Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Muon Collider: Overview of accelerator R&D needs

Diktys Stratakis (Fermilab)

Inaugural US Muon Collider Meeting

August 09, 2024

On behalf of US Muon Collider R&D Coordination Group

Inspirations of the MuC R&D plan

- Results from the Muon Accelerator Program
- Studies from the IMCC collaboration → International MUON Collider Collaboration
- Muon Collider Forum Report
  - Presented at Snowmass and published in JINST
- Muon Collider R&D Coordination Group
  - Presented at the P5 Townhalls & submitted to the P5 panel
- Muon Collider Princeton Workshop (Feb. 2024)
  - By invitation only to discuss organization & R&D plans
- Fermilab Muon Collider Task Force Report
- DOE response to P5 report (R. Rameika talk at @ FNAL)
  - Targeted panels will review Fermilab accelerator complex & demos (~ 3-5 y)

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SNOWMASS'2021 ACCELERATOR FRONTIER
Muon Collider Forum report

Summary of Muon Collider Study and Ask for the 2023 P5
US Muon Collider R&D Coordination Group

Summary of the Fermilab Task Force on Muon Collider Accelerator
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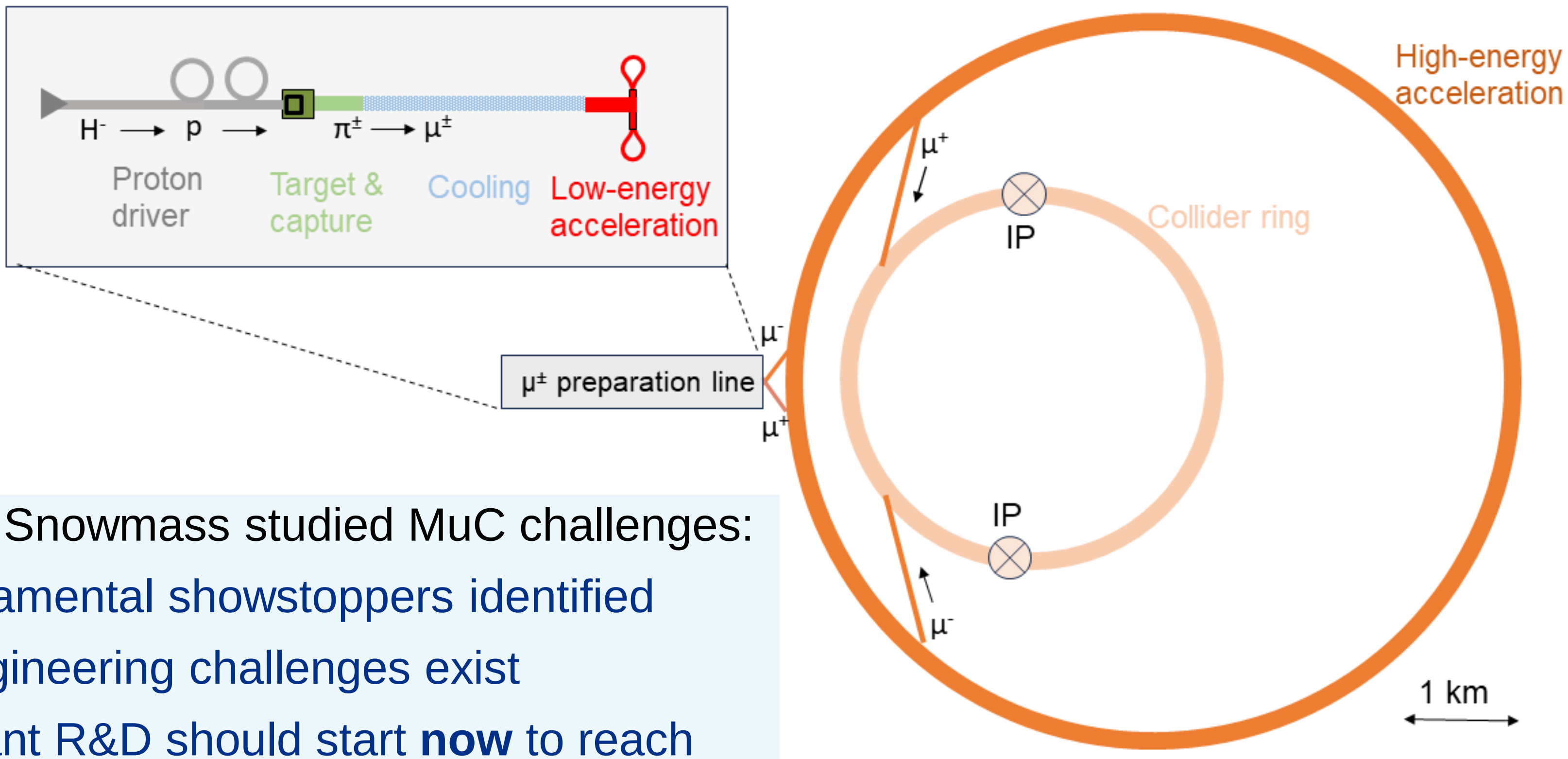
Report from DOE
Regina Rameika
Associate Director of the Office of Science for High Energy Physics
2024 Fermilab Users Meeting
July 12, 2024

Princeton Muon Collider Organizational Workshop
Feb 22 – 24, 2024
Princeton University
America/New_York timezone

Machine overview

- Goal is to get to **10 TeV center-of-mass energy**
- Two approaches: Staging in **energy** (3 TeV to 10 TeV) or in **luminosity**



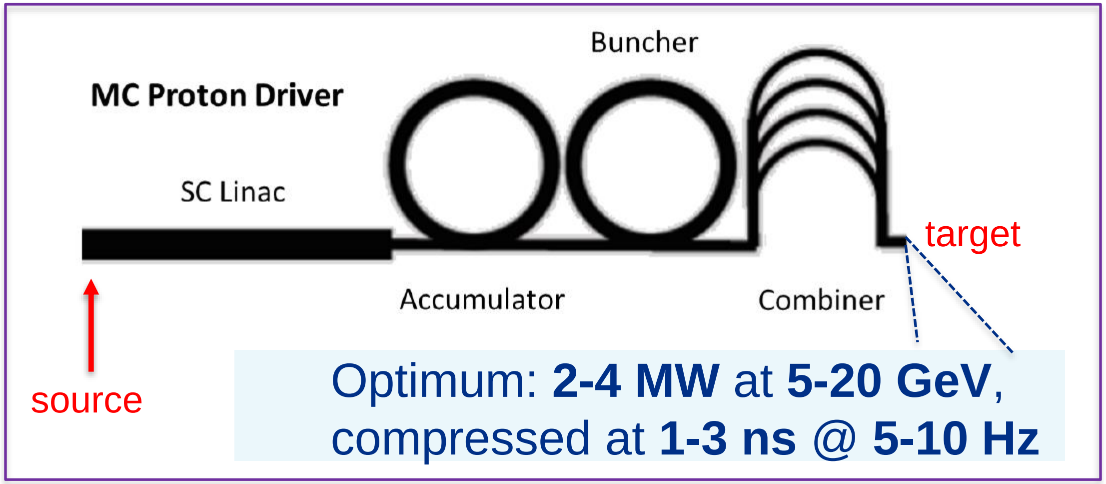
IMCC & US Snowmass studied MuC challenges:

– No fundamental showstoppers identified

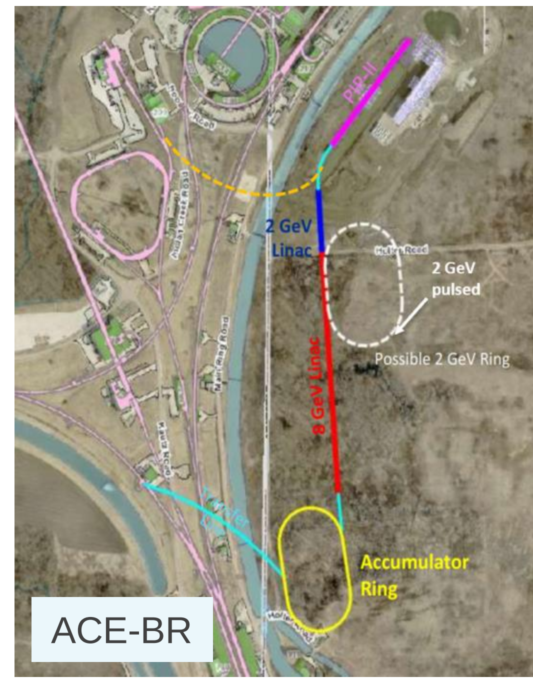
– BUT engineering challenges exist

– Significant R&D should start **now** to reach readiness of construction in the 2040s

MuC proton driver

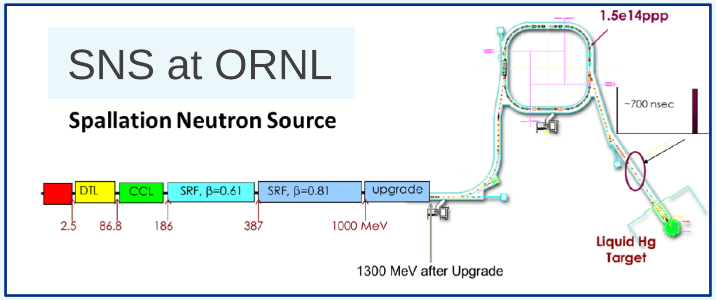


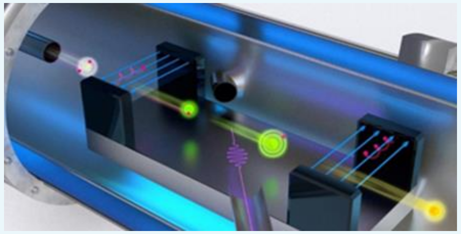
- Accelerator Complex Evolution (ACE) plan will open a path for new facilities at Fermilab
  - PIP-II linac will double the proton flux at 8 GeV
  - Accelerator upgrades (ACE-MIRT) will deliver MW scale beam at 120 GeV to LBNF
  - Designs for booster replacement (ACE-BR) will be developed for the targeted panel (3-5 years). **Will open a path towards MW scale beams at 8 GeV**



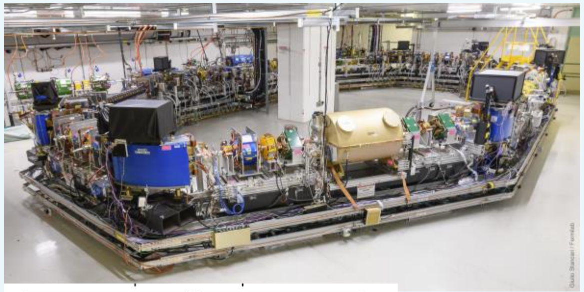
Proton driver R&D plan

- Begin an R&D program to identify modifications and upgrades to the Fermilab accelerator complex necessary to provide a proton driver compatible with a future MuC
  - Have a conceptual design report ready for the targeted panels (3-5 years)
- Carry out scaled experiments at existing facilities that are analogs to a MuC proton driver
  - Will secure our choices for the design of the final facility

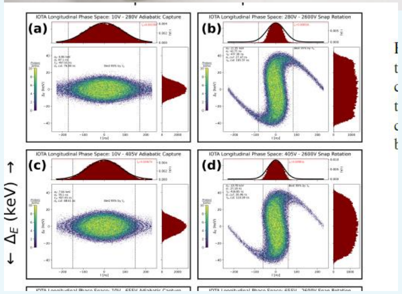




- Bunch accumulation
- Bunch compression
- Laser assisted charge stripping

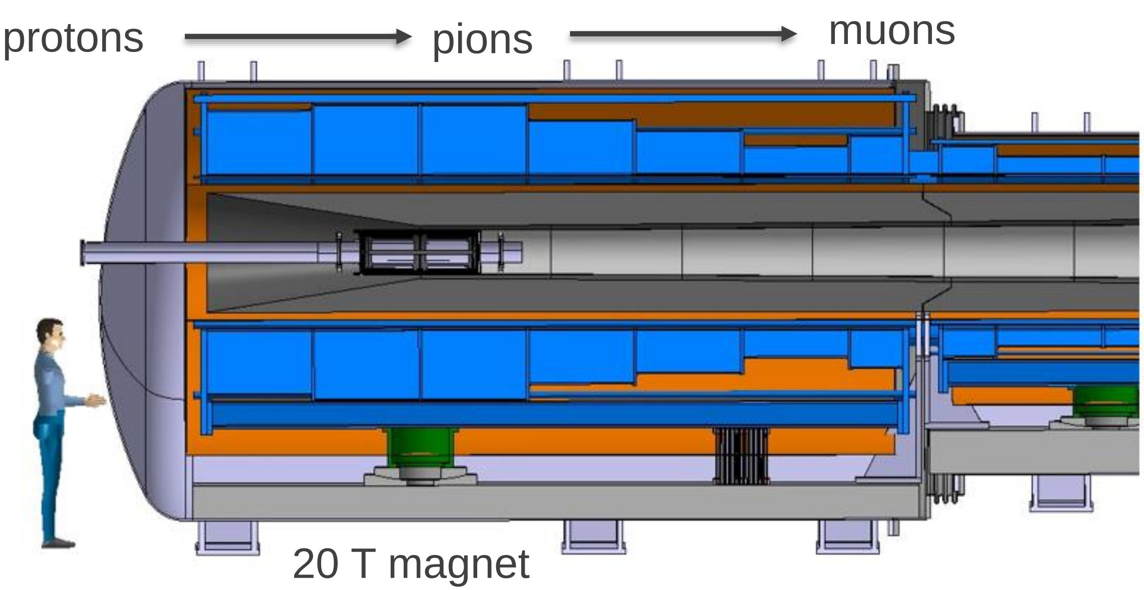


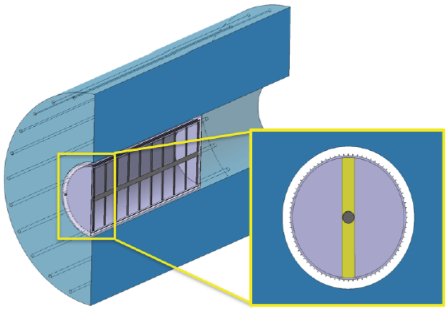
IOTA at FNAL



- Instrumentation
- Bunch compression under extreme space-charge

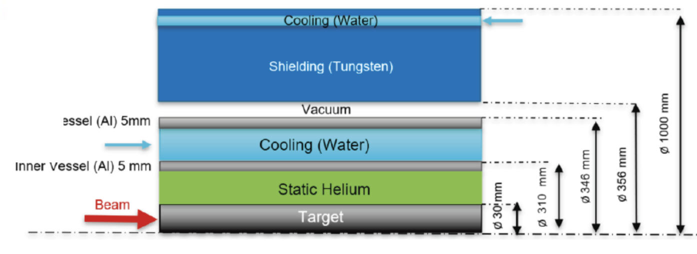
MuC target





'igure 1: Current Muon Collider target 3D concept.

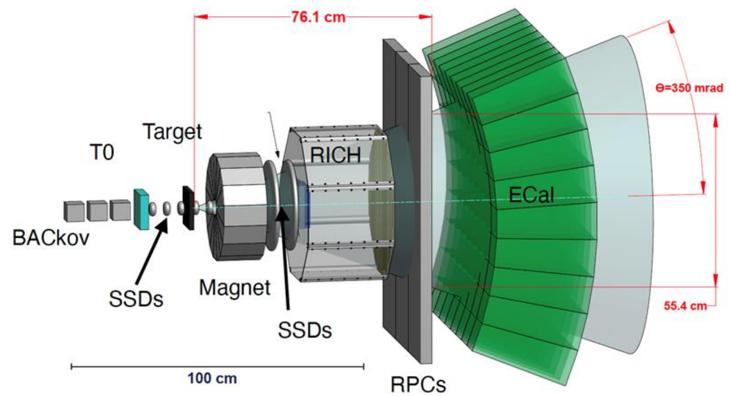
gure 2 schematically details the bodies, dimensions and
:rials of the current proposal.



- In 2007, a proof-of principle test validated the concept with a liquid Hg target. Technology was OK but some safety concerns (ref)
- Recent work shows promising results with graphite or tungsten but still significant R&D is needed to confirm that
  - Puts MuC targets in synergistic path with ongoing and proposed experiments

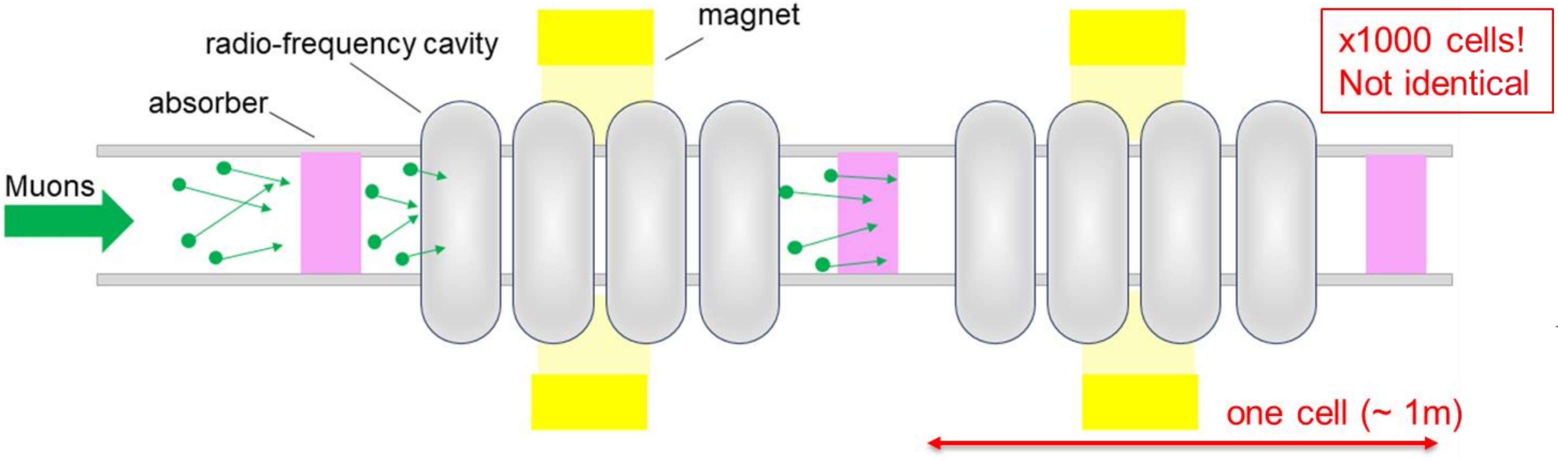
Target R&D plan

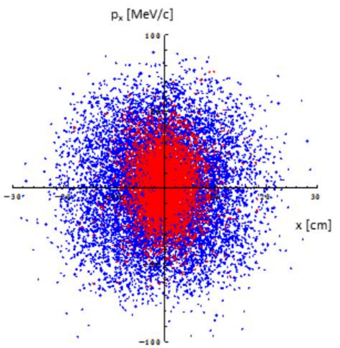
- The short proton bunch is a unique challenge for MuC & mitigating the instantaneous energy deposition is crucial
  - Establish partnership with RaDIATE: international collaboration lead by Fermilab to examine material and radiation damage for targets
  - Will enable access to test equipment and beam irradiation facilities globally to test different material at various conditions
- Optimize design through simulation & experimentation
  - High-performance computing to determine target concept and shape and to identify best compound mix to maximize pion yield
  - Incorporate AI/ML methods
  - Pion yield measurements using the EMPHATIC spectrometer



RaDIATE Collaboration
Radiation Damage In Accelerator Target Environments

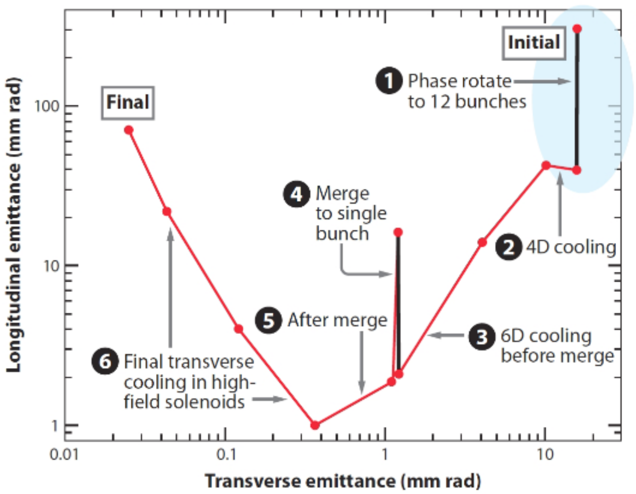
Muon Collider ionization cooling

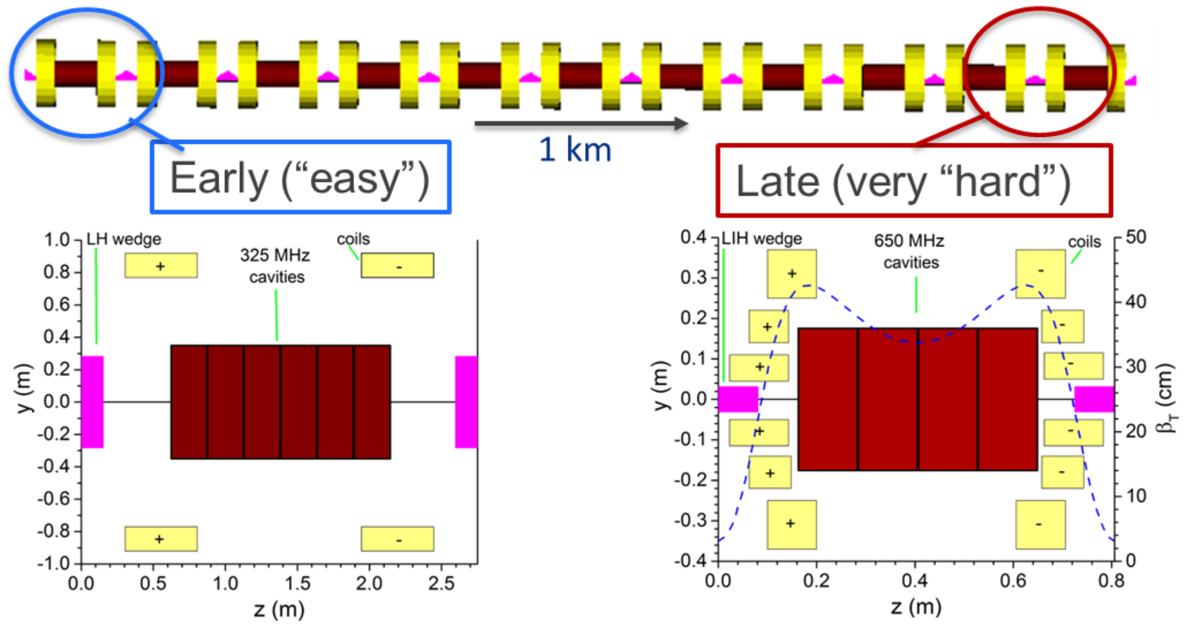




- Ionization cooling channel contains
  – Solenoids that start at 2 T and extend to 20+ T at the end
  – NC cavities (<1 GHz) that have to operate within multi-T field
  – Absorbers that can tolerate the large intensity
- Physics of ionization cooling has been demonstrated by MICE
  - Demonstrated a 10% emittance reduction

Cooling R&D plan





- 6D emittance needs be cooled by 6-orders of magnitude
  – Concepts & designs **in place** that are only a small factor above this goal; transmission not great
- Further improvements are needed so that:
  – Deliver a end-to-end design that meets the MuC criteria
  – Take into account engineering aspects
  – Improve performance with latest technology advances & AI/ML methods

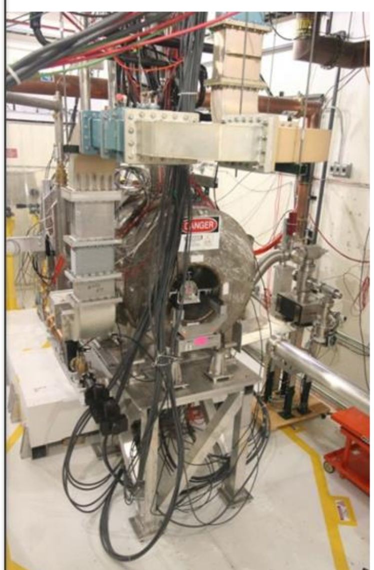
Motivation for a cooling demonstrator

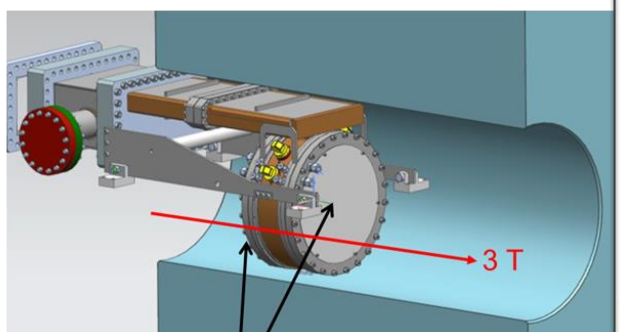
- As a next step it is critical to benchmark a realistic cooling lattice
  - This will give us the input, knowledge, and experience to design a real, buildable cooling channel for a MuC
- It will advance magnet technology since we will design, prototype and test HTS solenoids similar to those needed 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

NC RF technology

- Behavior of NC cavities in B-fields (up to 3 T) was tested at Fermilab
- Facility decommissioned and needs to be re-established
  - Study new methods to achieve high–gradients (gas, materials, rf pulse)
  - Development of power sources for < 1 GHz cavities
  - Carry out tests at > 3 T fields

Vacuum cavities

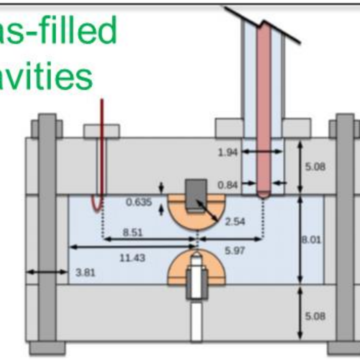


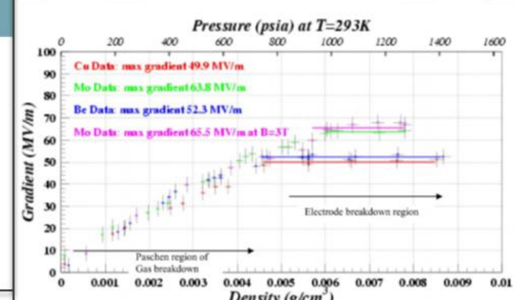


removable plates (Cu, Al, Be)

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



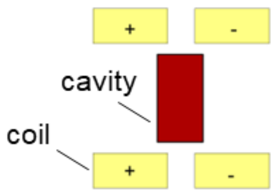


Fermilab

Muon demonstrator staging

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

Phase-I



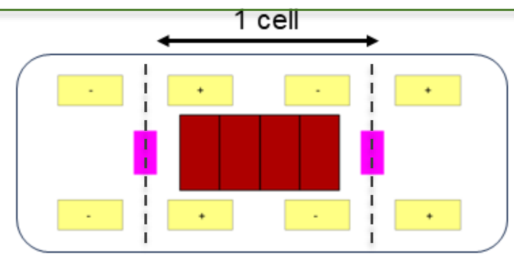
RF studies in B-fields

Material studies & cryogenic Cu

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

< 7 years from today

Phase-II



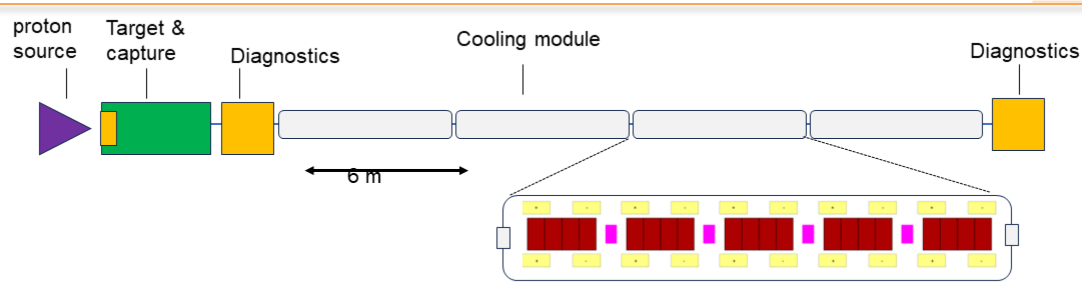
Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

7-10 years

Phase-III



Full demonstrator with beam

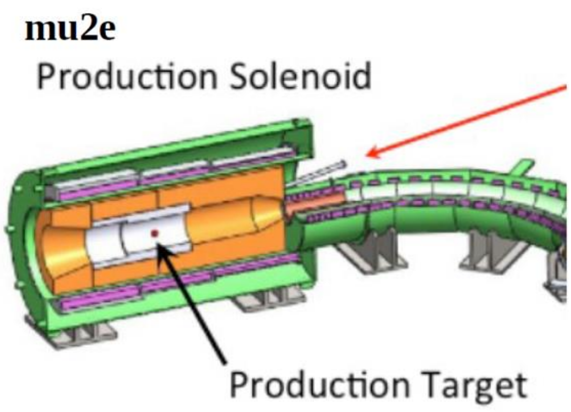
Coils producing 7-10 T axial fields

Potential to achieve 50% or more 6D cooling

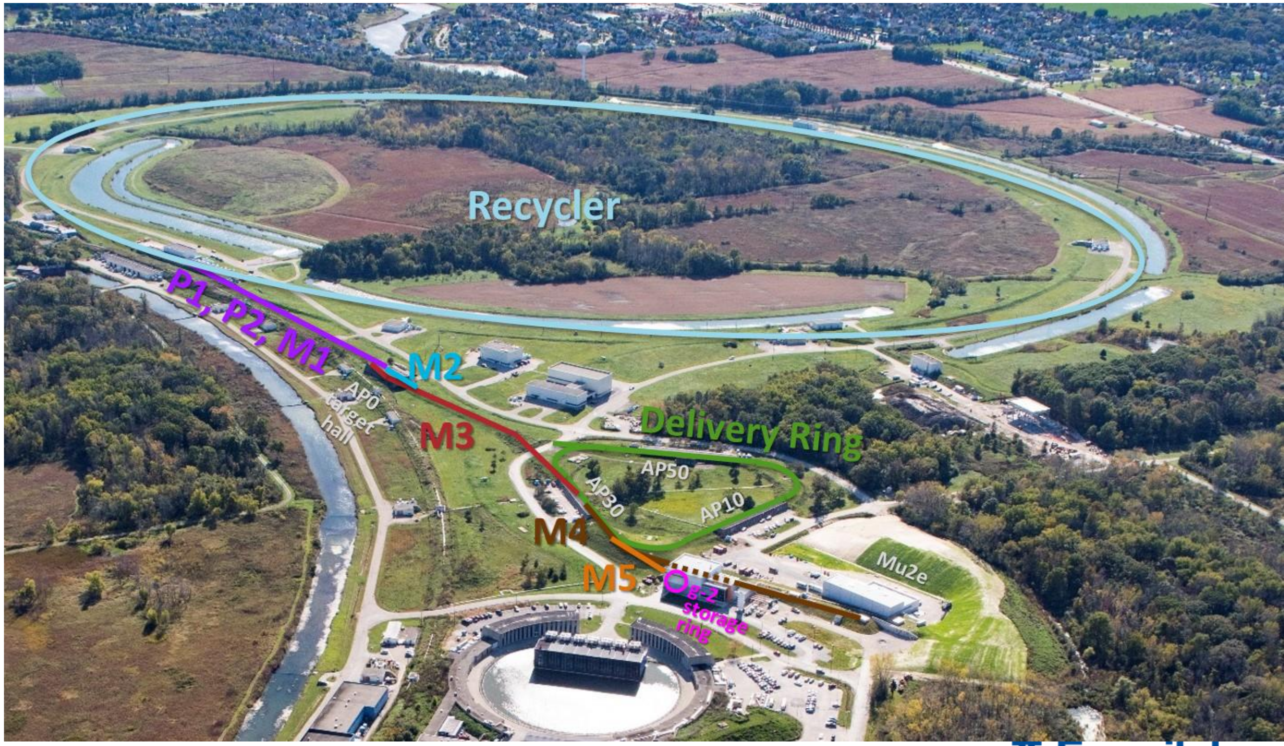
>10 years from today

Demo 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



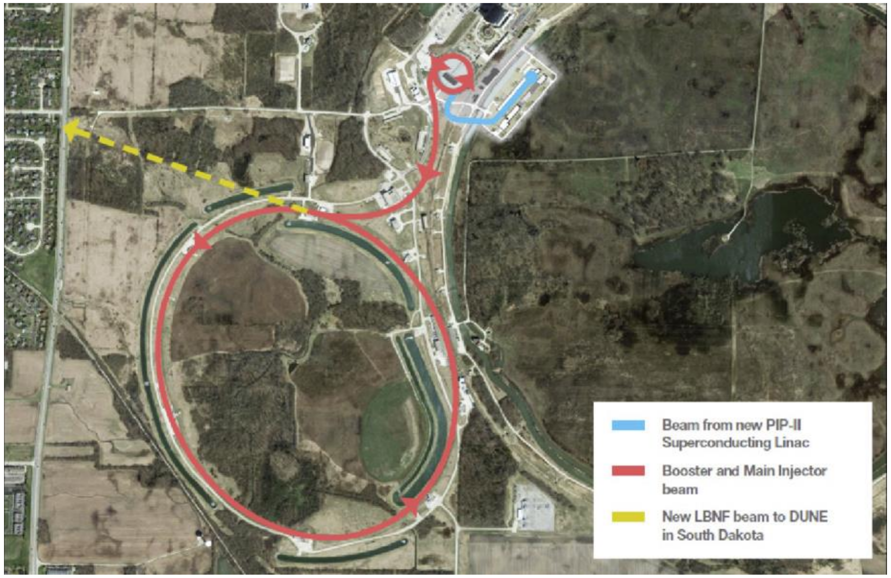
Excellent opportunity to examine targets under 5 T field



Fermilab

Demo options during the ACE-MIRT phase

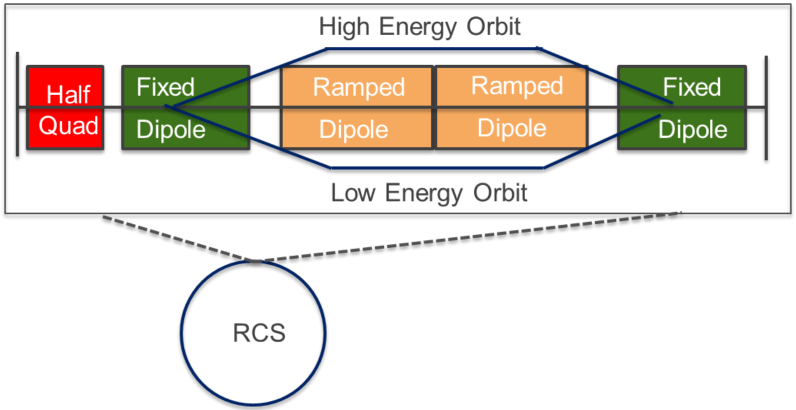
- The PIP-II proton accelerator will provide the intensity sufficient to power a new generation of high energy facilities at Fermilab
  - Proton flux at 8 GeV increases during PIP-II era
  - The 12-24 kW available for 8 GeV program would be suitable for a muon cooling demonstrator
  - Other options at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

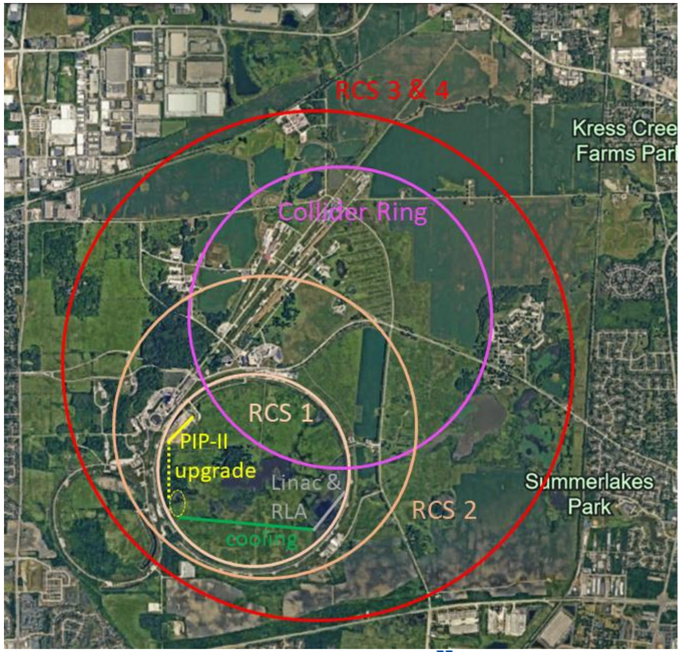
Table 1: Parameters for Fermilab proton complex. *8-GeV beam power given for what is available simultaneous with 120-GeV program.

Muon Collider TeV Acceleration

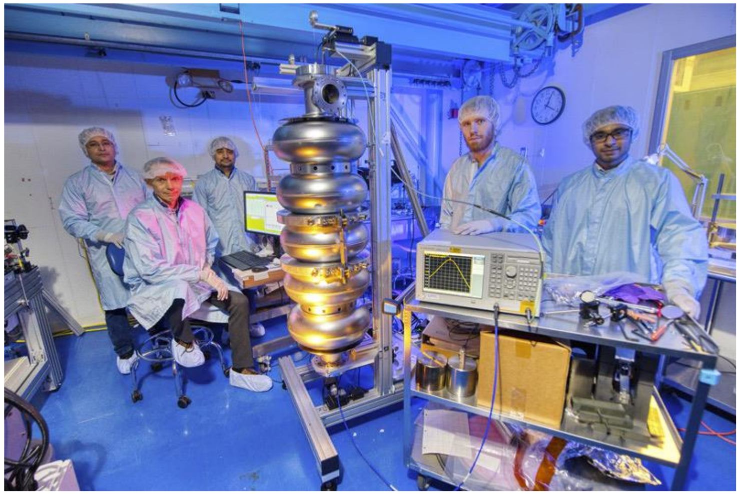


Injection Energy, GeV	173	450	1725	3560
Extraction Energy, GeV	**450**	**1725**	**3560**	**5000**
Circumference (m)	6280	10500	16500	16500
Ramped Dipole Length (m)	5233	7448	10670	8383
Fixed Dipole Length (m)		1897	3689	5972
Turns	46	106	160	180
Max ramped dipole field (T)	1.8	1.8	1.8	1.8
Max fixed dipole field (T)		12	15	15
Ramp rate (T/s)		970	440	363

- TeV acceleration with Rapid Cycling Synchrotrons (RCS)
  - Designs include a combination of fixed field SC magnets and fast ramping magnets (up 1000T/s)
  - First HTS prototype achieved 300 T/s and plans underway to reach 1000 T/s



TeV acceleration R&D

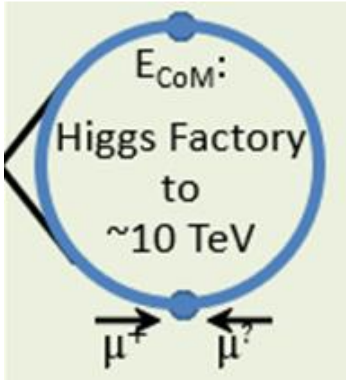


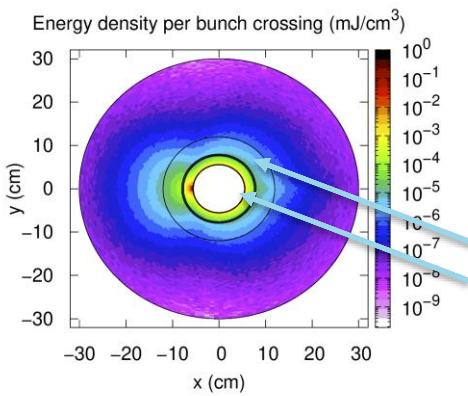
5 cell elliptical cavities @ 650 MHz for PIP-II

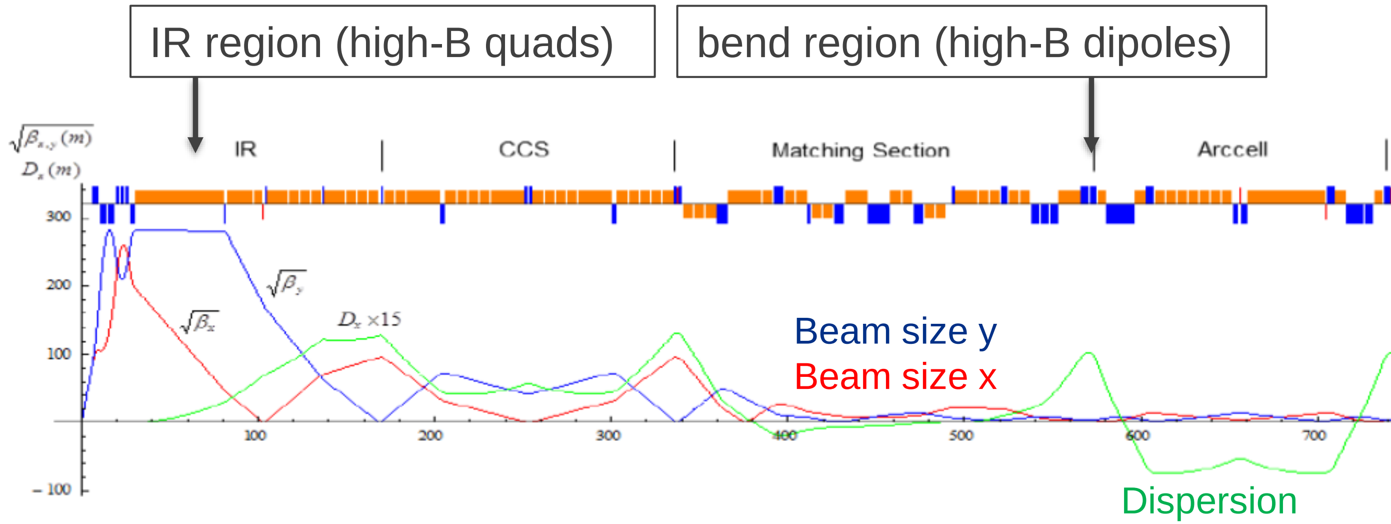
Cryomodule @ 1300 MHz for LCLS-II

- Develop self-consistent accelerator lattice towards a 10 TeV collider
  - Investigate the beam-cavity interactions in all parts of the accelerator
- Design and test MuC style SRF cavities (325, 650, 1300 MHz)
  - Synergy opportunities with other programs (ILC, FCC-ee)
- Proof-of-principle tests for power management for rapid cycling magnets

Muon Collider Collider ring

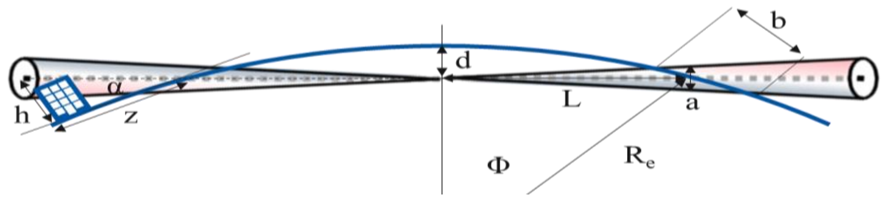






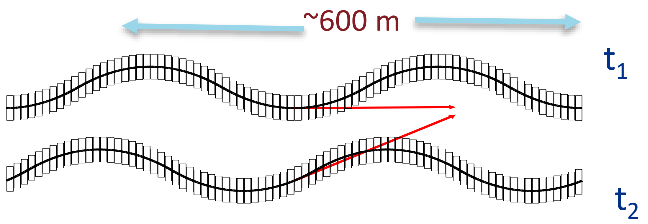
- Designs in place for 3 TeV MuC with specs within the HL-LHC range
- 10 TeV more challenging since it requires a smaller β (5→ 1.5 mm)
  - Requires significant developments in HTS magnet space (IR Quads @ 15-20 T and 12-16 T dipoles with large aperture (~150 mm) for shielding

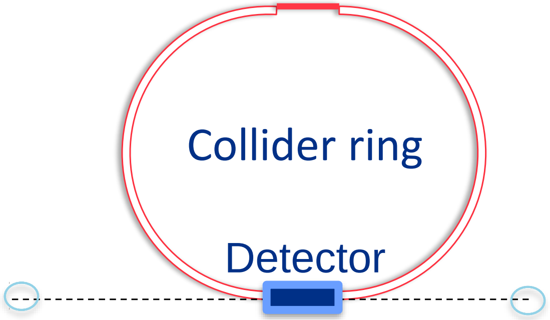
Neutrino Flux Mitigation



Aim to have **negligible impact from arcs** (<10 μSv/year). For comparison airline flight 3 μSv/hour

- Arcs:
  - 3 TeV at 200m depth – acceptable
  - 10 TeV needs 200m + “wobble” the beam
- The straights may require acquisition of small land



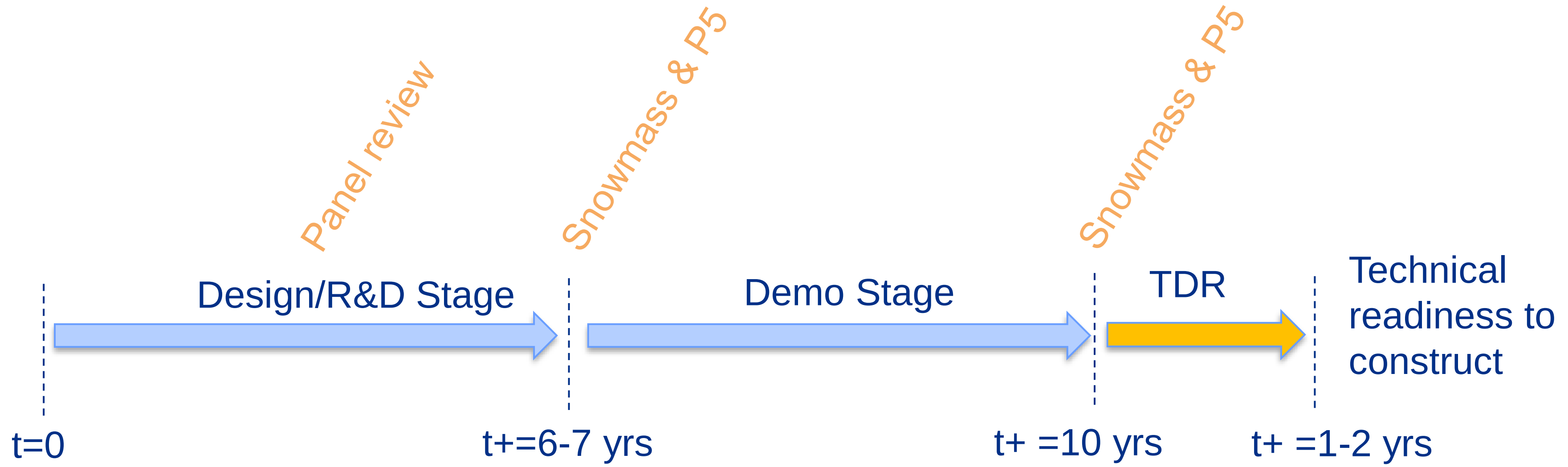


- Need to further develop the mitigation strategy, investigate impacts on the beam dynamics, … and study opportunities with high energy neutrino beams

Simulation needs

- Maintain existing codes for MuC accelerator simulation
  - ICOOL (BNL) & G4beamline (Muons Inc) default codes during MAP
  - Simple to use; very beneficial for training next generation experts
- Simulation of physical processes is the key
  - Collective effects, space-charge, wake-fields are not captured
  - Can be important in some parts of the channel
  - Need to develop new simulation tools to capture these effects
- Most optimizations were done “by hand”: Improve performance with AI/ML methods
- Utilize high-performance computing
  - During MAP days we benefited from the NERSC cluster

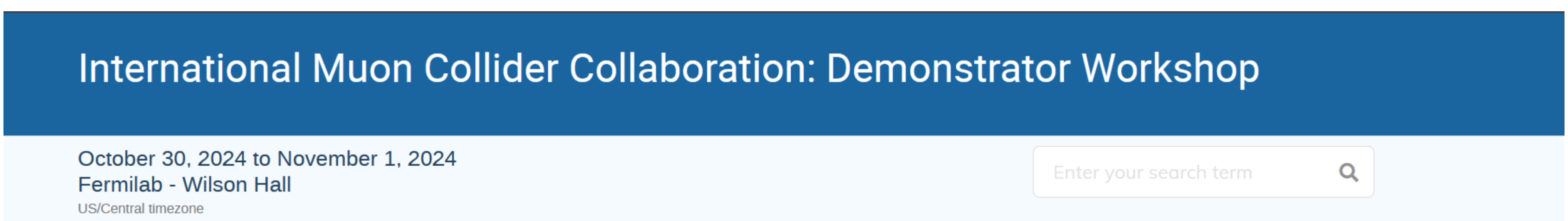
US Muon Collider timeline



- Panel review goals (next 4-5 years)
  - Conceptual design report for Fermilab accelerator upgrades towards a MuC front end + costs
  - Conceptual design report for the demonstrator + costs
  - Reference design report for facility in simulation
- The actual construction start time is subject to:
  - Successful outcome of the proposed extensive R&D program
  - Availability of funding + resources

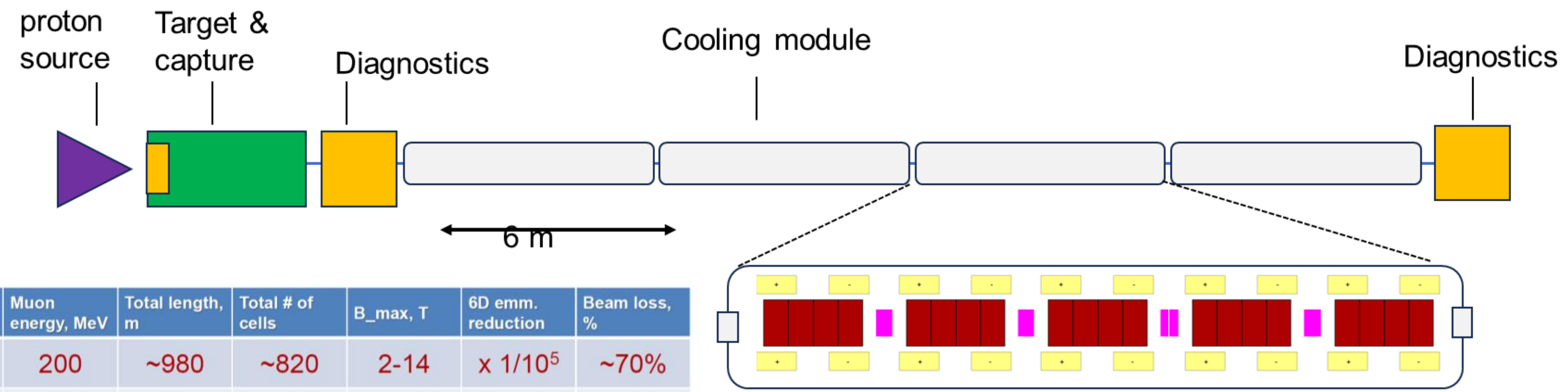
Summary

- Realization of a Muon Collider requires significant R&D and a demonstrator/ prototyping program stretching over the next 2 decades
- Many opportunities to contribute to cutting-edge R&D: for university and national labs, student and professors, scientist and engineers
- Strong P5 support opens the door for a broader US engagement
- 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
- IMCC Muon Collider Demonstrator workshop in October



Full demonstrator R&D plan

- Studies & comparisons of candidate sites within Fermilab, including location, size, beam parameters and needed infrastructure
- Development of the initial engineering design for the demonstrator target & cell (including absorber, magnet and RF design development)
- Investing synergies with other applications
- Have a conceptual design with cost estimates for the collider panel (~3-5 years)



	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

US R&D accelerator roadmap (~5 year plan)

Design
- Integrated design of all MuC subsystems
- Physics processes (space-charge, beam loading, radiation, HOM)

Proton Driver
- Study needed beam manipulations at existing facilities (SNS, IOTA)
- Define additions to Fermilab accel. complex to support MuC

Targets
- Extend R&D program for high-power targetry & irradiated materials
- Synergistic with Fermilab ACE-MIRT and SNS

Magnets
- Design and modeling studies of late stage cooling solenoids
- Design and prototyping of demonstrator solenoids
- Design & prototyping of fast-ramping magnets & power supply

RF Cavities
- R&D on high-gradient NC cavity designs
- Design and prototype cavities for the demonstrator
- Conceptual designs of SRF for accelerator lattices

Demonstrator
- Conceptual design of a demonstrator for cooling technology
- Site exploration (CERN, Fermilab) & begin Phase-I of testing