Muon Collider

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On behalf of the International Muon Collider Collaboration

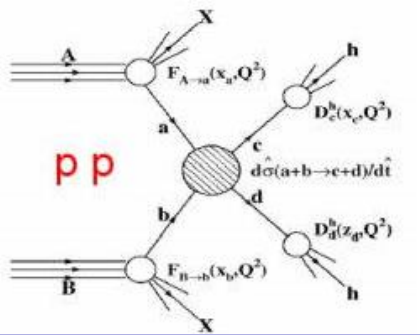
Bonn, October 2024

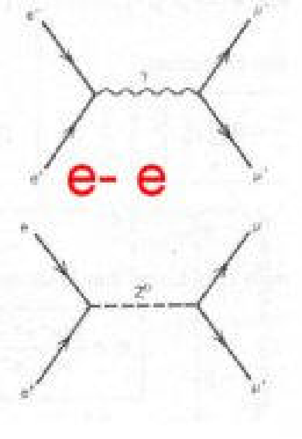
This project has received funding from the European Union's Research and Innovation programme under GAs No 101094300 and No 101004730.

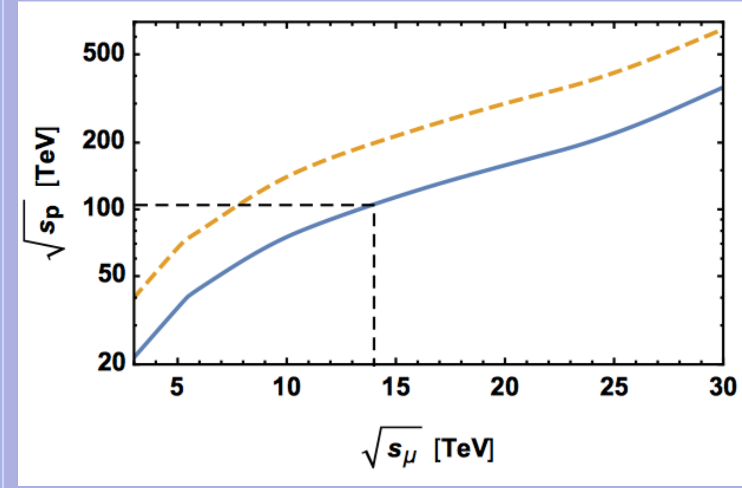
Physics Goals

Energy for discovery reach

10-14 TeV lepton collisions comparable to 100-200 TeV proton collisions







Leptons make the full energy available for particle production, protons only a fraction

Luminosity must increase as E_{cm}^2 as production cross sections decrease

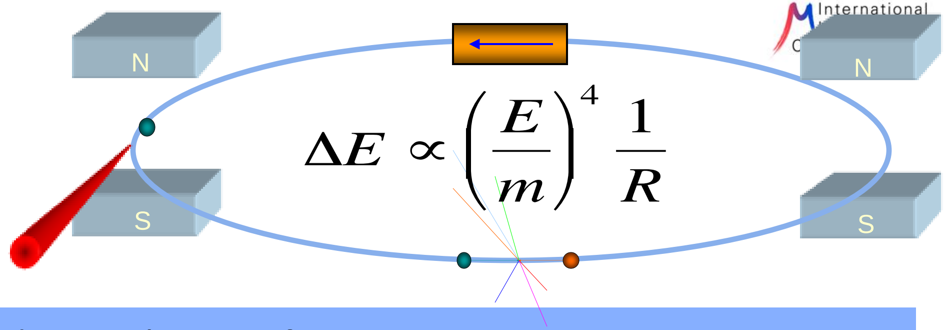
Theorists defined goals:
Yields constant number of events in the s-channel

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

High-energy Colliders

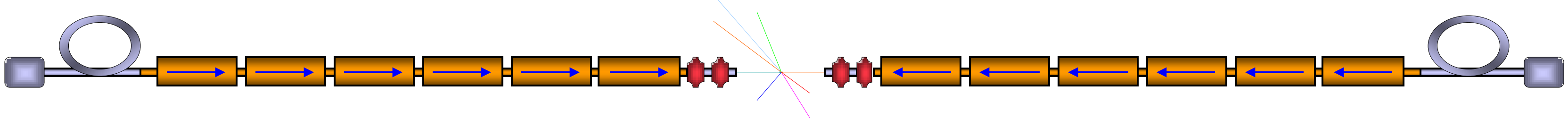
Electron-positron rings are **multi-pass** colliders limited by synchrotron radiation: **LEP, FCC-ee, CEPC**

Hence **proton rings** are energy frontier: **LHC, FCC-hh, SppC**



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

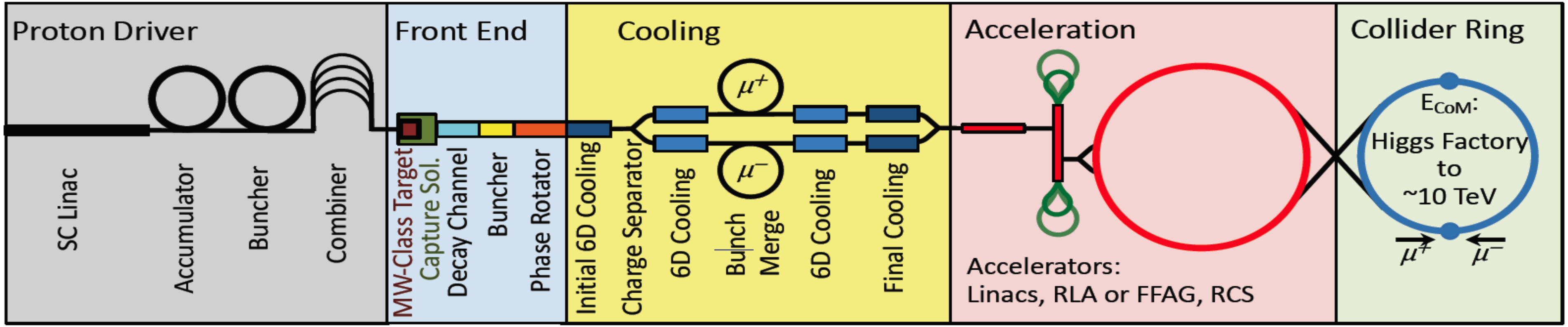
Electron-positron linear colliders avoid synchrotron radiation, but **single pass: SLC, ILC, CLIC**
Typically cost proportional to energy and power proportional to luminosity,



Novel approach: **muon collider** (the first of its kind)
Large mass suppresses synchrotron radiation => **multi-pass**
Fundamental particle requires less energy than protons
But lifetime at rest only 2.2 μs
Proportional to energy

Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is τ = γ x 2.2 μs



Short, intense proton bunch

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

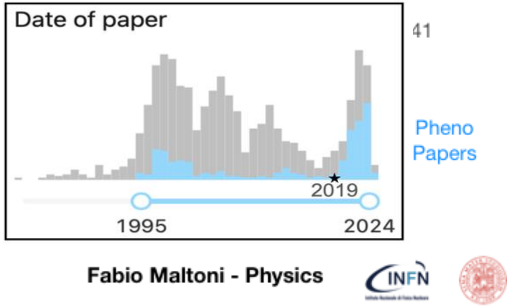
Acceleration to collision energy

Collision

A new Interest in Muon Colliders

From, e.g., Snowmass21 EF report draft:

> *"A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar to that of a 100 TeV proton-proton collider. [...] muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. [...] Multi-TeV muon colliders will have the benefit of excellent signal to background [...] One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential."*



from F. Maltoni at IMCC Annual Meeting

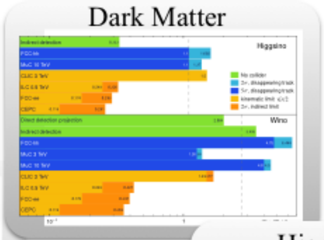
A. Wulzer, F. Maltoni, P. Meade et al.

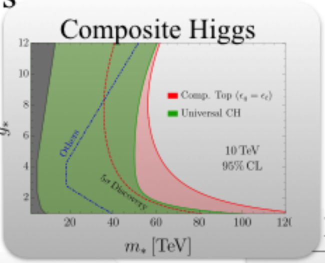
O(150) authors, 15 editors, 100 papers

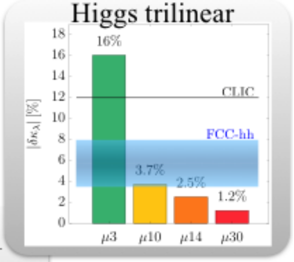
DELPHES card available

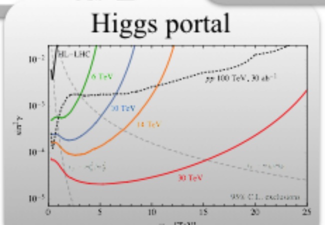
Selected summary plots, from Snowmass21 reports:

2 IMCC reports, plus Muon Collider Forum report. Total of 15 editors, ~150 authors, based on ~100 papers from 3 past years







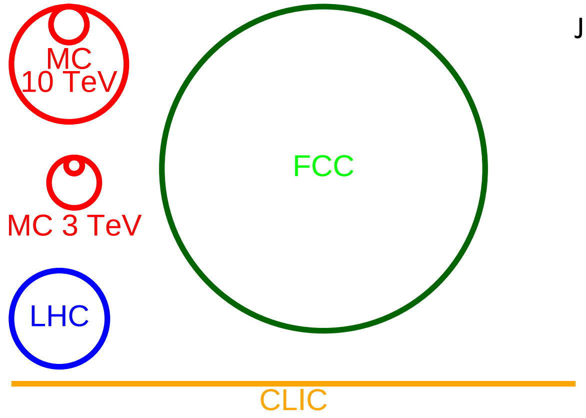


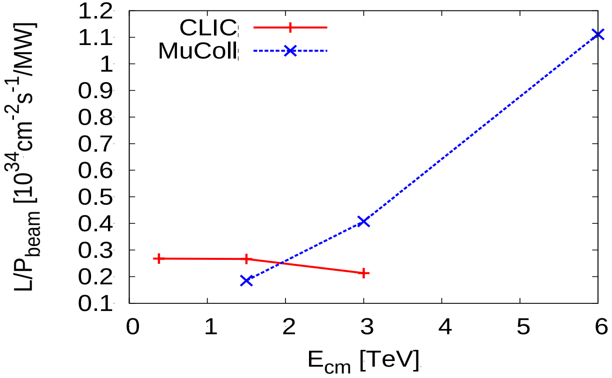
Higgs couplings

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV +ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

Muon Collider Promises





US Snowmass Implementation Task Force: Th. Roser, R. Brinkmann, S. Cousineau, D. Denisov, S. Gessner, S. Gourlay, Ph. Lebrun, M. Narain, K. Oide, T. Raubenheimer, J. Seeman, V. Shiltsev, J. Straight, M. Turner, L. Wang et al.

	CME [TeV]	Lumi per IP [$10^{34}cm^{-2}s^{-1}$]	Years to physics	Cost range [B$]	Power [MW]
FCC-ee	0.24	8.5	13-18	12-18	290
ILC	0.25	2.7	<12	7-12	140
CLIC	0.38	2.3	13-18	7-12	110
ILC	3	6.1	19-24	18-30	400
CLIC	3	5.9	19-24	18-30	550
MC	3	1.8	19-24	7-12	230
MC	10	20	>25	12-18	300
FCC-hh	100	30	>25	30-50	560

Judgement by ITF, take it *cum grano salis*

IMCC Goals

Develop high-energy muon collider as option for particle physics:

- Muon collider promises **sustainable** approach to the **energy frontier**
  - limited power consumption, cost and land use
- **Technology** and **design advances** in past years
- Reviews in Europe and US found **no unsurmountable obstacle**

Accelerator R&D Roadmap identifies the required work

- Has been developed with the global community

Goals are

- Assess and develop the muon collider concept for a O(10 TeV) facility
- Identify potential sites to implement the collider
- Develop an initial muon collider stage that can start operation around 2050
- Develop an R&D roadmap toward the collider

IMCC: International Muon Collider Collaboration

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

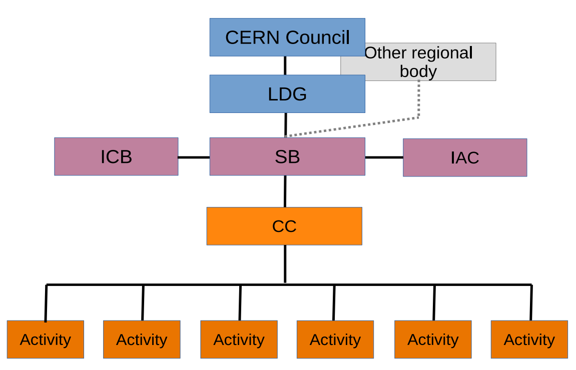
Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment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

http://arxiv.org/abs/2201.07895

Muon Collider Community

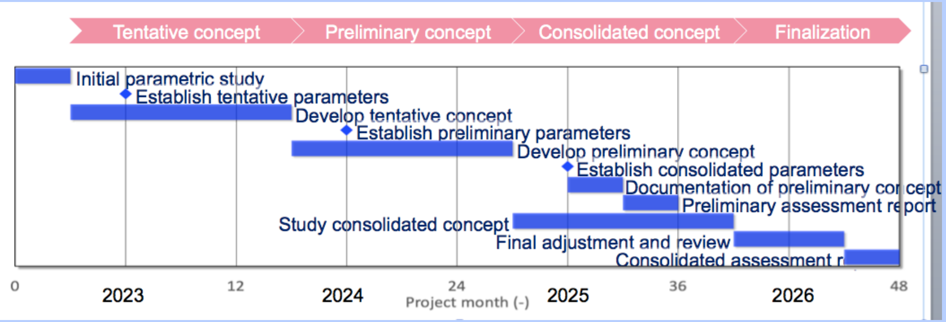
CERN-hosted **collaboration**

O(70) partners, 60+ already signed MoC



EU Design Study helped to kick-start collaboration (since March 2023, EU+Switzerland+UK and partners)

EU support also helps with funding in institutes



Looking for **new partners**

- In particular US
- But also other regions

Increase resources of partners with other **funding requests**:

- Submit to **HORIZON-INFRA-2024-TECH**
  - Focus on magnet technologies
- **National funding agencies**

IMCC Partners

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham

IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
Mal	**Univ. of Malta**
EST	***Tartu University***

SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical University**
CH	**PSI**
	University of Geneva
	EPFL
BE	**Univ. Louvain**
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
China	***Sun Yat-sen University***
	IHEP
	Peking University
KO	**KEU**
	Yonsei University

US	**Iowa State University**
	University of Iowa
	Wisconsin-Madison
	University of Pittsburgh
	Old Dominion
	Chicago University
	Florida State University
	RICE University
	Tennessee University
	MIT Plasma science center
	Pittsburgh PAC
India	***CHEP***

US	FNAL
	LBL
	JLAB
	BNL

US P5: The Muon Shot

MuCol

International MUON Collider Collaboration

Particle Physics Project Prioritisation Panel (P5) endorses muon collider R&D: ”This is our muon shot”

Recommend joining the IMCC
Consider FNAL as a host candidate
US is already particpating to the collaboration

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A “muon shot” aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

SCI AM

AUGUST 28, 2023 | 10 MIN READ

Particle Physicists Dream of a Muon Collider

After years spent languishing in obscurity, proposals for a muon collider are regaining momentum among particle physicists

nature

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EDITORIAL | 17 January 2024

US particle physicists want to build a muon collider – Europe should pitch in

A feasibility study for a muon smasher in the United States could be an affordable way to maintain particle physics unity.

US ambition:

- Want to reach a 10 TeV parton level collisions
- Timeline around 2050
- Fermilab option for demonstator and hosting
- Reference design in a “few” years

Informal discussion with DoE (Regina Rameika, A. Patwa):

- DoE wants to maintain IMCC as a **global collaboration**
- **Addendum to CERN-DoE-NSF agreement** is in preparation

IMCC prepares options for Europe and for the US in parallel

Tentative Staged Target Parameters

MuCol

International MUON Collider Collaboration

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

Muon Collider Luminosity Scaling

Fundamental limitation
Requires emittance preservation and advanced lattice design
Applies to MAP scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

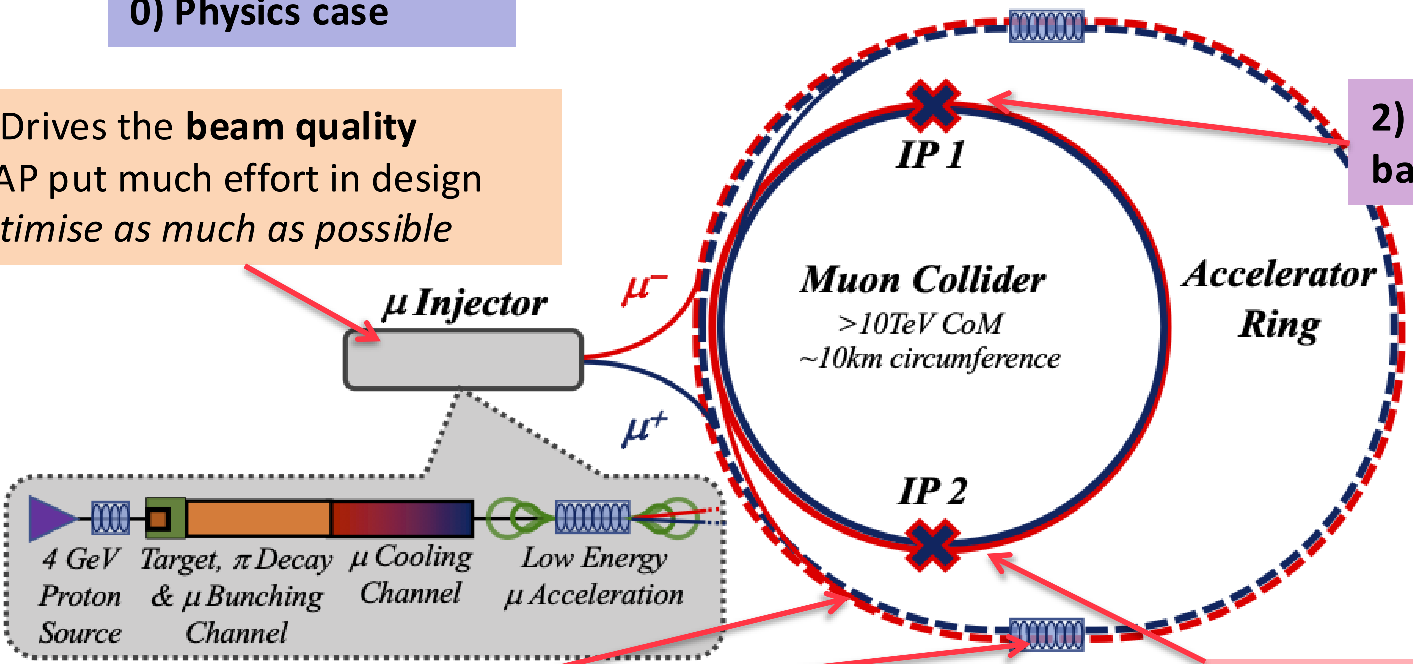
Luminosity per power increases with energy
Provided technologies can be made available

Constant current for required luminosity scaling

Key Challenges

0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible



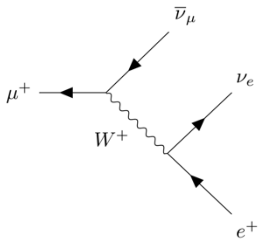
2) Beam-induced background

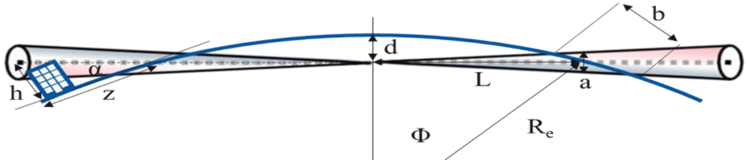
1) Dense neutrino flux
mitigated by mover system
and site selection

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

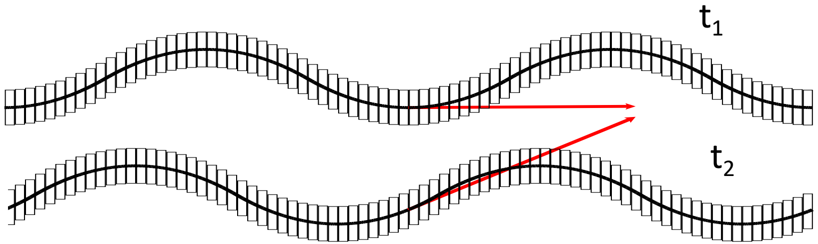
Muon Decay and Neutrino Flux

Muon decays in collider ring
- Impact on detector, see Daniele
- 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



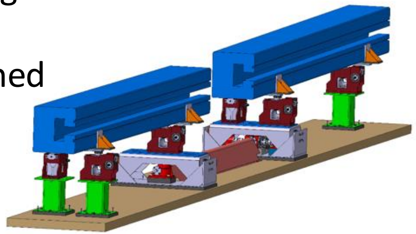
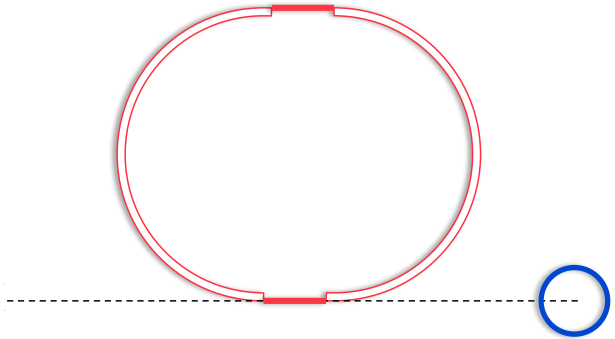


Fig. 7.23: Mock-up of the proposed magnet movement system.

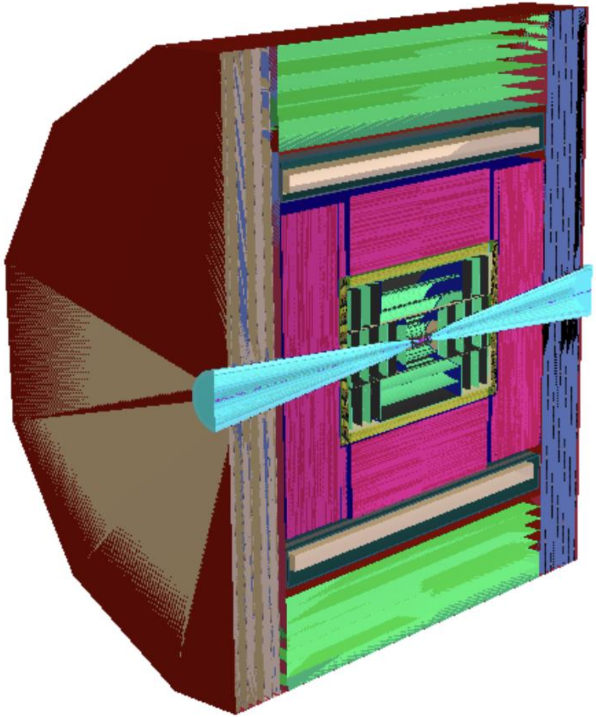


Impact of experimental insertions
- 3 TeV design acceptable with no further work
- But better acquire land in direction of experiment, also for 10 TeV

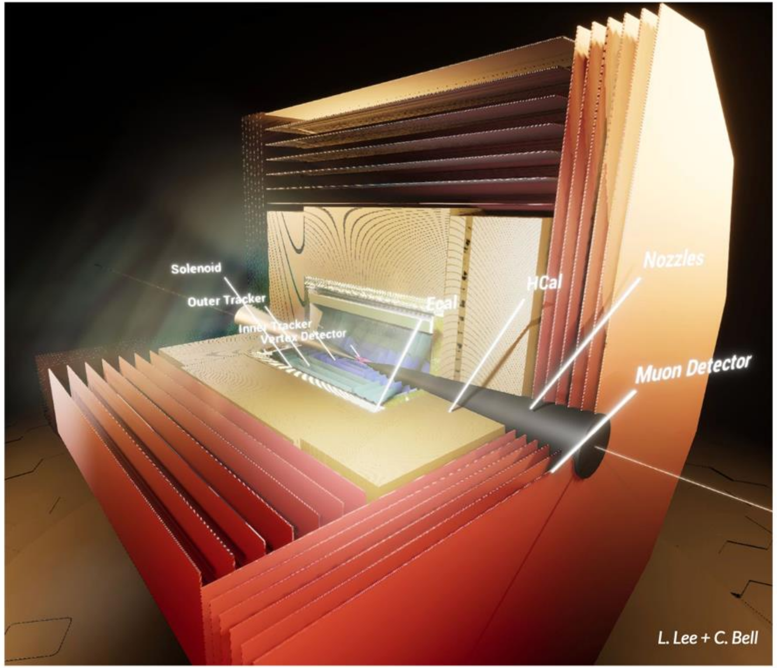
Physics and Detector Concepts

Two detector concepts are being developed

MUSIC
(MUon Smasher for Interesting Collisions)

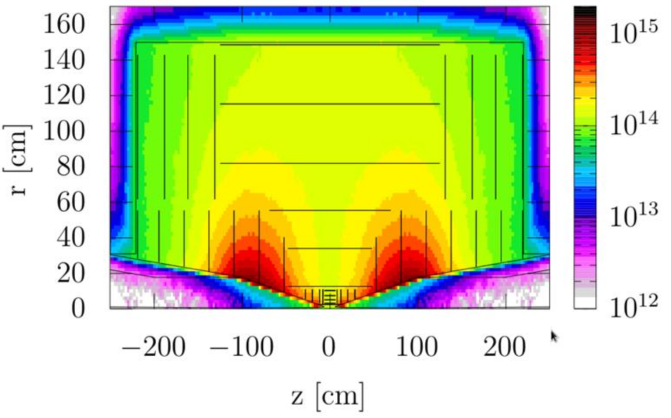


MAIA
(Muon Accelerator Instrumented Aperatus)

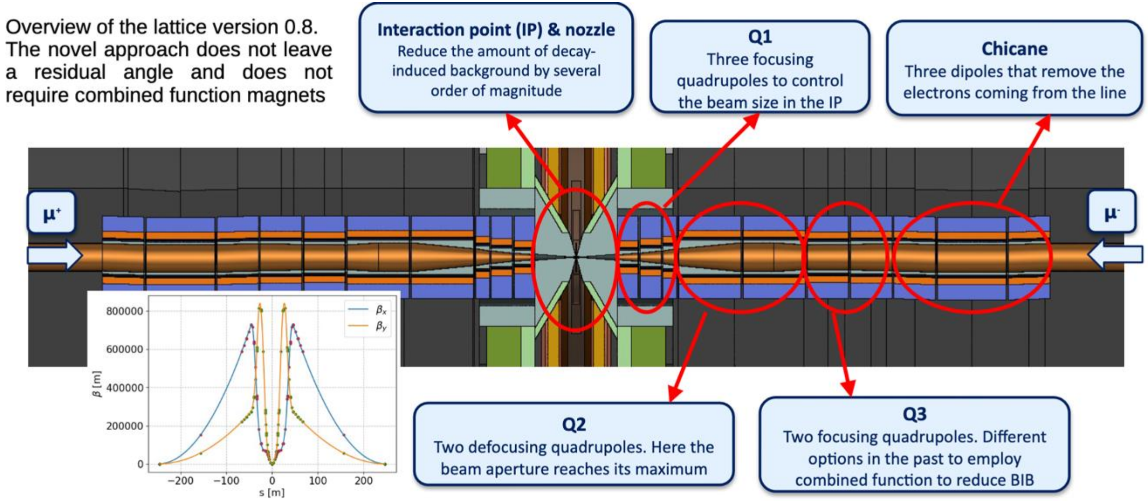


Beam-induced Background

- Muon decay is dominant
- Incoherent pairs is significant in inner layers
- Synchrotron radiation does not matter much
- Muon loss remains to be studied with source terms
- Coherent and trident cascade pairs expected not important



Detailed studies with FLUKA



Per year of operation (~140d)	Ionizing dose	Si 1 MeV neutron-equiv. fluence
Vertex detector	200 kGy	3×10^{14} n/cm²
Inner tracker	10 kGy	1×10^{15} n/cm²
ECAL	2 kGy	1×10^{14} n/cm²

Beam-induced Background

Studies at 3 TeV showed that physics measurements can be done

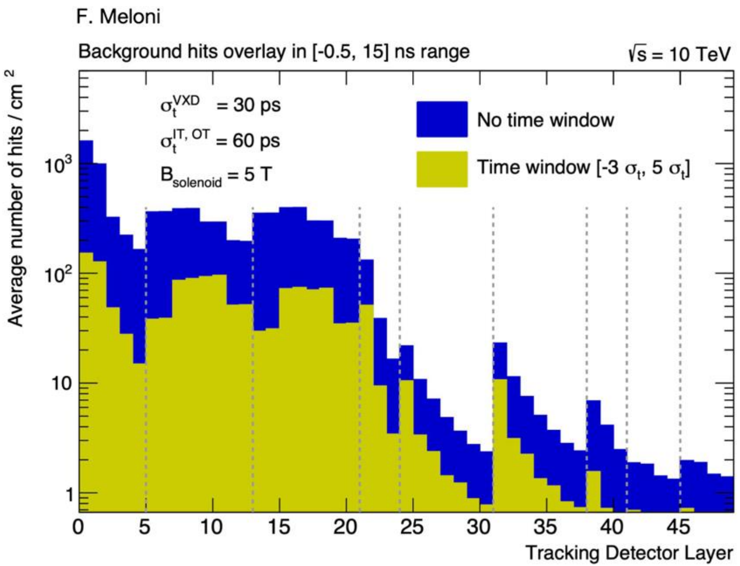
- But improvement potential exists

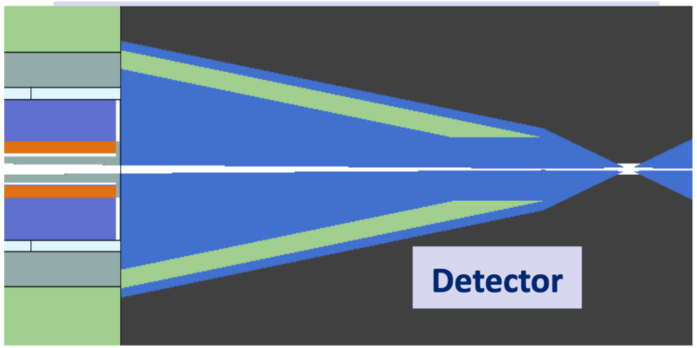
Studies at 10 TeV are starting

Background is reduced using timing and directional information

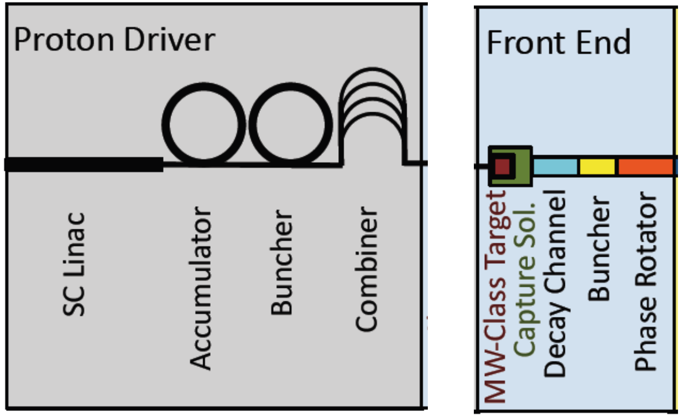
- Optimisation of mask is ongoing

Background has impact on reconstruction efficiencies





Proton Complex and Target



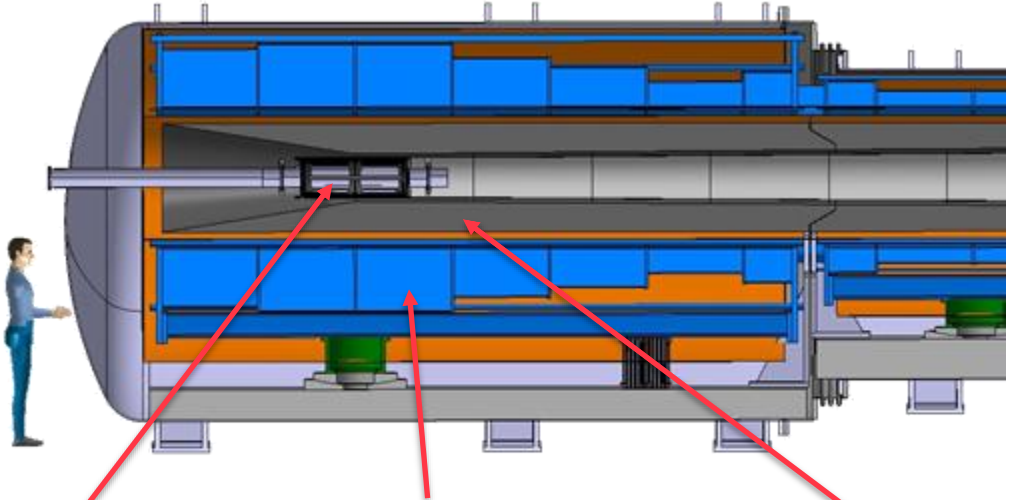
protons → (in target) → pions → (decay) → muons

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 will focus on merging beam into high-charge pulses

Optimisation of parameters planned



Graphite **Target**

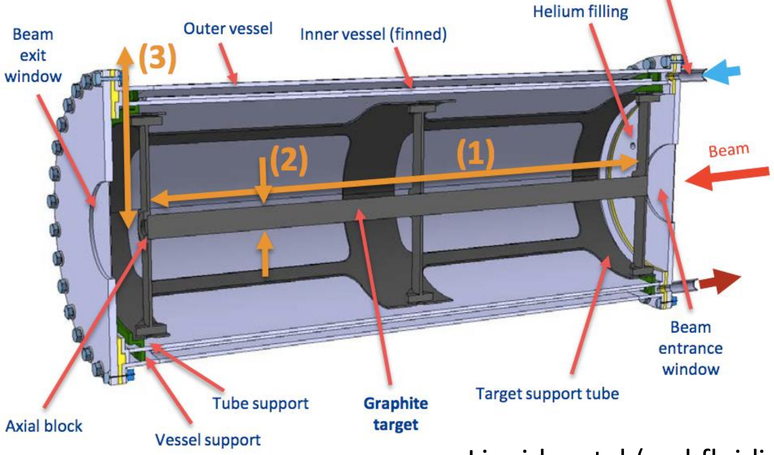
20 T **solenoid**
to guide pions and muons

Tungsten shielding
To protect magnet

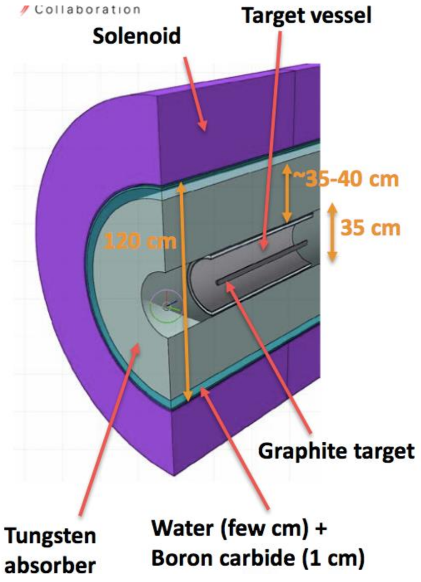
Target Design

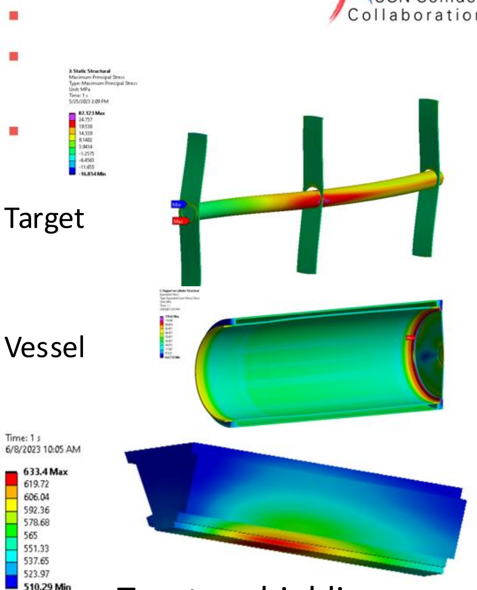
2 MW, 5 x 10^{14} protons/pulse, 5 GeV (0.4 MJ), 5 Hz
- graphite rod with 15 mm radius

Started studying alternative 4 MW target
- Graphite
  or liquid lead
- or fluidised tungsten



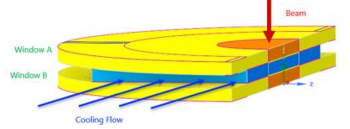
CNGS target
3.5 x 10^{13} protons/pulse, 400 GeV (2.2 MJ), 1/6 Hz





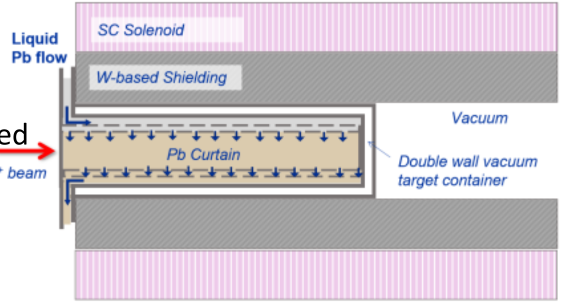
Tunsten shielding

Window

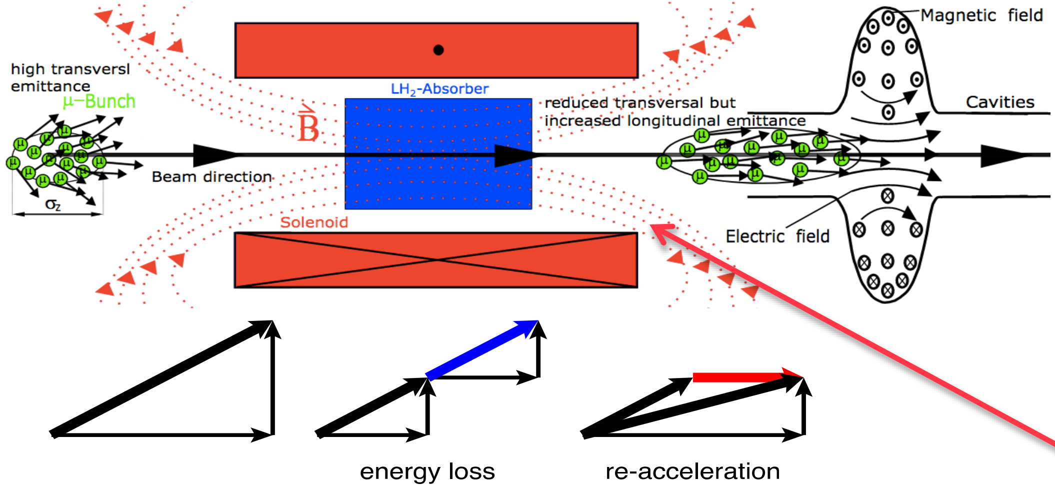


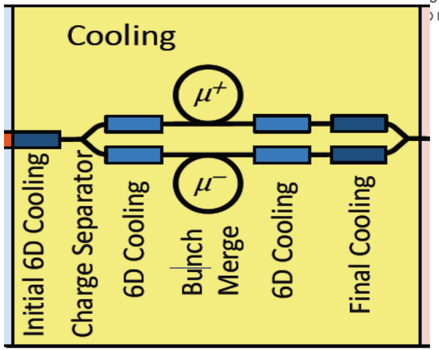
A. Lechner, D. et al.

Liquid metal (and fluidised tungsten) as alternative
Collaboration w. ENEA



Final Cooling Principle





High field solenoids minimise beta-function and impact of multiple scattering

Energy loss = cooling Multiple scattering = heating

$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

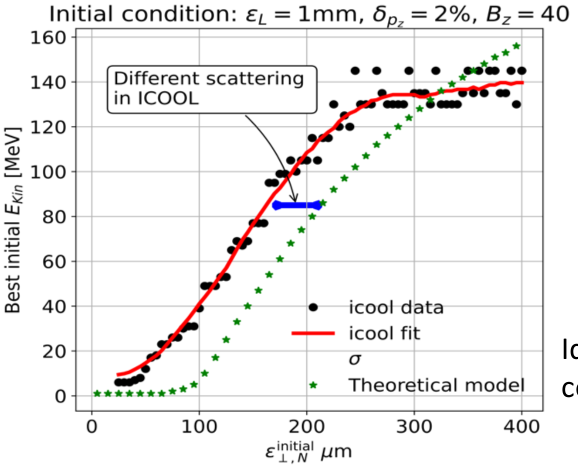
Muon Cooling Performance

MAP design achieved 55 um based on achieved fields (28 T)

Currently in 24-30 um range (goal 22.5 um)

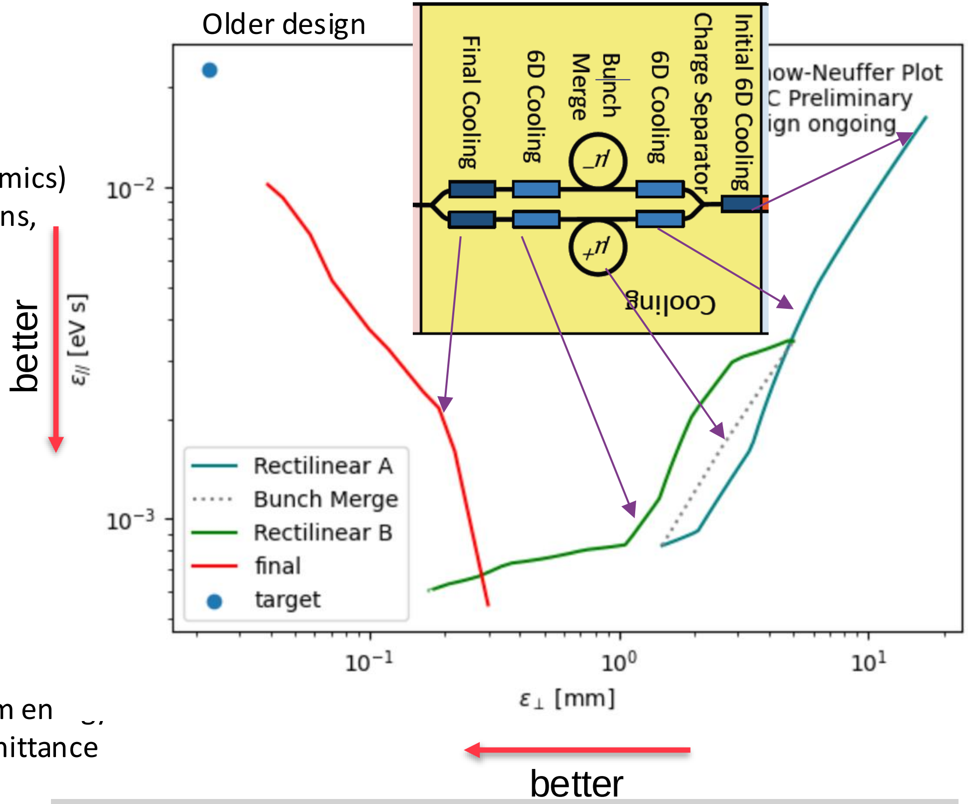
- In one design longitudinal emittance much better than target
  - But field in one solenoid is 50 T
- Need about 50% more muons
  - Can improve transmission (most losses due to beam dynamics)
  - or more initial muons (4 MW target yields 90% more muons, but have to deal with more beamloading)

B. Stechauner at al.



Identification of optimum energy for cooling as function of emittance

Older design

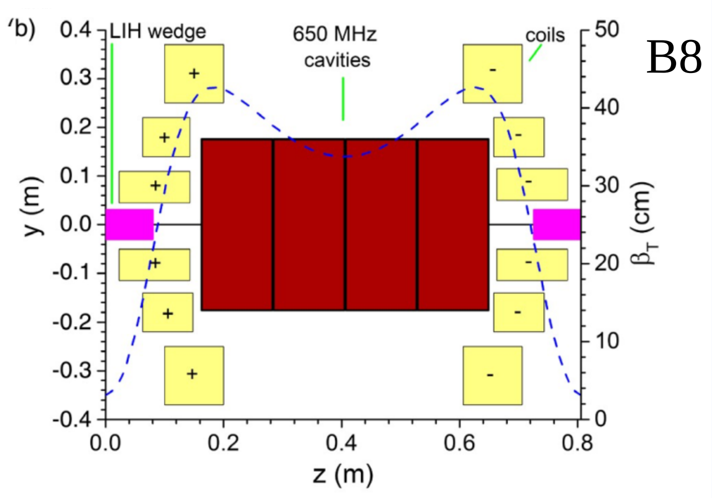


Ch. Rogers, Zhu Ruihu, R. Taylor, B. Stechauner, E. Vol, D.S. et al.

Cooling Cell Technology

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

L. Rossi et al. (INFN, Milano, STFC, CERN), J. Ferreira Somoza et al.



Most complex example 12 T

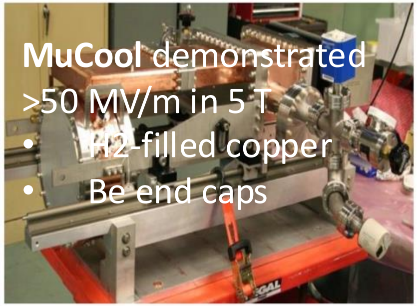
Windows and absorbers for high-density muon beam
- Pressure rise mitigated by vacuum density
- Tests in HiRadMat

RF cavities in magnetic field

MAP demonstrated higher than goal gradient

Improve design based on theoretical understanding

Preparation of **new test stand**, but needs funding
- Test stand at CEA (700 MHz, need funding)
- Test at other frequencies in the UK considered
- Use of CLIC breakdown experiment considered



C. Marchand, Alexej Grudiev et al. (CEA, Milano, CERN, Tartu)

High-field Magnet Technology

Superconducting magnets reach highest fields, three main technologies for the cables

NbTi (niob-titanium, operating at 2-4 k)

- is standard, **used in LHC** limited to O(8 T)

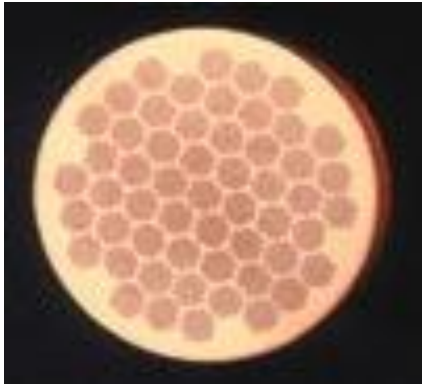
Nb_3Sn (niobium-tin, operating at 2-4 K)

- Can reach O(16 T)
- Difficult technology, needs to mature further
- Expensive
- Used in some points for HL-LHC
- Foreseen for FCC-hh also in arcs

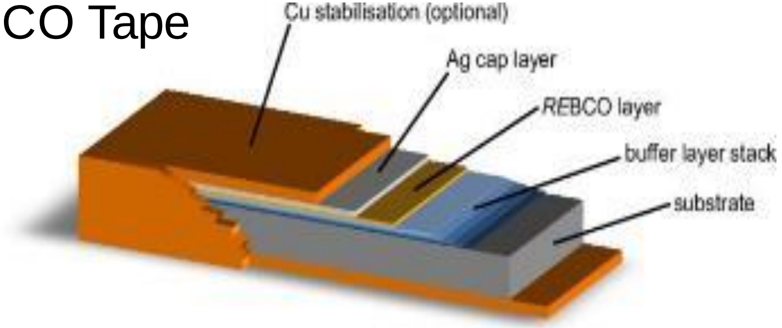
HTS (high-temperature superconductor, operating 20 K)

- Different options exist, e.g. REBCO
- In solenoids > 30 T demonstrated
- Still expensive and technology challenges
- Applications in other fields, e.g. medical, fusion reactors, power generators for wind energy, engines, …

Cut through a cable with superconductor embedded in copper, so some remains conductivity in case of a quench



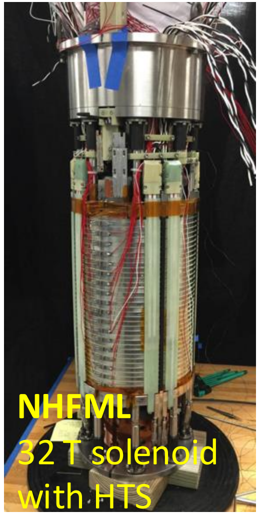
REBCO Tape



Solenoid R&D

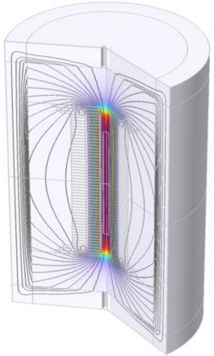
Started **HTS solenoid** development for high fields
Synergies with fusion reactors, NRI, power generators for windmills, …

A Portone, P. Testoni,
J. Lorenzo Gomez, F4E



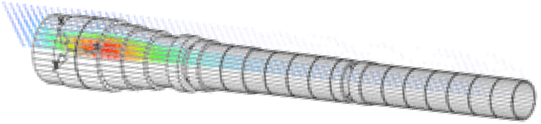
Final Cooling solenoid
Goal 40 T
Estimation of limit

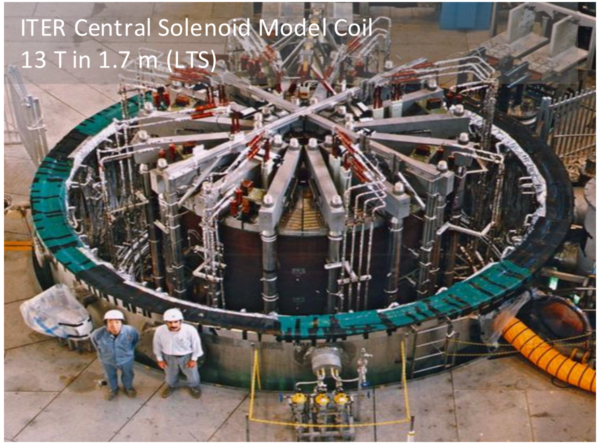
$B_{max} \approx 55$ T



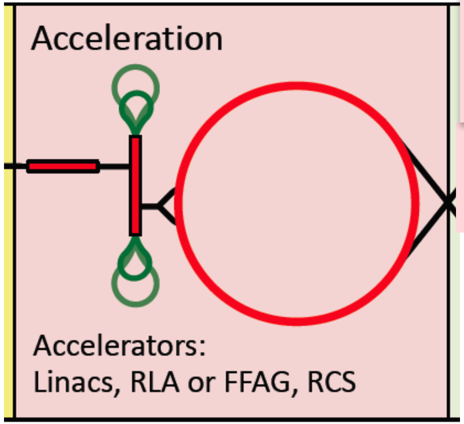
Target solenoid, 20 T, 20 K

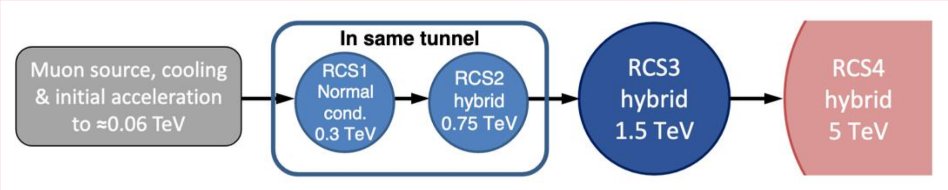
15 T Nb_3Sn with 5 T resistive insert
Or 20 T HTS seems possible
Relevant for advanced fusion reactors





Acceleration Complex

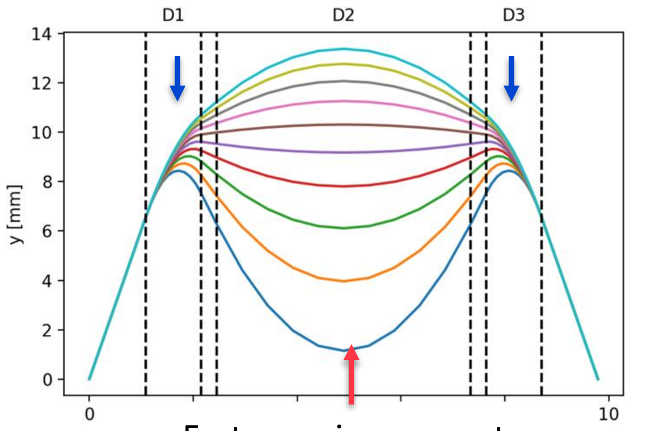




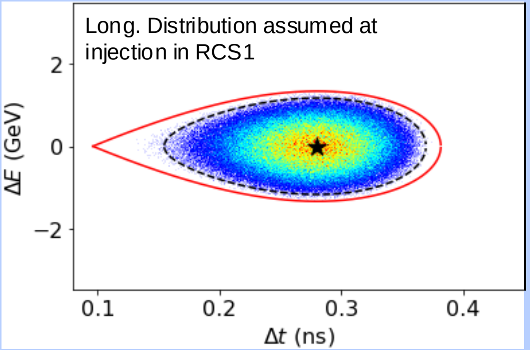
Core is sequence of pulsed synchrotron (0.4-11 ms)

- Alternative FFA

Superconducting magnets



Fast-ramping magnets



RF:

1.3 GHz cavities appear possible

- in spite of high bunch charge

Lattice and integration: A. Chance et al. (CEA)
Long. dynamics and RF systems: H. Damerell, U. van Rienen, A. Grudiev et al. (Rostock, Milano, CERN)
Power converter: F. Boattini et al.
Magnets: L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)
FFA: S. Machida et al. (RAL)

Lattice:

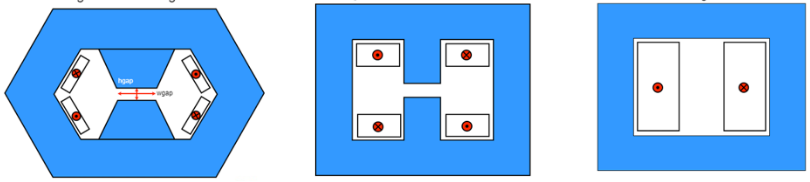
Hybrid design works

Can spread RF in the arcs

Fast-ramping Magnet System

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

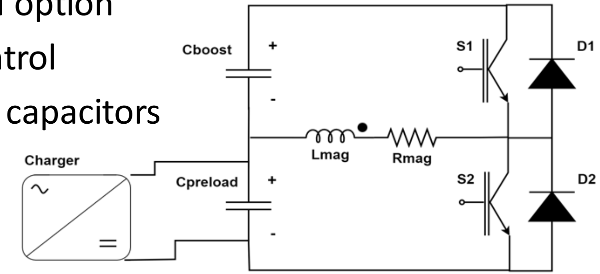
Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

Commutated resonance

Attractive novel option

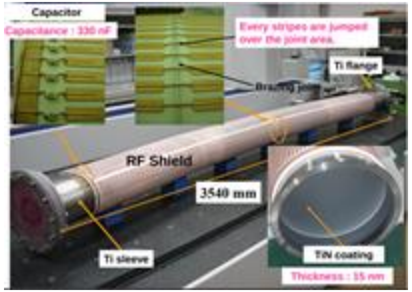
- Better control
- Much less capacitors



Beampipe study

Eddy currents vs impedance

Maybe ceramic chamber with stripes



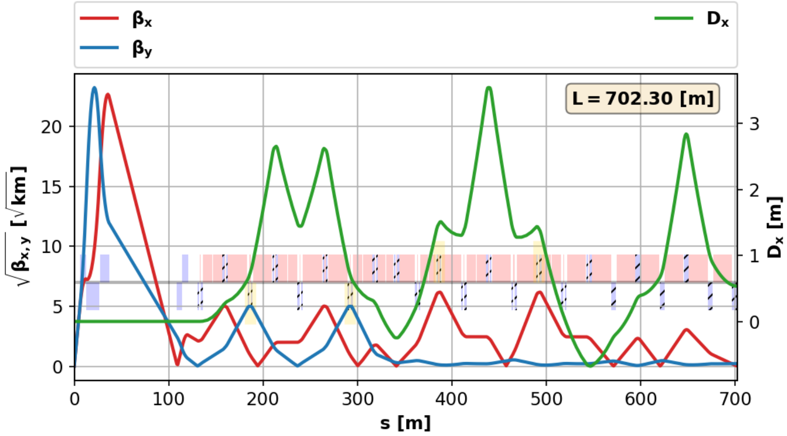
F. Boattini et al.
D. Amorim et al.

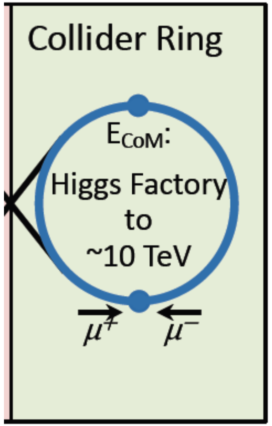
Collider Ring

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



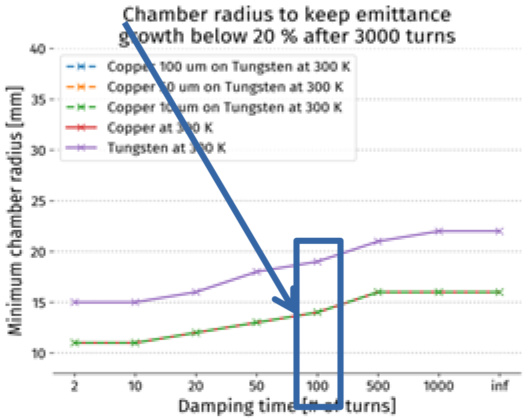


K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas

E. Metral, D Amorim et al. (CERN)

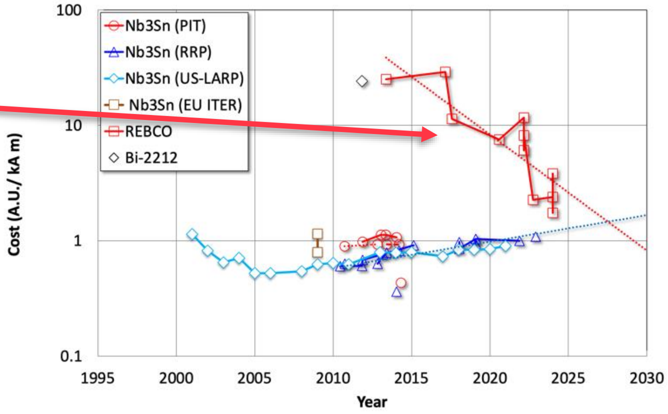
Impedance studies

Single beam instability limits OK with conservative feedback



Collider Ring Technology

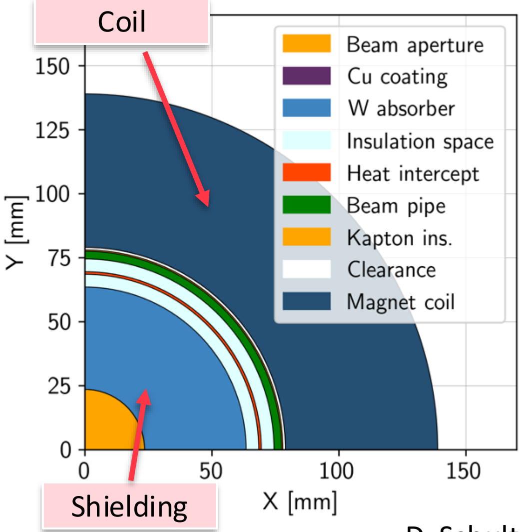
Large aperture to shield magnet
HTS cost is coming down
- Used for other applications
- Hard to predict the cost

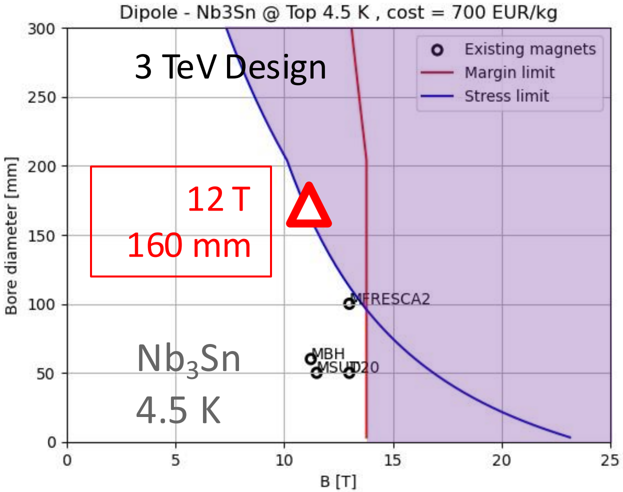


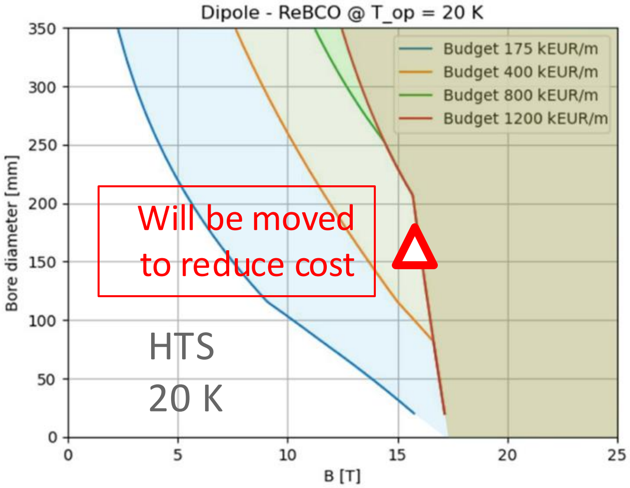
Shielding of muon decay loss (500 W/m):
FLUKA: 20-40 mm tungesten (OK to safe)
- Few W/m in magnets
- No problem with radiation dose

$\Rightarrow$ Magnet coil radius 59-79 mm

Nb3SN good up to 11-12 T
HTS can go higher
- Mainly a question of cost
- Needs technical development



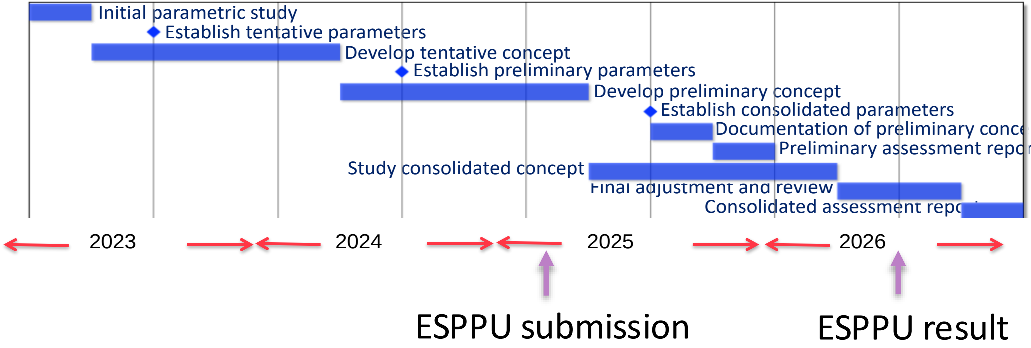




IMCC Plans

For the **ESPPU,** will deliver

- **Evaluation report**, including tentative cost and power consumption scale estimate
- **R&D plan**, including some scenarios and timelines
- Requires to push as hard as possible with existing resources



After ESPPU submission:

- Will fulfill EU contract
    - **Final deliverable is report on all R&D**
- Will have some US process after the ESPPU
    - Likely requires **Reference Design**
- LDG wants to maintain momentum
    - **EU Roadmap** continues

Continue together to develop green field concept

- Avoid becoming site specific before funding agencies put the resources on the table

Develop **site specific versions** as derived approaches

Note: IMCC will prepare all reports together as a global community

Implementation Considerations

Reviewing timeline (still evolving)

- Uncertainties from physics case (e.g. HL-LHC), society development, budget profile etc.
- Identify shortest possible timeline
  - Technically limited, success-oriented schedule

Considered important for the timeline

- Muon cooling technologies and integration
- Magnet technology
- Detector technologies
- Civil engineering

Technology readiness appears possible by 2040

- Provided funding is being made available
- Main limitation from the magnet technology

Consensus of magnet experts (review panel):

- Anticipate technology to be **mature in O(15 years):**
  - **HTS solenoids** in muon production target, 6D cooling and final cooling
    - HTS tape can be applied more easily in solenoids
    - Strong synergy with society, e.g. fusion reactors
  - **Nb_3Sn 11 T magnets** for collider ring (or HTS if available): 150mm aperture, 4K
- This corresponds to 3 TeV design
- Could build 10 TeV with reduced luminosity performance
  - Can recover some but not all luminosity later

Staging Approaches

Assumptions:

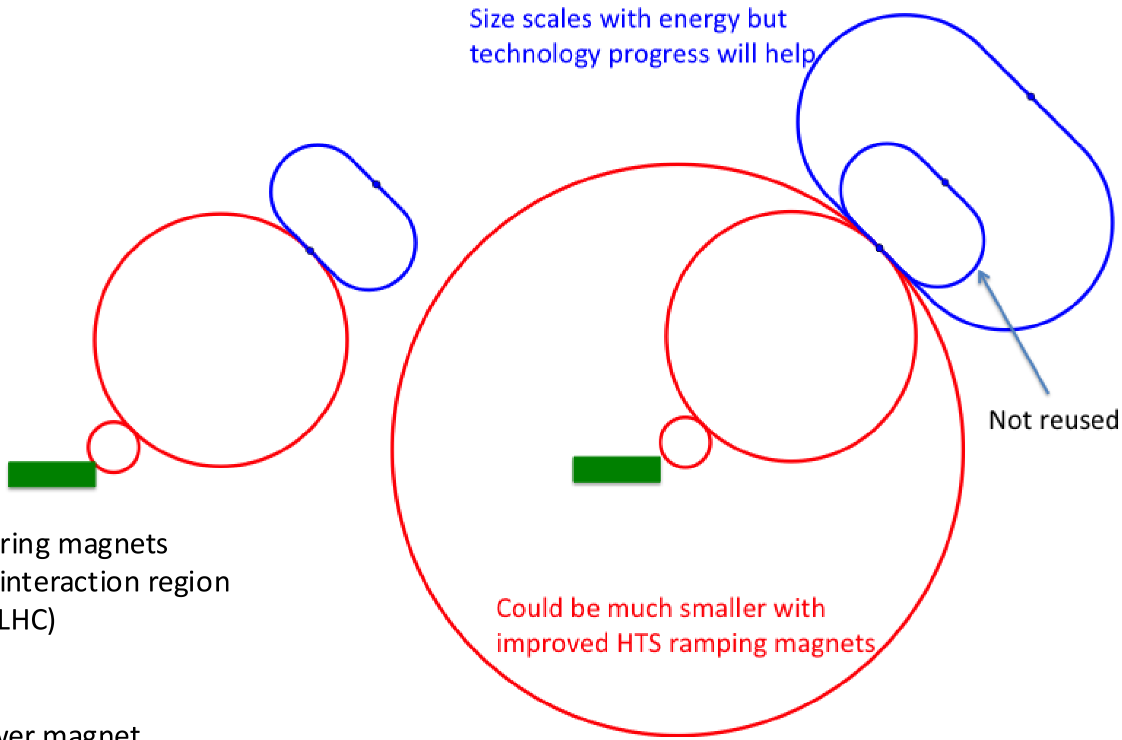
- In O(15 years):
  - HTS technology available for solenoids
  - Nb_3Sn available for collider ring
- In O(25 years):
  - HTS available for collider ring

Scenario 1: Energy staging

- Start at lower energy (e.g. 3 TeV)
- Build additional accelerator and collider ring later
- Requires less budget for first stage
- 3 TeV design takes lower performance into account

Scenario 2: Luminosity staging

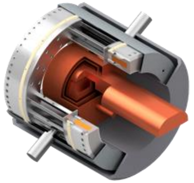
- Start at with full energy, but less performant collider ring magnets
- Main sources of luminosity loss are collider arcs and interaction region
  - Can recover interaction region later (as in HL-LHC)
  - But need full budget right away
  - Some luminosity loss remains (O(1.5))
  - More power for the collider ring required (lower magnet temperature)

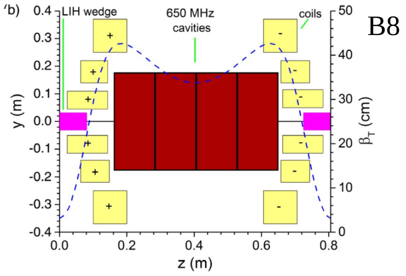


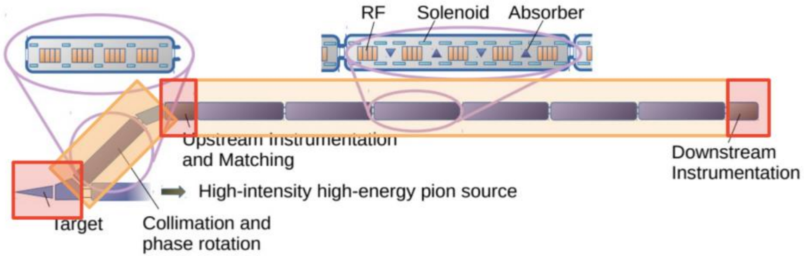
R&D Programme

Broad R&D programme can be distributed world-wide

Muon cooling technology
- **RF test stand** to test cavities in magnetic field
- **Muon cooling cell** test infrastructure
- **Demonstrator**
  - At CERN, FNAL, ESS, JPARC, …
  - Workshop in October at FNAL







Magnet technology
- HTS solenoids
- Collider ring magnets with Nb3Sn or HTS

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

Many **other technologies** are equally important now to support that the muon collider can be done and perform

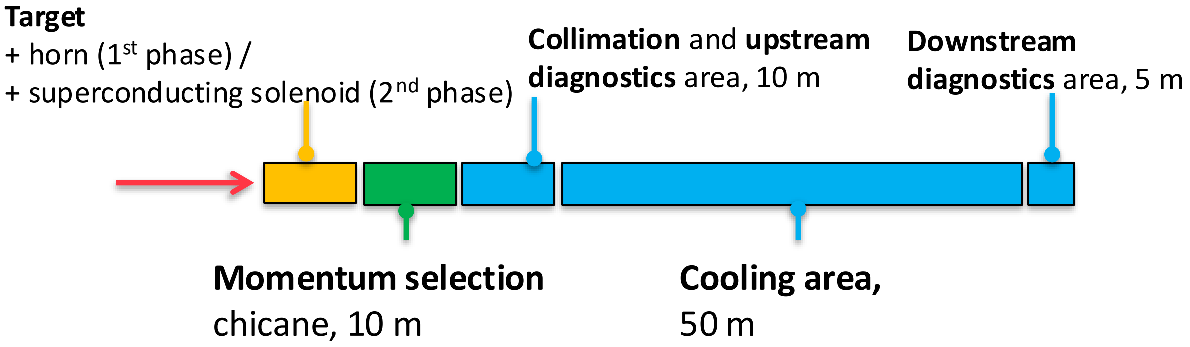
Training of **young people**

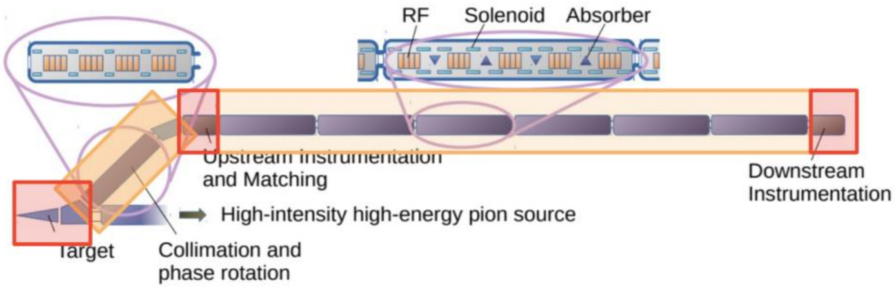
Strong synergy with HFM Roadmap and RF efforts

Test Facility

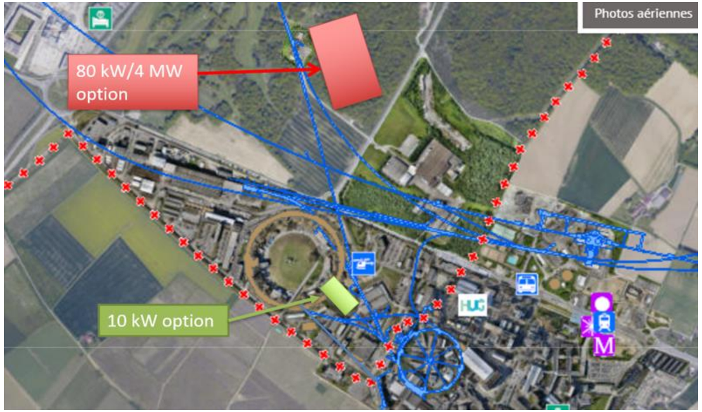
Look for an existing proton beam with significant power

Different sites are being considered
- CERN, FNAL, ESS are being discussed
- J-PARC also interesting as option



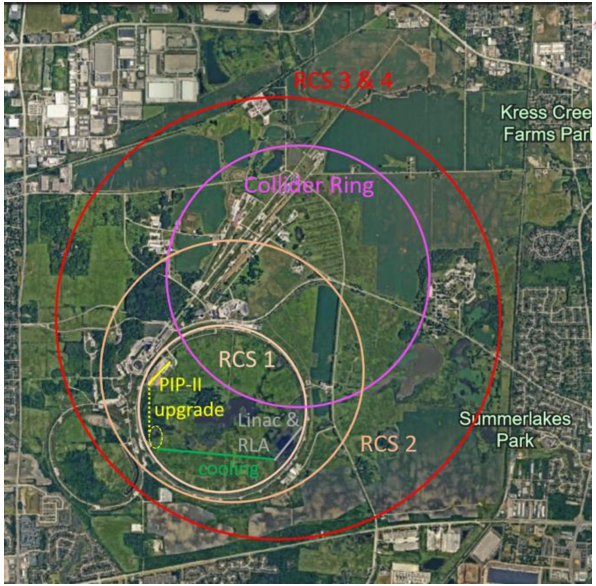


Site choices at CERN, FNAL study in preparation



Site Studies

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

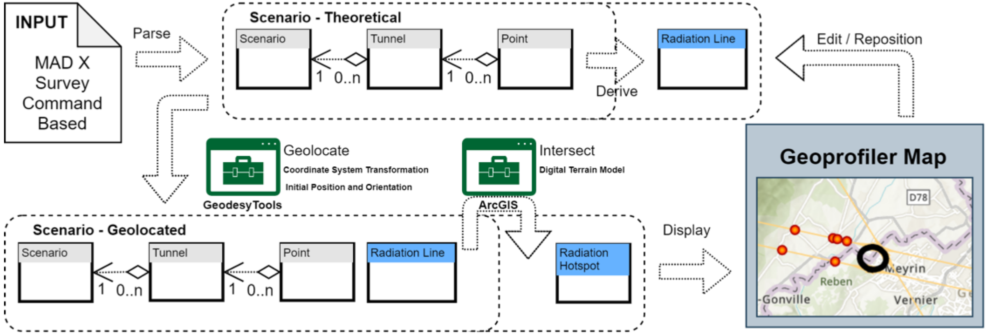


Study is mostly site independent

- 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)

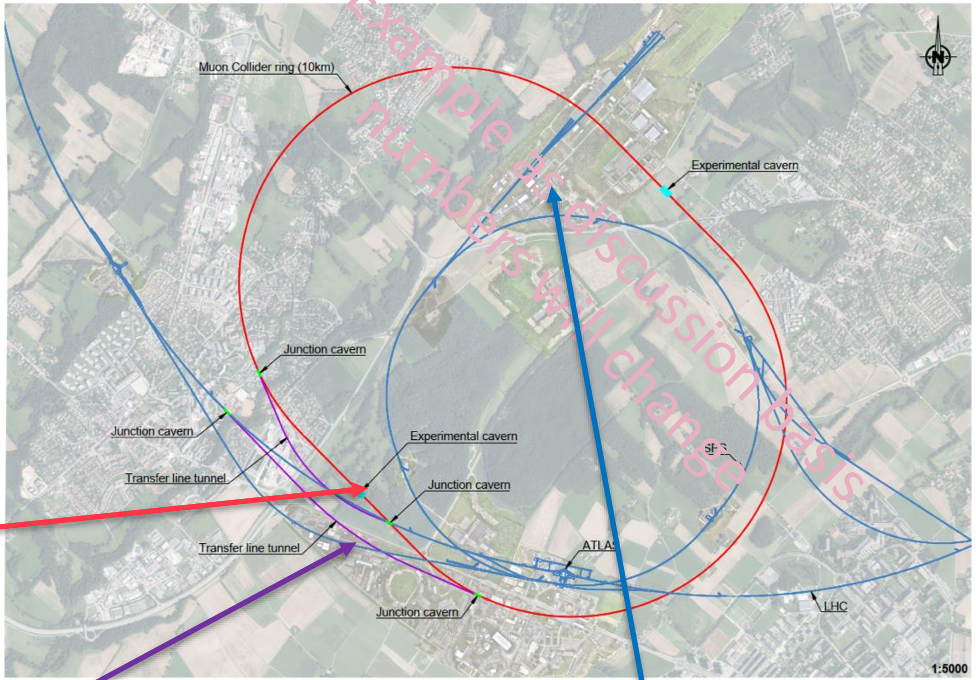
Example CERN Site

MuCol

International MUON Collider Collaboration

First look is promising:

- Collider ring **mitigates neutrino flux from experiments**
    - Some work required to ensure adjacent arcs are negligible
- Good connection to LHC tunnel
- Muon beam cooling complex on CERN land injecting into SPS



Collider ring (10 TeV)
Both experiments on CERN land

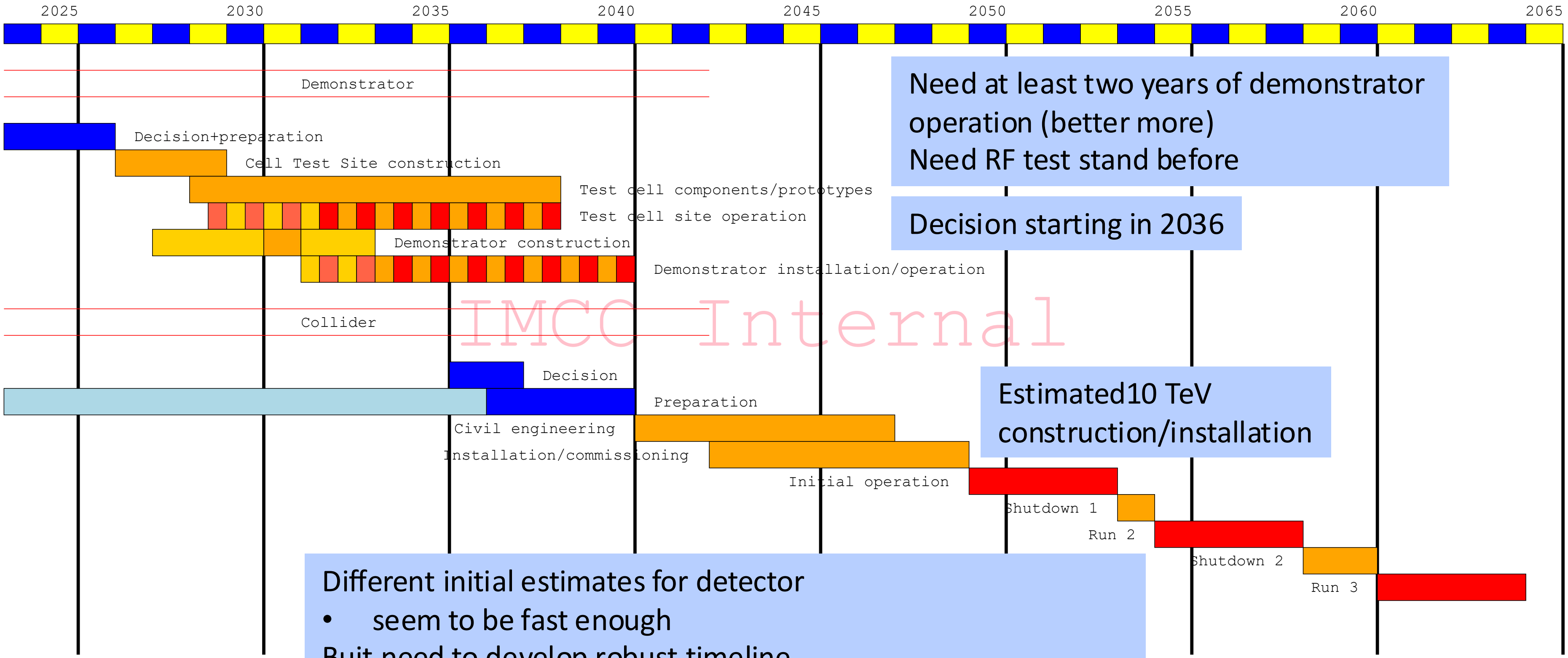
Transferline maximum slope 6%

Potential location of muon cooling complex

Several studies remain to be done

Tentative Timeline (Fast-track 10 TeV)

Only a basis to start the discussion, will review this year



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

Decision starting in 2036

Estimated10 TeV construction/installation

Different initial estimates for detector
- seem to be fast enough

Buit need to develop robust timeline

Cost Estimate

Led by Carlo Rossi, who also does it for CLIC

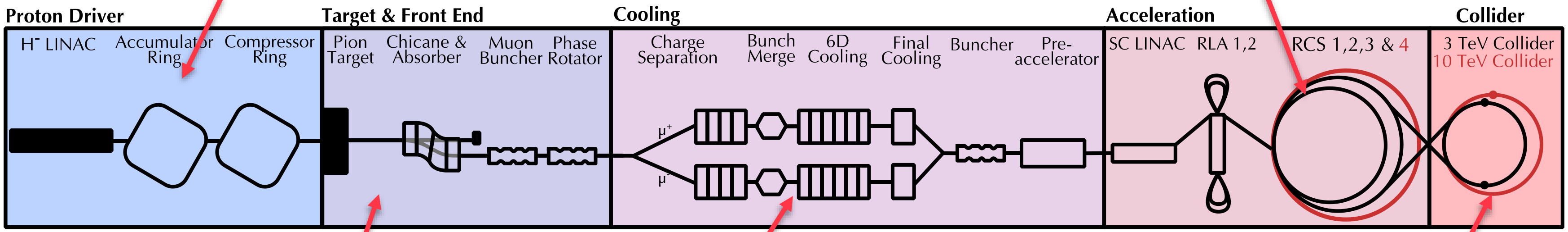
Cost estimate is based on Project Breakdown Structure

- Fill in information at the level it is available to us
- Identify uncertainties
- Make trade-offs
- But cannot optimize at this moment

Overall optimisation not yet done and probably needs time to fully conclude

Detailed studies ongoing of fast-ramping magnet and RF cost and trade-off

Proton complex similar to SPL



Mostly driven by magnet cost

Input data exists, but no optimisation for cost

Magnet cost estimates exist for different configurations

Synergies and Outreach

Training of young people
- Novel concept is particularly challenging and motivating for them

Technologies
- Muon collider needs HTS, in particular solenoids
- Fusion reactors
- Power generators
- Nuclear Magnetic Resonance (NMR)
- Magnetic Resonance Imaging (MRI)
- Magnets for other uses (neutron spectroscopy, detector solenoids, hadron collider magnets)
- Target is synergetic with neutron spallation sources, in particular liquid metal target (also FCC-ee)
- High-efficiency RF power sources and power converter
- RF in magnetic field can be relevant for some fusion reactors
- High-power proton facility
- Facilities such as NuStorm, mu2e, COMET, highly polarized low-energy muon beams
- Detector technologies
- AI and ML

Physics

Conclusion

R&D progress is increasing confidence that the collider is a unique, sustainable path to the future

- Not as mature as some other projects
- Need to do more R&D

Started exploring the implementation at CERN using existing infrastructure

- Looks promising including neutrino flux mitigation

Cost estimate has started

We expect that a first collider stage can be operational by 2050

- If the resources ramp up sufficiently
- If decision-making processes are efficient

Need to continue ramping up the momentum

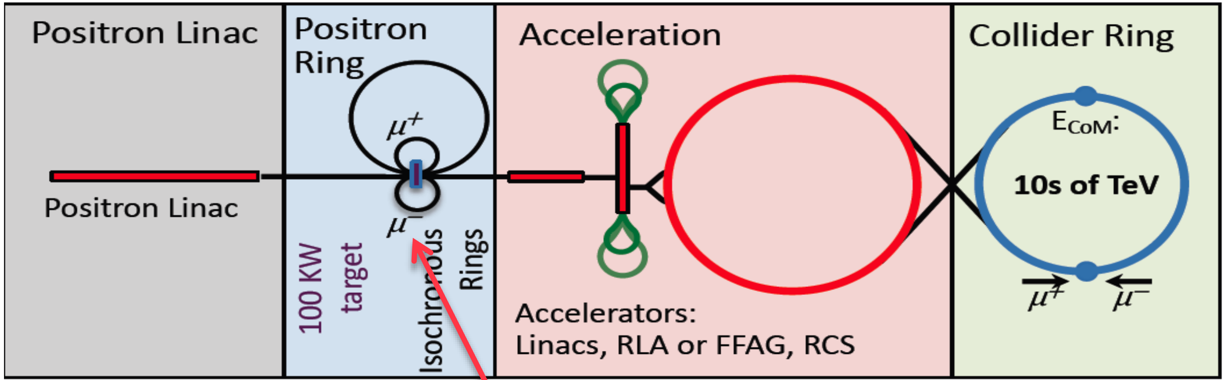
http://muoncollider.web.cern.ch To join contact muon.collider.secretariat@cern.ch

Reserve

Alternatives: The LEMMA Scheme

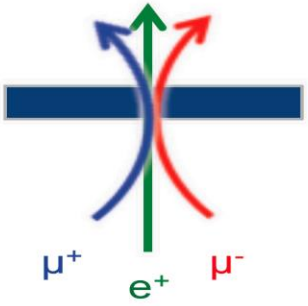
LEMMA scheme (INFN) P. Raimondi et al.

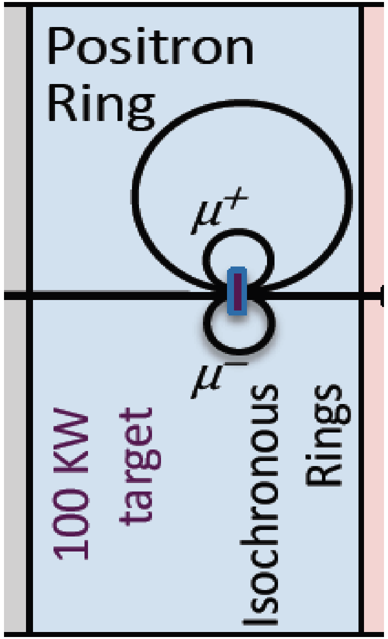
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at
- Uses Bethe-Heitler production with electrons



45 GeV positrons to produce muon pairs
Accumulate muons from several passages

$$e^+e^- \rightarrow \mu^+\mu^-$$





Excellent idea, but nature is cruel

Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme

⇒ **Need same game changing invention**

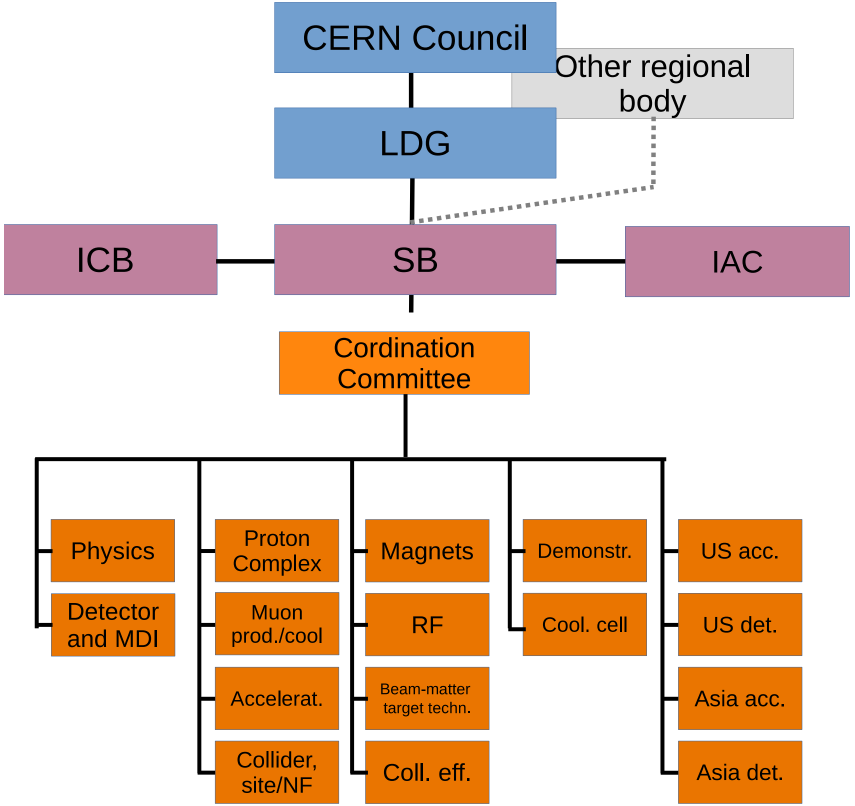
Organisation

Collaboration Board (ICB)
- Elected chair: **Nadia Pastrone**

Steering Board (ISB)
- Chair **Steinar Stapnes**
- CERN members: Mike Lamont, Gianluigi Arduini
- ICB members: Dave Newbold (STFC), Mats Lindroos (ESS), Pierre Vedrine (CEA), N. Pastrone (INFN)
- Study members: SL and deputies
- Will add US but wait for US decision on members

Advisory Committee
- To be defined, discussion in SB

Coordination committee (CC)
- Study Leader: **Daniel Schulte**
- Deputies: **Andrea Wulzer, Donatella Lucchesi, Chris Rogers**



EU Design Study

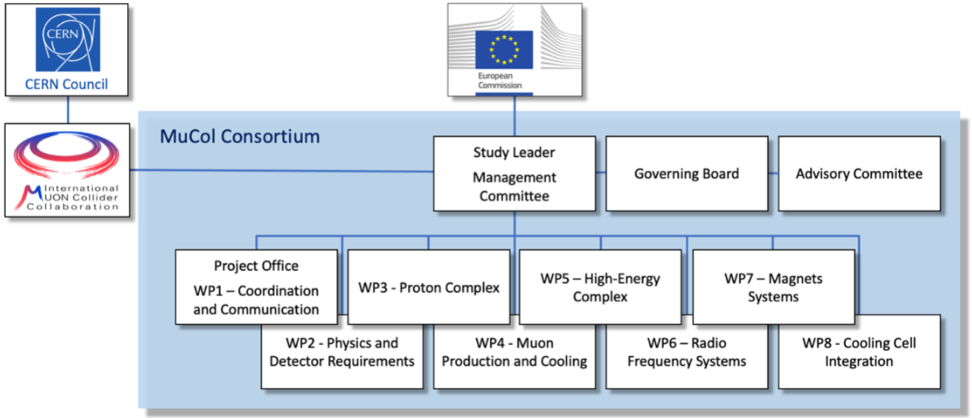
Has been approved summer 2022

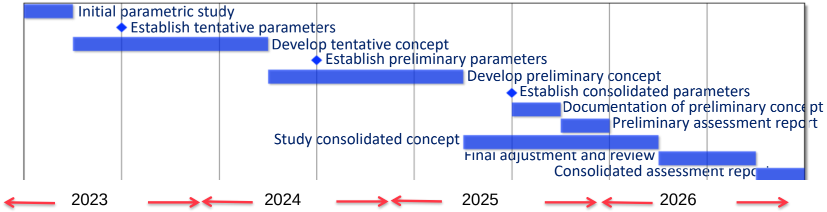
- Very helpful to kick-start collaboration

Reapproved early 2023

- It appears that there has been some issue with the refereeing of several projects, probably not directly with the muon collider

Brings 3 MEUR from the European Commission, the UK and Switzerland and about 4 MEUR from the partners
Basically nothing for CERN





Kick-off meeting in March 2023:
https://indico.cern.ch/event/1219912

Many thanks to all that contributed

https://mucol.web.cern.ch

Sat celeriter fieri quidquid fiat satis bene

US P5 Ask

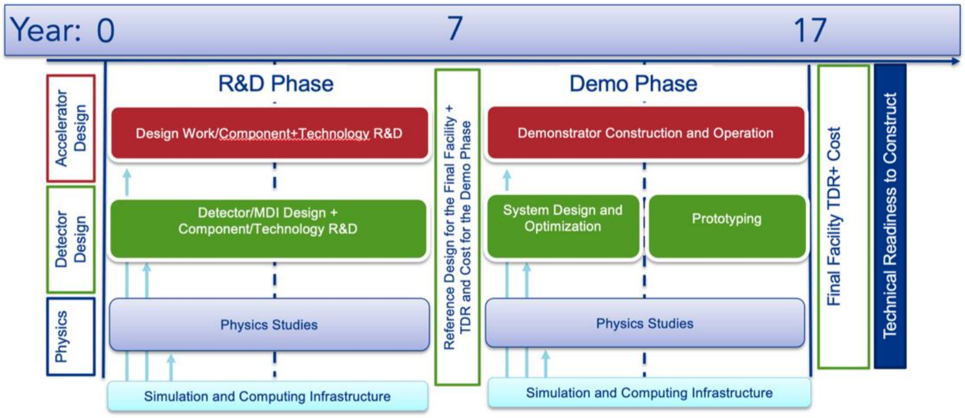
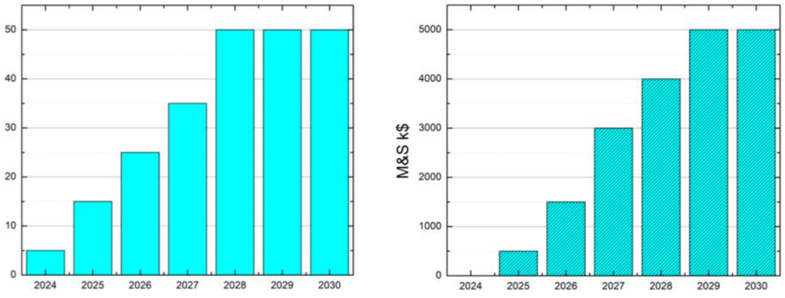


Figure 1: A sketch of the proposed muon collider R&D timeline, along with high-level activities, milestones, and deliverables.



: FTE and M&S profiles for accelerator R&D corresponding to the first phase of the . We assume here that funding can start in 2024. The M&S is in FY23 dollars and n is not included in these estimates.

S. Jindariani, D. Stratakis, Sridhara Dasu et al.

Goal is to contribute as much as Europe

Start of construction a bit later than in Roadmap

Will try to harmonise/define scenarios once US joins

Total resources would approach Roadmap

- Some increase in Europe and Asia assumed
- 1-2 years delay
- But profile is different

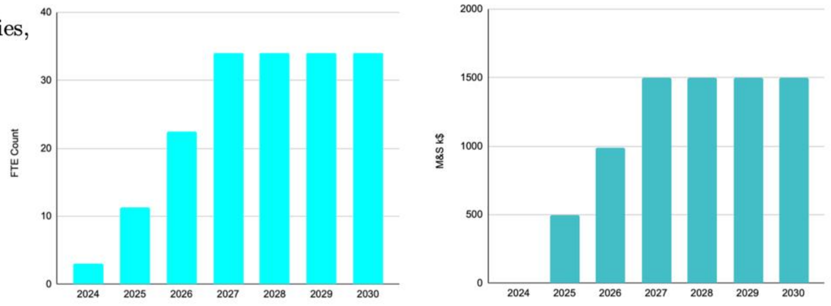


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

Muon Collider Luminosity Scaling

Fundamental limitation

Requires emittance preservation and advanced lattice design

Applies to MAP scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

Luminosity per power increases with energy
Provided technologies can be made available

Constant current for required luminosity scaling

Staging

MuCol

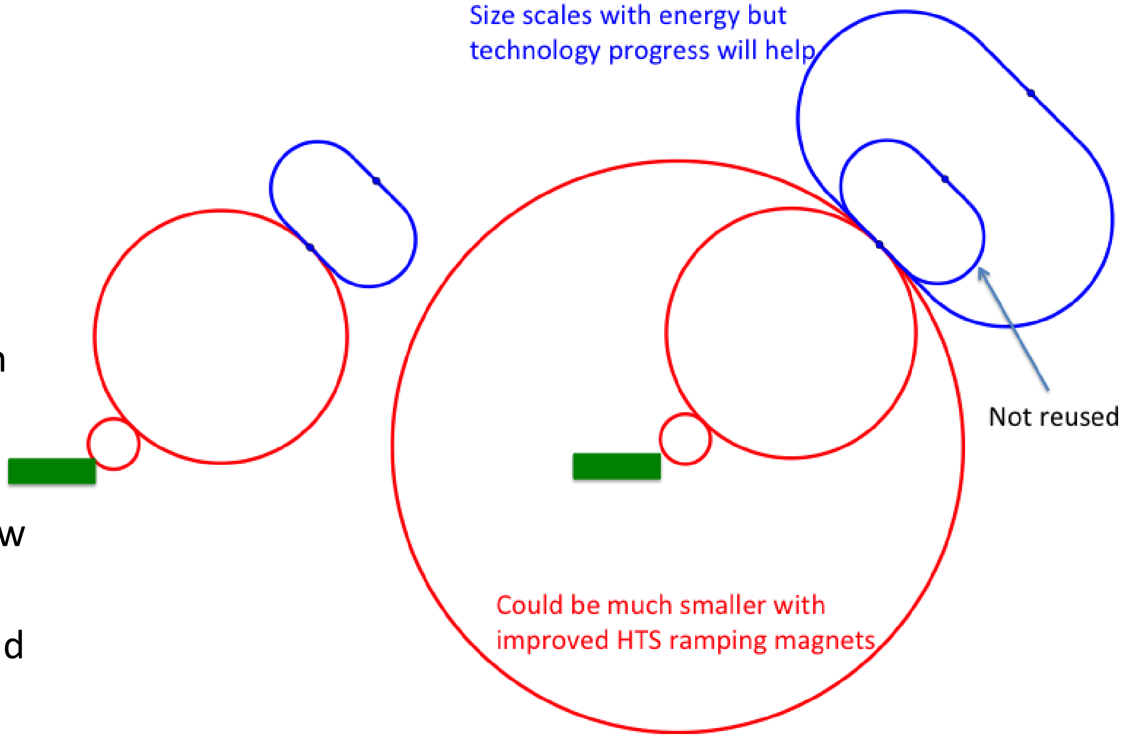
International MUON Collider Collaboration

Ideally would like full energy right away, but staging could lead to faster implementation

- Substantially less cost for a first stage
- Can make technical compromises
  - e.g. 8 T NbTi magnets would increase collider ring from 4.5 to 6 km and reduce luminosity by 25%
- Timeline might be more consistent with human lifespan

Upgrade adds one more accelerator and new collider ring

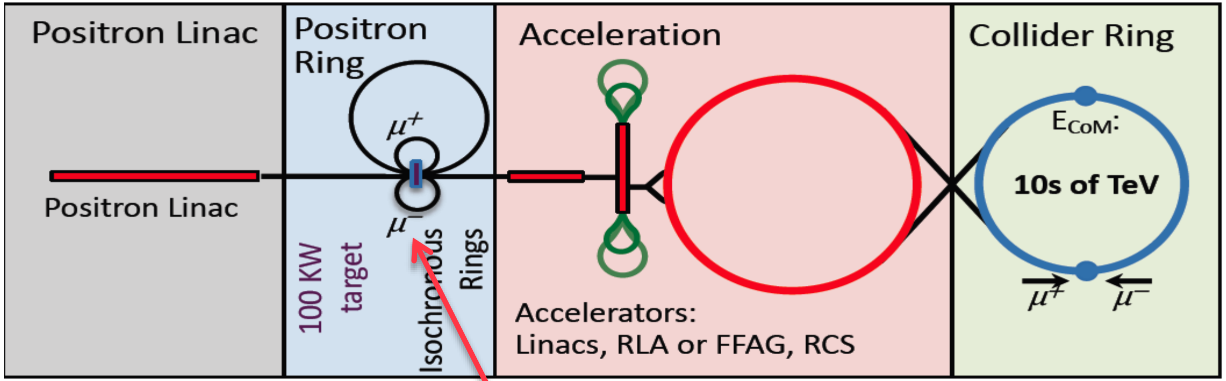
- only first collider ring is not being reused



Alternatives: The LEMMA Scheme

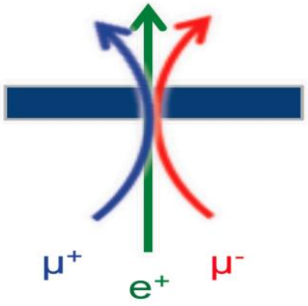
LEMMA scheme (INFN) P. Raimondi et al.

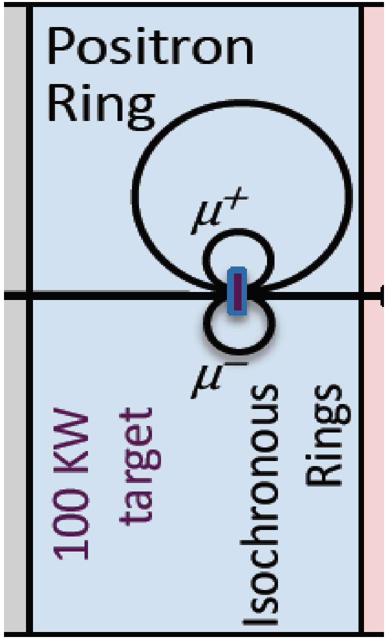
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at
- Uses Bethe-Heitler production with electrons



45 GeV positrons to produce muon pairs
Accumulate muons from several passages

$$e^+e^- \rightarrow \mu^+\mu^-$$



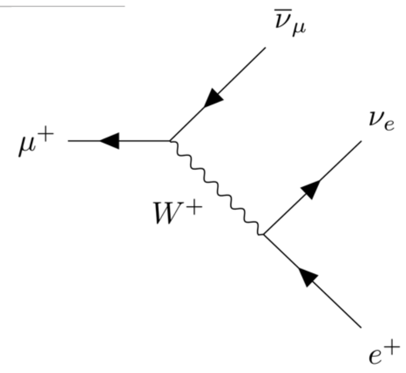


Excellent idea, but nature is cruel

Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme

$\Rightarrow$ **Need same game changing invention**

Muon Decay



About 1/3 of energy in electrons and positrons:

Experiments needs to be protected from **background** by masks

- simulations of 1.5, 3 and 10 TeV
- optimisation of masks and lattice design started
- first results look encouraging
- will be discussed at ICHEP

Collider ring magnets need to be shielded from losses

Losses elsewhere will also need to be considered but are less severe

D. Lucchesi, A. Lechner, C Carli et al.

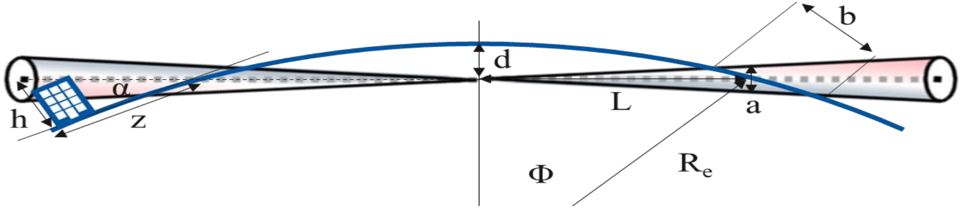
Neutrino flux to have negligible impact on environment

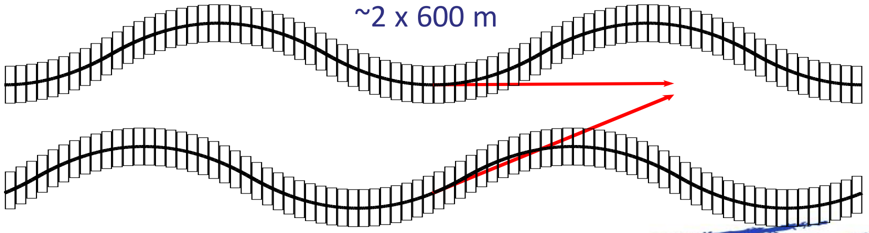
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

Above about 3 TeV need to make beam point in different vertical directions

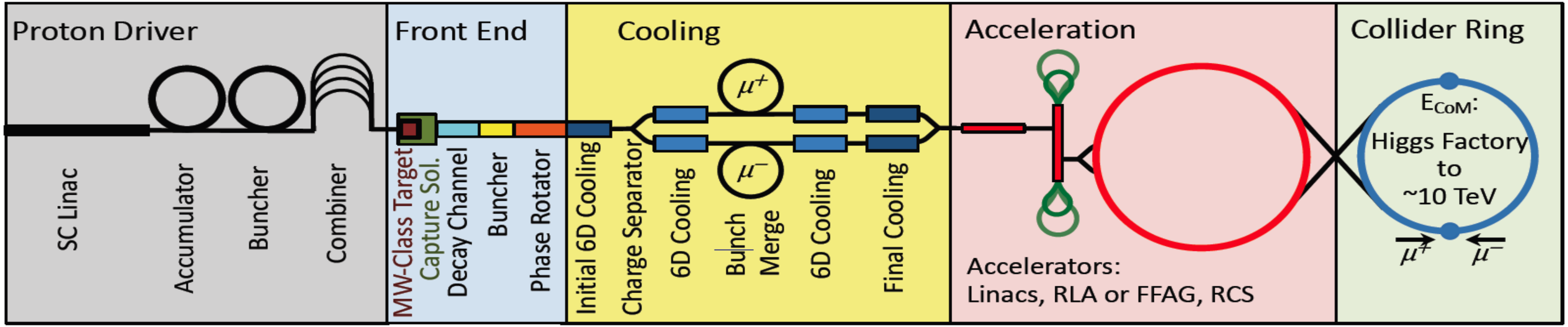
Mechanical system with 15cm stroke, 1% vertical bending

Length of pattern to be optimised for minimal impact on beam





Key Challenges



Proton complex
- Compressing protons to few bunches

Target
- Target
- Solenoid

Cooling channel
- Channel design
- Solenoids
- RF in magnetic field
- Absorbers
- Integration

RCS
- Beam dynamics
- Ramping magnets
- Power converter
- RF system

Collider ring
- Optics
- Magnets
- Neutrino flux
- Detector background

Roadmap

In **aspirational scenario** can make **informed decisions**:

Three main deliverables are foreseen:

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

R&D Plan

The R&D plan will describe the R&D path toward the collider, in particular during the CDR phase, and will comprise the elements below.

- An integrated concept of a muon cooling cell that will allow construction and testing of this key novel component.
- A concept of the facility to provide the muon beam to test the cells.
- An evaluation of whether this facility can be installed at CERN or another site.
- A description of other R&D efforts required during the CDR phase including other demonstrators.

This R&D plan will allow the community to understand the technically limited timeline for the muoncollider development after the next ESPPU.

Minimal Scenario

MuCol

International MUON Collider Collaboration

Will allow **partially informed decisions**

- No conceptual design of neutrino flux and alignment system
- No alternative superconducting fast-ramping magnet system
- Several collider systems would (almost) not be covered, in particular
  - the linacs
  - the target complex
  - the proton complex
  - engineering considerations of the muon cooling cells
  - alternative designs for the final cooling system, acceleration, collider ring
- No RF test stand would be constructed for the muon cooling accelerating cavities
- No conceptual design of a muon cooling cell for the test programme
- No conceptual design of a muon cooling demonstrator facility
- No concept of RF power sources
- No tests/models to develop solenoid technology.

Key Technologies

Magnets

- Superconducting solenoids for target and cooling profit from developments for society
  - target solenoid comparable to ITER central solenoid fusion
  - 6D cooling solenoids similar and wind power generators, motors
  - final cooling solenoids synergetic with high-field research, NMR
- Collider ring magnets
  - profit from developments for other colliders FCC-hh, stress-managed magnets
- Fast-ramping normal-conducting magnet system
  - HTS alternative, power converter

RF systems

- superconducting RF, normal-conducting RF, efficient klystrons

Target, cooling absorbers, windows, shielding

Neutrino mitigation mover system, cooling cell integration, …

Detector

Key Technologies, cont.

RF systems

- Normal-conducting cooling cavities in magnetic field
  - profit from CLIC work
- Superconducting accelerator RF
  - profit from ILC, …
- Efficient power sources
  - profit from CLIC work

Beam-matter interaction

- Proton target
- Cooling absorbers
- Shielding (accelerator and detector)

Mechanical system

- Neutrino flux mitigation system
- Muon cooling cell integration

Collaboration Vision

IMCC is an **international** collaboration and aims to

- Enlarge the collaboration
  - Physics interest in all regions, strong US contribution to the muon collider physics and detector, interest in Japan
  - First US university have joined collaboration, try to see how to move forward, also with labs
- Combine the R&D efforts for the design and its technologies
  - Critical contributions in all relevant fields in the US
- Consider several sites for the collider
  - CERN would be one, FNAL and others should also be considered
  - A proposal with alternative sites is stronger for a single site
- Consider several sites for the demonstrators
  - E.g. Muon production and cooling demonstrator at CERN, FNAL, ESS, JPARC
  - e.g. RCS at ESRF or elsewhere
  - Target tests
  - …

Initial 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}

Note: currently focus on 10 TeV, also explore 3 TeV

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

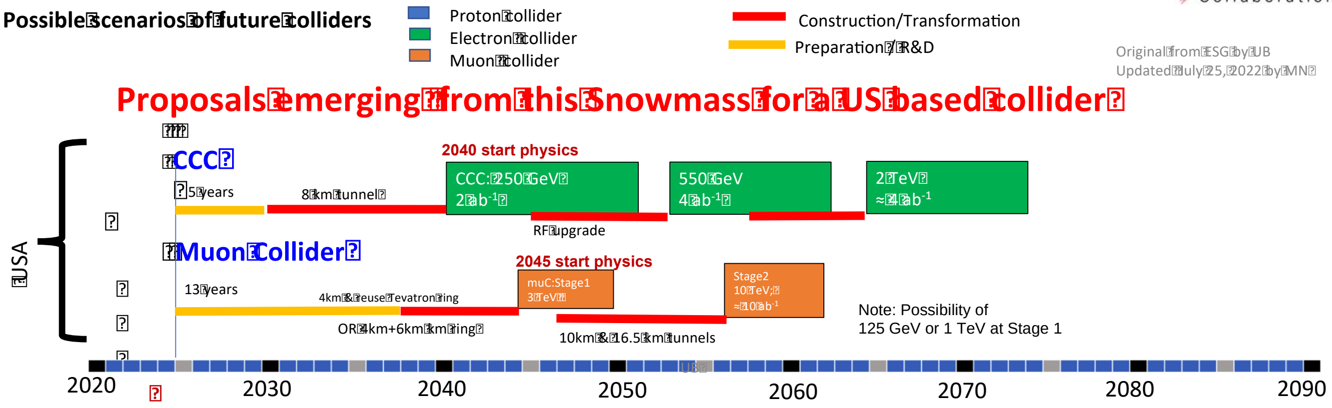
Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40	2 (6)
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	MW	5.3	14.4	20	28
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	
β	mm	5	1.5	1.07	
ε	µm	25	25	25	
$\sigma_{x,y}$	µm	3.0	0.9	0.63	

US Snowmass

Strong interest in the US community in muon collider
- seen as an energy frontier machine
- decoupled from LC

US community wants funding for **R&D**
- **Goal: match European effort**

Community interested in the US to **host a muon collider**



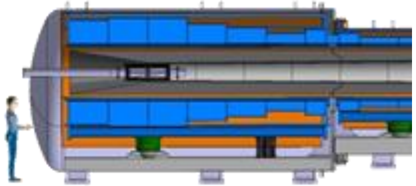
- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

Consider proposing hosting ILC in the US.

Meenakshi Narain: Energy Frontier / Large Experiments, Snowmass Community Summer Study July 17-26, 2022

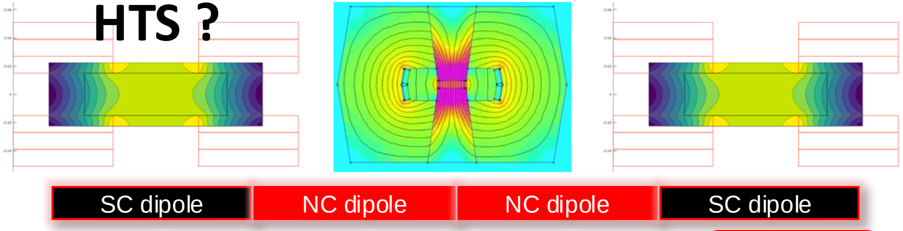
Muon Collider magnets

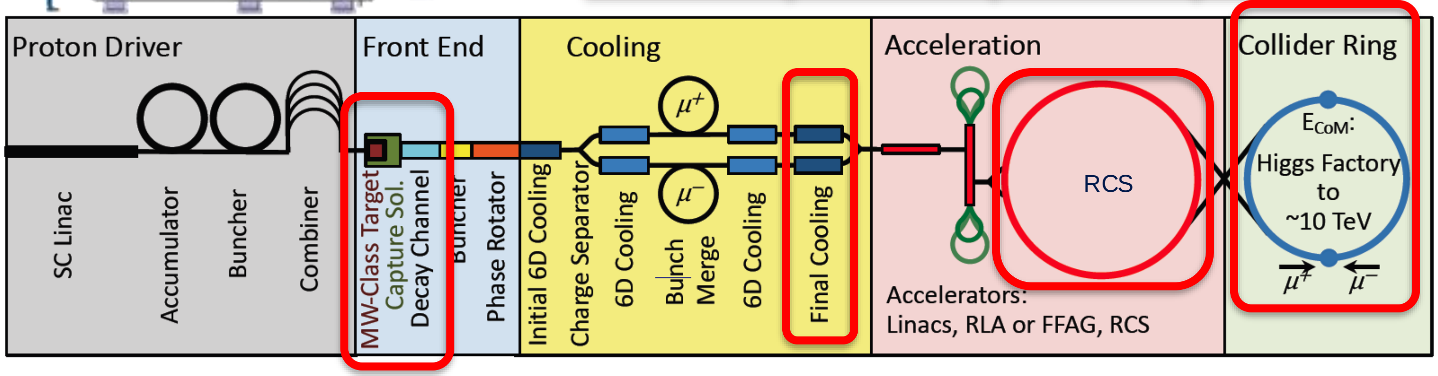
20 T, 200 mm **HTS !**
Radiation heat load ≈ 5...10 kW
Radiation dose: 80 MGy



NC ±1.8 T, 400 Hz
100 mm x 30 mm

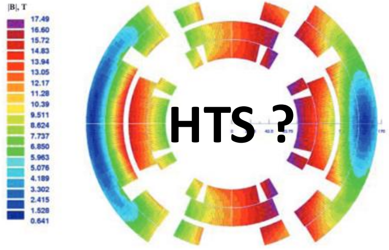
SC < 10T
100 mm x 30 mm





> 40 T, 60 mm

16 T peak, 150 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20...40 MGy



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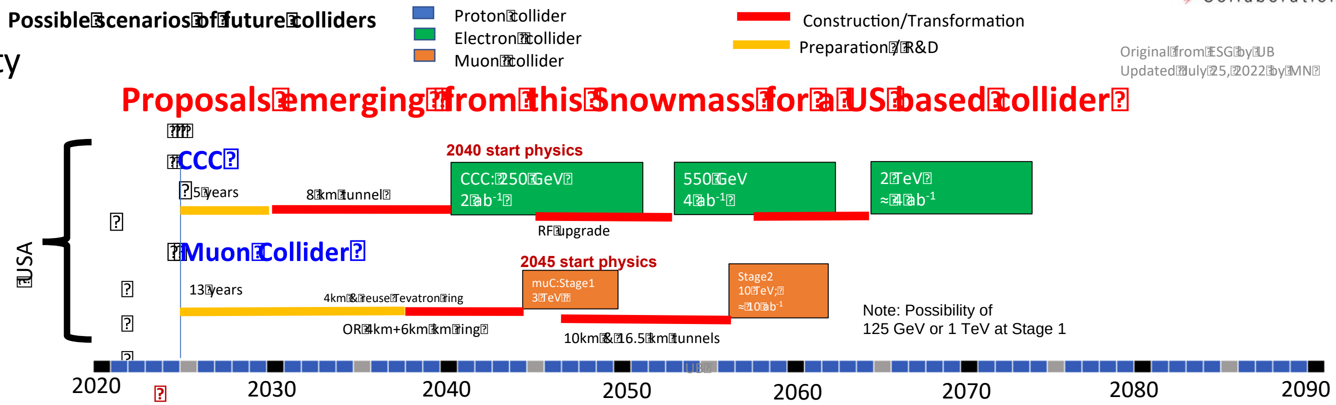

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Meenakshi Narain: Energy Frontier / Large Experiments, Snowmass Community Summer Study July 17-26, 2022

Coordination Committee Members

Physics	Andrea Wulzer
Detector and MDI	Donatella Lucchesi

Protons	Natalia Milas
Muon production and cooling	Chris Rogers
Muon acceleration	Antoine Chance
Collider	Christian Carli

Magnets	Luca Bottura
RF	Alexej Grudiev, Dario Glove
Beam-matter int. target systems	Anton Lechner
Collective effects	Elias Metral

Cooling cell design	Lucio Rossi
Demonstrator	Roberto Losito

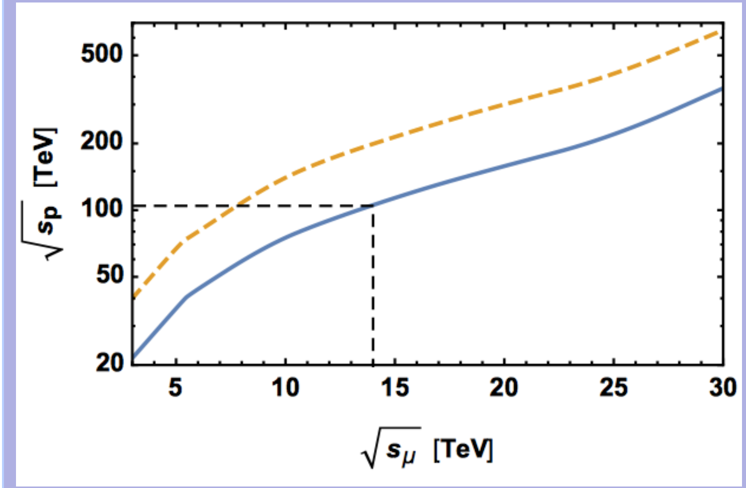
US (detector)	Sergo Jindariani
US (accelerator)	Mark Palmer
Asia (China)	Jingyu Tang
Asia (Japan)	tbd

A strengthening on the physics and detector side is planned

Physics Goals

Full lepton energy available for production of new particles, in protons only a fraction

Discovery reach
10-14 TeV lepton collisions are comparable to 100-200 TeV proton collisions for production of heavy particle pairs



Need more luminosity at higher energies as production cross section decreases

Luminosity goal
(Similar to $L(E_{CM} > 0.99\ E_{CM,0})$ CLIC at 3 TeV)
$4x10^{35}\ cm^{-2}s^{-1}$ at 14 TeV

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

Yields constant number of events in the s-channel

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

Physics Studies

Details on physics case, detector and accelerator can be found in

- Snowmass white papers https://indico.cern.ch/event/1130036/
- EPJC report in preparation

Used tentative detector performance specifications in form of DELPHES card

- based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)
- Please find the card here: https://muoncollider.web.cern.ch/node/14

M. Selvaggi, W. Riegler, U. Schnoor, A. Sailer, D. Lucchesi, N. Pastrone, M. Pierini, F. Maltoni, A. Wulzer et al.

Initial detector simulation studies at 1.5 and 3 TeV indicate that this is a **good model**

Now moving to 10 TeV

D. Lucchesi, F. Meloni et al.

If you are interested to contribute please contact me or the responsible deputies:

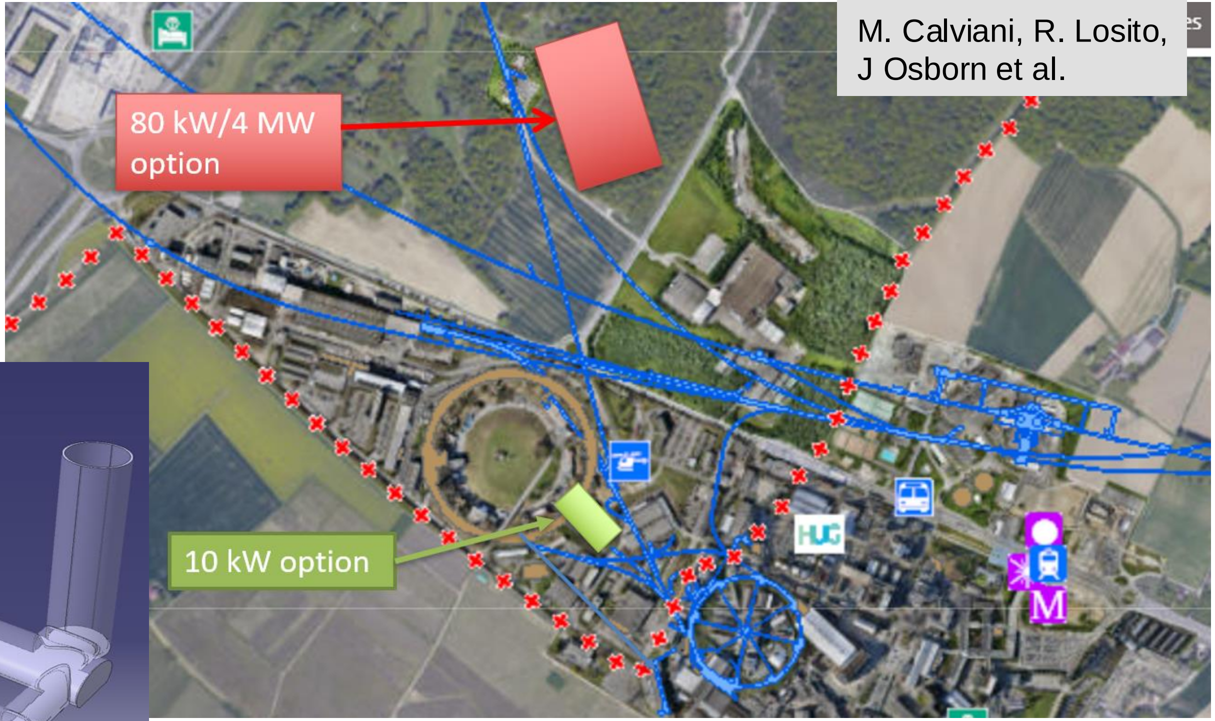
Andrea Wulzer (Physics) and **Donatella Lucchesi (Detector and MDI)**

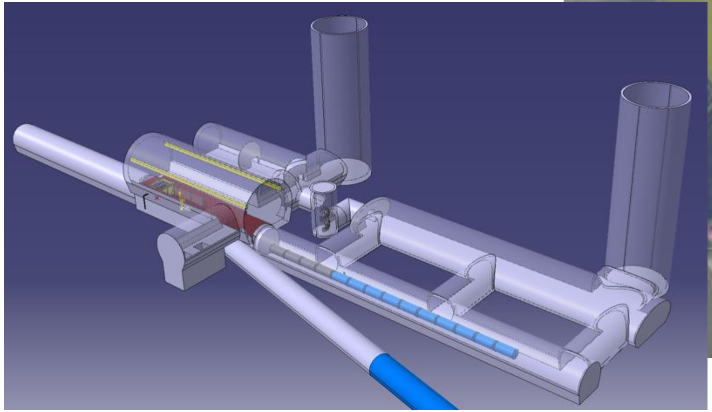
Possible CERN Locations

Consider nTOF-like beam from PS for cooling experiment:

- 1 pulse of 10^{13} p at 20 GeV per 1.2 s, i.e. 27 kW
- maybe O(100kW) possible

If SPL were, installed could use its beam, e.g. 5 GeV, 4 MW





Collider Site Studies

Study is mostly site independent
However, some considerations are being made
Candidate sites are **CERN, FNAL,** potentially others **(**ESS, JPARC, …)

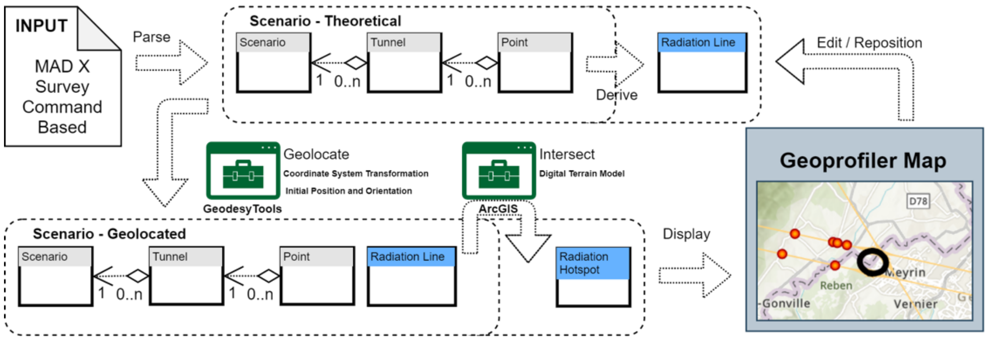
- FNAL takes test facility into account in their ACE plans

But need some site considerations

Main site concern:
Neutrino flux mitigation
Neutrinos in direction of experimental insertions need to be mitigated by site choices

Main site benefit:
Potentially significant cost saving from reusing exiting infrastructure

Will study this later



Potential site next to CERN identified

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

Muon Collider Timeline (Roadmap)

Technically limited timeline

To be reviewed considering progress, funding and decisions

Muon collider important in the long term

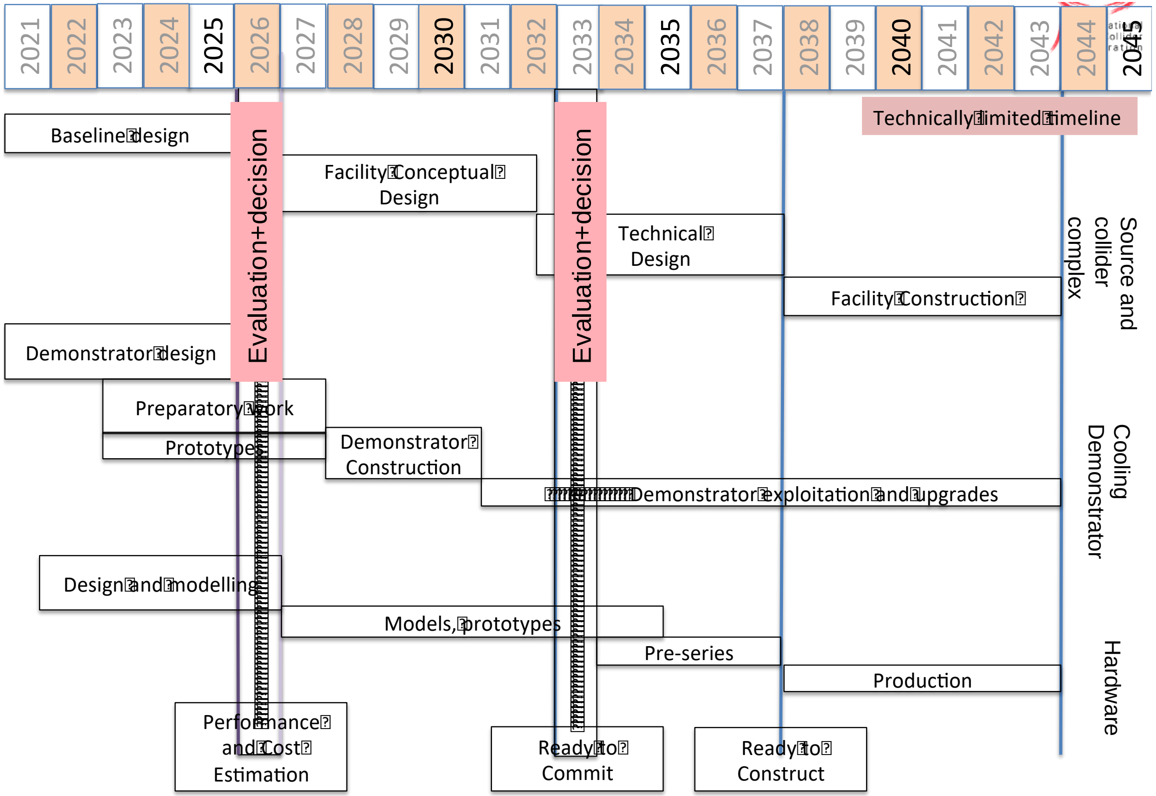
- Even after potential FCC-hh

But also **plan B as next project in Europe** and maybe **plan A in US** and elsewhere

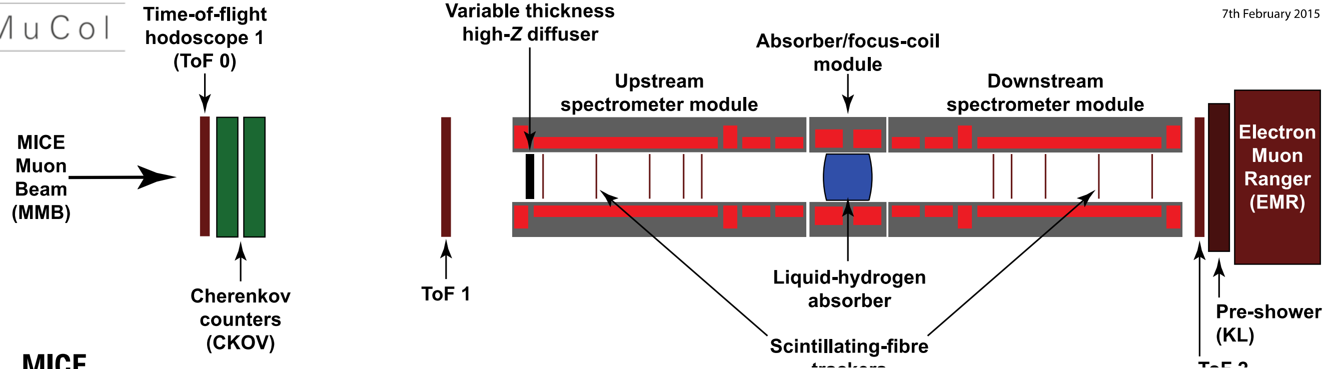
Fast track option if require next as project after HL-LHC:

- Lower energy initial option, e.g. 3 TeV
- Upgrade to 10 TeV later
  - Little extra cost

Subject to funding

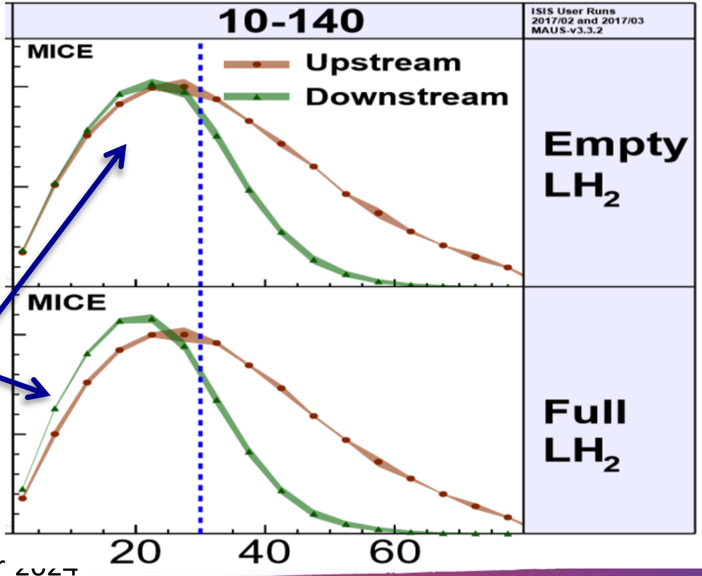


MICE: Cooling Demonstration



MICE

Principle of ionisation cooling has been demonstrated
Use of data for benchmarking is still ongoing



More particles at smaller amplitude after absorber is put in place

Nature vol. 578, p. 53-59 (2020)

More complete experiment with higher statistics, more than one stage required

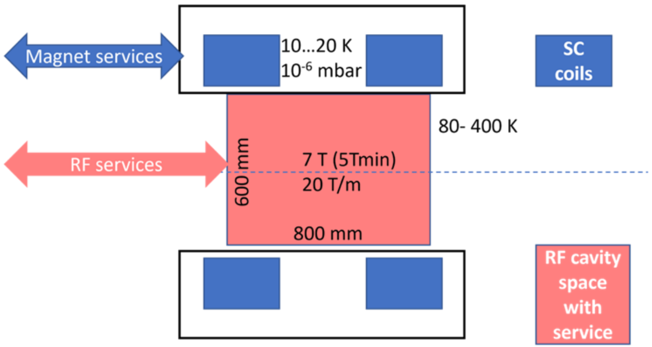
Integration of magnets, RF, absorbers, vacuum is engineering challenge

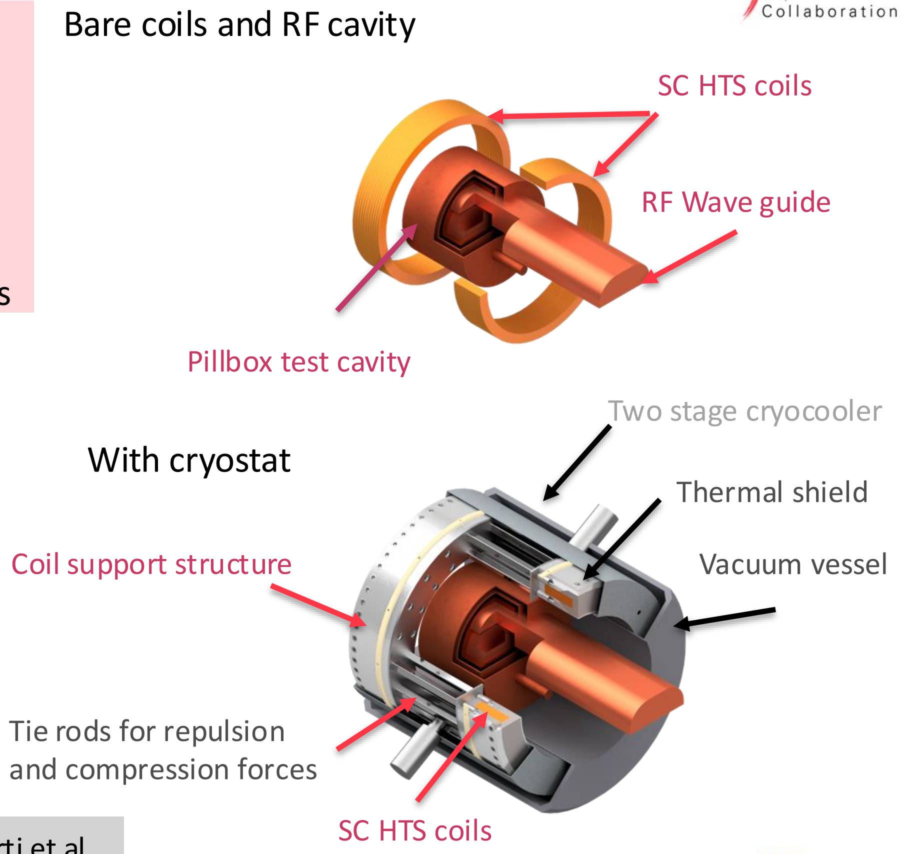
RF Test Stand

Module work focuses on RF test stand at this moment

- Important ensure timely R&D plan
- Try to identify infrastructure for this
  - CEA, INFN, Cockroft, CERN, …
  - Will not be cheap so need to find resources

Schematic of the RFMF test facility single cryostat



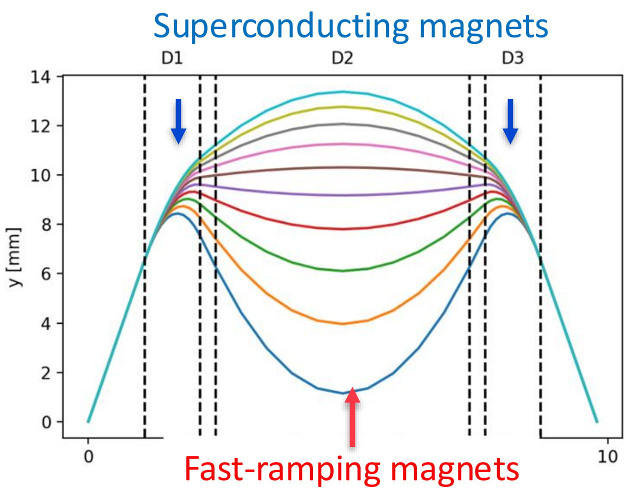


L. Rossi, C. Marchand, D. Giove, A. Gurdiev, G. Ferrand, M. Castoldi, S. Sorti et al.

Use of SPS and LHC Tunnels

Filling factor of green field studies for the arcs
Consider hybrid and non-hybrid designs

Use robust assumptions for the magnets (10 T static and 1.8 T ramping magnets)



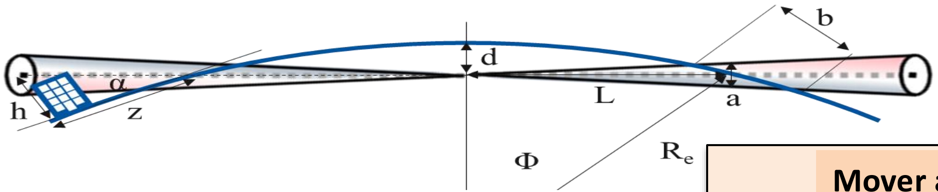
		Scenario 1	Scenario 2a	Scenario 2b
SPS	RCS 1	380*	380*	380*
	RCS 2	---	860	860
LHC	RCS 3	1250*	2700	2700
	RCS 4	---	---	4000

Stronger magnets or better filling factors would allow 10 TeV

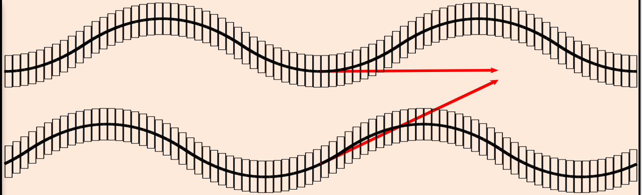
Need to confirm whether LHC cross section can house two RCSs

Neutrino Flux

Goal: **similar to LHC**: limit neutrino flux to have **negligible impact**, "fully optimised" (10% of MAP goal)
Verify performance of concept to be good for 14 TeV

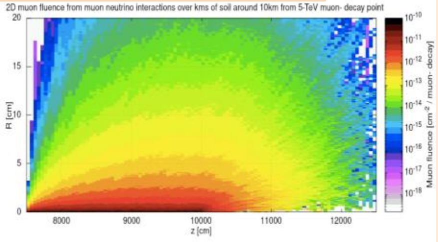


Mover and support system



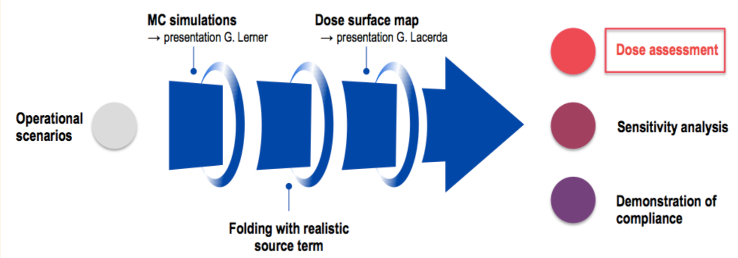
F. Bertinelli et al. (CERN, Riga)

FLUKA dose studies



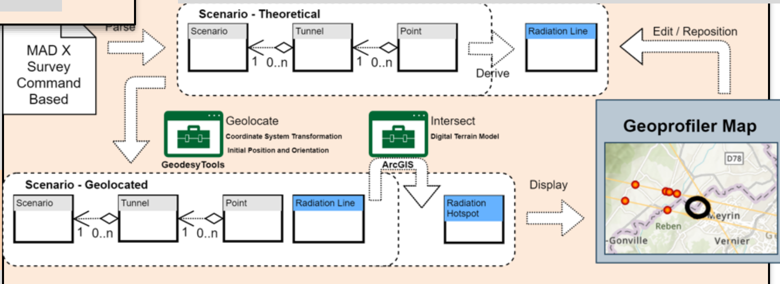
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme

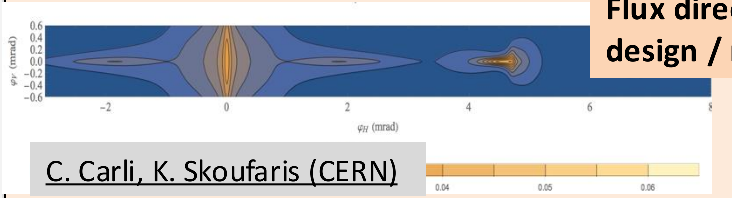


C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

G. Lacerda, Y. Robert, N. Guilhaudin (CERN)



Flux direction map / lattice design / mover impact on beam



C. Carli, K. Skoufaris (CERN)

Mitigation: Site choice tool

Magnet Roadmap

Consensus of experts (review panel):

- Anticipate technology to be **mature in O(15 years):**
  - **HTS solenoids** in muon production target, 6D cooling and final cooling
    - HTS tape can be applied more easily in solenoids
    - Strong synergy with society, e.g. fusion reactors
  - **Nb_3Sn 11 T magnets** for collider ring (or HTS if available): 150mm aperture, 4K
- This corresponds to 3 TeV design
- Could build 10 TeV with reduced luminosity performance
  - Can recover some but not all luminosity later

Still under discussion:

- Timescale for HTS/hybrid collider ring magnets
- For second stage can use **HTS or hybrid collider ring magnets**

Strategy:

- HTS solenoids
- Nb_3Sn accelerator magnets
- HTS accelerator magnets

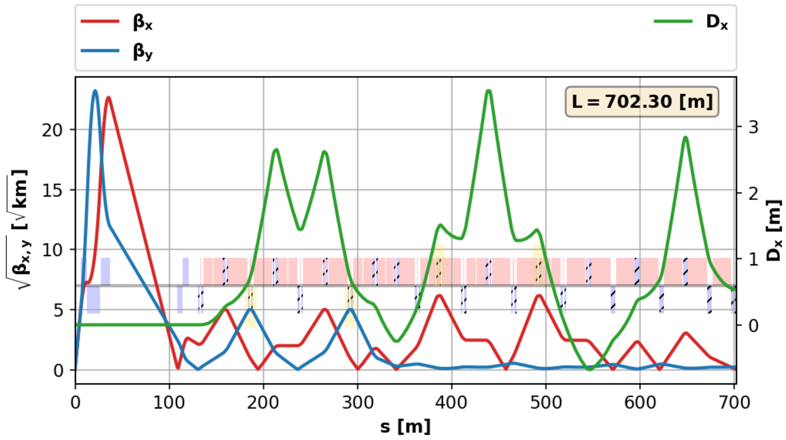
Seems technically good for any future project

Collider Ring

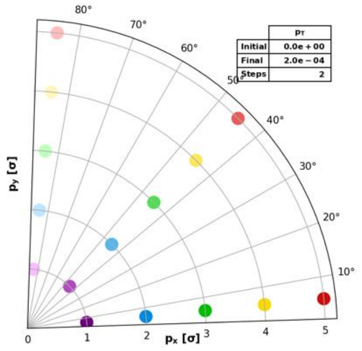
Challenges:
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

MAP developed 4.5 km ring for 3 TeV with Nb_3Sn
- magnet specifications in the HL-LHC range

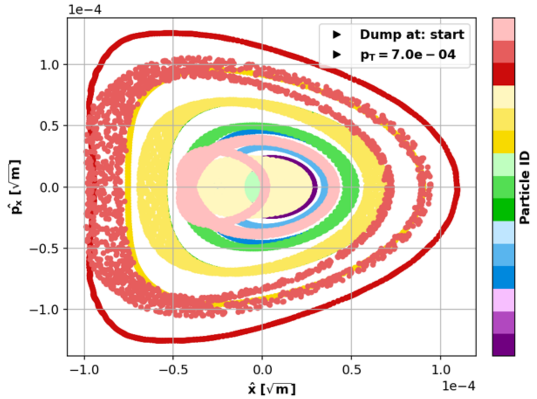
Work progressing on **10 TeV collider ring**
- around 16 T HTS dipoles or lower Nb_3Sn
- final focus based on HTS



K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas



p_T [%]	DA_{min} [σ]
0.07	5
0.08	4
0.09	3
0.1	<1



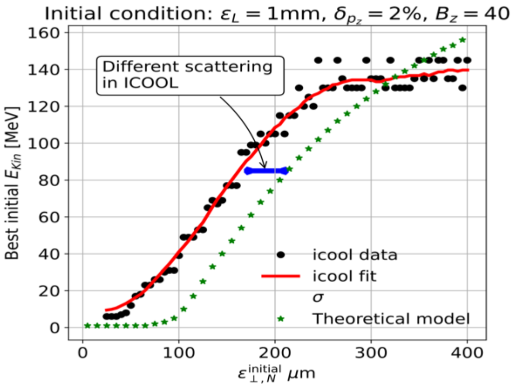
Important progress: V0.6 good dynamic aperture at almost 0.1% off-energy, approaching the target

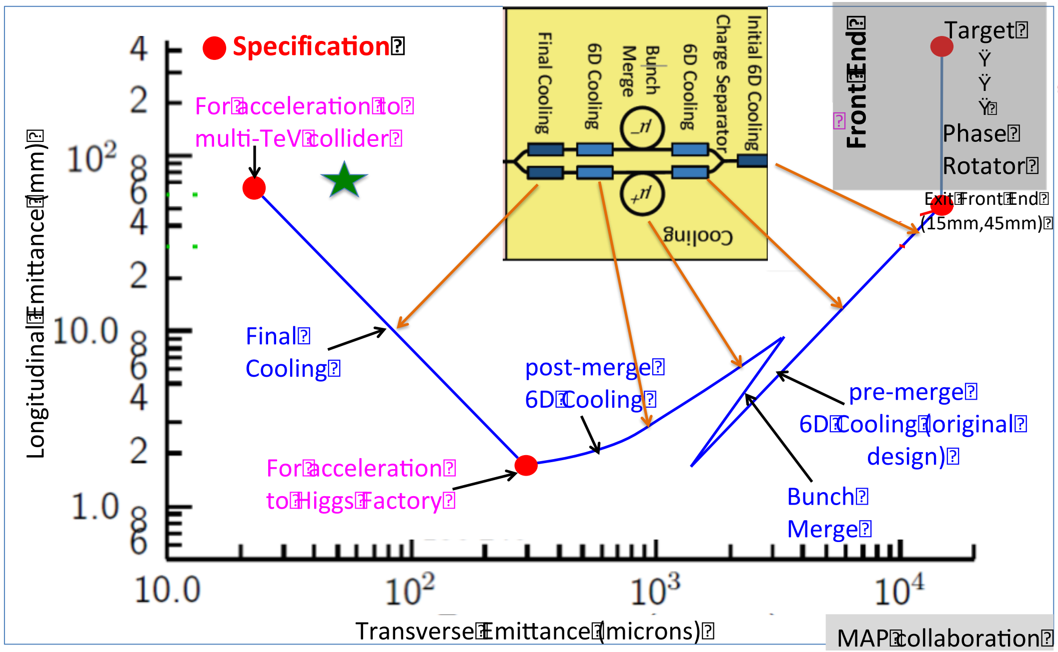
Muon Cooling Performance

MAP design achieved 55 um based on achieved fields

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

A. Latina, E. Fol, B. Stechauner at al.





Simple 50 T design achieves 24 um and better longitudinal emittance

- Need to improve transmission by factor 1.6 (large part of losses due to beam dynamics not muon decay)
- Higher power target would increase charge by factor 1.9
  - But need to work on beamloading in accelerator chain

Ch. Rogers, Zhu Ruihu, R. Taylor, B. Stechauner, E. Vol et al.

Are working on more detailed design

- 40 T solenoid
- Including windows
- Final absorbers are H2 vapor
- 30 um transverse emittance

Collider Ring Technology

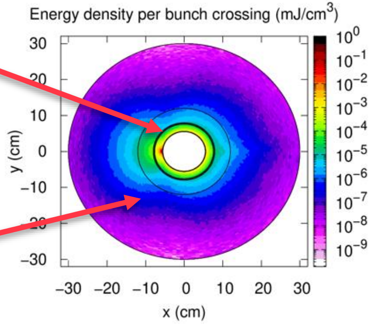
L. Bottura et al.

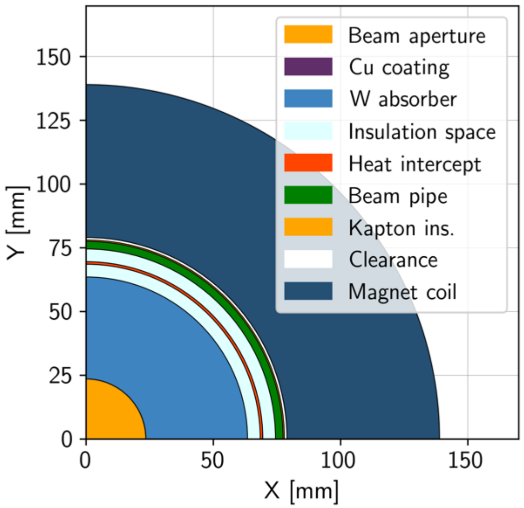
Power loss due to muon decay 500 W/m
FLUKA simulation of **shielding:**
Require 30-40 mm tungsten
- Few W/m in magnets
- No problem with radiation dose

Shielding

A. Lechner
D. Calzolari
(CERN)

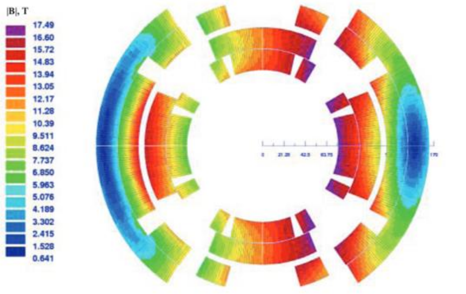
Coil

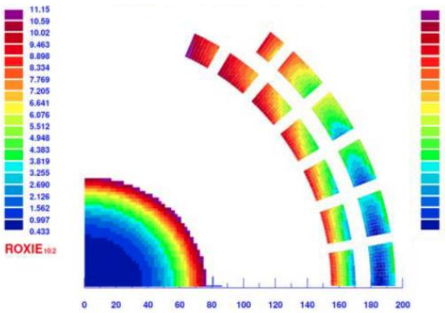




K. Skoufaris, Ch. Carli, D. Amorim, A. Lechner, R. Van Weelderen, P. De Sousa, L. Bottura et al.

Initial **estimate of magnet field limits**:
11 T for Nb_3Sn, more for HTS/hybrid
Need **stress management**





Different **cooling scenarios** studied
< 25 MW power for cooling possible
Shield with CO_2 at 250 K (preferred) or water
Support of shield is important for heat transfer
Discussion on options for magnet cooling

R. Van Weelderen, P. De Sousa