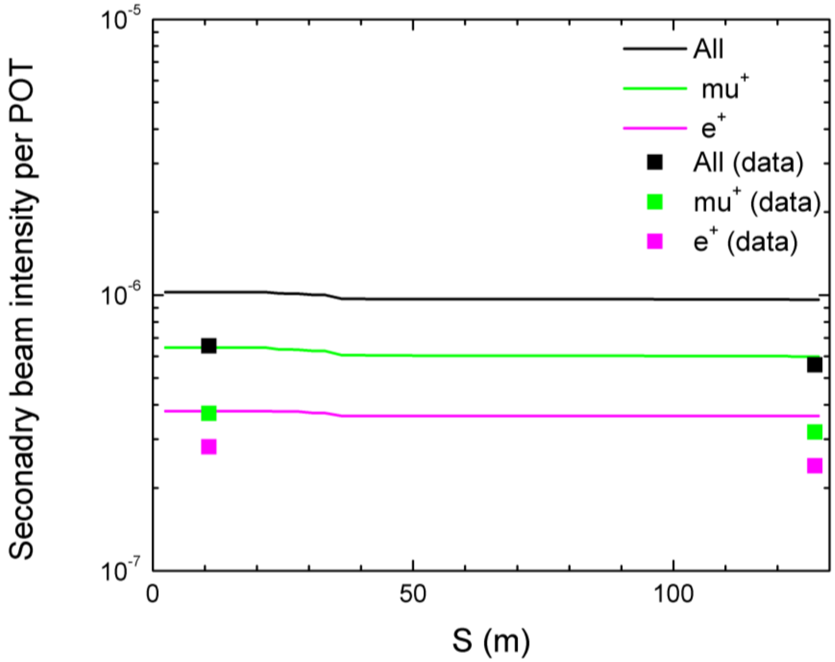
Performance within M4 & M5 lines

- Good news:
  - Measured & simulated transmission along the M4-M5 is ~90%
  - The measured mu+/e+ ratio is 57/43 and is close to the 62/38 from tracking

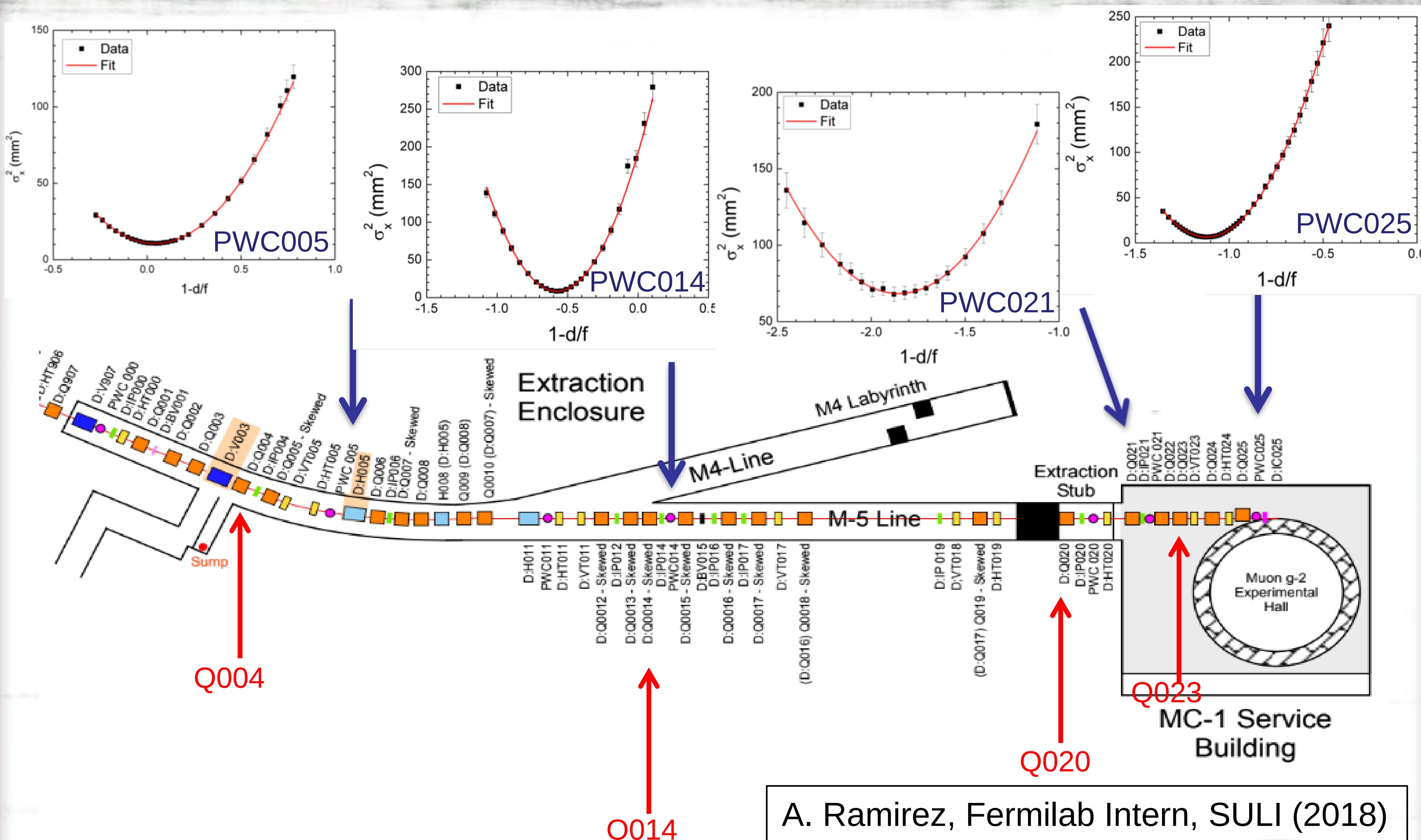


Performance within M4 & M5 lines

- Not so good news:
  - The delivered beam is about 1/3 compared to the baseline design
  - This is mainly because of the aperture cuts at injection
  - However a better simulation of the magnetic apertures is needed to quantify this effect

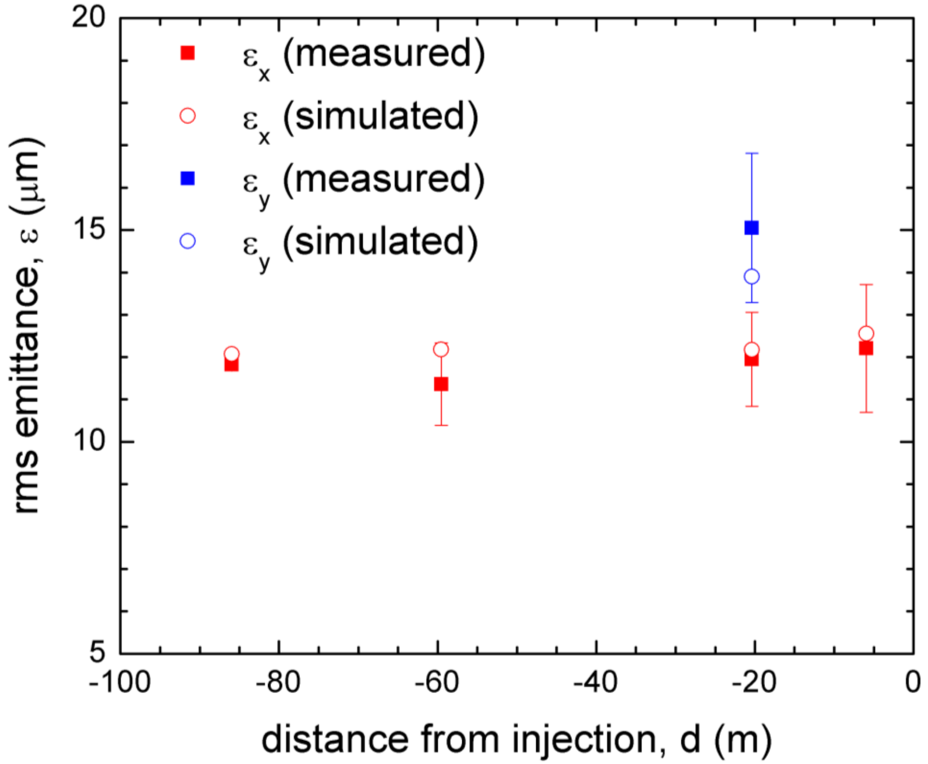


Optics along the M5 line



A. Ramirez, Fermilab Intern, SULI (2018)

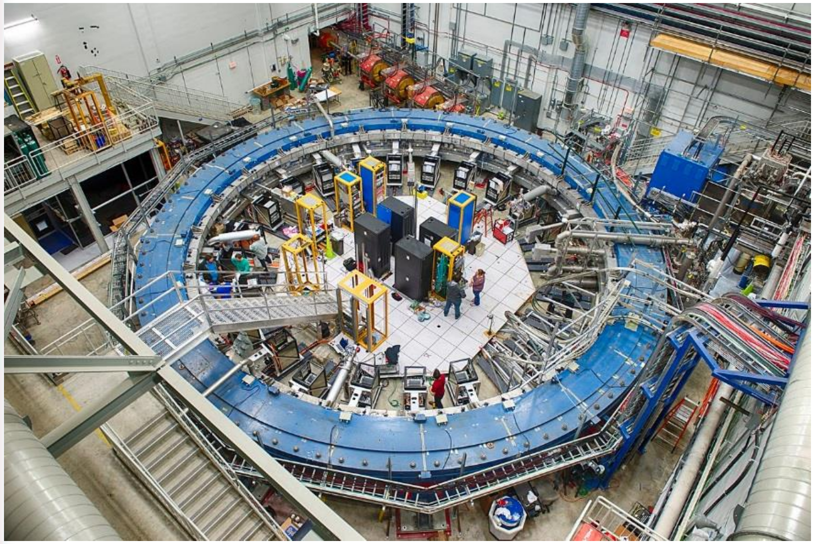
Measuring the beam emittance (M5)

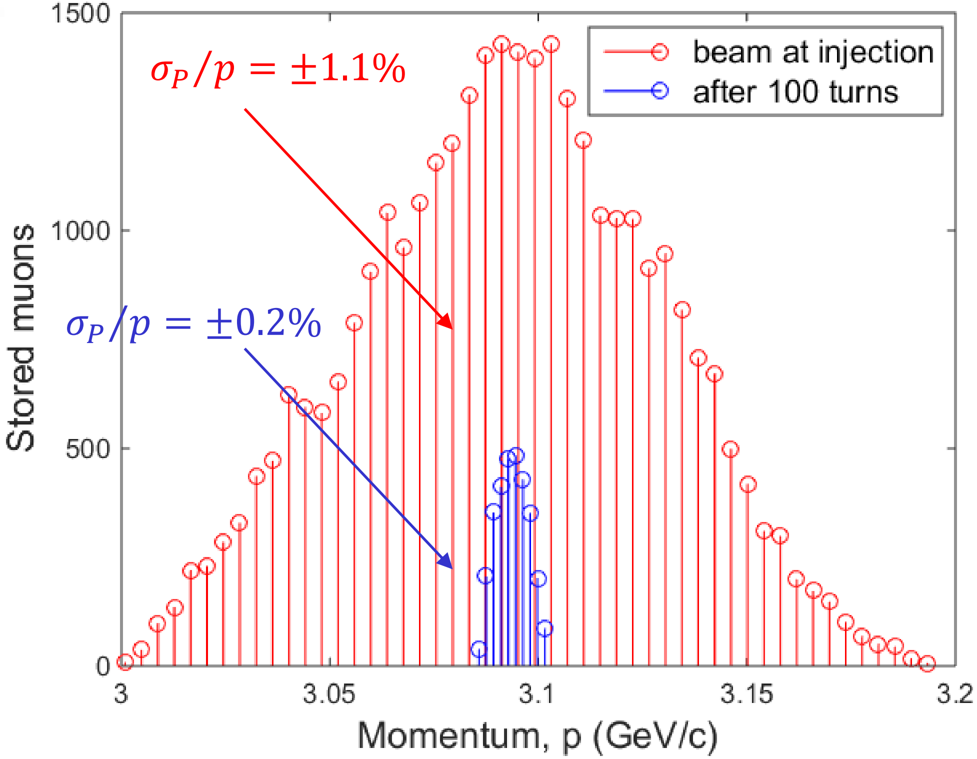


- The horizontal emittance is preserved, suggesting minor, if any, mismatch, positioning or field errors, which are typically associated with substantial emittance growth

Future improvements

Momentum acceptance

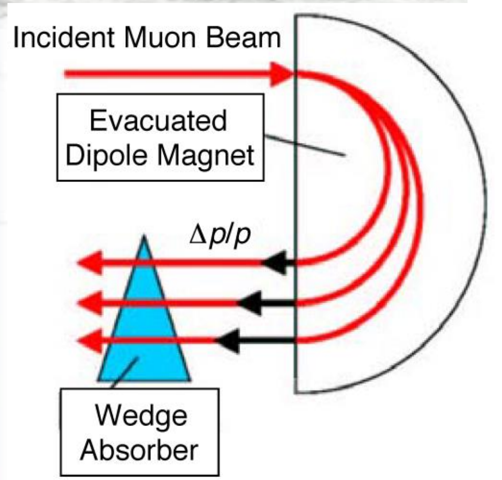


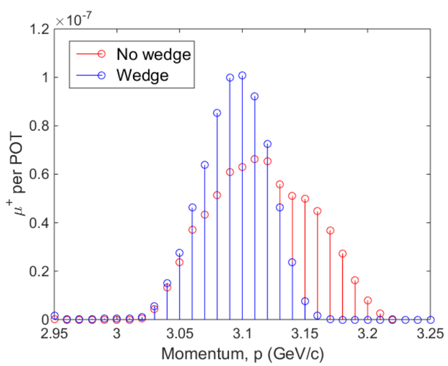


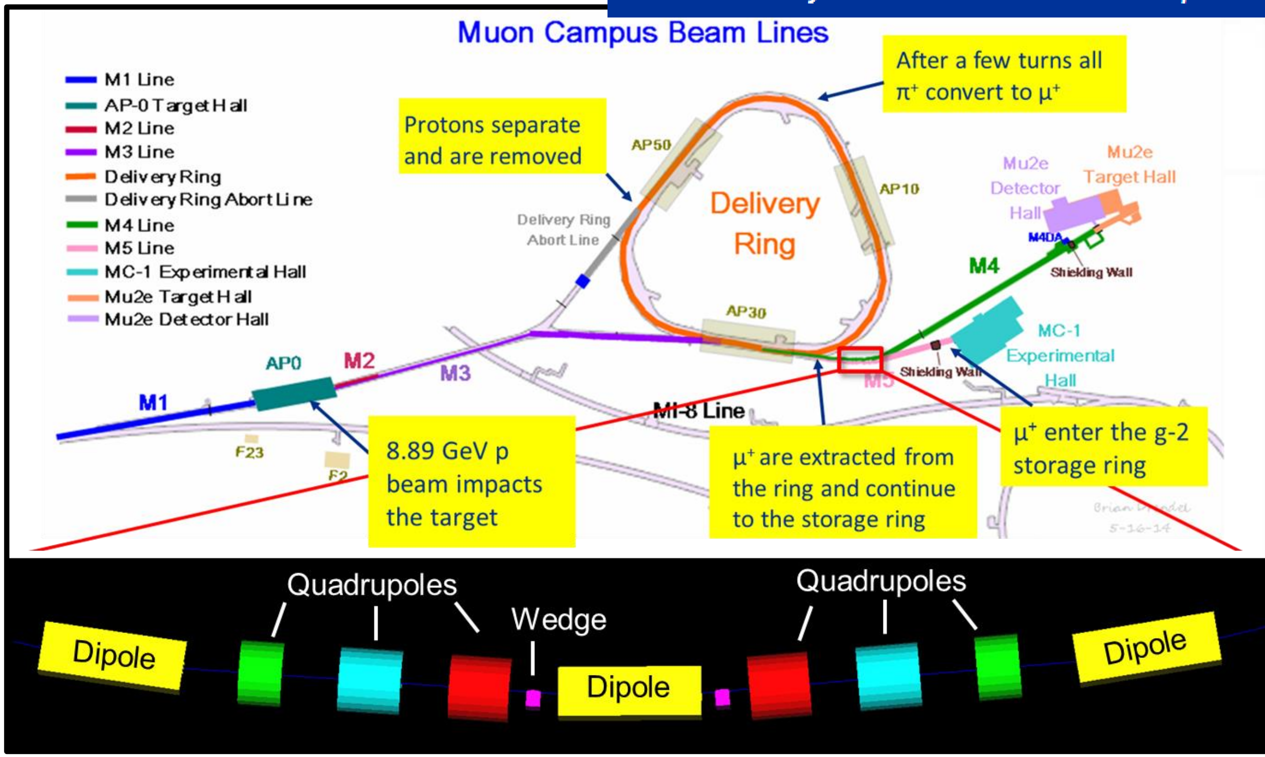
- The Muon g-2 Experiment storage ring accepts only a fraction of the muons delivered by the Muon Campus

Fully funded two-year program

LDRD at Fermilab
Laboratory Directed Research and Development







- We propose a wedge absorber for momentum selection and reduction of the momentum spread for the muon beams generated on the Muon Campus (tomorrow’s lecture)

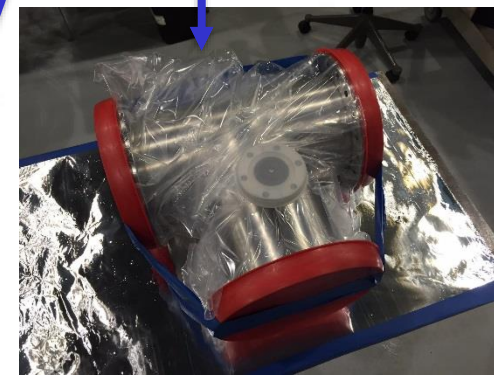
Fabrication and installation progress

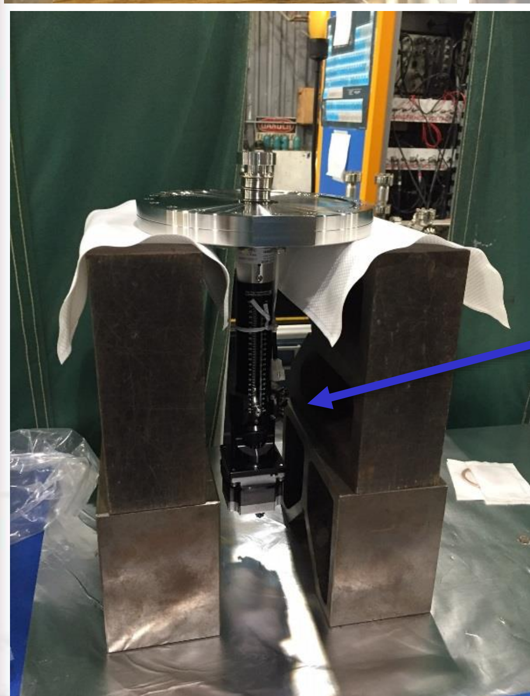
Polyethylene wedge

Boron Carbide wedge

New power supplies for downstream optical matching

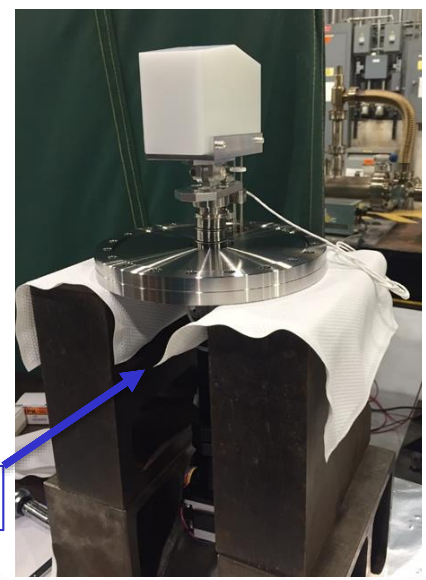
Wedge housing



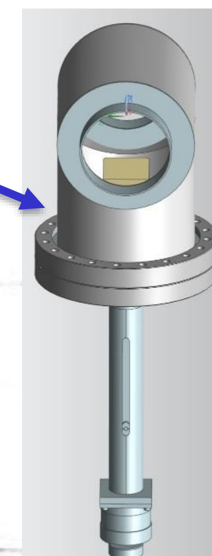


Wedge insertion actuator
with submillimeter precision

Motion-control tests



Design of complete mechanical assembly

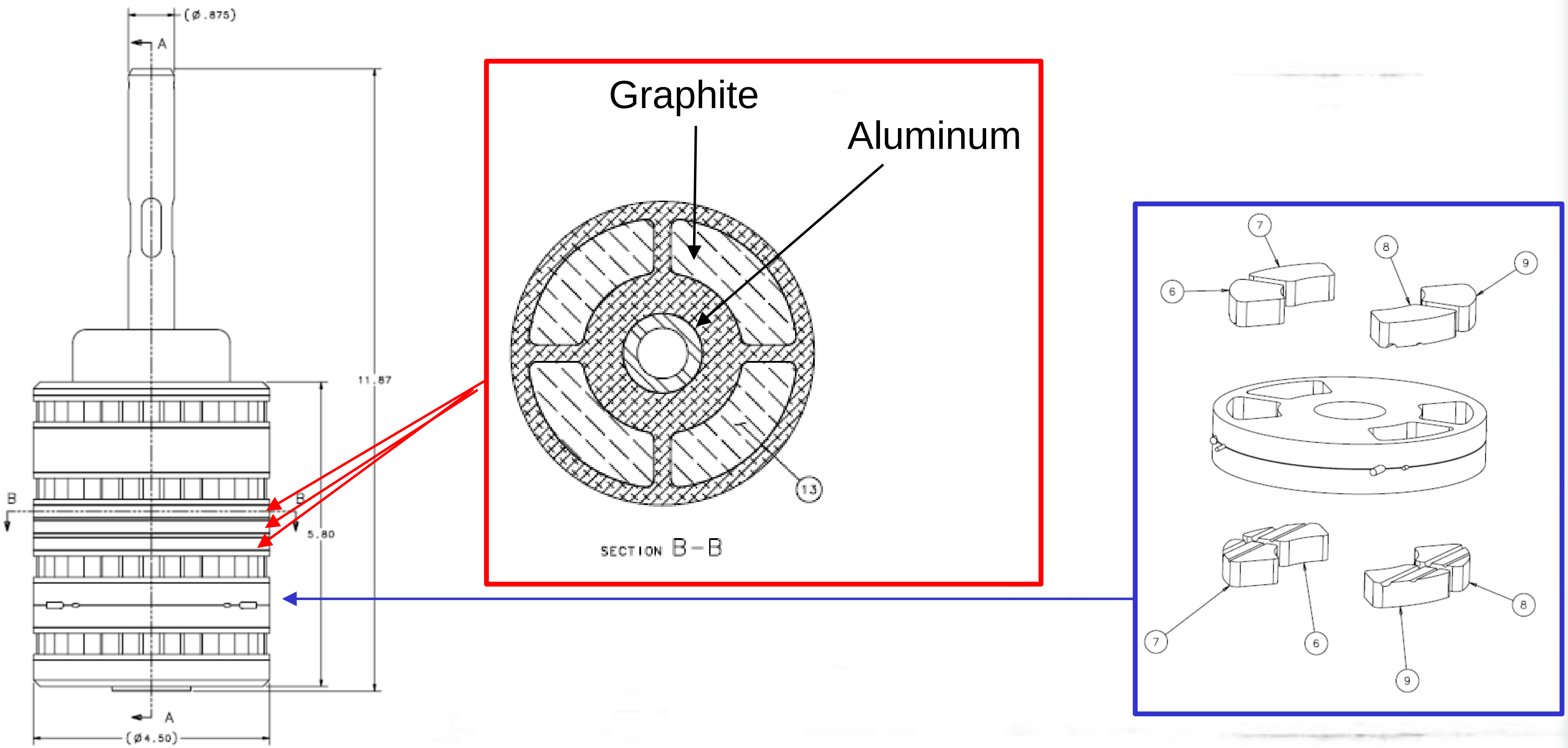


Further plans to improve accelerator performance

- M1/ Target improvements:
  - Continue to work on achieving design spot size at the target, but hard to do and only modest yield increase expected
  - Developing a test target with thin disks and rods to boost yield
- M2/M3 beam transport improvement:
  - Momentum collimators installed in M2 & M3 will aid analysis
- Stored muons enhancement
  - Thinner vacuum window at the end of M5 is ready for installation

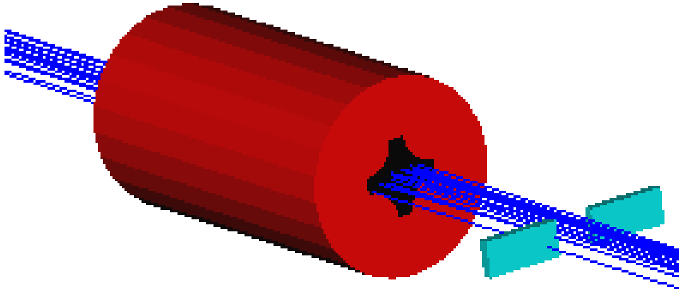
New target concept

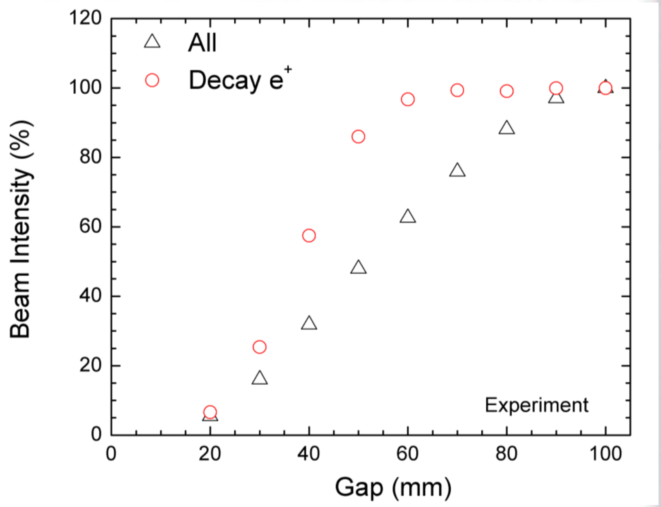
- Concept, dating from the 1990’s, is to surround a thin target with air or lower Z material. Some pions that would otherwise be scattered or absorbed are able to survive



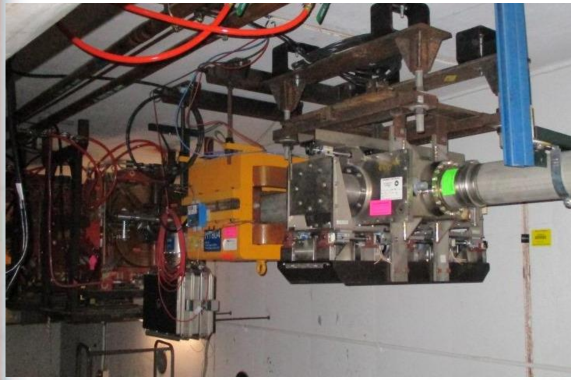
Momentum collimators

- Collimator has the potential to reduce the beam intensity by more than 40% without affecting stored muons

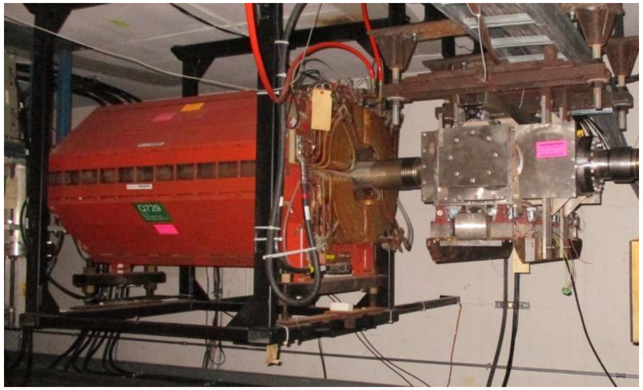




M2 line

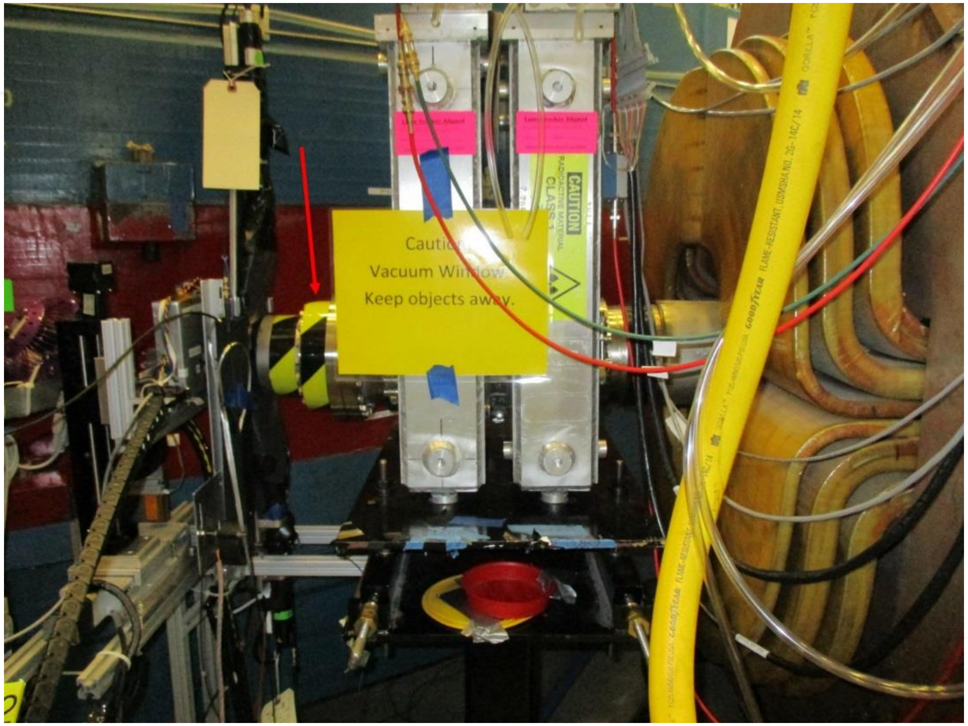


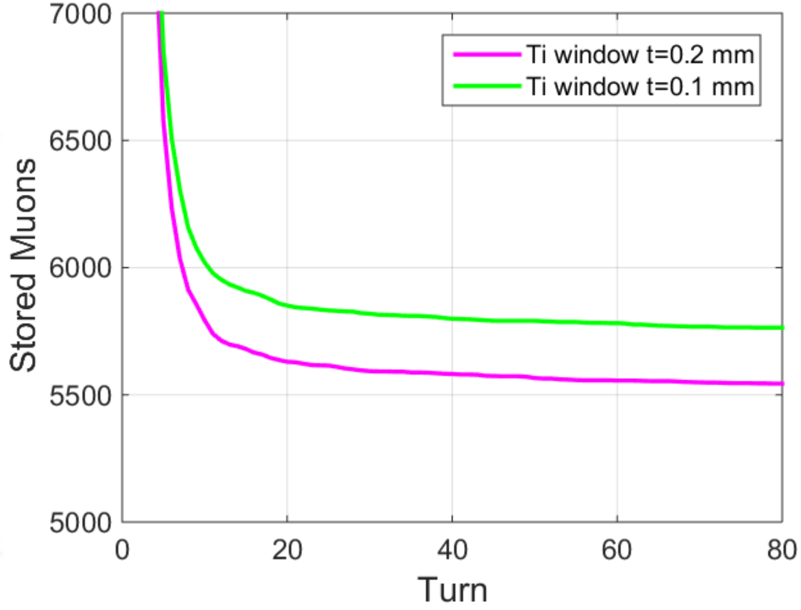
M3 line



Delivery Ring

New window installation at the M5 end





- A reduction of the window thickness from 0.2 to 0.1 mm is expected to increase the number of stored muons

Conclusions (1)

- For the M2-M3 lines, we found good agreement between the simulated and measured beam intensity
- This demonstrates that the target and the following beamlines can produce, capture, and deliver to the DR, a secondary beam within the baseline design parameters
- The measured muon rate over 100 DR turns follows the exponential decay law suggesting minimal aperture losses. Most likely, this means that extraction works well, too.
- The beam optics along the M5 line agree reasonable well with the simulation and the emittance is conserved
- Two independent measurements found the mu+ to e+ ratio to be 57/43 which agrees reasonable well with the simulation

Conclusions (2)

- There is a discrepancy between measurement and simulation of the g-2 delivered beam intensity of ~ 1/3 with the latter predicting a higher transmission
- While the precise geometry of all magnetic apertures has to be accounted in the model in order to obtain a quantitative comparison, it is likely that a fraction of the beam is lost during injection to the DR.
- Should mostly affect no-storable muons. Momentum collimators will be installed to further check this hypothesis.
- Through Fermilab's LDRD program we have been awarded a grant to design, install and test a wedge in the Muon Campus which is expected to increase the stored muons for g-2