Introduction and Timeline

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.

ESPPU

Collaboration produced ESPPU input:

- Short, **ten-page** report (10p)
- **Addendum** to answers specific questions from ESPPU (18p)
- **Back-up document** (406p)
    - Assessment of collider status
    - R&D Plan
    - Important US contributions
    - Final polishing is ongoing, you Urgently sign up to support

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)
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Chris Rogers[2] (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
[1]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[2]STFC Rutherford Appleton Laboratory (RAL), Harwell Oxford, United Kingdom

Addendum to: The Muon Collider
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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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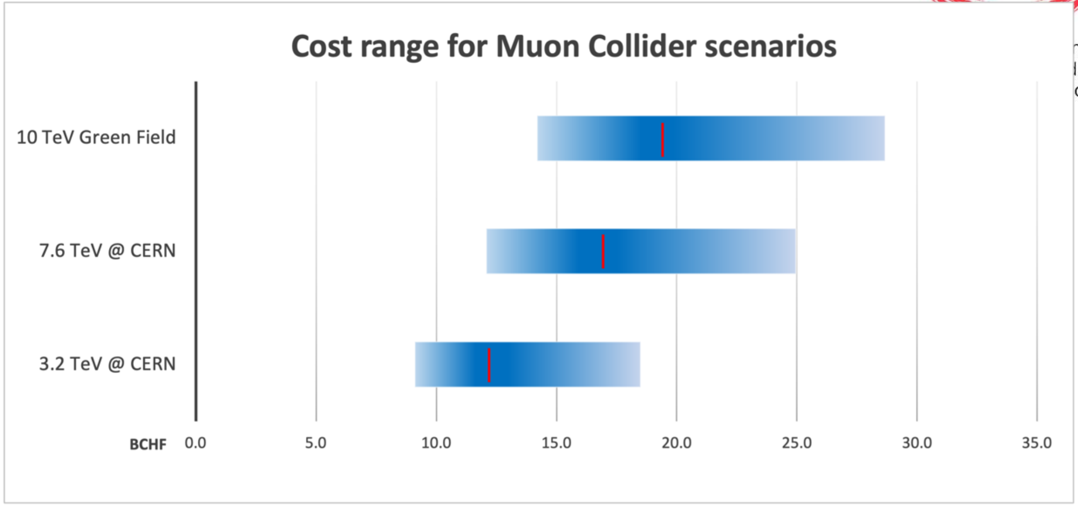
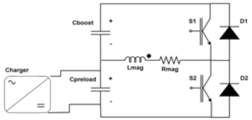
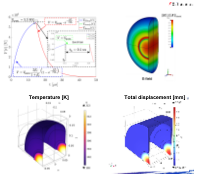
R&D Progress

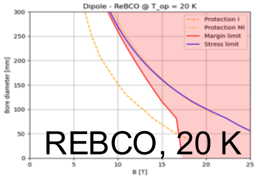
Design of many collider areas has progressed

- Lattice designs
- Technologies
- Detectors and MDI
- Demonstrator scope and design
- **Cost and power consumption scale**

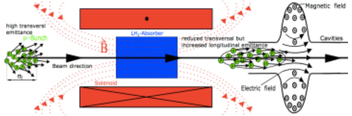


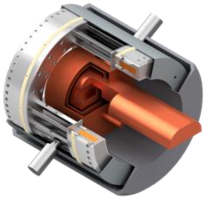






	Unit	CERN 3.2 TeV	CERN 7.6 TeV	Green Field 10 TeV
Proton Driver	MW	16.70	16.70	16.70
6D Cooling	MW	11.76	11.76	11.76
RLAs	MW	10.77	10.77	10.77
RCSs	MW	44.19	108.93	124.68
Collider	MW	10.00	4.10	4.10
General Cooling and Ventilation	MW	20.00	20.00	20.00
Total Power consumption	MW	113.42	172.26	188.01



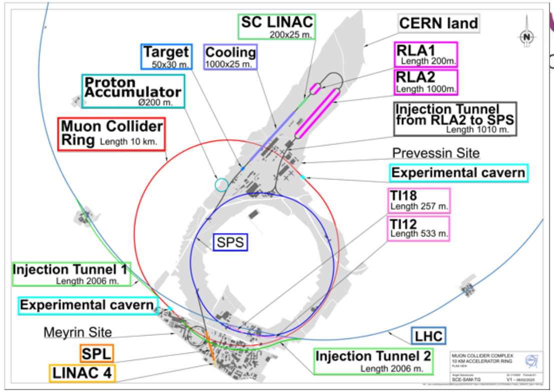


Site Specific Designs

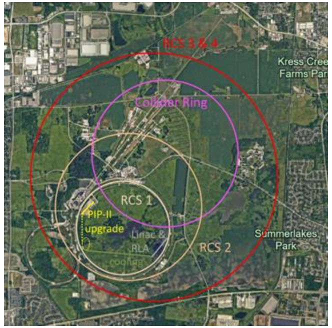
Started studies for concrete site at CERN and Fermilab

- At CERN re-use SPS and LHC and construct facility on CERN land
- Neutrino flux appears solvable

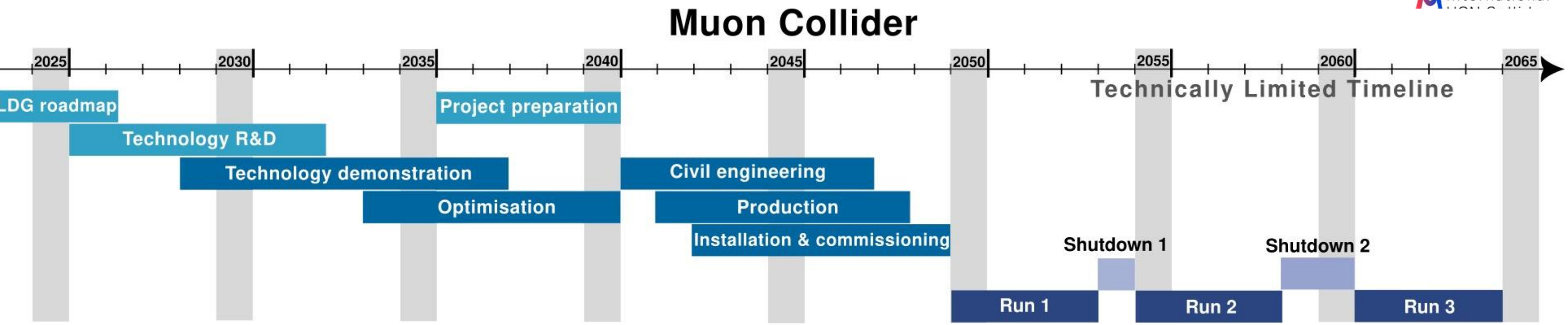
- Adjusted parameters (3.2 and 7.6 TeV)
- Stage with one tunnel or two different tunnels
    - Use of different technologies



CERN-specific muon collider parameters						
Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3.2	7.6	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.9	7.9	2.0	10.1
Collider circumference	C_{coll}	km	11	11	4.8	8.7
Collider arc peak field	B_{arc}	T	4.8	11	11	14
Collider dipole technology			NbTi	Nb_3Sn or HTS	Nb_3Sn	HTS



Timeline and R&D Programme

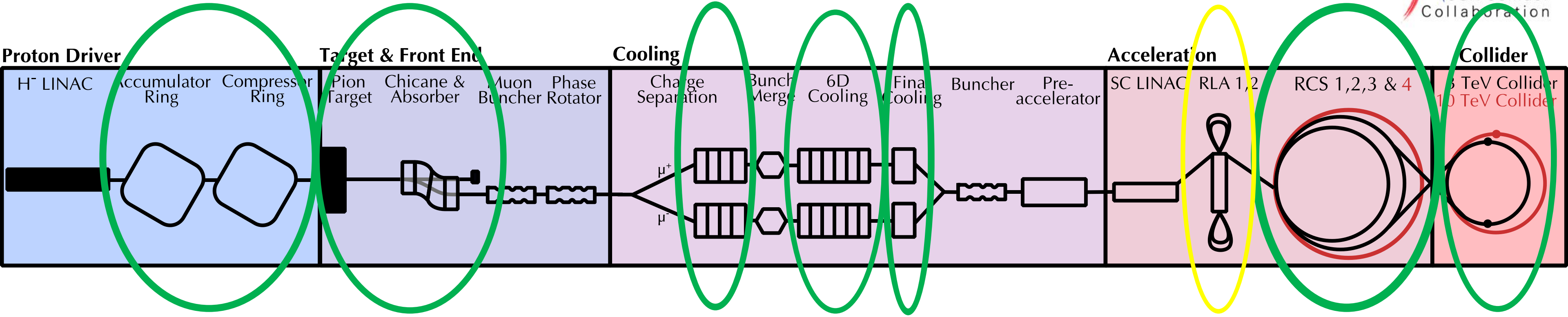


Goal is to be able to commit to a muon collider in 2036 to enable collider by 2050

- Considering the timeline drivers:
  - Magnet technologies: this excludes high-field HTS dipoles
  - Muon cooling technologies
  - Start-to-end design
  - Detector optimization

Ramping up of programme to rapidly gain confidence and balance risk vs R&D cost

Muon Collider CTEs and R&D Plan



- 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
- Mover system

R&D programme key ingredients:

- Start-to-end design and optimization
- Magnet technologies
- RF technologies
- Cooling technology

- Demonstrator
- Detector R&D and optimization
- Other technologies

R&D Deliverables and Resources

Technologies	Deliverables	Key parameters and goals
	Magnets	
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K

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

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Fast-ramping magnet system	Prototype magnet string and power converter	30 mm x 100 mm, 1.8 T, 3.3 T/s
LTS collider dipole	Demonstrate Nb_3Sn collider dipole	160 mm diameter, 11 T, 4.5 K, 5 m long
HTS RCS dipole	Demonstrate RCS HTS dipole	30 mm x 100 mm, 10 T, 20 K, 1 m long
HTS collider dipole	Demonstrate HTS collider dipole	140 mm diameter, 14 T, 20 K, 1 m long
HTS collider quadrupole	Demonstrate HTS IR quadrupole	140 mm diameter, 300T/m, 4.5K, 1m long
	Radiofrequency	
Muon cooling RF cavities	Design, build and test RF cavities	352 MHz and 704 MHz in 10 T field
Klystron prototype	Design/build with Industry 704 MHz (and later 352 MHz) klystron	20 MW peak power, 704 MHz / 352 MHz
RF test stands	Assess cavity breakdown rate in magnetic field	20-32 MV/m, 704 MHz–3 GHz cavities in 7–10 T
SCRF cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)
	Muon Cooling	
First 6D cooling cell	Build and test first cooling cell	
5-cell module	Build and test first 5-cell cooling module	
Cooling demonstrator	Design and build cooling demonstrator facility	Infrastructure to test cooling modules with muon beam
Final cooling absorber	Experimental determination of final cooling absorber limit	3×10^{12} muons, 22.5 µm emittance, 40 T field
	Design & Other Technologies	
Neutrino flux mover system	Protoype components and tests as needed	Range to reach O(±1mradian)
Beam Instrumentation	Instrumentation component designs	Protoype components and tests as needed
Target Studies	Target design and test of relevant components	0.4 MJ/pulse, 5 Hz
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures

R&D Deliverables and Resources

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SCRF cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)
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Material (MCHF)	1.6	3.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

Totals:

Duration 10 years

Accelerator: 300 MCHF material, 1800 FTEy

Detector: 20 MCHF material, 900 FTEy

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

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)

Tentative IAC Charge

Review the R&D plan and give guidance for improvements

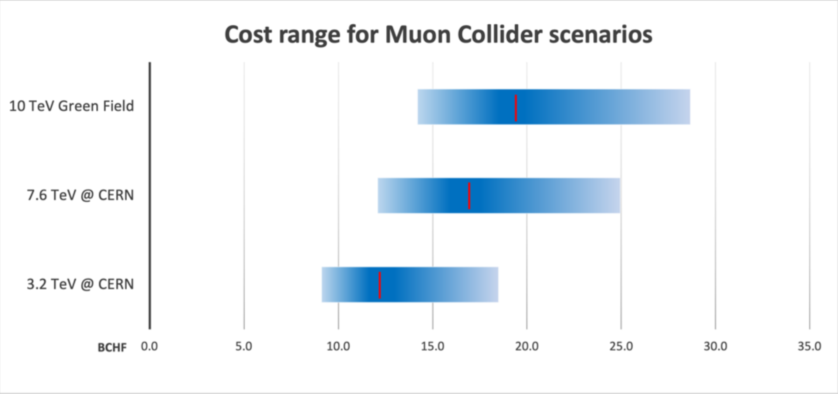
- Is the scope of the programme adequate?
- Is the timeline realistic?
- Does the programme set the right priorities?
- Are we exploiting synergies sufficiently and is there additional potential that we should explore?
- Do you have guidance for the muon collider and R&D plan strategy?

Reserve

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

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This is a great basis for future developments and optimisation

See Carlo on Wednesday

Scope (see Addendum)

- **Magnet technology** developments: HTS solenoids for muon production and cooling; and collider ring dipoles and fast-ramping magnet systems.
- **RF technologies**: components such as klystrons; cavities working in high magnetic field and with high beam loading; and test infrastructure.
- **Muon cooling technology**: the technologies for muon cooling and their integration into the 6D cooling and the final cooling system.
- **The muon cooling demonstration programme**: integration and test of cooling technologies; performance verification; and development of key components like HTS solenoids and RF systems.
- **Design and technologies**: study of key design challenges, including collider modelling; lattice optimization; advanced simulations; site impact studies to balance cost, efficiency, and risk; and technical developments as target, RF and MDI.
- **Detector R&D priorities**: simulation; technology; and software to enhance physics output while reducing beam-induced backgrounds

R&D Plan Resources

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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**

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	INFN, Univ. Padova
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	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***

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 Goals

Proposed R&D programme

- Goal: Assess whether muon collider is feasible
  - Enables to start decision process
- 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

Supporting R&D Timelines

Timeline is based on time required for R&D on the critical path

- High-field magnets
- Muon cooling technology and demonstrator