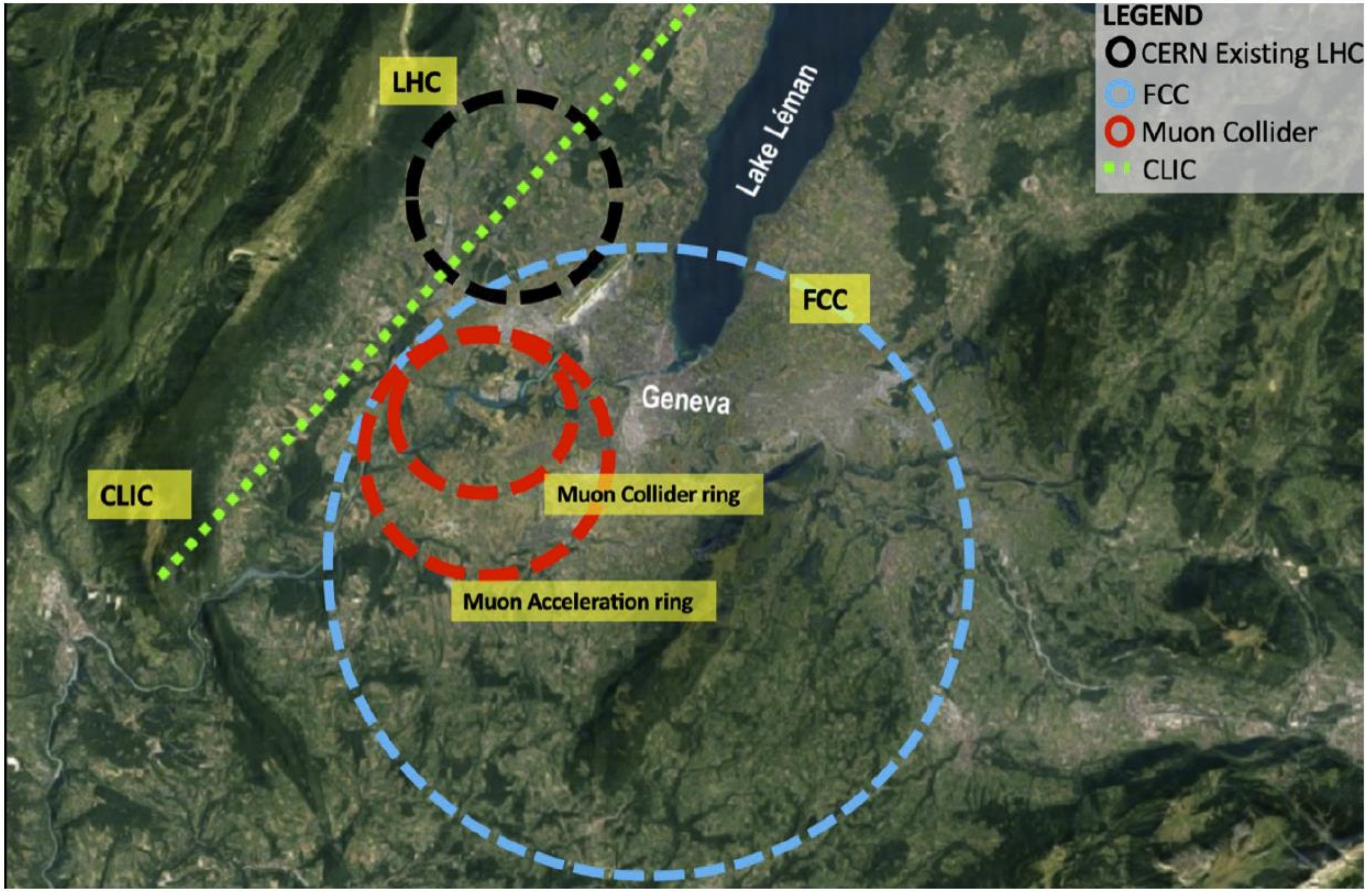
Muon Collider Accelerator R&D for experimentalists

Diktys Stratakis (Fermilab)

Colliders of Tomorrow @ Fermilab

October 19, 2023

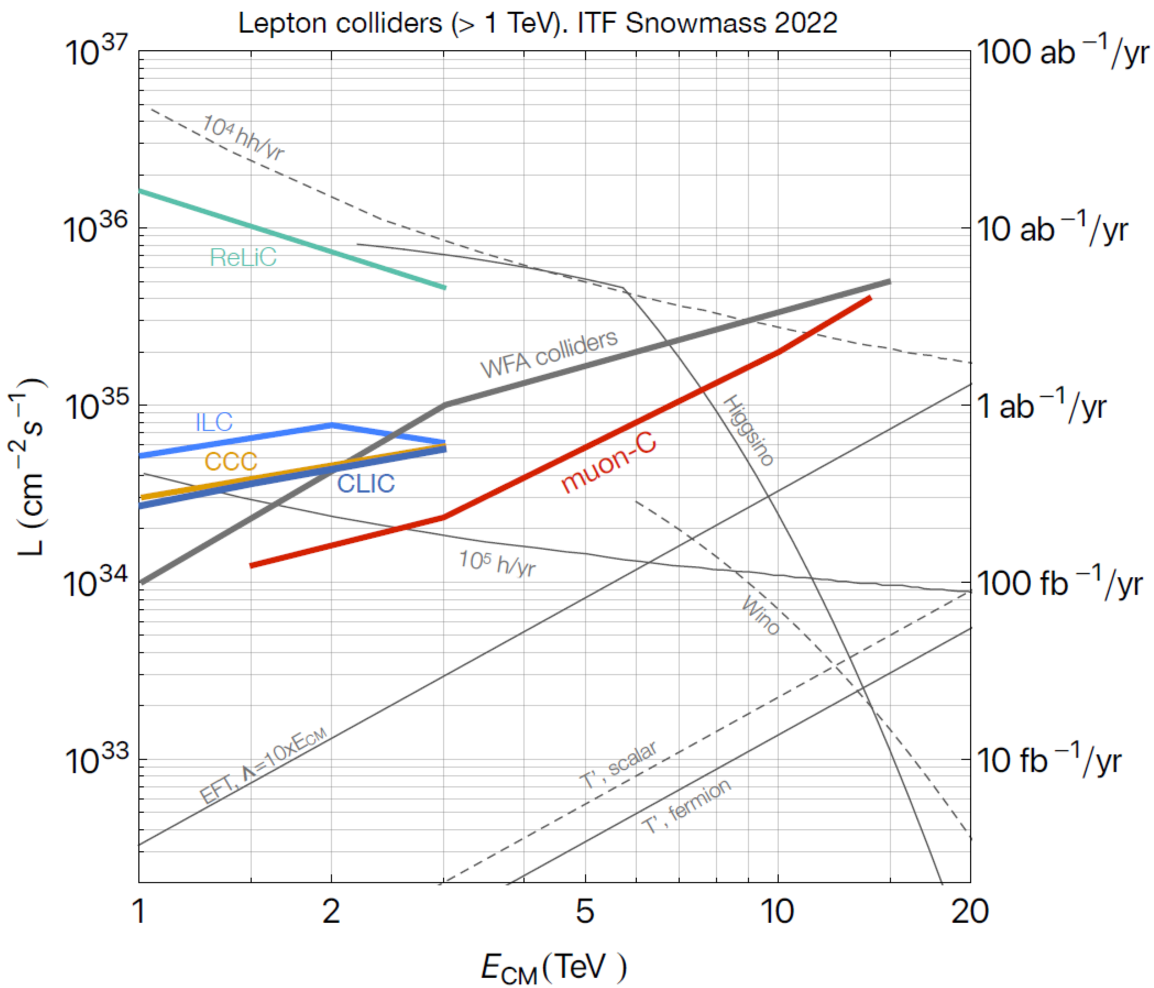
Compactness



- A Muon Collider offers a precision probe of fundamental interactions, in a smaller footprint as compared to electron or proton colliders

Efficiency

More details: Snowmass'21 ITF report



Electric power: ~450-1000 MW
Cost: ~18-80 $B

Electric power: ~320 MW
Cost: 12-18 $B

- In a **Muon Collider**, luminosity improves substantially with energy

History (1)

- **1960s:** First mention of Muon Colliders in the literature
- **1990s-2010:** Design studies through US institutional collaborations
- **2011-2016:** Muon Accelerator Program (MAP) was approved and supported by DOE to address key feasibility issues of a MC
  - Focused on a proton-driver based solution
  - Considered colliders at 1.5, 3 and 6 TeV
- **2022:** Muon Colliders become part of the European Accel. R&D Roadmap:
  - **International Muon Collider Collaboration (IMCC) has formed**, hosted at CERN for now

History (2)

- **2022:** US Snowmass study reveal strong interest on Muon Colliders:
  - Presented the Muon Collider Forum Report: a coherent vision for Muon Colliders from the US perspective
  - Proposed and presented a National Collider Initiative
  - **Received strong support from the global community**
- **2023:** Formation of the US Muon Collider R&D coordination group:
  - Initiated and supported by the Fermilab directorate
  - It’s goal was to provide input to the P5 panel on Muon Collider research
  - Its ASK was presented at two P5 town-hall meetings (BNL and SLAC)

Target parameters (from IMCC)

Start → Goal

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
<B>	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
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Target integrated luminosities

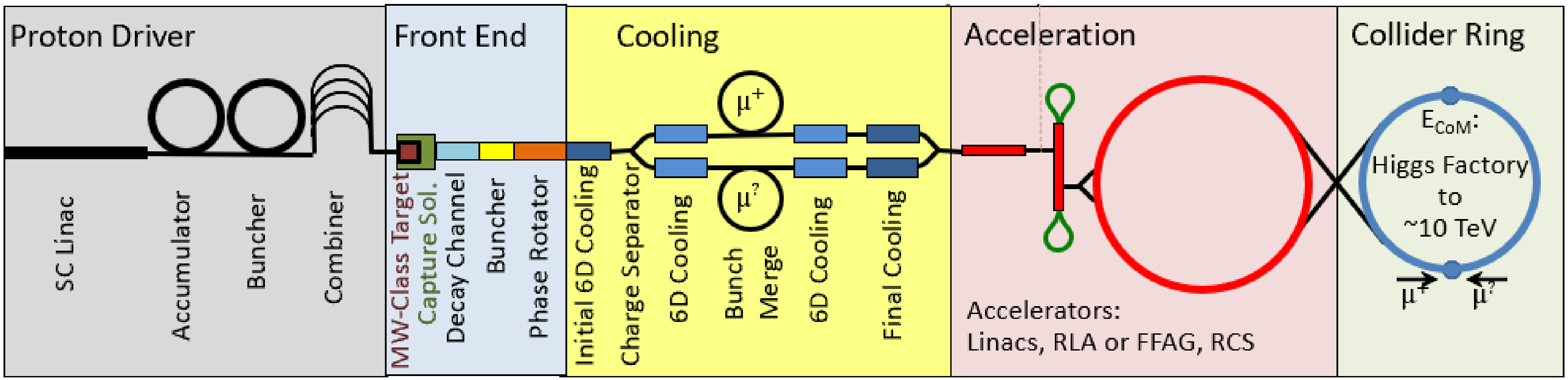
$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

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

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

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

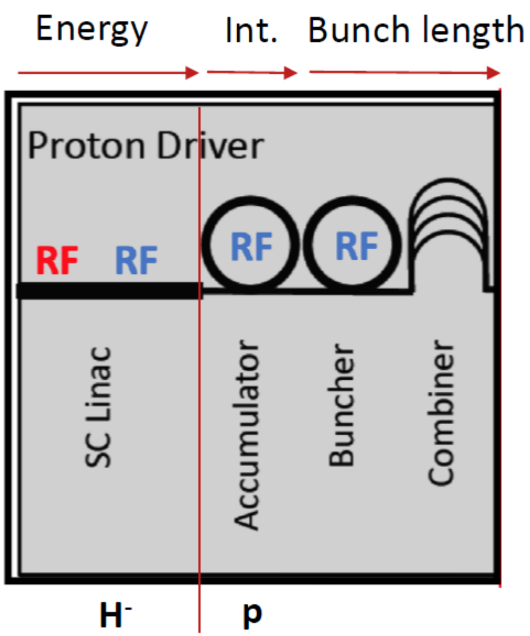
Luminosity for a MuC

- **Luminosity** is a measure of the collider efficiency
  - Given by

$$\boxed{L = \frac{N_+ N_- n_C f}{4\pi \sigma_x \sigma_y}}$$

- **High** charge per muon bunch of each sign
  - Requires a **powerful** proton driver, **high-yield** target & **fast** acceleration
- **Small** transverse beam size
  - Requires beams with a **low** transverse emittance
  - Requires **very strong** focusing magnets in the IR
- **Many** collisions in the collider ring
  - Requires **strong** dipole magnets to minimize the collider ring radius

MuC proton driver: Concept & technology needs



- Technology requirements for MuC driver:
  - Linac to: deliver ~5 GeV, ~10^{14} H- in ~ 1 ms
  - Accumulator ring to: (1) stripping H- → protons, (2) create four, 20 ns bunches
  - Buncher to: 20 ns → ~ns scale bunches
  - Combiner to: combine four bunches into one
  - Alternative: Replace part of the linac with a rapid cyclic synchrotron

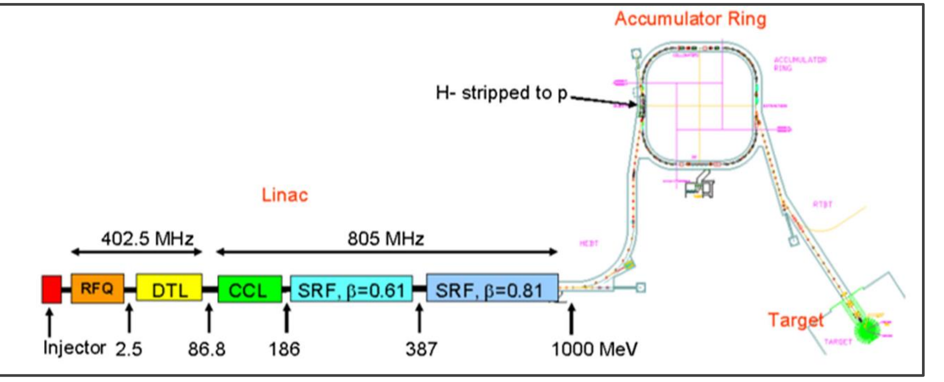
- Peak performance: **1-4 MW** proton beam @ **5-20 GeV**, compressed to **1-3 ns** bunches at a **5-10 Hz** frequency
  - Low frequency is preferred; it boost the luminosity (for the same power)

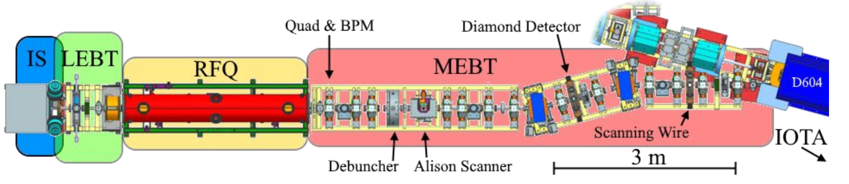
MuC proton driver: Moving forward

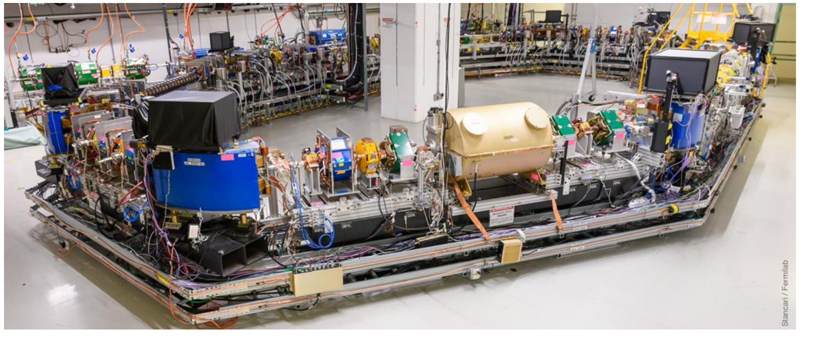
- Proton driver **does not** involve **new** technology or breakthroughs
  - See Jeff Eldred Talk (from Aug. 3st)
- However, a good understanding of concepts such as injection stripping, ~ns bunch compression and bunch combining is needed
  - **Excellent topics for PhD students, Postdocs, Early Career scientists not necessary accel. experts**
  - We need a detailed **beam dynamics study** of the above concepts.
  - We need **proof-of-principle** tests to dedicated facilities to confirm simulation findings AND extrapolate to MuC conditions
  - Suitable facilities **exist in the US** and expressed interest to help us!

MuC proton driver: Moving forward

- SNS @ Oak Ridge National Laboratory
  - 1.8 MW facility with 1-1.3 GeV beam
  - Excellent place to test injection stripping and bunch compression
- IOTA/FAST @ Fermilab
  - Unique capabilities facility
  - Intense space-charge 2.5 MeV p beam
  - Excellent place to understand how space-charge influences the process







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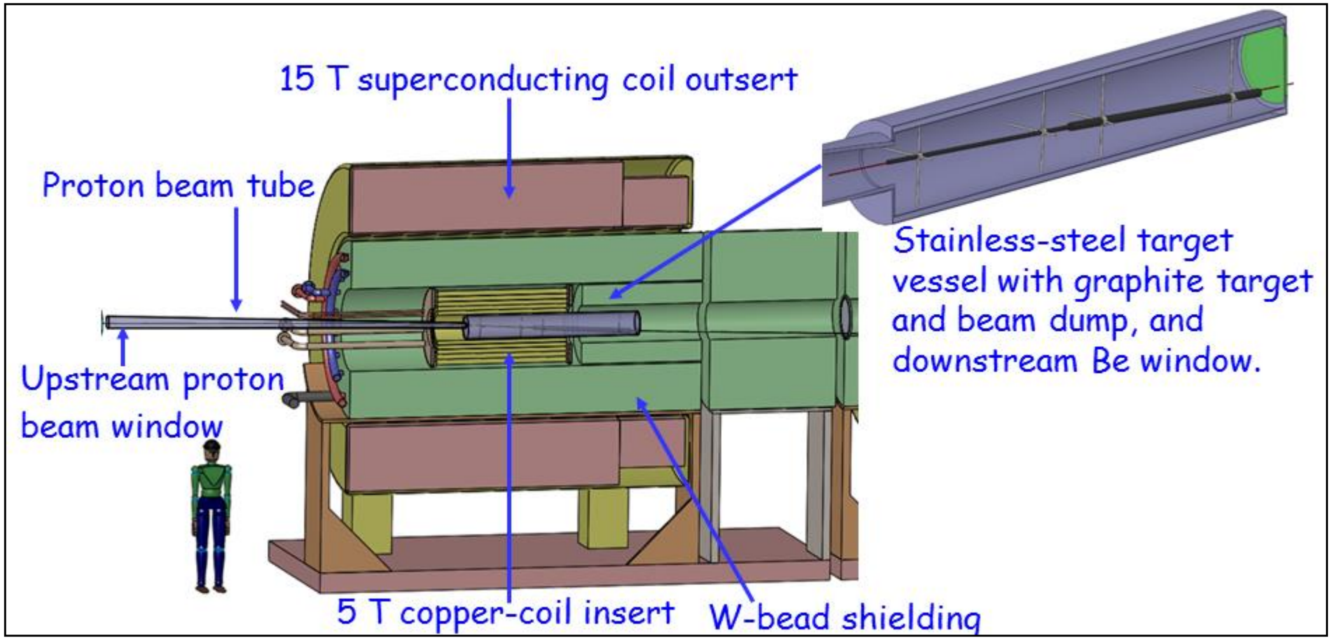
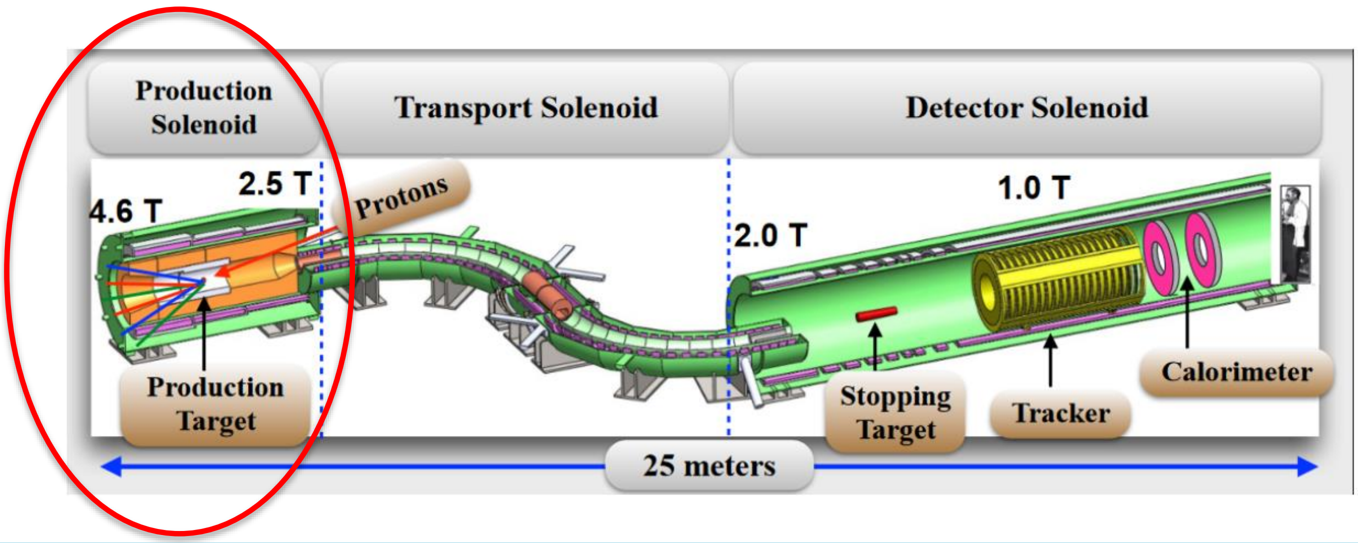
MuC target: Concept & technology needs



- 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

MuC target: Path forward

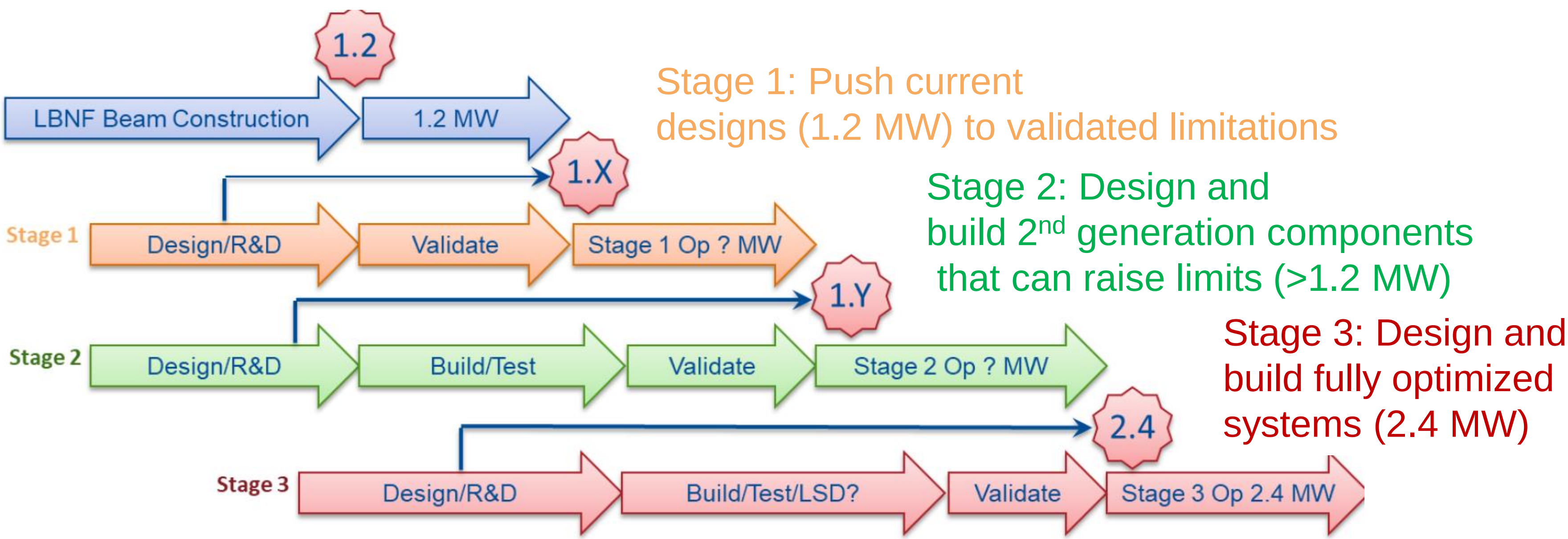
- In 2007, a proof-of principle test **validated** the concept with a liquid Hg target. **Technology was OK** but some safety concerns (ref)
- Recent work shows **promising results** with more friendly materials (graphite or tungsten) (ref)
- Combined with the strong demand of high-power targets puts the MuC in a **synergistic path** with many future experiments
  - One example is the Fermilab Mu2e experiment



MuC target: Path forward

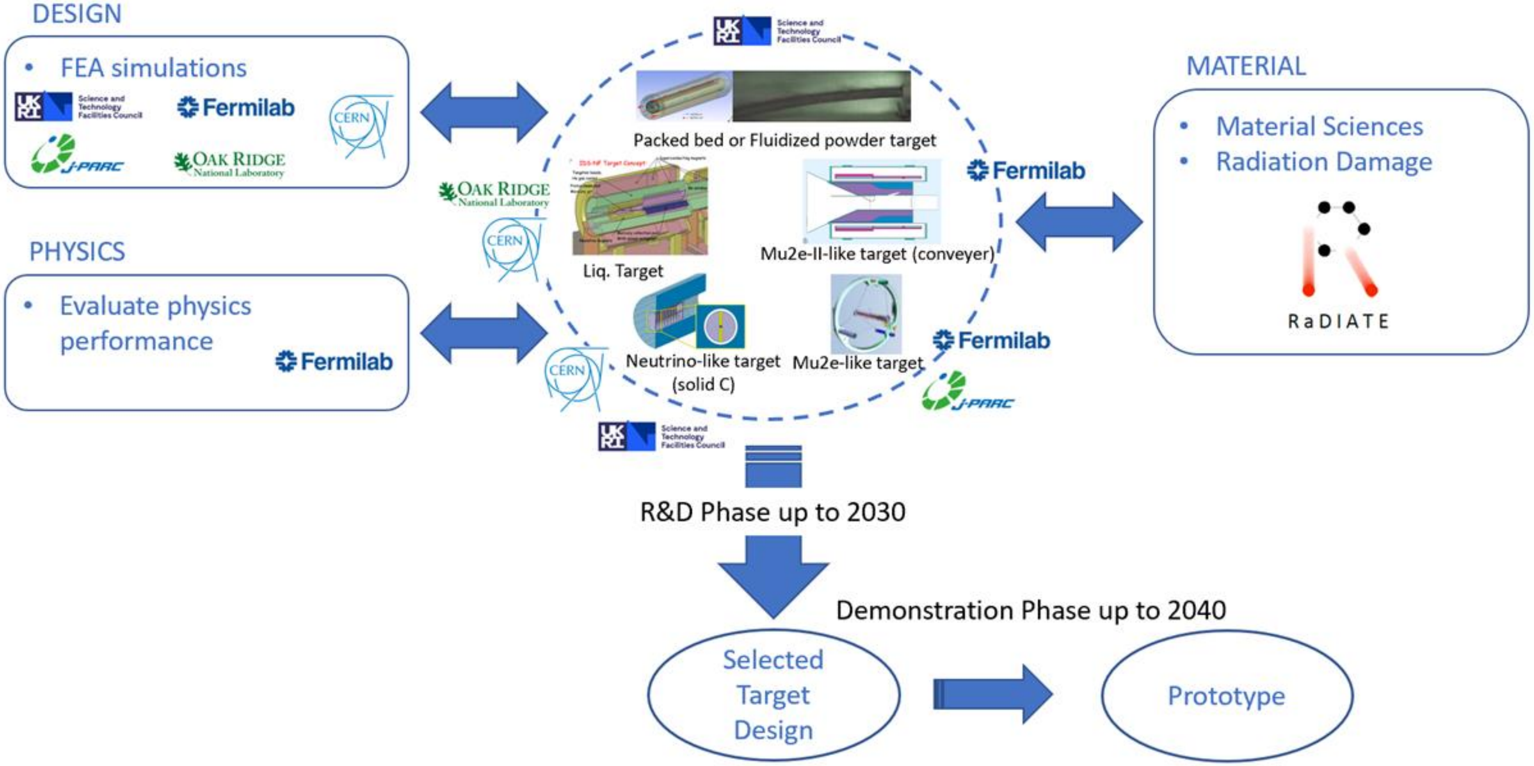
Fermilab ACE Science Workshop
Jun 14 – 15, 2023
America/Chicago timezone

- LBNF plans to use protons which will operate at 1.2 MW to start and will be upgradable to 2.4 MW
- To deliver this power, the **Fermilab Accelerator Complex Evolution (ACE)** has been proposed to P5
  - Include a **target R&D program for 1.2+ MW** beam powers in the next decade
  - This program will **extremely benefit** the targetry R&D for a MuC

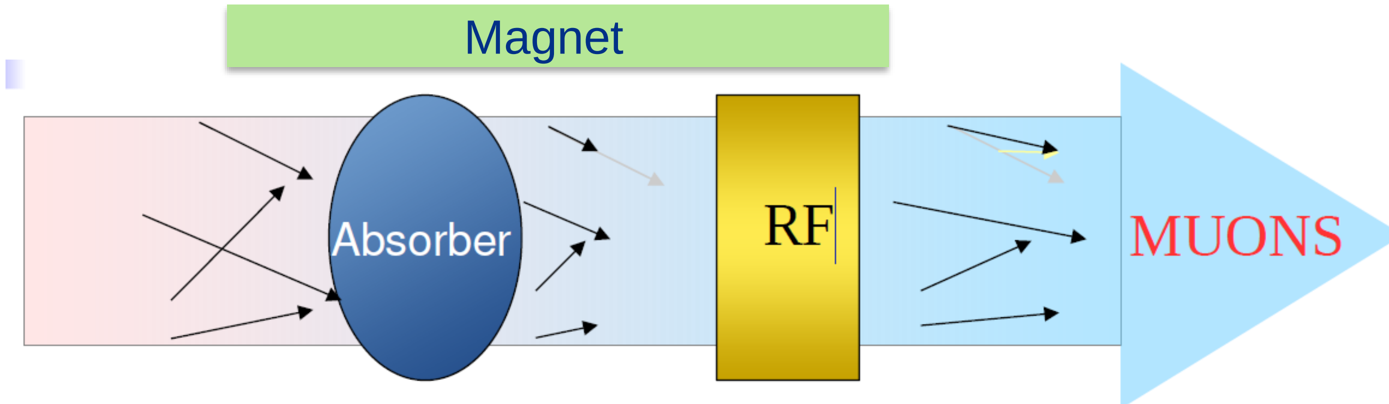


MuC target: Path Forward

- High Power Targetry Roadmap (ref) proposed to GARD plans to have a MuC prototype in the **late 2030s**
  - **Targetry is not only accelerator science: It combines expertise from the fields of material, radiation shielding and detector science.**

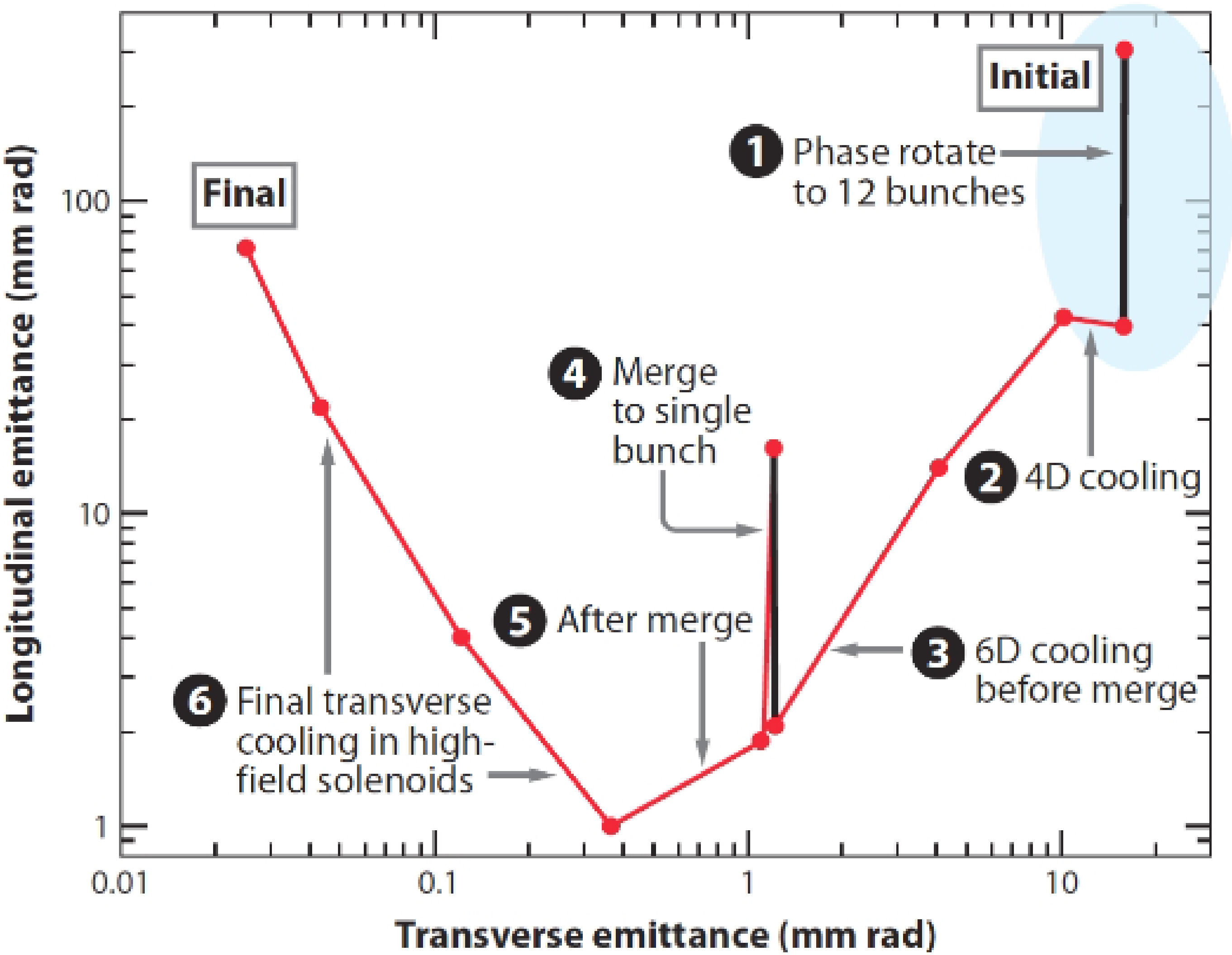


MuC cooling – Concept & technology needs



- Technology requirements for MuC cooling:
  - Large bore solenoidal magnets: From 2 T (500 mm IR), to 20+ 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)

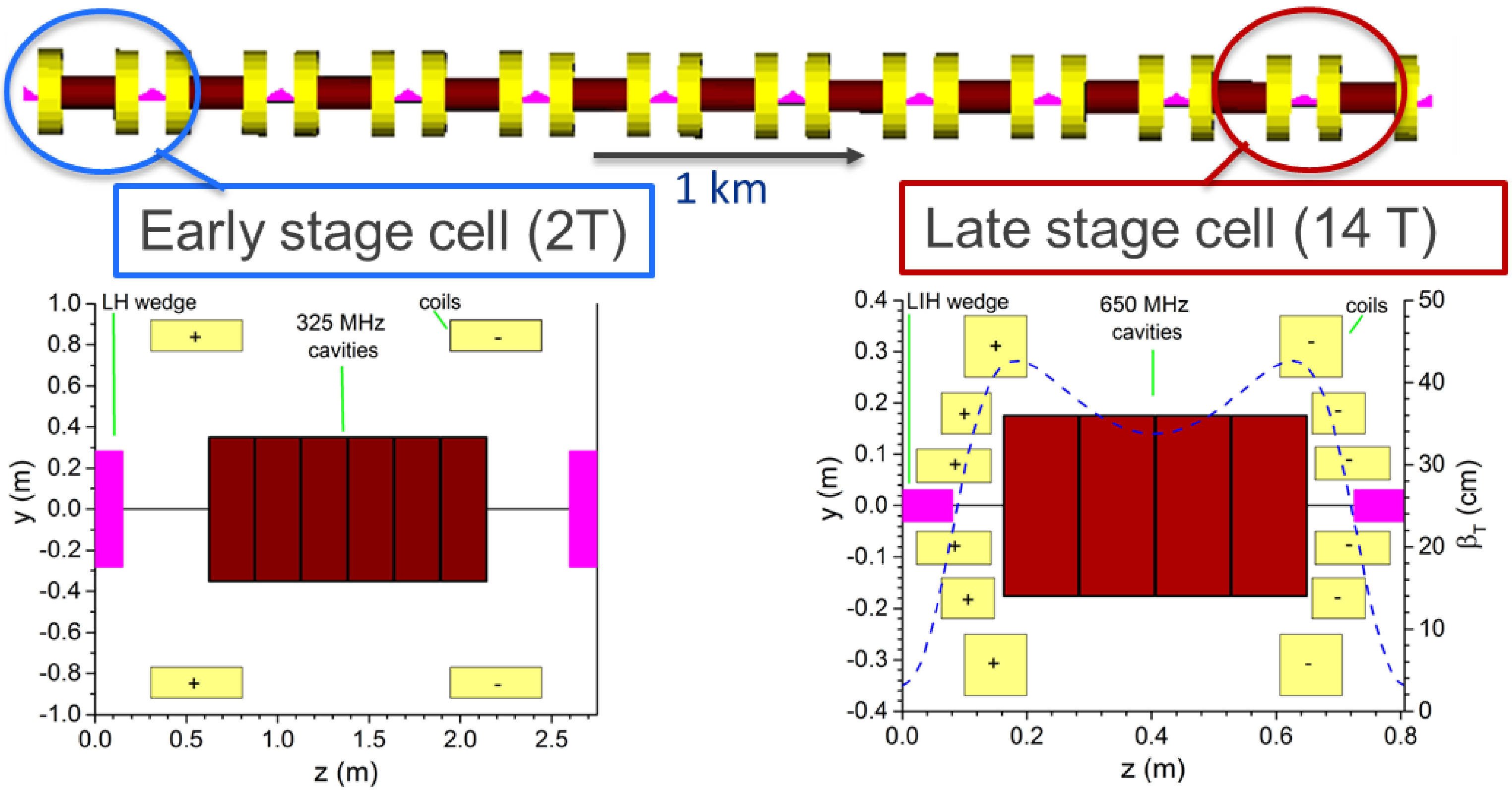
Baseline for muon cooling



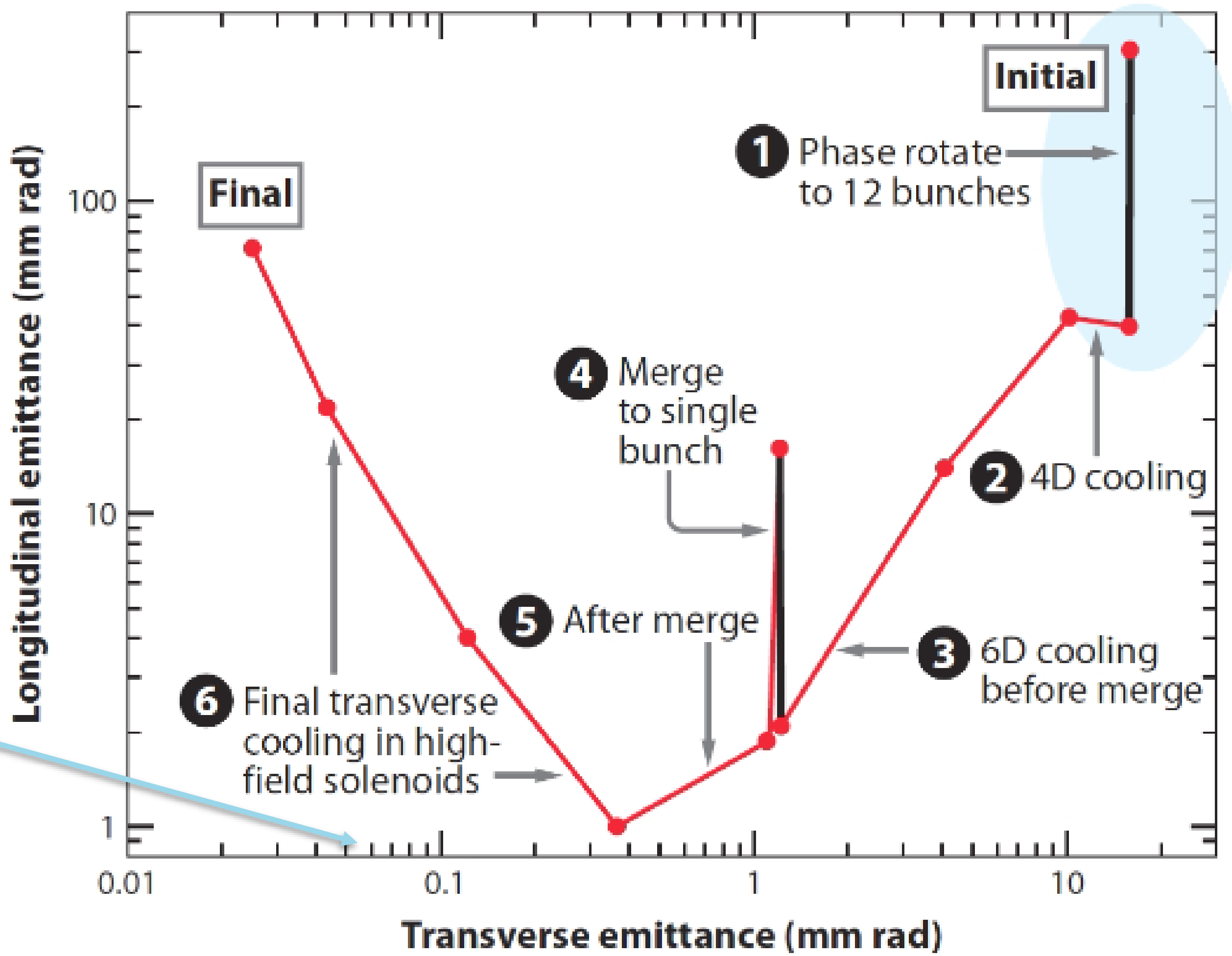
6D emittance reduction by 6 orders of magnitude

MuC cooling (design): Past experience

- Lattice designs have been developed for MuC ionization cooling
  - Parameters used was **very conservative** compared to existing technology
  - There is a lot of room for improvement (next slide)



MuC cooling (design) : Moving forward



Lowest transv. emittance achieved

- Optimization algorithms have been progressed rapidly over the last decade. Implementation of these can be **a game changer**.

MuC cooling (design) : Moving forward

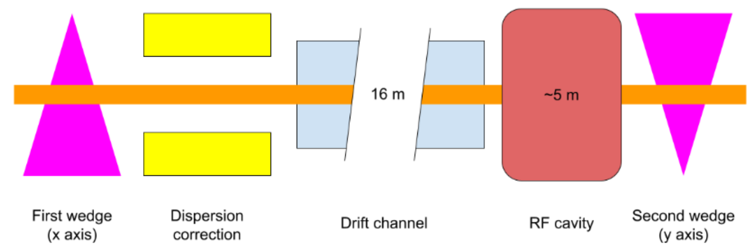
FERMILAB-POSTER-23-218-AD-STUDENT

Final Cooling with Thick Wedges for a Muon Collider

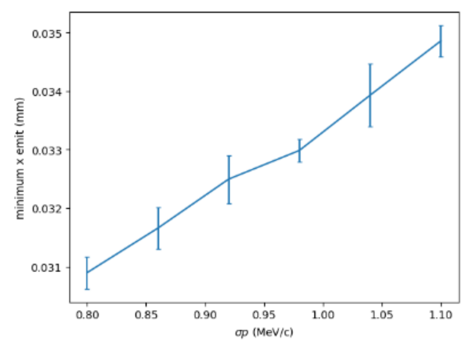
Daniel Fu, University of Chicago – SULI program
Diktys Stratakis, Fermi National Accelerator Laboratory
David Neuffer, Fermi National Accelerator Laboratory

Introduction

A muon collider is a particle accelerator that collides muons rather than protons or electrons. The muons for such an accelerator would be generated by the decay of pions produced in the collision of a proton beam with a target. These muons are produced with high transverse and longitudinal emittance, which must be reduced before they enter the accelerator. The final step of this process is 4D cooling, reducing the transverse emittance of the beam while allowing the longitudinal emittance to grow. We modeled one such method of achieving 4D cooling, consisting of two thick wedges separated by a drift channel and RF cavity for phase rotation.



Above: Diagram of 4D cooling pathway. Diamond was used as the wedge material for this study.

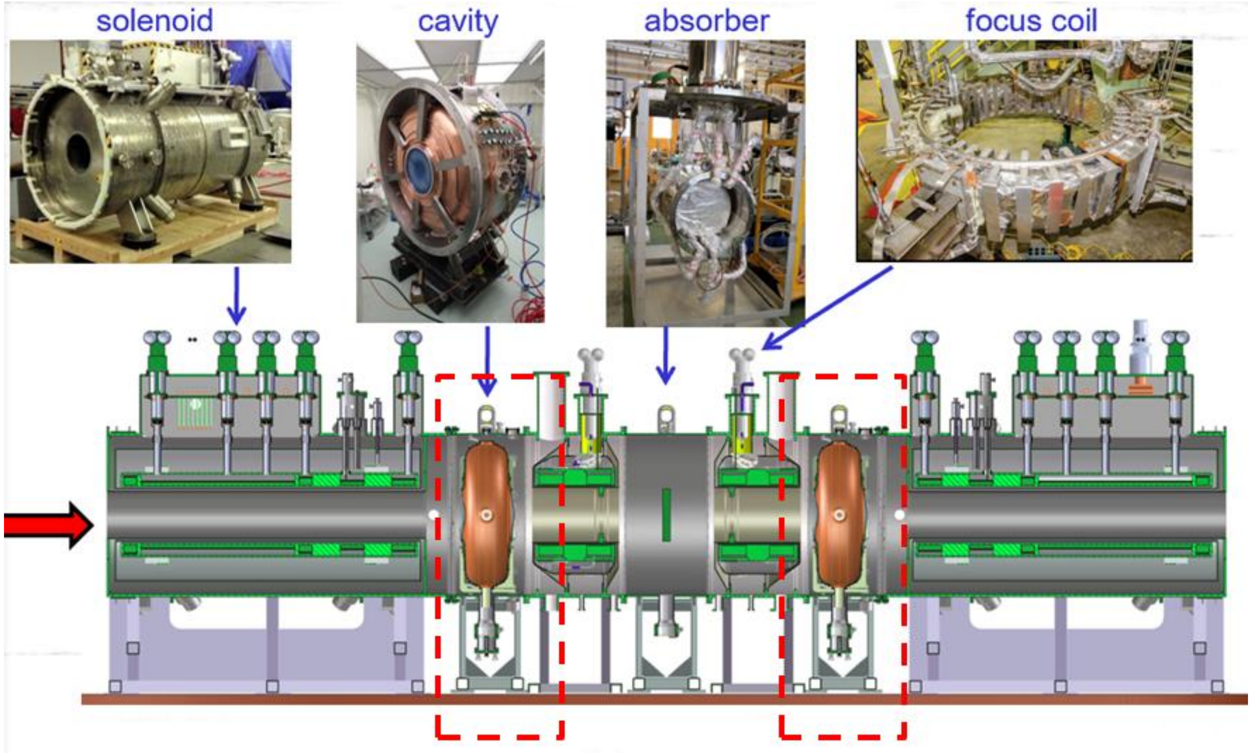


wedges and RF cavity.

- This is an example that shows that by taking advantage of an 8 weeks intern program we can make huge progress!

MuC cooling (exp.): Past experience

- Muon Ionization Cooling Experiment (MICE) at Rutherford Appleton Lab (UK) demonstrated ionization cooling for the first time!
- A sample lattice was build and showed O(10%) **transverse cooling**



MuC cooling (exp.): Past experience

- Tested with two different absorbers: LH_2 and LiH
- More particles move to the core with absorbers (cooling!)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Demonstration of cooling by the Muon Ionization Cooling Experiment

The MICE collaboration

Department of Atomic Physics, St. Kliment Ohridski University of Sofia, Sofia, Bulgaria
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Sichuan University, China
Sezione INFN Milano Bicocca, Dipartimento di Fisica G. Occhialini, Milano, Italy
Sezione INFN Napoli and Dipartimento di Fisica, Università Federico II, Complesso Universitario di Monte S. Angelo, Napoli, Italy
Sezione INFN Pavia and Dipartimento di Fisica, Pavia, Italy
Sezione INFN Roma Tre e Dipartimento di Fisica, Roma, Italy
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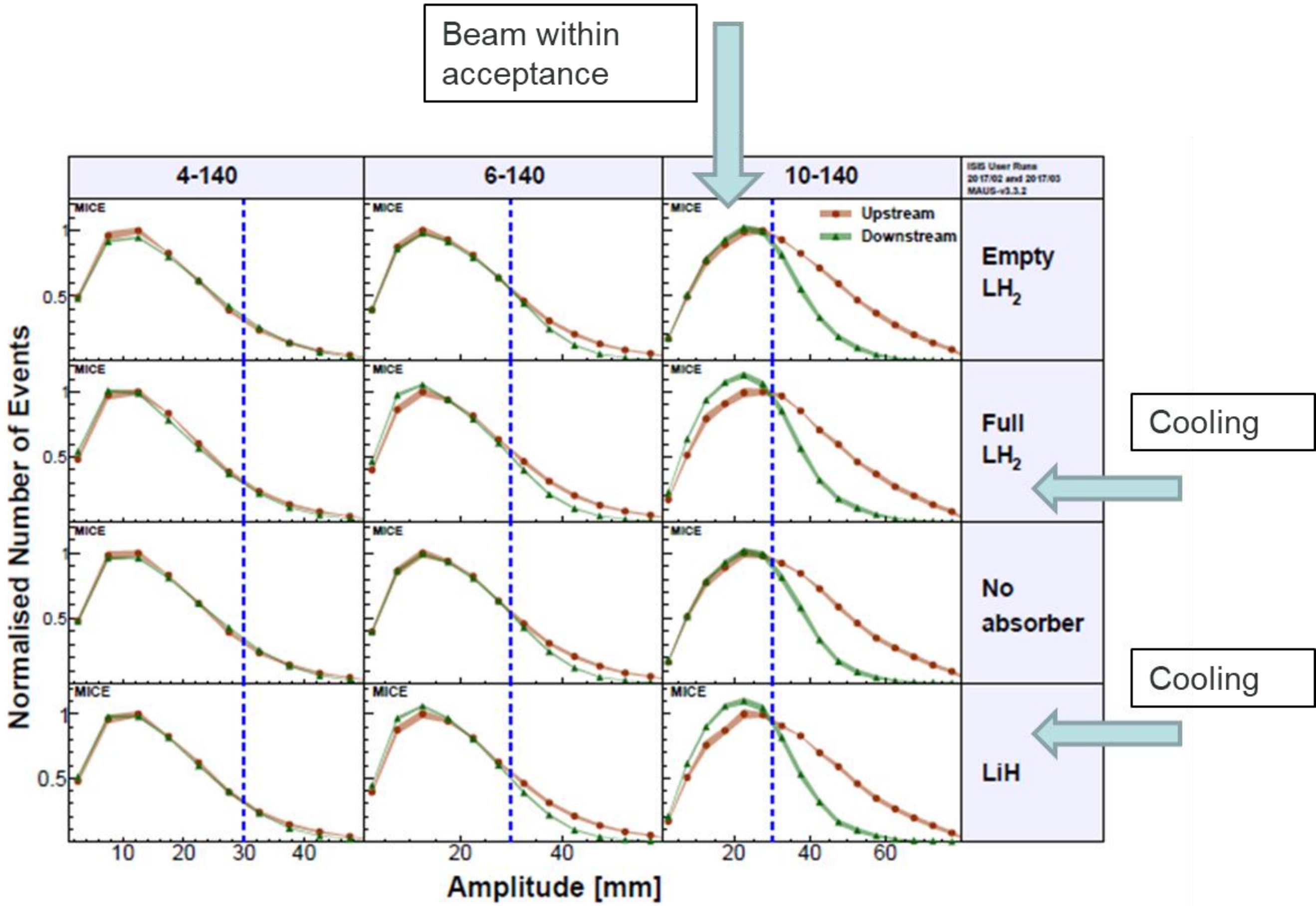
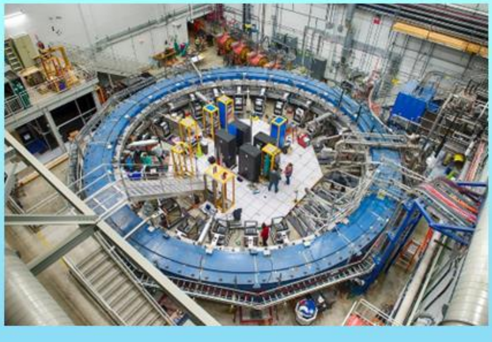
University of California, Riverside, CA, USA

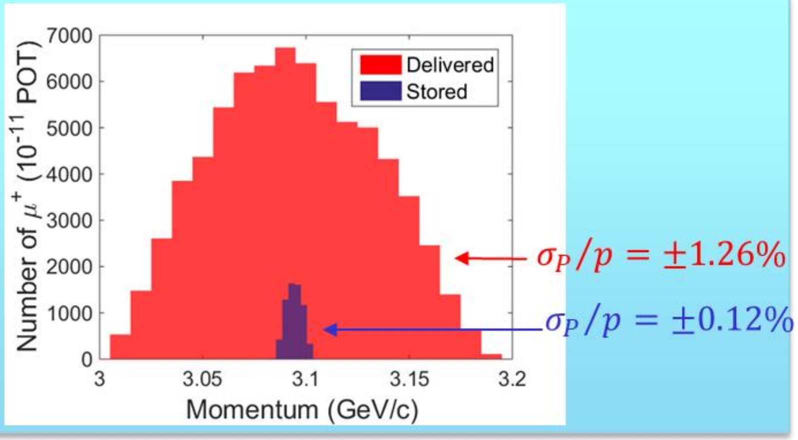


MuC cooling (exp.): Past experience

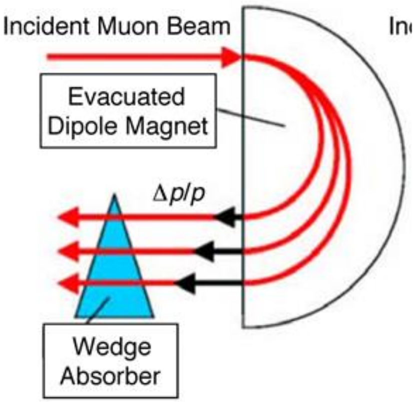
- Demonstrated **longitudinal ionization cooling** using the Fermilab Muon g-2 Experiment storage ring

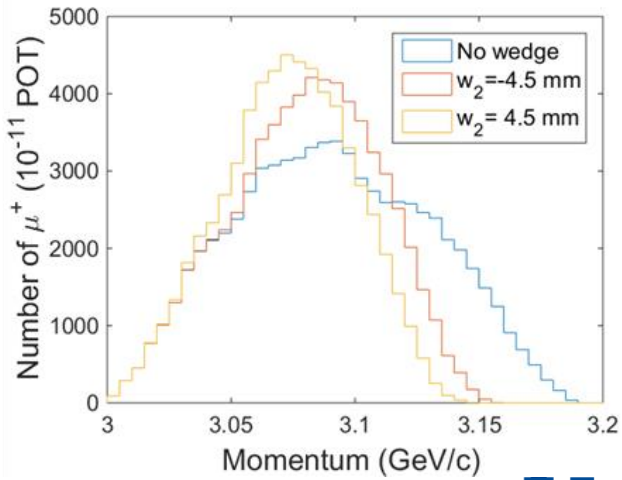
CURRENT SCHEME





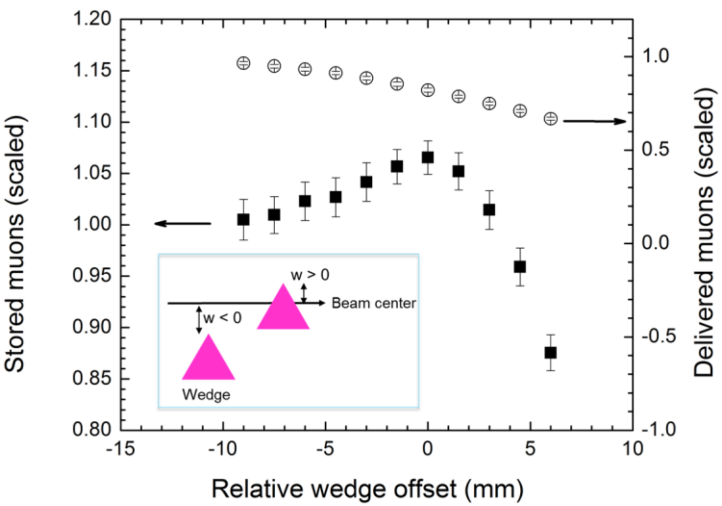
IMPROVED SCHEME

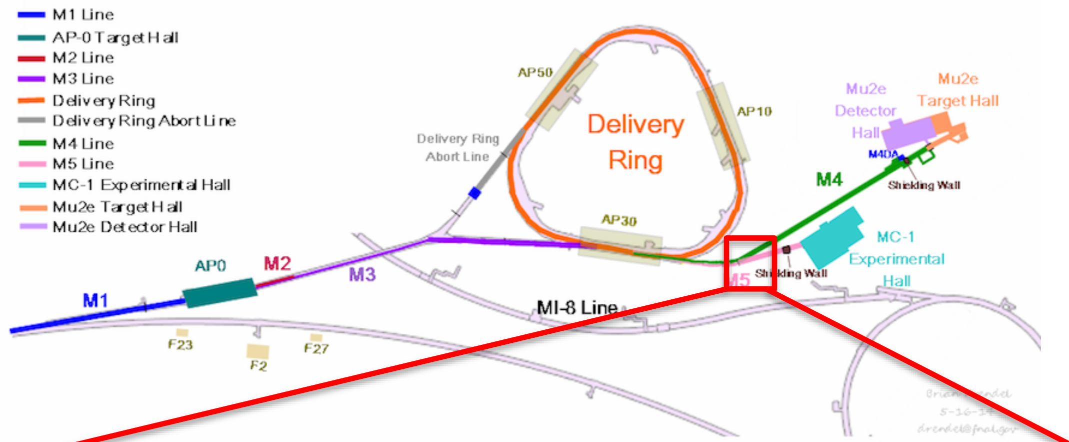


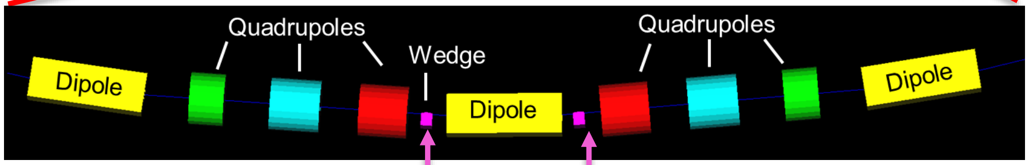


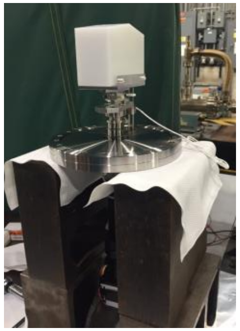
MuC cooling (exp.) Past experience

- Proof-of-principle: Demonstrated a gain up to 8% in stored muons with a polyethylene wedge.









LDRD at Fermilab

Laboratory Directed Research and Development

Another example that benefited from students!

Nick Amato (2019)
Master's Thesis, **NIU** (Syphers)
Title: Improved momentum spread for precision experiments using wedges

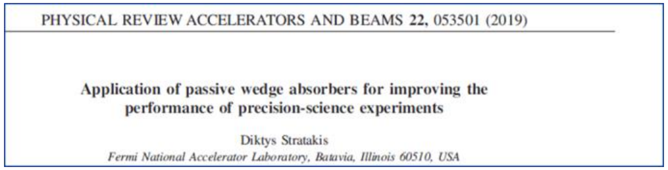
Lauren Carver (2019)
Fermilab Intern
Title: Modeling a wedge absorber for the g-2 Experiment

Jerzy Manczak (2018)
Fermilab Intern
Title: Modeling a wedge absorber for the Mu2e Experiment

Joe Bradley (2017)
Fermilab Intern
Title: Material & geometry study of a wedge absorber for the g-2 Experiment

Grace Roberts (2020)
Fermilab Intern
Title: Optimizing injection for a wedge based Muon g-2 Experiment

Ben Simons(2020)
NIU grad. student
Title: Tuning beam optics for the Muon Campus



PHYSICAL REVIEW ACCELERATORS AND BEAMS 22, 053501 (2019)

Application of passive wedge absorbers for improving the performance of precision-science experiments

Diktys Stratakis
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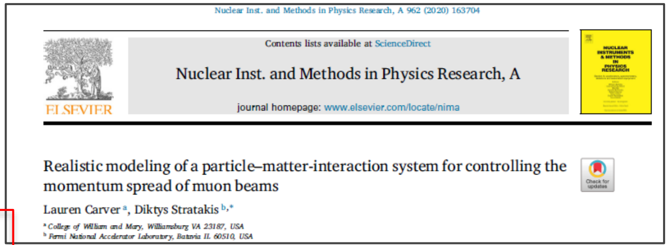

Nuclear Inst. and Methods in Physics Research, A 962 (2020) 163704

Contents lists available at ScienceDirect
Nuclear Inst. and Methods in Physics Research, A
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Realistic modeling of a particle–matter-interaction system for controlling the momentum spread of muon beams

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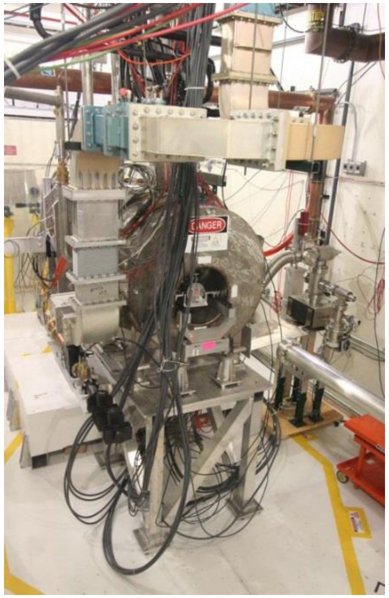
A parametric analysis for maximizing beam quality of muon-based storage ring experiments

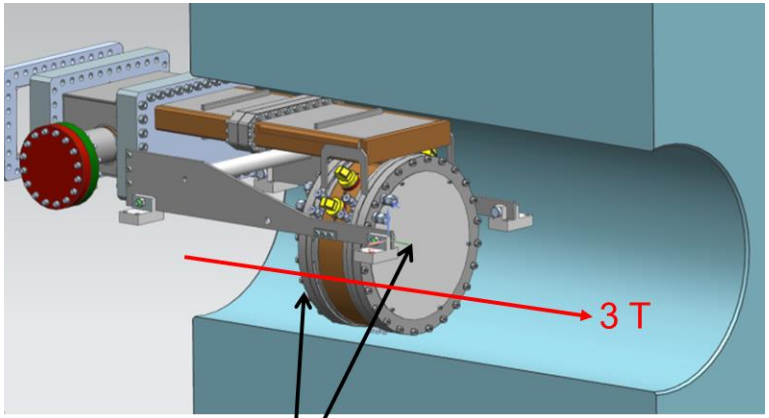
Grace Roberts [a], Diktys Stratakis [b,*]
[a] Purdue University, Department of Physics, West Lafayette, IN 47906, USA
[b] Fermi National Accelerator Laboratory, Batavia IL 60510, USA

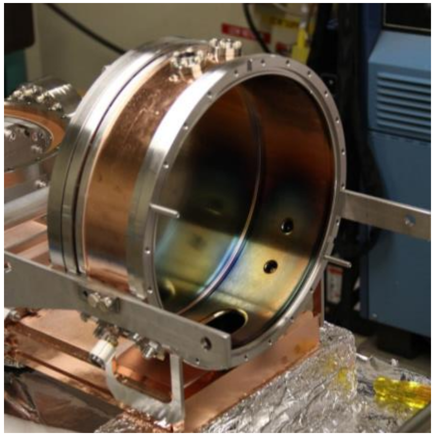
Fermilab

MuC cooling (exp.): Past experience

- Cooling designs need placement of cavities within multi-T B-fields
  - Limits the technology to normal conducting NC) cavities. Some evidence that the B-field makes operation of these cavities difficult
- Behavior of NC cavities in B-fields (up to 3 T) was tested at Fermilab
  - **Understanding the mechanism of breakdown and explore alternative materials is an open topic**







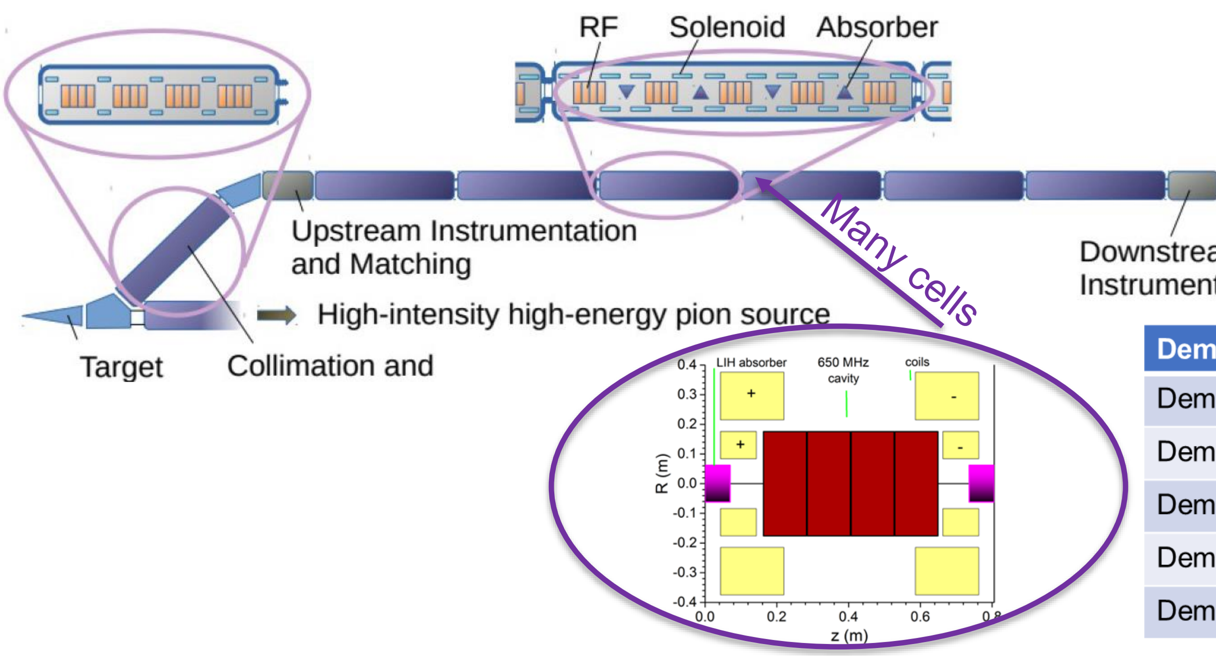
removable plates (Cu, Al, Be)

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

No change in gradient!

The need of a cooling demonstrator

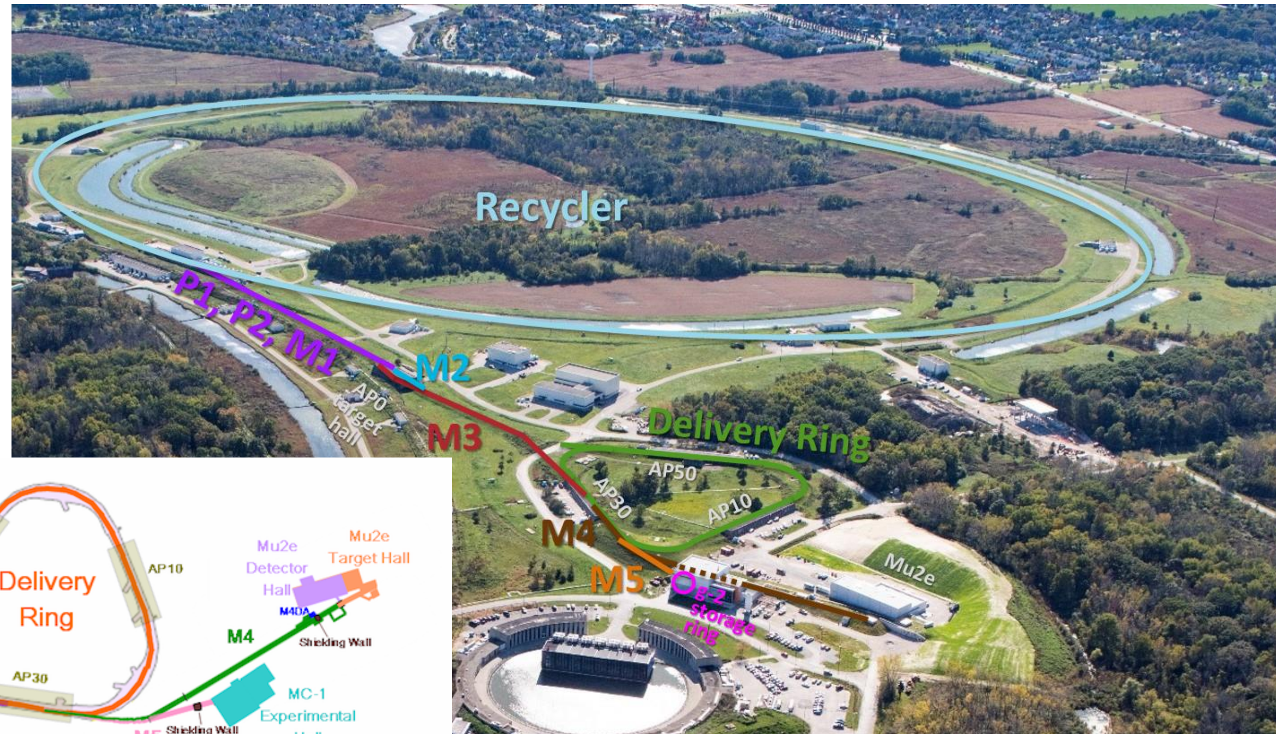
- It is **critical** to benchmark a **realistic** MuC cooling lattice
  - This will give us the input, knowledge, and experience to design a real, buildable cooling channel for a MuC
  - **Possibilities for hosting such a facility in the US exist**
  - **Tremendous opportunity for interns, PhD students, Postdocs…**



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

Fermilab Muon Campus

- Designed to provide beam for the Muon g-2 and Mu2e experiments
    - Muon g-2 experiment ended Summer of 2023



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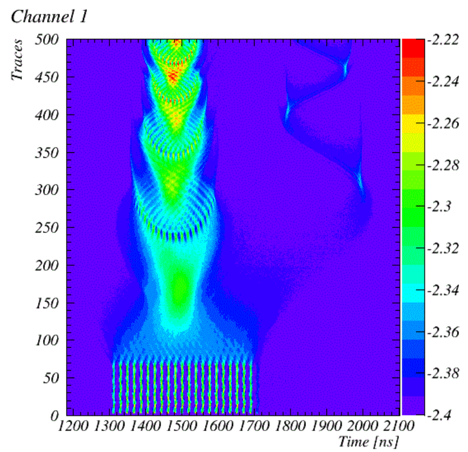
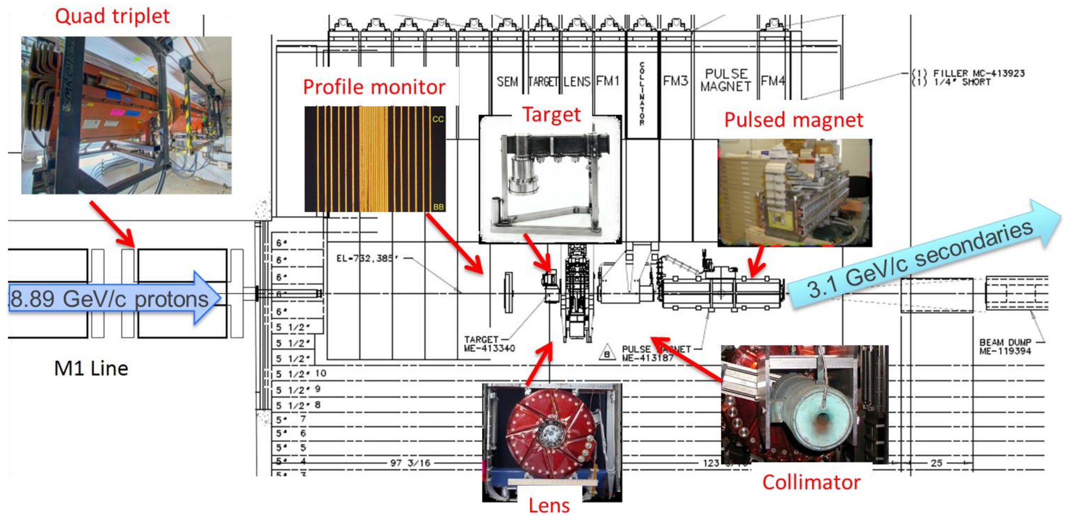
Muon Campus capabilities

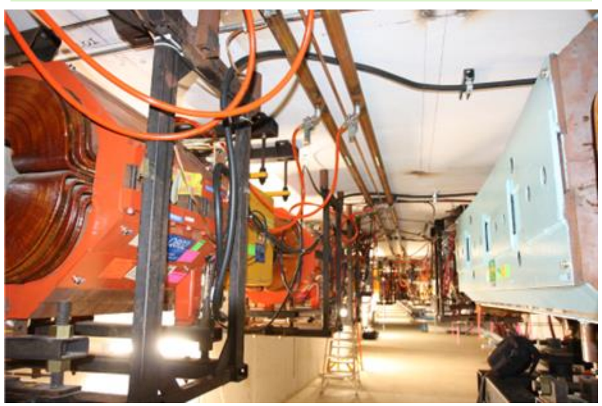
RF system to create short 8 GeV bunches before target



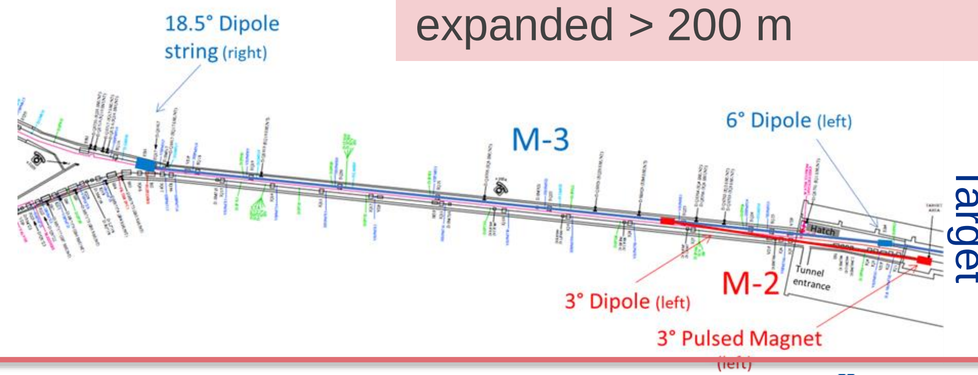
Target can serve as a test-bed for material studies



Two beamlines; instrumentation available

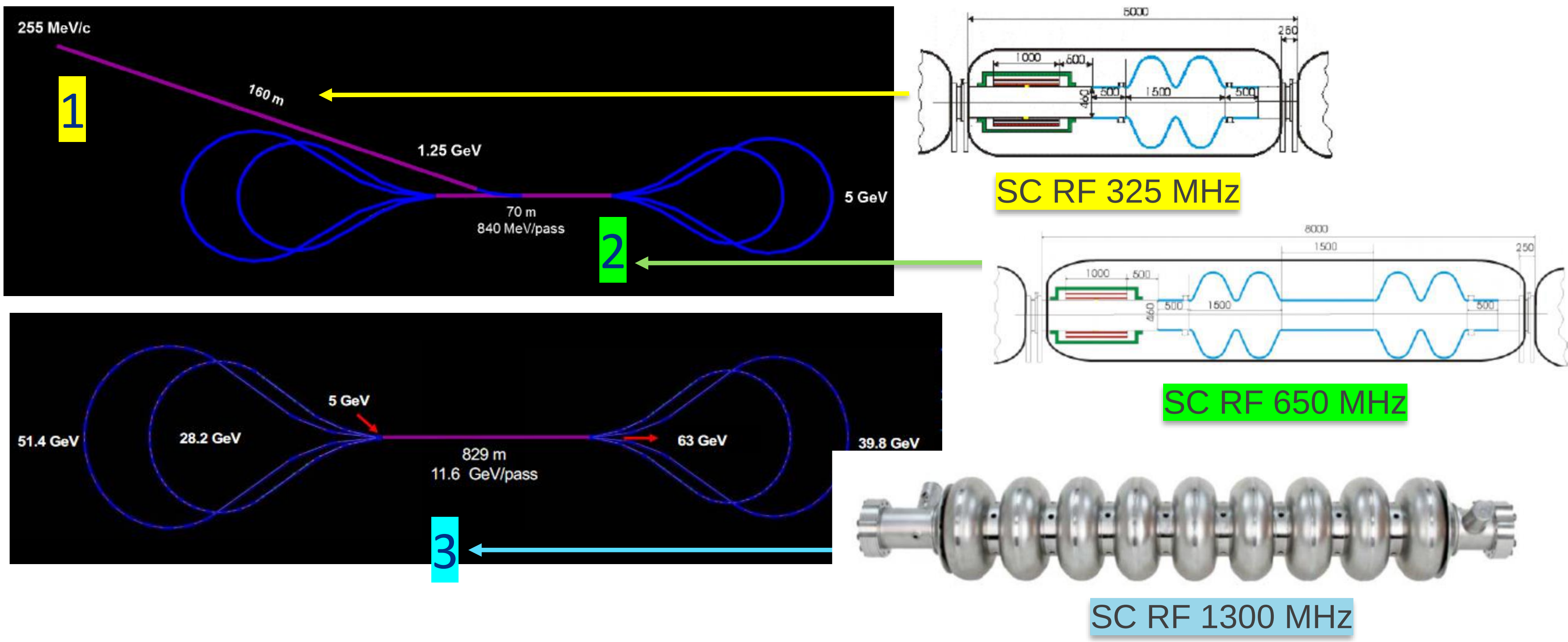


Line after target can be expanded > 200 m



Fermilab

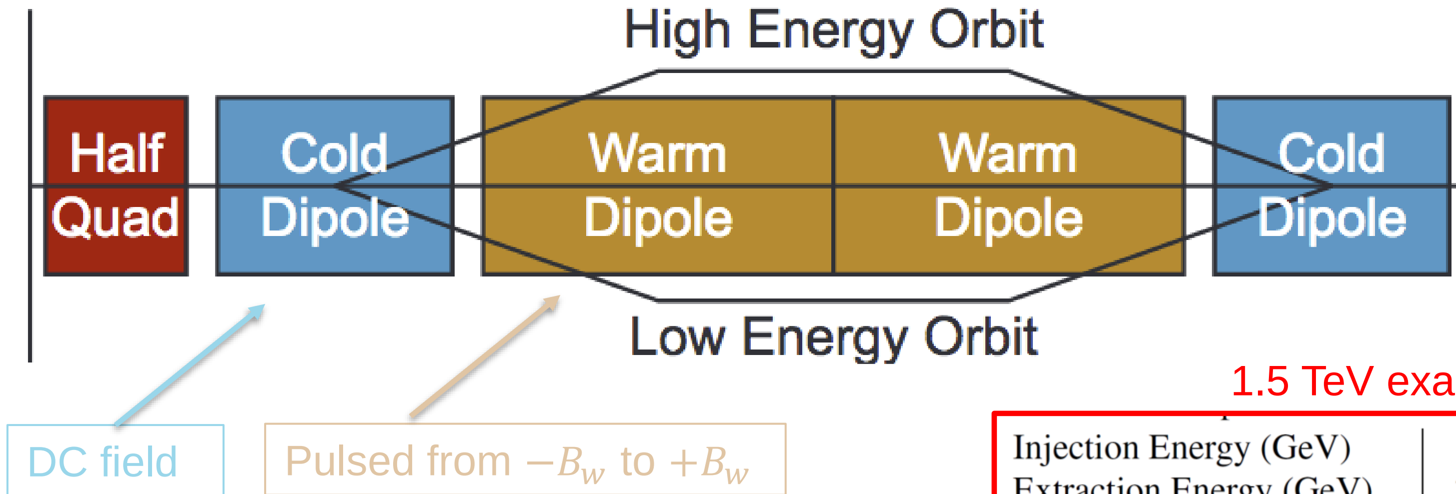
MuC GeV acceleration – Concept & technology needs



- Technologies requirements for a Muon Collider:
  - Superconducting (SC) linacs and Recirculating linear accelerators (RLAs)
  - Low frequency SC RF cavities that need to operate at high gradients

Fermilab

MuC TeV acceleration – Concept & technology needs

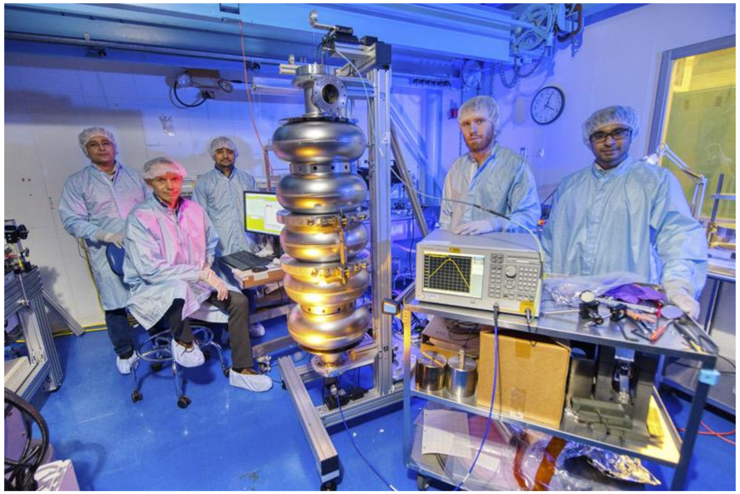


1.5 TeV example

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

MuC acceleration: Path forward

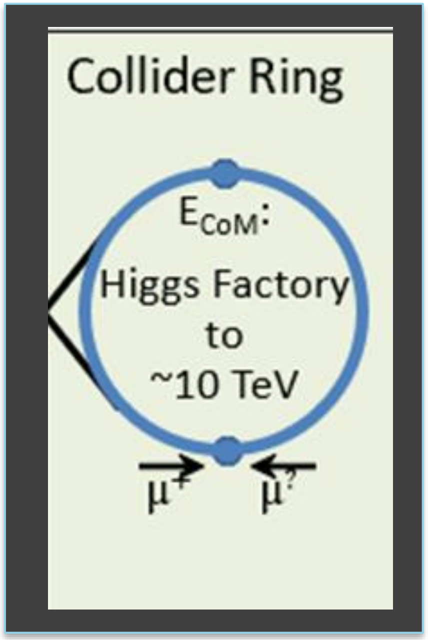


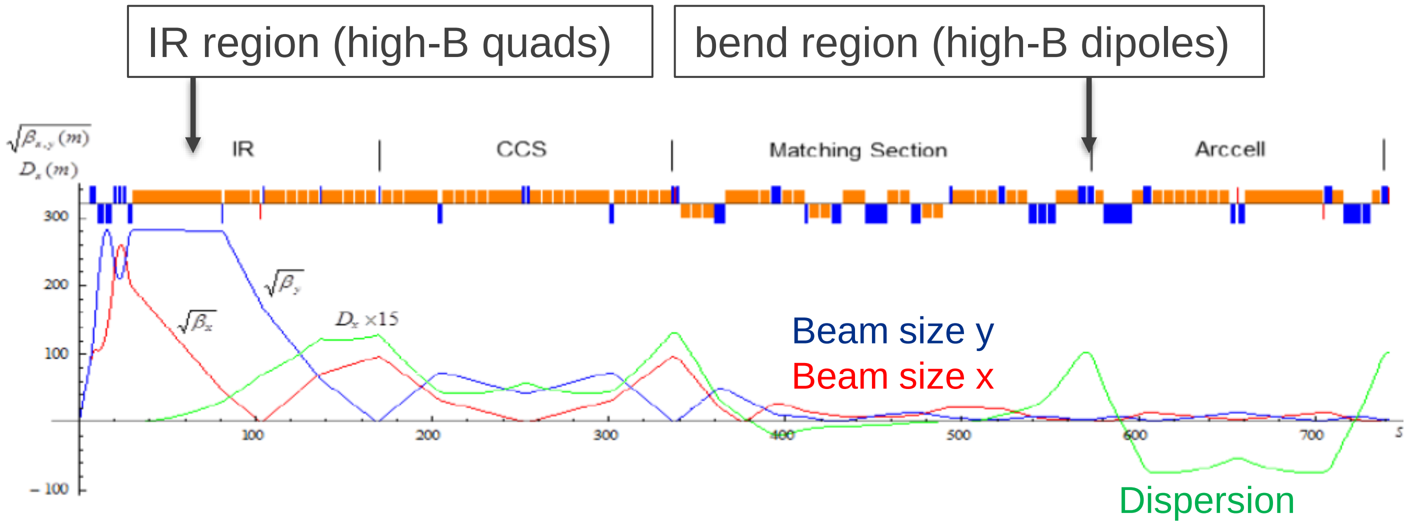
5 cell elliptical cavities @ 650 MHz for PIP-II

Cryomodule @ 1300 MHz for LCLS-II

- Develop self-consistent accelerator lattice towards a 10 TeV collider
    - Students from US site started looking at this; more help is needed!
- 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

MuC collider ring – Concept & technology needs



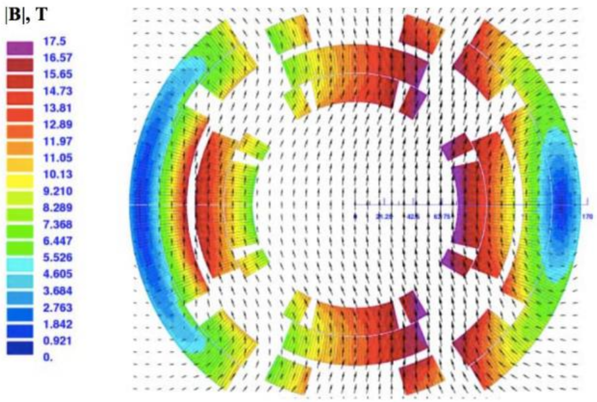


- Technology requirements for a MuC collider ring
  - Strong quadrupole focusing at IR (15-20 T for 10 TeV)
  - High-field dipoles for min. ring size & max. luminosity (12-16 T for 10 TeV)
  - Dipoles with large aperture (~150 mm) to allow for shielding
  - Mitigation system for the neutrino flux from muon decays

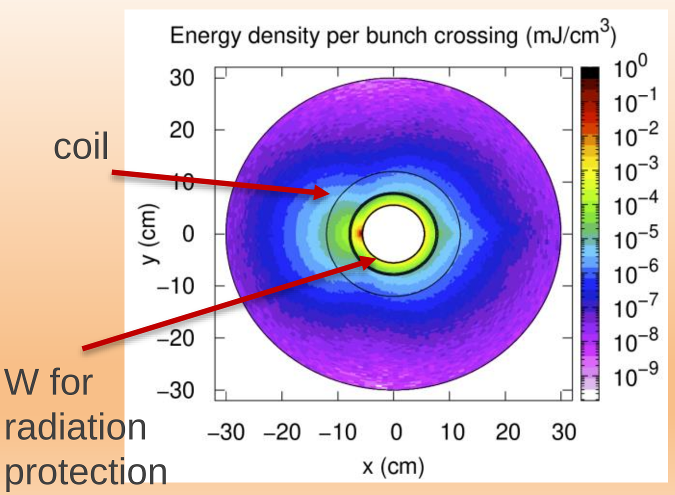
Muon Collider ring – Past experience & path forward

- Complete lattice design in place for a 3 TeV collider
  - Magnet specs are within HL-LHC range
- Parameters for a 10 TeV colliders are more demanding. Preliminary designs are in place [ref]
  - Higher dipoles fields (12-16 T)
  - IR quads in the 15-20 T range
  - **Have to push the magnet technology beyond existing limits**
- Radiation studies suggest that shielding protection for both 3 TeV and 10 TeV are **the same**

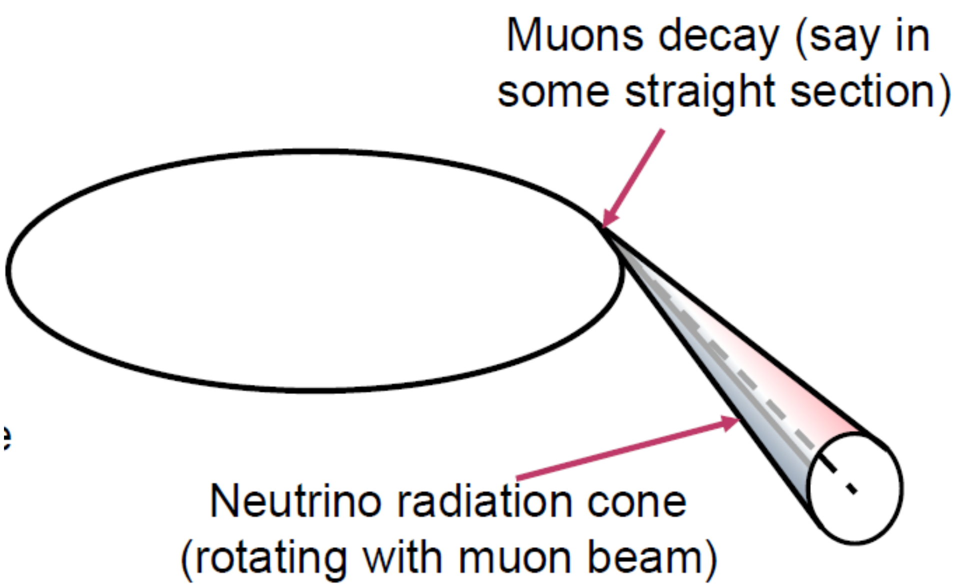
3 TeV dipole magnet

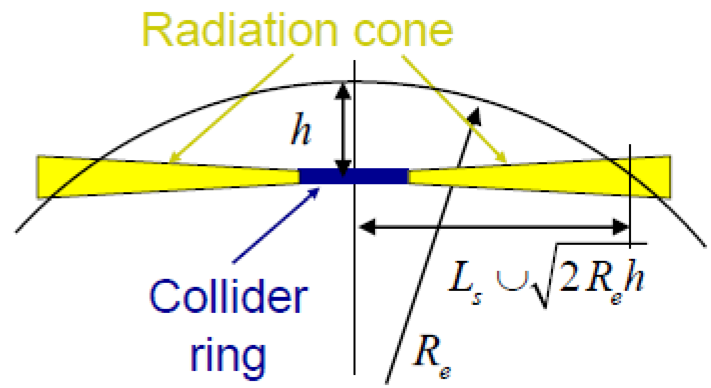


10 TeV radiation studies



Neutrino radiation

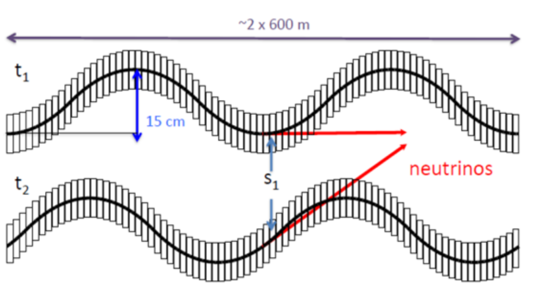




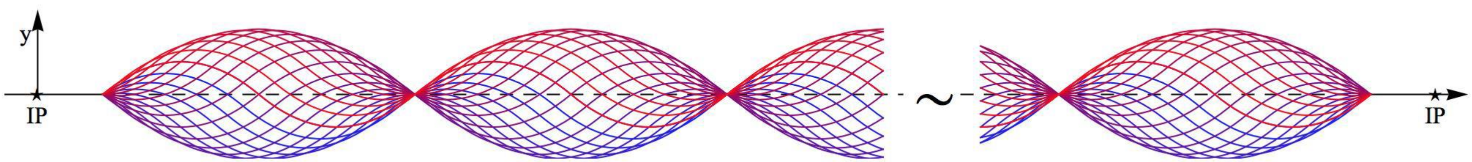
- Radiation due to neutrino beam reaching the earth
  - Narrow radiation cone for a short piece of the machine
  - Strong increase of maximum dose with muon energy
  - Matter in front does not help but makes the situation worse

Neutrino flux mitigation system

Solution: A mechanical system that will disperse the neutrino flux by periodically deforming the collider ring arcs vertically with remote movers;



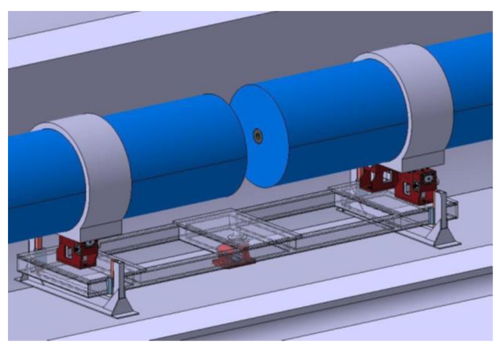
Legal limit: 1 mSv/year
MAP goal: <0.1 mSv/year
IMCC goal: <10 µSv/year
LHC : <5 µSv/year



Vertical slope modulation ~ 1 mrad

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

Working on different approaches for experimental insertion



14th International Particle Accelerator Conference,Venezia JACoW Publishing
450-231-8 ISSN: 2673-5490 doi: doi/jacow-ipac2023-mopl166/index.html

NEUTRINO GENERATED RADIATION FROM A HIGH ENERGY MUON COLLIDER

C. Carli, C. Ahdida, D. Calzolari, G. Lacerda, G. Lerner, A. Lechner, D. Schulte, K. Skoufaris, Y. Robert, CERN, Geneva, Switzerland

Requires significant R&D and proof-of principle tests

Post-Snowmass: US Muon Collider R&D coordination group formation

- 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, Sergo Jindariani, and Diktys Stratakis

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)

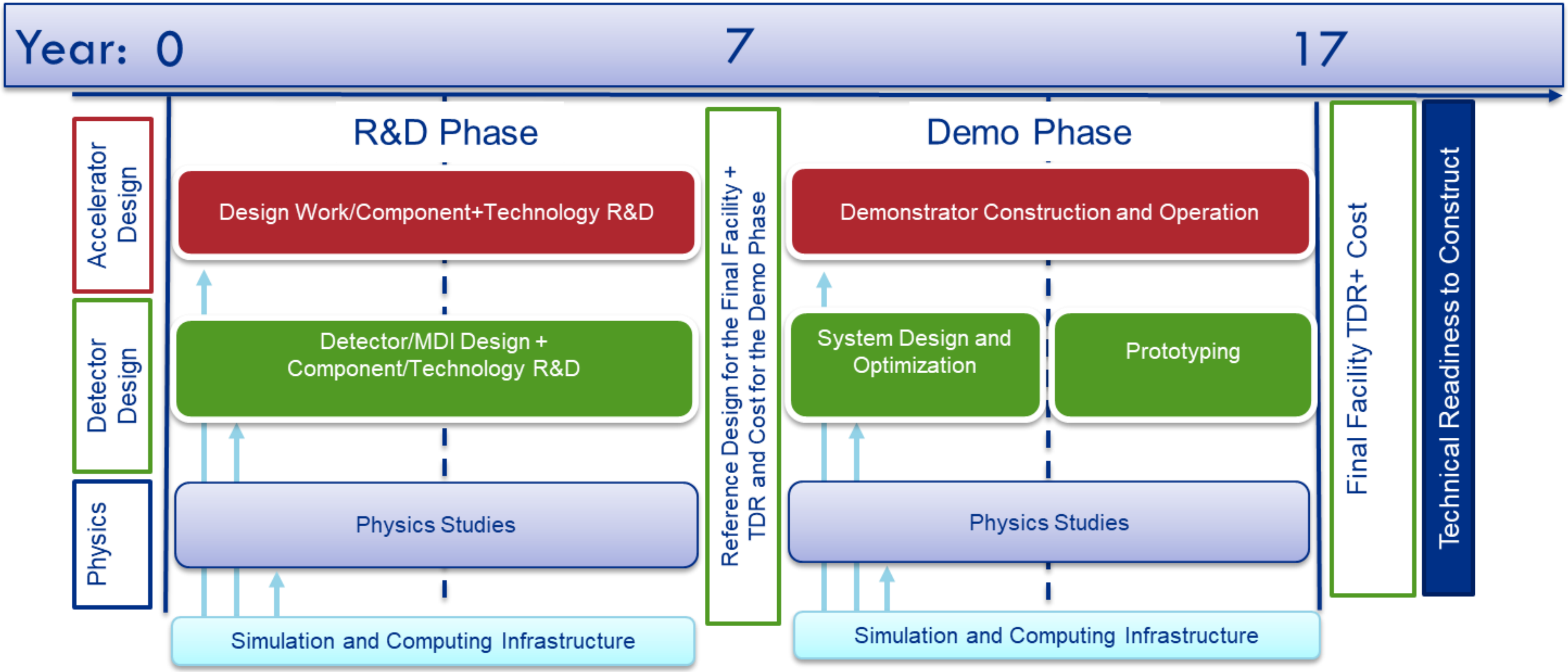
Electronics/TDAQ
Darin Acosta (Rice), Isobel Ojalvo (Princeton), Michael Begel (BNL)

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

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

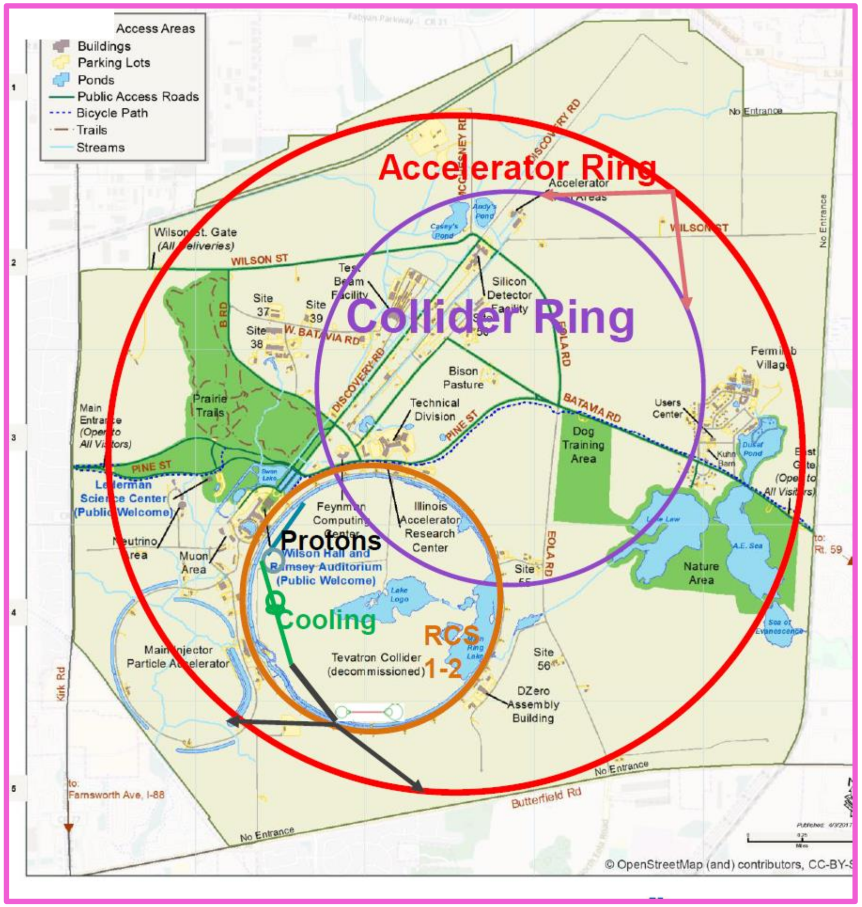
International Liaisons:
Daniel Schulte (CERN), Chris Rogers (RAL), Donatella Lucchesi (INFN), Federico Meloni (DESY)

US Muon Collider timeline



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



- Developing a baseline design is needed
  - Work started between Stony Brook University and BNL – more help is needed!

Proposed MuC accelarator US R&D (next 5 years)

Some examples

Design and Simulation work

- MuC proton driver design
- Accelerator & collider designs for a FNAL MuC
- Neutrino flux mitigation for a FNAL MuC
- Ionization cooling design work

Some examples

Prototyping & tests

- Bunch compression & proton stripping
- Target material & performance studies
- Fast ramping magnet prototypes
- Low-frequency SRF cavity prototyping & testing

Some examples

Demonstrator

- Explore facility options for a full demo
- Design & prototype (if possible) 1.5 cooling cell
- Deliver a TDR for a demo facility with costs

- A 10-page **R&D summary** document submitted to P5 (link). Includes the R&D plan, timeline, FTE and M&S needs.

Summary (1)

- MC offers a unique opportunity for energy frontier collider with high luminosity
- Physics & technology landscape has significantly changed recently
  - Explosion of physics interest in muon colliders as indicated by the number of publications, activities in IMCC, Muon Collider Forum, and Snowmass white papers
- No fundamental show-stoppers in physics and technology have been identified
  - Nevertheless, engineering challenges exist in many aspects of the design and targeted R&D is necessary in order to make further engineering and design progress
- **There are numerous opportunities for everyone to get involved!**
- **Accelerator non experts are very welcome to help us!**

Backup

What has changed since over the last decade?

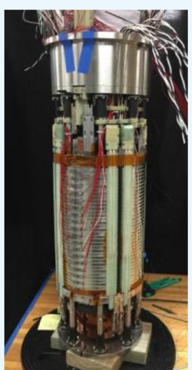
- Lattice design
  - Developed designs for all MuC subsystems, including a promising solution for a neutrino flux mitigation system
- Targets
  - Significant developments on MW-class target concepts due to the strong demand by many experiments.
- Magnet technology
  - Development of high-field solenoids & dipoles with specs close to the MuC needs
- RF technology
  - Demonstrated high-gradient operation of NC cavities in B-fields (50 MV/m @ 3T)
  - SCRF cavity gradients for a MuC are within reach of current technology
- Ionization cooling concept demonstration
  - Physics of ionization cooling has been demonstrated; many publications

MuC magnet technology: Path Forward

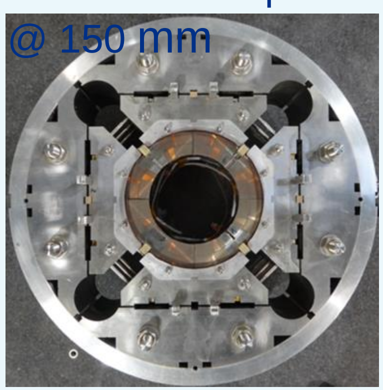
MuC section	Type	10 TeV MuC needs	Status
Cooling	Solenoid	30-50 T @ 50 mm	32 T @ 32 mm
Acceleration	Rapid cycling mag.	1.8 T @ 5 kT/s (30 mm x 100 mm)	1.8 T @ >5 kT/s (1.5 mm x 36 mm)
Collider Ring	Dipole	12-16 T @ 150 mm	11-12 T @ 120 mm
IR	Quadrupole	15-20 T @ 150 mm	11-12 T @ 150 mm

- 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 Rate Ramp for RCS					
Collider Dipoles					
IR Quads					
Alternatives R&D					
HTS for collider magnets					