Muon Collider Development

R. Rimmer

SRF Frontiers Workshop, Jlab, Nov 12-14 2025

MC (recent) Timeline

Long and rich history of Muon Collider research in the US pre-2020, including most recently the Muon Accelerator Program (**MAP**)

Muon Collider timeline since 2020

2020: 2019 European Strategy, Muon Colliders become part of the EU Accel. R&D Roadmap:

• Community meetings, followed by formation of the International Muon Collider Collaboration (**IMCC**) with CERN as the host laboratory

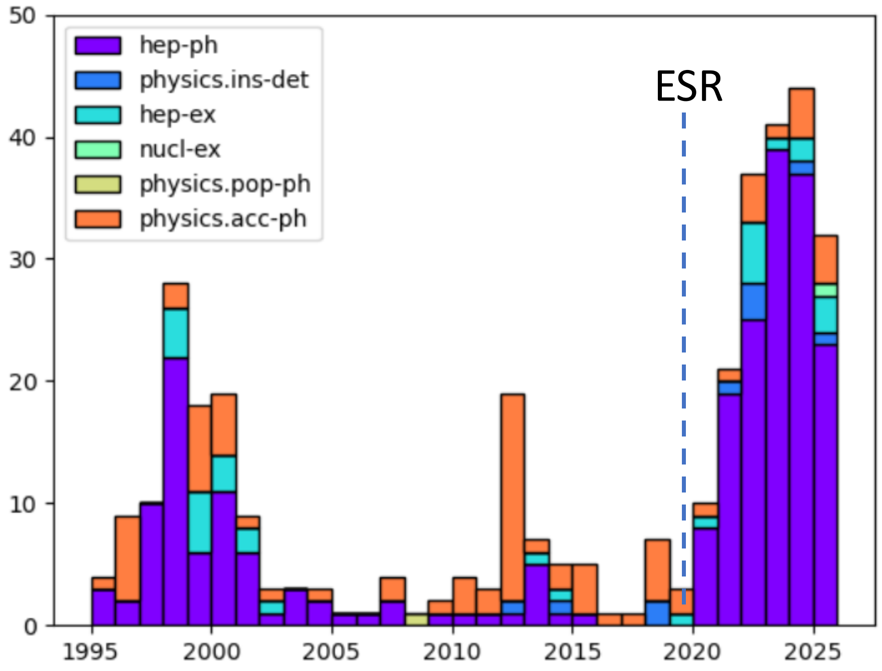
2021 - 2022: US Snowmass study reveals strong interest in Muon Colliders
• Muon Collider Forum Report: a vision from the US perspective
2023: Formation of the US Muon Collider R&D coordination group:
• Provide input to the P5 panel on US-based Muon Collider research

• Input document submitted to P5:
2023-2025: P5 and NAS Reports released, both providing strong support for Muon Collider

2024: PI meeting in Princeton focused on R&D Priorities:
2025: Formation of a US Muon Collider Collaboration (**USMCC**)

2025 Formation of National Laboratory Accelerator Study Group (**NLASG**)

Sergo Jindariani (Fermilab)



Annual MC related publications

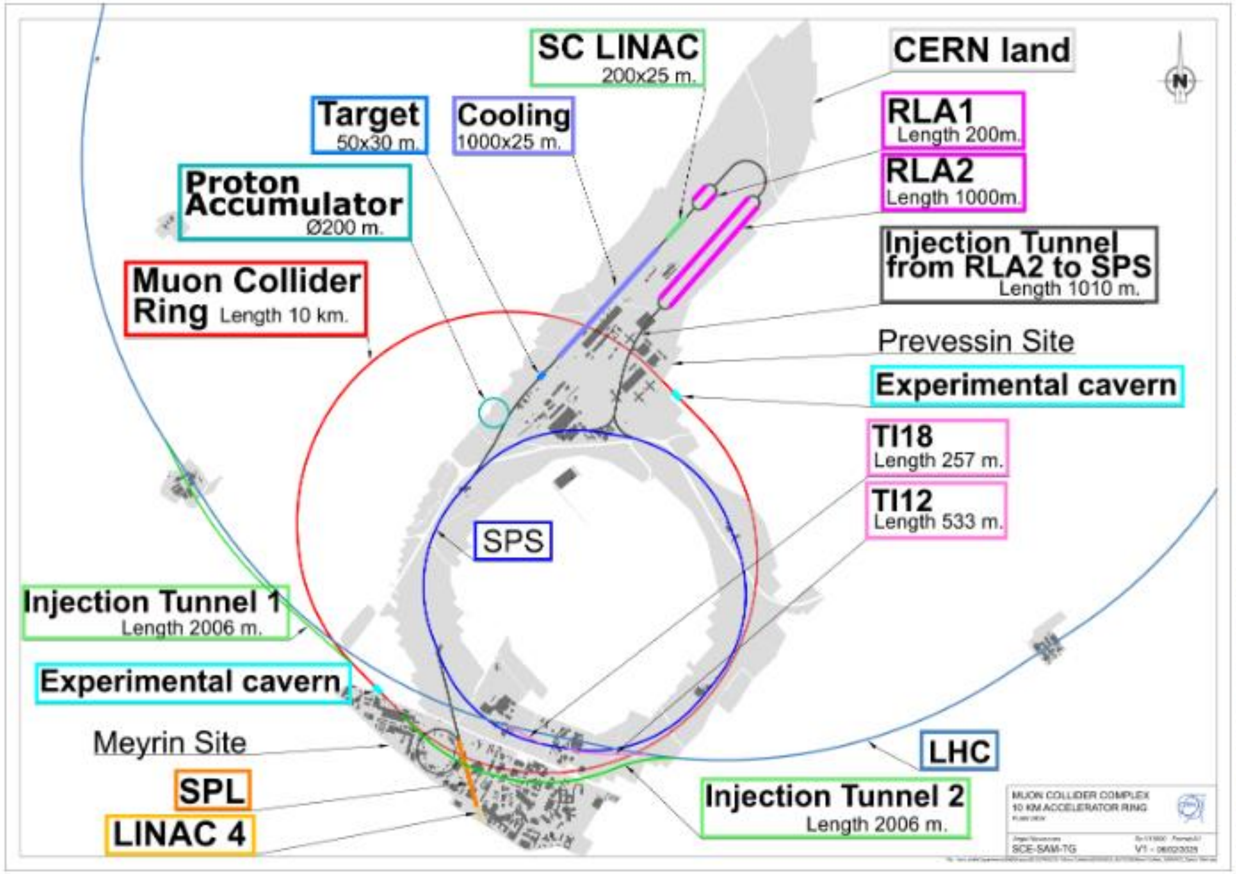
Statements from the P5 and NAS panel reports

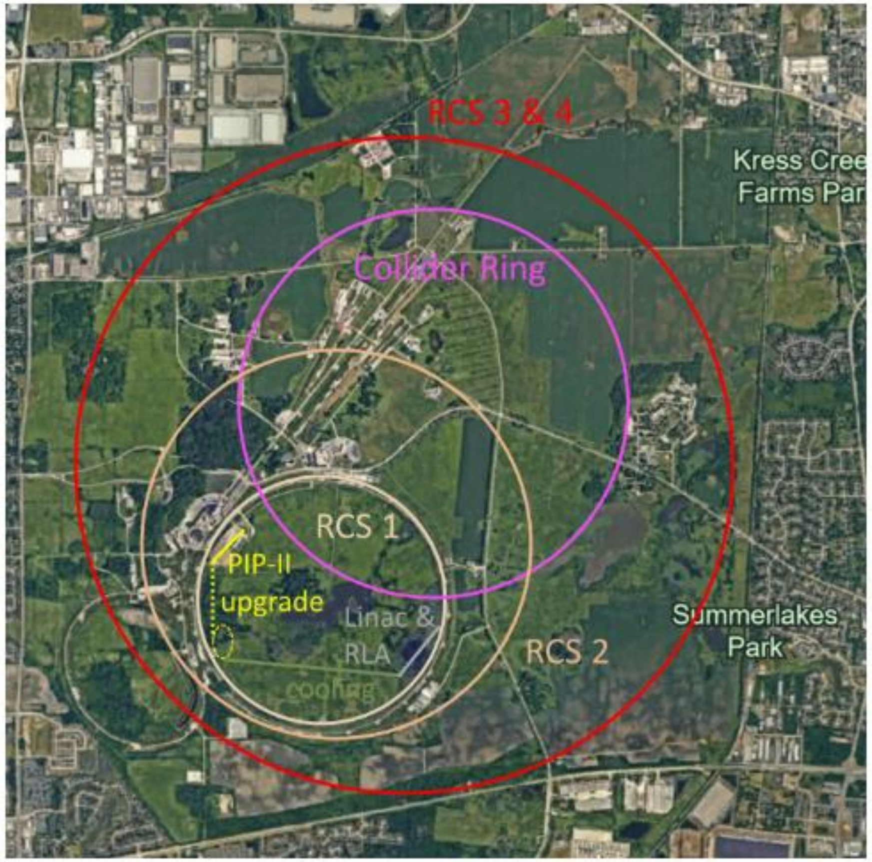
P5: **Invest in a comprehensive initiative to develop the resources**—theoretical, computational, and technological—essential to realizing our 20-year strategic vision. This includes an **aggressive R&D program that**, while technologically challenging, **could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.**

NAS EPP Recommendation 1: **The United States should host the world's highest-energy elementary particle collider around the middle of the century.** This requires **the immediate creation of a national muon collider research and development program** to enable the construction of a demonstrator of the key new technologies and their integration.

CERN and FNAL concepts

Utilize as much as possible of existing or upgraded infrastructure
Green field design also possible





Future timeline

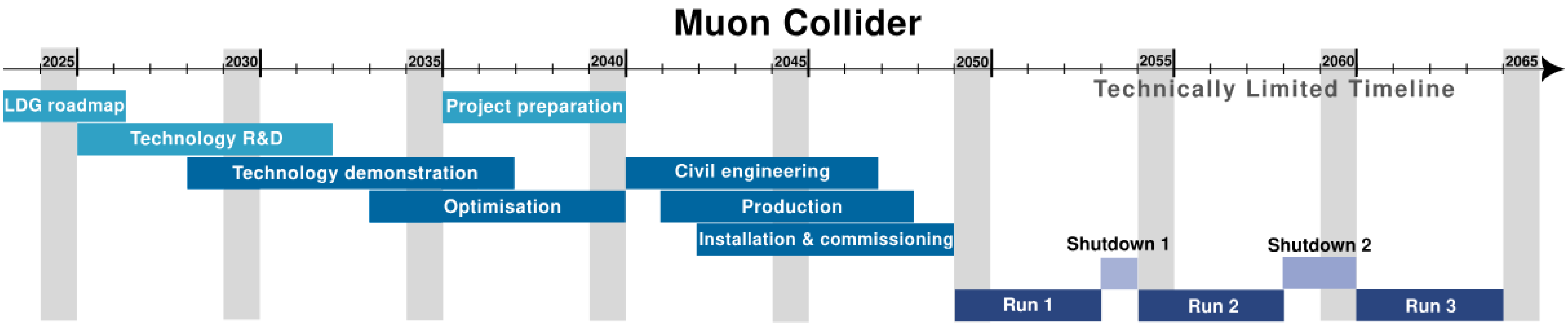


Fig. 5: Technically limited muon collider timeline.

https://indico.cern.ch/event/1439855/contributions/6461618/attachments/3045996/5381966/ESPPU_MuonCollider.pdf

Similar concepts in USA and EU

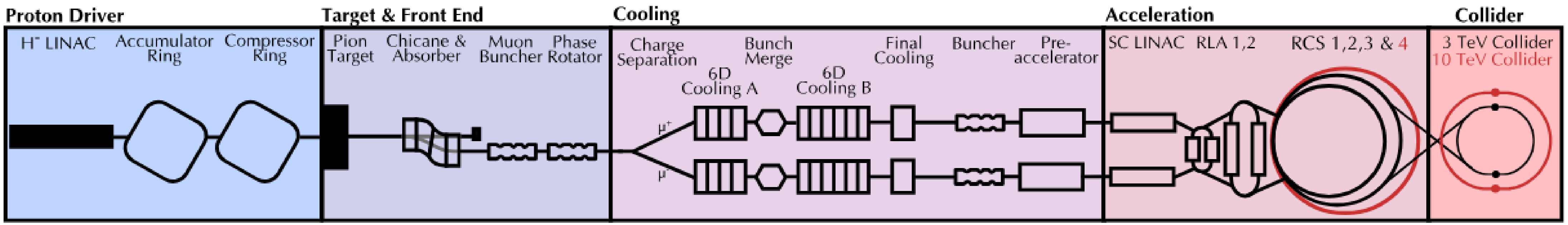
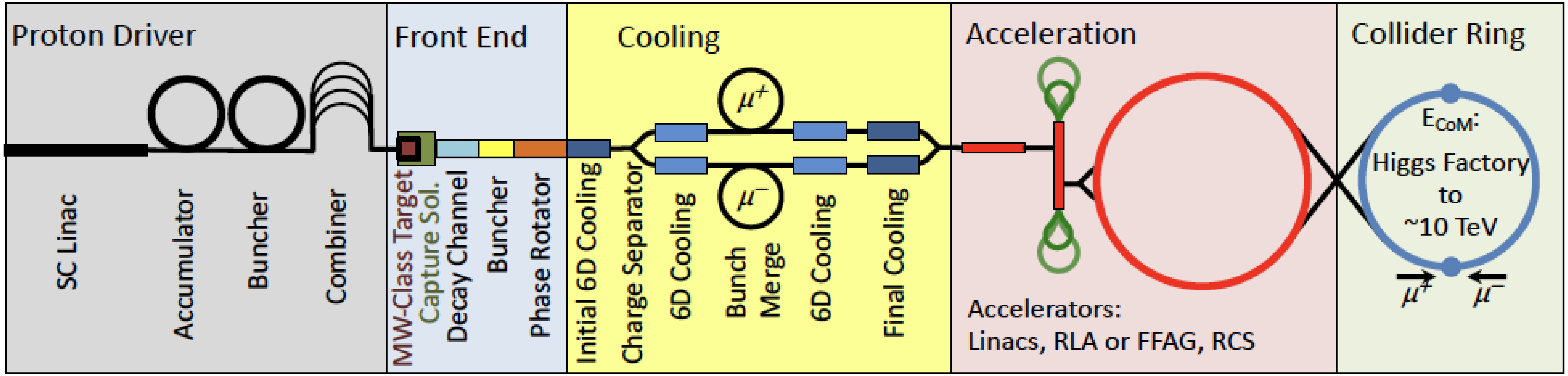


Fig. 1: Conceptual layout of the muon collider.



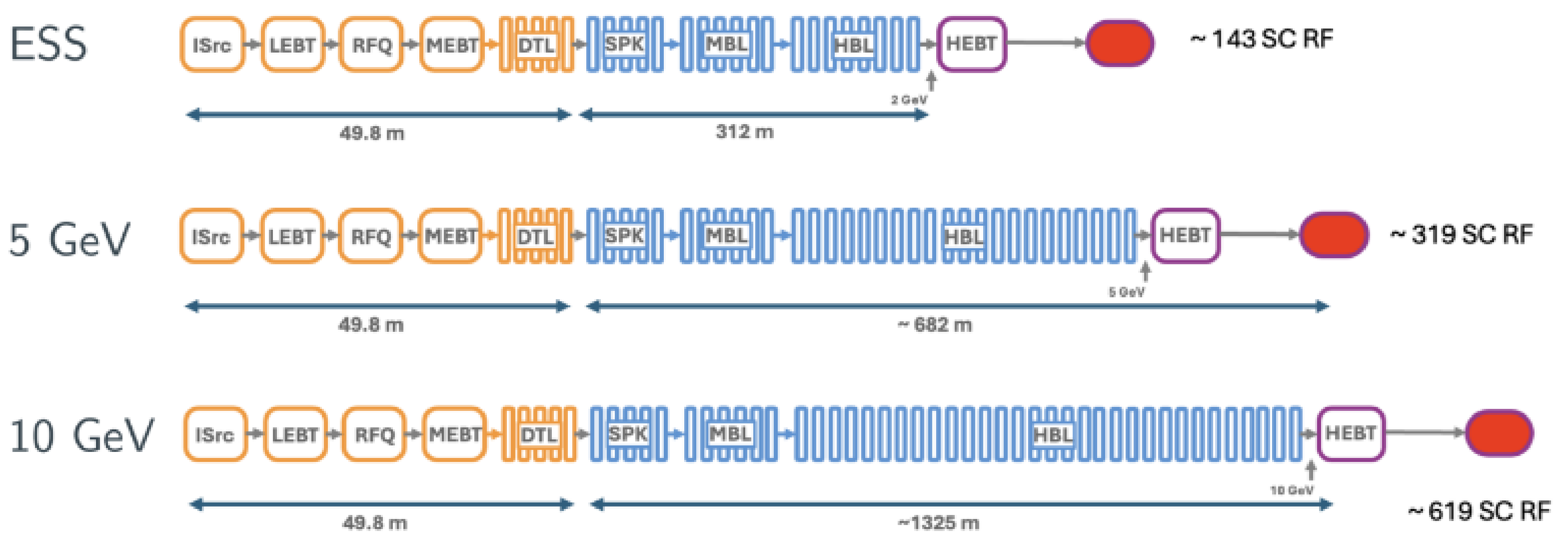
Proton Driver R&D

At IPAC24, FNAL & CERN proton driver scenarios have similar approach to linacs, and different CR/AR choices.

Parameter	CERN	FNAL
Energy	10 GeV	8 GeV
Rep Rate	5 Hz	10 Hz
Macro Linac Current	40 mA	25 mA
Macro Pulse Duration	2 ms	2 ms

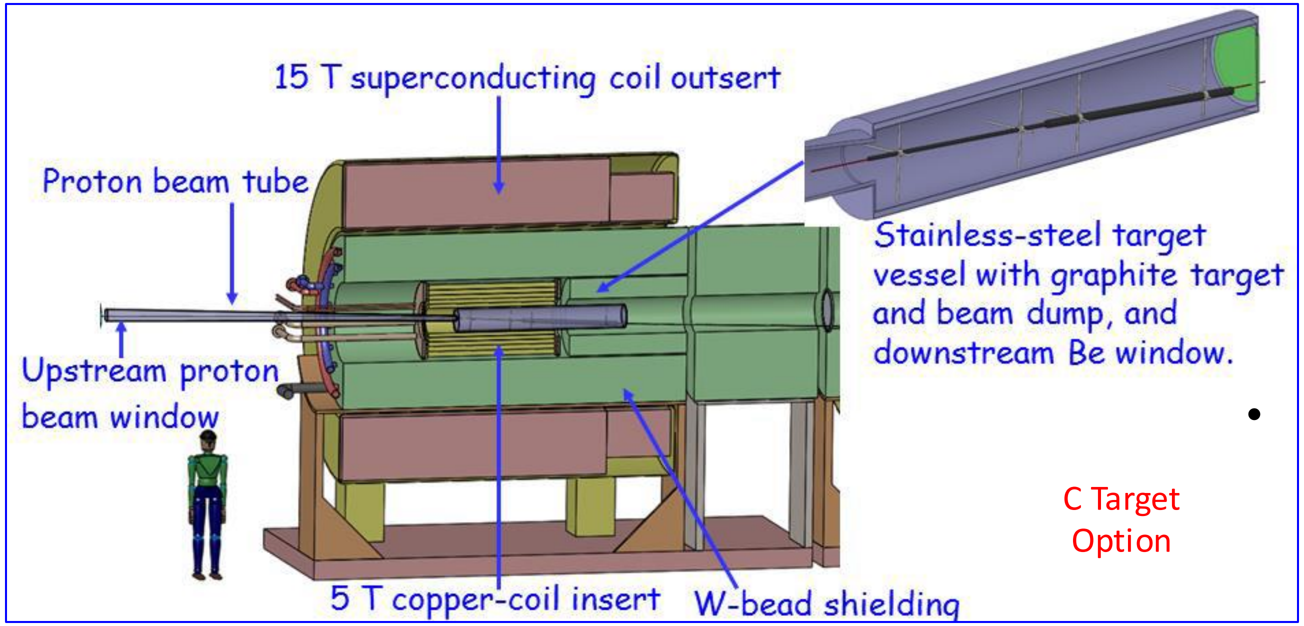
← PIP-III?

Linac design is an extension of the ESS Linac…



Technology ready? Could benefit from further R&D, Nb_3Sn?

Target

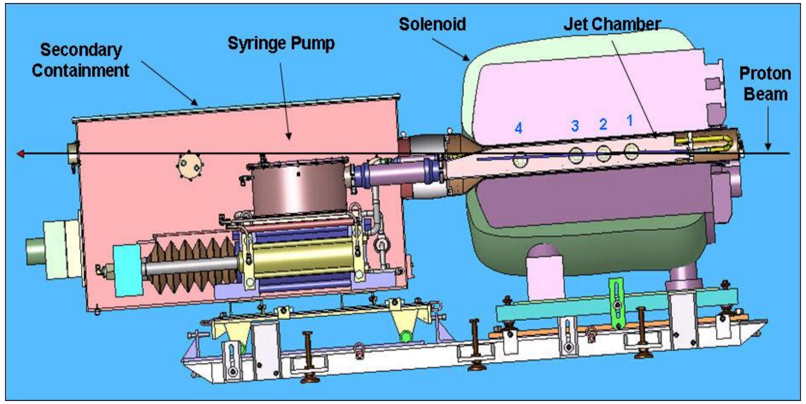


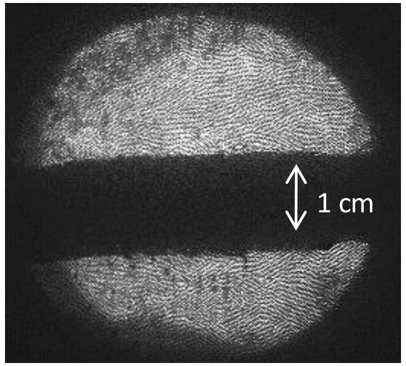
NB: This design is probably outdated. However, it illustrates several critical challenges

~4MW in 20T field

SNS and ESS are approaching this power level

Layout of MERcury Intense Target (MERIT)

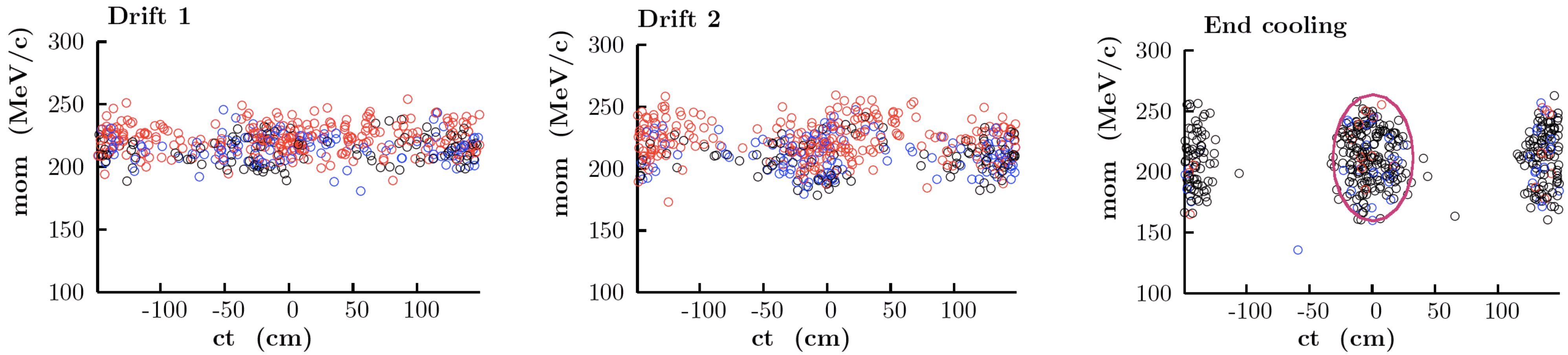




- MERIT was conducted in 2007 at the CERN nTOF11 beamline
  - A proof-of-principle demonstration of a free liquid-metal (Hg) jet target with intense proton beams, within a 15-T solenoidal field
  - Used 14 & 24 GeV protons, up to 16 bunches/pulse, with 3.5e12 protons/bunch at a 67 mrad beam angle relative to the solenoid axis
  - 360 beam pulses in total
  - The mercury jet was magnetically confined as predicted by MHD simulation
  - Secondary particle flux was observed using diamond detectors (no PID)

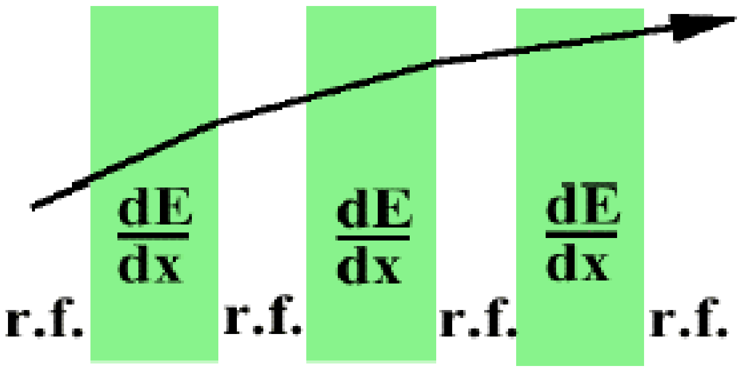
Kirk Macdonald, Princeton

Bunching, capture ionization cooling



Phase rotated beam is bunched and captured in **NCRF** channel before cooling.

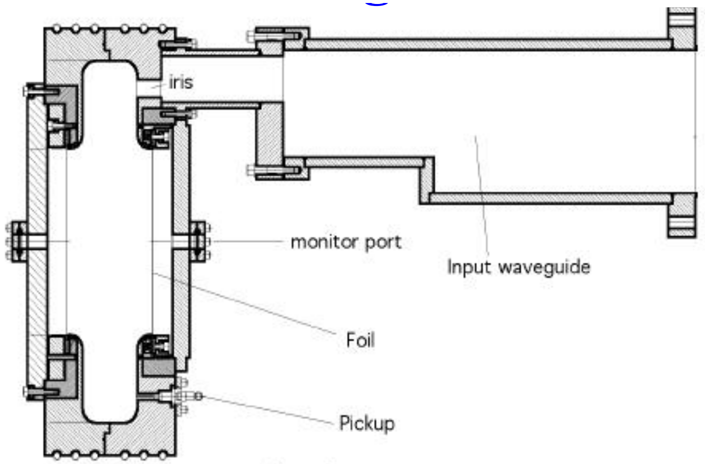
Ionization cooling



Requires multi-T solenoid channel
Prohibits use of SRF

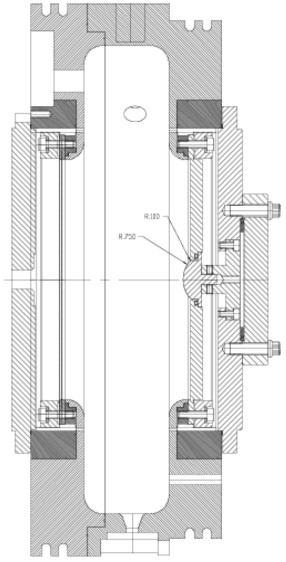
So simple it must work!
Demonstration of realistic ionization cooling was core purpose of Mucool and MICE
Involves absorbers, RF, solenoid channel, instrumentation, integration, etc.

RF Breakdown in high magnetic field

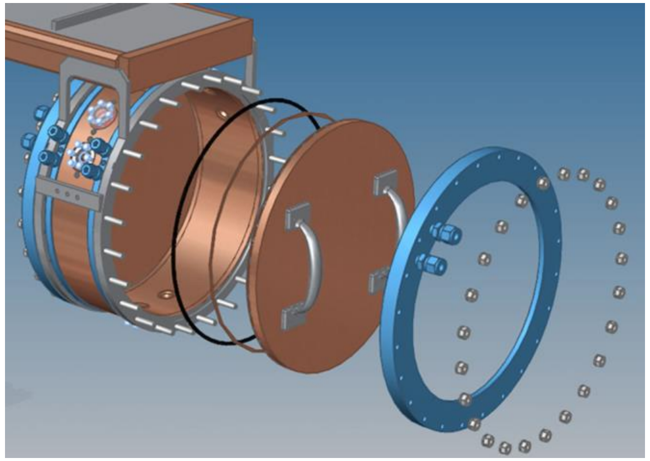


LBNL 805 MHz high power test cavity

LBNL 5 T test solenoid installed



Button cavity



Final “Be” cavity

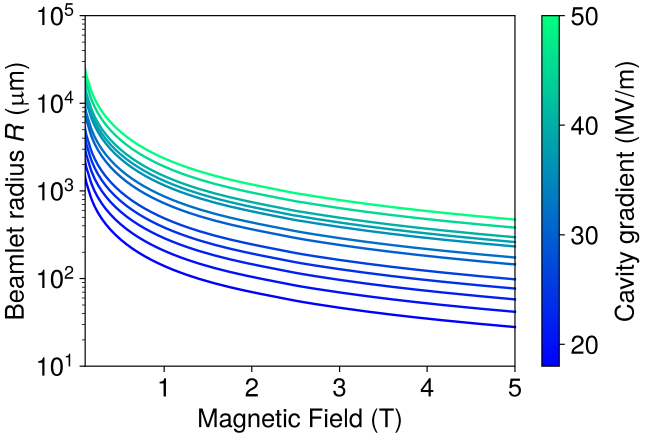


FIG. 1. Beamlet radius on impact vs magnetic field for a range of (copper) cavity gradients, assuming a prolate spheroidal emitter 1.77 μm wide and 62.0 μm long, consistent with $\beta = 385$. Space charge imposes a lower limit on beamlet size, even at very large magnetic fields.

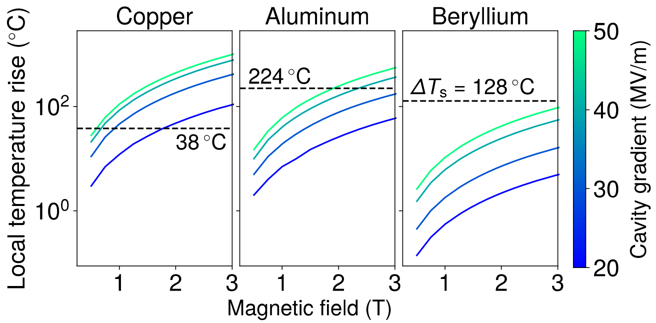


FIG. 2. Semi-log plot of local ΔT for Cu, Al, and Be cavities at various gradients and across a range of solenoidal magnetic field strengths. ΔT_s [Eq. (4)] is indicated in each plot by a horizontal, dashed line. Note that for Be, the local temperature rise is lower than ΔT_s for a broad range of gradients and magnetic fields.

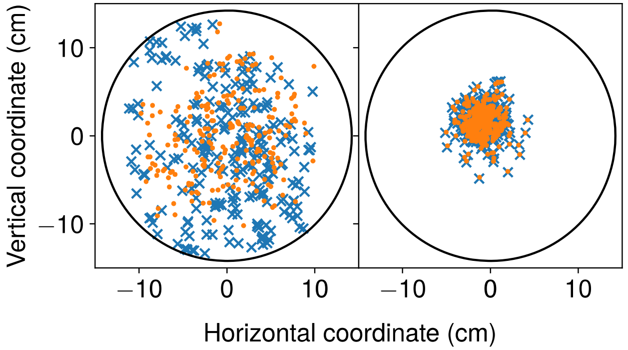
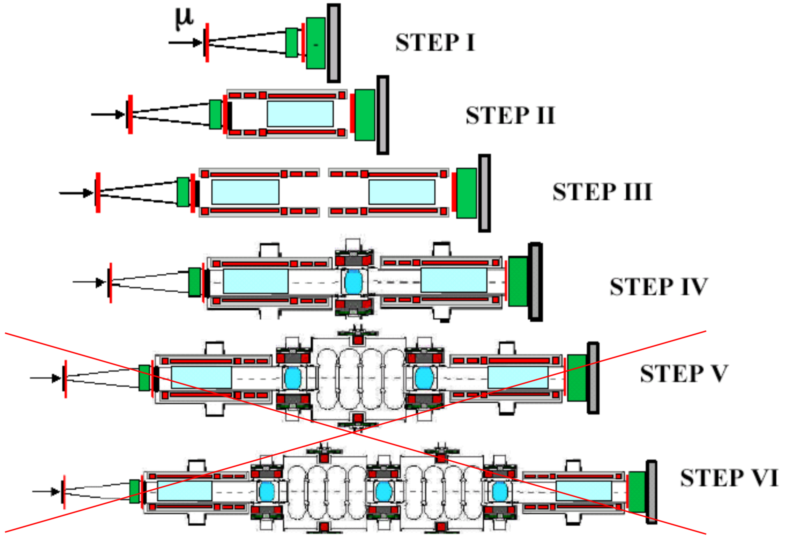


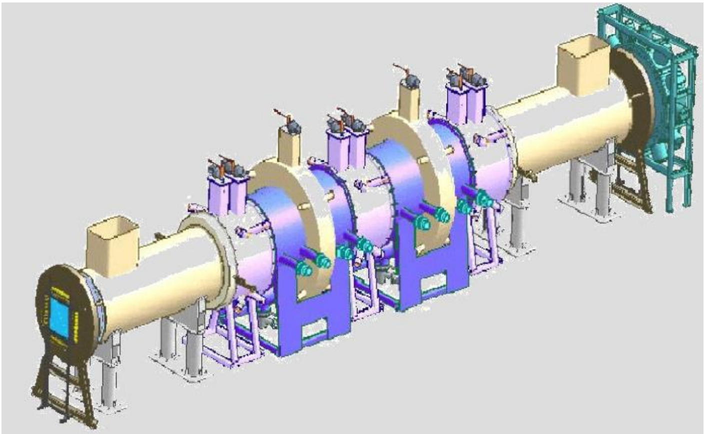
FIG. 6. Map of breakdown damage sites on copper cavity walls after high-power conditioning in zero-tesla external magnetic field (left) and three-tesla field (right). Damage locations are shown from the perspective of the “downstream” cavity wall in the foreground of Fig. 4; blue x’s denote damage on the upstream wall and orange dots denote damage on the downstream wall. Breakdown damage in a three-tesla magnetic field exhibits a one-to-one correspondence between opposite cavity walls.

PHYSICAL REVIEW ACCELERATORS AND BEAMS 23, 072001 (2020) Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration, D. Bowring et. Al.

Ionization cooling demonstration(s)

MICE experiment at RAL





Program terminated without installing RF after DOE canceled MAP

CERN proposals

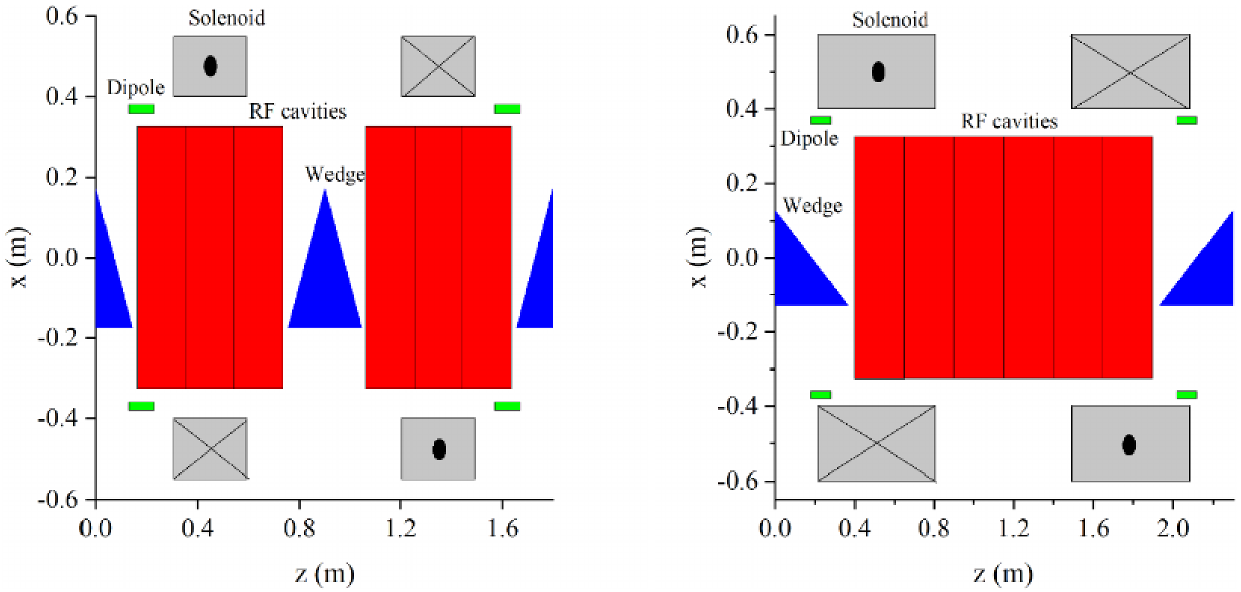
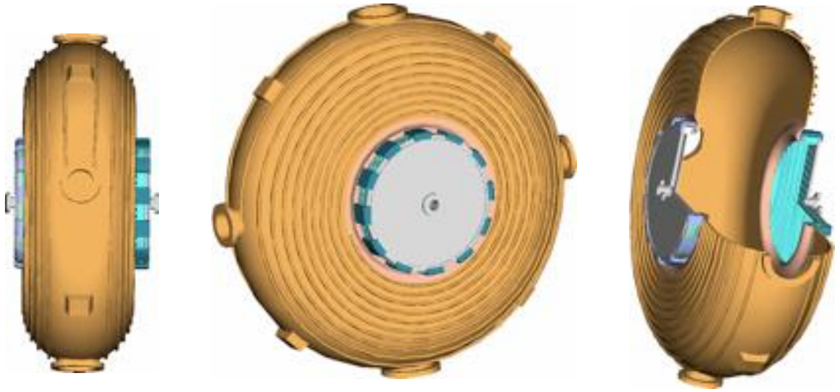


Figure 5.2.4: Schematic of the (left) A-type and (right) B-type cooling cell layout.

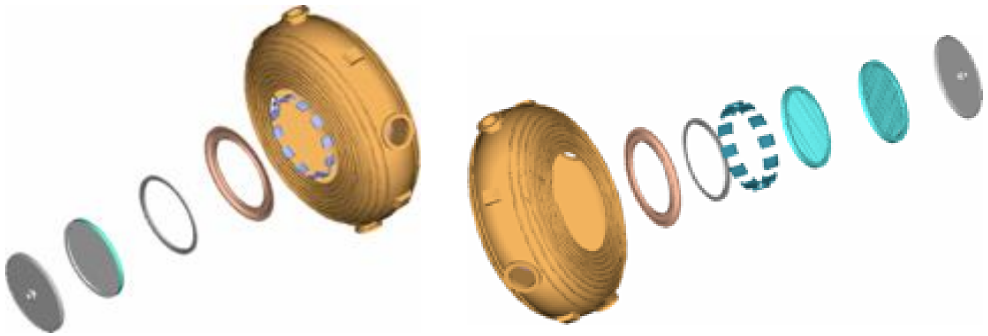
21-32 MV/m NCRF in high magnetic fields,
352-704 MHz, 2.5-17T

New demonstrators being proposed at FNAL and CERN
New cavity designs under way in LBNL and CERN

High-gradient RF (ANL/FNAL/IIT/LBNL/U.Miss/JLab)



201.25 MHz cavity conceptual design

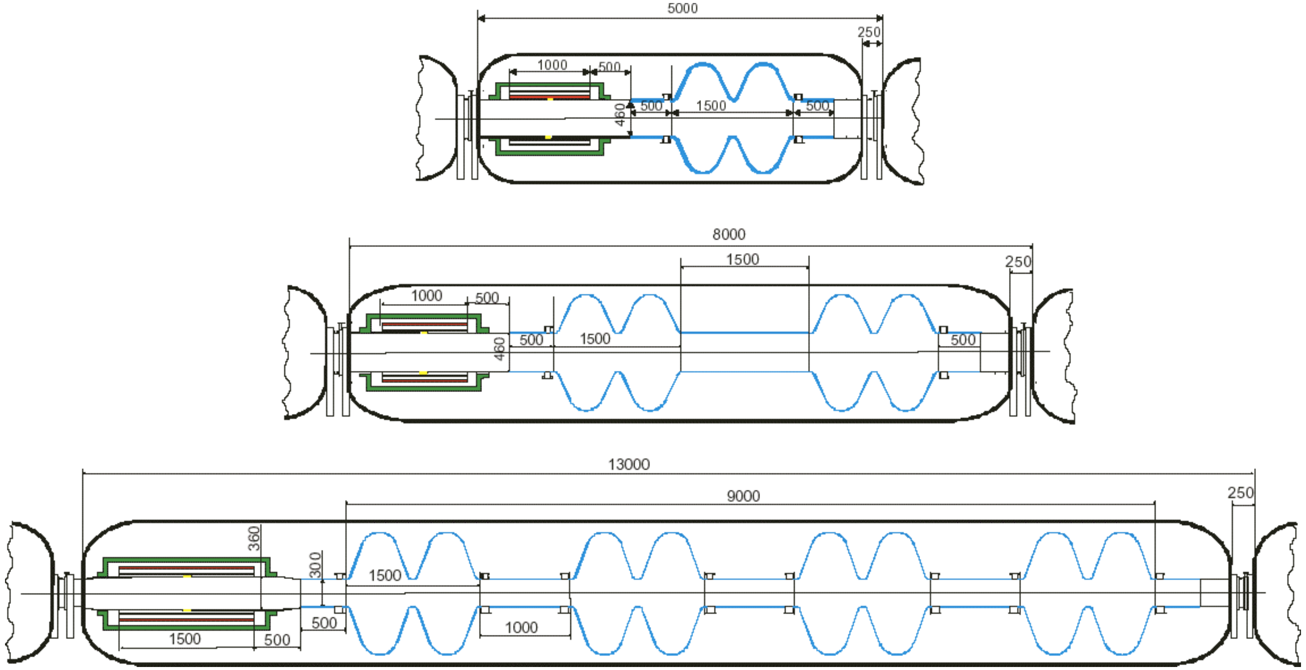


Exploded views showing foil and grid mounting hardware

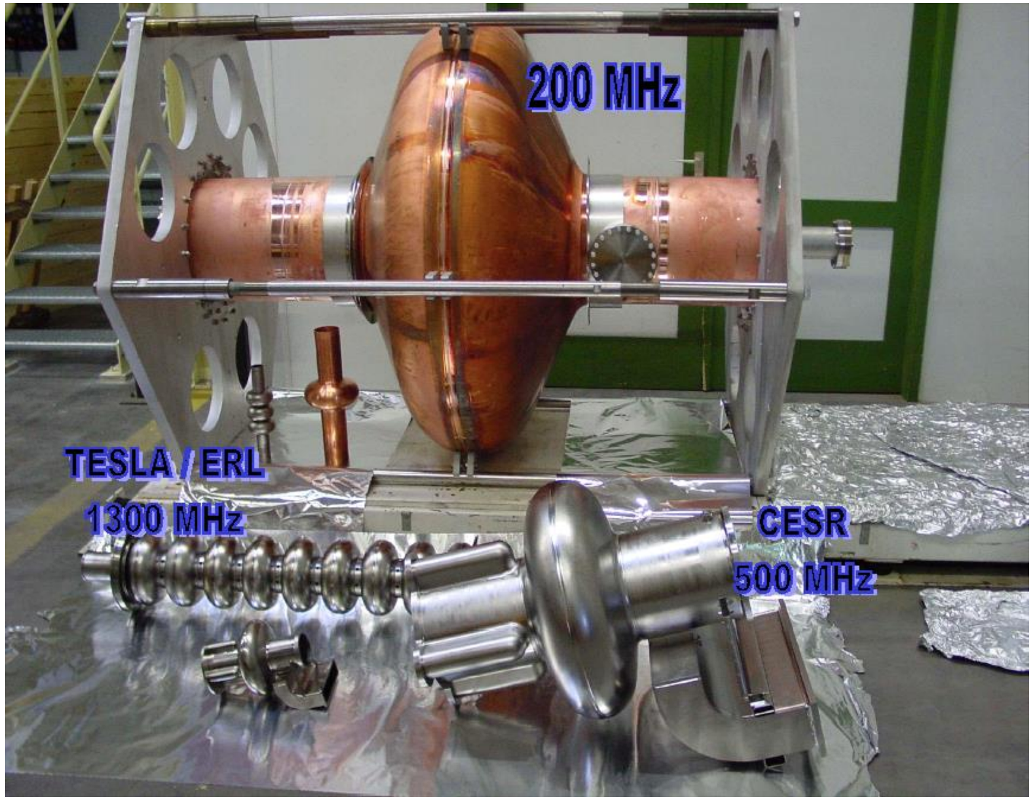
First 200 MHz cavity welded and EP'd by Jlab. Assembled in clean room

Initial SRF acceleration

Low frequency cavities (Nb on Cu) interleaved with solenoids

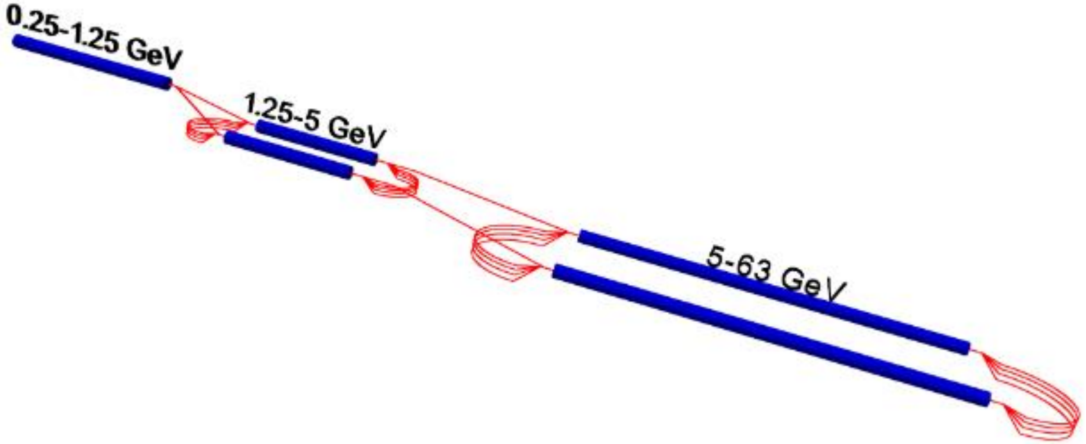


200 MHz Superconducting cavity R&D (Cornell, CERN)

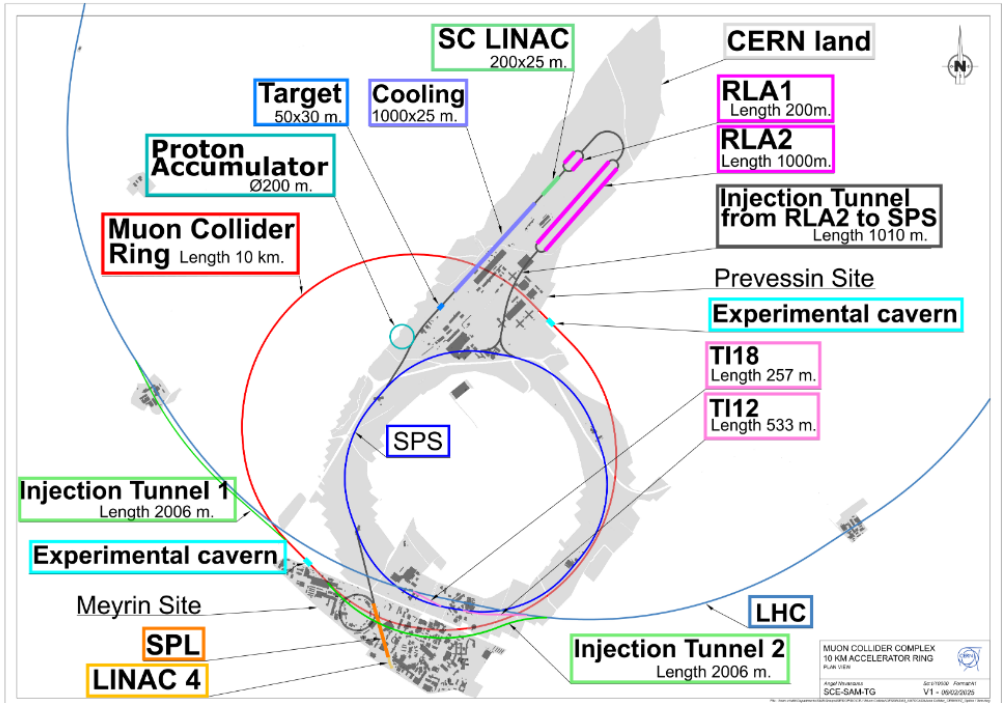


Expect Qo = 4.6 x 10^9 at 4.5 K and 1.0 x 10^{10} at 2.5 K
NbCu cavities have a "Q Slope" requiring x3 power at 15 MV/m accelerating gradient

High-Energy Acceleration, RLA's and RCS's



	RLA1		RLA2	
Initial energy [GeV]	1.25		5	
Final energy [GeV]	5		63	
Energy gain per pass [GeV]	0.85		13.5	
Frequency [MHz]	352	1056	352	1056
No. SRF cavities	36	4	600	80
RF length [m]	61.2	3.4	1020	68
RF gradient [MV/m]	15	25	15	25
Passes	4.5		4.5	
Linac length [m]	–		915	
Arc lengths [m]	–		≈ 300	



ESPPU Muon Collider Report – MUON COLLIDER IMPLEMENTATION – March 31, 2025

Parameter	Unit	RCS 1 SPS	RCS 2 LHC	RCS 3 LHC	All
Synchronous phase	°	135	135	135	-
Combined beam current (μ^+, μ^-)	mA	37.5	8.58	7.35	-
Total RF voltage	GV	21.4	61	62.8	145.2
Total number of cavities	-	686	1958	2017	4661
Total number of cryomodules	-	77	218	225	520
Total RF section length	m	974	2760	2850	6584

1.3 GHz Tesla type

Conclusions

- MC can offer a pathway to 10 TeV
- Can be realized on the FNAL site or at CERN
- Much interesting R&D left to do
- Lots of SRF needed
- Can benefit from progress in SRF materials and designs in the next 10+ years