Muon Collider Demonstrator Program

Diktys Stratakis (Fermilab)

Secondary Beams at JLAB

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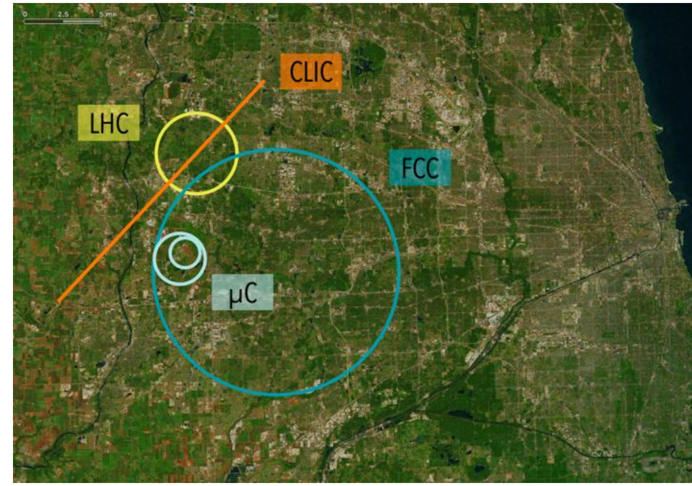
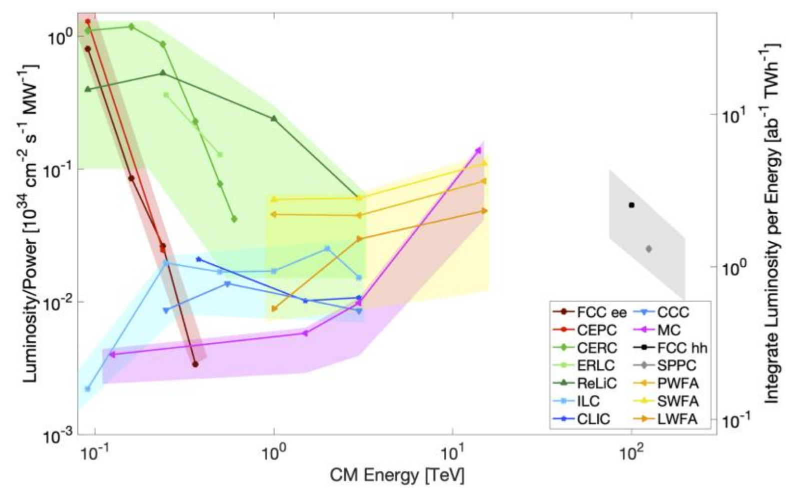
Motivation

- **Muons** as compared to **protons**
  - Are leptons & use all energy in a collision
  - Need less collision energy for same physics
- **Muons** as compared **electrons**
  - Muons emit little synchrotron radiation
  - Acceleration in rings possible to many TeV
- A Muon Collider (MuC) can serve as **energy reach** and **precision** machine at the **same** time
- In a MuC, **luminosity** to power ratio improves substantially with energy





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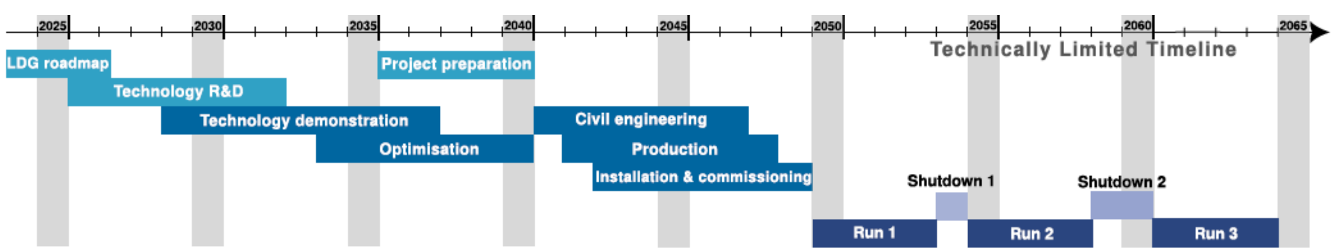
International Muon Collider Collaboration (IMCC)

- International Muon Collider R&D activities are coordinated by the IMCC
  - Very active collaboration since 2021, over 50 institutions have signed formal agreements
  - Progress on many fronts of the accelerator & detector design
- US scientists actively engaged with IMCC
  - US representatives in IMCC leadership
  - 7 Universities signed MoU, more to come
  - DOE – CERN collaborative agreement in progress, that will enable labs to official join

International MUON Collider Collaboration

MuCol



The USMCC

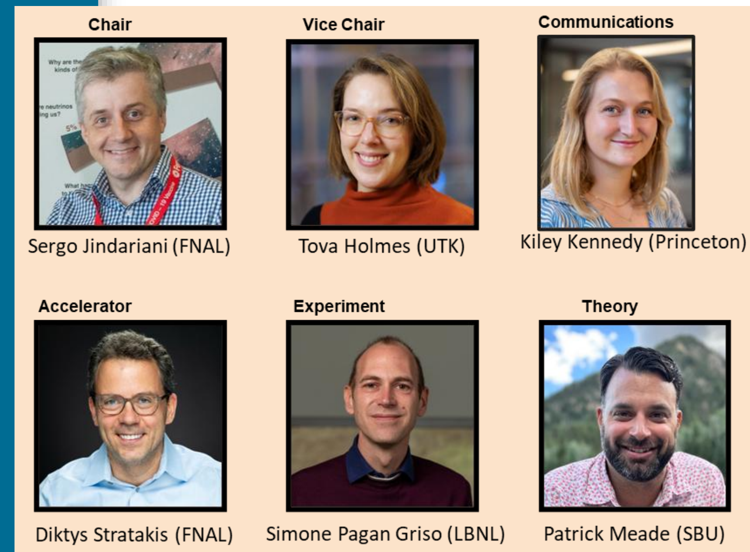
USMCC

www.muoncollider.us

Ratified a charter on May 8, 2025

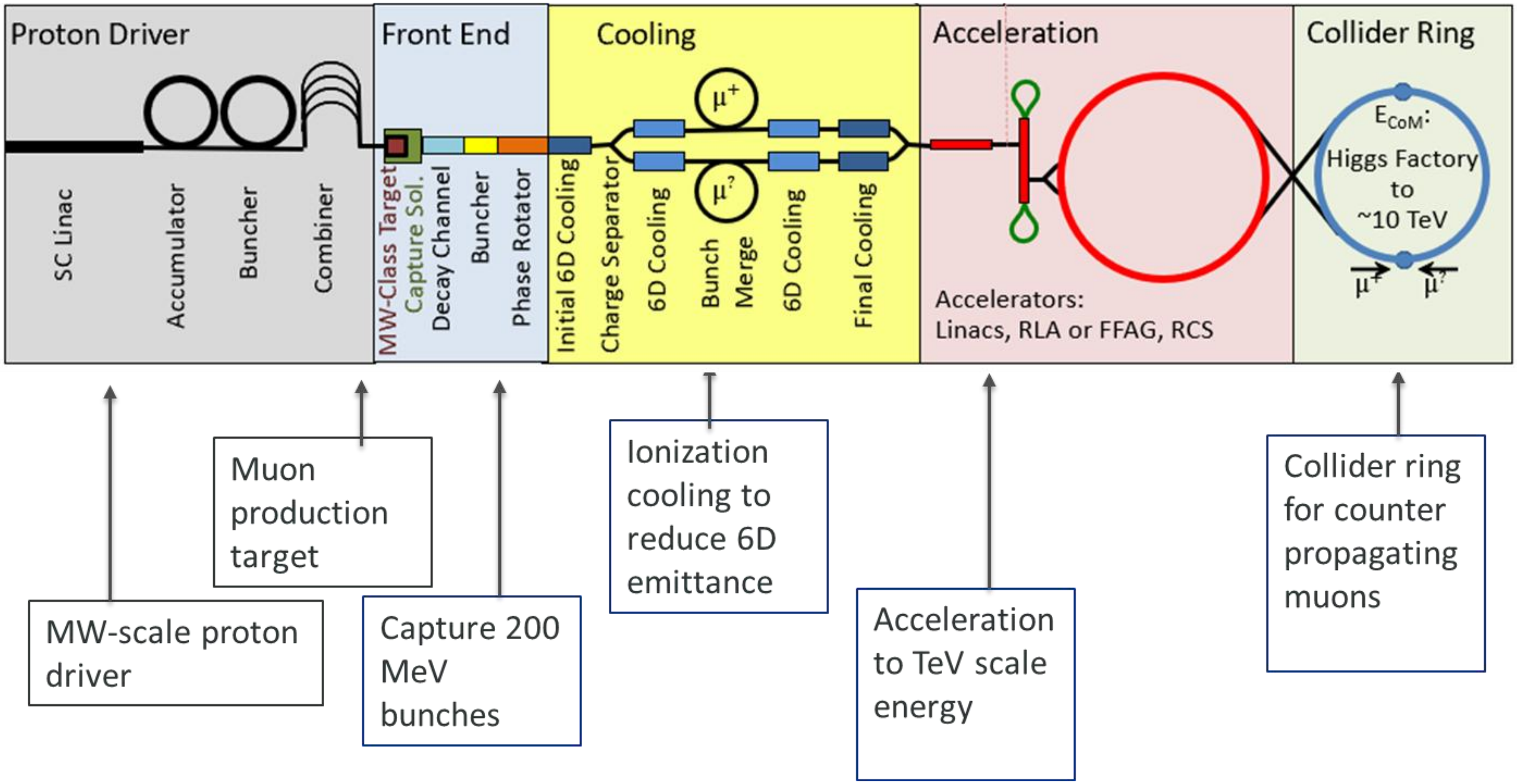
Elected Leadership on July 31

- Define necessary work for mid-P5 panel
- Design a US demonstrator
- Engage with the international community
- Create a long-term vision for Fermilab that leads to a muon collider
- Build on a theory-driven physics case



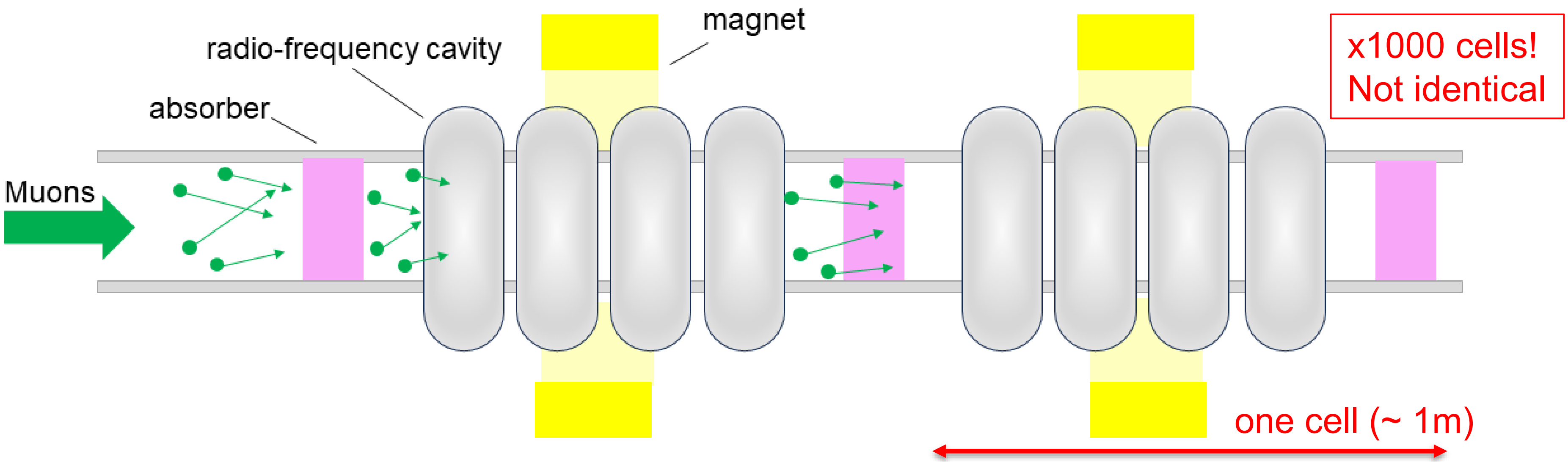
- Currently nearly 250 members. Still possible to join USMCC!
- Self subscribe to the mailing list

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?

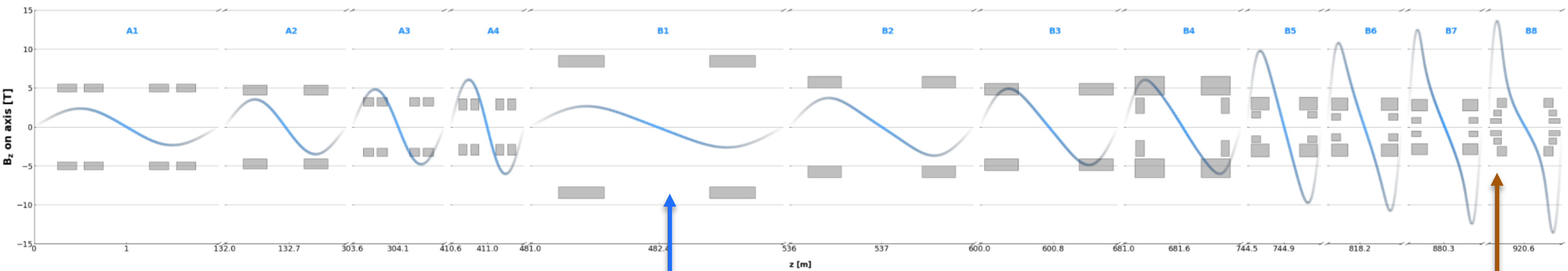
Concept of ionization cooling

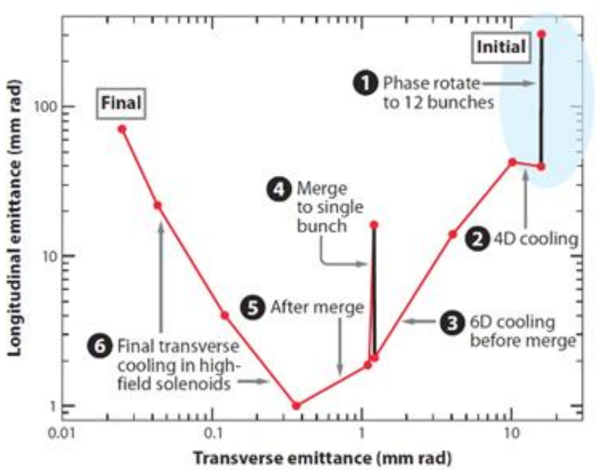


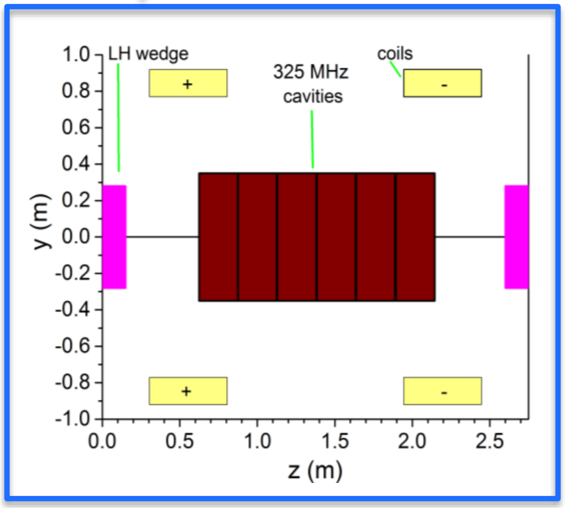
- Considerations for MuC cooling:
  - Beam size must be small at the absorber to reduce scattering
  - Absorbers with low Z and large energy loss must be selected
  - Magnetic field has to increase in strength over distance to keep cooling
  - The magnetic field, makes normal conducting (NC) cavities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

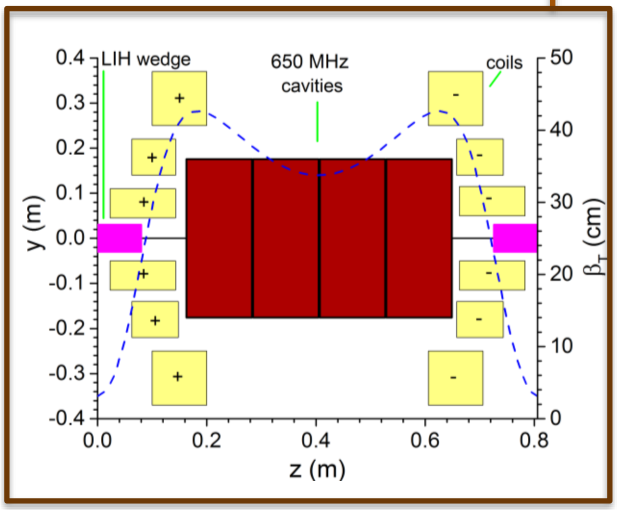
Integration & technology questions

- 12 stages, with each stage having ~ 100 identical cells
- Field progressively increases from 2 T to >14 T









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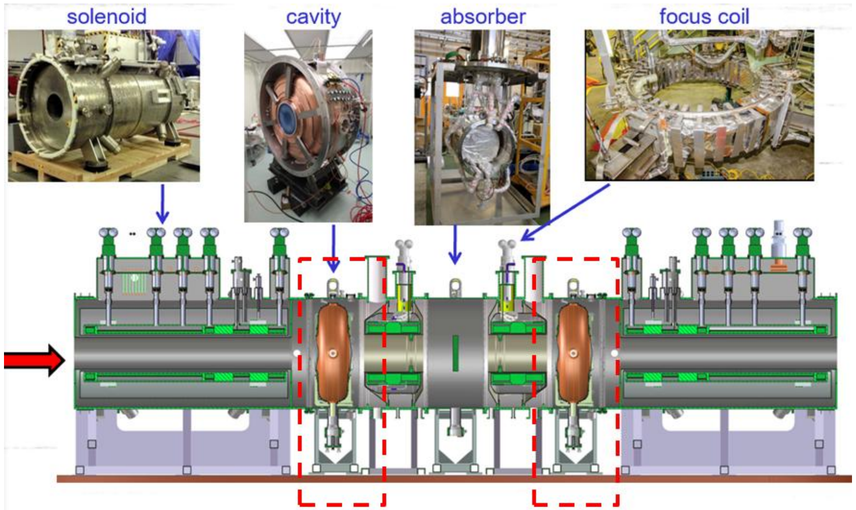
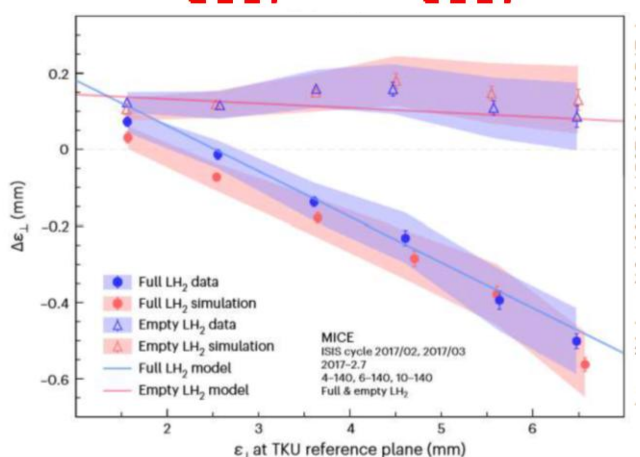
Principle verification

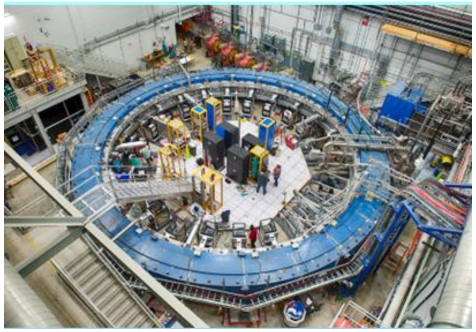
- Physics of ionization cooling has been demonstrated in two occasions

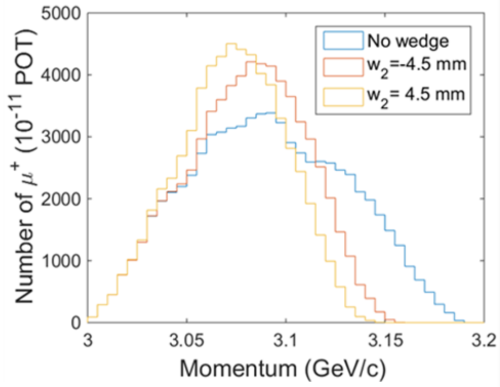
MICE Experiment

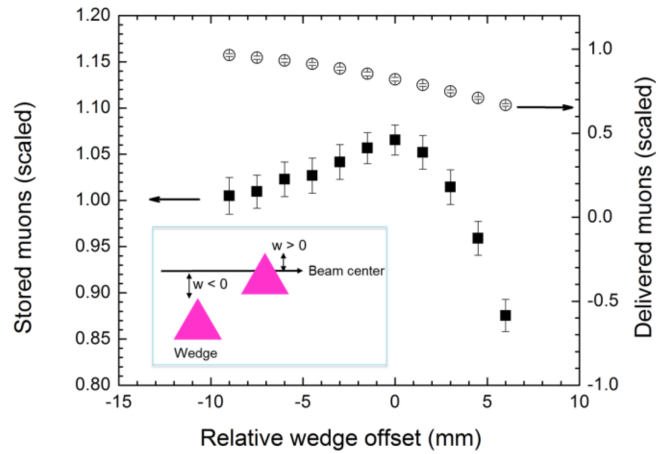


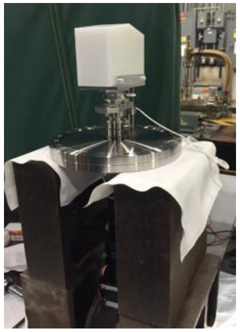


Fermilab Muon g-2 Experiment









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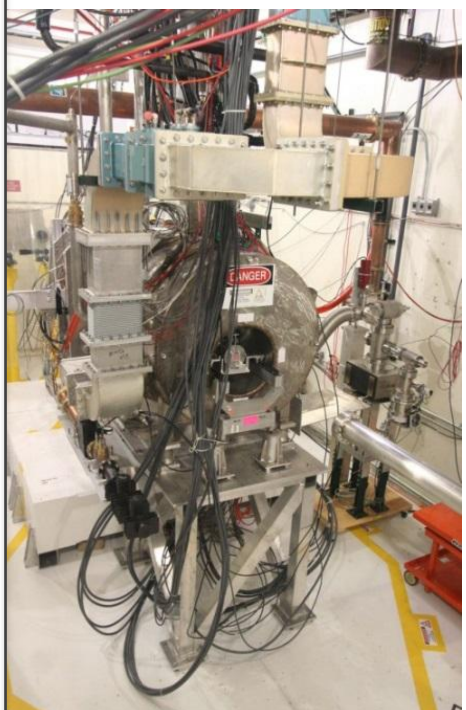
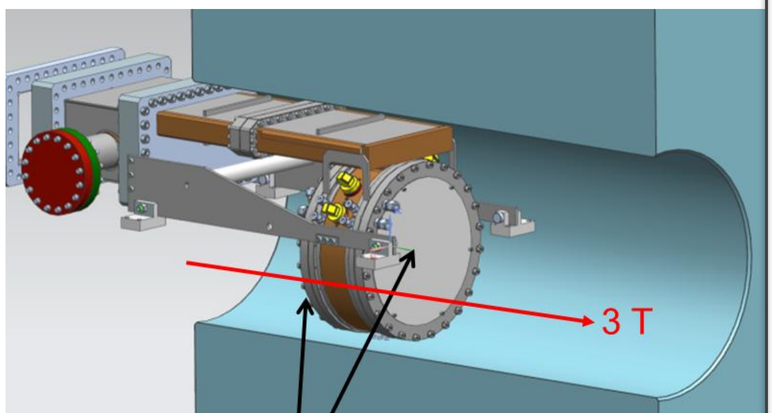
NC cavities in magnetic fields

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

Vacuum cavities

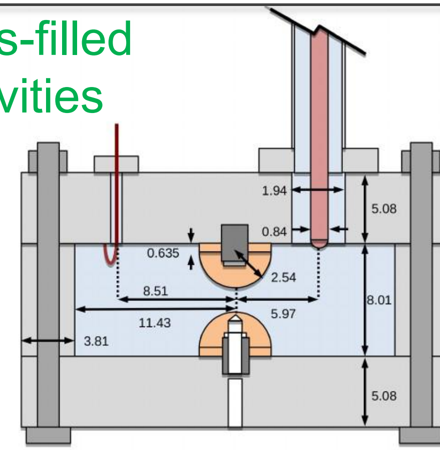


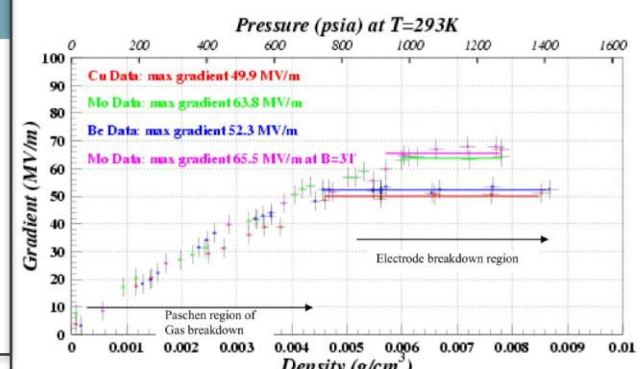


removable plates (Cu, Al, Be)

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





Tests at higher B-field needed!

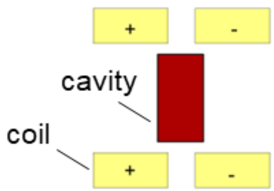
Motivation for a cooling demonstrator

- 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

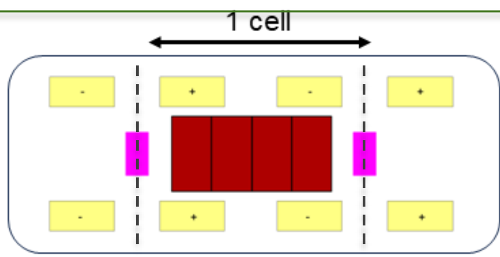
Phase-I



RF studies in B-fields

Material studies & cryogenic Cu

Phase-II

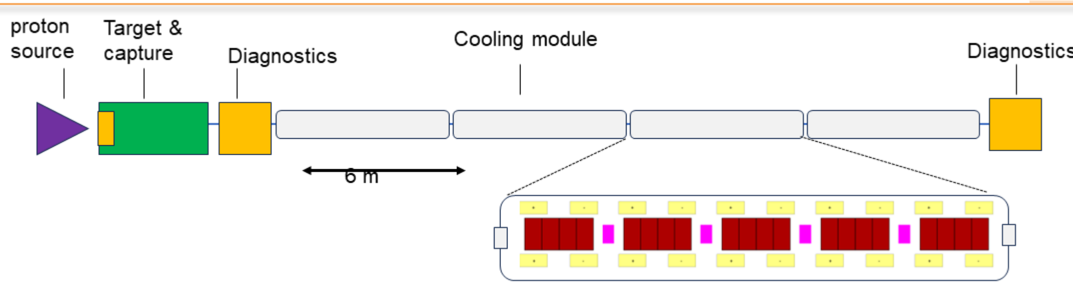


Cell integration studies

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

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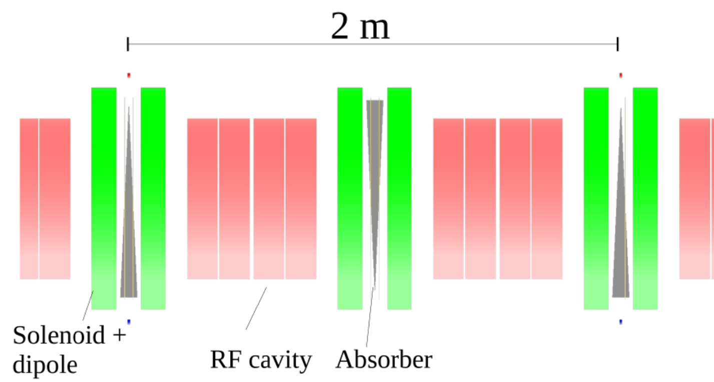
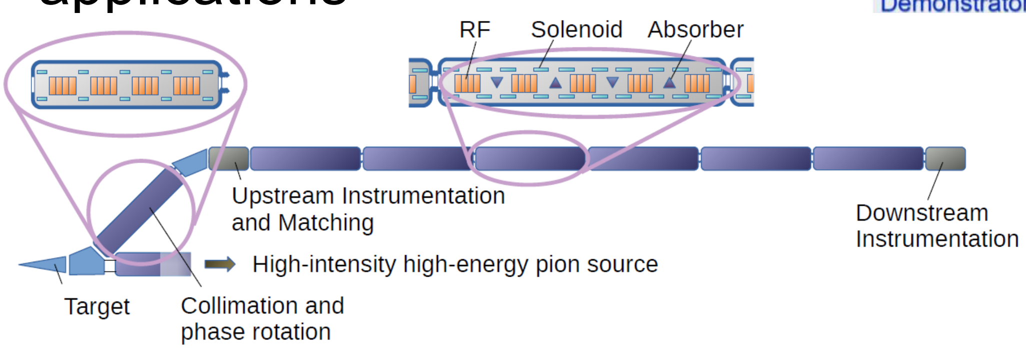
Full demonstrator with beam

- Design in progress
  - Muon source, target and transport
  - Beam transport
  - Cooling channel
- Investing synergies with other applications



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

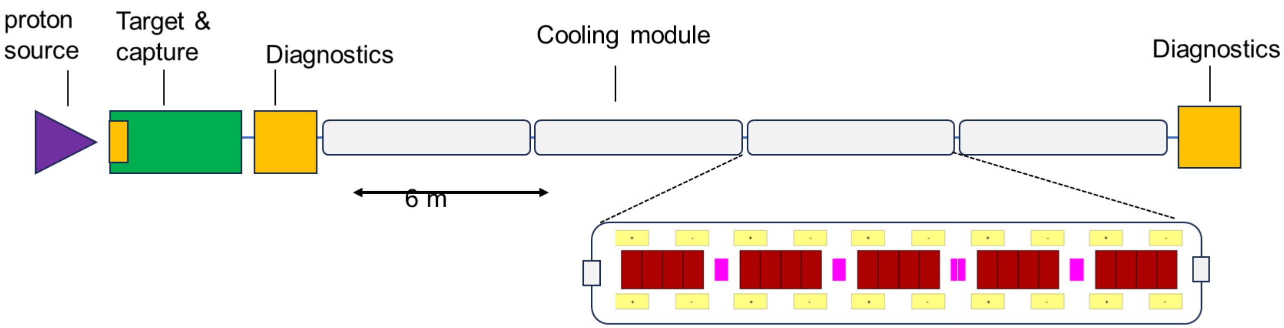
	Muon energy, MeV	Total length, m	Total # of cells	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	2-14	x 1/10^5	~70%
Demonstrator	200	48	24	0.5-7	x 1/2	4-6%



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

Fermilab and CERN have started design work to host such a Cooling Demonstrator

Candidate locations at CERN

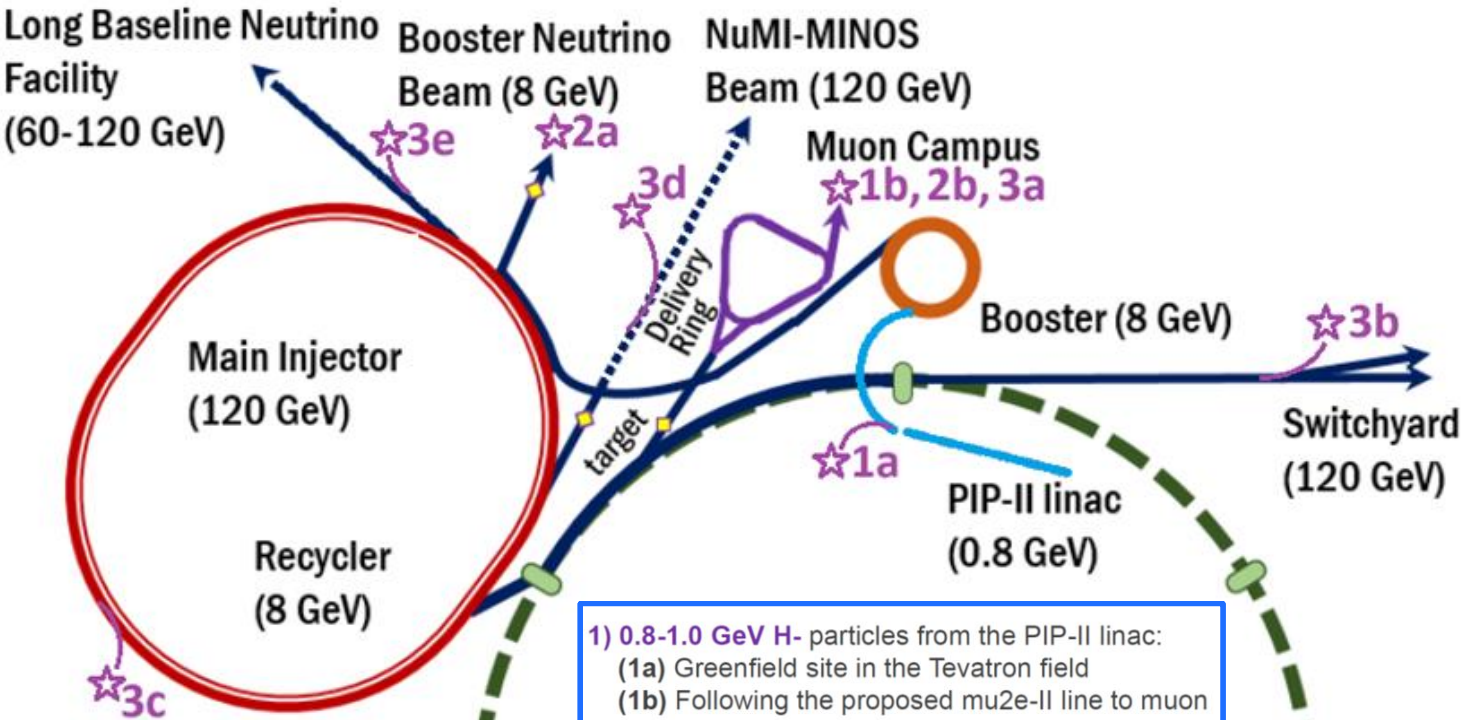


100+ m is desired

CTF3: ~10 kW beam power, plenty of space but requires a new extraction line from the PS

TT7: Less intense, less space, but no need for a new PS extraction line

Candidate locations at Fermilab

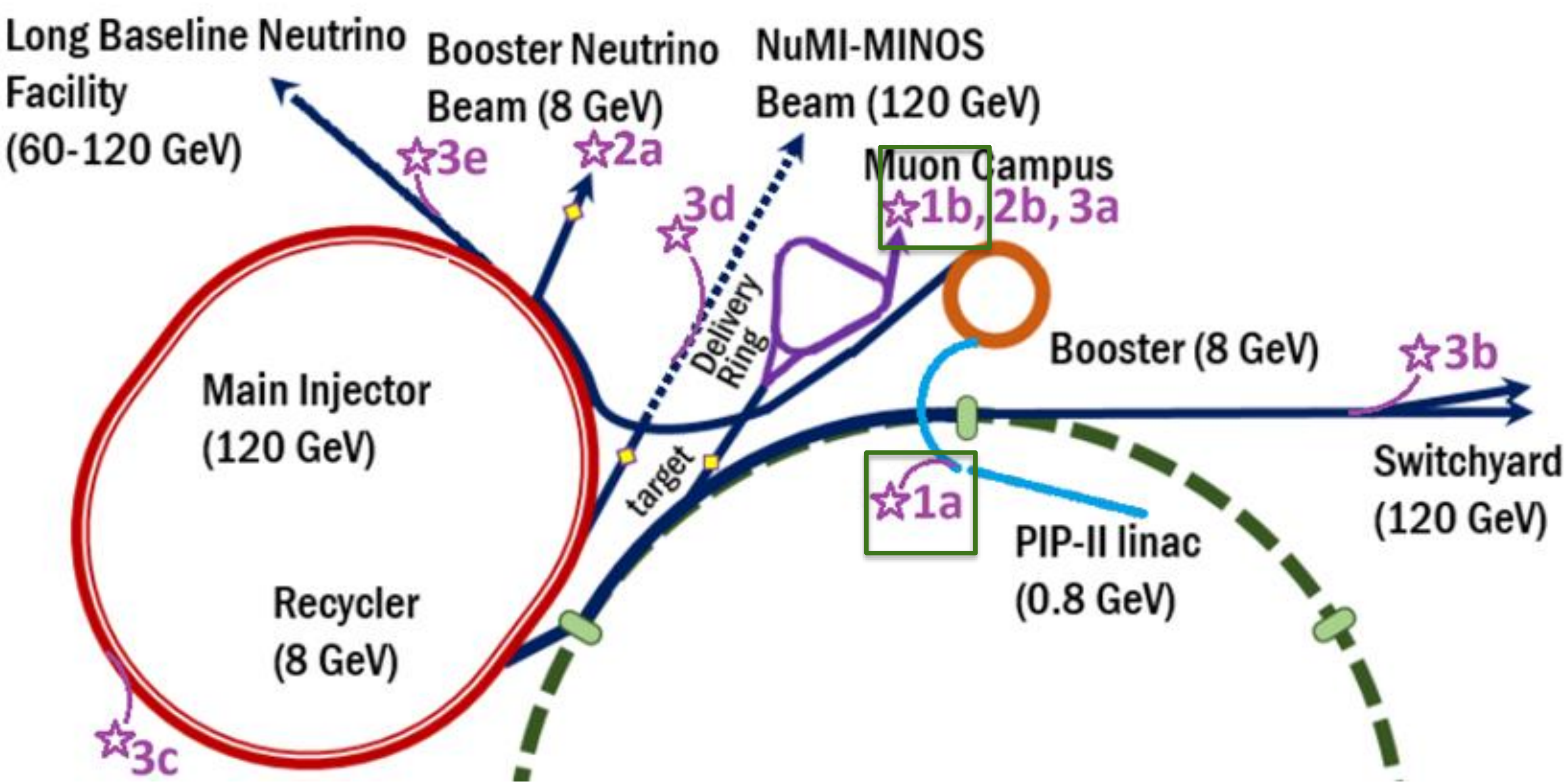


1) 0.8-1.0 GeV H- particles from the PIP-II linac:
- **(1a)** Greenfield site in the Tevatron field
- **(1b)** Following the proposed mu2e-II line to muon campus.

2) 8 GeV protons from the Booster:
- **(2a)** At the present day short-baseline neutrino
- **(2b)** At present day muon campus site.

3) 8-120 GeV protons from the Main Injector:
- **(3a)** Split off P1 Muon Campus line.
- **(3b)** Split off P1 Meson line.
- **(3c)** Split off MI Abort beamline.
- **(3d)** At the present day NuMI beamline.
- **(3e)** Split off LBNF beamline.

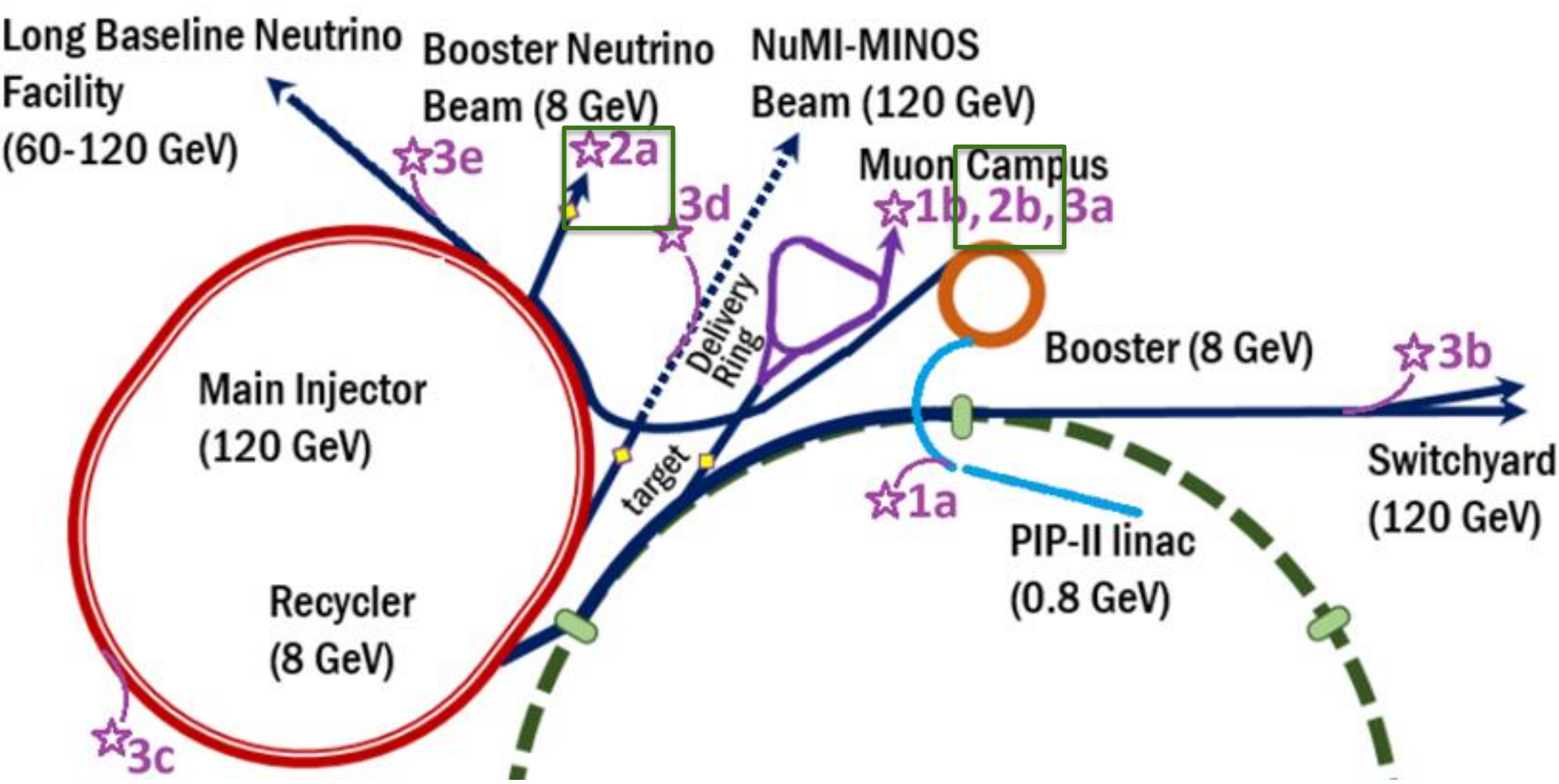
0.8-1.0+ GeV scenarios at Fermilab



0.8-1.0+ GeV protons from PIP-II linac

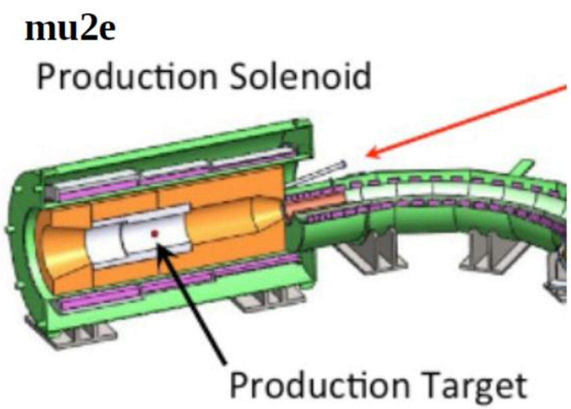
- Excellent proton availability
  - CW operation of the PIP-II linac would supply 1.6 MW of beam power, only 1% which is used for the Fermilab booster (the rest is potentially available for experiments)
- Green field sitting near PIP-II linac
  - Abundant real-estate in the Tevatron field, proximity to PIP-II power/cryo
  - Scenarios to send this beam to Muon Campus for Mu2e-II are under study
- Expect 0.8 GeV particles but 1.0+ GeV scenarios are also considered
- Synergies with other proposed experiments are possible
  - Proposed low-energy muon facility (muSR)
  - Proposed Fermilab facility for dark discovery (F2D2) beam dump physics program

8 GeV scenarios at Fermilab

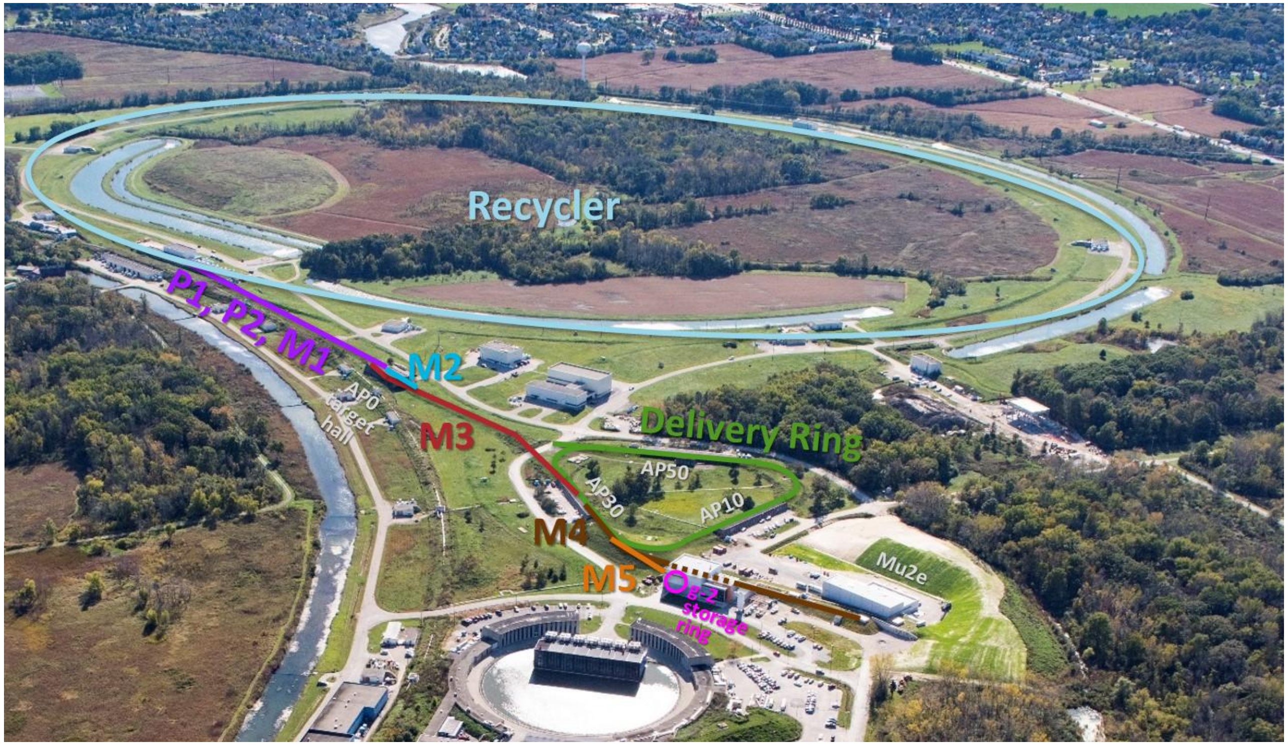


Site at Fermilab: Muon Campus

- Designed to provide beam for the Muon g-2 and Mu2e experiments



Excellent opportunity to examine targets under 5 T field



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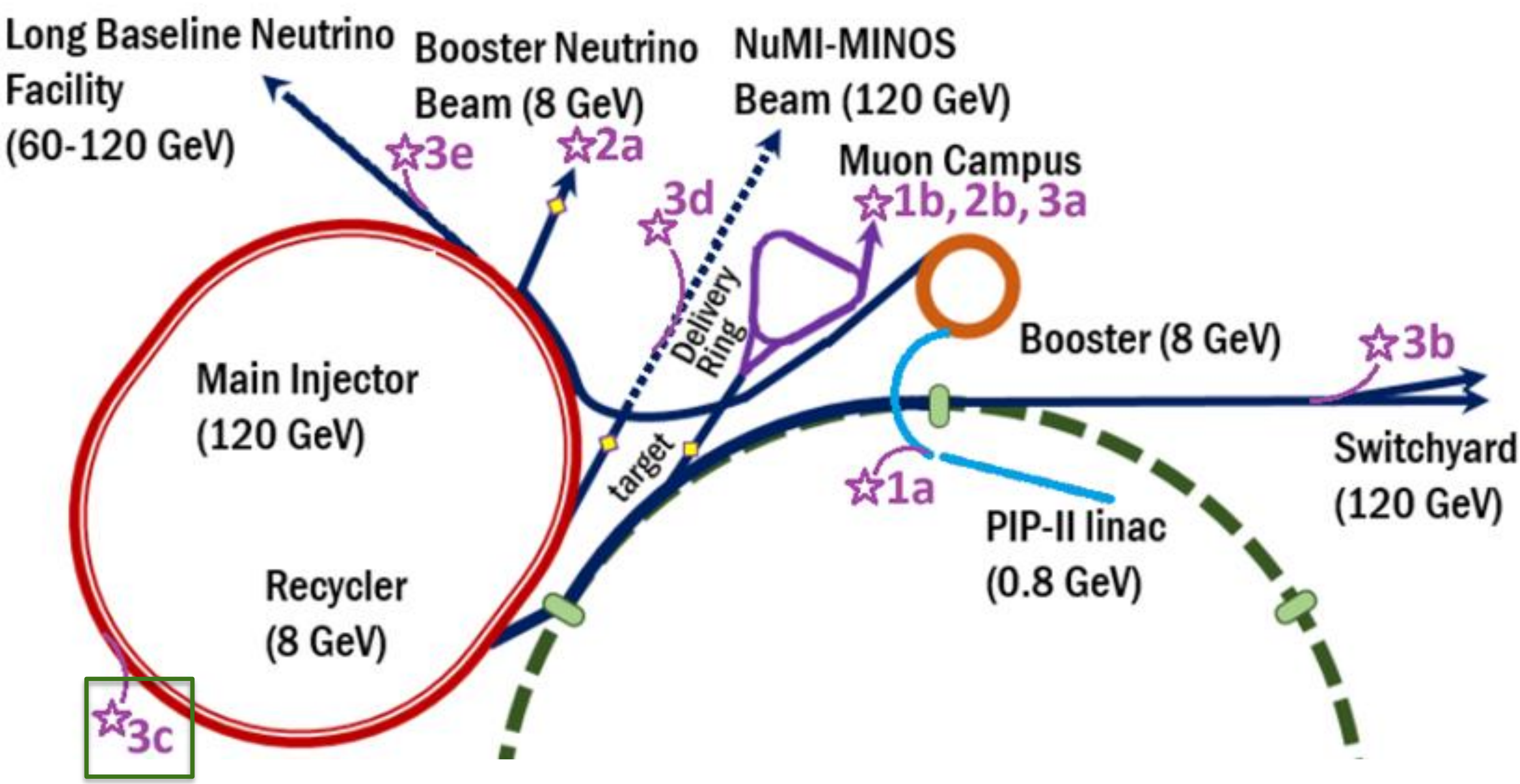
8 GeV protons from the booster

- Excellent proton availability
  - 81 bunches, each 1.2 ns separated at 19 ns intervals, 6.5e12 protons in 1.5 microsecond pulse
- Sitting at Muon Campus
  - Options to manipulate beam in Recycler before Muon Campus
  - Can start at the end of the Mu2e program (2033) and take advantage of existing tunnel and infrastructure.
  - Will require use of the Recycler which is parasitic to the LBNF program
  - A 7% reduction of LBNF 2.1 MW beam power for ~ 10 kW at 8 GeV
- Siting at the Short-Baseline Neutrino Target Hall
  - Can start at the end of the SBN program (3-5 years)
  - No impact on LBNF: corresponds roughly to a 10+ kW at 8 GeV

8-120 GeV scenarios at Fermilab



8-120 GeV protons from Fermilab Main Injector

- Low-duty factor intense proton pulse
  - 972 bunches each 2 ns separated at 19 n intervals, 78e12 protons in 9 microsecond pulse
- Direct extraction from Main Injector
  - Multiple beamline options, depending real estate and infrastructure needs
  - MI abort was the planned site for NuSTORM
  - Operation is parasitic to the LBNF program: A 5% reduction in 2.1 MW LBNF beam corresponds to 105 kW at 120 GeV
- 8-120 GeV tunable energy
  - Proton energy can be set by the demonstrator needs, option to vary the energy in some locations

Future Steps

- 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
- Fermilab with access to high-power proton beams and technological expertise, is the ideal place for a Cooling Demonstrator
  - It requires dedicated studies for designing this facility and exploring its implementation within the Fermilab accelerator complex.
- LDRD has been awarded to Explore candidate sites of a cooling Demonstrator facility within Fermilab (2-3 years)
  - Good enough to look at sites within Fermilab and evaluate performance
  - Evaluate risks and carry out preliminary engineering designs
  - Will require more funding for final engineering design and detailed cost analysis