This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

Report on Task 5.1: MUST MUon collider STrategy network

Nadia Pastrone INFN-Torino

INFN - CERN (+BINP) – CEA – IJCLAB – KIT – PSI – UKRI (BNL-USA not beneficiary)

I.FAST Period 2 Review, 15.07.2024

Task structure and objectives

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)

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

MUST plays a crucial role and is part of the international collaboration

- **MS15:** International workshop on muon source design **M18** ➔ *Report*
- **MS16:** International workshop to define R&D plans **M36** ➔ *Report delayed **M40***
- **D5.1:** International collaboration plans towards a multi-TeV muon collider **M46**

International Muon Collider Collaboration
IMCC @ CERN

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

Towards a Muon Collider *Eur.Phys.J.C* 83 (2023) 9, 864

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**, ...
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 facilities' options (neutrino/higgs factory)
- Define **R&D path**

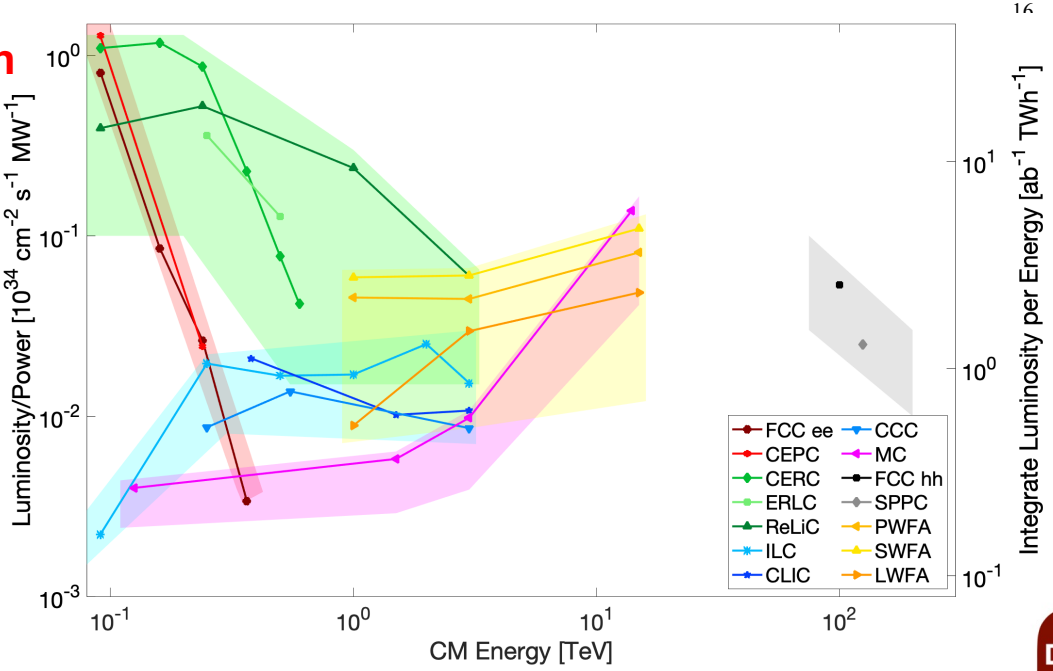
NEW ESPPU
Input documents due by March 31 2025

Energy efficiency of present and future colliders

Thomas Roser et al., Report of the Snowmass 2021 Collider Implementation Task Force, Aug 2022

Luminosity per power consumption

- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Luminosity is per IP and integrated luminosity assumes 10^7 sec/year
- Data points are provided to the ITF by proponents of the respective machine
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



The effective energy reach of hadron colliders (LHC, HE-LHC and FCC-hh) is approximately a factor of seven lower than that of a lepton collider operating at the same energy per beam

Muon Collider

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

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

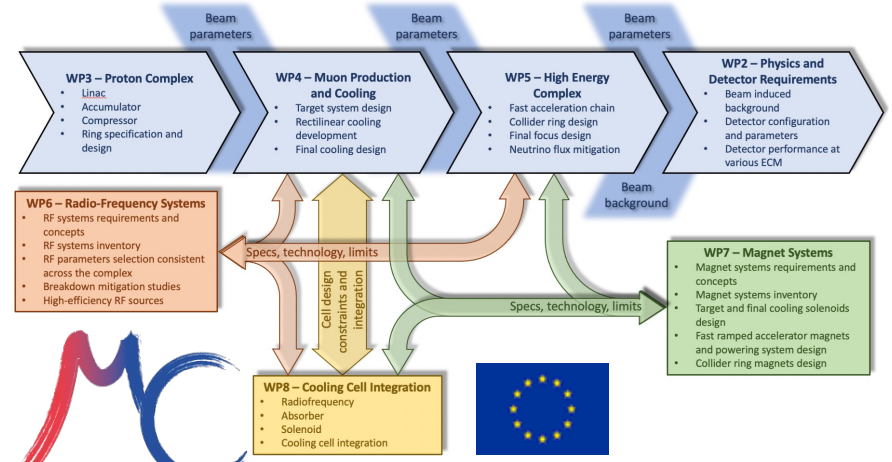
High-energy probes
Di-boson, di-fermion, tri-boson, EFT, compositeness, …

Muon physics
Lepton Flavor Universality, b → sμμ, muon g-2, …

Unique physics potential

Recent progress

MuCol – EU INFRA-DEV project
A Design Study for a Muon Collider complex at 10 TeV center of mass



MuCol

https://mucol.web.cern.ch/

Tentative parameters available

This project has received funding from the European Union's Research and Innovation programme under GA No 101094300

Strong commitment of the International Community to:

- ✓ consolidate the baseline design of the facility at 10+ TeV
- ✓ design/optimize the facility and the experiment: **R&D plan**
- ✓ identify priorities and synergies

Accelerator R&D Roadmap
implementation
Detector R&D Roadmap
implementation ➔DRD collaborations

Interim Report ready to be submitted

Exploring the Quantum Universe

https://www.usparticlephysics.org/2023-p5-report/

Now preparing for formal U.S. Community engagement after P5 Report

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Key Challenges of the facility

- **Initial focus on two energy ranges:**
  - **3 TeV** technology ready for construction in 10-20 years
  - **10+ TeV** with more advanced technology

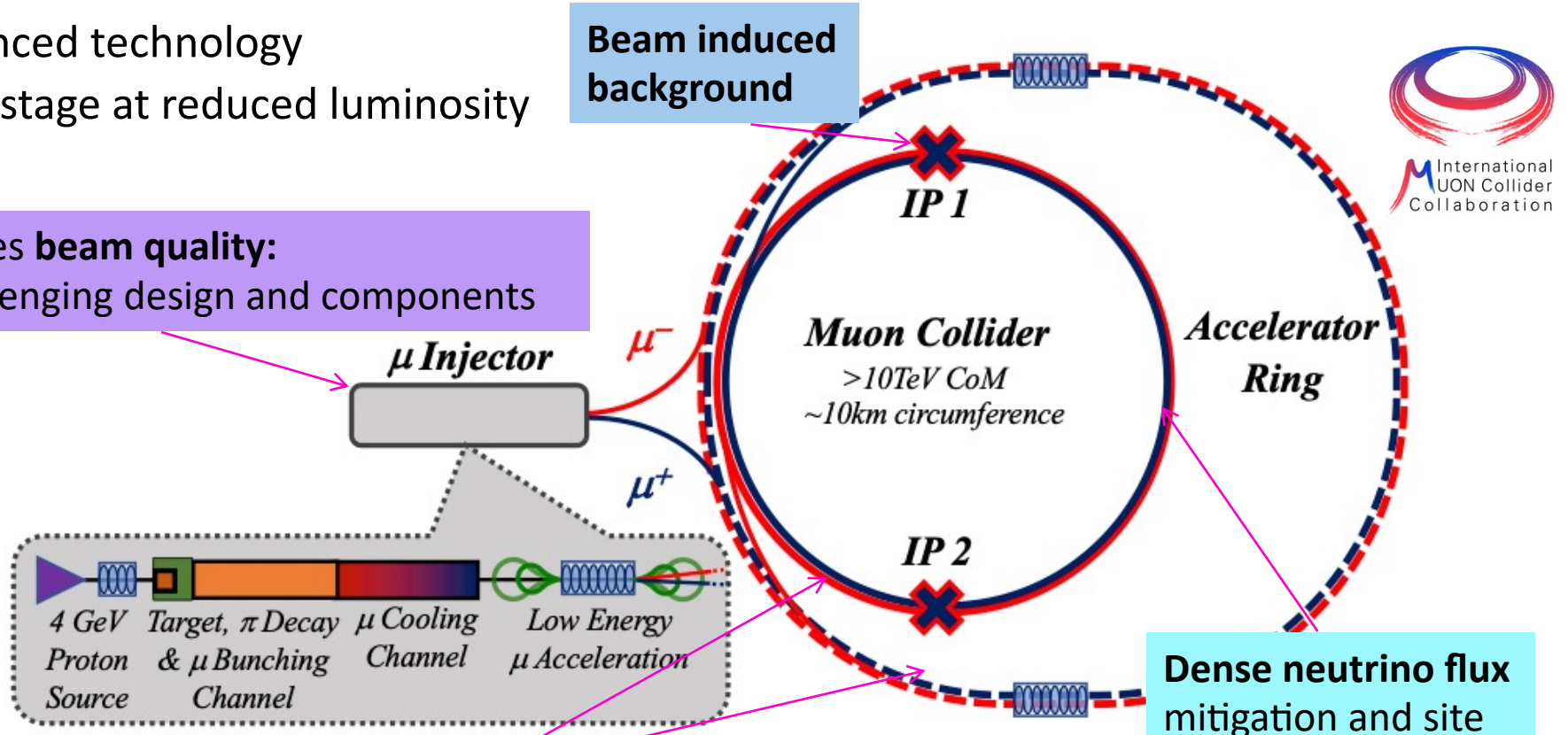
NEW OPTION: initial 10 TeV stage at reduced luminosity

Proton driver production
Baseline @ International Design Study

Beam induced background

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

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



Dense neutrino flux mitigation and site

10+ TeV completely new regime to explore!

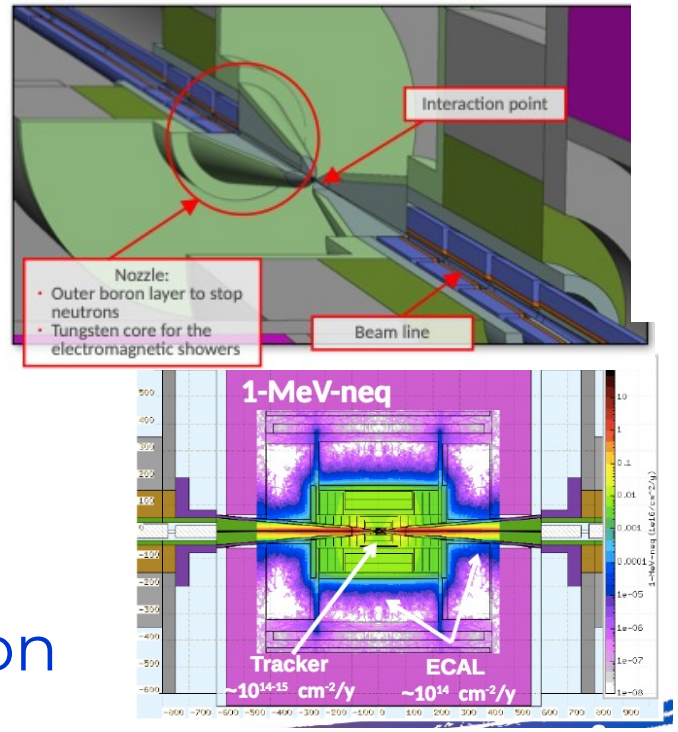
Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

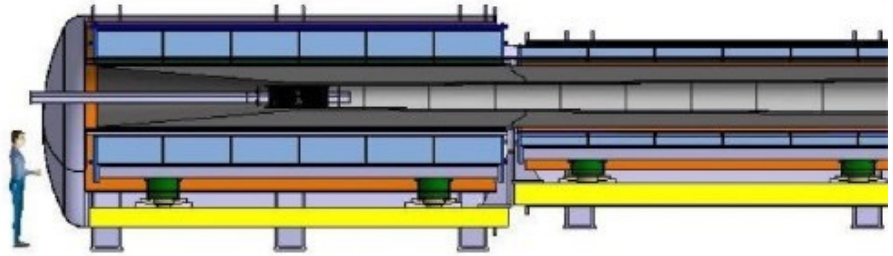
Muon Collider Forum Report

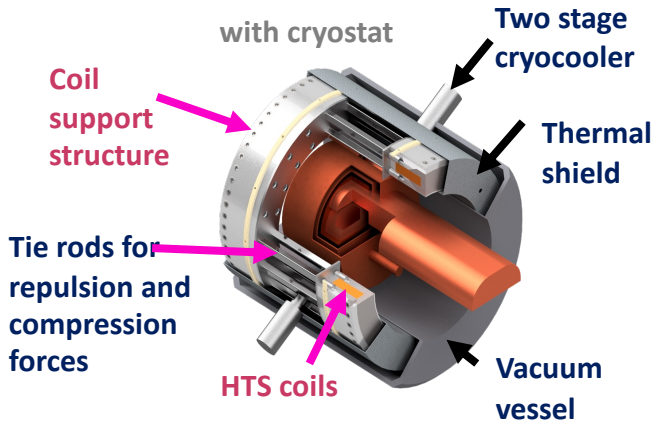
Summary of activities towards R&D plans

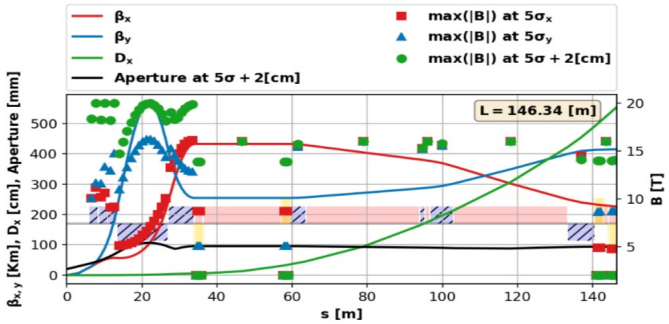
Each WP is working to identify challenges and R&D plans towards a baseline design:

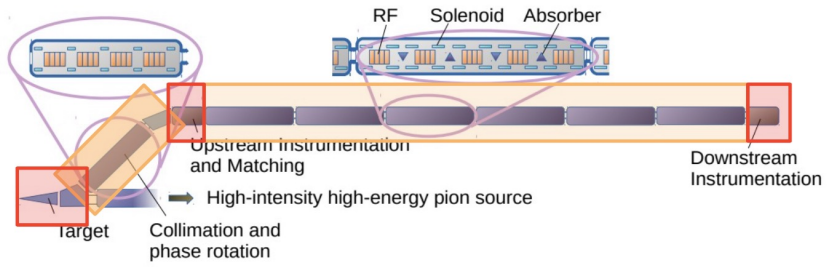
- Physics and MDI
- Proton complex
- Target design
- Muon Cooling
- Accelerator Complex
- Collider Ring
- RF Technology
- Magnet Technology
- Cooling cell integration
- Demonstrator

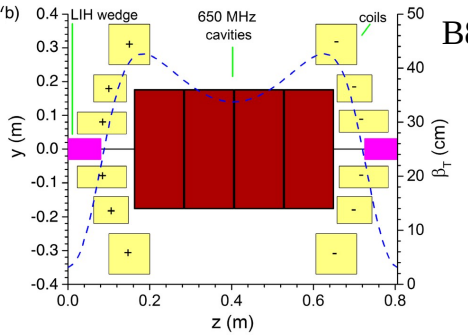












R&D plans – timelines – priorities

Fully included in the agenda of the next
International Annual Meeting @ **CERN March 12-15, 2024**
➔ **MDI workshop** @ CERN March 11-12, 2023

➔**first lattice at the 10 TeV centre of mass energy ➔ Machine Detector Interface** (MDI)
➔**RF and magnet technology (including HTS) test plans are on-going**
➔**Integration of a cooling cell ➔ Planning for a demonstrator is mandatory**
➔**MuCol Cooling cell Workshop** @ CERN January 18-19, 2024

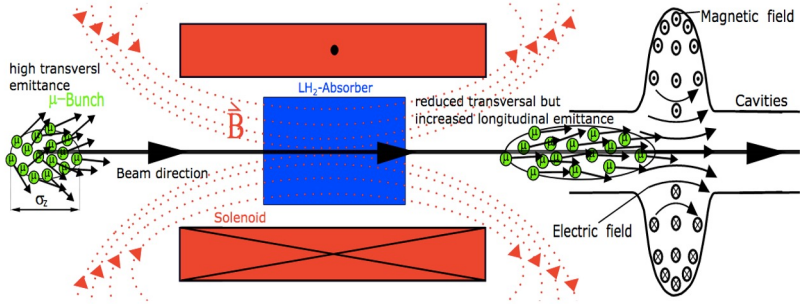
➔Interim Report @ Accelerator R&D Roadmap and MuCol

➔ All progress on technology studies, design study of each component and first lattice @ 10 TeV
➔ Machine Detector Interface (MDI) Design ➔ Beam Induced Backgroud mitigation
➔ **Experiment Design @ 10 TeV ➔ Detector Magnet choice and design under study**
➔ **IMCC Detector and MDI workshop** ➔ Detector R&D and Full simulation studies

Cooling Channel towards a Demonstrator

TO DESIGN A HIGH-EFFICIENT IONIZATION COOLING CHANNEL:

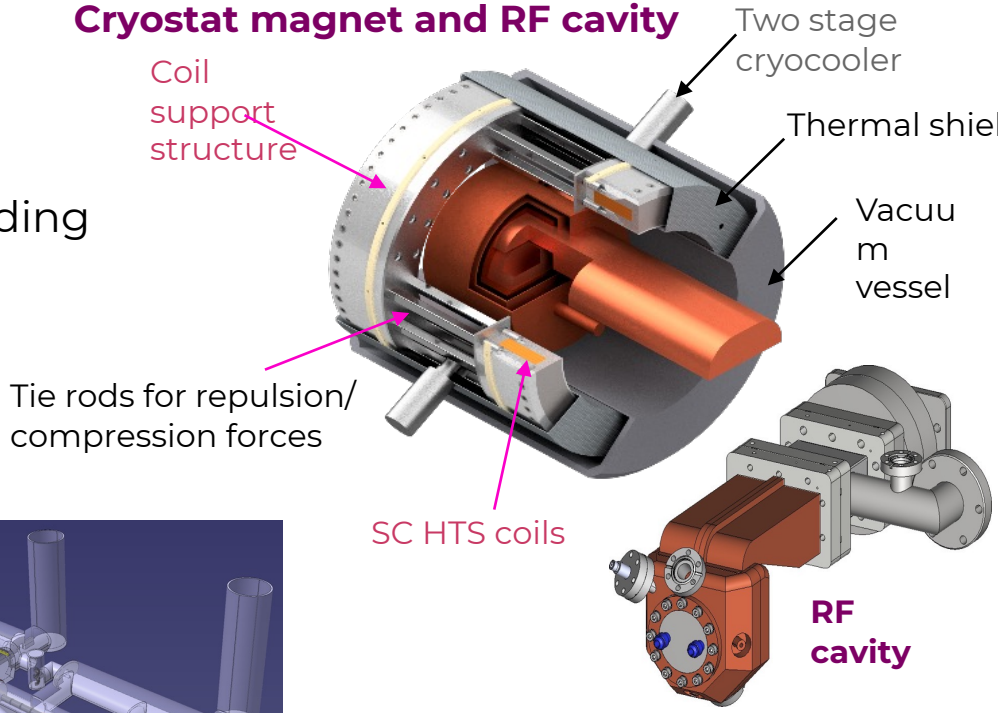
- **the performance of a normal conducting cavity may degrade when the cavity is operated in strong magnetic fields**
- **the magnetic fields cause RF cavity breakdown at high gradients**



***Targeted R&D is required - Dedicated Test stand* (RFMF)**

- design and machine prototypes for a compact full scale cavity (power coupler and full set of diagnostics) able to fit within **a solenoid with a useful bore of maximum 450-500 mm**
- design of the split coil for the RF cavities test and test of
- **new technology for HTS coils**, based on NI (non-insulated) winding

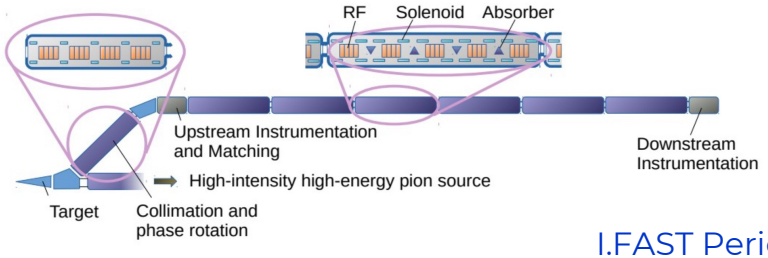
Cryostat magnet and RF cavity

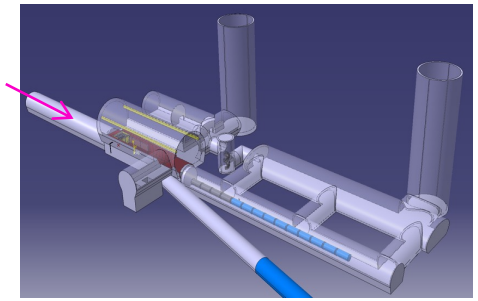


Planning **demonstrator facility @ CERN and @ FNAL** with muon production target and cooling stations

Suitable **site exists** on CERN land and can use **PS proton beam**

- could combine with **NuStorm** or other option





Step forward

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

MS15: International workshop on muon source design **M18** ➔ *Report*
MS16: International workshop to **define R&D plans** **M36** ➔ *Report M40*
D5.1: International collaboration plans towards a multi-TeV muon collider **M46**

- **Evaluation report**

Including cost and power consumption scale estimate

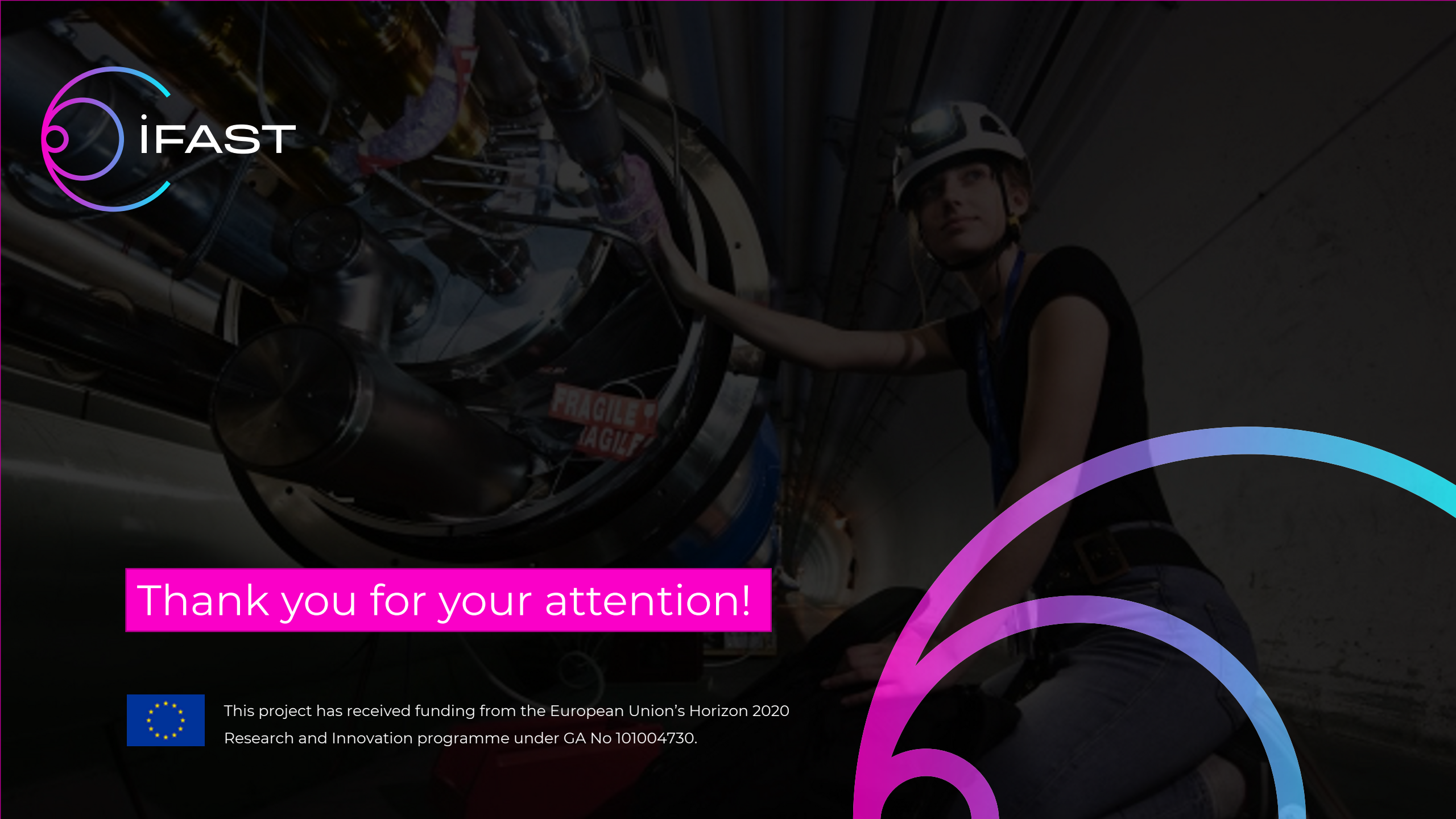
- **R&D plan:** magnets, RF test-end, cooling

This requires some scenarios and timeline

Investigating synergies on physics and technologies

- **Initial study for the demonstrator**

May 2025



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Thank you for your attention!

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

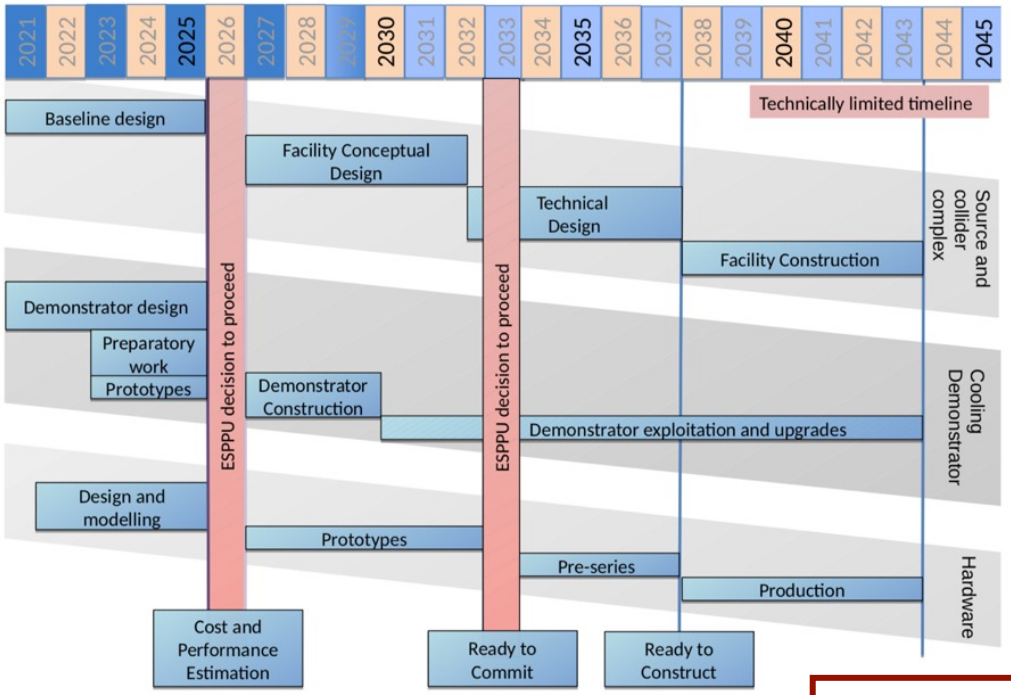
Accelerator R&D Roadmap

Bright Muon Beams and Muon Colliders

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

presented to CERN Council in December 2021
published https://arxiv.org/abs/2201.07895
now under implementation by LDG + Council…

Technically limited timeline



Development path to deliver a 3 TeV muon collider by 2045

Scenarios

Aspirational		Minimal	
[FTEy]	[kCHF]	[FTEy]	[kCHF]
445.9	11875	193	2445

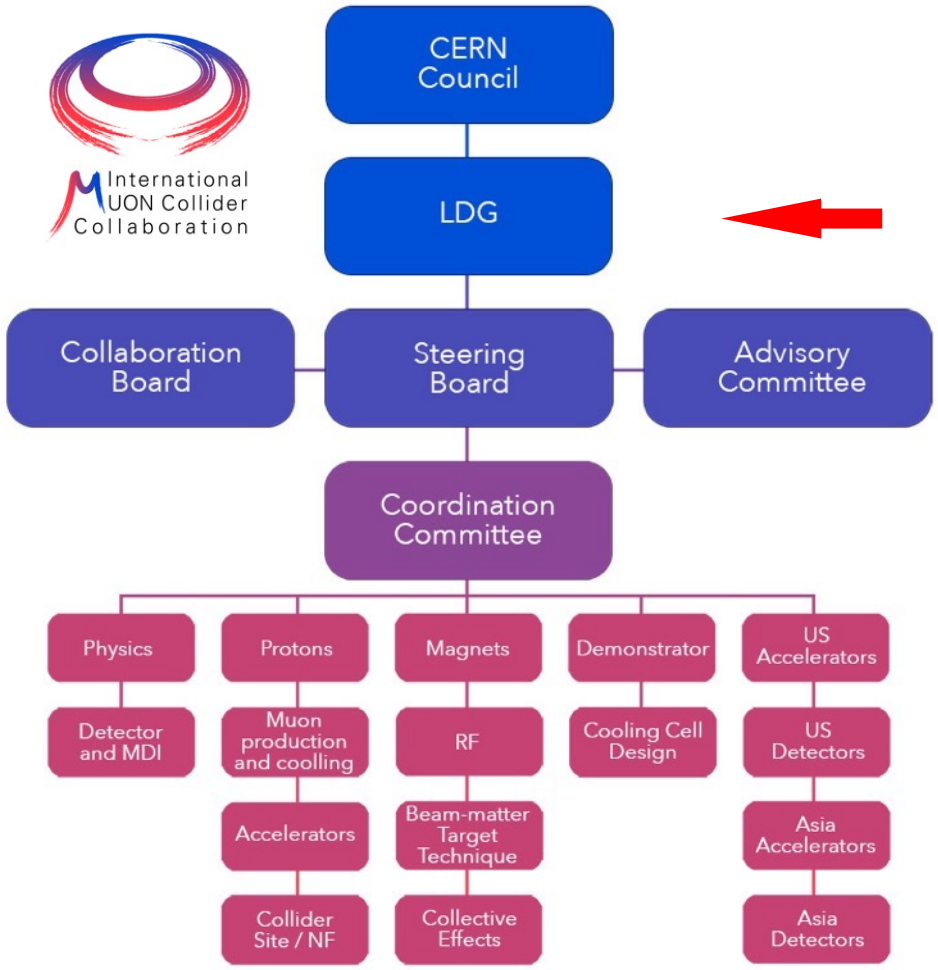
~ 70 MeU/5 years

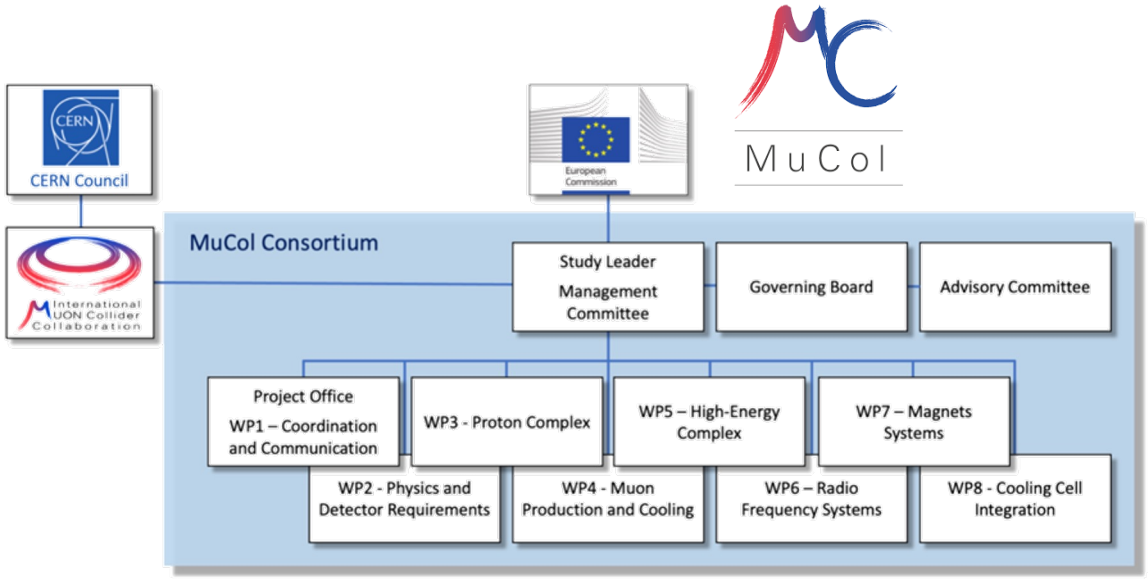
Roadmap Plan

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [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

Project organization

International Muon Collider Collaboration





MuCol EU Design Study

Memorandum of Cooperation @ CERN
19 countries: IT, US, UK, FR, DE, CH, ES…
… CHI, KO, IN….. Interest from Japan
80 institutes

IMCC included as: "**Experiments and Projects under Study**"
https://greybook.cern.ch/experiment/detail?id=IMCC

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)

- **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

- 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