Riunione Referee – 25 luglio 2024

R&D Muon Collider

Stato collaborazione internazionale IMCC attività INFN in corso e future - sinergie

Nadia Pastrone INFN TORINO

International MUON Collider Collaboration

Gruppi **INFN** *in* ***RD_MUCOL @ CSN1*** **121 persone/30.2 FTE**

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

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

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

iFAST aMUSE AIDA innova EURO-LABS IRIS MuCol

HORIZON-INFRA-2022-DEV-01-01

Motivation for a multi-TeV Muon Collider

Strong interest in **high-energy, high-luminosity lepton collider**

- combines **precision physics** and **discovery reach**
- application of hadron collider technology to a lepton collider

Muon collider promises **sustainable** approach to the **energy frontier**

- limited power consumption, cost and land use ➔ **site evaluation and reuse of existing tunnels**

Technology and **design advances** in past years

- reviews of the muon collider concept in Europe and US found **no insurmountable obstacle**
- **identified required R&D**, documented in accelerator R&D Roadmap
- first parameters' report submitted October 2023

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

NEW OPTION: initial 10 TeV stage at reduced luminosity

Interim report https://arxiv.org/abs/2407.12450

Strong support by P5 Report @ December 2023

NEW

European Strategy for Particle Physics Update

Input documents due by March 31 2025

Council approval expected June 2026

Accelerator R&D Roadmap

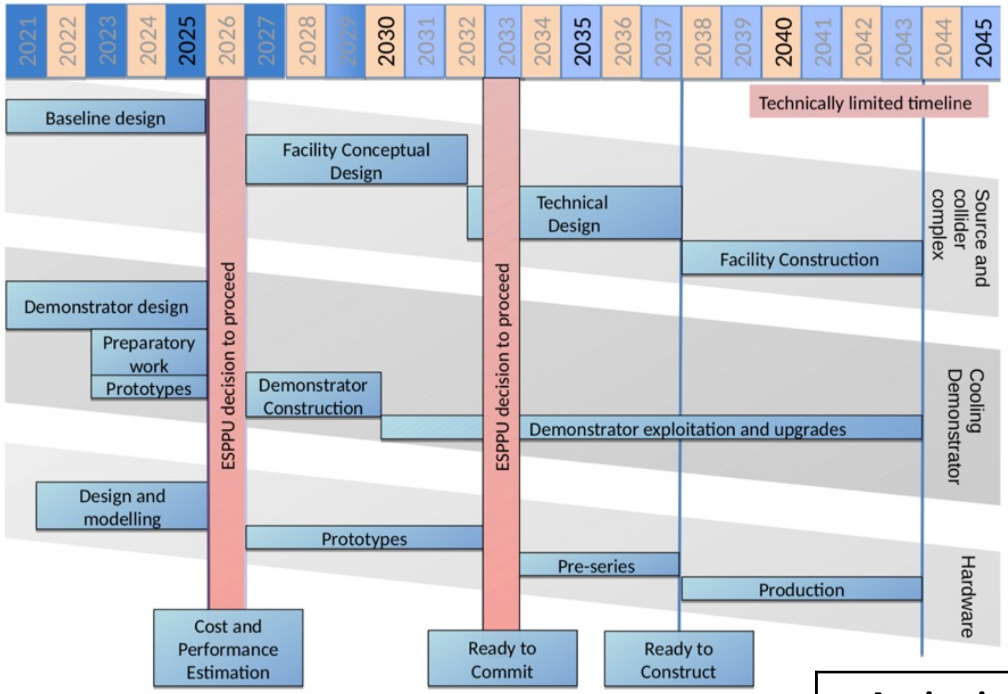
Bright Muon Beams and Muon Colliders

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**

International MUON Collider Collaboration

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

MDI

Dipoles/solenoids
High field
(Nb3Sn, HTS?)

RF cavities
SC e NC

Cooling cell
Demonstrator

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

International Muon Collider Collaboration @ CERN

International
MUON Collider
Collaboration

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**.

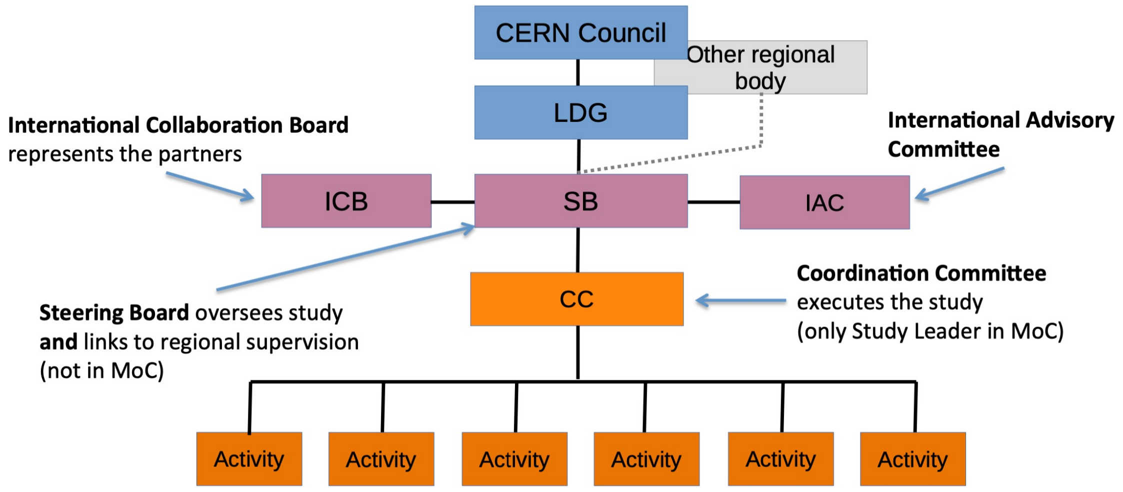
Scope:
- Focus on the high-energy frontier and two energy ranges:
– **3 TeV** if possible with technology ready for construction in 10-20 years
– **10+ TeV** with more advanced technology, **the reason to choose muon colliders**
- Explore synergies with other options (neutrino/higgs factory)
- Define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

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

IMCC Organization after the Roadmap

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

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



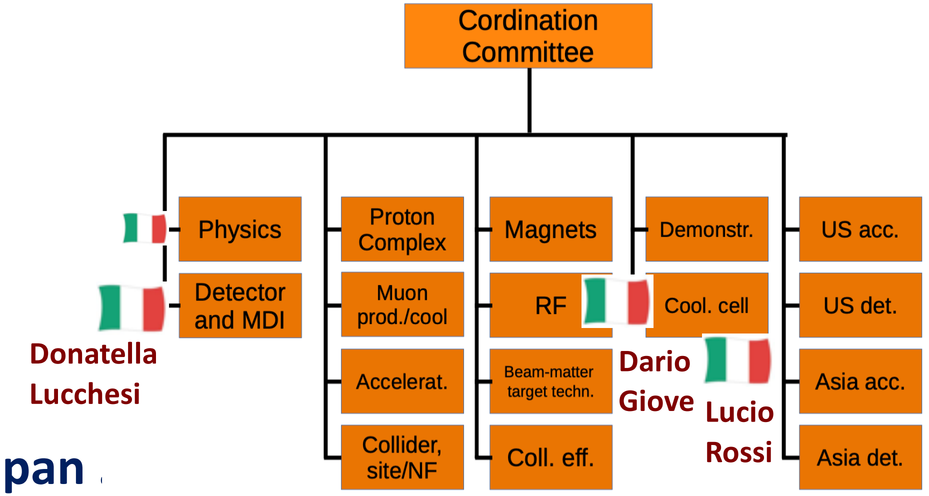
MoC signed by CERN CEA INFN STFC-RAL ESS IHEP
and different universities in EU, US, China

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

80 institutes

- **Collaboration Board (ICB)**
  - Elected chair : **Nadia Pastrone**
- **Steering Board (SB)**
  - Chair **Steinar Stapnes**,
  - CERN members: Mike Lamont, Gianluigi Arduini,
    Dave Newbold (STFC), Pierre Vedrine (CEA),
    Beate Heinemann (DESY)
    ICB chair and SL and deputies
- **International Advisory Committee (IAC)**
  - Chair **Ursula Bassler (IN2P3)**

Coordination Committee



Resources
Addenda
Grey Book
@ CERN

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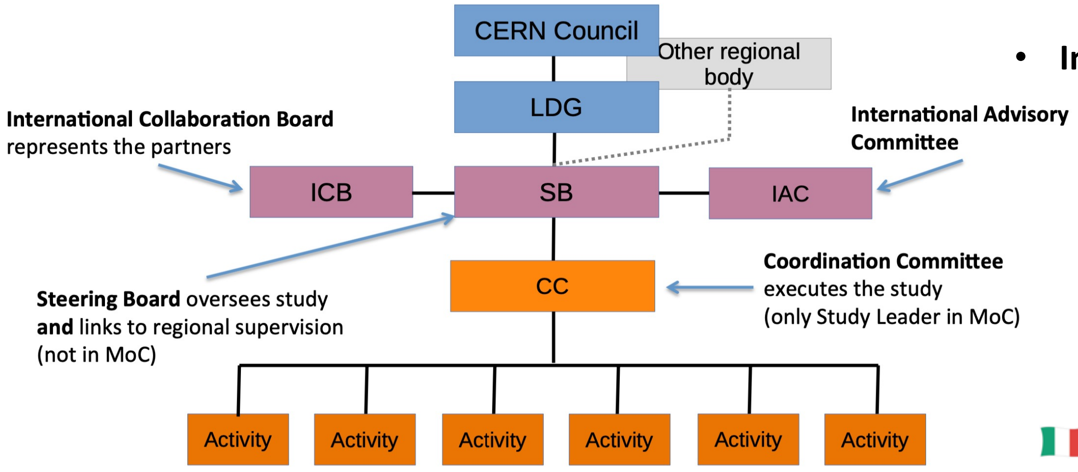

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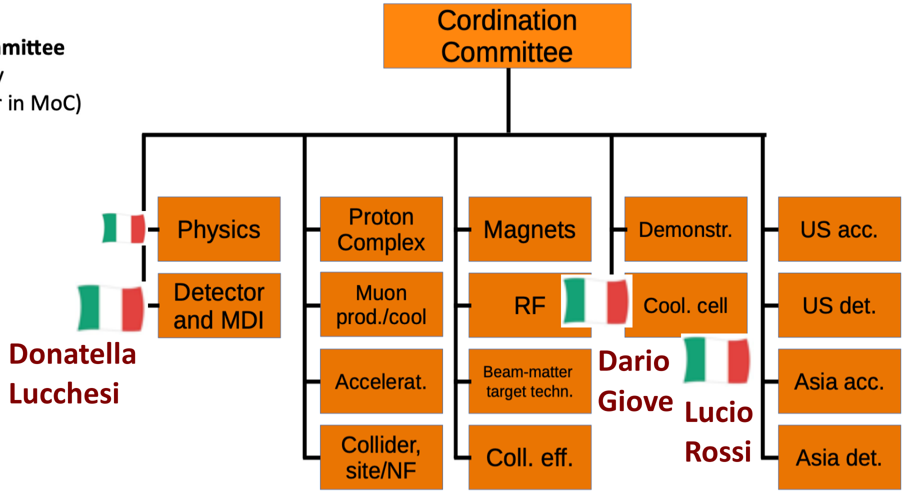
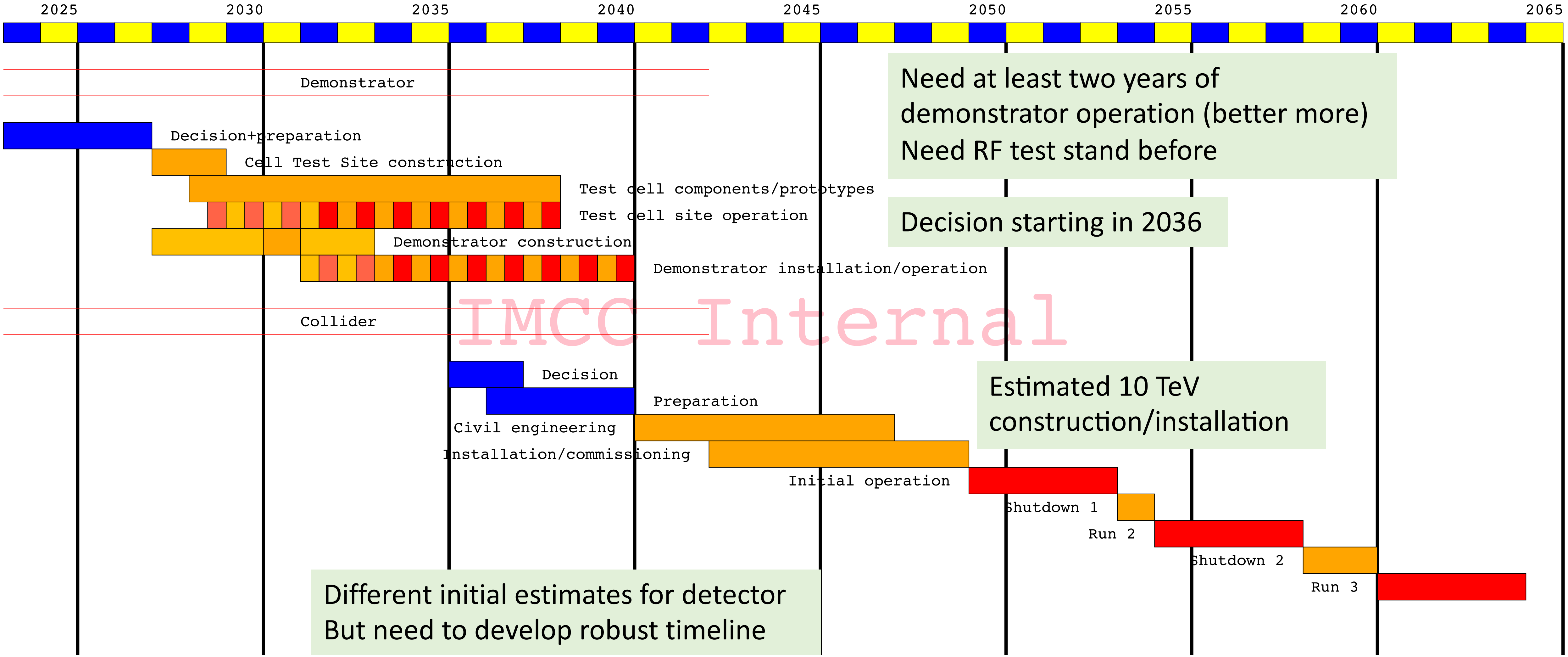


Resources – Addenda – Grey Book @ CERN

Tentative Timeline (Fast-track 10 TeV)

Only a basis to start the discussion, will be reviewed this year



Need at least two years of demonstrator operation (better more)
Need RF test stand before

Decision starting in 2036

Estimated 10 TeV construction/installation

Different initial estimates for detector
But need to develop robust timeline

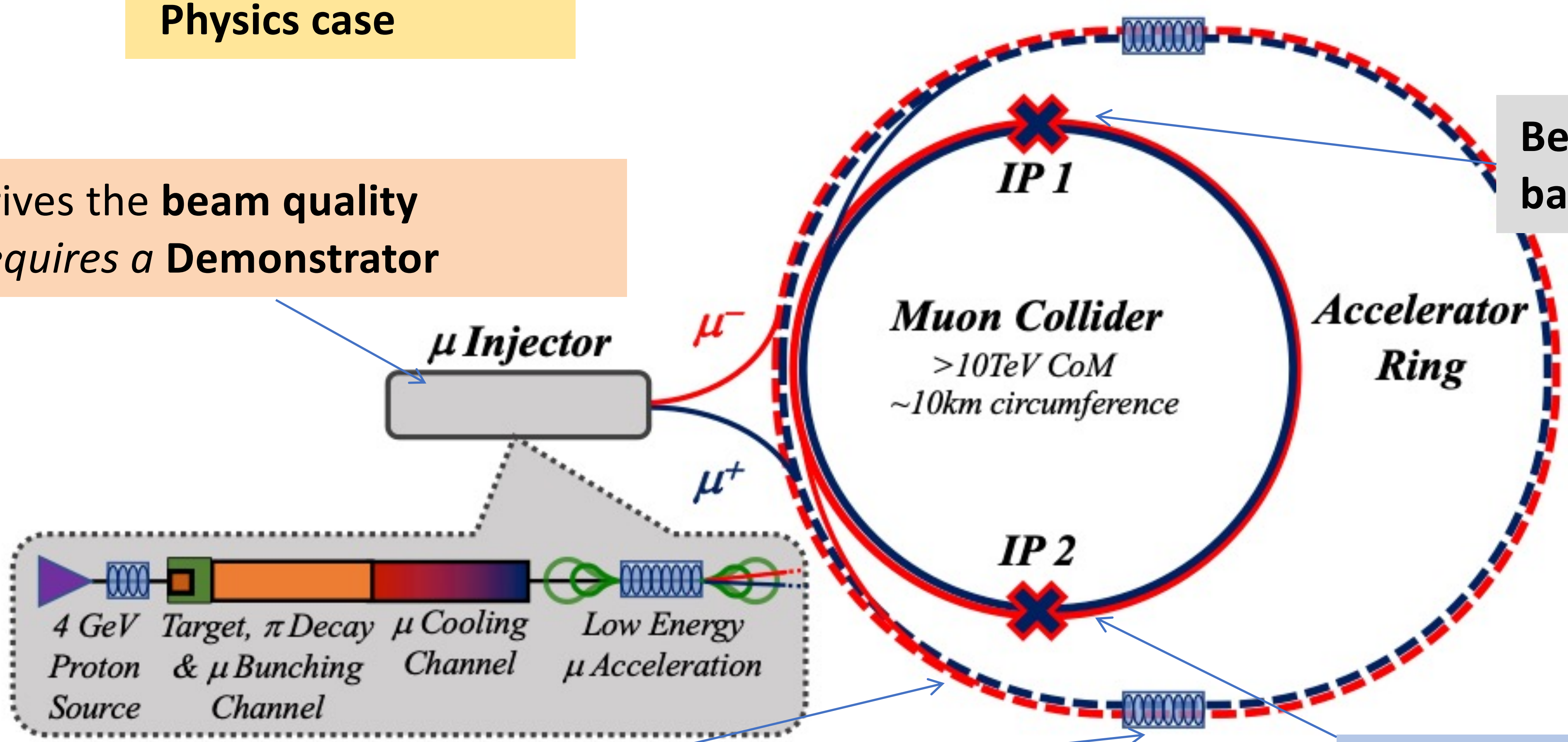
IMCC Internal

Key Challenges @ 10 TeV

Physics case

Experiment design

Drives the **beam quality**
Requires a **Demonstrator**



Beam-induced background

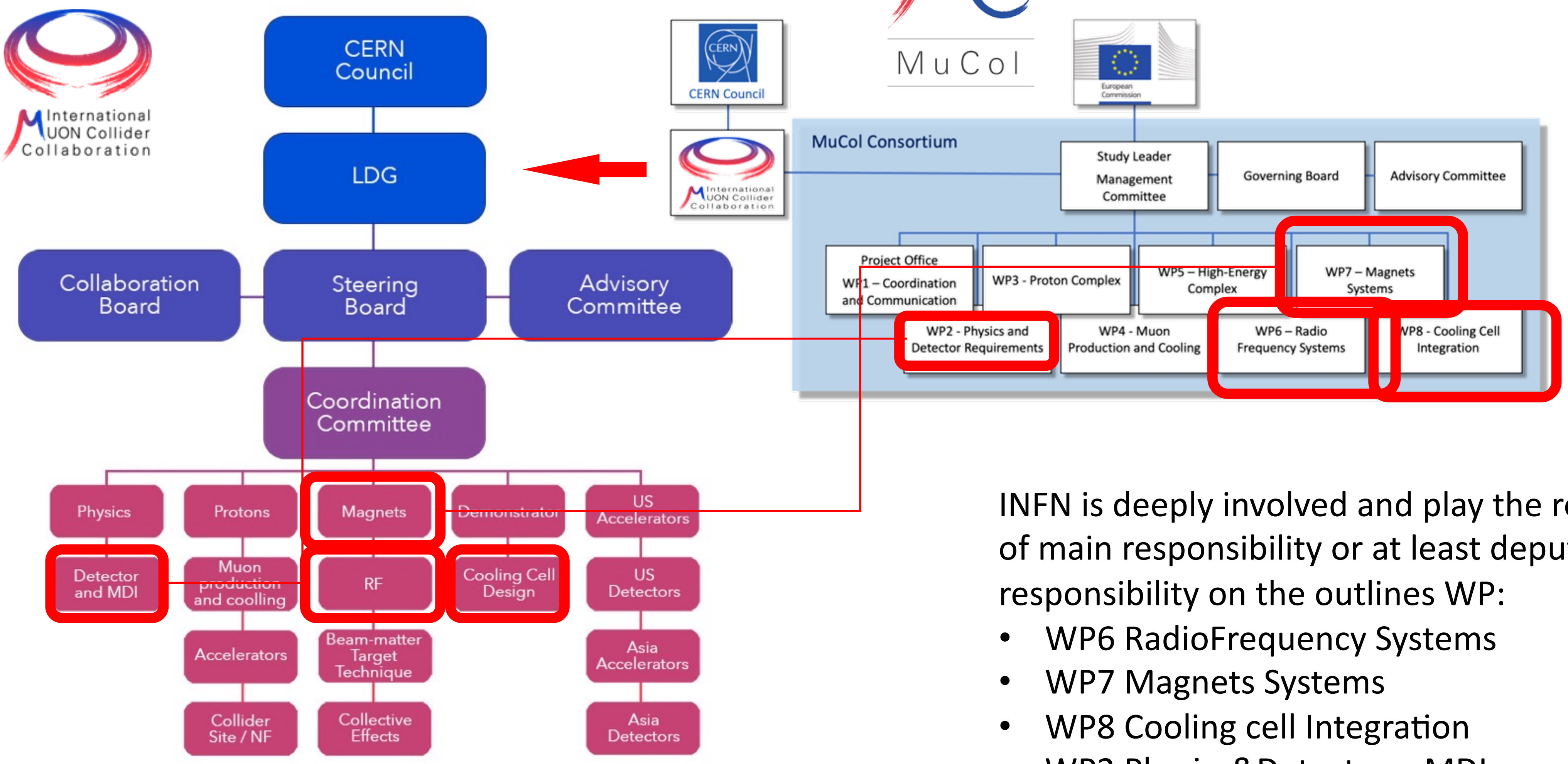
Dense neutrino flux mitigated by mover system and **site selection**

Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

Project Organization

International Muon Collider Collaboration

MuCol EU Design Study



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

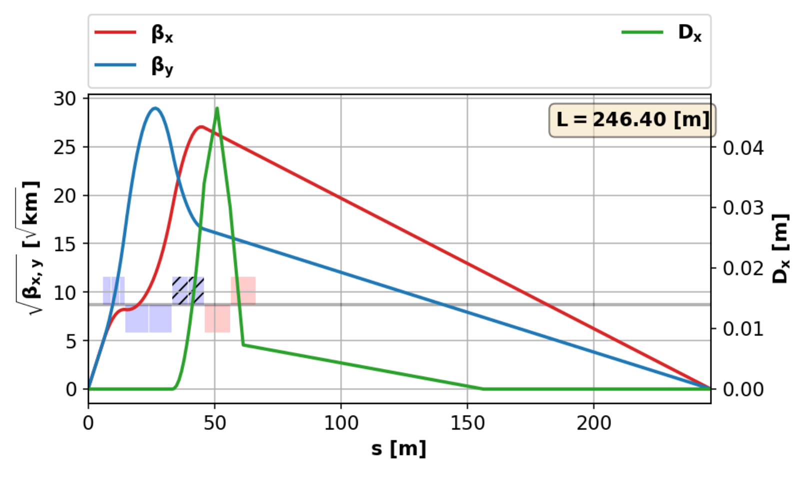
- WP6 RadioFrequency Systems
- WP7 Magnets Systems
- WP8 Cooling cell Integration
- WP2 Physics&Detector – MDI

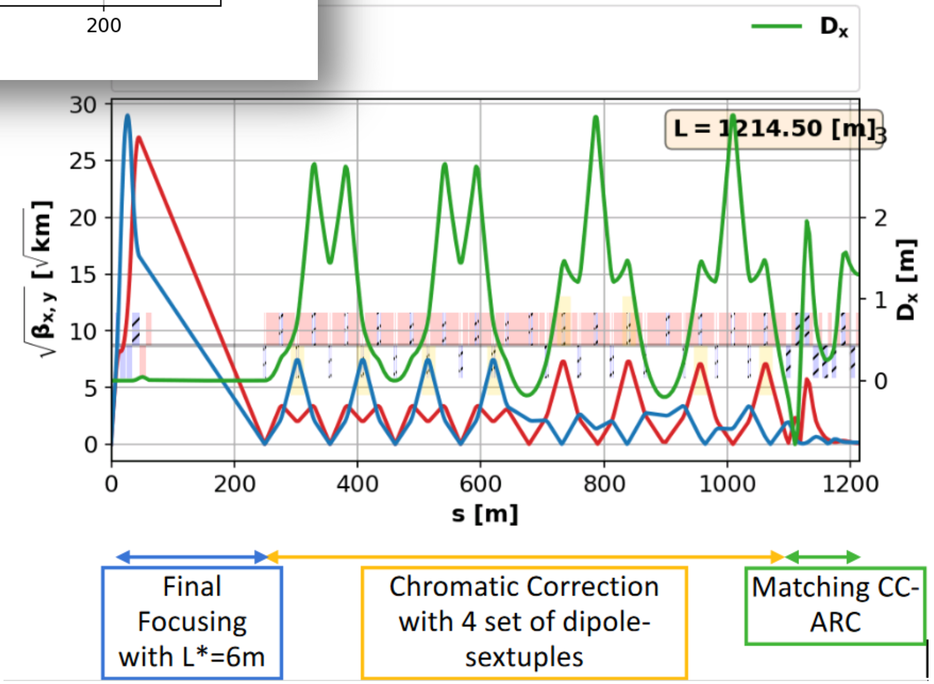
Status of IR lattice design @ 10 TeV

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

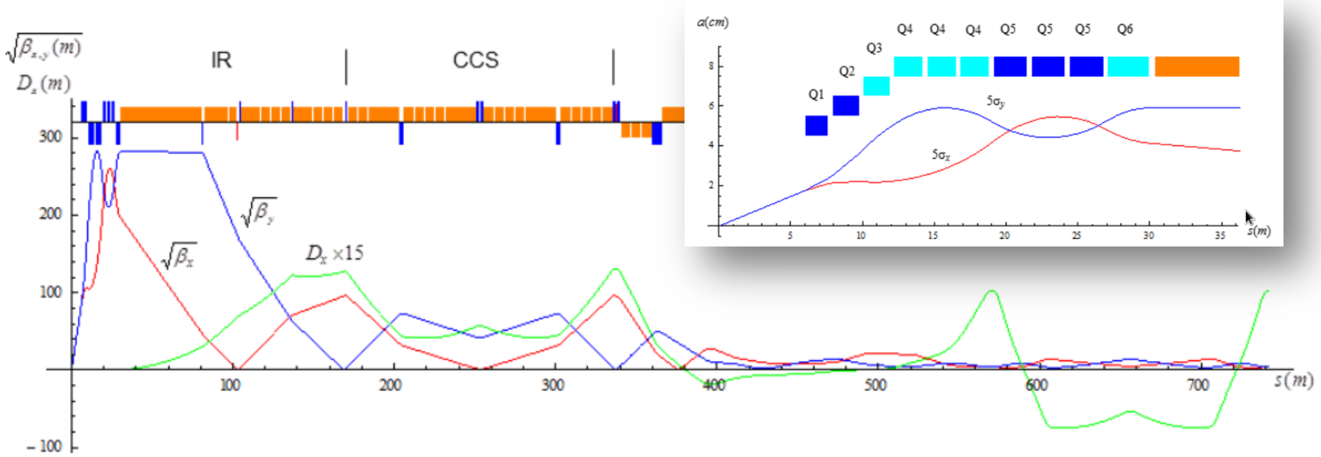
	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Version	**US MAP**	**IMCC (v0.7)**
FF scheme	Quadruplet (with dipolar component)	Triplet (with dipolar component)
ß*	5 mm	1.5 mm
L*	6 m	6 m
Max. field at inner bore	12 T	20 T

10 TeV IR lattice (IMCC):





3 TeV IR lattice (MAP):



Attività R&D Acceleratori
simulazioni – prototipi – misure di laboratorio

International MUON Collider Collaboration

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

Highlights 2024

International MUON Collider Collaboration

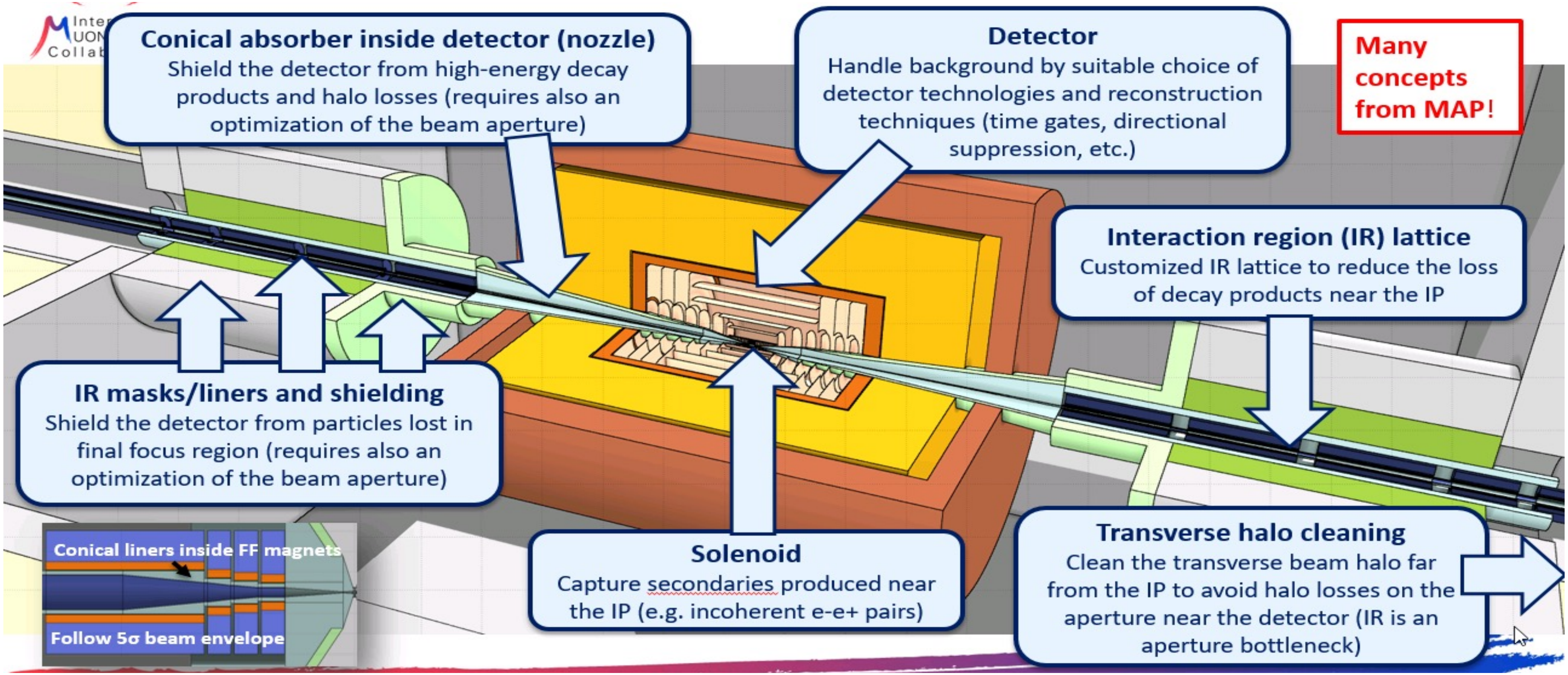
- New lattice @ 10 TeV ==> design new detector/magnet @ 10 TeV
- MuCol EU project driving cooling cell design/integration
- MuCol Cooling Cell Workshop @ CERN January 18-19
- MDI Workshop @ CERN March 11-12
- IMCC Annual Meeting @ CERN – March 12-15
- INFN at the 2025/6 European Strategy for Particle Physics Update @ Roma
- LDG Community Workshop on Accelerators Roadmap – meeting @ BNL June 6-7
- IMCC Detector and MDI Workshop @ CERN June 25-26
- IPAC 2024 – ICHEP 2024 …..
- Inaugural US Muon Collider Meeting @ FNAL August 7-9

- **Input documents by March 2025**

Machine Detector Interface - 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)



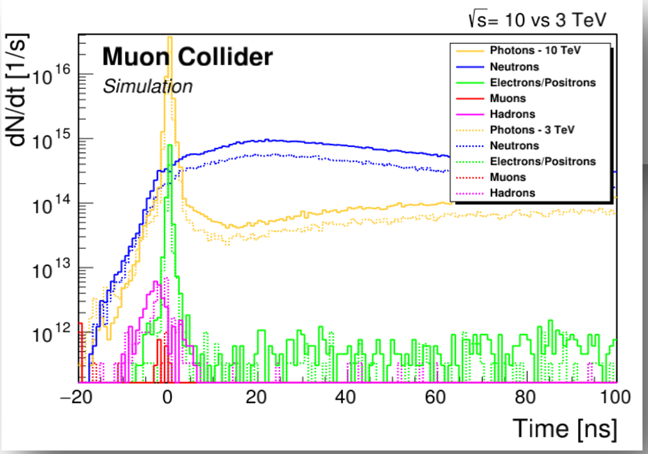
MDI – Status and next steps

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

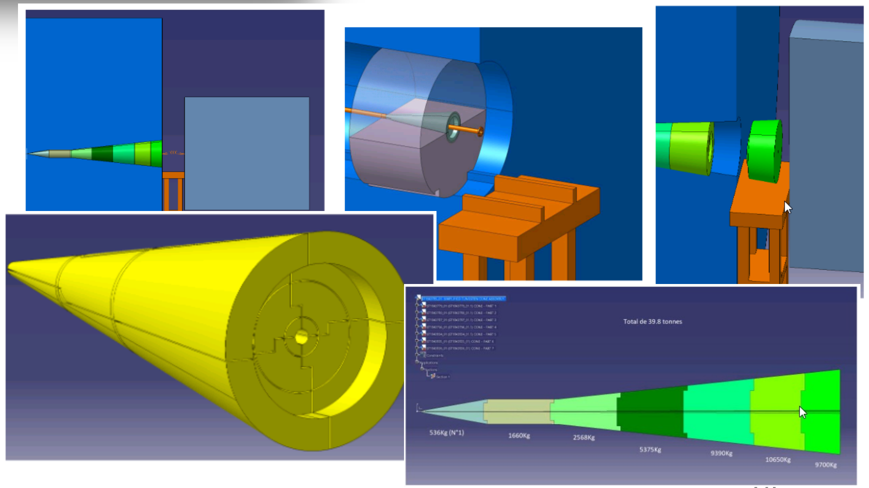
The design of the interaction regions at $\sqrt{s} = 3$ TeV (Fermilab) and $\sqrt{s} = 10$ TeV (CERN) are now available.



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.

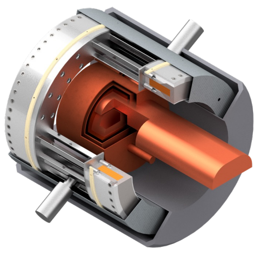
The technical design of the nozzle started:

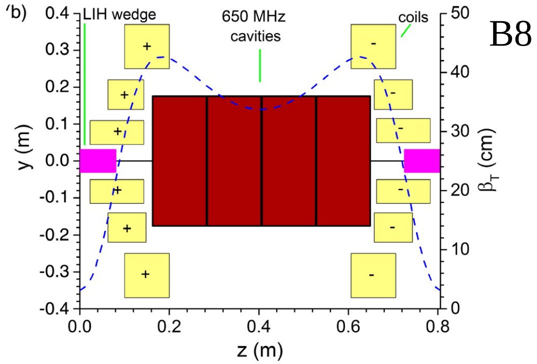
- Integration and support inside detector
- Shielding segmentation and assembly
- Selection of specific material (tungsten heavy alloy) → machining is an important aspect
- Heat extraction (cooling)
- Alignment, vibrations, tolerances, etc.
- Dedicated vacuum chamber inside nozzle



Time-critical Developments

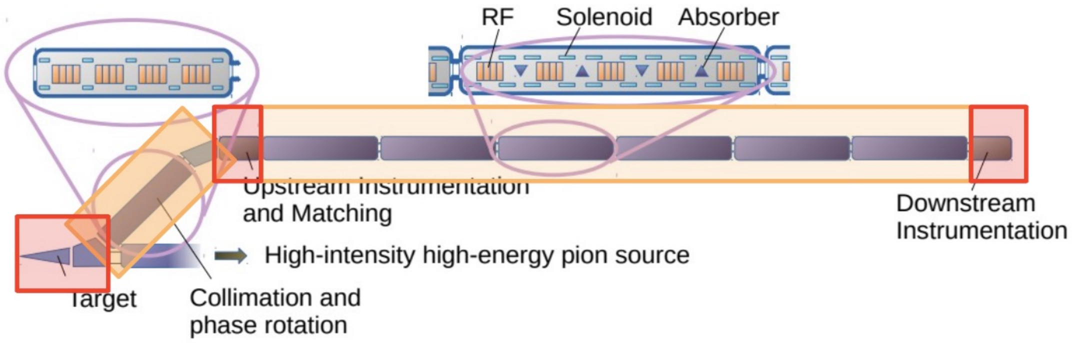
Identified three main technologies that can limit the timeline





Muon cooling technology

- **RF test stand** to test cavities in magnetic field
- **Muon cooling cell** test infrastructure
- **Demonstrator**
  - Muon beam production and cooling in several cells



Magnet technology

- HTS solenoids
- Collider ring magnets with Nb3Sn or HTS

Important Developments

Detector technology and design

- Can do the important physics with near-term technology
- But available time will allow to improve further and exploit AI, MI and new technologies

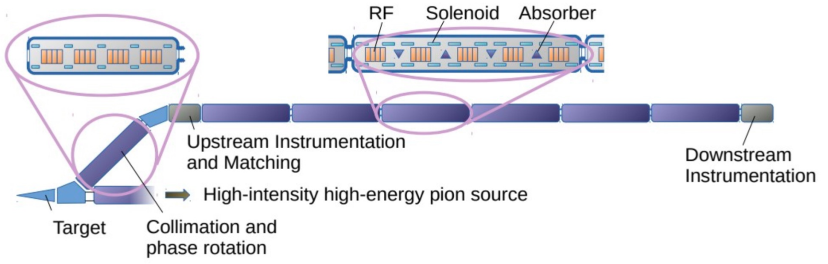
Attività INFN – FTE – progetti in sinergia

International MUON Collider Collaboration

SEDE		FTE	MuCol	AIDA/PRIN	ATTIVITA'					
		*100		I.FAST/IRIS	FISICA/SIMULAZIONI	R&D DETECTOR	ACCELERATORI	COMMENTO	PRIN	DRD
BA		360			x	x		Fisica HCAL HPTPC	calo	x
BO	DTZ	125			x		x	Fisica teo e Fast ramping Magnets		
FE	DTZ	60				x	x	Cristalli		x
GE		160	130				x	Magneti		
LNF		270	30			x		CRILIN	calo	x
LNL	DTZ	10					x	RF +(bersagni sottili)		
LNS	DTZ		135				x	RF		
MI		235	65	80			x	Magneti e RF		
MIB	DTZ	20				x		Test facility-dimostratore		
NA	DTZ	10	10				x	RF		
PI	DTZ	40			x			Fisica Detector		
PD		415	20	10	x	x	x	Fisica Detector Calcolo MDI Dimostratore		x
PV		185			x	x		Fisica e picosec+ generatori teo	gas	x
RM1		260	20	10	x		x	MDI fisica e bersagli/materiali		x
RM3	DTZ	10			x			fisica		
TO		295	20	5	x	x	x	fisica R&D detector MDI e accel	gas	x

		RD_MUCOL	MuCol	AIDA/PRIN/IRIS/I_FAST/aMUSE
TOT FTE	30,2	24,6	4,5	1,1

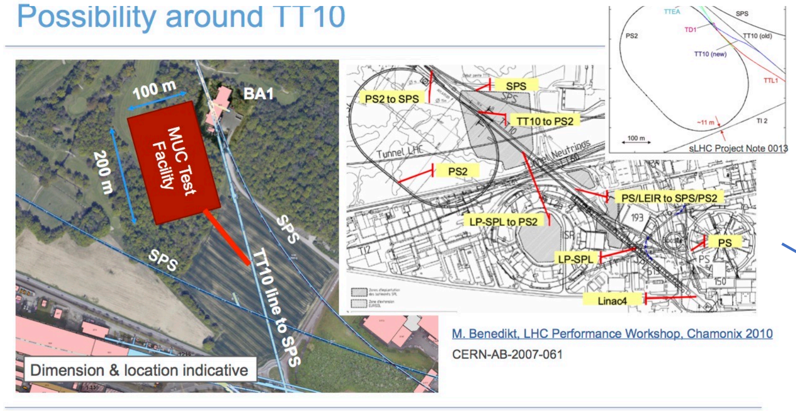
Demonstrator Facility: a crucial step forward!



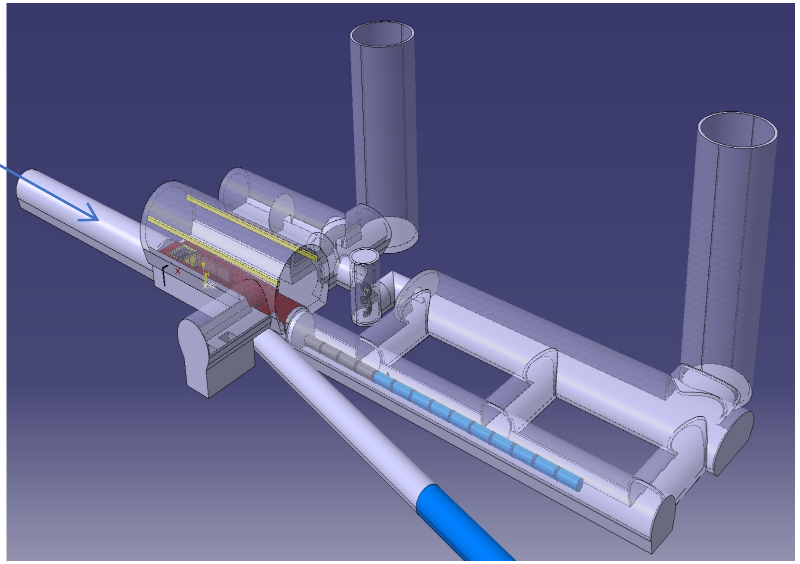
Planning **demonstrator** facility with muon production target and cooling stations

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

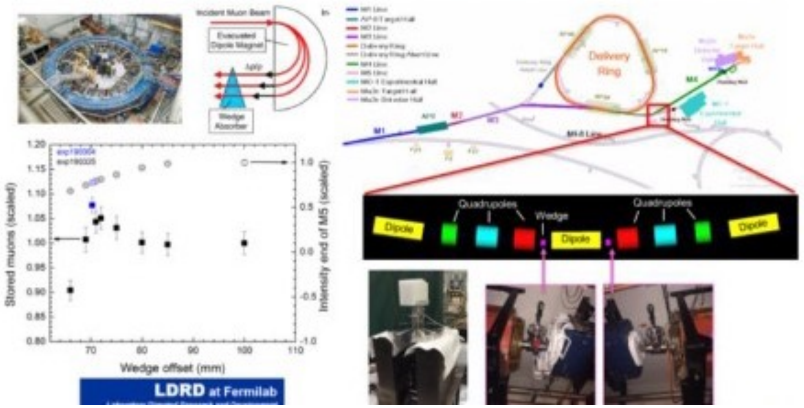
- could combine with **NuStorm** or other option



@ CERN



@ FNAL



International Muon Collider Collaboration: Demonstrator Workshop

@ FNAL October 30 – November 1, 2024

Always investigating synergies on physics and technologies

Grazie!
domande?

High-priority future initiatives [..]

In addition to the high field magnets the **accelerator R&D roadmap** could contain:

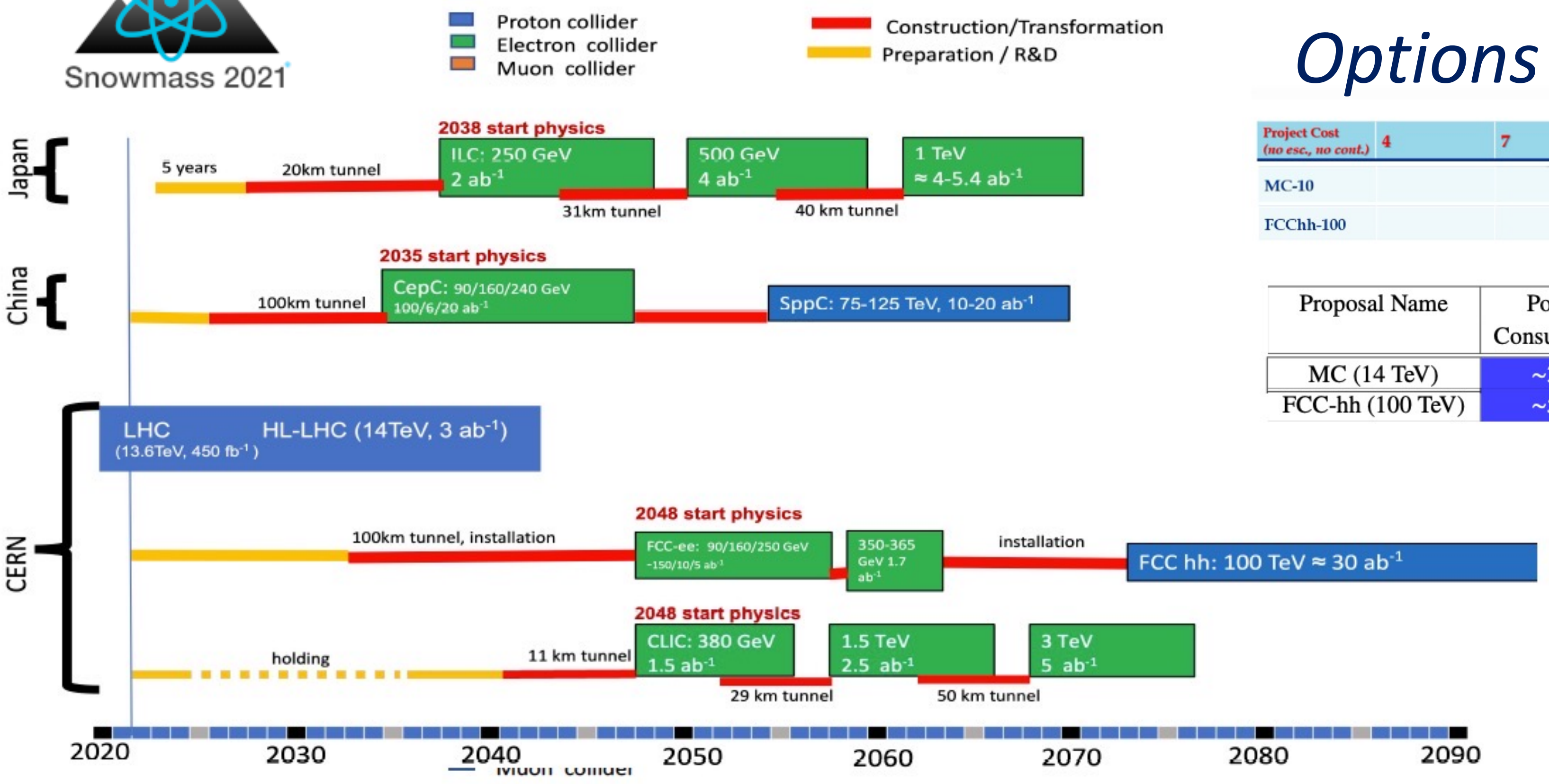
[..] an **international design study** for a **muon collider**, as it represents a **unique opportunity** to achieve a ***multi-TeV energy domain*** *beyond the reach of e^+e^- colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The **biggest challenge** remains to produce an intense beam of cooled muons, but *novel ideas are being explored.*

International
MUON Collider
Collaboration

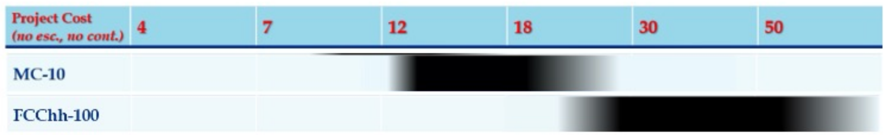
Grazie!
e domande?

extras

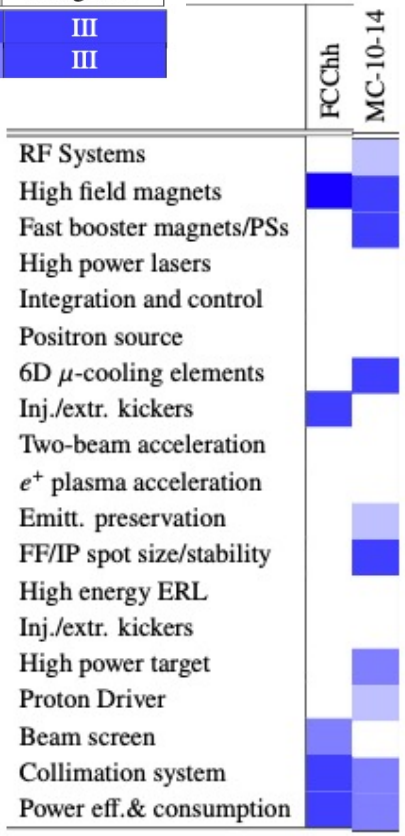
Colliders timescale: Snowmass2021



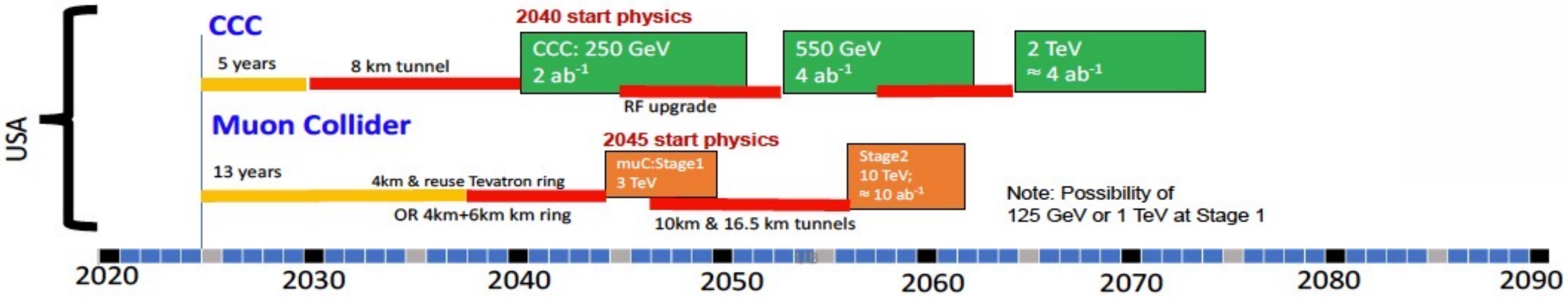
Options @ 10 TeV Scale



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



Proposals emerging from Snowmass 2021 for a US based collider

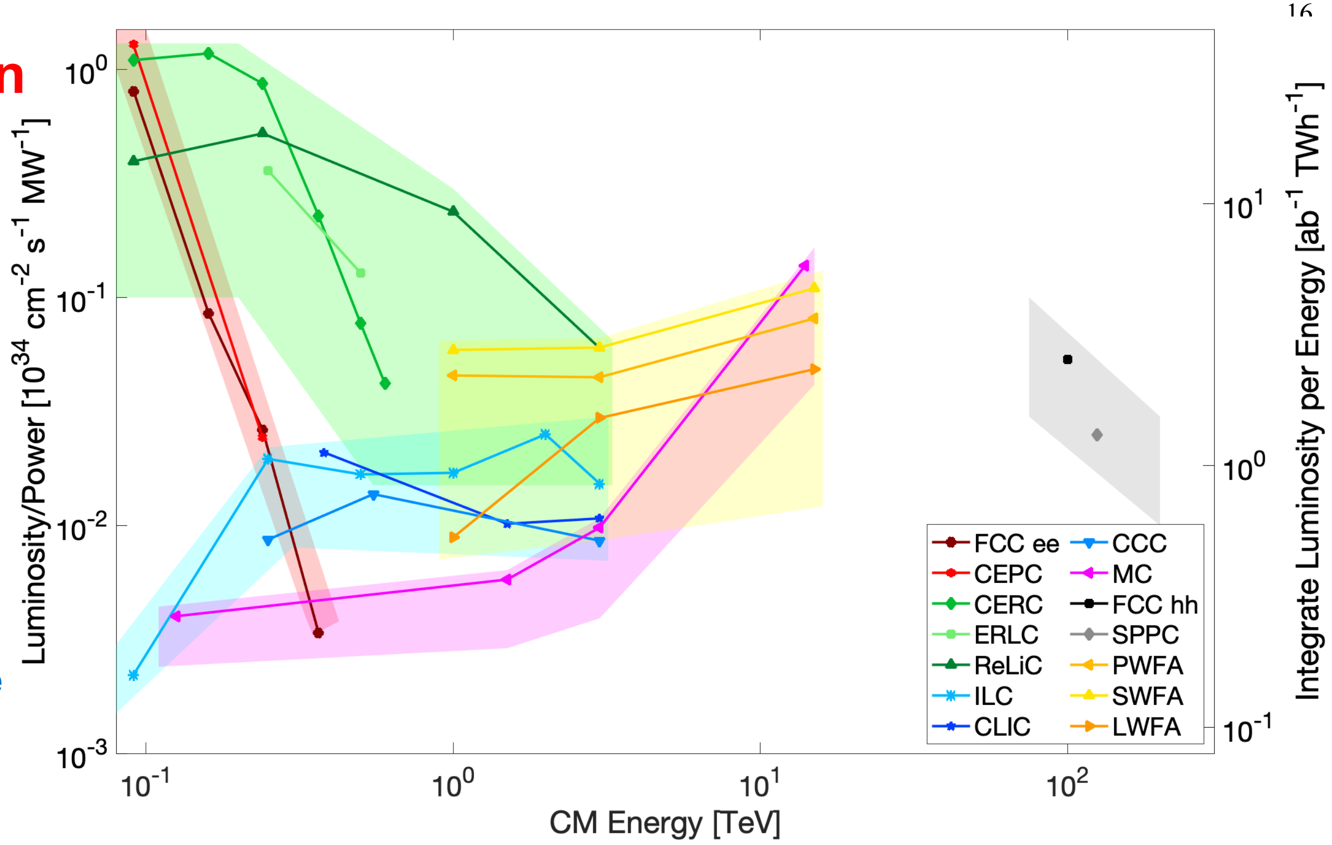


Energy efficiency of present and future colliders

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

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

U.S. P5: Intenational Partnership

International MUON Collider Collaboration

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

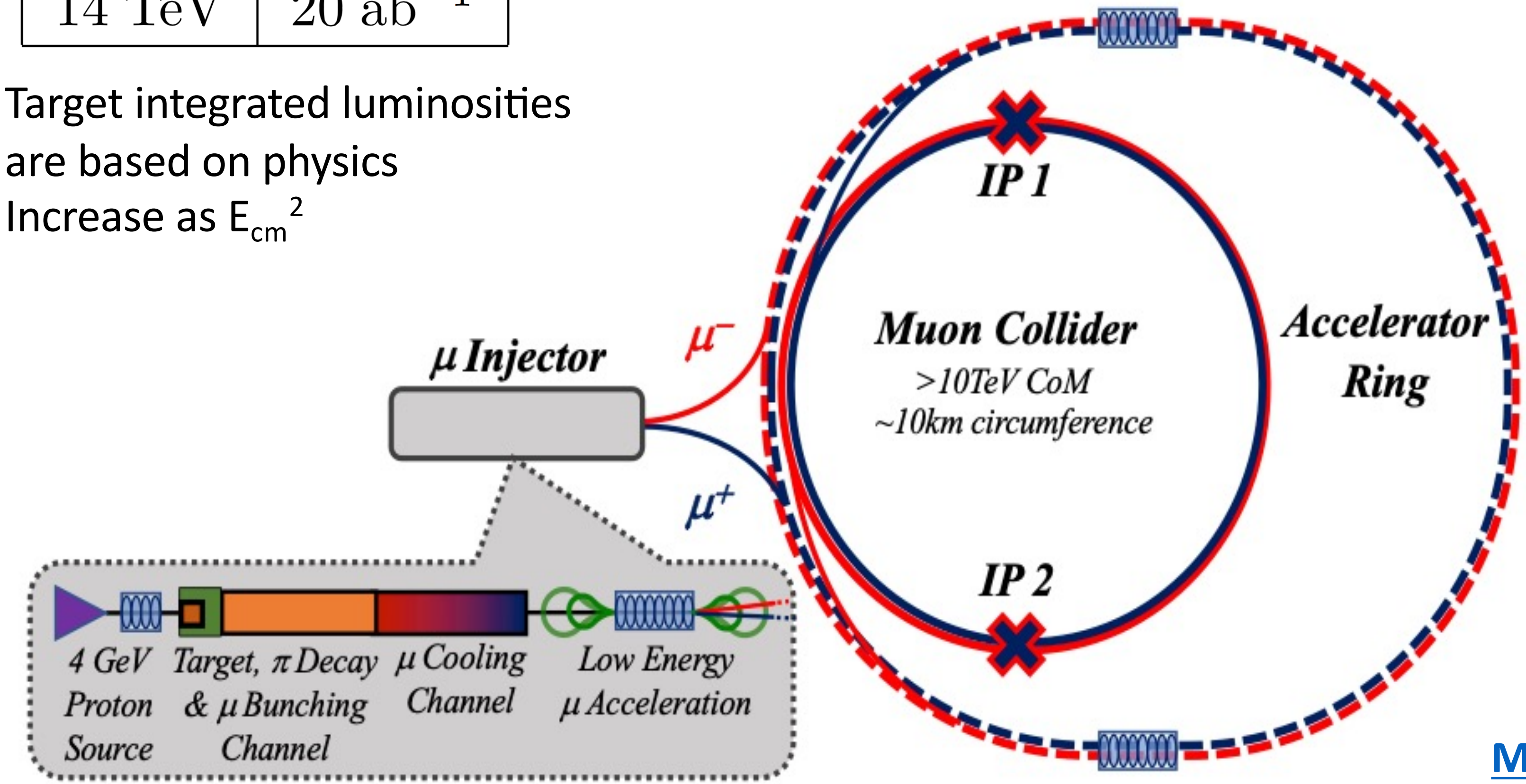
Proton driver production as baseline

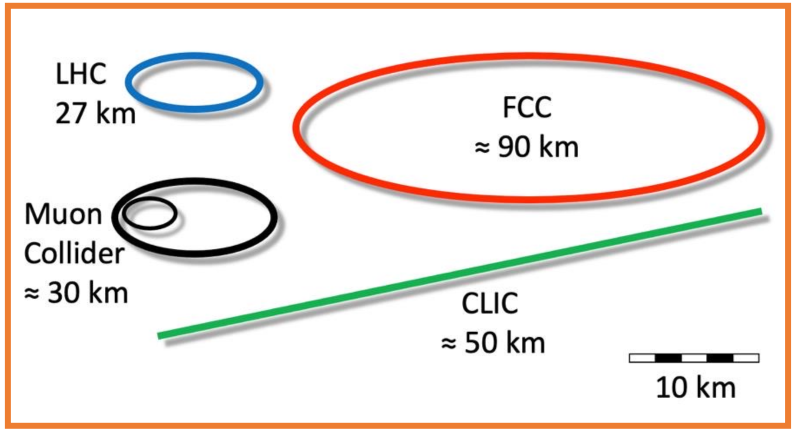
$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Target integrated luminosities are based on physics

Increase as E_{cm}^2

10+ TeV completely new regime to explore!





Muon Collider Forum Report **Sept 2022**

Tentative Staged Target Parameters

Target integrated luminosities

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

Need to spell out scenarios

Need to integrate potential performance limitations for technical risk, cost, power, …

Parameter	Unit	3 TeV	10 TeV	10 TeV	10 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**	**tbd**	**13**
N	10^{12}	2.2	1.8	1.8	1.8
f_r	Hz	5	5	5	5
P_{beam}	**MW**	**5.3**	**14.4**	**14.4**	**14.4**
C	km	4.5	10	15	15
<B>	T	7	10.5	7	7
ε_L	MeV m	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	tbd	0.1
σ_z	mm	5	1.5	tbd	1.5
β	mm	5	1.5	tbd	1.5
ε	µm	25	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	1.3	0.9

Examples as discussion basis
numbers will change

Unique background conditions

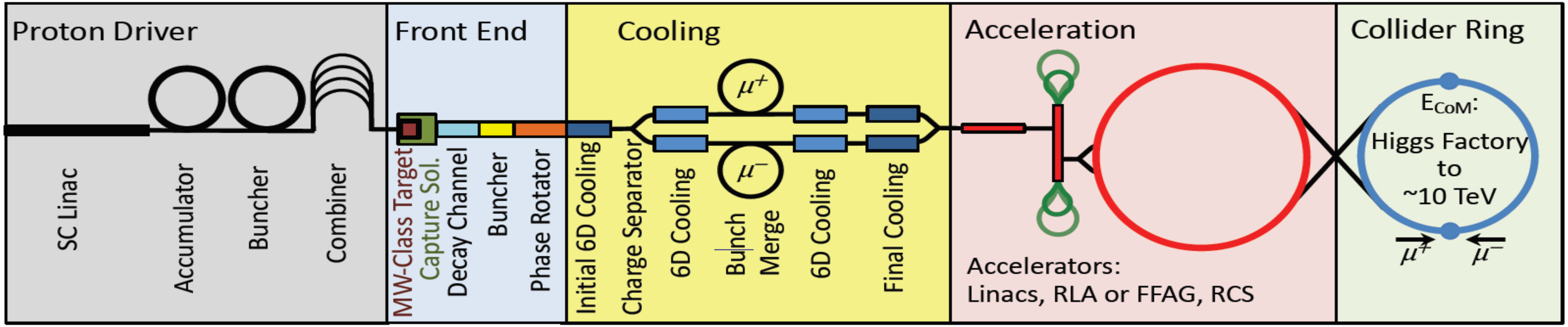
	Description	Relevance as background
Muon decay	**Decay of stored muons around the collider ring**	**Dominating source**
Synchrotron radiation by stored muons	Synchrotron radiation emission by the beams in magnets near the IP (including IR quads → large transverse beam tails)	**Small**
Muon beam losses on the aperture	Halo losses on the machine aperture, can have multiple sources, e.g.: • Beam instabilities • Machine imperfections (e.g. magnet misalignment) • Elastic (Bhabha) μμ scattering • Beam-gas scattering (Coulomb scattering or Bremsstrahlung emission) • Beamstrahlung (deflection of muon in field of opposite bunch)	**Can be significant** (although some of the listed source terms are expected to yield a small contribution like elastic μμ scattering, beam-gas, Beamstrahlung)
Coherent e^-e^+ pair production	Pair creation by real* or virtual photons of the field of the counter-rotating bunch	**Expected to be small** (but should nevertheless be quantified)
Incoherent e^-e^+ pair production	Pair creation through the collision of two real* or virtual photons emitted by muons of counter-rotating bunches	**Significant**

The present and on-going detector studies take into account only the dominant background from muon decays

→ **beam-induced background (BIB)**

Collider Facility Concept

Fully driven by muon lifetime – lifetime is $\tau = \gamma \times 2.2\ \mu s$



Short, intense proton bunch

Protons produce pions which decay into muons muons are captured

Ionisation cooling of muon in matter

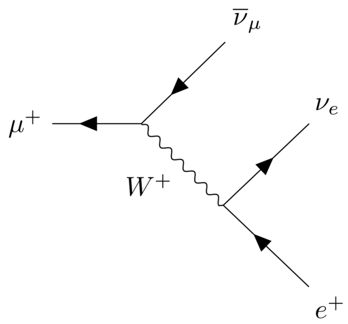
Acceleration to collision energy

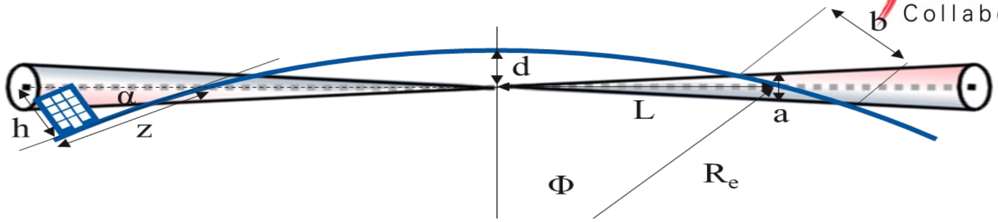
Collision

Proton driven Muon Collider Concept (MAP collaboration)

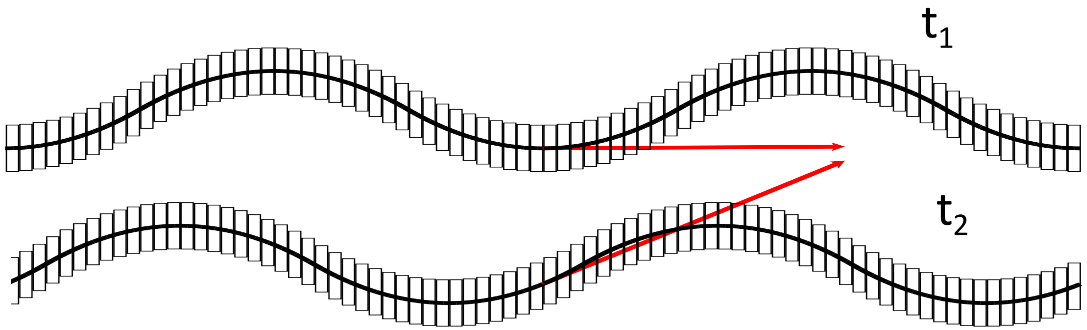
Muon Decay and Neutrino Flux

Muon decays in collider ring
- Impact on detector
- Have to avoid dense neutrino flux





Aim for **negligible impact from arcs**
- Similar impact as LHC
- At 3 TeV this is the case for 200 m depth
- At 10 TeV go from acceptable to negligible with mover system
  - Mockup of mover system planned
  - Impact on beam to be checked



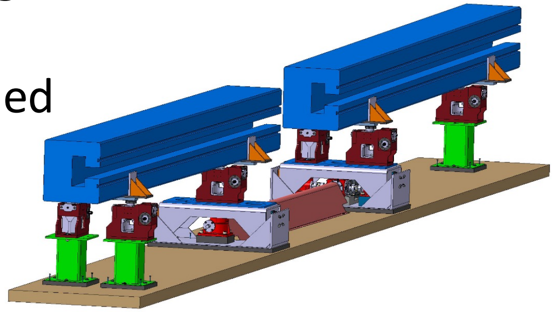
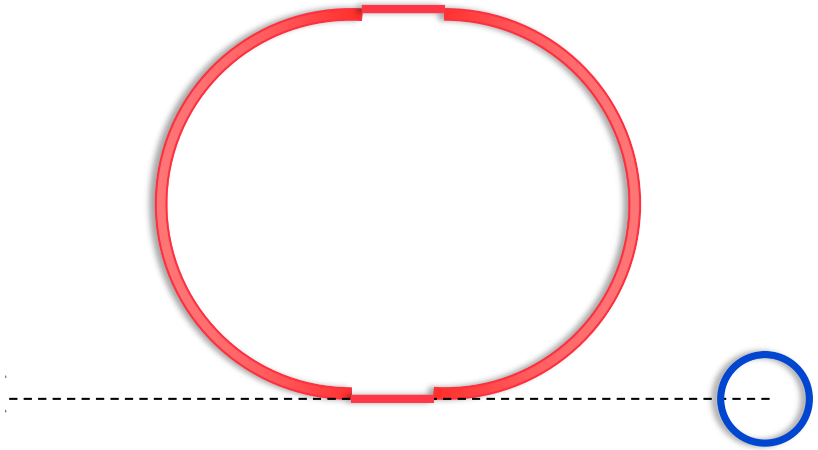


Fig. 7.23: Mock-up of the proposed magnet movement system.

Impact of experimental insertions
- 3 TeV design acceptable with no further work
- But better acquire land in direction of experiment, also for 10 TeV



Site Studies

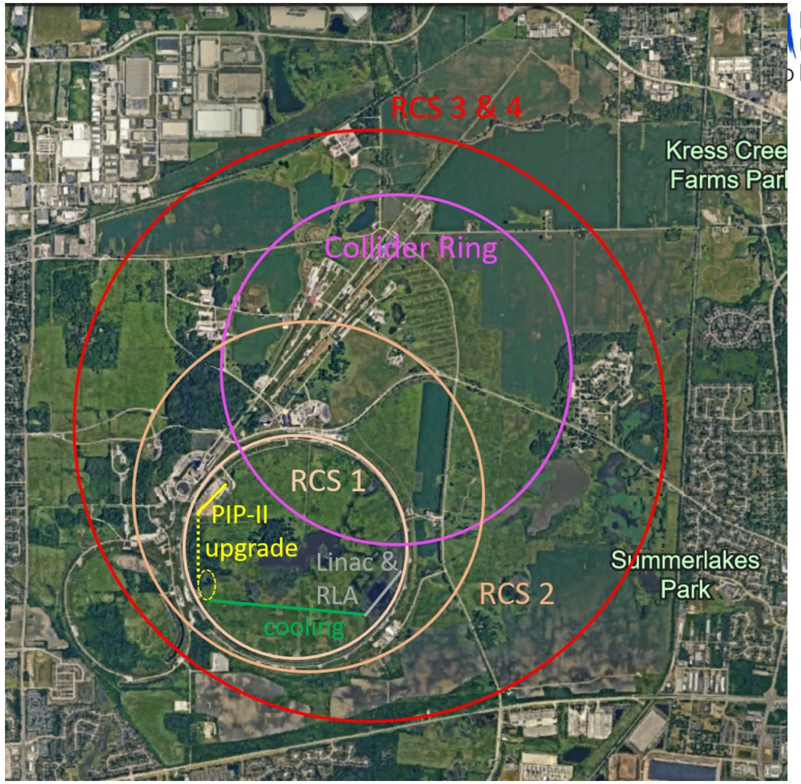
Candidate sites **CERN, FNAL,** potentially others **(**ESS, JPARC, …)

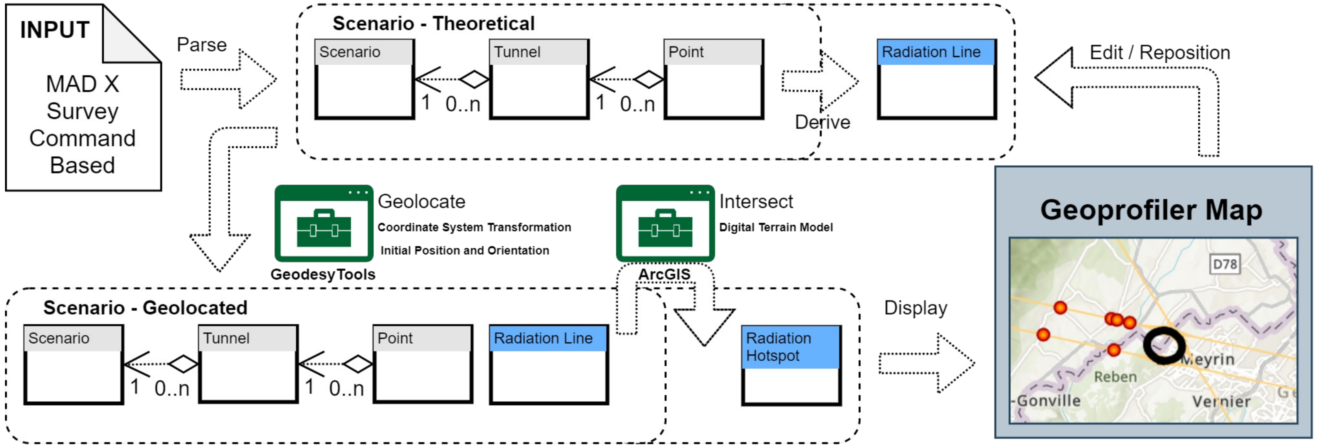
Study is mostly site independent

- Main benefit is existing infrastructure
- Want to avoid time consuming detailed studies and keep collaborative spirit
- Will do more later

Some considerations are important

- Neutrino flux mitigation at CERN
- Accelerator ring fitting on FNAL site

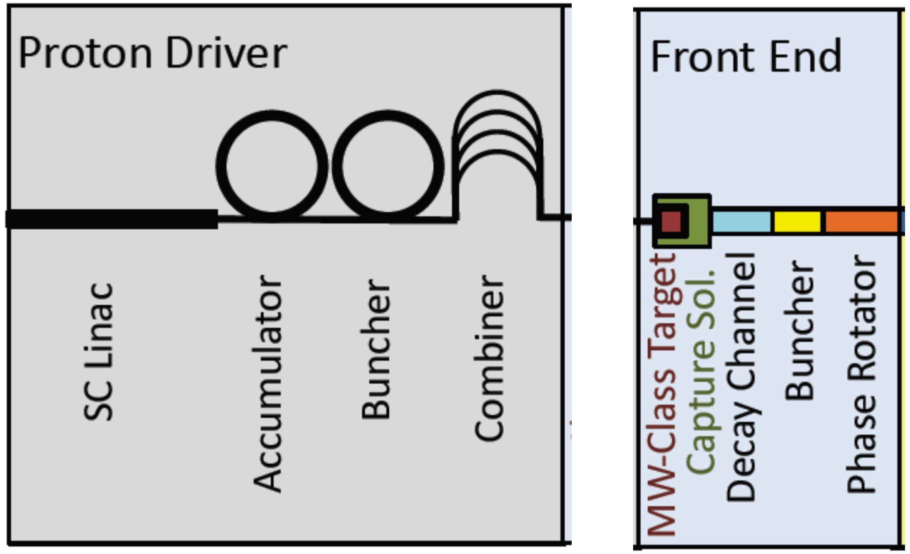




Potential site next to CERN identified

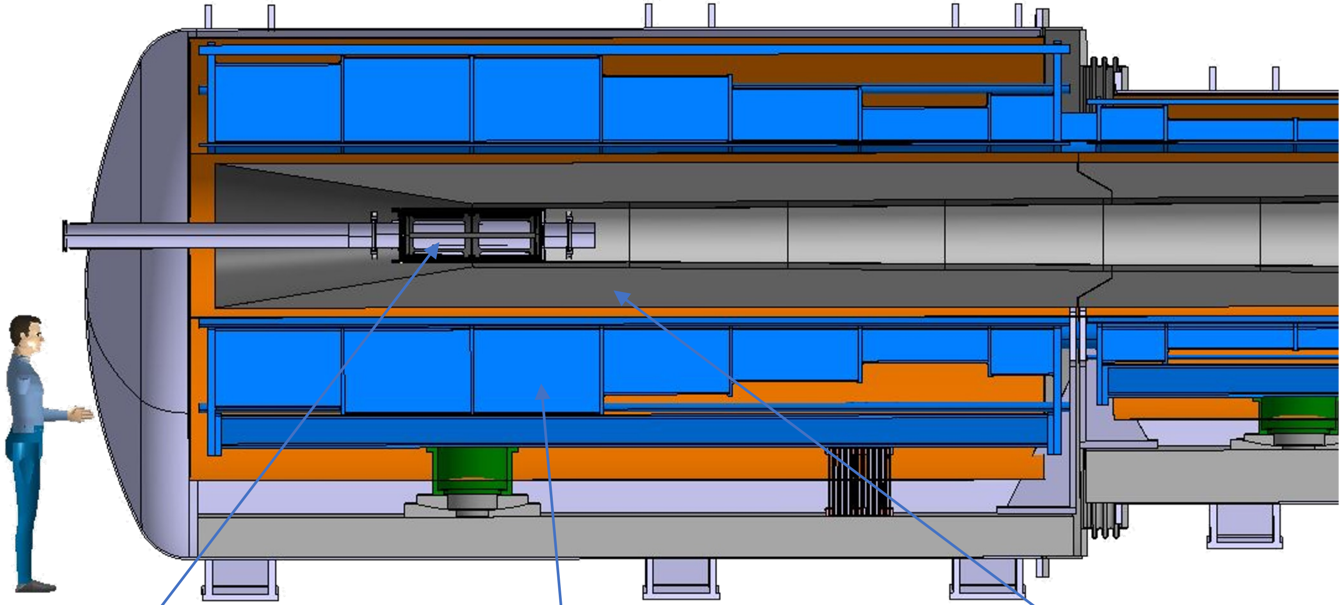
- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura
- Detailed studies required (280 m deep)

Proton Complex and Target



protons —in target→ pions —decay→ muons

400 kJ protons to produce 5 x 10^{13} captured muon pairs



5 GeV proton beam, 2 MW = 400 kJ x 5 Hz
Power is at hand

ESS and Uppsala are woring on merging beam into high-charge pulses

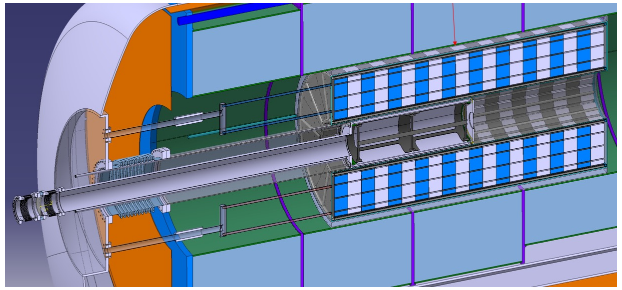
- Indication is that 10 GeV would be preferred

Target Technologies

Target solenoid design ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert

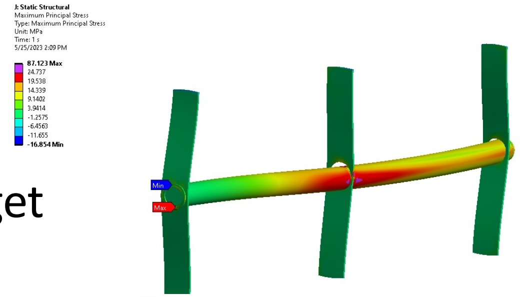
FLUKA studies:
2 MW target: stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

Integration

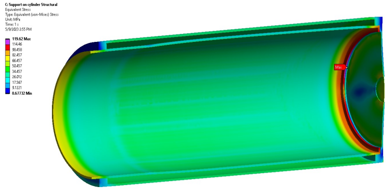


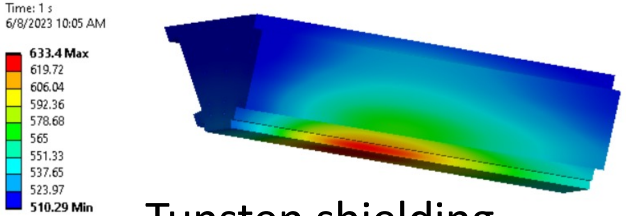
Cooling, vacuum, mechanics, …

Target



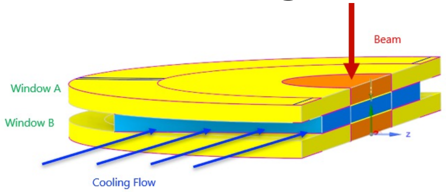
Vessel





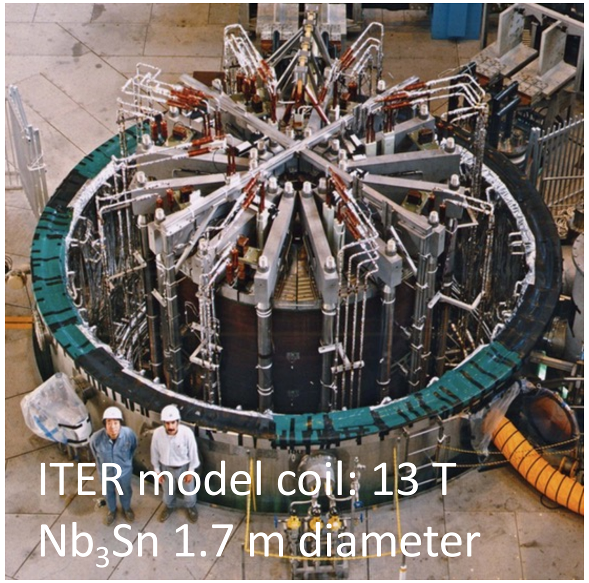
Tunsten shielding

Window



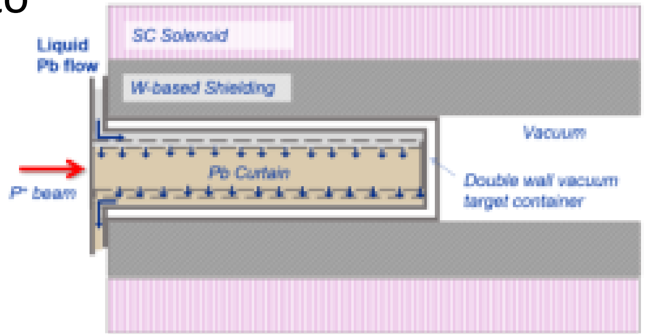
HTS target solenoid: 20 T, 20 K

Our work is relevant for fusion

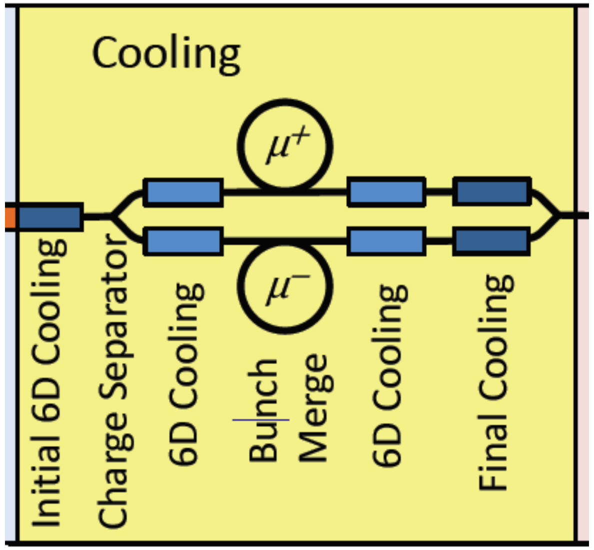


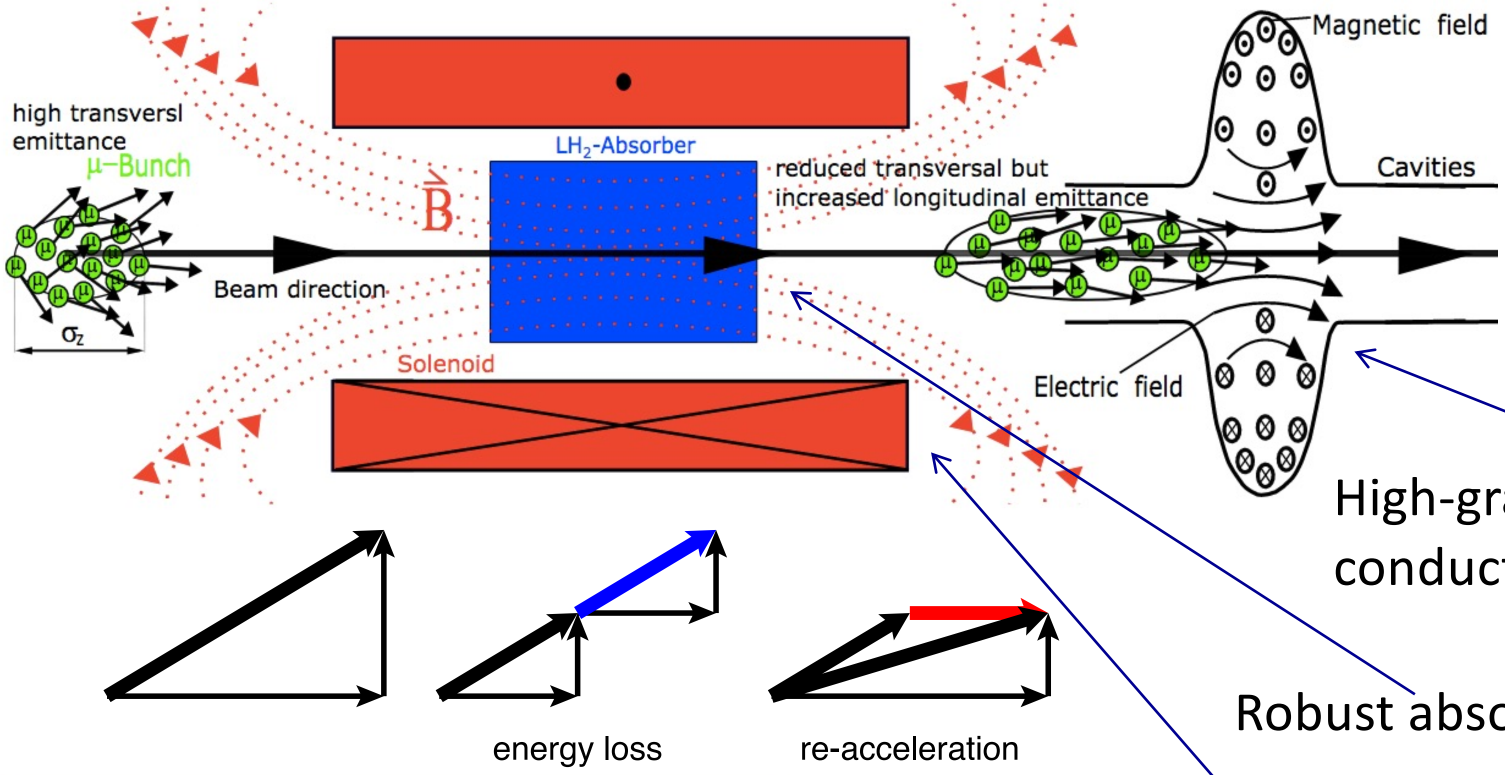
ITER model coil: 13 T
Nb_3Sn 1.7 m diameter

Liquid metal target
Serious alternative to graphite



Muon Cooling Principle

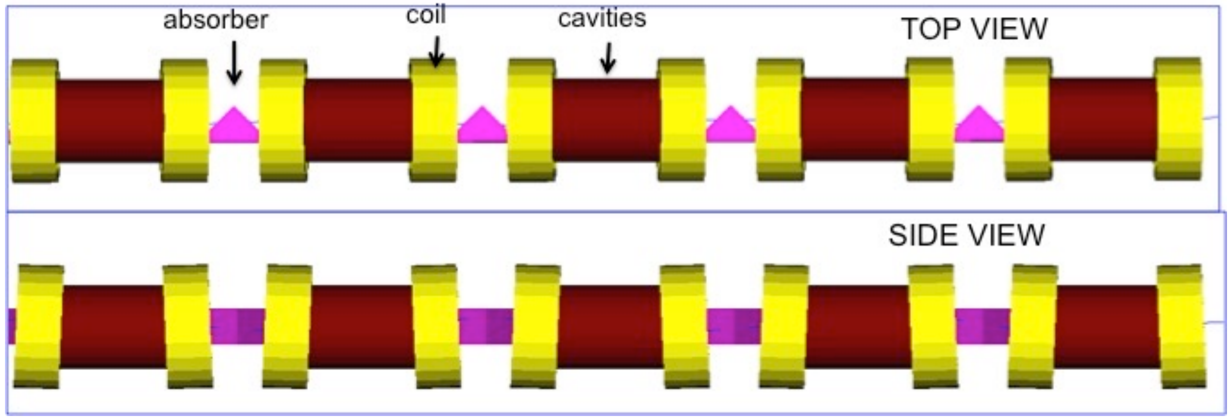




High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid



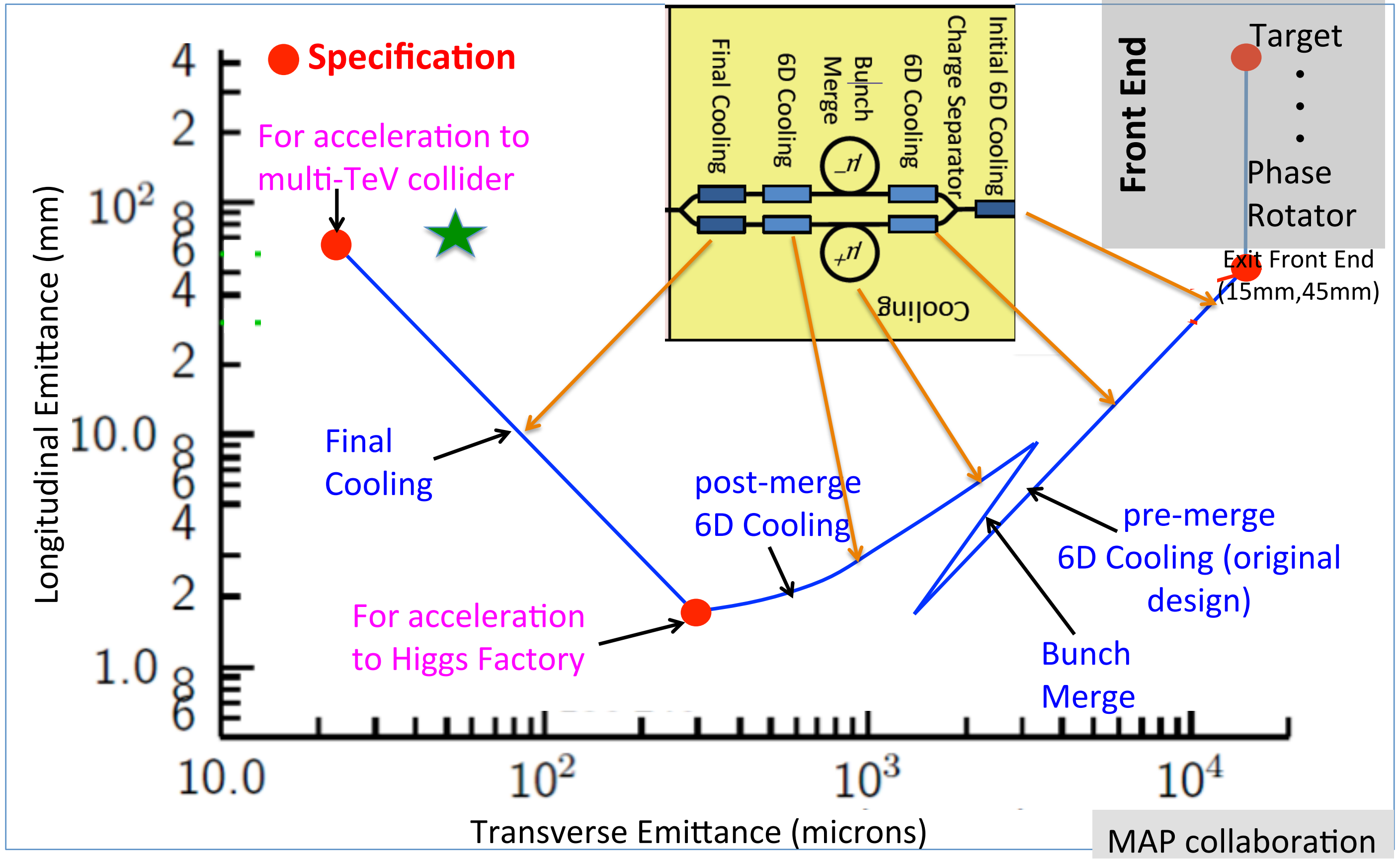
Principle has been demonstrated in MICE
Nature vol. 578, p. 53-59 (2020)

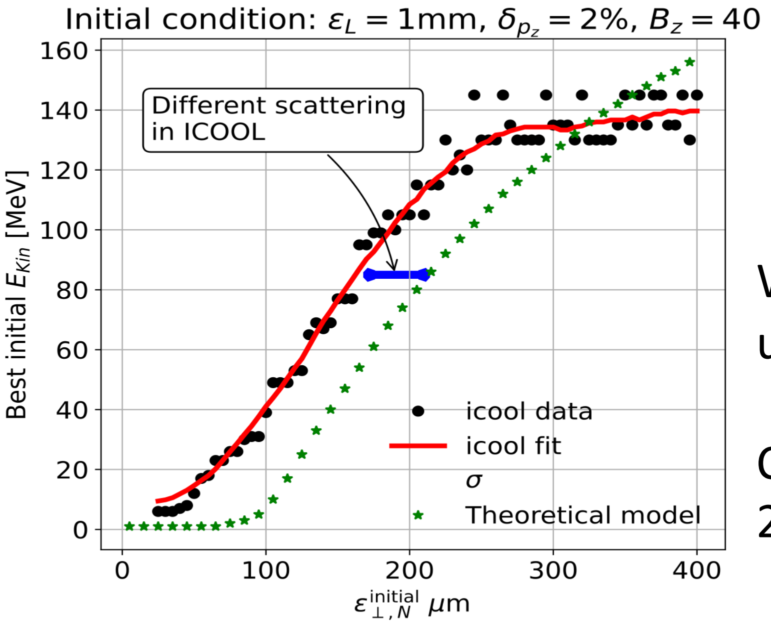
Muon Cooling Performance

MAP design achieved 55 um based on achieved fields

Can expect better hardware

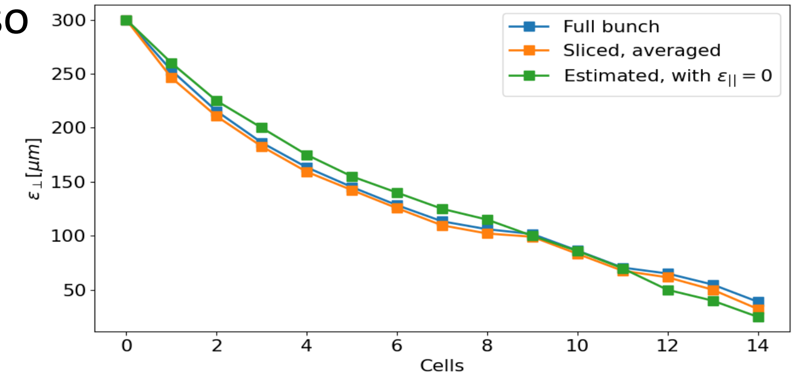
Integrating physics into **RFTRACK**, a CERN simulation code with single-particle tracking, collective effects, …





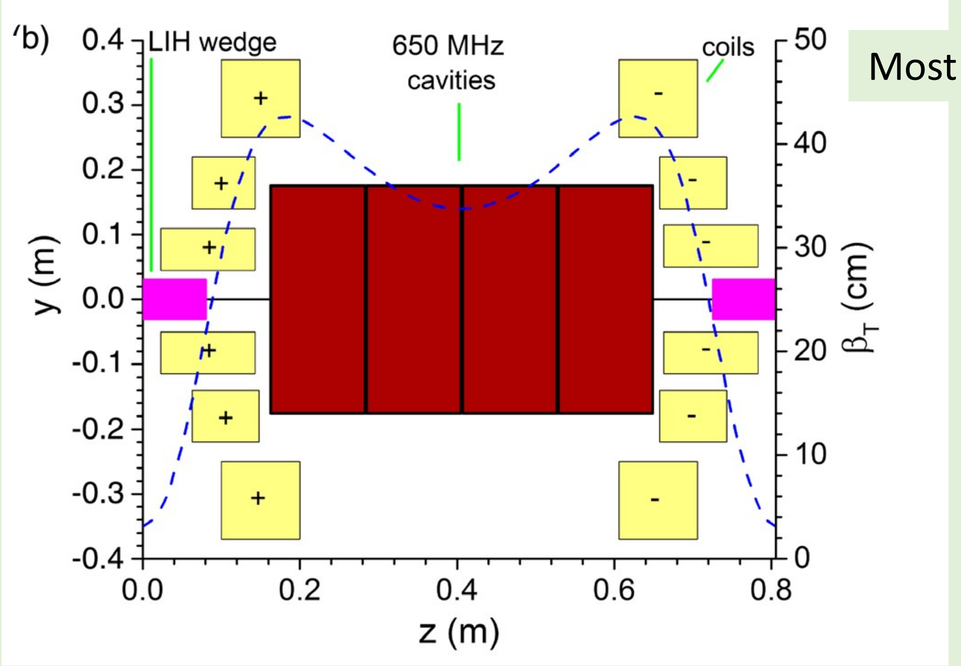
Working on **improved, systematic design**, also using better magnets and RF

Currently improved from 55 um to 33 um, 25 um is the goal



Cooling Cell Technologies

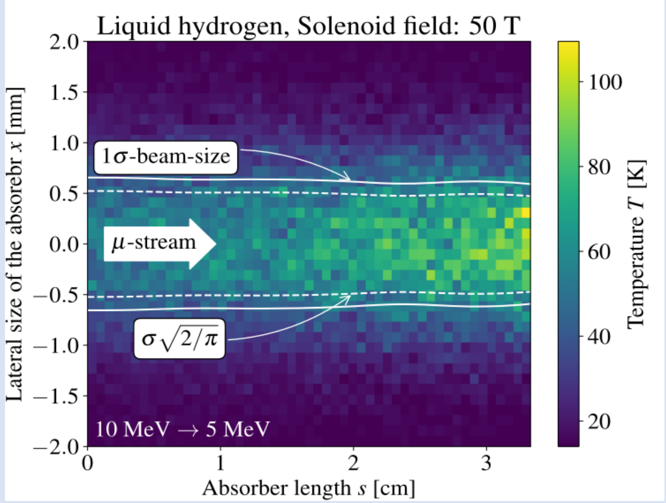
Are developing example **cooling cell with integration**
- tight constraints
- additional technologies (**absorbers**, instrumentation,…)
- early preparation of **demonstrator facility**



Most complex example 12 T

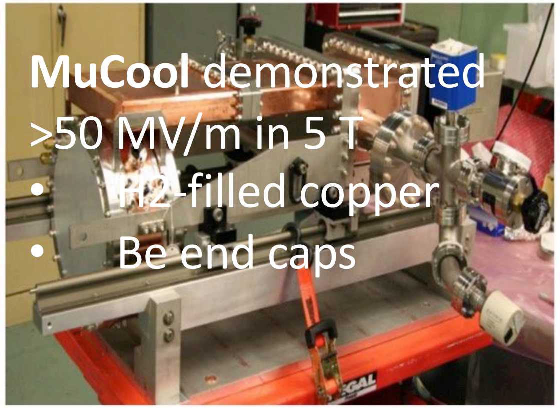
HTS solenoids
Ultimate field for final cooling
Also consider cost

Windows and absorbers
- **H**igh-density muon beam
- Pressure rise mitigated by vacuum density
- First tests in HiRadMat



RF cavities in magnetic field
Gradients above goal demonstrated by MAP
New test stand is important
- Optimise and develop the RF
- Different options are being explored
- Need funding

⇒ Dario



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

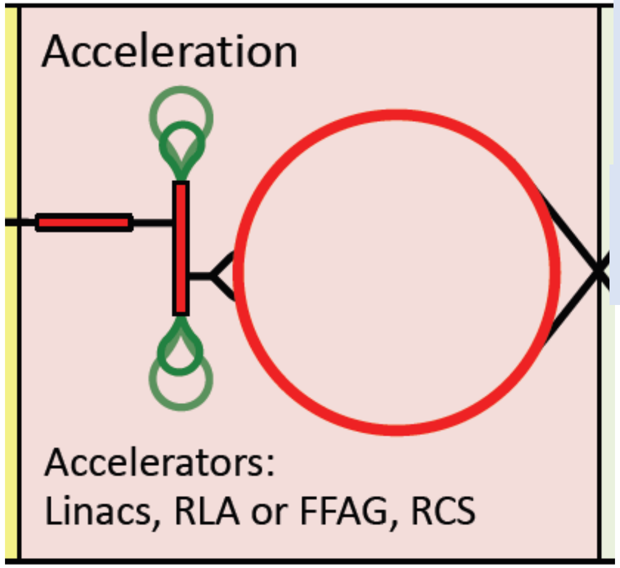
For these reason in addition to the general design of the MC CC magnets and of the magnets of the collider ring, the LASA magnet team of the MC, pursue to design two test stand configurations:

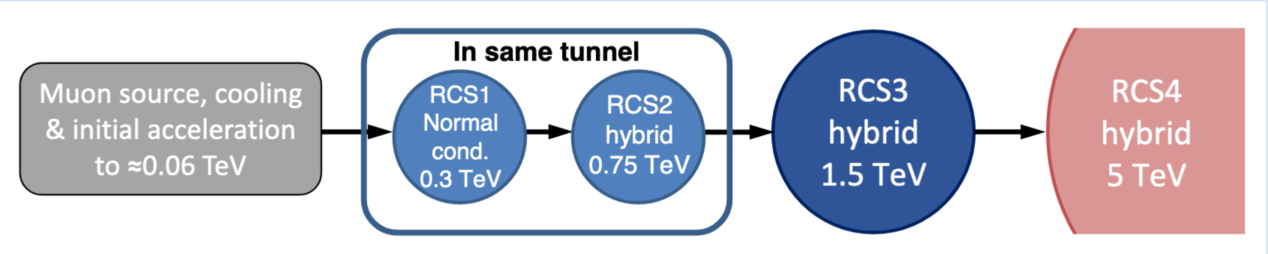
- ✓ Large size split coils (for 704 MHz, i.e. 700 mm free RT bore) needed at the end for a finale integration and functional test
- ✓ A smaller size (for 3 GHz system, i.e. 350 mm free RT bore) that would allow to build the facility with moderate cost

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

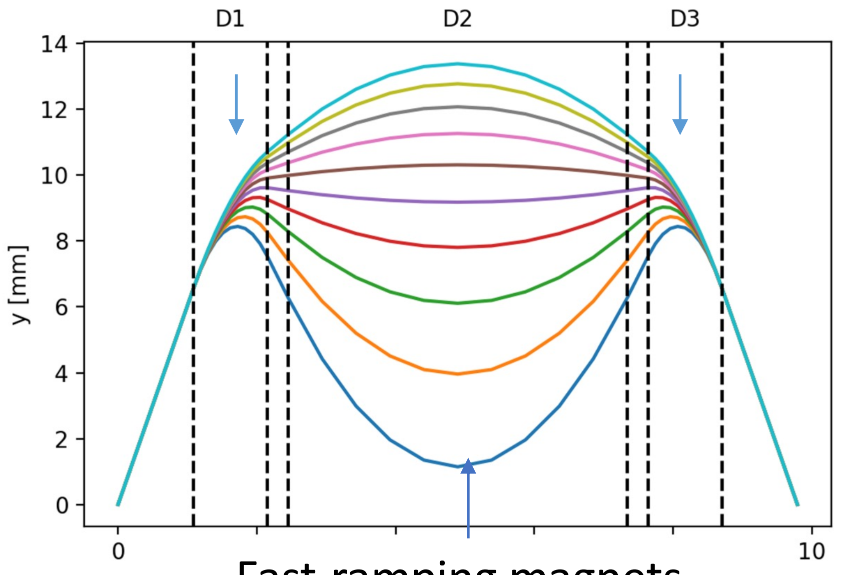
Acceleration Complex



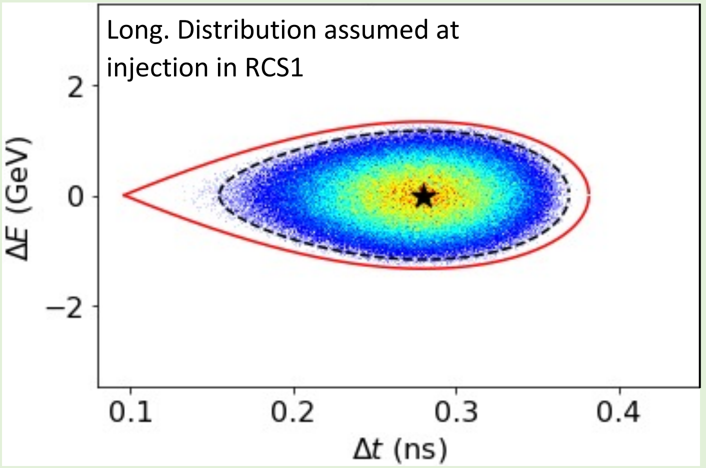


Core is sequence of pulsed synchrotron (0.4-11 ms)
- Alternative FFA

Superconducting magnets



Fast-ramping magnets



RF:

1.3 GHz cavities appear possible

- in spite of high bunch charge

Lattice:

Hybrid design works

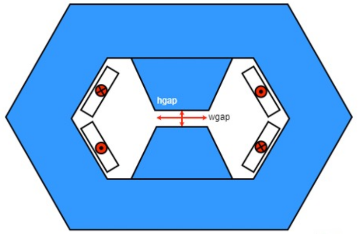
Can spread RF in the arcs

Fast-ramping Magnet System

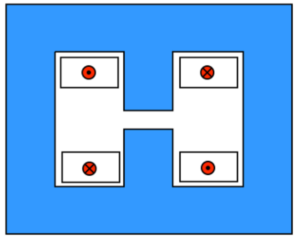
Differerent power converter options investigated

Efficient energy recovery for resistive dipoles (O(100MJ))

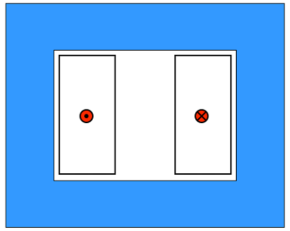
Synchronisation of magnets and RF for power and cost



5.07 kJ/m



5.65…7.14 kJ/m



5.89 kJ/m

FNAL 300 T/s HTS magnet

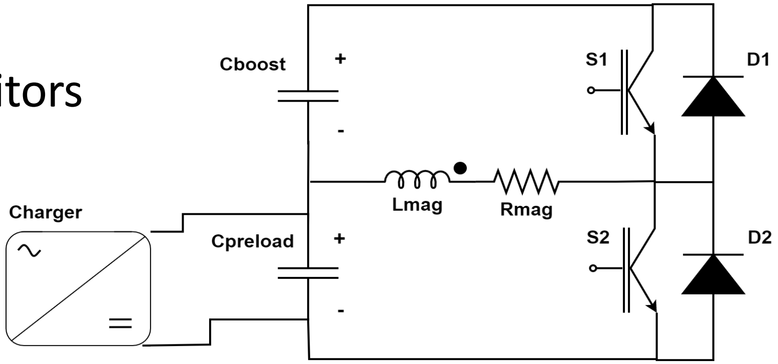
Could consider using HTS dipoles for largest ring

Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Commutated resonance

Attractive new option

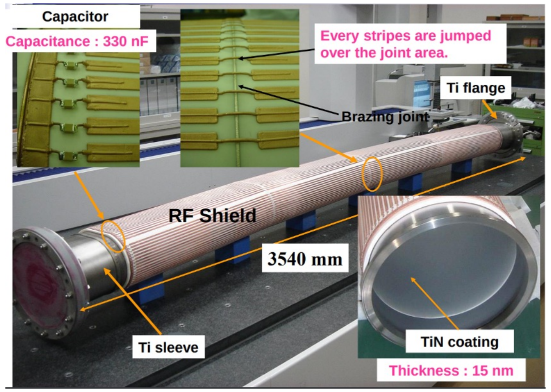
- Better control
- Much less capacitors



Beampipe study

Eddy currents vs impedance

Maybe ceramic chamber with stripes

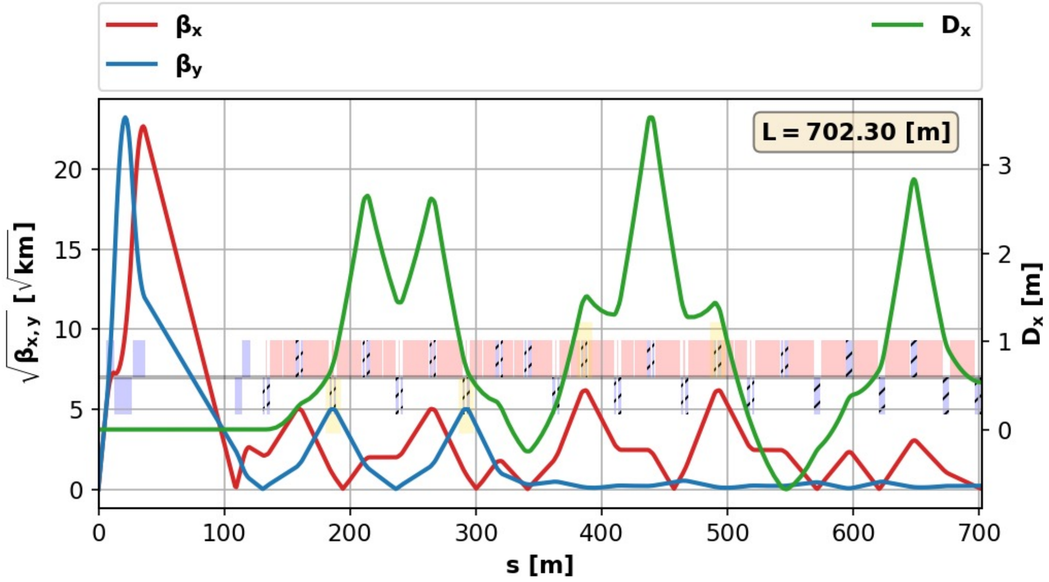


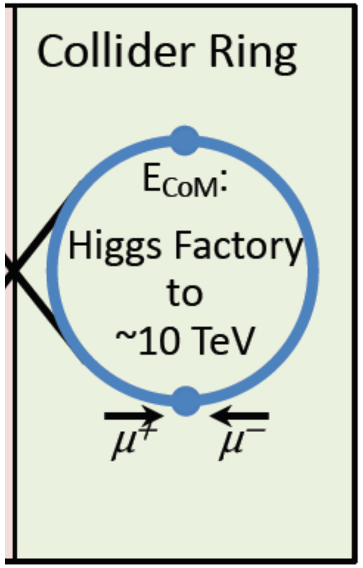
Collider Ring

High performance 10 TeV challenges:
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

3 TeV:
MAP developed 4.5 km ring with Nb_3Sn
- magnet specifications in the HL-LHC range
- 5 mm beta-function

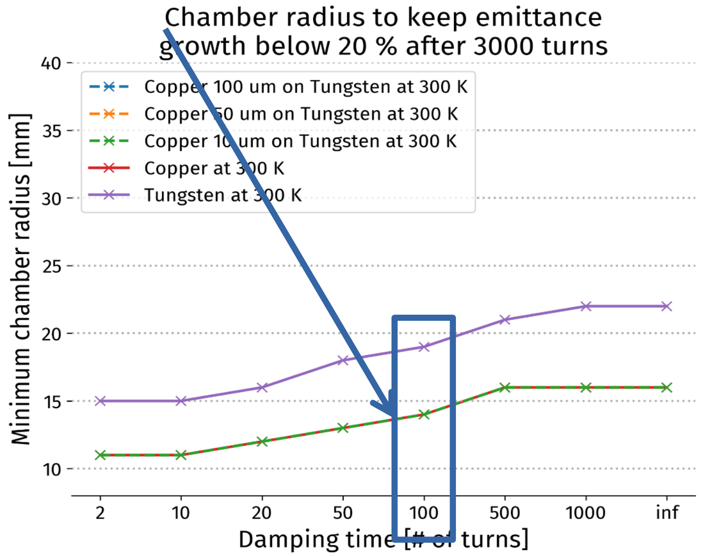
10 TeV collider ring in progress:
- around 16 T HTS dipoles or lower Nb_3Sn
- final focus based on HTS
- Need to further improve the energy acceptance by small factor



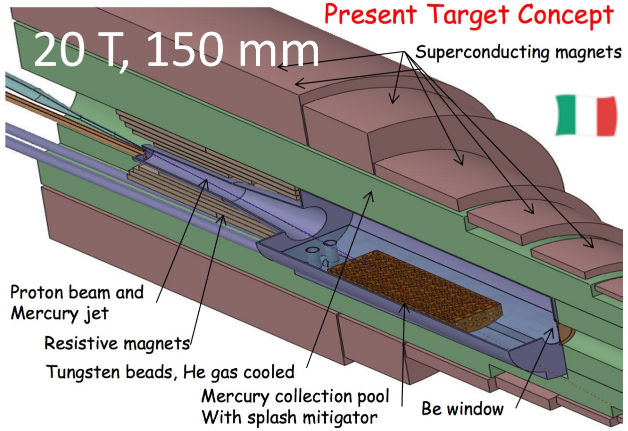


Impedance studies

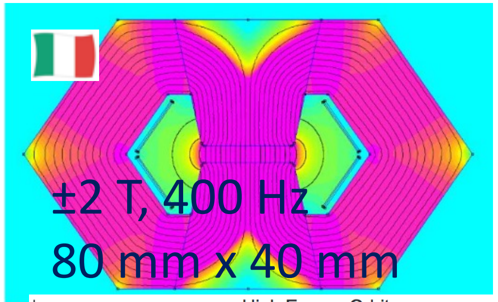
Single beam instability limits OK with conservative feedback

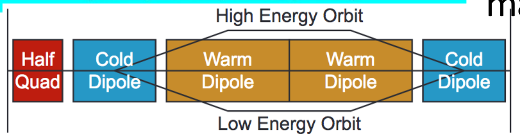


Magnet Demands @ Muon Collider



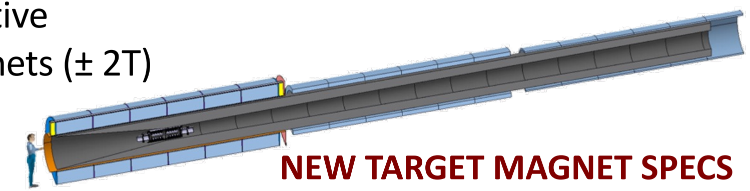
High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads





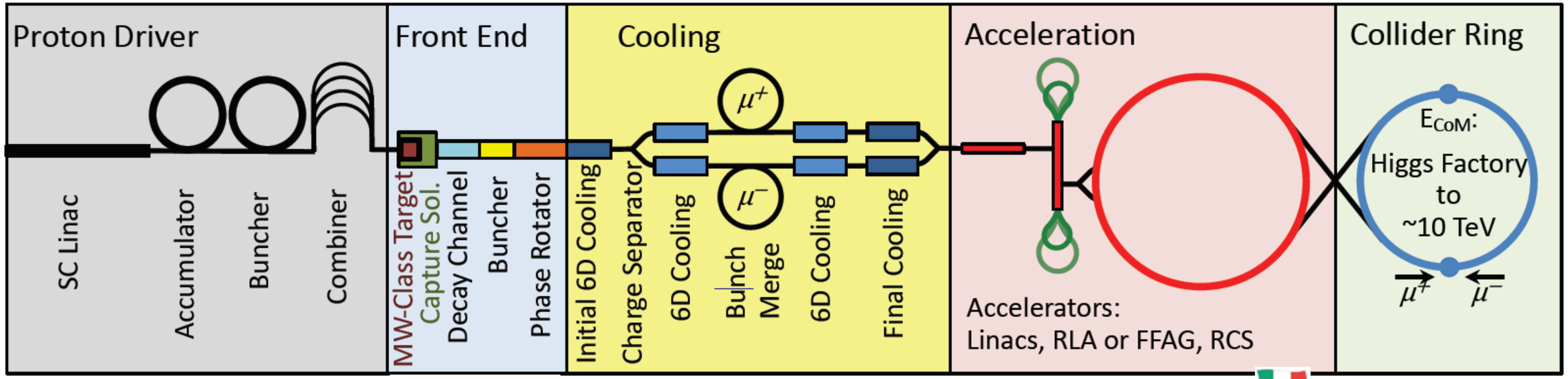
Combination of DC SC magnets (10 T) and AC resistive magnets (± 2T)

International
MUON Collider
Collaboration

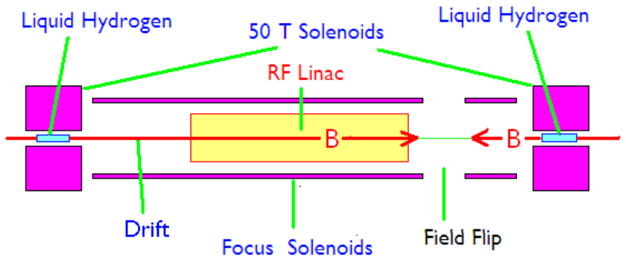


NEW TARGET MAGNET SPECS

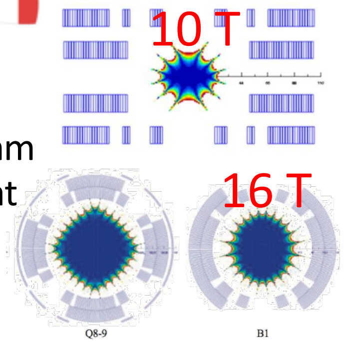
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy



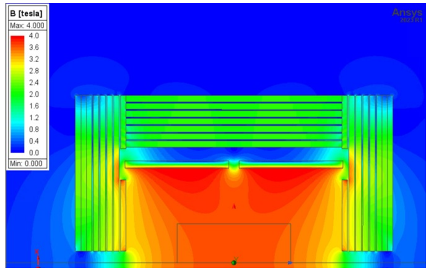
Ultra-high-field solenoids (40…60 T) to achieve desired muon beam cooling



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

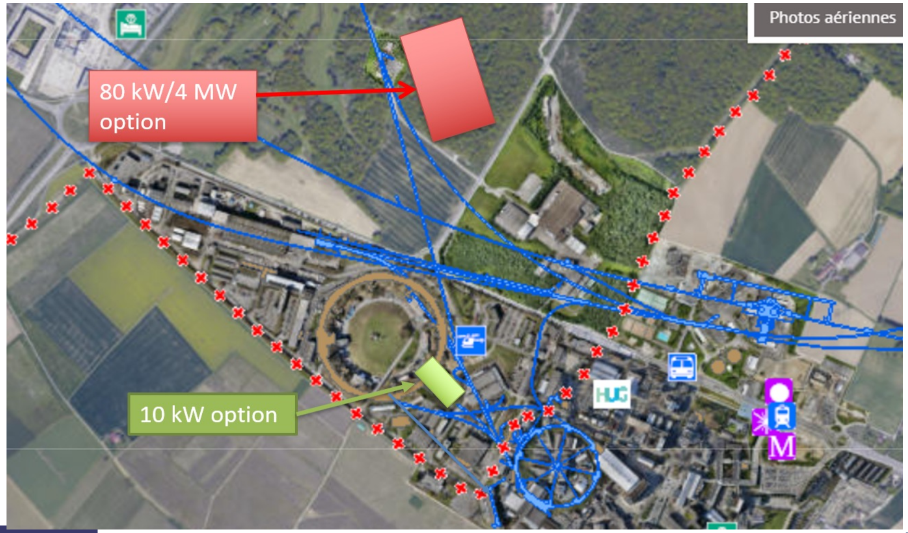


Detector Magnet
to be designed for 10TeV

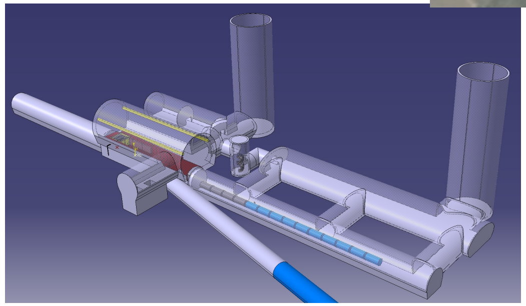


CDR Phase, R&D and Demonstrator Facility

Broad R&D programme can be distributed world-wide
- **Models** and **prototypes**
  - Magnets, Target, RF systems, Absorbers, …
- **CDR** development
- **Integrated tests**, also with beam

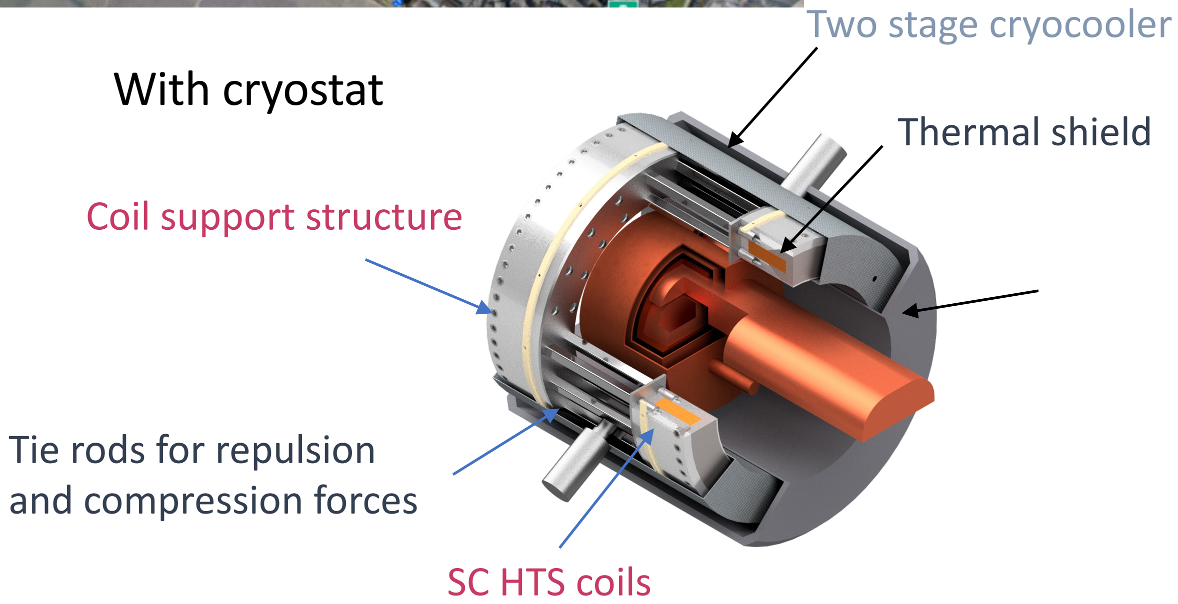


Cooling demonstrator is a key facility
- look for an existing proton beam with significant power



Different sites are being considered
- CERN, FNAL, ESS …
- Two site options at CERN

Muon cooling module test is important
- INFN is driving the work
- Could test it at CERN with proton beam



Implementation plan options: staging

Important timeline drivers:

Magnets

- HTS technology available for solenoids (expected in 15 years)
- Nb_3Sn available for collider ring, maybe lower performance HTS (expected in 15 years)
- High performance HTS available for collider ring (may take more than 15 years)

Muon cooling technology (expected in 15 years, with enough resources)

Detector technologies and design (R&D plan starting, finalized design expected in 15 years)

Energy staging

- Start at lower energy (e.g. 3 TeV, design takes lower performance into account)

Luminosity staging

- Start at 10 TeV with the highest reachable energy, but lower luminosity
- Main luminosity loss sources are arcs and interaction region
  - Can later upgrade interaction region (as in HL-LHC)

Consider reusing **LHC tunnel** and other infrastructures