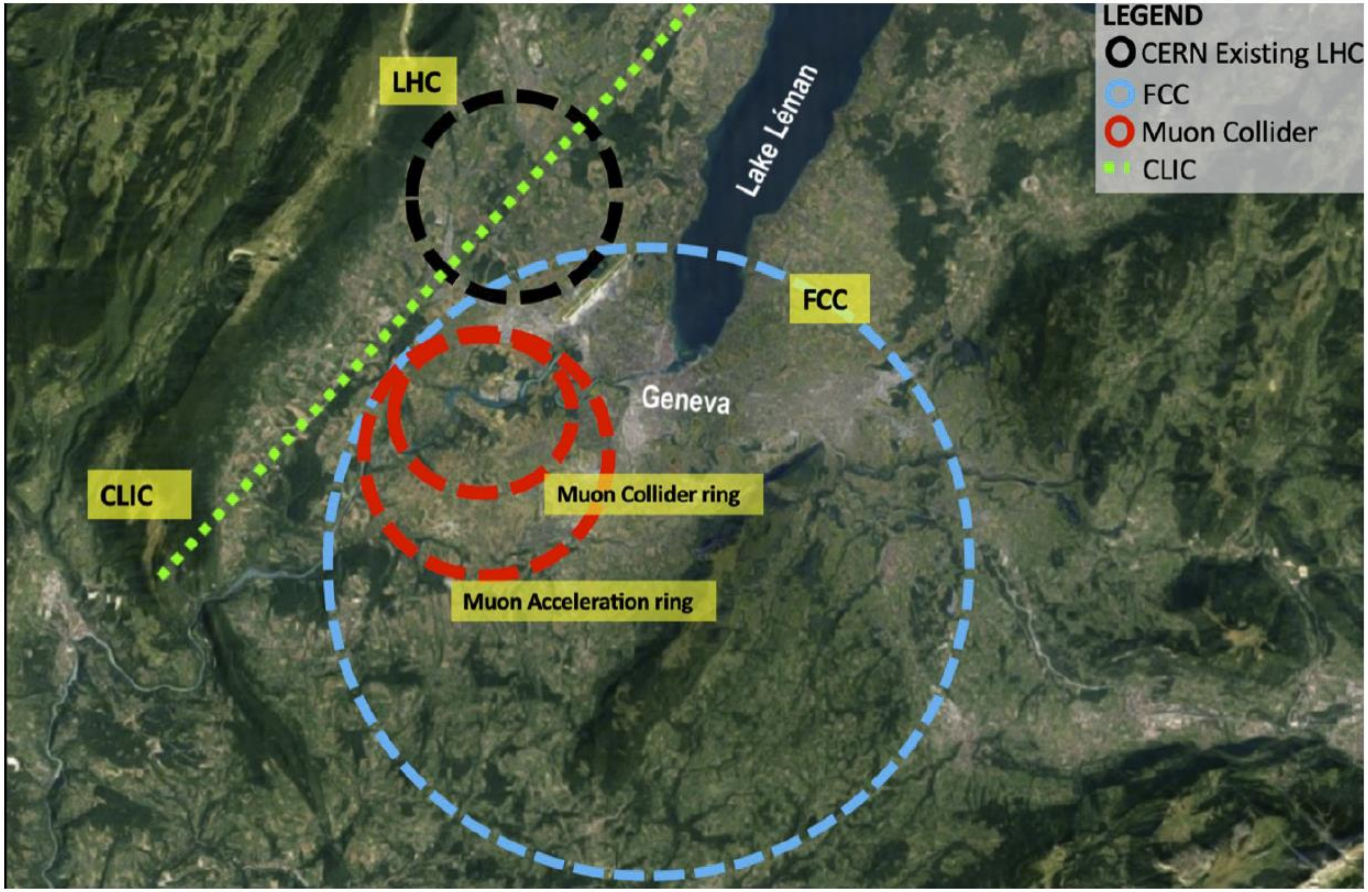
The US effort towards a Muon Collider

Diktys Stratakis (Fermilab)

Princeton Muon Collider Workshop

February 22, 2024

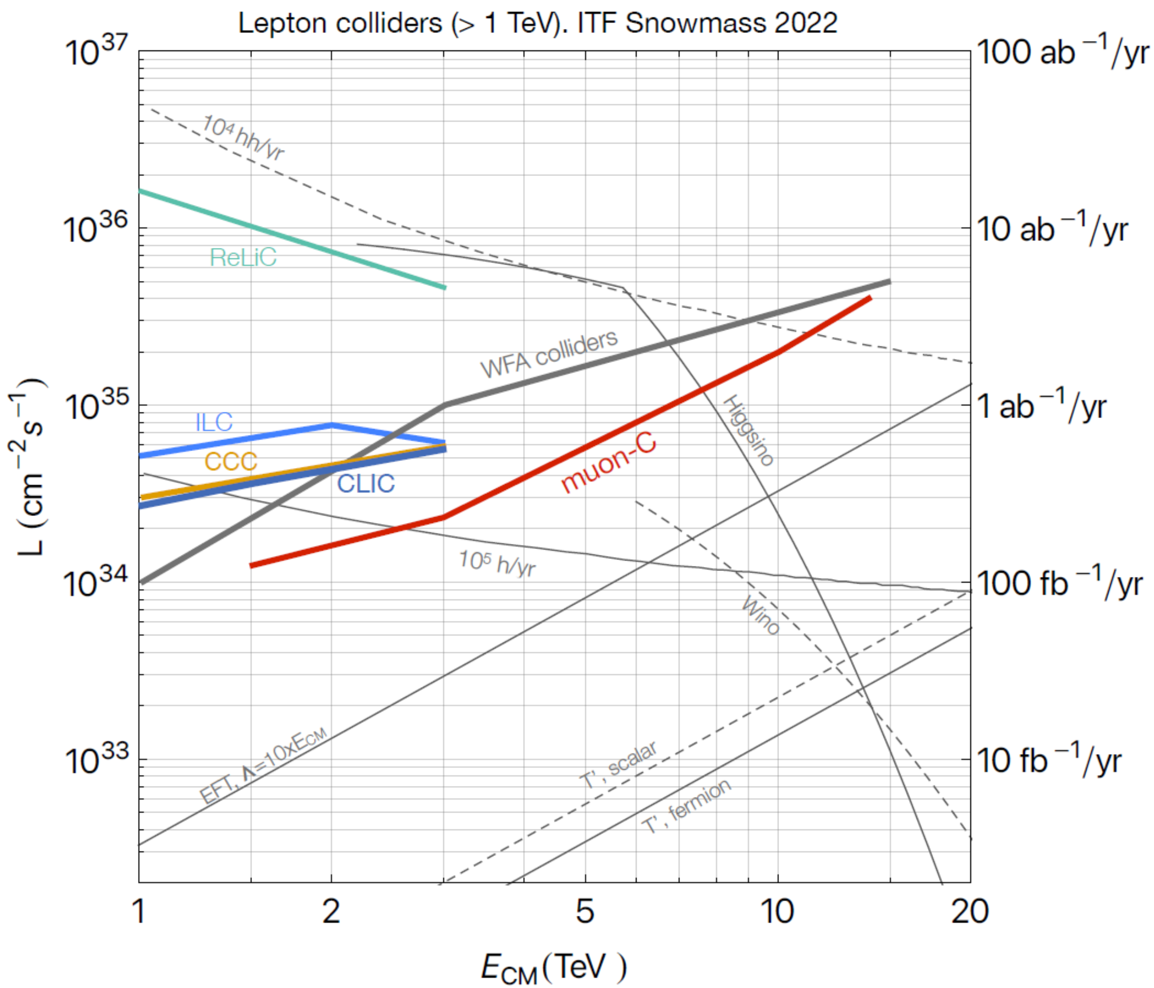
Compactness



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

Efficiency

More details: Snowmass’21 ITF report



WFA Colliders

Electric power: ~450-1000 MW

Cost: ~18-80 B$

Muon Colliders

Electric power: ~320 MW

Cost: 12-18 B$

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

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History

- **1960s:** First mention of Muon Colliders in the literature
- **1990s:** Design studies through US institutional collaborations
- **2011:** Muon Accelerator Program was approved by DOE
  - Focused on a proton-driver solution; 1.5, 3 and 6 TeV colliders; ended in 2016
- **2021:** Muon Colliders become part of the EU Accel. R&D Roadmap
  - International Muon Collider Collaboration (IMCC) formed, CERN host for now
- **2022:** US Snowmass study reveal strong interest on Muon Colliders
  - Presented the Muon Collider Forum Report: a vision from the US side
- **2023:** Formation of the US Muon Collider R&D coordination group
  - Provided to the P5 panel a plan for Muon Collider R&D from the US side
- **2023:** P5 report released; strong support on Muon Collider activities

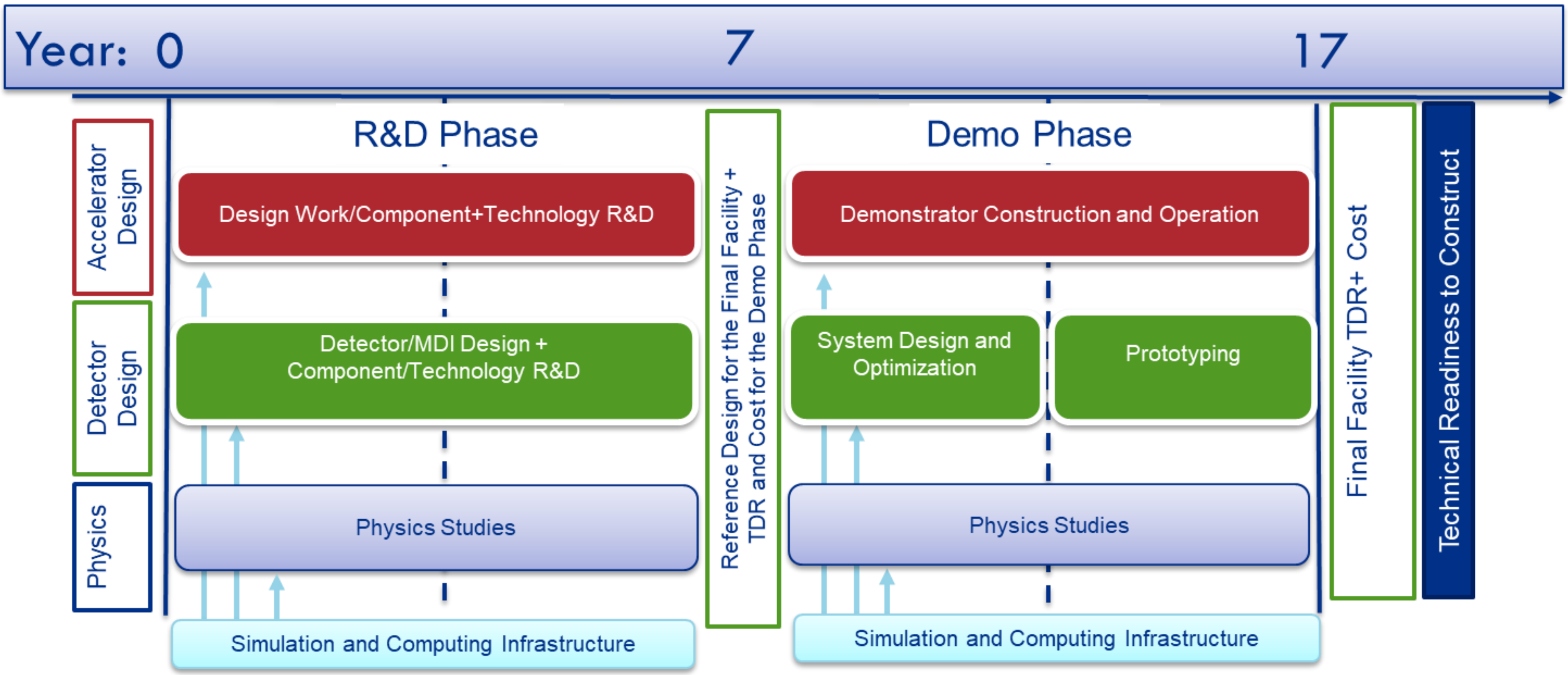
US effort (pre-Snowmass): MuC Forum

- The forum established a strong collaboration between the AF+EF+TF frontiers for Muon Collider (MuC) research
  - Goal was to make a **strong** physics case for MuC and inform the community
  - Monthly meetings and dedicated workshops for 18+ months before Snowmass
  - Lined-up a plan for Muon Collider R&D in the US
  - Identified synergies with other programs
  - Published all findings as a "**MuC Forum report**" and presented it in the Snowmass meeting: ~180 authors, 50+% are early career scientists
- Forum conclusions:
  - **10 TeV** is the most attractive option
  - No fundamental showstoppers identified
  - BUT engineering challenges exist
  - **The R&D should start now!**

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

Muon Collider Forum Report

US effort (post-Snowmass) : MuC coordination group



- R&D coordination group was formed to provide input to P5
  - Focus on 10 TeV accelerator & detector design
  - Develop R&D plan, cost, deliverables and timeline

A 10-page **R&D summary** document submitted to P5 (link)

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International effort

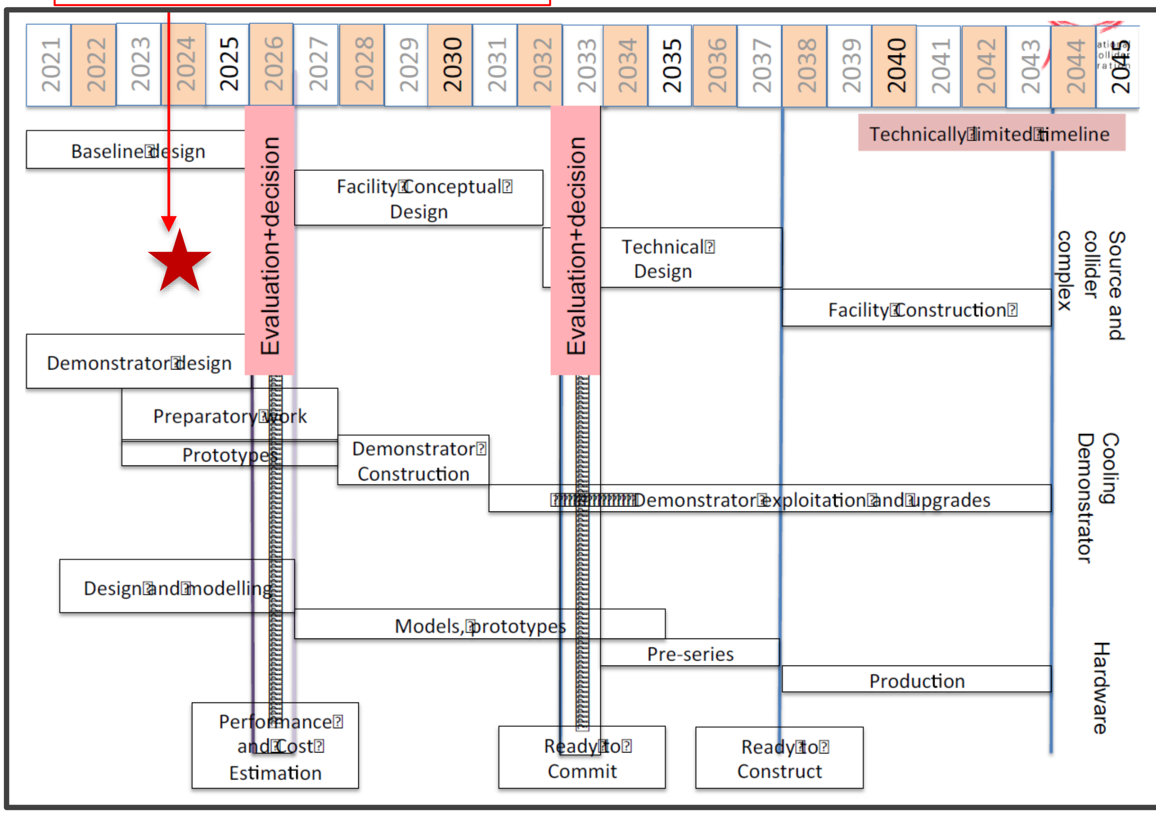
- IMCC formation in 2022; CERN is host for now
- 50+ partner institutions, 30+ signed formal agreement
- Several US institutions started to join
- IMCC has **~1/2** of the FTEs to deliver the technical limited timeline

AS OF TODAY: (1) Initial baseline defined, (2) Interim design report is in preparation

MuCol

International MUON Collider Collaboration

Technical limited timeline



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Target parameters (from IMCC)

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

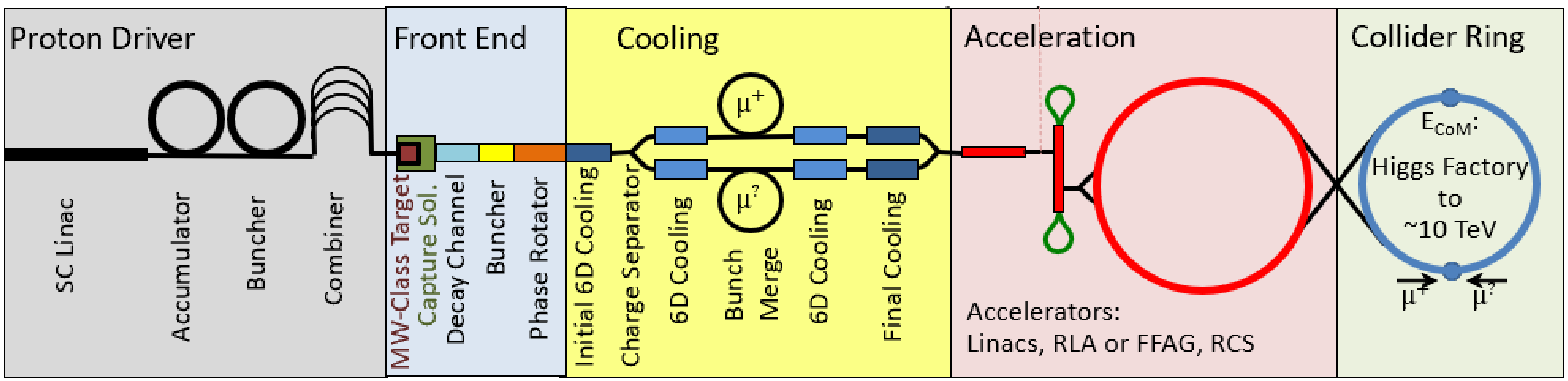
- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

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

Parameter	Unit	3 TeV (Start?)	10 TeV (GOAL)	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

Goal is a 10 TeV collider, potential initial stage at 3 TeV

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

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Luminosity for a MuC

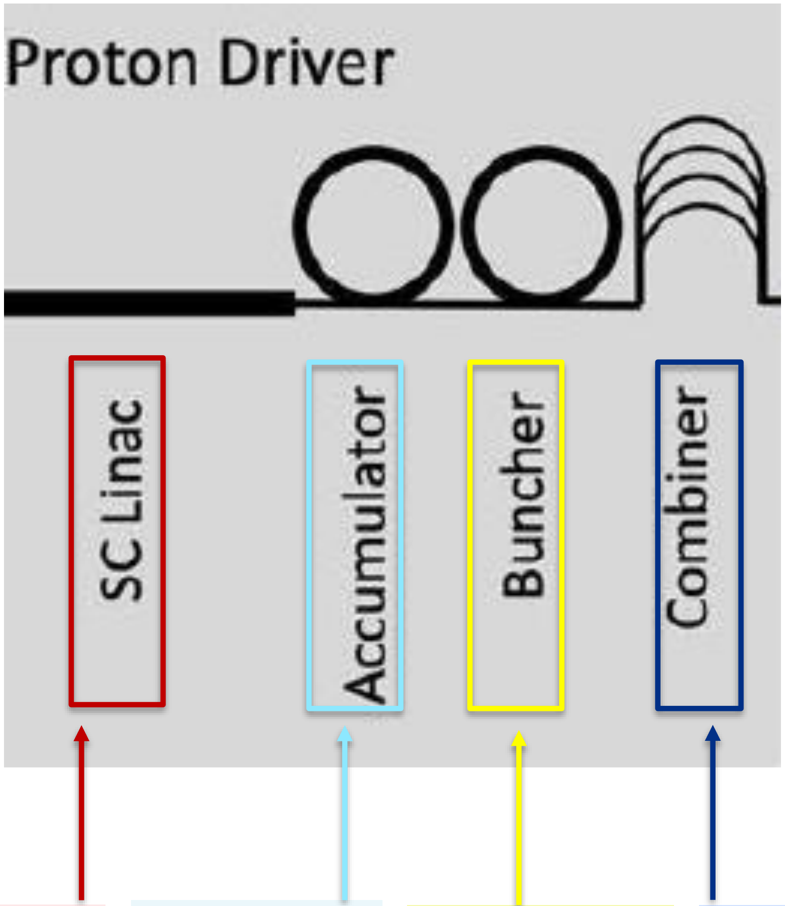
$$L = \frac{N_+ N_- n_C f}{4\pi\sigma_x\sigma_y}$$

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

A MuC is an interplay between **MAGNET**, **RF CAVITY** and **TARGET** technologies which have to be pushed to their limits for peak efficiency

Talks at this workshop: MAGNETS (K. Amm), RF CAVITY (T. Luo & S. Belomestnykh), TARGET (K. Yonehara)

MuC proton driver: What is needed?



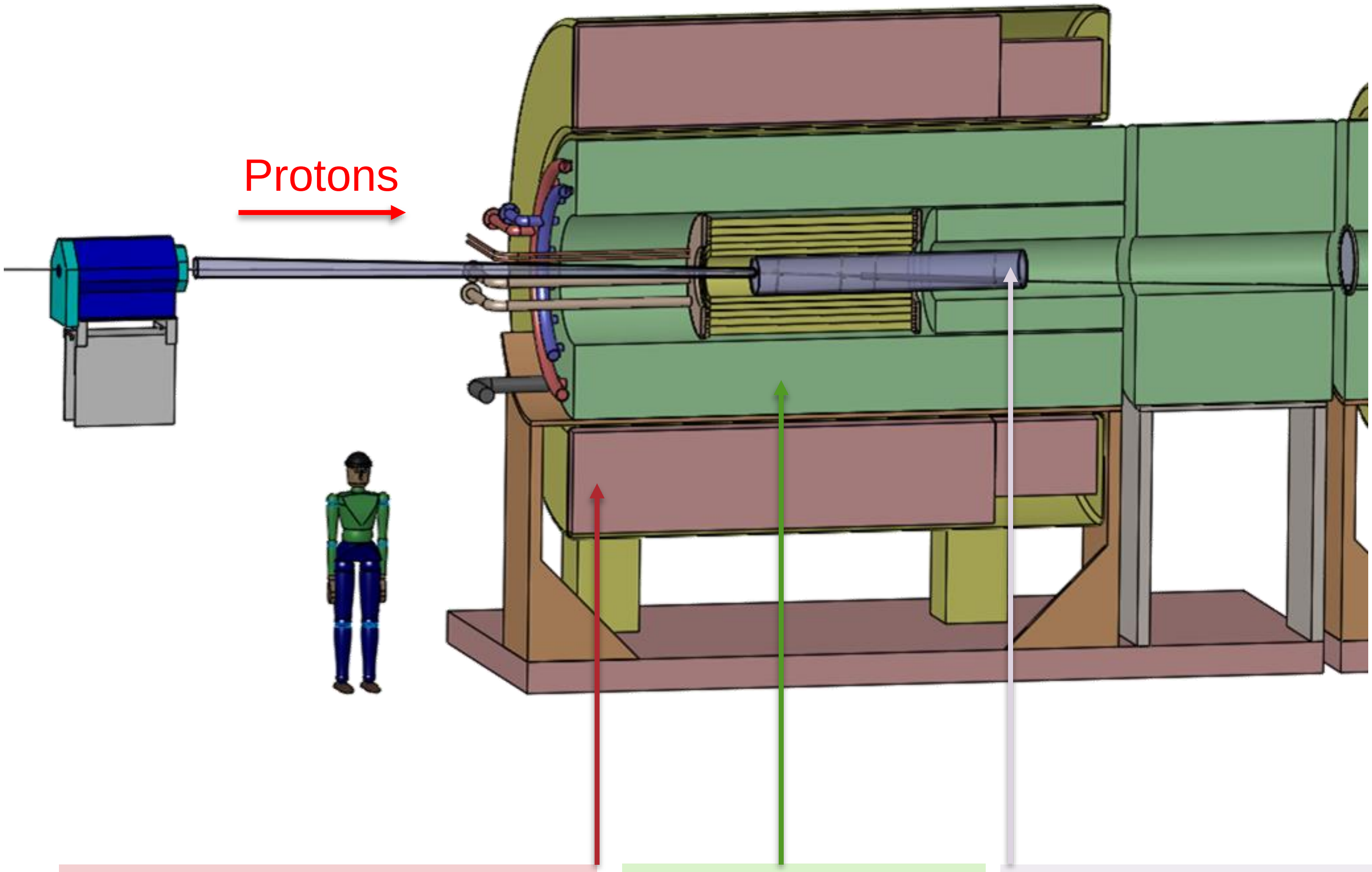
Linac or Linac+RCS to accelerate protons to **5-20 GeV**

Boost intensity to ~$\mathbf{10^{14}}$

Compress to **ns** scale

Deliver MW scale bunches at **5-10 Hz**

MuC target: What is needed?



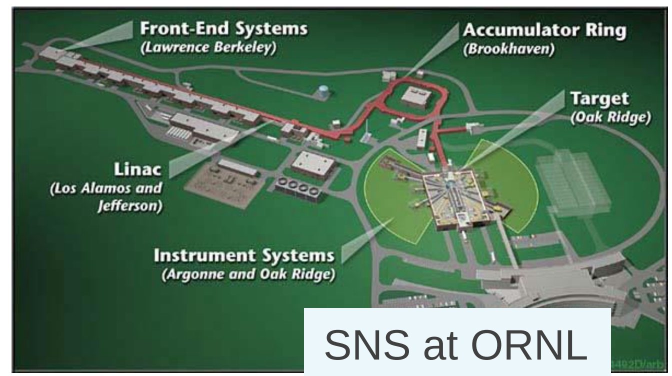
Strong solenoids (~**15 T**) with a large aperture (~**2 m**) around the target

Shielding for magnet protection

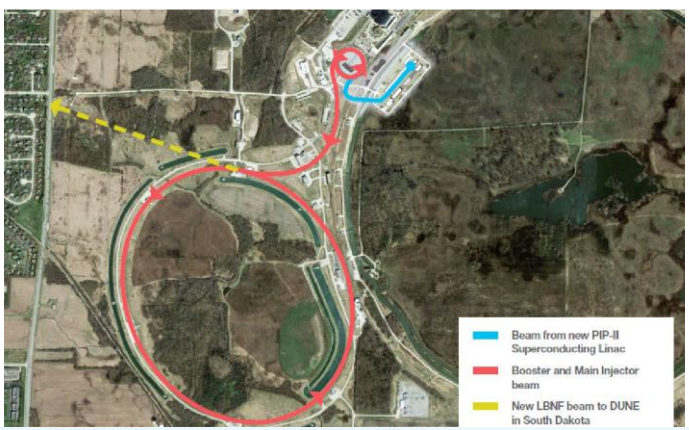
Targets than can produce many muons and are tolerant to MW beams

MuC p driver + target: Moving forward

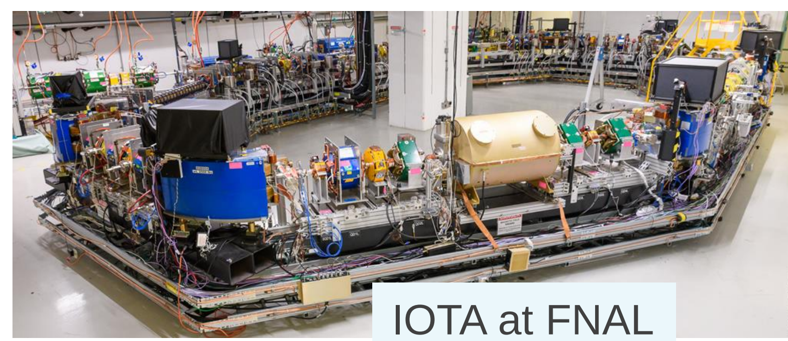
- In the long term, **Fermilab's ACE program** could become the basis for developing a proton driver and a target station for a MuC
  - See talk by S. Valishev
- In the short term, several concepts can be studied by doing scaled experiments at **existing facilities**
  - See proton driver talk by A. Hoover
  - See target talk by K. Yonehara



SNS at ORNL

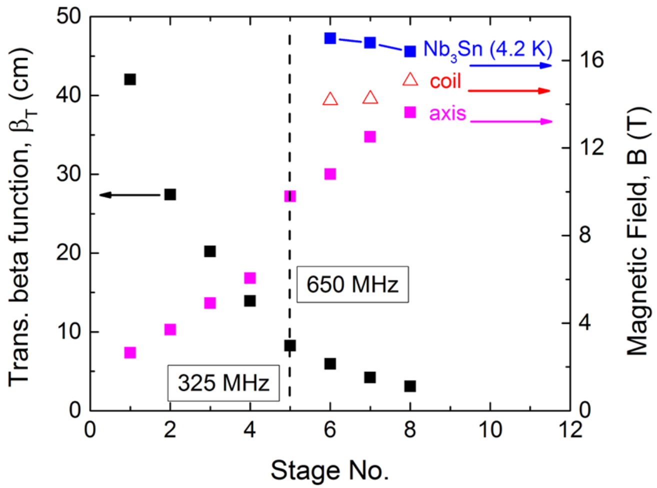


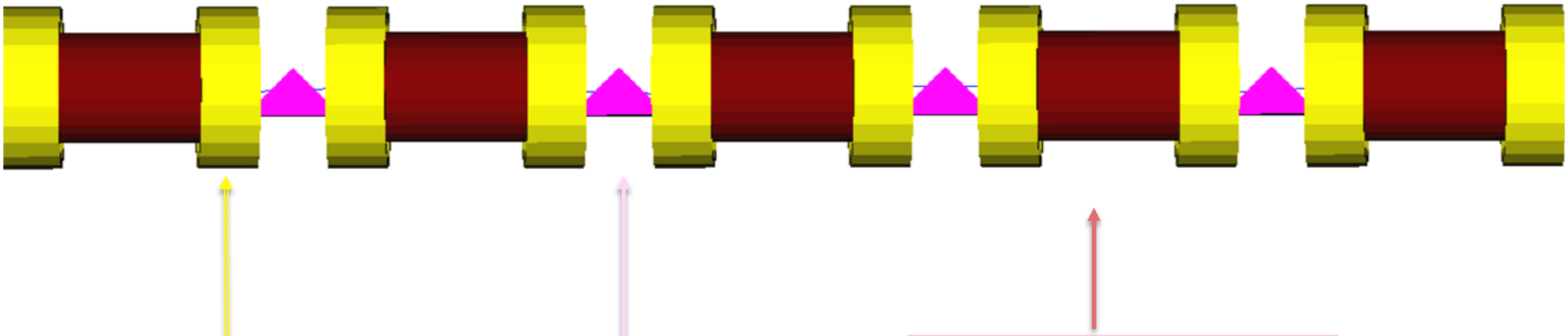
Accel. Complex in PIP-II era at FNAL



IOTA at FNAL

MuC cooling: What is needed?





Large bore solenoids:
2 T (500 mm IR) → **20+ T** (50 mm IR) (**1000+ units**)

Absorbers that can tolerate large muon intensities

RF cavities (**300-800 MHz**) that can operate in multi-T fields (**1000+ units**)

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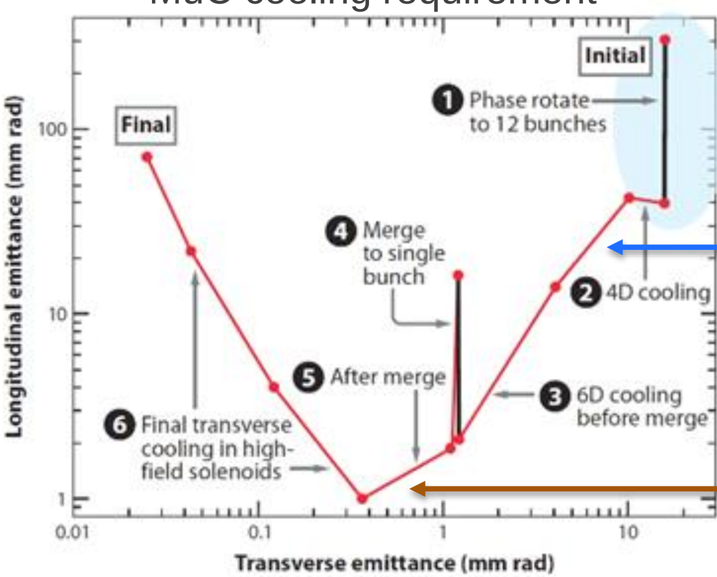
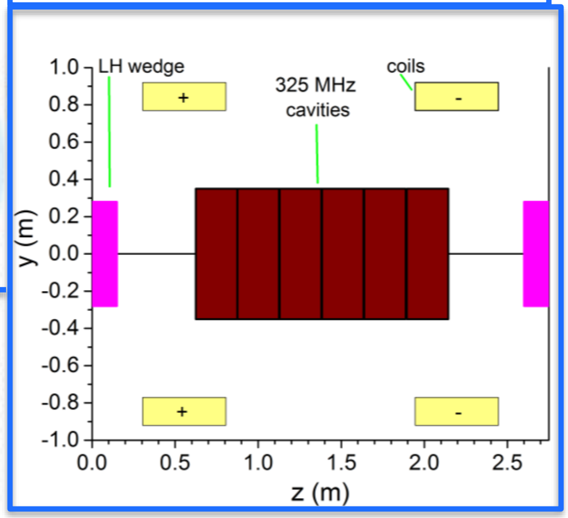
MuC cooling: Path forward (design)

- Deliver a end-to-end design that meets MuC luminosity criteria
- Take into account engineering aspects
- Improve performance with AI/ML methods and latest technology
    - FNAL-UChicago (K. Di Petrillo & YK Kim) collaboration has started

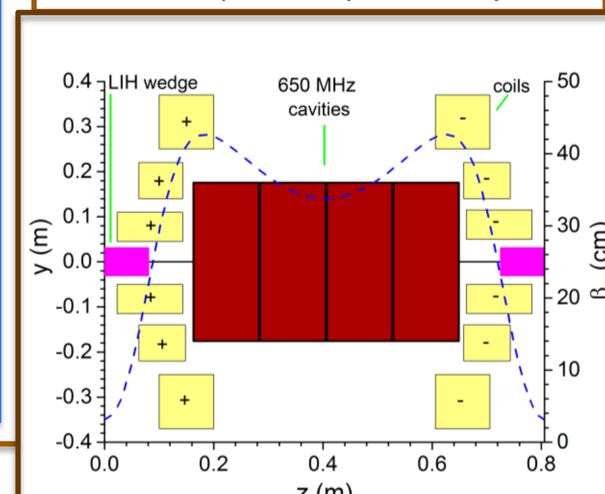
MuC cooling requirement



Early cell (“easy”) – 2T peak

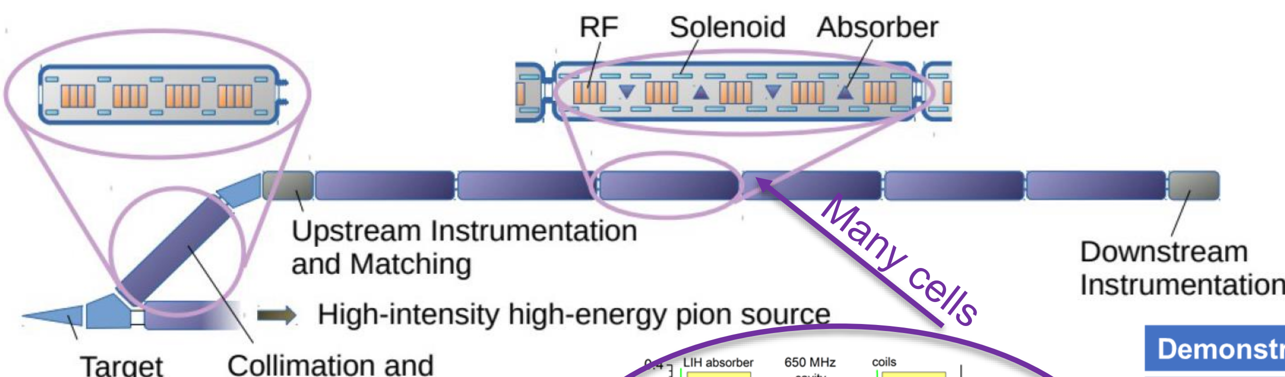


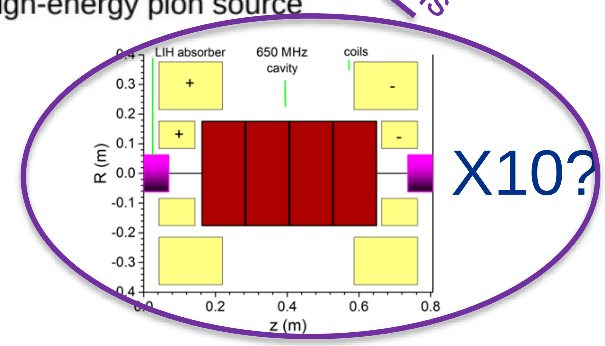
Late cell (“hard”) – 14 T peak



MuC cooling: Path forward (demonstrator)

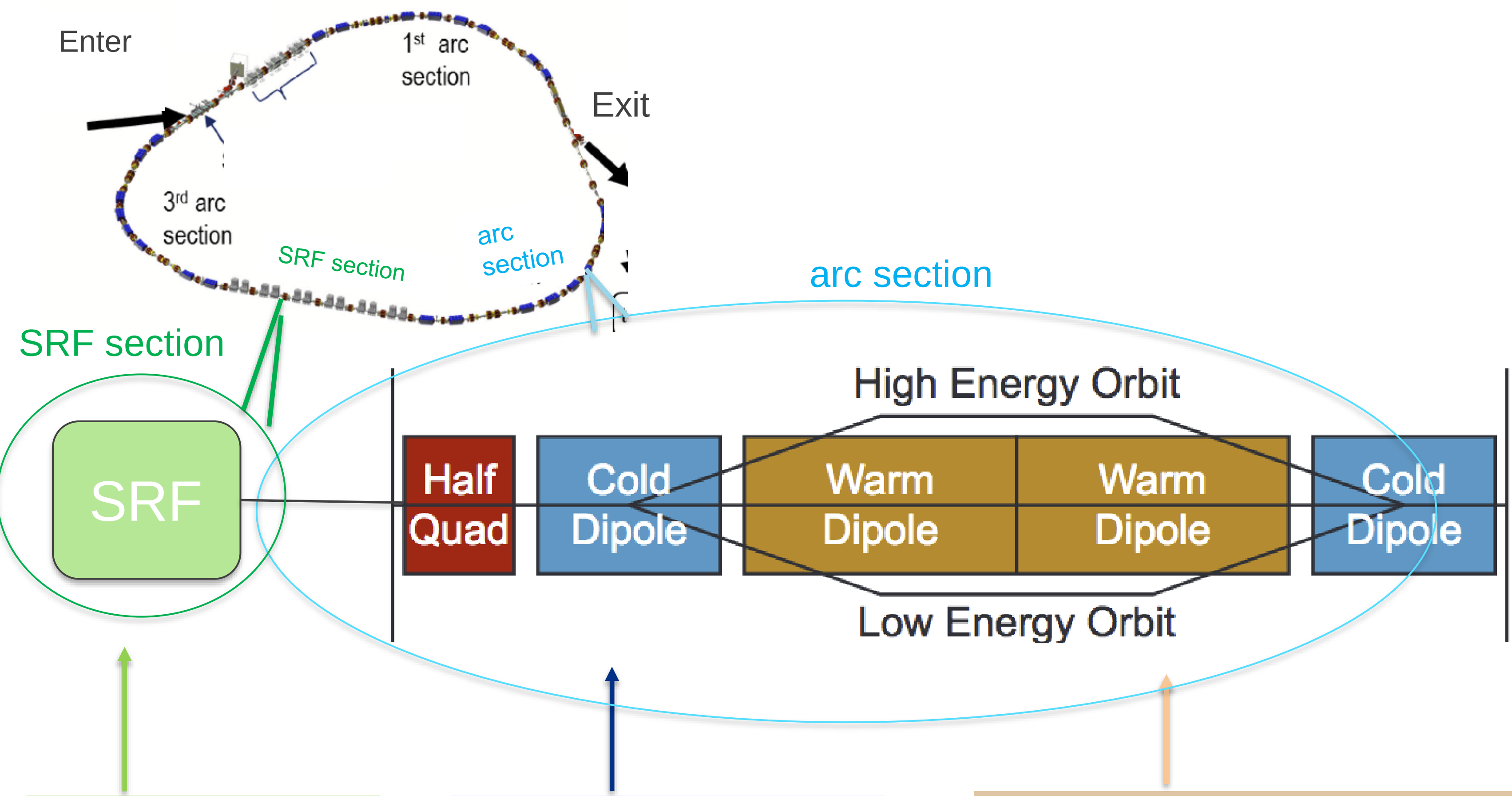
- Benchmark a **realistic** cooling lattice to give us the input, knowledge, and experience to design a real, buildable cooling channel for a MuC
- In the next years we need: (1) conceptual design of a demonstrator facility that allows testing cooling technology (2) Site exploration & cost estimate of a demo facility
  - More details see J.S. Berg talk





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

MuC acceleration: What is needed

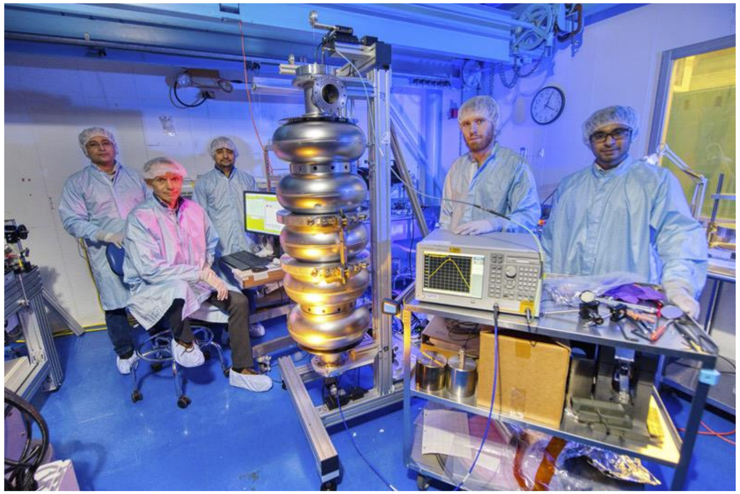


High-gradient SRF (**325-1300 MHz**)

8-10 T dipole magnets (**150 mm** bore)

Fast-ramping (**~ms**) magnets (**±1.8 T**) with **reliable** power management sources

MuC acceleration: Path forward



5 cell elliptical cavities @ 650 MHz for PIP-II

Cryomodule @ 1300 MHz for LCLS-II

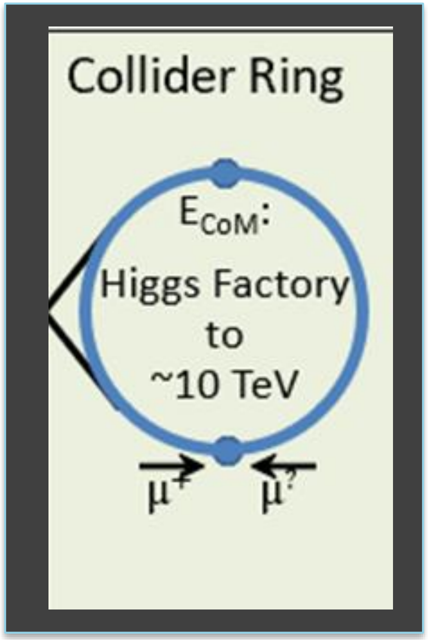
- Develop accelerator lattice designs towards a 10 TeV collider
  - Design is site specific! Considering a US MuC, needs dedicated US resources.
- Design and test MuC style SRF cavities (325, 650, 1300 MHz)
  - Fermilab, JLAB, MSU and other US institutions have significant experience
  - Synergy opportunities with other programs (ILC, FCC-ee)
- Proof-of-principle tests for power management of cycling magnets

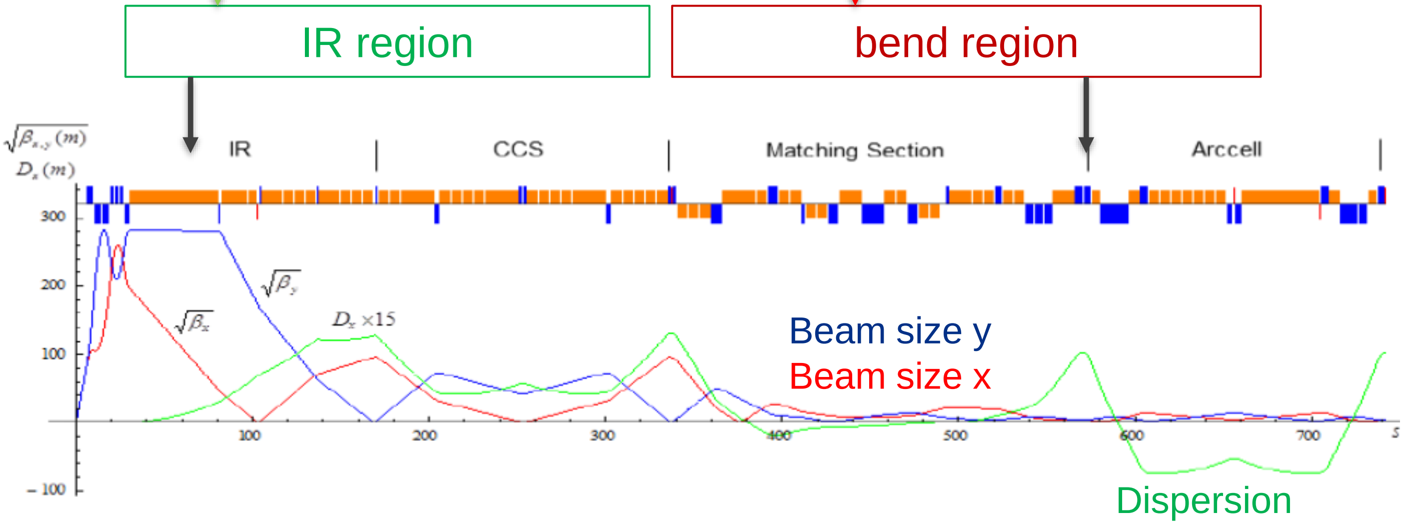
MuC collider ring – What is needed

IR Quads with strong fields (**15-20 T for 10 TeV**)

Strong field dipoles (**12-16 T for 10 TeV**) and large aperture **(~150 mm)**

Mitigation system for the neutrino flux from muon decays

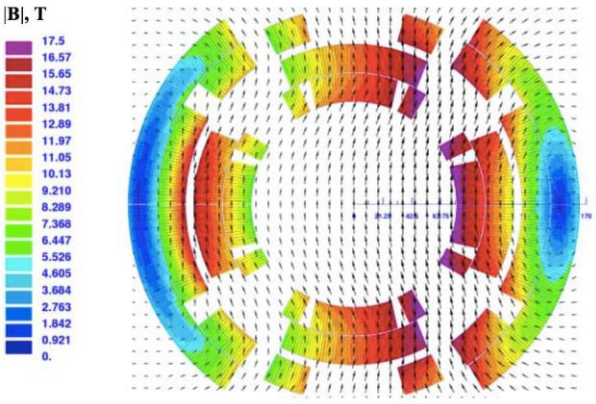




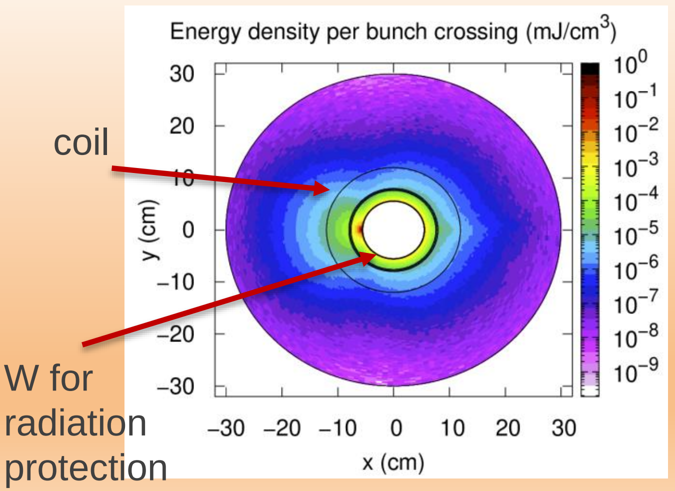
MuC collider ring – Path forward

- 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



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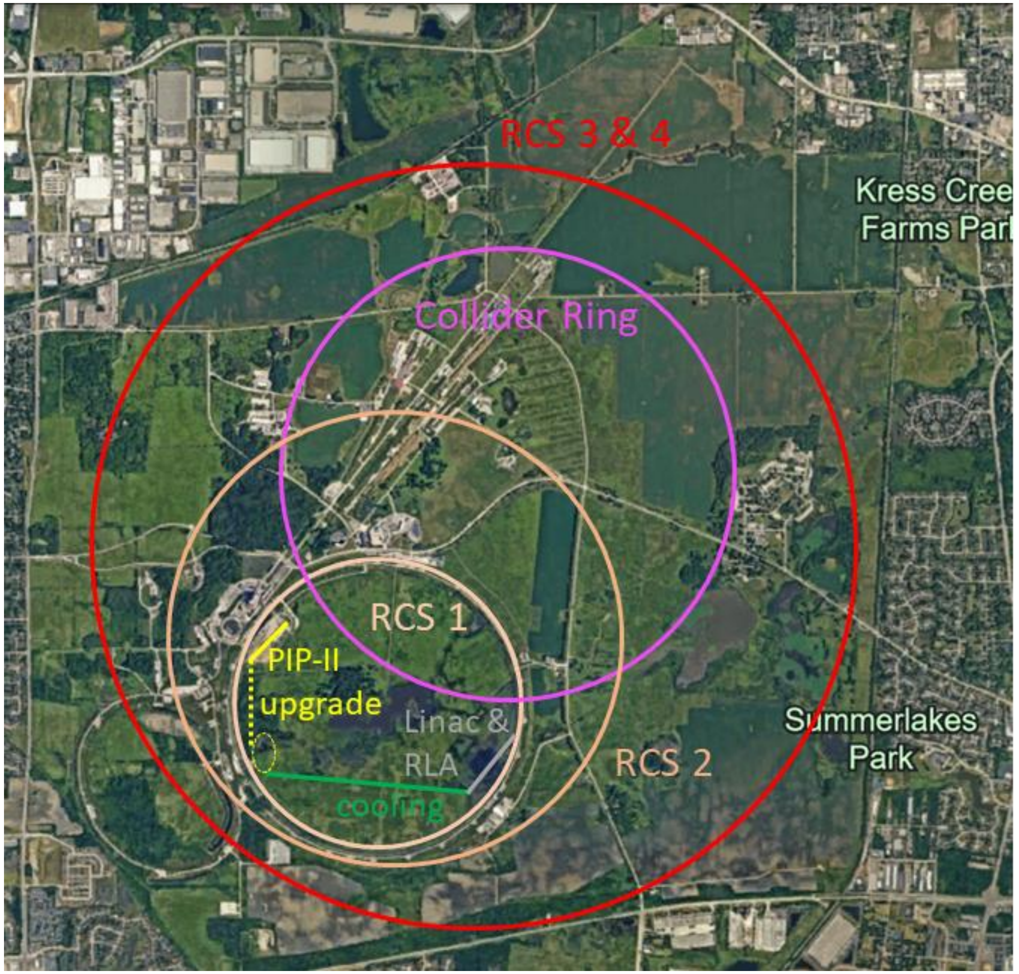
Muon Collider at Fermilab

- **10 TeV MuC** concept is 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
  - Could be combined with RCS #2



- In the next years we like to have a baseline design including a neutrino flux mitigation system

Proposed MuC accelarator R&D (next 5-7 years)

Design and Simulation work →

Some examples

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

Prototyping & tests →

Some examples

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

Demonstrator →

Some examples

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

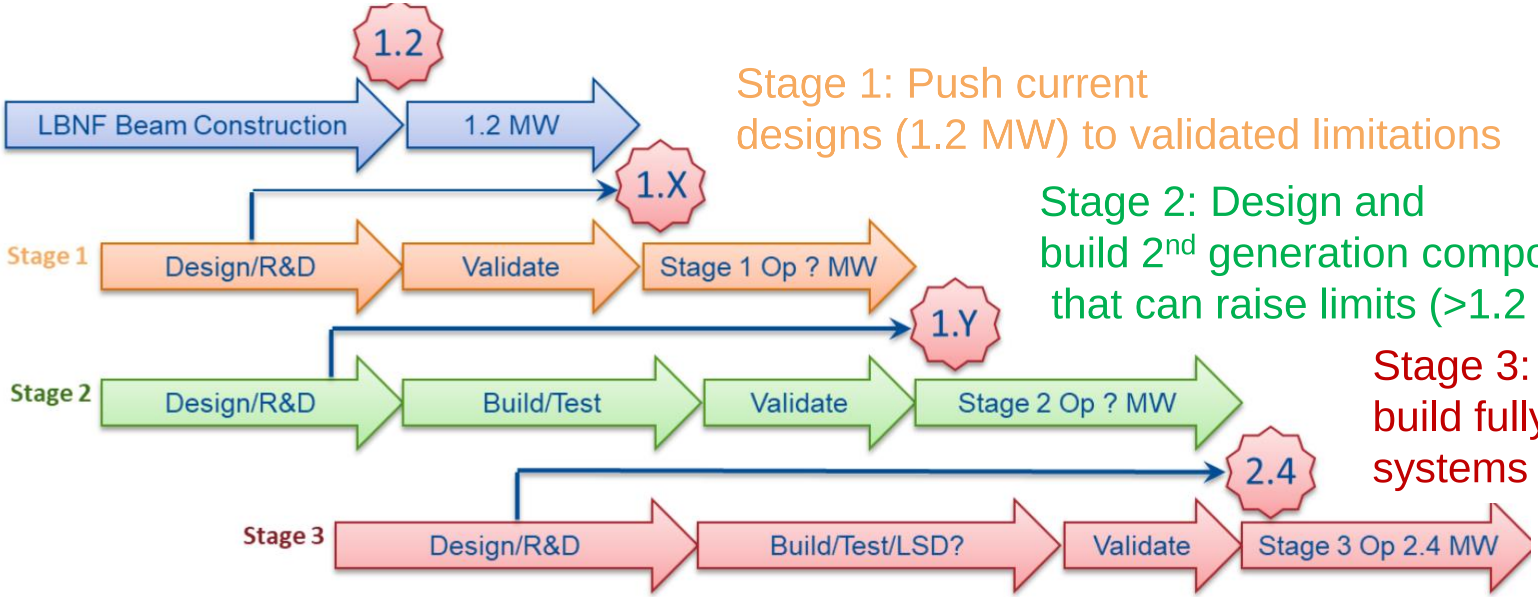
Summary

- MC offers a unique opportunity for EF collider with high luminosity
- Physics & technology landscape has significantly changed recently
  - Explosion of physics interest in MuC as indicated by the number of publications, activities in IMCC, Muon Collider Forum, Snowmass white papers, P5 vision…
- No fundamental show-stoppers in physics and technology have been identified, however major developments in all areas are required
- P5 report opens the door for a strong R&D program in the US
- Next steps:
  - Understand funding mechanisms
  - Organization of US efforts
  - Develop and R&D plan in both accelerator and detector design
- **There are numerous opportunities for everyone to get involved!**
- **Accelerator non-experts are very welcome to help us!**

Backup

MuC target: Path forward

- 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



Stage 1: Push current designs (1.2 MW) to validated limitations

Stage 2: Design and build 2nd generation components that can raise limits (>1.2 MW)

Stage 3: Design and build fully optimized systems (2.4 MW)

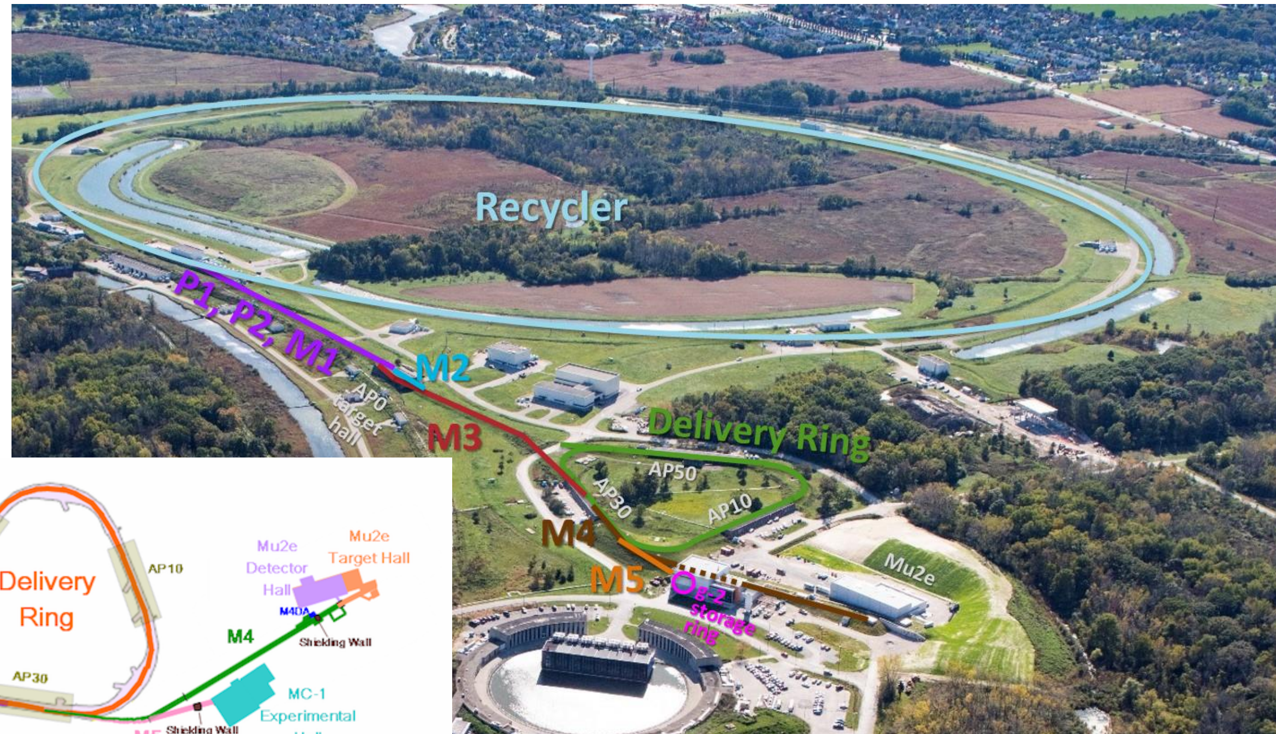
What has changed since over the last years?

- 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 and results are published

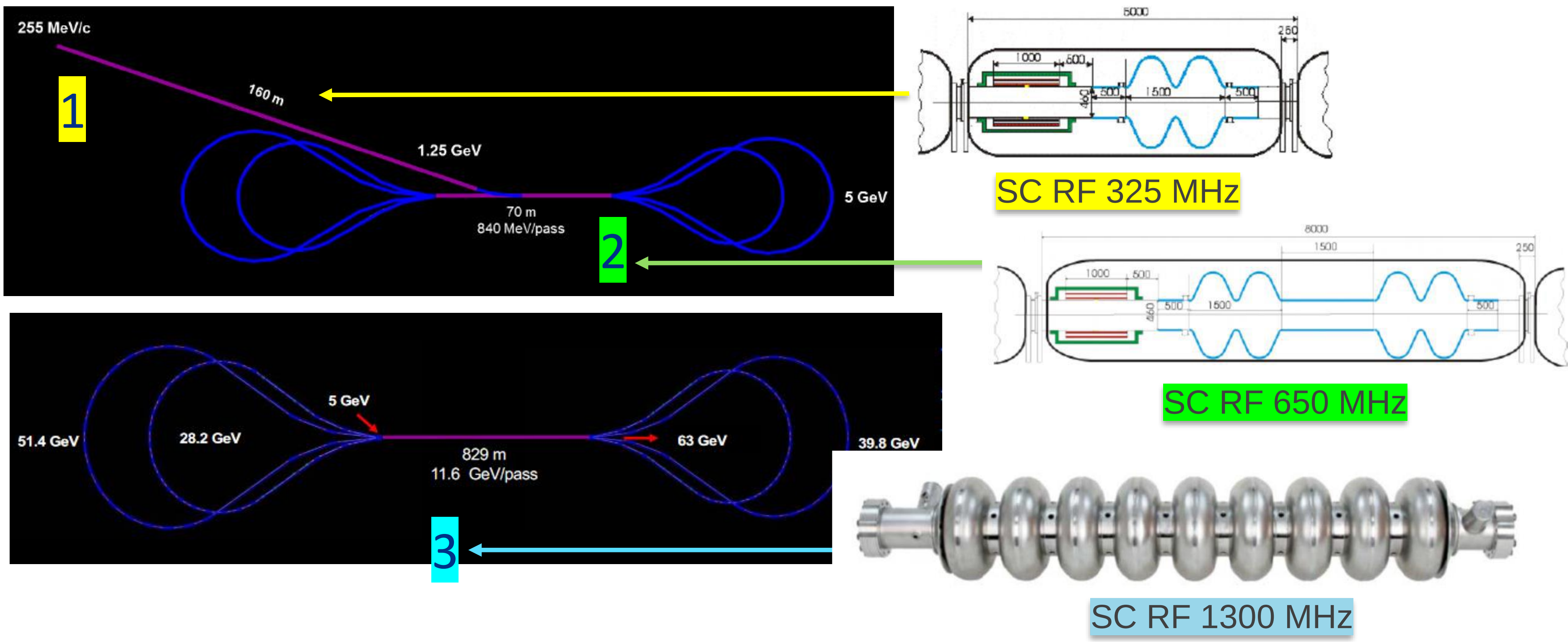
A possible site: Fermilab Muon Campus

- Designed to provide beam for the Muon g-2 and Mu2e experiments
  - Muon g-2 experiment ended this year → Beamlines are available

Muon Campus offers:
- Proton source
- Target
- Muon beamlines
- Experienced team



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