Muon Collider and synergies with LC

an accelerator perspective

Tianhuan Luo, on behalf of US Muon Collider Community

LCWS23, 05/15/2023

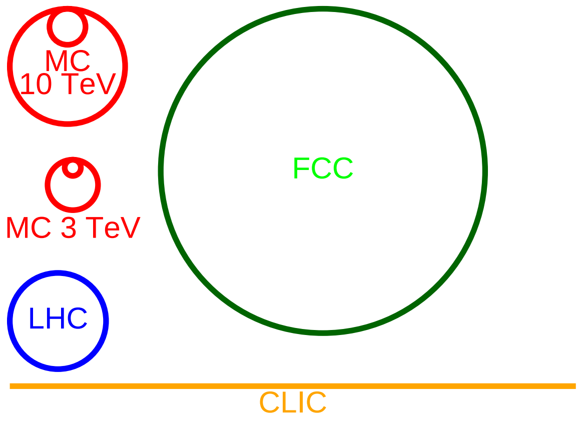
BERKELEY LAB

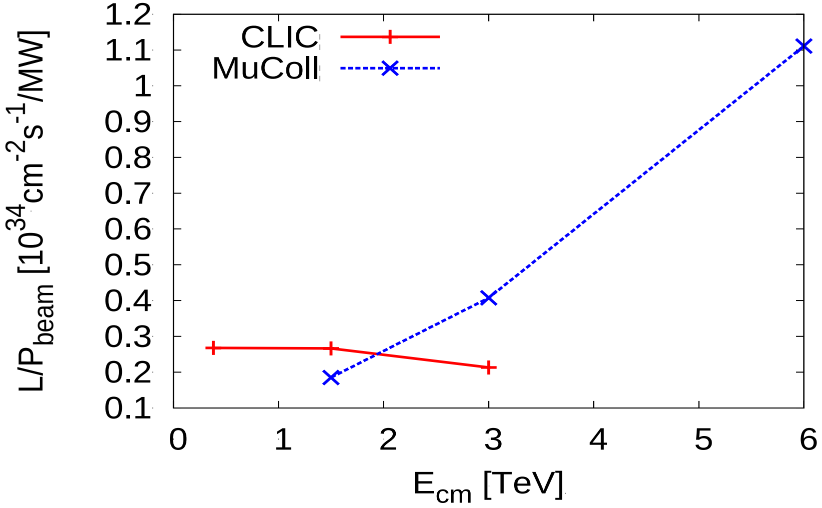
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

Why Muons?

- **Muons** as compared to **protons**
  - Muons are elementary particles and all their energy in a collision is used.
  - As a result, need much less collision energy for the same physics.
- **Muons** as compared **electrons**
  - Muons emit little synchrotron radiation, ~ 200 times heavier than electrons.
  - As a result, acceleration in rings possible up to many TeV.
  - Little bremsstrahlung at the interaction region.
- In a **Muon Collider**, luminosity to beam power ratio improves substantially with energy
- A Muon Collider combines **a small footprint** and a **high energy efficiency**!





Main challenges

- Muons are difficult to produce
    - Most effective way is tertiary production from a multi-MW proton beam on a target: protons → pions → muons
    - Beams must be bunched and cooled to produce luminosity in a collider
- Muons decay
    - All manipulations must be done **fast**
        - Capture
        - Bunching
        - Cooling
        - Acceleration
    - Electrons from muon decays deposit significant energy in the accelerator components and physics detectors
    - Neutrinos from muon decays can produce ionizing radiation far from the accelerator complex

A brief history of muon collider

1960s

Muon storage ring first mentioned in the literature in 1965.

1970s to 90s

Concepts for a MuC and the required muon cooling were developed. A MuC collaboration delivered a design study in 1999.

2000-2011

The Neutrino Factory and Muon Collider Collaboration (NFMCC) was formed to validate the critical design concepts for the Neutrino Factory (NF) and the MuC

2011 - 2016

The Muon Accelerator Program (MAP) assessed the feasibility of the technologies required for the construction of the NF and the MuC, producing a number of significant milestones.

2022

Muon Colliders became part of the European Accel. R&D Roadmap. International Muon Collider Collaboration (IMCC) has formed and is hosted by CERN.

2022

Snowmass study revealed strong interest on MuC, and produced the Muon Collider Forum Report: a coherent vision for Muon Colliders from the US perspective.

2023

Formation of the US Muon Collider R&D coordination group, which coordinates and provides community input to P5 on MuC research

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SLC full operation started in 1989

2000-2011

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ILC TDR published in 2013.

CLIC CDR published in 2012.

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Why a muon collider NOW?

- New Physics Needs:
  - The LHC run indicates the absence of definitive signs of new physics up to the TeV scale, pointing to the next Energy Frontier collider at 10+ TeV scale.
  - Muon collider: a promising pathway to very high energy beyond ee or hh paradigm.
- Detector readiness:
  - Large leap in detector technologies in part from R&D done for HL-LHC upgrades.
  - Feasibility of good quality physics in Muon Collider environment established in simulation.
- Accelerator readiness:
  - Muon Accelerator Program (MAP) design & simulation work have demonstrated via simulation the performance of realistic system designs for nearly all of the sub-systems required for a muon collider.
  - Key technological progress: multi-MW proton sources, high-power target, demonstration of RF in magnetic field, high field magnets, good solution for neutrino flux mitigation, etc.
  - Muon Ionization Cooling Experiment (MICE): confirmed muon ionization cooling principle, engineering demonstration of key subsystems and their integrations.

International Efforts

- In 2020, following the 2018 European Strategy process, CERN Laboratory Directors Group initiated a Muon Collider feasibility study.
- In 2022, the International Muon Collider Collaboration (IMCC) was formed and hosted at CERN.
- Several US universities started to join, many more expressed interest.
- IMCC planning assumes a significant US participation to develop the baseline project and the best siting option (including US siting).

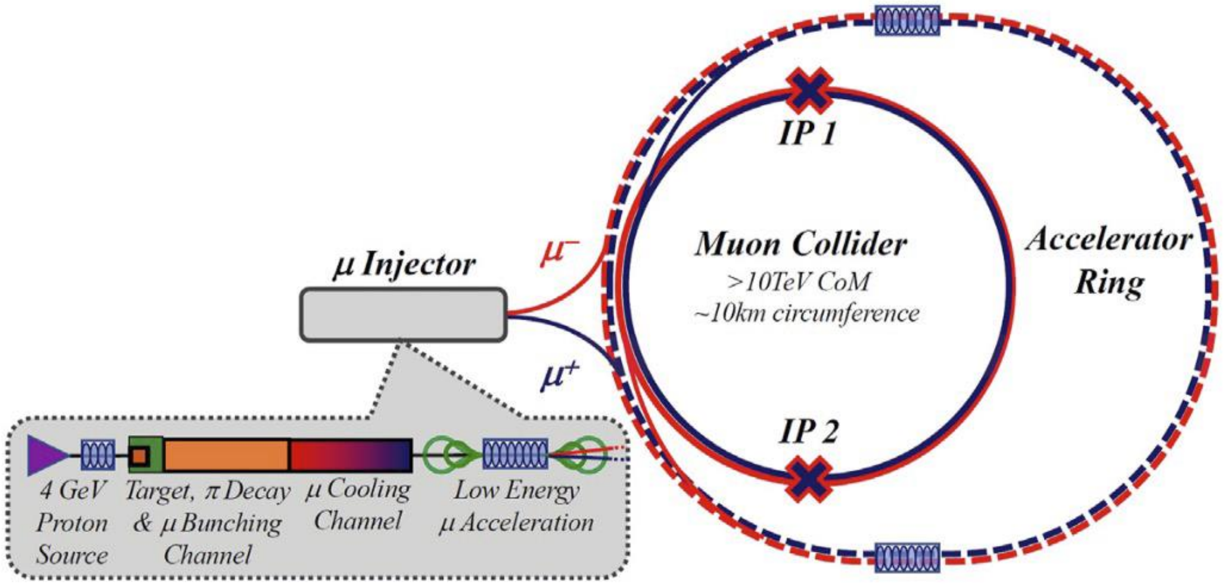
IMCC Meeting, CERN, Oct 2022

International
MUON Collider
Collaboration

https://muoncollider.web.cern.ch/

IMCC Target parameters

- The goal is to get to **10 TeV center-of-mass energy**
- Consider proton driver based Muon Collider
- Staging at 3 TeV is the current baseline
- Aim to have two detectors but only one experiment assumed now



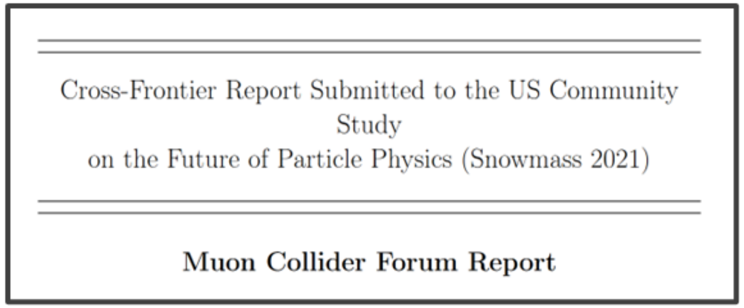
@ 3 TeV ~ 1 ab^{-1} 5 years

@ 10 TeV ~ 10 ab^{-1} 5 years

Enthusiasm on a muon collider is surging in US

Snowmass Muon Collider Forum

- The forum established a strong collaboration between the AF+EF+TF frontiers for Muon Collider (MuC) research.
- MuC was the most studied machine during Snowmass. Many new results & papers, propagated to the EF vision.



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

Muon Collider Forum Report

~180 authors, 50+% are early career scientists

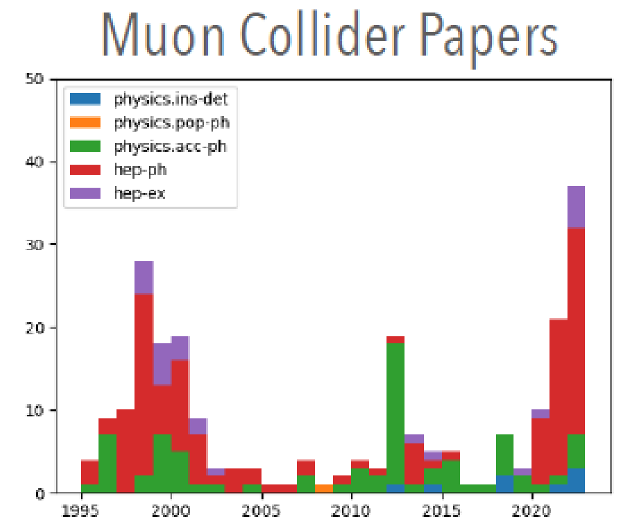
Workshop on Muon Driven Colliders

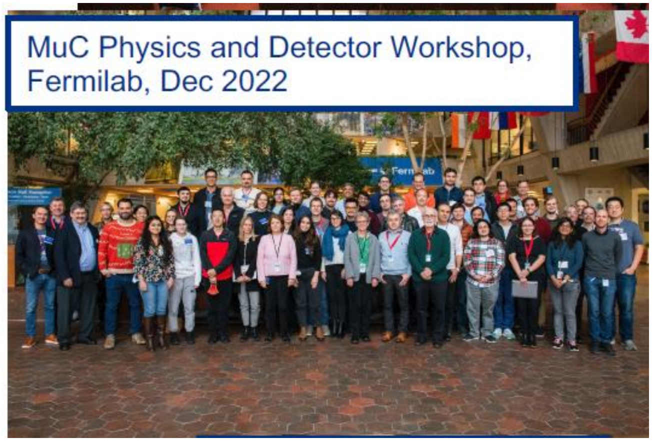
Jan 26, 2022, 10:00 AM → Jan 27, 2022, 1:00 PM US/Pacific

Zoom

Description In preparation for the Snowmass 2022 white paper from Muon Collider Forum, this workshop is dedicated to review the current status in Accelerator Physics and Technology and identify critical R&D areas for future Muon Collider, including a site filler option in the US.

Registration *You are registered for this event.*





MuC Physics and Detector Workshop, Fermilab, Dec 2022

Muon Collider

196 Tweets

Muon Collider

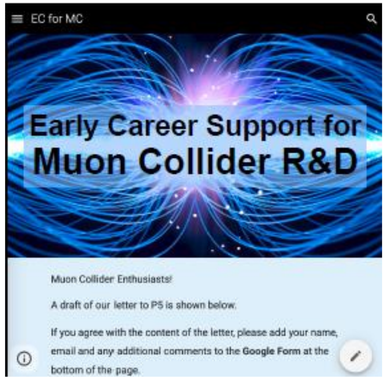
@MuonCollider

Account for a future muon collider.
Follow for muon collider updates, facts & discussion

Swag: redbubble.com/people/muon-co...

Joined December 2022

51 Following **778** Followers



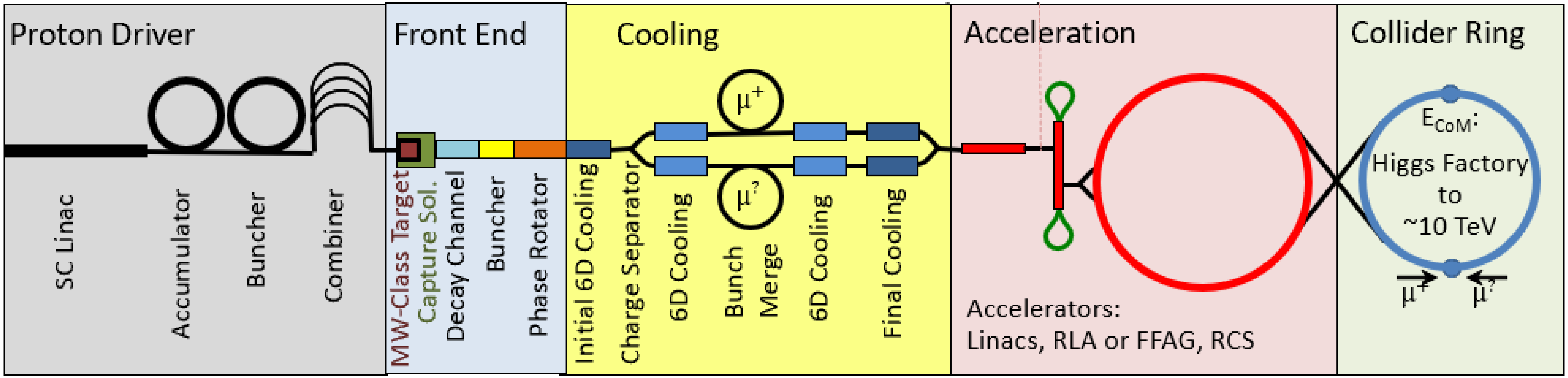
Muon Collider Enthusiasts!

A draft of our letter to P5 is shown below.

If you agree with the content of the letter, please add your name, email and any additional comments to the **Google Form** at the bottom of the page.

KITP Workshop, Santa Barbara, March 2023

Machine overview



MW-scale proton driver

Muon production target

Capture 200 MeV bunches

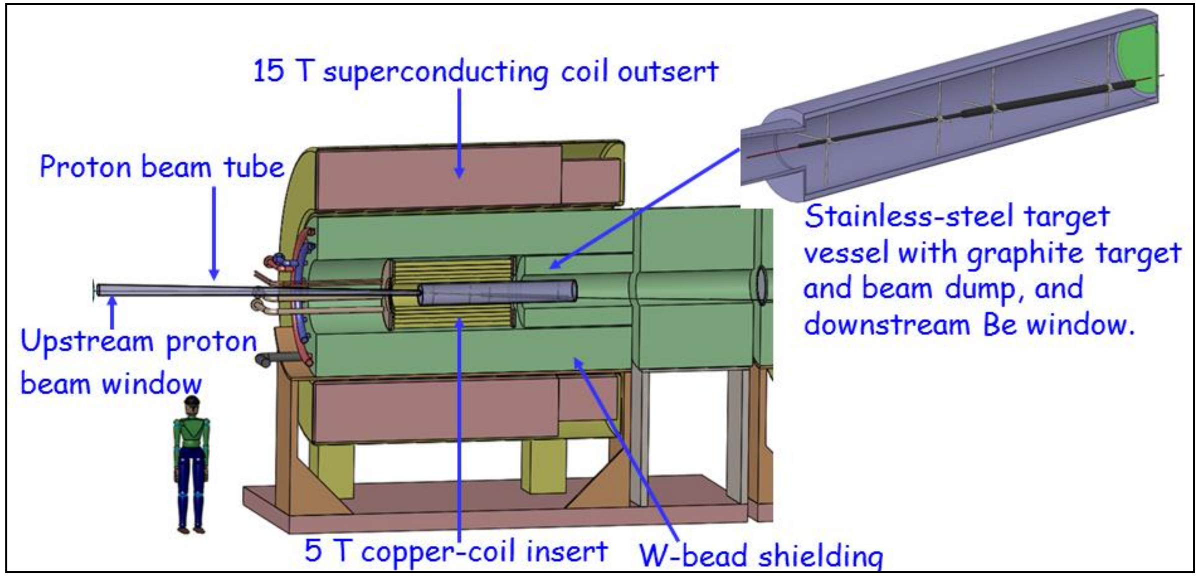
Ionization cooling to reduce 6D emittance

Acceleration to TeV scale energy

Collider ring for counter propagating muons

- Requires a 1-4 MW proton beam, 5-15 GeV in energy, compressed to 1-3 ns bunches.
- Proton driver has strong synergies with Fermilab Proton Accelerator Complex Evolution (ACE) plan.

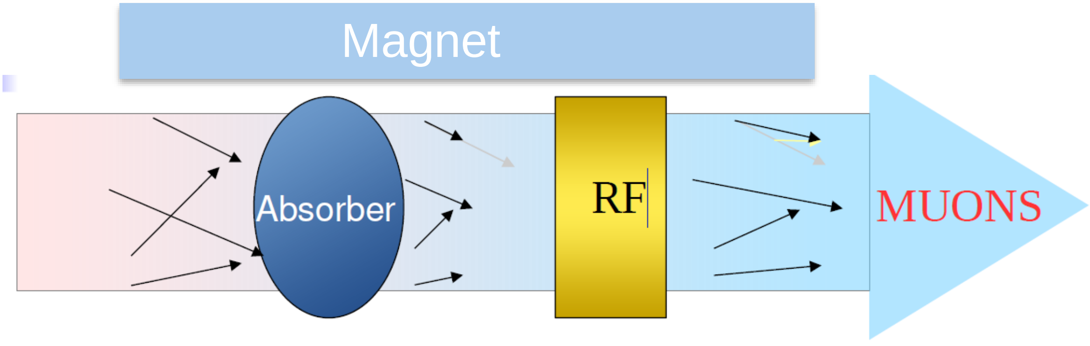
MW target for muon production

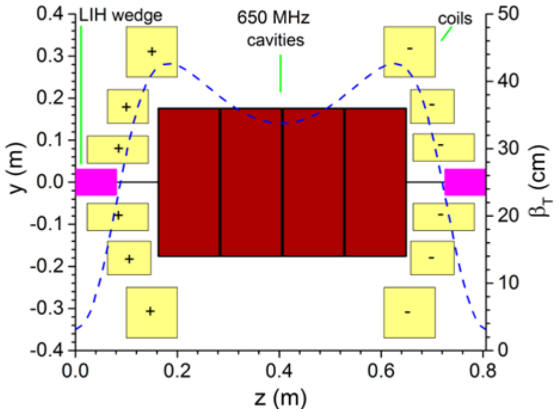


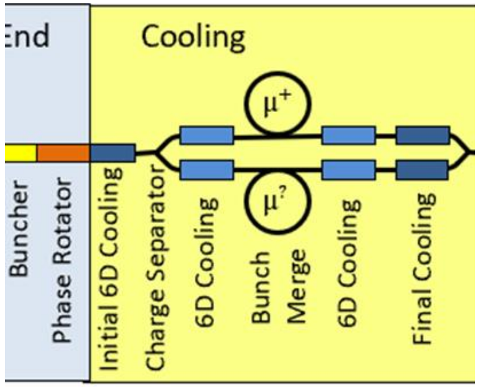
- Recent work shows promising results with C or W but still significant R&D is needed to confirm that the target can withstand 2+ MW
- High-power targets development is in a synergistic path with many future experiments, including LBNF, Mu2e, proposed Mu2e-II, AMF.
- MuC targetry is included in the proposed GARD High Power Targetry Roadmap with a plan to have a prototype in the late 2030s.

- 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

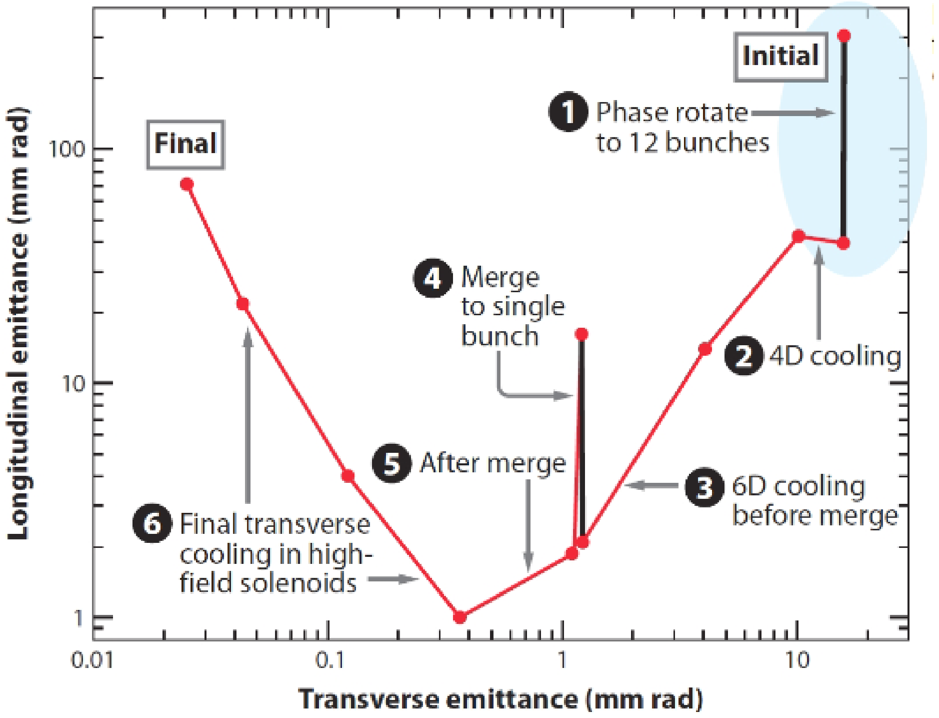
Cooling – reduce 6D emittance by 6 orders in short time





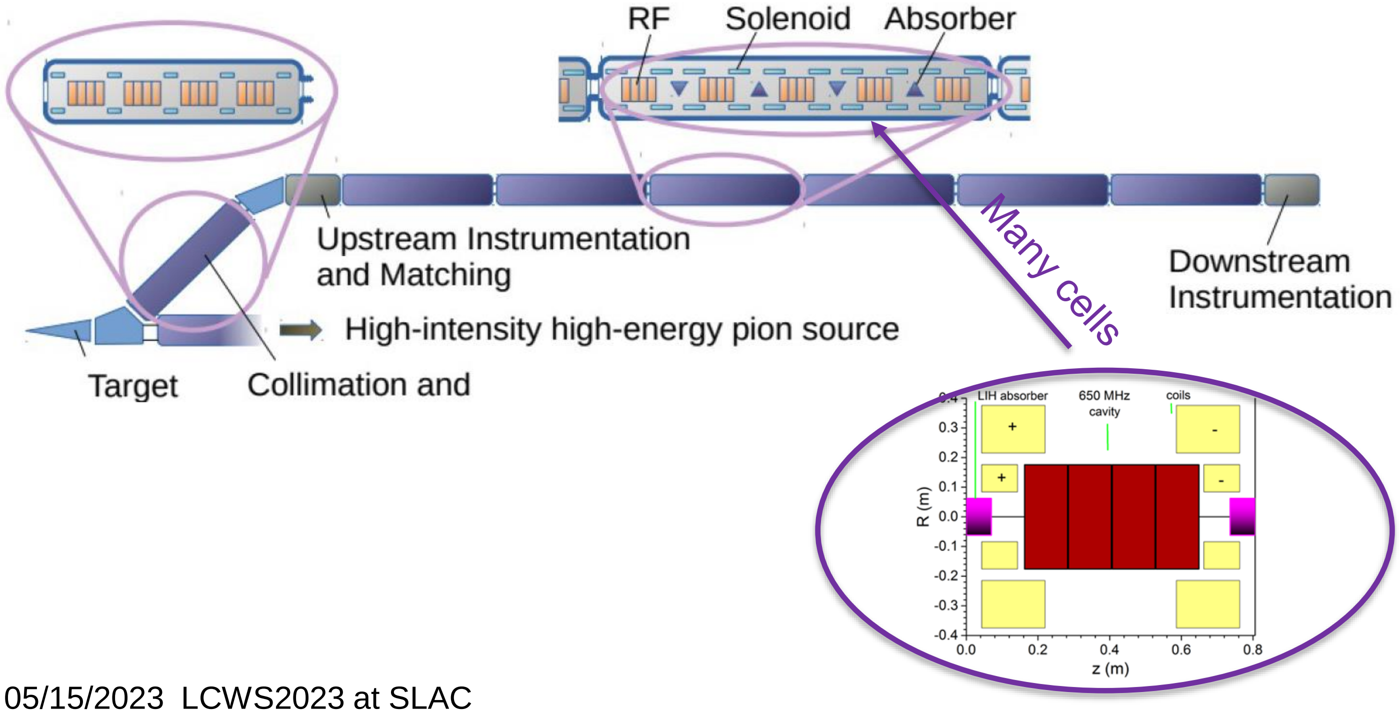


- Technology requirements for MuC cooling:
  - Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
  - Normal conducting rf that can provide high-gradients within a multi-T fields
  - Absorbers that can tolerate large muon intensities
  - Integration: Solenoids coupled to each other, near high power rf & absorbers)



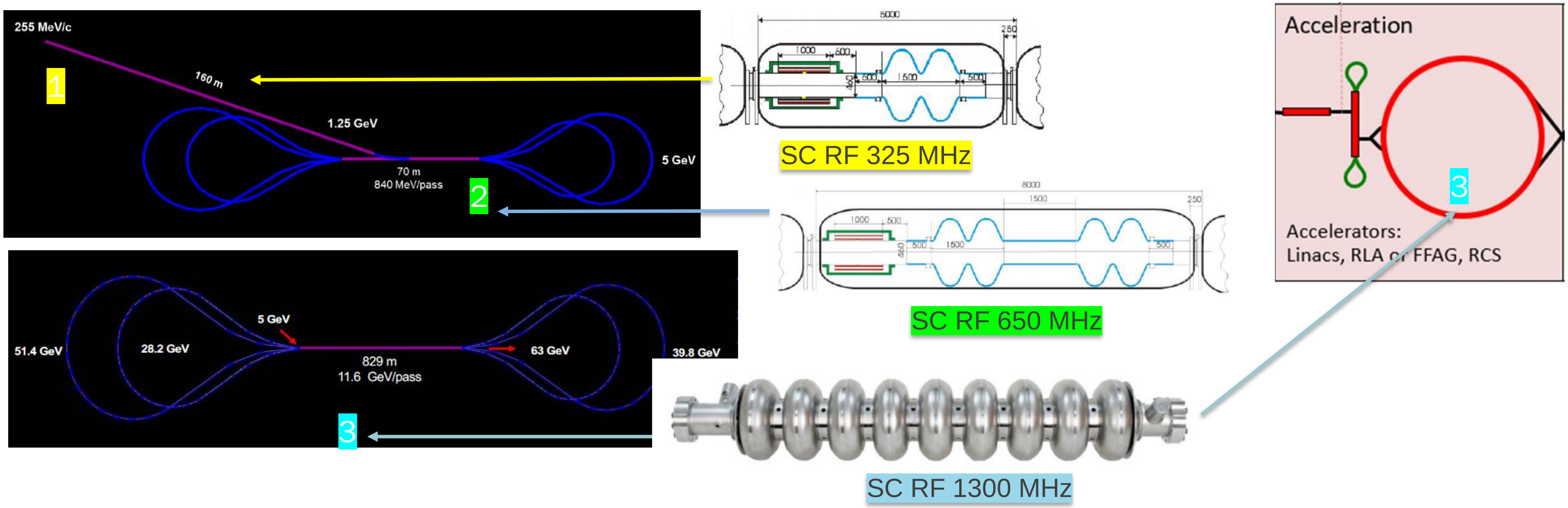
Cooling Demonstrator

- While the physics of ionization cooling has been shown, it is **critical** to benchmark with 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 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

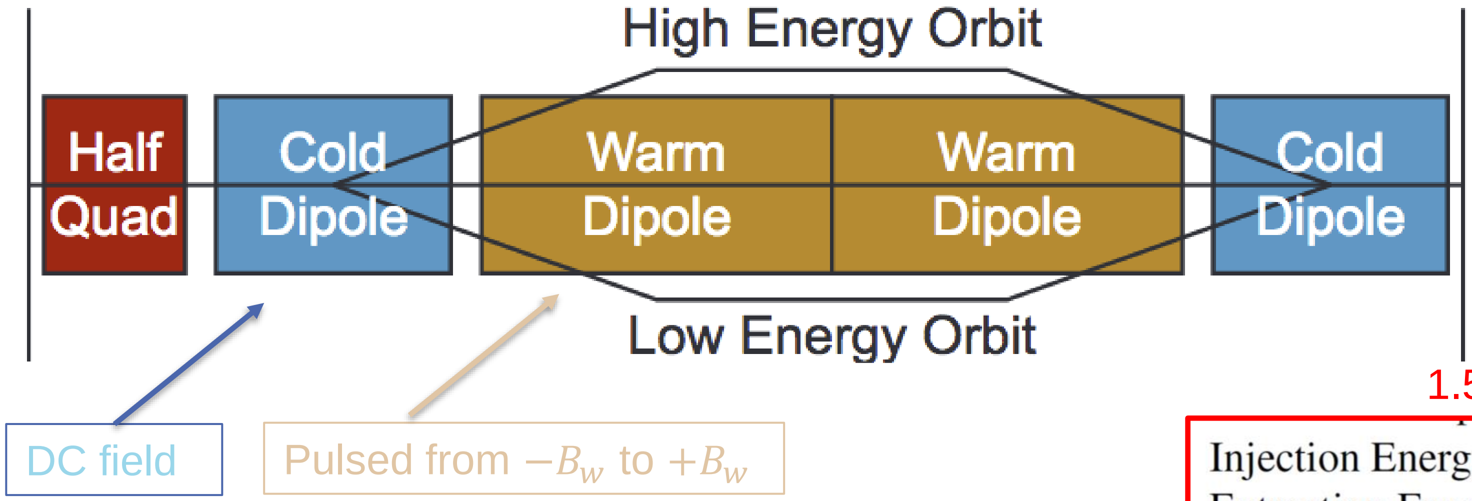
Acceleration: high gradient UHF/L band SRF



- Technologies requirements for a Muon Collider:
  - Superconducting linacs, Recirculating linear accelerators (RLAs) and Rapid Cycling Synchrotron (RCS).
  - SC RF that: (1) starts at a low frequency ~ 325 MHz, up to 1.3 GHz, (2) operates at high-gradients up to 30+MV/m.

- Extensive SRF production experience from PIP-II, LCLS-II…
- Synergy with ILC, FCC-ee… for further advancing the SRF gradient.

Acceleration: SC and faster ramping NC magnets

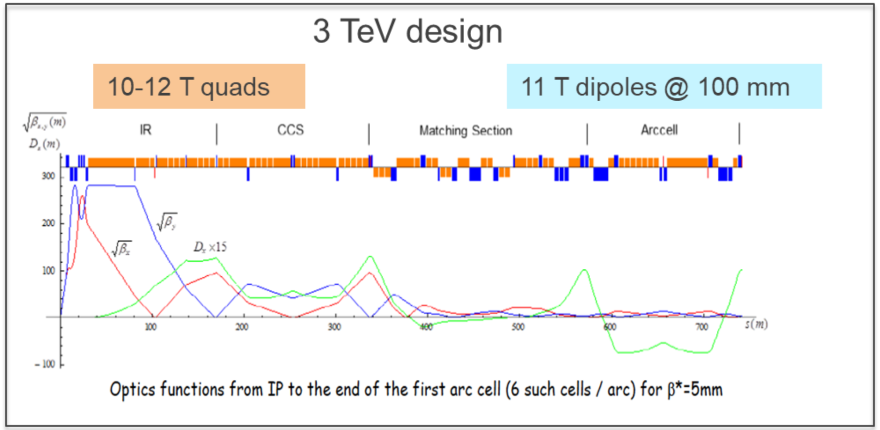


1.5 TeV RCS example

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
  - Fast ramping magnets (<0.5 ms) accompanied with a 8-10 T DC magnet
  - Good energy storage and power management for pulsed magnets

Collider ring: strong SC magnets and neutrino flux mitigation

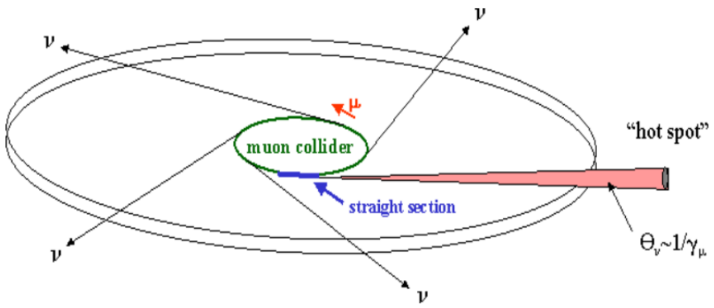


3 TeV design

10-12 T quads

11 T dipoles @ 100 mm

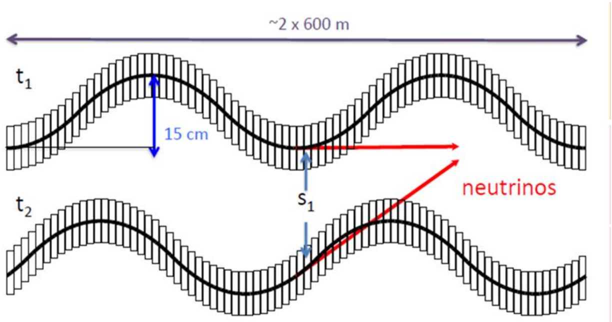
Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm



One solution for 10 TeV MuC, meeting LHC dose rate requirement: A mechanical system that will disperse the neutrino flux by periodically deforming the collider ring arcs vertically with remote movers; (D. Schulte, IPAC 22)

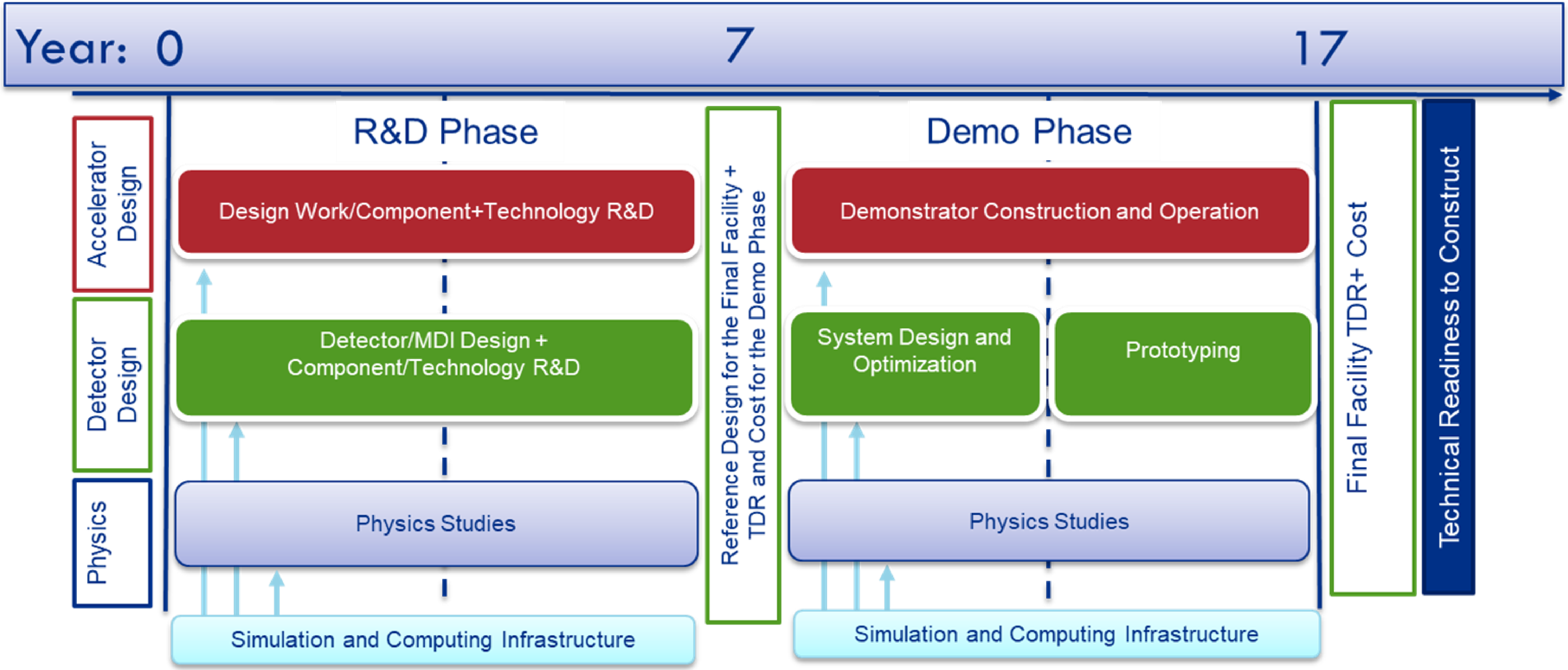
Lattice design in place for a 3 TeV collider with optics and magnet parameters within existing technology limits. 10 TeV design is ongoing.

- Technology requirements for a Muon Collider (10 TeV)
  - Strong quad focusing (> 12 T at IR)
  - High-field dipoles (12-16 T) with large aperture (~150 mm) for shielding
  - Mitigation system for the neutrino flux from muon decays



Other solutions are also available. (N. Mokhov)

US Muon Collider timeline



Year: 0 7 17

R&D Phase

Demo Phase

Accelerator Design

Detector Design

Physics

Design Work/Component+Technology R&D

Detector/MDI Design + Component/Technology R&D

Physics Studies

Simulation and Computing Infrastructure

Reference Design for the Final Facility + TDR and Cost for the Demo Phase

Demonstrator Construction and Operation

System Design and Optimization

Prototyping

Physics Studies

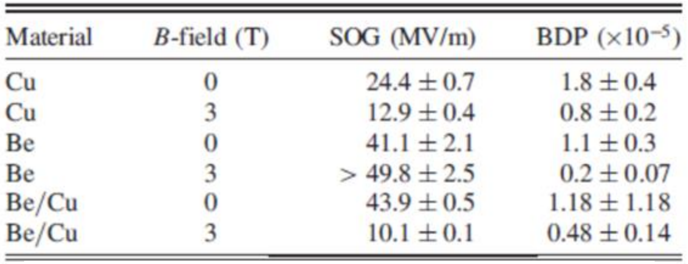
Simulation and Computing Infrastructure

Final Facility TDR+ Cost

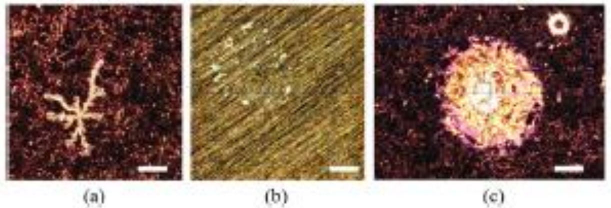
Technical Readiness to Construct

Synergies with LC: NCRF for ionization cooling

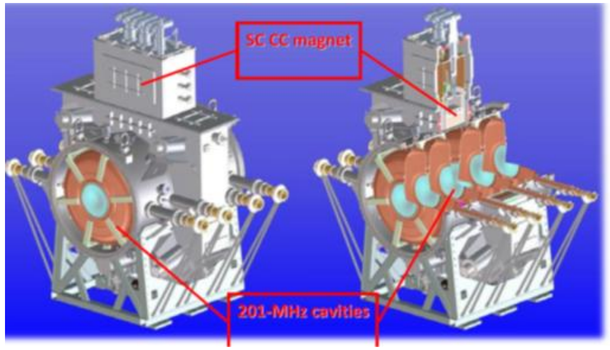
- High gradient acceleration
  - High gradient RF in multi-Tesla magnetic field is an essential element for ionization cooling.
  - External B field significantly reduced the achievable gradient.
  - Understanding and mitigating this gradient degradation have been a focus for ionization cooling development. Significant progress has been made, further developments are needed.
  - Strong synergies with LC high gradient RF study.
- C^3 LINAC
  - Cool copper cavity: extend its superior resilience to RF breakdown to strong B background and UHF band.
  - Distributed coupling for iris-enclosed cavities.
  - Engineering commonalities such as the compact integration of high power NCRF and cryogenics.



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



MAP modular cavity, D. Bowring et al.



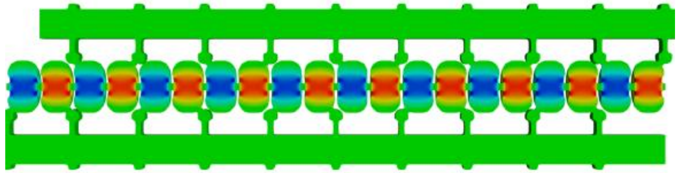
A 4-cell RF module for ionization cooling, designed for MICE.

Joint MAP & High Gradient RF Collaboration Workshop

November 1–4th, 2011 at Lawrence Berkeley National Laboratory

Please register by Friday, October 14th, 2011. ** Registration has been extended to October 31, 2011

Looking forward more in the future!



S. Tantawi et al.

Synergies with LC: SRF for acceleration

- 1.3 GHz SRF cavity
  - MuC: 30+ MV/m for RLA and RCS
  - ILC: specification of 31.5 MV/m. 30+ MV/m has been achieved, further progress likely to lead to 40+ MV/m.
- SRF R&D to further advance the gradient and other properties
  - New cavity designs: shape re-optimization, traveling wave structure, etc.
  - New cavity materials such as Nb3Sn
- HOM damping
  - MuC: Strong HOMs in RLA and RSC, due to very high bunch intensities.
  - ILC: HOM damper development for accelerating LINAC and Crab Cavity.

Summary

- MuC offers a promising paradigm to explore 10+TeV energy frontier, with compact foot print and high energy efficiency.
- The enthusiasms and collaborations are building up in US across physics, detector and accelerator communities.
- Technical readiness of a MuC has improved considerably over the last decade. Several elements have strong synergies with other programs, including LCs.
- Engineering challenges still exist and significant R&D is needed to improve a MuC risk profile. Unique elements require dedicated efforts.
- Concreted R&D plans have been made and presented to P5.
- International collaboration with IMCC and others.

Thank you for your attention

This presentation is largely based on the following contributions:

D. Stratakis, “Towards a Muon Collider accelerator”, presented at P5 Town Hall at SLAC.

S. Jindariani, “Towards Muon Collider detectors” , presented at P5 Town Hall at BNL.

Snowmass Muon Collider Forum Report.

And many others.

US Muon Collider R&D coordination group

- 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 (Wisconsin), Sergo Jindariani, Diktys Stratakis (Fermilab)

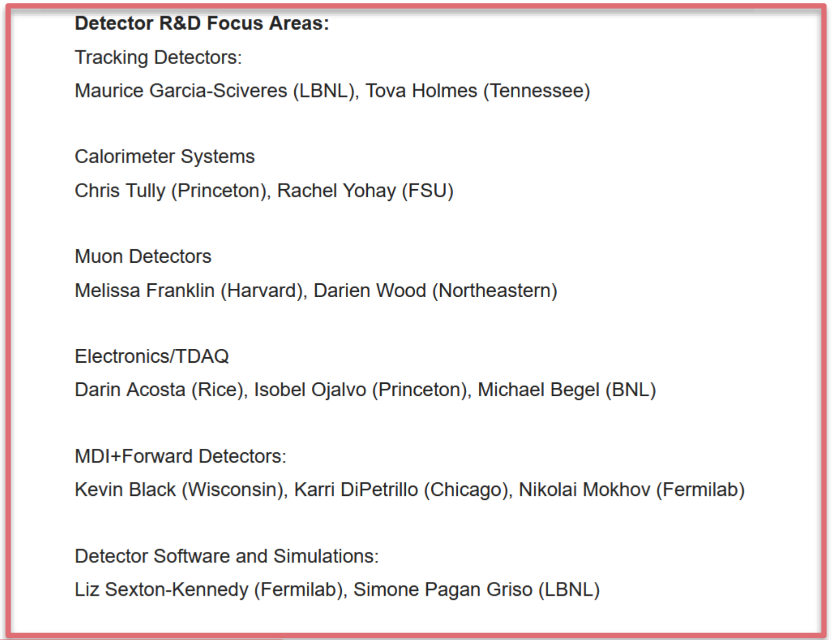
Physics Case Development:
Patrick Meade (Stony Brook), Nathaniel Craig (UCSB)

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)

COM energy: μμ vs pp

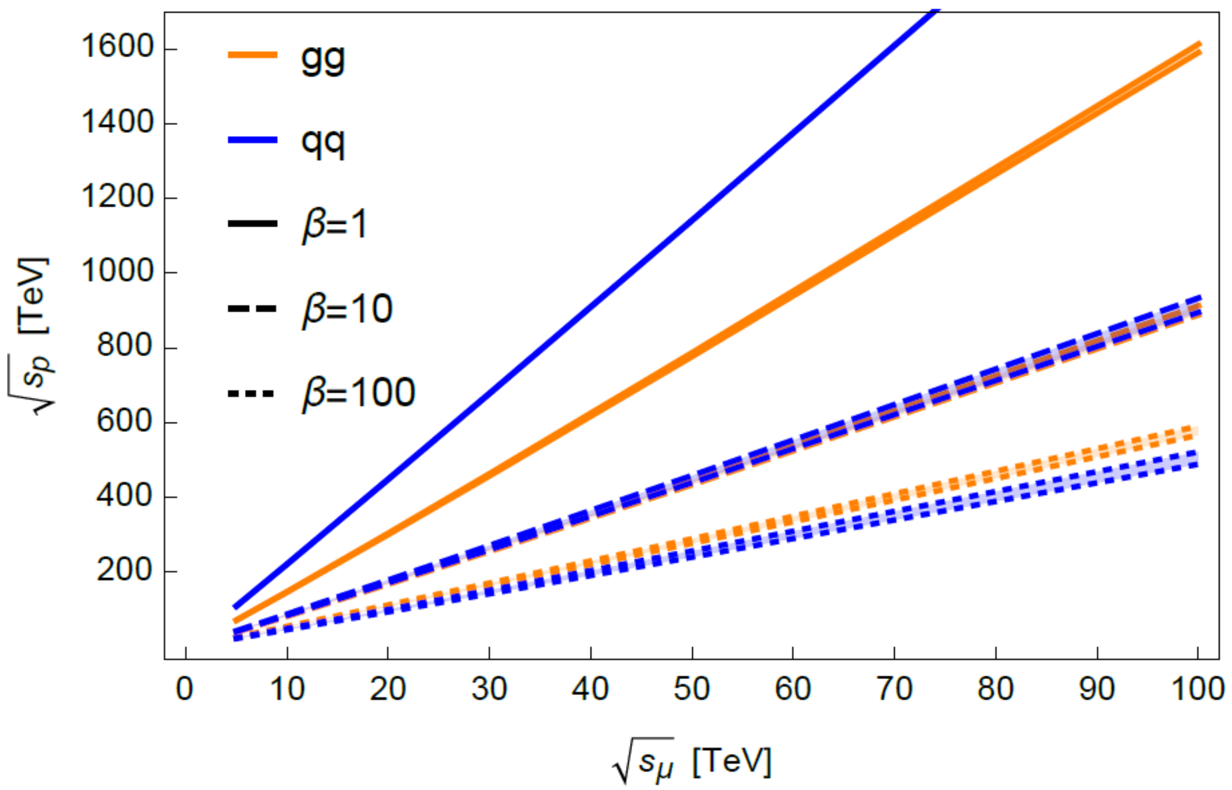


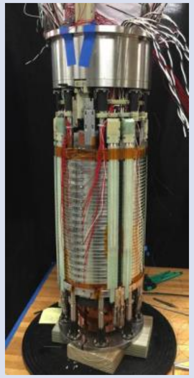
Figure 3: The COM energy for a proton collider $\sqrt{s_p}$ and a muon collider $\sqrt{s_\mu}$ such that the $2 \to 2$ cross sections are the same based on different assumptions for the partonic cross sections characterized by β. Separate curves for gluon and quark annihilation channels are shown, with the bands given by two choices of PDFs, i.e. NNPDF3.0LO and CT18NNLO [12].

Muon Collider Magnets

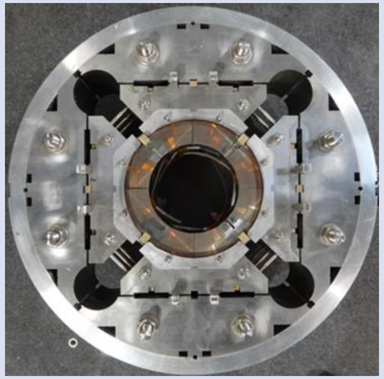
MuC section	Type	10 TeV MuC needs	Status
Cooling	Solenoid	30-50 T @ 50 mm	32 T @ 32 mm
Acceleration	Rapid cycling mag.	1.8 T @ 5 kT/s (30 mm x 100 mm)	1.8 T @ >5 kT/s (1.5 mm x 36 mm)
Collider Ring	Dipole	12-16 T @ 150 mm	11-12 T @ 120 mm
IR	Quadrupole	15-20 T @ 150 mm	11-12 T @ 150 mm

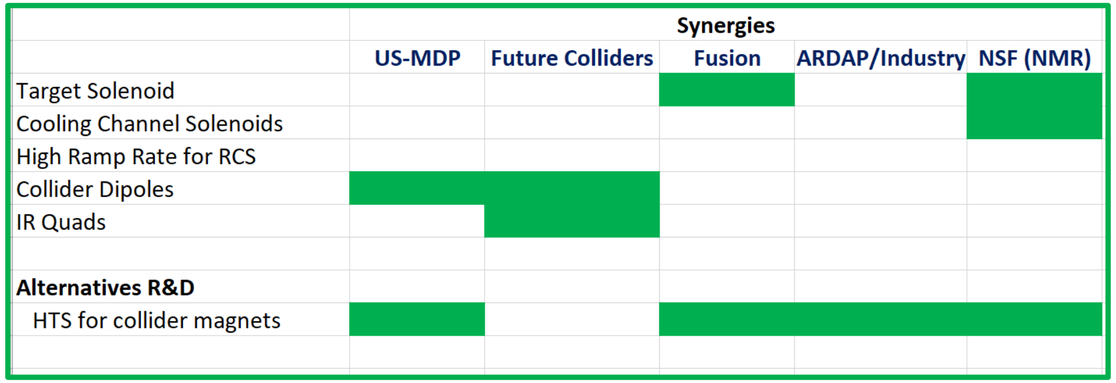
- Many synergies with other programs possible.
  - However rapid cycling magnets are unique for a MuC and need out attention!

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