1st Annual Meeting, May 5 - 2022

MUon collider STrategy network - MUST

Nadia Pastrone INFN-Torino
for the MUST team
INFN - CERN (+BINP) – CEA – IJCLAB – KIT – PSI – UKRI
(BNL-USA not beneficiary)

Task 5.1

….

It will serve as the common ground for a growing international muon-collider collaboration

MUST will support to establish an international collaboration and develop an optimized R&D roadmap towards a future muon collider, including the definition of optimum test facilities and possible intermediate steps

Web page:
http://muoncollider.web.cern.ch
Mailing lists to subscribe:
Login at: https://e-groups.cern.ch
search for “muoncollider”
i.e. -FACILITY@cern.ch

MUST goals – before/after ESPPU

Task 5.1: MUon colliders STrategy network (MUST) M1 – M48

- Support the effort to **design a muon collider** and to **project and plan the required R&D**
- **Consolidate the community** devoted to develop an international future facility
- Prepare the platform to **disseminate** the information (website, meetings, tools)

ESPPU

*[..] an **international design study** for a **muon collider***
***unique opportunity** to achieve a multi-TeV energy domain*

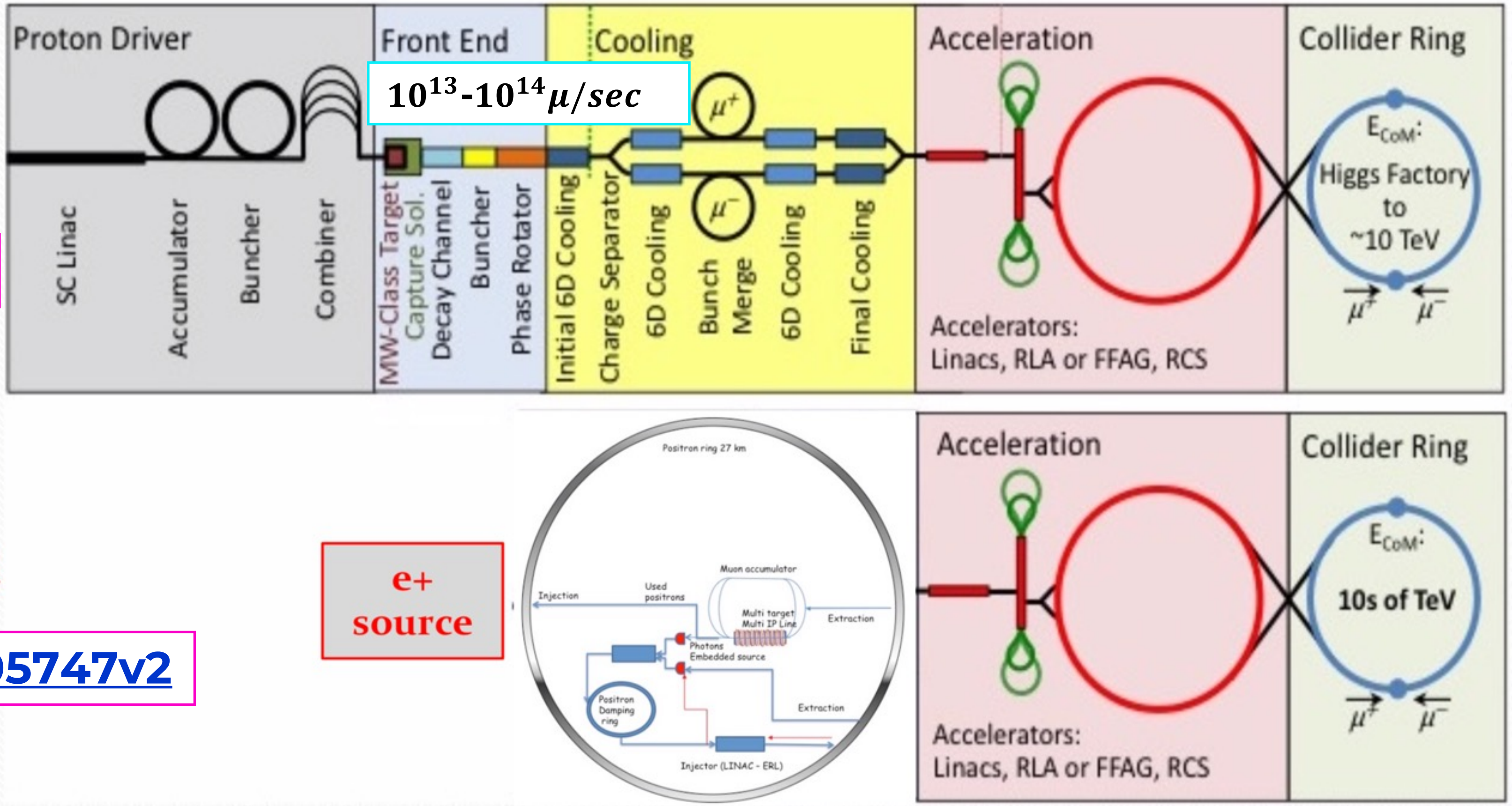
MUST can play a crucial role

- **MS15:** International workshop on muon source design **M18** → *Report*
- **MS16:** International workshop to define R&D plans **M36** → *Report*
- **D5.1:** International collaboration plans towards a multi-TeV muon collider **M46**

proton (MAP) vs positron (LEMMA) driven muon source

MAP

MUON JINST



LEMMA

arXiv:1905.05747v2

➔ **need consolidation** to overcome technical limitations to reach higher muon intensities

Key Challenges of the facility

- **Focus on two energy ranges:**

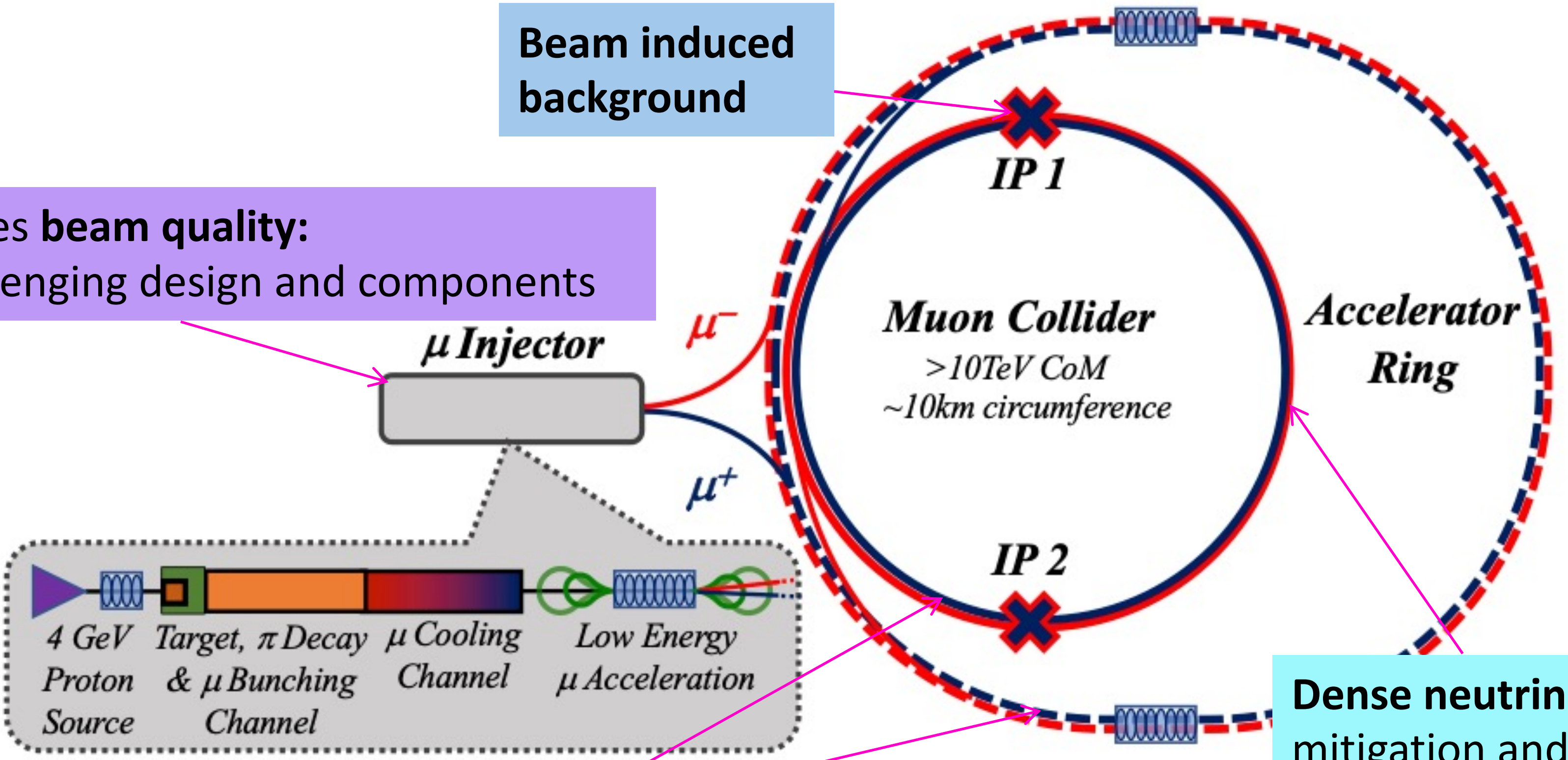
– **3 TeV** technology ready for construction in 10-20 years

– **10+ TeV** with more advanced technology

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	$1\ \mathrm{ab}^{-1}$
10 TeV	$10\ \mathrm{ab}^{-1}$
14 TeV	$20\ \mathrm{ab}^{-1}$

10+ TeV completely new regime to explore!

Proton driver production
Baseline @ International Design Study



Beam induced background

Drives **beam quality:**
challenging design and components

Dense neutrino flux mitigation and site

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

iFAST

Accelerator R&D Roadmap
Bright Muon Beams and Muon Colliders

Panel members: **D. Schulte**,(Chair), M. Palmer (Co-Chair), T. Arndtl, A. Chancé, J. P. Delahaye, A.Faus-Golfe, S.Gilardoni, P.Lebrun, K.Long, E.Métral, N.Pastrone, L.Quettier, T.Raubenheimeru, C.Rogers, M.Seidel, D.Stratakis, A.Yamamoto
Associated members: A. Grudiev, R. Losito, D. Lucchesi

- Detailed review and plan forward prepared by the international Roadmap panel
- Community was involved: 3 Community Meetings (May-July-October)

  ➔ https://indico.cern.ch/category/14577/
- and a dedicated Muon Collider Physics and Detector Workshop

The Roadmap document: https://arxiv.org/abs/2201.07895
was presented to CERN Council in December 2021
now an **Implementation plan** has to be establish

Community Meeting - WG

***Radio-Frequency (RF):** Alexej Grudiev (CERN), Jean-Pierre Delahaye (CERN retiree), Derun Li (LBNL), Akira Yamamoto (KEK)*

***Magnets:** Lionel Quettier (CEA), Toru Ogitsu (KEK), Soren Prestemon (LBNL), Sasha Zlobin (FNAL), Emanuela Barzi (FNAL)*

***High-Energy Complex (HEC):** Antoine Chance (CEA), J. Scott Berg (BNL), Alex Bogacz (JLAB), Christian Carli (CERN), Angeles Faus-Golfe (IJCLab), Eliana Gianfelice-Wendt (FNAL), Shinji Machida (RAL)*

***Muon Production and Cooling (MPC):** Chris Rogers (RAL), Marco Calviani (CERN), Chris Densham (RAL), Diktys Stratakis (FNAL), Akira Sato (Osaka University), Katsuya Yonehara (FNAL)*

***Proton Complex (PC):** Simone Gilardoni (CERN), Hannes Bartosik (CERN), Frank Gerigk (CERN), Natalia Milas (ESS)*

***Beam Dynamics (BD):** Elias Metral (CERN), Tor Raubenheimer (SLAC and Stanford University), Rob Ryne (LBNL)*

***Radiation Protection (RP):** Claudia Ahdida (CERN)*

***Parameters, Power and Cost (PPC):** Daniel Schulte (CERN), Mark Palmer (BNL), Philippe Lebrun (CERN retiree and ESI), Mike Seidel (PSI), Vladimir Shiltsev (FNAL), Jingyu Tang (IHEP)*

***Machine Detector Interface (MDI):** Donatella Lucchesi (University of Padova and INFN), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergo R Jindariani (FNAL)*

***Synergy:** Kenneth Long (Imperial College), Roger Ruber (Uppsala University), Koichiro Shimomura (KEK)*

***Test Facility (TF):** Roberto Losito (CERN), Alan Bross (FNAL), Tord Ekelof (Uppsala University)*

Physics & Detector:
Donatella Lucchesi *(University of Padova and INFN)*

WG 1: **Physics Potential:** Andrea Wulzer (EPFL&CERN) et al.
WG 2: **Detector performance (with several focus areas)**
WG 3: **Detector R&D and Software & Computing development**

Roadmap panel conclusions

GOAL

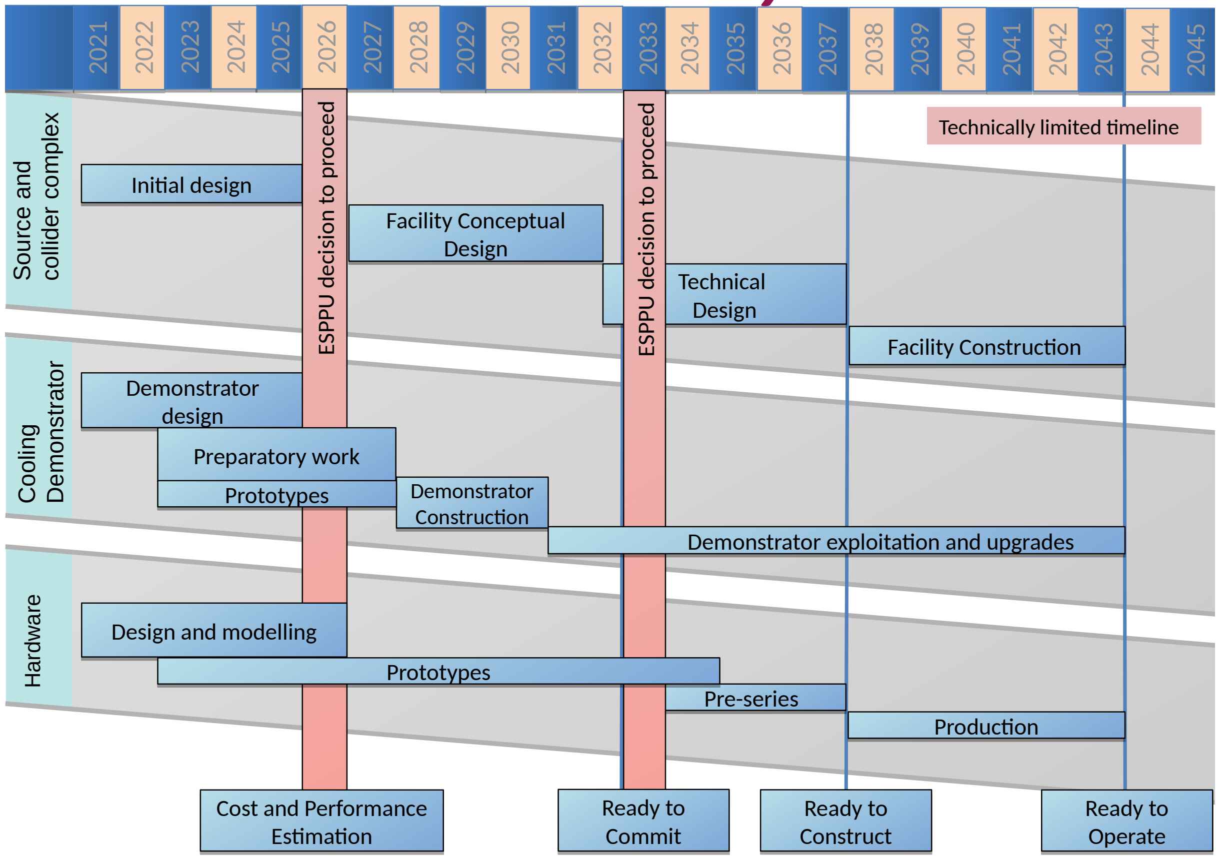
In time for the next European Strategy for Particle Physics Update, aim to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**

The panel endorsed this ambition and concludes that:

- The MC presents enormous potential for fundamental physics research at the energy frontier
- At this stage the panel did not identify any showstopper in the concept and sees strong support of the feasibility from previous studies
- It identified important R&D challenges

The panel has identified a development path that can address the major challenges and deliver a 3 TeV muon collider by 2045

Technically limited timeline



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Source and collider complex

Initial design

Facility Conceptual Design

Technical Design

Facility Construction

Cooling Demonstrator

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Hardware

Design and modelling

Prototypes

Pre-series

Production

ESPPU decision to proceed

ESPPU decision to proceed

Cost and Performance Estimation

Ready to Commit

Ready to Construct

Ready to Operate

Accelerator Key Challenge Areas

- **Physics potential** evaluation, including **detector concept and technologies**

- Impact on the environment
  - The **neutrino flux mitigation** and its impact on the site (first concept exists)
  - The **machine induced background** impact the detector, and might limit the physics

- **High-energy systems** after the cooling (acceleration, collision, ...)
  - Fast-ramping magnet systems
  - High-field magnets (in particular for 10+ TeV)

- Some technology challenges more important at 10 than at 3 TeV
  - higher dipoles fields in collider (O(15 T))
  - stronger final focus quadrupoles (O(18-20 T))
  - shorter bunches in cavities of last accelerator ring
  - more performant accelerator ring systems to cut length and cost

- **High-quality muon beam production**
  - Special RF and high peak power
  - Superconducting solenoids
  - Cooling string demonstration (cooling cell engineering design, demonstrator design)

- **Full accelerator chain**
  - e.g. proton complex with H- source, compressor ring ➔ test of target material

Roadmap Accelerator R&D

Three main deliverables are foreseen for Muon Collider:

- a **Project Evaluation Report** for the next ESPPU will contain an assessment of whether the 10 TeV muon collider is a promising option and identify the required compromises to realise a 3 TeV option by 2045. In particular the questions below would be addressed.
  - What is a realistic luminosity target?
  - What are the background conditions in the detector?
  - Can one consider implementing such a collider at CERN or other sites, and can it have one or two detectors?
  - What are the key performance specifications of the components and what is the maturity of the technologies?
  - What are the cost drivers and what is the cost scale of such a collider?
  - What are the power drivers and what is the power consumption scale of the collider?
  - What are the key risks of the project?
- an **R&D Plan** that describes a path towards the collider;
- an **Interim Report** by the end of 2023 that documents progress and allows the wider community to update their view of the concept and to give feedback to the collaboration.

Roadmap scenarios

Roadmap identifies muon collider challenges and two R&D scenarios to address them

An **full scenario**

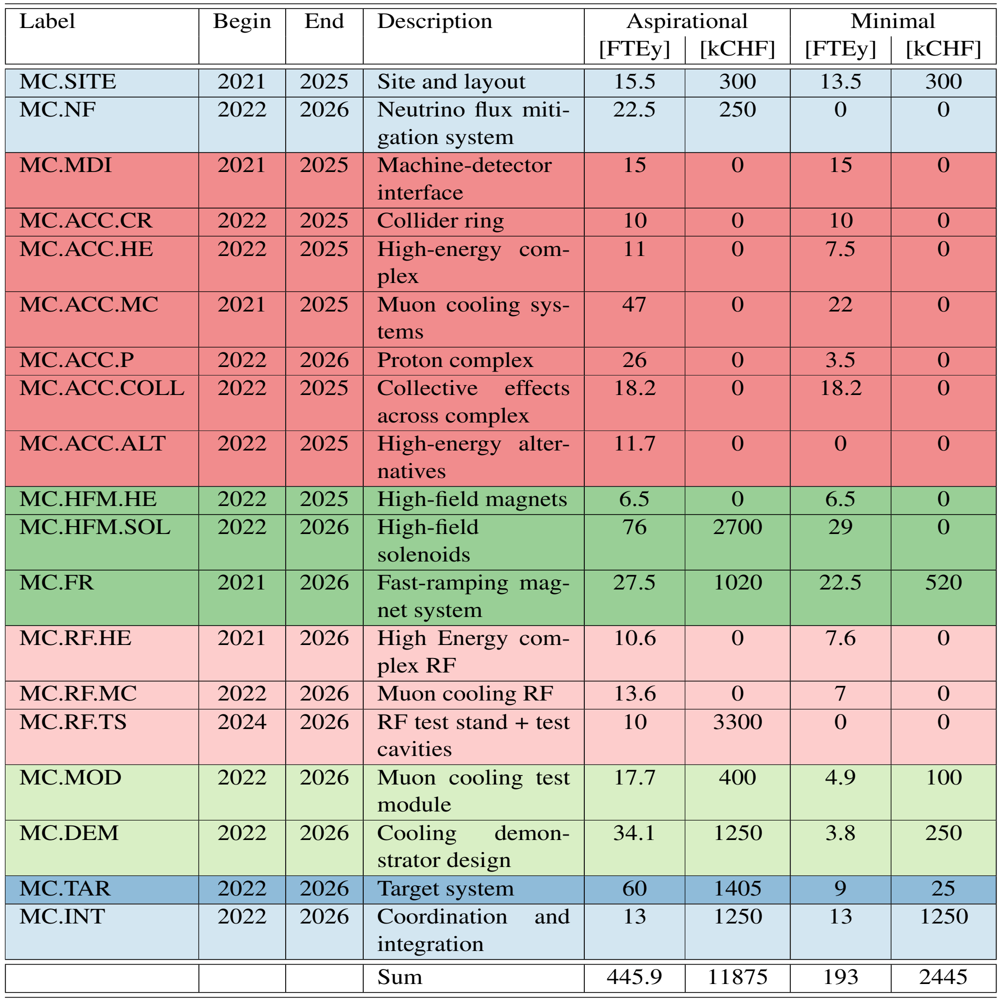
full achievement of objectives, about 5 years

A **reduced scenario**

only a subset of objectives can be achieved, 5 years

Aspirational		**Minimal**	
[FTEy]	**[MCHF]**	**[FTEy]**	**[MCHF]**
446	**12**	**193**	**2.5**
65 MCHF/5 years		**27 MCHF/5 years**	

http://arxiv.org/abs/2201.07895



Label	Begin	End	Description	Aspirational		Minimal	
				[FTEy]	[kCHF]	[FTEy]	[kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

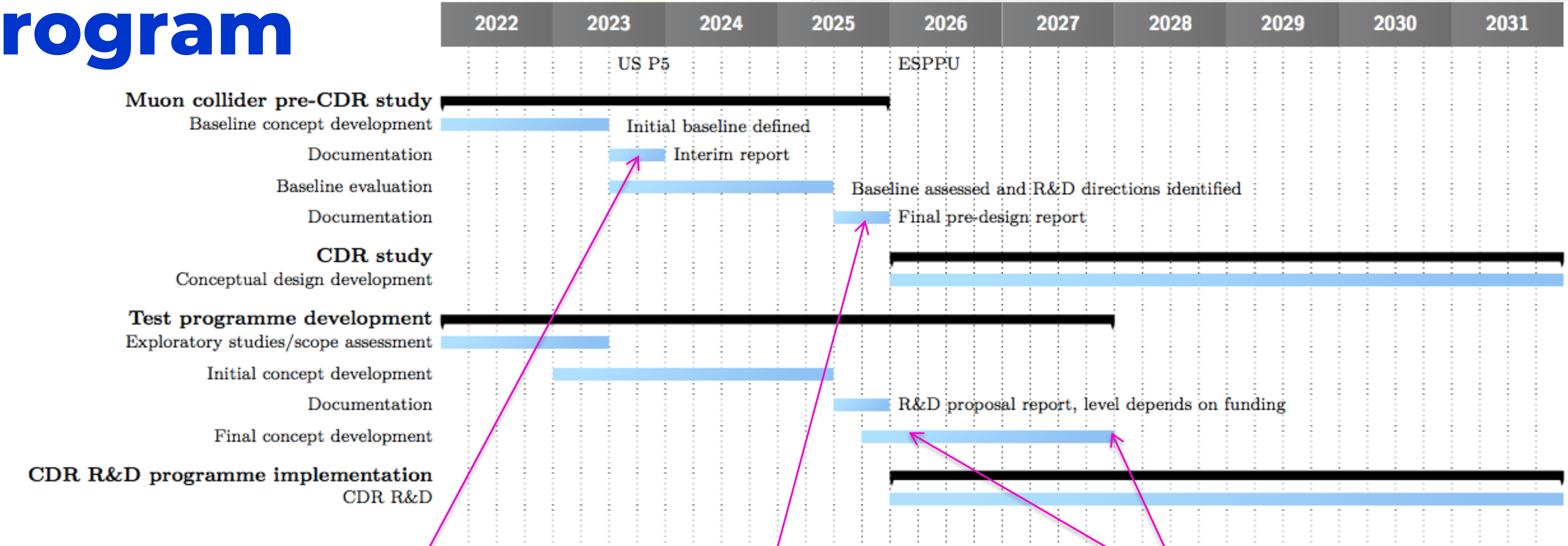
Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment and similar costs. Colours are included for comparison with the resource profile Fig. 5.7.

R&D Program

MS15 M18 muon source design

MS16 M36 R&D

D5.1 M46 collaboration plans towards a multi-TeV muon collider



2023
Interim Report to gauge progress
Initial baseline defined

2025
Assessment Report

2025-2027
R&D plan will be refined

SnowMass process ongoing

US SnowMass Muon Collider Forum **since 2021**
share ideas and studies across frontiers

Snowmass/P5 process in the US ➔ **ready by 2023**

5 SnowMass whitepapers submitted March 2022:

arXiv:2203.08033	A Muon Collider Facility for Physics Discovery
arXiv:2203.07256	Muon Collider Physics Summary
arXiv:2203.07261	The physics case of a 3 TeV muon collider stage
arXiv:2203.07964	Simulated Detector Performance at the Muon Collider
arXiv:2203.07224	Promising Technologies and R&D Directions for the Future Muon Collider Detectors

EU Design Study

International Muon Collider Collaboration
Project Leader: *Daniel Schulte*

JUST SUBMITTED

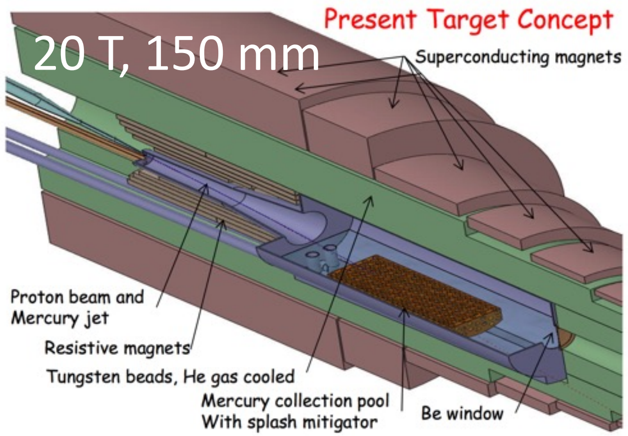
HORIZON-INFRA-2022-DEV-01-01: Research infrastructure concept development
Type of Action: Research and Innovation Actions
Develop a conceptual design for the collider

INFRA-DEV WP	I.FAST WP links
1. Integration and management	
2. Physics&Detector vs BIB	
3. Proton complex	➔ WP4
4. Muon production and cooling	➔ WP4 (Innovative beam windows) – WP8 – WP9
5. High-energy complex and MDI	➔ WP8-WP9
6. RF systems	➔ WP9
7. Magnets (see next slides)	➔ WP8
8. Muon cooling cell - integration	➔

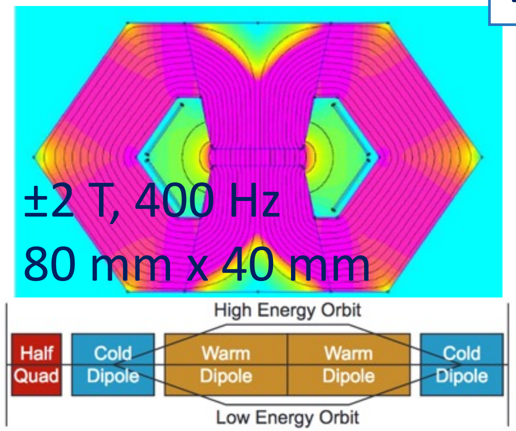
EU DESIGN STUDY PROPOSAL WORKSHOP for details

Magnets demand

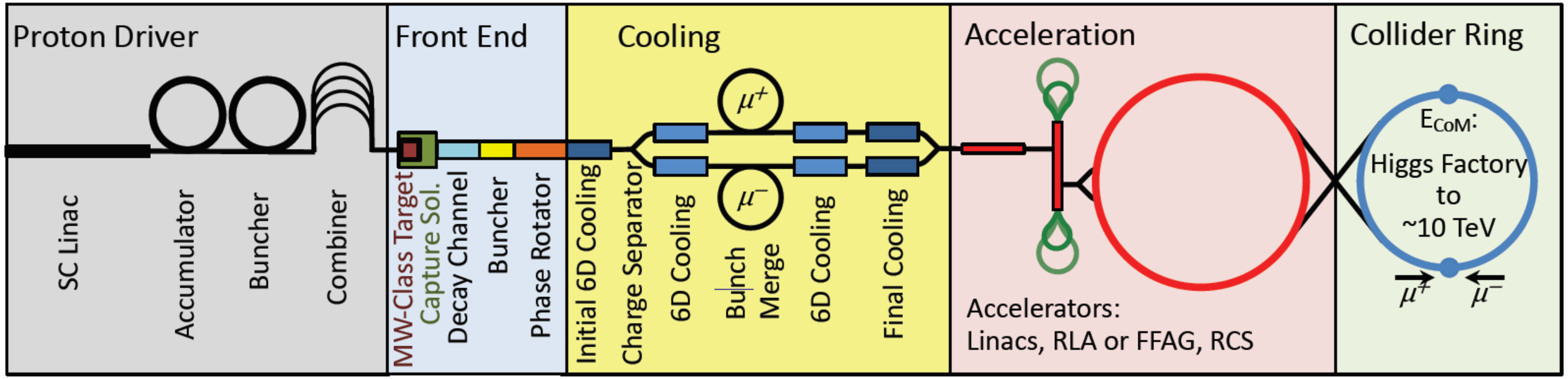
Luca Bottura



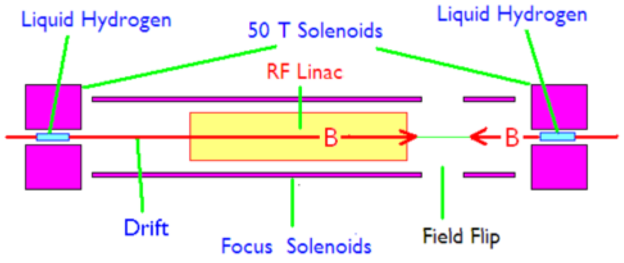
High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads



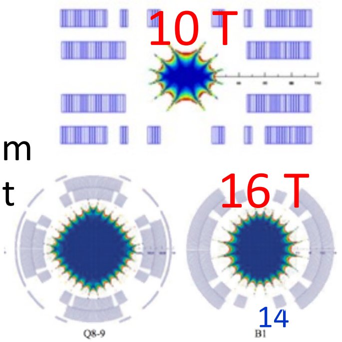
Combination of DC SC magnets (10 T) and AC resistive magnets (± 2T)



Ultra-high-field solenoids (40…60 T) to achieve desired muon beam cooling



Open midplane or large dipoles and quadrupoles in the range of 10…16 T, bore in excess of 150 mm to allow for shielding against heat (500 W/m) and radiation loads



Magnet preliminary Summary

Luca Bottura et al

Complex	Magnet	**Field Gradient** (T) / (T/m)	**Field rate** (T/s)	**Aperture** (mm)	**Length** (m)	**Heat load** (kW/m)	Candidate Technologies
Target and Capture	Solenoid	20	N/A	150	1	100	Hybrid (SC+resistive) All-SC (LTS+HTS)
Cooling	Solenoid	2…14 40…60	N/A	1000…50 50	1 0.5	TBD TBD	All SC (LTS+HTS)
Accelerator	NC Dipole	± 2	500 10,000	80x40	5	TBD	SC (LTS) DC + NC AC SC (LTS) DC + SC (HTS) AC FFAG
Collider	Dipole	10…16	N/A	150	15	0.5	Nb_3Sn or Nb-Ti+HTS
	Quadrupole	250…300	N/A	150	10	TBD	Nb_3Sn or Nb-Ti+HTS

Magnet R&D impact on Science and Society

Luca Bottura

R&D on the magnet technology necessary for a muon collider has multiple implications for other fields of science, industry and society.
Below some relevant examples:

- The ***target solenoid*** requires large fields (15 T) in a large bore (2 m), in the range of field and geometry relevant for a **full-body MRI** of the next generation, or **solenoid magnets for fusion**
- Ultra-high field solenoids (40…60 T) with modest bore (50 mm) as required by the ***final cooling stage*** share the challenges of **magnets for high-field science**, as well as **solenoids for NMR spectroscopy**
- The fast-ramped magnets planned in the **acceleration stage** (4 T field swing, 400 Hz) are relevant to the development of rapid cycled synchrotrons for intense beams, **nuclear physics, medical applications**, and **accelerator-driven reactors and transmutation systems**
- Energy and power management for the **fast ramped magnets** in the accelerator complex, typically tens of MJ on the time scale of 1 ms, i.e. tens of GW, share challenges with **pulsed power conversion for high-field magnets**, as well as energy storage and power management for the power grid
- Large aperture dipoles and quadrupoles for the **collider** will profit from the stress-management techniques developed for **High-Field Magnets**

Planning ahead

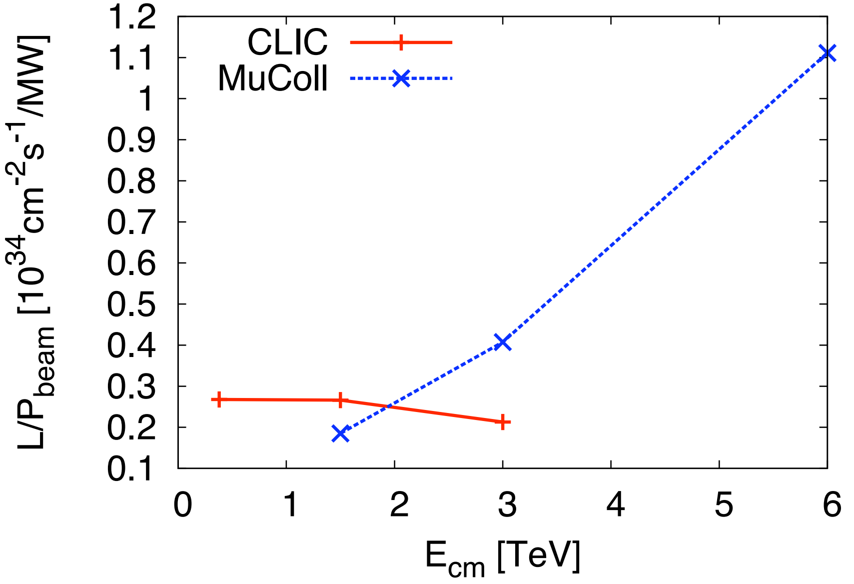
- **AMBITION**: successful implementation of an **international plan** to address all studies and key issues towards the design of a muon collider capable to reach multi-TeV collision energies with an adequate luminosity for high-precision measurements and new discoveries.
  ➔ **pre-conceptual design report with cost and power scale and evaluate risks**
  ➔ **prepared R&D programme**
- **CHALLENGES**: establish an organized international collaboration to address key issues and plan future steps. Evaluate reuse of existing infrastructures taking into account neutrino radiation hazards. Design of needed **test facilities** to address final feasibility.

MUST is actively contributing to:

- Network in EU & other regions: USA – ASIA - activities ongoing at SnowMass21 process
- Promote synergies with other projects/industries for technologies R&Ds

Conclusions

- Muon collider is most promising project for future high-energy, high-luminosity lepton collisions
  ➔ Going well beyond CLIC at 3 TeV, the highest energy concept
- So far no technical obstacle identified to realise 3 TeV by 2045
- Roadmap aspirational programme will deliver R&D programme
- **Opportunities for important R&D exists ⇔ I.FAST**
  - Fast ramping magnet systems
  - High-field solenoids
  - High-field normal-conducting RF
  - Integrated design of muon cooling system and demonstrator



Highlight talk tomorrow by **Elena Fol**

A 10 TeV Muon Collider design:
key technologies and challenges

SUSTAINABILITY TO BE FINALLY DEMONSTRATED
cost effective ➔ need real study to confirm cost
power efficient ➔ need a more detailed study
compact site ➔ more with better ramping magnets

Thanks to many colleagues:

MAP and LEMMA collaborations
CERN Muon Collider Working Group
Roadmap Accelerator R&D Muon Panel
IMCC Collaboration
SnowMass AF4 & AF and Muon Collider Forum

Thanks for your attention!

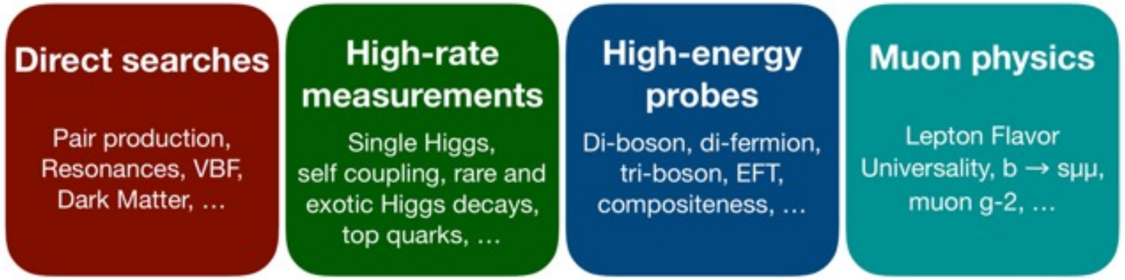
I.FAST International workshop on muon source design (MS15)
will be soon announced ➔ please suggest contributions

This project has received funding from the European Union's
Horizon 2020 Research and Innovation programme under GA No101004730

extras

Physics potential

A dream machine to probe unprecedented energy scales and many different directions at once!



Direct searches
Pair production, Resonances, VBF, Dark Matter, …

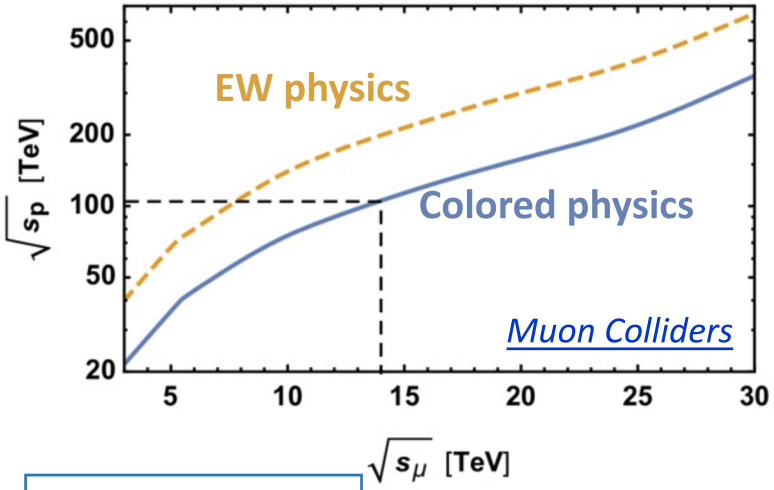
High-rate measurements
Single Higgs, self coupling, rare and exotic Higgs decays, top quarks, …

High-energy probes
Di-boson, di-fermion, tri-boson, EFT, compositeness, …

Muon physics
Lepton Flavor Universality, $b \to s\mu\mu$, muon g-2, …

Muon Collider can be the game changer!

Energy at which $\sigma_{pp} = \sigma_{\mu\mu}$



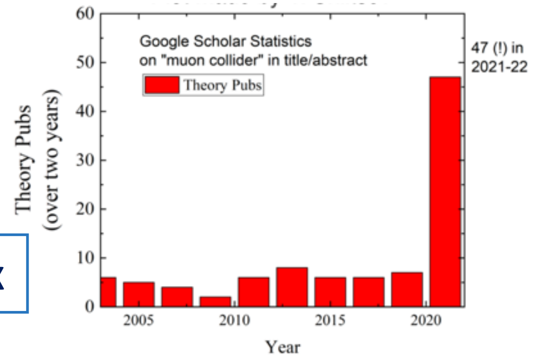
Andrea Wulzer

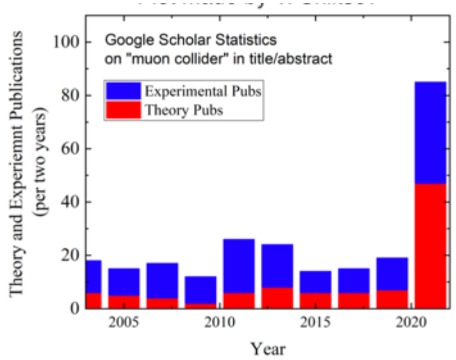
Great and growing interest in the theory community ➔ many papers recently published, as:

The Muon Smasher's Guide,
https://doi.org/10.48550/arXiv.2103.14043

Strong and crucial synergies to design the machine and the experiment to reach the physics goals with energy and luminosity allowing % precision measurements

➔ **Physics benchmarks steer machine parameters and experiment design**





Vladimir Shiltevx

A unique facility

Muons – fundamental particles –
leptons ~ 200 times heavier than electron
decay with lifetime at rest of 2.2 μs

Jan 2021 **nature physics**

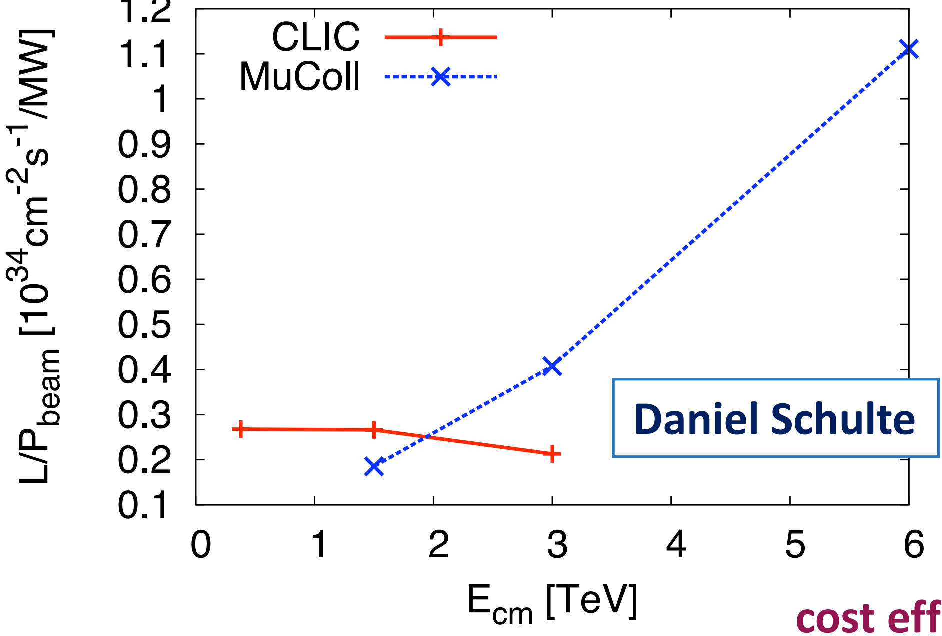
[Muon colliders to expand frontiers of particle physics](#)

K.Long, D.Lucchesi, M.Palmer, N.Pastrone, D.Schulte, V. Shiltsev

an idea over 50 years old has now the opportunity to become feasible

ESPP Input document: Muon Colliders

Energy Efficiency



Daniel Schulte

Overwhelming physics potential:
- **Precision measurements**
- **Discovery searches**

Challenging Facility Design:
- **Key issues/risks**
- **R&D plan - synergies**

cost effective ➔ need real study to confirm cost
power efficient ➔ need a more detailed study
compact site ➔ more with better ramping magnets

International Collaboration

Project Leader: *Daniel Schulte*

Objective:
In time for the next European Strategy for Particle Physics Update, the Design Study based at CERN since 2020 aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.
It will **provide a baseline concept**, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.
It will also **identify an R&D path to demonstrate the feasibility of the collider**.

Scope:
- Focus on the high-energy frontier and two energy ranges:
  - **3 TeV** if possible with technology ready for construction in 10-20 years
  - **10+ TeV** with more advanced technology, **the reason to choose muon colliders**
- Explore synergies with other options (neutrino/higgs factory)
- Define **R&D path**

Web page: http://muoncollider.web.cern.ch

Task 5.1: MUST
(INFN, CERN, CEA, CNRS, KIT, PSI, UKRI)
[..]
A Europe-wide network is essential for the development of the collider design and technology, which will serve as a common forum to coordinate with the growing international muon-collider efforts, including the US-MAP collaboration, sharing data and results.

Task 5.1: MUon colliders STrategy network (MUST) *(INFN, CERN, CEA, CNRS, KIT, PSI, UKRI)*
A multi-TeV Muon Collider could be a unique discovery machine and the best tool to fully study the Higgs boson, if demonstrated to be feasible. A Europe-wide network is essential for the development of the collider design and technology, which will serve as a common forum to coordinate with the growing international muon-collider efforts, including the US-MAP collaboration, sharing data and results.

The muon collider requires an intense muon source, fast muon acceleration to high energies and efficient collisions to provide high luminosity.

The muon beams can be produced either using an intense proton beam (the MAP design) or a positron beam (the novel LEMMA scheme), the former is more mature, but the latter potentially yields better beam parameters. Any other options will be further studied, if considered feasible.

The fast acceleration stage and the collider ring are critical for the collider cost, power consumption and performance, and technologies that can be developed in synergy with other future projects.

The decay of muons produces intense fluxes of neutrinos and electrons, sources of background in the machine and in the detector.

Dedicated technology development and close collaboration between the accelerator and the detector will be needed to address this issue.

This task will provide a platform to discuss the plans for key R&D and test facilities as well as disseminate the information on muon colliders activities.

It contains two main sub-task: the muon source (positron and proton driven) and the overall collider design.

The partners of this Task are those who already contributed to the process of updating the European Particle Physics Strategy coordinated by the CERN Working Group on Muon Colliders. The organisation of the muon collider efforts will follow the EU Strategy.

Demonstrator and test facilities

Production and cooling complex novel and unique to the muon collider

- Many components are unconventional
  - ✓ e.g. high-gradient cavities in magnetic field with Be windows or filled with gas
  - ✓ massive use of absorbers in the beam path
- Novel technologies beyond MAP design can be considered
  - ✓ e.g. very short RF pulse to reduce breakdown probability
- Compact integration is required to maximise muon survival
  - ✓ complex lattice design optimisation
- Almost no experience with beam in these components, MICE has been a limited model (no RF, single muons)

⬇

Test Facility is needed where muons are produced and cooled

Luminosity and parameters goals

Target integrated luminosities

$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ \text{ab}^{-1}$

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

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

@ 14 TeV ~ 20 ab^{-1} 5 years

Note: currently no staging
Would only do 10 or 14 TeV

- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

Tentative target parameters
Scaled from MAP parameters

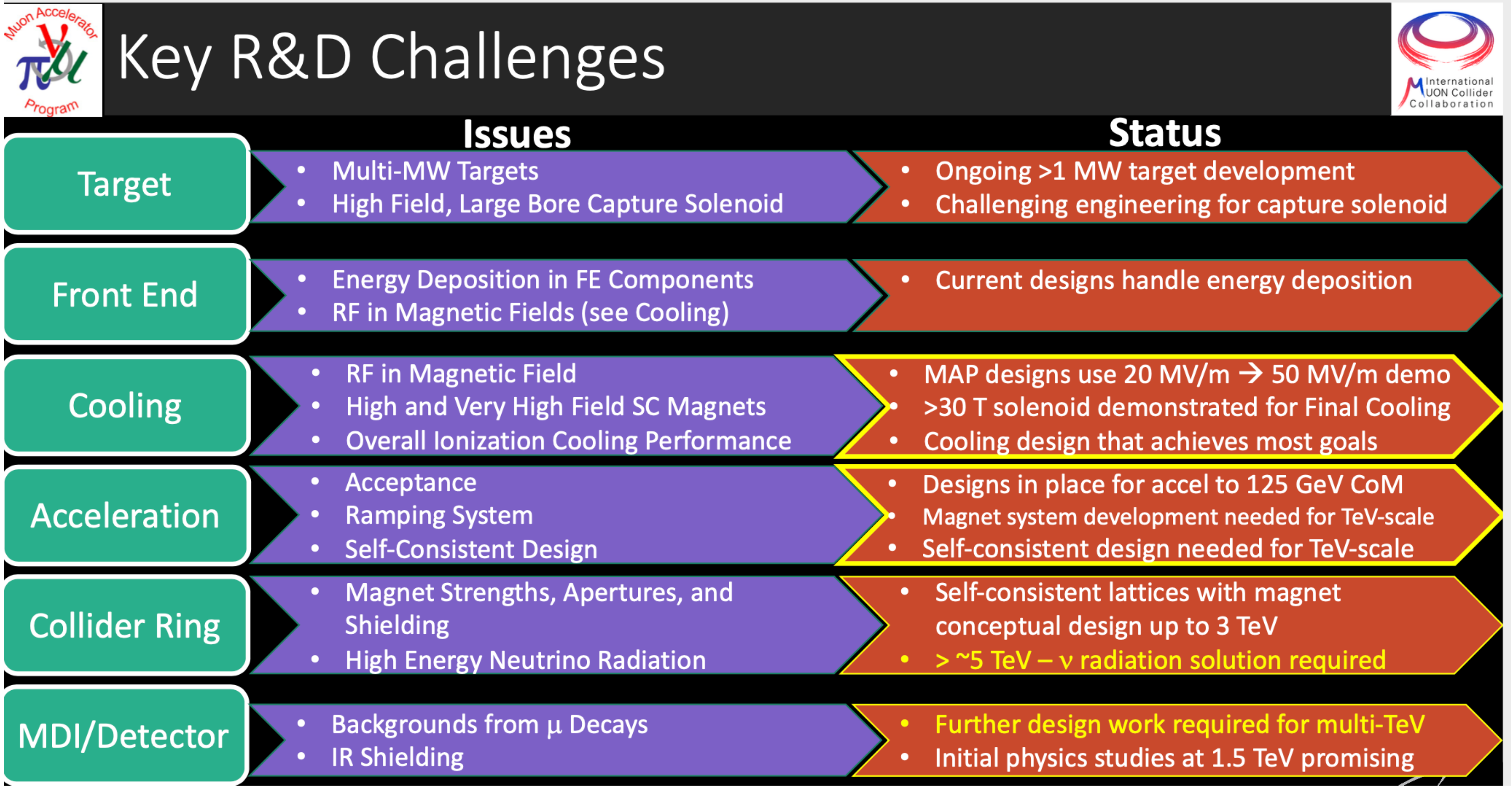
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

Comparison:
CLIC at 3 TeV: 28 MW

Now study if these parameters lead to realistic design with acceptable cost and power

Key R&D challenges

Mark Palmer



Key R&D Challenges

	Issues	Status
Target	• Multi-MW Targets • High Field, Large Bore Capture Solenoid	• Ongoing >1 MW target development • Challenging engineering for capture solenoid
Front End	• Energy Deposition in FE Components • RF in Magnetic Fields (see Cooling)	• Current designs handle energy deposition
Cooling	• RF in Magnetic Field • High and Very High Field SC Magnets • Overall Ionization Cooling Performance	• MAP designs use 20 MV/m → 50 MV/m demo • >30 T solenoid demonstrated for Final Cooling • Cooling design that achieves most goals
Acceleration	• Acceptance • Ramping System • Self-Consistent Design	• Designs in place for accel to 125 GeV CoM • Magnet system development needed for TeV-scale • Self-consistent design needed for TeV-scale
Collider Ring	• Magnet Strengths, Apertures, and Shielding • High Energy Neutrino Radiation	• Self-consistent lattices with magnet conceptual design up to 3 TeV • > ~5 TeV – ν radiation solution required
MDI/Detector	• Backgrounds from μ Decays • IR Shielding	• Further design work required for multi-TeV • Initial physics studies at 1.5 TeV promising

Summary of IMC RF systems

https://www.dropbox.com/s/2e71dj9bzomglwm/MC_RF%20Summary%20Draft.xlsx?dl=0

System			Driver			Front-End	Cooling			Acceleration			Collider	TOTAL	CLIC
Sub-system			Driver Linac H- (SPL like)		Accum &Comp	Capture& Bunching	Initial	6D (2 lines)	Final (2 lines)	Injector Linac	RLAs (2stages)	RCS (3stages)	Ring	IMC	Acceleration
Reference expert			F.Gerigk		?	D.Neuffer	C.Rogers	D.Stratakis	C.Rogers	A.Bogacz		S.Berg	E.Gianfelice		
	Energy	GeV/c	0.16	5	5	0.255	0.255	0.255	0.255	1.25	62.5	1500	1500		1500
Beam (system exit)	# bunches (μ+ or μ-)	#	40 mA		1	12	12	1	1	1	1	1	1		312
	Charge/bunch	E12			500	3.57	2.56	7.21	4.39	3.73	3.17	2.22	2.20		3.72E-03
	Rep Freq	Hz	5	5	5	5	5	5	5	5	5	5	5		50
	Norm Transv Emitt	rad-m				1.5E-02	3.0E-03	8.3E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05		660/20E-06
	Beam dimens. (H/V) in RF	mm	?	?	?	?	?	?	?	?	?	?	?		1?
	Norm Long Emitt	rad-m				4.5E-02	2.4E-02	1.8E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03		
	Pulse/Bunch length	m	2.2 ms		0.6 (2ns)	1.1E+01	1.1E+01	9.2E-02	9.2E-02	4.6E-02	2.3E-02	2.3E-02	5.0E-03		4.4E-05
	Power (μ+ and μ-)	W	6.40E+04	2.2E+06	2.0E+06	1.8E+04	1.3E+04	3.0E+03	1.8E+03	7.6E+03	3.2E+05	5.4E+06	5.3E+06		2.8E+07
RF cavities	Technology		NC Linac4	SC	SC	NC	NC	NC Vacuum	NC	SC	SC	SC	SC		NC High Grad
	Number of cavities	#	23	244	2	120	367	7182	32	52	360	2694	?	11076	149000
	RF length	m	46	237	1	30	105	1274	151	82	1364	2802	?	6092	30000
	Frf	MHz	352	704	44	326to493	325	325-650	20-325	325	650-1300	1300	800	4 to 1300	12000
	Grf	MV/m	1-3.7	19 - 25	2	20	20 to 25	19-28.5	7.2-25.5	20	25 to 38	35	?	1 to 38	100
	Aperture	mm	28	80		?	?	?	?	300	150	75	120	28 to 300	2.75
	Magnetic Field	T	0	0		2	3T	1.7-9.6	1.5-4	0	0	0	0	0 to 9.6	0
	Installed RF field	MV	169	5700	4	434	2618	30447	1836	1640	50844	98062	250	1.92E+05	3.00E+06
	Beam Energy gain	MeV	160	4840	0	0	0	0	0	1250	62500	1437000	0	1.51E+06	1.50E+06
	Recirculations	#	1	1		1	1	1	1	1	4.5 to 5	13 to 23	1000	1 to 1000	1
	RF Power/pulse (η=0.6)	MW	25	220	3.E-01	99	429	1172	43	52	360	2024	1.98E-02	4425	1.2E+07
RF power sources	Technology		klystron	klystron						Klytron-IOT					Two Beam
	Cavities/Power Source	#	23	244		4				1 to 2	1 to 2				2
	RF Pulse (fill+beam) estim.	ms	2.20	2.20	3.20	0.10	0.10	0.10	0.10	0.03	0.06	0.73	14.80		0.142
	Prf/Power Source	MW	11.7	1.93						1	1				15
	Total Power Sources	#	17	244		30				52	341			?	1638
	Installed Peak RF Power	MW	34	275		164	515	1407	52	52	341	2429	2.38E-02	5269	2.46E+04
	Average RF power (η=0.6)	MW	0.27	2.13	0.01	0.05	0.21	0.59	0.02	0.01	0.11	14.88	0.00	18.28	143
	Wall plug power (η=0.6)	MW	0.45	3.55	0.01	0.08	0.36	0.98	0.04	0.01	0.18	24.81	0.00	30.46	289