Cooling system design

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IMCC Muon Collider Demonstrator Workshop, Fermilab

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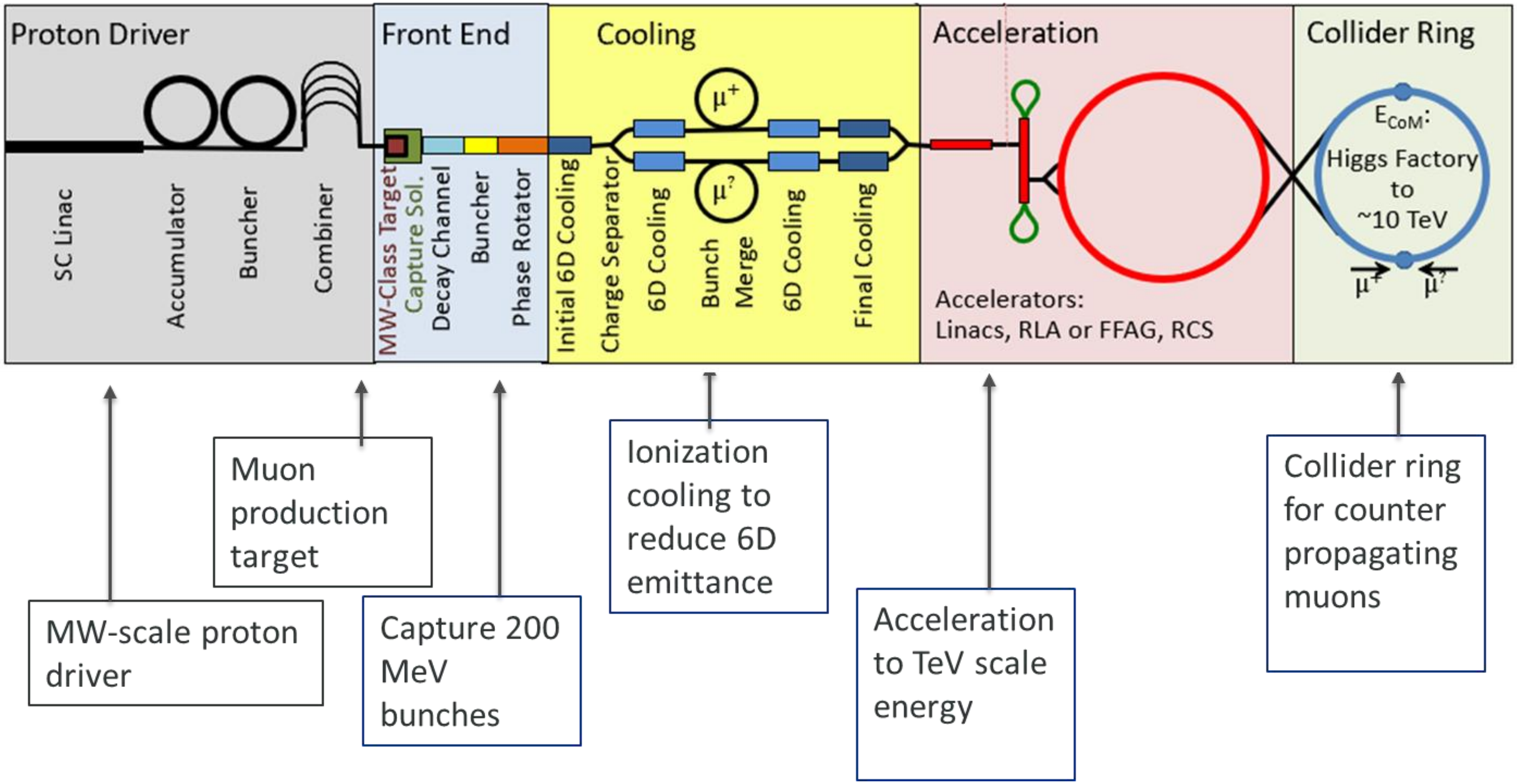
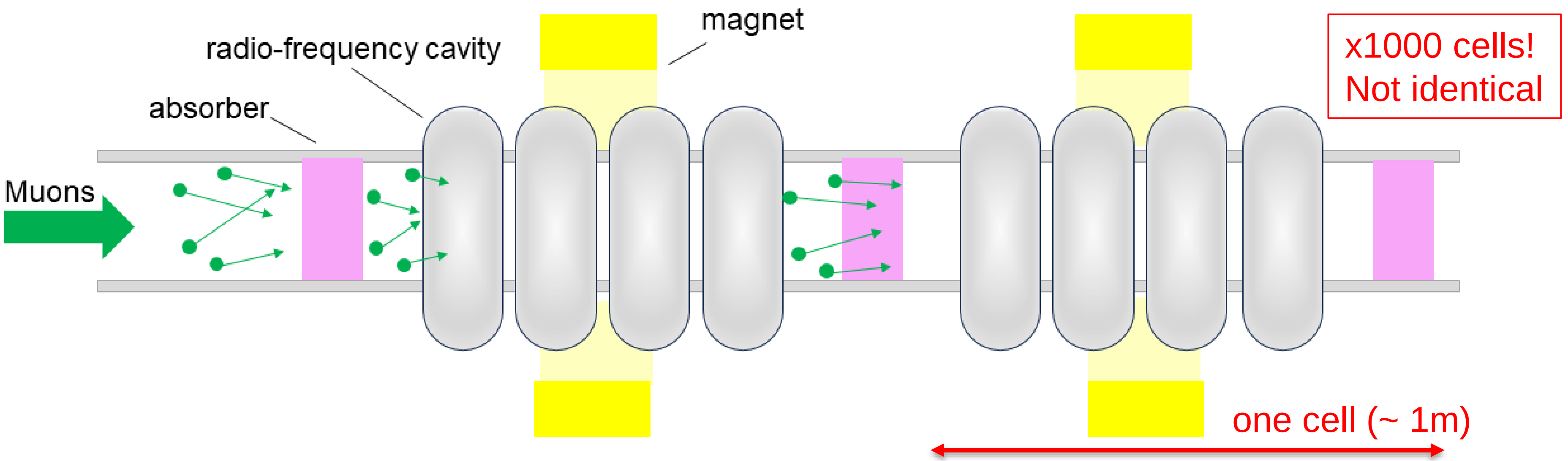
Muon Collider overview



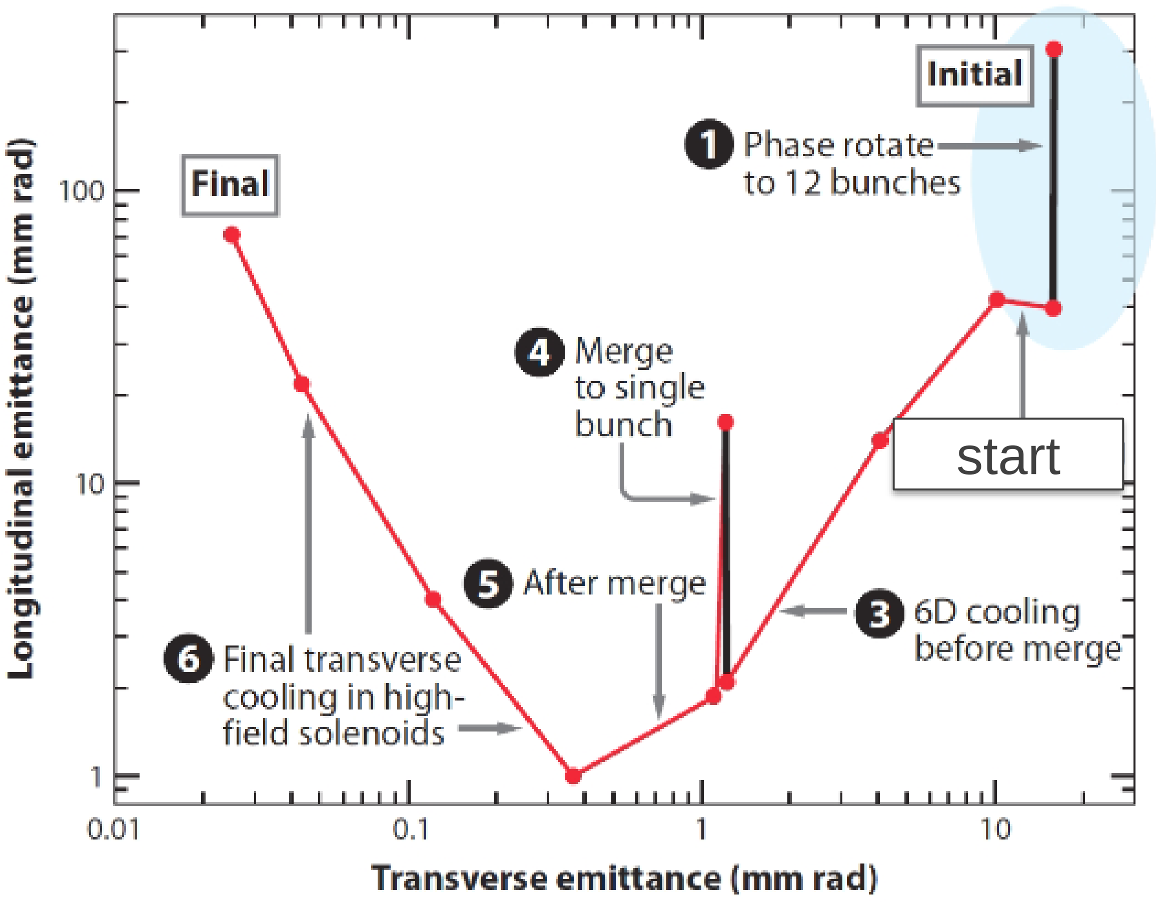
- Cooling has huge leverage on the overall machine design
  - What proton power is required? What target technology to choose?
  - What luminosities can be envisioned?

Concept of ionization cooling



- Considerations for MuC cooling:
  - Beam size must be small at the absorber to reduce scattering
  - Absorbers with low Z and large energy loss must be selected
  - Magnetic field has to increase in strength over distance to keep cooling
  - The magnetic field, makes normal conducting (NC) cavities the only option

Muon cooling baseline



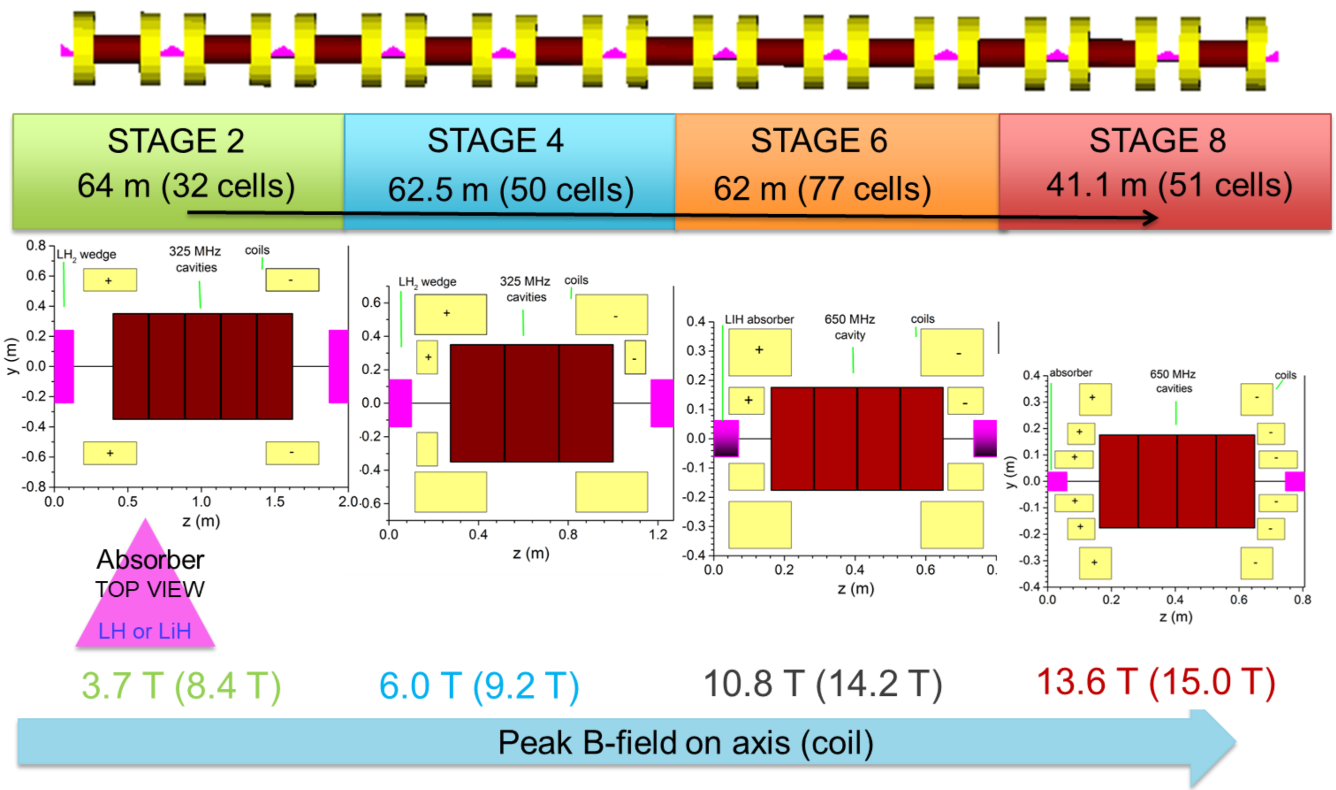
3, 5: Large bore magnets, from 2 T (500 mm IR), to 14 T (50 mm IR)

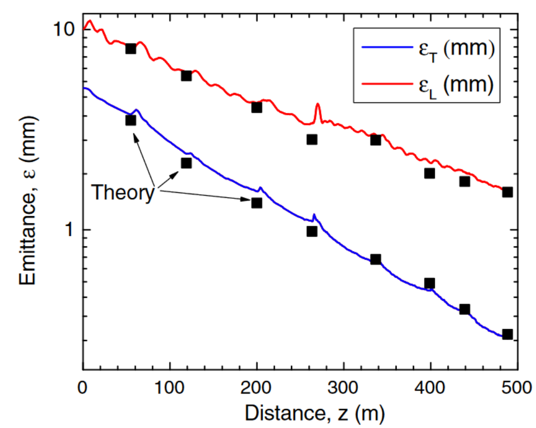
3, 5: Low frequency NC rf cavities (200 - 800 MHz) within multi-T fields

6: High-field solenoids (30-40 T) with 25 mm IR (about 10)

Design & simulation studies for cooling

- During the MAP-era a complete design of a Muon Collider cooling system was developed; further improved by the IMCC
- Simulation findings look very promising but more R&D is needed in order to benchmark some of the assumptions

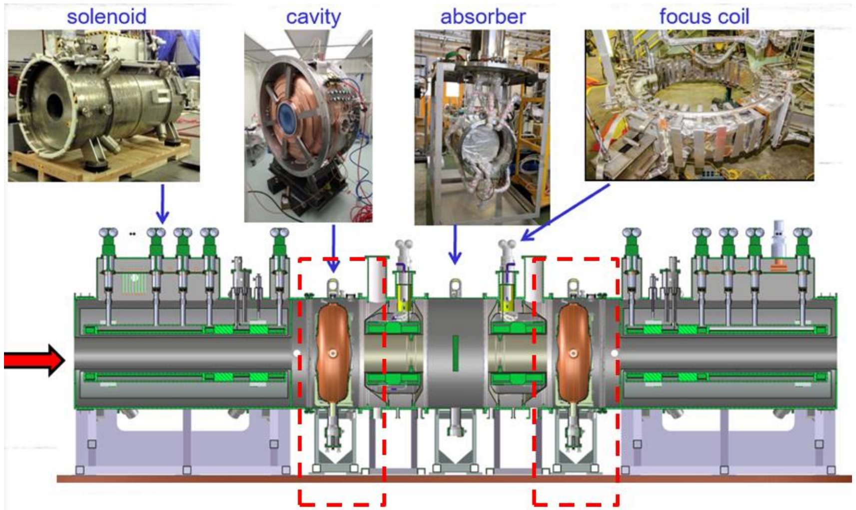


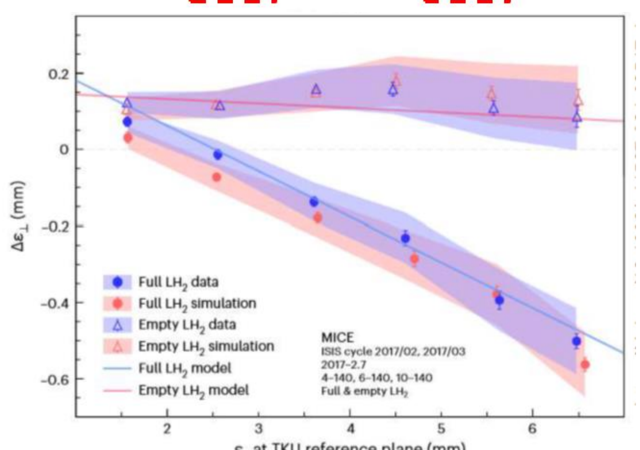


Principle verification

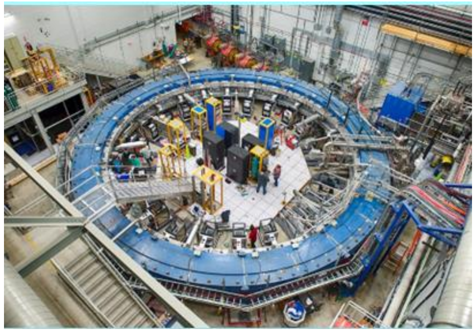
- Physics of ionization cooling has been demonstrated in two occasions

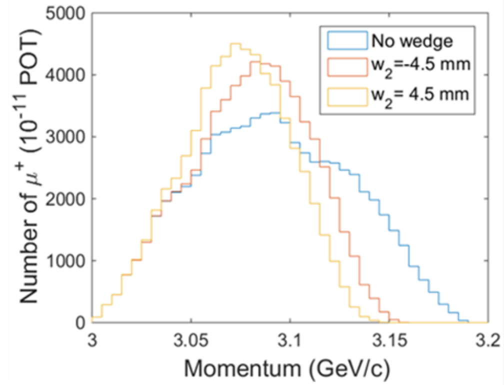
MICE Experiment

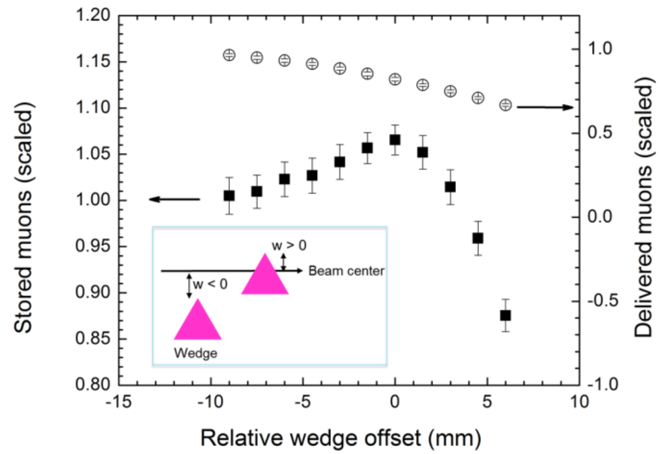


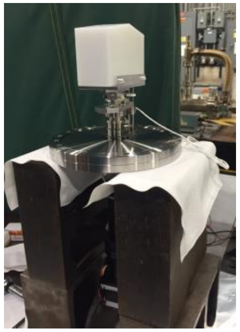


Fermilab Muon g-2 Experiment





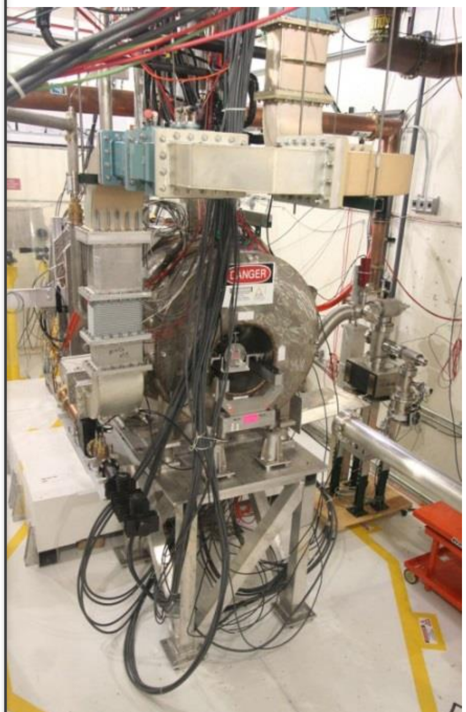


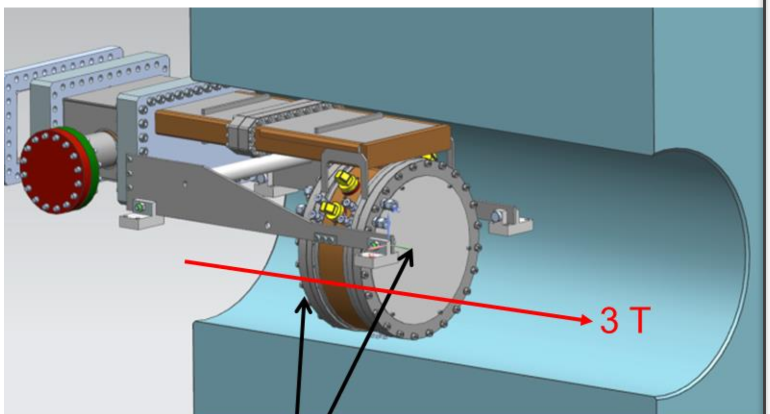


NC cavities in magnetic fields

- Behavior of NC cavities in B-fields (up to 3 T) was tested at Fermilab
  - Two technologies have demonstrated mitigation
  - Very encouraging!

Vacuum cavities

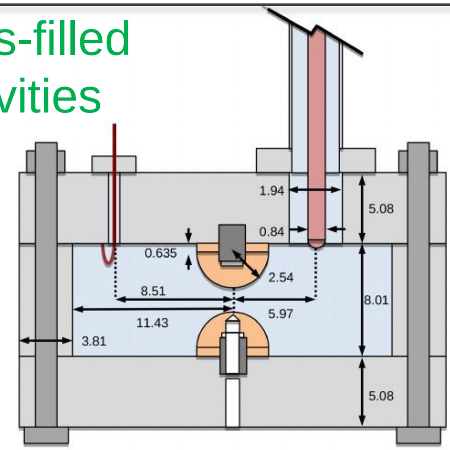


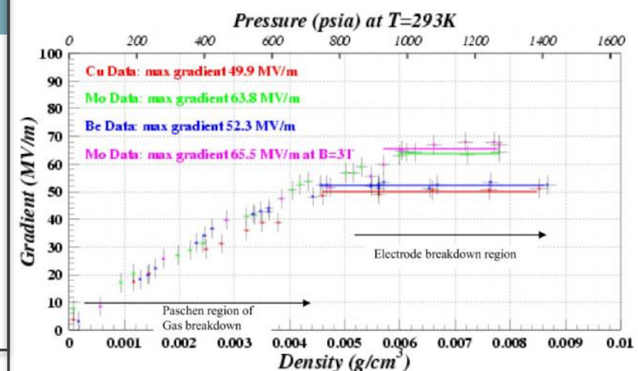


removable plates (Cu, Al, Be)

Material	B-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be/Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be/Cu	3	10.1 ± 0.1	0.48 ± 0.14

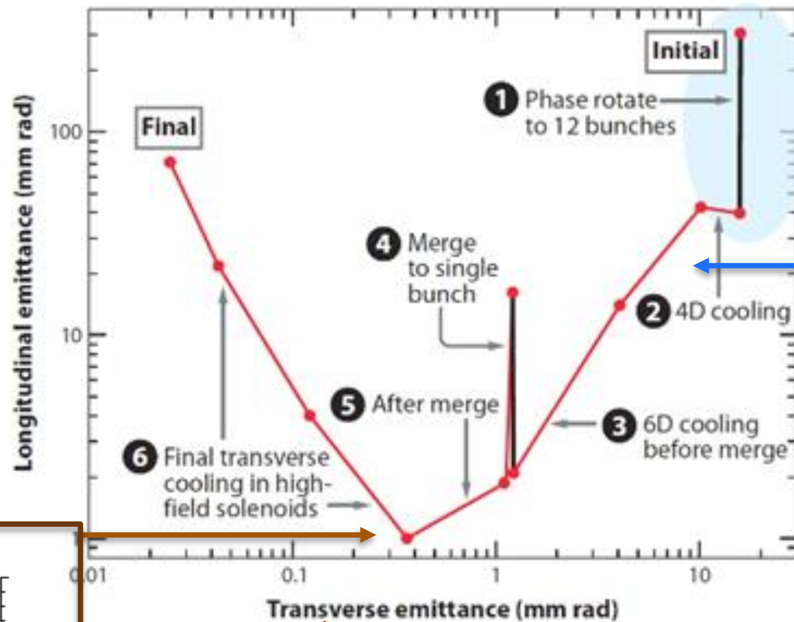
Gas-filled cavities

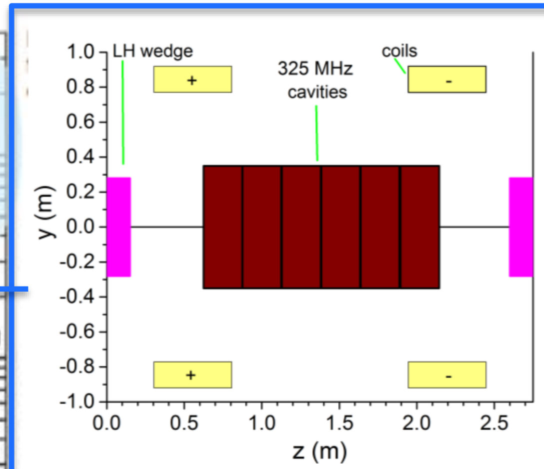




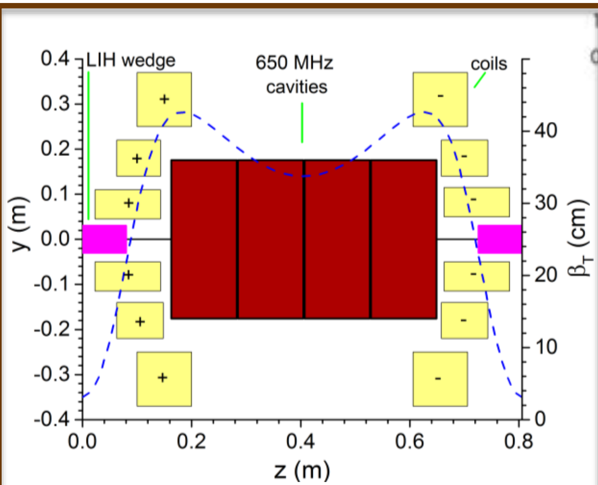
More R&D with vacuum & gas-filled rf + tests at higher B-field needed

Integration challenges





Early cell (“easy”) – 2T peak



Late cell (“hard”) – 14 T peak

Several multi-T solenoidal coils
Very tight space between rf and coils
Very tight space between coils
rf cavities exposed to multi-T fields

Fermilab

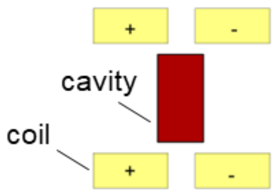
Motivation for a cooling demonstrator

- The principle of ionization cooling has been demonstrated
- As a next step it is critical to benchmark a realistic cooling lattice
  - This will give us the input, knowledge, and experience to design a real, operational cooling channel for a MuC
- It will advance magnet technology since we will design, prototype and test solenoids similar to those needed for a MuC
  - Synergistic with fusion reactors and axion dark matter searches
- It will advance rf cavity technology since we will design, prototype and test NC cavities similar to those need for a MuC
  - Opportunity to develop efficient klystrons that can be useful for future colliders
  - Opportunity to develop technology towards very high-gradient rf cavities for future colliders

Muon demonstrator staging

- Detailed parameters will depend on available funding and resources

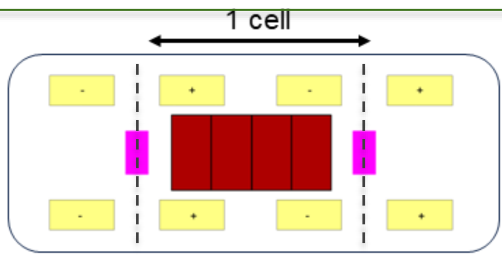
Phase-I



RF studies in B-fields

Material studies & cryogenic Cu

Phase-II

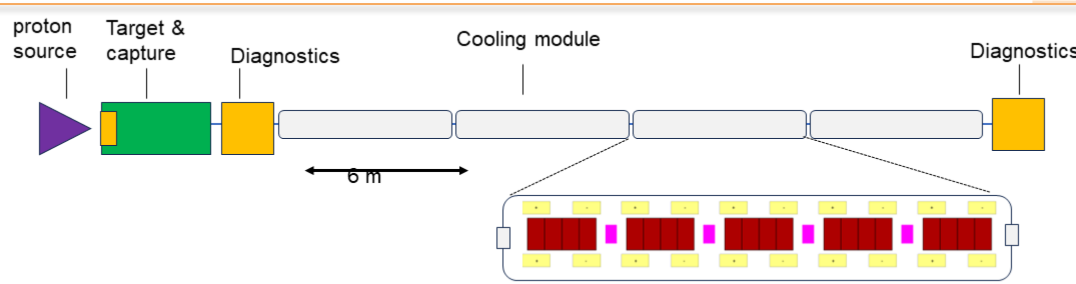


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III



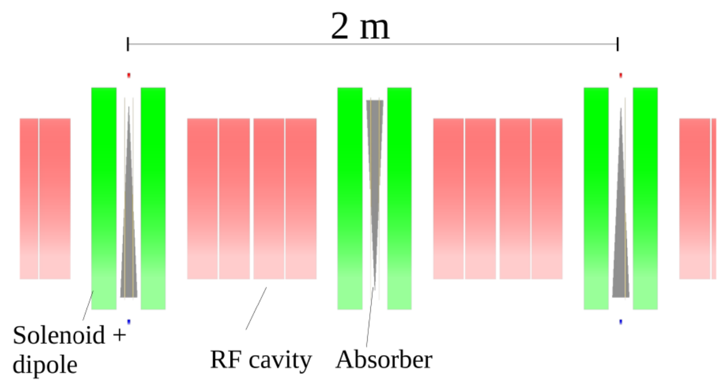
Full demonstrator with beam

Coils producing 7T axial fields

Potential to achieve 50% 6D cooling

Full demonstrator with beam

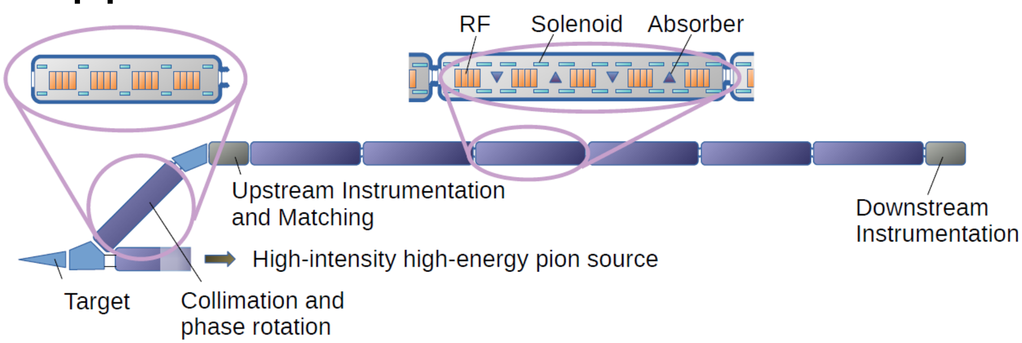
- Design in progress
  - Muon source, target and transport
  - Beam transport
  - Cooling channel

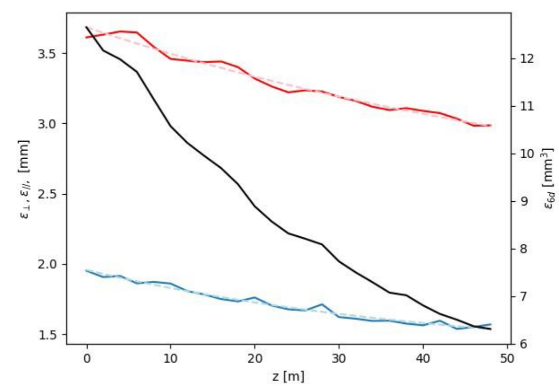


Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH

- **Design may be informed by the siting options**
- Investing synergies with other applications

	Muon energy, MeV	Total length, m	Total # of cells	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	2-14	x 1/10^5	~70%
Demonstrator	200	48	24	0.5-7	x 1/2	4-6%

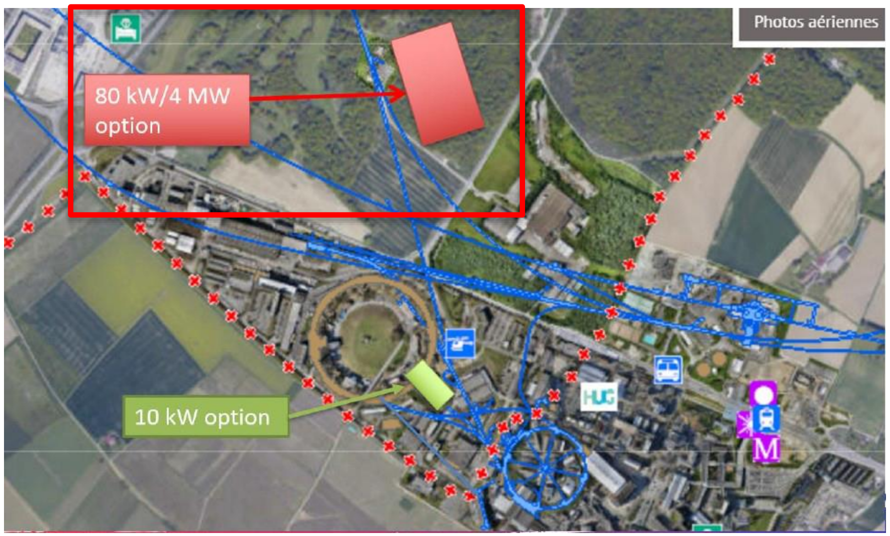


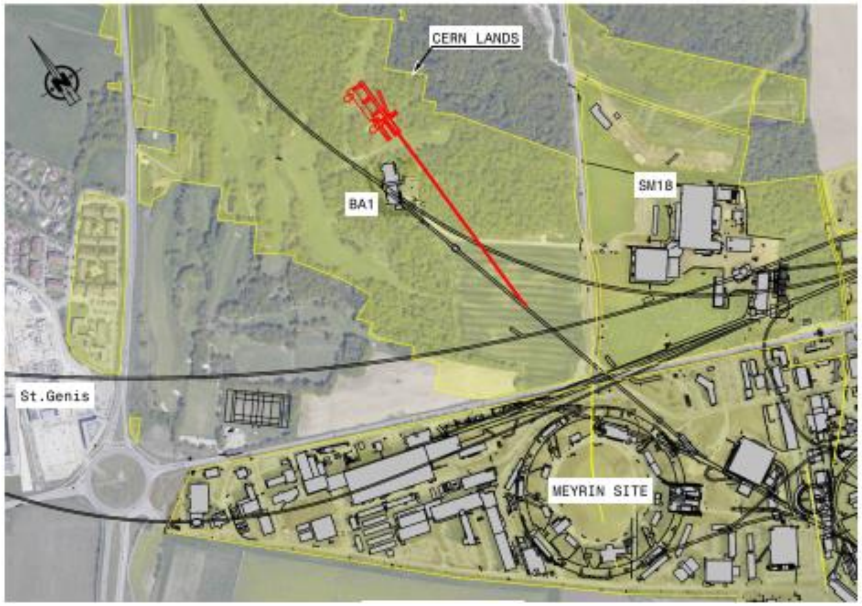


C. Rogers, Phys. Sci. Forum **2023**, 8(1), 37

Site at CERN: High power option

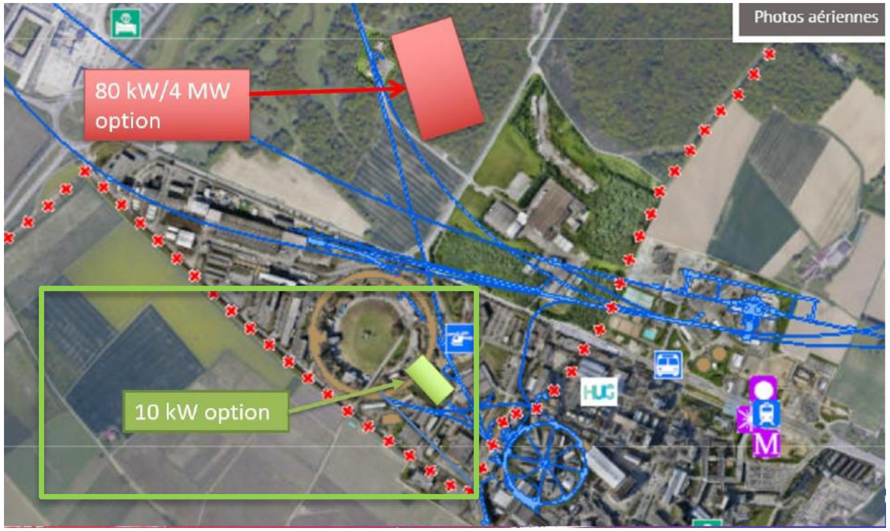
- TT10 is the transfer line between CERN PS and SPS
- From TT10 a new beamline would be extracted via a tunnel to the proposed Muon Collider Demonstrator Facility
    - 80 kW beam power
    - 20+ GeV with 10^{13} proton pulses of a few ns
    - Expensive option

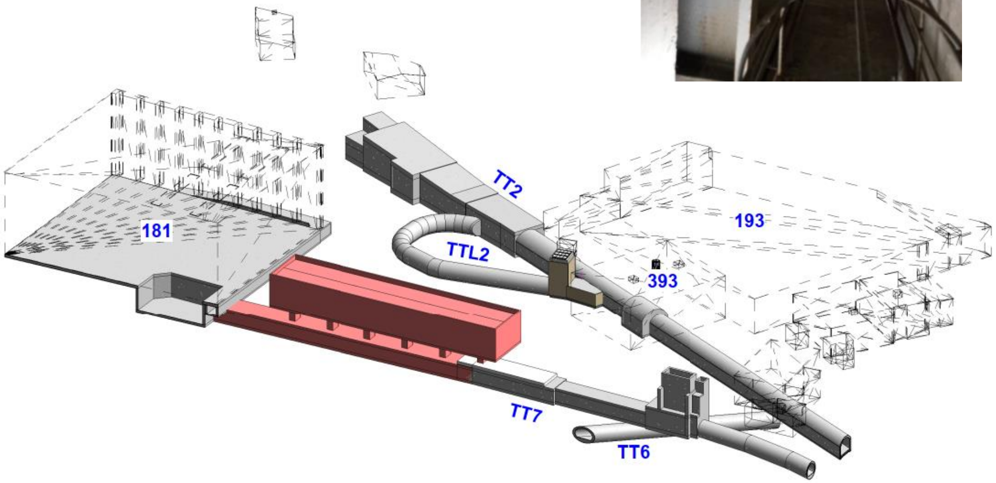




Site at CERN: Low power option

- Reuse the line of the Big European Bubble Chamber experiment
  - 10 kW beam power
  - 20+ GeV with 10^13 proton pulses of a few ns
  - Cheaper option

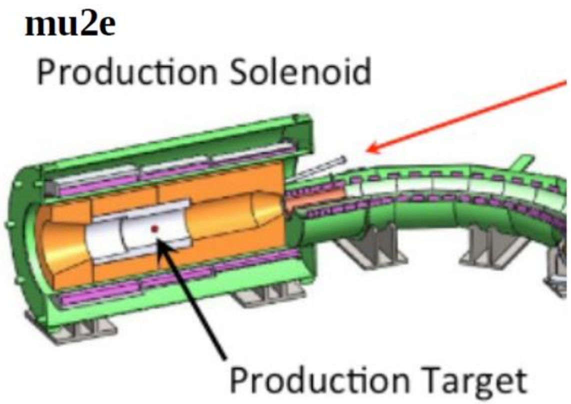




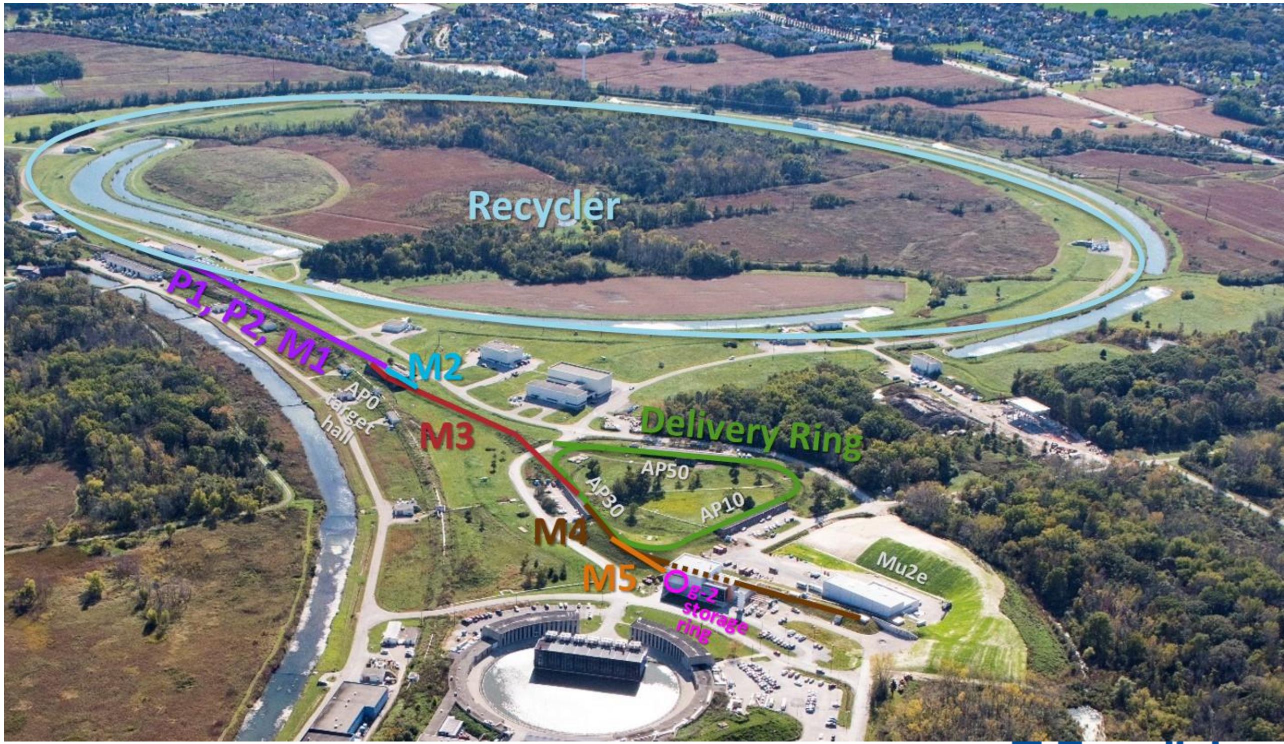
Fermilab

Site at Fermilab: Muon Campus

- Designed to provide beam for the Muon g-2 and Mu2e experiments
  - Capable to deliver **8 kW** beam at **8 GeV** to the Mu2e production target
  - Available tunnel space to run the demonstrator without interfering with Mu2e
  - Production target is similar to the MuC target

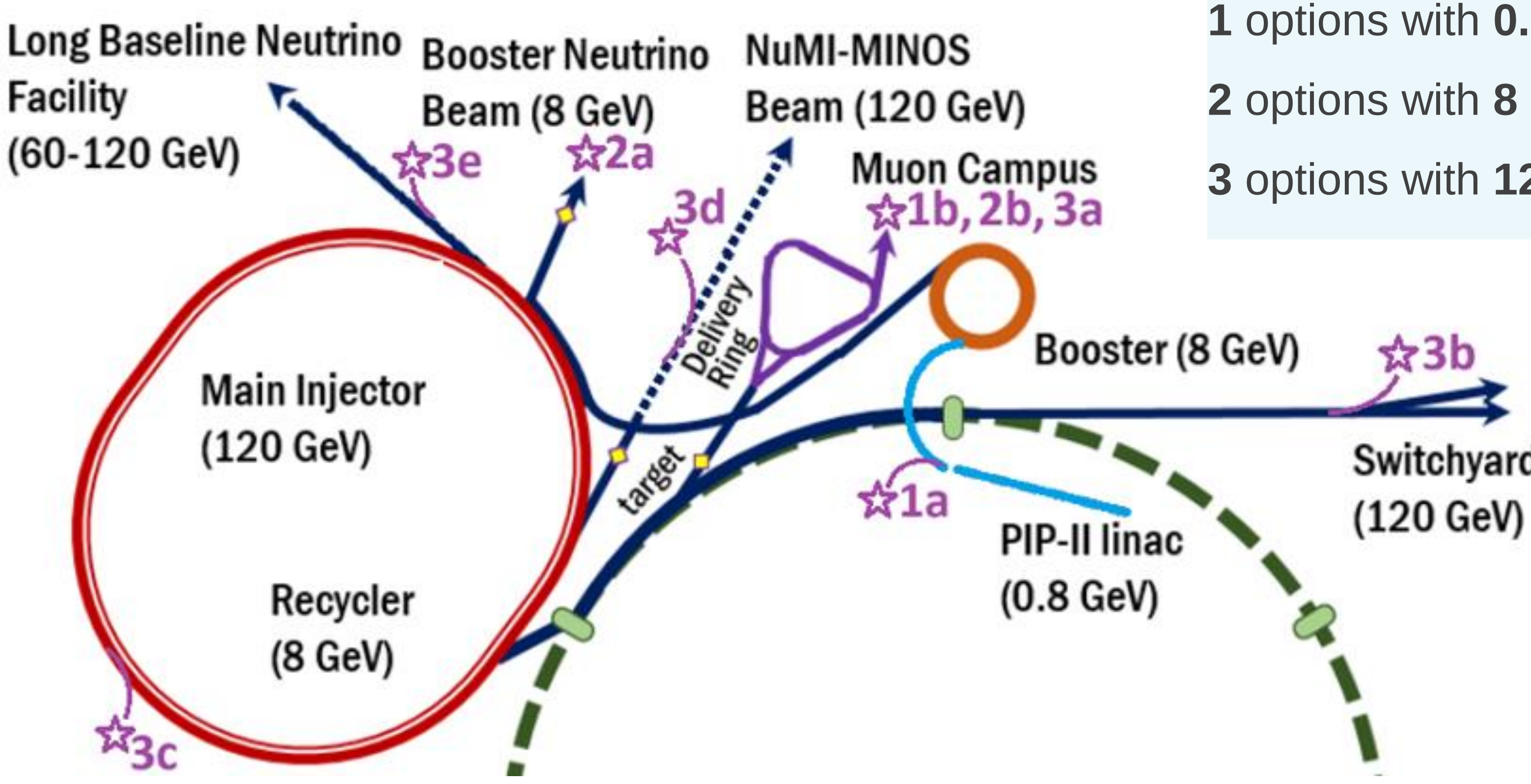


Excellent opportunity to examine targets under 5 T field



Other sites at Fermilab

- Several candidate locations are available and will be explored
- **More details see Jeff Eldred talk on Friday**



1 options with **0.8- 2GeV**

2 options with **8 GeV**

3 options with **120 GeV**

Timeline

- Per P5, a **targeted panel** is expected to review demonstrator facilities in the collider R&D portfolios later this decade
  - In preparation for this, we need to prepare a Demonstrator conceptual design AND a detailed study on possible US sitting locations
  - US funding currently only accessible via laboratory discretionary funds and university research programs
- EU Strategy Update approval by CERN in 2026
  - Based on the outcome, the decisions of the targeted panel and the funding scenarios (in the US and Europe) a site for a demonstrator can be selected later
- US and IMCC should **join forces & work together**
  - Advance in the design for the demonstrator with engineering drawings
  - Proceed with the rf tests in the magnetic fields + refine rf technology
  - Design and prototype needed components (magnets, rf, rf power sources)