



Cooling Demonstrator Program for the Muon Collider

Diktys Stratakis (Fermilab)

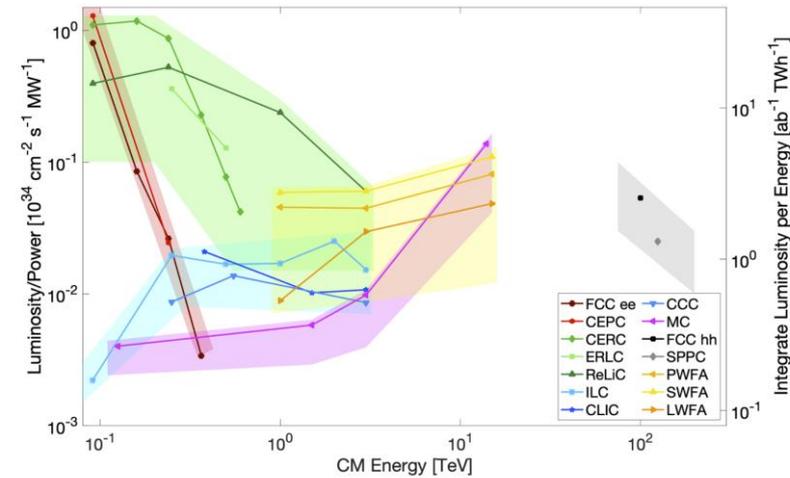
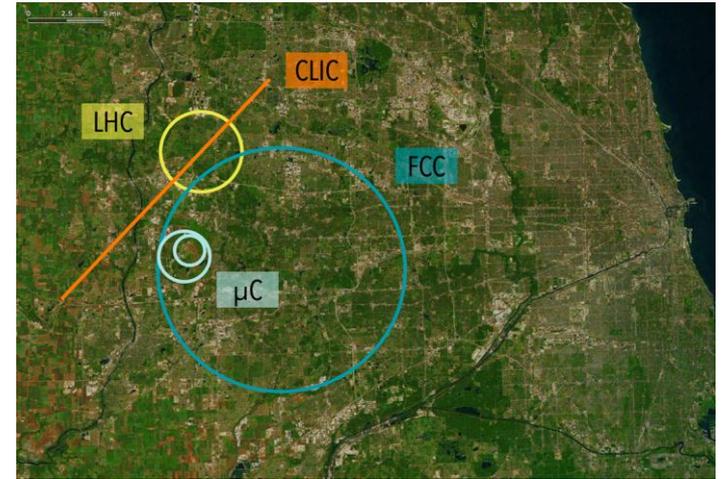
On behalf of the US Muon Collider Collaboration

COOL'25

October 27, 2025

Motivation

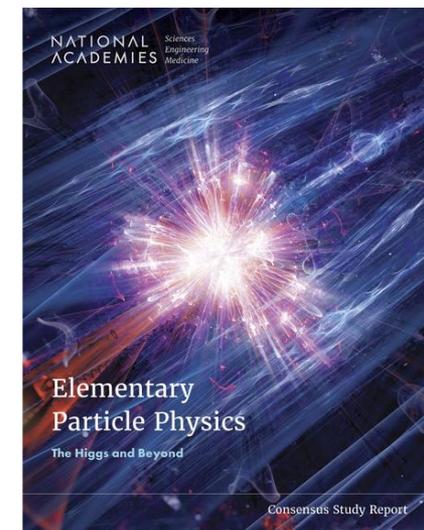
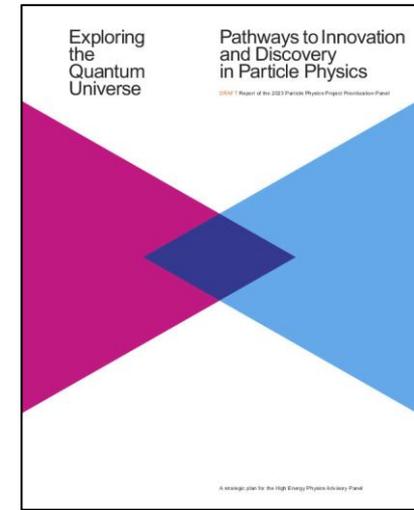
- **Muons** as compared to **protons**
 - Are leptons & use all energy in a collision
 - Need less collision energy for same physics
- **Muons** as compared **electrons**
 - Muons emit little synchrotron radiation
 - Acceleration in rings possible to many TeV
- A Muon Collider (MuC) can serve as **energy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



Statements from P5 and NAS panel reports

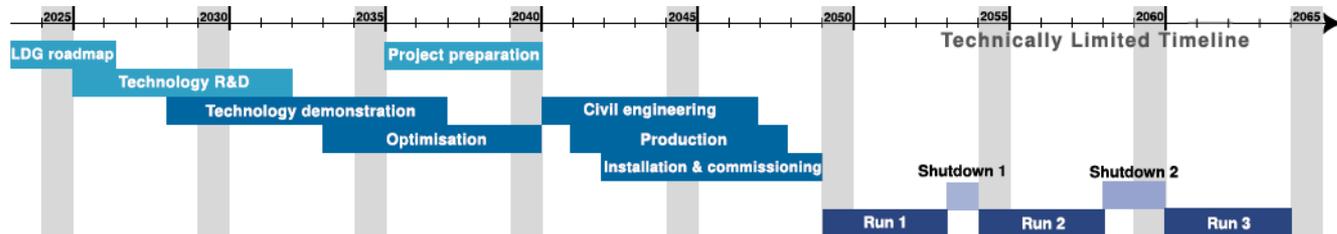
P5: Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, At the end of the path is an unparalleled global facility on US soil... ***This is our muon shot***

NAS EPP (Rec #1): **The United States should host the world's highest-energy elementary particle collider around the middle of the century.** This requires **the immediate creation of a national muon collider research and development program** to enable the construction of a demonstrator of the key new technologies and their integration.



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



Muon Collider parameters

Start → Goal

Target integrated luminosities

| \sqrt{s} | $\int \mathcal{L} dt$ |
|------------|-----------------------|
| 3 TeV | 1 ab ⁻¹ |
| 10 TeV | 10 ab ⁻¹ |
| 14 TeV | 20 ab ⁻¹ |

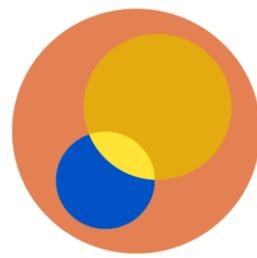
Note: currently focus on 10 TeV, also explore 3 TeV

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

Feasibility addressed, will evaluate luminosity performance, cost and power consumption

| Parameter | Unit | 3 TeV | 10 TeV | 14 TeV |
|--------------------|---|-------|--------|--------|
| L | 10 ³⁴ cm ⁻² s ⁻¹ | 1.8 | 20 | 40 |
| N | 10 ¹² | 2.2 | 1.8 | 1.8 |
| f _r | Hz | 5 | 5 | 5 |
| P _{beam} | MW | 5.3 | 14.4 | 20 |
| C | km | 4.5 | 10 | 14 |
| | T | 7 | 10.5 | 10.5 |
| ε _L | MeV m | 7.5 | 7.5 | 7.5 |
| σ _E / E | % | 0.1 | 0.1 | 0.1 |
| σ _z | mm | 5 | 1.5 | 1.07 |
| β | mm | 5 | 1.5 | 1.07 |
| ε | μm | 25 | 25 | 25 |
| σ _{x,y} | μm | 3.0 | 0.9 | 0.63 |

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

Chair



Sergo Jindariani (FNAL)

Vice Chair



Tova Holmes (UTK)

Communications



Kiley Kennedy (Princeton)

Accelerator



Diktys Stratakis (FNAL)

Experiment



Simone Pagan Griso (LBNL)

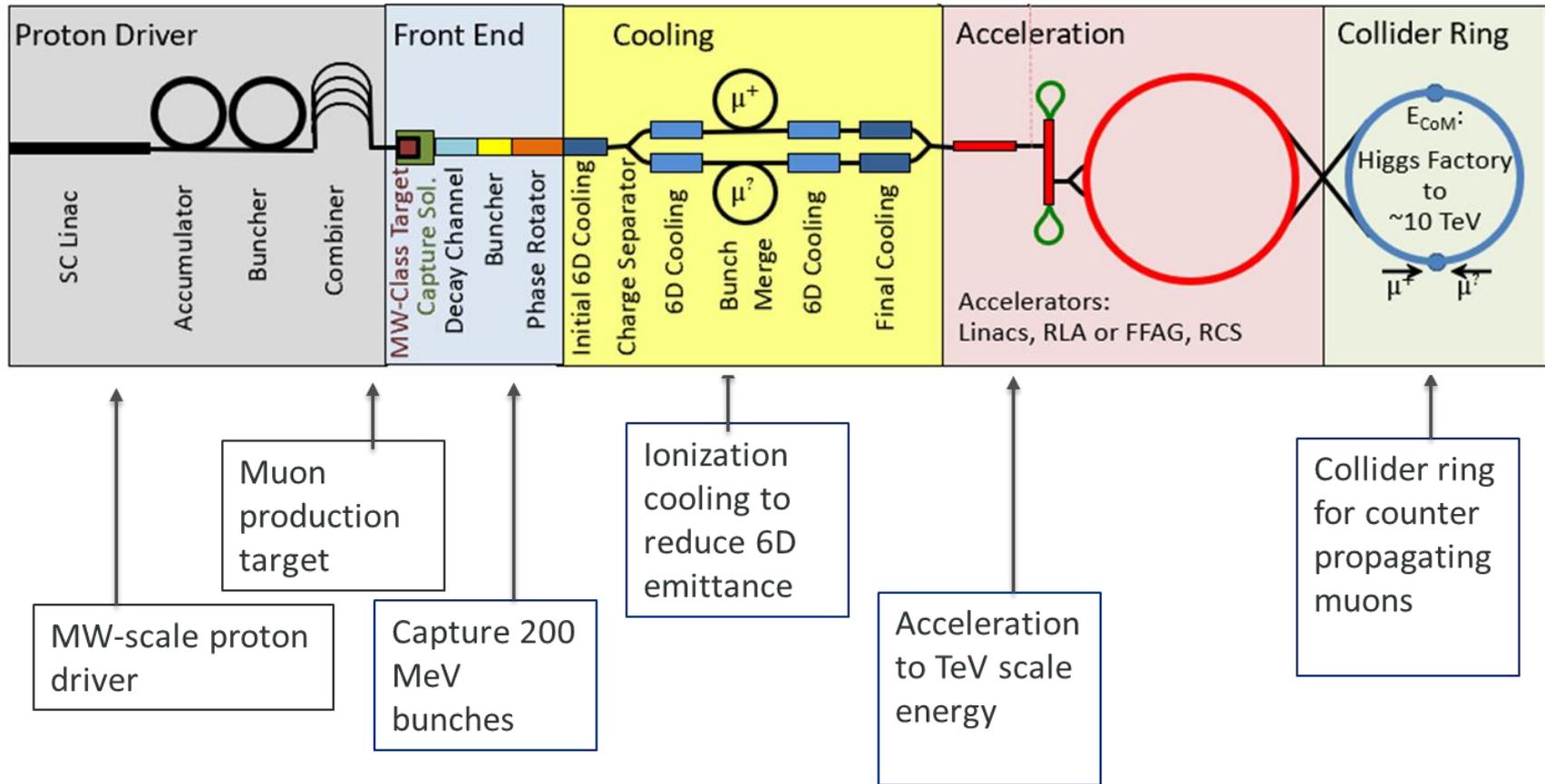
Theory



Patrick Meade (SBU)

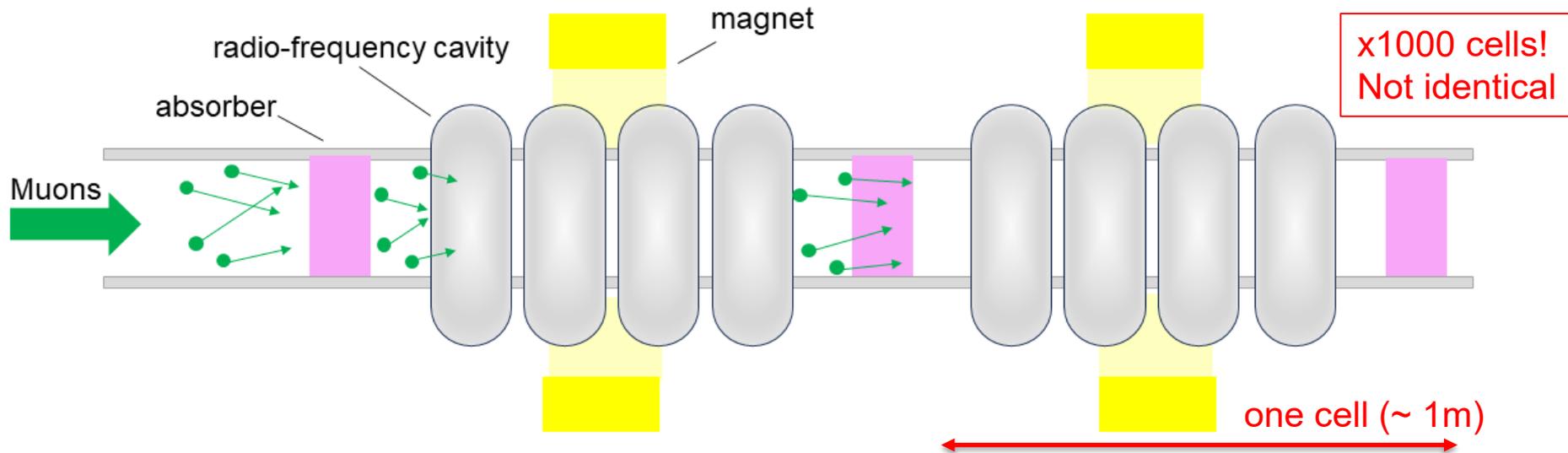
- Currently 250+ members. Still possible to join USMCC!
- Self subscribe to the [mailing list](#)

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

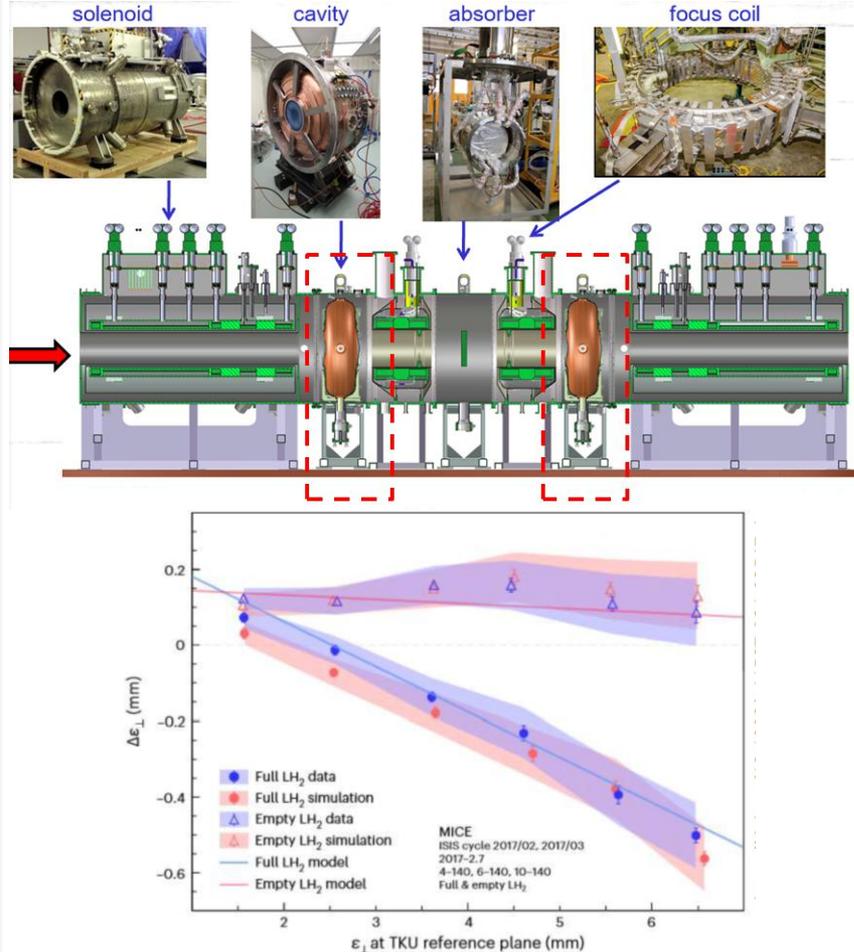


- Considerations for MuC cooling:
 - Beam size must be small at the absorber to reduce scattering
 - Absorbers with low Z and large energy loss must be selected
 - Magnetic field has to increase in strength over distance to keep cooling
 - The magnetic field, makes normal conducting (NC) cavities the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

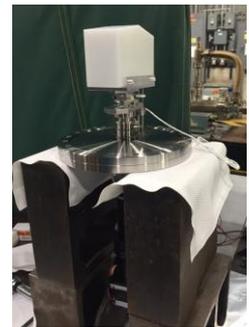
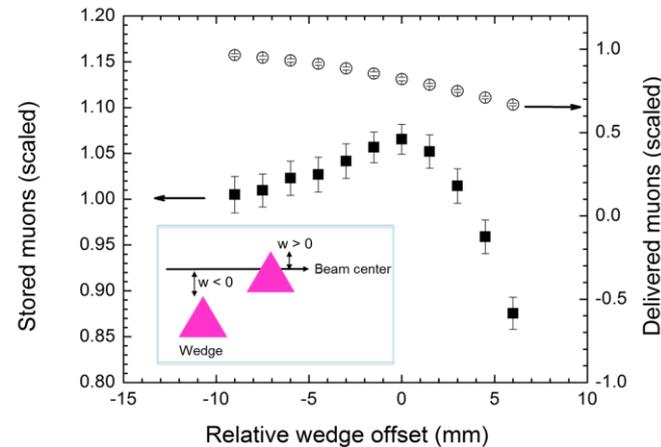
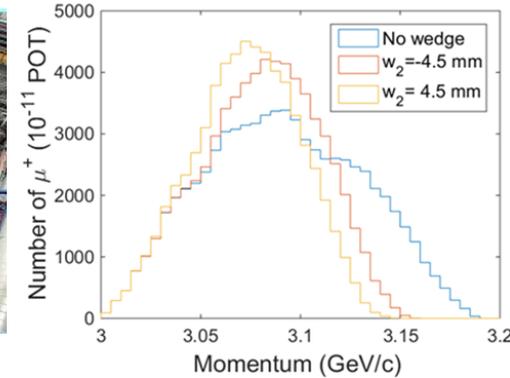
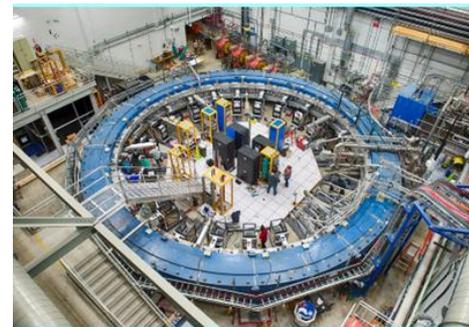
Principle verification

- Physics of ionization cooling has been demonstrated in two occasions

MICE Experiment

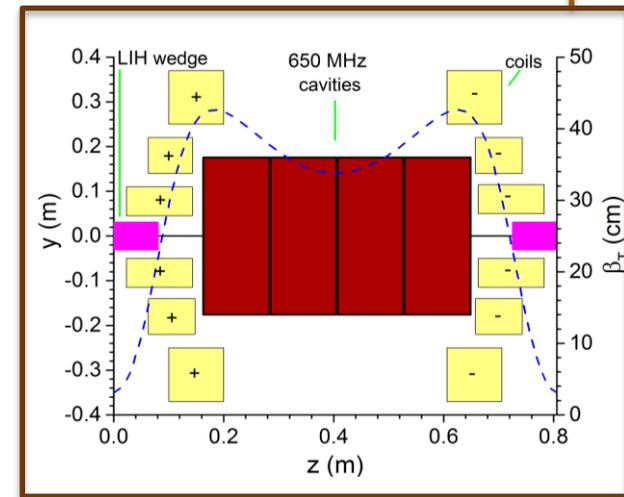
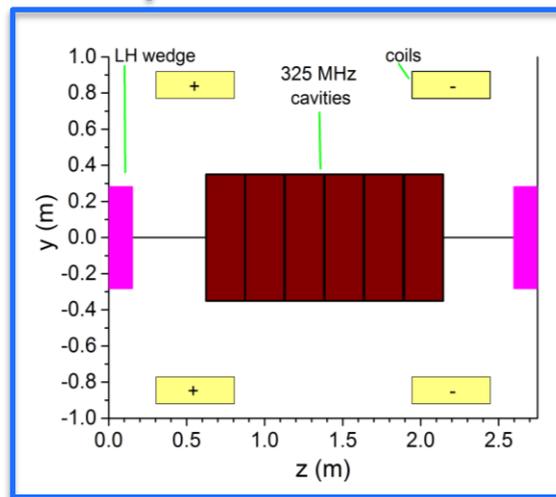
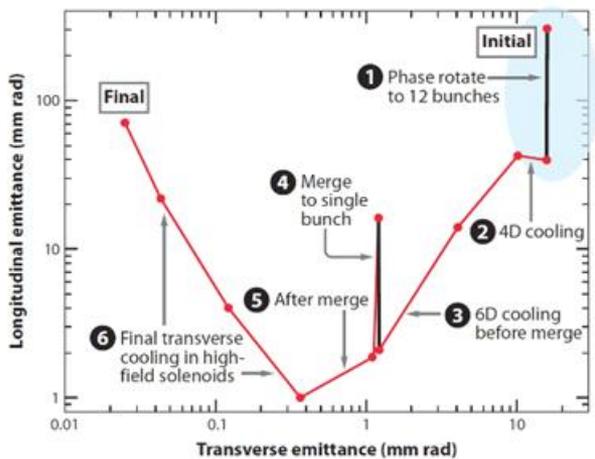
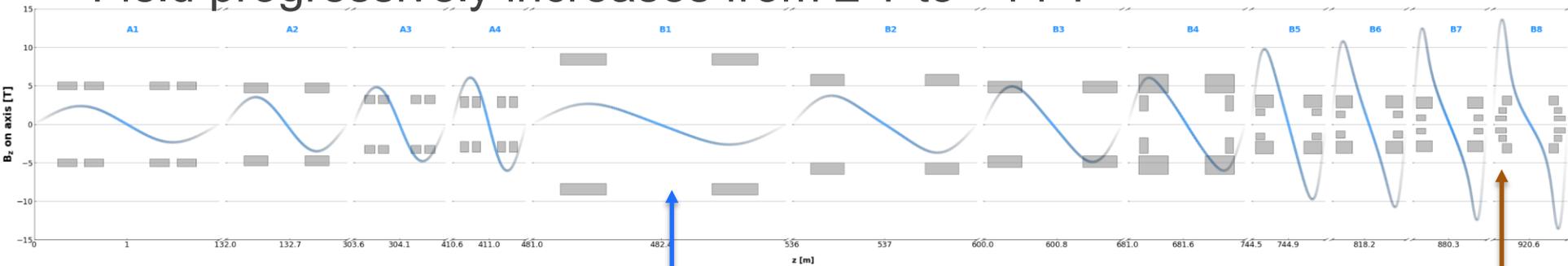


Fermilab Muon g-2 Experiment

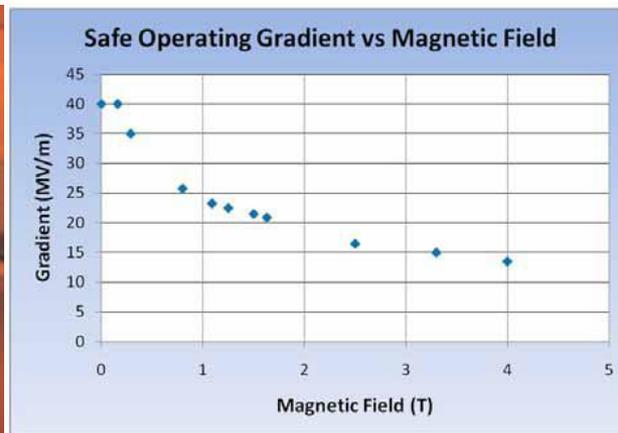
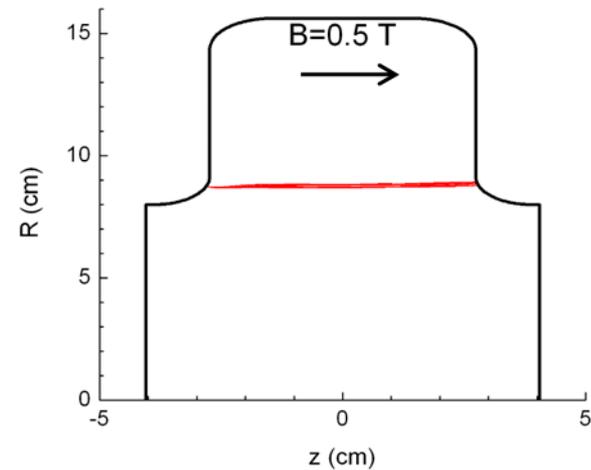
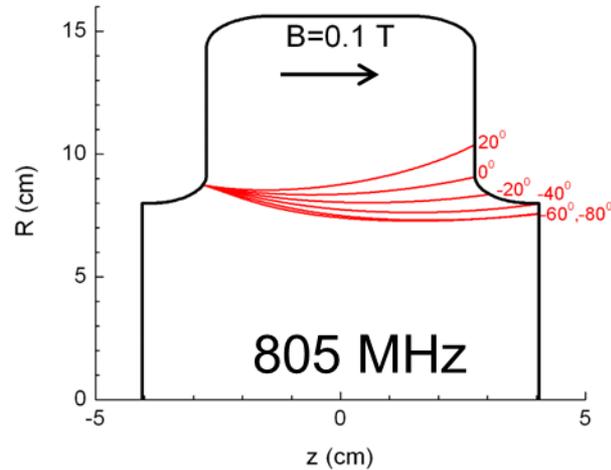
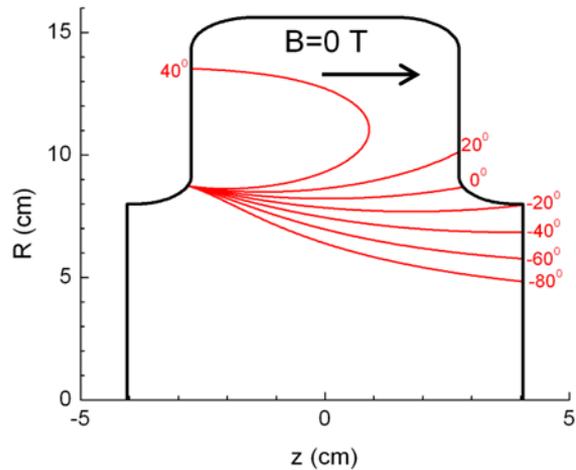


Integration & technology questions

- 12 stages, each with ~100 identical cells
- Total length: 945 m; Total # of solenoids: 3000+
- Field progressively increases from 2 T to >14 T



Cavities in B-fields



Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

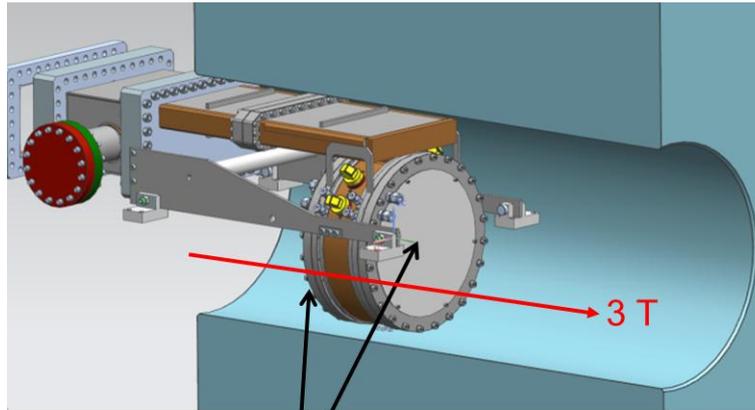
journal homepage: www.elsevier.com/locate/nima

Effects of external magnetic fields on the operation of high-gradient accelerating structures

Diktys Stratakis*, Juan C. Gallardo, Robert B. Palmer

Cavities in B-fields

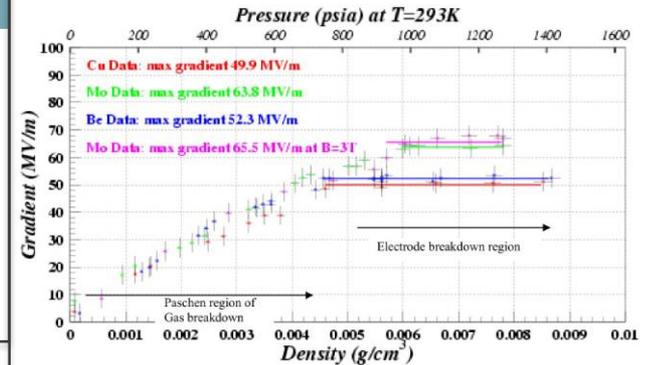
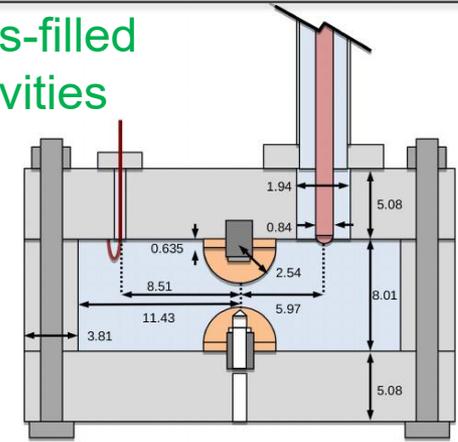
Vacuum cavities



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



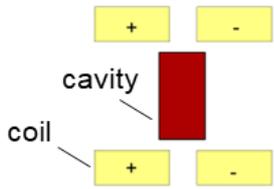
Need $B > 3T$

Benefits of a cooling demonstrator program

- 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

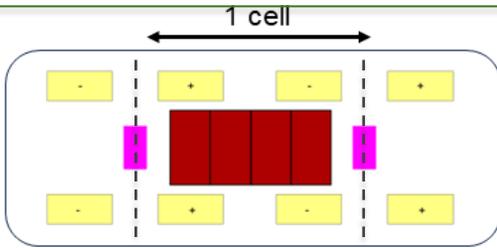
Phase-I



RF studies in B-fields

Material studies & cryogenic Cu

Phase-II

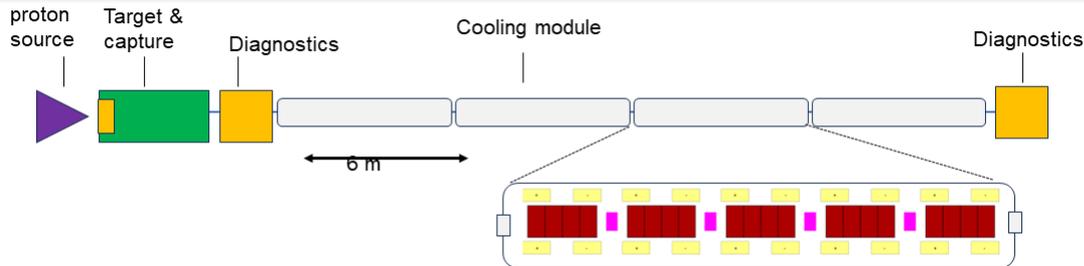


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III



Full demonstrator with beam

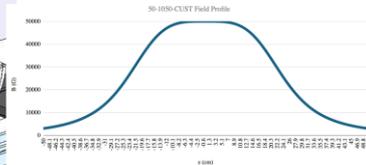
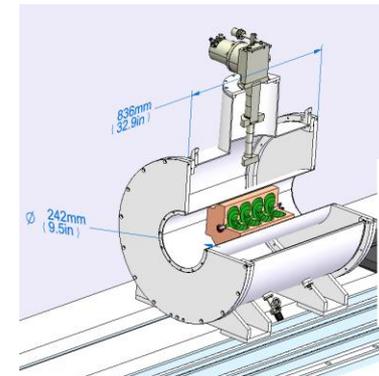
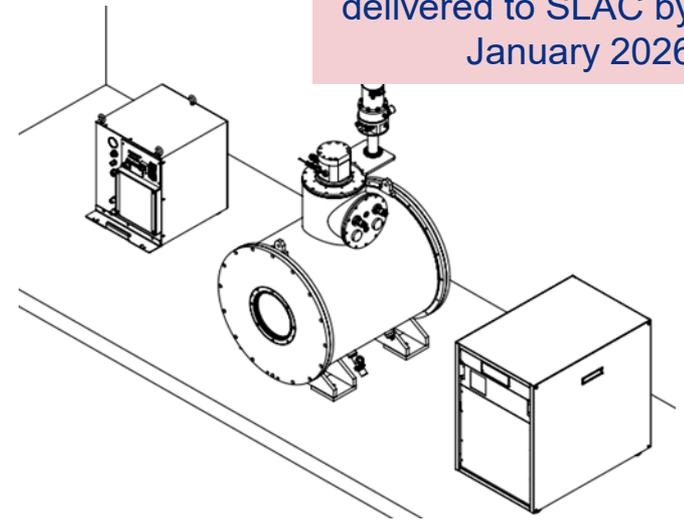
Coils producing 7T axial fields

Potential to achieve 50% 6D cooling

New Test Area at SLAC for NC cavity research

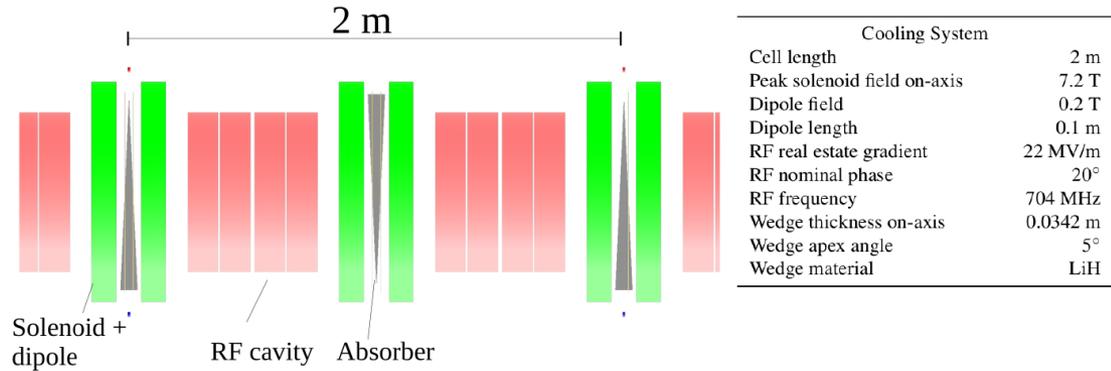
- Extend SLAC's high power RF testing capabilities to include external B-fields
- Measurements of the field emission and associated damage will be used to benchmark simulation models.
- SLAC LDRD proposal on the works to design NC cavities specifically for ionization cooling
 - Scaled to S-band, and to test them with high power RF in the new 5 T solenoid

Drawing of 5 T solenoid from Cryomagnetics to be delivered to SLAC by January 2026



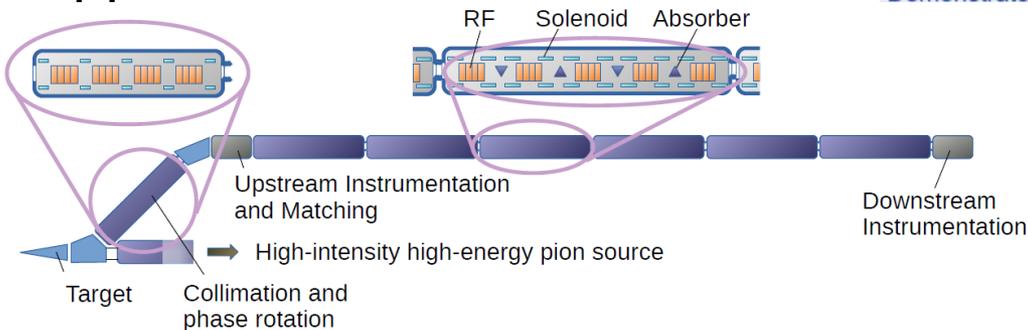
Full demonstrator with beam

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



- Investing synergies with other applications

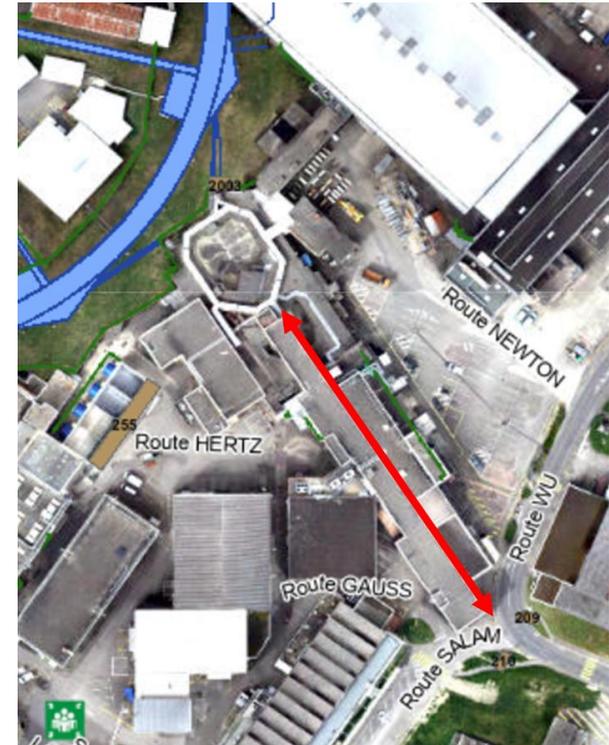
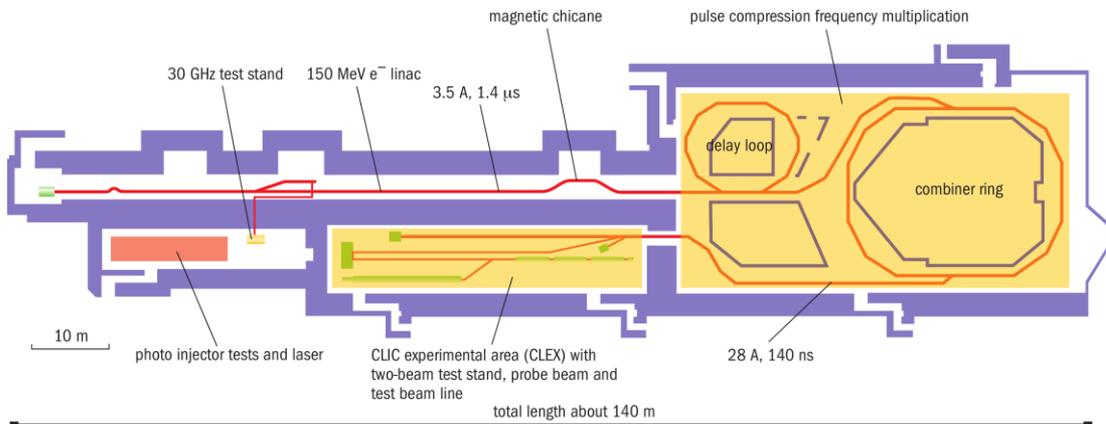
| | Muon energy, MeV | Total length, m | Total # of cells | B_max, T | 6D emm. reduction | Beam loss, % |
|---------------|------------------|-----------------|------------------|----------|-------------------|--------------|
| Full scale MC | 200 | ~980 | ~820 | 2-14 | $\times 1/10^5$ | ~70% |
| Demonstrator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



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

Candidate locations at CERN (1)

- CTF3 area
 - No extraction in the PS
 - ~ 100 m tunnel available
 - Limited to < 10 kW average beam power
 - ~ 2×10^6 muons/bunch
 - Klystron gallery available

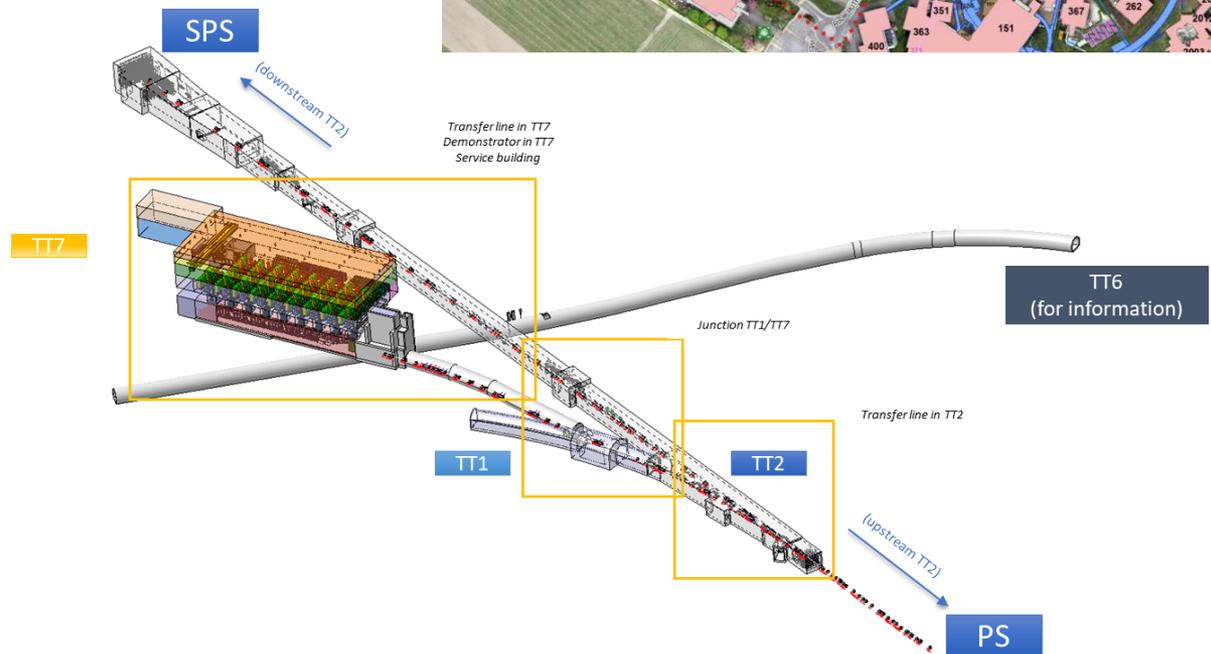


Candidate locations at CERN (2)



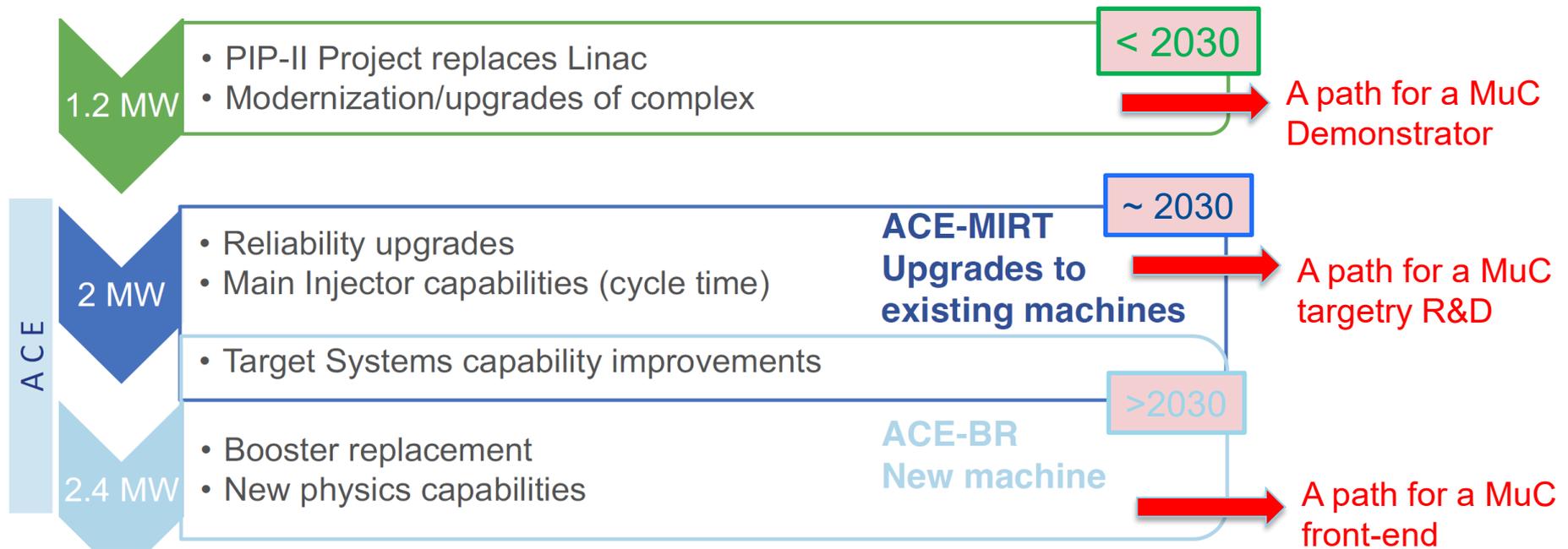
- **TT7 tunnel**

- Does not require a new beam extraction in the PS
- Muon intensity lower than CTF3
- Detailed parameters under study



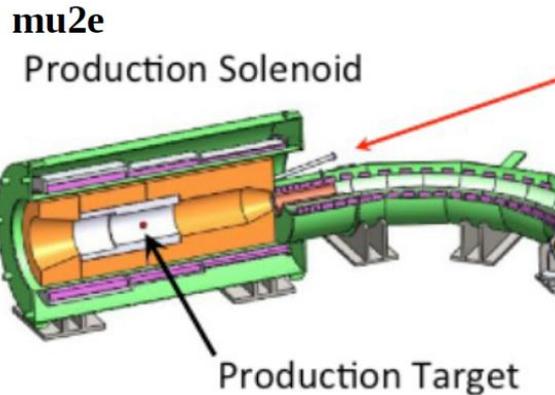
Fermilab accelerator upgrades

- Fermilab's ACE program will upgrade the accelerator complex

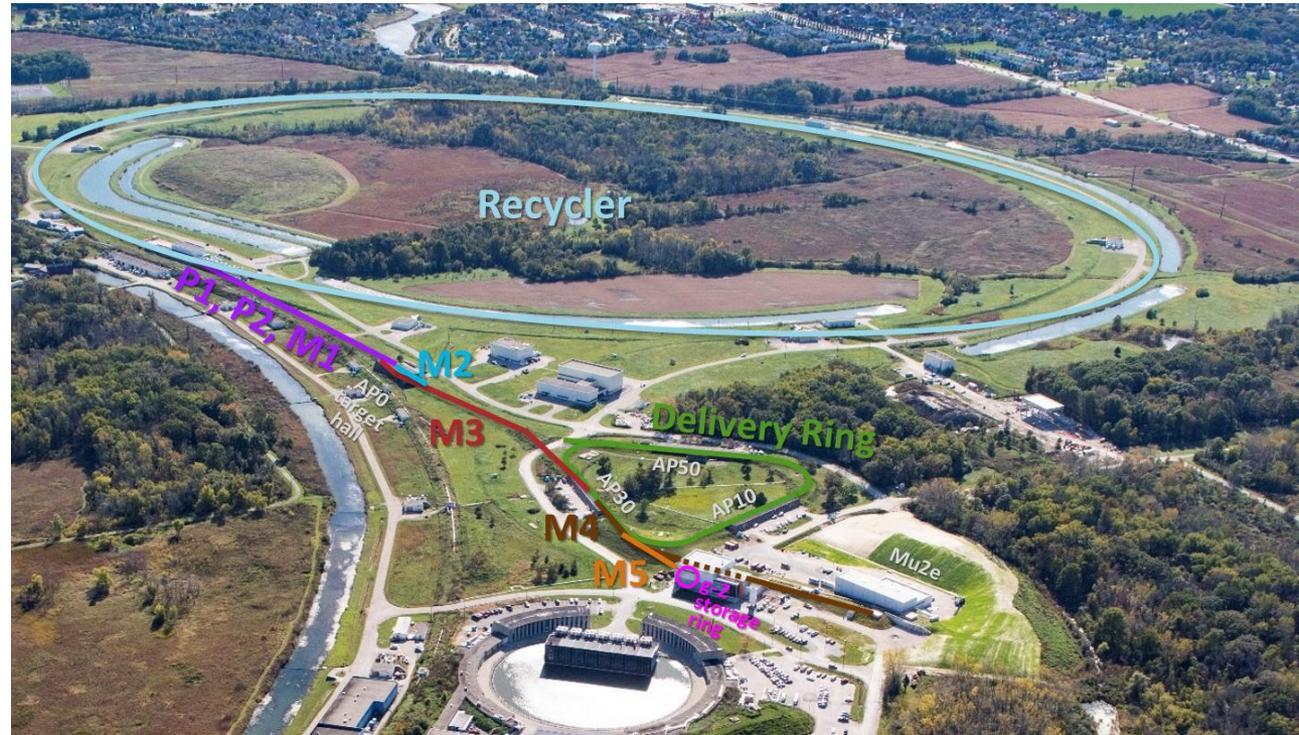


Demonstrator at Fermilab: Muon Campus

- 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

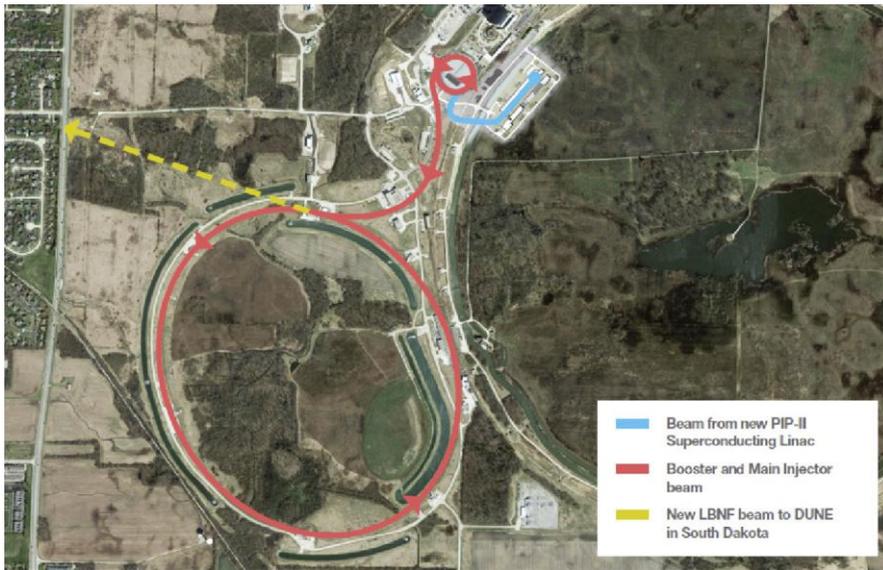


Excellent opportunity to examine targets under 5 T field



Demonstrations options during the PIP-II

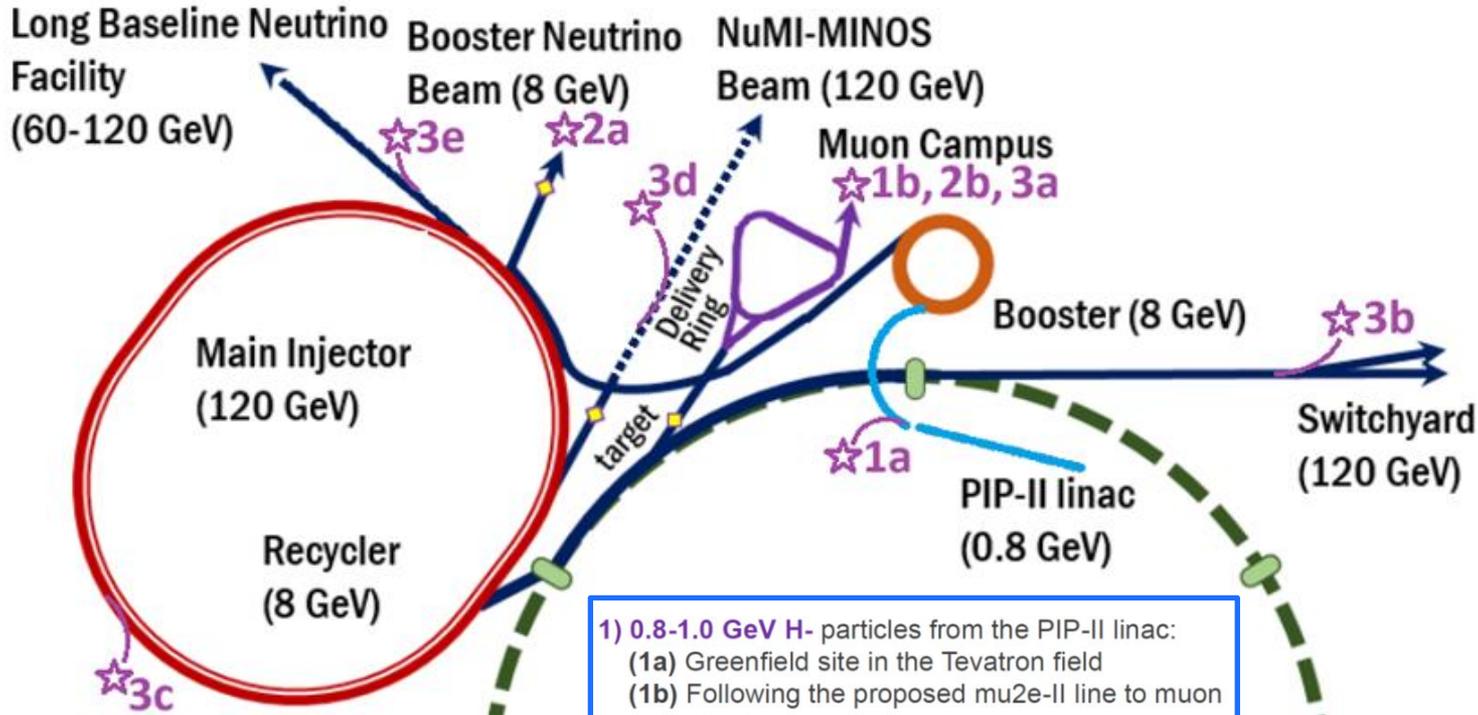
- The PIP-II proton accelerator will provide the intensity sufficient to power a new generation of high energy facilities at Fermilab
 - Proton flux at 8 GeV increases during PIP-II era
 - The 12-24 kW available for 8 GeV program would be suitable for a muon cooling demonstrator
 - Other options at lower or higher energies should be explored



| | | | |
|----------------------|----------|---------|------------|
| Linac | Achieved | PIP-II | ACE-MIRT |
| Current | 20-25 mA | 2 mA | 2 mA |
| Energy | 0.4 GeV | 0.8 GeV | 0.8 GeV |
| Booster | Present | PIP-II | ACE-MIRT |
| Intensity | 4.8e12 | 6.5e12 | 6.5e12 |
| Energy | 8 GeV | 8 GeV | 8 GeV |
| Rep. Rate | 15 Hz | 20 Hz | 20 Hz |
| 8-GeV Power* | 25 kW | 80 kW | 12-24 kW |
| Main Injector | Present | PIP-II | ACE-MIRT |
| Intensity | 58e12 | 78e12 | 78e12 |
| Cycle Time | 1.133s | <1.2 s | ~0.65 s |
| 120-GeV Power | 0.96 MW | ~1.2 MW | 1.9-2.3 MW |

Table 1: Parameters for Fermilab proton complex. *8-GeV beam power given for what is available simultaneous with 120-GeV program.

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.

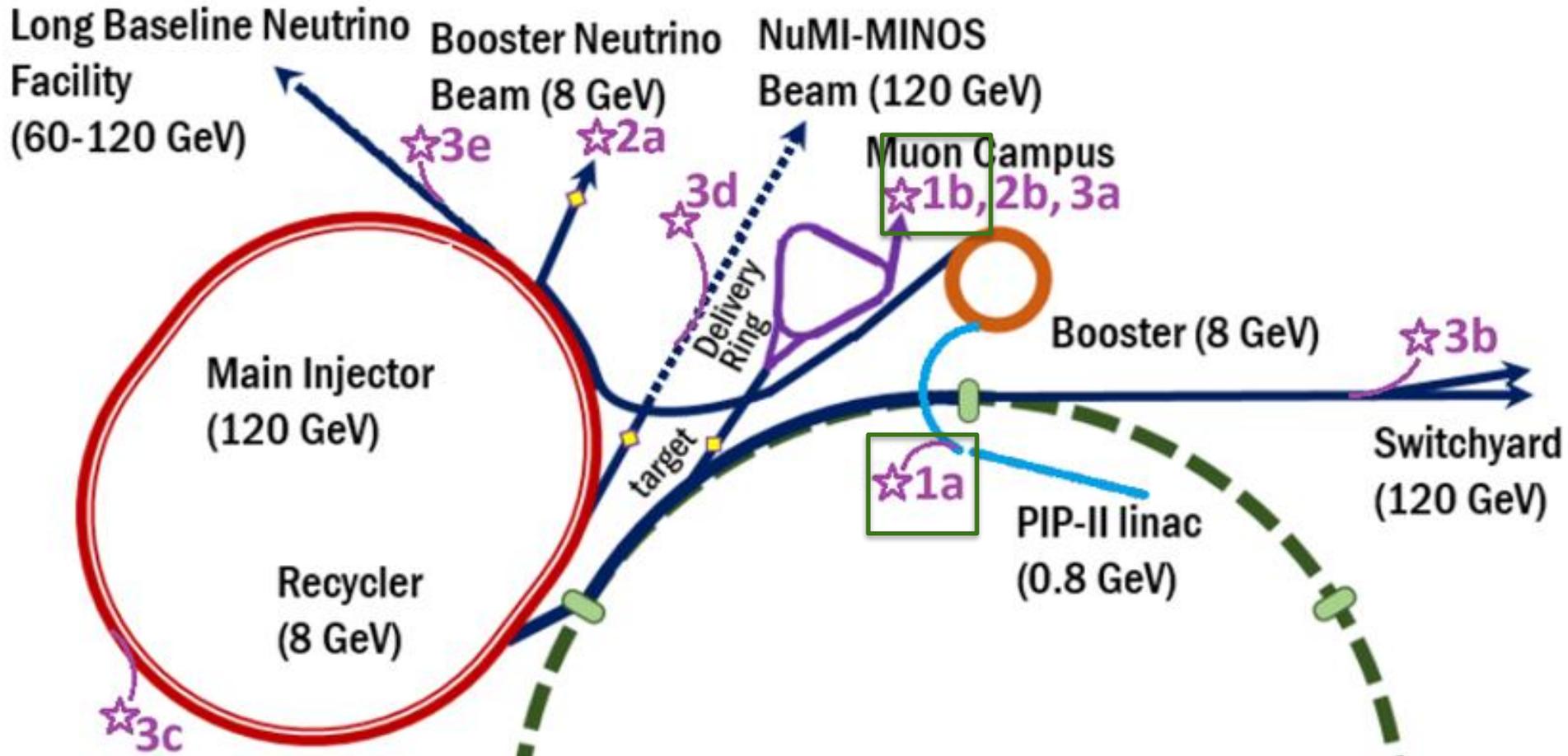
Future Steps

- 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, appears well suited 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

Summary

- Realization of a Muon Collider requires significant R&D and a demonstrator/ prototyping program stretching over the next two decades
- Strong P5 support opens the door for a broader US engagement
- Many opportunities to contribute to cutting-edge R&D: for university and national labs, student and professors, scientist and engineers
- Big challenges to solve across accelerator/theory/experiment - need people, resources, creative ideas – please join the effort

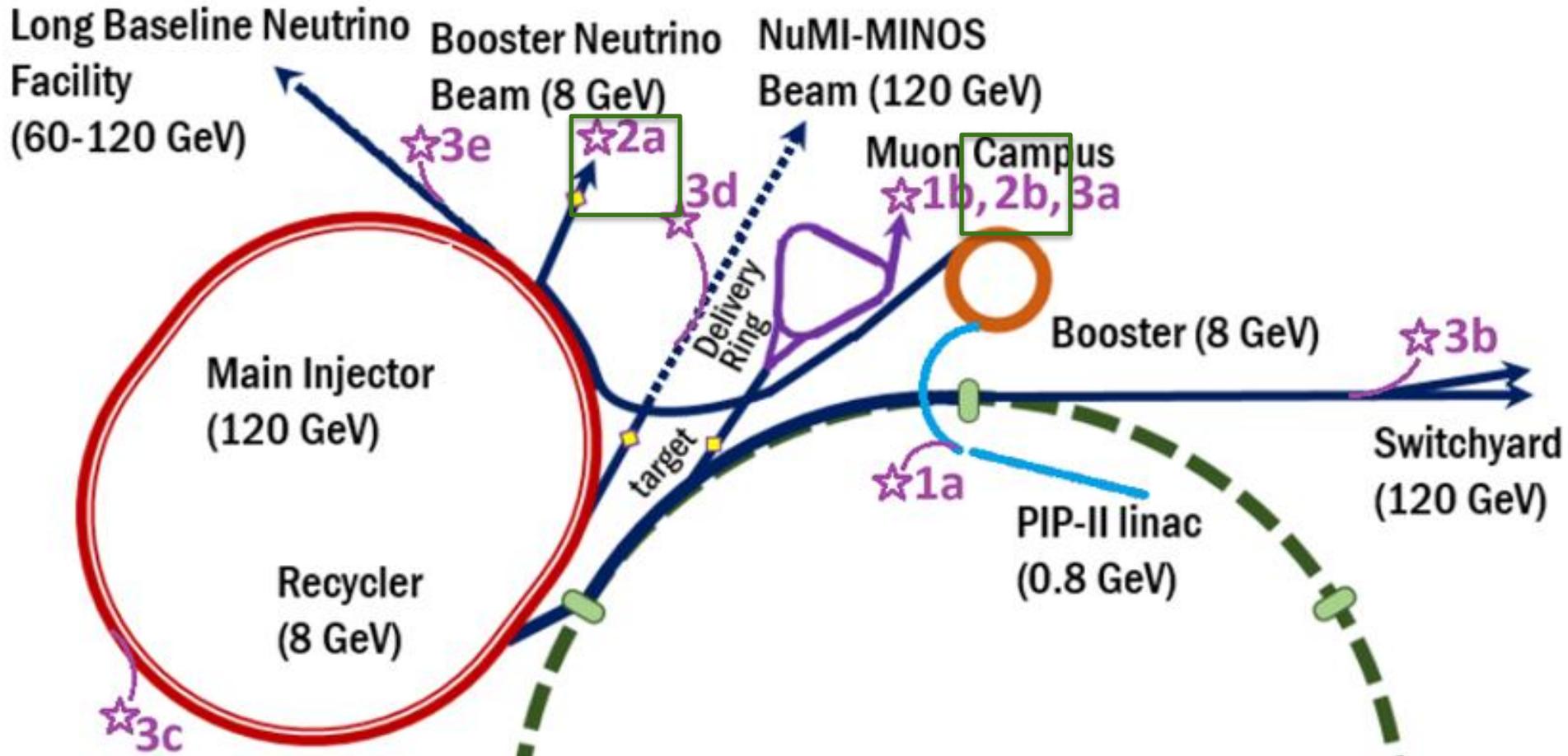
0.8-1.0+ GeV scenarios at Fermilab



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
- 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



8 GeV protons from the booster

- Excellent proton availability
 - 81 bunches, each 1.2 ns separated at 19 ns intervals, 6.5×10^{12} 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