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U.S. DEPARTMENT OF ENERGY | Office of Science

The US effort towards making a Muon Collider

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Muons4Future 2025

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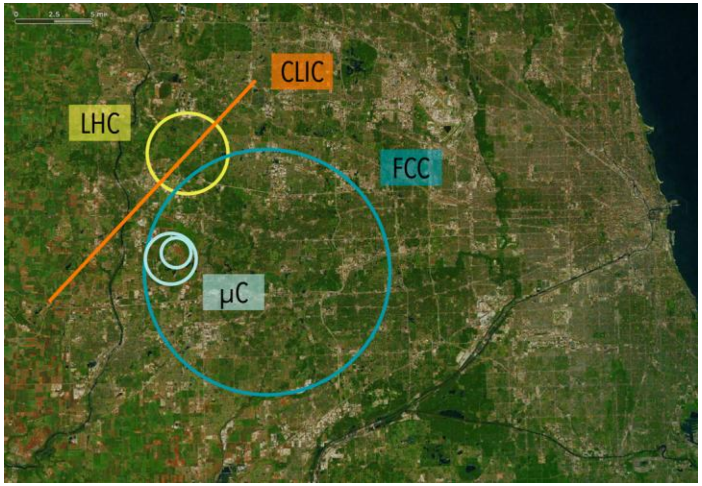
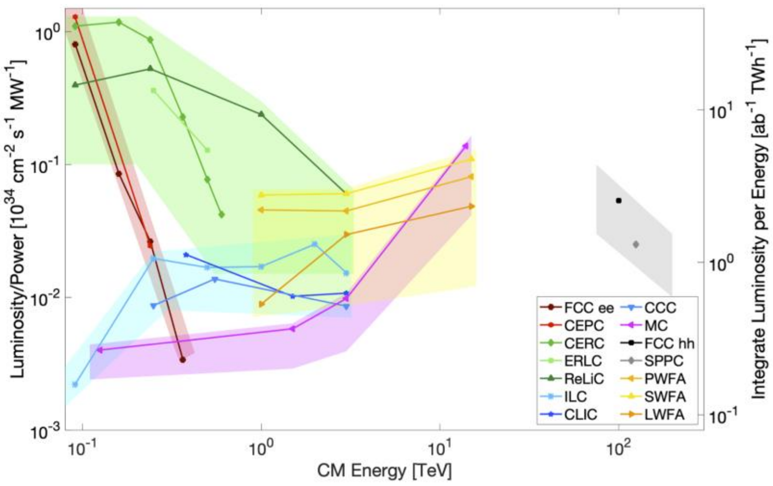
Outline

- Motivation
- History of Muon Colliders
- Accelerator design
- Technology requirements
- US effort and future possibilities
- Summary

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





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History

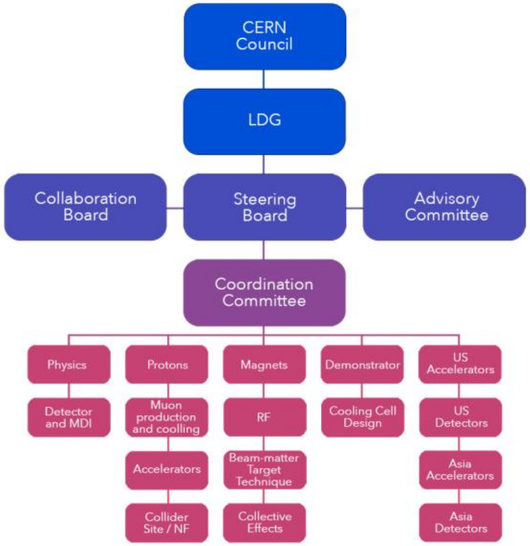
- 2011-2016: **Muon Accelerator Program** has developed key concepts, designs and technologies for a MuC up to 6 TeV.
- In 2021, the International Muon Collaboration (IMCC) was formed
  - IMCC goal is to develop a baseline design of a 10 TeV MuC and build the associated R&D program for such machine. Hosted in CERN for now.
- 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”

Global effort

- International Muon Collider R&D activities are coordinated by the IMCC
  - Very active collaboration since 2021, over 50 institutions have signed formal agreements
- Progress on many fronts of the accelerator & detector design
- US scientists actively engaged with IMCC
  - Informal engagement during Snowmass
  - US representatives in IMCC leadership
  - 7 Universities signed MoU, more to come
  - DOE – CERN collaborative agreement in progress, that will enable labs to official join

International MUON Collider Collaboration

MuCol



US MuC community planning after P5

- February 2024: Self-invitation only workshop at Princeton
  - Discussed and documented R&D status, needs & priorities.
  - Formulated a plan towards a US MuC Collaboration (US MCC)
- August 2024: First US MuC community meeting at Fermilab
  - Informed, engaged and educated the US community on MuC R&D
  - 300+ participants
- October 2024: IMCC Demonstrator workshop at Fermilab
  - Discussed a plan towards a MuC Demonstrator either at Fermilab or CERN
  - 100+ participants

Muon Collider parameters

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

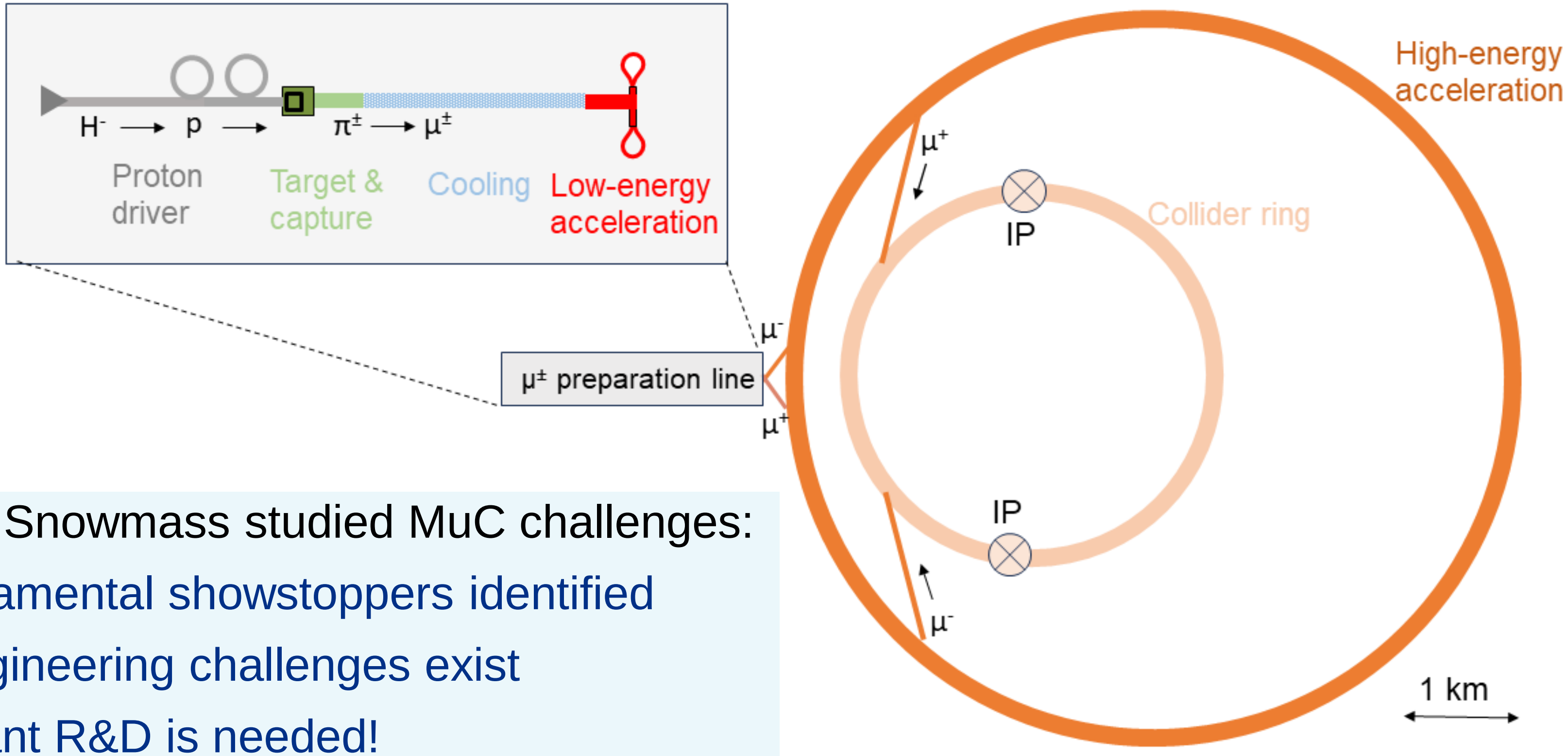
Feasiblity addressed, will evaluate luminosity performance, cost and power consumption

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

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**



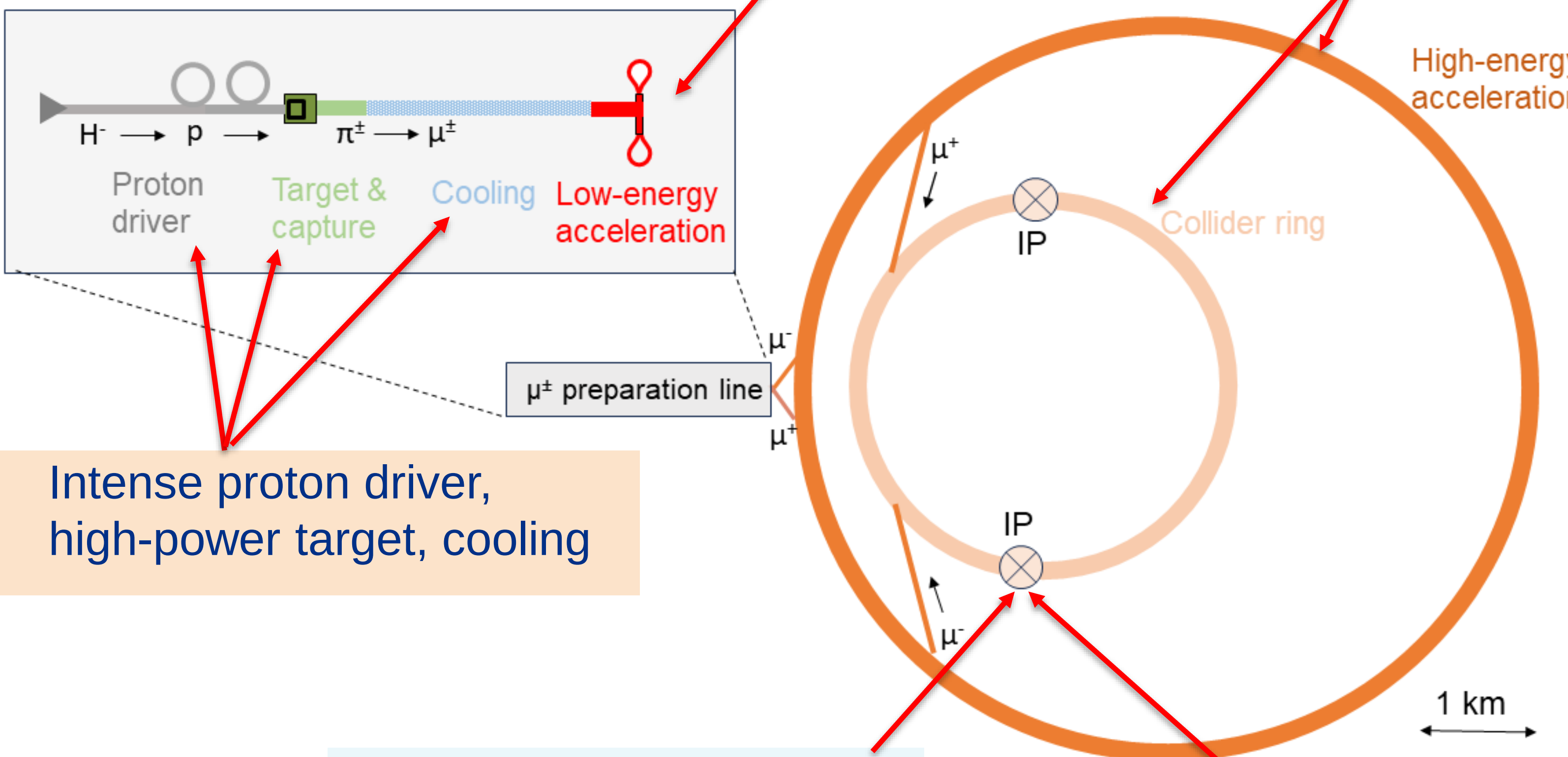
IMCC & US Snowmass studied MuC challenges:

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

Major Challenges

High-gradient SRF cavities for acceleration

Challenging magnets in many places

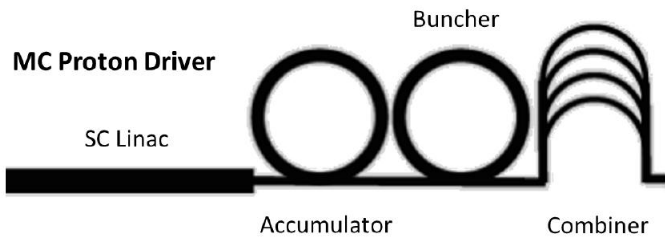


Intense proton driver, high-power target, cooling

Dense neutrino flux needs to be mitigated

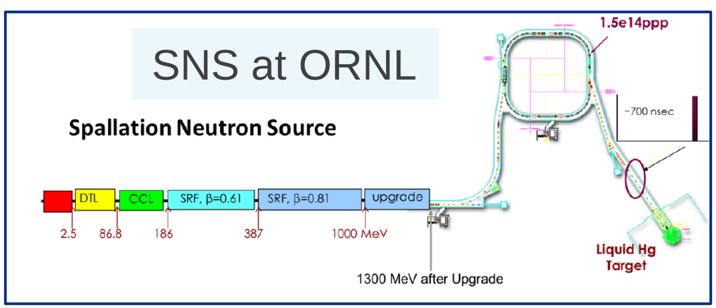
Beam induced background in the detectors

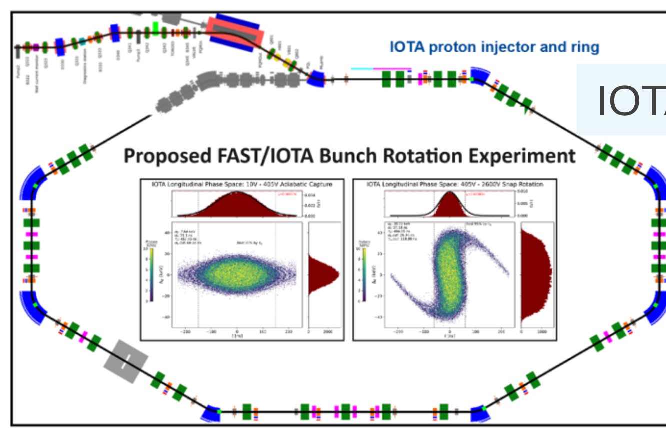
Muon Collider: Proton driver



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

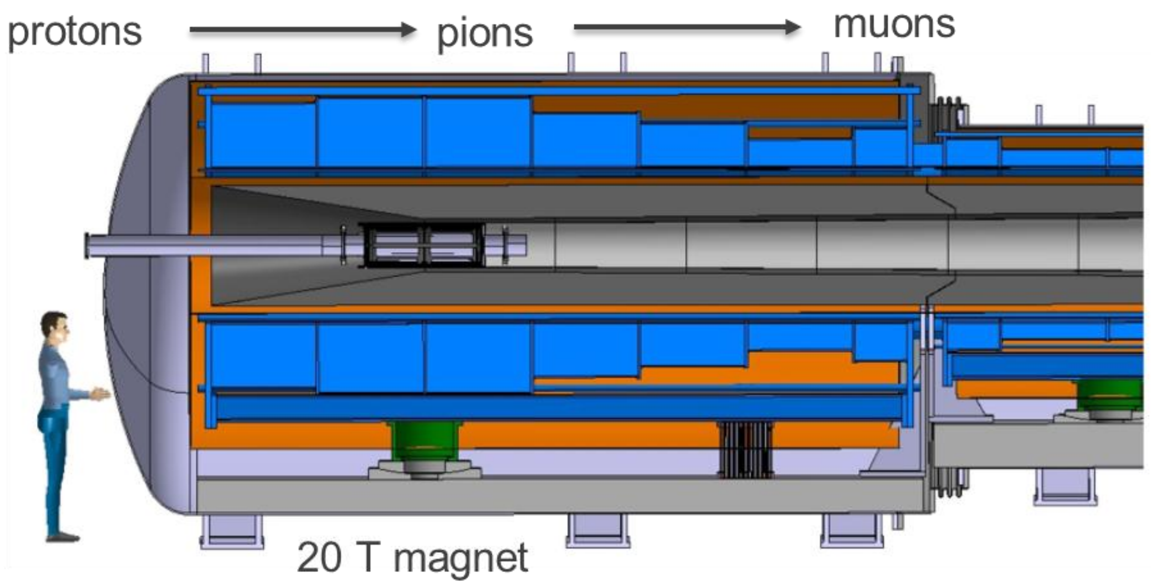
- Multi-MW proton sources exist globally (ex. PIP-II, SNS, ESS)
  - R&D is needed to adapt and extend such facilities to MuC requirements
- Involves beam manipulations that require experimental demonstrations
  - These can be studied at existing facilities that are analogs to a MuC proton driver





IOTA at FNAL

Target



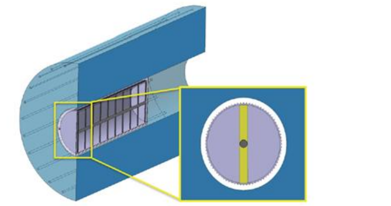
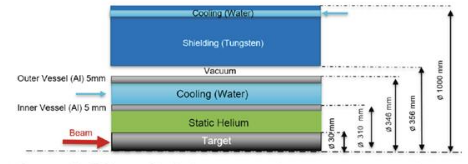


Figure 1: Current Muon Collider target 3D concept.

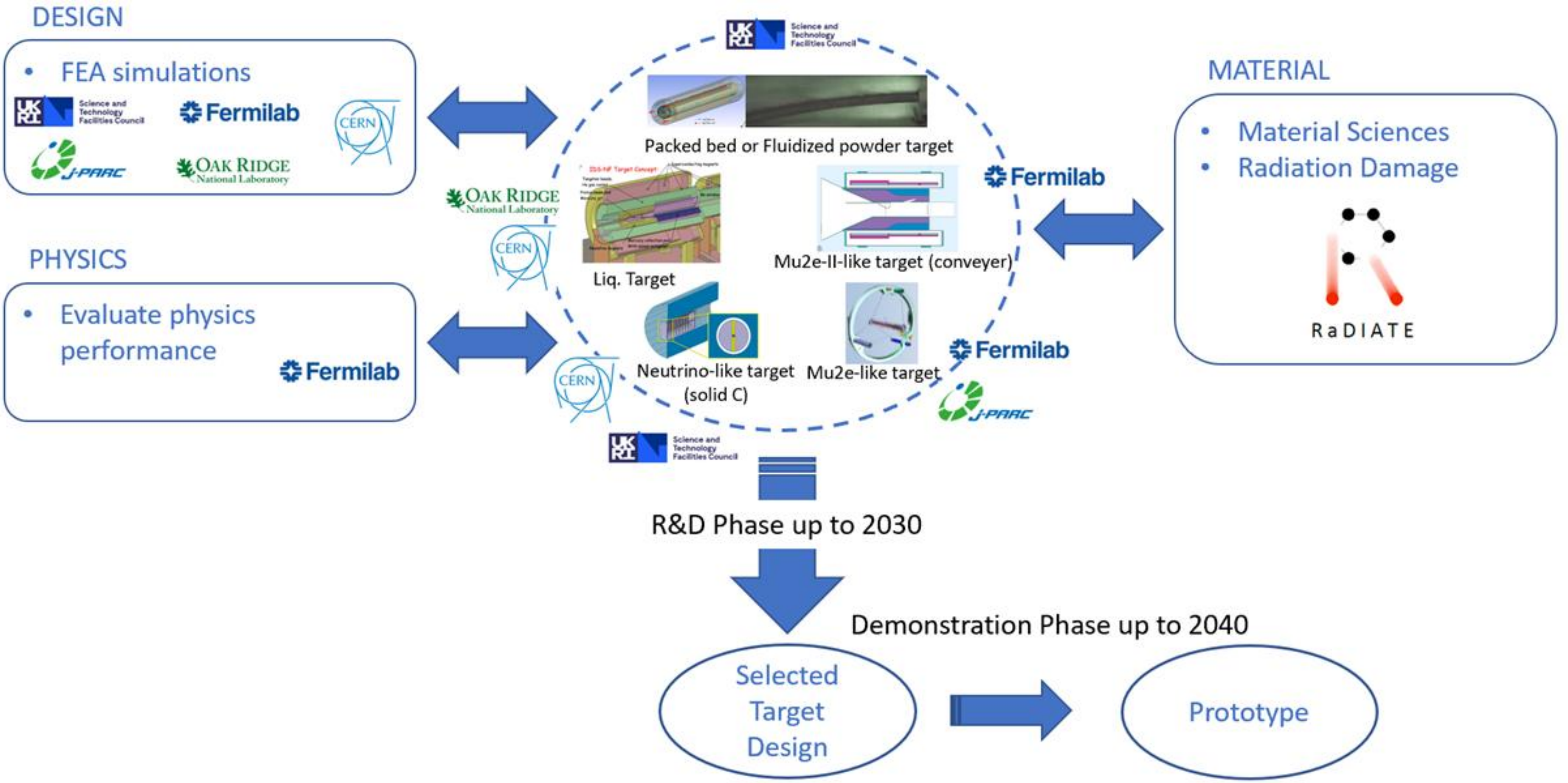
Figure 2 schematically details the bodies, dimensions and materials of the current proposal.



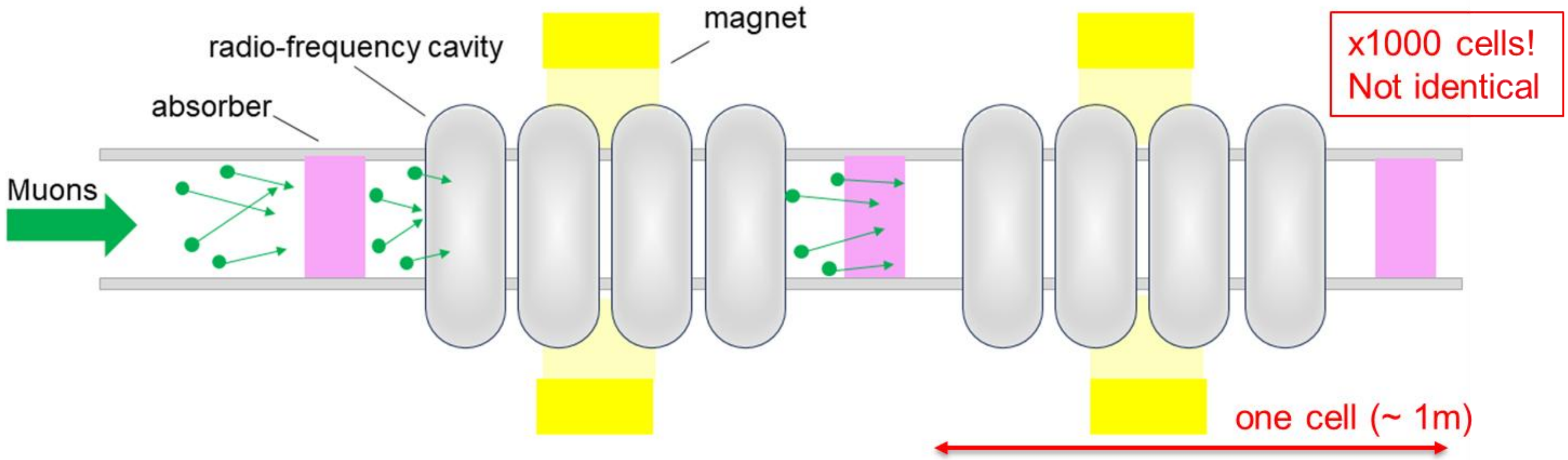
- Energy deposition on target beyond any present operational facility
  - Trigger mechanical and radiation damage which can degrade quality of target
- Target is enclosed in a multi-T solenoid
  - Can induce radiation damage and heat load to the coil
- R&D shows promising results with graphite or fluidized tungsten
  - Opens a path for synergies with other experiments

Muon Collider target roadmap

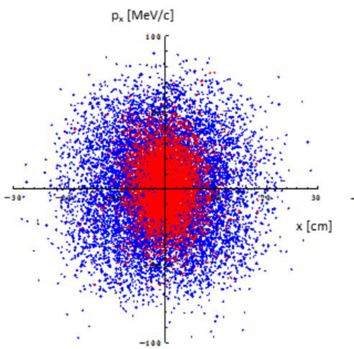
- A High-Power Targetry roadmap, was formulated to guide DOE-OHEP office for planning and prioritizing future R&D activities (ref)



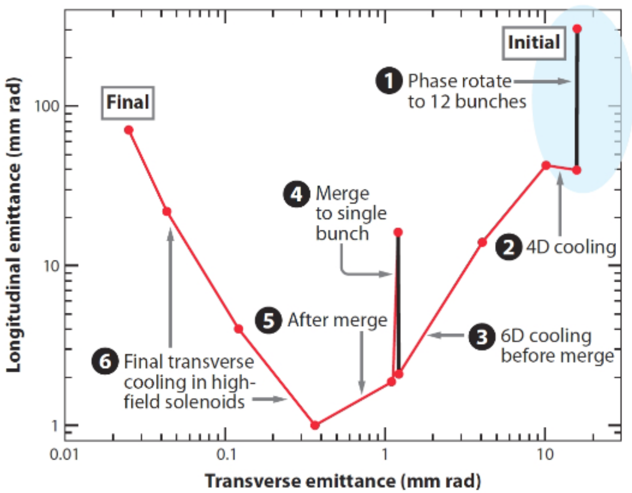
Ionization cooling

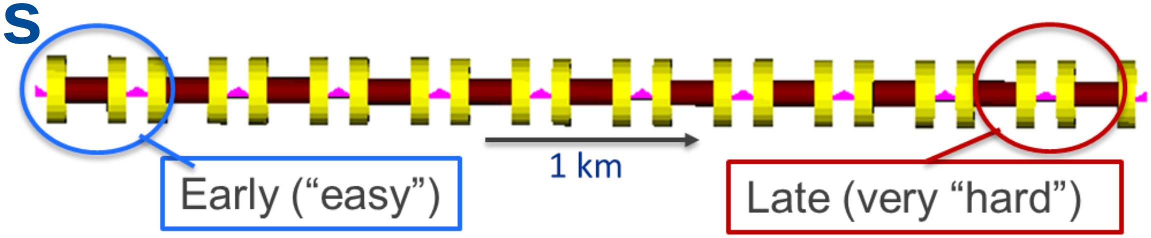


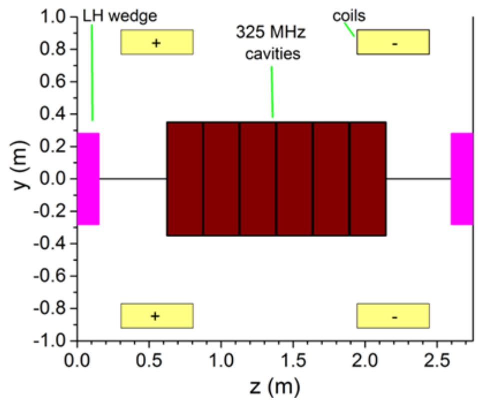
- Ionization cooling channel contains
  - Solenoids that start at 2 T and extend to 20+ T at the end
  - NC cavities (<1 GHz) that have to operate within multi-T field
  - Absorbers that can tolerate the large intensity

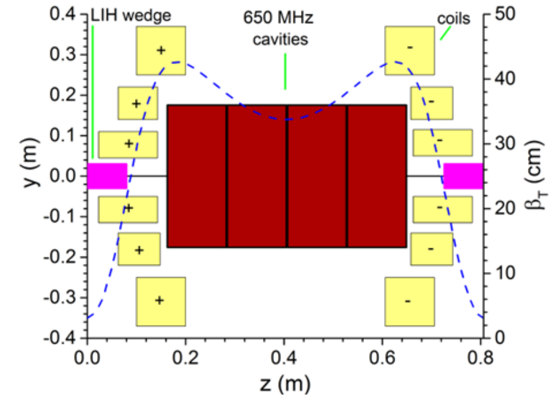


Cooling R&D needs



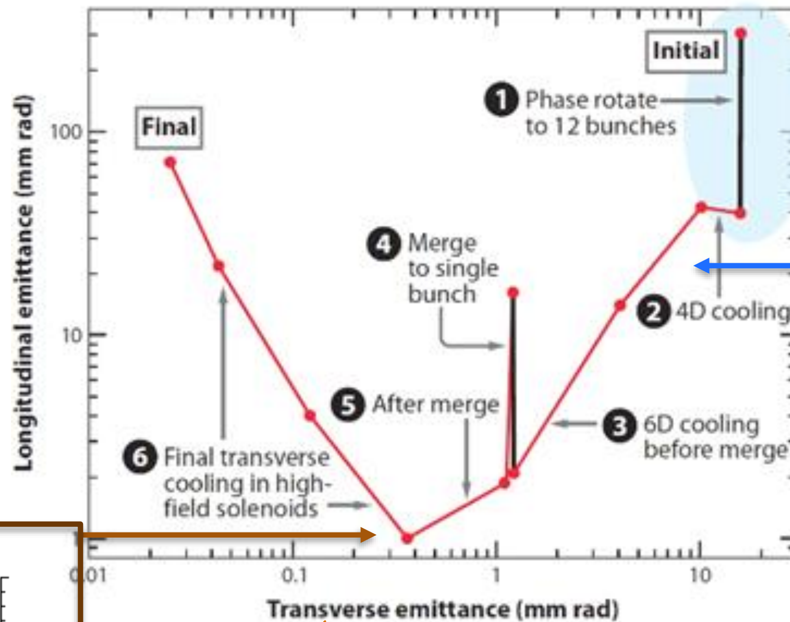


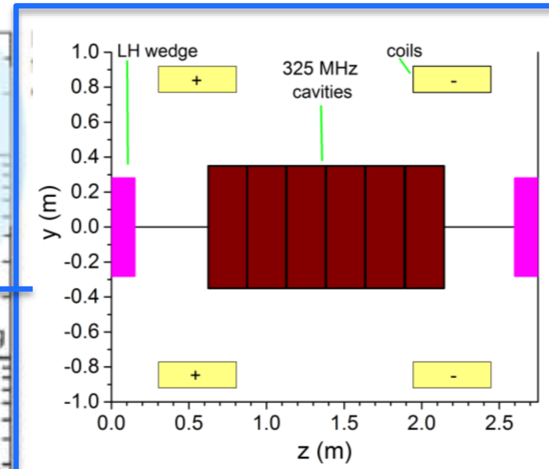




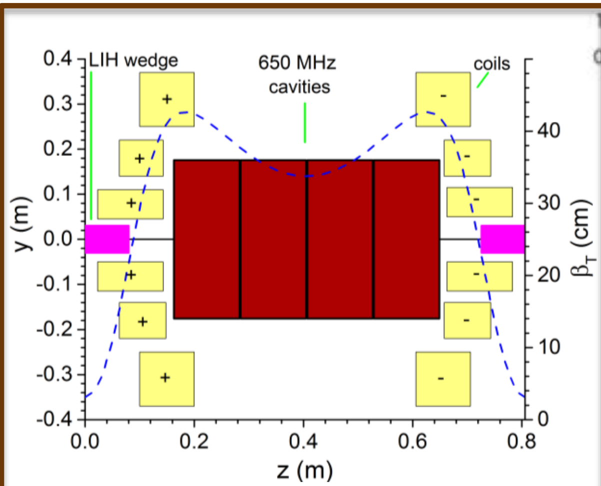
- 6D emittance needs be cooled by 6-orders of magnitude
  - Concepts & designs **in place**
- Further improvements are needed so that:
  - Deliver an end-to-end design and take into account engineering aspects and latest technology improvements
  - Improve performance with latest technology advances & AI/ML methods

Integration challenges





Early cell ("easy") – 2T peak



Late cell ("hard") – 14 T peak

Several multi-T solenoidal coils
Very tight space between rf and coils
Very tight space between coils
rf cavities exposed to multi-T fields

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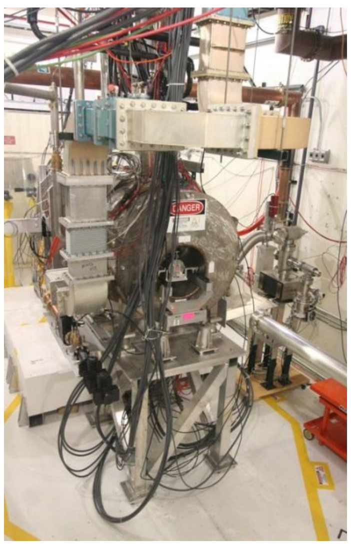
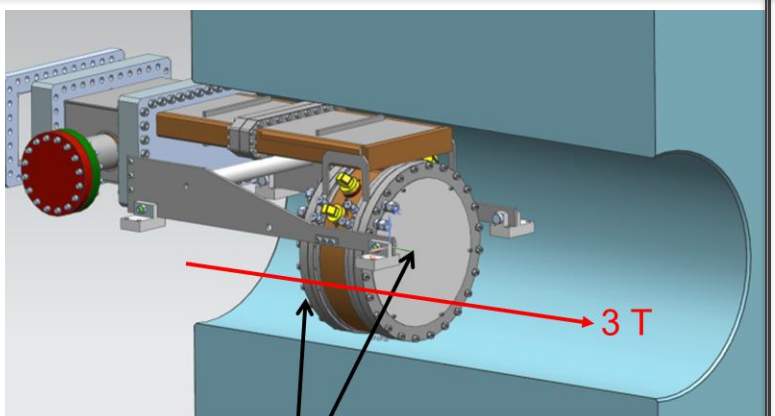
NC cavities in magnetic fields

- Evidence that B-field makes operation of cooling rf cavities difficult
- RF breakdown depend on the **thermo-mechanical properties** of the build material
  - We need an R&D program to test rf materials and rf technologies
  - We need facilities to test rf cavities in multi-T fields

Vacuum cavities

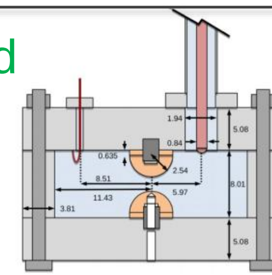


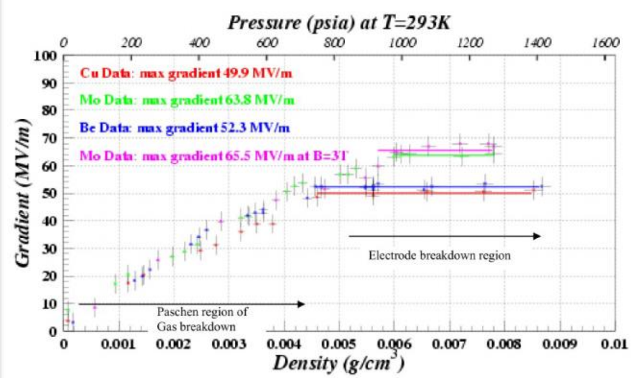


removable plates (Cu, Al, Be)

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

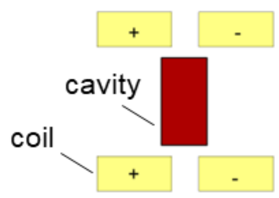




Cooling Demonstrator roadmap

- A sequence of cooling cells will give us the input, knowledge, and experience to design a real, operational cooling channel for a MuC

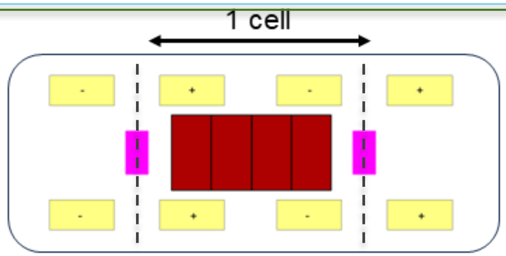
Phase-I



Verify RF performance in B-fields

Test materials and RF concepts

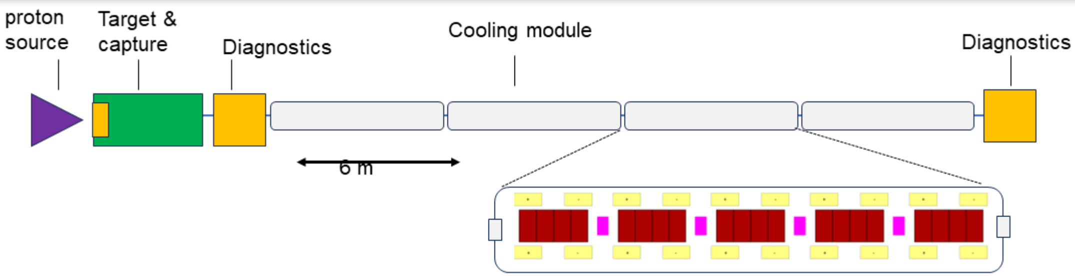
Phase-II



Address integration issues

Test engineering

Phase-III



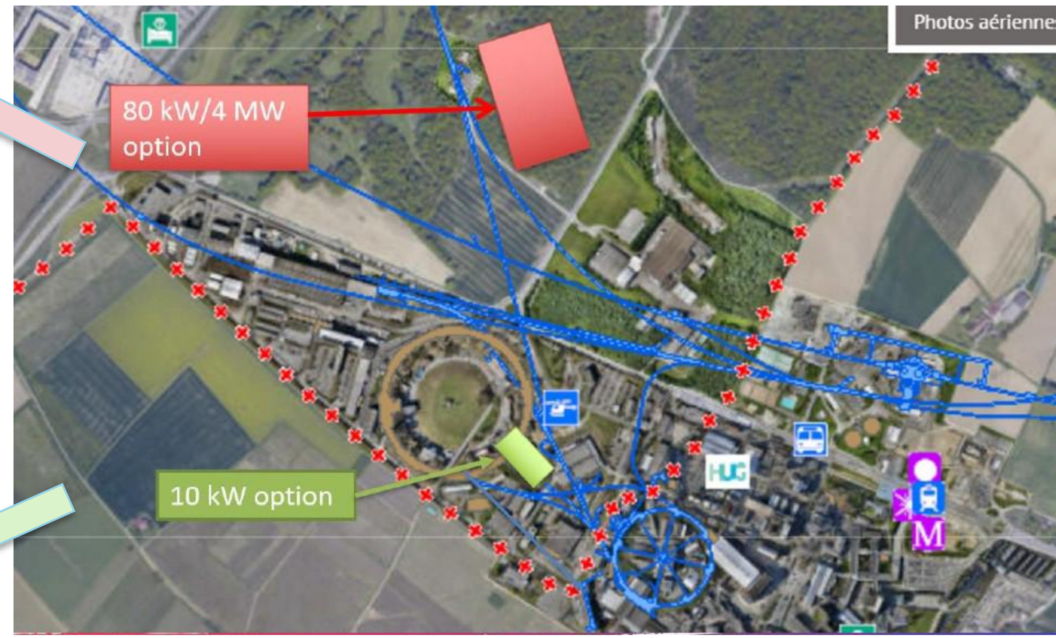
Full demonstrator with beam

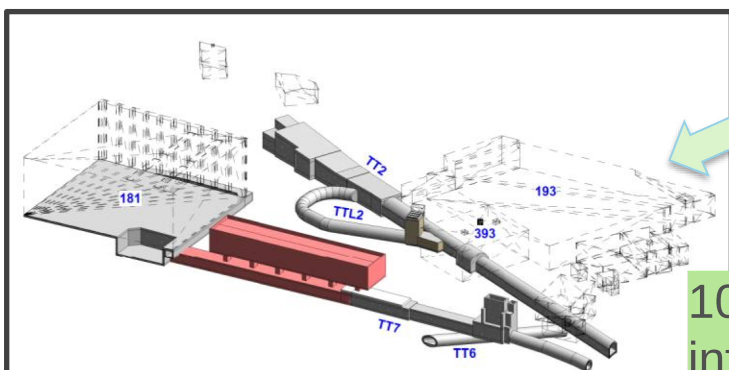
Test operation and instrumentation

Candidate locations at CERN

- Low and high-power options under consideration at CERN

80 kW beam power but requires a new tunnel for the beam line

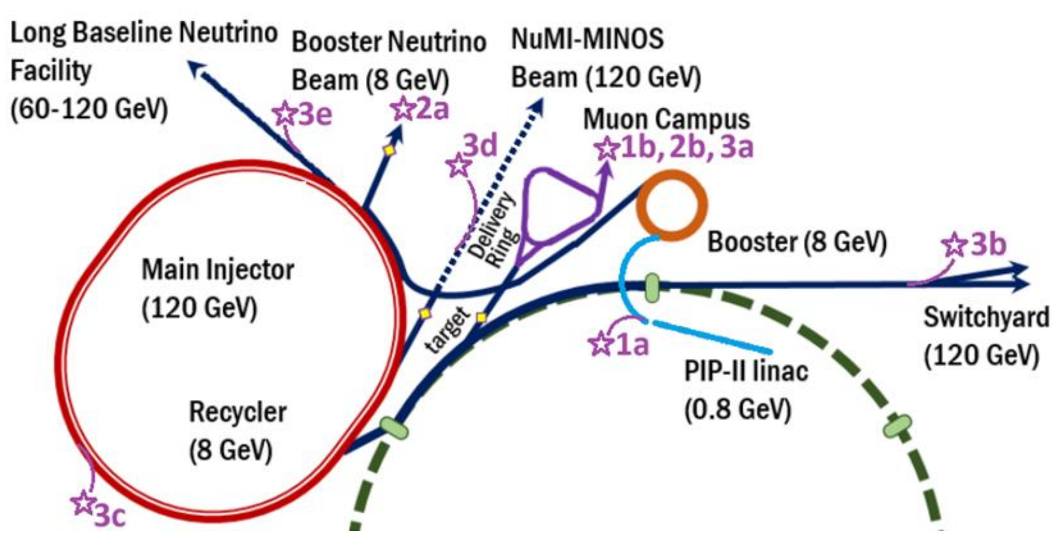




10 kW beam power using existing infrastructure

Candidate locations at Fermilab

- Fermilab with access to high-power proton beams and technological expertise, has great potential to host a Cooling Demonstrator
  - It requires dedicated studies for designing this facility and exploring its implementation within the Fermilab accelerator complex.
  - An effort to explore candidate sites within Fermilab is expected begin soon.

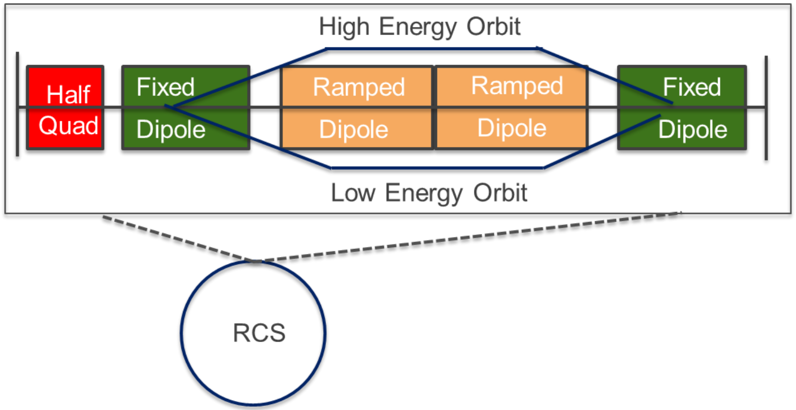


1 options with **0.8- 2GeV**

2 options with **8 GeV**

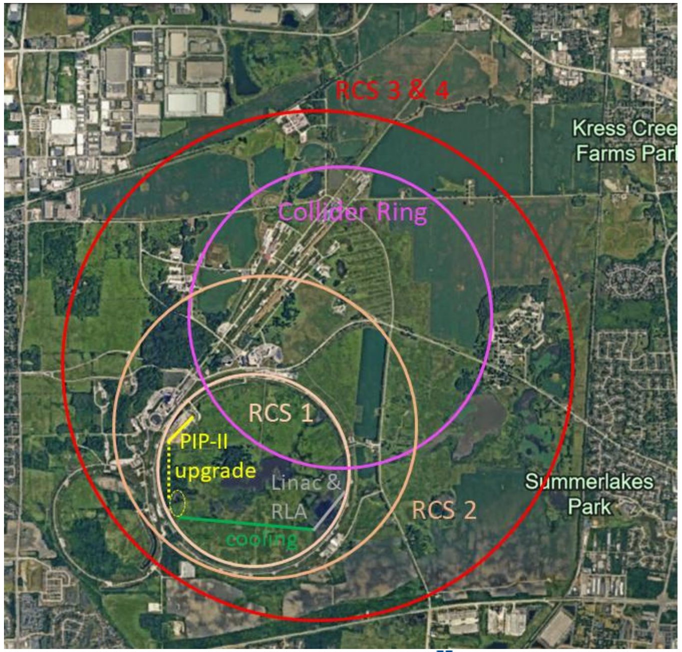
3 options with **120 GeV**

TeV Acceleration

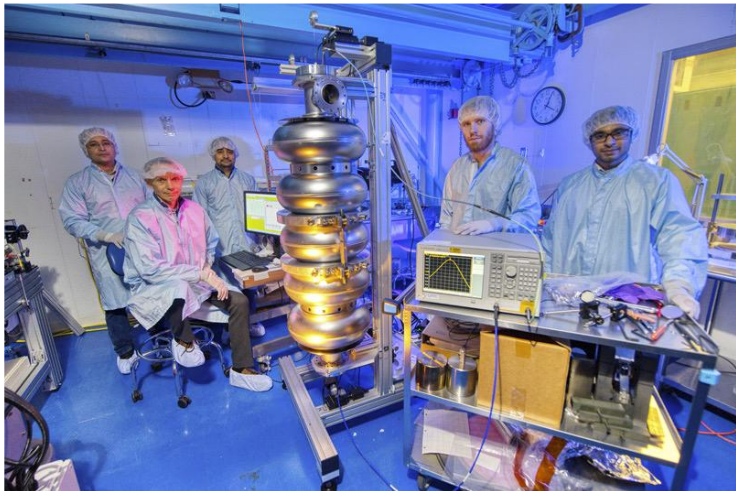


Injection Energy, GeV	173	450	1725	3560
Extraction Energy, GeV	**450**	**1725**	**3560**	**5000**
Circumference (m)	6280	10500	16500	16500
Ramped Dipole Length (m)	5233	7448	10670	8383
Fixed Dipole Length (m)		1897	3689	5972
Turns	46	106	160	180
Max ramped dipole field (T)	1.8	1.8	1.8	1.8
Max fixed dipole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

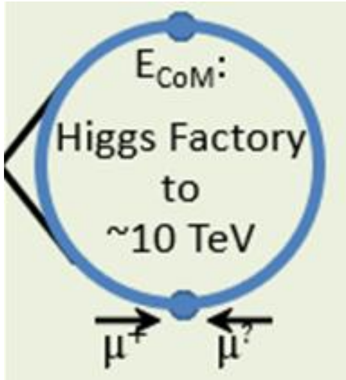


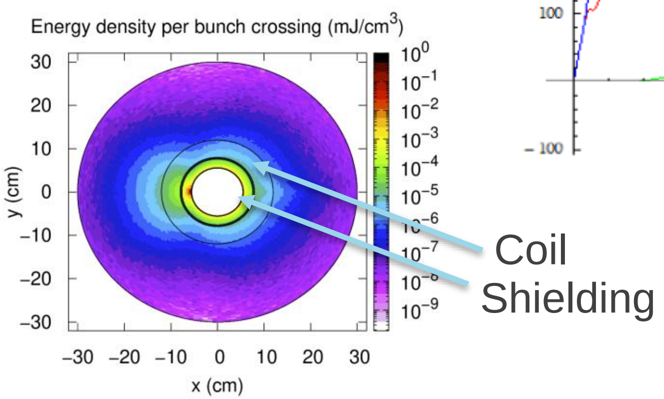
5 cell elliptical cavities @ 650 MHz for PIP-II

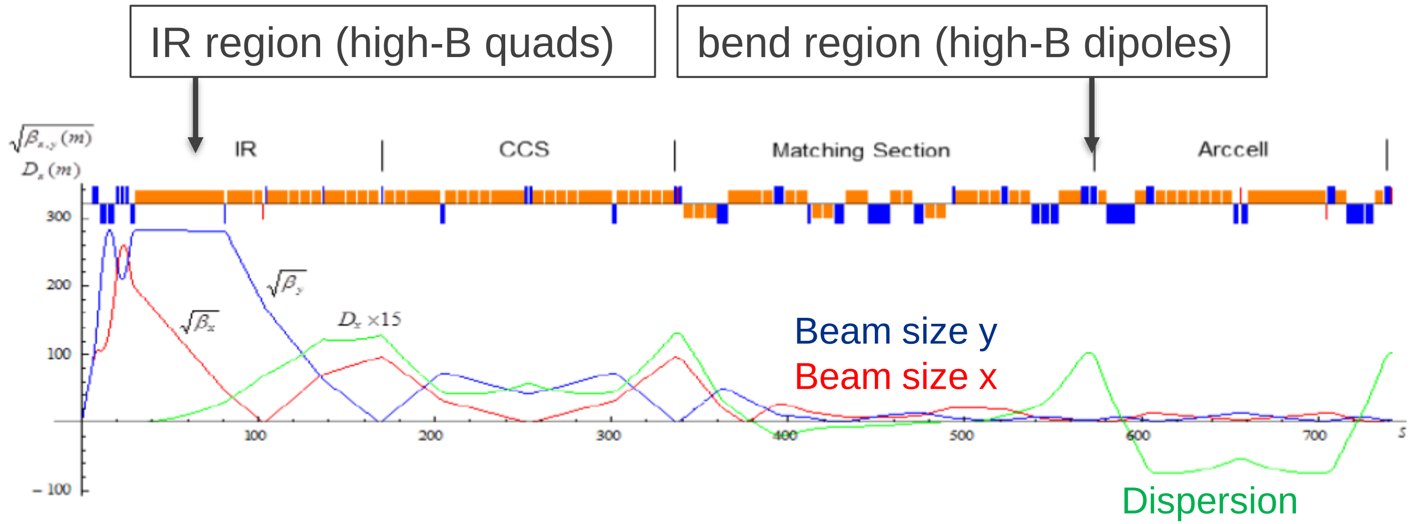
Cryomodule @ 1300 MHz for LCLS-II

- 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

Collider ring





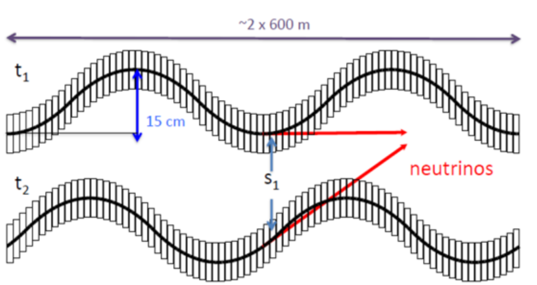


A. Frasca et al. WEPR26, WEPR27
S. Fabbri et al., THBN1

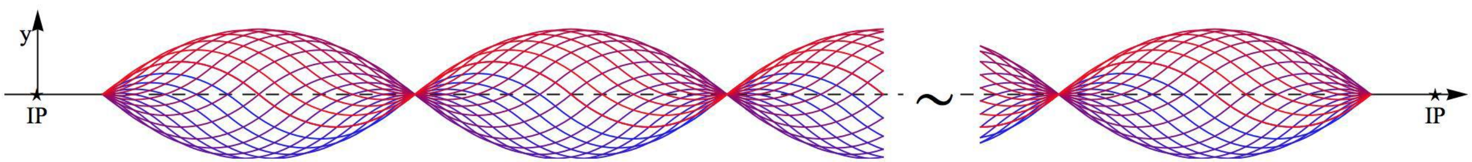
- Designs in place for 3 TeV MuC with specs within the HL-LHC range
- 10 TeV more challenging since it requires a smaller β (5→ 1.5 mm)
  - Requires significant developments in HTS magnet space (IR Quads @ 15-20 T and 12-16 T dipoles with large aperture (~150 mm) for shielding

Neutrino radiation mitigation system

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



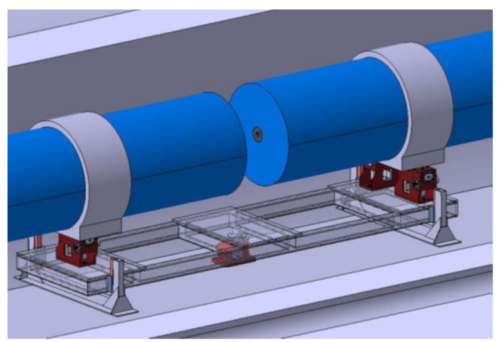
Legal limit: 1 mSv/year
MAP goal: <0.1 mSv/year
IMCC goal: <10 µSv/year
LHC : <5 µSv/year

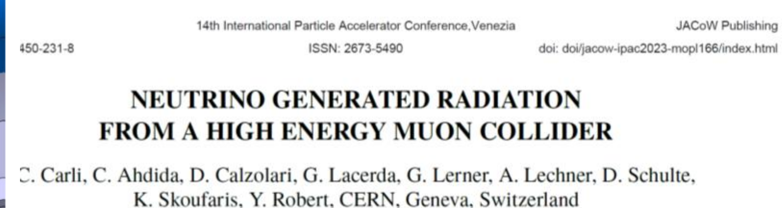


Vertical slope modulation ~ 1 mrad

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

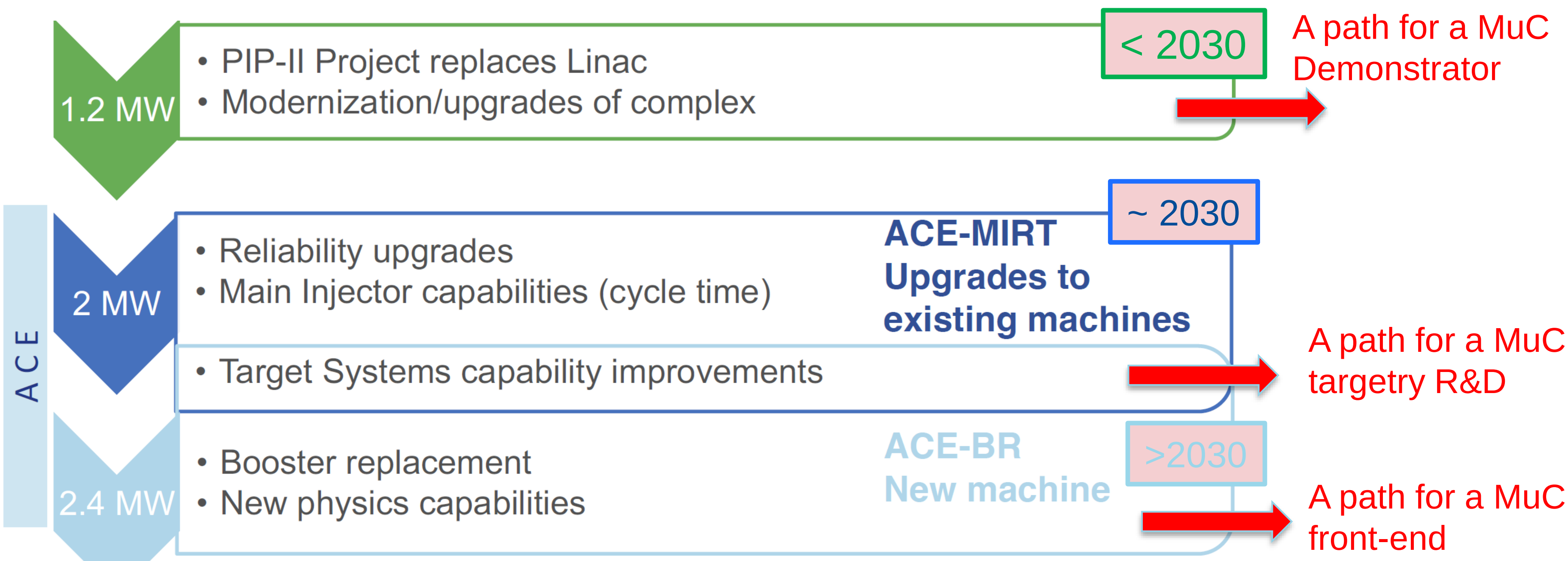
NEUTRINO GENERATED RADIATION FROM A HIGH ENERGY MUON COLLIDER

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

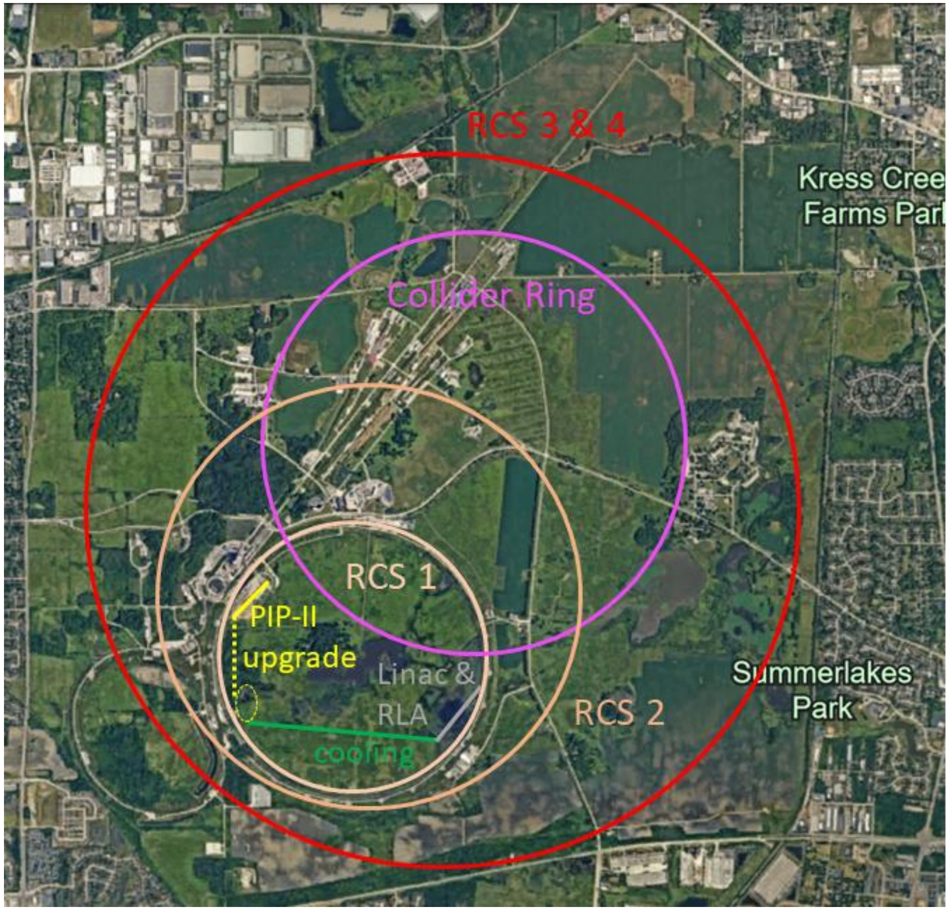
Muon Collider in the US: The ACE program

- **Fermilab's ACE program** could become <u>the basis</u> for developing a proton driver and a target station for a MuC
  - Includes a rigorous target R&D program for 2+ MW beams in the next decade
  - Synergies for proton driver, targetry and SRF R&D as well as for the Demonstrator program



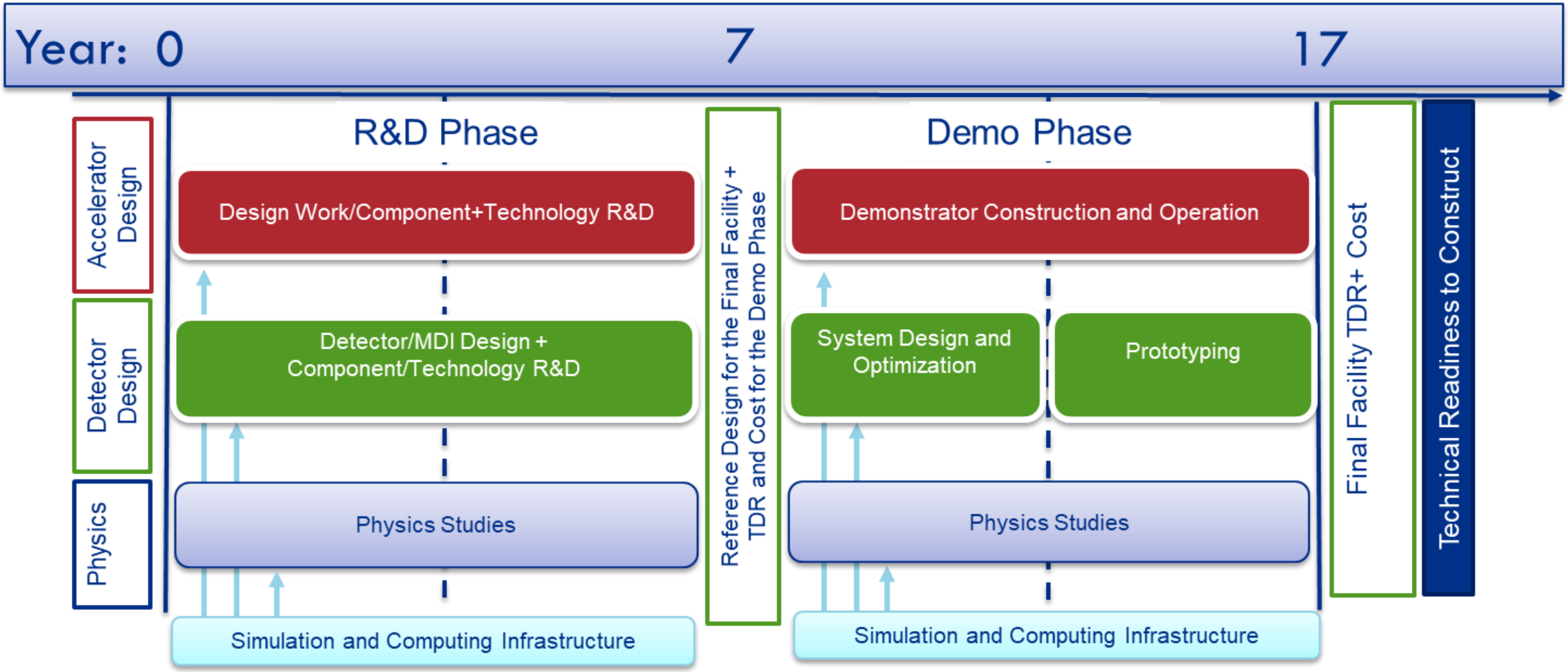
Muon Collider at Fermilab

- **10 TeV MuC** concept in place
- Proton source
  - Post-ACE driver -> Target
- Ionization cooling channel
- Acceleration (4 stages)
  - Linac + RLA → **173 GeV**
  - RCS #1 → **450 GeV (Tevatron size)**
  - RCS #2 → **1.7 TeV (col. ring size)**
  - RCS #3, 4 → **5 TeV (site fillers)**
- Collider ring, 10.5 km long



This design is very preliminary. Need further, more detailed development

Muon Collider timeline (as shown to P5)



- 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 two 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
- However, DOE-HEP funding not at the level assumed in the P5 scenarios
  - Currently in the US, limited funds are accessible via laboratory discretionary funds, university research programs and theory efforts
  - Not enough to carry out the work discussed here