3rd Annual Meeting, Paris April 18 - 2024

International Muon Collider Collaboration
Structure and progress

International MUON Collider Collaboration

Nadia Pastrone INFN-Torino

for the MUon collider STrategy network - MUST team

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

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

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

iFAST

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

Unique physics potential

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

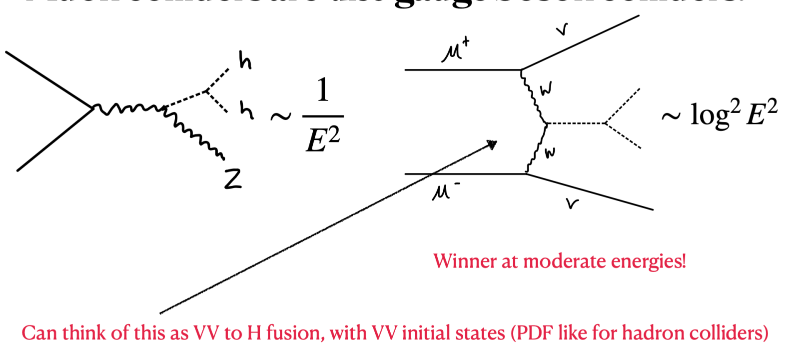
Direct searches
Pair production, Resonances, VBF, Dark Matter, …

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, …

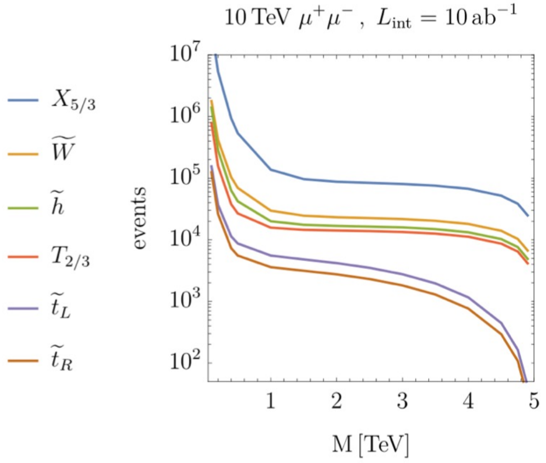
Muon physics
Lepton Flavor Universality, b → sμμ, muon g-2, …

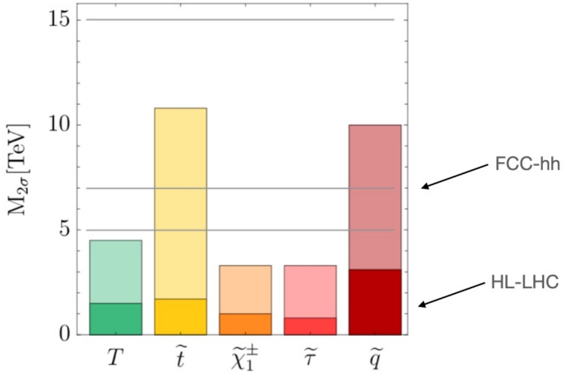
Muon colliders are *also* gauge boson colliders!



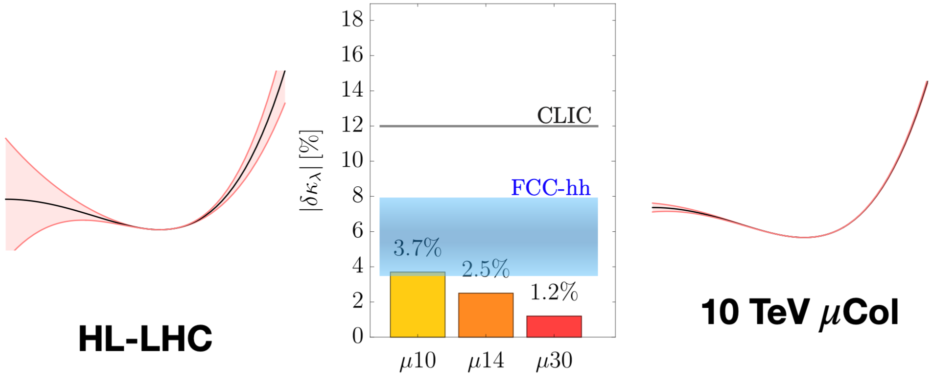
Strong and crucial synergies to design the machine and the experiment to reach the physics goals with energy and luminosity allowing % precision measurements

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





High energy lets us finally improve on Higgs Potential



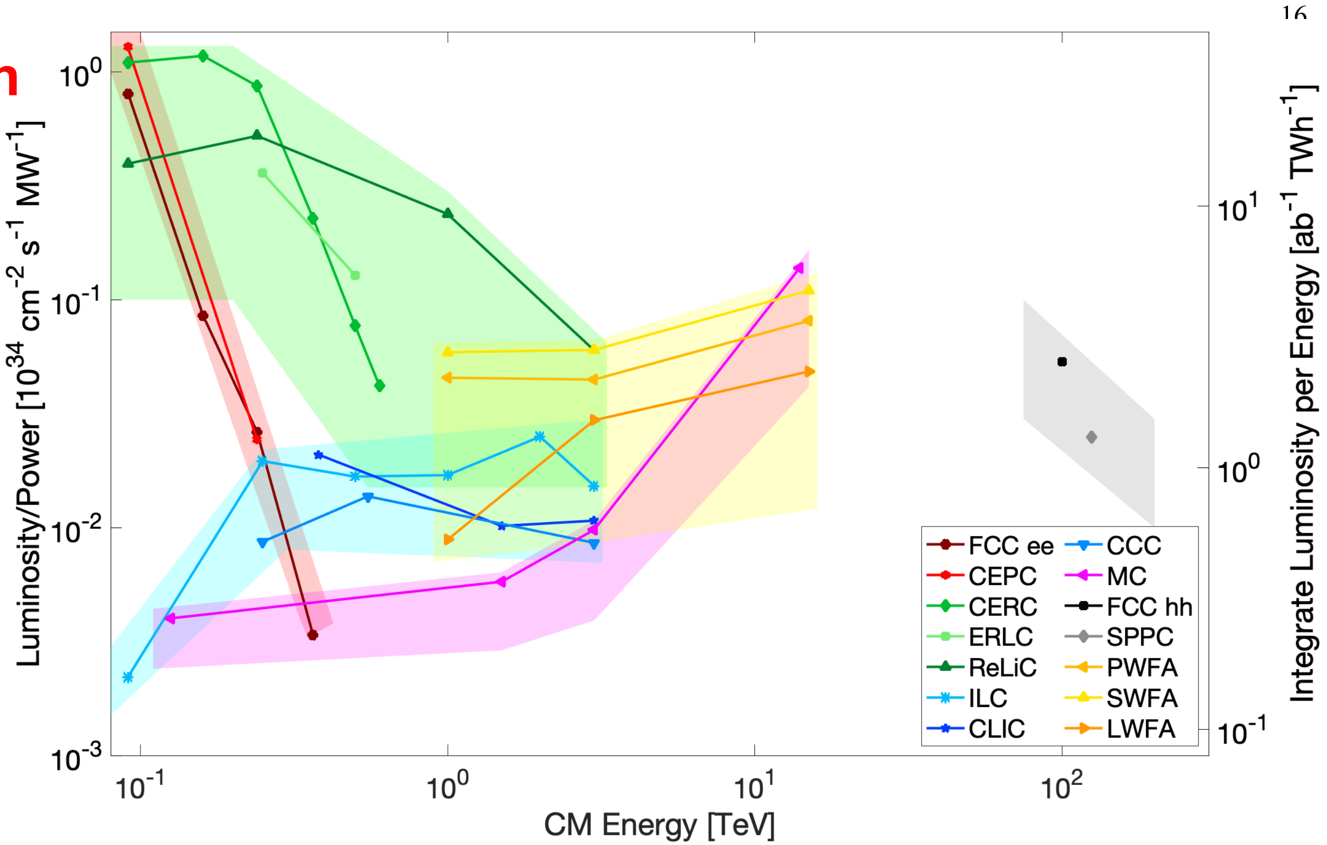
Note that we can get to threshold for EW phase transition at EW scale with FCC-hh and μCol

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

US P5 Report – December 2023

Exploring the Quantum Universe

P5 report & Muon Collider & key messages

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

...

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

...

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

4a) Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, **muon**, or possible wakefield technologies, including an **evaluation of options for US siting of such a machine**, with a **goal of being ready to build major test facilities and demonstrator facilities within the next 10 years**

[see sections 3.2, 5.1, 6.5, and also Recommendation 6]

IMCC @ CERN

After the ESPPU recommendation in June 2020:
Laboratory Directors Group (LDG) initiated the Muon Collider Collaboration July 2, 2020

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

NEW ESPPU
Input documents due by
March 31 2025

US P5 – International partnership

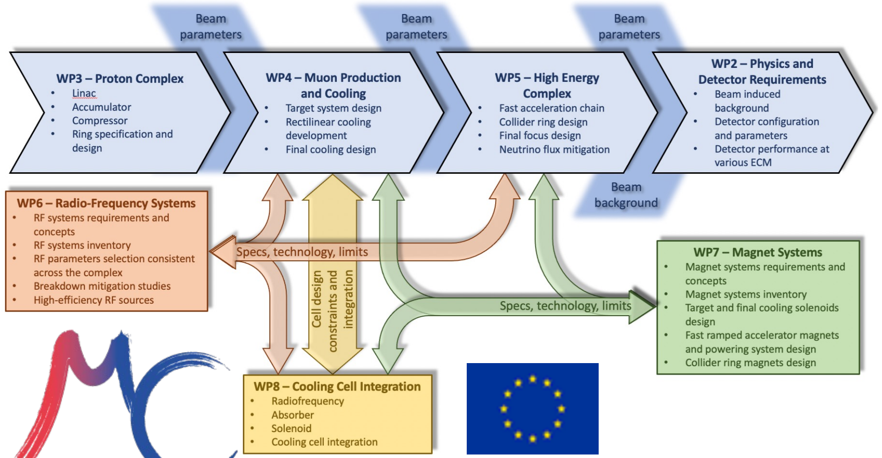
Stability of the program requires implementing the framework for our international partnerships!

In the case of the Higgs factory, crucial decisions must be made in consultation with potential international partners. The FCC-ee feasibility study is expected to be completed by 2025 and will be followed by a European Strategy Group update and a CERN council decision on the 2028 timescale. The ILC design is technically ready and awaiting a formulation as a global project. **A dedicated panel should review the plan for a specific Higgs factory once it is deemed feasible and well-defined;** evaluate the schedule, budget and risks of US participation; and give recommendations to the US funding agencies later this decade (Recommendation 6). **When a clear choice for a specific Higgs factory emerges, US efforts will focus on that project, and R&D related to other Higgs factory projects would ramp down.**

Parallel to the R&D for a Higgs factory, **the US R&D effort should develop a 10 TeV pCM collider (design and technology)**, such as a muon collider, a proton collider, or possibly an electron-positron collider based on wakefield technology. **The US should participate in the International Muon Collider Collaboration (IMCC) and take a leading role in defining a reference design.** We note that there are many synergies between muon and proton colliders, especially in the area of development of high-field magnets. R&D efforts in the next 5-year timescale will define the scope of test facilities for later in the decade, paving the way for initiating **demonstrator facilities within a 10-year timescale** (Recommendation 6).

Progress since the last Annual meeting

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

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

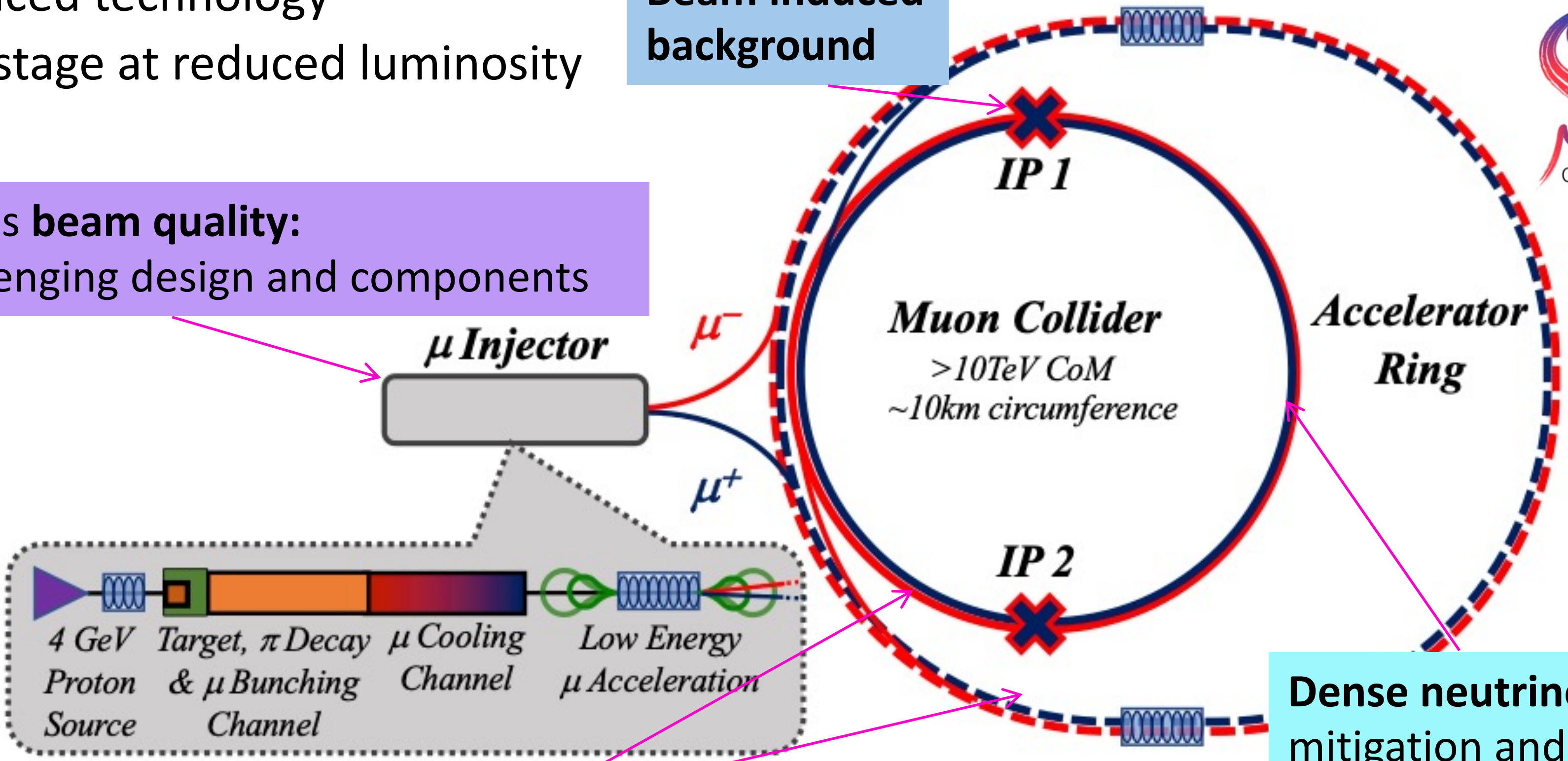
NEW OPTION: initial 10 TeV stage at reduced luminosity

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

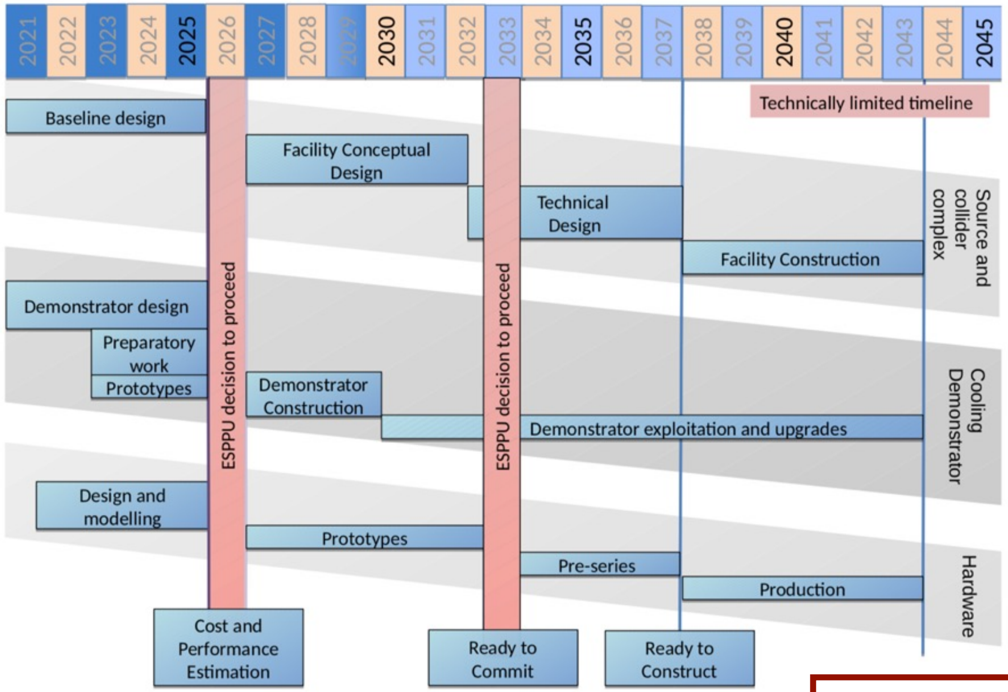
Accelerator R&D Roadmap

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

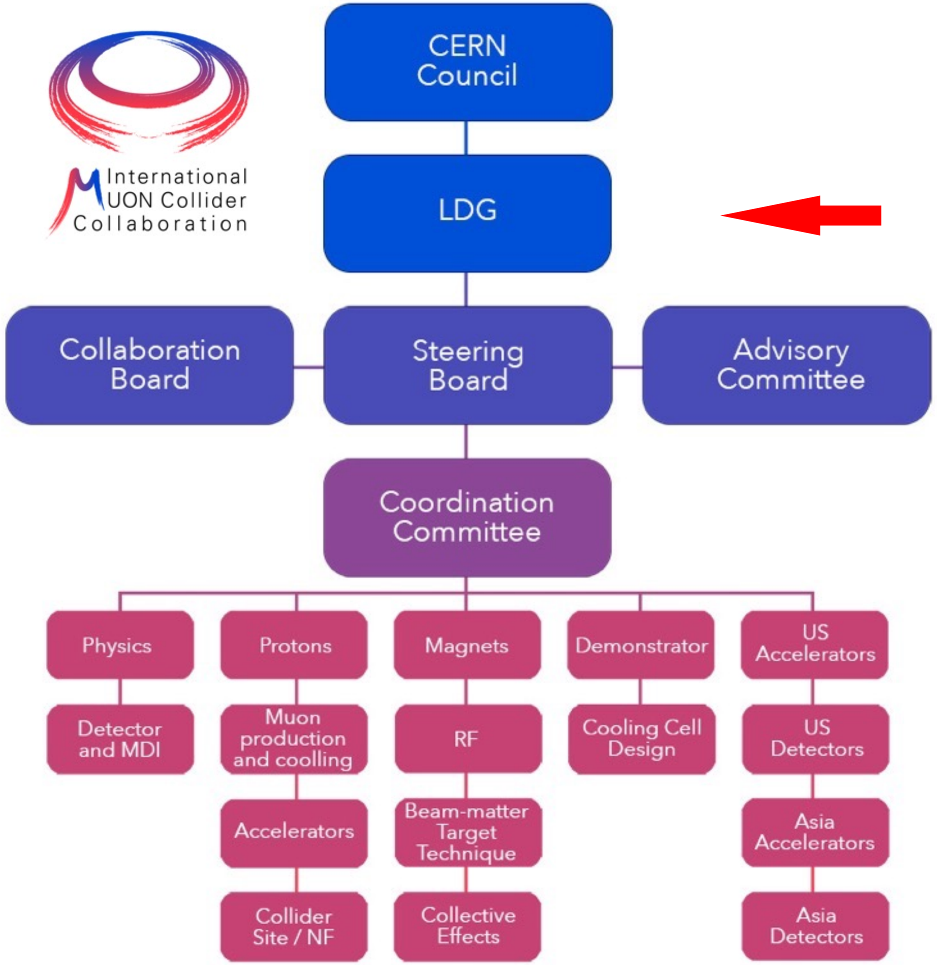
~ 70 Meu/5 years

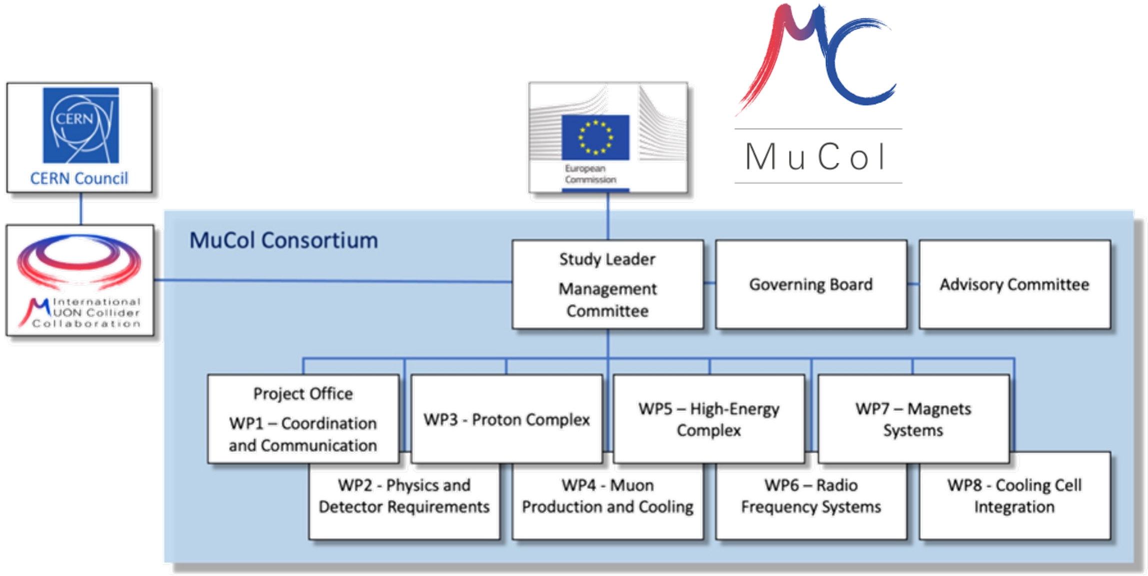
Roadmap Plan

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

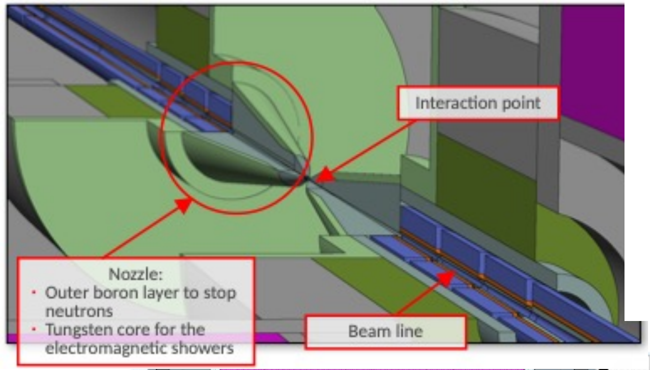
iFAST

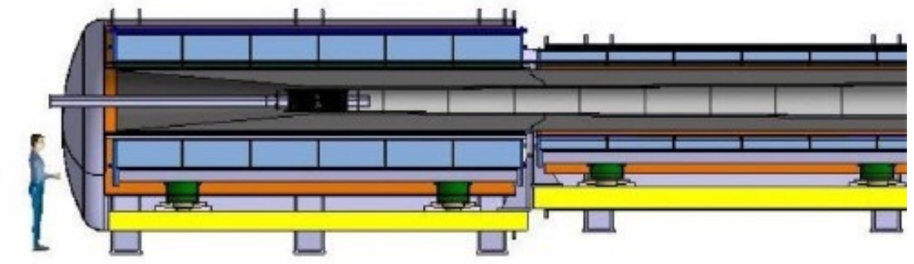
IMCC included as: “**Experiments and Projects under Study”**
https://greybook.cern.ch/experiment/detail?id=IMCC

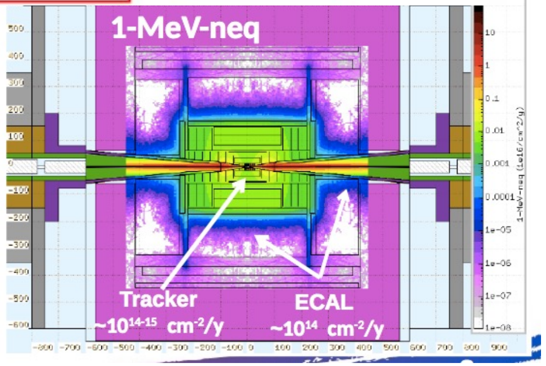
Summary of activities towards R&D plans

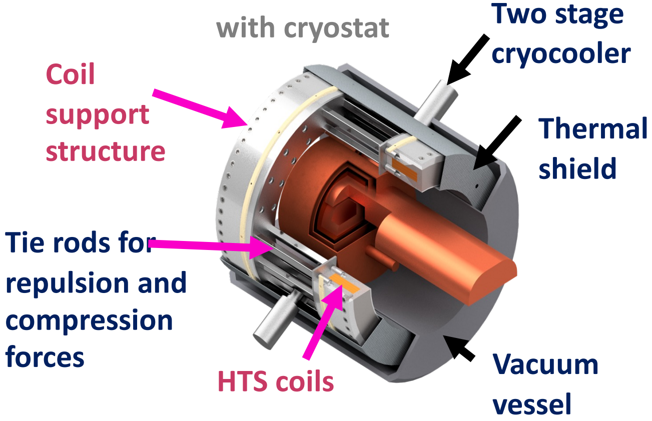
Each WP is working to identify challenges and R&D plans towards a baseline design:

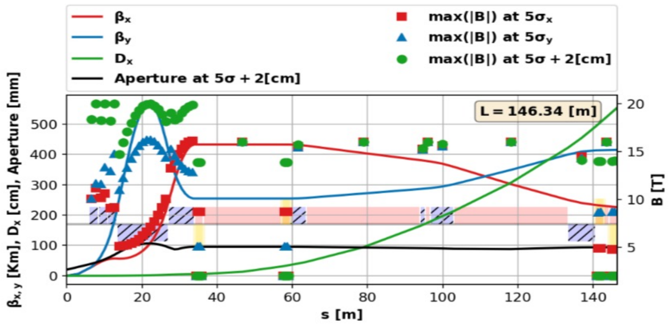
- Physics and MDI
- Proton complex
- Target design
- Muon Cooling
- Accelerator Complex
- Collider Ring
- RF Technology
- Magnet Technology
- Cooling cell integration
- Demonstrator

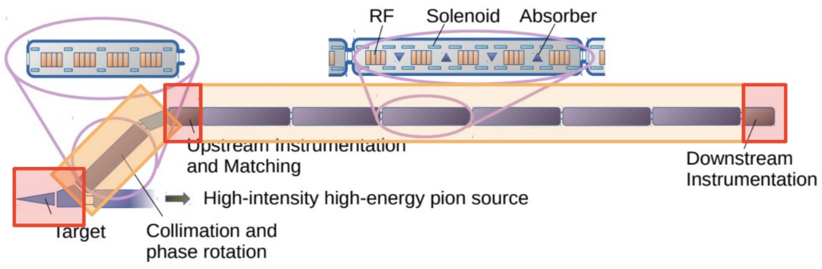


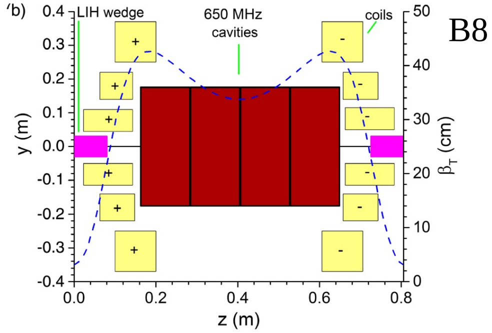












R&D plans – timelines – priorities

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

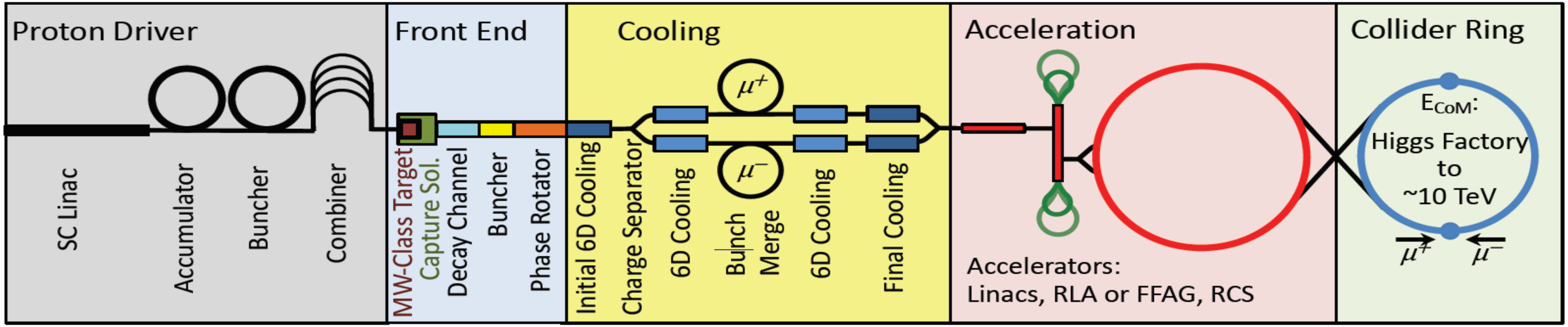
- ➔ All progress on technology studies, design study of each component and first lattice @ 10 TeV
- ➔ Machine Detector Interface (MDI) Design ➔ Beam Induced Backgroud mitigation

➔ **Experiment Design @ 10 TeV** ➔ **Detector Magnet choice and design under study**

- ➔ Detector R&D and Full simulation studies

Machine concept

Fully driven by muon lifetime, otherwise would be easy



Short, intense proton bunch

Protons produce pions which decay into muons muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

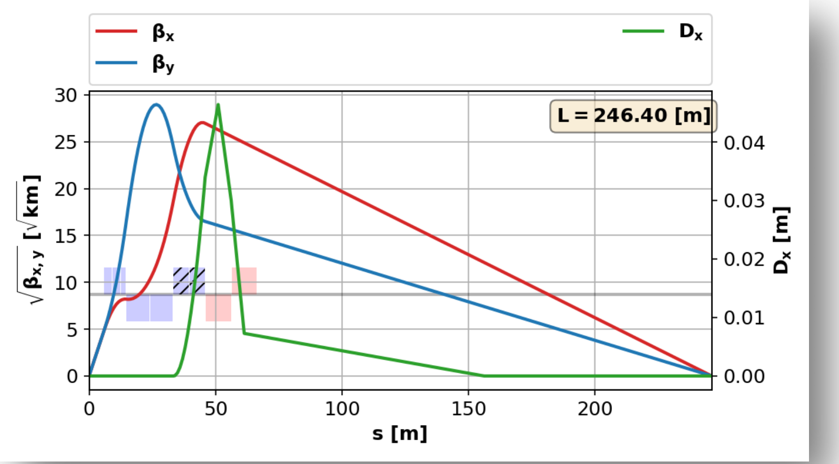
Collision

Proton driven Muon Collider Concept (MAP collaboration)

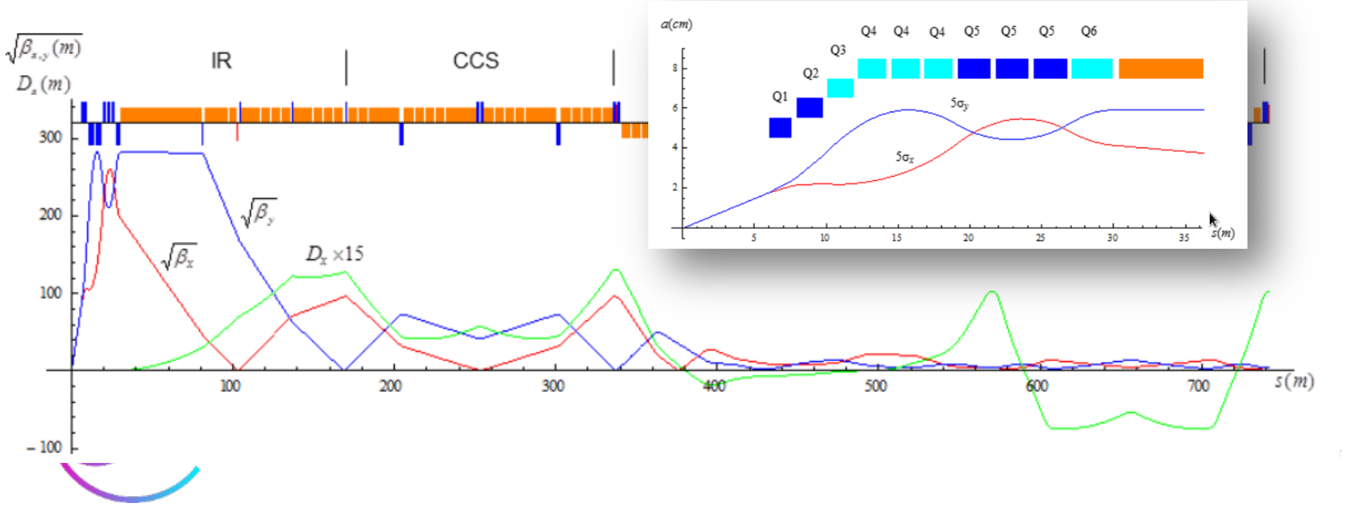
Status of IR lattice design @ 10 TeV

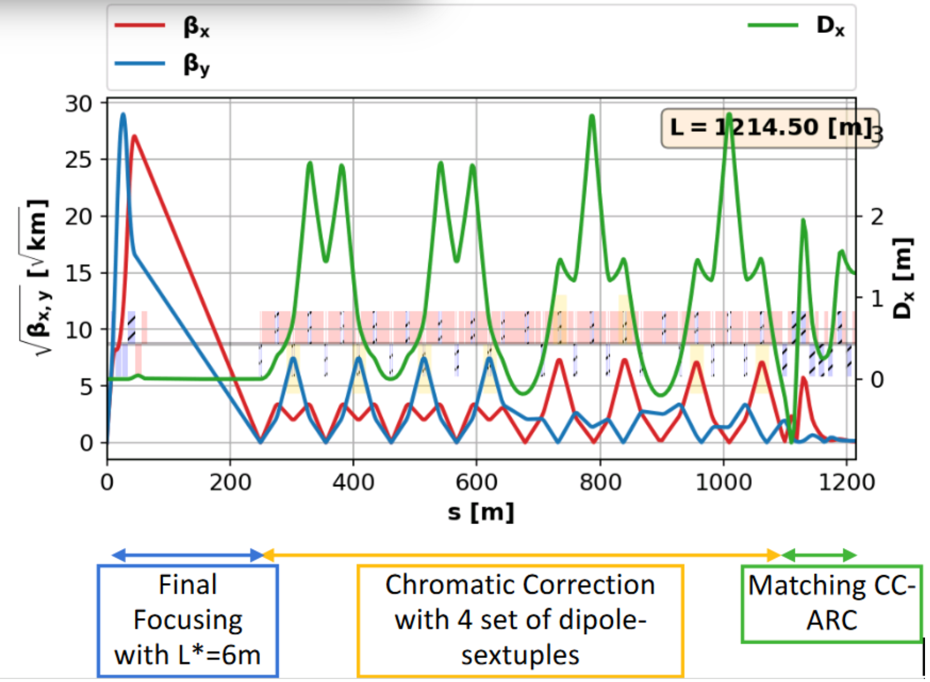
Challenges: small ß*, large ß functions in FF, strong chromatic effects

	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Version	**US MAP**	**IMCC (v0.7)**
FF scheme	Quadruplet (with dipolar component)	Triplet (with dipolar component)
ß*	5 mm	1.5 mm
L*	6 m	6 m
Max. field at inner bore	12 T	20 T



3 TeV IR lattice (MAP):

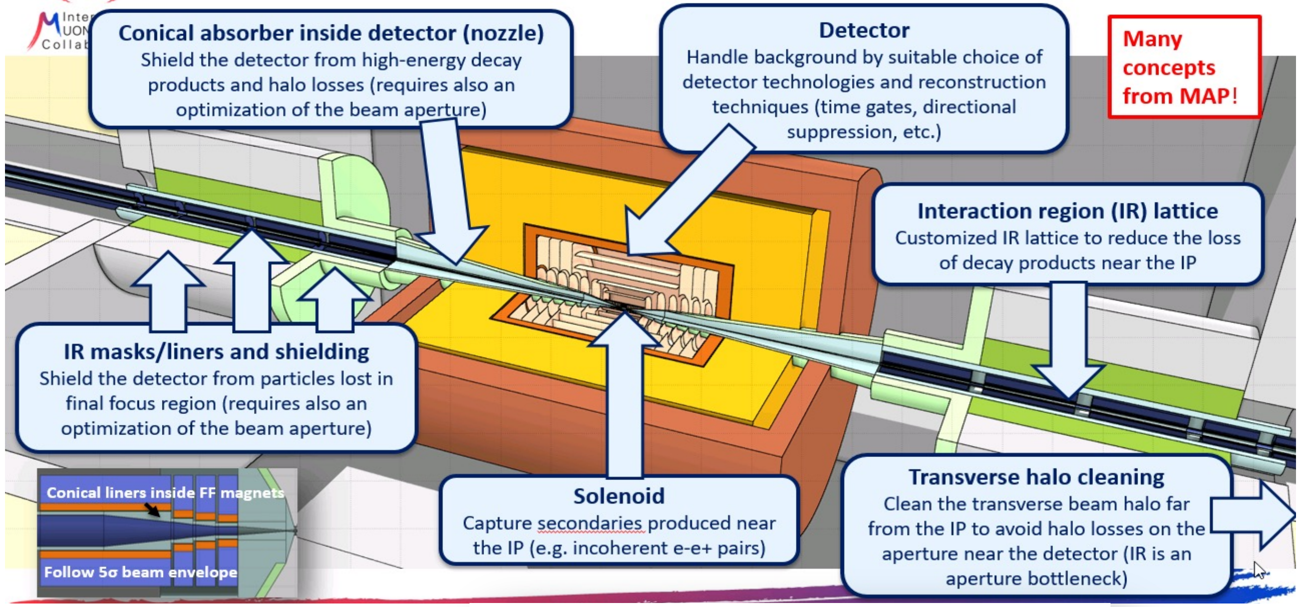




Beam-induced Background

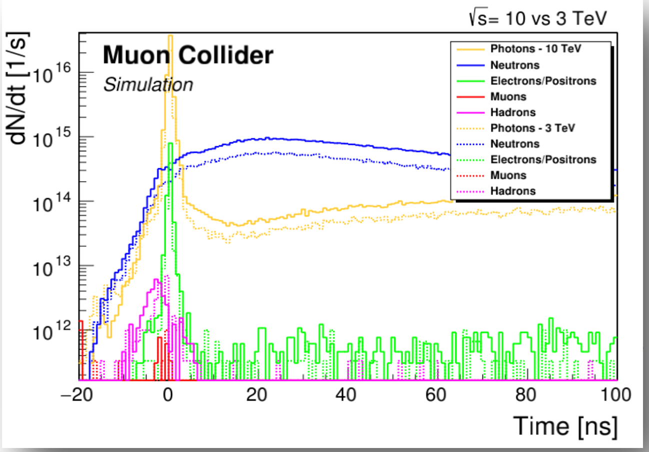
Background is a significant driver for MDI design - background sources:

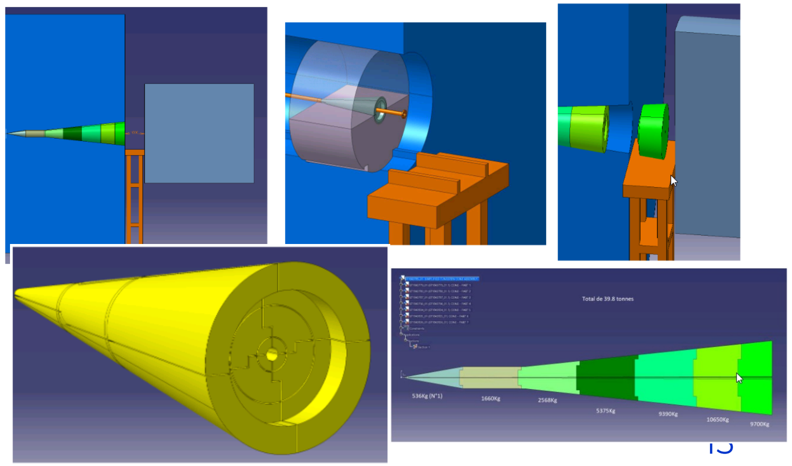
- **Muon decay**
- Beam halo losses and Beam-beam (mainly incoherent e-/e+ pair production)



The technical design of the nozzle started:

- Integration and support inside detector
- Shielding segmentation and assembly
- Selection of specific material (tungsten heavy alloy)
  → machining is an important aspect
- Heat extraction (cooling)
- Alignment, vibrations, tolerances, etc.
- Dedicated vacuum chamber inside nozzle

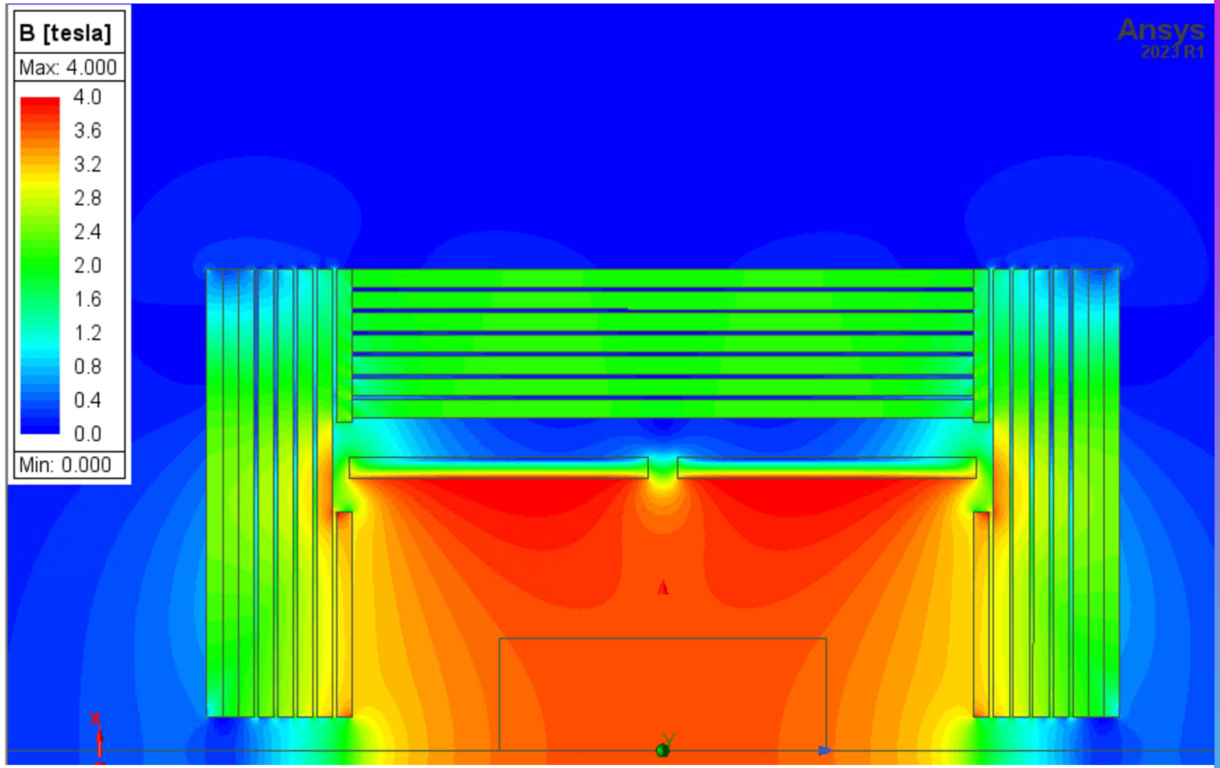




Preliminary study in detector magnet

Detector magnet workshop – 5 October 2023

Upon request from Detector group, some preliminary calculations on a possible solution for a detector solenoid has been performed, based on CMS cable

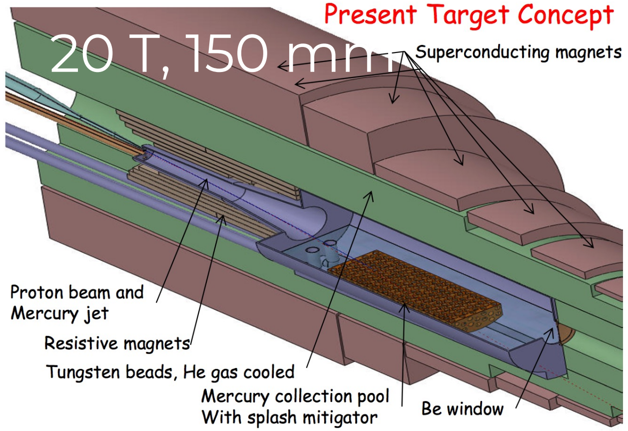


Main features:

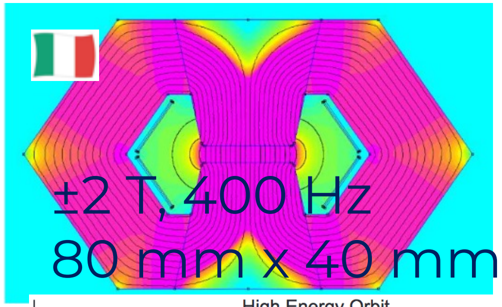
- Tracker region: -2200 < z < 2200, 0 < r < 1500
- B at IP: 3.66 T
- B = 3.60 ± 0.08 T
- Field uniformity: ±2.3%
- (Almost no optimisation)
- Max Br = 0.12 T
- Stored energy: 2.25 GJ
- Current density: 12.3 MA/m^2
- Total coil thickness: 288 mm
- Current: 19.5 kA
- Cable size: 72 x 22 mm^2
- Inductance: 11.85 H

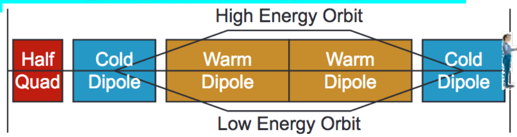
Main show stopper: no one produces aluminium stabilised cables
Main advantage: similar to something existing & working

Magnet Demands @ Muon Collider

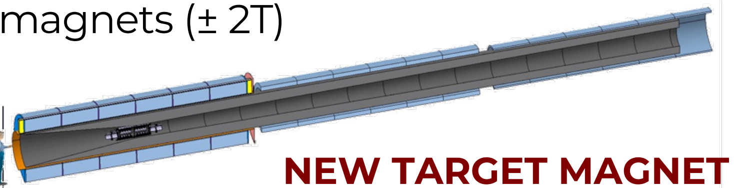


High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads



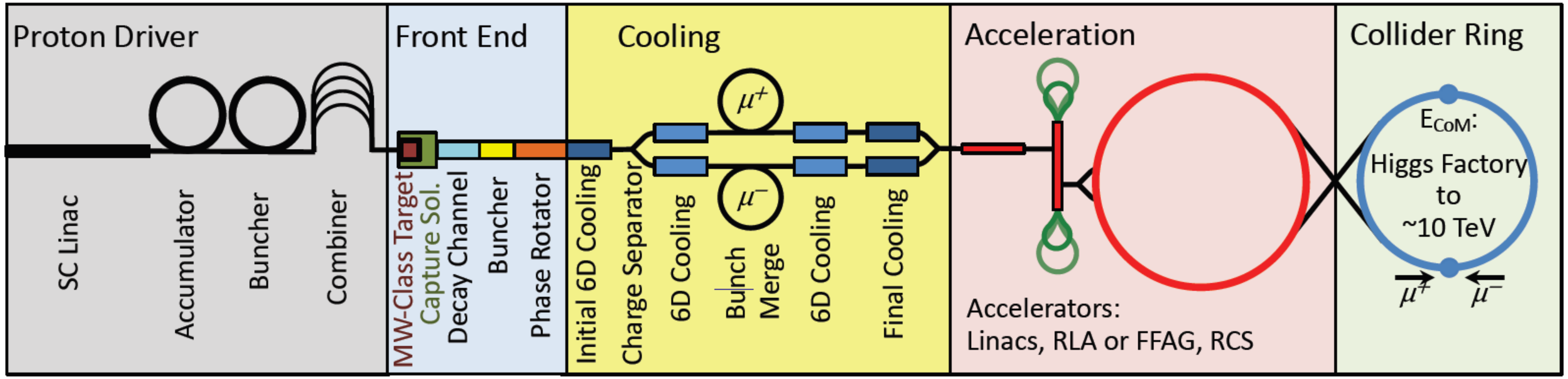


Combination of DC SC magnets (10 T) and AC resistive magnets (± 2T)

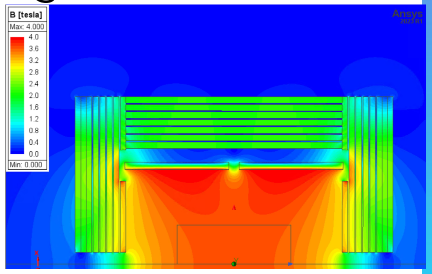


NEW TARGET MAGNET SPECS

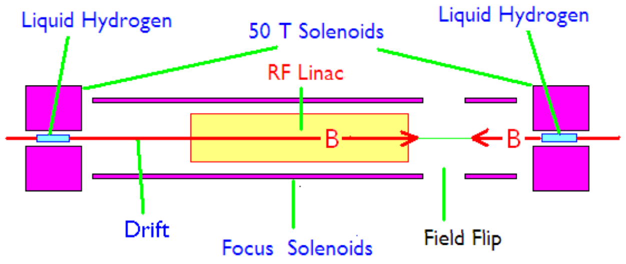
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy



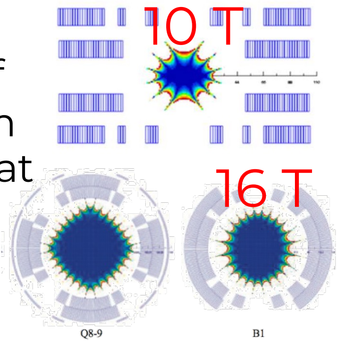
Detector Magnet to be designed for 10TeV



Ultra-high-fiel
solenoids (40…60 T
to achieve desire
muon beam coolin



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



iFAST

Collider Ring Magnets

- assessing realistic performance targets for the large bore (range of 150 mm) collider magnets in close collaboration with beam optic, MDI, and energy deposition studies
- focusing on the design of the combined functions dipoles in the arc, which are a good sample of the magnet challenges
- 3 TeV collider: low-temperature superconducting (LTS) magnets with fields up to 10 T will be explored
- 10 TeV collider: will require fields up to 16 T
- huge electromagnetic force in such magnets is a severe limitation for the use of known coil technology, and especially for Nb3Sn
- The study will consider adopting a stress management mechanical system, which is an innovative approach for accelerator magnets, especially to be adapted to combined functions magnet. HTS materials are a less mature technology with superior tolerance to stress and strain and expected to unfold their potential for magnettechnology in the next future.

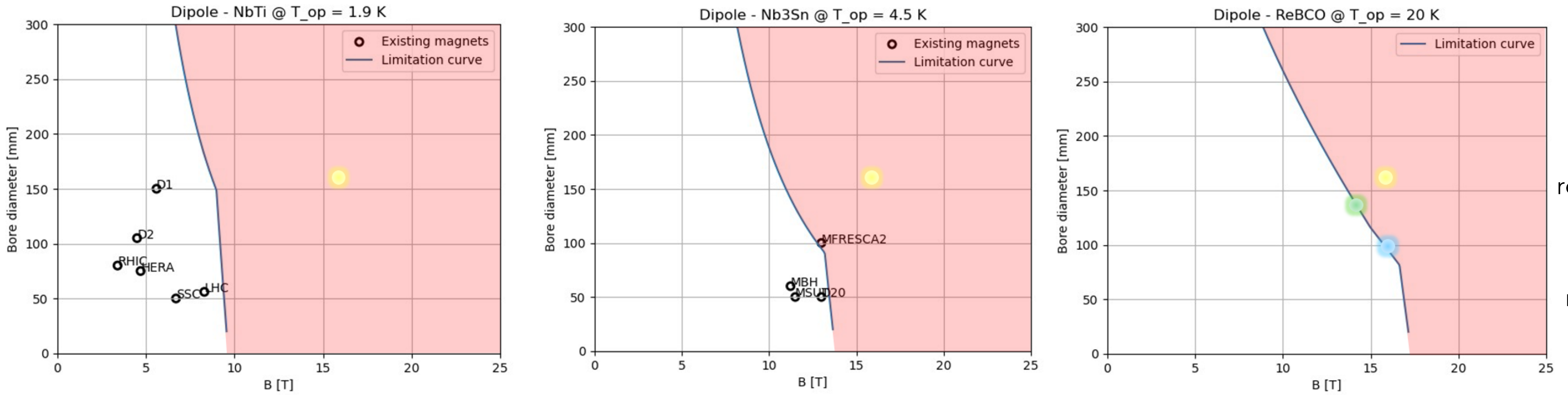
Towards realistic performances

<u>AIM</u>: Assess realistic performance targets for the collider ring magnets

Constraints and limits:

- Margin on the critical surface
- Maximum hot spot temperature during quench (i.e. transition to normal state)
- Maximum stress in the coils and in the support structures
- Maximum cost

Upper limits to magnet performance (in terms of magnetic field and aperture) were assessed using an innovative and comprehensive approach [ref], also presented at MT28], which exploits analytical evaluations and FEM codes to include in the calculation all the constrains listed before. The results are the plots below for NbTi, Nb3Sn and REBCO.



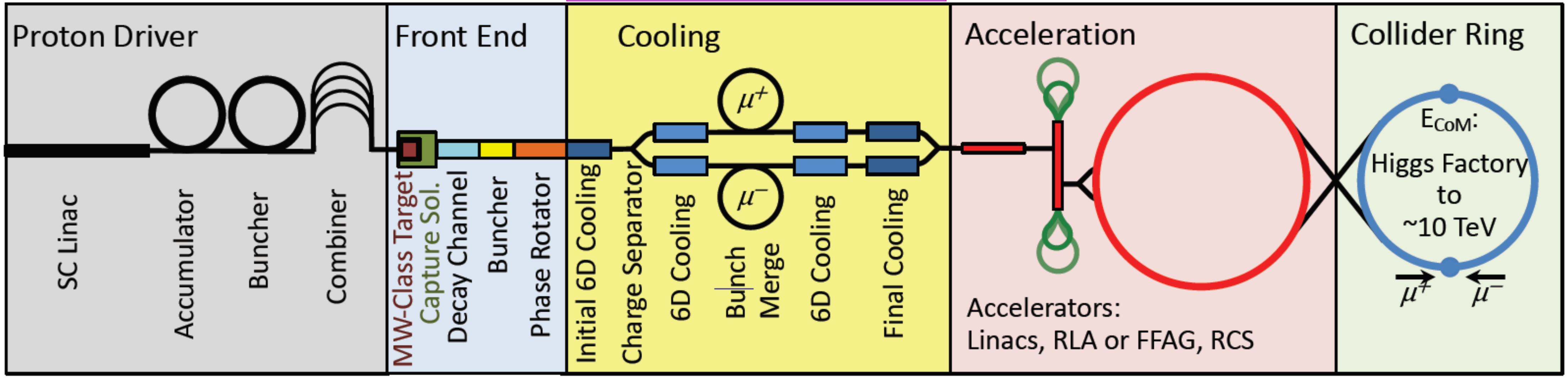
initial requirement for collider dipoles

Actual requirments

Thanks to this study, the feasible region has been assessed and new lattice calculations are on-going

Muon Collider RF system

4000 RF cavities
2500 Solenoid Coils



Linac: ~1-5 ms
- SNS: **402.5, 805** MHz
- ESS, SPL, CERN-L4: **352, 704** MHz
- PIP-II: **325, 650** MHz

Muon cooling RF
- Many frequencies in Buncher, Rotator, Merge, Final Cooling
- Cooling cells have two harmonic frequencies:
  - MAP: **325, 650** MHz
  - Alternative: **352, 704** MHz

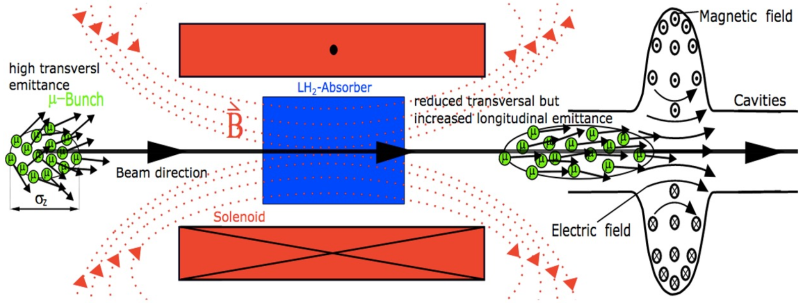
Accelerator SRF
- LA, RLA: ~1-10 ms
  - MAP: **325, 650** MHz
  - CERN-L4, SPL, ESS: **352, 704** MHz
- Rings: CW
  - MAP: 1300 MHz (very high)
  - LEP: 352 MHz; LHC: 400 MHz
  - FCC: 400, 800, 650(?) MHz
  - CEPC: 650 MHz

iFAST

Cooling Channel

TO DESIGN A HIGH-EFFICIENT IONIZATION COOLING CHANNEL:

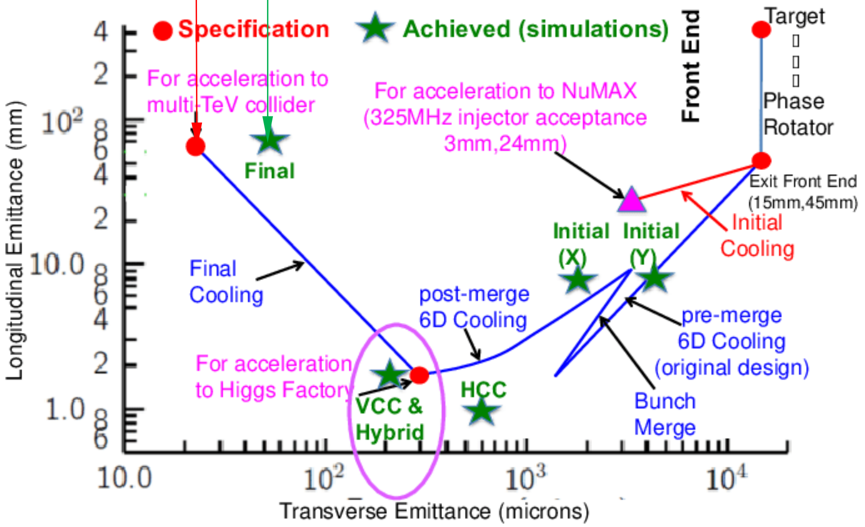
- **the performance of a normal conducting cavity may degrade when the cavity is operated in strong magnetic fields**
- **the magnetic fields cause RF cavity breakdown at high gradients**



40…60 T required

30 T assumed in MAP

A field of 40 T (minimum), up to 60 T (target) is needed to meet emittance specification at the end of the cooling stage



NC RF system for muon capture and cooling

very large and complex RF system

with high peak power – under study

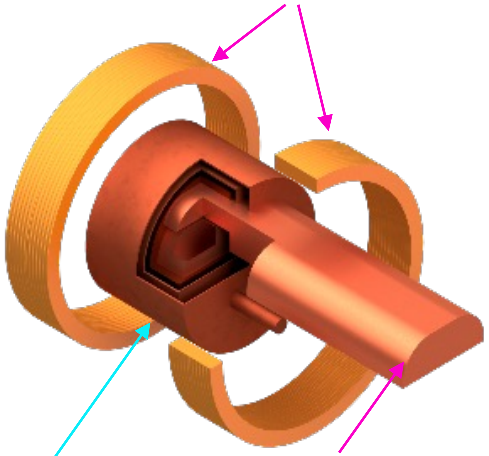
Region	Length [m]	N of cavities	Frequencies [MHz]	Peak Gradient [MV/m]	Peak RF power [MW/cav.]
Buncher	21	54	490 - 366	**0 - 15**	1.3
Rotator	24	64	366 – 326	**20**	2.4
Initial Cooler	126	360	325	**25**	**3.7**
Cooler 1	400	1605	325,	**22, 30**	
Bunch merge	130	26	108	**~ 10**	
Cooler 2	420	1746	32	**22, 30**	
Final Cooling	140	96	3		
Total	**~1300**	**3951**			**=> ~12GW**

TBD TBD TBD

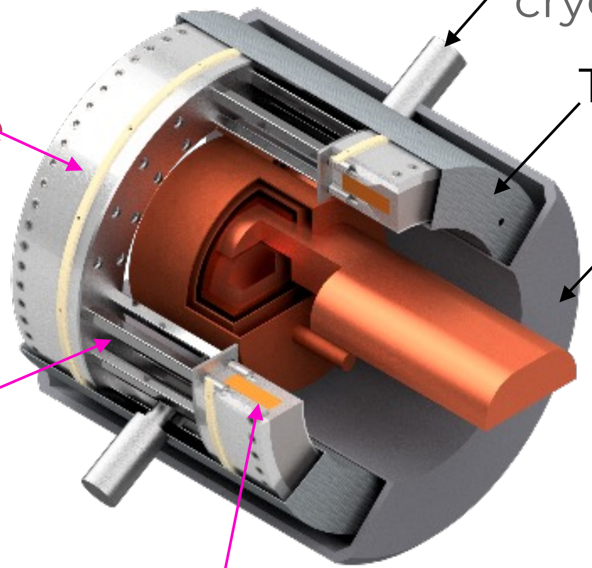
***Solenoids for a muon collider need to be compact** (reduce cost),*
***mechanically strong** (withstand extraordinary e.m. forces)*
***and well protected against quench** (large stored energy)*

Muon cooling cell – design

Bare coils and RF cavity



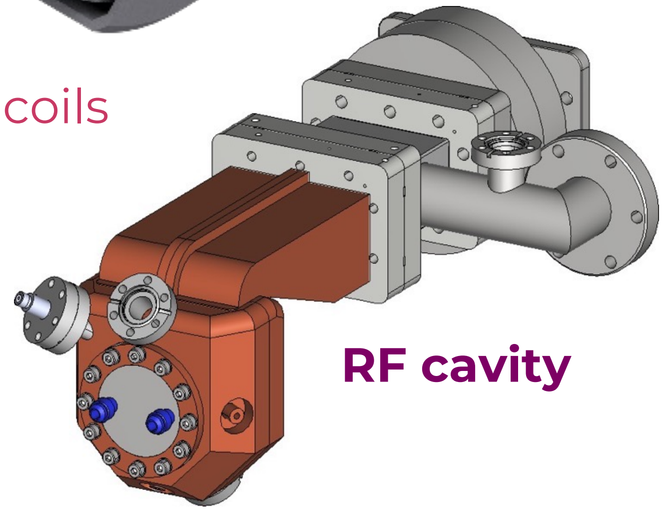
With cryostat



Targeted R&D is required

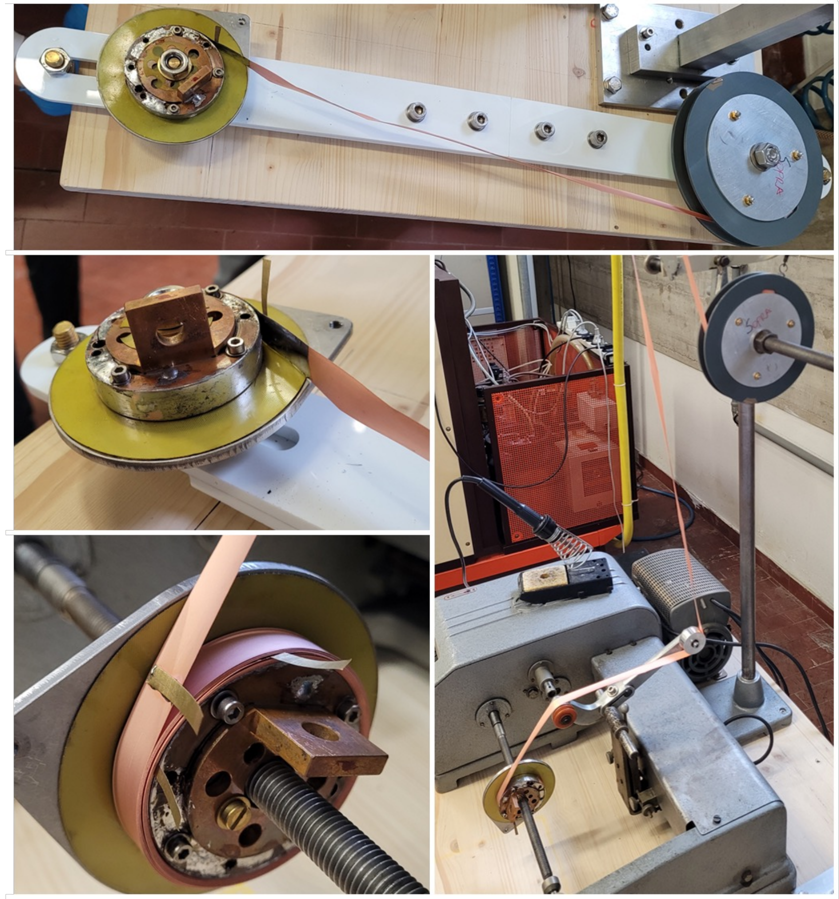
***Dedicated Test stand* (RFMF)**

- 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



RF cavity

HTS tape

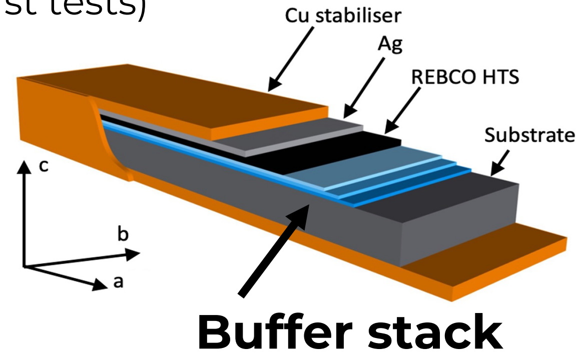


HTS tape: 5 km of 4 mm

General scope: use of the HTS tape for learning about non-insulation technology (a novelty that recently is changing the way how magnets are designed.

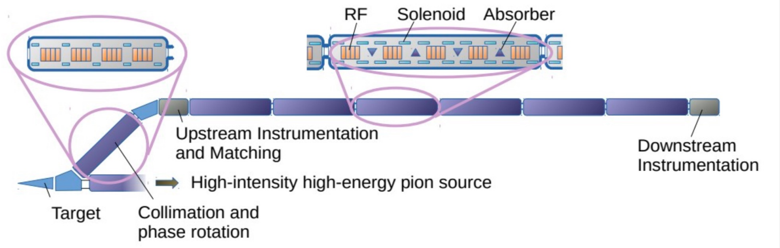
Focused scope: build a series of small coils and a final one that would allow to validate the design of the Split Coils of the RFMFTF (Radio Frequency in Magnetic Field Test Facility).

Winding of the first Ni coil at LASA (Dec 2023)
Test carried out until breakage at a few hundred of mT, in LN.
Lesson learnt: new winding procedure to densify packing factor (Low performance HTS tape used for first tests)



Reference REBCO tape (CERN courtesy)	
Substrate (material/thickness)	Stainless steel / 50 µm
Cu stabilizer (type/thickness)	Electroplated / 20 µm per side
(Re)BCO thickness	≈2.5µm
Dimensions (width x thickness)	12.1 mm x 0.11 mm

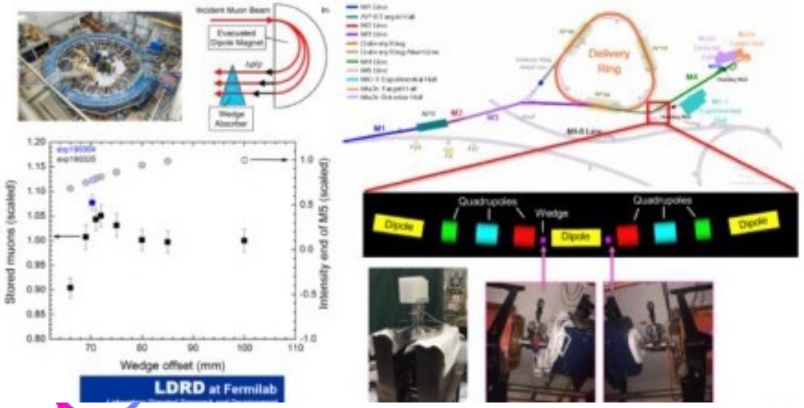
Demonstrator Facility: a crucial step



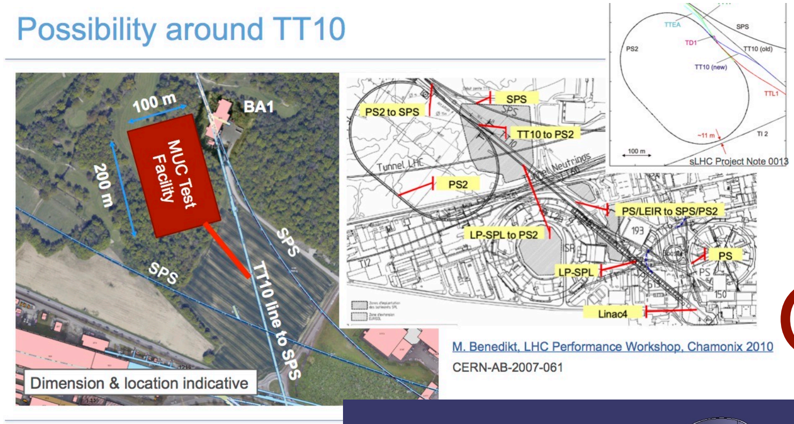
Planning **demonstrator** facility with muon production target and cooling stations

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

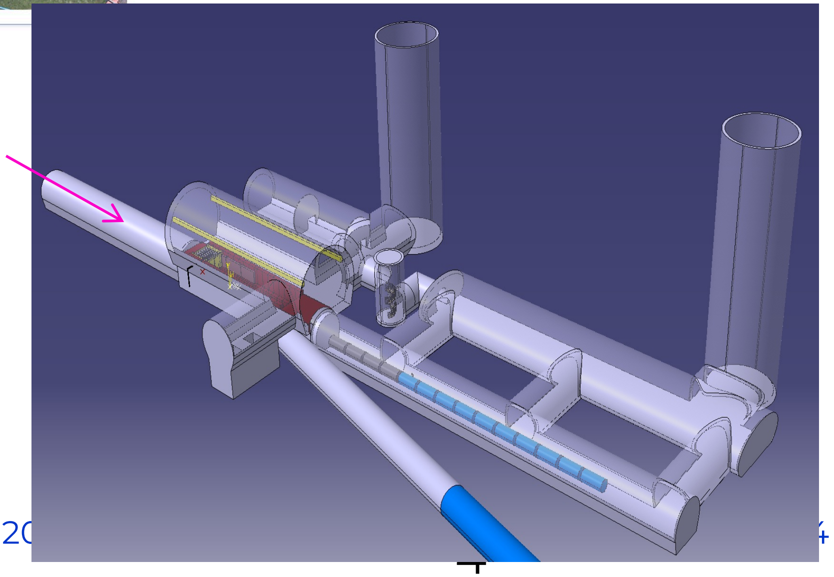
- could combine with **NuStorm** or other option



@ FNAL



@ CERN



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*
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

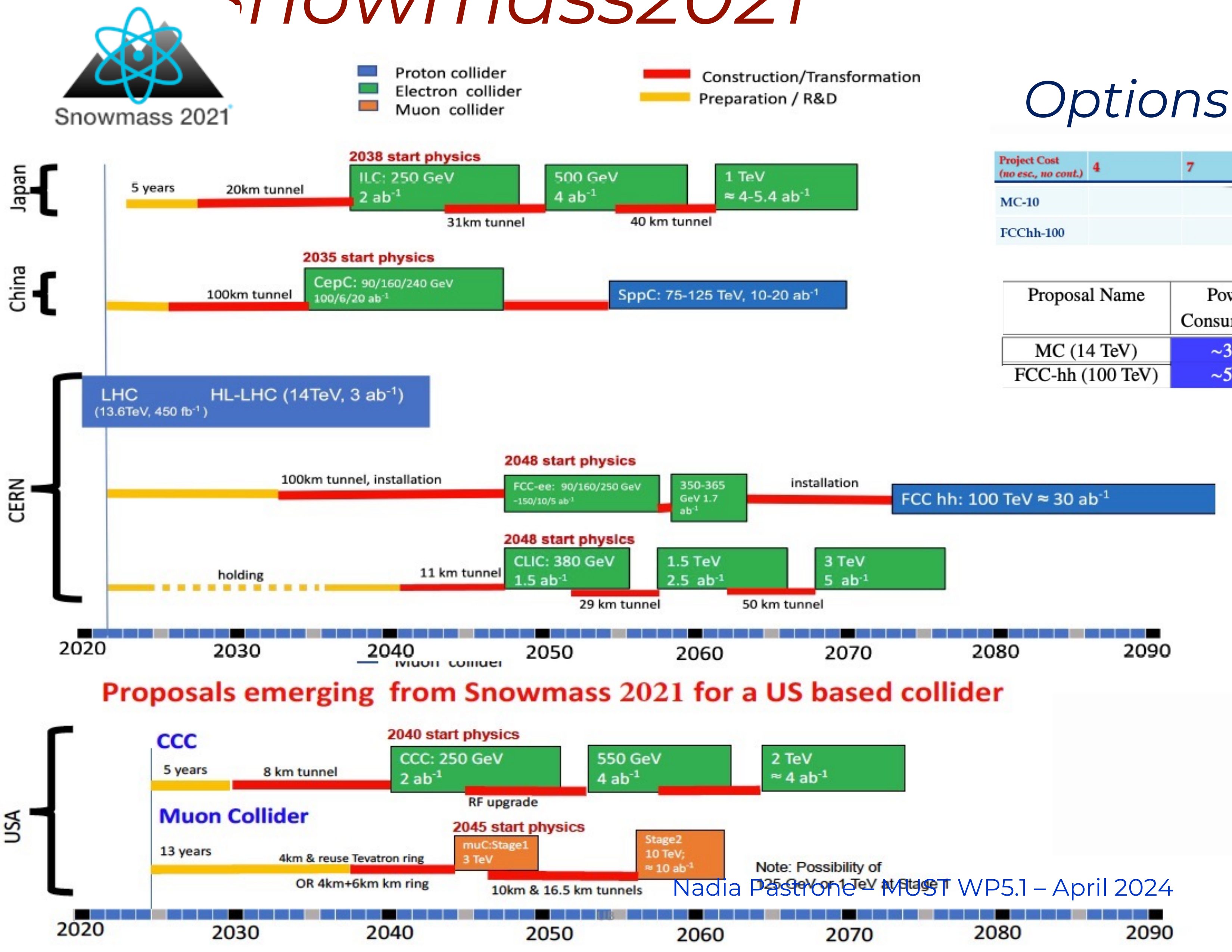
- **Initial study for the demonstrator**

May 2025

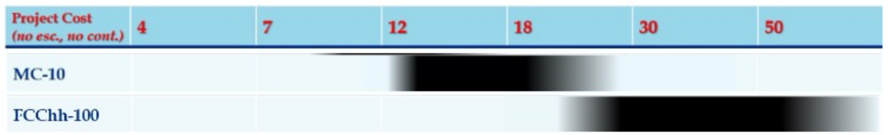
25

extras

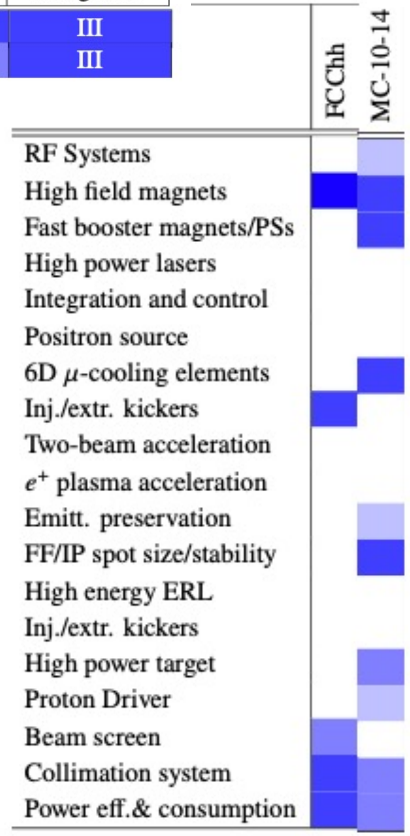
Colliders timescale: Snowmass2021



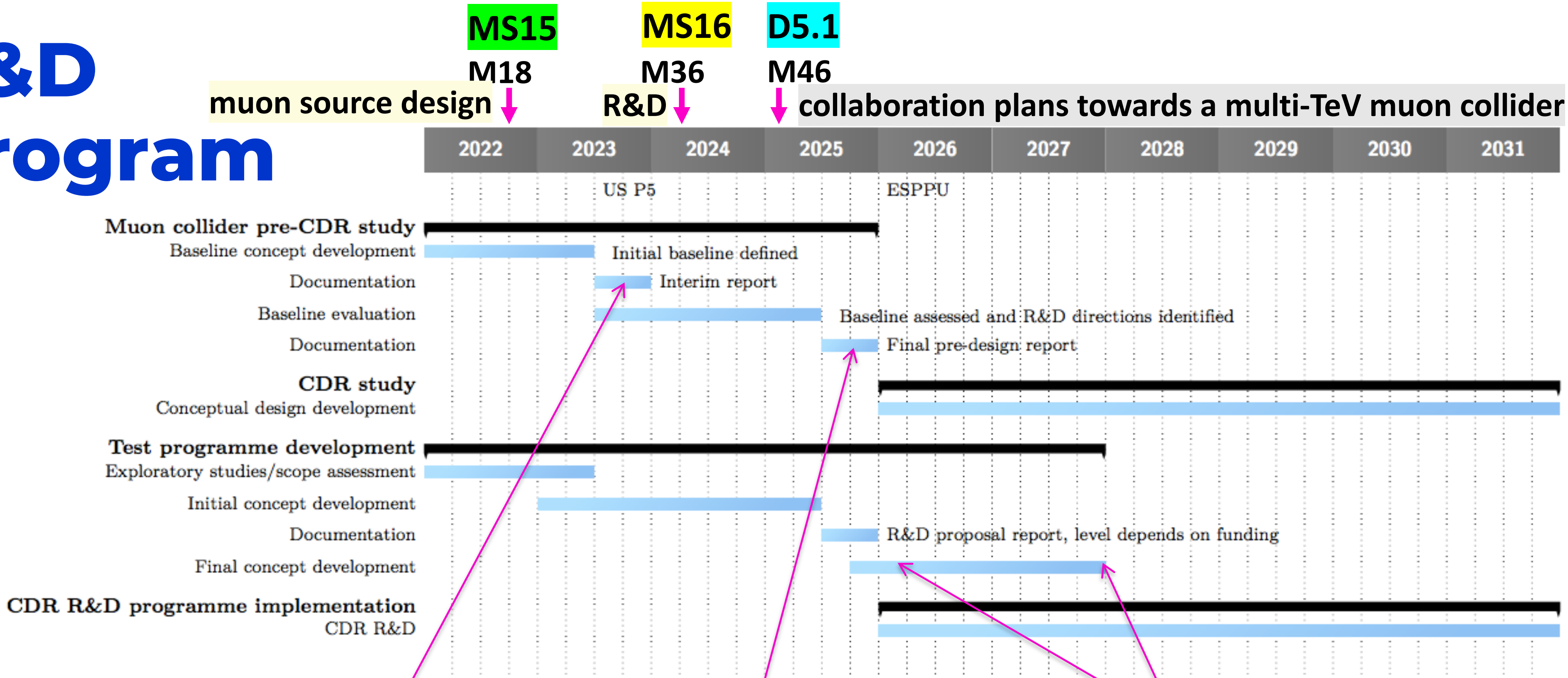
Options @ 10 TeV Scale



Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
MC (14 TeV)	~300	27 km	III	III
FCC-hh (100 TeV)	~560	91 km	II	III



R&D Program



2024
Interim Report to gauge progress
Initial baseline defined

2025
Assessment Report

2025-2027
R&D plan will be refined

Collider magnets challenges

AIM: Assess realistic performance targets for the collider ring magnets

Main challenges:

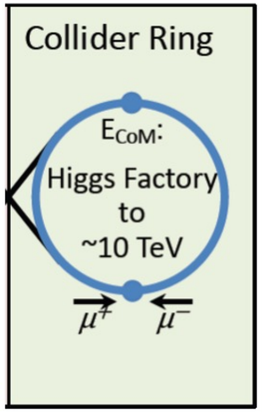
- **High magnetic field to have a compact collider-> 16T (L_{ring}=10 km, E_{μ}^{COM}=10 TeV)**
  - ➢ Status of the art: LHC NbTi dipoles, 8T @ 1.9 K.
  - ➢ B_{MAX}(NbTi)=8 T -> o achieve a higher magnetic field, new superconducting materials, assembly technologies, stress management and quench protection techniques are required!
  - ➢ $F_{Lorentz} \propto B^2$-> higher magnetic field-> higher stress!
- **Large aperture** (150 mm) to host radiation shielding for the muon decay product
  - ➢ $F_{Lorentz}$ scales with the aperture: higher aperture -> higher stress! (N.B. LHC dipole aperture = 56 mm)
- Straight sections must be avoided to minimize the radiation induced by the collimated neutrino beams -> **combined function magnets** are required (dipoles+quadrupoles, dipoles+sextupoles) -> design and stress managment much more complicated!

3 TeV collider (5 km ring):

- Close to state of the art
- ~11T/150mm (Nb_3Sn)
- 600 magnets, 5 m length
- Operating temperature: 4.5 K

10+ TeV collider (10 km ring):

- HTS magnets, R&D is required
- ~15T/150mm (ReBCO, hybrid)
- 1200 magnets, 5 m length
- Operating temperature: 4.5...20 K



There are currently no technological solutions for the required specifications, such magnets must be designed and demonstrated from scratch! There are several R&D programs on going to build high-field dipole demonstrators, but no one has the specific requirements necessary for the muon collider.