Muon Collider Accelerator Development

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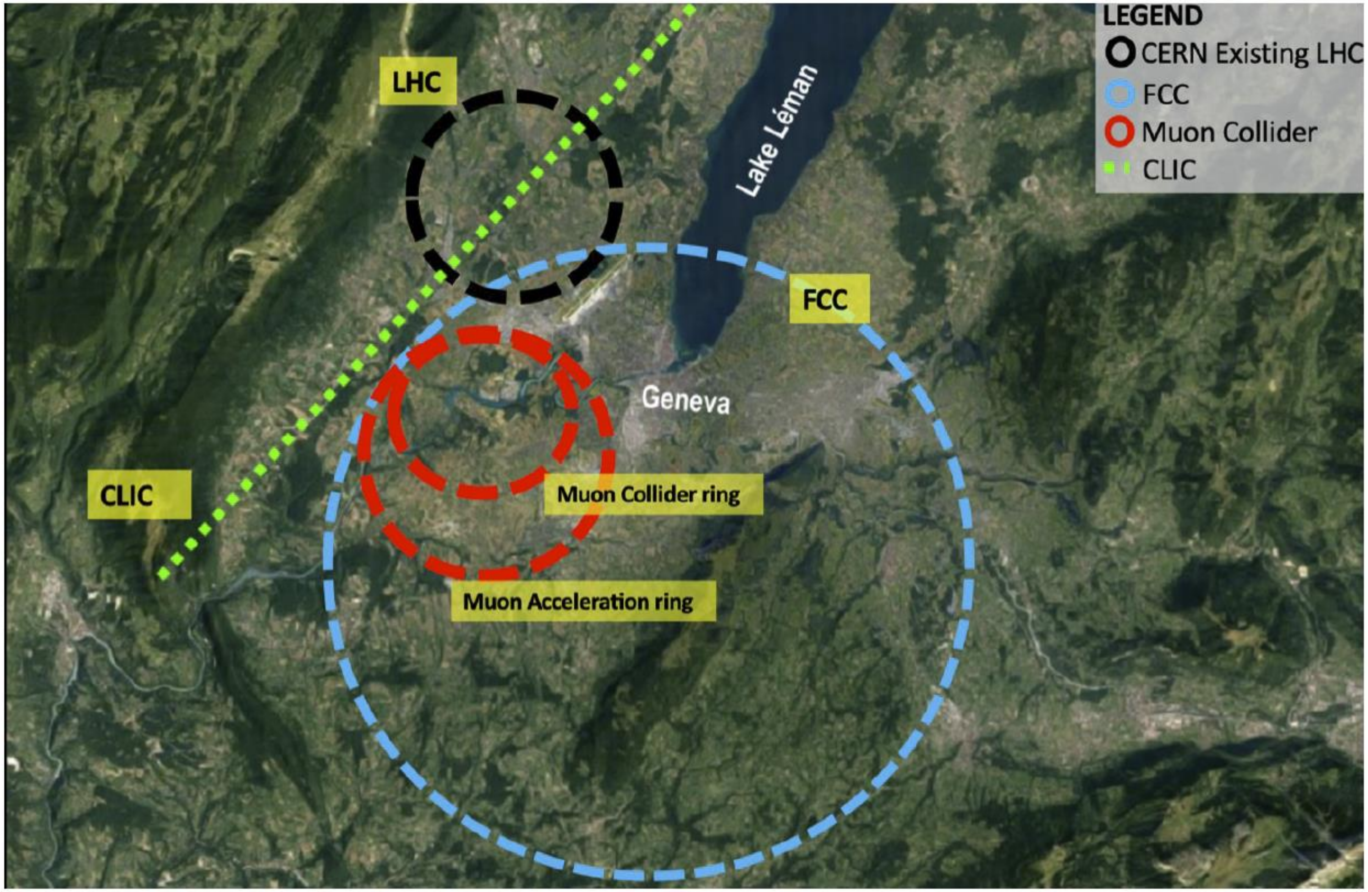
Muon Collider Physics Benchmark Workshop (Pittsburgh, PA)

November 16, 2023

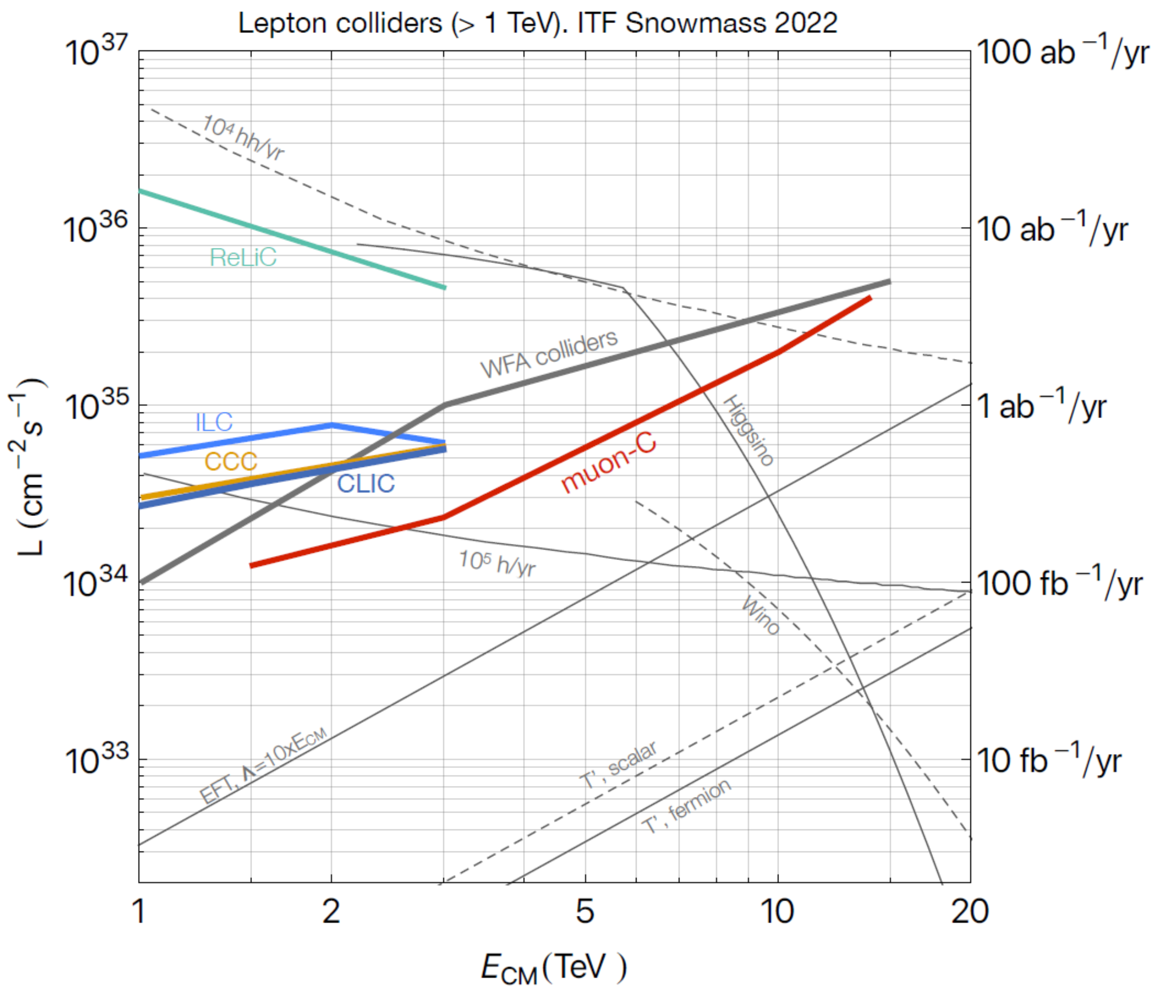
Compactness



- 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]



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

- **1960s:** First mention of Muon Colliders in the literature
- **1990s-2010:** Design studies through US institutional collaborations
- **2011-2016:** Muon Accelerator Program was approved by DOE
  - Focused on a proton-driver solution; studied 1.5, 3 and 6 TeV colliders
- **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 perspective
  - Proposed and presented a National Collider Initiative
- **2023:** Formation of the US Muon Collider R&D coordination group
  - Provided input to the P5 panel on US-based Muon Collider research

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

Start? (3 TeV) — GOAL (10 TeV)

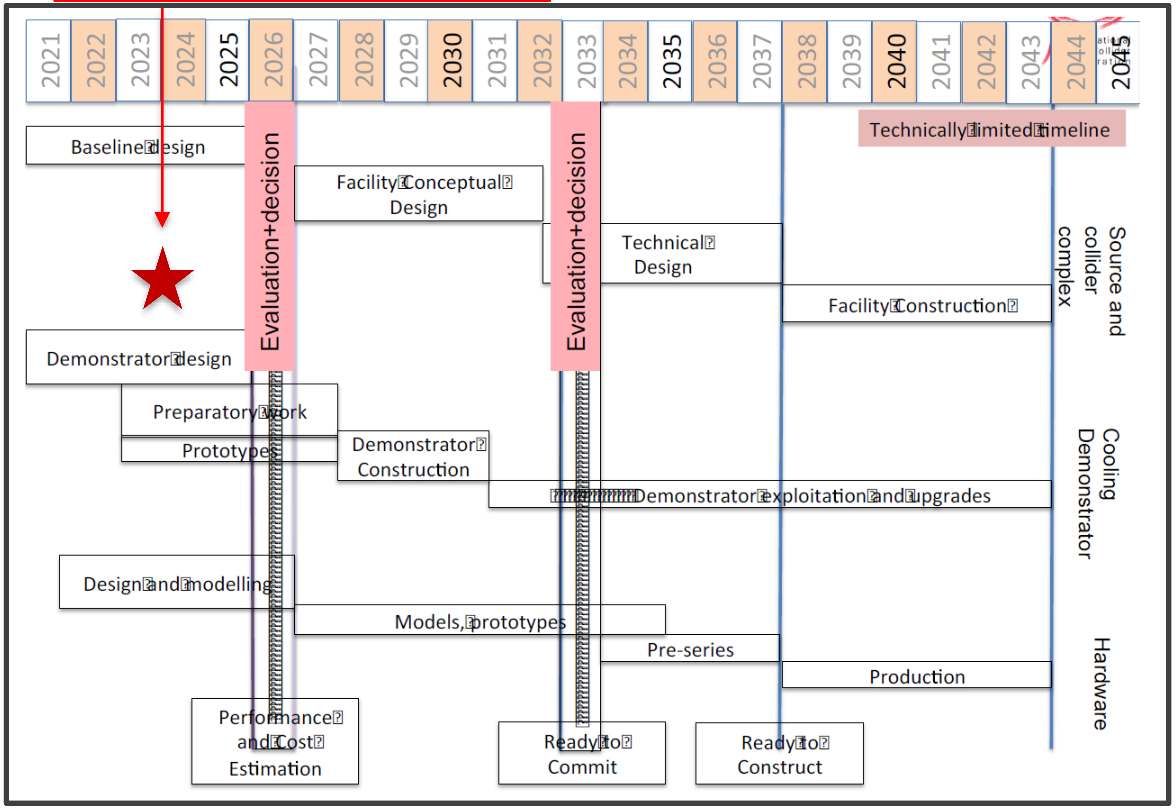
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

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

European effort @ present

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

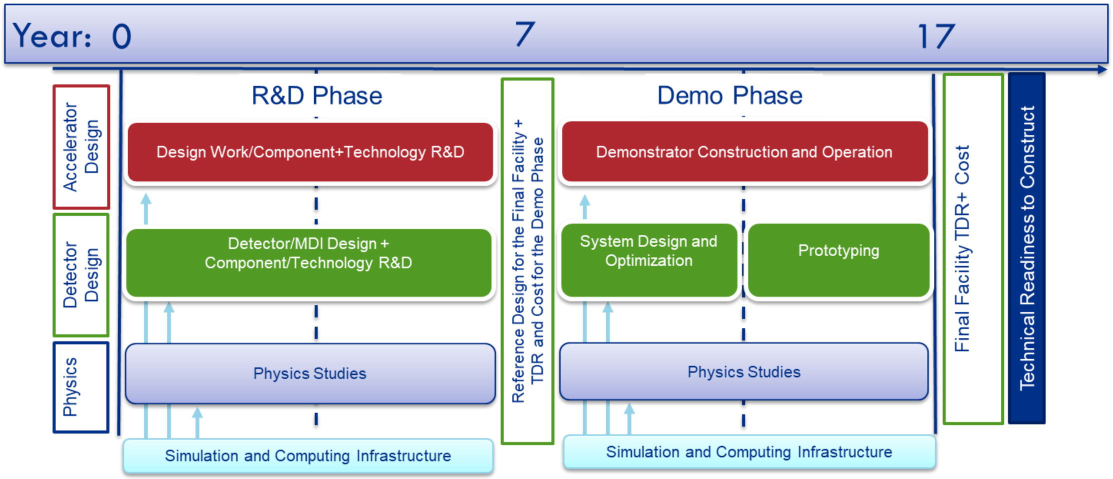
AS OF TODAY: (1) Initial baseline defined, (2) Interim design report is in preparation



Technical limited timeline

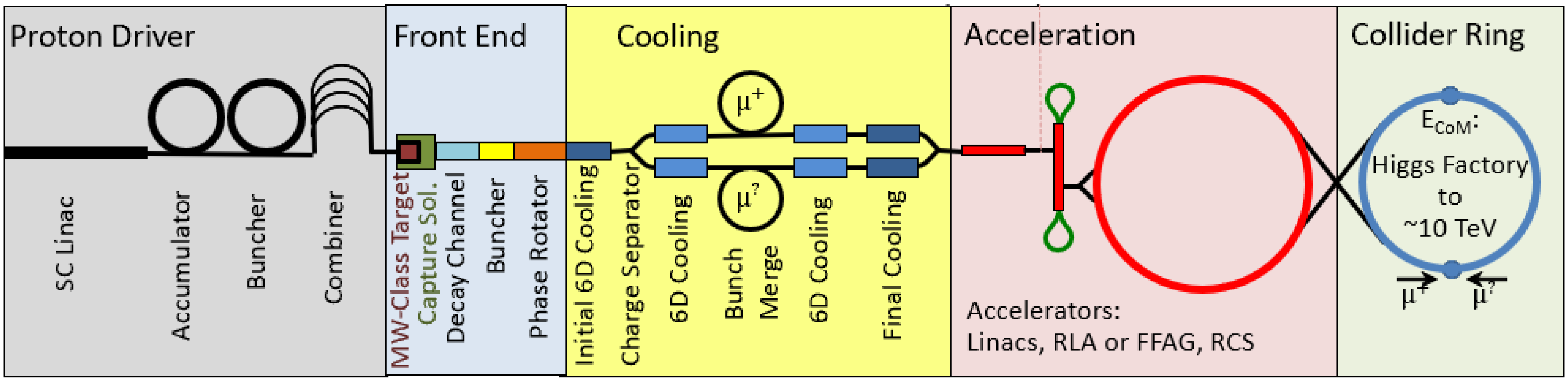
US effort @ present

- Enthusiasm about MuC is surging in the US
- R&D coordination group was formed to provide input to P5
  - Focus on 10 TeV accelerator & detector design
  - Develop R&D plan, activities, budget, deliverables
- Ramp-up budget profile
  - **Enable the US to compete for hosting a Muon Collider**



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

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

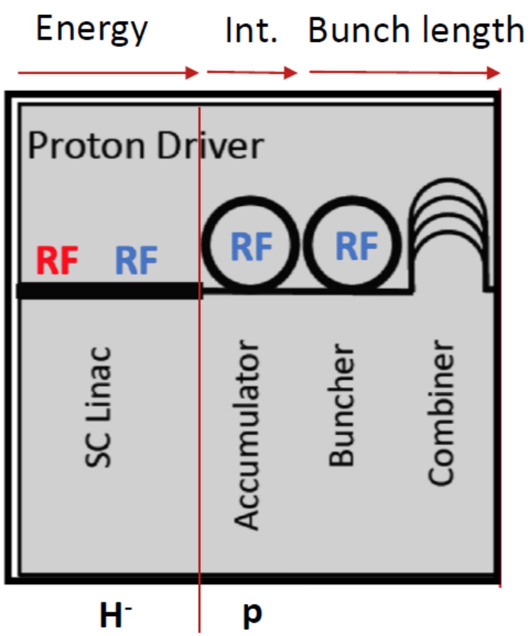
- **Luminosity** is a measure of the collider efficiency
  - Given by
$$L = \frac{N_+ N_- n_C f}{4\pi\sigma_x\sigma_y}$$
- **High** charge per muon bunch of each sign
  - Requires a **powerful** proton driver, **high-yield** target & **fast** acceleration
- **Small** transverse beam size
  - Requires 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

A MuC is an interplay between magnet, rf cavity and target technologies which have to be pushed to their limits for peak efficiency

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

MuC proton driver: Concept & technology needs



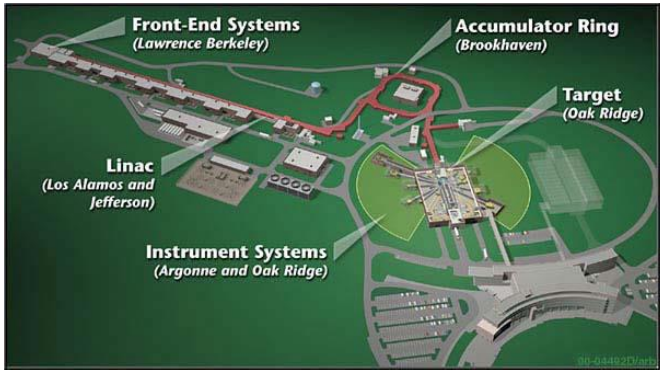
- Technology requirements for MuC driver:
  - Linac to: deliver ~5 GeV, ~10^{14} H- in ~ 1 ms
  - Accumulator ring to: (1) stripping H- → protons, (2) create four, 20 ns bunches
  - Buncher to: 20 ns → ~ns scale bunches
  - Combiner to: combine four bunches into one

- 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; provides a luminosity boost (for the same power)

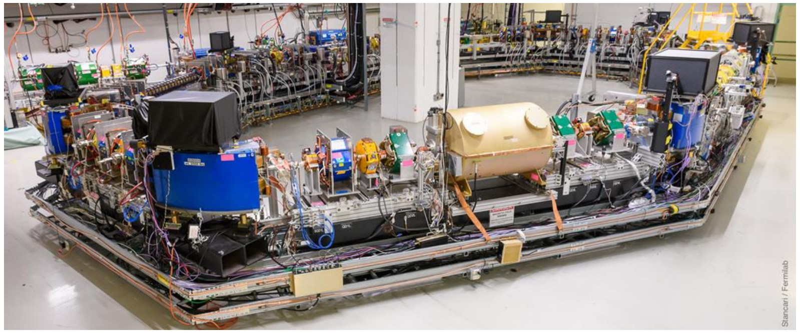
MuC proton driver: Moving forward

- Proton driver **does not** involve **new** technology or breakthroughs
- However, a good understanding of concepts such as injection stripping, ~ns bunch compression and bunch combining is needed
  - 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!

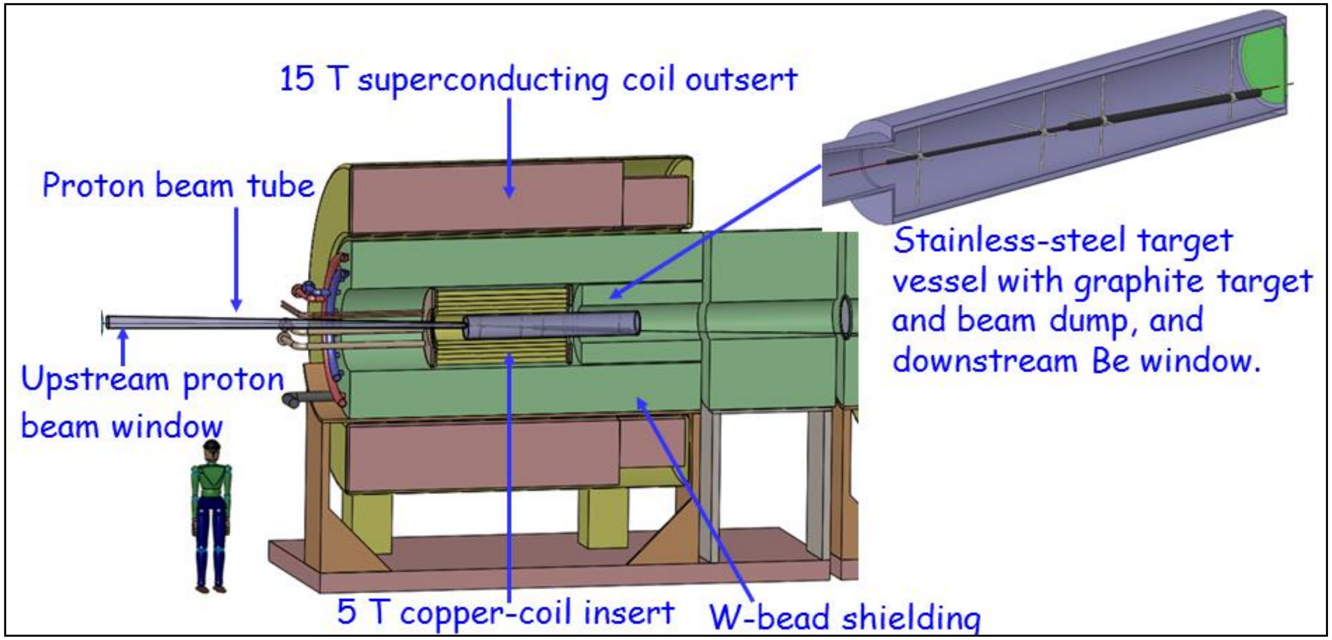
Oak Ridge SNS linac



Fermilab IOTA facility



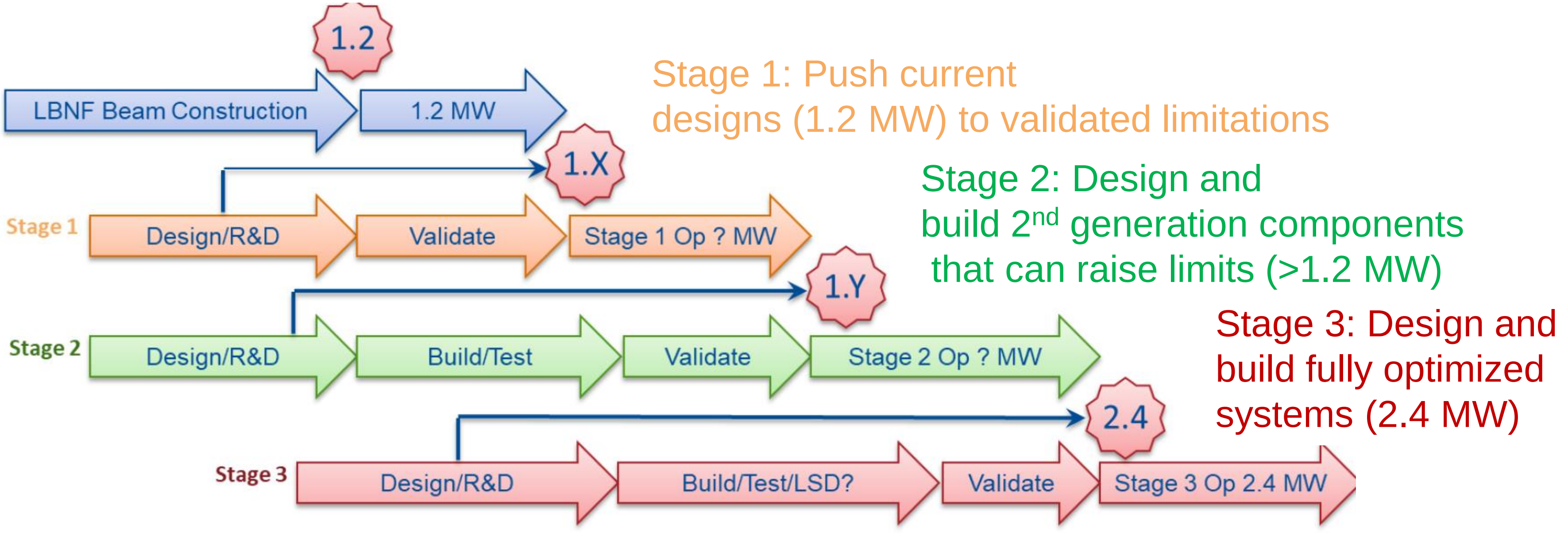
MuC target: Concept & technology needs



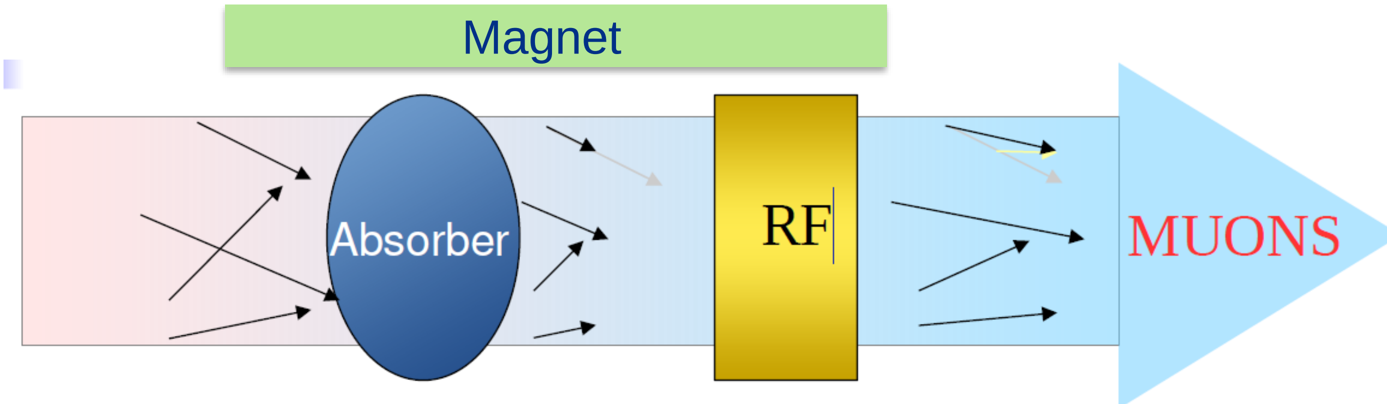
- Technology requirements for MuC targets:
  - Target materials that produce high muon yield & are tolerant to MW beams
  - Strong solenoidal magnet (15-20T) to maximize capture, with large aperture (2+ m) to allow shielding

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



MuC cooling – Concept & technology needs

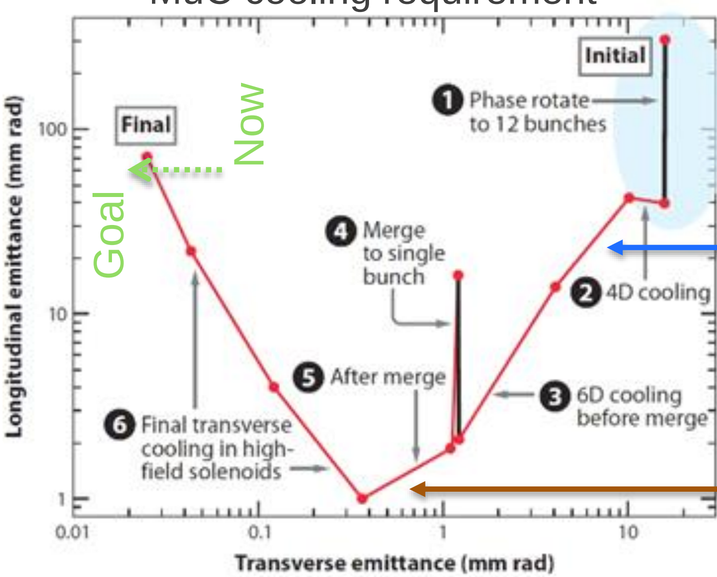


- Technology requirements for MuC cooling:
  - Large bore solenoidal magnets: From 2 T (500 mm IR), to 20+ T (50 mm IR)
  - Normal conducting rf that can provide high-gradients within a multi-T fields
  - Absorbers that can tolerate large muon intensities
  - Integration: Solenoids coupled to each other, near high power rf & absorbers)

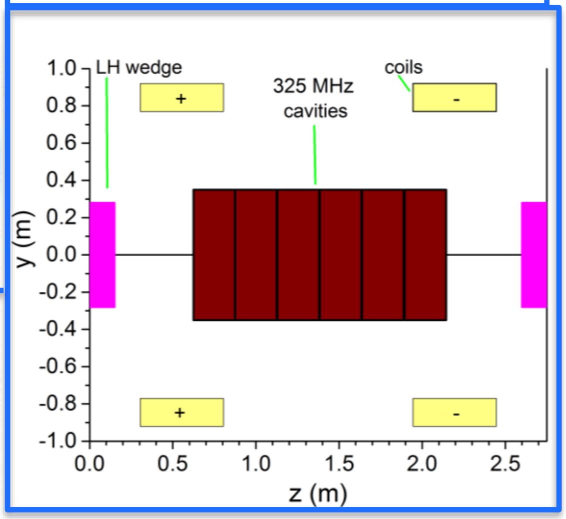
MuC cooling: Path forward (design)

- Good progress in all cooling section designs over the last years. **BUT**, the final cooling **did not** achieve our goals [ref]
- Goals for next **5-7 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

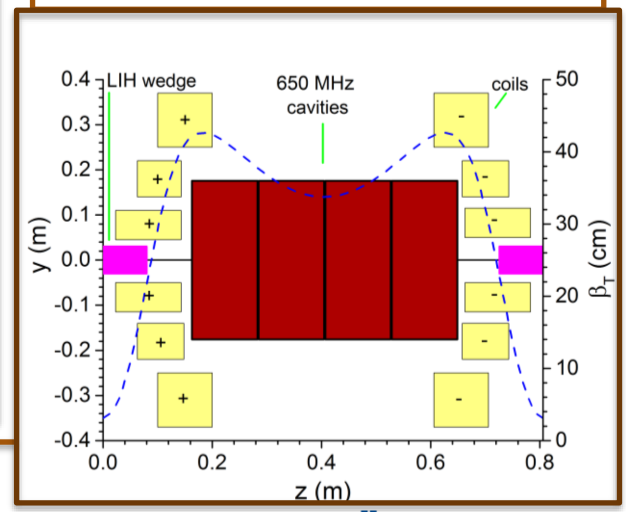
MuC cooling requirement



Early cell ("easy") – 2T peak

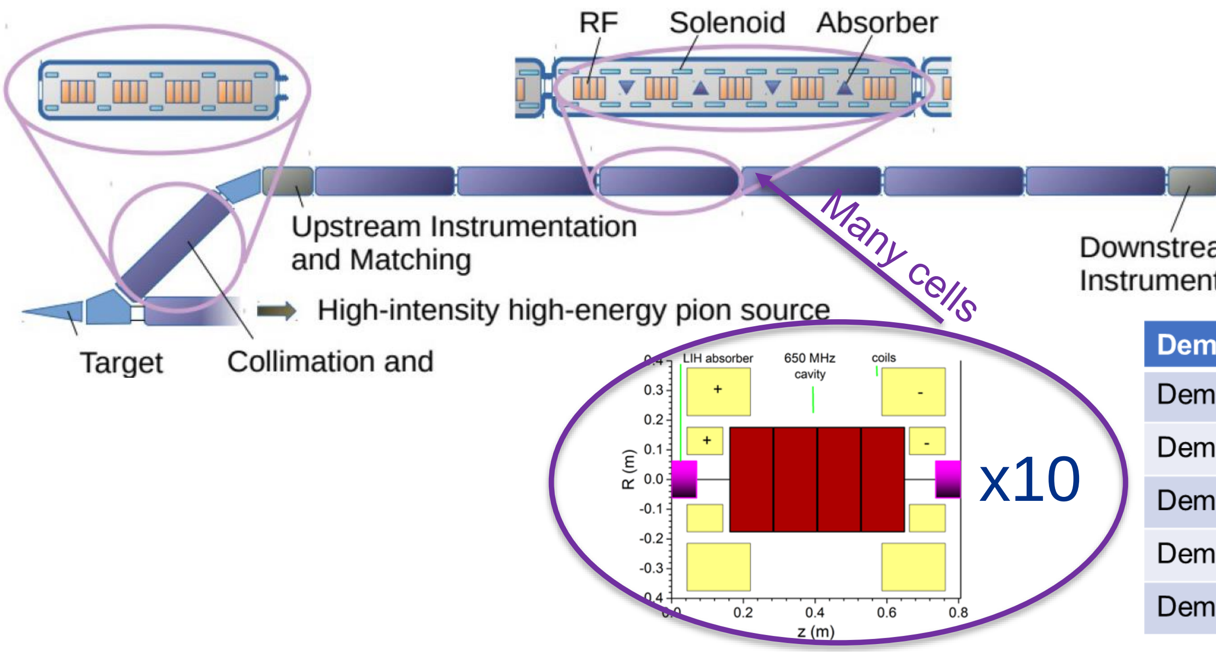


Late cell ("hard") – 14 T peak



MuC 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 **5-7 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

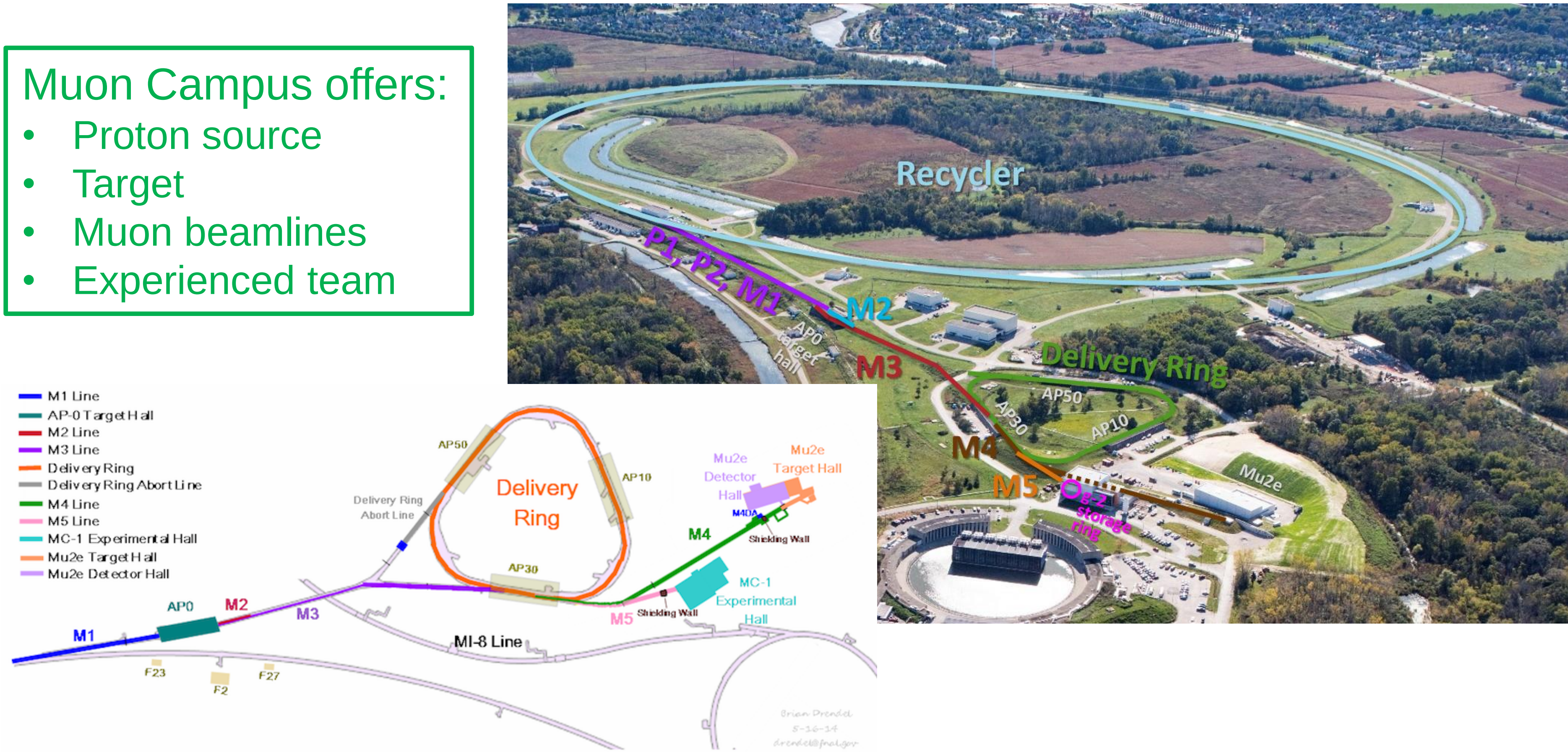


Demonstrator plan
Demonstrate operation of NC rf in B-field environment
Demonstrate forces between coils are manageable
Demonstrate performance of absorbers
Demonstrate performance of instrumentation system
Demonstrate 6D cooling with a realistic set-up

A possible site: Fermilab Muon Campus

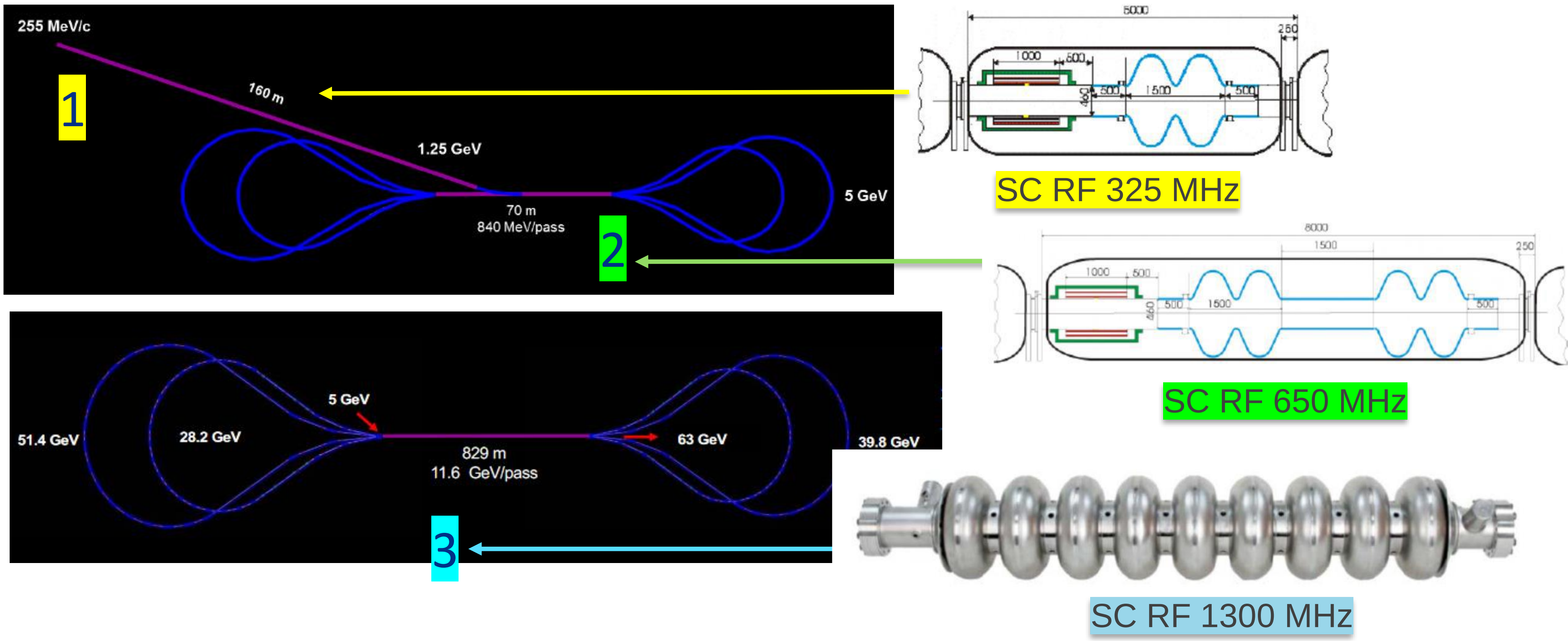
- Designed to provide beam for the Muon g-2 and Mu2e experiments
  - Muon g-2 experiment ended this year → Beamlines are available

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



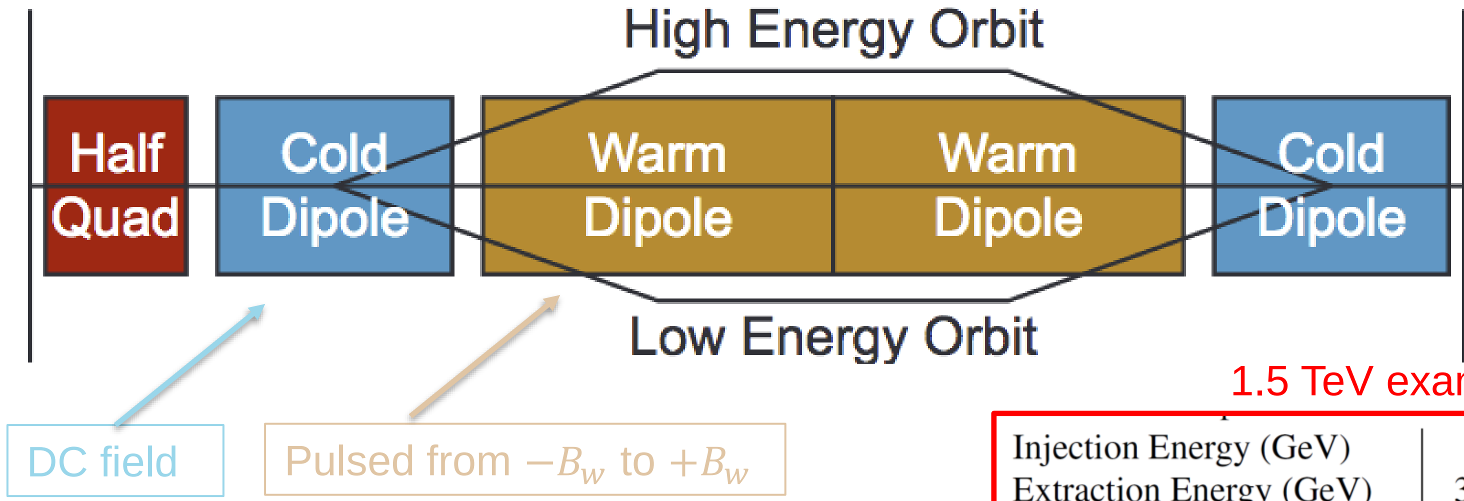
Fermilab

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

MuC TeV acceleration – Concept & technology needs

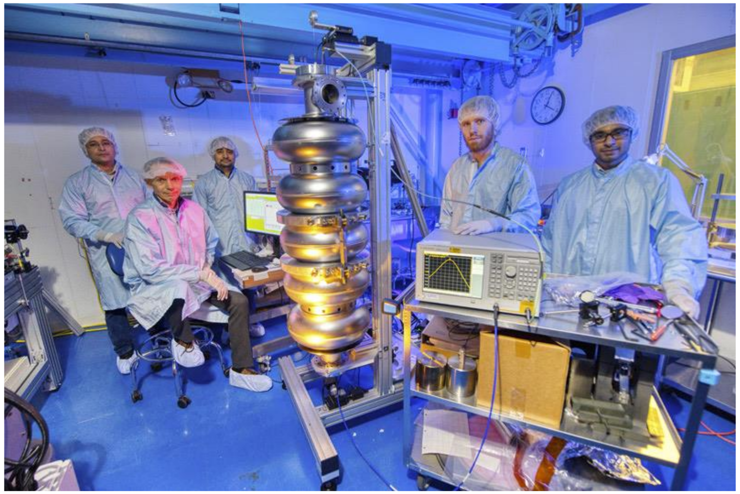


1.5 TeV example

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
  - Rapid Cycling Synchrotron accelerators
  - Fast ramping magnets (<0.5 ms) accompanied with a 8-10 T DC magnet
  - Energy sources with good power management for pulsed magnets

MuC acceleration: Path forward

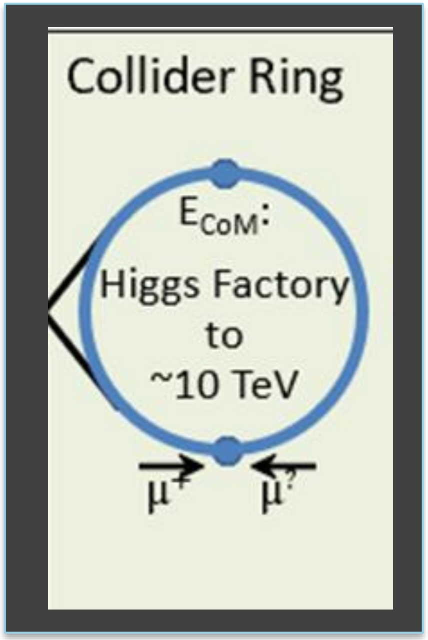


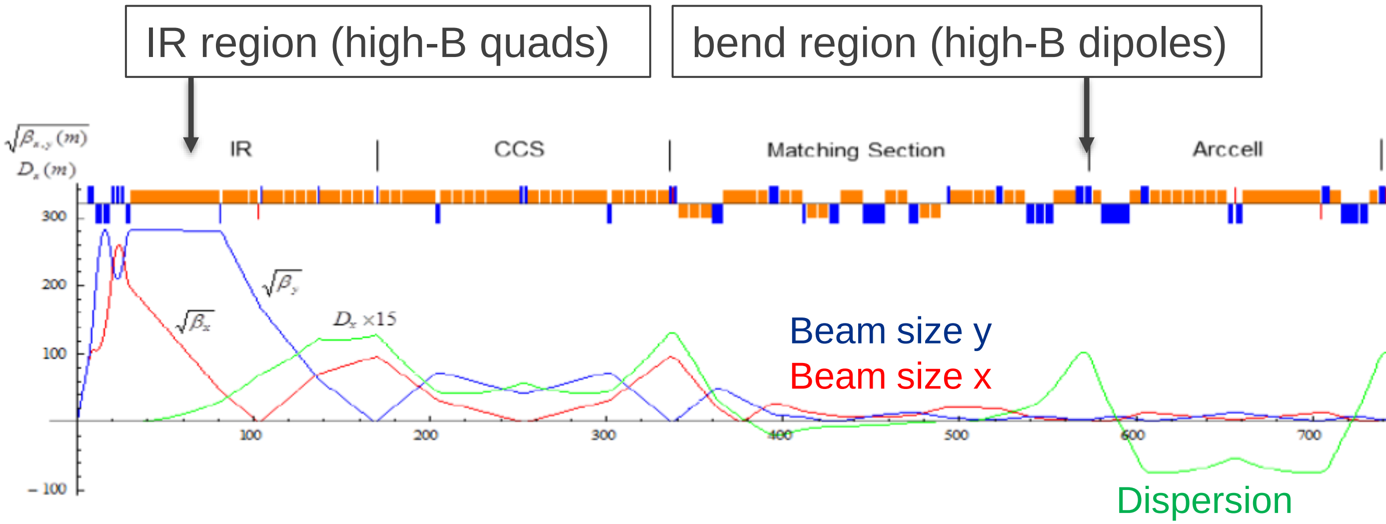
5 cell elliptical cavities @ 650 MHz for PIP-II

Cryomodule @ 1300 MHz for LCLS-II

- Develop 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 – Concept & technology needs



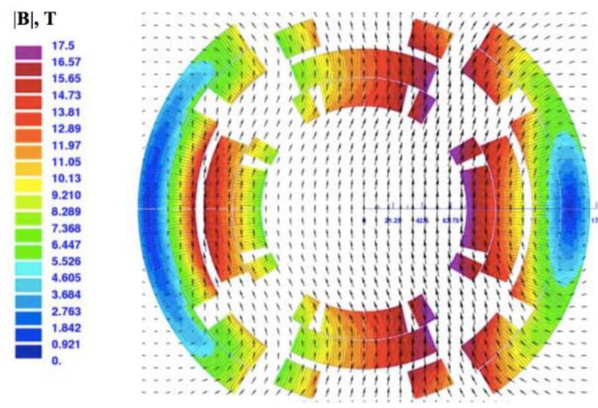


- Technology requirements for a MuC collider ring
  - Quadrupoles with strong fields for the IR (15-20 T for 10 TeV)
  - Dipoles with strong field (12-16 T for 10 TeV) and large aperture (~150 mm) to allow for shielding
  - Mitigation system for the neutrino flux from muon decays

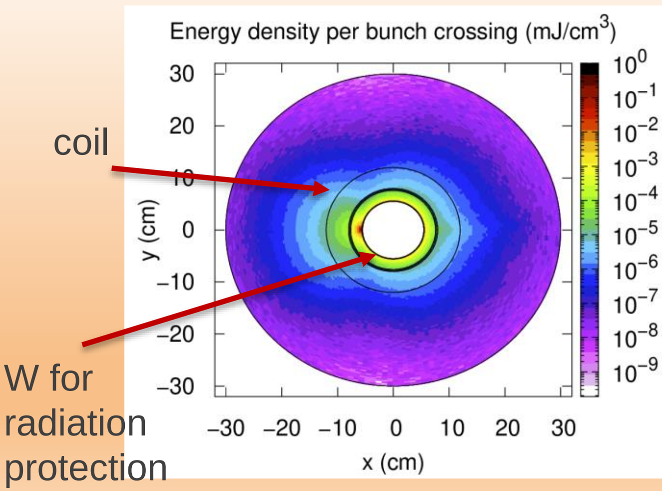
MuC collider ring – Path forward

- 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

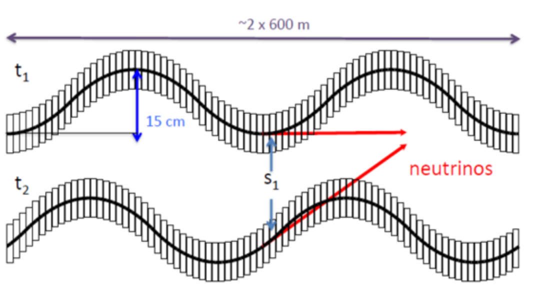


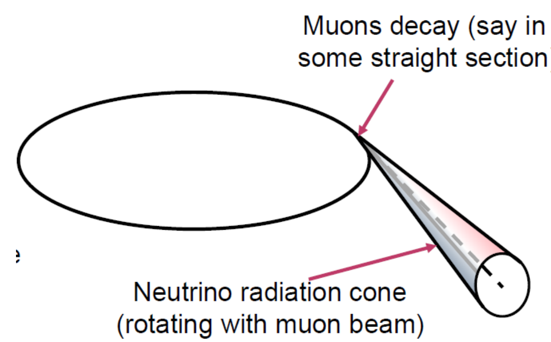
10 TeV radiation studies

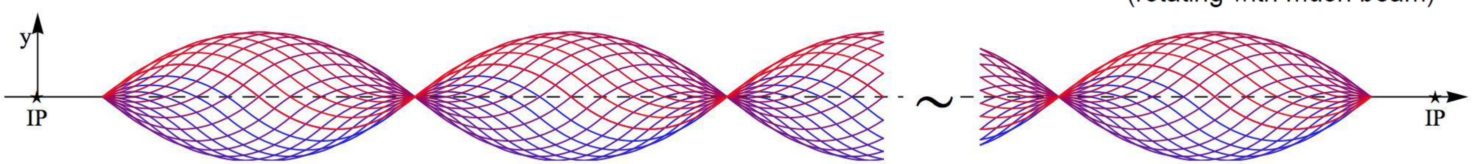


Neutrino flux mitigation system

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



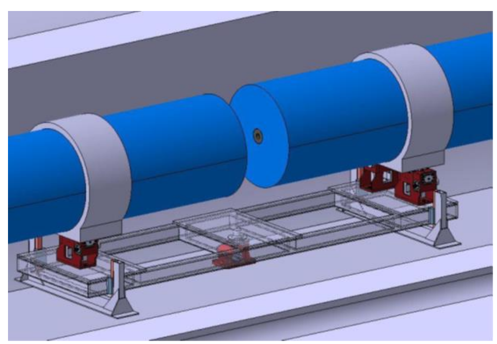




Vertical slope modulation ~ 1 mrad

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

Working on different approaches for experimental insertion



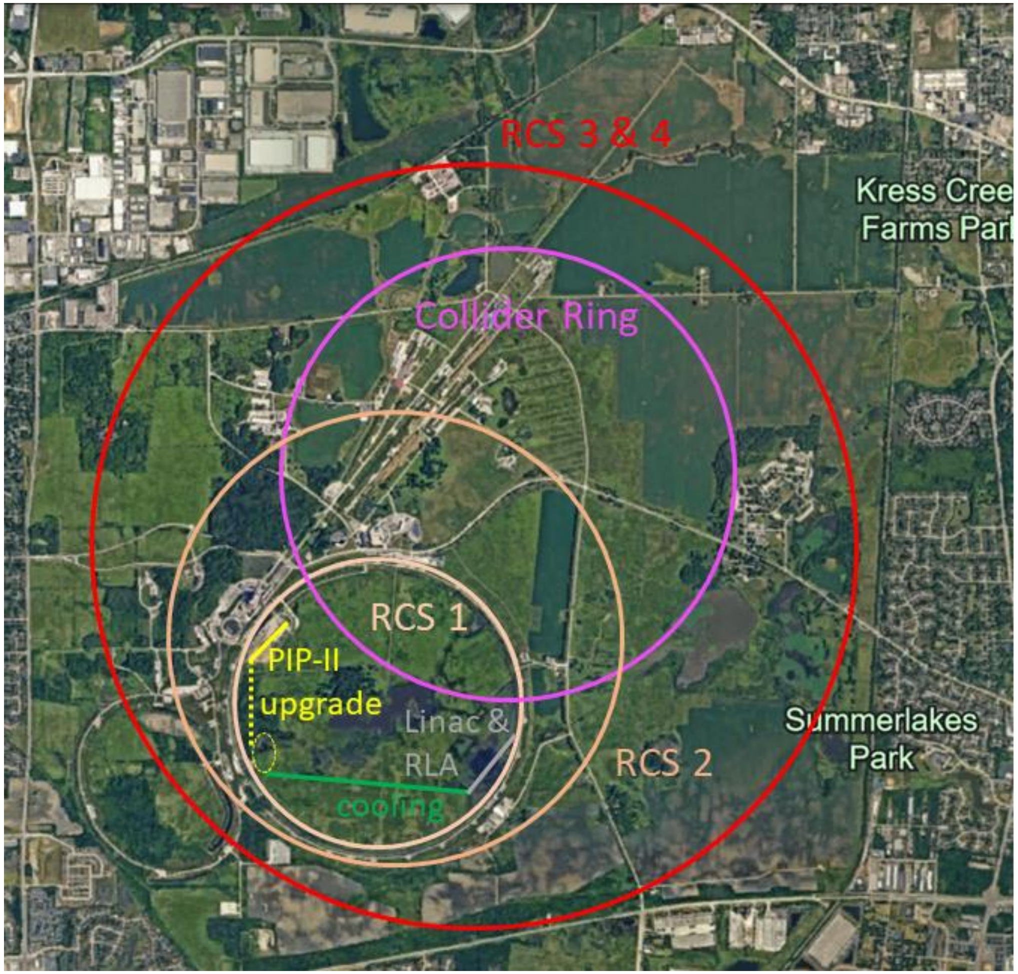
Legal limit: 1 mSv/year
MAP goal: <0.1 mSv/year
IMCC goal: <10 µSv/year
LHC : <5 µSv/year

Requires significant R&D and proof-of principle tests

Fermilab

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 5-7 years we like to have a baseline design including a neutrino flux mitigation system

Proposed MuC accelarator US 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 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