Muon Collider R&D

Diktys Stratakis (Fermilab)

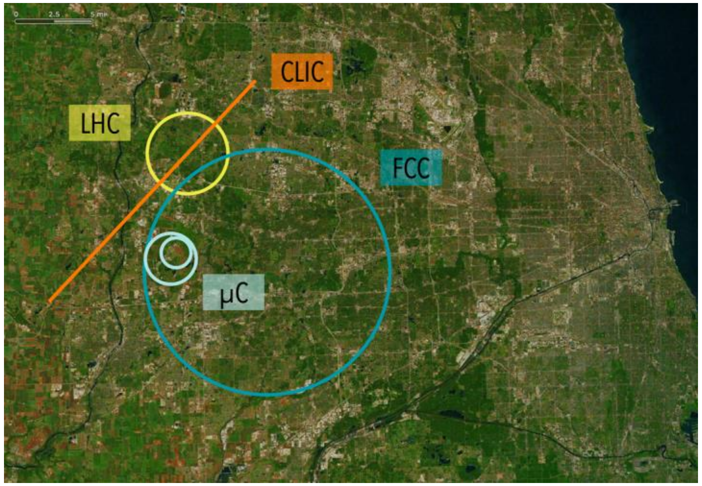
NuFact 2024, Argonne National Laboratory, USA

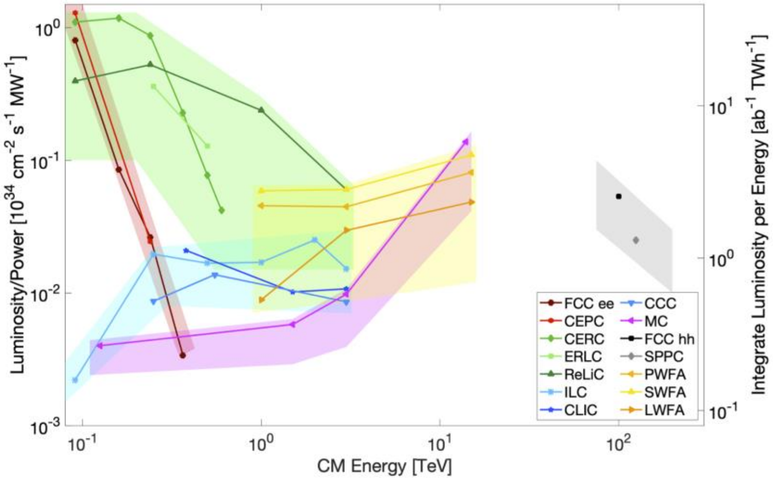
September 18, 2024

On behalf of US Muon Collider R&D Panel and
International Muon Collider Collaboration

Motivation

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



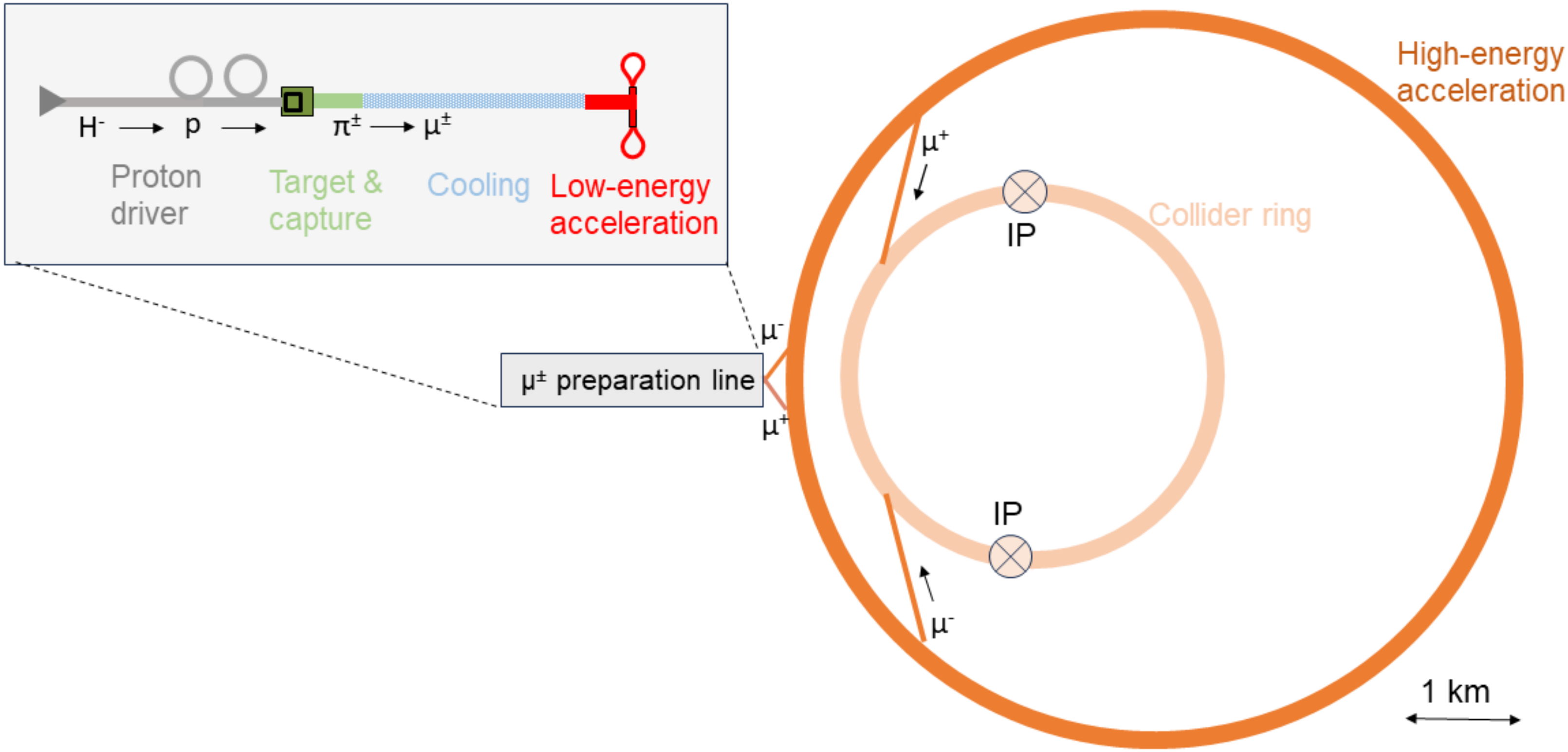


Global effort

- 2011-2016: **Muon Accelerator Program** has developed key concepts, designs and technologies for a MuC up to 6 TeV.
- Strong surge of interest in MuC within the theoretical and experimental communities. Shift of emphasis towards **10 TeV**.
- In 2021, the International Muon Collaboration (IMCC) was formed
  - IMCC goal is to develop a baseline design of a 10 TeV MuC and build the associated R&D program for such machine. CERN is host for now.
  - Studies suggest that readiness of construction can achieved in the 2040s
- In 2023, the P5 panel **recommended** that the US should develop a collider with 10 TeV parton collision energies, such a MuC
  - “In particular, a MuC presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US”
  - “The US should participate in the IMCC and take a leading role in defining a reference design”

Machine overview

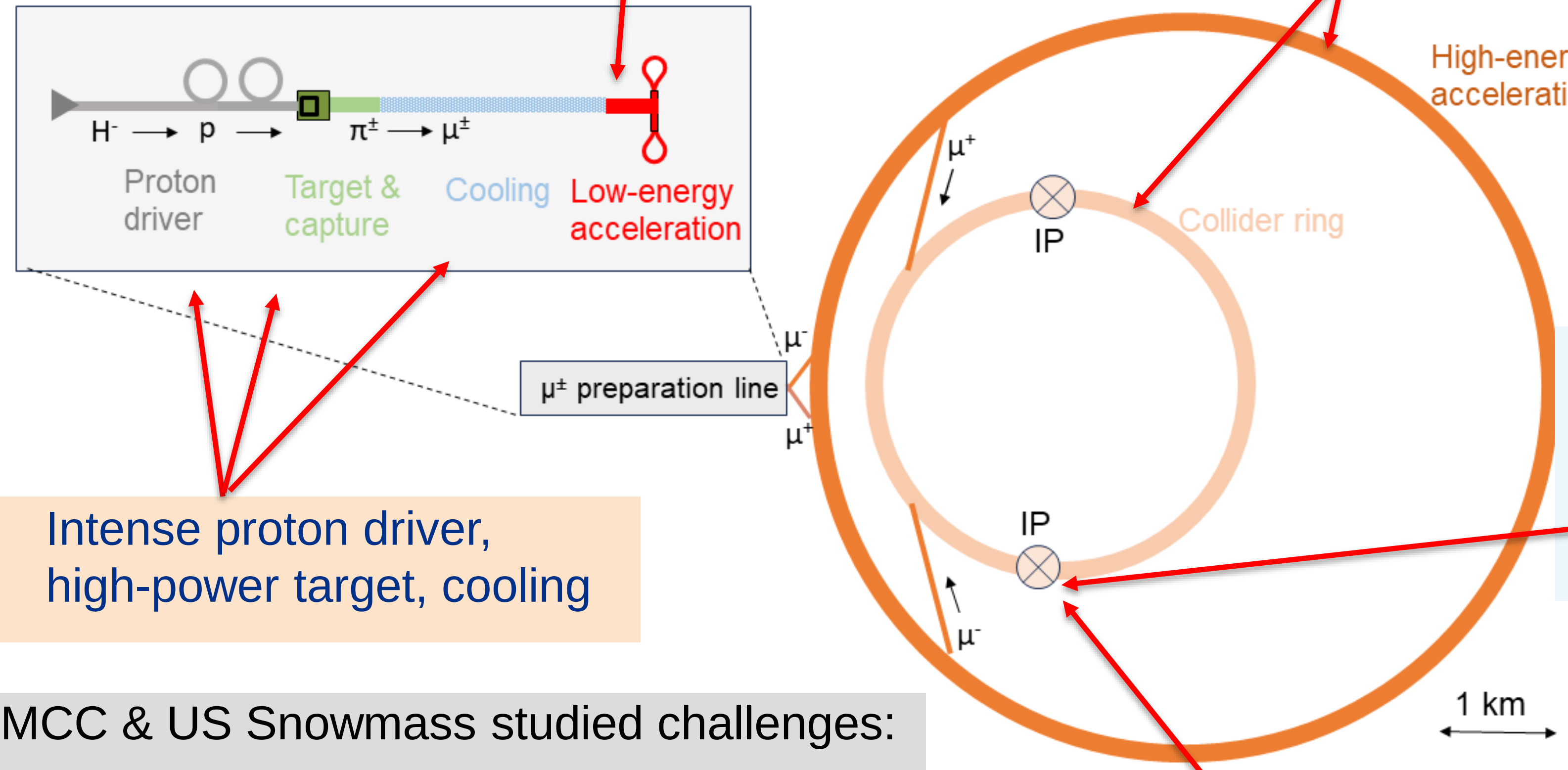
- Goal is to get to **10 TeV center-of-mass energy**
- Two approaches: Staging in **energy** (3 TeV to 10 TeV) or in **luminosity**



Challenges

High-gradient SRF cavities for acceleration

Challenging magnets in many places



Dense neutrino flux needs to be mitigated

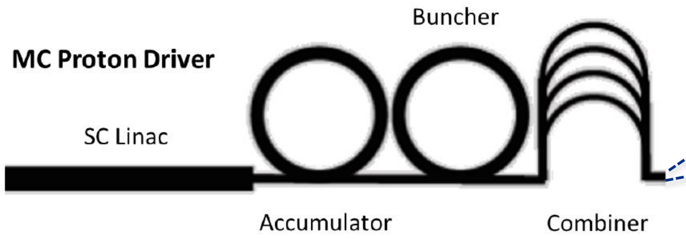
Intense proton driver, high-power target, cooling

Beam induced background in the detectors

IMCC & US Snowmass studied challenges:

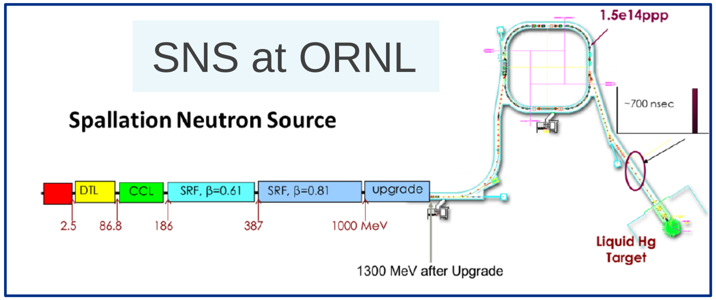
- No fundamental showstoppers identified
- BUT engineering challenges exist
- Significant R&D is needed!

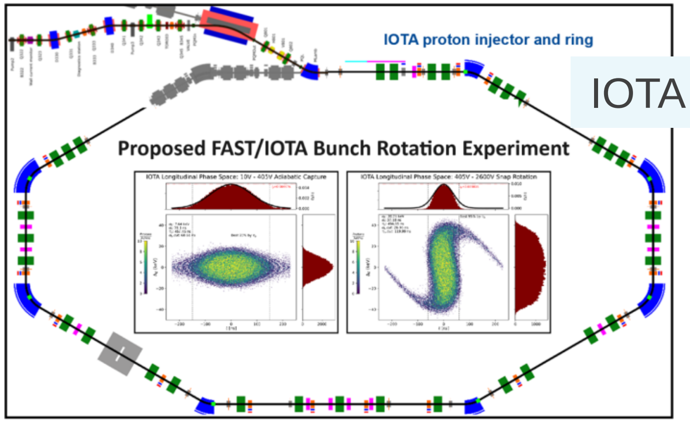
Proton driver



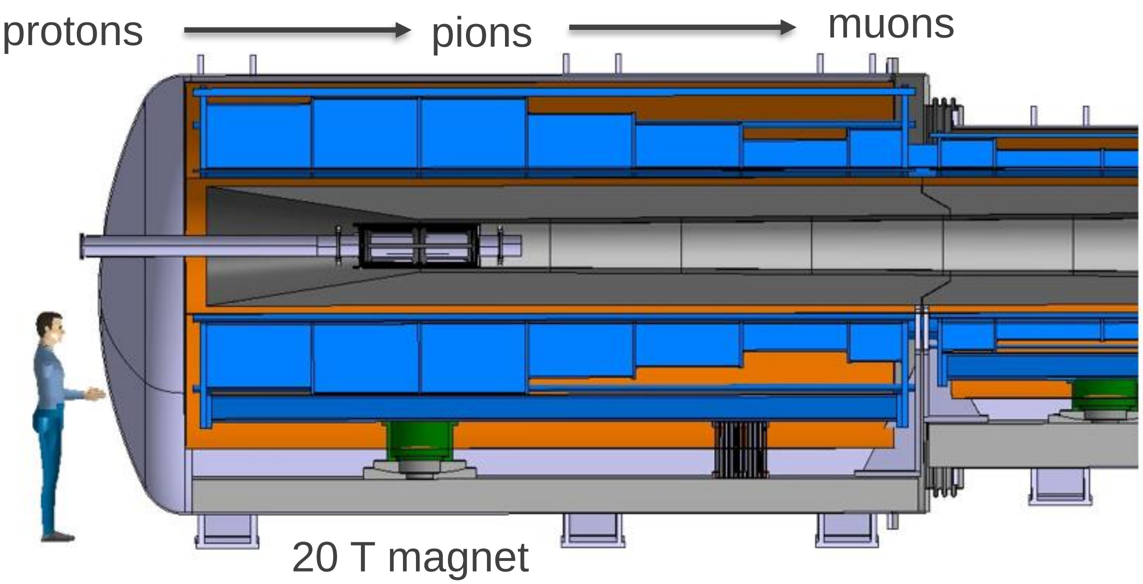
Optimum: **2-4 MW** at **5-20 GeV**,
compressed at **1-3 ns @ 5-10 Hz**

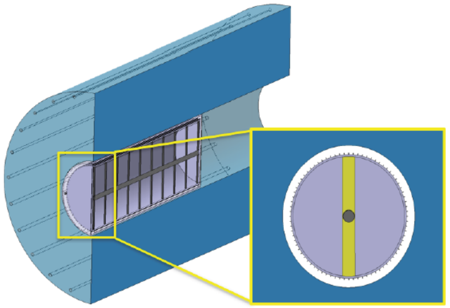
- Multi-MW proton sources exist globally (ex. PIP-II, SNS, ESS)
  - R&D is needed to adapt and extend such facilities to MuC requirements
- Involves beam manipulations that require experimental demonstrations
  - These can be studied at existing facilities that are analogs to a MuC proton driver


SNS at ORNL


IOTA at FNAL

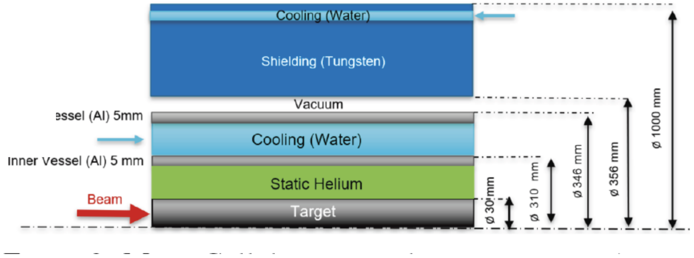
Target and capture





igure 1: Current Muon Collider target 3D concept.

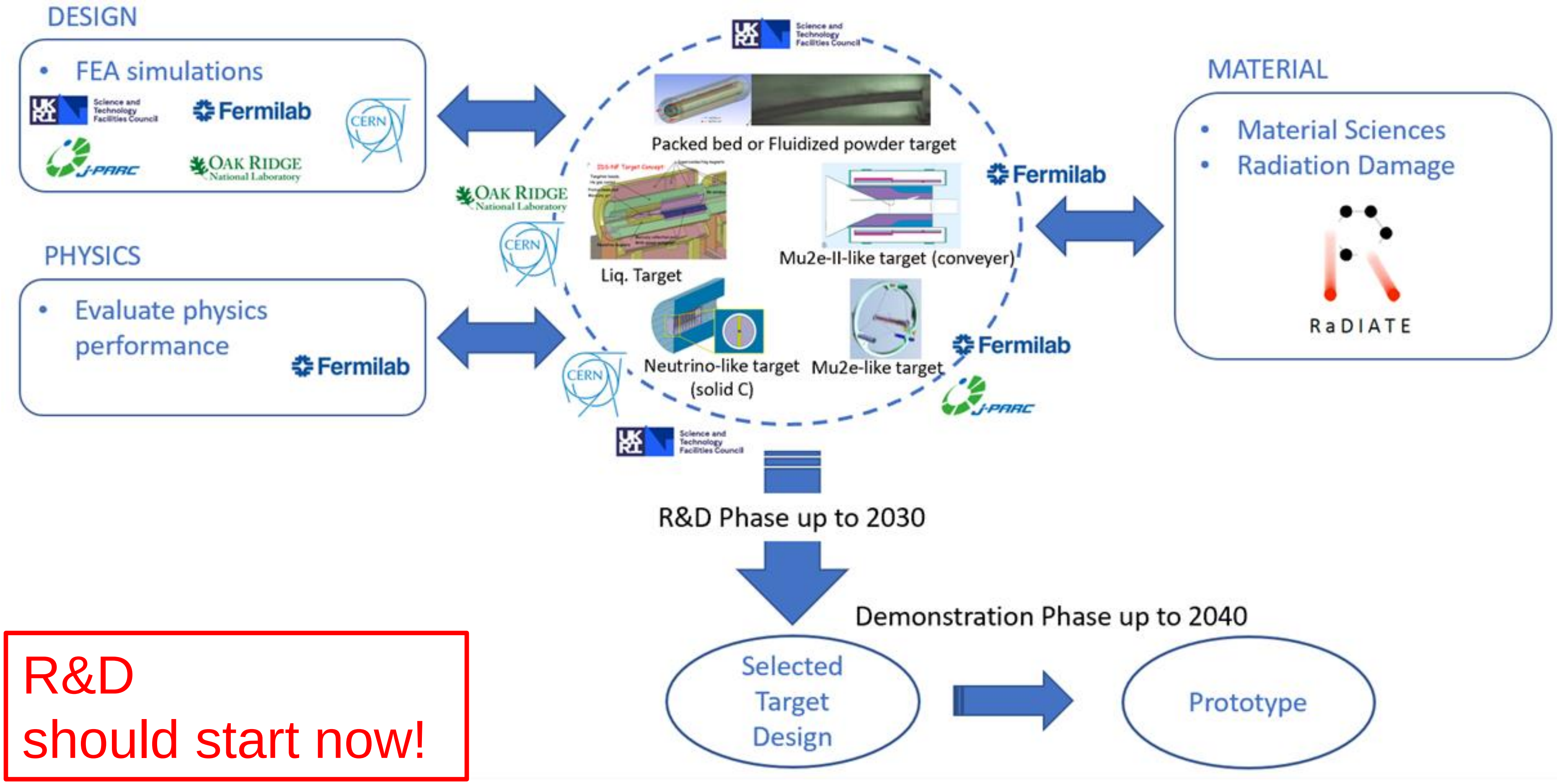
gure 2 schematically details the bodies, dimensions and
rials of the current proposal.



- 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

MuC targetry roadmap

- MuC targets are included in the proposed GARD High Power Targetry Roadmap (ref) with a plan to have a prototype **late 2030s**



DESIGN

- FEA simulations

PHYSICS

- Evaluate physics performance

MATERIAL

- Material Sciences
- Radiation Damage

R&D Phase up to 2030

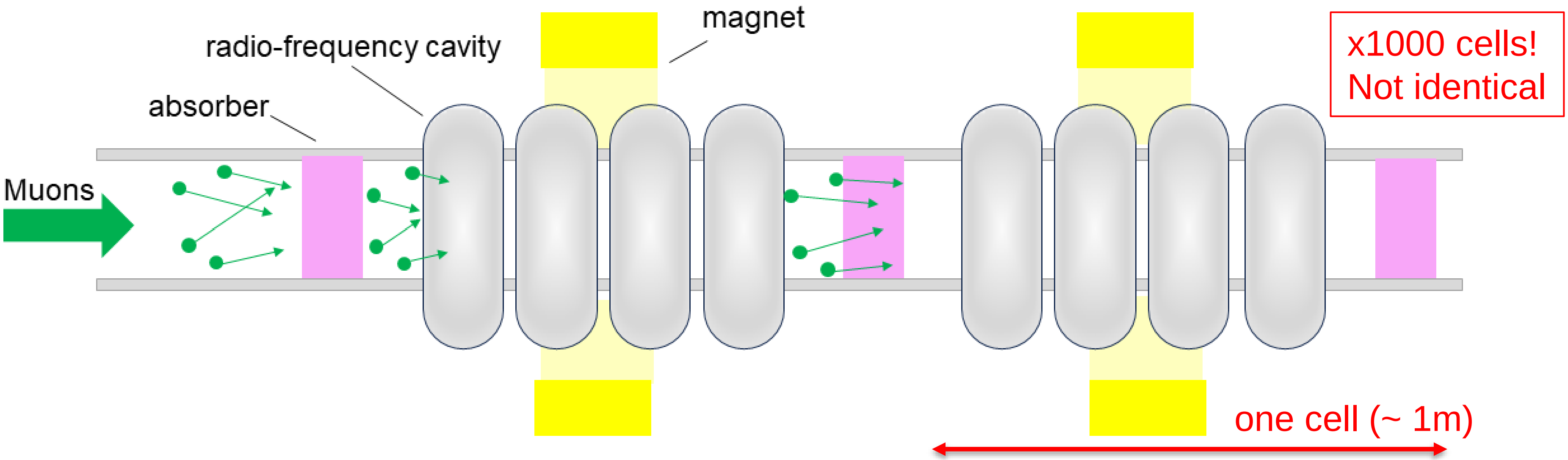
Demonstration Phase up to 2040

Selected Target Design

Prototype

R&D
should start now!

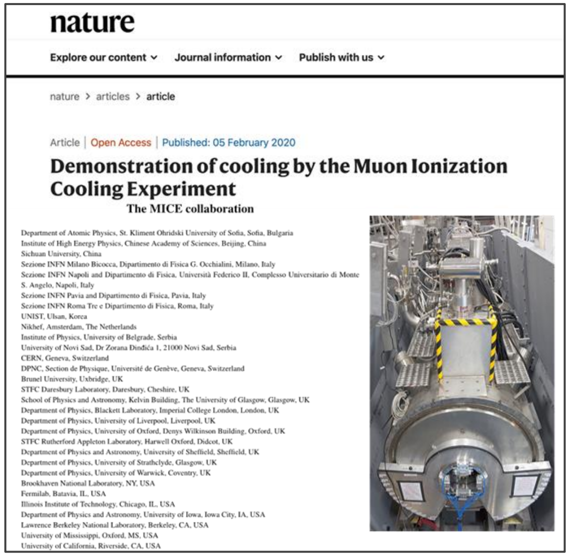
Ionization cooling



- Solenoids that start at 2 T and extend to 20+ T at the end
  - 32 T has been achieved in a SC solenoid with bore like that needed for cooling
- NC cavities (<1 GHz) that can sustain high-gradients in multi-T fields
  - This has been demonstrated with a 805 MHz @ 3 T; tests at higher fields need

Muon cooling proof-of-principle experiment

- 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**



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Demonstration of cooling by the Muon Ionization Cooling Experiment

The MICE collaboration

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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
UNIST, Ulsan, Korea
Nikhef, Amsterdam, The Netherlands
Institute of Physics, University of Belgrade, Serbia
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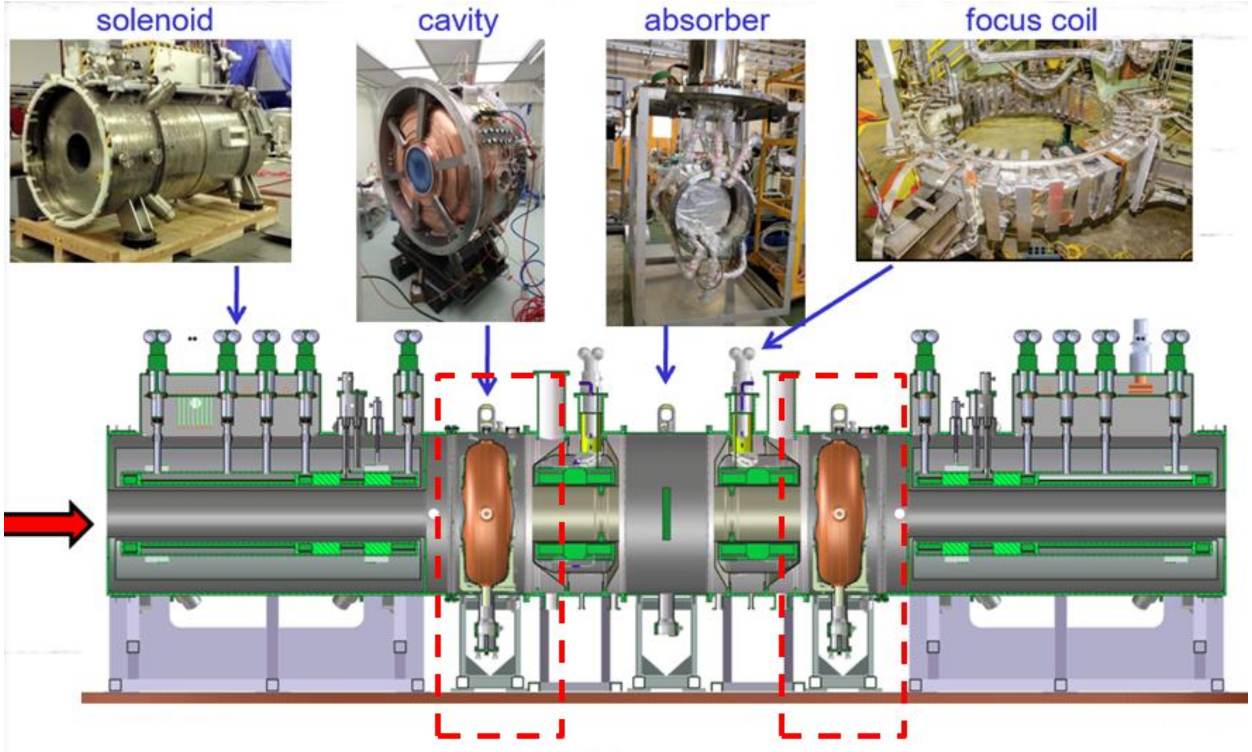
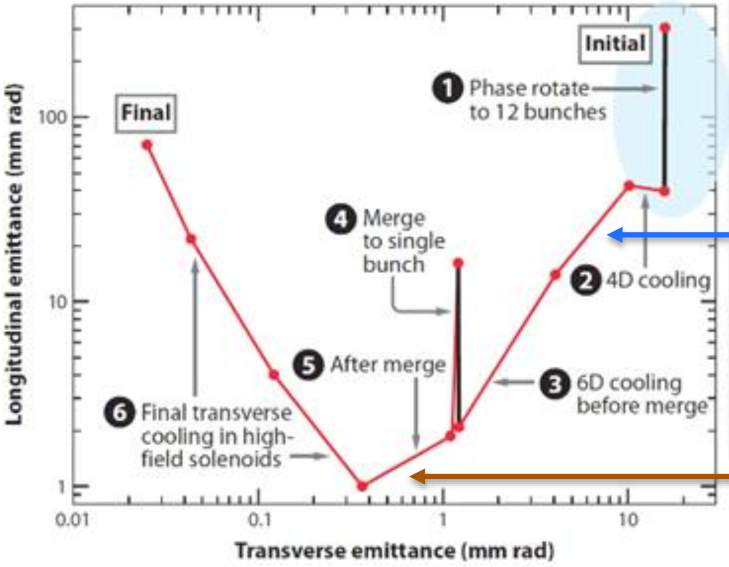
Brunel University, Uxbridge, UK
STFC Daresbury Laboratory, Daresbury, Cheshire, UK
School of Physics and Astronomy, Kelvin Building, The University of Glasgow, Glasgow, UK
Department of Physics, Blackett Laboratory, Imperial College London, London, UK
Department of Physics, University of Liverpool, Liverpool, UK
Department of Physics, University of Oxford, Denys Wilkinson Building, Oxford, UK
STFC Rutherford Appleton Laboratory, Harwell Oxford, Didcot, UK
Department of Physics and Astronomy, University of Sheffield, Sheffield, UK
Department of Physics, University of Strathclyde, Glasgow, UK
Department of Physics, University of Warwick, Coventry, UK
Brookhaven National Laboratory, NY, USA
Fermilab, Batavia, IL, USA
Illinois Institute of Technology, Chicago, IL, USA
Department of Physics and Astronomy, University of Iowa, Iowa City, IA, USA
Lawrence Berkeley National Laboratory, Berkeley, CA, USA
University of Mississippi, Oxford, MS, USA
University of California, Riverside, CA, USA



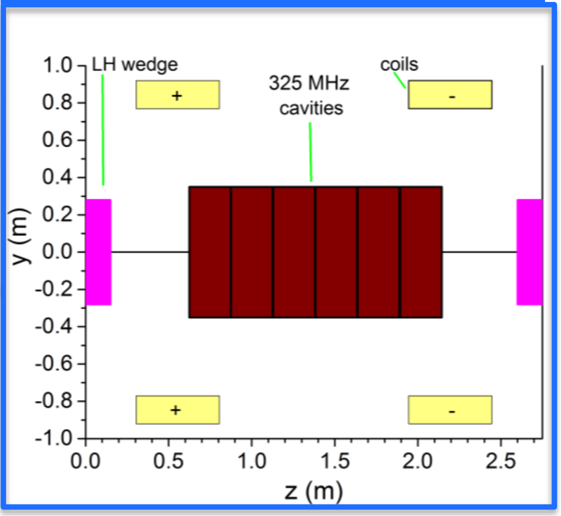
Ionization cooling design

- 6D emittance needs be cooled by 6-orders of magnitude
  - Concepts & designs **in place** to achieve this goal
- Further improvements are needed so that:
  - (1) take into account engineering aspects (2) improve performance with latest technology advances

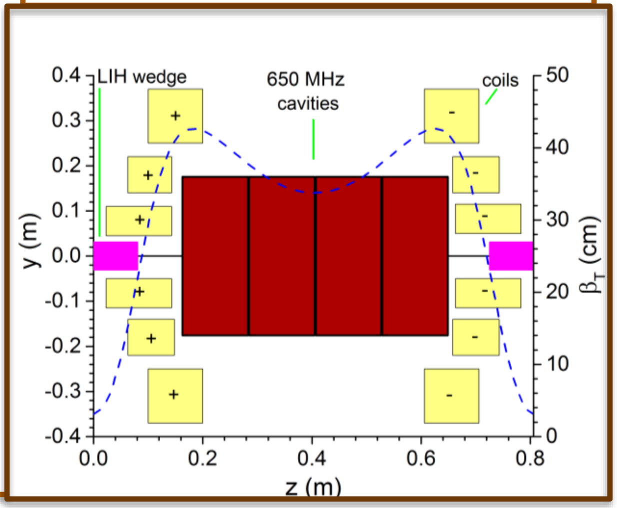
MuC cooling requirement



Early cell (“easy”) – 2T peak



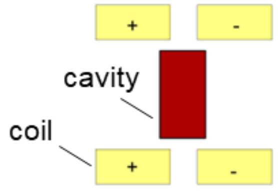
Late cell (“hard”) – 14 T peak



Muon cooling demonstrator roadmap

- Next step is to study **integration** by building ionization cooling cells that resemble a realistic channel
  - Parameters are aspirational and may change based on available resources

Phase-I

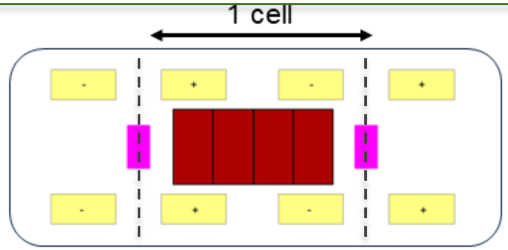


RF studies in B-fields

Material studies & cryogenic Cu

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

Phase-II

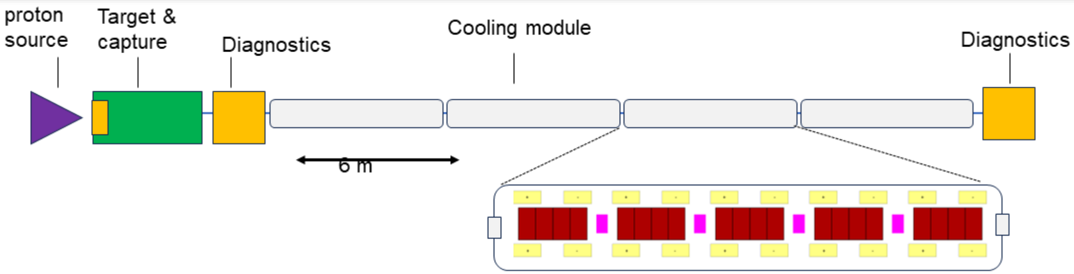


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III

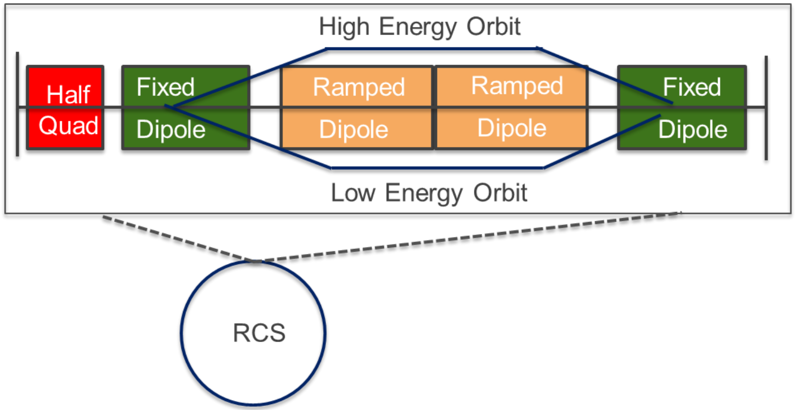


Full demonstrator with beam

Coils producing 7-10 T axial fields

Potential to achieve 50% 6D cooling

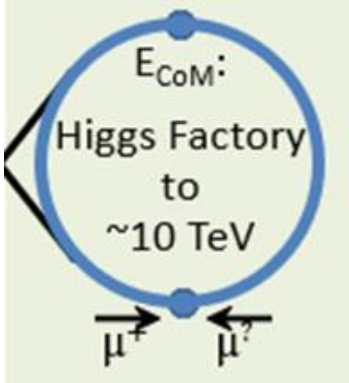
Muon Collider: TeV Acceleration

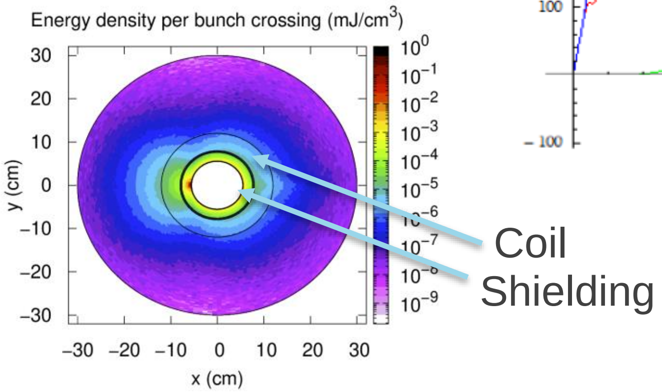


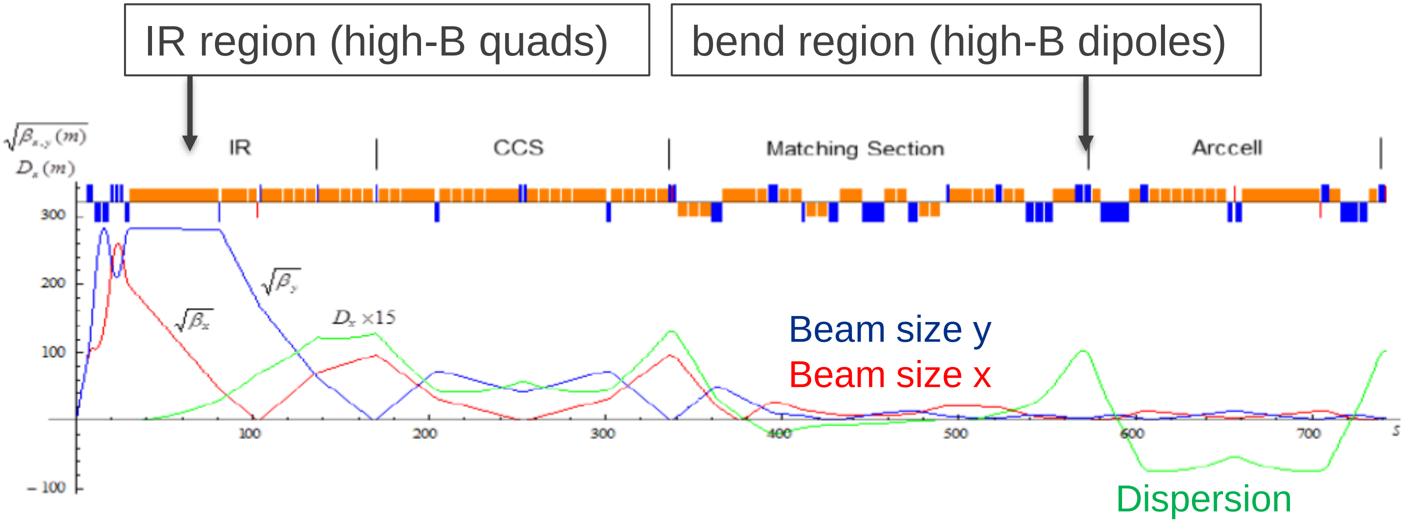
Injection Energy, GeV	173	450	1725	3560
Extraction Energy, GeV	**450**	**1725**	**3560**	**5000**
Circumference (m)	6280	10500	16500	16500
Ramped Dipole Length (m)	5233	7448	10670	8383
Fixed Dipole Length (m)		1897	3689	5972
Turns	46	106	160	180
Max ramped dipole field (T)	1.8	1.8	1.8	1.8
Max fixed dipole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

- TeV acceleration with Rapid Cycling Synchrotrons (RCS)
  - Conceptual designs in place for up to 5+5 TeV
  - Designs include a combination of fixed field SC magnets (12-15 T) with fast ramping magnets (up to 1000 T/s)
  - First HTS prototype achieved 300 T/s and plans underway to reach 1000 T/s
  - Developing an efficient power management for these pulsed magnets is a key aspect and more R&D is needed

Muon Collider: Collider ring

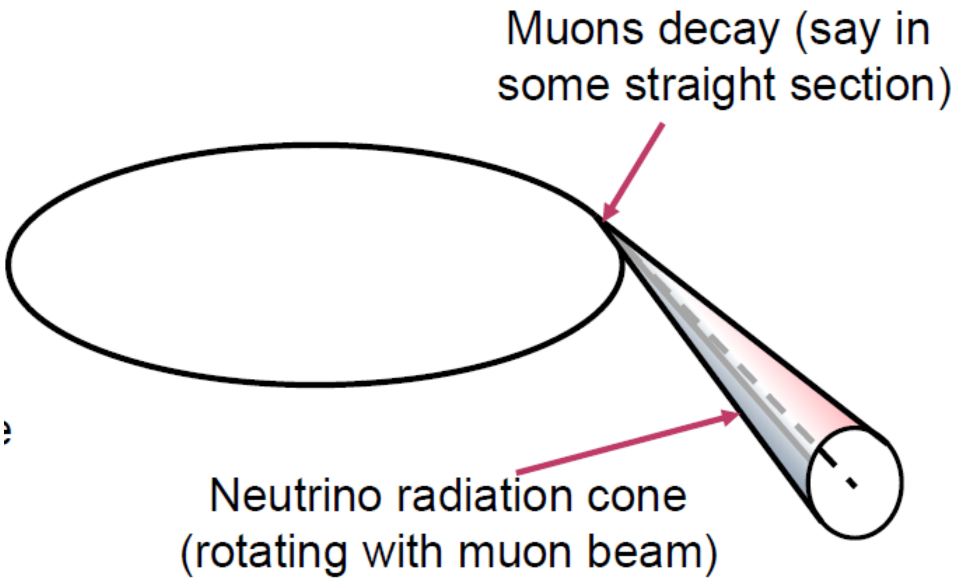


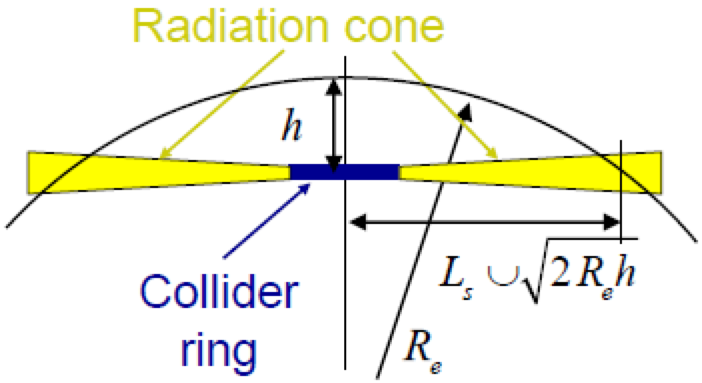




- Designs in place for 3 TeV MuC with specs within the HL-LHC range
- 10 TeV more challenging since it requires a smaller β (5→ 1.5 mm)
  - Requires significant developments in HTS magnet space (IR Quads @ 15-20 T and 12-16 T dipoles with large aperture (~150 mm) for shielding

Neutrino radiation

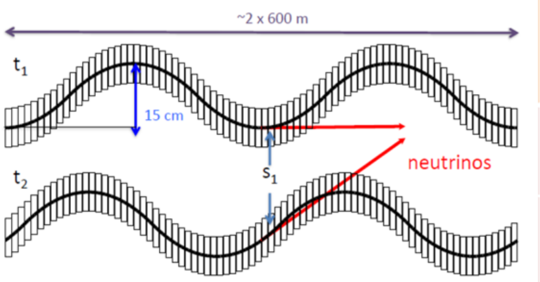




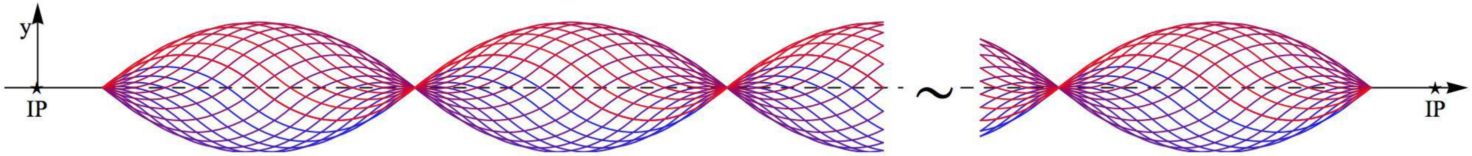
- Radiation due to neutrino beam reaching the earth
  - Narrow radiation cone for a short piece of the machine
  - Strong increase of maximum dose with muon energy
  - Matter in front does not help but makes the situation worse

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;



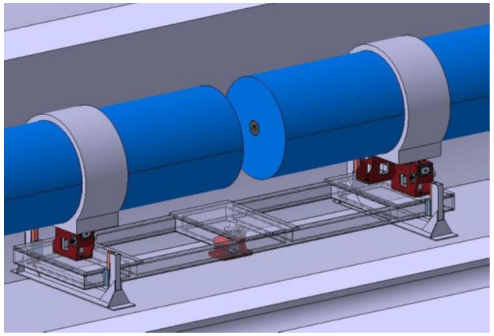
Legal limit: 1 mSv/year
MAP goal: <0.1 mSv/year
IMCC goal: <10 µSv/year
LHC : <5 µSv/year

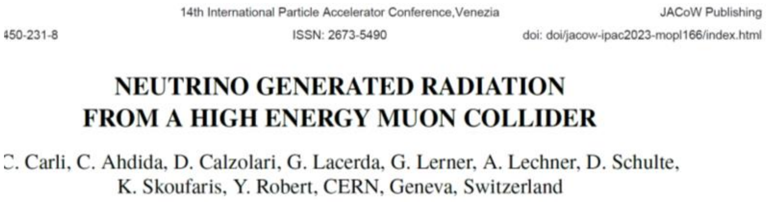


Vertical slope modulation ~ 1 mrad

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

Working on different approaches for experimental insertion





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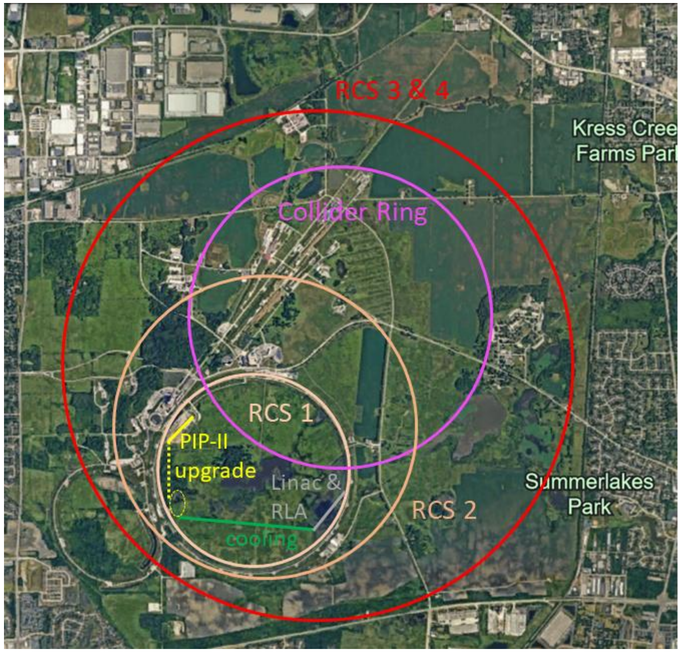
NEUTRINO GENERATED RADIATION
FROM A HIGH ENERGY MUON COLLIDER

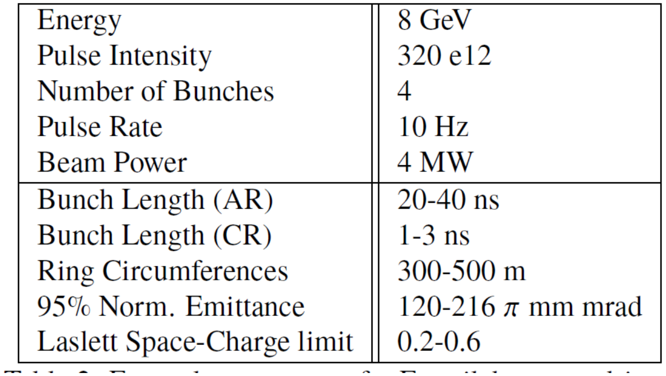
C. Carli, C. Ahdida, D. Calzolari, G. Lacerda, G. Lerner, A. Lechner, D. Schulte,
K. Skoufaris, Y. Robert, CERN, Geneva, Switzerland

Requires significant R&D and proof-of principle tests

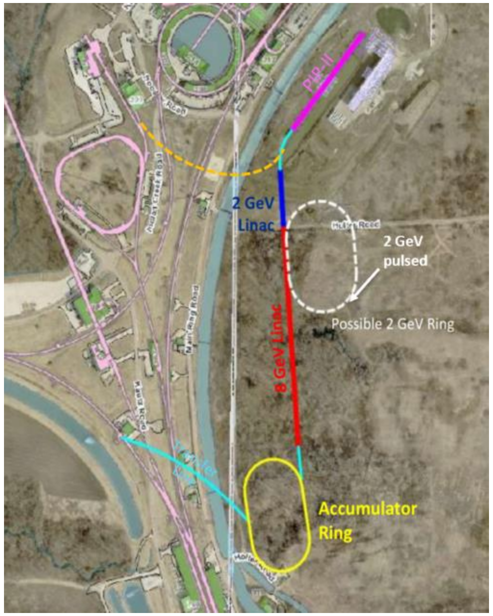
Muon Collider in the US

- Fermilab Accelerator Complex Evolution plan opens a path towards supporting new muon facilities
- A design for a 10 TeV MuC in the Fermilab site has been developed
  - Assumes a booster replacement and extension of the PIP-II linac to 8 GeV
  - Acceleration rings fit in the Fermilab site and one can fit in the Tevatron ring



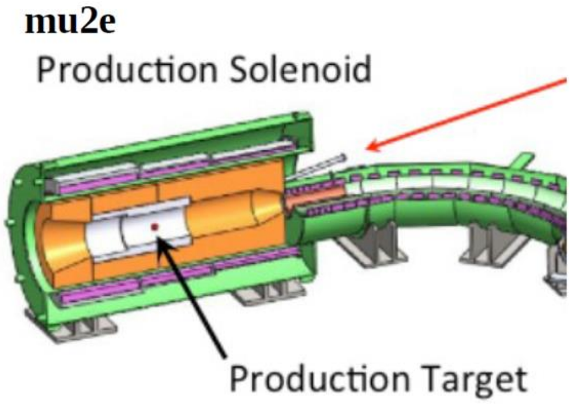


Energy	8 GeV
Pulse Intensity	320 e12
Number of Bunches	4
Pulse Rate	10 Hz
Beam Power	4 MW
Bunch Length (AR)	20-40 ns
Bunch Length (CR)	1-3 ns
Ring Circumferences	300-500 m
95% Norm. Emittance	120-216 π mm mrad
Laslett Space-Charge limit	0.2-0.6

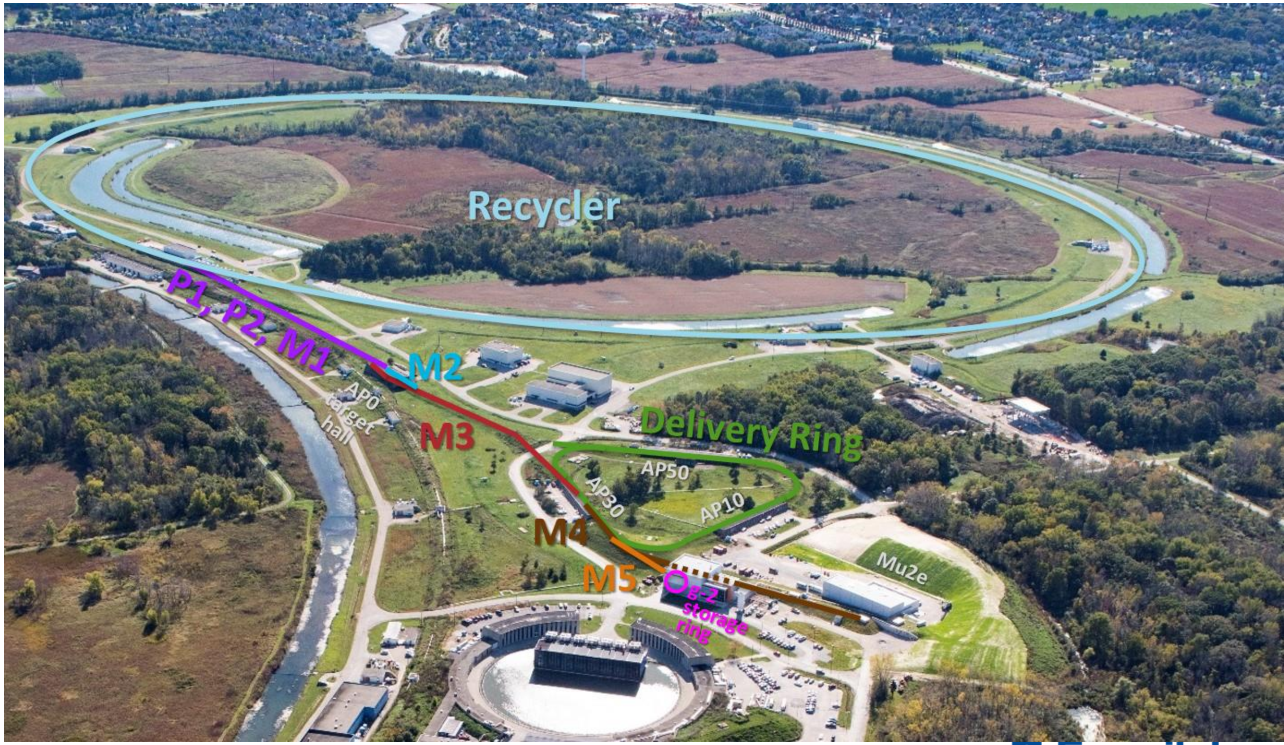


Demonstrator possibilities in the US

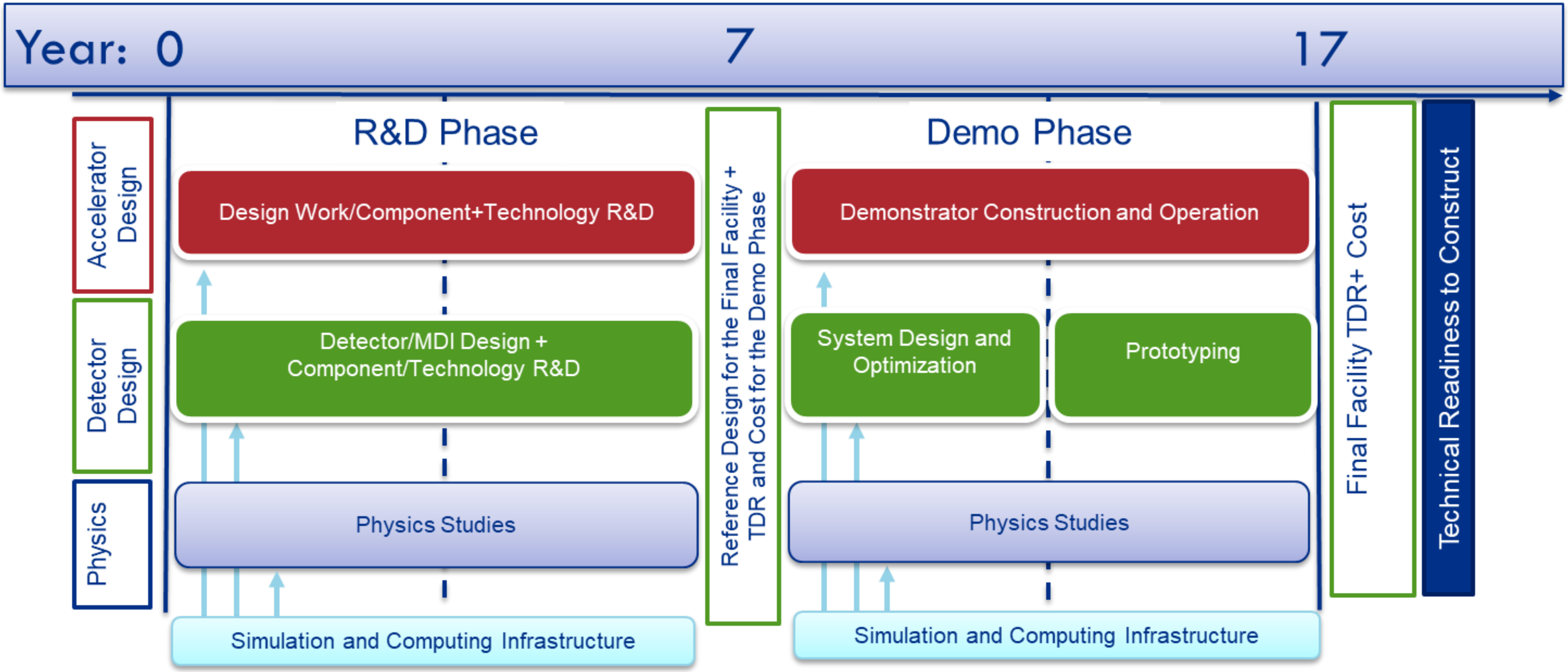
- Designed to provide beam for the Muon g-2 and Mu2e experiments
  - Capable to deliver **8 kW** beam at **8 GeV** to the Mu2e production target
  - Available tunnel space to run the demonstrator without interfering with Mu2e
  - Production target is similar to the MuC target



Excellent opportunity to examine targets under 5 T field



US Muon Collider timeline



- By 2030, achieve enough technical maturity for the construction of the muon cooling demo facility in 2030s and potential construction of the collider facility in the 2040s.

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

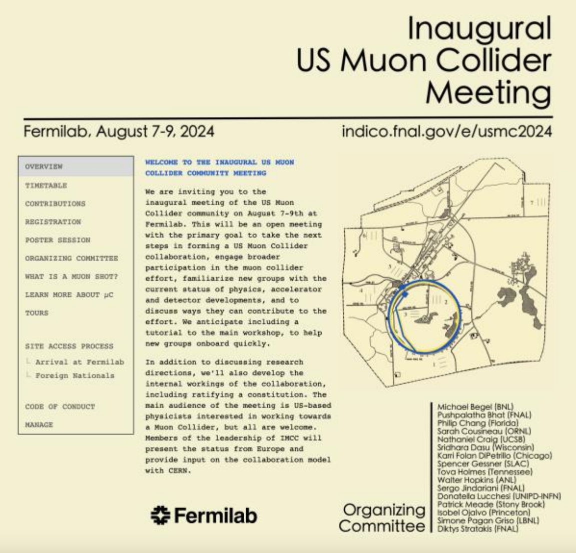
Demonstrator

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

Muon Collider Meetings at Fermilab

- US Muon Collider Community Meeting August 7-9th, 2024 at Fermilab: https://indico.fnal.gov/e/usmc2024

~300 registrants!



Inaugural
US Muon Collider
Meeting

Fermilab, August 7-9, 2024
indico.fnal.gov/e/usmc2024

WELCOME TO THE INAUGURAL US MUON COLLIDER COMMUNITY MEETING

We are inviting you to the inaugural meeting of the US Muon Collider community on August 7-9th at Fermilab. This will be an open meeting with the primary goal to take the next steps in forming a US Muon Collider collaboration, engage broader participation in the muon collider effort, familiarize new groups with the current status of physics, accelerator and detector developments, and to discuss ways they can contribute to the effort. We anticipate including a tutorial to the main workshop, to help new groups onboard quickly.

In addition to discussing research directions, we'll also develop the internal workings of the collaboration, including ratifying a constitution. The main audience of the meeting is US-based physicists interested in working towards a Muon Collider, but all are welcome. Members of the leadership of IMCC will present the status from Europe and provide input on the collaboration model with CERN.

Fermilab

Organizing Committee

Michael Begel (BNL)
Pushpalatha Bhat (FNAL)
Philip Chang (Florida)
Sarah Cousineau (ORNL)
Nathaniel Craig (UCSB)
Sridhara Dasu (Wisconsin)
Karri Folan DiPetrillo (Chicago)
Spencer Gessner (SLAC)
Tova Holmes (Tennessee)
Walter Hopkins (ANL)
Sergo Jindariani (FNAL)
Donatella Lucchesi (UNIPD-INFN)
Patrick Meade (Stony Brook)
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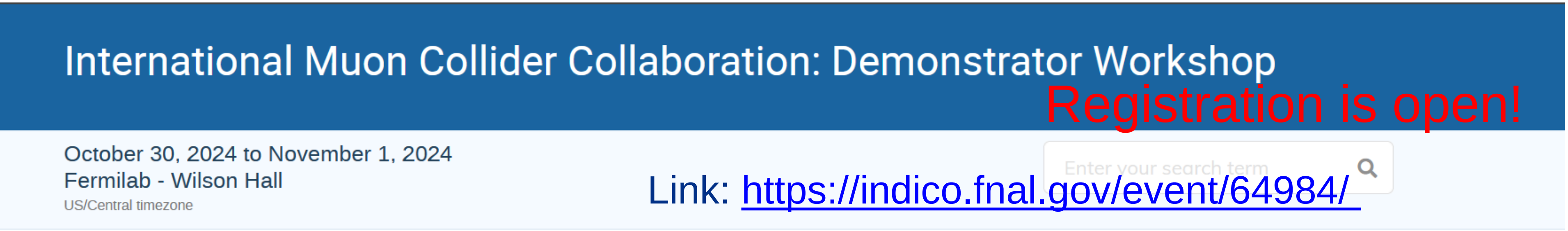
Simone Pagan Griso (LBNL)
Diktys Stratakis (FNAL)



International Muon Collider Collaboration: Demonstrator Workshop

October 30, 2024 to November 1, 2024
Fermilab - Wilson Hall
US/Central timezone

Registration is open!

Link: https://indico.fnal.gov/event/64984/

Next steps

- Muon Collider community plans to self-organize towards the formation of a US Muon Collider organization
- The goals will be
  - Facilitate collaborative work, communication and coordination across involved US institutions
  - Preparation and planning for deliverables for the Collider Panels (~ 5 years) and the next P5 (~10 years)
  - Conduct work related to studies of domestic sittings
  - Build next generation experts
- Assume all members are part of the IMCC too
- Help with preparation for the next European Strategy Update

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
- Stay in touch
  - Join our mailing list here

Extra