Challenging of muon acceleration for muon colliders

Story based on Fermilab Accelerator Complex Evolution

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HB2023 Workshop

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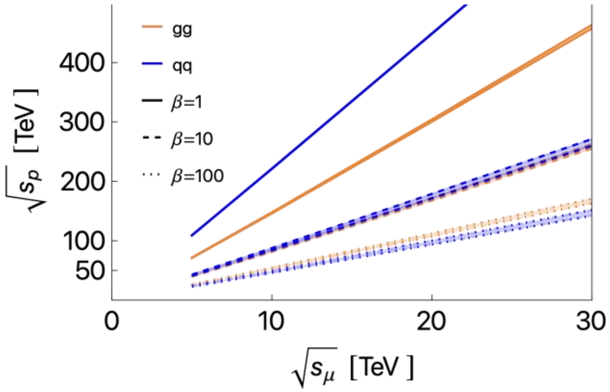
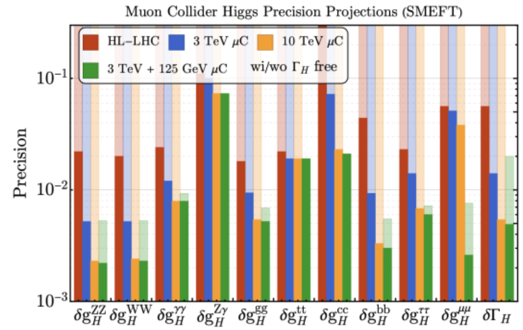
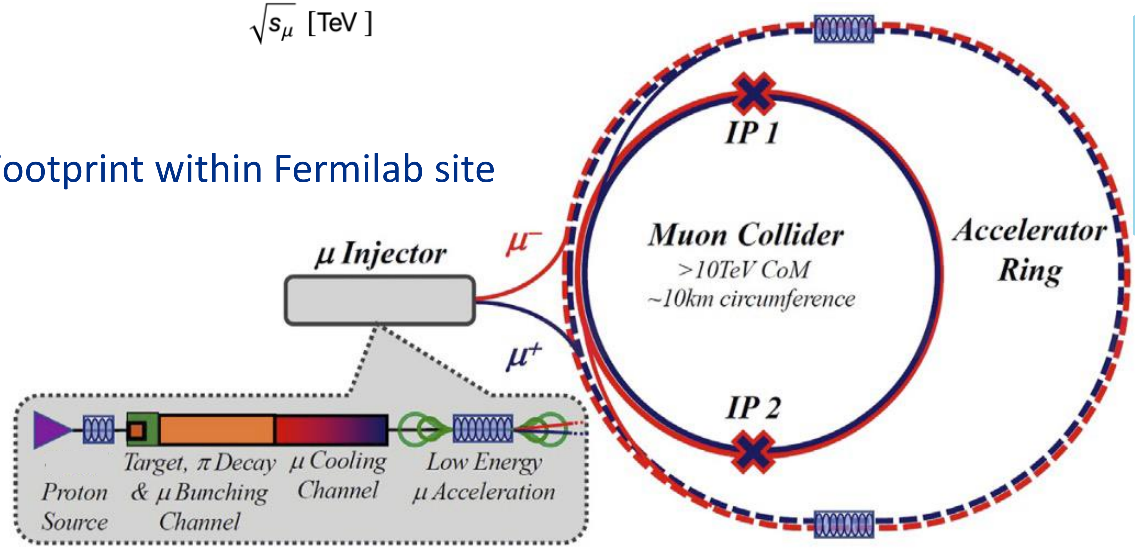
Discovery Machine MuC Design Parameter





- MuC COM can be fully utilized for physics events
- Clean lepton collision event allows for precise measurements

Footprint within Fermilab site



@ 3 TeV	~	1	ab^{-1}	5 years
@ 10 TeV	~	10	ab^{-1}	5 years

$$\mathcal{L} = \frac{N_{\mu^+} N_{\mu^-} \cdot f N_{IP} R}{4\pi\sigma_x \cdot \sigma_y}$$

f: Revolution of beam in the ring
N_{IP}: Number of interaction points
R: Beam repetition rate

Muon Acceleration Requirement

- Make muon beam phase space as small as possible (small σ_x, σ_y)
- Maintain muon beam intensity as much as possible (large N_{μ^+}, N_{μ^-})

Challenge in Initial Stage Muon Acceleration

- Proton Driver (Find extra slides in “Backup”)
  - Intense proton beam (~10^{14} protons per bunch, small spot size ~5 mm, bunch length 1~3 ns, and repetition is 5~10 Hz) with kinetic energy range 5-20 GeV
  - Beam parameter is limited by the **space charge effect**
- Pion Production Target and Pion/Muon Capture Channel
  - Target must stand for the impact of extremely intense proton beam
  - Heat deposition system, beam dump, and beam absorbers are needed without losing production and capture efficiencies
  - Capture magnet (baseline design is a solenoid magnet) must survive in extremely high radiation environments
- Muon Ionization Cooling (Find extra slides in “Backup”)
  - Maximize cooling decrement and minimize particle loss

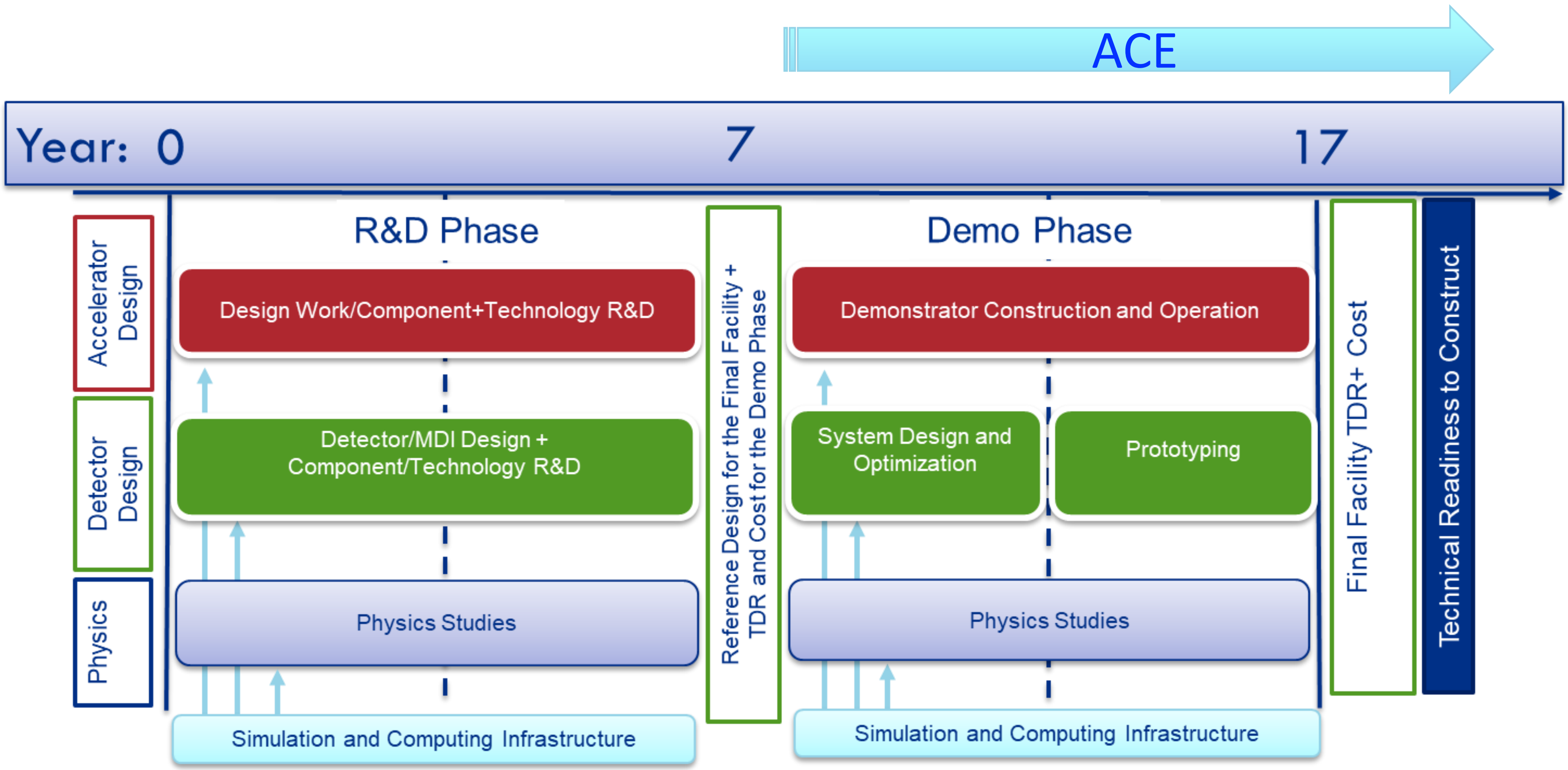
R&D are necessary to tackle these challenges

Accelerator Complex Evolution (ACE) plan

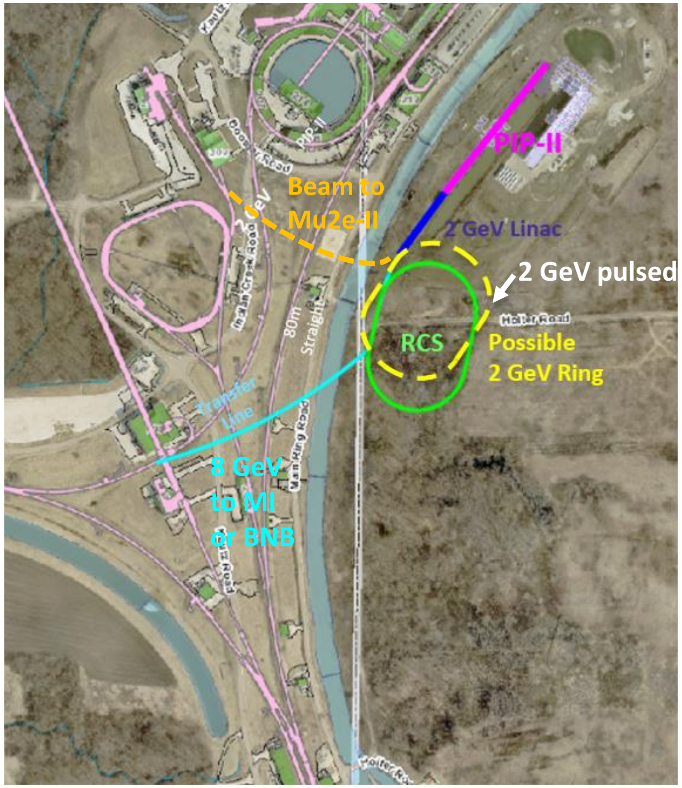
- Increase protons on target to DUNE Phase I detector by
  - Shortening the Main Injector cycle time to increase beam power
  - Upgrading target systems for up to 2.4 MW
  - Improving reliability of the Complex
- Establish a project to build a Booster replacement to
  - Provide a robust and **reliable** platform for the future of the Accelerator Complex
  - Ensure high intensity for DUNE Phase II CP-Violation measurement
  - Enable the **capability** of the complex to serve precision experiments and searches for new physics with beams from 1-120 GeV
  - Create the **capacity** to adapt to new discoveries
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research

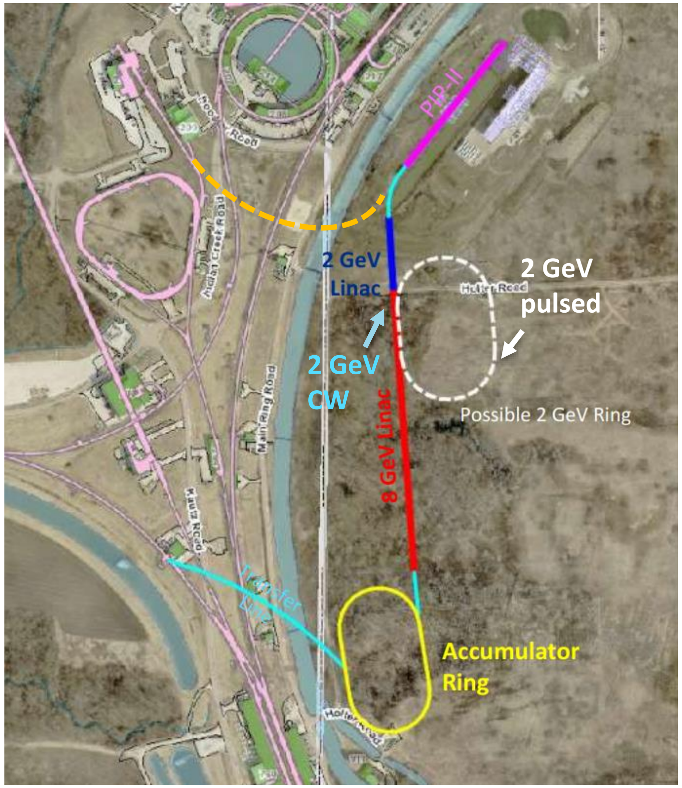
Courtesy of M. Convery, ACE workshop 2023 at Fermilab
J. Eldred also presents in HB2023

Suggested US Muon Collider R&D timeline to P5



Example Booster replacement options and possible add-ons





Courtesy of M. Convery, ACE workshop 2023 at Fermilab

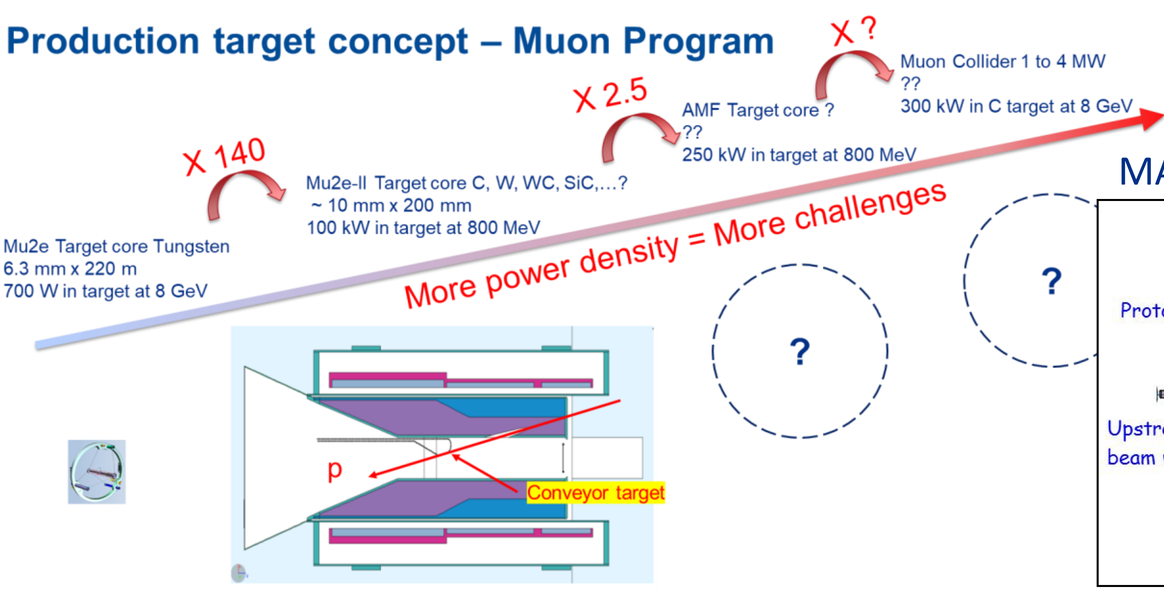
Possible 8 GeV Booster Beam parameter in Demo Phase

- Share beam with BNB and LBNF programs
- Booster provides 1.8μs pulses every 20 Hz of 6.5e12 protons at 8 GeV
- Impacted by MI cycle rate, but at least as high as present

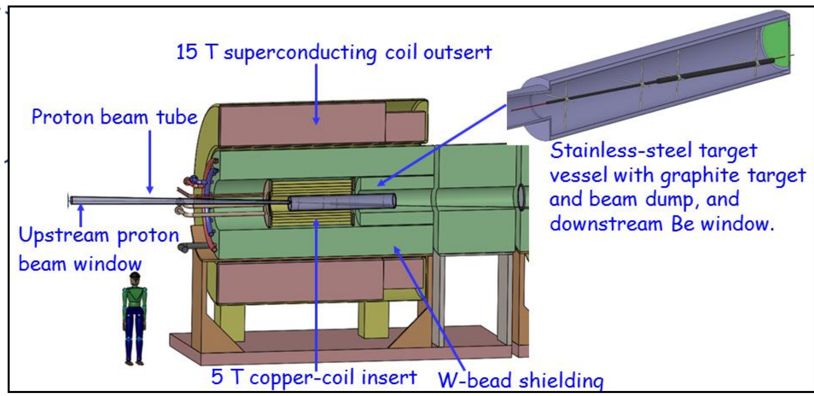
		PIP-II Booster		
Operation scenario	**Present**	**PIP-II**	**A**	**B**
MI 120 GeV ramp rate	**1.333**	**1.2**	0.9	**0.7**
Booster intensity	**4.5**			**6.5**
Booster ramp rate	15			**20**
Number of batches	12		12	
MI power	0.865	**1.2**	1.7	**2.14**
cycles for 8 GeV	6	12	6	2
Available 8 GeV power	29	**83**	56	**24**

Milestone of Targetry R&D for Future Projects

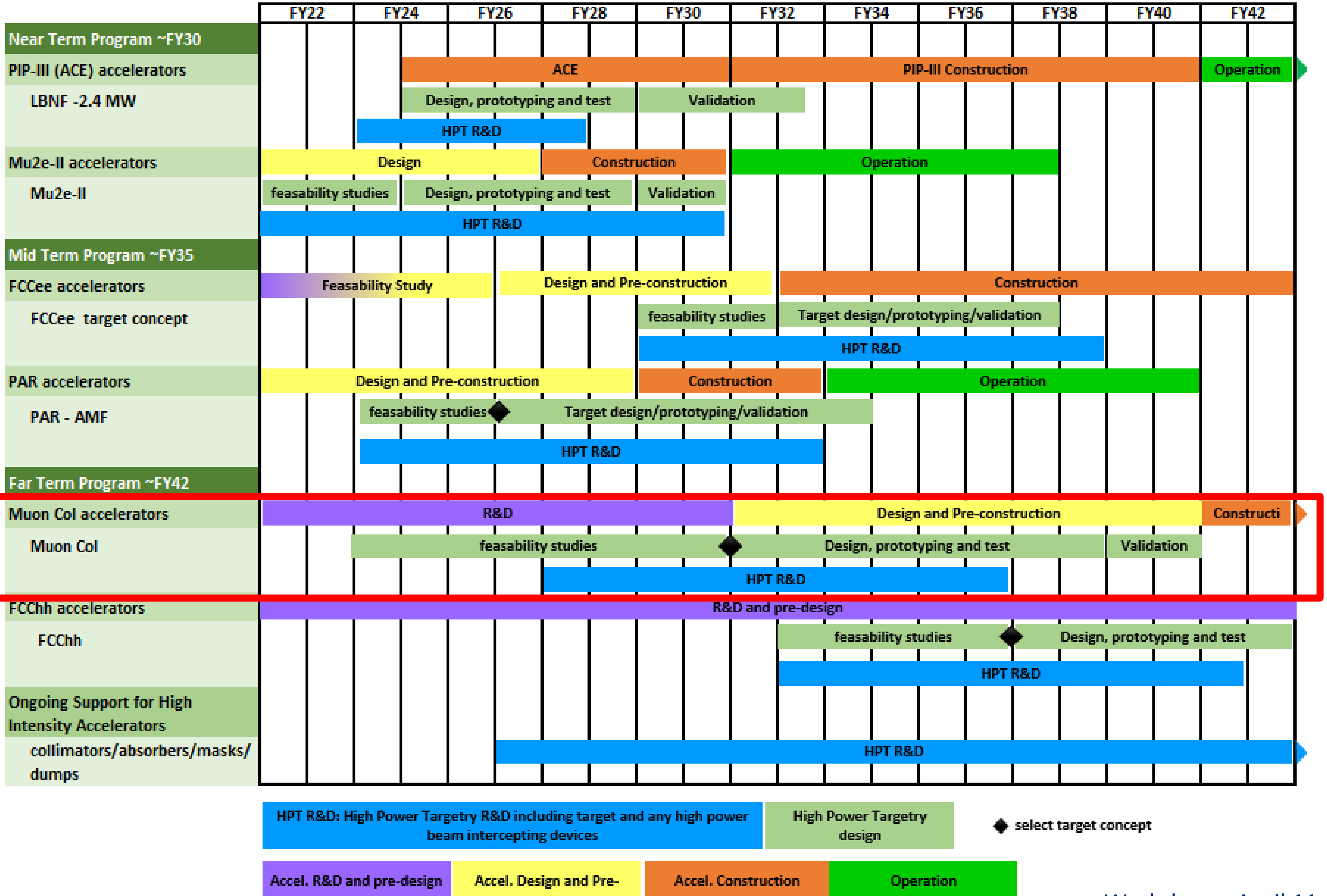
- High Power Target technology has been developed for neutrino program
  - Established 1.2 MW graphite target for LBNF
  - ACE plan pushes the target R&D to produce 2+ MW target
- ACE plan opens more high power target applications
  - Target R&D roadmap to support Mu2e+, AMF and MuC



MAP + IMCC design



Proposed Roadmap of Targetry R&D



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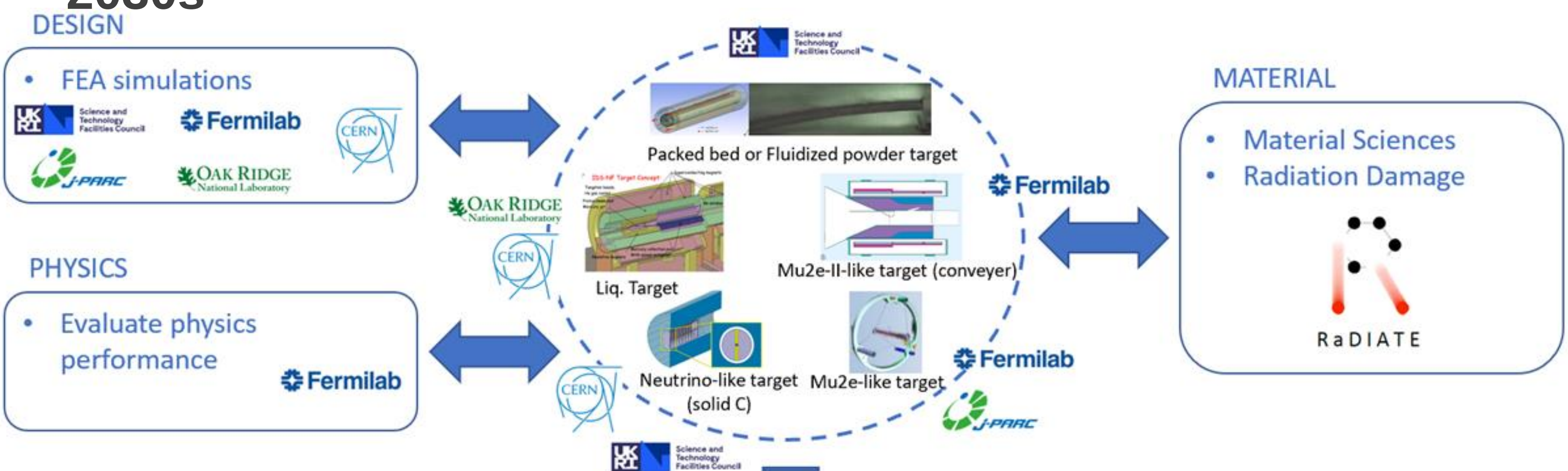
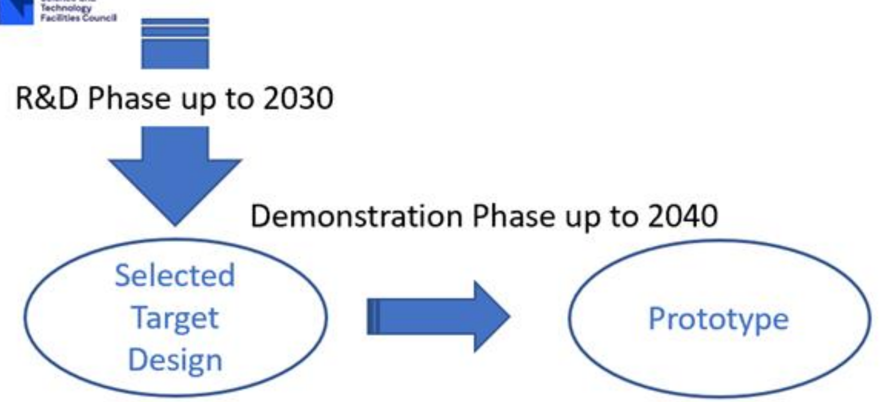
International Targetry R&D programs

- MuC targetry is included in the proposed GARD High Power Targetry Roadmap with a plan to have a prototype in the **late 2030s**



ACE & SNS are potential to carry on the high power target R&D

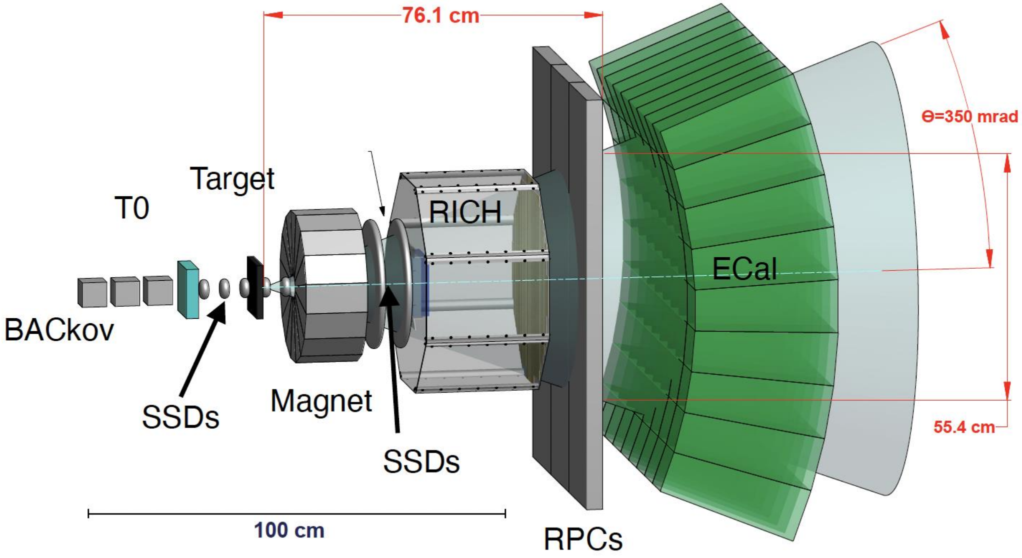


R&D
should start now!

Optimize MuC Target performance

- Select the building material including shielding block, beam window based on the material study
  - Study radiation & thermal stresses of building materials (RaDIATE)
- Design dimensions of target system from engineering and physics point views
  - Pion yield study
    - Angular distribution
    - Target Z dependence
    - Energy dependence
    - Hadronic shower

EMPHATIC
for yield study

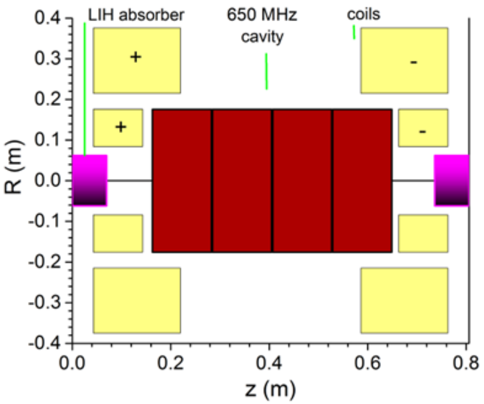


Muon Cooling Channel Hardware R&D

Collaborate with International Muon Collider Collaboration (IMCC)

- High gradient RF cavity in strong magnetic fields
  - Study cold RF cavity with various wall materials (Cu, Be, Al)
  - Beam window
  - Power coupler
  - High power RF source
  - Gas-plasma process in gas-filled cavities (beam needed)
- Prototype cooling cell
  - Integrate high field magnet coils
  - Infrastructure
    - LN2
    - RF waveguide
    - Beam instrumentation

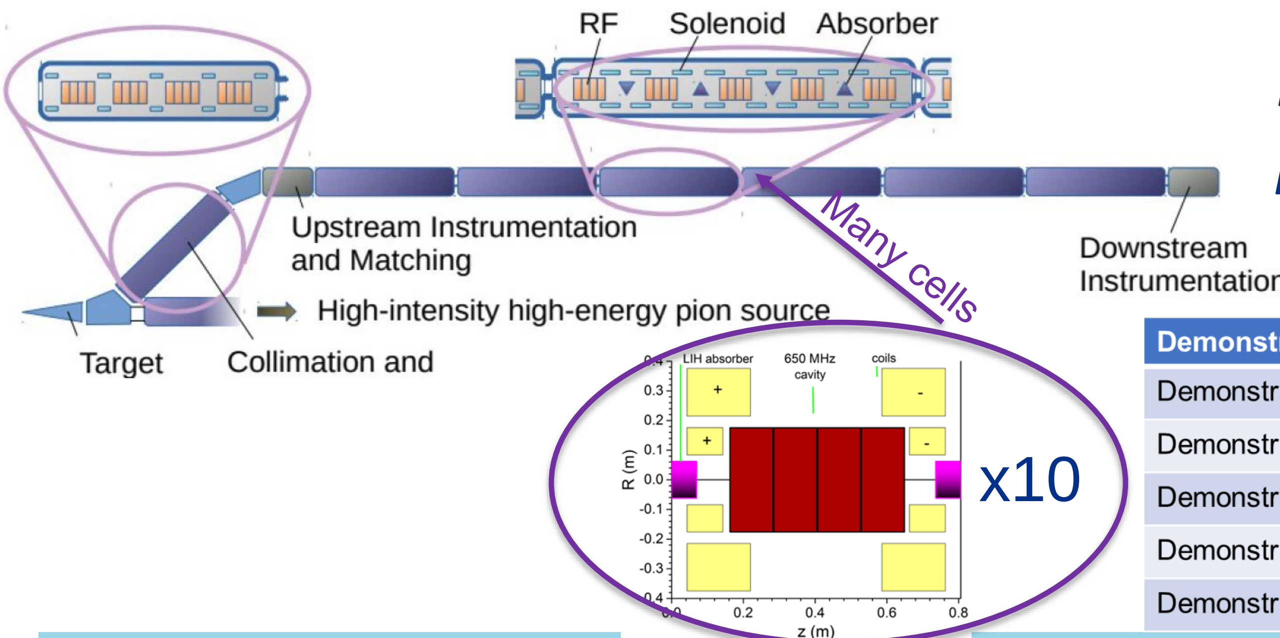
Example cooling cell



Muon Collider cooling: Path forward (demonstrator)

Collaborate with International Muon Collider Collaboration (IMCC)

- While the physics of ionization cooling has been shown it is **critical** to benchmark a **realistic** MuC cooling lattice
  - This will give us the input, knowledge, and experience to design a real, buildable cooling channel for a MuC
  - Next **5 years:** (1) A conceptual design of a demonstrator facility that allows testing the technology for cooling (2) Site exploration & cost estimate of a demo facility (3) Engineering design & start fabrication of a 1.5 prototype cooling cell



Demonstrator concept proposed by IMCC

Demonstrator plan
Demonstrate operation of NC rf in B-field environment
Demonstrate forces between coils are manageable
Demonstrate performance of absorbers
Demonstrate performance of instrumentation system
Demonstrate 6D cooling with a realistic set-up

Summary

- Concepts of Muon Colliders were reviewed by the HEP community in the US Snowmass and the P5 townhall meetings
  - White paper contains comprehensive narratives of the concepts which includes ACE and Booster replacement plan
  - P5 will release the report in December
- R&D for challenging of muon acceleration was presented in the meetings
  - Muon Cooling Channel Hardware R&D and Demonstrator will be a critical path; These concepts are shared with IMCC
  - Target R&D will utilize 8 and 120 GeV ACE beam in synergy with the Fermilab physics program; SNS shows an interest in conducting the R&D related with target and proton driver as well

Backup

Courtesy of S. Nagaitsev, ACE workshop 2023 at Fermilab

Present IMCC Baseline parameters

International MUON Collider Collaboration

- Beam Power: 2 MW
- Rep. rate: 5 Hz
- Beam spot size: ~ 5 mm (1σ)
- Bunch length: 2 ns (rms)
- Beam Energy: 5 and 10 GeV
- Linac + 2 rings (initial design)

This talk

- Beam Power: 2 MW
- Rep. rate: 10 Hz
- Beam spot size: ~ 5 mm (1σ)
- Bunch length: 2 ns = 0.6 m (rms)
- Beam Energy: 8 GeV
- Linac + 2 rings (initial design)
  - Combine 4 bunches on target

S. Nagaitsev | 06/14/23 8 Jefferson Lab

Courtesy of S. Nagaitsev, ACE workshop 2023 at Fermilab

What's important?

- Accumulator (accumulates 4 proton bunches):
  - Stripping injection and painting
  - Injection-related beam losses
  - Instabilities
    - Landau damping and feed-backs
  - Extraction kicker and septum magnet

$$P = 4N_b qEf_0 = 2\ \mathrm{MW}$$

- Buncher (rotates bunches by 90-degrees in the long phase-space):
  - Space-charge effects
  - Large energy spread (~1% rms)
  - Instabilities
    - Landau damping and feed-backs
  - Extraction kicker and septum magnet

$$\delta\nu \approx -\frac{3N_b r_p}{2\pi\beta\gamma^2\varepsilon_{n,rms}}\frac{C}{\sqrt{2\pi}\sigma_s} = -\frac{3r_p P}{4\sqrt{(2\pi)^3}\beta\gamma^2\sigma_s qEf_0}\frac{C}{\varepsilon_{n,rms}}$$

$\approx 2\times10^{-7}$???

$\delta\nu \approx -0.2$ -- Conservative approach

Tension: larger beam emittance makes magnets, kickers, rf systems more expensive, a shorter circumference, C, leads to superconducting magnets (also more expensive)

Courtesy of S. Nagaitsev, ACE workshop 2023 at Fermilab

Space-charge tune shift

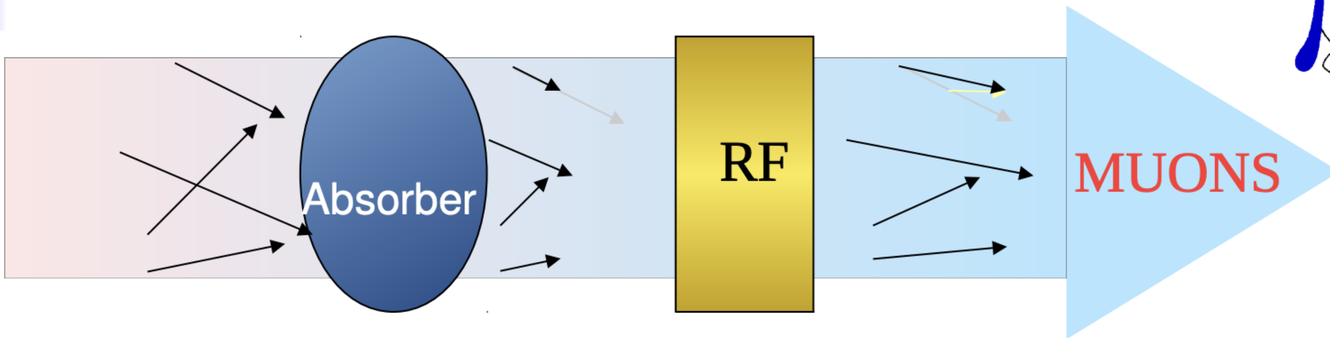
- SC tune shift $\delta\nu \approx -2\times10^{-7}\dfrac{C}{\varepsilon_{n,rms}}$ (this expression ignores the dispersive beam size)
  - Emittance: $\varepsilon_{n,rms} \approx 100\ \mu\text{m}$
  - Dispersive beam size helps with reducing the effective tune shift and may be important

$$\delta\nu_x \sim \left\langle \frac{\beta_x}{\sigma_x(\sigma_x+\sigma_y)} \right\rangle_s \qquad \sigma_x = \sqrt{\frac{\beta_x\varepsilon_{n,rms}}{\beta\gamma} + \left(D_x\frac{\delta p}{p}\right)^2}$$

- We would like to limit the SC tune shift to ~0.2 at extraction from the Buncher
  - This gives us $C \approx 100\ \text{m}$ -- Buncher circumference
  - Dispersion may help with space-charge but we must remember that the ring must have a large momentum acceptance (~few%)

- Thus, our first conclusion:
  - The Buncher ring should be about 100 m in circumference with 4 bunches

Ionisation Cooling



- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more parallel
- Multiple Coulomb scattering from nuclei ruins the effect
  - Mitigate with tight focussing
  - Mitigate with low-Z materials
  - Equilibrium emittance where MCS cancels the cooling
- Verified by the Muon Ionisation Cooling Experiment (MICE)

Courtesy of C. Rogers, NuFACT workshop 2022

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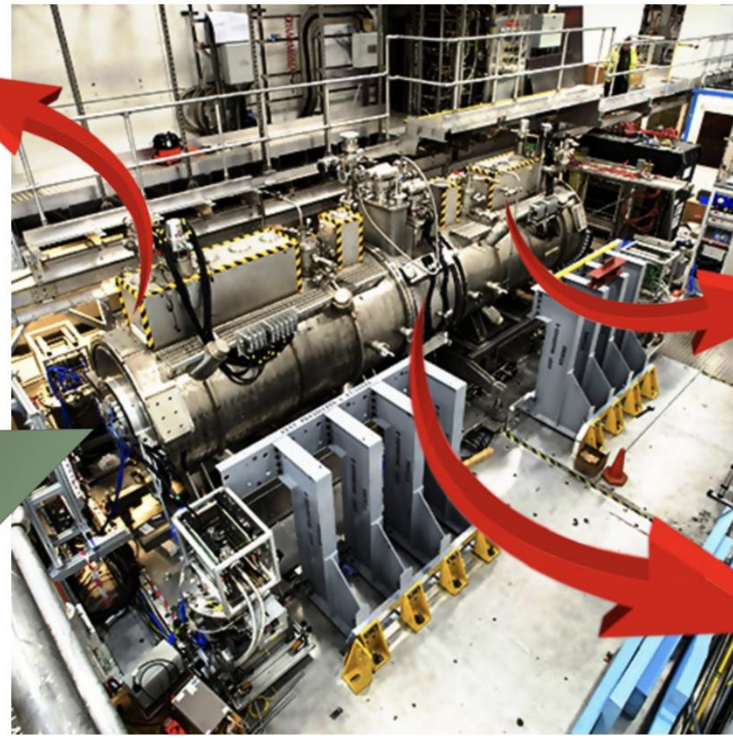
Experimental set up

Measure muon position and momentum upstream



Beam

Measure muon position and momentum downstream

Cool the muon beam using LiH, LH_2, or polyethylene wedge absorbers

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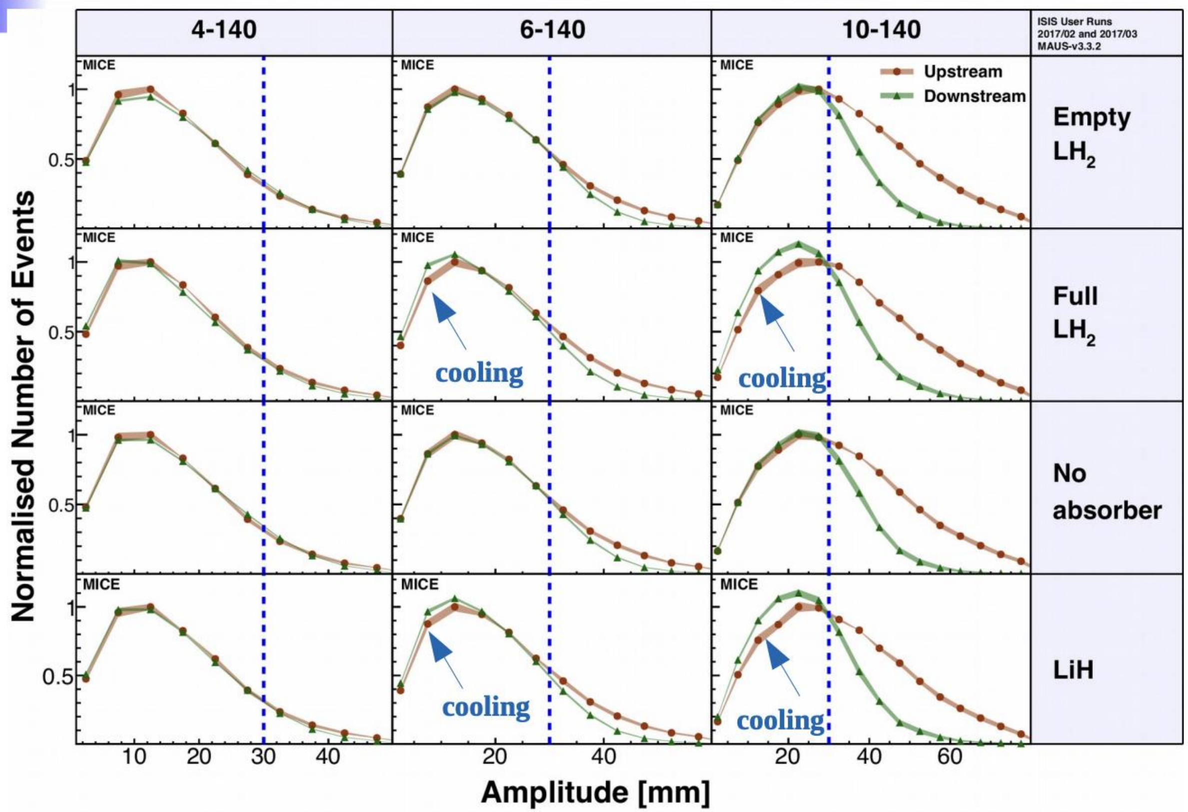
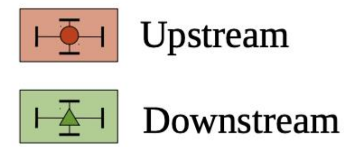
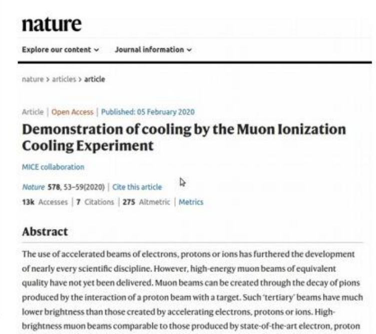
Change in Amplitude Across Absorber



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Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

Nature **578**, 53–59(2020) | Cite this article

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Abstract

The use of accelerated beams of electrons, protons or ions has furthered the development of nearly every scientific discipline. However, high-energy muon beams of equivalent quality have not yet been delivered. Muon beams can be created through the decay of pions produced by the interaction of a proton beam with a target. Such 'tertiary' beams have much lower brightness than those created by accelerating electrons, protons or ions. High-brightness muon beams comparable to those produced by state-of-the-art electron, proton

- No absorber → slight decrease in number of core muons
- With absorber → increase in number of core muons
  - Cooling signal

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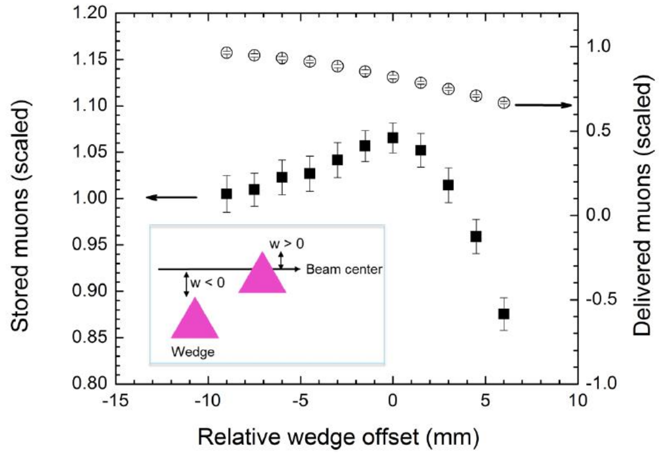
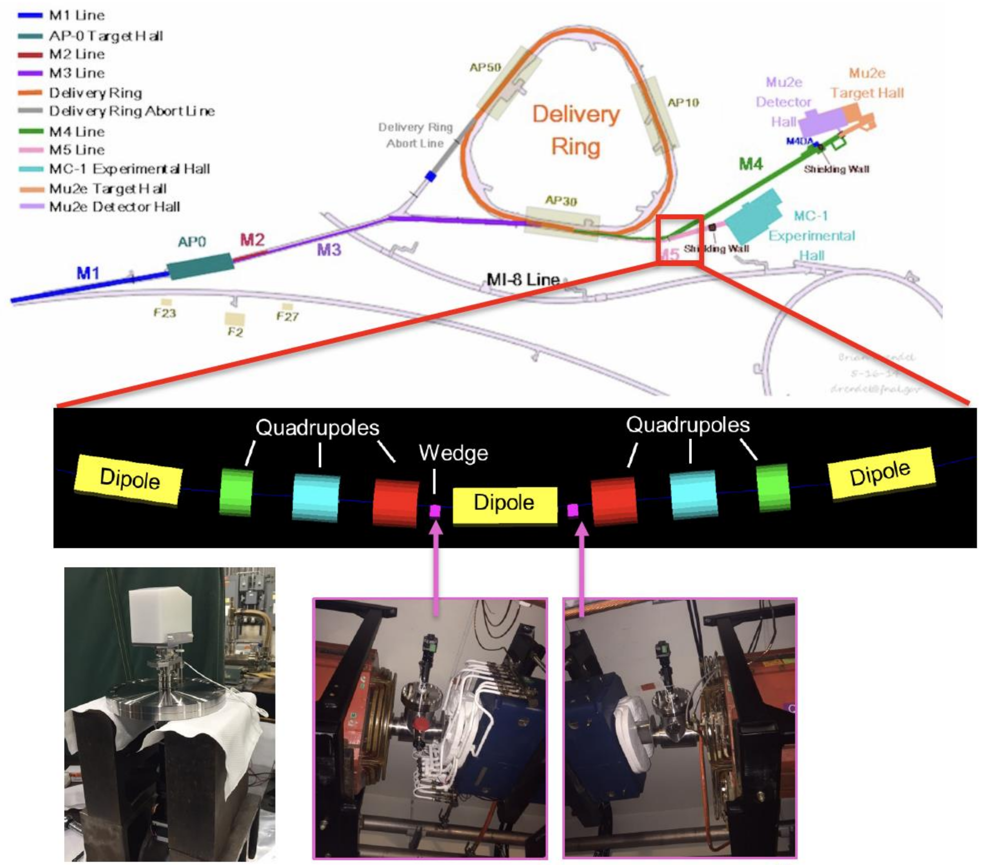
Muon Collider cooling: Past experience

- Proof-of-principle: Demonstrated a gain up to 8% in stored muons with a polyethylene wedge.

Compress momentum phase space by using wedge absorber





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