IMCC and MuCol Status and Direction

D. Schulte
On behalf of the International Muon Collider Collaboration

IMCC Annual Meeting, May, 2025

Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

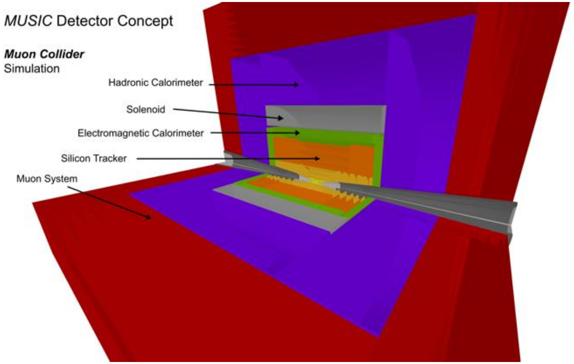
Collaboration

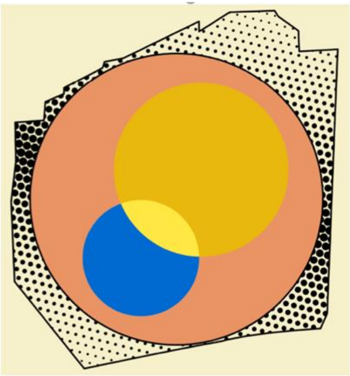
Collaboration is growing
- US had their inauguration meeting O(300) participants in person
- Now have two detector studies, MUSIC and MAIA
- Strong interest from Early Career Scientists

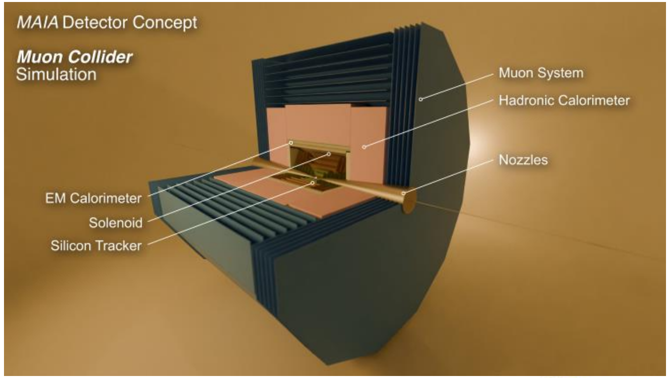
Increasing contributions from experts that are not yet formal members of the collaboration
- e.g. for the R&D plan

Publication and Speaker Committee is seeing an increasing number of publications also from partners that are not yet formally in the collaboration
- Accommodating rules are effective

See Mark and Massimo







ESPPU

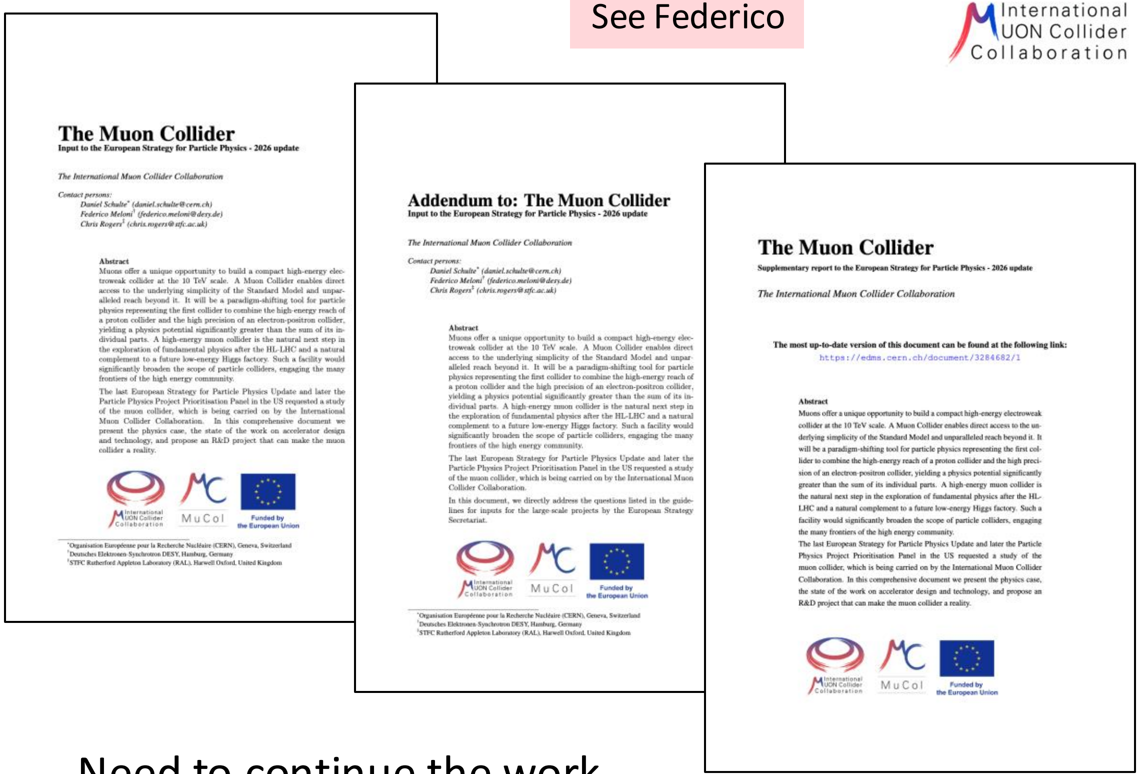
Collaboration produced ESPPU input

- Ten-page report
- Answers to specific questions
- Back-up document
    - Assessment of collider status
    - R&D Plan
    - Important US contributions
    - Final polishing is ongoing, you Urgently sign up to support

Many thanks to all

- Who did the work
- Who wrote the text
- Who edited the text
- Core editors Federico, Chris, Taylor

See Federico



The Muon Collider
Input to the European Strategy for Particle Physics - 2026 update

The International Muon Collider Collaboration

Contact persons:
Daniel Schulte (daniel.schulte@cern.ch)
Federico Meloni (federico.meloni@desy.de)
Chris Rogers (chris.rogers@stfc.ac.uk)

Abstract
Muons offer a unique opportunity to build a compact high-energy electroweak collider at the 10 TeV scale. A Muon Collider enables direct access to the underlying simplicity of the Standard Model and unparalleled reach beyond it. It will be a paradigm-shifting tool for particle physics representing the first collider to combine the high-energy reach of a proton collider and the high precision of an electron-positron collider, yielding a physics potential significantly greater than the sum of its individual parts. A high-energy muon collider is the natural next step in the exploration of fundamental physics after the HL-LHC and a natural complement to a future low-energy Higgs factory. Such a facility would significantly broaden the scope of particle colliders, engaging the many frontiers of the high energy community.

The last European Strategy for Particle Physics Update and later the Particle Physics Project Prioritisation Panel in the US requested a study of the muon collider, which is being carried on by the International Muon Collider Collaboration. In this comprehensive document we present the physics case, the state of the work on accelerator design and technology, and propose an R&D project that can make the muon collider a reality.

Organisation Européenne pour la Recherche Nucléaire (CERN), Geneva, Switzerland
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
STFC Rutherford Appleton Laboratory (RAL), Harwell Oxford, United Kingdom

Addendum to: The Muon Collider
Input to the European Strategy for Particle Physics - 2026 update

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In this document, we directly address the questions listed in the guidelines for inputs for the large-scale projects by the European Strategy Secretariat.

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The Muon Collider
Supplementary report to the European Strategy for Particle Physics - 2026 update

The International Muon Collider Collaboration

The most up-to-date version of this document can be found at the following link:
https://edms.cern.ch/document/3284682/1

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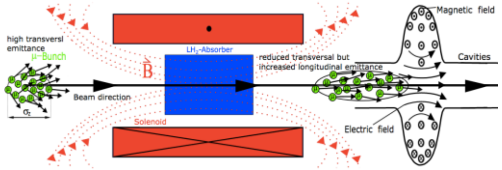
Need to continue the work

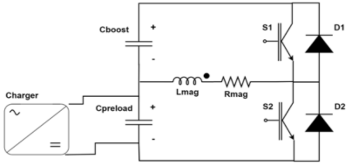
R&D Progress

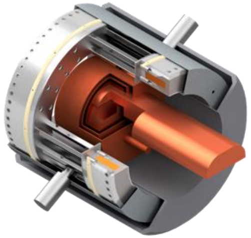
Design of many collider areas has progressed

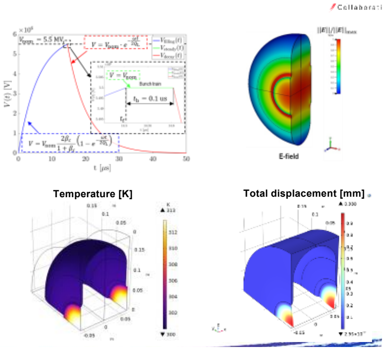
- Lattice design
  - Proton accumulator and compressor ring
  - Much better muon cooling performance
  - RCS lattice designs
  - Collective effects
  - …
- Technologies
  - Realistic magnet performance targets, conceptual designs
  - High-efficiency power converter design
  - RF cavities for muon cooling
  - Muon cooling module conceptual design
  - Cooling absorbers
  - Target design
  - ….
- Detectors and MDI
- Demonstrator scope and design

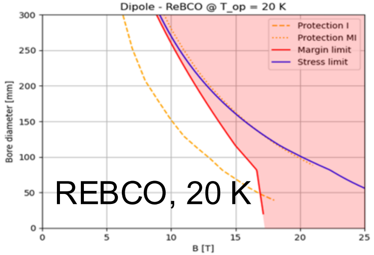
Will be covered later today and during the week











See Tao, Chris, and Massimo

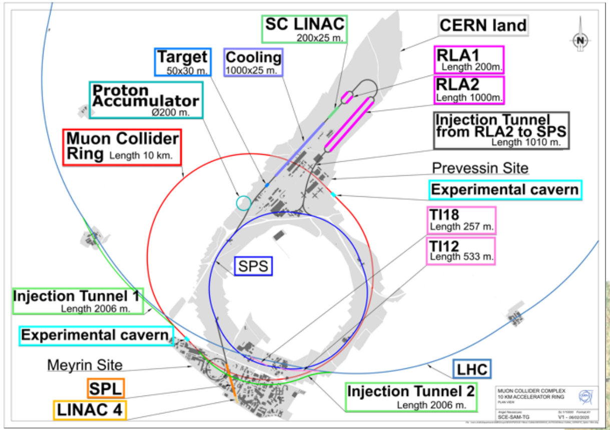
Site Studies

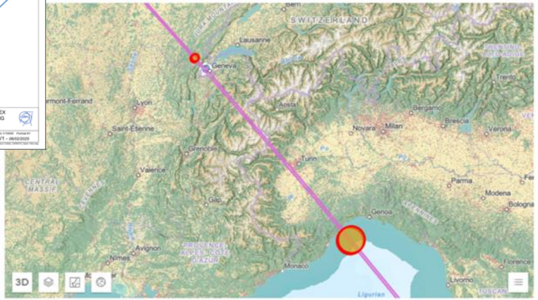
We focused sofar on green-field design
- Easiest to learn about the muon collider
- Common design for all regions

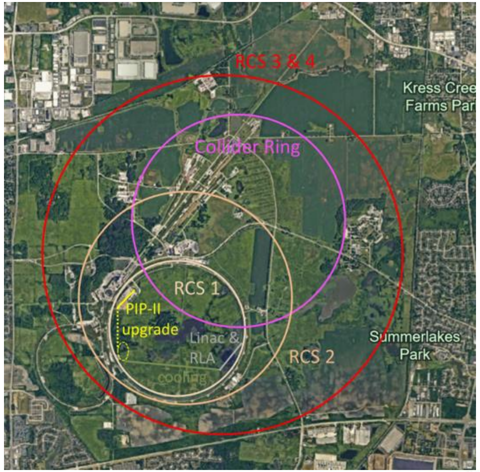
Site studies at CERN and Fermilab are progressing
- Need to consider realistic implementation
- Happy to include any other site

Tentative conclusions for CERN
- Could potentially reuse SPS and LHC tunnels
- All surface construction potentially on CERN site or very close
- Neutrino flux may be OK
- More detailed studies are required

Tentative conclusion for Fermilab
- Could stay on site
- More detailed studies are required







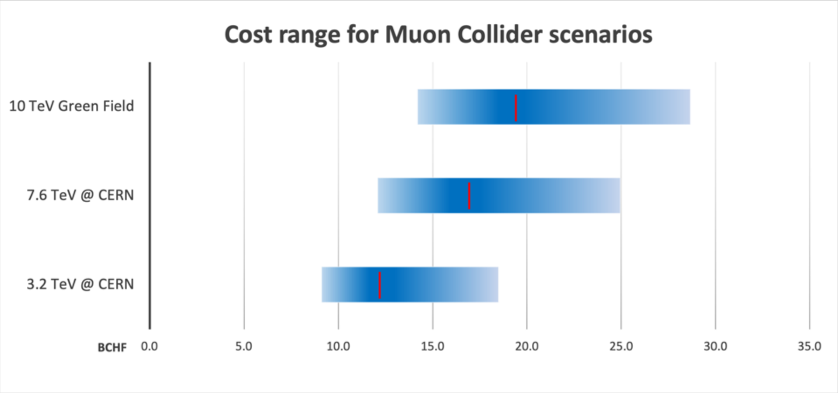
See Ed and Jeff

Cost and Power Consumption

Determined the cost scale for the collider

Different sources of uncertainty

- No design for all systems
  - Error bar in both directions
- Technologies (e.g. HTS cost development)
  - Error bar in both directions
- Design has not been optimised for cost
  - Error bar only to lower cost



Estimated power consumption of the collider

Some sources of uncertainty exist

- Several MW for cooling of losses in RCS cavities required

	Unit	CERN 3.2 TeV	CERN 7.6 TeV	Green Field 10 TeV
Proton Driver	MW	16.70	16.70	16.70
6D Cooling	MW	11.76	11.76	11.76
RLAs	MW	10.77	10.77	10.77
RCSs	MW	44.19	108.93	124.68
Collider	MW	10.00	4.10	4.10
General Cooling and Ventilation	MW	20.00	20.00	20.00
Total Power consumption	MW	113.42	172.26	188.01

This is a great basis for future developments and optimisation

See Carlo on Wednesday

Timeline and R&D Programme

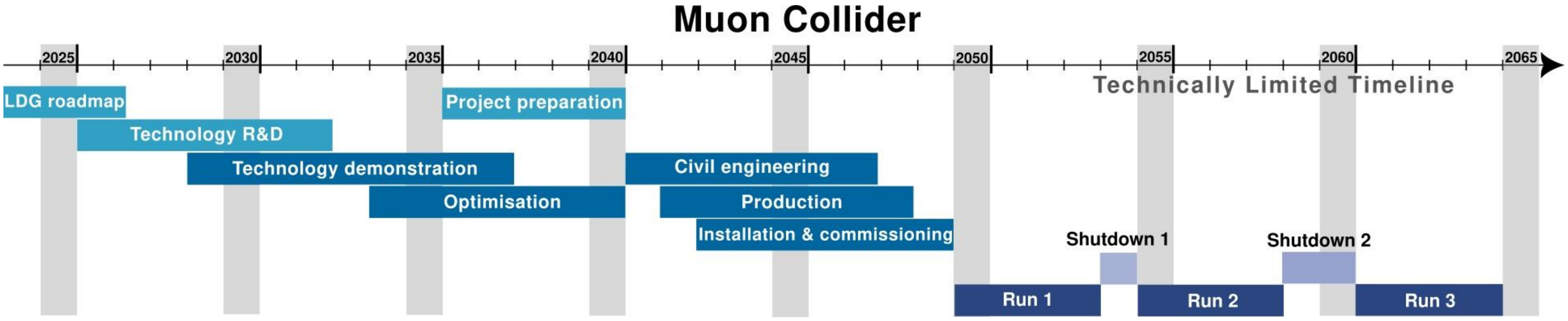
Goal is to be able to commit to a muon collider

- Initial phase to rapidly increase confidence
- Implementation minimum 10 years
- 320 MCHF material (machine 300 MCHF)
- 2700 FTEy (machine 1800FTEy)
- Then will need to develop full range of components and pre-series with industry

Main ingredients

- Detector
- Muon cooling technology
- Magnet technology
- RF technology
- Accelerator design
- Other technologies

See R&D session on Wednesday



Note: LDG

Reviewed the progress and the proposed R&D plan

- Good progress noted, estimated that 75% of Roadmap goals have been achieved

Reviewers: Norbert Holtkamp (chair), Mei Bai, **Frederick Bordry**, Nuria Catalan-Lasheras, **Barbara Dalena,** Massimo Ferrario, Andreas Jankowiak, Robert Rimmer, Herman ten Kate, Peter Williams

Recommendations:

- **Develop a Start-to-End Performance Simulator:** Create a comprehensive simulation framework to assess the robustness of key parameters, including luminosity, cost, and energy consumption. This tool should enable performance optimization, sensitivity analysis, and risk mitigation across the entire collider complex.
- **Define and fund a High-Field HTS and RF Development Strategy:** Establish a clear roadmap for the development of the high-field HTS magnet and the RF systems, including well-defined specifications and performance targets. Securing dedicated funding is essential to advance these critical technologies.
- **Conduct an Independent Review of Scope, Schedule, and Costs:** An urgent, independent evaluation is needed to assess the overall scope, timeline, and budget of the Muon Collider R&D program for the period 2026-2036. This review will be crucial to ensure that funding requests for this R&D phase are well-justified and aligned with project objectives.

Mike Seidel (LDG chair) wants to improve the effectiveness of LDG

- Prepare a Roadmap update during the ESPPU process (early 2026)

R&D Plan Implementation

The IAC will review the R&D plan
- Starts this Wednesday

We need to refine the plan
- Scope
- Define intermediate deliverables and clarify staging
- Estimates and plans exist for the key cost driver
  - Magnets
  - Muon cooling technology
  - Detector
- Some parts need improvements to be fully defined
- Arbitration of resource estimates required in some places

IAC regular members:
Ursula Bassler (IN2P3, interim Chair)
Mauro Mezzetto (INFN)
Hongwei Zhao (Inst. of Modern Physics, IMP)
Akira Yamamoto (KEK)
Maurizio Vretenar (CERN)
Stewart Boogert (Cockcroft)
Sarah Demers (Yale)
Giorgio Apollinari (FNAL)

Experts for this review
Waiting for all confirmations

Need to secure resources
- Promising developments

See R&D session on Wednesday

Will best prepare our **Global Muon Collider R&D Roadmap** before
- **Working group with technical representation from partners to prepare** (as for MuCol)

Way Forward

See R&D session on Wednesday

ESPPU will make some recommendation
- A US and other regional/national strategy processes will follow
- It will take years to see the decisions by CERN Council and funding agencies

We must focus on the R&D to mature the design and technologies
Muon collider is an excellent project
- Promises an exciting project from the medium to very long term
  - With interest to host it in more than region
- It is challenging and innovative
- Motives Early career scientists
- Has strong synergies with other science
  - E.g. technologies relevant for FCC
  - Need to develop physics case of intermediate stages
- Has strong synergies with societal applications
  - From wind power generators to fusion reactors

Will use R&D plan proposal as basis for a **Global Muon Collider R&D Roadmap**
- Feed this into LDG
- Ramp-up the securing of resources (Budgets, LDG, EU-cofounding, grants in the US and elsewhere)
- Promising developments exist

Example Prospective Resources

Already successful
- MuCol, IFAST, MUSIC, …
- Fermilab site study
- Grants for US detector work
- DoE grant for RF test stand at SLAC
- …

LDG might
- Integrate final cooling solenoid in the HFM programme
- Strengthen the HFM programme contribution to magnet protection studies
- Explore RF panel contributions

Other grant requests
- E.g. one for MUSIC calorimetry

Other sources to try
- Increased contributions from partners
- More grants
- …

EU co-funding request via IFAST2
- Power converter (PSI, CERN and Infineon)
- FFAG (UKRI and ESS)
- Modulator for klystron (INFN and Scandinova)
- Mover system (CERN and ?)

Collaboration on target solenoid with fusion magnet technology

F4P
EUROFusion
ENI
Gauss Fusion

Physics case for intermediate facilities
- Could leverage extra funding

Will try to collect this centrally

Conclusion

- Making great progress
  - Thanks to all the hard and dedicated work

- Need to push on
  - Performing R&D
  - Securing resources, with support from strategy processes
  - Engaging early career experts
  - Contributing to dealing with challenges that society is facing

I think we can be a little proud of what we achieved

- Received many supportive mails and comments

- To join contact muon.collider.secretariat@cern.ch
- http://muoncollider.web.cern.ch

Reserve

IMCC Partners

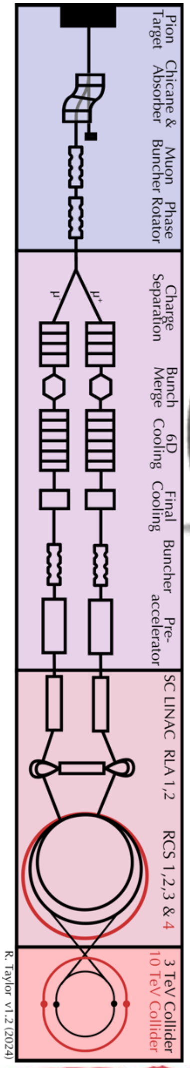
IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
	Ecoles des Mines St-Etienne
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
	University of Birmingham
	University of Cambridge
NL	**University of Twente**

IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, LASA, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
Mal	**Univ. of Malta**
EST	**Tartu University**
PT	**LIP**
SE	**ESS**
	University of Uppsala

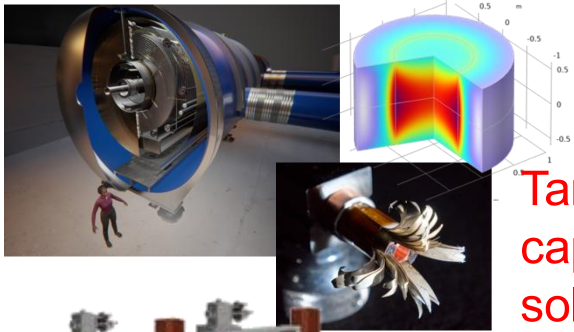
FI	**Tampere University**
	HIP, University of Helsinki
LAT	**Riga Technical University**
CH	**PSI**
	University of Geneva
	EPFL
	HEIA-FR
BE	**Univ. Louvain**
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
China	***Sun Yat-sen University***
	IHEP
	Peking University
	Inst. Of Mod. Physics, CAS
	University of CAS
KO	**Kyungpook National University**
	Yonsei University
	Seoul National University
India	***CHEP***

Signed MoC (58), ***requested MoC***, contributor

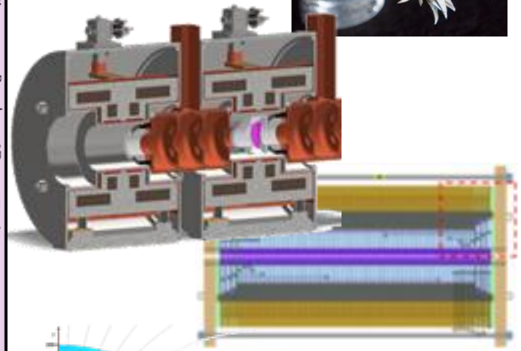
Ty	
CA	Université Laval
US	**Iowa State University**
	University of Iowa
	Wisconsin-Madison
	University of Pittsburgh
	Old Dominion
	Chicago University
	Florida State University
	RICE University
	Tennessee University
	MIT Plasma science center
	Pittsburgh PAC
	Yale
	Princeton
	Stony Brook
	Stanford/SLAC
	…
DoE labs	FNAL
	LBNL
	JLAB
	BNL
Brazil	***CNPEM***



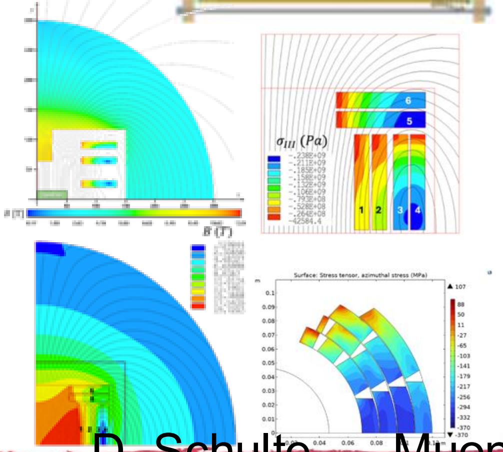
R. Taylor v1.2 (2024)



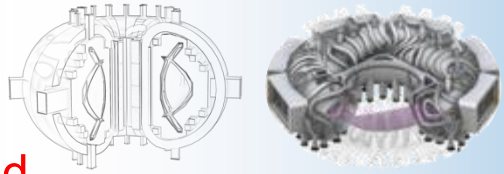
Target and capture solenoid



Muon beam cooling solenoids



Accelerator and collider magnets



Magnetically confined fusion

F4E

EUROFusion

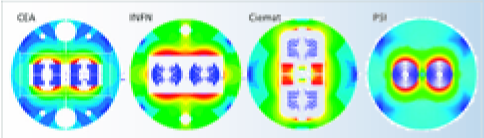
Gauss Fusion

ENI

UHF science, NMR and MRI

LNCMI

NHMFL



HEP and power applications

HFM

FCC-hh

Muon Collider Roadmap CTEs

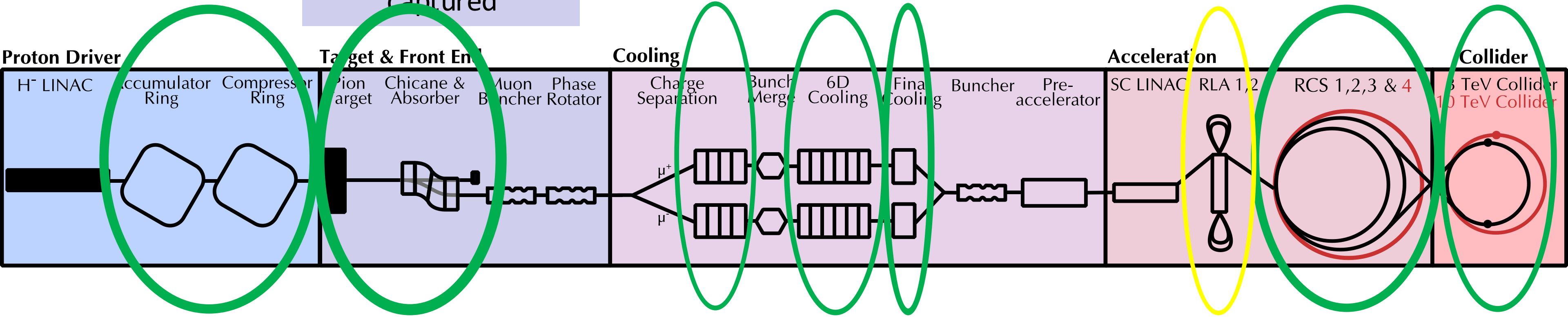
Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision



- Proton driver bunch compression

- Graphite target
- Target solenoid

- Muon cooling design
- 6D cooling solenoids
- 6D cooling RF cavities
- Final cooling solenoids

- Pulsed magnets and power converters
- RCS RF system

- Collider ring dipoles
- Final focus quadrupoles

Identified and prioritized with community
Other areas need now also to be addressed (some work started)

Tentative Accelerator Design Resources

Area	Tasks	FTE
Proton complex	Accumulator ring; combiner ring; target delivery system	2.6
Target	Spent beam and losses; higher-power alternative	1.3
Front end	Capture efficiency	1.3
Cooling	System design optimisation; capture efficiency, tolerances	3.9
Final cooling	System design optimization; tolerances	2.6
Bunch merge	Lattice design	1.3
Linacs	Lattice design	1.3
Transfer lines	Injection/extraction in rings and transfer lines	1.3
RCS	Lattice design; neutrino flux mitigation; loss mitigation, tolerances, operational cons.; eddy currents	3.9
Collider ring	Neutrino flux mitigation/tolerances; optimisation of energy acceptance; magnet field imperfections	3.9
MDI	Continued support to detectors	1.3
Start-to-end studies	Code development; collection and simulation of lattices; system specification optimization; version control	3.9
Collective effects	All “conventional” collective effects along the complex	2.6
Longitudinal dynamics	All along the complex; rings; linacs/cooling	2.6
Losses	RCS cavities and cold magnets; all along complex	3.9
Neutrino flux mitigation	Neutrino flux studies along the whole complex	1.3
Absorber collective effects	Model the collective effects on the absorber and back on the beam	2.6
Demonstrator	Modelling of demonstrator specific designs	3.9
Sum		**45.5**

R&D Plan Fundamentals

The current R&D is based on the prioritised LDG Accelerator R&D Roadmap

- Goal: Assess whether investment into R&D is justified
- Design of systems containing largest risk for overall performance
- Design of the Critical Technology Elements (CTE)
- Strong interplay exists between CTE and system design
- Use state-of-the-art components where-ever possible

Proposed R&D programme

- Goal: Assess whether muon collider is feasible
- Ramp-up of resources to balance risk and investment
  - E.g. RF test stand -> cooling cell power test -> demonstrator to test one module -> several modules
- Further improve systems and expand study to all systems (start-to-end)
  - Use state-of-the-art components where possible and profit from R&D elsewhere
- Address the CTEs experimentally

Innovative nature of muon collider

- Requires to carefully prioritise the R&D
- Motivates early career scientists and engineers
- Results in important synergy with societal applications, e.g. collaborations with ENI and Infineon

R&D Plan Resources

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6