Towards a Muon Collider *accelerator*

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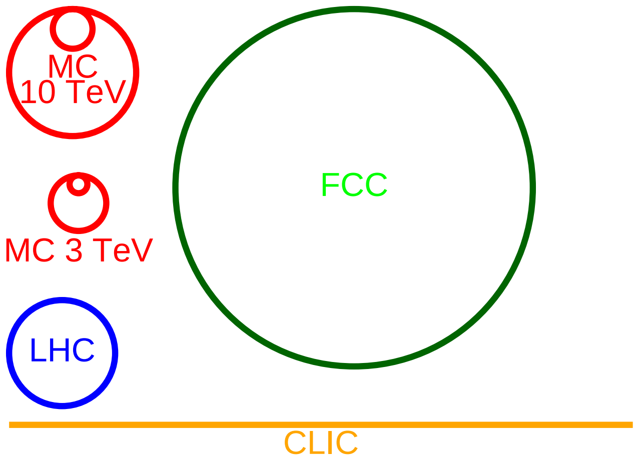
P5 Town Hall at SLAC

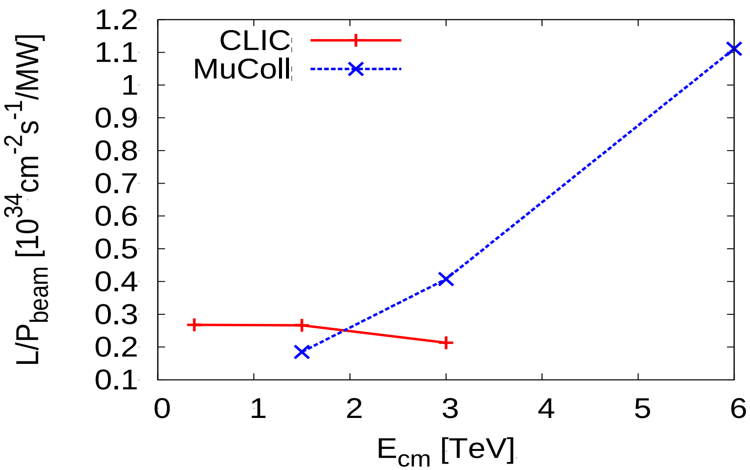
May 3rd, 2023

On behalf of US Muon Collider Community,
International Muon Collider Collaboration, and
Snowmass Muon Collider Forum

Why muons?

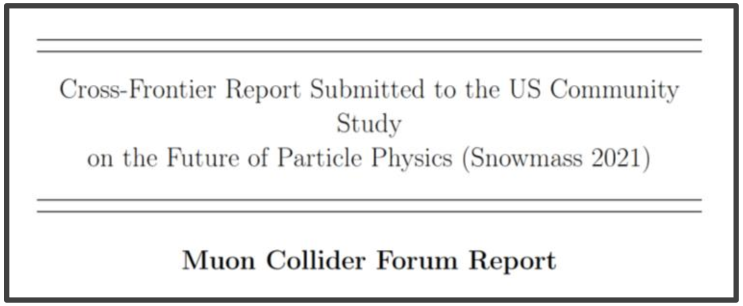
- **Muons** as compared to **protons**
  - Muons are elementary particles and all their energy in a collision is used
  - As a result, need less collision energy for the same physics
- **Muons** as compared **electrons**
  - Muons emit little synchrotron radiation
  - As a result, acceleration in rings possible up to many TeV
- In a **Muon Collider**, luminosity to power ratio improves substantially with energy
- A Muon Collider combines **a small footprint** and **high energy efficiency**!





Snowmass Muon Collider Forum

- The forum established a strong collaboration between the AF+EF+TF frontiers for Muon Collider (MuC) research
  - Monthly meetings and dedicated workshops for 18+ months before Snowmass
  - MuC Forum report is now public: ~180 authors, 50+% are early career scientists
- Forum conclusions:
  - No fundamental showstoppers identified
  - BUT engineering challenges exist
  - Significant R&D is needed to improve a MuC risk profile


Cross-Frontier Report Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Muon Collider Forum Report

- MuC was the most studied machine during Snowmass. Many new results & papers, propagated to the EF vision.

International Effort

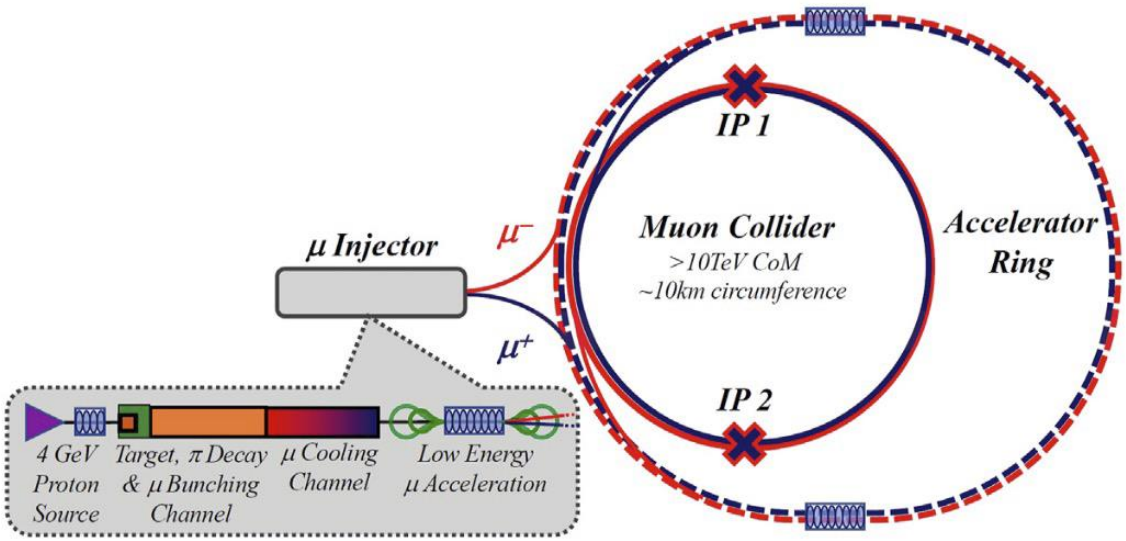
- In 2020, following the 2018 European Strategy process, Laboratory Director’s Group initiated a Muon Collider feasibility study
- In 2022, the International Muon Collaboration (IMCC) was formed and hosted at CERN
- Several US universities started to join, many more expressed interest
- IMCC planning assumes a significant US participation to develop the baseline project and the best siting option (including US siting)

International MUON Collider Collaboration

https://muoncollider.web.cern.ch/

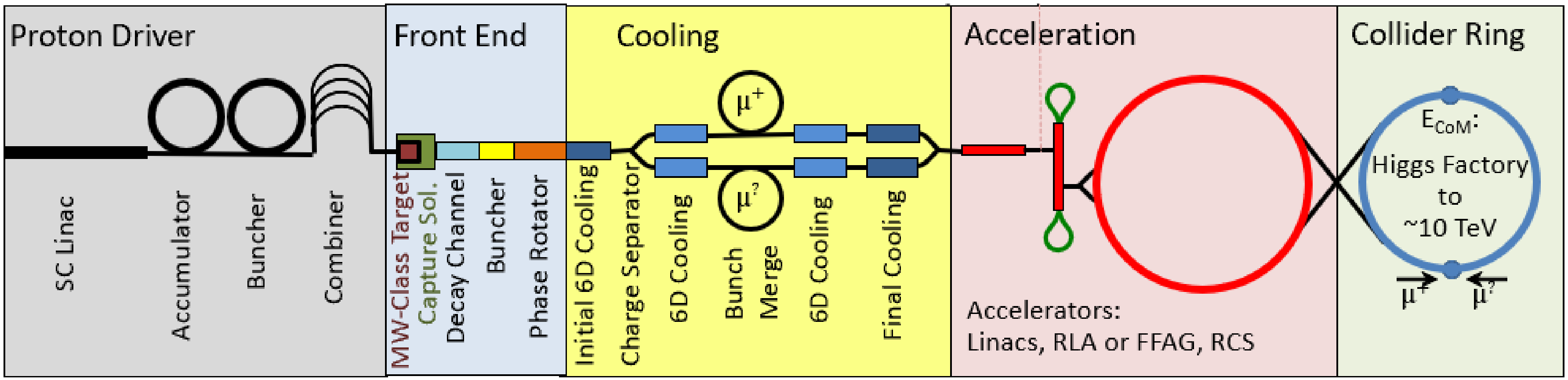
Target parameters

- The goal is to get to **10 TeV center-of-mass energy**
- Consider proton driver based Muon Collider
- Staging at 3 TeV is the current baseline
- Aim to have two detectors but only experiment assumed now



@ 3 TeV	~	1 ab^{-1}	5 years
@ 10 TeV	~	10 ab^{-1}	5 years

Machine overview



MW-scale proton driver

Muon production target

Capture 200 MeV bunches

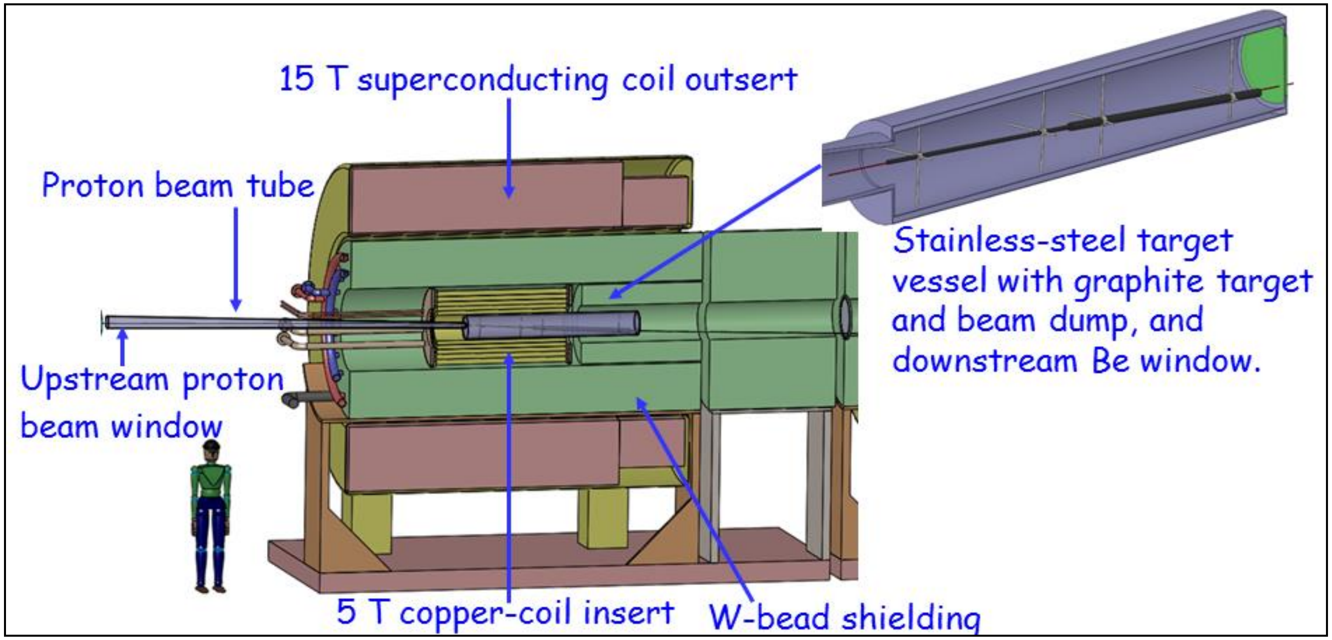
Ionization cooling to reduce 6D emittance

Acceleration to TeV scale energy

Collider ring for counter propagating muons

- Requires a **1-4 MW** proton beam @ **5-20 GeV**, compressed to **1-3 ns** bunches at a **5-10 Hz** frequency

Muon Collider target: Concept & technology needs



- Technology requirements for MuC targets:
  - Target materials that produce high muon yield
  - Placement in a high-field solenoid (15-20T) to maximize capture
  - Materials tolerant to thermal shock and fatigue from MW-scale beams
  - Shielding system that protects the capture magnet and surrounds
  - Large solenoid aperture to allow for shielding

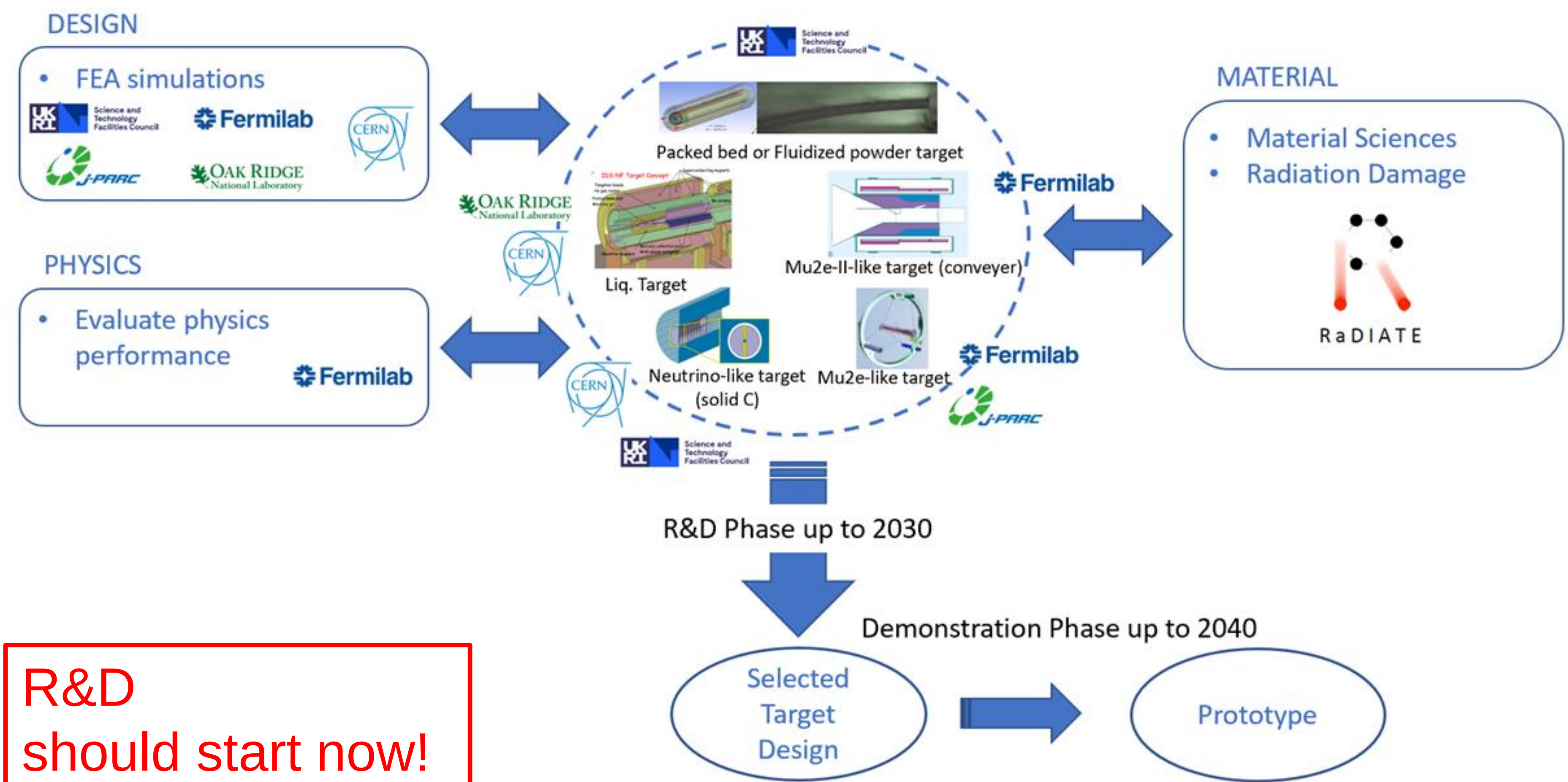
Muon Collider target: Path forward (1)

- In 2007, a proof-of principle test validated the concept with a liquid Hg target. Technology was OK but some safety concerns
- Recent work shows promising results with C or W but still significant R&D is needed to confirm that the target can withstand 2+ MW
- This fact, combined with the strong demand of high-power targets puts the MuC in a synergistic path with many future experiments:

Experiment	Material	Energy	Target in Sol	Synergy with Muon Colliders
LBNF Phase-1	C	120 GeV	No	Material test, physics performance
Mu2e	W	8 GeV	YES	Material test, physics performance, magnet integration
Mu2e-II (proposed)	C, W,…	800 MeV	YES	Same, but **higher** power density of Mu2e
AMF (proposed)	C, W, …	800 MeV	YES	Same, **even higher** power density of Mu2e-II

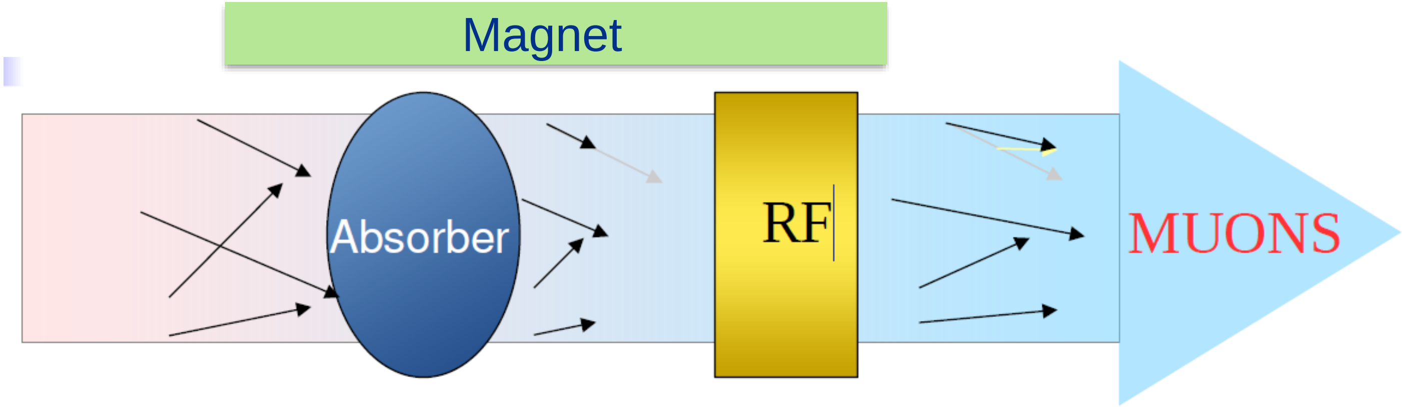
Muon Collider target: Path forward (2)

- MuC targetry is included in the proposed GARD High Power Targetry Roadmap with a plan to have a prototype in the **late 2030s**



R&D
should start now!

Muon Collider cooling – Concept & technology needs

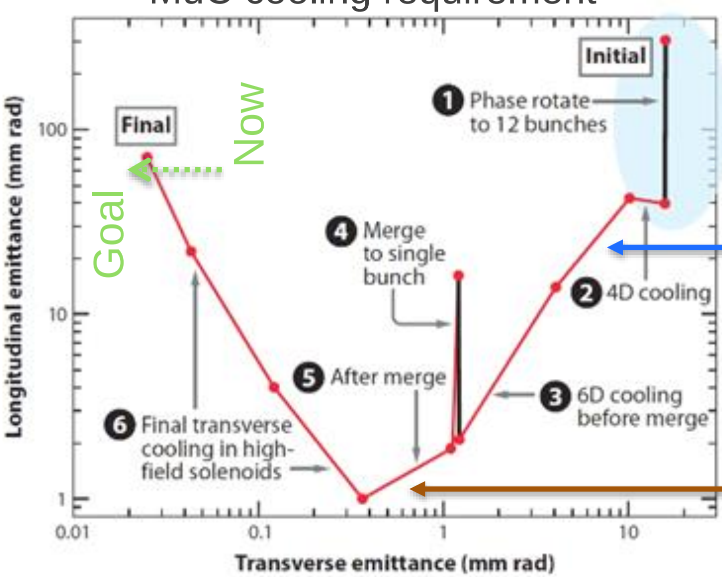


- Technology requirements for MuC cooling:
  - Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
  - Normal conducting rf that can provide high-gradients within a multi-T fields
  - Absorbers that can tolerate large muon intensities
  - Integration: Solenoids coupled to each other, near high power rf & absorbers)

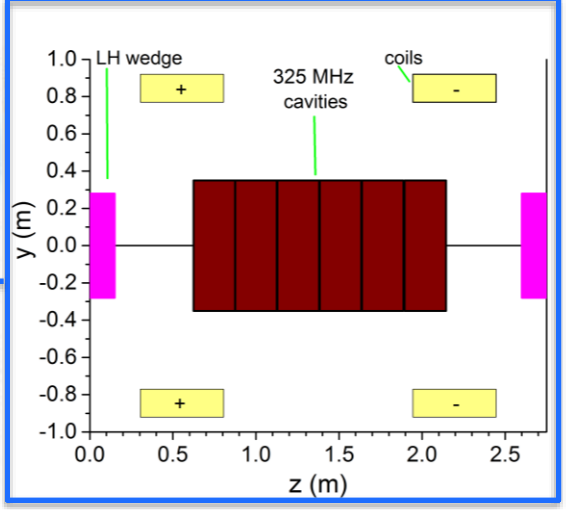
Muon Collider cooling: Path forward (design)

- Good progress in all cooling section designs over the last years. **BUT**, the final cooling **did not** achieve our goals [ref]
- Goals for next **5 years**:
  - (1) Deliver a realistic end-to-end design that meets the MuC criteria (2) take into account engineering aspects of the design and (3) improve performance with AI/ML methods and latest technology advancements

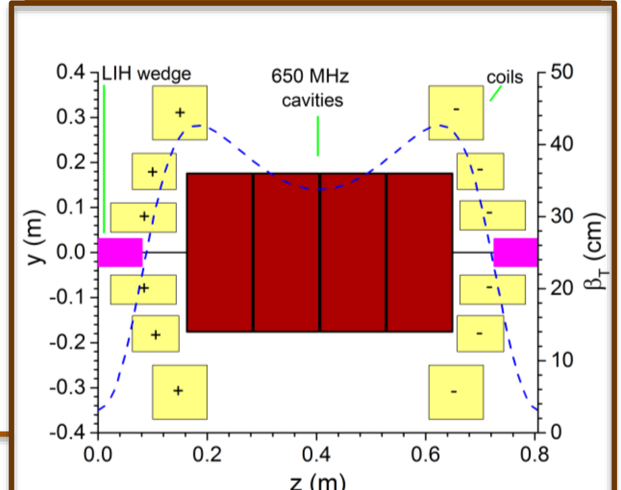
MuC cooling requirement



Early cell (“easy”) – 2T peak

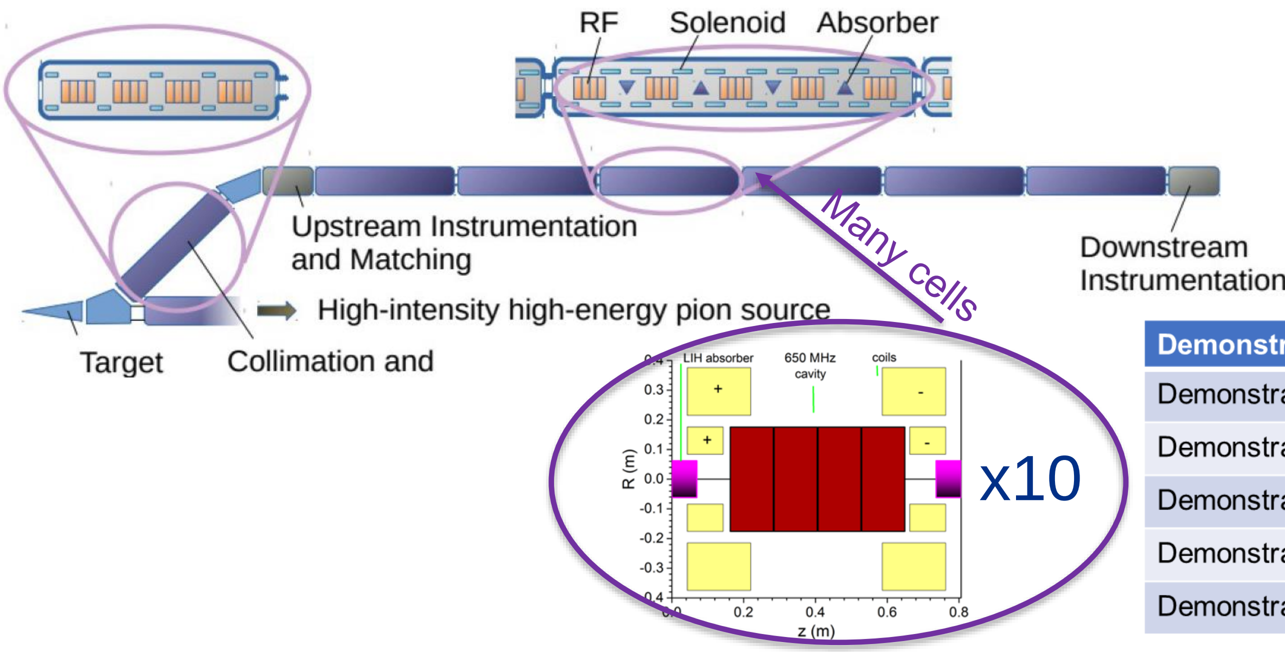


Late cell (“hard”) – 14 T peak



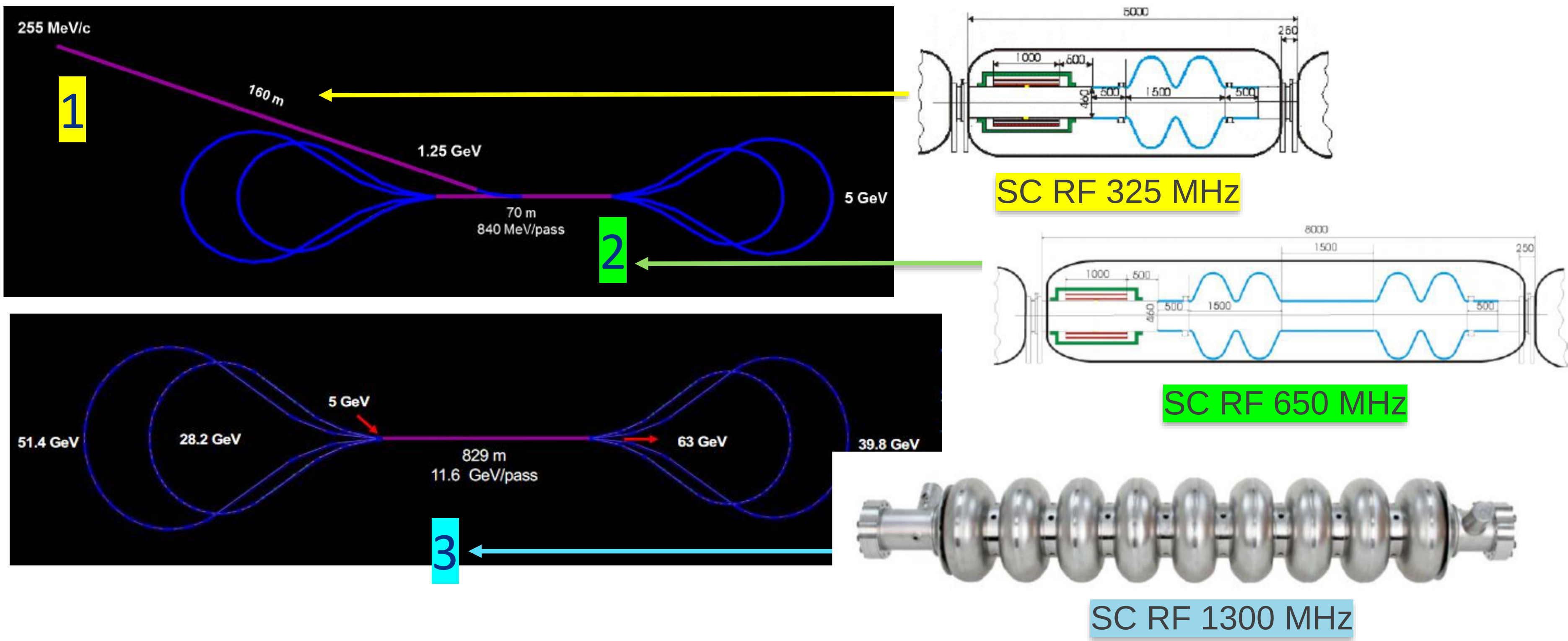
Muon Collider cooling: Path forward (demonstrator)

- While the physics of ionization cooling has been shown [ref] it is **critical** to benchmark a **realistic** MuC cooling lattice
  - This will give us the input, knowledge, and experience to design a real, buildable cooling channel for a MuC
  - Next **5 years:** (1) A conceptual design of a demonstrator facility that allows testing the technology for cooling (2) Site exploration & cost estimate of a demo facility (3) Engineering design & start fabrication of a 1.5 prototype cooling cell



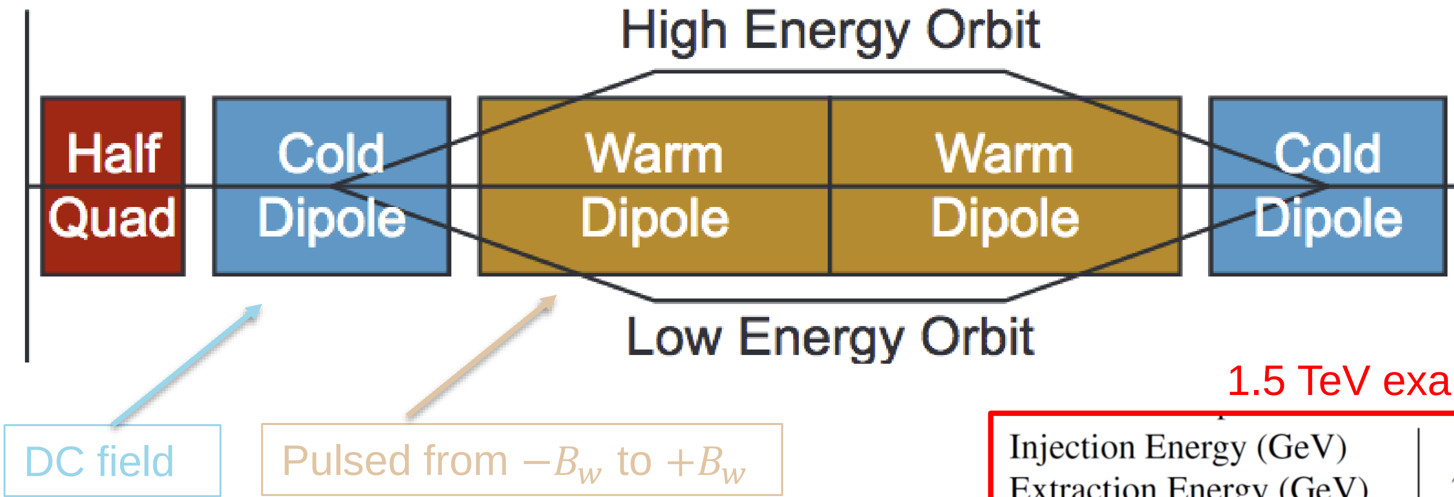
Demonstrator plan
Demonstrate operation of NC rf in B-field environment
Demonstrate forces between coils are manageable
Demonstrate performance of absorbers
Demonstrate performance of instrumentation system
Demonstrate 6D cooling with a realistic set-up

Acceleration to GeV – Concept & technology needs



- Technologies requirements for a Muon Collider:
  - Superconducting linacs and Recirculating linear accelerators (RLAs)
  - SC RF that: (1) starts at a low frequency ~ 325 MHz, (2) operate at high-gradients

Acceleration to TeV – Concept & technology needs

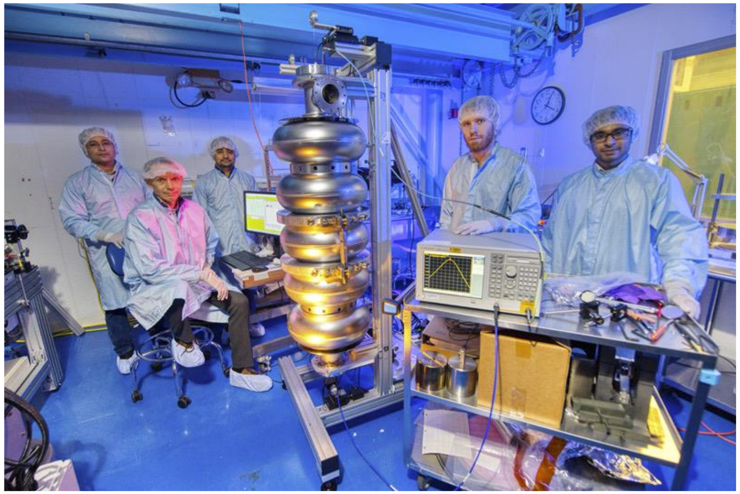


1.5 TeV example

Injection Energy (GeV)	63	303	750
Extraction Energy (GeV)	303	750	1500
Circumference (m)	5210	5210	9361
Fixed Dipole Length (m)	—	1103	2358
Ramped Dipole Length (m)	4229	3126	5240
Turns	13	25	23
Time (ms)	0.23	0.43	0.72
Cavity Power (kW)	950	950	530

- Technologies needs for a Muon Collider
  - Hybrid Rapid Cycling Synchrotron accelerators
  - Fast ramping magnets (<0.5 ms) accompanied with a 8-10 T DC magnet
  - Good energy storage and power management for pulsed magnets

Muon Acceleration: Path forward

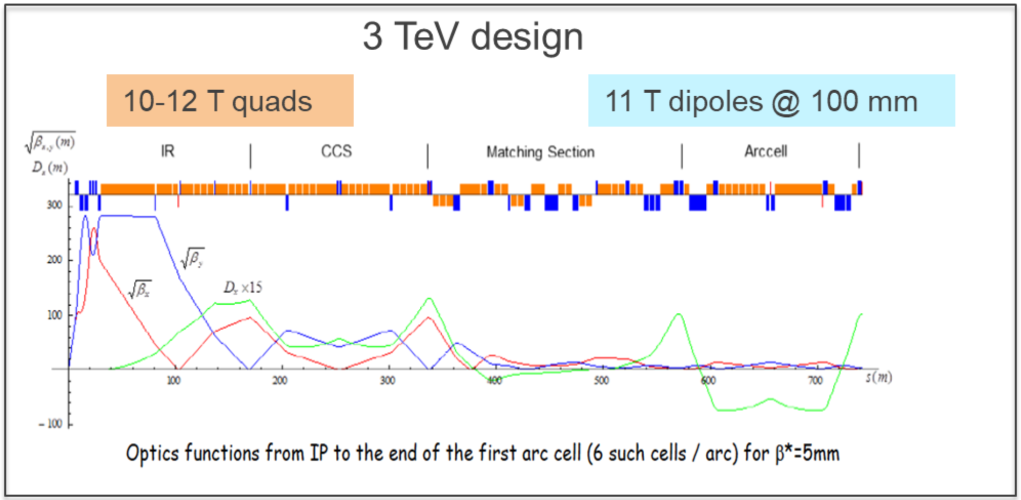


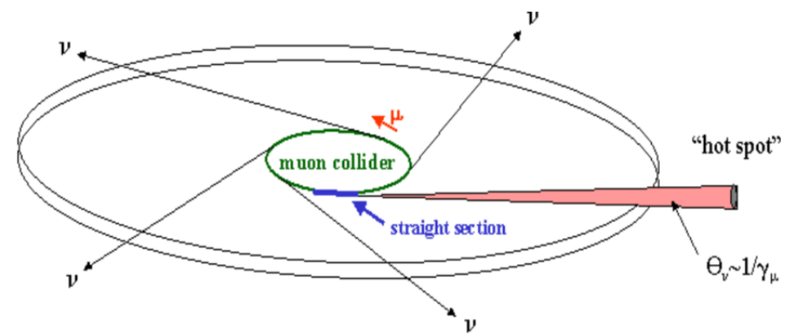
5 cell elliptical cavities @ 650 MHz for PIP-II

Cryomodule @ 1300 MHz for LCLS-II

- In the next **5 years** develop self-consistent accelerator lattice designs towards a 10 TeV collider
  - Investigate the beam-cavity interactions in all parts of the accelerator
- Utilize the extensive experience of the US on SRF for:
  - Design and testing SRF cavities for a MuC (325, 650, 1300 MHz)
  - Investigate alternative superconductors for pushing the gradient
  - Synergy opportunities with other programs (ILC, FCC-ee, GARD)

Muon Collider ring – Concept & technology needs

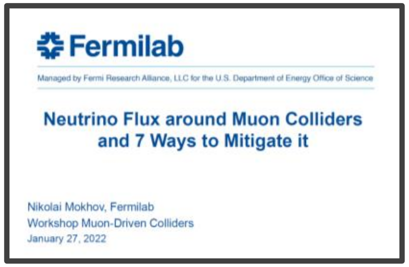


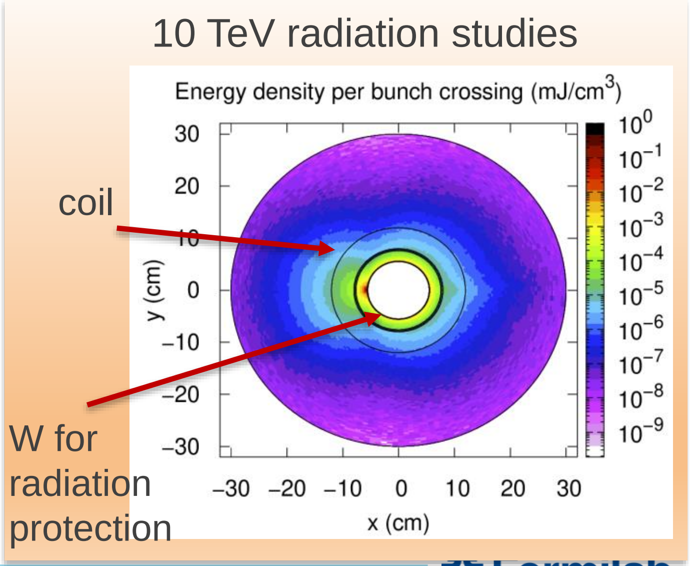


- Technology requirements for a Muon Collider (10 TeV)
  - Strong quad focusing (> 12 T at IR)
  - High-field dipoles (12-16 T) with large aperture (~150 mm) for shielding
  - Mitigation system for the neutrino flux from muon decays

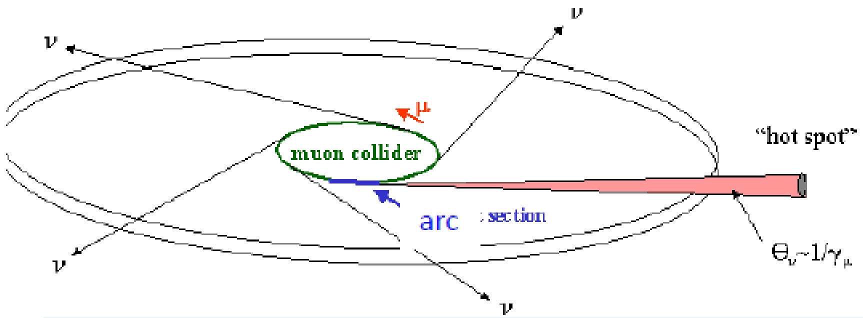
Muon Collider ring – Path forward

- Lattice design in place for a 3 TeV collider with optics and magnet parameters within existing technology limits
- In the next **5-years**: Develop design concepts for a 10 TeV collider
  - Preliminary concepts for 10 TeV published [ref] but more work is needed
  - Develop conceptual magnet designs with shielding from beam decay
- Several solution for Neutrino flux mitigation proposed and need to be evaluated
  - Examples include situating the collider ~200 m underground [ref] or move lattice over time [ref] or a combination of the two
  - Promising example to follow (next slide)


Fermilab
Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science
Neutrino Flux around Muon Colliders and 7 Ways to Mitigate it
Nikolai Mokhov, Fermilab
Workshop Muon-Driven Colliders
January 27, 2022

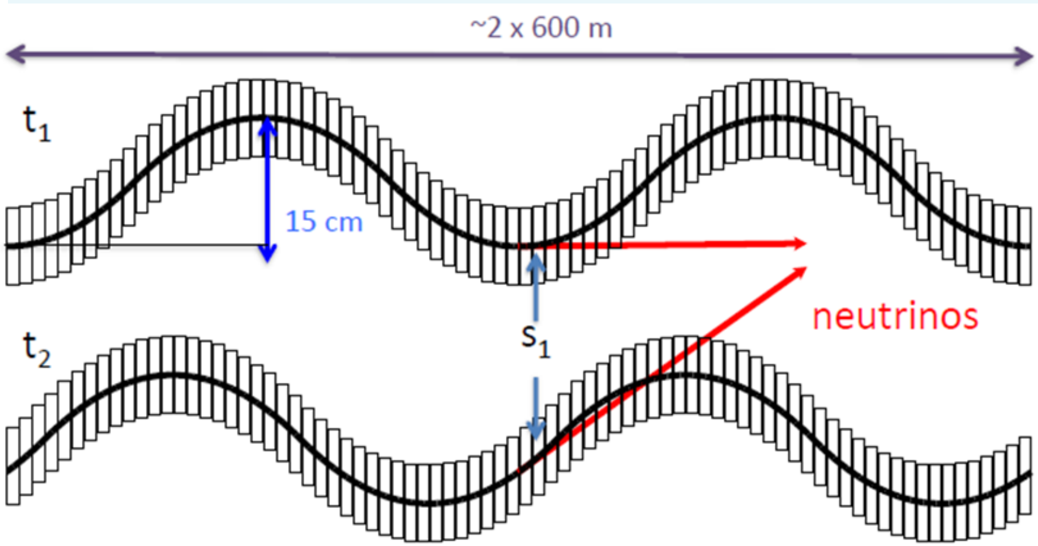


Neutrino flux mitigation system



Legal limit: 1 mSv/year
MAP goal: <0.1 mSv/year
IMCC goal: <10 µSv/year
LHC : <5 µSv/year

Solution: A mechanical system that will disperse the neutrino flux by periodically deforming the collider ring arcs vertically with remote movers; (Schulte, IPAC 22)



Could work even for 14 TeV collider at 200 m

Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

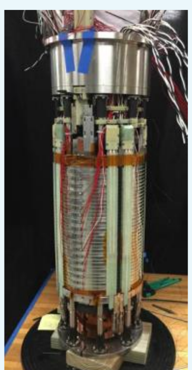
Requires significant R&D and proof-of principle tests

Muon Collider Magnets: Path Forward

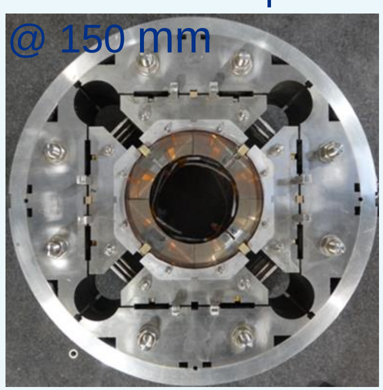
MuC section	Type	10 TeV MuC needs	Status
Cooling	Solenoid	30-50 T @ 50 mm	32 T @ 32 mm
Acceleration	Rapid cycling mag.	1.8 T @ 5 kT/s (30 mm x 100 mm)	1.8 T @ >5 kT/s (1.5 mm x 36 mm)
Collider Ring	Dipole	12-16 T @ 150 mm	11-12 T @ 120 mm
IR	Quadrupole	15-20 T @ 150 mm	11-12 T @ 150 mm

- Many synergies with other programs possible.
  - However rapid cycling magnets are unique for a MuC and need out attention!

32T @ NHMFL



LHC-HL 12 T quad @ 150 mm



	Synergies				
	US-MDP	Future Colliders	Fusion	ARDAP/Industry	NSF (NMR)
Target Solenoid			■		■
Cooling Channel Solenoids					■
High Ramp Rate for RCS					
Collider Dipoles	■	■			
IR Quads		■			
Alternatives R&D					
HTS for collider magnets	■		■	■	■

ACE and Muon Collider

- Muon Collider proton driver needs are beyond existing facilities
- Fermilab ACE program offers several synergies with Muon Collider R&D
- The ACE booster replacement plan may provide a path for a MuC front-end
  - ACE parameters are being defined. ACE physics workshop in June 14-15th will investigate synergies and options, including front-end for a MuC

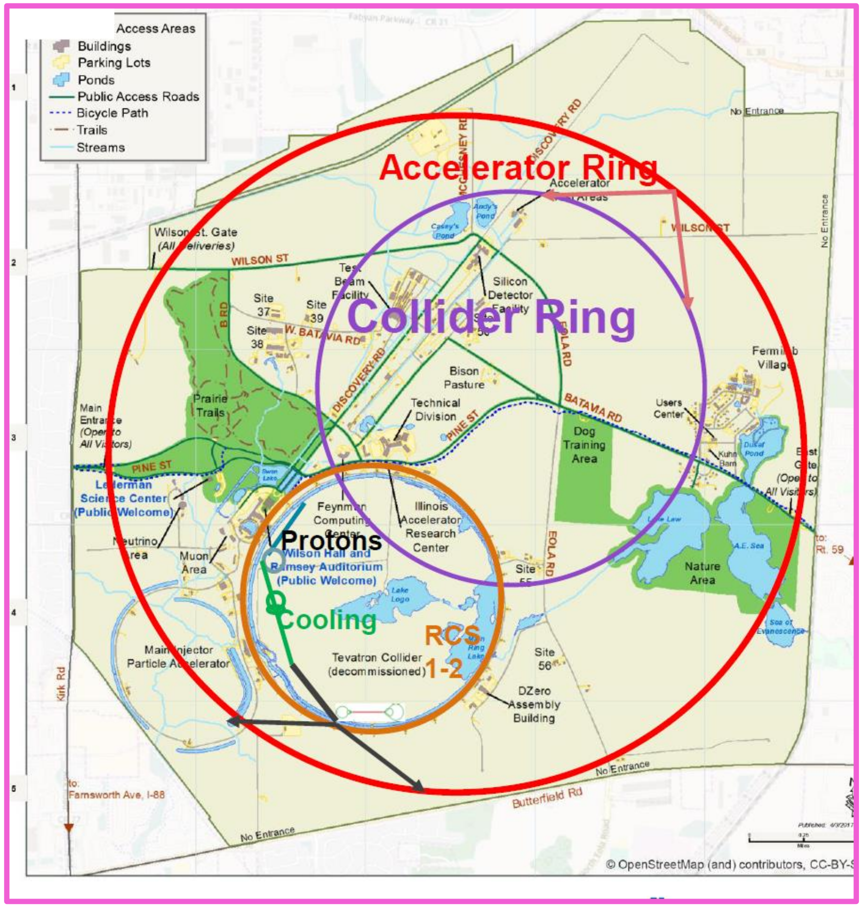
Muon Collider Proton Driver Parameters	
Energy	5-15 GeV
Rep. rate	5-10 Hz
Ave. Beam Power	1-4 MW
Proton structure	1-3 ns bunch with ~10^{14}

Synergies with ACE program

ACE	Target	SRF	Proton Driver
Main injector upgrade	YES		
Booster replacement	YES	YES	YES

Muon Collider @ Fermilab

- A concept design for a Fermilab **6-10 TeV MuC** is in place
- Proton source
  - Post-ACE driver -> Target
- Ionization cooling channel
- Acceleration (3 stages)
  - Linac + RLA → **65 GeV**
  - RCS #1, #2 → **1 TeV (Tevatron size)**
  - RCS #3 → **3-5 TeV (site filler)**
- 6-10 TeV collider
  - Collider radius: 1.65 km



- In the next **5 years**, have a baseline design including the neutrino flux mitigation system

Fermilab

US Muon Collider R&D coordination group

- In March, R&D coordination group formed to provide input to P5
- Focus on key elements of **10 TeV accelerator & detector design**
  - Develop R&D plan, activities, budget and deliverables
  - Chairs: Sridhara Dasu (Wisconsin), Sergo Jindariani, Diktys Stratakis (Fermilab)

Physics Case Development:
Patrick Meade (Stony Brook), Nathaniel Craig (UCSB)

Accelerator R&D Focus Areas:
Muon source:
Mary Convery (Fermilab), Jeff Eldred (Fermilab), Sergei Nagaitsev (JLAB), Eric Prebys (UC Davis)

Machine design:
Frederique Pellemoine (Fermilab), Scott Berg (BNL), Katsuya Yonehara (Fermilab)

Magnet systems:
Steve Gourlay (Fermilab), Giorgio Apollinari (Fermilab), Soren Prestemon (LBNL)

RF systems:
Sergey Belomestnykh (Fermilab), Spencer Gessner (SLAC), Tianhuan Luo (LBNL)

Detector R&D Focus Areas:
Tracking Detectors:
Maurice Garcia-Sciveres (LBNL), Tova Holmes (Tennessee)

Calorimeter Systems
Chris Tully (Princeton), Rachel Yohay (FSU)

Muon Detectors
Melissa Franklin (Harvard), Darien Wood (Northeastern)

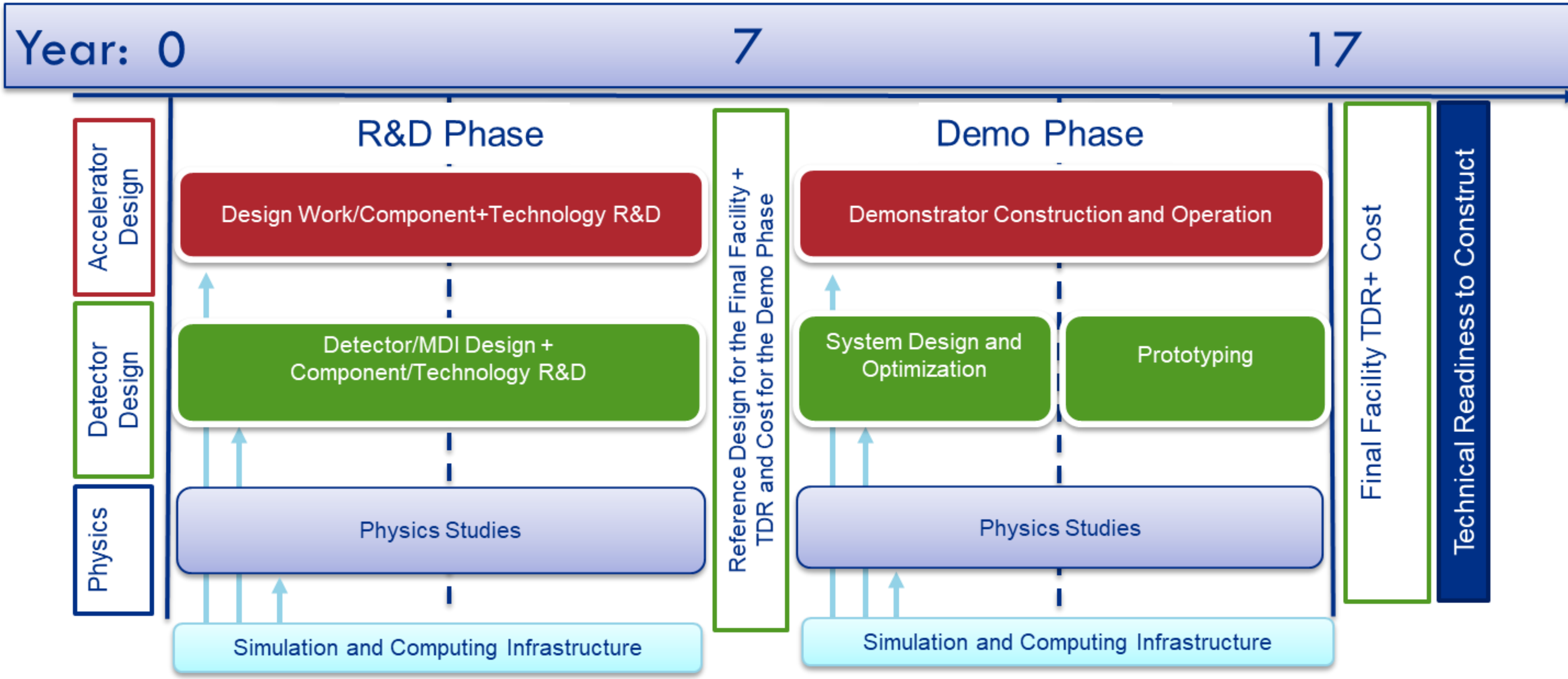
Electronics/TDAQ
Darin Acosta (Rice), Isobel Ojalvo (Princeton), Michael Begel (BNL)

MDI+Forward Detectors:
Kevin Black (Wisconsin), Karri DiPetrillo (Chicago), Nikolai Mokhov (Fermilab)

Detector Software and Simulations:
Liz Sexton-Kennedy (Fermilab), Simone Pagan Griso (LBNL)

International Liaisons:
Daniel Schulte (CERN), Chris Rogers (RAL), Donatella Lucchesi (INFN), Federico Meloni (DESY)

US Muon Collider timeline



A possible MuC US R&D roadmap for accelerator

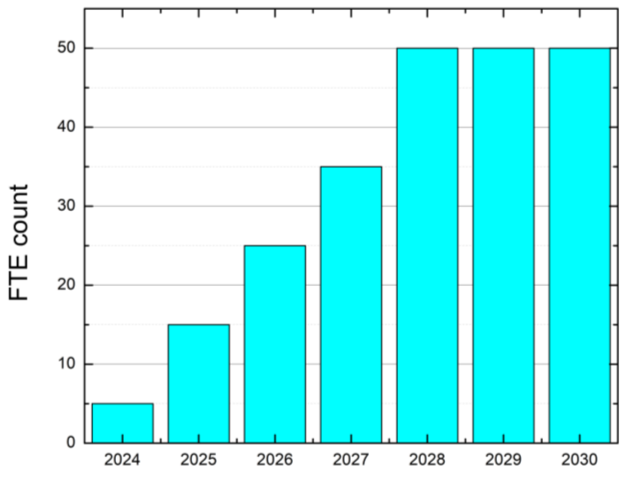
2024-2030

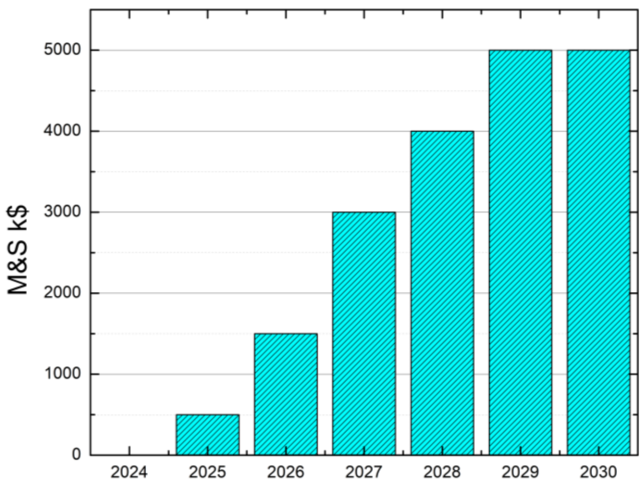
- Complete design & simulation of the whole MuC complex, including a neutrino flux mitigation system (include designs for a Fermilab MuC option)
  - Take into account engineering aspects of the design, establish operating parameters and develop technology concepts with potential to meet these parameters
- Proceed with (limited) prototyping & technology R&D
  - Rapid cycling dipoles: magnet prototype, including its power deliver system
  - Proton bunch compression tests at existing facilities
  - Target material study & pion yield measurement at existing facilities
  - Design and testing of high gradient SRF cavities (325, 650, 1300 MHz)
  - Engineering design and begin fabrication of a 1.5-cell cooling cell prototype

  (Synergistic with other programs)
- Define what we like to **further test**, how and where after 2030
- **By 2030, achieve enough technical maturity for the construction of the demo facility in 2030s and potential construction of the collider facility in the 2040s.**

It is crucial for the US to engage **NOW** if we want an MC as a future option!

US R&D budget estimate 2024-2030 (Accelerator)





- **2024+**: Ramp-up budget profile so that US accelerator experts can engage with the international Muon Collider effort
- **~2030**: **Goal:** Deliver a MuC **reference design report** and a **TDR report** for the demonstrator facility with **cost** estimates
- **2030+**: Develop technology to be ready to commit, verify performance of all components
  - Significant ramp-up is needed. Cooling channel demonstrator is expected to be the cost driver

Summary

- MC offers a unique opportunity for energy frontier collider with high luminosity
- Physics & technology landscape has significantly changed recently
- We have established a highly motivated group to address challenges for a Muon Collider
- As also presented at BNL, we are asking P5 to:
  - Recommend establishing a Muon Collider R&D program with the aim for delivering a **RDR report** for the final facility & **TDR report** for the demo facility by 2030 AND with an overall goal of having a **TDR for the final facility** by 2040
  - Recommend that DOE and NSF recognize Muon Collider work within the AF base program proposals
  - Support the formation of a US Muon Collider effort to coordinate US impact while engaging in the international effort
  - Enable US to compete for hosting a Muon Collider

Extra

Muon Collider Synergies

Facility/Experiment	Physics Goals	Synergy
nuStorm	Short baseline neutrino program, including searches for sterile neutrino and cross section measurements	100kW proton source, muon production and collection, storage ring operation
Dark Sector searches	Searches for particles from Dark Sectors produced in fixed target experiments using high intensity proton beam	MW class high-intensity proton beams
Charged Lepton Flavor Violation (e.g. AMF)	Searches for rare lepton flavor violating processing (mu2e, mu2eg, mu3e, etc)	MW class proton source, muon production and collection, storage ring
Beam dump experiments	Searches for exotic particles (dark photons, Lmu-Ltau, etc) in muon beam dump experiments	100kW – MW proton source, muon production and collection, partial cooling and acceleration
Neutrinos from collider beam muon decays	DIS in neutrino-nucleus interactions, better nuclear PDF, atmospheric neutrinos FASERv like experiment with smaller flux uncertainties	Everything up to multi-TeV energy collider beams
Muon Ion Collider	A broad program addressing many fundamental questions in nuclear and particle physics	Everything up to multi-TeV energy collider beams

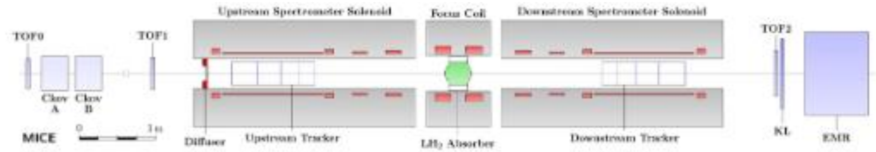
Muon Collider Challenges

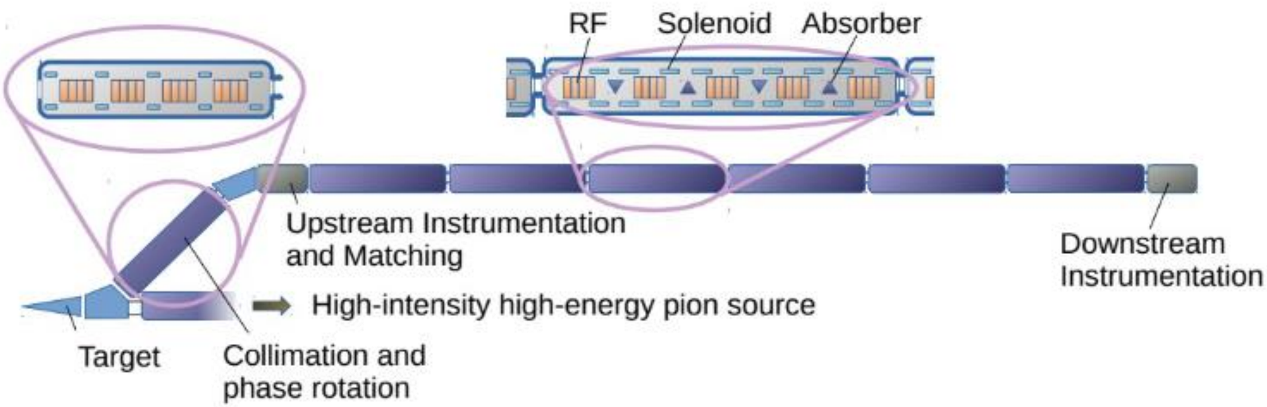
Challenge	Progress	Future work
Multi MW proton sources with short bunches	Multi-MW proton sources have been and are being produced for spallation neutron sources and neutrino sources (SNS, ESS, J-PARC, Fermilab)	Refine design parameters, including proton acceleration to 5-10 GeV. Accumulation and compression of bunches.
Multi MW targets	Neutrino targets have matured to 1+MW. RADIATE studies of novel target materials and designs aim at 2.4MW.	Develop target design for 2 MW and short muon collider bunches. Produce a prototype in 2030s.
Production solenoid	ITER Nb3Sn central solenoid with similar specifications and rad levels produced	Study cryogenically stabilized superconducting cables and validate magnet cooling design. Investigate possibility of HTS cables.
Cooling channel solenoids	Solenoid with 30+T field now exists at NHMFL. Plans to design 40+T solenoids in place.	Extend designs to the specs of the 6D cooling channel, fabrication for the demo experiment
Ionization cooling	MICE transverse cooling results published. Long.cooling via emittance exchange demonstrated at g-2.	Optimize with higher fields and gradients. Demonstrate 6D cooling with re-acceleration and focusing
RF in magnetic field	Operation of up to 50 MV/m cavity in magnetic field demonstrated, results published	Design to the specs of the 6D demo, experimen; fabrication

Muon Collider Challenges

Challenge	Progress	Future work
Fast Ramping Magnets	Demonstrated 5000+ T/s with 1. 8T	We need to design a efficient power supply system for these magnets
Neutrino Flux Effects	Mitigation strategies based on placing the collider ring at 200m and introducing beam wobble has been shown to achieve necessary reduction up to 10-14 TeV	Study mechanical feasibility, stability and robustness of the mover's system and impact on the accelerator and the beams
Detector shielding and rates	Demonstrated to be manageable in simulation with next generation detector technologies	Further develop and optimize 3 and 10 TeV detector concepts and MDI. Perform detector technology R&D and demonstration.
Large aperture storage ring magnets	12-15T Nb3Sn magnets have been demonstrated	Design and develop larger aperture magnets 12-16T dipoles
Low-beta IR collider design and dynamic aperture	Lattice design in place for a 3 TeV collider with optics and magnet parameters within existing technology limits	Develop lattice design for a 10 TeV collider

Proposed cooling demonstrator vs MICE





	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style