Muon Collider Progress

D. Schulte
On behalf of the International Muon Collider Collaboration

Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

BNL, June, 2024

Collaboration

Goal is to 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 did not find any unsurmountable obstacle
- Accelerator R&D Roadmap identifies required work

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

Target integrated luminosities are based on physics

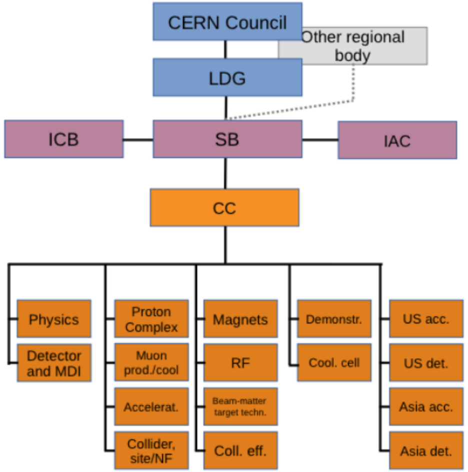
Increase as E_{cm}^2

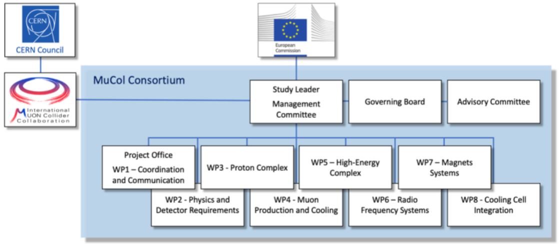
International collaboration with many members

- Support from the EU
- Reports to LDG/CERN Council
- And other funding agencies in the future

Goal is staged approach

- Collider operational by 2050
- Reach 10+ TeV





MoC and Design Study Partners

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International MUON Collider Collaboration

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical Univers.**
CH	**PSI**
	University of Geneva
	EPFL
EST	***Tartu University***
BE	**Univ. Louvain**

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
US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	BNL
	Florida State University
	RICE University
	Tennessee University

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**

China	***Sun Yat-sen University***
	IHEP
	Peking University
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
KO	**KEU**
	Yonsei University
India	***CHEP***

US	FNAL
	LBL
	JLAB
	Chicago

US P5: The Muon Shot

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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

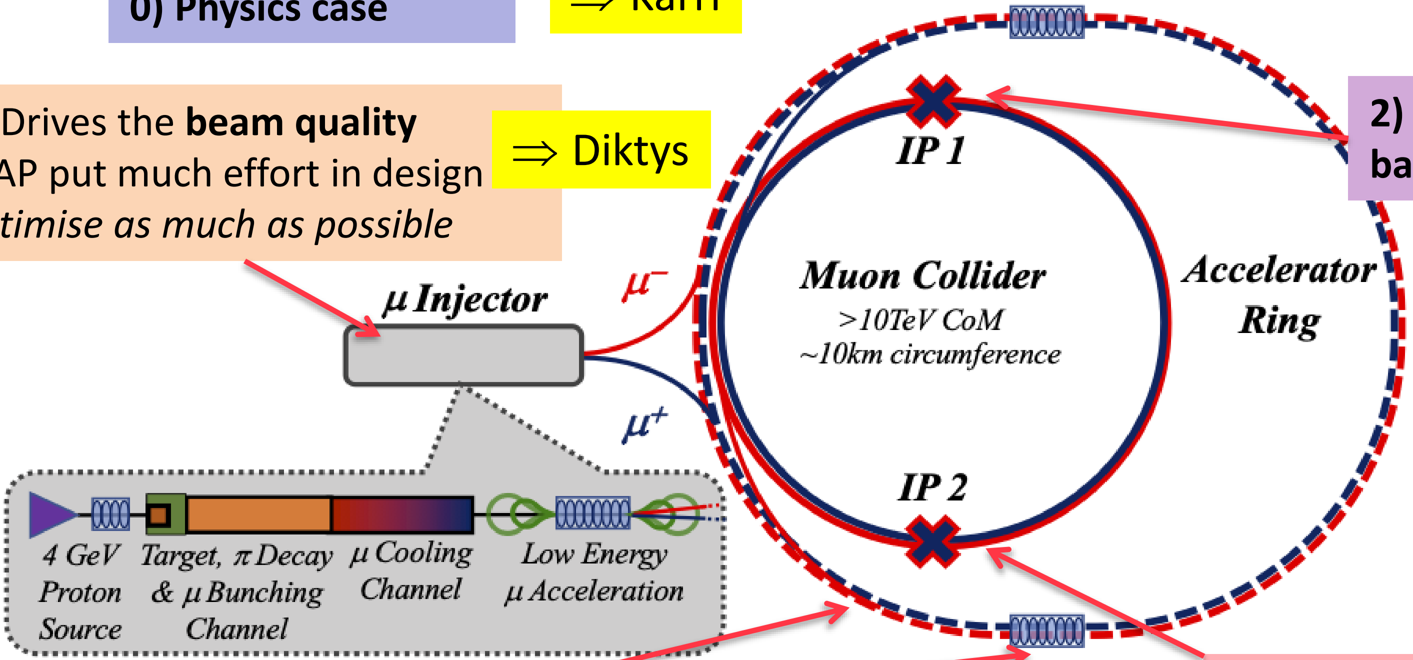
IMCC prepares options for Europe and for the US in parallel

Key Challenges

0) Physics case ⇒ Karri

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

2) Beam-induced background ⇒ Karri



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

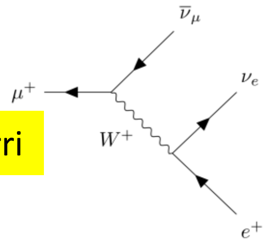
3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

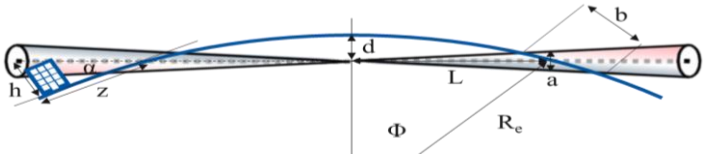
Muon Decay and Neutrino Flux

Muon decays in collider ring

- Impact on detector
- Have to avoid dense neutrino flux

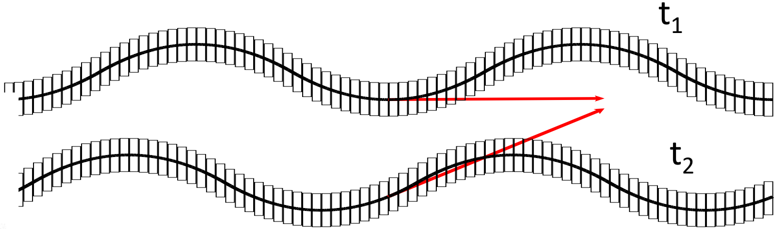
$\Rightarrow$ Karri





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



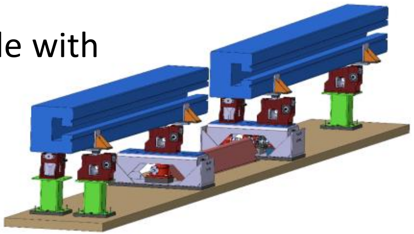
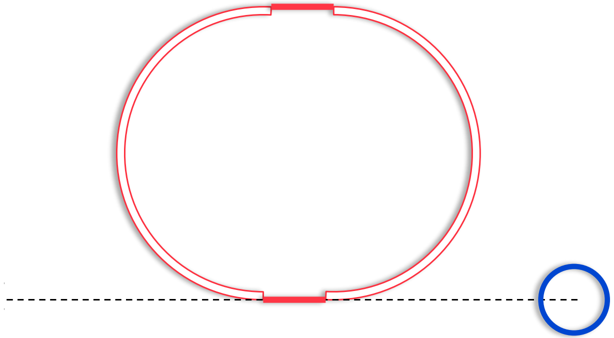


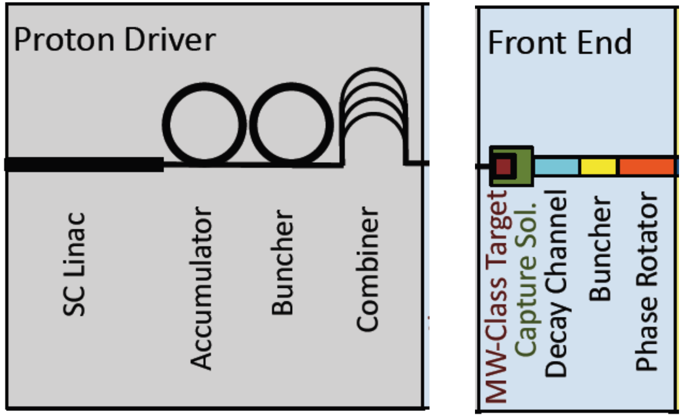
Fig. 7.23: Mock-up of the proposed magnet movement system.

Impact of experimental insertions

- 3 TeV design acceptable with no further work
- But better acquire land in direction of experiment, also for 10 TeV
- Detailed studies idetified location and orientation close to CERN
    - Poiint to uninhabited area in Jura and Mediterranian sea



Proton Complex and Target



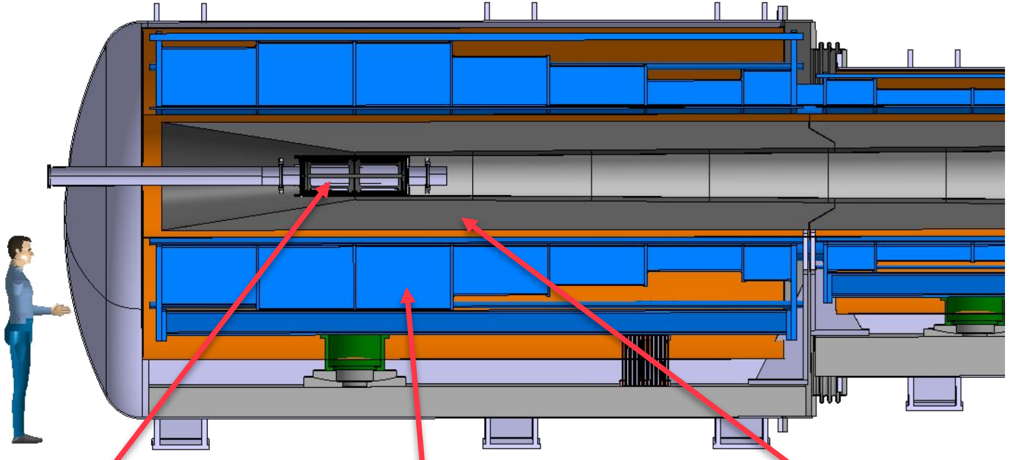
5 GeV proton beam, 2 MW = 400 kJ x 5 Hz
Power is at hand
Will now look into 4 MW

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

- Indication is that 10 GeV would be preferred

protons —in target→ pions —decay→ muons

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



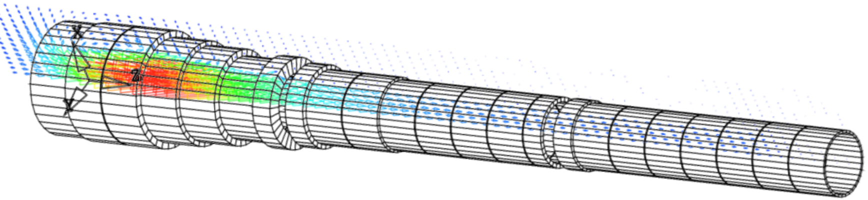
Graphite **Target**

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

Tunsten shielding
To protect magnet

Target Technologies

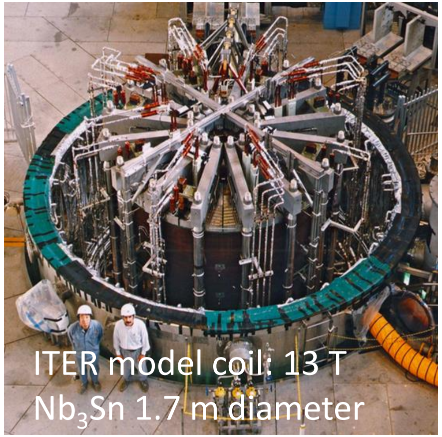
Target solenoid design ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert



HTS target solenoid: 20 T, 20 K

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

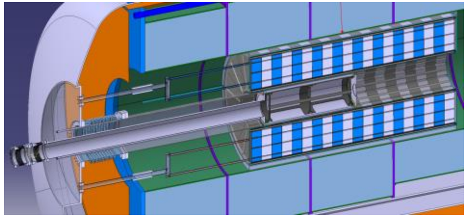
Our work is relevant for fusion



ITER model coil: 13 T
Nb_3Sn 1.7 m diameter

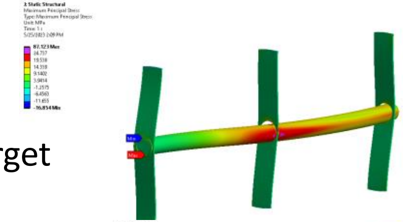
FLUKA studies:
2 MW target: stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

Integration

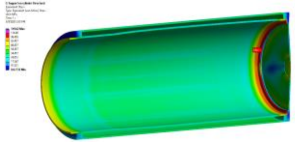


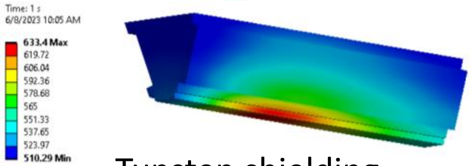
Cooling, vacuum, mechanics, …

Target



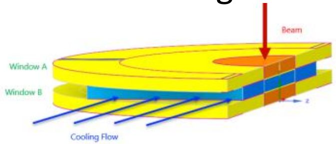
Vessel





Tunsten shielding

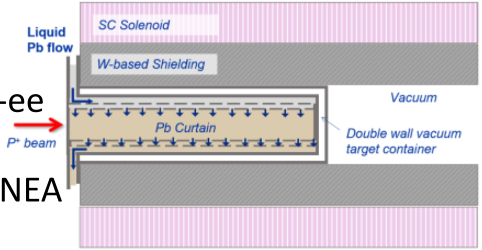
Window



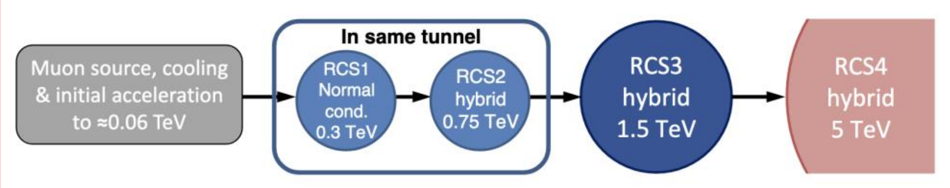
A. Lechner, D. et al.

Liquid metal target
Serious alternative
Also needed for FCC-ee

Collaboration with ENEA



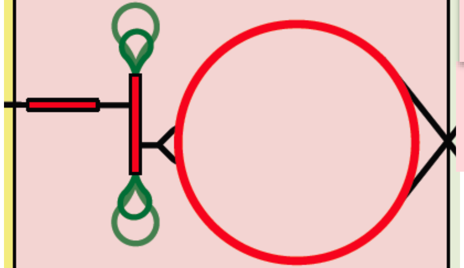
Acceleration Complex



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

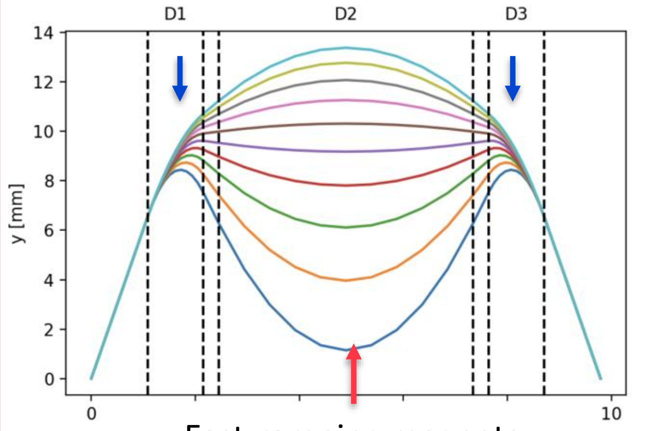
- Alternative FFA

Acceleration

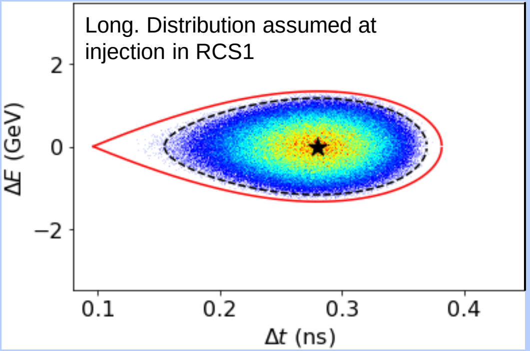


Accelerators:
Linacs, RLA or FFAG, RCS

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

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)

Fast-ramping Magnet System

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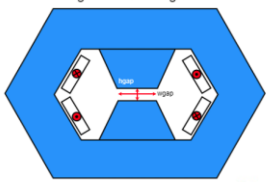
Efficient energy recovery for resistive dipoles (O(100MJ))

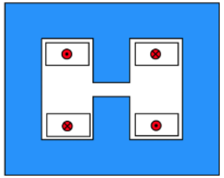
Synchronisation of magnets and RF for power and cost

Hourglass frame magnet



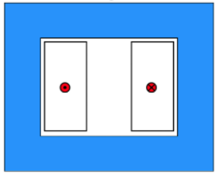
5.07 kJ/m

H magnet



5.65…7.14 kJ/m

Window frame magnet



5.89 kJ/m

FNAL 300 T/s HTS magnet

Could consider using HTS dipoles for largest ring

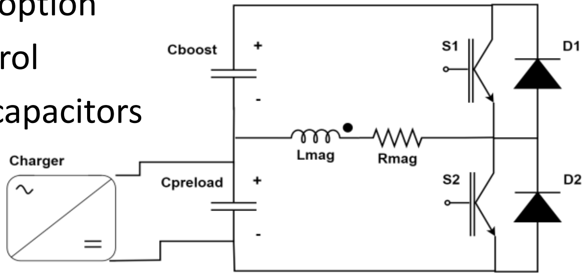
Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

Commutated resonance

Attractive novel option

- Better control
- Much less capacitors

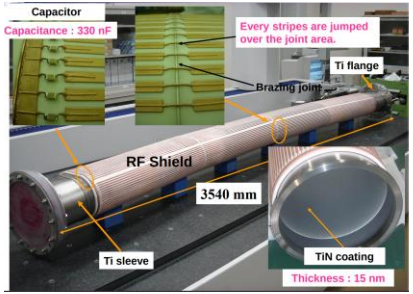


Beampipe study

Eddy currents vs impedance

Maybe ceramic chamber with stripes

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

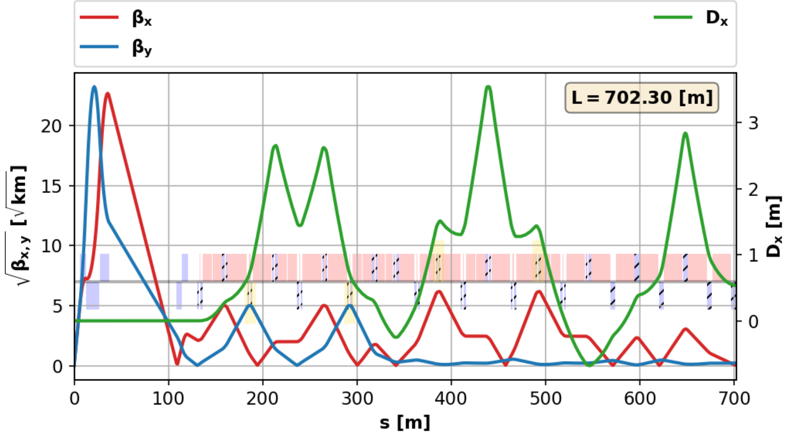


Collider Ring

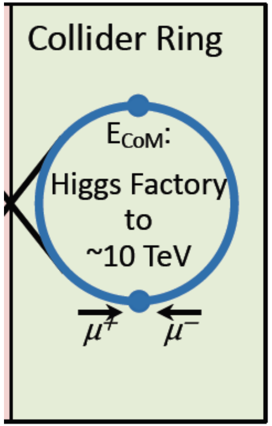
High performance 10 TeV challenges:
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

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



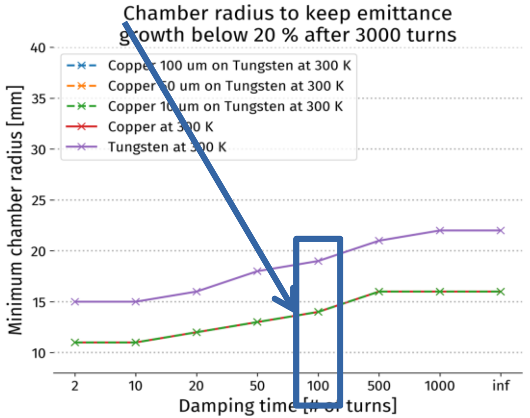
K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas



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

Impedance studies

Single beam instability limits OK with conservative feedback



Collider Ring Technologies

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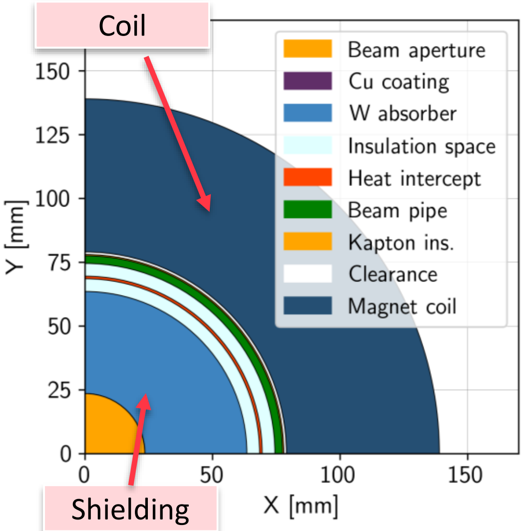
International

Power loss due to muon decay 500 W/m
FLUKA simulation of required **shielding:**
20-40 mm tungsten shielding (about OK-safe)

- Few W/m in magnets
- No problem with radiation dose

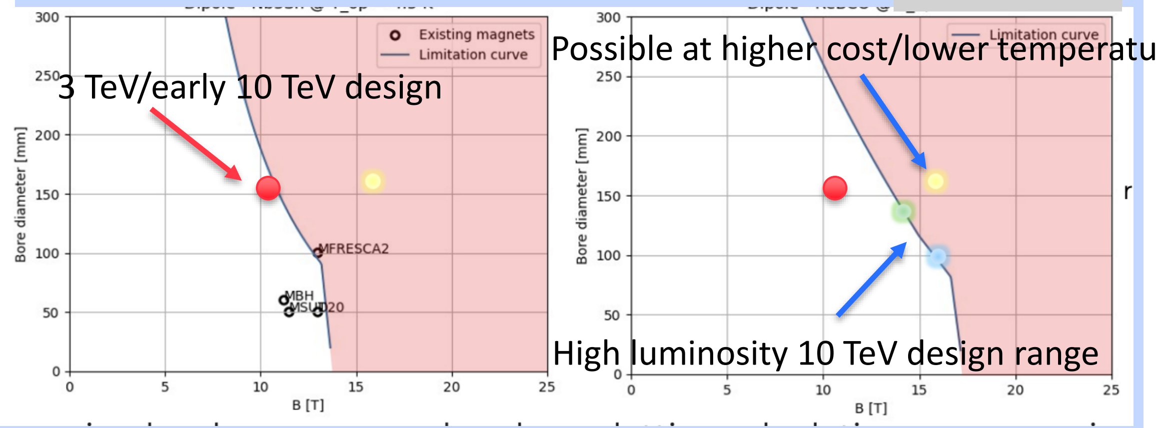
⇒ Magnet coil radius 59-79 mm



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

Study of magnet limitations (stress, loadline, cost, …)

D. Novelli,
L. Bottura et al.



Nb3Sn at 4.5 K and 15 cm aperture
Can reach ~11 T, stress and margin limited
Maturity expected in 15 years
OK for current 3 TeV/early 10 TeV design

HTS at 20 K and 10-14 cm aperture
Can reach 16-14 T, cost limited

- Factor 3 cost reduction assumed

Can reach 16 T and 16 cm with more material or lower temperature
Maturity takes likely >15 years

- But maybe OK in 15 years at lower performance, similar to Nb3Sn

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

Staging

Important timeline drivers:

Magnets

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

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

Detector technologies and design (expect in 15 years))

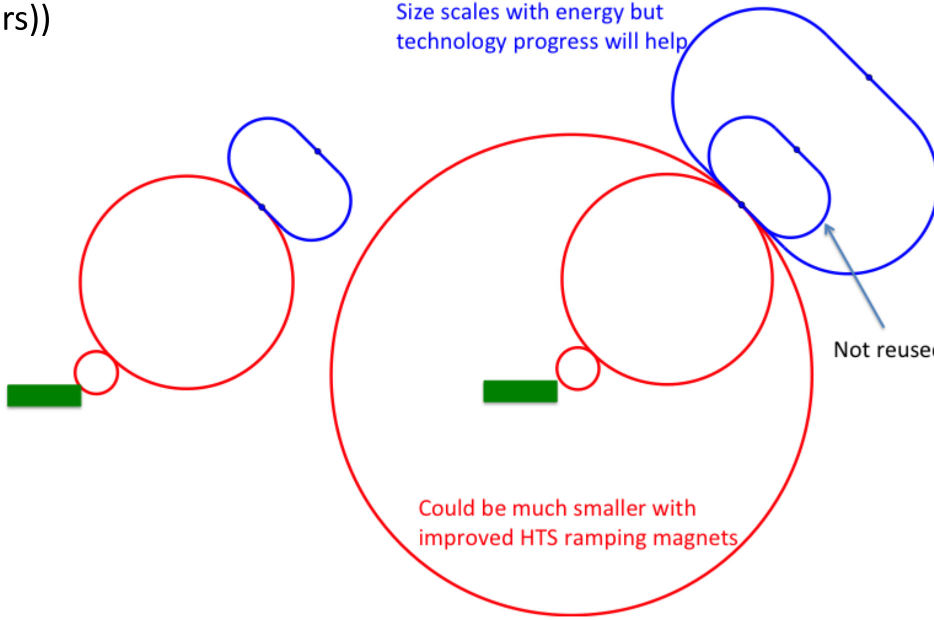
Energy staging

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

Luminosity staging

- Start at with full 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



Tentative Staged Target Parameters

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Target integrated luminosities

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

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

Tentative Timeline (Fast-track 10 TeV)

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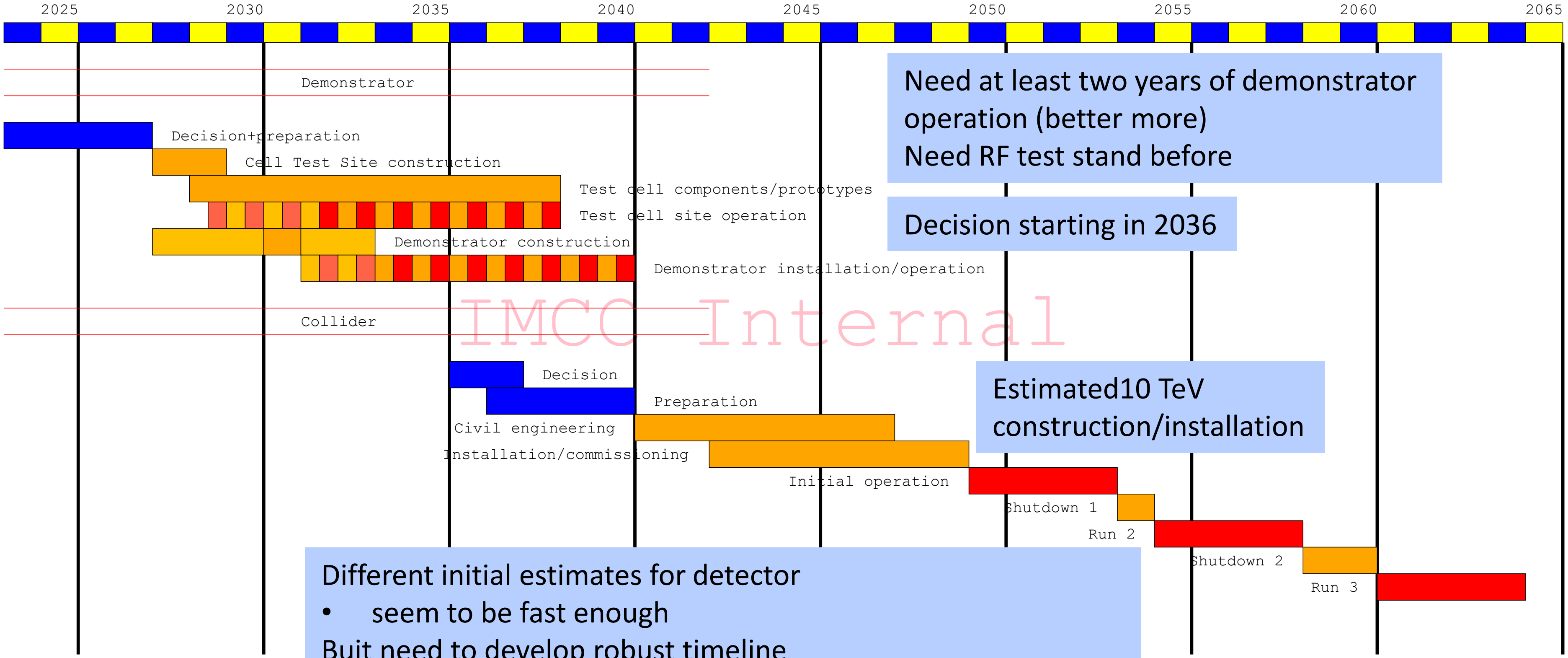
Only a basis to start the discussion, will review this year



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

Very Short-term Plan

Just finished Interim Report
- Design
- Challenges
- Plan until 2026

IAC has been **formed** and **reviewed interim report** as a first task

IAC regular members:
Ursula Bassler (IN2P3, interim Chair), Mauro Mezzetto (INFN) Hongwei Zhao (Inst. of Modern Physics, IMP), Akira Yamamoto (KEK), Maurizio Vretenar (CERN), Stewart Boogert (Cockcroft), Sarah Demers (Yale), Giorgio Apollinari (FNAL)
Experts for Interim Report review
Marica Biagini (INFN), Luis Tabarez (CIEMAT), Giovanni Bisoffi (INFN), Jenny List (DESY), Halina Abramowicz (Tel Aviv), Lyn Evans (CERN)

Contents

Will focus on advanced **ESPPU:**
- **March 2025**, deliver promised ESPPU reports
  - **Evaluation report**, including tentative cost and power consumption scale estimate
  - **R&D plan**, including some scenarios and timelines

This requires to push as hard as possible with existing resources

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ESPPU Plan

International MUON Collider Collaboration

Continue to develop green field design

- Lattices, components, beam dynamics, …

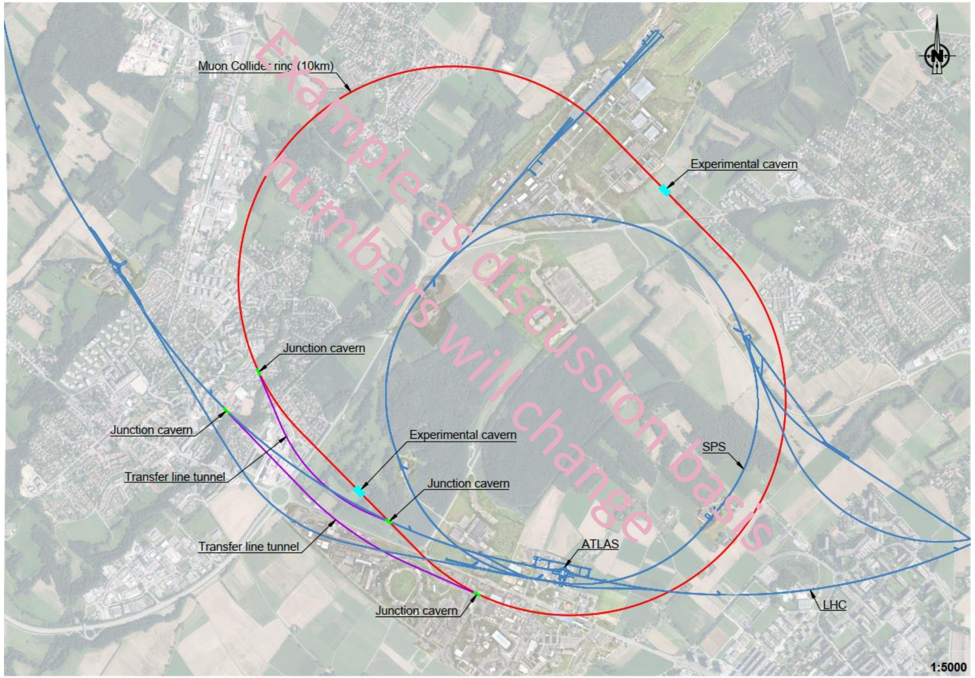
Explore implementation at CERN using existing infrastructure (e.g. SPS and LHC tunnels)

- Similar effort for FNAL

Develop adjusted parameter tables for implementation at CERN

First look is promising:

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



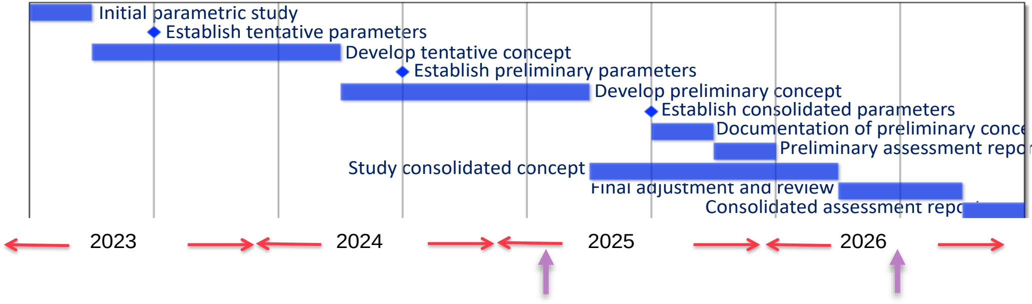
Expected CM energy reach (robust technology assumptions)

- 2.5 - 5.5 – (8 TeV with two RCS in LHC)
- Need to study implementation of components in existing tunnels
- Could improve with better magnets

Medium-term Plan

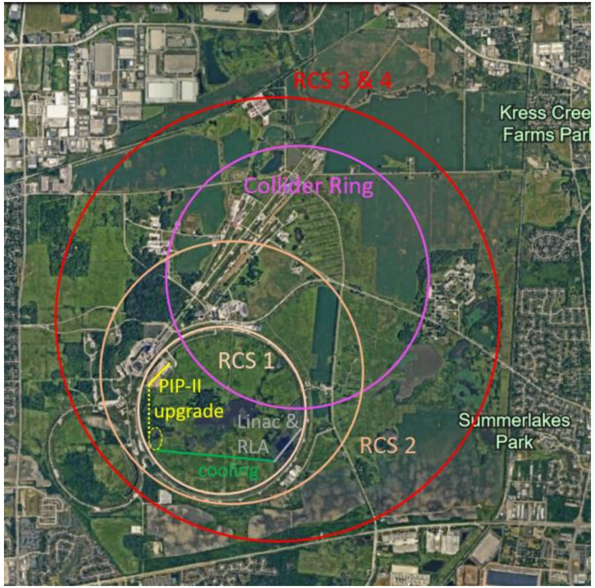
March 2025, deliver promised ESPPU reports

February 2027, Fulfill EU contract
- **Final deliverable is report on all R&D**



ESPPU submission

ESPPU result



Expect **US process** after the ESPPU
- Likely US wants a **Reference Design**
- **Demonstrator design**

Will fully support the required studies

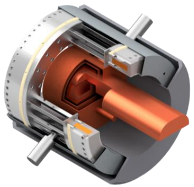
LDG wants to increase the momentum that we built up
- **EU Roadmap** continues

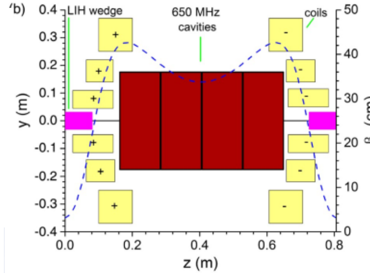
First exploration shows muon collider can fit on FNAL site

Continuation as attractive option for Europe and for the US

R&D Programme

Broad R&D programme can be distributed world-wide

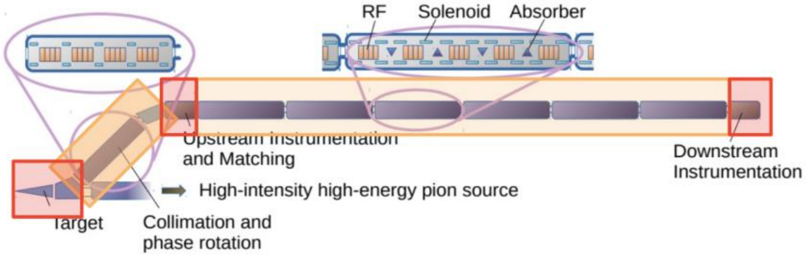




B8

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

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

Muon collider has a compelling physics case

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

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

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

The muon collider collaboration has grown since the last ESPPU

- See it will grow even more

Strong synergies with other fields ranging from particle physics to societal application

Need to continue ramping up the momentum

Many thanks to the collaboration for all the work

To join contact muon.collider.secretariat@cern.ch

Reserve

Recent Results: Interim Report

MuCol

International MUON Collider Collaboration

IAC regular members:
Ursula Bassler (IN2P3, interim Chair)
Mauro Mezzetto (INFN)
Hongwei Zhao (Inst. of Modern Physics, IMP)
Akira Yamamoto (KEK)
Maurizio Vretenar (CERN)
Stewart Boogert (Cockcroft)
Sarah Demers (Yale)
Giorgio Apollinari (FNAL)

Experts for this review
Marica Biagini (INFN)
Luis Tabarez (CIEMAT)
Giovanni Bisoffi (INFN)
Jenny List (DESY)
Halina Abramowicz (Tel Aviv)
Lyn Evans (CERN)

The IAC reviewed the Interim Report and prepared an excellent report on their findings

Contents

Proposal: EuMAHTS

MuCol

Luca Botture et al.

Submitted to INFRA-2024-TECH-01-01

EuMAHTS Accelerating HTS

International MUON Collider Collaboration

Focus on HTS development
O(10 Meur) request

Strategy and context

Material and technology

Three core components (6 MEUR)

- 40 T solenoid, 50 mm bore
- 10 T/10 MJ/300 mm solenoid
- HTS undulator

Test infrastructure

WP1 - Coordination and Communication (L. Bottura, P. Vedrine)
WP2 – Strategic Roadmap (A. Ballarino, L. Rossi)
WP3 – Industry Co-innovation (J.M. Perez, S. Leray)
WP4 – HTS Magnets Applications Studies (P. Vedrine, M. Statera)
WP5 – Materials and Technologies (D. Bocian, A. Bersani)
WP6 – 40T-class all-HTS solenoid (B. Bordini, P. Vedrine)
WP7 – 10T/10MJ-class all-HTS solenoid (S. Sorti, C. Santini)
WP8 – K=2 all-HTS undulator (S. Casalbuoni, M. Calvi)
WP9 – Test Infrastructures (G. Willering, E. Beneduce)

Short name	Country	Status
CERN	IERO	B
EMFL	Belgium	B
TAU	Finland	B
CEA	France	B
ESRF	France	B
EUXFEL	Germany	B
GSI	Germany	B
KIT	Germany	B
INFN	Italy	B
UMIL	Italy	B
UTWENTE	Netherlands	B
IFJ-PAN	Poland	B
PK	Poland	B
CIEMAT	Spain	B
CSIC	Spain	B
PSI	Switzerland	A
TERA-CARE	Switzerland	A
UNIGE	Switzerland	A
CNRS	France	A
HZDR	Germany	A
RU-NWO	Netherlands	A

IMCC Organisation

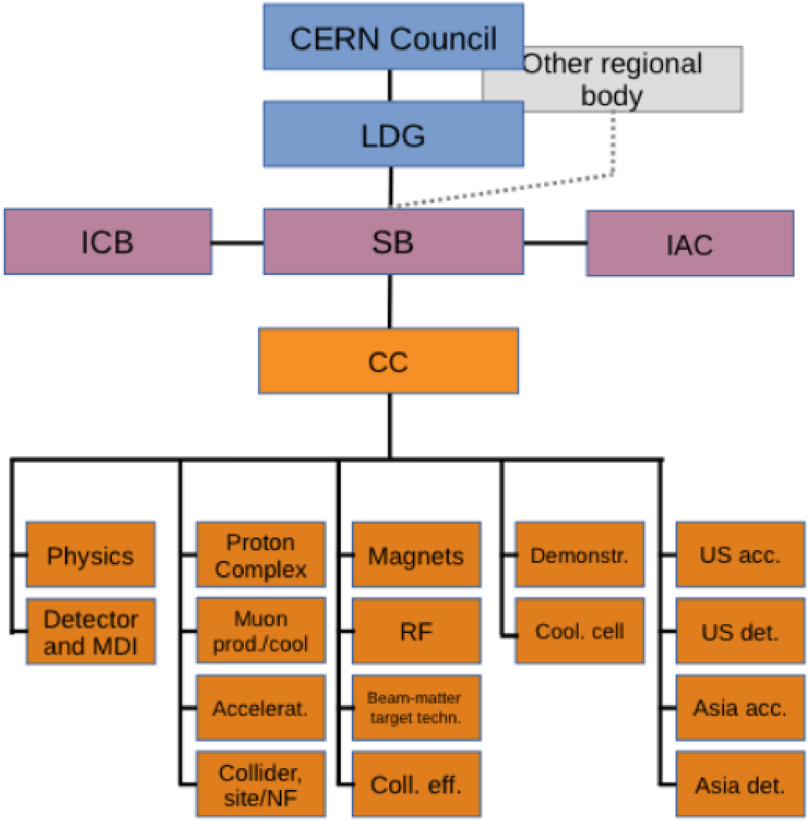
Collaboration Board (ICB)
- Elected chair: **Nadia Pastrone**
- **50 full members, 60+ total**

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), Beate Heinemann (DESY)
- Study members: SL and deputies

Advisory Committee

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

Will integrated the US also in the leadership



Magnet Roadmap

MuCol

International MUON Collider Collaboration

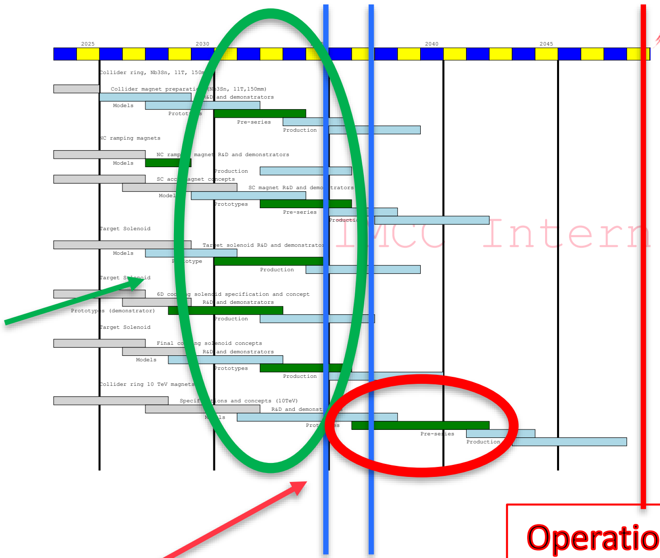
Assume: Need prototype of magnets by decision process

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 10 TeV HTS/hybrid collider ring magnets
- For second stage can use **HTS or hybrid collider ring magnets**



Operation start

2036+2037 decision process

Strategy:

- HTS solenoids
- Nb_3Sn accelerator magnets
- HTS accelerator magnets

Seems technically good for any future project

Solenoid R&D

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

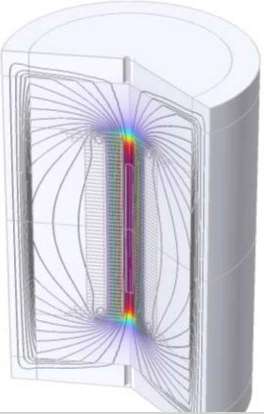
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

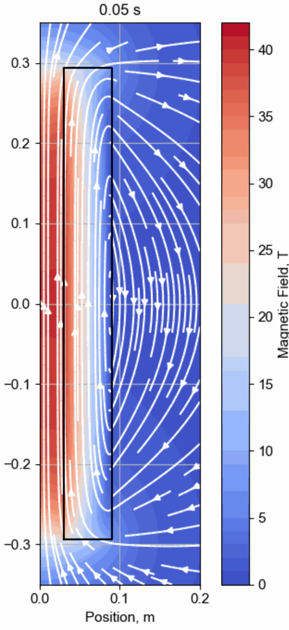
Final Cooling solenoid

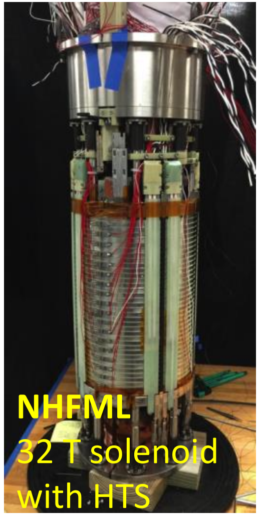
$$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}$$

σ_{max} = 600 MPa

$B_{max} \approx$ **55 T**

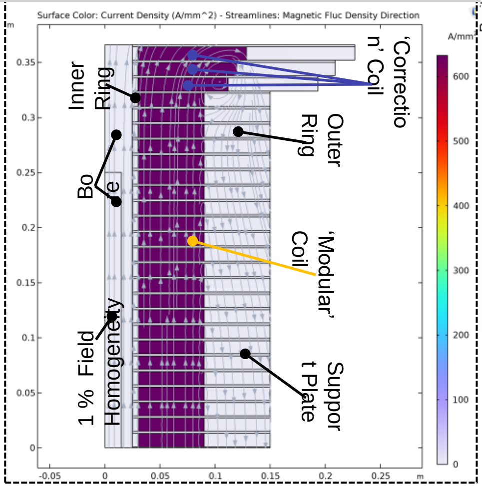


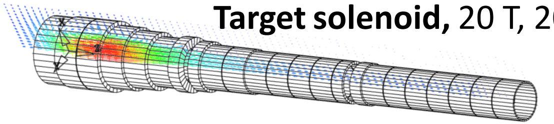




32 T LTS/HTS solenoid demonstrated

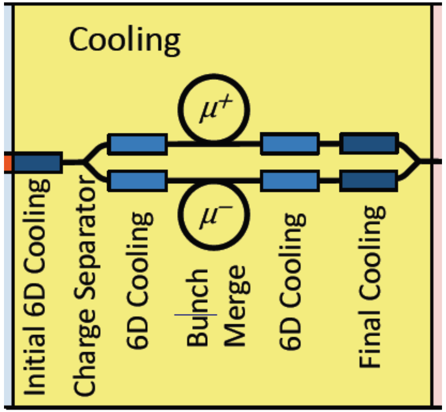
A. Dudarev, B. Bordini, T. Mulder, S. Fabbri



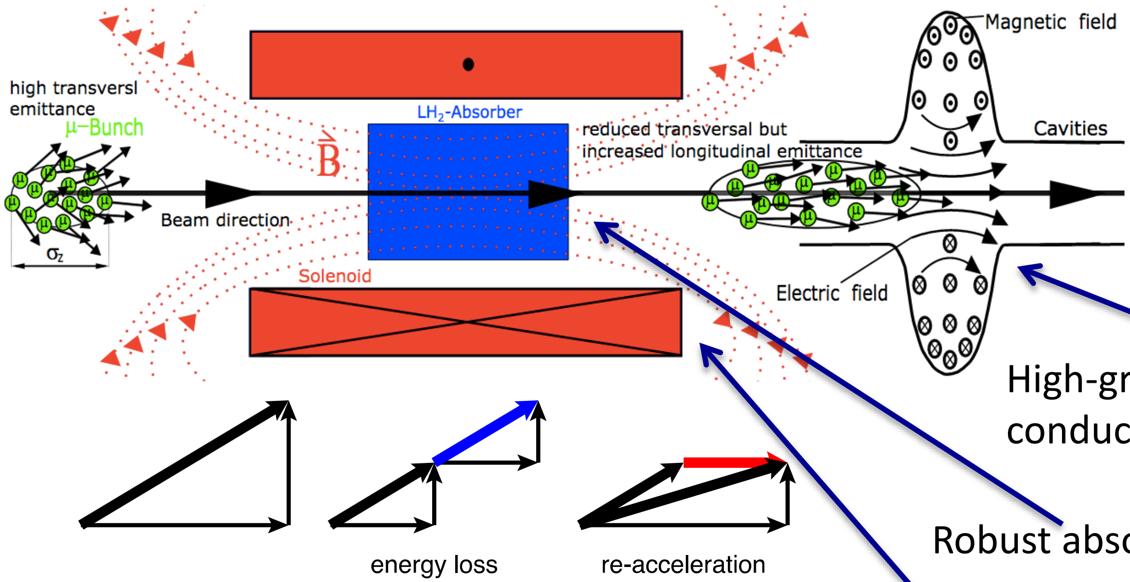


Target solenoid, 20 T, 20 K

Muon Cooling Principle



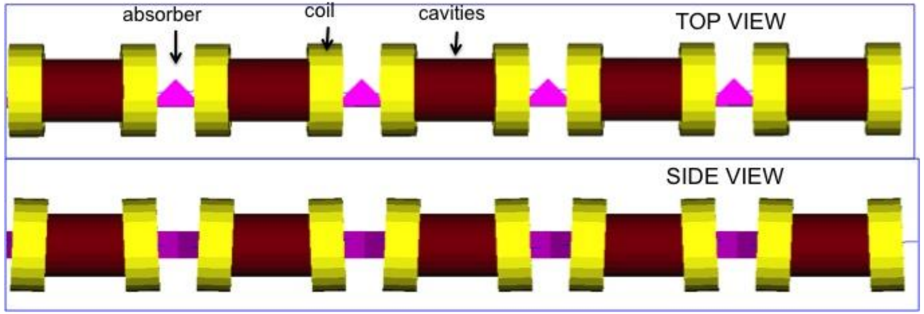
C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)



High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid



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

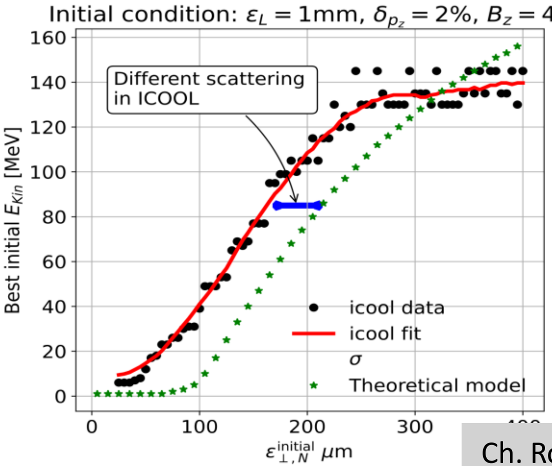
Muon Cooling Performance

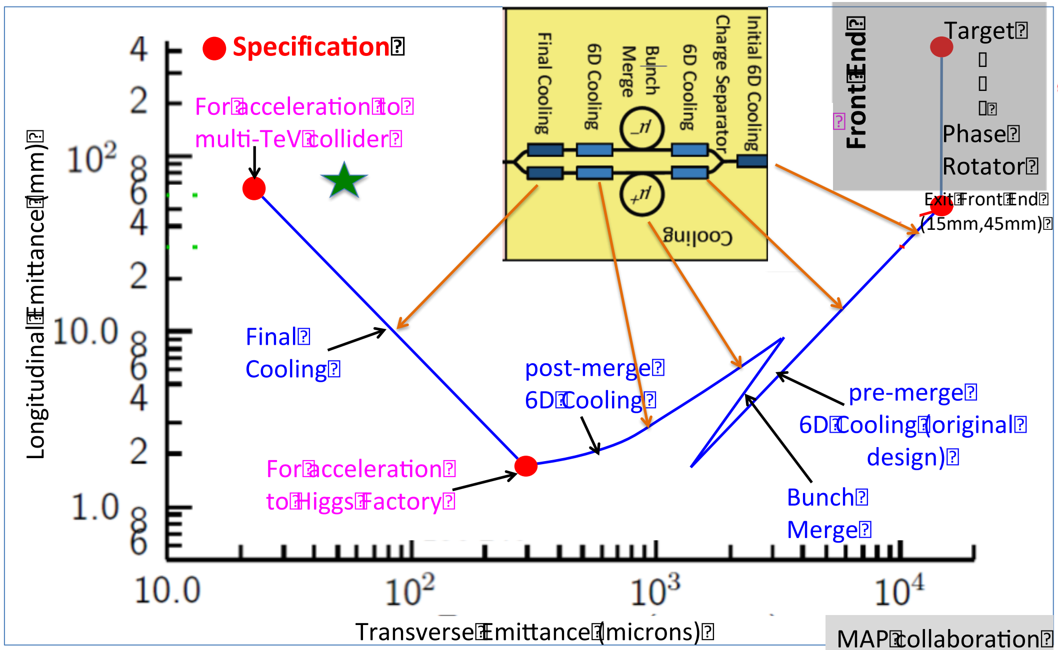
MAP design achieved 55 um based on achieved fields

Can expect better hardware

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

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

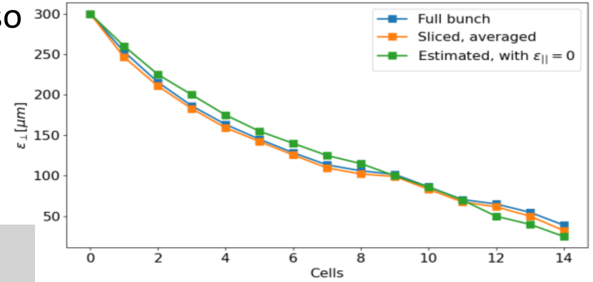




MAP collaboration

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

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

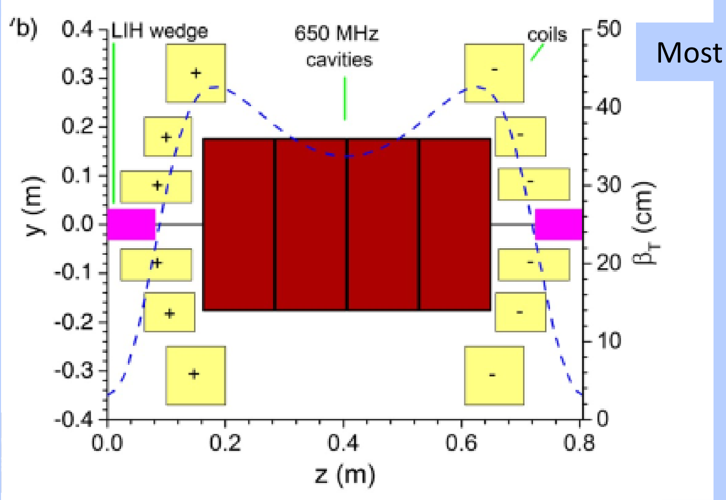


Ch. Rogers, Zhu Ruihu, R. Taylor, B. Stechauner, E. Vol et al.

Cooling Cell Technologies

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

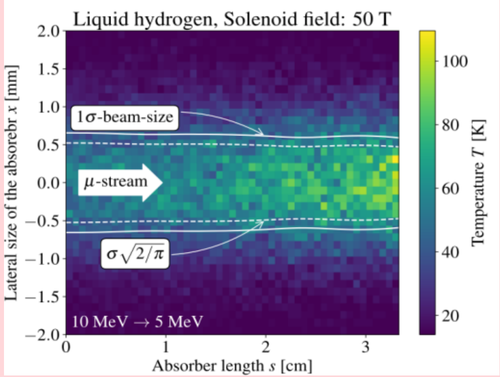
L. Rossi et al. (INFN, Milano, STFC, CERN), J. Ferreira Somoza et al.



Most complex example 12 T

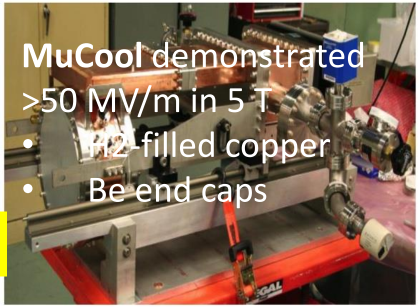
HTS solenoids ⇒ Marco
Ultimate field for final cooling
Also consider cost

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

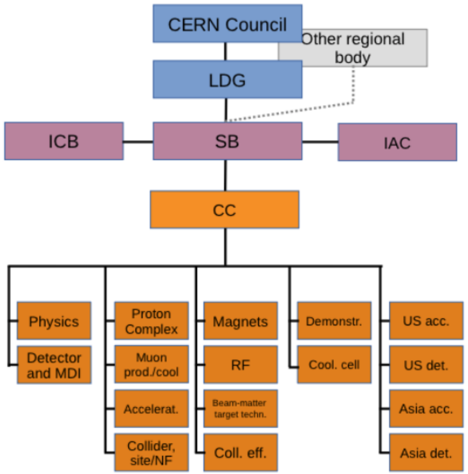


D. Giove, C. Marchand, Alexej Grudiev et al. (Milano, CEA, CERN, Tartu)

International Muon Collider Collaboration (IMCC)

IMCC was founded in 2021

- Reports to CERN Council
- Anticipate it will also report to DoE and other funding agencies
- 50 full members, a few additional contributors



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

http://arxiv.org/abs/2201.07895

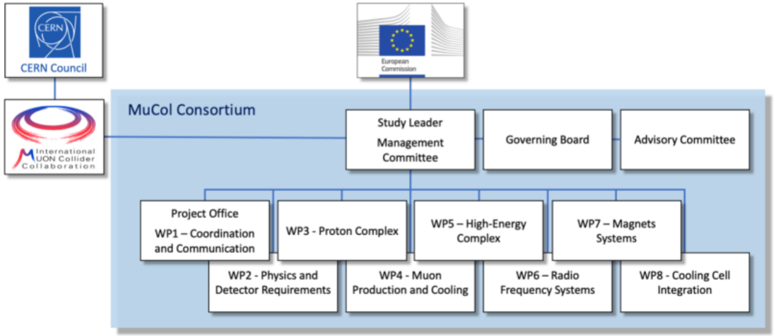
IMCC goals

- 10 TeV high-luminosity collider
  - Higher energies to be explored later
- Develop initial stage to start operation by 2050
  - Lower energy or luminosity
- Identify potential sites
- Implementing workplan following priorities from Roadmap

MuCol (EU co-funded)

MuCol

International MUON Collider Collaboration

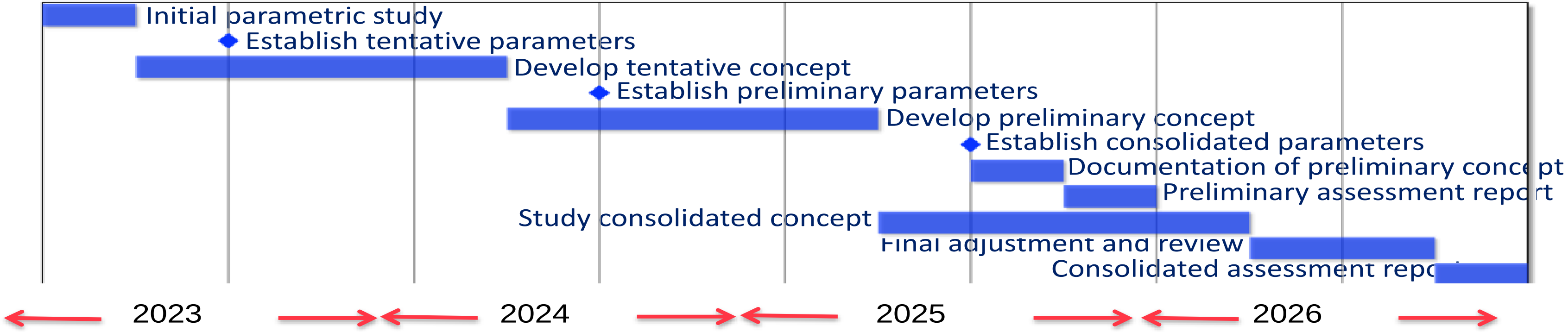


Started March 2023, lasts until early 2027

3 MEUR from the EU, the UK and Switzerland, about 4 MEUR from the partners, CERN leads and contributes

Final deliverable is a report on the full IMCC R&D results

EU officer will come on 19th June.



Staging

Important timeline drivers:

Magnets:

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

Muon cooling technologies and integration

- Expect to be able with enough resources

Detector technologies and design

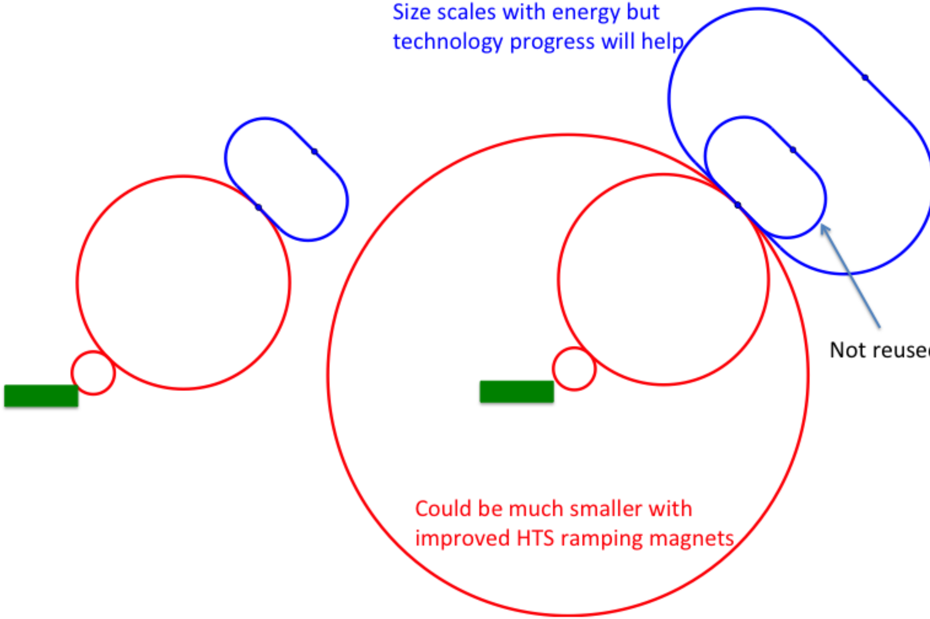
- Can do the important physics with near-term technology

Energy staging

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

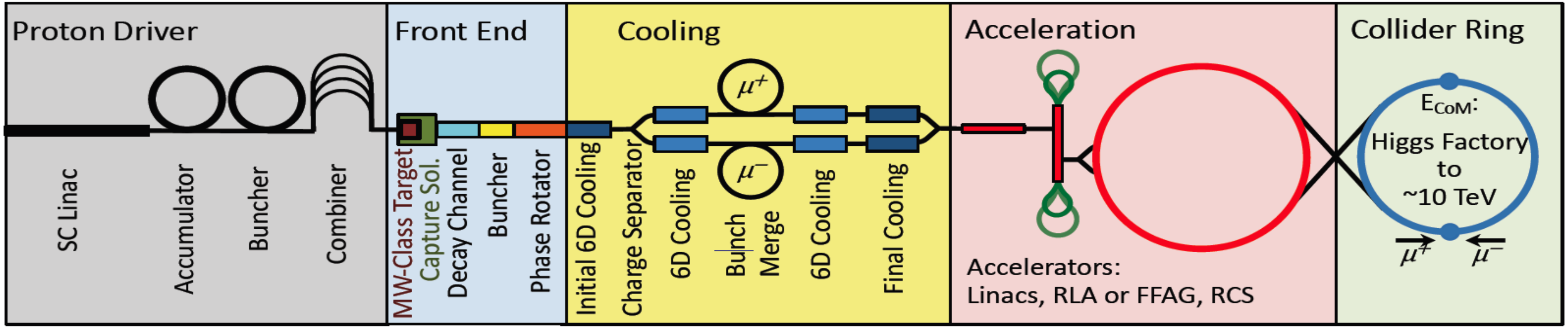
Luminosity staging

- Start at with full energy, but less luminosity collider ring magnets
- Main luminosity loss sources are arcs and interaction region
  - Can later upgrade interaction region (as in HL-LHC)



Muon Collider Overview

Would be easy if the muons did not decay
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

CDR Phase, R&D and Demonstrator Facility

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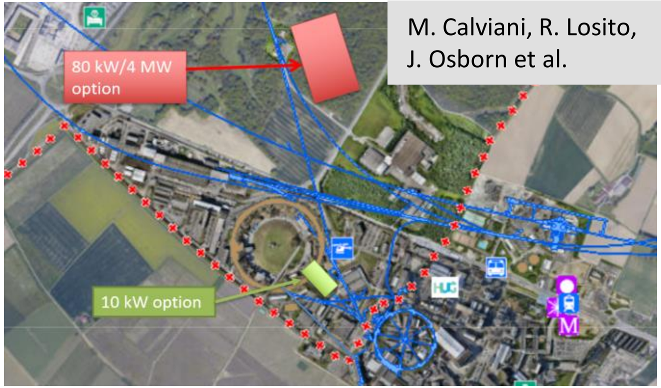
International MUON Collider Collaboration

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

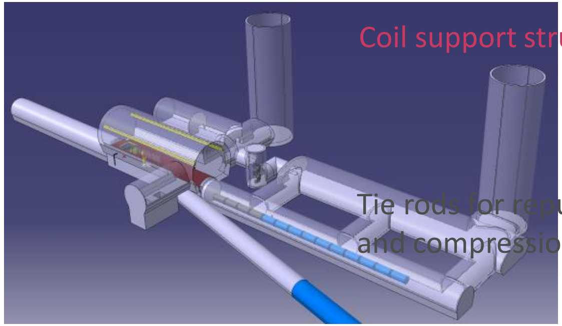


M. Calviani, R. Losito, J. Osborn et al.

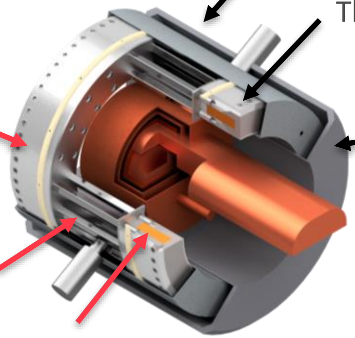
Cooling demonstrator is a key facility
- look for an existing proton beam with significant power

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

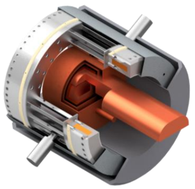


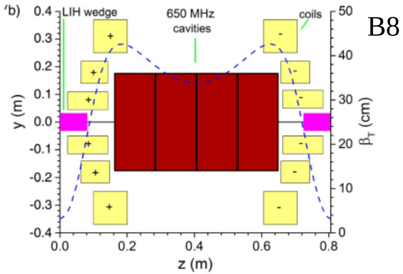
With cryostat

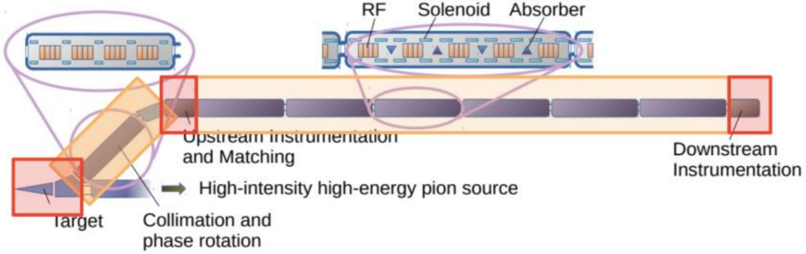


Time-critical Developments

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

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

Other technologies can be accelerated with sufficient funding

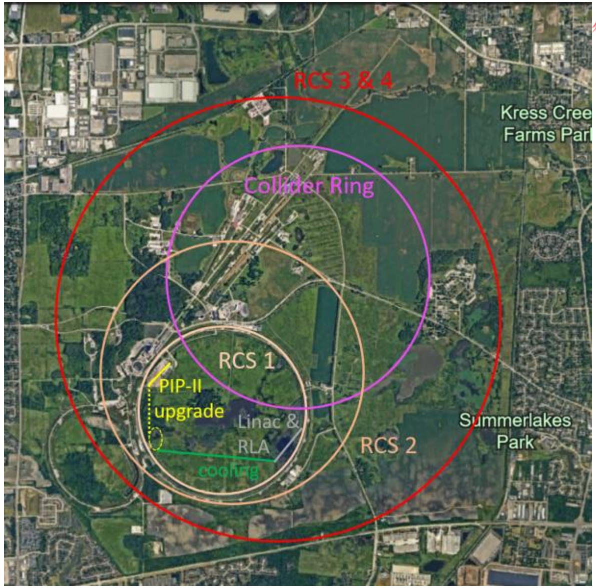
- But they are equally important now to support that the muon collider can be done and perform

Site Studies

MuCol

International UON Collider Collaboration

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

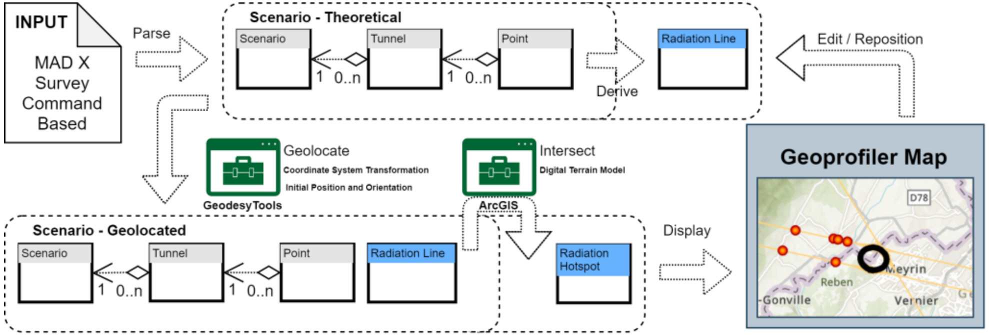


Study is mostly site independent

- 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)