Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Muon Collider Demonstrator & Sitting

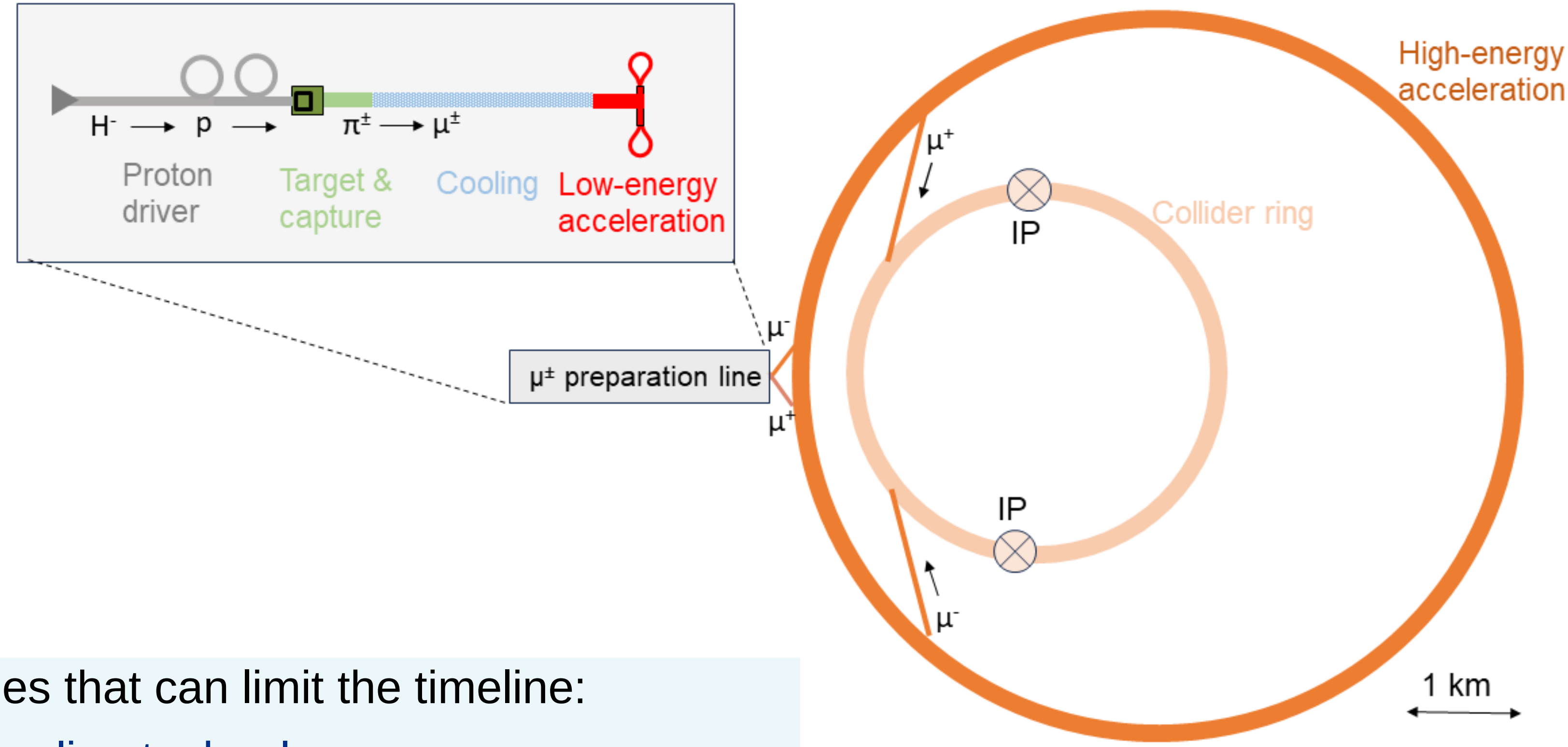
Diktys Stratakis (Fermilab)
On behalf of the International Muon Collider Collaboration

LDG meeting and accelerator R&D workshop, BNL, USA
June 07, 2024

International
MUON Collider
Collaboration

Muon Collider overview

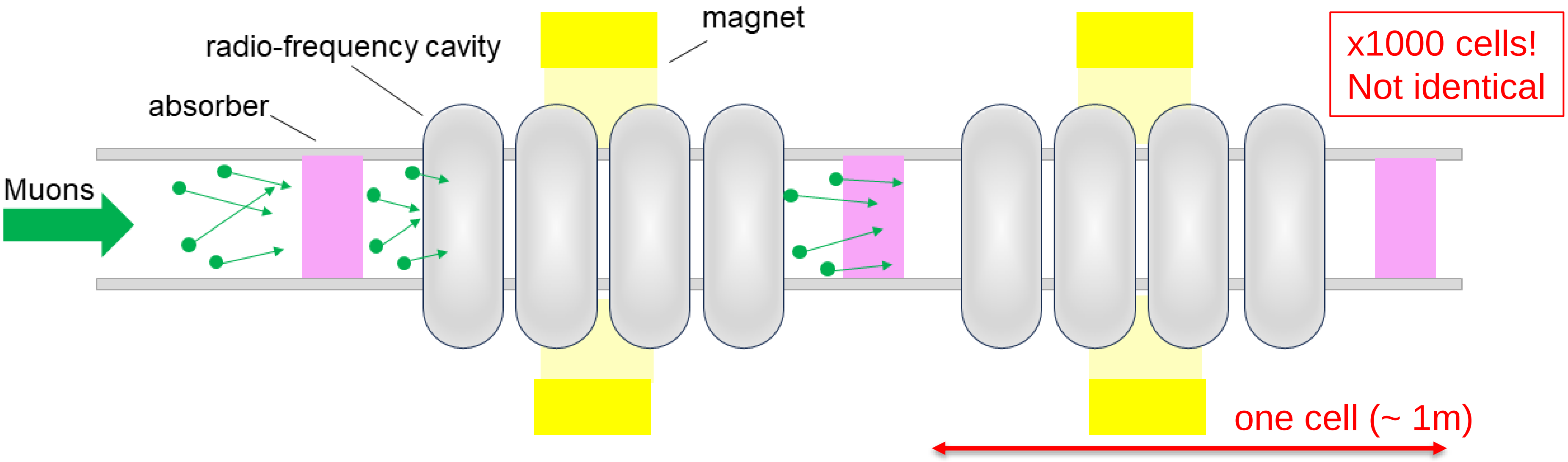
- Goal is to get to **10 TeV center-of-mass energy**



Technologies that can limit the timeline:

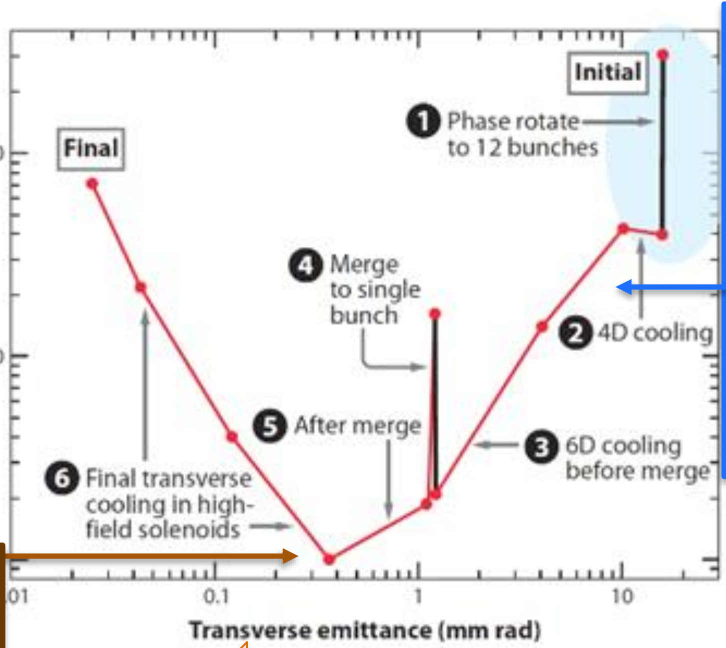
- Muon cooling technology
- Magnet technology (high-field + fast ramp)

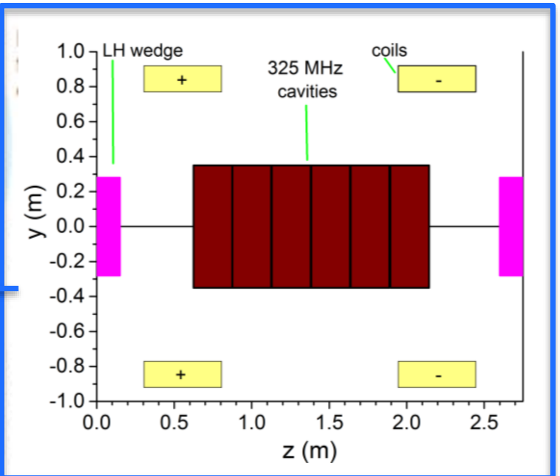
Ionization cooling concept



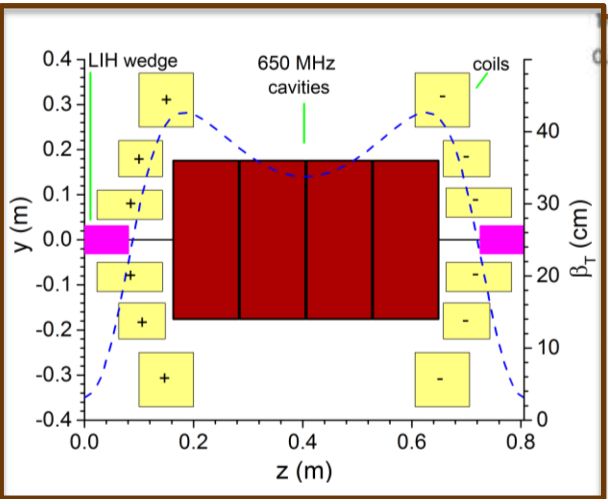
- Solenoids that start at 2 T and extend to 20+ T at the end
    - 3000+ units in the whole channel
- NC cavities (<1 GHz) that can sustain high-gradients in multi-T field
    - 3000+ units in the whole channel

Ionization cooling requirement





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

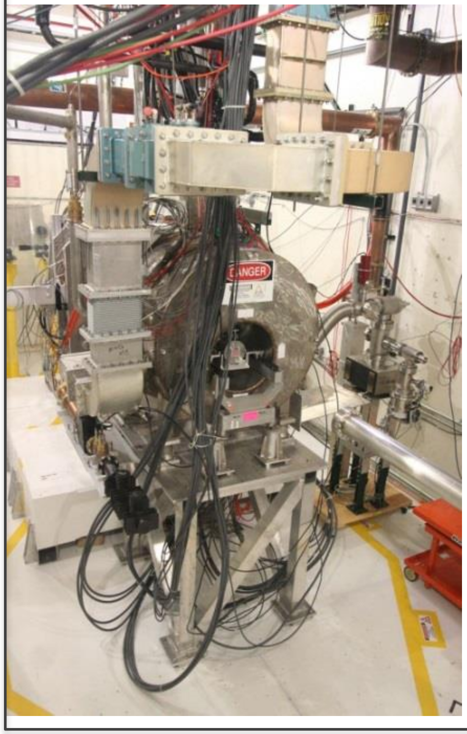
Motivation for a cooling demonstrator

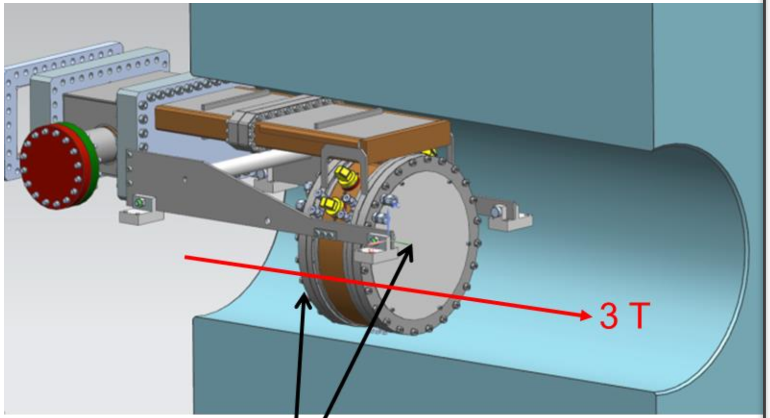
- MICE has demonstrated the principle of ionization cooling
- As a next step it is critical to benchmark a realistic cooling lattice
  - This will give us the input, knowledge, and experience to design a real, buildable cooling channel for a MuC
- It will advance magnet technology since we will design,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

Past experience

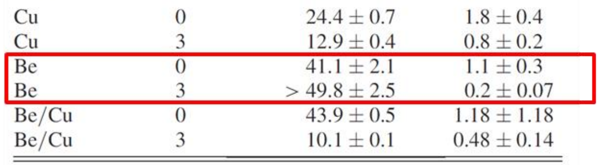
- Cooling designs need placement of cavities within multi-T B-fields
- Behavior of NC cavities in B-fields (up to 3 T) was tested at Fermilab
  - Two technologies have demonstrated mitigation but **more work** is needed!

Vacuum cavities



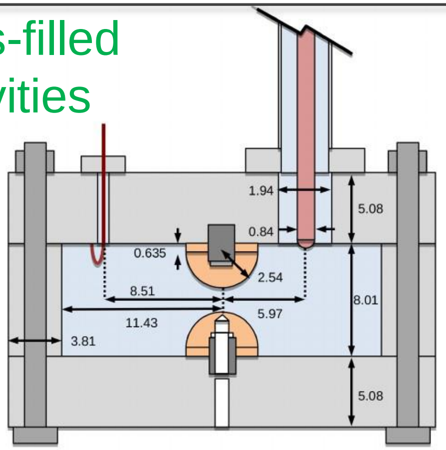


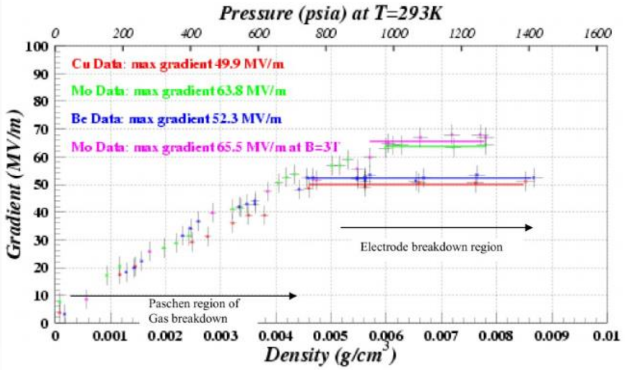
removable plates (Cu, Al, Be)



Material	*B*-field (T)	SOG (MV/m)	BDP ($\times10^{-5}$)
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 ± 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



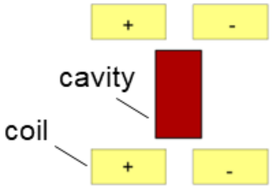


More R&D with vacuum & gas-filled rf + tests at higher B-field needed

Muon demonstrator staging

- Parameters are aspirational and may need modifications based on available funding and resources

Phase-I

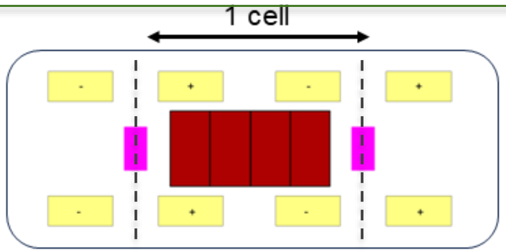


RF studies in B-fields

Material studies & cryogenic Cu

600-800 MHz NC cavity, with coils making 10-14 T on axis

Phase-II

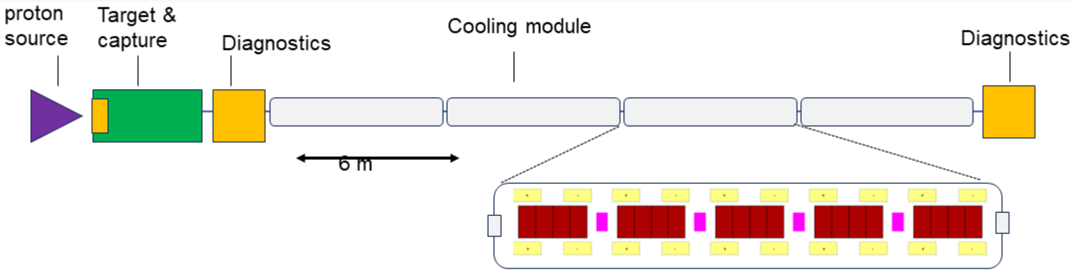


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III

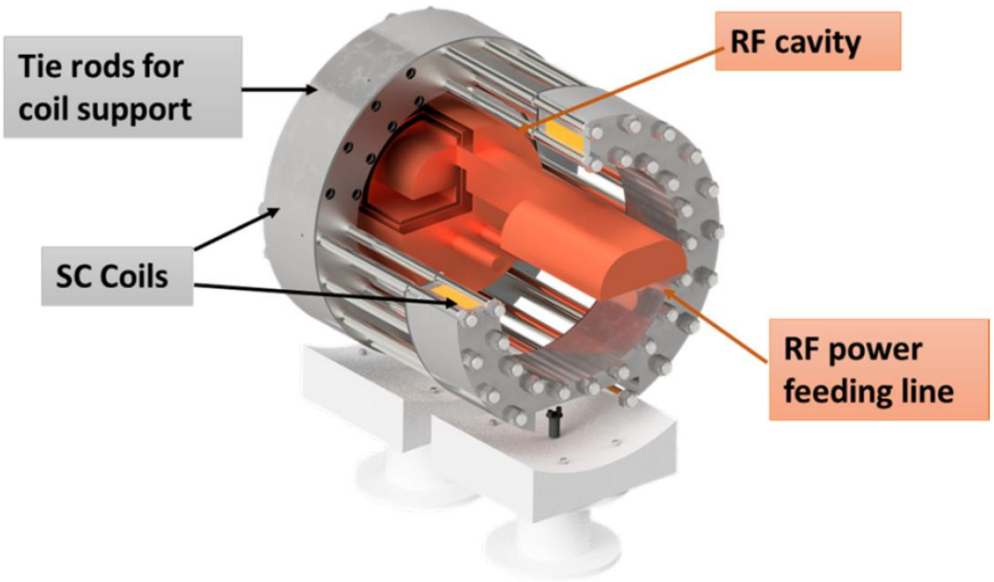


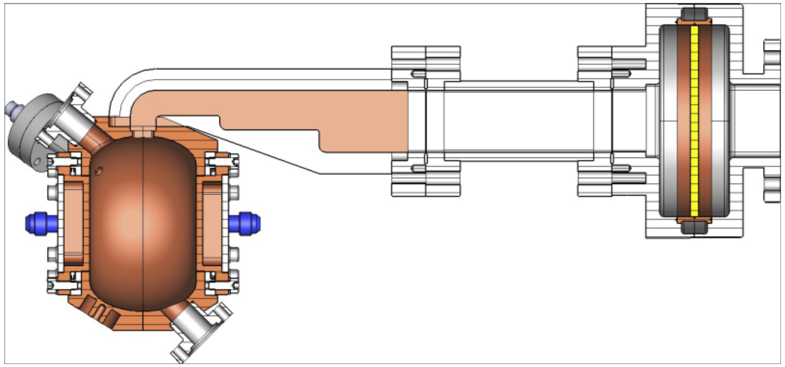
Full demonstrator with beam

Coils producing 7-10 T axial fields

Potential to achieve 50% 6D cooling

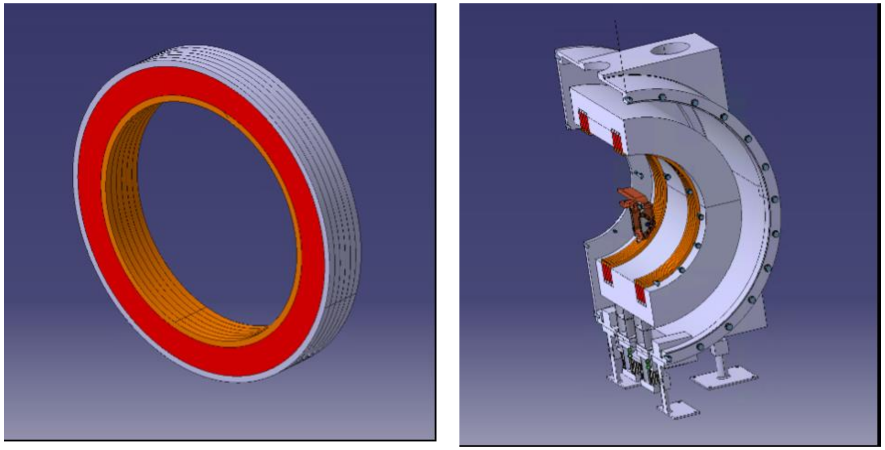
RF and Magnetic Field Test Facility (RFMFTF)

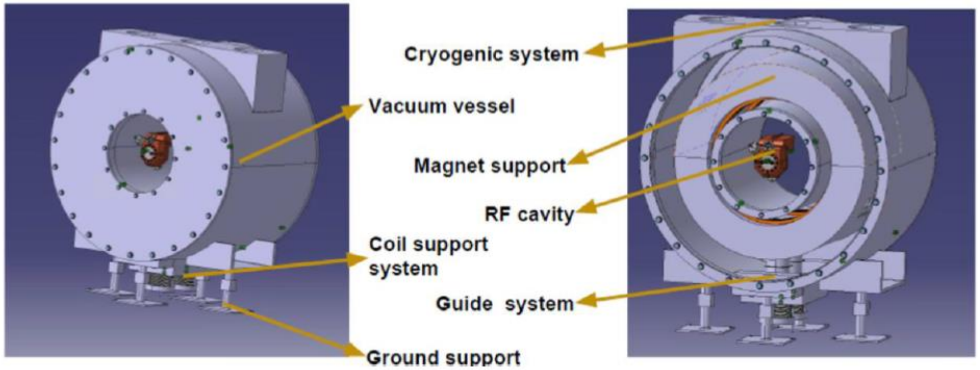




- Significant cost to perform tests at the desired frequency (< 1 GHz)
- RFMFTF at INFN-LASA is available for rf studies and investigations
  - Will allow the testing of NC rf cavities at very high B-fields
  - To reduce cost, the cavity considered is at a higher frequency (3 GHz)
  - **Superior opportunity** to test integration of magnet and rf system for cooling
  - **Superior opportunity** to test material technologies for cooling rf cavities

Magnet technology R&D for the demonstrator

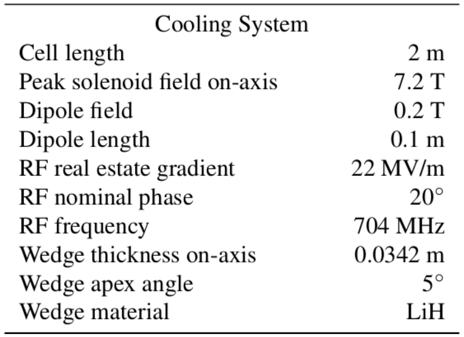




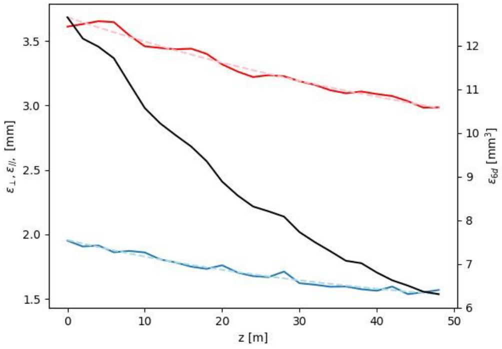
- A HTS magnet design at 20 K, capable of **7 T** field at its center, is pursued
  - Fully worked magnetic and mechanical model developed
  - First phase 300 mm for a 3 GHz rf; second phase 700 mm bore for < 1 GHz rf (with more resources + funding)
  - Excellent **opportunity** to advance HTS magnet technology for muon cooling
- Will have the shape of a solenoidal doublet, that can be energized both with same and opposite polarity, **like the actual cooling cell**

Full demonstrator with beam

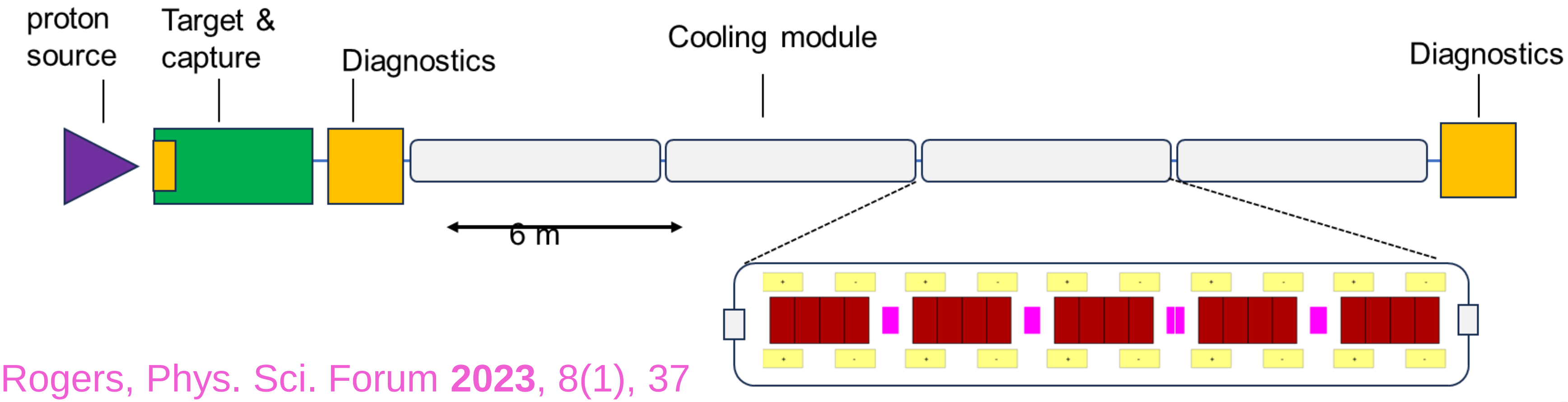
- Design in progress
  - Muon source, target and transport
  - Beam transport
  - Cooling channel
- **Design may be informed by the siting options**
- Investing synergies with other applications



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



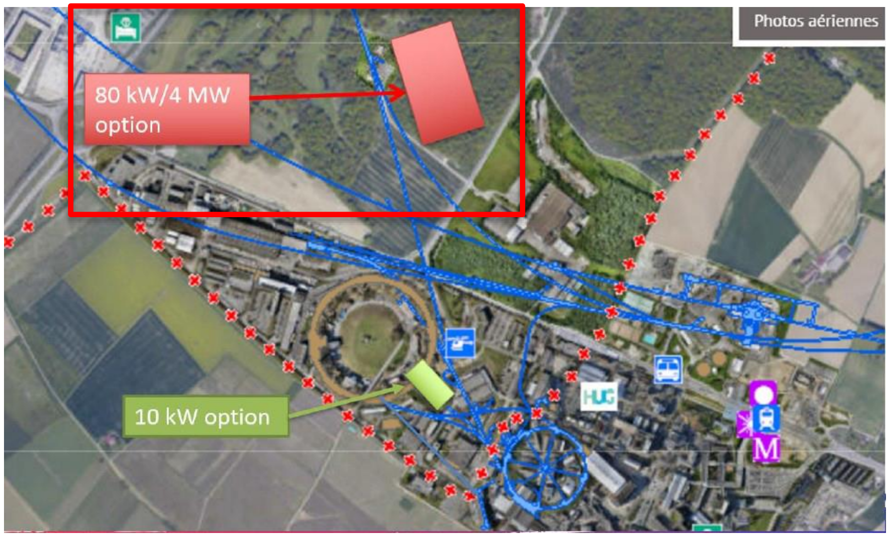
	Muon energy, MeV	Total length, m	Total # of cells	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	2-14	$x\ 1/10^5$	~70%
Demonstrator	200	48	24	0.5-7	x 1/2	4-6%

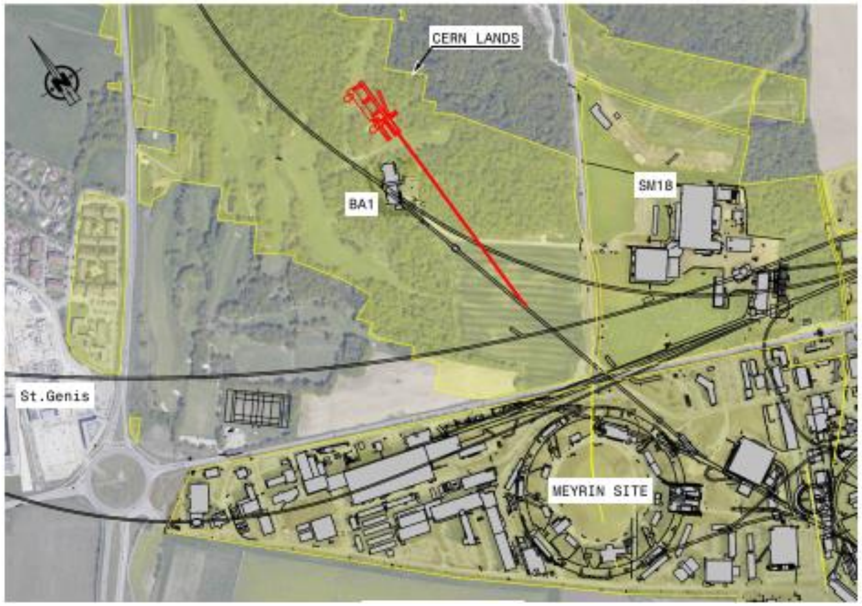


C. Rogers, Phys. Sci. Forum **2023**, 8(1), 37

Site at CERN: High power option

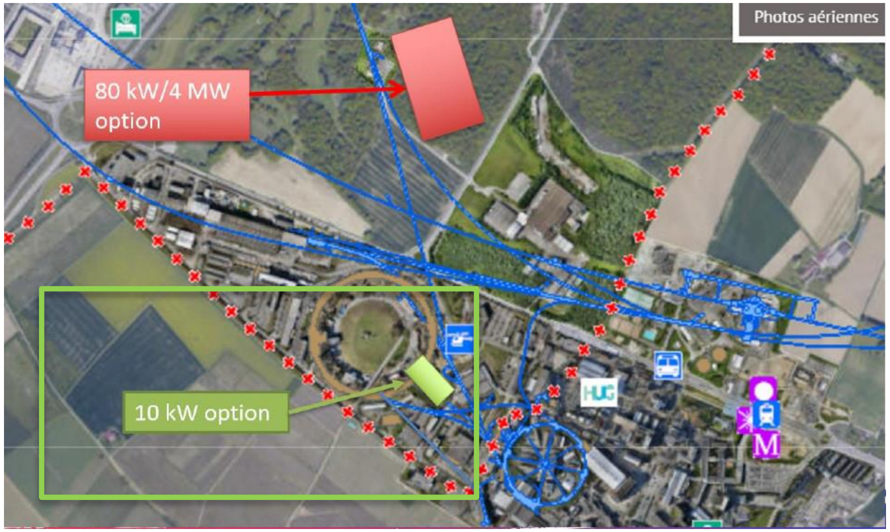
- TT10 is the transfer line between CERN PS and SPS
- From TT10 a new beamline would be extracted via a tunnel to the proposed Muon Collider Demonstrator Facility
  - 80 kW beam power
  - 20+ GeV with 10^{13} proton pulses of a few ns
  - Expensive option

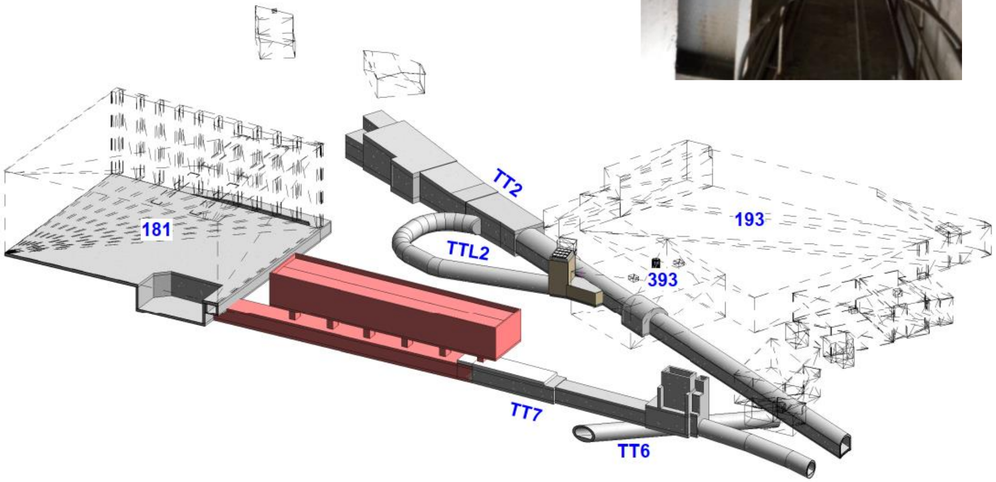




Site at CERN: Low power option

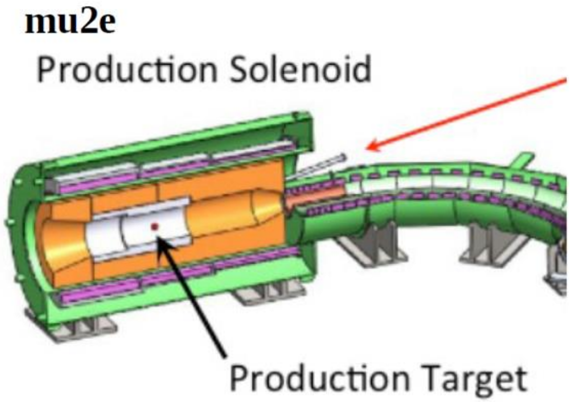
- Reuse the line of the Big European Bubble Chamber experiment
  - 10 kW beam power
  - 20+ GeV with 10^13 proton pulses of a few ns
  - Cheaper option



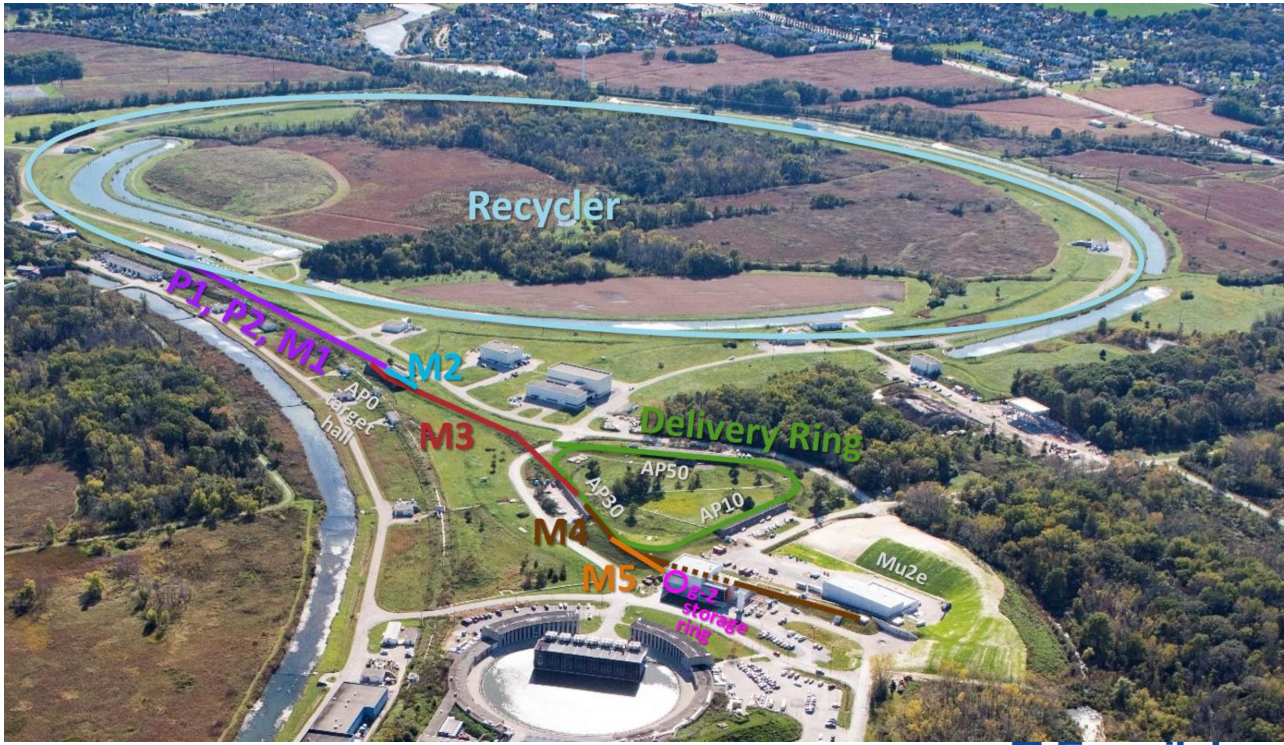


Site at Fermilab: Muon Campus

- 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

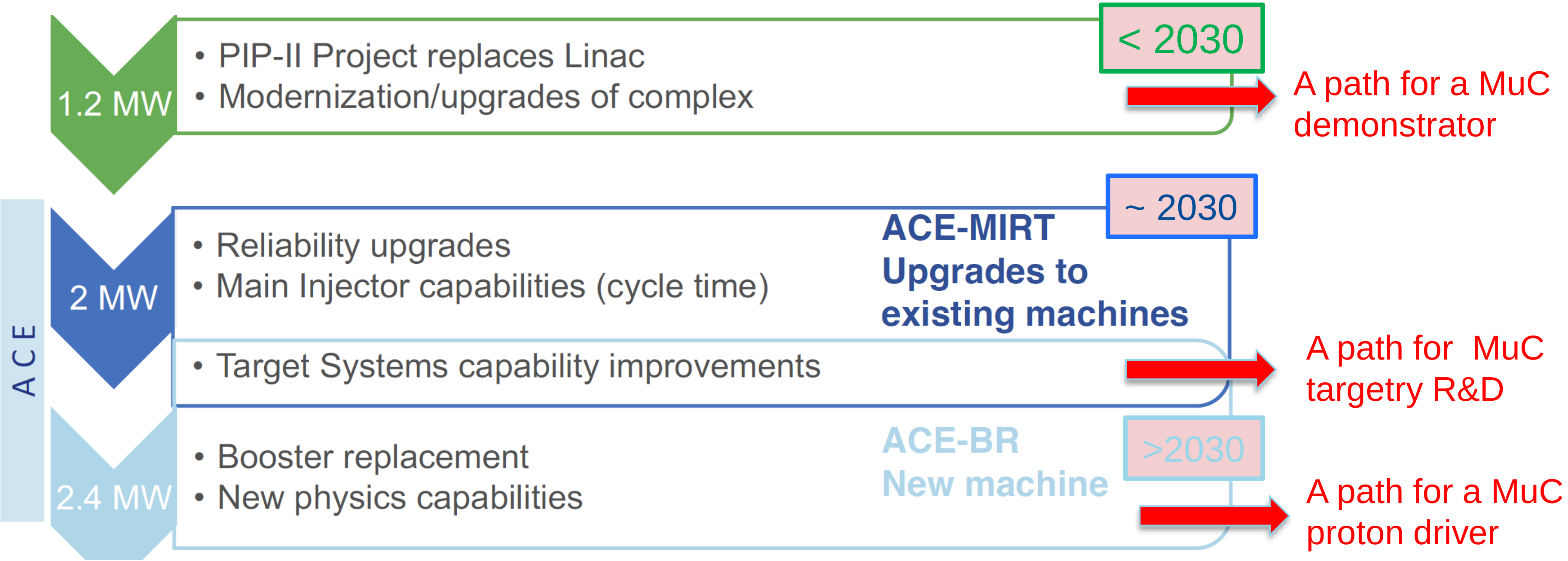


Excellent opportunity to examine targets under 5 T field



Fermilab acceleration evolution plan

- **Fermilab’s ACE program** could become the basis for developing a proton driver and a target station for a MuC
  - Includes a rigorous target R&D program for 2+ MW beams in the next decade
  - Can serve as a basis for a MuC demo facility and a MuC front-end



1.2 MW
- PIP-II Project replaces Linac
- Modernization/upgrades of complex

< 2030

A path for a MuC demonstrator

ACE

2 MW
- Reliability upgrades
- Main Injector capabilities (cycle time)

ACE-MIRT Upgrades to existing machines

~ 2030

- Target Systems capability improvements

A path for MuC targetry R&D

2.4 MW
- Booster replacement
- New physics capabilities

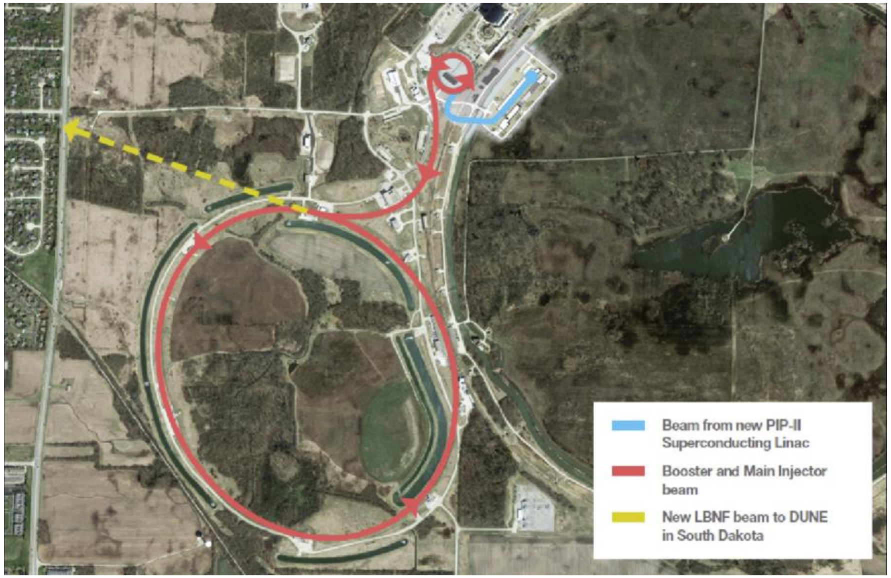
ACE-BR New machine

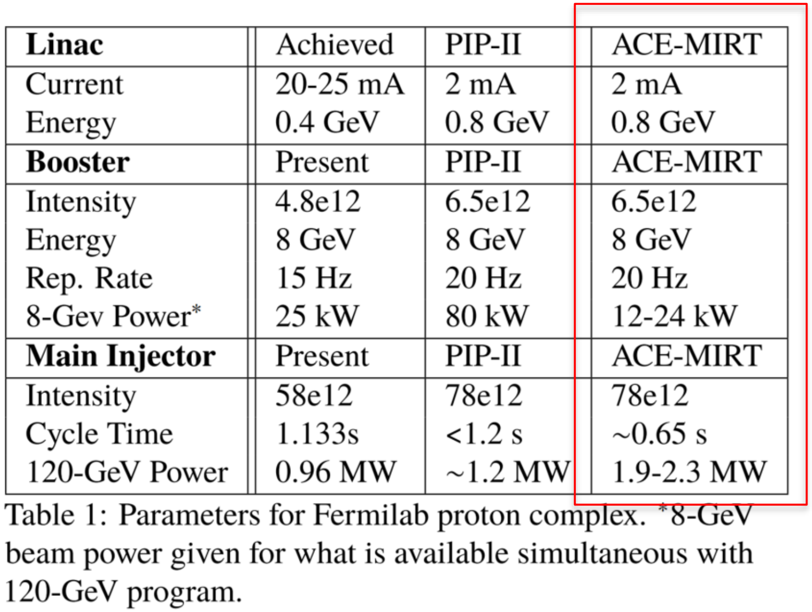
>2030

A path for a MuC proton driver

Possibilities during the ACE-MIRT phase

- 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



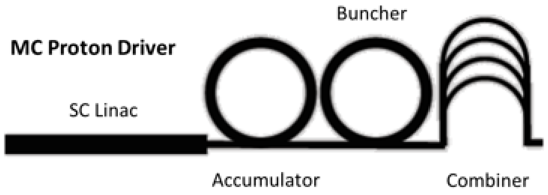


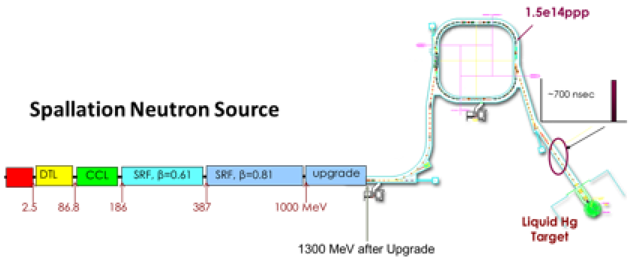
Linac	Achieved	PIP-II	ACE-MIRT
Current	20-25 mA	2 mA	2 mA
Energy	0.4 GeV	0.8 GeV	0.8 GeV
Booster	Present	PIP-II	ACE-MIRT
Intensity	4.8e12	6.5e12	6.5e12
Energy	8 GeV	8 GeV	8 GeV
Rep. Rate	15 Hz	20 Hz	20 Hz
8-Gev Power*	25 kW	80 kW	12-24 kW
Main Injector	Present	PIP-II	ACE-MIRT
Intensity	58e12	78e12	78e12
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.

SNS and Muon Collider R&D

- SNS much like proton driver



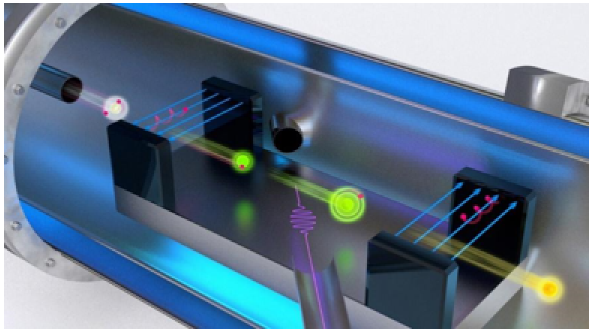


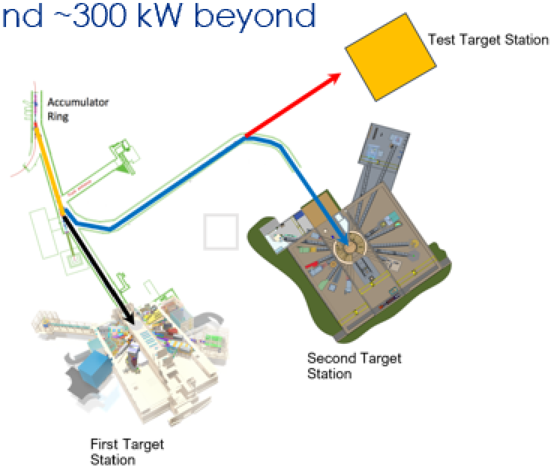
Parameter	SNS (nominal)	MC Proton Driver (compressed)
P (MW)	2.8	2 – 4
T (GeV)	1.3	5 – 30
N_p (10^{14})	2.2	0.4 – 10
R (Hz)	60	5 – 10
σ_z (m)	95	0.3 – 0.9
K	$2.6 \cdot 10^{-7}$	$1.6 \cdot 10^{-9} - 1.7 \cdot 10^{-5}$

Area	Potential contribution
Proton driver design	Guidance
Linac design	Guidance, simulations, and experiments
Beam accumulation	Experimental demonstration of a new technology
Proton pulse formation	Experimental verification
Code benchmarking	Experimental validation
Intensity-related instabilities	Specifications and experimental validation
Space-charge mitigation	Development and experimental demonstration of a new technique
Proton target design	Guidance and components tests
Muon ionization cooling	Components tests

- >800 spare kW for 10 years and ~300 kW beyond

- Laser-Assisted Charge-Exchange (LACE) injection test ONLY at SNS



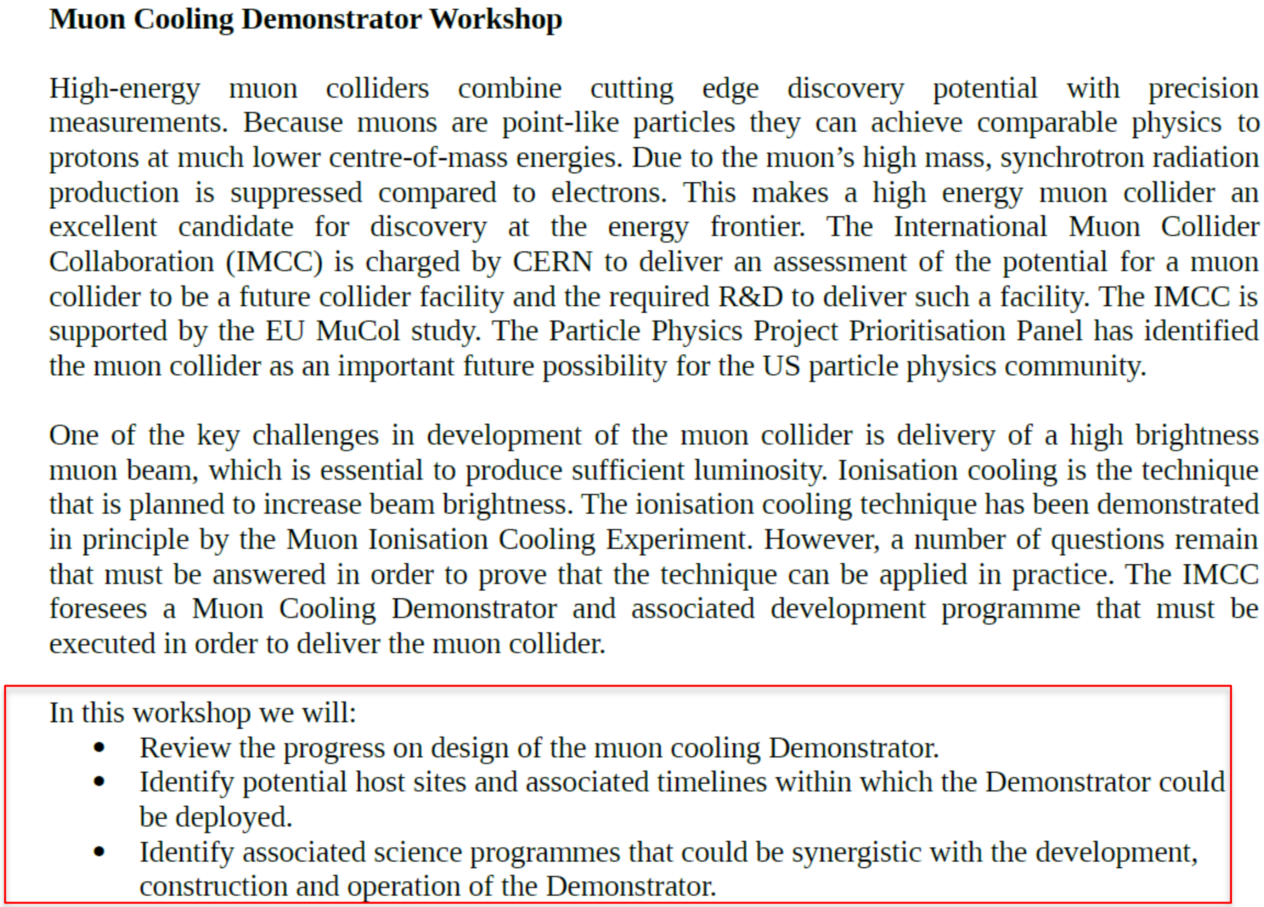


Timeline

- Currently in the US, limited funds are accessible via laboratory discretionary funds, university research programs and theory efforts
  - Expect funding to appear as we progress through the 3-year budget cycle at DOE
- Per P5, a **targeted panel** is expected to review test & demo facilities in the collider R&D portfolios within **next 3-5 years**
  - Goal is to prepare a demonstrator conceptual design, with US sittings
- EU Strategy Update approval by CERN in 2026
  - Based on the outcome and available 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)

IMCC Muon Collider Demonstrator Workshop

- Plan to hold a workshop at Fermilab the week of October 28th
  - With conveners from the global community



Muon Cooling Demonstrator Workshop

High-energy muon colliders combine cutting edge discovery potential with precision measurements. Because muons are point-like particles they can achieve comparable physics to protons at much lower centre-of-mass energies. Due to the muon's high mass, synchrotron radiation production is suppressed compared to electrons. This makes a high energy muon collider an excellent candidate for discovery at the energy frontier. The International Muon Collider Collaboration (IMCC) is charged by CERN to deliver an assessment of the potential for a muon collider to be a future collider facility and the required R&D to deliver such a facility. The IMCC is supported by the EU MuCol study. The Particle Physics Project Prioritisation Panel has identified the muon collider as an important future possibility for the US particle physics community.

One of the key challenges in development of the muon collider is delivery of a high brightness muon beam, which is essential to produce sufficient luminosity. Ionisation cooling is the technique that is planned to increase beam brightness. The ionisation cooling technique has been demonstrated in principle by the Muon Ionisation Cooling Experiment. However, a number of questions remain that must be answered in order to prove that the technique can be applied in practice. The IMCC foresees a Muon Cooling Demonstrator and associated development programme that must be executed in order to deliver the muon collider.

In this workshop we will:

- Review the progress on design of the muon cooling Demonstrator.
- Identify potential host sites and associated timelines within which the Demonstrator could be deployed.
- Identify associated science programmes that could be synergistic with the development, construction and operation of the Demonstrator.

Summary

- Muon Collider is an exciting future collider option. A machine that can provide both precision and energy reach for future discoveries
- Realization of a MuC requires significant R&D & demonstrator/ prototyping program stretching over the next 2 decades
- IMCC has done considerable progress on demonstrator work
    - A design is in place with two site options in CERN as well as a plan for testing cooling components (rf test stand)
- Strong P5 support opens the door for a broader US engagement
    - Paves the way for exploring US sitting options for the demonstrator
- Many opportunities to contribute to cutting-edge R&D: for university and national labs, student and professors, scientist and engineers