Terza Giornata Acceleratori – LNF

R&D Muon Collider per European Strategy

Nadia Pastrone

Gruppi **INFN** *in* ***RD_MUCOL @ CSN1*****:** 118 persone/24 FTE

RD_MUCOL @ CSN1 – ESPP_A_MUCOL @ GE – UE-MUCOL – UE-I_FAST

BA BO FE GE MI MIB LNF LNL LNS NA PD PV RM1 RM3 TO TS

Physics, Detector R&D, MDI, Crystals/Targets, Accelerator Activities

INFN-LNF , 4 aprile 2024

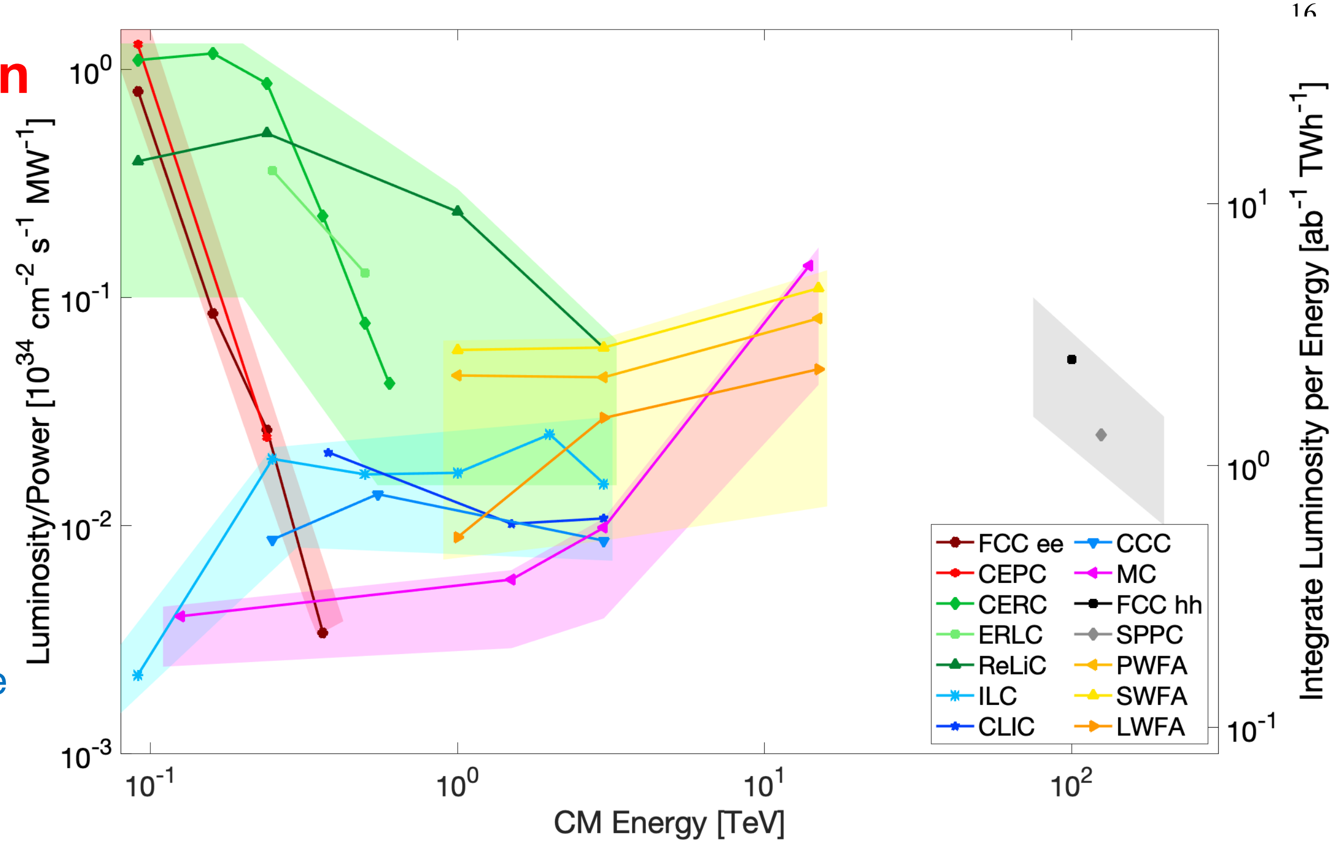
HORIZON-INFRA-2022-DEV-01-01

Energy efficiency of present and future colliders

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

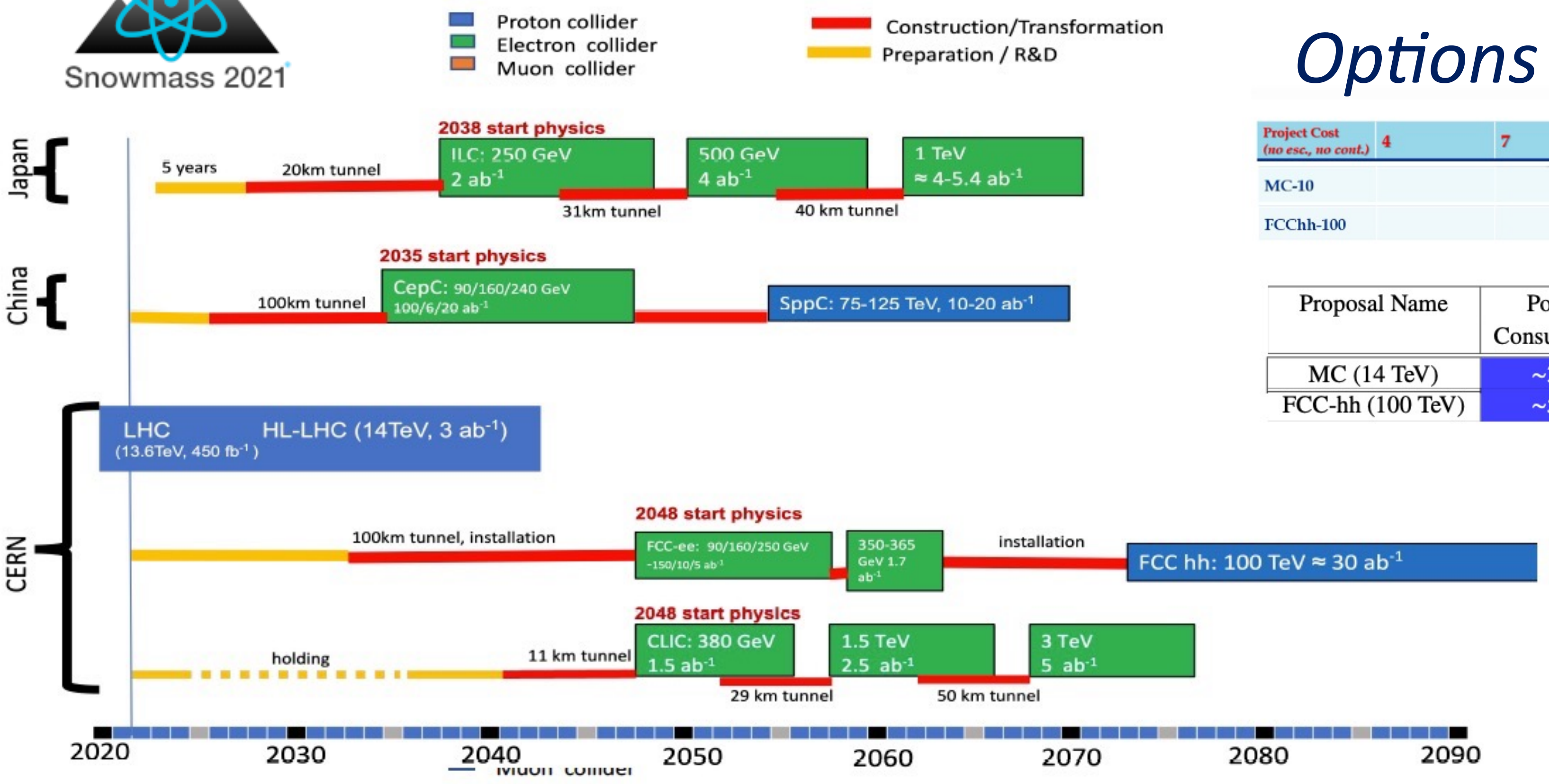
Luminosity per power consumption

- 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.

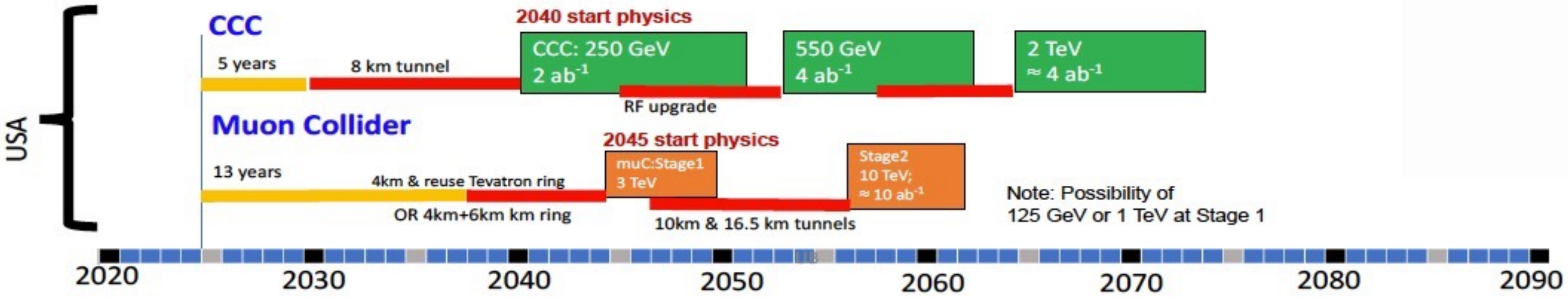


The effective energy reach of hadron colliders (LHC, HE-LHC and FCC-hh)
is approximately a factor of seven lower than
that of a lepton collider operating at the same energy per beam

Colliders timescale: Snowmass2021

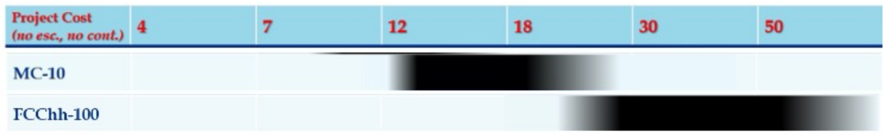


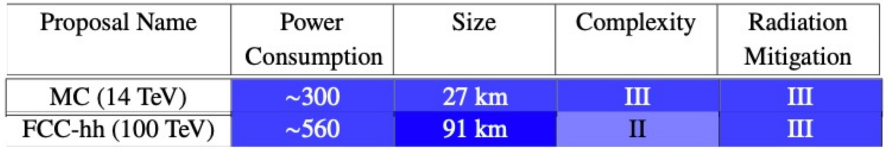
Proposals emerging from Snowmass 2021 for a US based collider



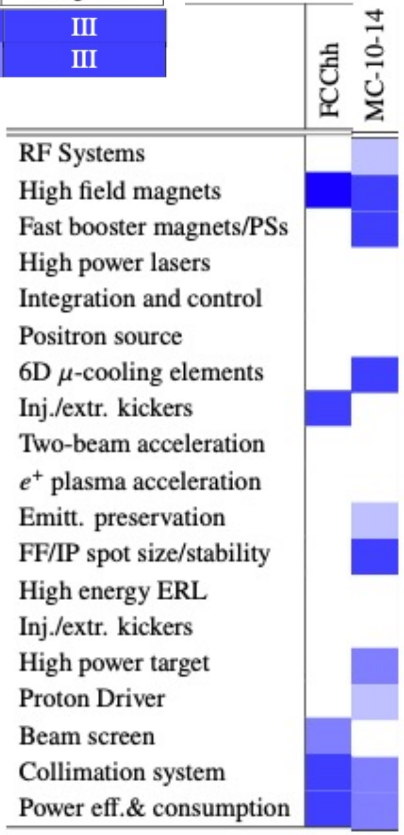
International
MUON Collider
Collaboration

Options @ 10 TeV Scale



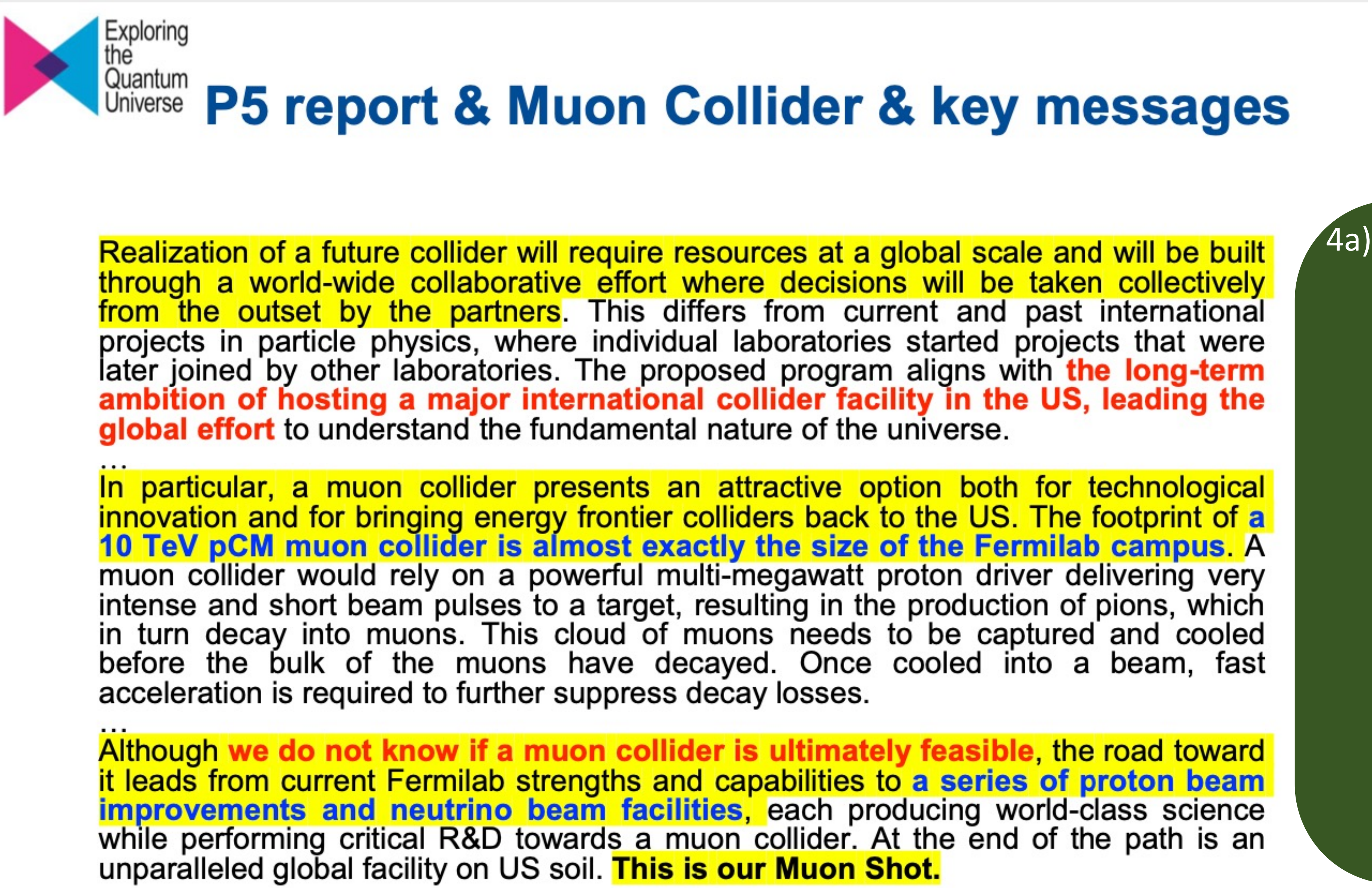


Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
MC (14 TeV)	~300	27 km	III	III
FCC-hh (100 TeV)	~560	91 km	II	III



	FCChh	MC-10-14
RF Systems		🟦
High field magnets	🟦	🟦
Fast booster magnets/PSs		🟦
High power lasers		
Integration and control		
Positron source		
6D μ-cooling elements		🟦
Inj./extr. kickers	🟦	
Two-beam acceleration		
e^+ plasma acceleration		
Emitt. preservation		🟦
FF/IP spot size/stability		🟦
High energy ERL		
Inj./extr. kickers		
High power target		🟦
Proton Driver		🟦
Beam screen	🟦	
Collimation system	🟦	🟦
Power eff.& consumption	🟦	🟦

U.S. 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]

International Muon Collider Collaboration @ 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 options (neutrino/higgs factory)
- Define **R&D path**

19 countries: CERN, IT, US, UK, FR, DE, CH, ES…… CHINA, KOREA, INDIA….. Interest from Japan …
80 institutes

U.S. P5: Intenational 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).

International Design Study facility

- **Focus on two energy ranges:**

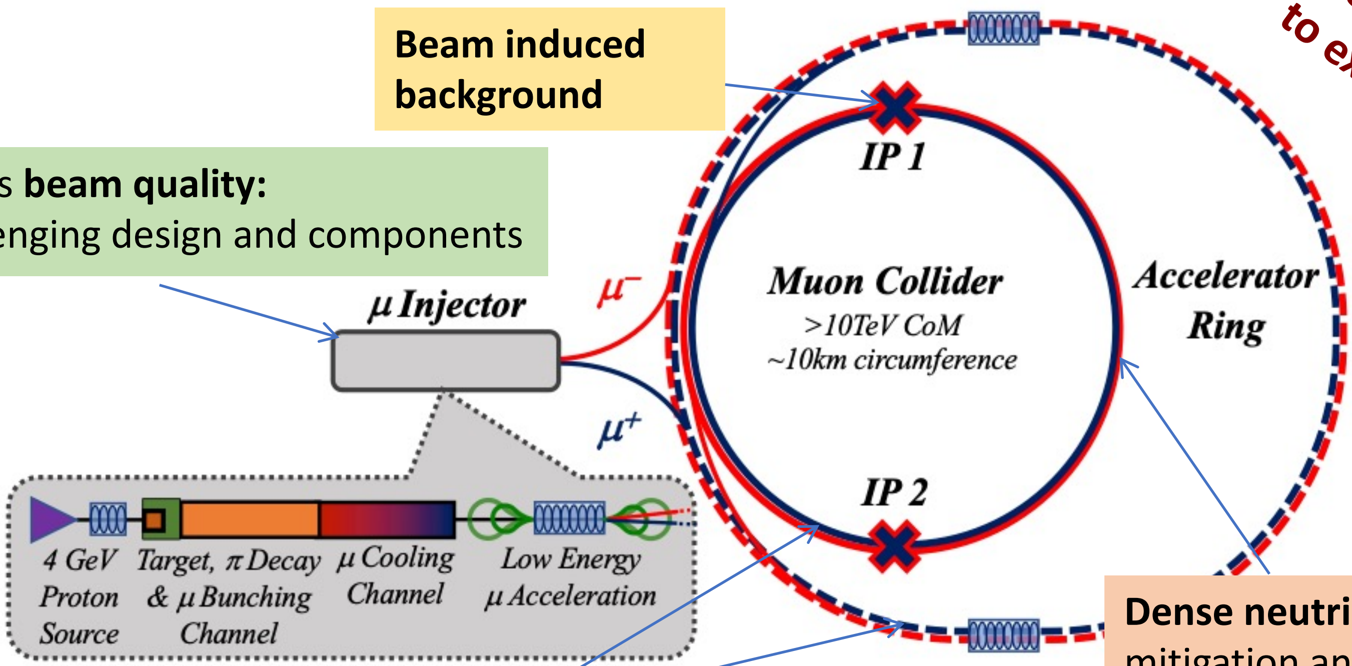
Proton driver production as baseline

3 TeV technology ready for construction in 10-20 years

10+ TeV with more advanced technology

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

10+ TeV completely new regime to explore!

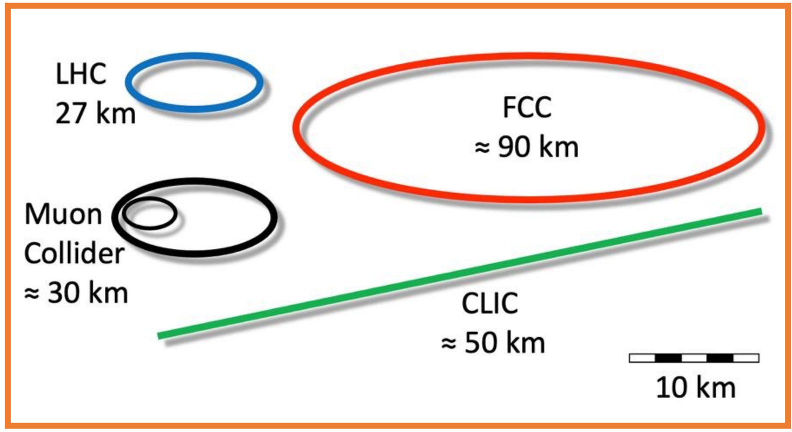


Beam induced background

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



Muon Collider Forum Report **Sept 2022**

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, …

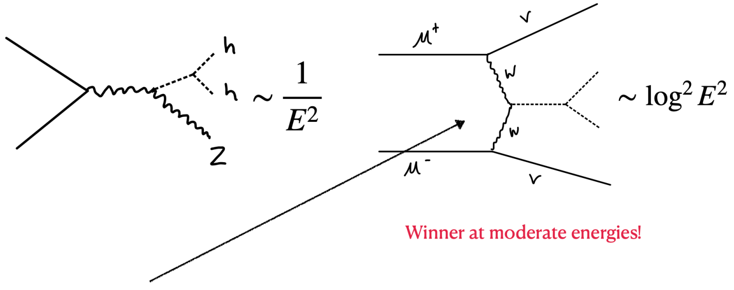
High-energy probes

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!

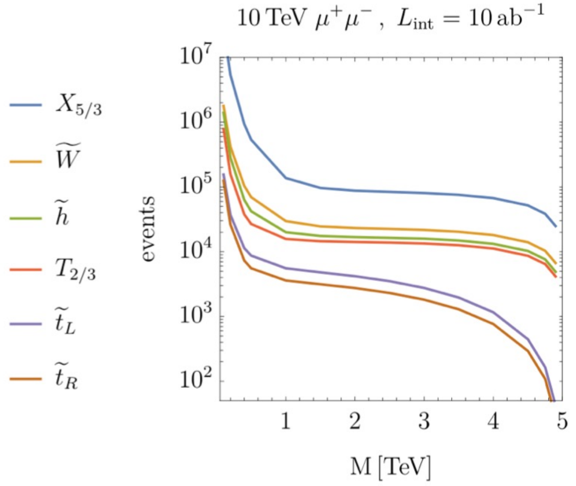


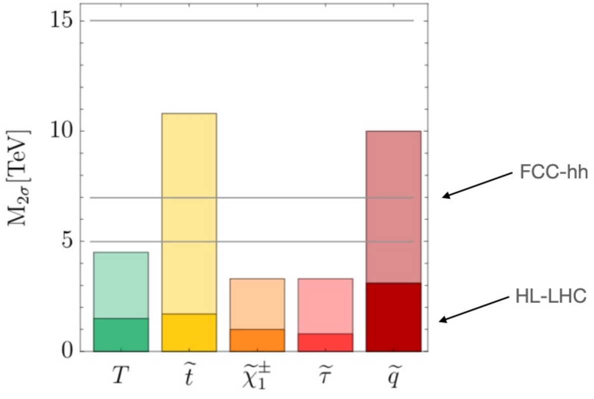
Winner at moderate energies!

Can think of this as VV to H fusion, with VV initial states (PDF like for hadron colliders)

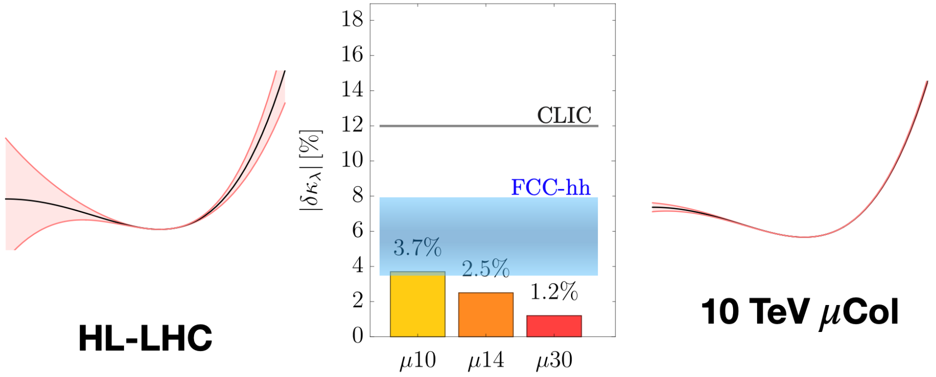
Strong and crucial synergies to design the machine and the experiment to reach the physics goals with energy and luminosity allowing % precision measurements

➔ **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

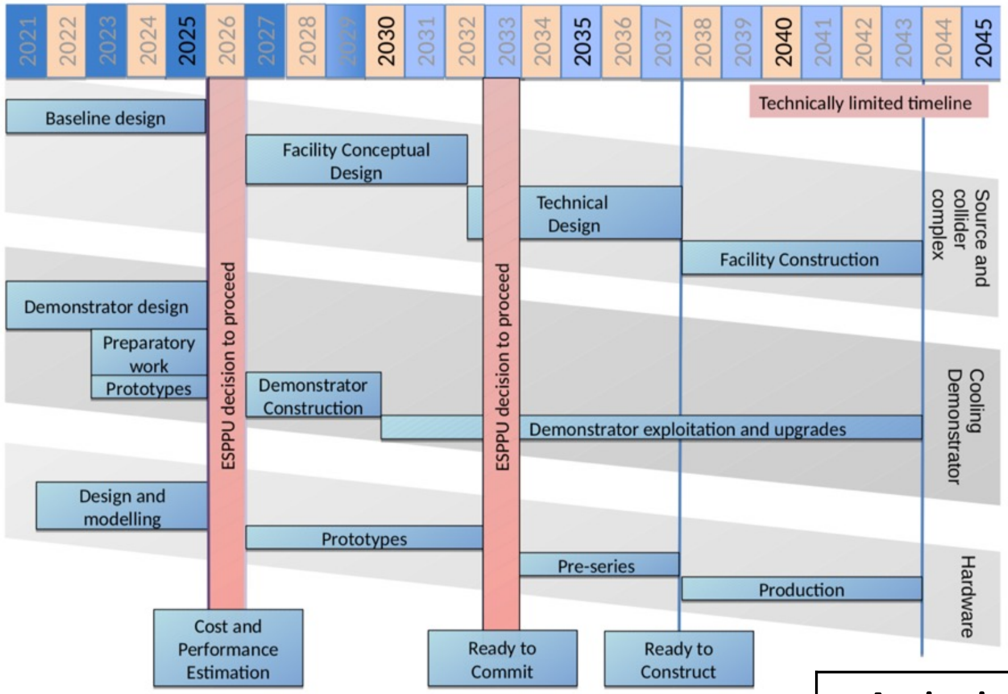
Accelerator R&D Roadmap

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

Roadmap Plan

MDI

Dipoli/solenoidi ad alto campo (Nb3Sn, HTS?)

Cavità RF SC e NC

Cooling cell Dimostratore

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

Scenarios

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

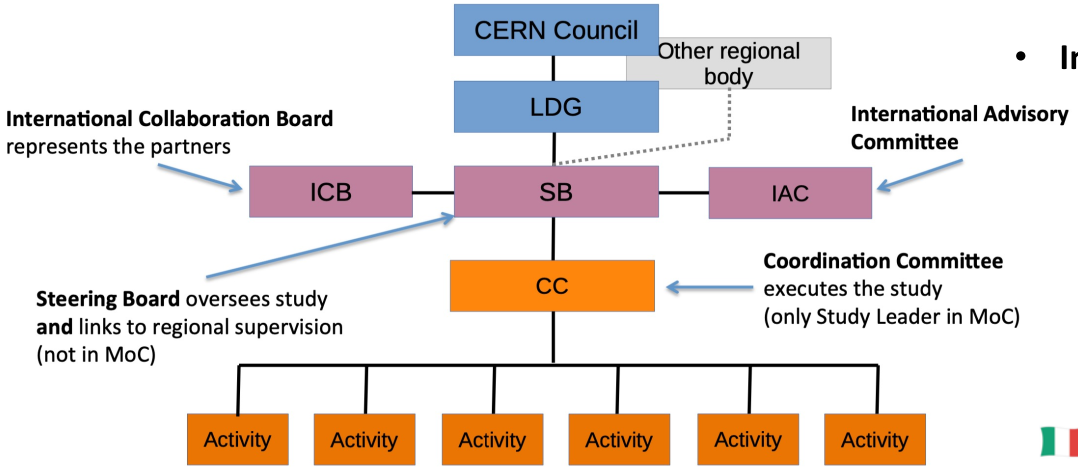
~70 Meu/5 years

IMCC Organization after the Roadmap

- Study Leader **Daniel Schulte**
  - Deputies: **Andrea Wulzer**, **Donatella Lucchesi**, **Chris Rogers**

- **Collaboration Board (ICB)**
  - Elected chair : **Nadia Pastrone**
- **Steering Board (SB)**
  - Chair **Steinar Stapnes**,
  - CERN members: Mike Lamont, Gianluigi Arduini, **Dave Newbold (STFC), Mats Lindroos (ESS), Pierre Vedrine (CEA)** , ICB chair and SL and deputies
- **International Advisory Committee (IAC)**

CERN is host organisation, can be transferred to other partner on request of CERN and with approval of ICB
Will review governance in 2024, US could join at that time



CERN Council

Other regional body

LDG

International Collaboration Board represents the partners

ICB

SB

IAC

International Advisory Committee

Steering Board oversees study **and** links to regional supervision (not in MoC)

CC

Coordination Committee executes the study (only Study Leader in MoC)

Activity

Activity

Activity

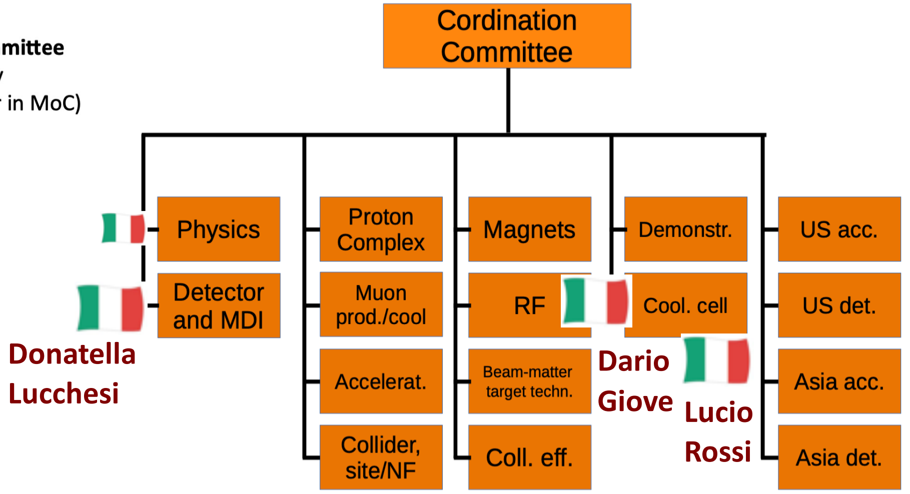
Activity

Activity

Activity

MoC signed by CERN CEA INFN STFC-RAL ESS IHEP and different universities in EU, US, China

Coordination Committee



Cordination Committee

Physics

Detector and MDI

Donatella Lucchesi

Proton Complex

Muon prod./cool

Accelerat.

Collider, site/NF

Magnets

RF

Beam-matter target techn.

Coll. eff.

Dario Giove

Demonstr.

Cool. cell

Lucio Rossi

US acc.

US det.

Asia acc.

Asia det.

Resources – Addenda – Grey Book @ CERN

Accelerator R&D Roadmap: implementation – towards next ESPPU

No insurmountable obstacle found for the muon collider ➔ but **important need for R&D**

Aim at **10+ TeV** and potential initial stage at **3 TeV**

NEW OPTION: initial 10 TeV stage at reduced luminosity

Full scenario deliverables by next ESPPU/other processes

- **Project Evaluation Report**
- **R&D Plan –** a path towards the collider

Allows to make **informed decisions**

First parameters' report submitted October 2023

Interim report by Spring 2024

Do not yet have the resources of the reduced scenario

- Priorities with available expertise and resources
- Are approaching O(40 FTE)
- Efforts to increase resources

NEW

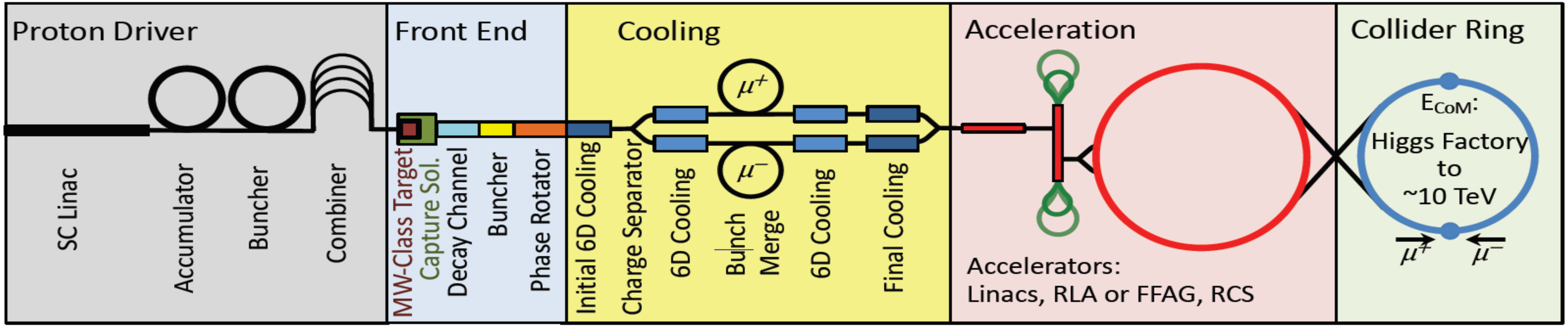
European Strategy for Particle Physics Update

Input documents due by March 31 2025

Council approval expected June 2026

Collider Concept

Fully driven by muon lifetime, otherwise would be easy



Short, intense proton bunch

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

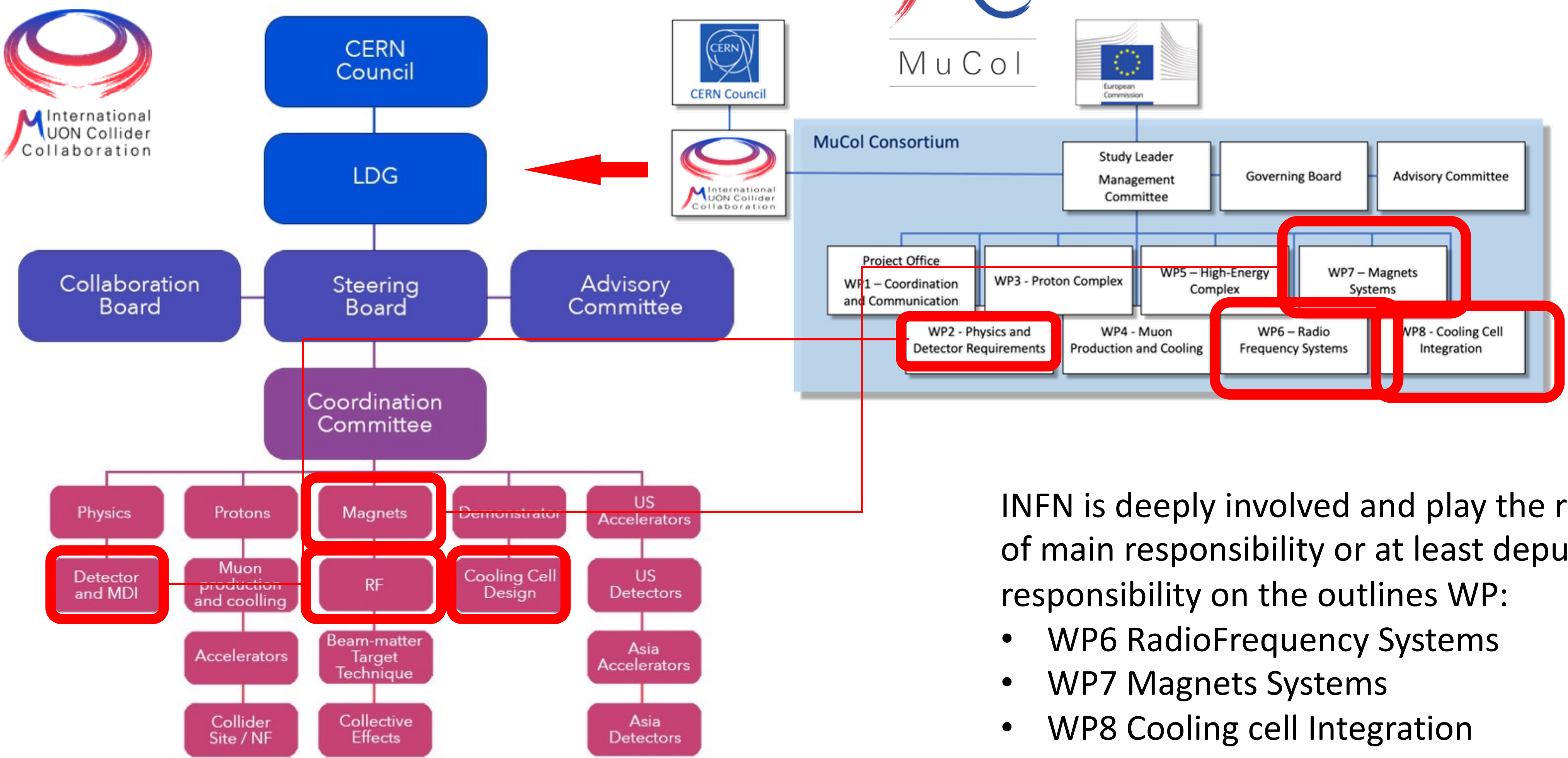
Protons produce pions which decay into muons muons are captured

Proton driven Muon Collider Concept (MAP collaboration)

Project Organization

International Muon Collider Collaboration

MuCol EU Design Study



CERN Council

LDG

Collaboration Board

Steering Board

Advisory Committee

Coordination Committee

Physics

Detector and MDI

Protons

Muon production and coolling

Accelerators

Collider Site / NF

Magnets

RF

Beam-matter Target Technique

Collective Effects

Demonstrator

Cooling Cell Design

US Accelerators

US Detectors

Asia Accelerators

Asia Detectors

CERN Council

International MUON Collider Collaboration

MuCol

European Commission

MuCol Consortium

Study Leader Management Committee

Governing Board

Advisory Committee

Project Office WP1 – Coordination and Communication

WP3 - Proton Complex

WP5 – High-Energy Complex

WP7 – Magnets Systems

WP2 - Physics and Detector Requirements

WP4 - Muon Production and Cooling

WP6 – Radio Frequency Systems

WP8 - Cooling Cell Integration

INFN is deeply involved and play the role of main responsibility or at least deputy responsibility on the outlines WP:

- WP6 RadioFrequency Systems
- WP7 Magnets Systems
- WP8 Cooling cell Integration
- WP2 Physics&Detector – MDI

Attività R&D Acceleratori

simulazioni – prototipi – misure di laboratorio

MI, GE, LNL, LNS, NA, PD, TO, TS (FE, RM1, RM3)

- Magneti (MI-LASA, GE) ➔ progetto ESPP, EU-MuCol (WP7)
- Radiofrequenze SC (SC-RF) (MI-LASA) ➔ progetto ESPP , EU-MuCol (WP6)
- Radiofrequenze NC-RF (MI-LASA,LNL,LNS,NA) ➔ progetto ESPP , EU-MuCol (WP6)
- Integrazione cooling cell (MI-LASA,LNL,LNS,NA,TO) ➔ EU-MuCol (WP8)
- Machine Detector Interface ➔ progetto ESPP (personale), EU-MuCol (WP2-WP5)

⬇

CRUCIALE PER STUDI DI FISICA E DETECTOR – PERFORMANCE MACCHINA

- *Cristalli per i fasci, misure di laboratorio per finestre sottili in fase di definizione*

ESPP_A_MUCOL ➔ approvato dal MAC INFN

WP1 - Machine Detector Interface

WP2 - Ionizing Cooling Cell design and integration:
  - normal-conducting RF cavities
  - high field solenoidal magnets

WP3 - Superconducting RF cavities: fast frequency tuner system

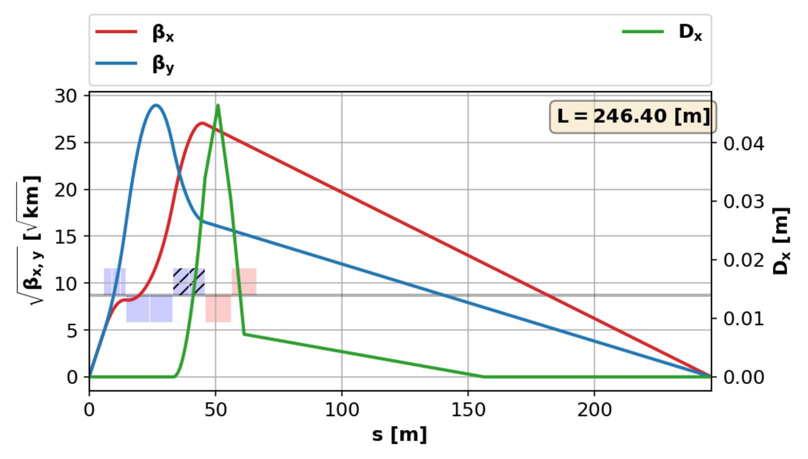
WP4 - High Field dipole Magnets technologies

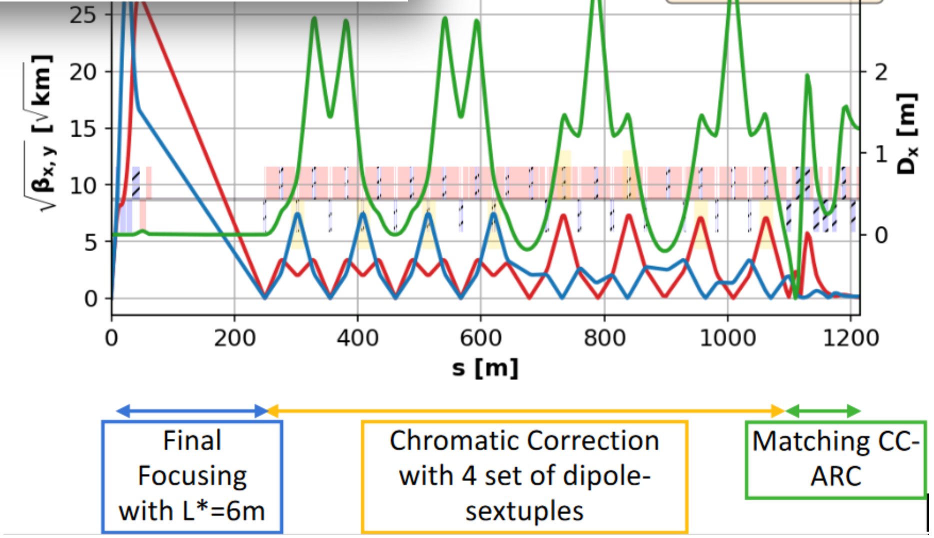
Status of IR lattice design @ 10 TeV

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

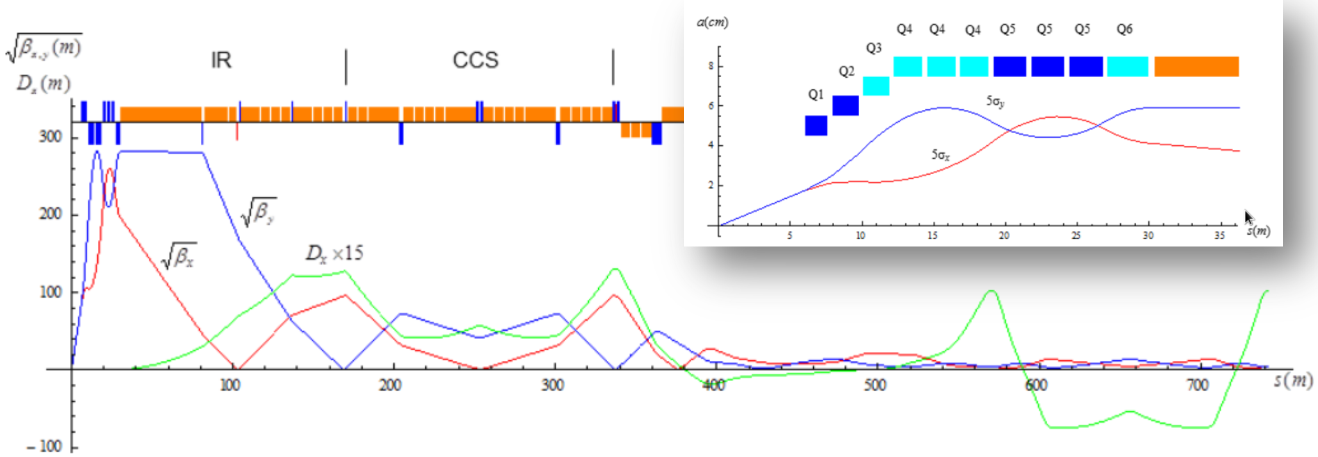
	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Version	**US MAP**	**IMCC (v0.7)**
FF scheme	Quadruplet (with dipolar component)	Triplet (with dipolar component)
ß*	5 mm	1.5 mm
L*	6 m	6 m
Max. field at inner bore	12 T	20 T

10 TeV IR lattice (IMCC):





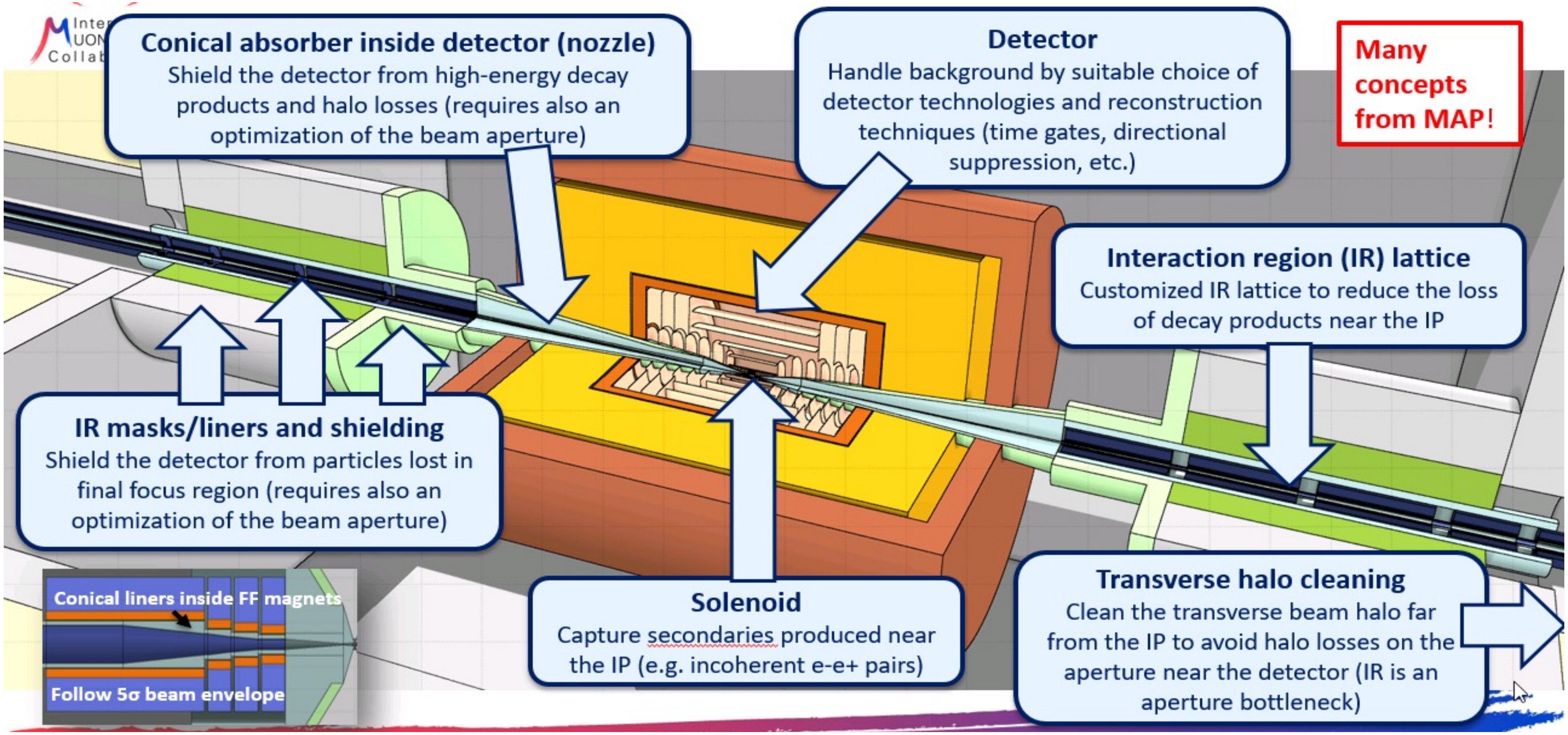
3 TeV IR lattice (MAP):



How to deal with the 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)



Conical absorber inside detector (nozzle)
Shield the detector from high-energy decay products and halo losses (requires also an optimization of the beam aperture)

Detector
Handle background by suitable choice of detector technologies and reconstruction techniques (time gates, directional suppression, etc.)

Many concepts from MAP!

Interaction region (IR) lattice
Customized IR lattice to reduce the loss of decay products near the IP

IR masks/liners and shielding
Shield the detector from particles lost in final focus region (requires also an optimization of the beam aperture)

Solenoid
Capture secondaries produced near the IP (e.g. incoherent e-e+ pairs)

Transverse halo cleaning
Clean the transverse beam halo far from the IP to avoid halo losses on the aperture near the detector (IR is an aperture bottleneck)

MDI – Status and next steps

1) Muon decay along the ring
2) Incoherent e^+e^- production during bunch crossing at IP
3) Beam halo losses

- At low energy, $\sqrt{s} = 3$ TeV, **1)** dominates Studies performed with MAP configuration
- At high energy, $\sqrt{s} \approx 10$ TeV, **1), 2), 3)** under evaluation

Workshop @ CERN
11 – 12 March
impressive progress

IMCC and MuCol MDI workshop 2024

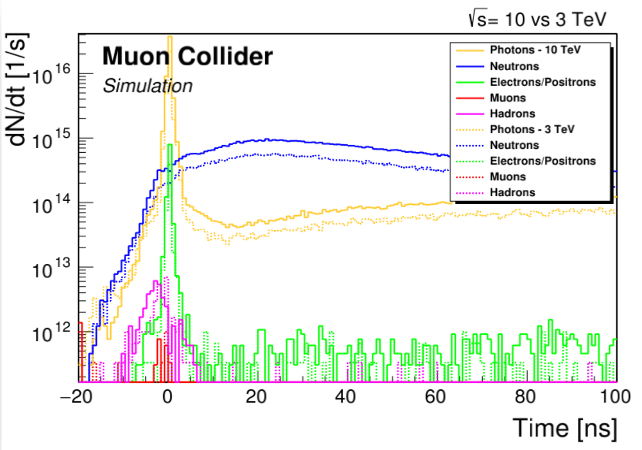
Mar 11 – 12, 2024
CERN
Europe/Zurich timezone

MuCol - A Design Study for a Muon Collider complex at the 10 TeV centre-of-mass energy is a European funded project devoted to high-energy muon collision studies. One of the work packages is dedicated to the investigation of the beam-induced background effects on the detector and to the definition of a detector including its performance.

The workshop will report on the progress of the MDI and interaction region design for the 3 TeV and 10 TeV muon colliders, reviewing conceptual and technical challenges. Past achievements will be summarized and open points as well as plans for future studies will be highlighted.

The workshop will also provide a summary of the detector design studies, with particular focus on the technology R&D required to mitigate the effect of the beam-induced background on the physics object reconstruction performance.

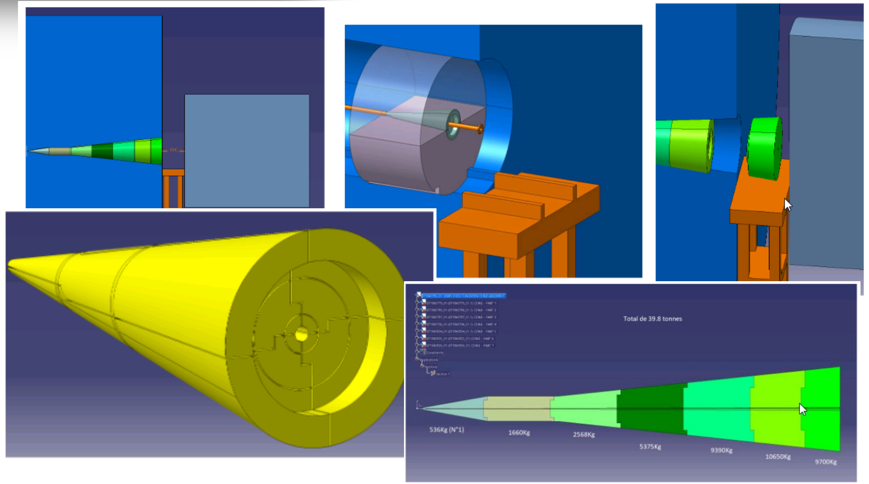
The design of the interaction regions at $\sqrt{s} = 3$ TeV (Fermilab) and $\sqrt{s} = 10$ TeV (CERN) are now available.



Beam-induced background is studied at both $\sqrt{s}$ by using the MAP detector absorber protection structure , nozzle. Optimization of a such a structure in progress.

The technical design of the nozzle started:

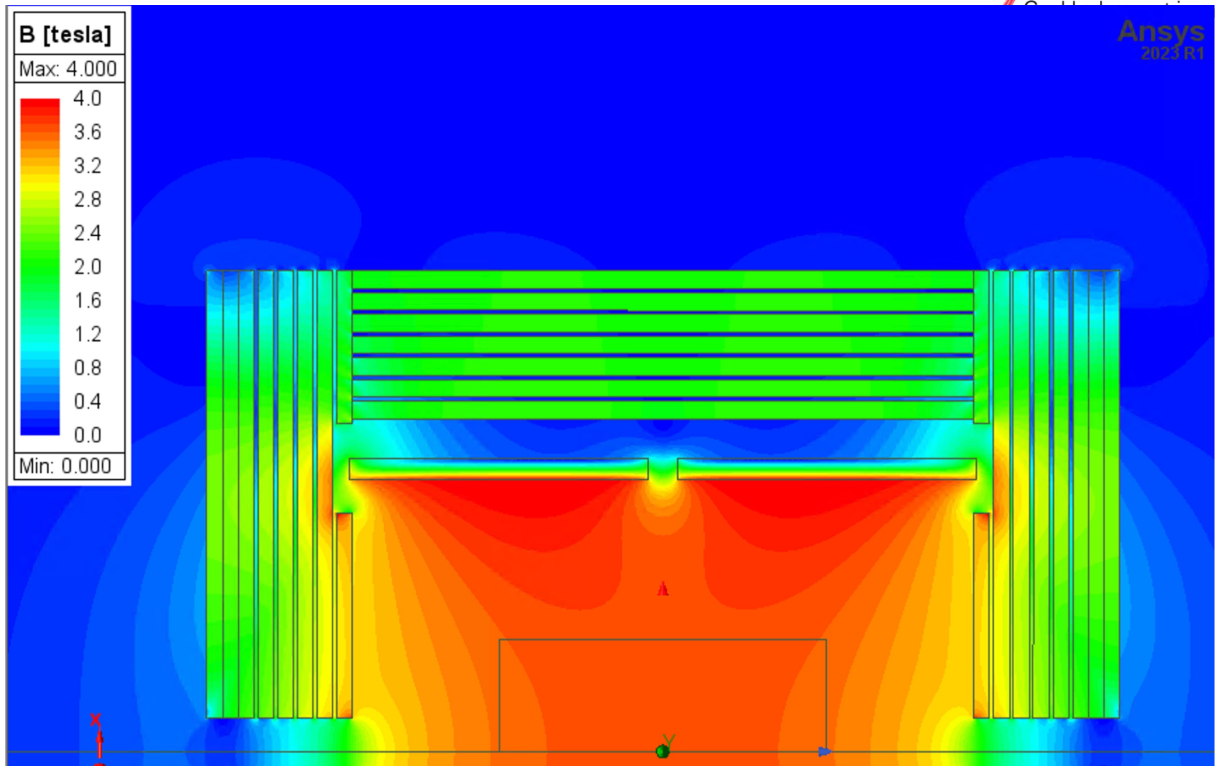
- Integration and support inside detector
- Shielding segmentation and assembly
- Selection of specific material (tungsten heavy alloy) → machining is an important aspect
- Heat extraction (cooling)
- Alignment, vibrations, tolerances, etc.
- Dedicated vacuum chamber inside nozzle



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 (A. Bersani)



Main features:

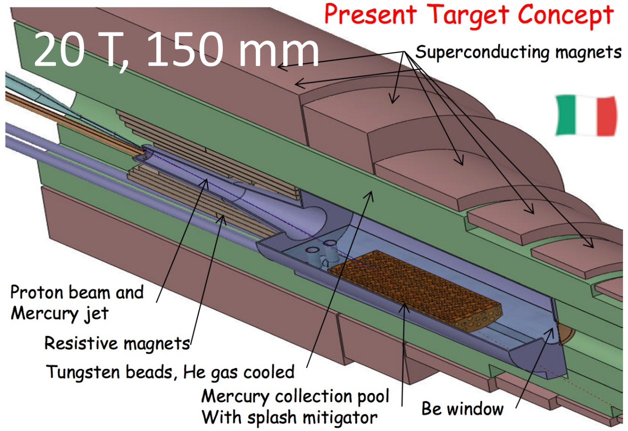
- Tracker region: -2200 < z < 2200, 0 < r < 1500
- B at IP: 3.66 T
- B = 3.60 ± 0.08 T
- Field uniformity: ±2.3%
- (Almost no optimisation)
- Max Br = 0.12 T
- Stored energy: 2.25 GJ
- Current density: 12.3 MA/m^2
- Total coil thickness: 288 mm
- Current: 19.5 kA
- Cable size: 72 x 22 mm^2
- Inductance: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

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

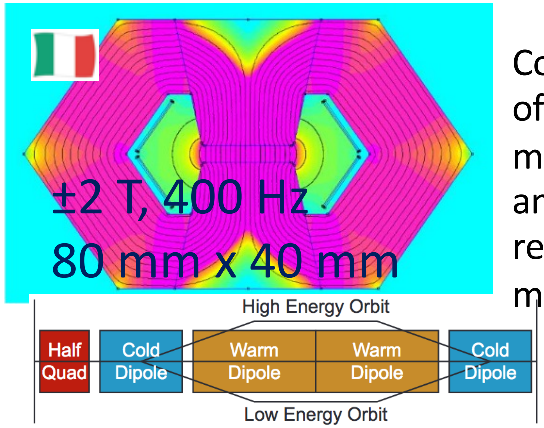
No manpower presently dedicated to this task

Magnet Demands @ Muon Collider

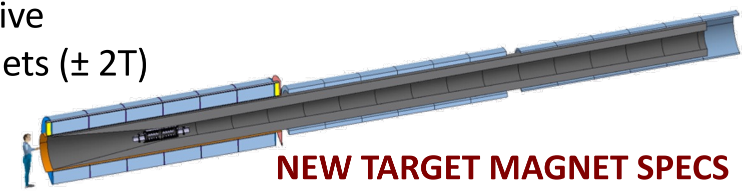
International MUON Collider Collaboration



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

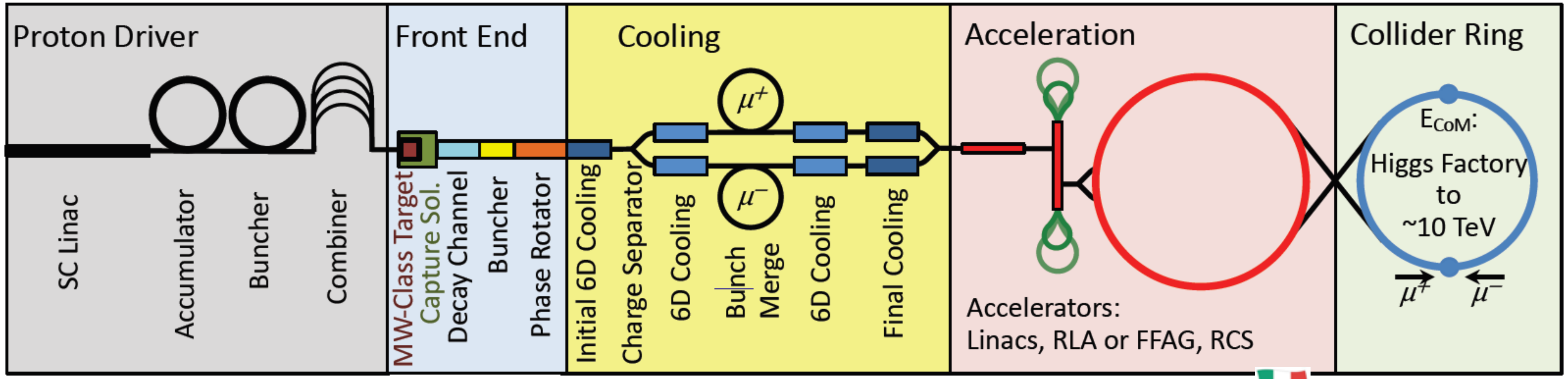


Combination of DC SC magnets (10 T) and AC resistive magnets (± 2T)

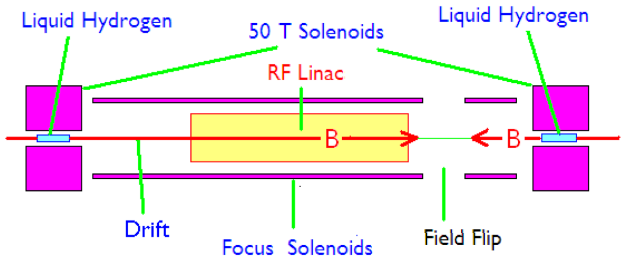


NEW TARGET MAGNET SPECS

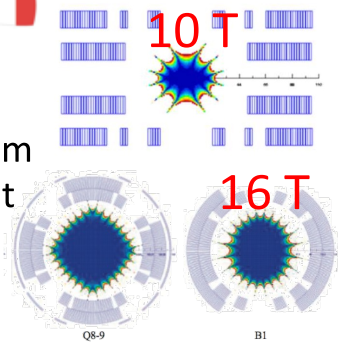
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy



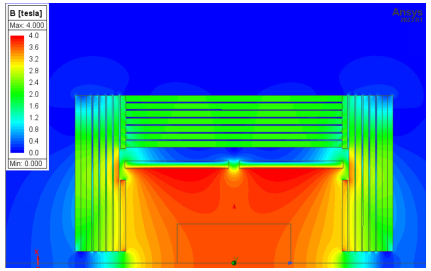
Ultra-high-field solenoids (40…60 T) to achieve desired muon beam cooling



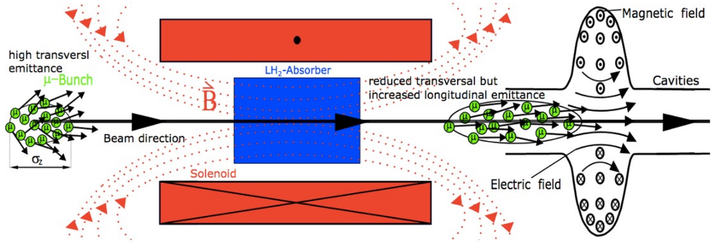
Open midplane or large dipoles and quadrupoles in the range of 10…16 T, bore in excess of 150 mm to allow for shielding against heat (500 W/m) and radiation loads

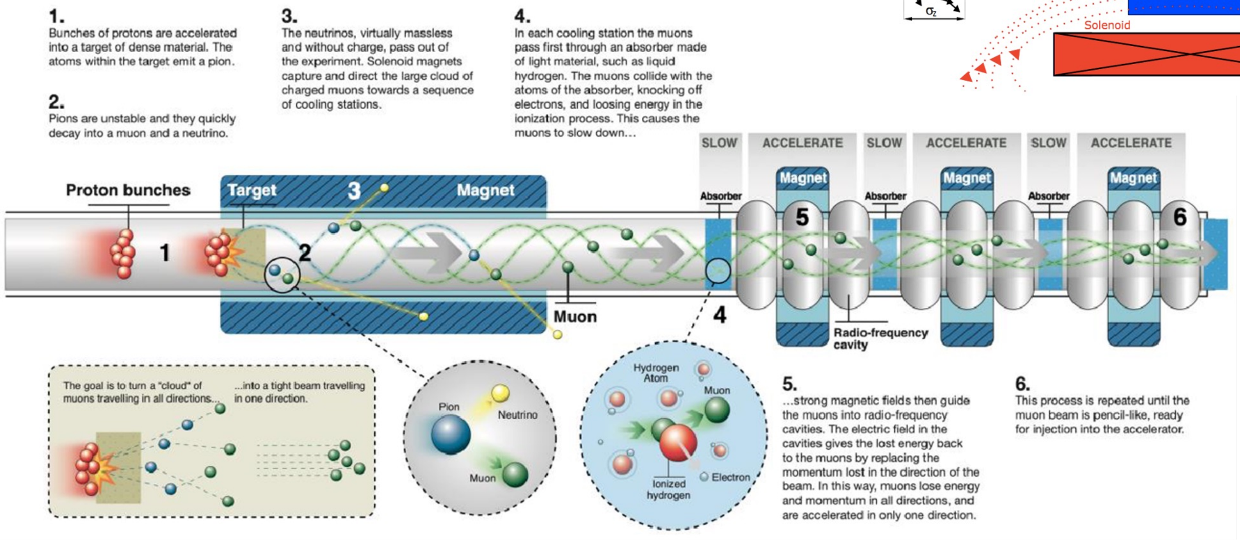


Detector Magnet to be designed for 10TeV



Cooling Channel





1\.
Bunches of protons are accelerated into a target of dense material. The atoms within the target emit a pion.

2\.
Pions are unstable and they quickly decay into a muon and a neutrino.

3\.
The neutrinos, virtually massless and without charge, pass out of the experiment. Solenoid magnets capture and direct the large cloud of charged muons towards a sequence of cooling stations.

4\.
In each cooling station the muons pass first through an absorber made of light material, such as liquid hydrogen. The muons collide with the atoms of the absorber, knocking off electrons, and loosing energy in the ionization process. This causes the muons to slow down...

5\.
...strong magnetic fields then guide the muons into radio-frequency cavities. The electric field in the cavities gives the lost energy back to the muons by replacing the momentum lost in the direction of the beam. In this way, muons lose energy and momentum in all directions, and are accelerated in only one direction.

6\.
This process is repeated until the muon beam is pencil-like, ready for injection into the accelerator.

The goal is to turn a "cloud" of muons travelling in all directions...

...into a tight beam travelling in one direction.

Fig. 3: Principle of the Muon Ionisation Cooling

NC RF system for muon capture and cooling

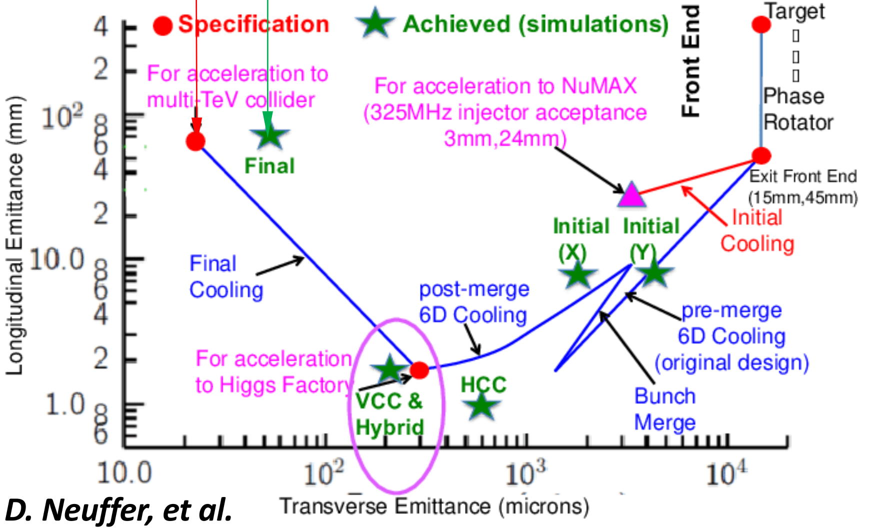
very large and complex RF system
with high peak power – under study

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 TBD TBD	**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 TBD		
Total	**~1300**	**3951**			=> ~12GW

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



D. Neuffer, et al.

***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)*

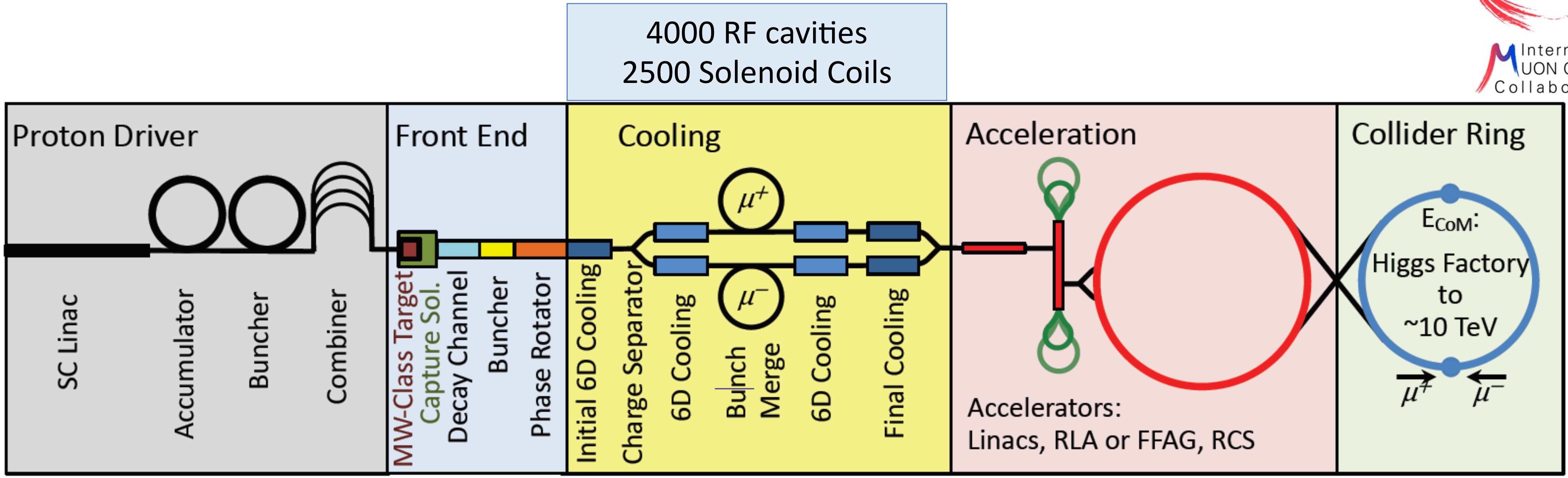
Targeted R&D is required to address these challenges

Ionization cooling: design and study of a cooling cell

R&D project (WP2):

- **conceptual design of the RF systems** for a Muon Collider Complex
- **specifications for the design of all RF cavities will be defined** (frequency, gradient, length, B-field,aperture
- **experimental activity focused to study and enhance the present comprehension of the intrinsic concepts that influence the break down rate of RF cavities submitted to strong magnetic fields will be carried out**
- define realistic solutions to mitigate the breakdown and provide guidance for the design and the fabrication of high gradient RF cavities that stand the strong magnetic fields required in a muon cooling channel.
- define and design the compact multiple-cavity module, with efficient frequency tuning and RF power feeding systems.
- in order to have strong solenoid fields, the cavity design should be as compact as possible in the transverse direction
- design and machine prototypes for a compact full scale cavity (with power coupler, full set of diagnostics for power levels and temperature distribution along with extensive breakdown diagnostics, thermal cooling channels) able to fit within **a solenoid with a useful bore of maximum 450-500 mm**
- the cavity must be able to move longitudinally within the solenoid to experience different level of magnetic field, due to the power scheme of the solenoid coils (a split coil design is foreseen).
- design of the split coil for the RF cavities test and test of **new technology for HTS coils**, based on NI (non-insulated) winding
- a small but significant model coil will be designed and built as a **first step toward the Split Coil Facility for the RF tests** and for the focusing solenoids of the Cooling Cell of the MC. The coil will also serve as thermal mock-up to evaluate the cryogenic losses: this is inscribed in the ambitious line to operate the Muon Collider magnets at 10-20 K. Therefore also the magnetic facility for RF breakdown test will be cooled at 10-20 K with gas or by solid conduction by cryocooler.

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

RF cavities: technical challenges

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.**

RF cavities has been designed, built and demonstrated stable operation at ~10 MV/m

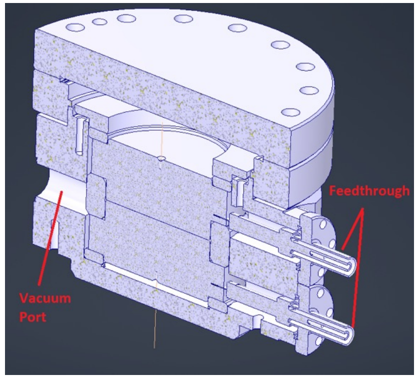
The contribution that we will provide in this scheme may be summarized in the following issues:

- Design the compact multiple-cavity module, with efficient frequency tuning and RF power feeding systems. In the cooling channel, the voltage in each segment requires multiple cavities or one LINAC with multiple cells. In order to have strong solenoid fields, the cavity design should be as compact as possible in the transverse direction.

- Study the possibilities offered by improved copper surface qualities, new copper based alloys or low Z materials as Berillium to improve the braeakdown properties of a NC cavity.

- Look into a suitable RF frequency choice (in the range 805 to 325 MHz) to define a trade off between the above discussed phenomena and the magnet design. This will contribute to the proposal of a demonstrator of a cooling channel section.

NC-RF R&D directions



- Stage 1: Design High gradient RF test facility in high Magnetic Field
  - Frequency: to be defined according to physical significance and costs evaluation
  - Magnetic field: 0 – 7 T, different field configurations (parallel-anti//)
  - Different materials: Cu, Be, Al, …
  - Different temperatures: Cryogenic NC
  - Different gases and pressure: 0 – few Bars
  - Different designs
  - Choice of the HTS Conductor tape (within the 4 candidates)
  - Choice of the design of the RFMF

- Stage 2: Prototype(s) for cooling test facility
  - Design of realistic RF cavity prototypes: frequency, beam aperture, integration
  - Choice of the winding configuration
  - Design and first single prototype coils
  - Specifications defined based on the results of Stage 1 and the (re-)design of the muon cooling complex (higher gradient,…)
  - Study of the integration of the colling cell: RF inside magnetic field with various powering, cooling, cryogenics, vacuum issue (like beryllium window), absorbers, diagnostics, etc.
  - Scope: study of the RFMF test facility and continue by tackling one real cell of the cooling section

Muon Collider related Test Stand Proposals for RF

Advanced phase of design related to a couple of tests stands:

- A DC HV test stand with pulsed capabilities embedded in 1 T magnetic field @ LASA
- A high power (10 MW) S band RF test stand to power a 2856 MHz RF cavity installed in the bore of a SC magnet (next)

The S band RF test stand may be installed in the AATF in the new building,
taking advantage of all the infrastructures we will have at that time (2025) and adding a RF power equipment.

Muon Collider test stand (RFMF)Magnet

International MUON Collider Collaboration

The test stand is a very god opportunity to :

- Test the magnetic system by building a prototype with characteristics near to final (at least for same cooling cells)
- R&D on HTS technology to increase the TRL which is critical for the Cooling Cell and for the collider ring
- Test the integration principle of the cooling cells in near-to-final conditions

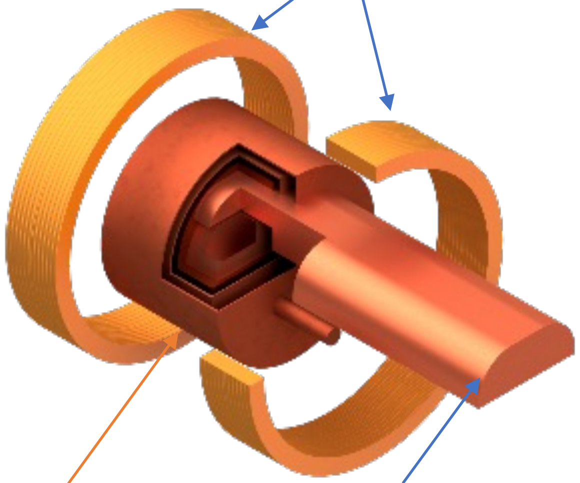
For these reason in addition to the general design of the MC CC magnets and of the magnets of the collider ring, the LASA magnet team of the MC, pursue to design two test stand configurations:

- ✓ Large size split coils (for 704 MHz, i.e. 700 mm free RT bore) needed at the end for a finale integration and functional test
- ✓ A smaller size (for 3 GHz system, i.e. 350 mm free RT bore) that would allow to build the facility with moderate cost

HTS conductor will be purchase in the next months (special project INFN ESPP_A_MUCOL)
→ 2024 start assembling and testing small/medium size coils to experiment HTS technologies:
Non-Insulated or partial insulated vs insulated conductor

First sketch
(scheme split coils in single cryostat)

Bare coils and RF cavity

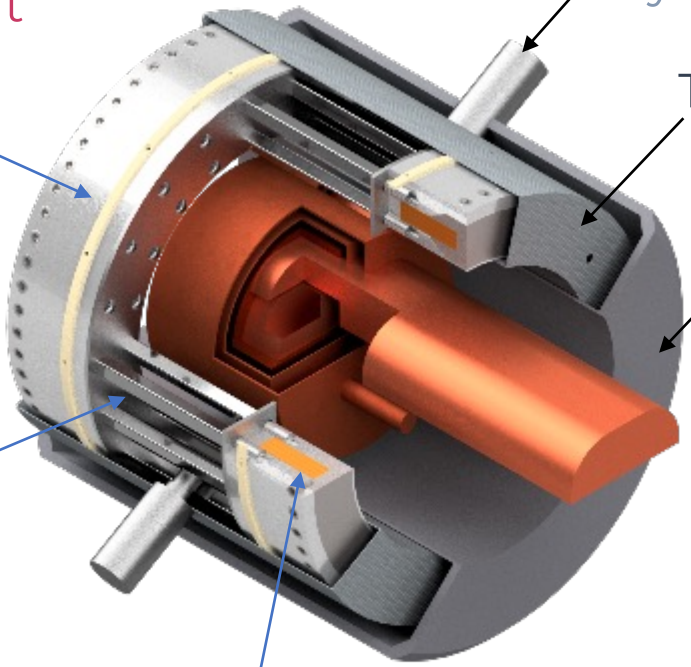


SC HTS coils

Pillbox test cavity

RF Wave guide

With cryostat



Two stage cryocooler

Coil support structure

Thermal shield

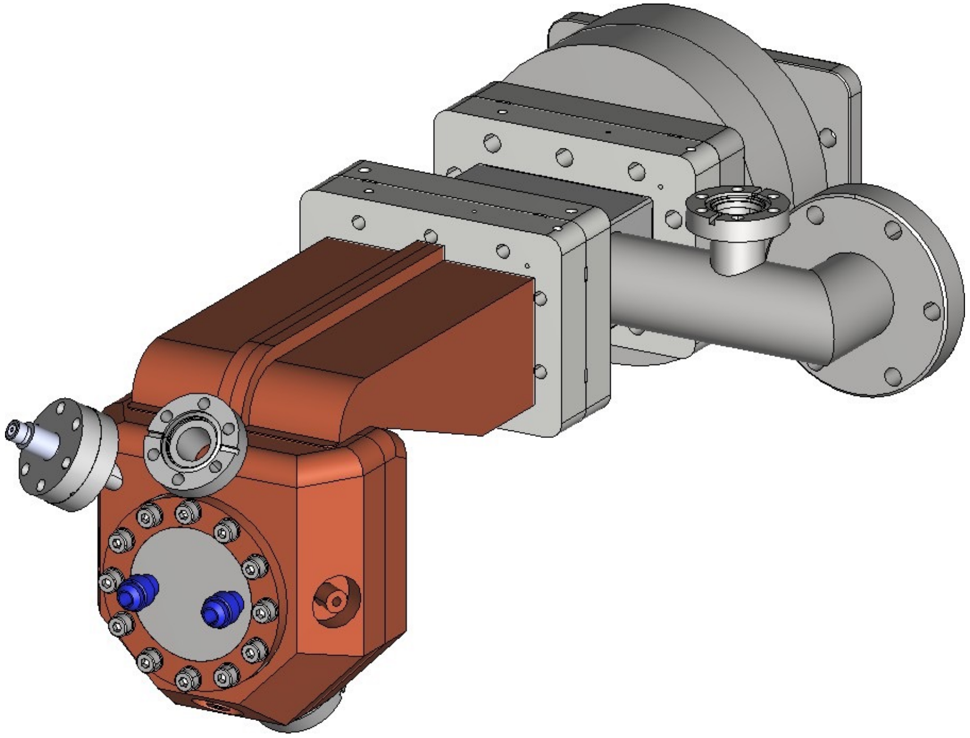
Vacuum vessel

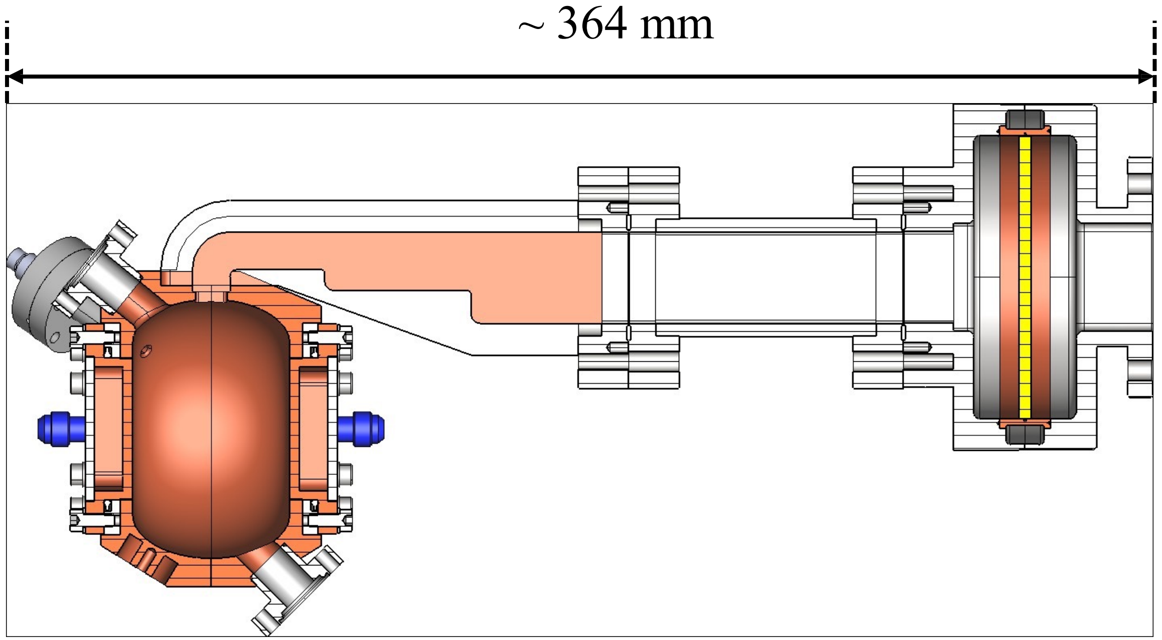
Tie rods for repulsion and compression forces

SC HTS coils

Sc magnet/cryostat sketch by M. Castoldi & Stefano Sorti, UMIL & INFN-LASA

Muon Collider test stand (RF design)

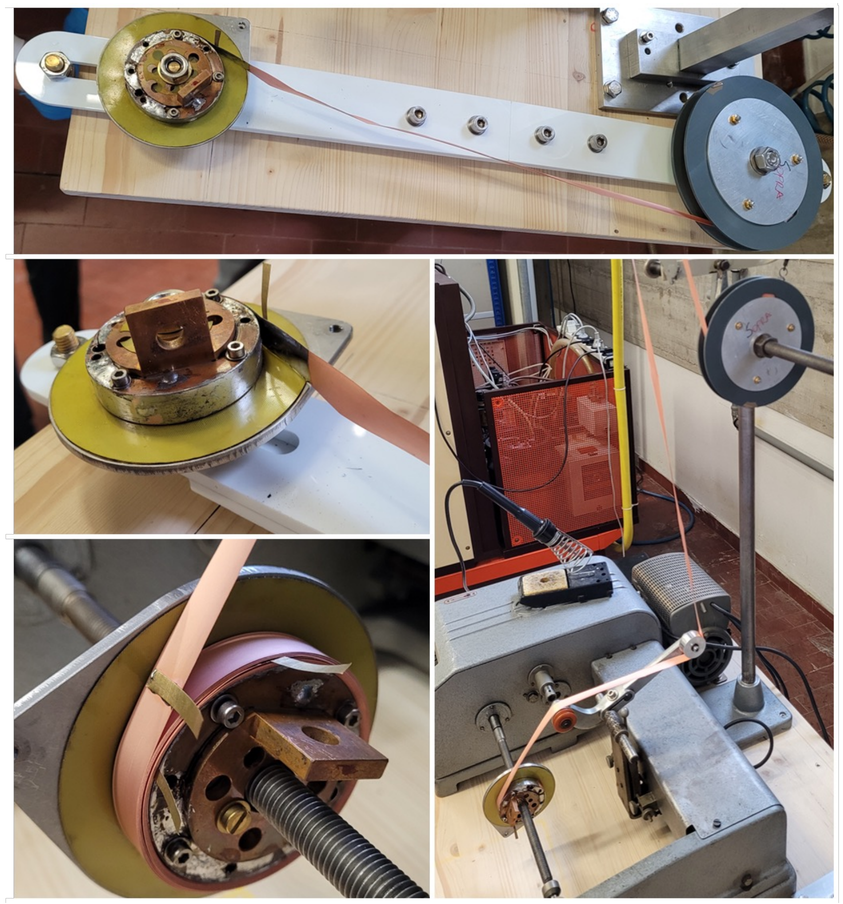




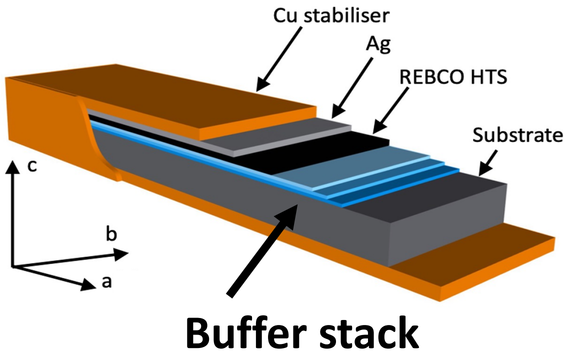
HTS tape

HTS tape: 5 km of 4 mm width (approx. 150 k€ included TVA)
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 RFMFTR (Radio Frequency in Magnetic Field Test Facility).
The HTS tape was deemed necessary in 2023 to get experience and allow validation in 2024/25.

1) tape at LASA mid-April (if custom procedure goes well…)
2) Inspection of the whole length and acceptance tst: May ‘24
3) Start experimental work (coil winding, conditioning and testing): June ‘24



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)

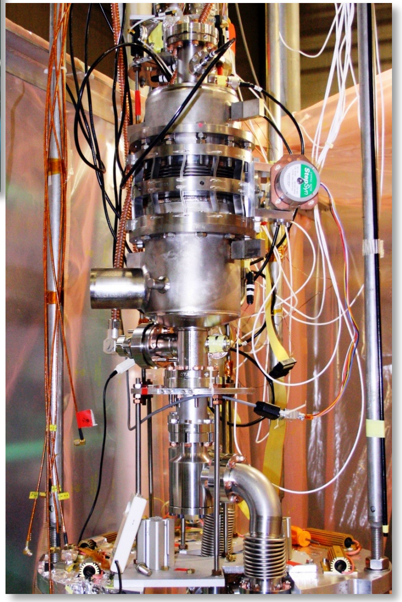


Reference REBCO tape (CERN courtesy)	
Substrate (material/thickness)	Stainless steel / 50 μm
Cu stabilizer (type/thickness)	Electroplated / 20 μm per side
(Re)BCO thickness	≈2.5μm
Dimensions (width x thickness)	12.1 mm x 0.11 mm

SC-RF: superconducting cavity tuning (WP3)

Hybrid RCSs to be used for MC generate **challenging scenario** for superconducting cavity tuning:

- Very **high gradient**, >30 MV/m, leading to Lorentz's force detuning above 1 kHz (~ E_{acc}^2)
- **Beam orbits drifts** during acceleration and so do f_{rev} and f_{RF}
- Even larger frequency shift, up to 2+ kHz to be controlled in addition to existing detuning
- Large time dynamics: RF pulse goes from 1/5 (RCS1) to 4 times (RCS4) the typical ILC RF pulse of 1.6 ms, to be compared to main modal frequencies that are in the order of 200 Hz (5 ms period).

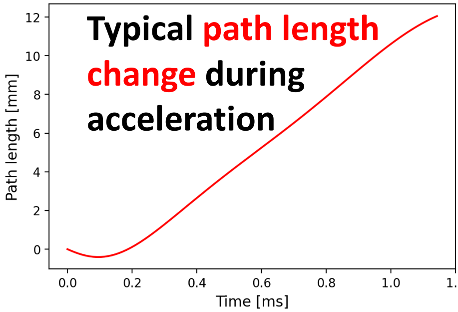


LASA tuner test setups, room T and cryogenic

✓**definition and purchasing of selected piezo systems**

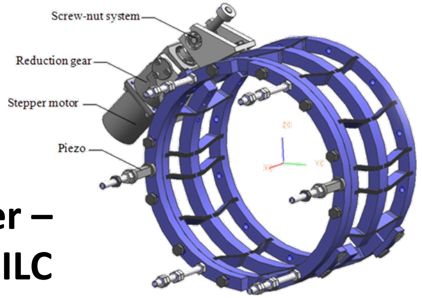
✓**experimental characterization of purchased piezo**

✓**experimental characterization of the full tuning system**



Typical path length change during acceleration

Activity proposed by INFN Milano aims to **design a fast-tuning strategy tailored to Muon Collider needs** further developing actual **state-of-the-art systems** successfully employed in SC linacs as Eu-XFEL, LCLS-II and others.

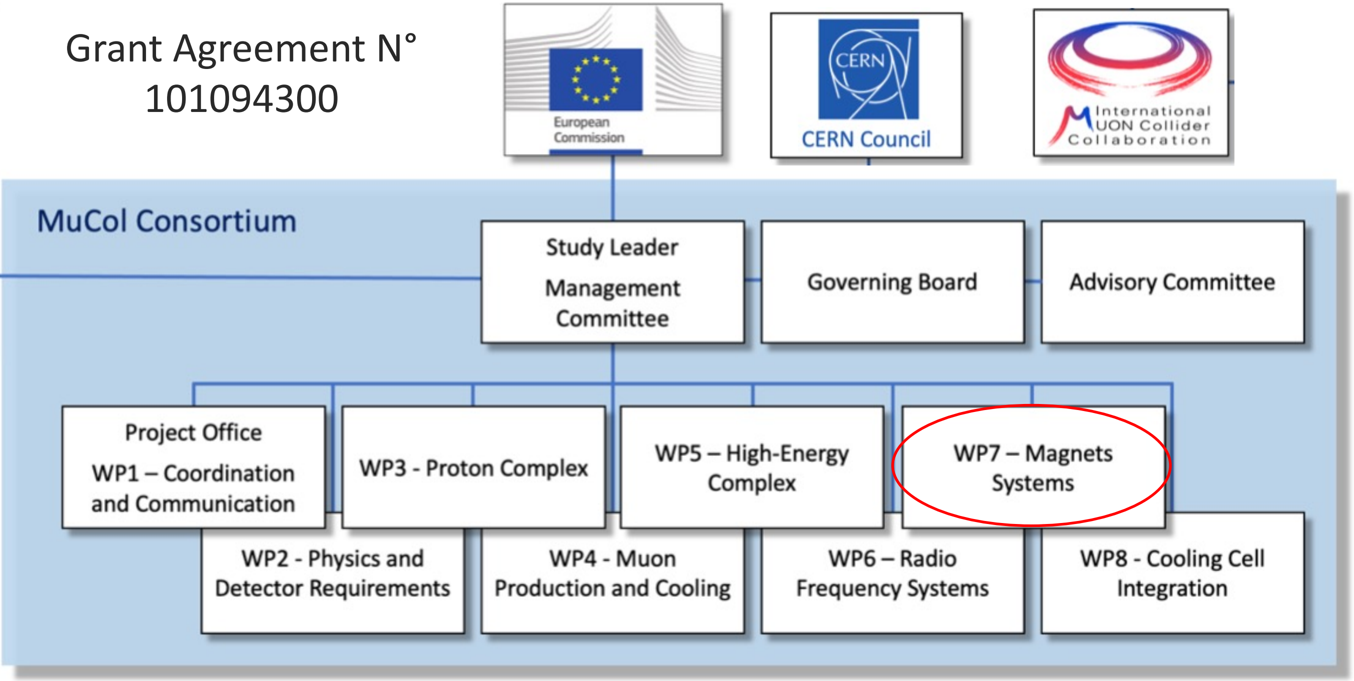


Coaxial Blade Tuner – baseline system for ILC

Collider Ring Magnets (WP4)

center-of-mass collider energy
@ 3 TeV
@ 10 TeV

Grant Agreement N°
101094300



European Commission

CERN Council

International MUON Collider Collaboration

MuCol Consortium

Study Leader
Management Committee

Governing Board

Advisory Committee

Project Office
WP1 – Coordination and Communication

WP3 - Proton Complex

WP5 – High-Energy Complex

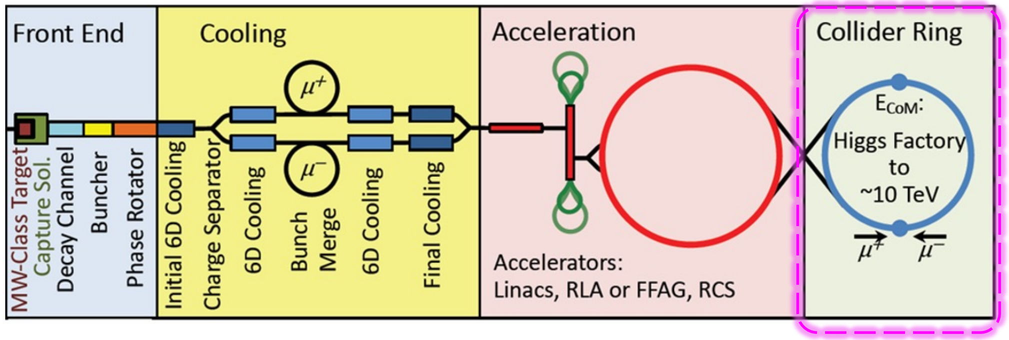
WP7 – Magnets Systems

WP2 - Physics and Detector Requirements

WP4 - Muon Production and Cooling

WP6 – Radio Frequency Systems

WP8 - Cooling Cell Integration



Accelerators:
Linacs, RLA or FFAG, RCS

WP7 – Magnet Systems

- Magnet systems requirements and concepts
- Magnet systems inventory
- Target and final cooling solenoids design
- Fast ramped accelerator magnets and powering system design
- Collider ring magnets design

- 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 a combined functions magnet. HTS materials are a less mature technology with superior tolerance to stress and strain and expected to unfold their potential for magnet technology in the next future.

Collider magnets challenges

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

Main challenges:

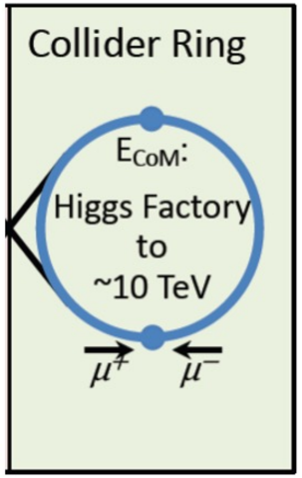
- **<u>High magnetic field to have a compact collider-> 16T (L_{ring}=10 km, E_{μ}^{COM}=10 TeV)</u>**
  - ➢ Status of the art: LHC NbTi dipoles, 8T @ 1.9 K.
  - ➢ B_{MAX}(NbTi)=8 T -> o achieve a higher magnetic field, new superconducting materials, assembly technologies, stress management and quench protection techniques are required!
  - ➢ $F_{Lorentz} \propto B^2$-> higher magnetic field-> higher stress!
- **<u>Large aperture</u>** (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 -> **<u>combined function magnets</u>** are required (dipoles+quadrupoles, dipoles+sextupoles) -> design and stress managment much more complicated!

<u>3 TeV collider (5 km ring):</u>

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

<u>10+ TeV collider (10 km ring):</u>

- 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.

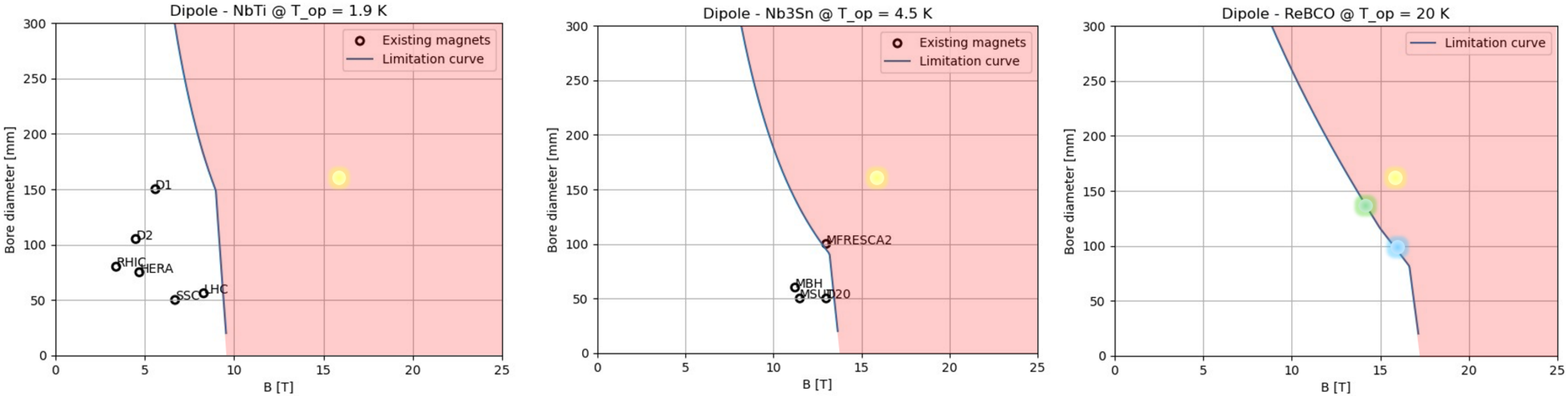
Towards realistic performances

AIM: 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

The initial proposal from beam dinamics falls largely in the forbidden area .Thanks to this study, the feasible region has been assessed and new lattice calculations are on-going

Muon Collider Magnets - comments

The magnets required for the collider are particularly challenging:

- to avoid collimated neutrino beams from muon decay, the straight lengths in the collider ring should be kept to an absolute minimum. To achieve this goal, the beam optics quadrupoles should be combined with the bending dipoles, featuring a high magnetic field (>10 T) and gradient (>100 T/m) in a large aperture (∼150 mm).
- The need for a high field derives from the compactness requirement to achieve high luminosity via high crossing frequency. The large aperture is fundamental to allocate a radiation (W) beam screen, which will protect the superconductors from the muon decay products (a radiation heat load of 500 W/m due to electrons, positrons, and their synchrotron photons).

All these constraints require cutting-edge technologies for the material choices, the mechanical layout, the quench protection, and the cooling.

Investigating synergies on physics and technologies

International
MUON Collider
Collaboration

29–31 May 2023 Venezia
Palazzo Franchetti
Istituto Veneto di Lettere, Scienze ed Arti


Muon4Future

September 6, 2023 h 14:35-18:00

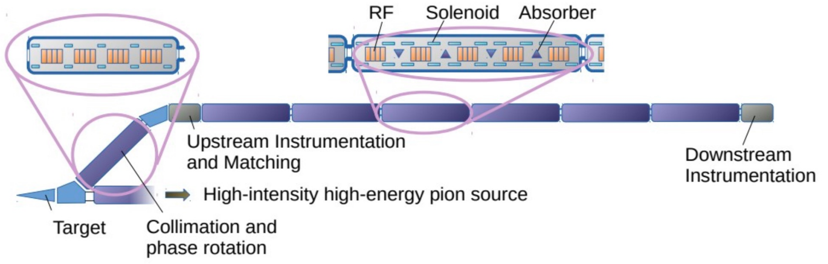
The Muon Collider: a superconducting technology driver for science and society


16th European Conference on
APPLIED SUPERCONDUCTIVITY
Bologna, Italy
3 - 7 September

EUCAS2023


13th ICFA Seminar on
Future Perspectives in High-Energy Physics
28 November – 1 December 2023
DESY, Hamburg

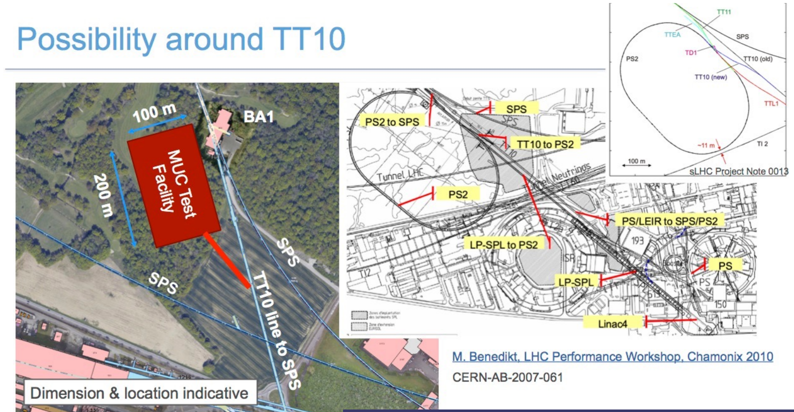
Demonstrator Facility: a crucial step forward!



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

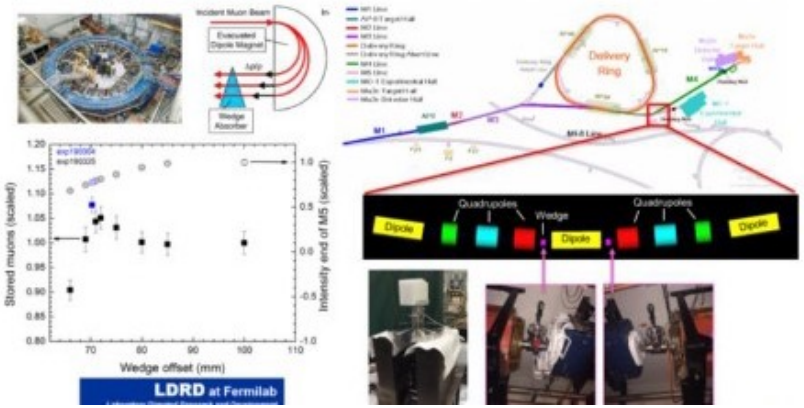

Possibility around TT10

Dimension & location indicative

M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061

@ CERN



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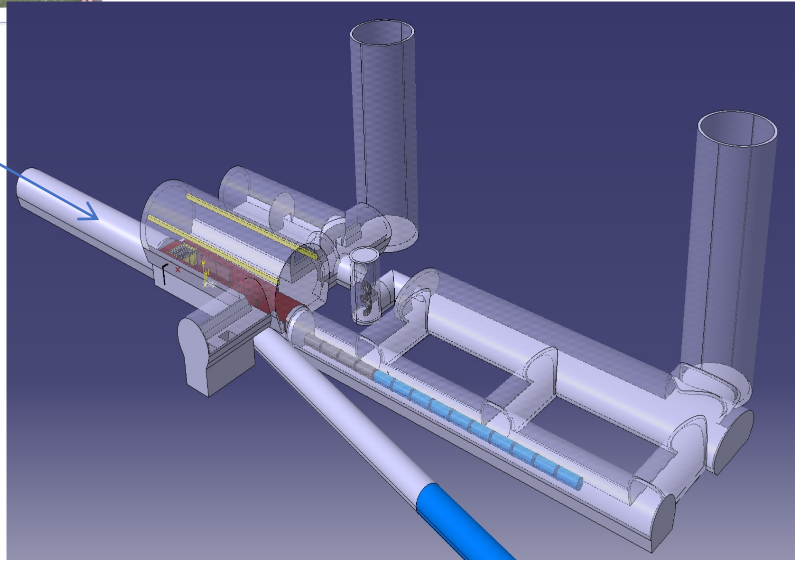

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MUON Collider
Collaboration

Grazie!
e domande?

extras

Key Challenge Areas

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

- Impact on the environment
  - **Neutrino flux mitigation** and its impact on the site (first concept exists)
  - **Machine Induced Background** impact the detector, and might limit 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 (cell engineering design, demonstrator design) 🇮🇹

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

High energy complex requires known components
➔ synergies with other future colliders

Muon4Future

Muon4Future

International
MUON Collider
Collaboration

> 70 people 2.5 days @ Venezia May 29-31, 2023

- Present and Future Muon Facilities: Present and Future Muon Facilities
- Muon Beams Technologies: Muon Beams Technologies
- High Energy Muon Beams Physics
- Muon Magnetic Moment and g-2: Muon Magnetic Moment and g-2
- Hadronic Vacuum Polarization
- Charge Lepton Flavor Violation: Charge Lepton Flavor Violation
- Charge Lepton Flavor Violation
- Muons in Other Fields

Discussion on synergies among the discussed **muon beam technologies**, **detectors**, and **physics measurements**. Identification of possible new measurements and experiments to be performed in a short time scale.

Design Study activities: EU project

MuCol

International
UON Collider
Collaboration

Total EU budget: 3 Meu start March 1 ‘23 – 4 years 18(+14) beneficiaries (associated)

HORIZON-INFRA-2022-DEV-01-01:
Research infrastructure concept development

INFN 510 keu **UniMI** 300 keu **UniPD** 100 keu + associate partners: UniBO, UniPV

MuCol study will produce a coherent description of a novel particle accelerator complex that will collide muons of opposite charge at the energy frontier. The study will target a centre-of-mass energy (ECM) of 10 TeV with 3 TeV envisaged as a first stage.

The main outcome of MuCol will be a **report** documenting the facility design that should demonstrate that:

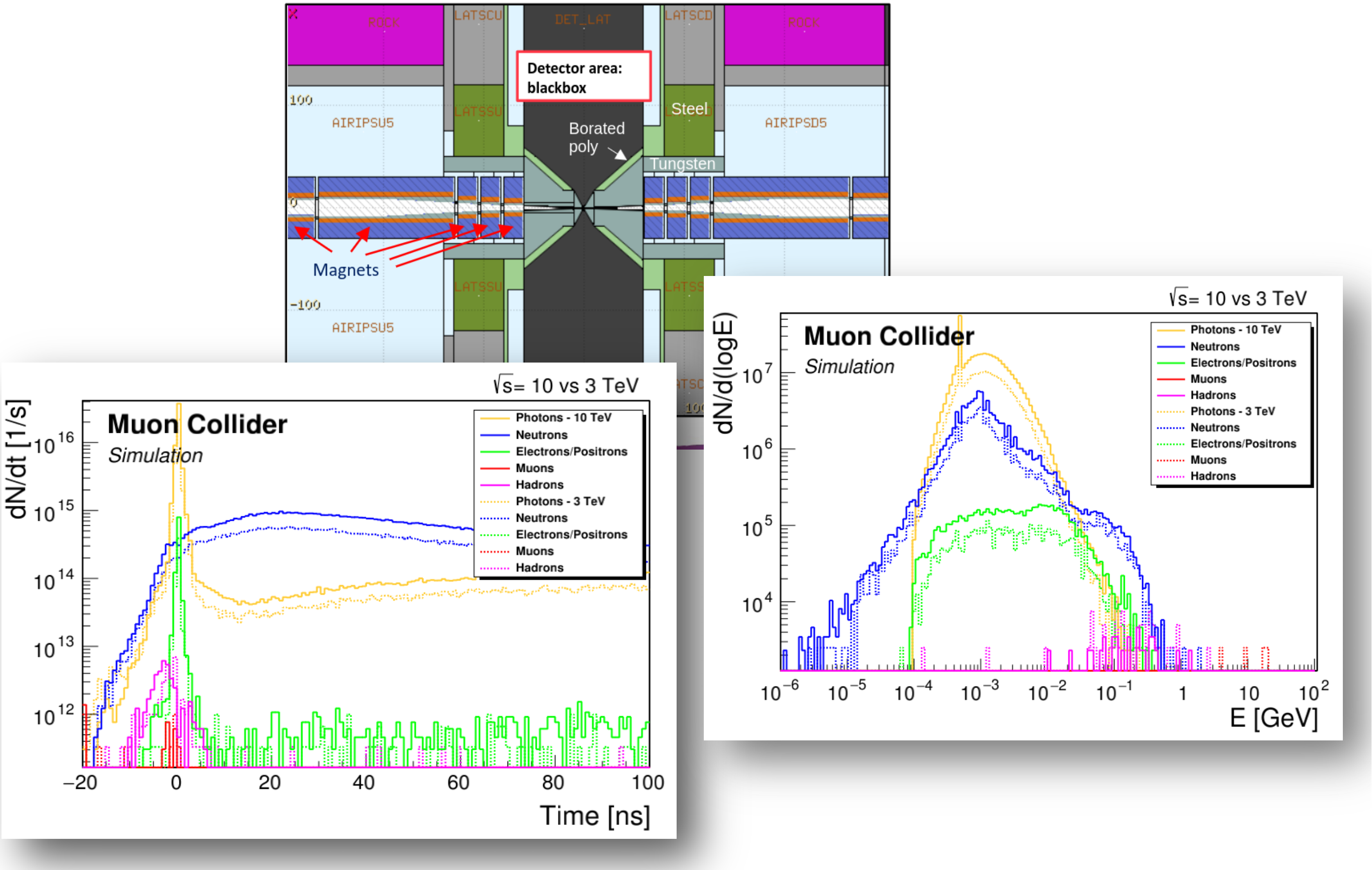
- the **physics case** of the muon collider is sound and **detector systems** can yield sufficient resolution and rejection of backgrounds;
- there are **no principle technology showstoppers** that will prevent the achievement of a satisfactory performance from the accelerator or from the detectors side;
- the muon collider provides **a highly sustainable energy frontier facility** as compared to other equivalent colliders;
- **exploiting synergies with other scientific and industrial R&D projects**, a valuable platform to provide Europe a leading edge not only in terms of discovery potential, but also for the development of associated technologies.

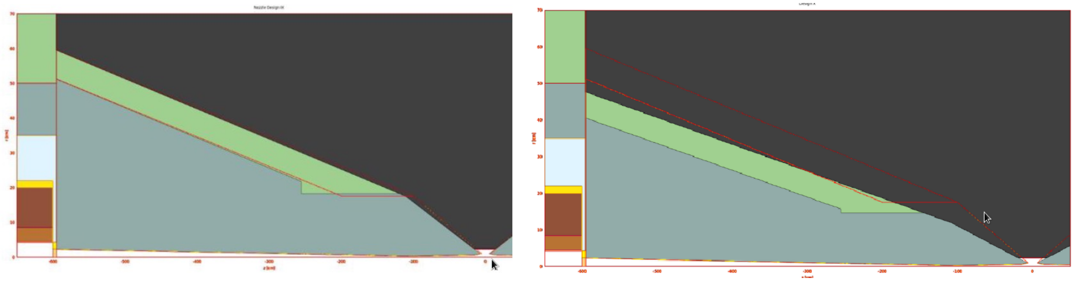
The final report will include a thorough assessment of benefits and risks of the accelerator and detector complex, including an evaluation of the scientific, industrial and societal return beyond high-energy physics, the cost scale and sustainability of the complex and the impact arising from an implementation on the CERN site.

Machine background studies and prospects for nozzle optimization

- **Background studies are key for the MDI design:**
  - Performed detailed simulations of 3 TeV and 10 TeV decay background, but still based on MAP nozzle
  - *Conceptual nozzle optimization (shape, material, aperture) for 3 TeV and 10 TeV is one of the top priorities for this year*
  - Different approaches for optimization are being explored (e.g. machine learning)

10 TeV background studies (IMCC lattice)





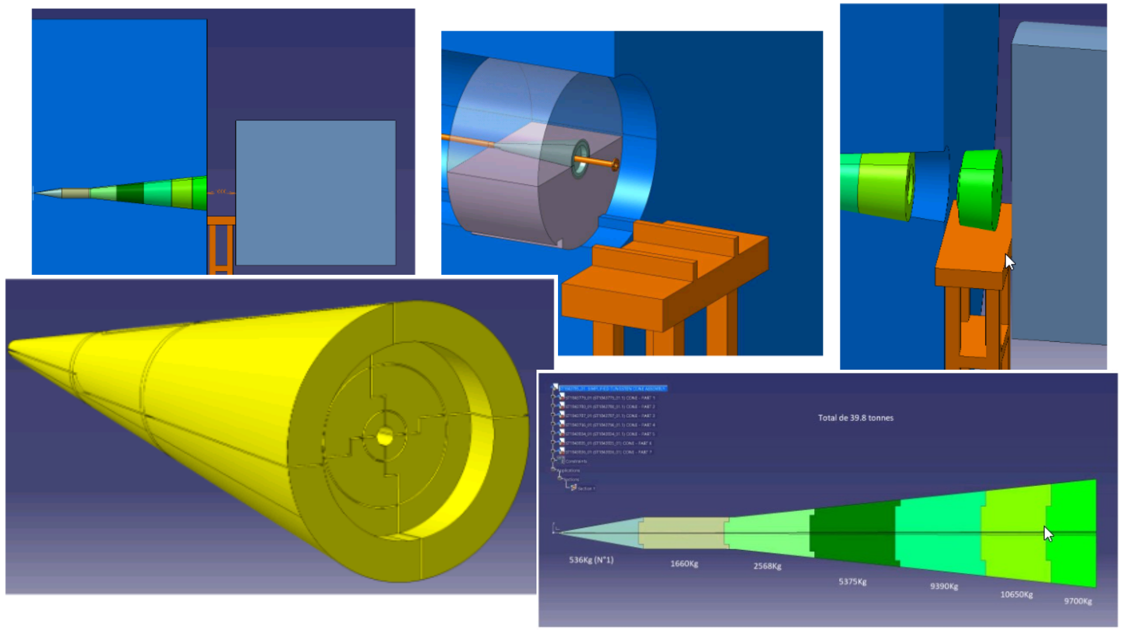
3 TeV background studies (MAP lattice)

Towards a technical nozzle design

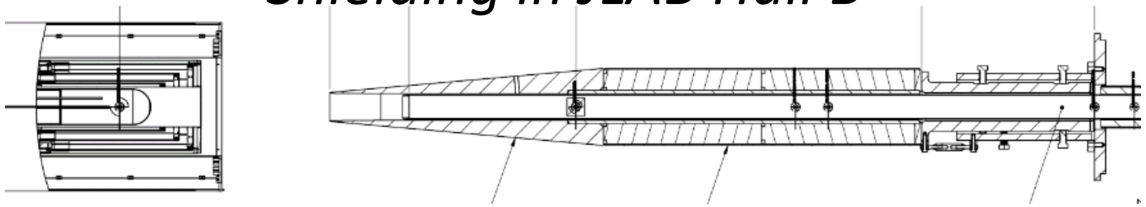
- **Many questions to be addressed, for example:**
  - Integration and support inside detector
  - Shielding segmentation and assembly
  - Selection of specific material (tungsten heavy alloy) → machining is an important aspect
  - Heat extraction (cooling)
  - Alignment, vibrations, tolerances, etc.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

Can learn from existing shielding projects, but do presently not have resources for a full technical design

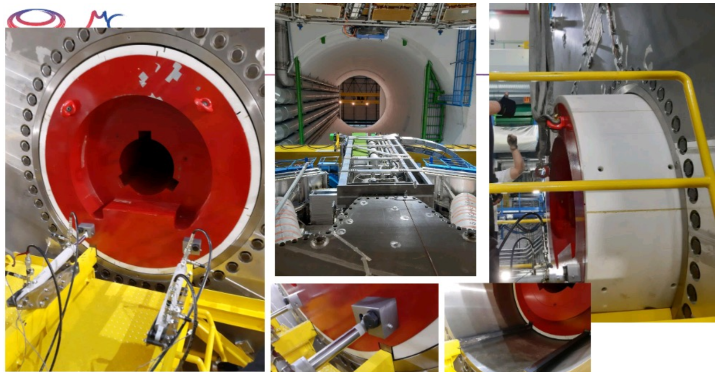
First consideration for nozzle segmentation:



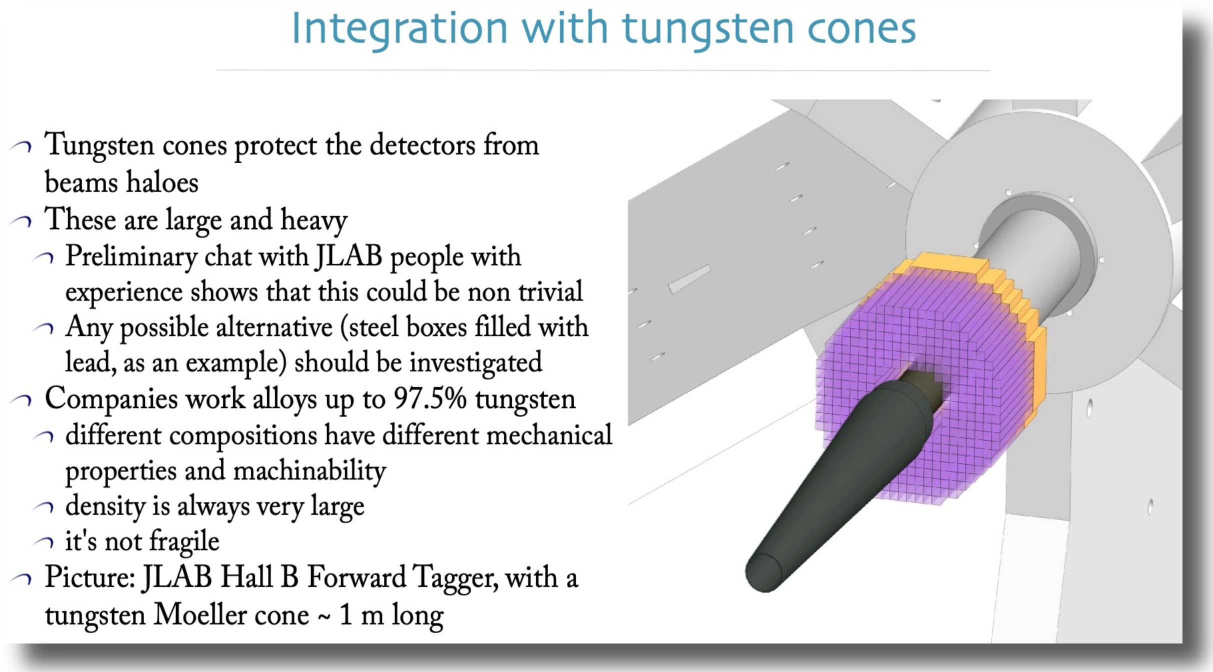
Shielding in JLAB Hall B



ATLAS shielding →



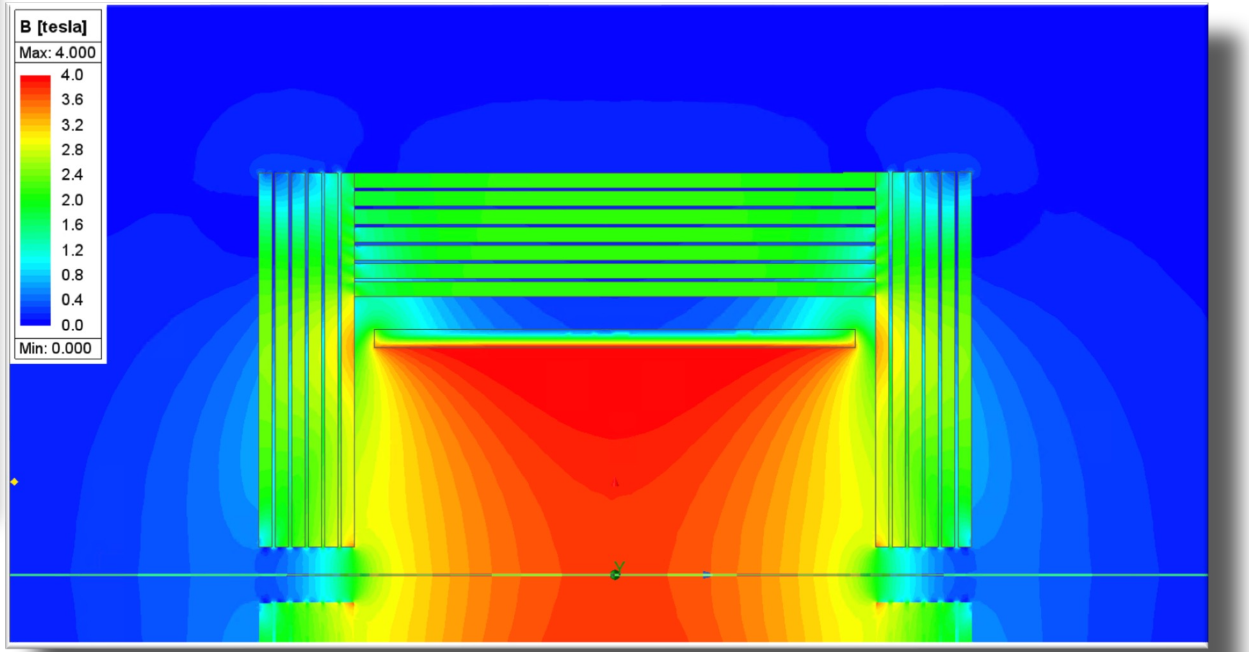
Nozzle and detector magnet



Integration with tungsten cones

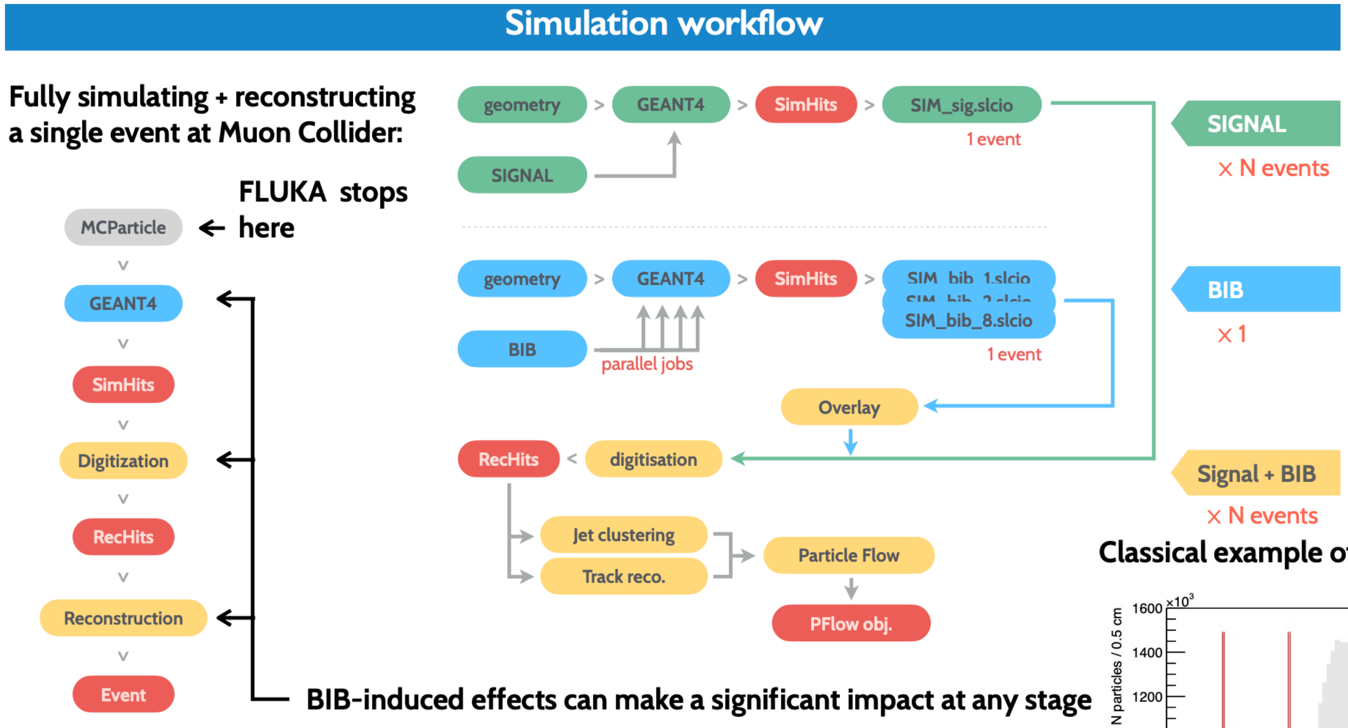
- Tungsten cones protect the detectors from beams haloes
- These are large and heavy
  - Preliminary chat with JLAB people with experience shows that this could be non trivial
  - Any possible alternative (steel boxes filled with lead, as an example) should be investigated
- Companies work alloys up to 97.5% tungsten
  - different compositions have different mechanical properties and machinability
  - density is always very large
  - it's not fragile
- Picture: JLAB Hall B Forward Tagger, with a tungsten Moeller cone ~ 1 m long

Nozzle structure and support need to be designed together with the detector magnet, the two infrastructure may help each other.



Realistic magnetic field map will be used in BIB generation and detector studies as soon as a decision is taken.

Beam-induced background simulation



Simulation workflow

Fully simulating + reconstructing a single event at Muon Collider:

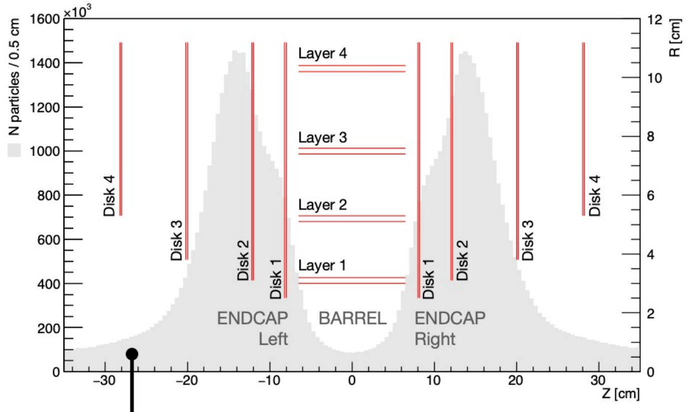
MCParticle ← FLUKA stops here

GEANT4 > SimHits > Digitization > RecHits > Reconstruction > Event

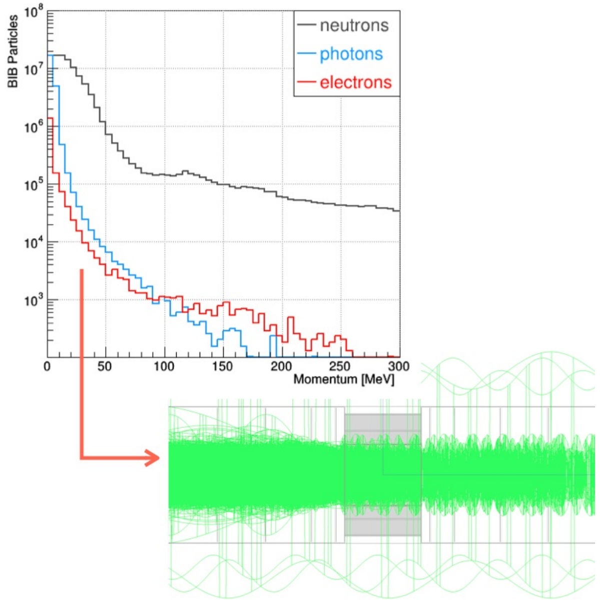
BIB-induced effects can make a significant impact at any stage

BIB produced by FLUKA propagated in the detector and overlaid to physics events.

Classical example of non-obvious BIB impact: Vertex Detector



distribution of BIB particles' exit points along the beam pipe



p_T of the BIB electrons defines the size of the loopers cloud

Effects of BIB on detector is not obvious: sub-detectors positions, interactions of primary particles with detector material, backscattering from other nozzles, ...