# Cooling studies in the US

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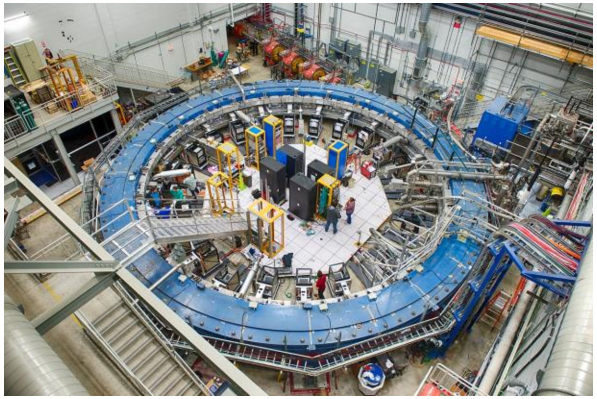
MUON Collider Collaboration Meeting
12 October 2022

# Outline

- Experimental studies on muon cooling in the US
  - Motivation
  - Concept
  - Results
  - Future studies
- Design studies on muon cooling in the US
  - Results accomplished during the MAP program
  - Future plans

# Fermilab Muon g-2 Experiment

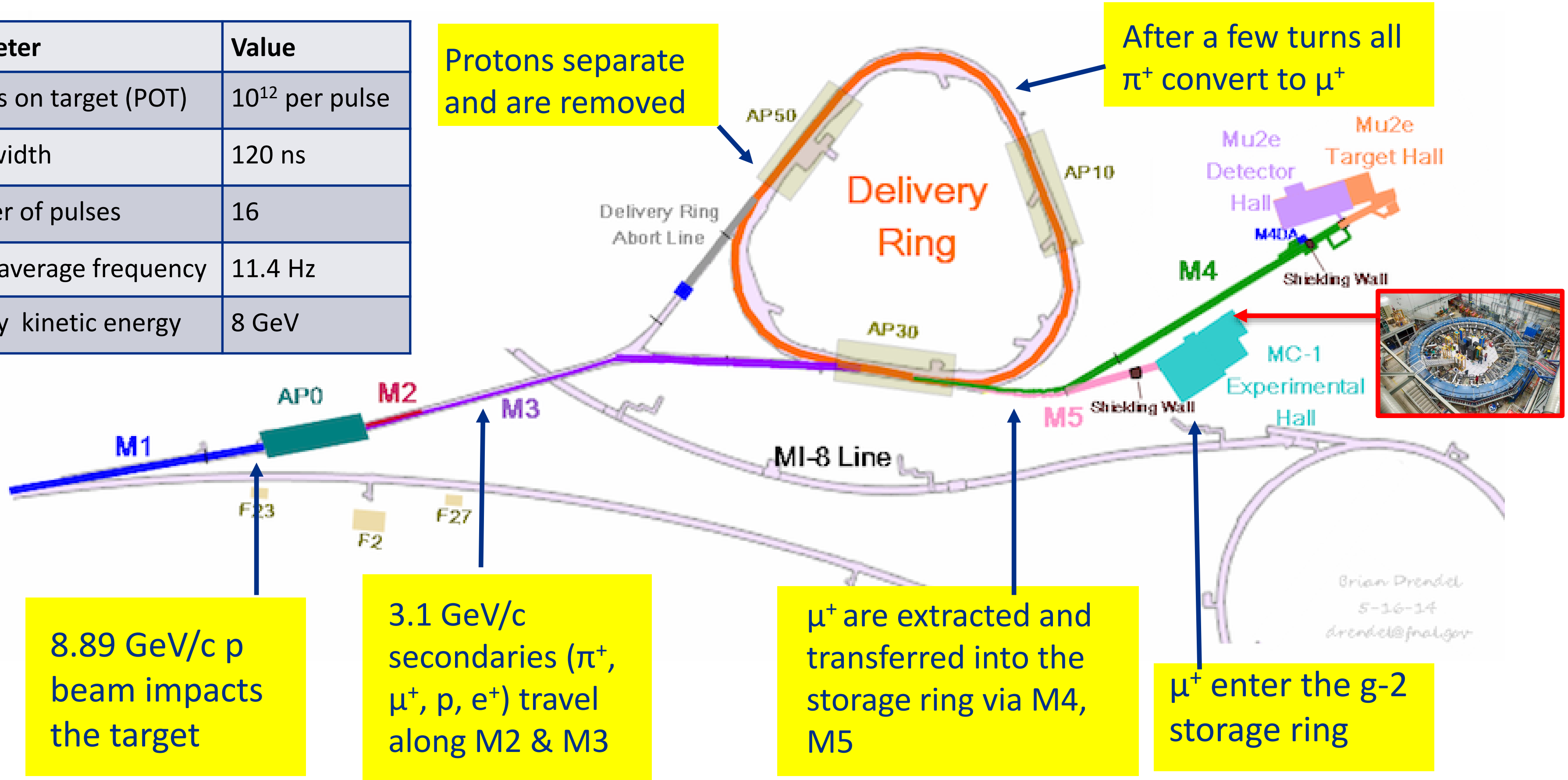
- Goal
  - Measure the muon anomalous magnetic moment (g-2) with 0.14 ppm uncertainty - a fourfold improvement of the BNL measurement (0.54 ppm)



- Approach
  - Circulate polarized muons in a uniform magnetic field and measure the precession frequency
  - 3.1 GeV/c muons to simplify Thomas-BMT equation: $\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \cancelto{0}{\left(a_\mu - \frac{1}{\gamma^2-1}\right)} \vec{\beta} \times \vec{E}\right]$
- Requirement
  - Requires delivery of $1.4\text{x}10^{14}$ muons in the ring which is x21 the statistics of the BNL experiment

# Muon Campus layout

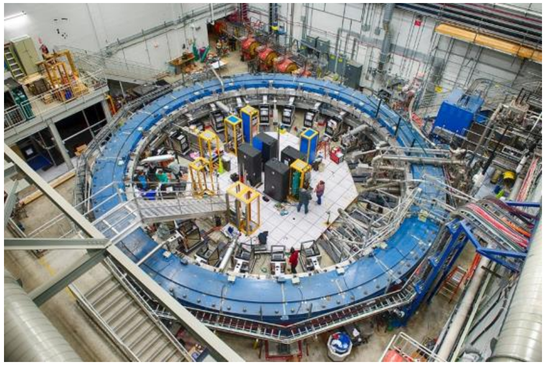
| Parameter | Value |
|---|---|
| Protons on target (POT) | $10^{12}$ per pulse |
| Pulse width | 120 ns |
| Number of pulses | 16 |
| Bunch average frequency | 11.4 Hz |
| Primary kinetic energy | 8 GeV |

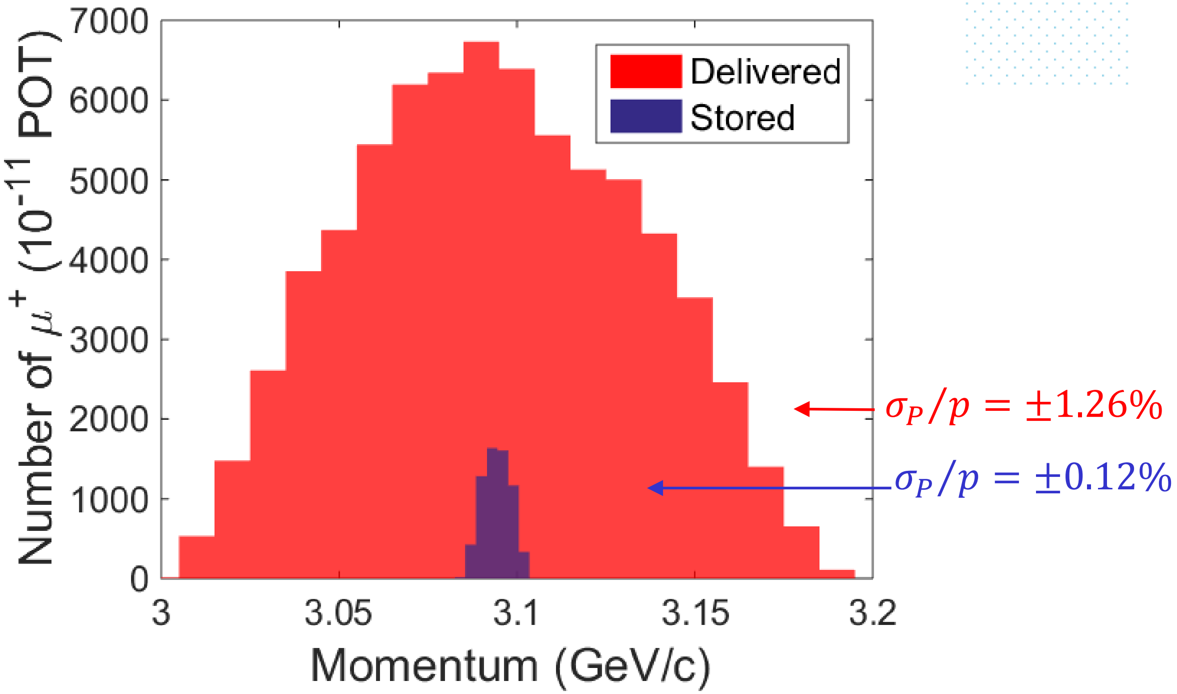



- Since 2018, Muon Campus has delivered ~ 19x BNLs and is expected to deliver the desired goal by the end of FY23

# Motivation for beam cooling

- The beam delivered to the storage ring of the Muon g-2 Experiment has a rms momentum spread of ~1.3%
- The ring accepts muons within ~0.1% of the magic momentum (~3.1 GeV/c) only. Nearly 90% of the incoming beam is lost.





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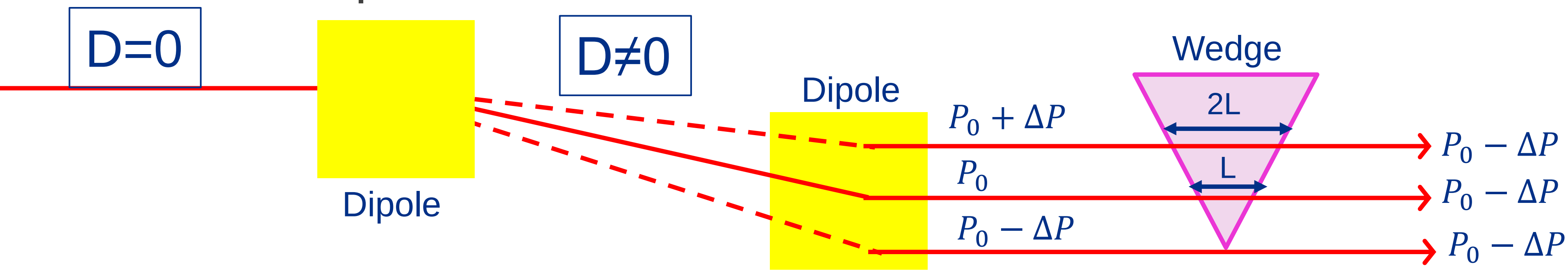
# Proposed improvement strategy

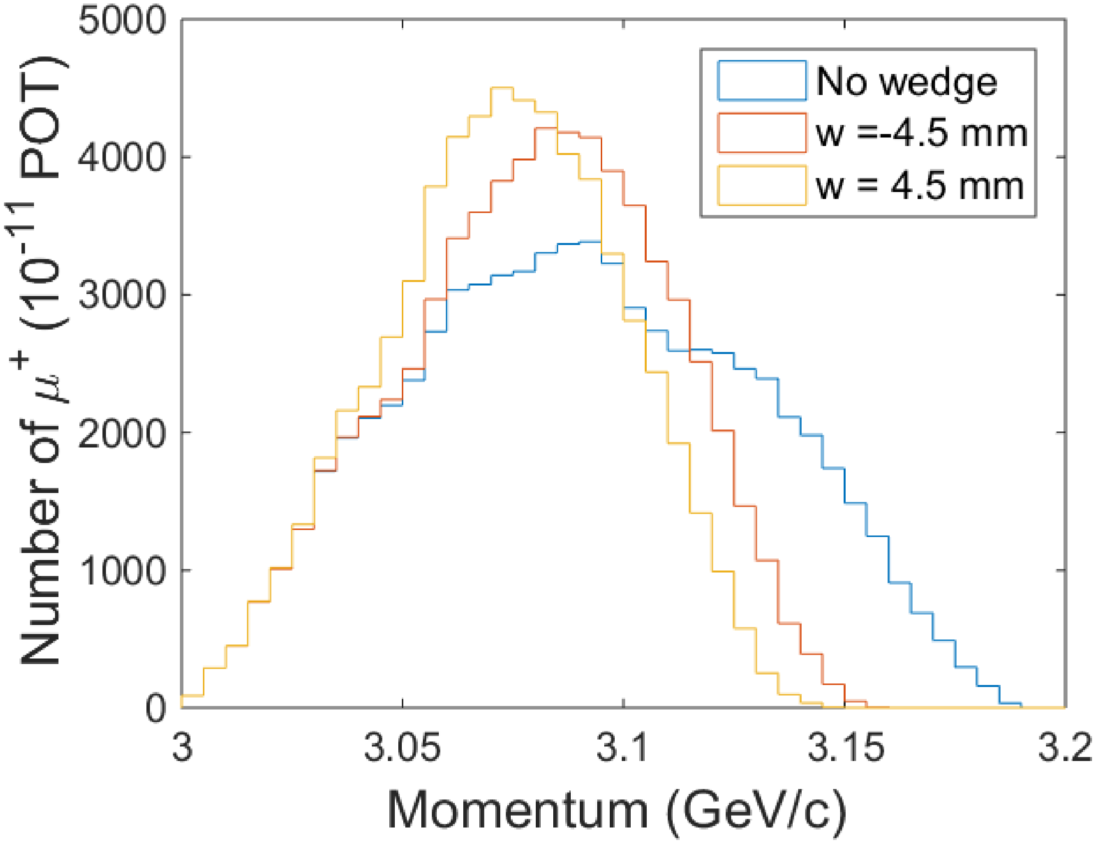
**LDRD at Fermilab**
*Laboratory Directed Research and Development*

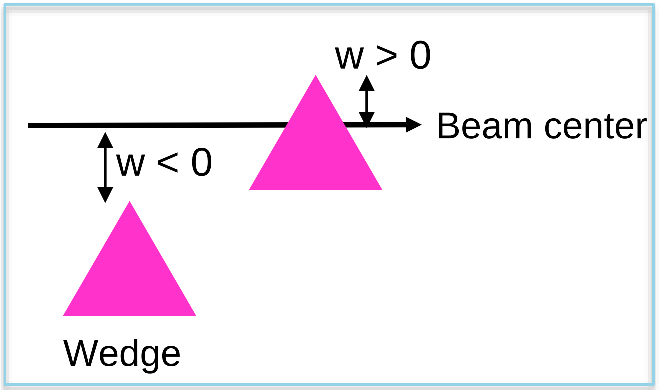
- First separate particles by momentum by guiding them into a dispersive area
- Then, pass the beam through a wedge absorber
- With a properly designed wedge, high-energy muons will lose more energy than low-energy ones. As a result, the overall energy spread of the beam is reduced
- Through Fermilab's LDRD program, in 2017, we have been awarded a grant to design, install and test a wedge in the Muon Campus



# Simulation of the concept

- Simulations of the wedge concept along the Fermilab Muon Campus revealed that a wedge can increase the number of stored muons for the Muon g-2 Experiment



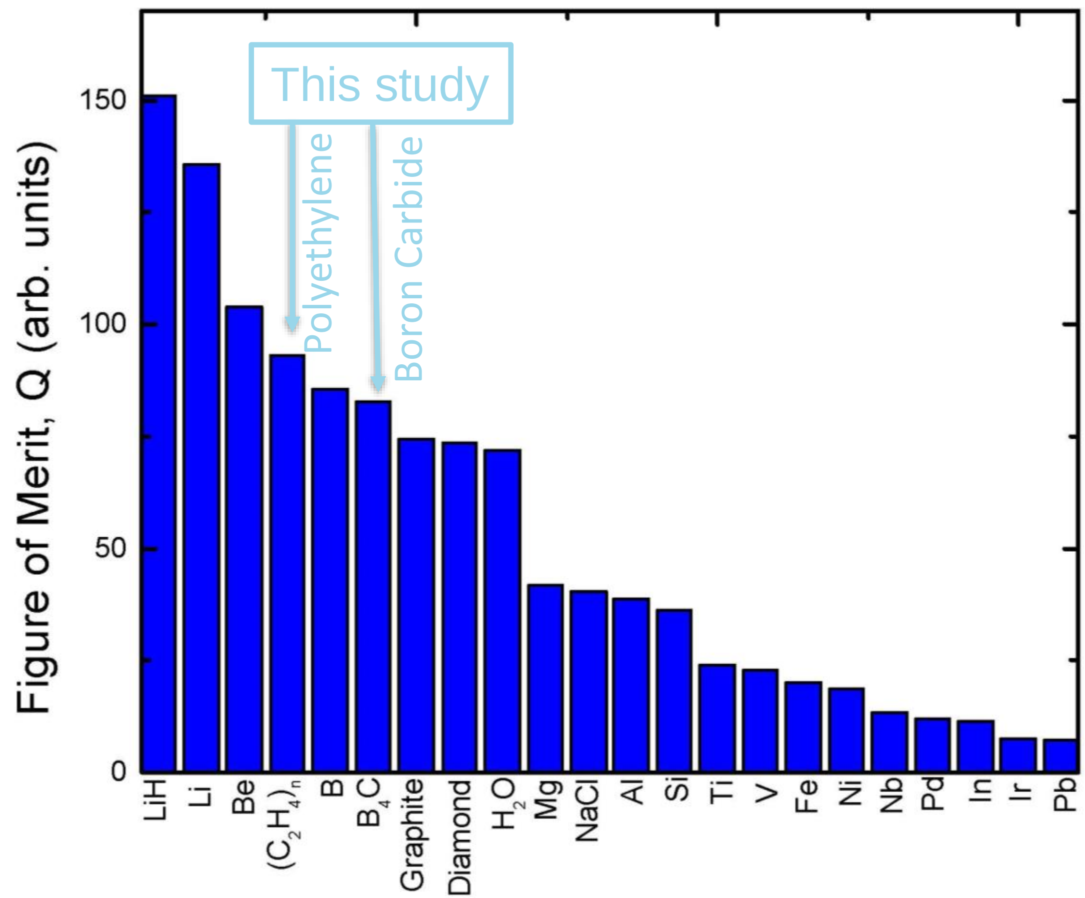



# Choice of material

- A figure of merit for each material can be obtained by taking the product of it's energy-loss and radiation length terms

Boron Carbide ($B_4C$)

| Quantity | Value | Units |
|---|---|---|
| <Z/A> | | |
| Specific gravity | | |
| Mean excitation energy | | |
| Minimum ionization | 4.157 | MeV cm$^{-1}$ |
| Nuclear collision length | 23.12 | cm |
| Nuclear interaction length | 33.27 | cm |
| Pion collision length | 33.92 | cm |
| Pion interaction length | 46.04 | cm |
| Radiation length | 19.89 | cm |
| Critical energy | 88.08 | MeV (for $e^+$) |
| Molière radius | 4.659 | cm |
| Plasma energy $\hbar\omega_p$ | | |
| Muon critical energy | | |



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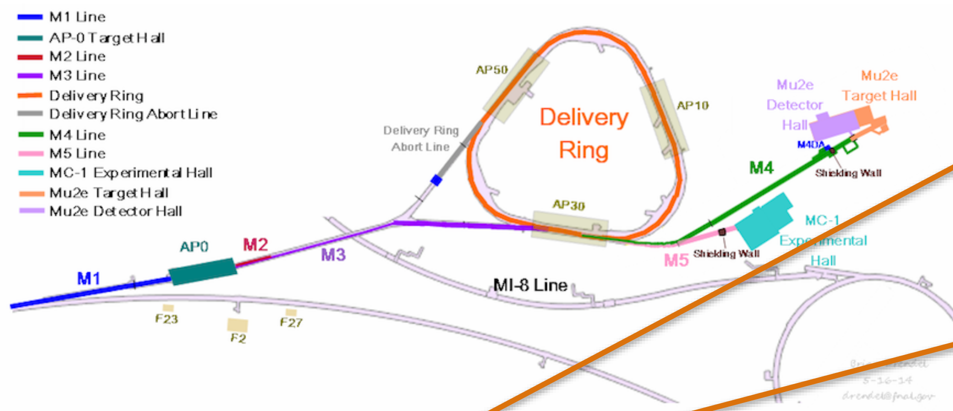
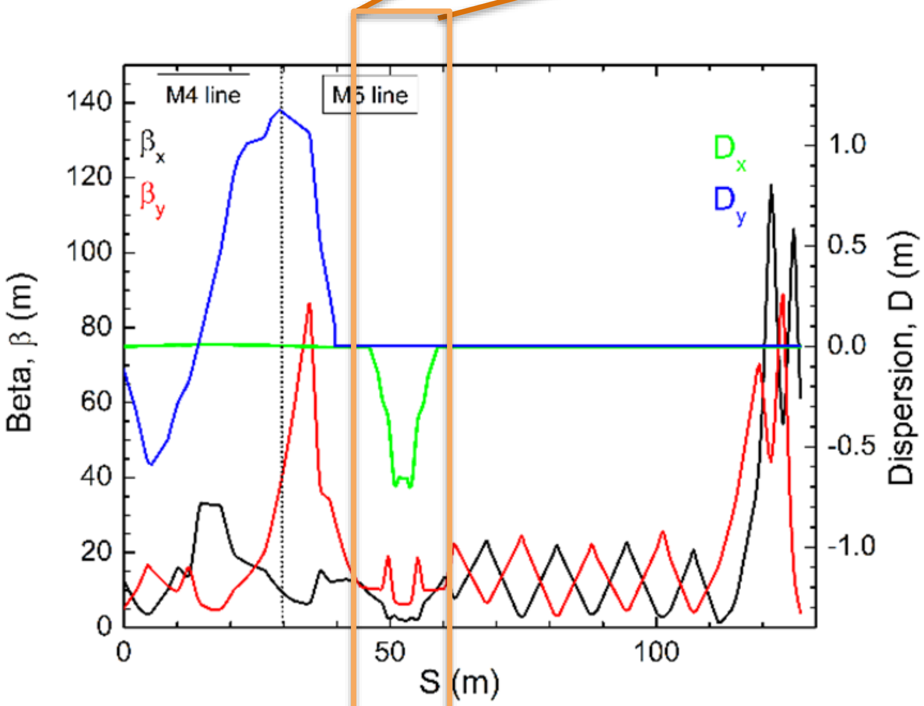
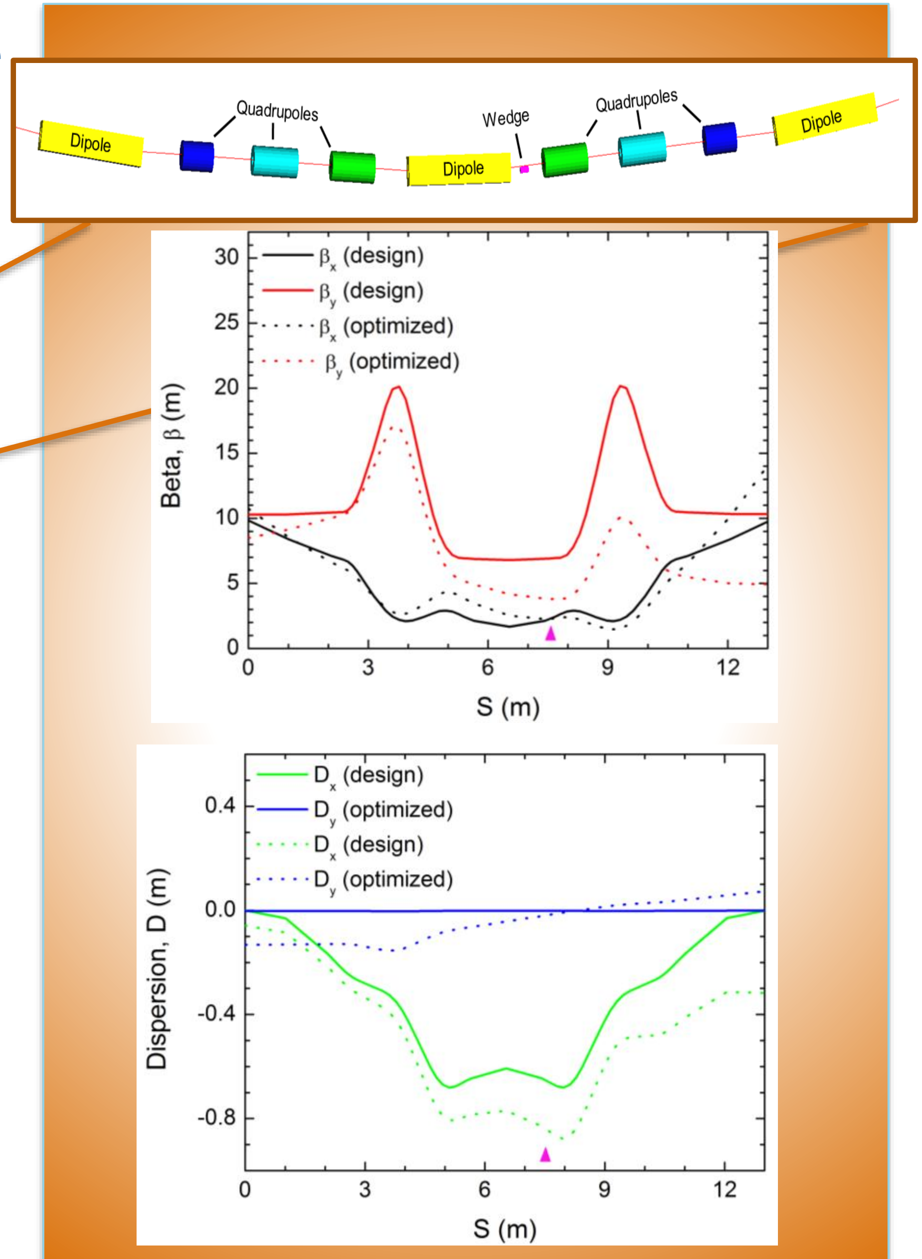
# Choice of location: M5 line

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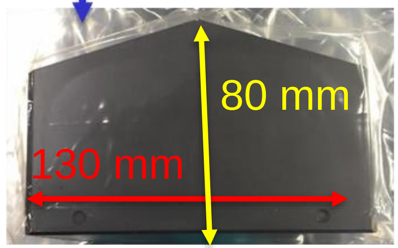
# Fabrication and installation progress (1)

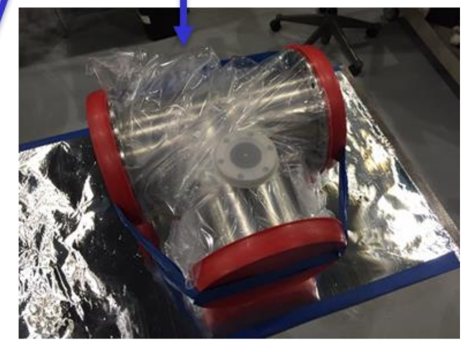
Polyethylene wedge

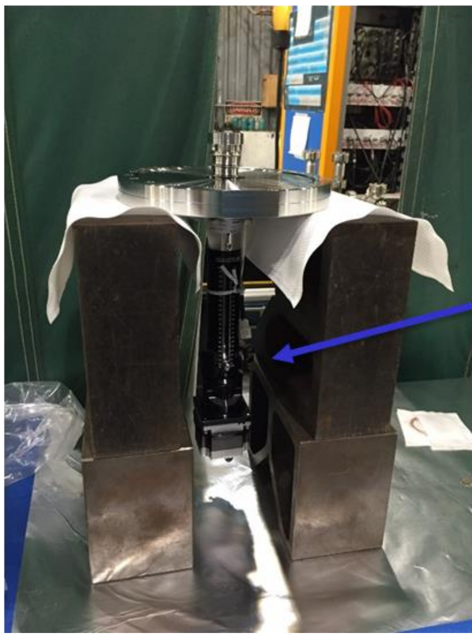
Boron Carbide wedge




New power supplies for downstream optical matching

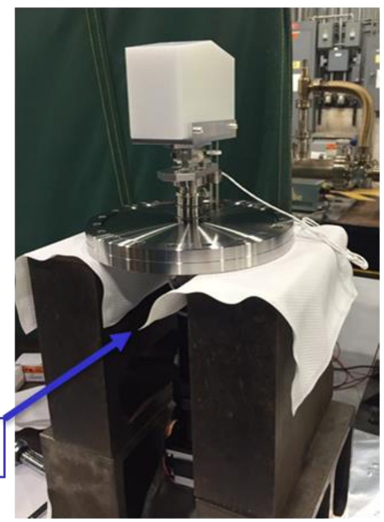
Wedge housing



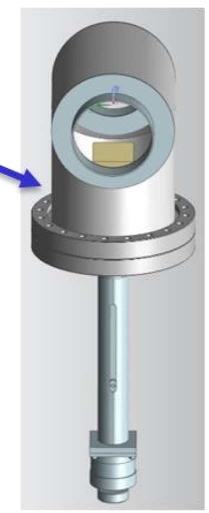


Wedge insertion actuator with submillimeter precision

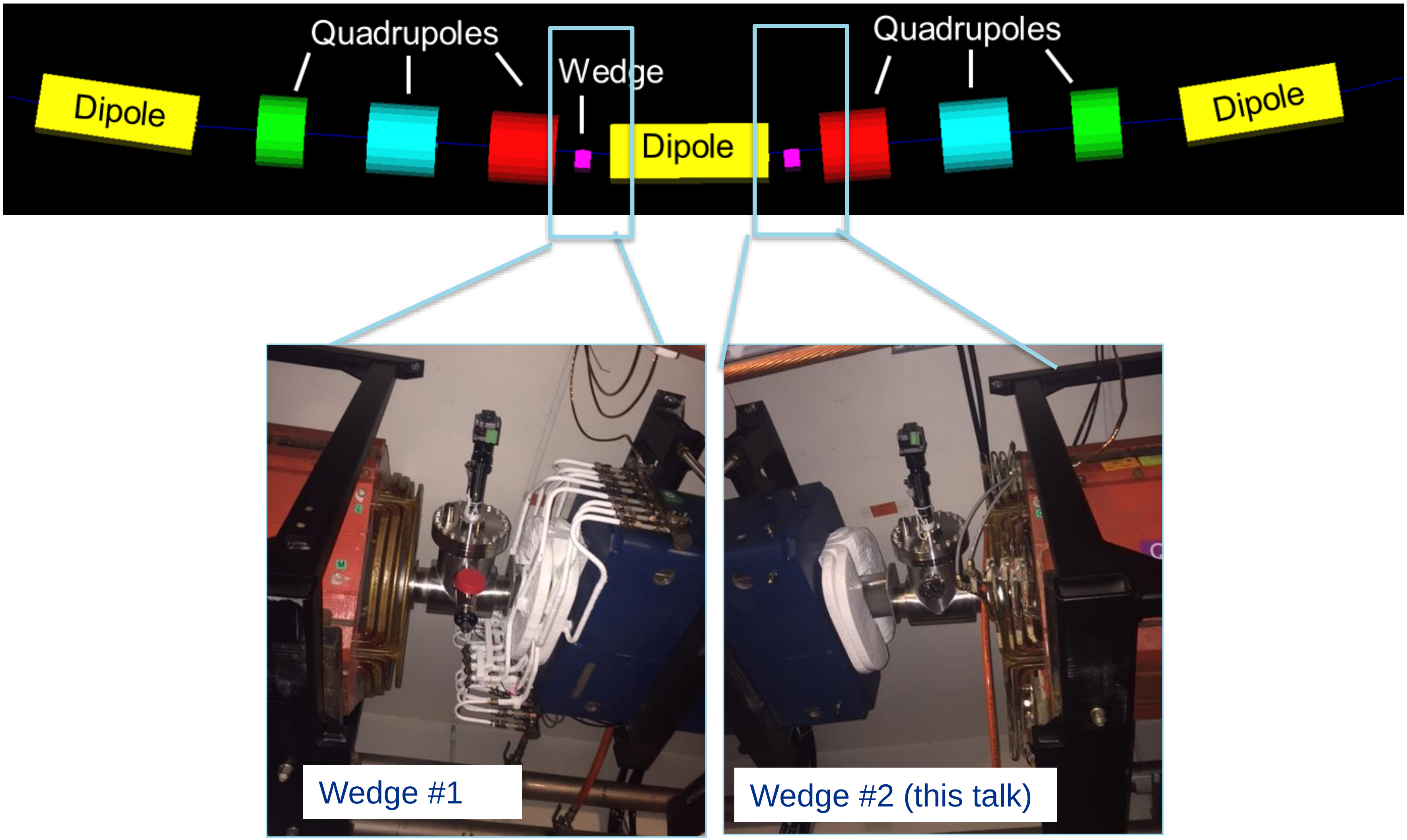
Motion-control tests



Design of complete mechanical assembly



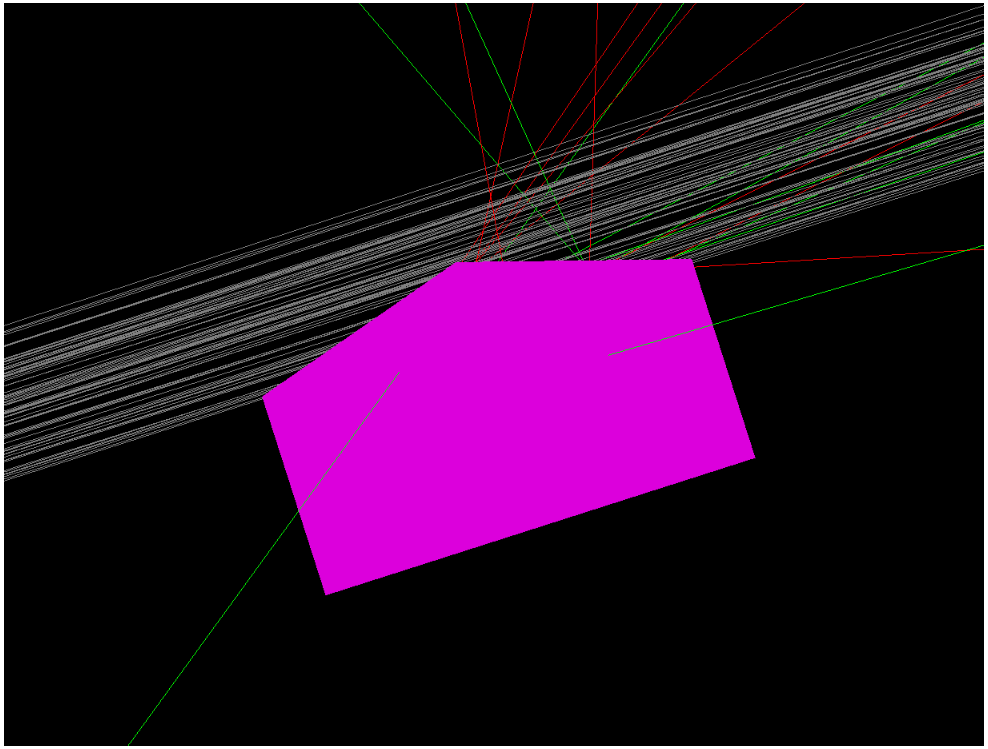
# Fabrication and installation progress (2)



# Simulated trajectories

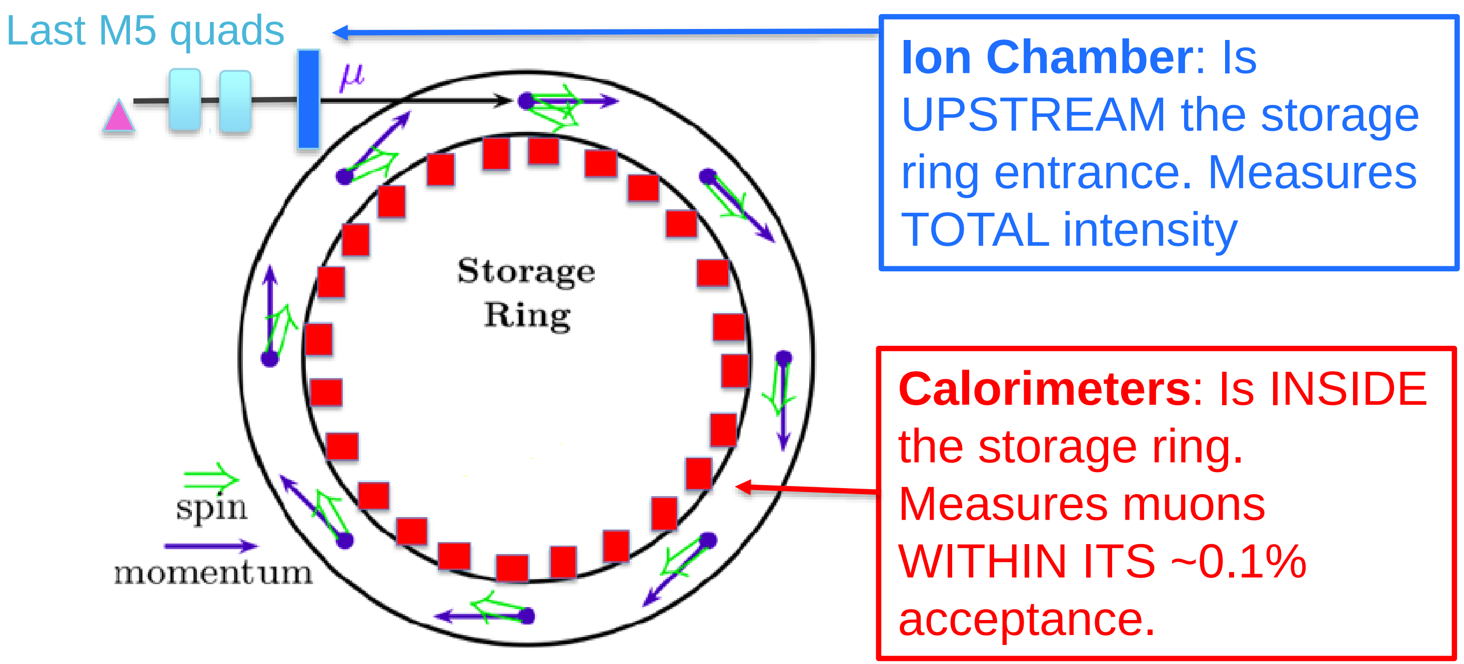
- Beam wedge covers roughly half of the beam
- The majority of beam-material interaction happens near the wedge apex

| Parameter | Value at wedge |
|---|---|
| Dispersion, $D_x$ | 0.85 m |
| Beta, $\beta_x$ | 2.3 m |
| Beta, $\beta_y$ | 3.8 m |
| Emittance rms, $\varepsilon$ | 12.0 µm |
| Sigma, $\sigma_x$ | 10.0 mm |



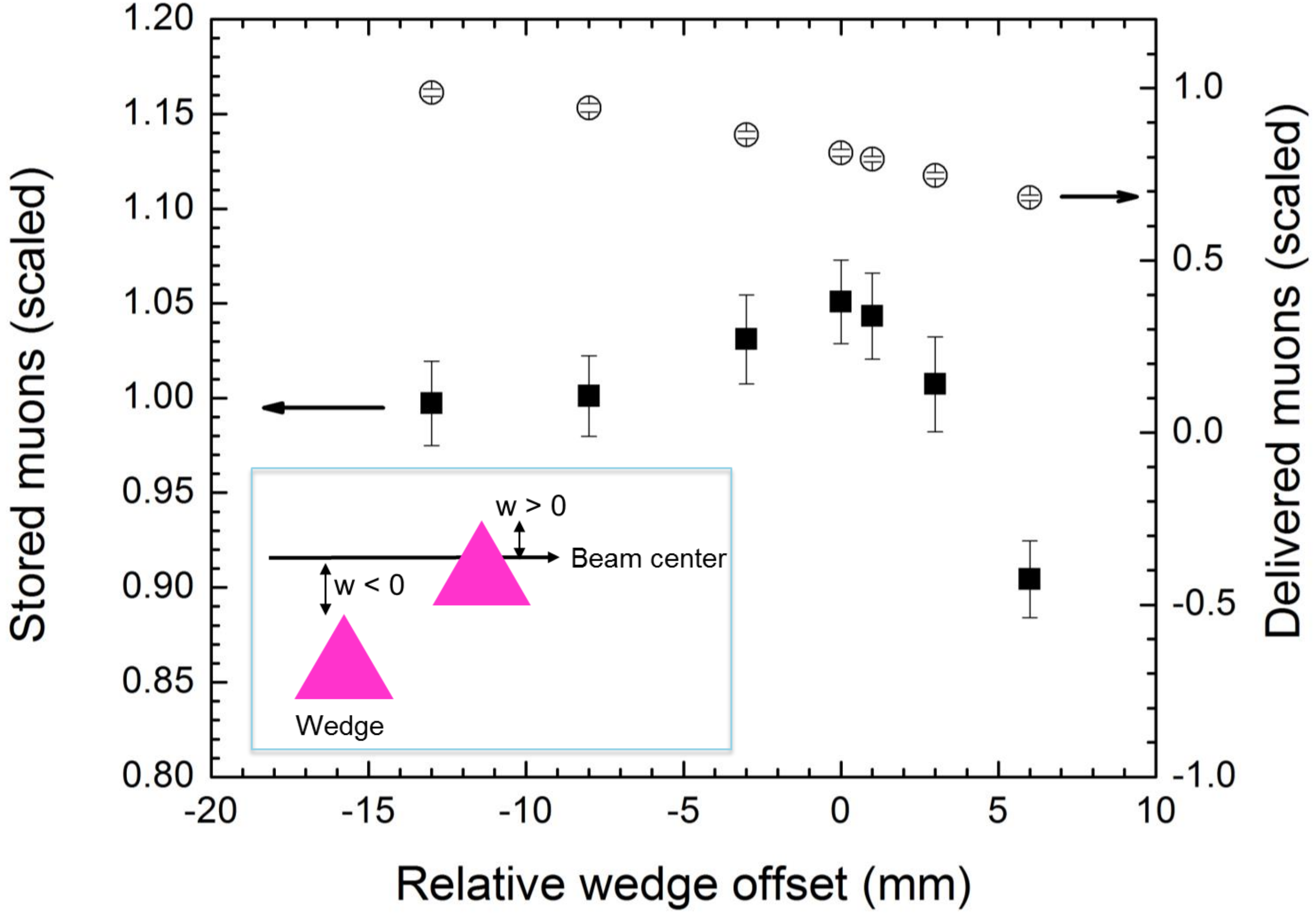
# Measuring Technique

- We measure beam intensity at two locations: (1) upstream of ring injection, and (2) inside the ring after thousand of turns
- Calorimeters measure only muons that fit within the ring's momentum acceptance. As a result this value provides a key parameter that governs the wedge performance.



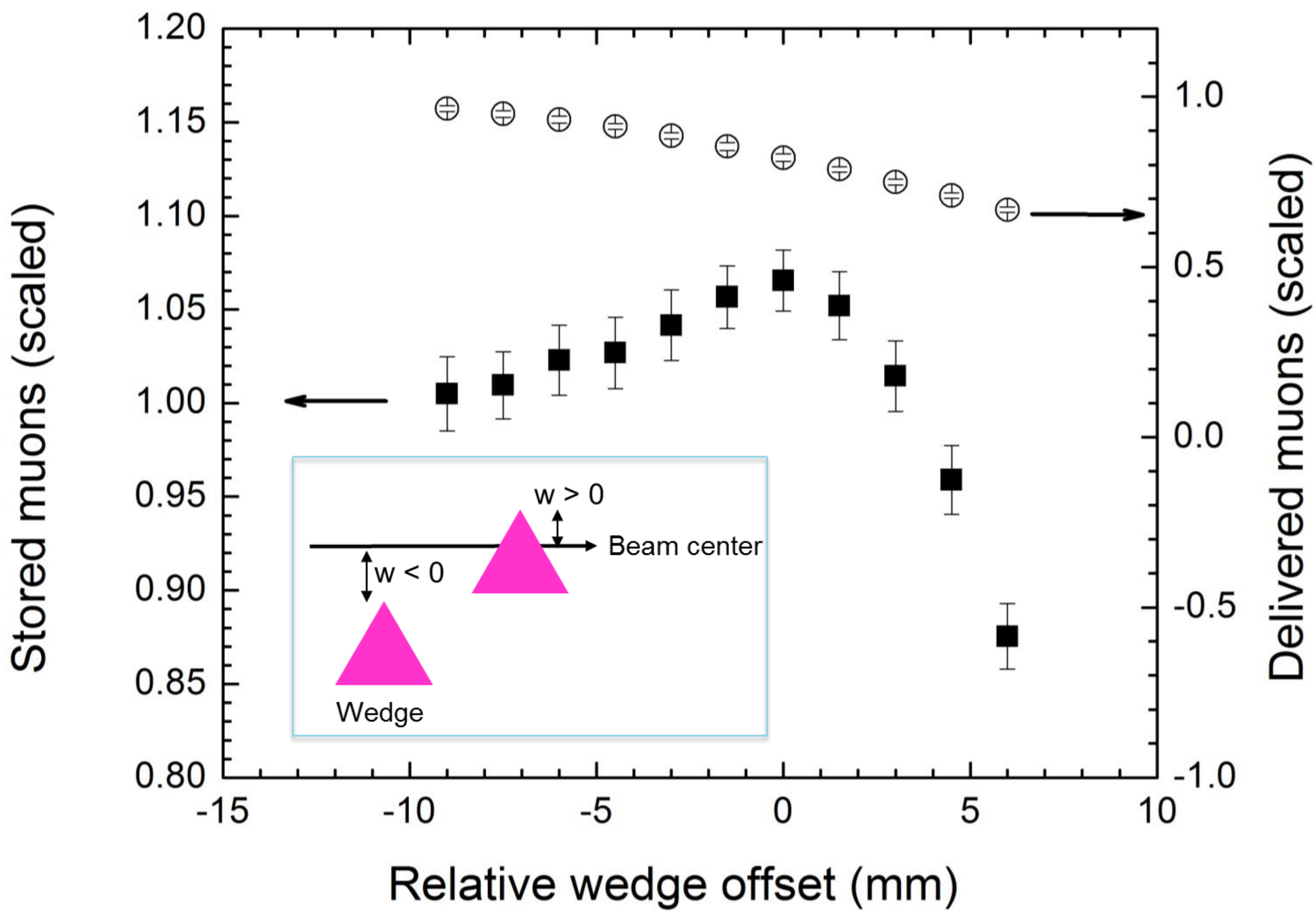
# Test with a Polyethylene wedge

- A polyethylene wedge provided a 5% gain in stored muons



# Test with a Boron Carbide wedge

- A boron carbide wedge provided a 7% gain in stored muons



# Conclusion

- The LDRD run for 3 years and finished in 2020
- Similar to MICE, demonstrated the emittance-exchange process i.e longitudinal cooling
- The novelty of our work is that it demonstrated direct applicability to an operational facility: Muon g-2 Experiment
- Showed an increase in storable muons by ~7%
- Showed numerically the potential to increase storable muons by 20% or more
  - Required significant change on optics/power supplies
  - Not possible given the time constraints of the experiment

# Muon g-2 cooling: Thanks to several students!

Nick Amato (2019)
Master's Thesis, **NIU** (Syphers)
Title: Improved momentum spread for precision experiments using wedges

Lauren Carver (2019)
Fermilab Intern
Title: Modeling a wedge absorber for the g-2 Experiment

Jerzy Manczak (2018)
Fermilab Intern
Title: Modeling a wedge absorber for the Mu2e Experiment

Joe Bradley (2017)
Fermilab Intern
Title: Material & geometry study of a wedge absorber for the g-2 Experiment

Grace Roberts (2020)
Fermilab Intern
Title: Optimizing injection for a wedge based Muon g-2 Experiment

Ben Simons(2020)
**NIU** grad. student
Title: Tuning beam optics for the Muon Campus

PHYSICAL REVIEW ACCELERATORS AND BEAMS 22, 053501 (2019)

Application of passive wedge absorbers for improving the performance of precision-science experiments

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Nuclear Inst. and Methods in Physics Research, A 962 (2020) 163704

Contents lists available at ScienceDirect
Nuclear Inst. and Methods in Physics Research, A
journal homepage: www.elsevier.com/locate/nima

Realistic modeling of a particle–matter-interaction system for controlling the momentum spread of muon beams

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Nuclear Inst. and Methods in Physics Research, A
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A parametric analysis for maximizing beam quality of muon-based storage ring experiments

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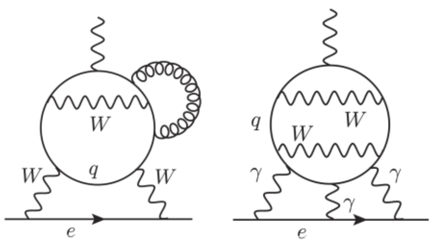
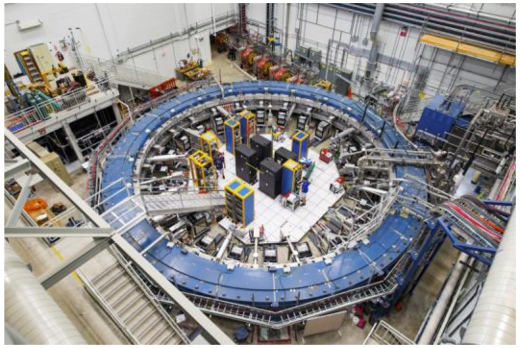
[a] *Purdue University, Department of Physics, West Lafayette, IN 47906, USA*
[b] *Fermi National Accelerator Laboratory, Batavia IL 60510, USA*

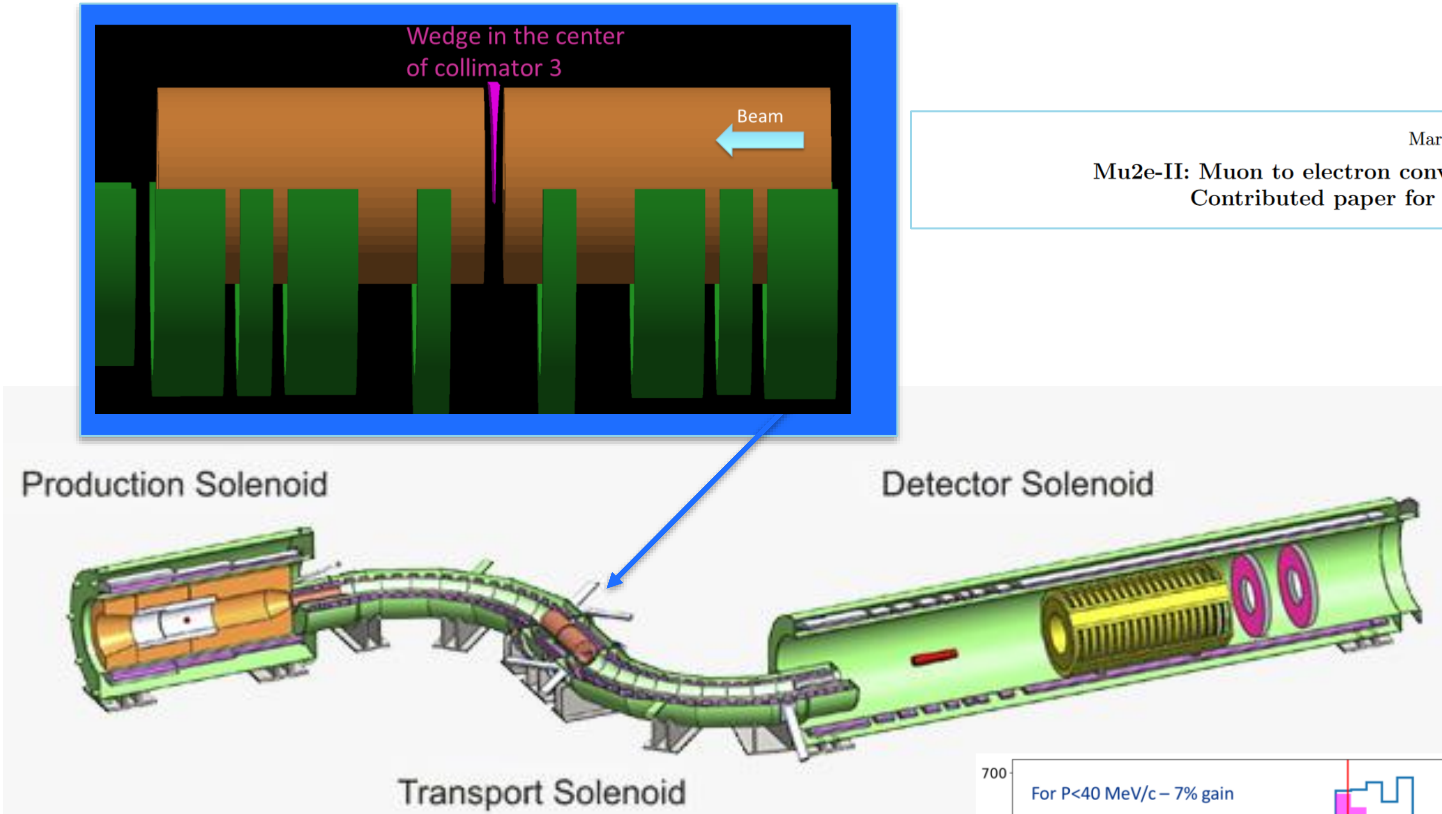
# Future work: EDM experiment

- There is considerable interest for an Electron Dipole Measurement (EDM) experiment at the Fermilab muon g-2 ring
- It will require the collection and transport of **300 MeV/c** muons along the Muon Campus
- Can open a path for wedge testing in a parameter regime that is closer to the actual cooling needed for a Muon Collider
- Simulations underway to estimate performance



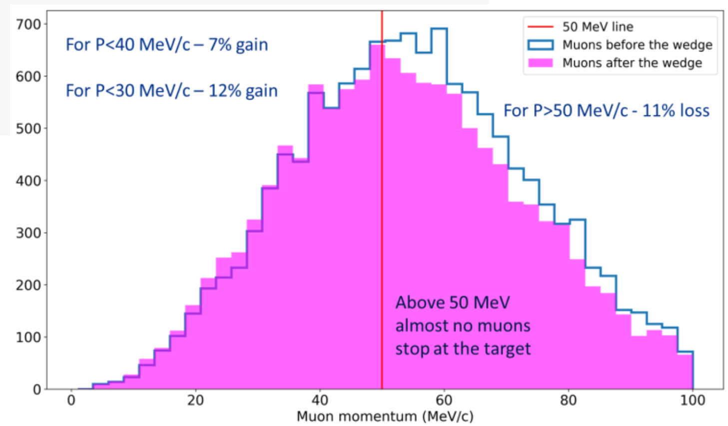
# Future work: Fermilab Mu2e-II Experiment



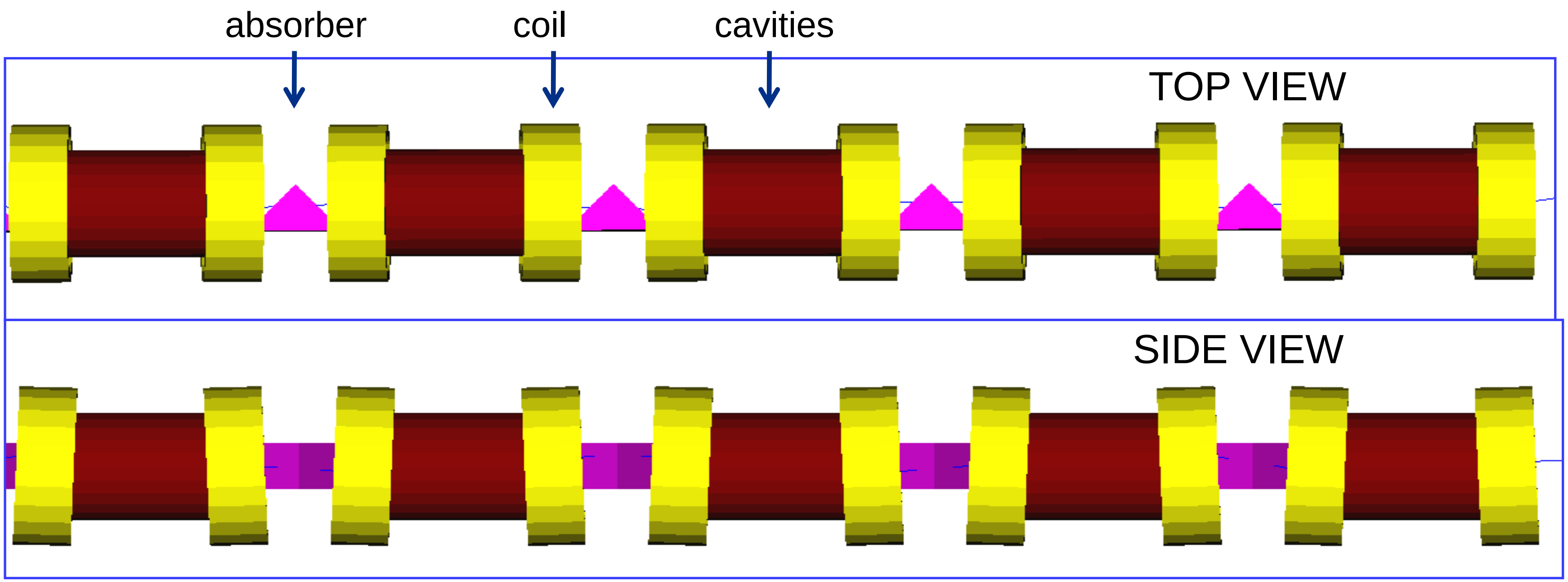

March 17, 2022

Mu2e-II: Muon to electron conversion with PIP-II
Contributed paper for Snowmass

- Goal is to increase muons in the 0-30 MeV/c range
- Concept works; its getting harder due to increased scattering



# Design: Rectilinear channel concept

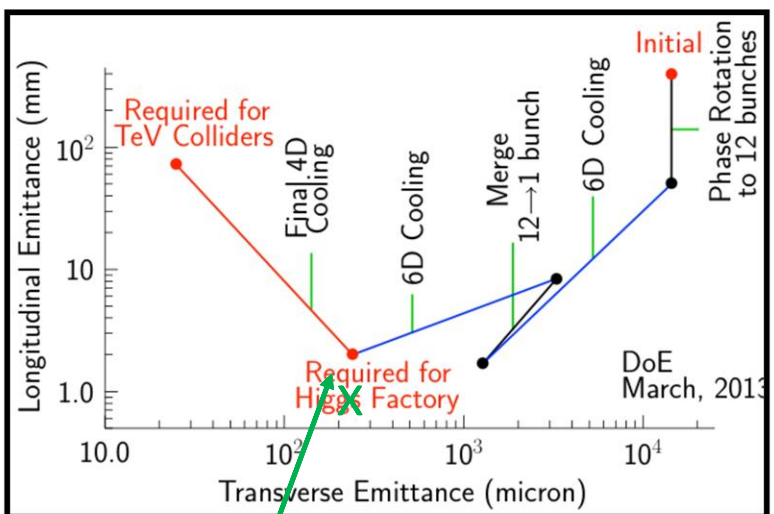



- Through the MAP program, we delivered 6D cooling designs in place with realistic assumptions
  - **Matched the desired performance goal**
  - Conservative limits on RF and magnet technology
  - Improvements expected with recent technology advancements

# Performance

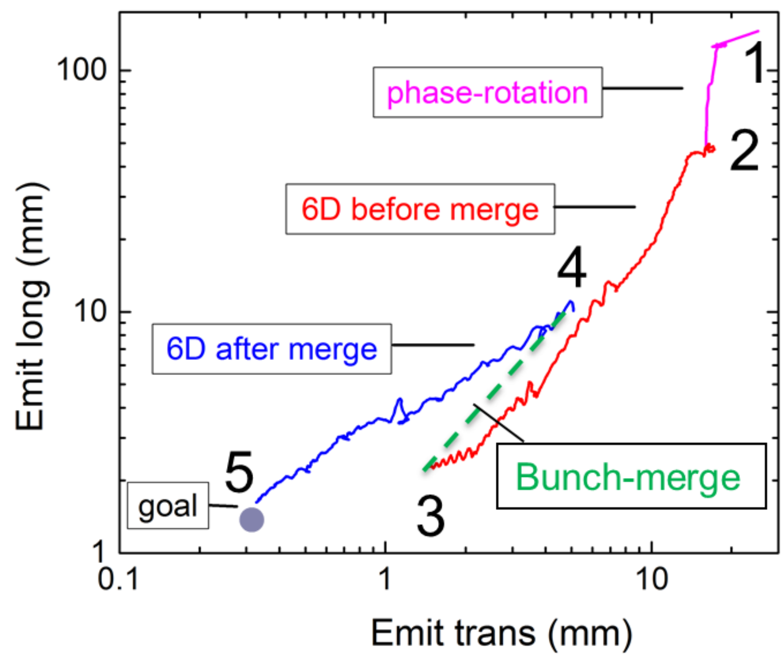
- Complete end-to-end simulation from the target (point 1)
- 6D emittance reduction by five orders of magnitude (point 5)
- Achieved emittances and transmissions specified by MAP
- Overall distance ~ 900 m

Baseline



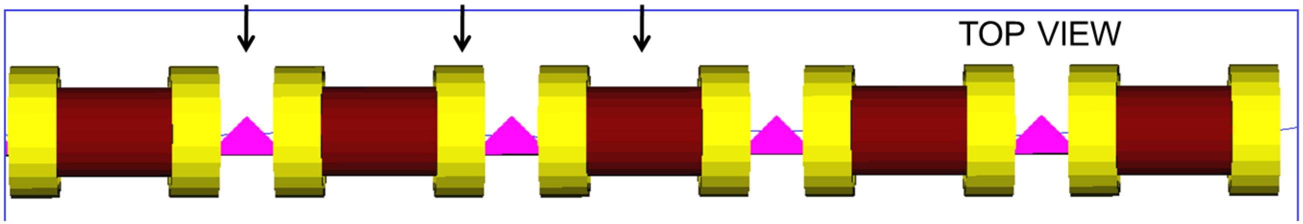

Emittances achieved

End-to-End to simulation



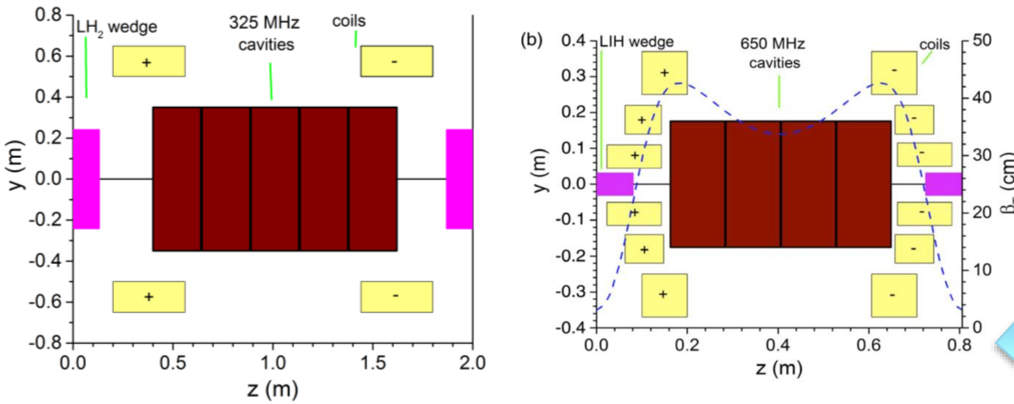
# Ionization cooling design for a MC – 6D cooling

- Multiple stages that vary in magnetic strength & rf requirements
  - 8 stages: B-Field and rf gradient progressively larger from stage to stage
  - **The cells are becoming more challenging in terns of engineering towards the end**

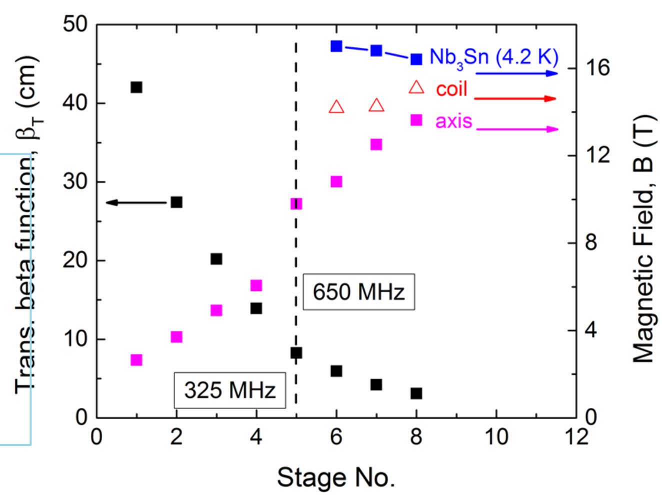



Early stage (2 T)

Late stage (14 T)




Closely packed coils Strong forces & stresses



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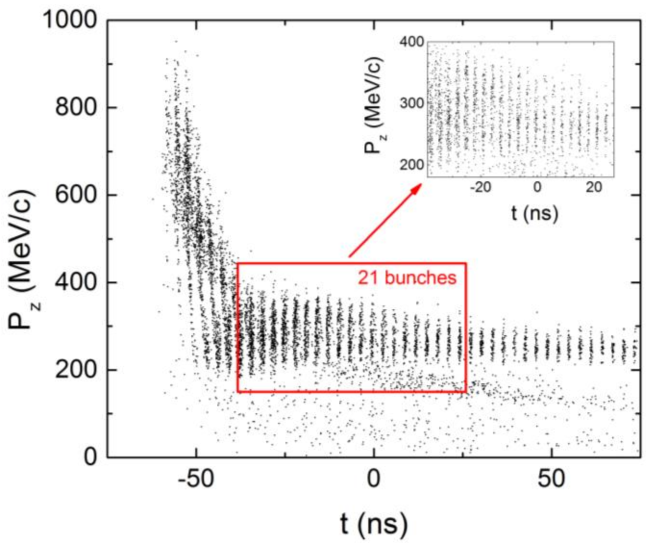
# Comments on performance

- Early stages had LH while later stages had LiH absorbers
- The starting distribution was the one delivered after phase-rotation in the front-end section
- The cooling "performance" was evaluated with the program ecalc9f based on "agreed" momentum cuts and acceptances
- Momentum cut we used to evaluate transmission was between 150 and 350 MeV/c

| Stage | $\varepsilon_T^{\mathrm{sim}}$ [mm] | $\varepsilon_L^{\mathrm{sim}}$ [mm] | $P_z^{\mathrm{sim}}$ [MeV/$c$] | $T$ [%] |
|---|---|---|---|---|
| Begin | 17.00 | 46.00 | 255 | |
| A1 | 6.28 | 14.48 | 238 | 70.6 |
| A2 | 3.40 | 4.64 | 229 | 87.5 |
| A3 | 2.07 | 2.60 | 220 | 88.8 |
| A4 | 1.48 | 2.35 | 215 | 94.6 |
| Begin | 5.10 | 10.04 | 209 | |
| B1 | 3.76 | 7.76 | 210 | 89.7 |
| B2 | 2.40 | 6.10 | 208 | 90.6 |
| B3 | 1.55 | 4.28 | 207 | 89.2 |
| B4 | 1.10 | 3.40 | 207 | 89.7 |
| B5 | 0.68 | 2.97 | 204 | 87.5 |
| B6 | 0.50 | 2.16 | 202 | 88.0 |
| B7 | 0.38 | 1.93 | 200 | 89.6 |
| B8 | 0.28 | 1.57 | 200 | 89.0 |



# Cooling: Where are we now

- Strong participation of the MC community at Snowmass
- Best case scenario: Muon Collider activities could resume in the US after a positive outcome of P5 next year
- Under that scenario, for Summer 2023
  - Expect to have 1-2 interns to work on Muon cooling designs
- For FY24
  - Submit a proposal through Fermilab's LDRD program
  - PhD student support through the Fermilab-Joint University program?
  - DOE funding?

# Topics of interest

- Recall that cooling has significant impact on PD requirements
- Past designs were conservative in magnet and rf technology
  – Critical to understand the impact of a higher solenoidal and rf fields on the overall design. Will this improve performance?
- What are the limits of 6D cooling
  – Don Summers showed that with higher fields and more stages we can cool more with a rectilinear channel. Is this beneficial?
- Study critical processes such beam loading or beam-absorber interactions
  – What modifications are needed if this becomes a problem?
- Final cooling alternatives: Benefits of Neuffer's wedge cooler?
- Explore cooling demonstrator options in the US