International MUON Collider Collaboration

MuCol

IMCC

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.

Here can in the future be a reference to US and other important funding

FNAL, August, 2024

IMCC Goals

Motivation to develop high-energy muon collider as option for particle physics:

- Want to go to **highest energy frontier**
  - Muon collider promises **sustainable** approach, (power, 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
- US and Asian representation in Panel, e.g. Mark Palmer has been Deputy Chair

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 is based on MoC, current host lab is CERN but can be changed later

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
	Pittsburg University
	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

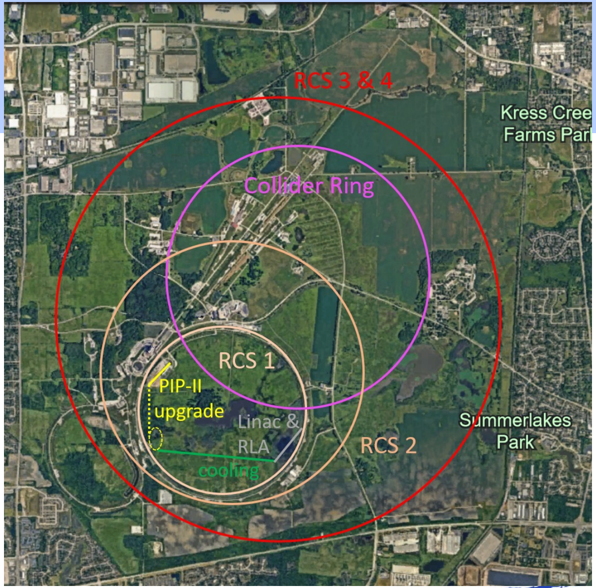
US has been instrumental in advancing the muon collider during Snowmass process
- See the contributions even increase after the process

Particle Physics Project Prioritisation Panel (P5) supports US ambition to host a 10 TeV parton-parton collider
- Endorses muon collider R&D: ”This is our muon shot”
- Recommend joining the IMCC and consider FNAL as a host candidate

Warmly welcome the US

Informal discussion with DoE (Regina Rameika, Abid Patwa):
- DoE wants to maintain IMCC as a **international collaboration**
- **Addendum to CERN-DoE-NSF agreement** is being preparation
  - Will allow labs to join
- Universities are joining already now

IMCC prepares options for Europe and for the US in parallel



IMCC Organisation

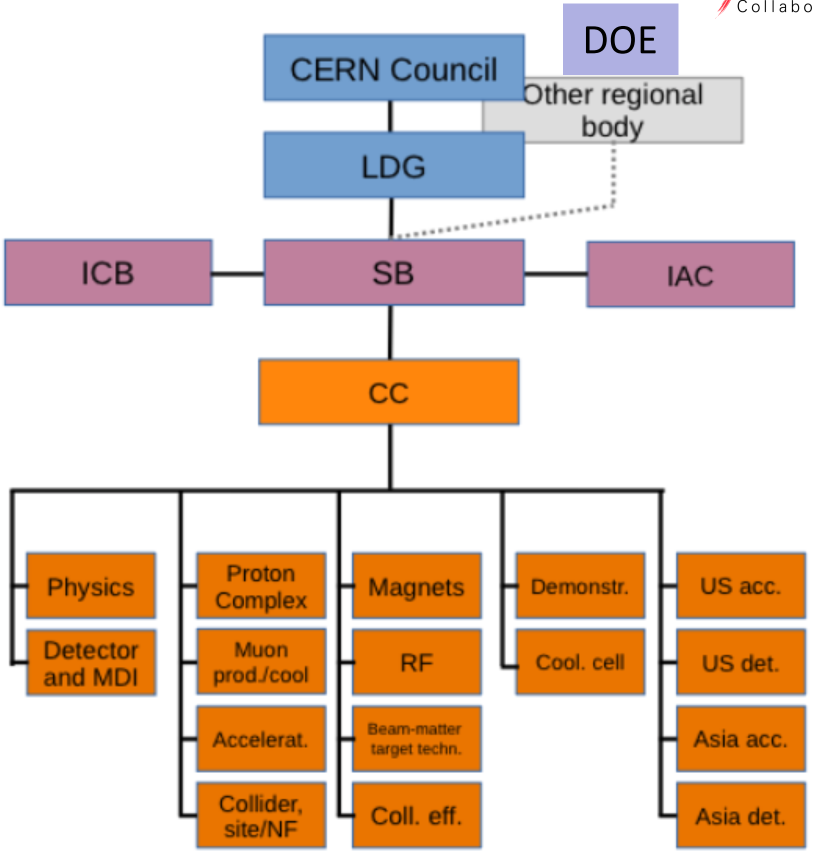
Collaboration Board (ICB)
- Elected chair: **Nadia Pastrone**
- **50 full members, 60+ total**

Steering Board (ISB)
- Chair **Steinar Stapnes**
- Members: Mike Lamont (CERN), Gianluigi Arduini (CERN), Dave Newbold (STFC), Mats Lindroos† (ESS), Pierre Vedrine (CEA), N. Pastrone (INFN), Beate Heinemann (DESY)
- Study members: SL and deputies
- US contact experts: Mark Palmer, Sergo Jindariani, Diktys Stratakis, Sridhara Rao Dasu

Advisory Committee

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

Will increase US leadership
- In particular, the CC and SB

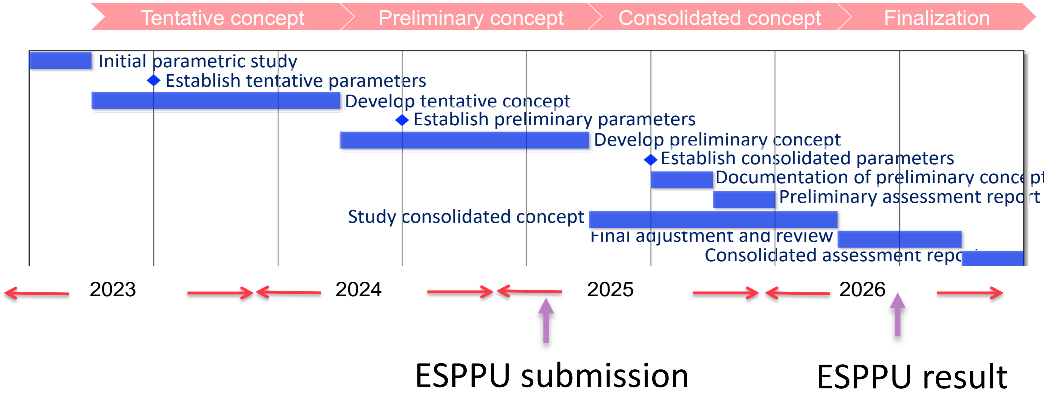


MuCol

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

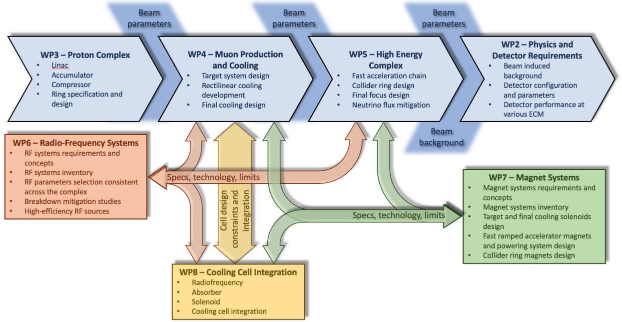
The **backbone** of the study in Europe

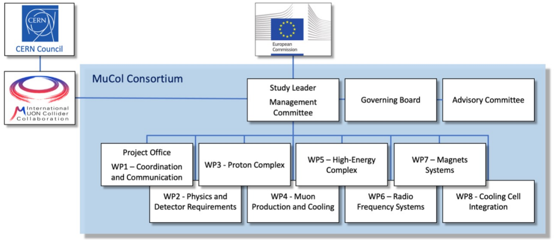
- 30 partners
- Instrumental to kick off collaboration
- Motivated partners to commit
- Added resources
- Motivated CERN to commit more
- Motivates new partners



Management similar to IMCC

Leader DS
Deputy: Chris Rogers
Technical coordinator Roberto Losito





MuCol Integration

MuCol deliverables are aligned with IMCC

- promises the IMCC Evalution and R&D Plan reports as its main deliverables
- MuCol contributes some part of it, the rest comes from IMCC at large

Gouvernance is aligned

- MuCol Governing Board is present at IMCC Collaboration Board
- MuCol GB decides sperately on issues related to the EU contract (e.g. distributing EU resources)
- The IMCC Coordination Committee is a superset of MuCol Management Committee
    - E.g. Gender Advisor of MuCol (who is from the US, by the way)
- MuCol endorsed IMCC Advisory Committee as it own Advisory Committee
- The IMCC and MuCol annual meetings are joint (and organised as one unit)
- Same team to guide IMCC and MuCol publications (IMCC rules take into account sub-projects)

MuCol partners put the logo on their talks, like any other logo from your funding agency, lab, …
We are happy to put any reference to other funding bodies on general IMCC talks

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 Giove
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
US (accelerator)	Diktys Stratakis
Asia (China)	Jingyu Tang
Asia (Japan)	tbd

Cost	Carlo Rossi
Publications	Elias Metral
Gender Advisor	Ej Bahng

Collaboration Board Chair	Nadia Pastrone
Steering Board Chair	Steinar Stapnes

CC Considerations for Future

Physics	Andrea Wulzer
Detector and MDI	Donatell… …cchesi

Protons	Na…
Muon production and cooling	…s
Muon acceleration	…e Chance
Collider	…ristian Carli

Magnets	Luca Bottura
RF	Alexej Grudiev, Dario Giove
Beam… target	Anton Lechner
Collective …ects	Elias Metral
Cooling cell design	Lucio Rossi

Additional US coordinators
Additional workpackages

Demonstrator CERN	
Demonstrator FNAL	
Site study CERN	
Site study FNAL	
Potential other site	

Site Specific

Cost	Carlo Rossi
Publications	Elias M…
Gender Advisor	F…
Other package (e.g. computing?)	

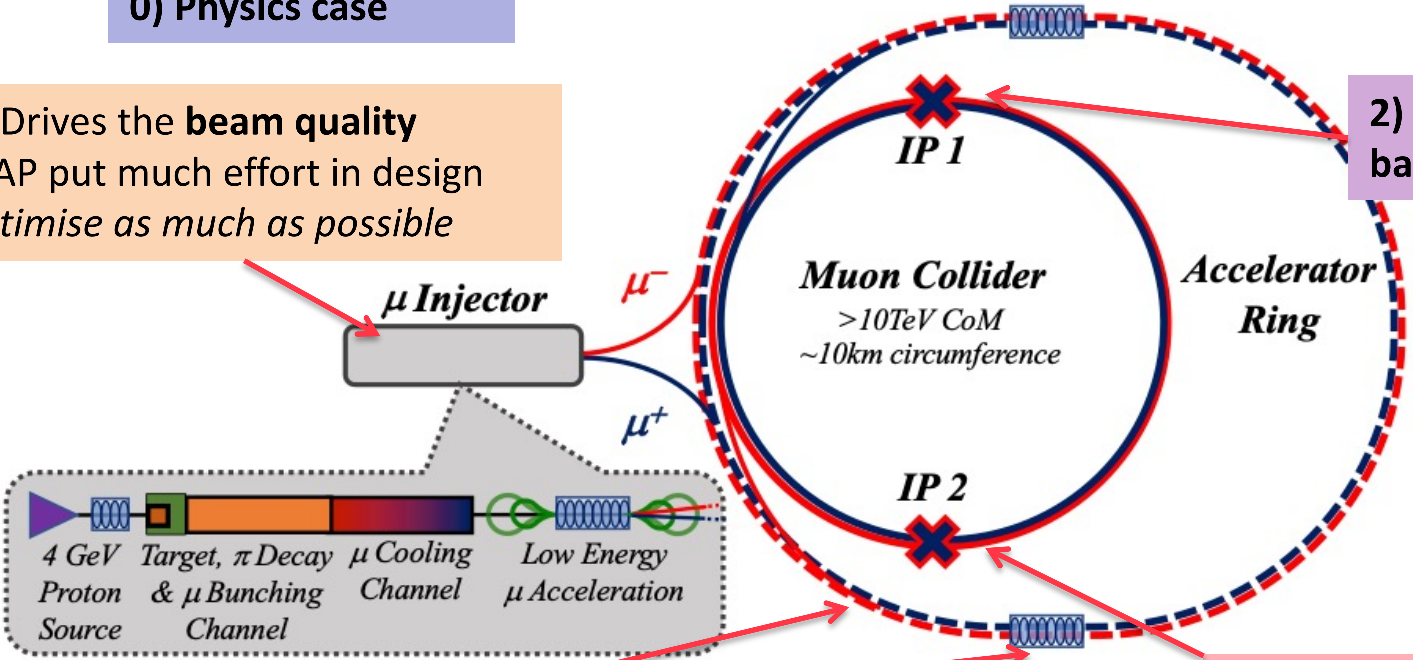
Additional US coordinators

Collaboration Board Chair	Nadia Pastrone
Steering Board Chair	Steinar Stapnes

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**

International MUON Collider Collaboration

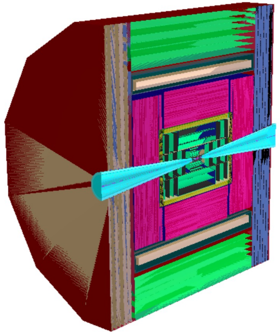
Important technical progress

But cannot cover it here

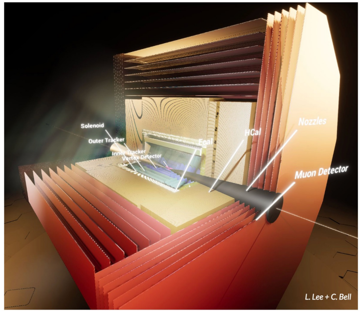
Physics and Detector Concepts

Two detector concepts are being developed

MUSIC
(MUon Smasher for Interesting Collisions)



A "New Detector Concept",
maybe a flashier name can be found



D. Schulte, Muon Collider, Birmingham, July 2024

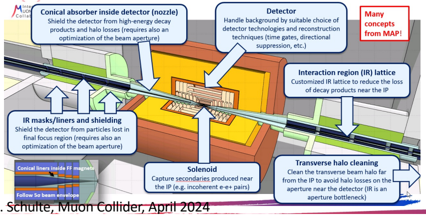
Technical progress

MDI and beam-induced background

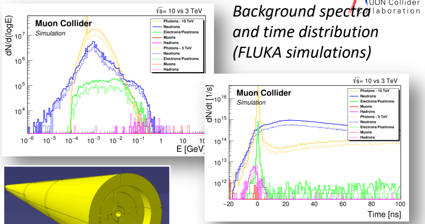
Activities in SY/STI:

- Detailed simulation of detector background and radiation damage by means of FLUKA
- Optimization of MDI (nozzle, shielding) and IR for 10 TeV collider ongoing,
- First engineering considerations for nozzle

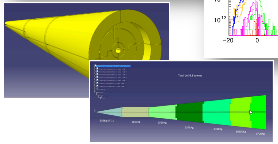
Integral approach for MDI design:



D. Schulte, Muon Collider, April 2024



Background spectra and time distribution (FLUKA simulations)



First engineering considerations for nozzle

Achievements (selection):

- Development of a 10 TeV IR lattice → impact of lattice design choices on the decay background
- First comparison of decay background for 3 TeV and 10 TeV + first BIB samples for detector studies
- First study of the incoherent pair production background and halo background (10 TeV)
- First estimates of the cumulative radiation damage in the detector (3 TeV and 10 TeV)
- First study of the nozzle optimization potential
- First study of forward muons (10 TeV)

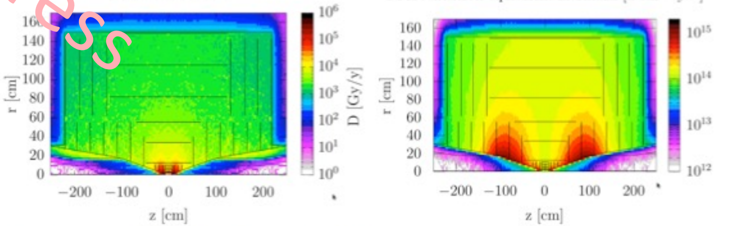
Main goals for ESPPU report:

- Optimization of the nozzle, absorbers, shielding for 3 TeV and 10 TeV, respectively
- Continue 10 TeV IR lattice development
- Engineering considerations for nozzle and integration with detector and solenoid
- Study the permissible halo-induced background in the IR (derive specs for halo cleaning)
- Refinement of incoherent pair production background
- Study radiation damage in IR magnets & detector

Radiation damage in detector (10 TeV)

For IMCC lattice version v0.4

Radiation damage estimates for 10 TeV (MAP nozzle, CLIC-like detector) Includes only contribution of decay-induced background!



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

IMCC plans for final ESPPU report:

- Redo radiation damage calculations with optimized 10 TeV nozzle and lattice (and new detector design)
- Calculate contribution of other source terms (e.g. incoherent pairs, halo losses)

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Muon Decay and Neutrino Flux

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

Aim for **negligible impact from arcs**
- Similar impact as LHC
- At 10 TeV go from acceptable to negligible with mover system
  - Mockup of mover system planned
  - Impact on beam to be checked

Detailed studies by RP and FLUKA experts
- Impact on surface
- Considering buildings

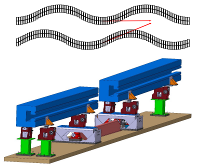
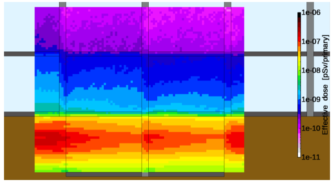
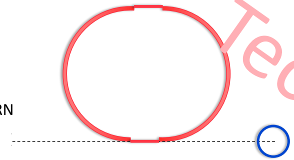


Fig. 7.23: Mock-up of the proposed magnet movement system.





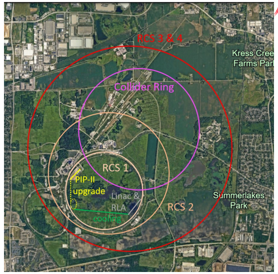
Impact of experimental insertions
- 3 TeV design acceptable with no further work
- But better acquire land in direction of straights, also for 10 TeV
- Detailed studies identified first location and orientation close to CERN
  - Poiint to uninhabited area in Jura and Mediterranian sea

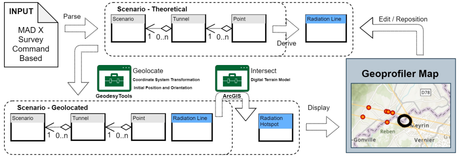
Site Studies

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

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

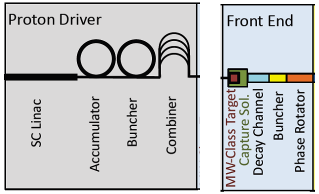
Some considerations are important
- Neutrino flux mitigation at CERN
- Accelerator ring fitting on FNAL site





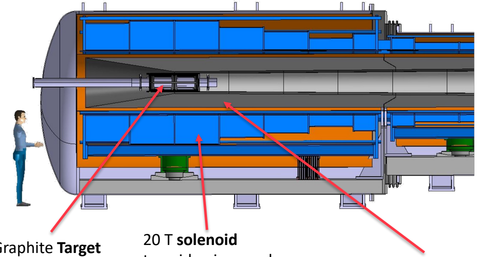
Potential site next to CERN identified
- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura
- Detailed studies required (280 m deep)

Proton Complex and Target



protons → in target → pions → decay → muons

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

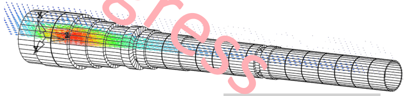


5 GeV proton beam, 2 MW = 400 kJ x 5 Hz
Power is at hand

ESS and Uppsala are woring on merging beam into high-charge pulses
- Indication is that 10 GeV would be preferred

Target Technologies

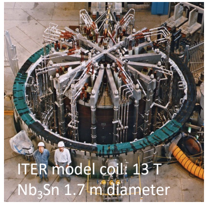
Target solenoid design ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert



HTS target solenoid: 20 T, 20 K

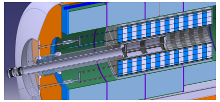
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

Our work is relevant for fusion



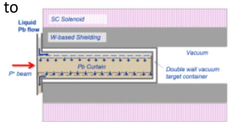
FLUKA studies:
2 MW target: stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

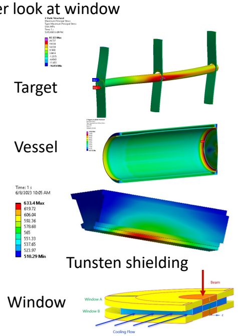
Integration



Cooling, vacuum, mechanics, …

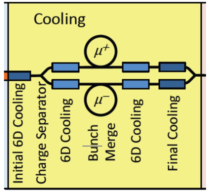
Liquid metal target
Serious alternative to graphite



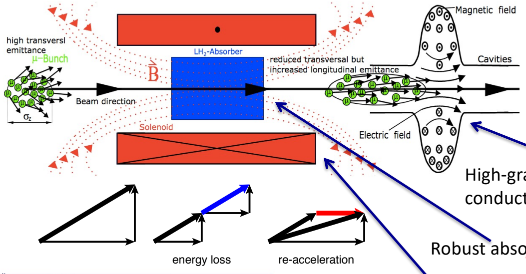


A. Lechner, D. et al.

Muon Cooling Principle



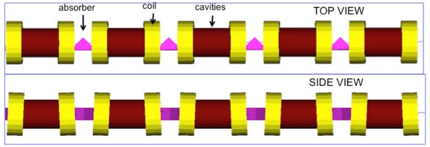
C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)



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 Simulations

Reminder: multiple scattering is not straightforward to simulate

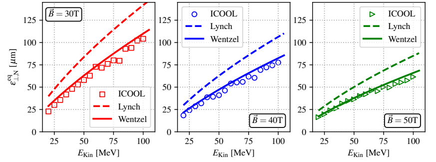
Developed RFTrack to allow simualtion of the muon cooling

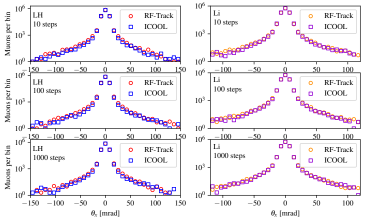
Integration of novel model in RFTrack

Benchmarking confirms validity

Recently discovered:
- Some bug in data extraction routine
- Step size dependence

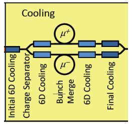
Both seem to be solved by now
- But would like to review previous results

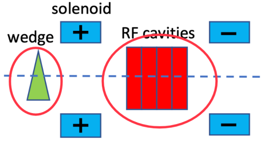




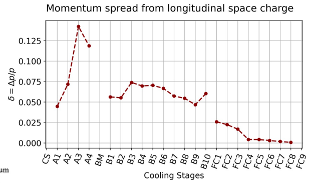
B. Stechauner, E. Fol, Taylor, A. Latina, P. Valdor et al.

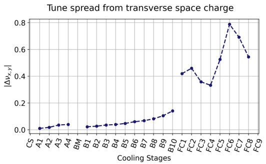
Collective Effects

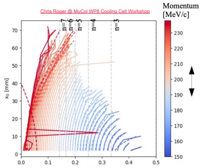




Zhu Ruihu @ Muon Cooling Working Group Meeting,01.26.2023







Activity started recently

J. Potdevin, T. Poeiloni, X. Buffat et al. (CERN)

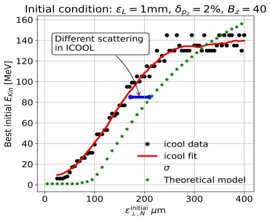
Muon Cooling Performance

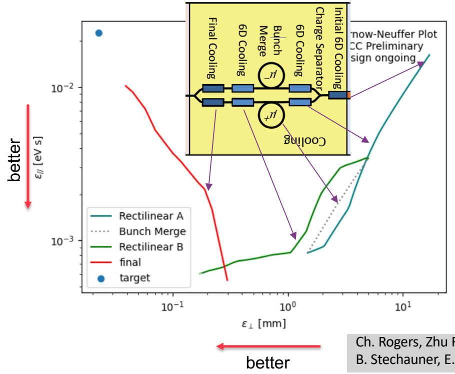
MAP design achieved 55 um based on achieved fields

Currently in 30-40 um range
- Need careful checks

Identification of optimum energy for cooling as function of emittance

B. Stechauner at al.





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

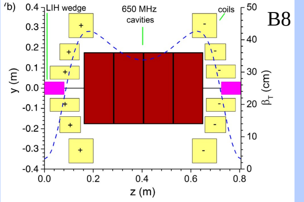
Cooling Cell Technology

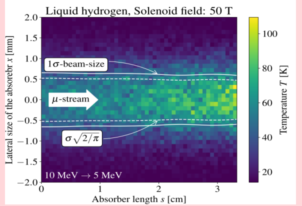
L. Rossi et al. (INFN, Milano, STFC, CERN),
J. Ferreira Somoza et al.

Integrated cooling cell

- tight constraints
- additional technologies (**absorbers**, instrumentation,...)
- early preparation of **demonstrator facility**

Most complex example 12 T





Identified windows and absorbers as critical for high-density muon beam

- Pressure rise mitigated by using H-gas with calibrated density
- First window test in HiRadMat

B. Stechauner, J. Ferreira Somoza et al.

Test of 1 um Si_3N_4:
Very high energy deposition (15x) leads to deformation but no rupture

D. Schulte, Muon Collider, May 2024

Technical progress

Solenoid R&D

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

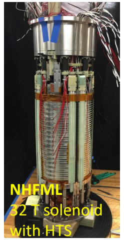
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

Final Cooling solenoid

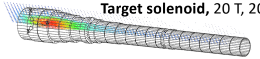
$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}$

σ_{max} = 600 MPa

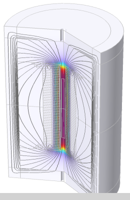
$B_{max} \approx$ 55 T

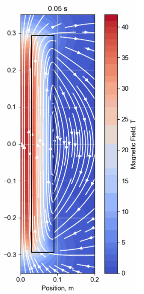


32 T LTS/HTS solenoid demonstrated

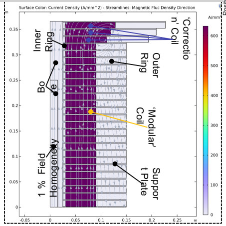


Target solenoid, 20 T, 20 K



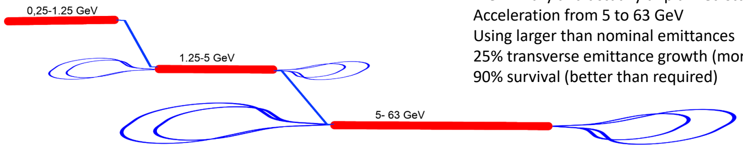


A. Dudarev, B. Bordini, T. Mulder, S. Fabbri

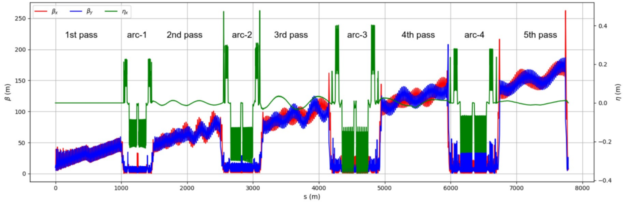


D. Schulte. Muon Collider. INFN. May 2024

Muon Initial Acceleration



Preliminary and actually unplanned study of RLA2:
Acceleration from 5 to 63 GeV
Using larger than nominal emittances
25% transverse emittance growth (more work required)
90% survival (better than required)

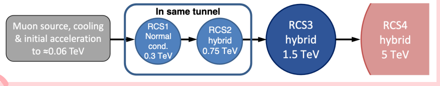


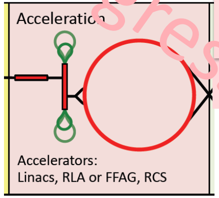
A. Aksoy

No more resources!
Avni left!

D. Schulte, Muon Collider, May 2024

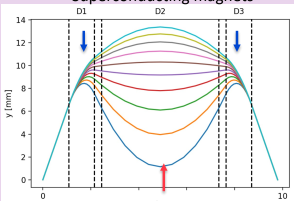
Acceleration Complex



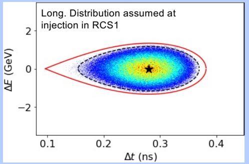


Core is sequence of pulsed synchrotron (0.4-11 ms)
Alternative FFA

Superconducting magnets



Fast-ramping magnets



RF:
1.3 GHz cavities appear possible
- in spite of high bunch charge

Lattice:
Hybrid design works
Can spread RF in the arcs

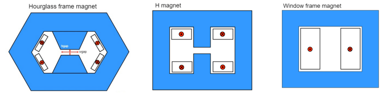
Lattice and integration: A. Chance et al. (CEA)
Long. dynamics and RF systems: H. Damerell, U. van Rienen, A. Grudiev et al. (Rostock, Milano, CERN)
Power converter: F. Boattini et al.
Magnets: L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)
FFA: S. Machida et al. (RAL)

D. Schulte, Muon Collider, INFN, May 2024

Fast-ramping Magnet System

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

Synchronisation of magnets and RF for power and cost



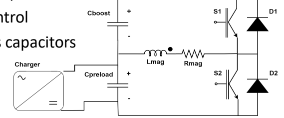
5.07 kJ/m | 5.65…7.14 kJ/m | 5.89 kJ/m

Differerent power converter options investigated

Commutated resonance (novel)

Attractive new option

- Better control
- Much less capacitors



FNAL 300 T/s HTS magnet

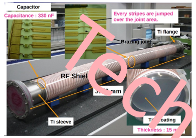
Could consider using HTS dipoles for largest ring

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

Beampipe study

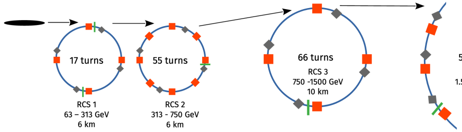
Eddy currents vs impedance

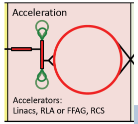
Maybe ceramic chamber with stripes

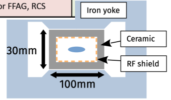


F. Boattini et al.

Collective Effects

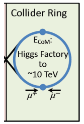


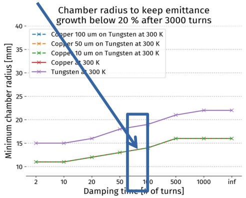




Impedance studies

Single beam instability limits OK with conservative feedback



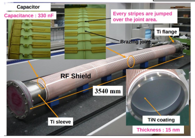


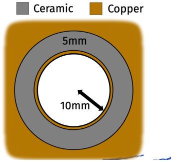
Beampipe study

Eddy currents vs impedance

Maybe ceramic chamber with stripes

Impedance model





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

Collider Ring

High performance 10 TeV challenges:

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

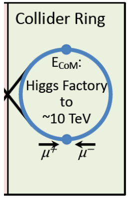
3 TeV:

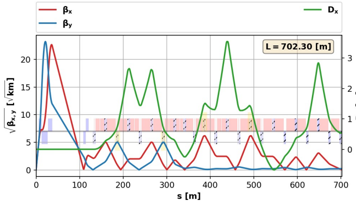
MAP developed 4.5 km ring with Nb_3Sn

- 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



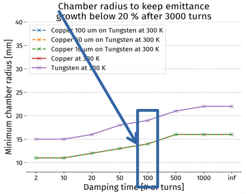


K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas

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

Impedance studies

Single beam instability limits OK with conservative feedback



Collider Ring Technologies

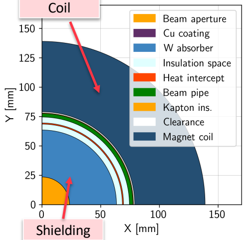
Power loss due to muon decay 500 W/m

FLUKA simulation of required **shielding:**

20-40 mm tungesten shielding (about OK-safe)

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

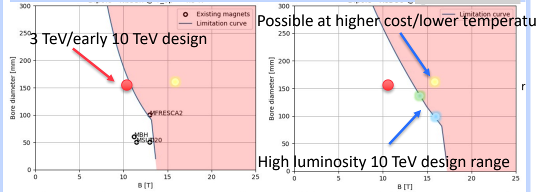
⇒ Magnet coil radius 59-79 mm



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.



Nb_3Sn 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 Nb_3Sn

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

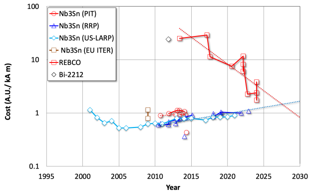
Dipole Cost

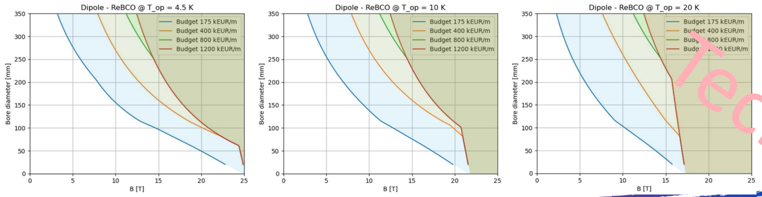
Key cost drivers are based on sound models
- E.g. RCS with trade-off between RF and magnet cost

A part of the cost will be based on scaling from other projects

A part of the cost depends on future developments of technology beyond our study
- E.g. cost of superconductor

Major cost optimisations remain to be done in the design





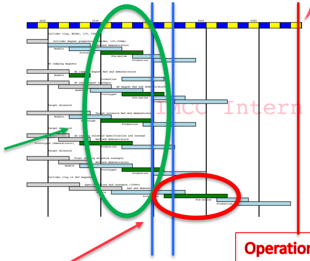
D. Schulte, Muon Collider, Birmingham, July 2024

Magnet Roadmap

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**



Strategy:
- HTS solenoids
- Nb_3Sn accelerator magnets
- HTS accelerator magnets

Seems technically good for any future project

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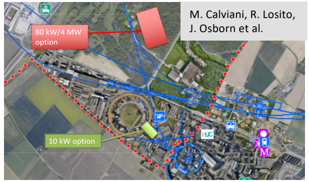
CDR Phase, R&D and Demonstrator Facility

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

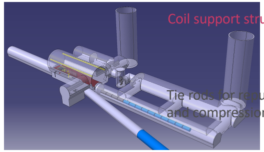
Cooling demonstrator is a key facility
- look for an existing proton beam with significant power

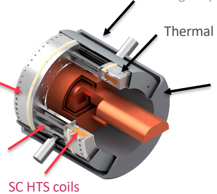
Different sites are being considered
- CERN, FNAL, ESS …
- Two site options at CERN

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



With cryostat





D. Schulte, Muon Collider, INFN, May 2024

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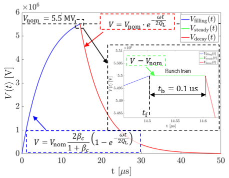
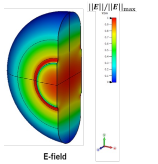
704 MHz cavity for the Muon Cooling (MC) Demonstrator

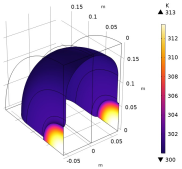
RF design and coupler RF-thermo-mechanical simulations

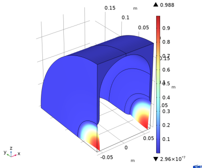
- RF simulations in CST Studio Suite®
  - Calculation of the pulse shape
  - Computation of the main RF figure of merits
  - Optimization of the cavity shape





- RF-thermo-mechanical simulations in COMSOL Multiphysics®
  - Thermally-induced stress-strain state and frequency detuning
  - Mechanical stress and deformations and Lorentz Force Detuning (LFD) analysis





D. Schulte, Muon Collider, April 2024

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Technology Maturity

Important timeline drivers:

- **Magnets**
  - HTS technology available for solenoids (expect mature for production 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 and demonstrator** (expect demonstrator operational in <10 years, with enough resources, allows to perform final optimization of cooling technology)
- **Detector technologies and design** (expect in 15 years)

Other technologies are also instrumental for performance, cost, power consumption and risk mitigation

- but believe that sufficient funding can accelerate their development sufficiently

Other important considerations for the timeline are

- Civil engineering
- Decision making
- Administrative procedures

Staging

Energy staging

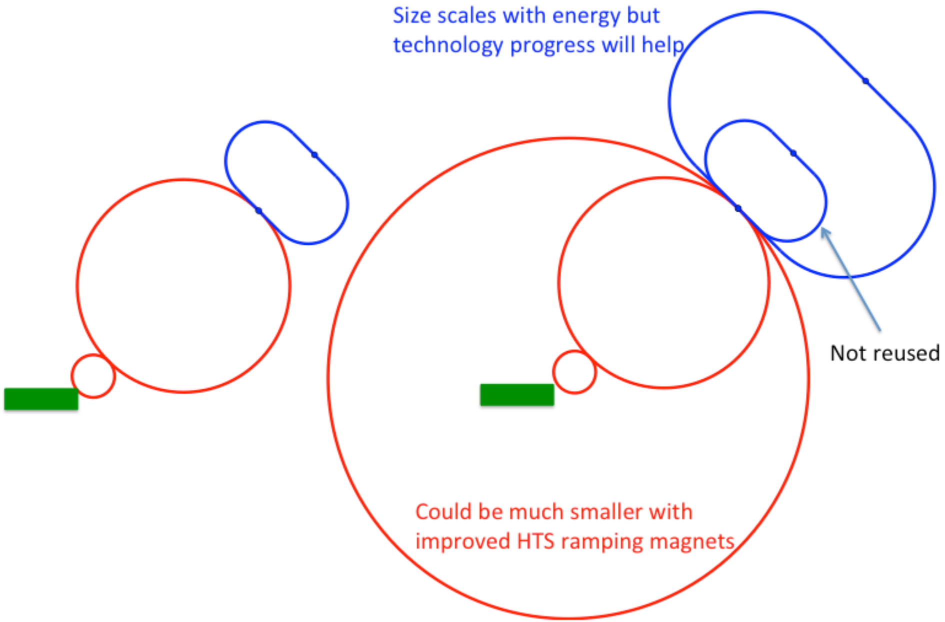
- Start at lower energy
- Current 3 TeV, design takes lower performance into account
- Splits cost, little increase in integrated cost

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)

Start considering reuse of existing infrastructures

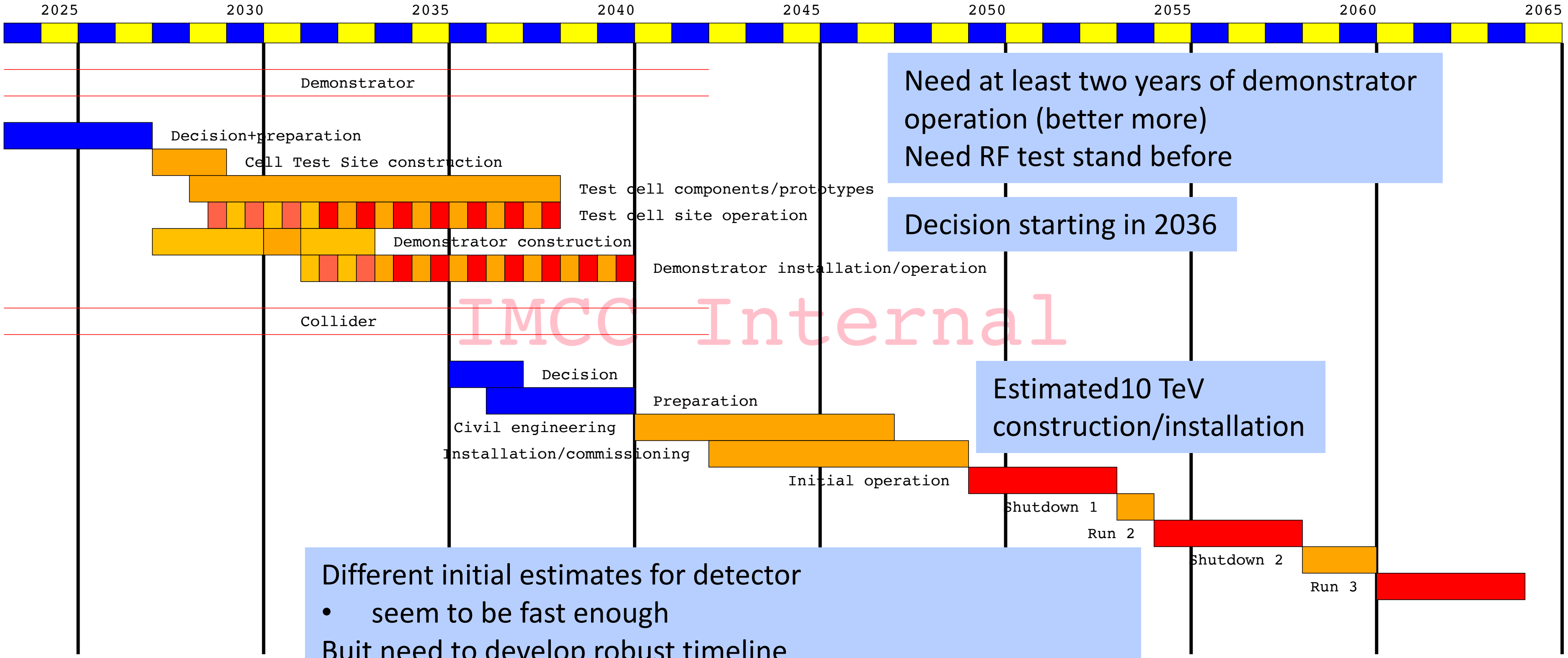
- But maintain green field



Tentative Timeline (Fast-track 10 TeV)

International MUON Collider Collaboration

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

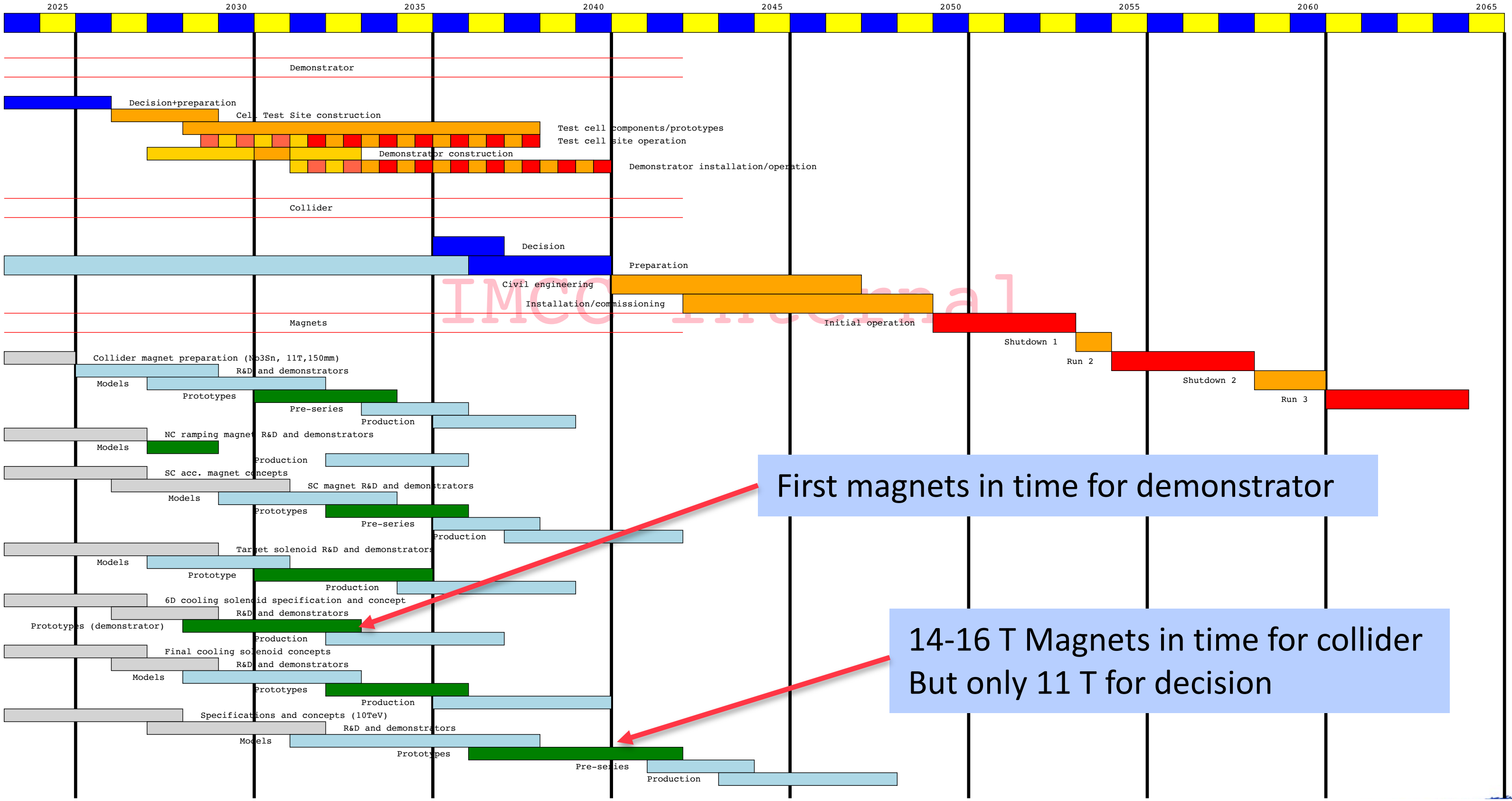
Estimated10 TeV construction/installation

Different initial estimates for detector
- seem to be fast enough

Buit need to develop robust timeline

Timeline with Magnets

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



First magnets in time for demonstrator

14-16 T Magnets in time for collider
But only 11 T for decision

IMCC Plans

IMCC is a world-wide collaboration

- Provide input to all regional processes
- Accelerator R&D Roadmap has been developed with global community

We want a muon collider

- Where it will be hosted will be in the hands of funding agencies
- One lesson to take from ILC

Medium-term plans:

- For the **ESPPU (March 2025),** will deliver planned reports to ensure support in Europe
- Will fulfill **EU contract (February 2027)**
  - **Final deliverable is report on all R&D**
- Will provide the required input to the process in the US that follows the ESPPU according to P5 recommendations (**2027?**)
  - Likely requires **Reference Design**
- Will provide input to any other processes

ESPPU

European Strategy Group
Represents member states, large laboratories, CERN management and invitees, e.g. Prof. Michael Tuts for the US

Preparatory Group
Prepares Briefing Book
To be appointed by CERN Council
Two members from the Americas

Strategy Secretariat
Karl Jakobs (Strategy Secretary)
Hugh Montgomery (SPC Chair)
Dave Newbold (LDG Chair)
Paris Sphicas (ECFA Chair)

Find more at: https://europeanstrategyupdate.web.cern.ch/welcome

Plan for ESPPU

International MUON Collider Collaboration

March 2025 deliver promised ESPPU reports

- **Evaluation report**, including tentative cost and power consumption scale
- **R&D plan**, including scenarios and timelines

This requires to push as hard as possible with existing resources

Present **green field** designs and continue to work on them

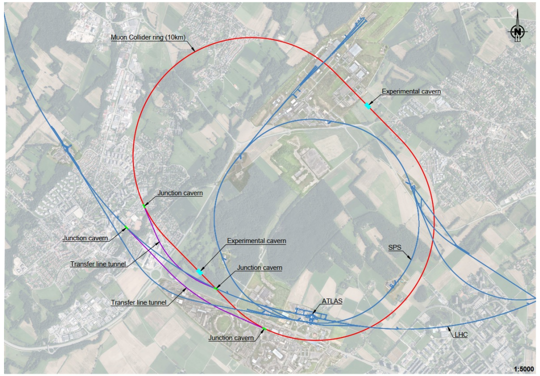
- International collaboration
- Parameters, lattice designs, component designs, beam dynamics, cost, …

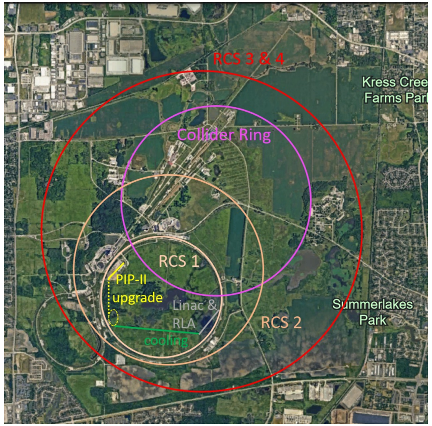
Perform example **civil engineering studies**

- CERN (collider and demonstrator)
- FNAL, the US started doing similar studies

Provide parameters tables for the implementation at existing sites (FNAL, CERN, …)

- Scaled from green field design using existing infrastructure
- Do not have the resources and time to make detailed designs for CERN and FNAL for ESPPU





Report Writing and Editing

Two levels of reports
- Concise version as input to briefing book (10pages?)
- Longer reports to support concise reports

Timeline
- September 2024: Overleaf in place for authors to start
- End of October 2024: Report ready for content editing
- End of December 2024: Draft ready for collaboration and the IAC
- End of January 2025: Report ready for copy editing (language)
- End of February 2025: Start of signature process
- End of March 2025: Report ready

Have to form **editorial team**
- Regular meetings
- Active role in writing
    - And pushing the other authors
- **Volunteers from the US welcome**
- **Can offer associate position for one person**

R&D Plan and Schedule

Will submit an R&D plan to ESPPU

- Allows to maintain momentum during and after the process

A common plan with the US

- You will join the effort of implementing it

Defining the scope of the R&D is critical

- Need to have realistic scope, address what is important, but do not overcommit
- Each work area proposes scope for that field, followed by arbitration on a higher level
- Identify the required resources and potential distribution of work
    - Based on the estimates of the different work areas

Important to establish that technically a timeline relevant for young peoples can be envisaged

- Needs to critically review proposed tentative timeline

Critical to agree on common technically limited timeline

- Implementation considerations may later change the implementation in the US and in Europe
- E.g. political developments, budgets, other projects, strategy decisions, …

Organisation

Longer run: Full merging of US effort with IMCC

Short-time: Fast contributions to the ESPPU

- **Physics case**
- Make a **common schedule** and **R&D plan**
  - In particular, specific items
    - Demonstrator development
    - Magnet development
    - Detector design
    - Other areas

Potential organisation:

- Appoint a **European** and a **US coordinator** for each area of the R&D report, where possible
- A small task force reviews and updates the current schedule
- The R&D plan coordinators review the schedule in more depth

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

Now integrate the US at eye level

Urgent key issues is preparation of ESPPU
- Need your help now

Then preparation of US process

Many thanks to the collaboration for all the work

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

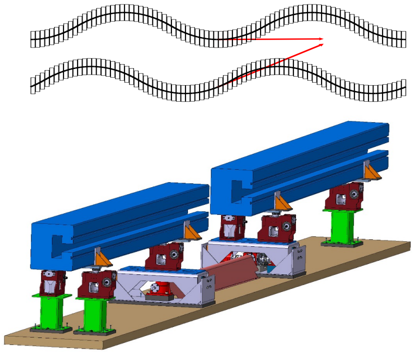
Reserve

Muon Decay and Neutrino Flux

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

Aim for **negligible impact from arcs**
- Similar impact as LHC
- At 10 TeV go from acceptable to negligible with mover system
  - Mockup of mover system planned
  - Impact on beam to be checked

Detailed studies by RP and FLUKA experts
- Impact on surface
- Considering buildings



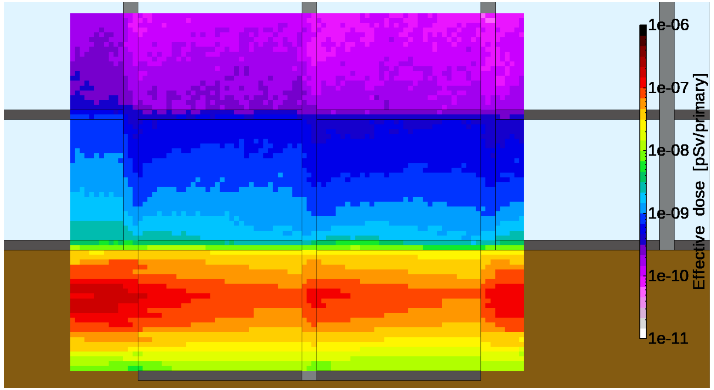
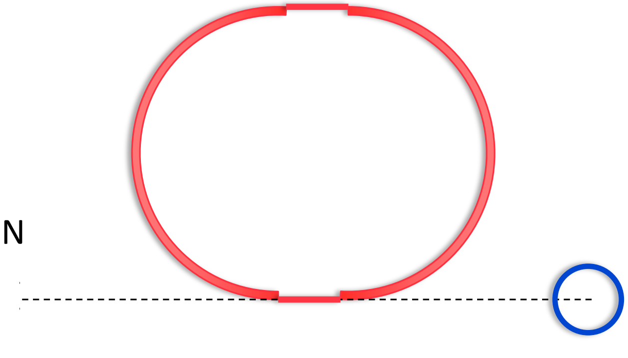


Fig. 7.23: Mock-up of the proposed magnet movement system.



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

US P5: The Muon Shot

It is great news that the P5 report makes so clear and prominent recommendations concerning muon collider R&D, participation in the International Muon Collider Collaboration (IMCC), and taking a leading role in the muon collider design process. This is the fruit of your excellent work during the Snowmass process.

Several US institutes are already members of the IMCC and members of the US community are already engaged in important roles.

The US expertise in the different fields, including physics, detectors, accelerators, technologies and project leadership will be instrumental to the progress of the muon collider design. In particular, the ambition of the US to host such a facility is excellent news and strengthens the motivation for R&D and demonstrator planning at a fast pace.

As already planed, we will revise the distribution of R&D efforts and the organisation with your help in 2024, reflecting the US efforts and resources. This will enable us to move forward in the most efficient way possible, with a much stronger collaboration, towards a muon collider design and hopefully implementation.

Welcome,

Daniel, Nadia and Steinar.

R&D Plan

Plan is to submit an R&D plan to ESPPU

- Allows to maintain momentum during and after the process
- Should be a global programme

A common plan with the US

Defining the scope of the R&D is critical

- Need to have realistic scope
- Address what is important
- But do not include non-essential items
- Each work areas should propose the scope for that field
- Followed by an arbitration on a higher level

Identify the required resources and potential distribution of work

- Based on the estimates of the different work areas

Schedule

Important to establish that technically a timescale consistent with young peoples' careers can be envisaged

- Needs to critically review proposed tentative timeline

Critical to agree on common technically limited timeline

- Implementation considerations may later change the implementation in the US and in Europe
- E.g. political developments, budgets, other projects, strategy decisions, …

Main technical areas to be considered for the timeline

- The muon cooling technology and the demonstrator
- The magnet technology
- The detector
- Start-to-end model of the collider
- Other technologies
- Site specific studies

R&D Plan Considerations

I do not think that we have the resources to make a full plan until the implementation of the project

- Focus on the next few years, a little less detailed for the longer term
- Include the items that technically drive the timeline
- Or that are important for the decision process

R&D reduces the risk of a project

- Will have diverging opinions about the importance of some items
- I expect that we need to define risk classes

Some key questions:

- What does the demonstrator really need to demonstrate?
- Do we need a demonstration of a hybrid synchrotron or is a demonstration of a cell sufficient?
- Which alternatives should be included?
- What is the path toward the magnets?

Dear US colleagues,

it is great news that the P5 report makes so clear and prominent recommendations concerning muon collider R&D, participation in the International Muon Collider Collaboration (IMCC) and taking a leading role in the muon collider design process. This is the fruit of your excellent work during the Snowmass process.

The US expertise in the different fields, including physics, detectors, accelerators, technologies and project leadership will be instrumental to the progress of the muon collider design. In particular, the ambition of the US to host such a facility is excellent news and strengthens the motivation for R&D and demonstrator planning at a fast pace.

As already planned, we will revise the distribution of R&D efforts and the organisation with your help in 2024, reflecting the US efforts and resources. We look forward to understanding your vision of the US participation, both in R&D areas and organisation. This will enable us to move forward in the most efficient way possible, with a much stronger collaboration, towards a muon collider design and hopefully implementation.

Several US institutes are already members of the IMCC and members of the US community are already engaged in important roles. We understand that it will take some time to ramp up the US effort. Three R&D areas are particularly critical for the timely implementation of a muon collider:

- The development of superconducting magnets in the different parts of the accelerator. Both HTS solenoids and superconducting accelerator magnets are needed. The US expertise, demonstrated for example in the HL-LHC magnets, will be instrumental.
- The development of the muon production and cooling technology and its demonstration in a facility. Developing more than one site option will make this effort more robust and US participation to the technology is essential.
- The detector concept and technologies R&D. The muon collider will reach lepton collision energies beyond those studied for other approaches, such as CLIC. The detector design and technologies will be challenging and should consider novel concepts of hard- and software. It appears to be prudent to develop alternative concepts to a good level of detail to ensure that we can take full advantage of the muon collider.

Obviously, US contributions in all other R&D fields will also be important.

Physics considerations will be instrumental in to develop implementation scenarios that are consistent with the interest in all regions addition to the technical R&D:

- the relative merits of an energy staging versus a luminosity staging of the muon collider;
- the overall physics performance and complementarity of a high-energy muon collider and a low energy Higgs factory;
- the complementarity of a high energy muon collider and a proton collider.

We are looking forward to an exciting development of the collider.

Welcome,

Daniel for the IMCC.

Areas of US Contribution

Need a start-to-end model of the muon collider

- More accelerator physicists

Need contributions to the key technology lines

- Muon cooling technology and demonstrator
- Magnets

Need contributions to the full range of accelerator technologies

- Neutrino flux mitigation, target, instrumentation, vacuum, …

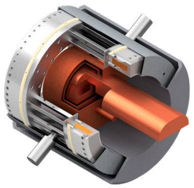
Need to increase the effort on at least two detector designs

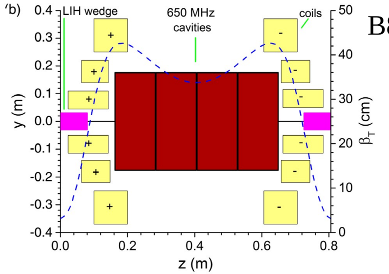
- Also considering the technologies

Site specific studies (demonstrator and collider)

R&D Programme

Broad R&D programme can be distributed world-wide

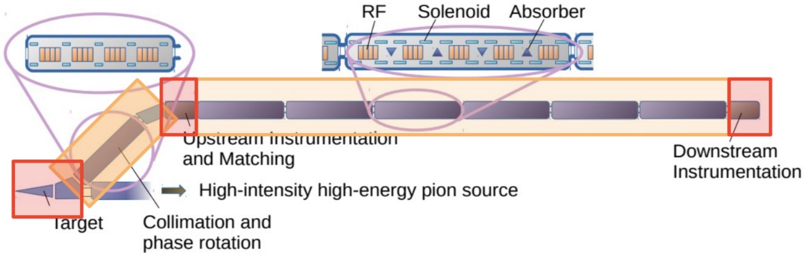




B8

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

Tentative Staged Target Parameters

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

Organisation Form

USMCC appears to focus on finding resources and monitor their use

- Would like to have US participate to the leadership

Almost everyone prefers to have the project in their region

- But better to have the project in a different region that not at all
- Site will be will decided by funding agencies of the different regions
    - A strong effort in other regions will help to convince funding agencies
    - Actually, a competition between funding agencies is best for everybody

Best setup is one coherent collaboration

- Addresses all challenges of the muon collider
- Establish its benefits for science and society
- Promote it toward society and funding agencies

Only a sub-part should focus on local implementation

- Not two project studies that collaborate but a collaboration that considers two or more sites

Very Short-term Plan

International MUON Collider Collaboration

Just finished Interim Report

- Design
- Challenges
- Plan until 2026

Contents

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CERN-2023-XXX

v

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)

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

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

Role of Higgs Factory

The community wants a higgs factory as a first step

- Will explore important questions and may point to new physics
- A higgs factory is currently considered in Japan (ILC), China (CEPC) and Europe (FCC-ee, LC at CERN)
- Need additional budget for CEPC, ILC and FCC, but probably not for linear collider at CERN
- The highest-energy facility would have to come after the higgs factory if it where in the same region

Note: I think that Europe will strive to maintain CERN as a leading laboratory with continued or increased budget

Catch:

Higgs factory results are unlikely available when a decision for 10 TeV has to be taken

- Aggressive lead time 15 years if sufficient preparation has been done
- Earliest potential higgs factory is CEPC approved 2025, ready 2035, results 2040

Consideration:

- We should strive to move toward the highest-energy facility with the largest discovery potential

Recent Results: Interim Report

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

CERN-2023-XXX

Contents

Proposal: EuMAHTS

MuCol

Luca Botture et al.

Submitted to INFRA-2024-TECH-01-01

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)

EuMAHTS
Accelerating HTS

International
MUON Collider
Collaboration

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

Magnet Roadmap

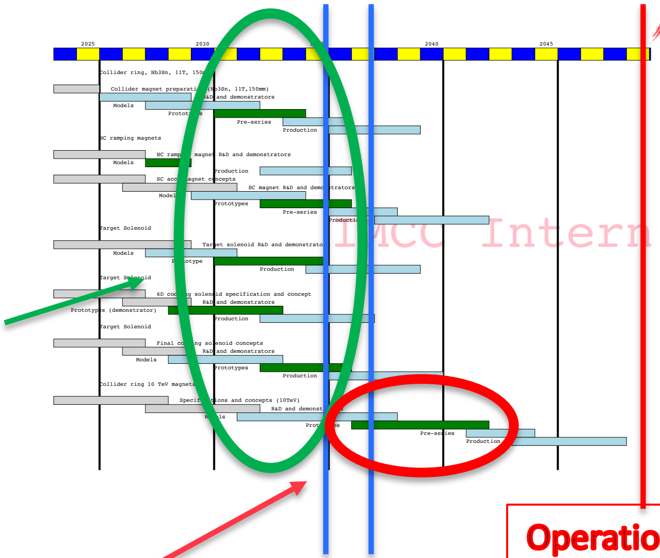
Assume: Need prototype of magnets by decision process

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, …

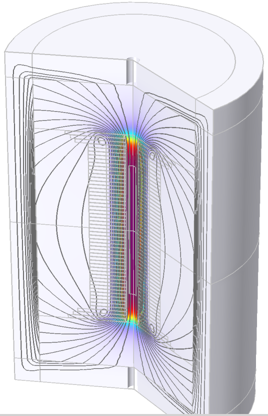
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

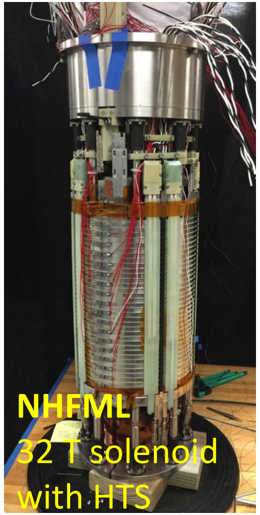
Final Cooling solenoid

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

σ_{max} = 600 MPa

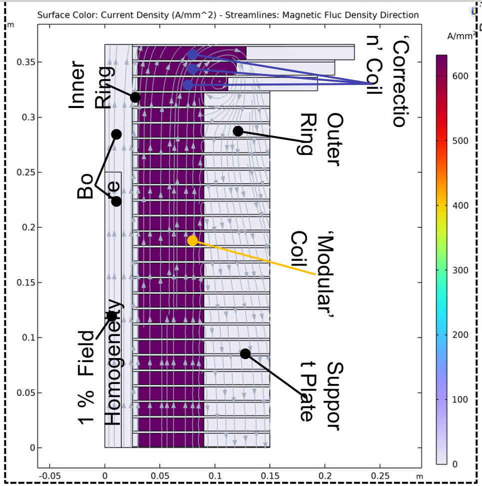
$\mathbf{B_{max} \approx 55\ T}$

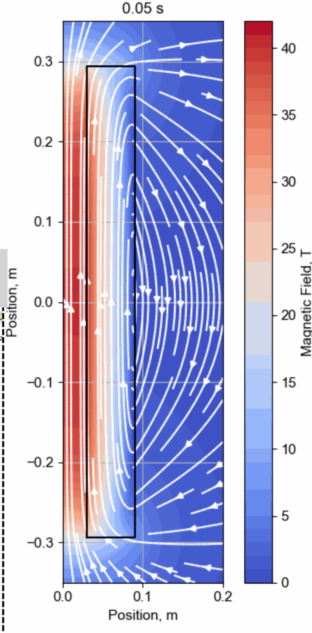


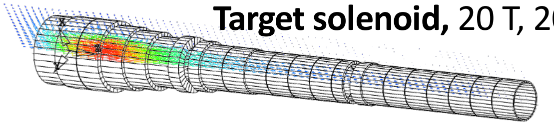


32 T LTS/HTS solenoid demonstrated

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



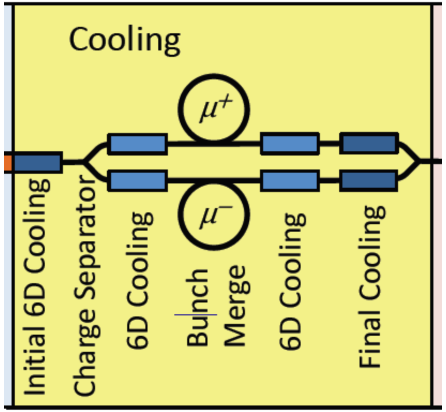




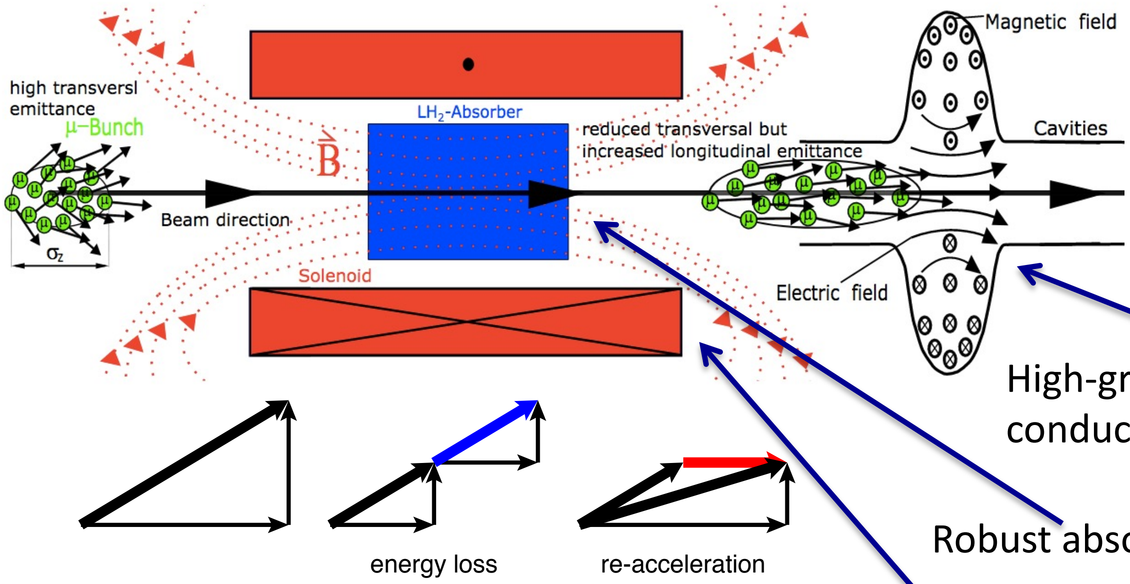
Target solenoid, 20 T, 20 K

Muon Cooling Principle

International
UON Collider
Collaboration



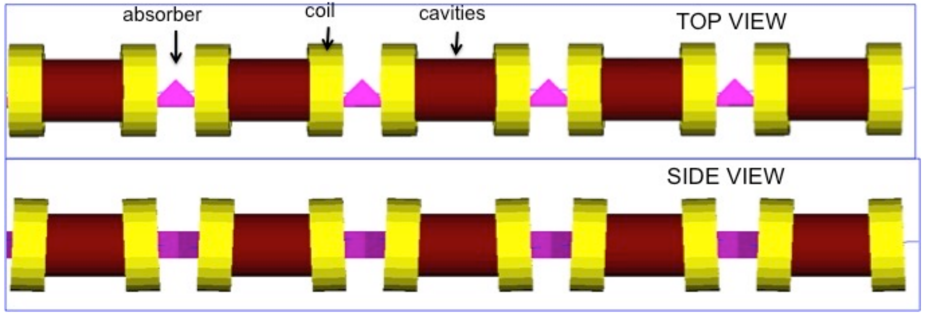
C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)



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

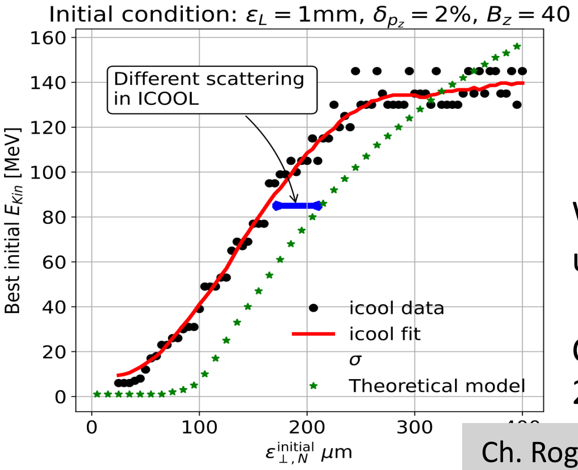
International MUON Collider Collaboration

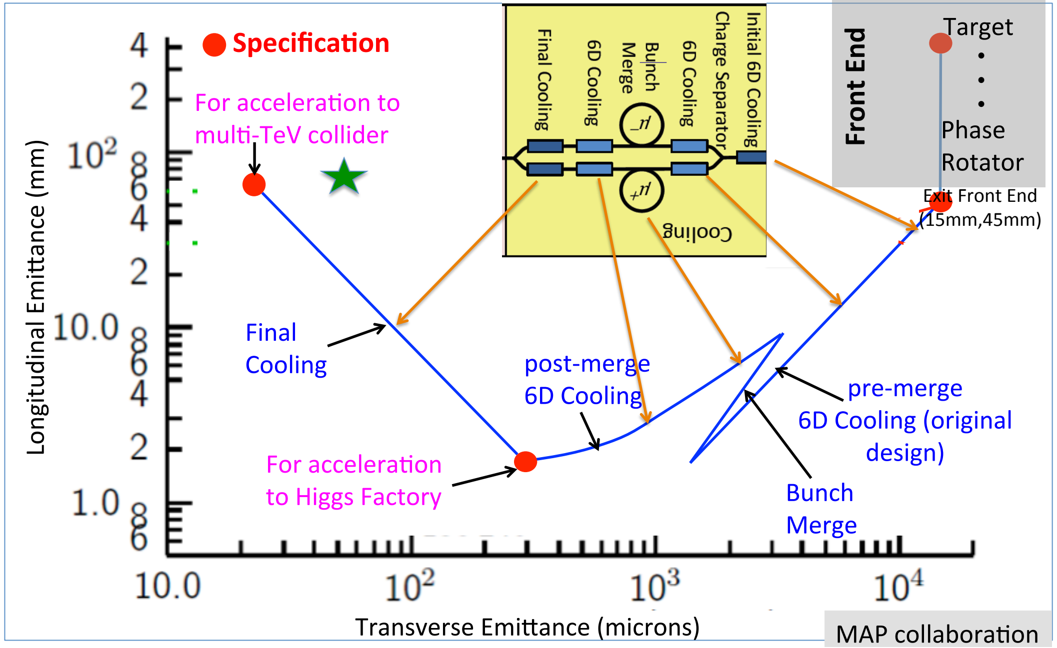
MAP design achieved 55 um based on achieved fields

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.

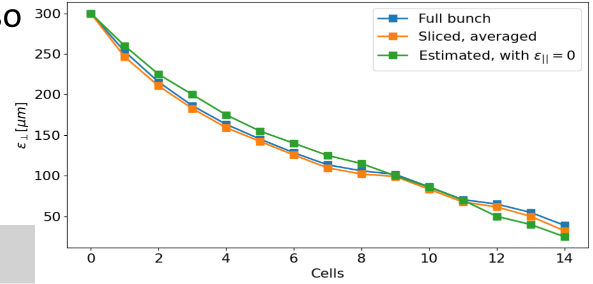




MAP collaboration

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

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

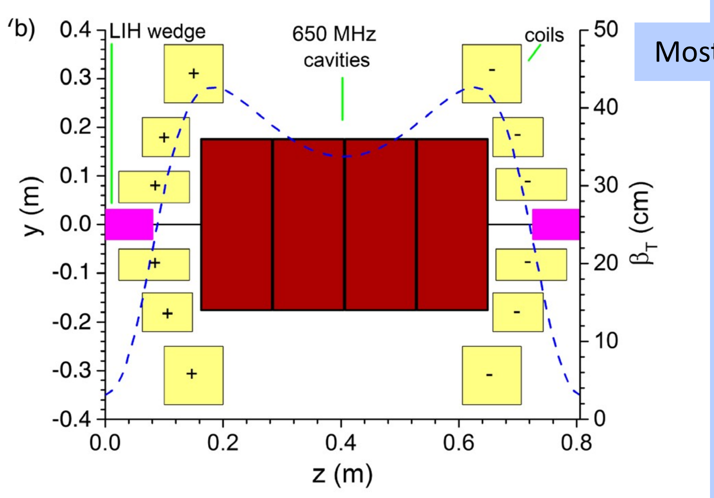


Ch. Rogers, Zhu Ruihu, R. Taylor, B. Stechauner, E. Vol et al.

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.

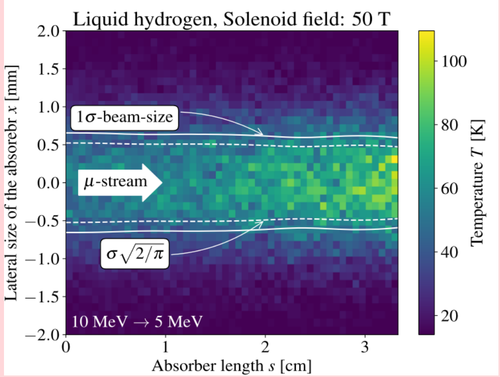


Most complex example 12 T

HTS solenoids
Ultimate field for final cooling
Also consider cost

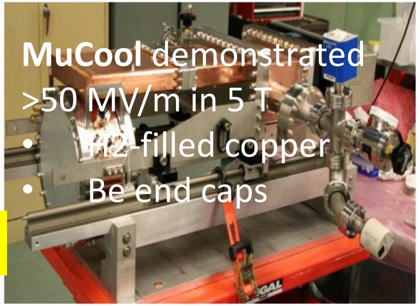
⇒ Marco

Windows and absorbers
- High-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

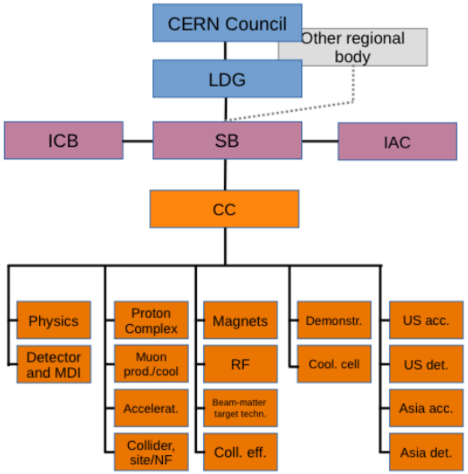


D. Giove, C. Marchand, Alexej Grudiev et al. (Milano, CEA, CERN, Tartu)

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

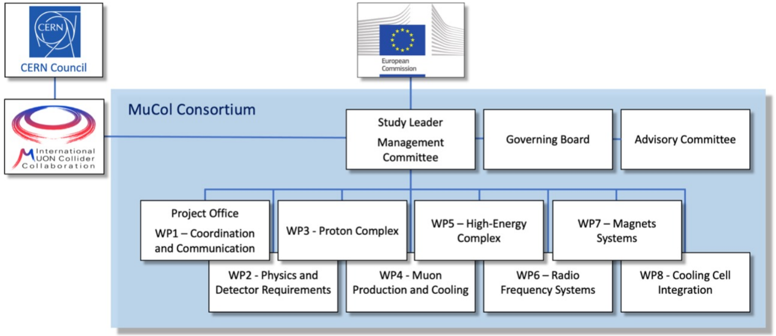
MuCol (EU co-funded)

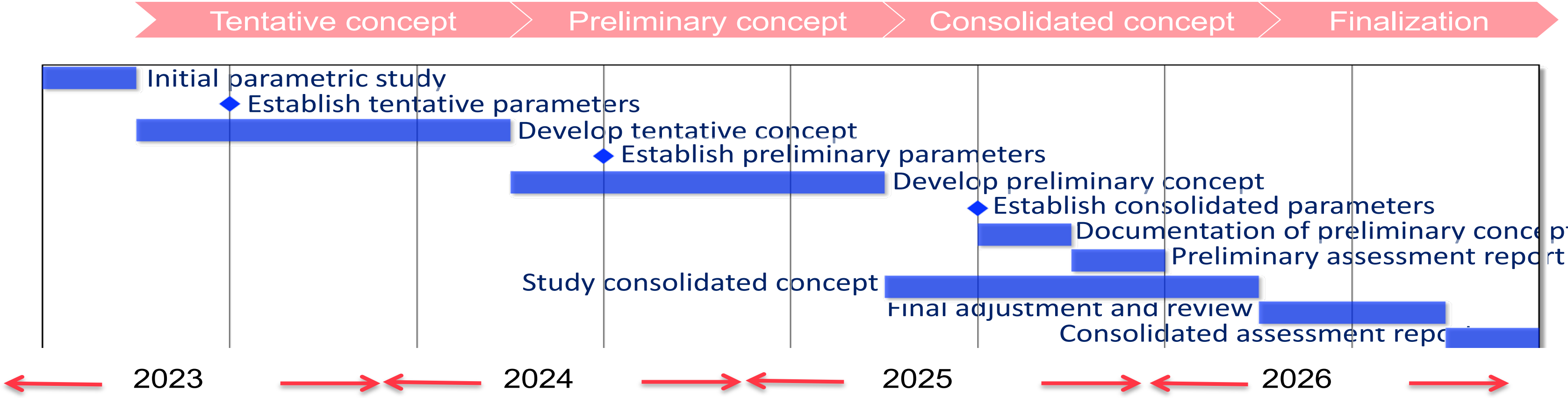
Started March 2023, lasts until early 2027

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

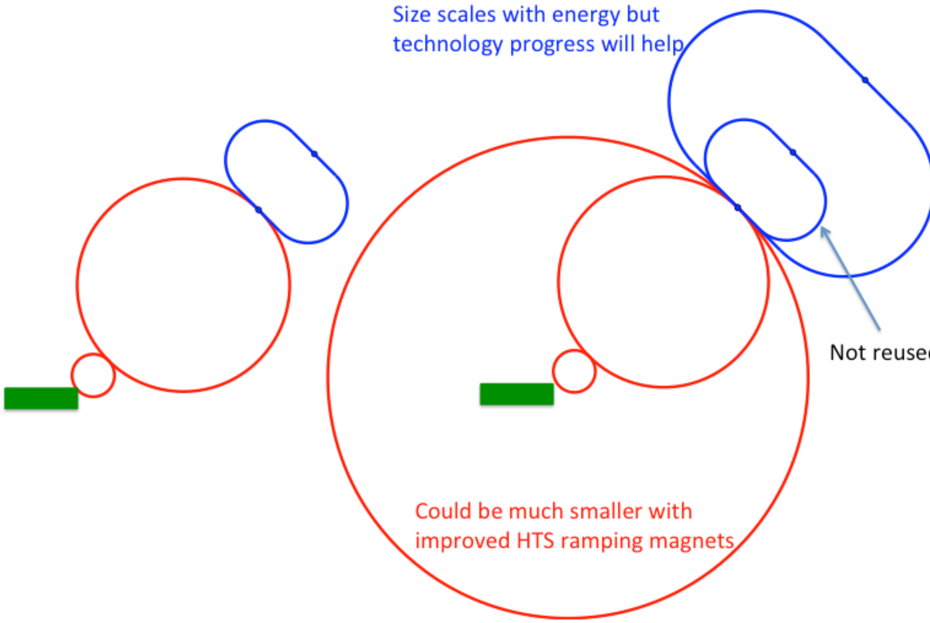
- Can do the important physics with near-term technology

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

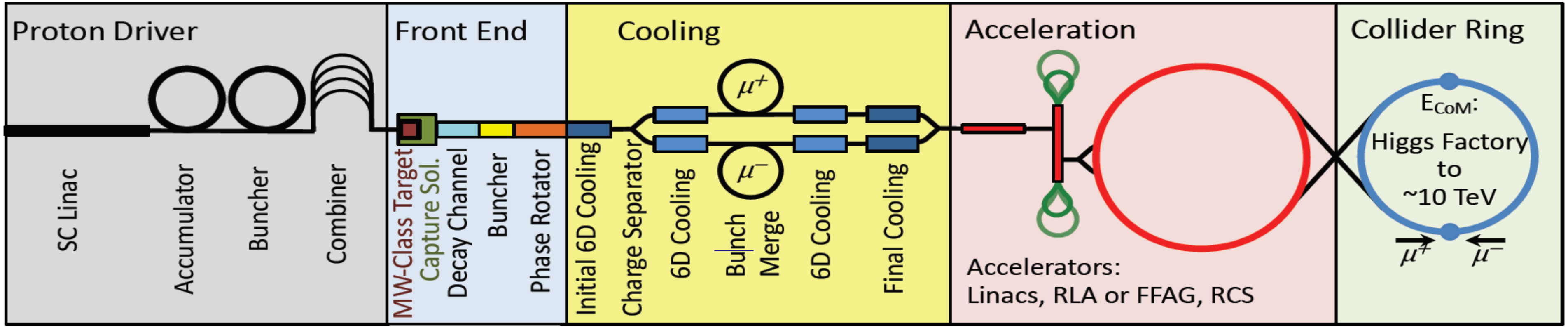
Luminosity staging

- 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

Broad R&D programme can be distributed world-wide

- **Models** and **prototypes**
  - Magnets, Target, RF systems, Absorbers, …
- **CDR** development
- **Integrated tests**, also with beam

Cooling demonstrator is a key facility

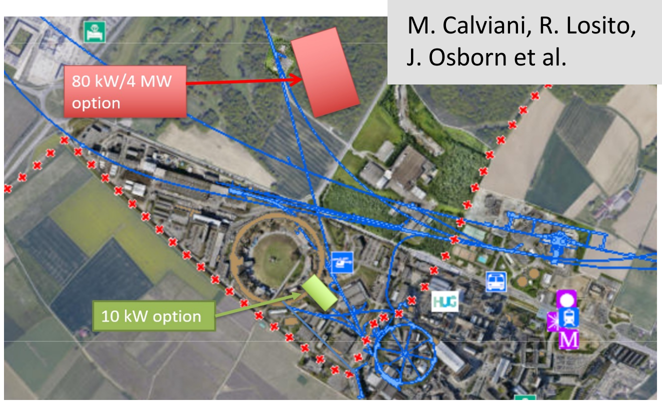
- look for an existing proton beam with significant power

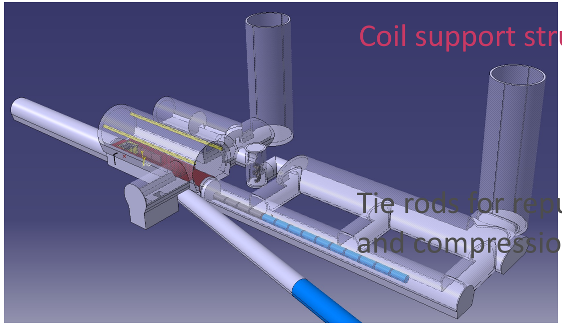
Different sites are being considered

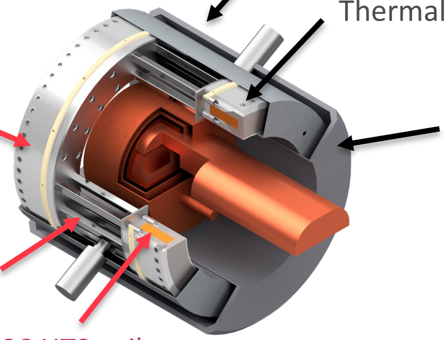
- CERN, FNAL, ESS …
- Two site options at CERN

Muon cooling module test is important

- INFN is driving the work
- Could test it at CERN with proton beam



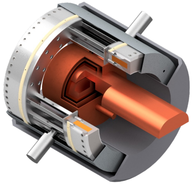


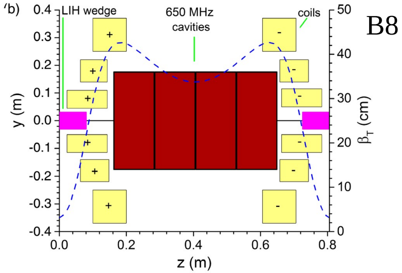


Time-critical Developments

International MUON Collider Collaboration

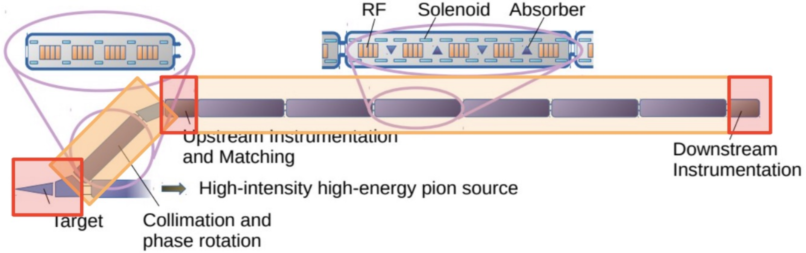
Identified three main technologies that can limit the timeline





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

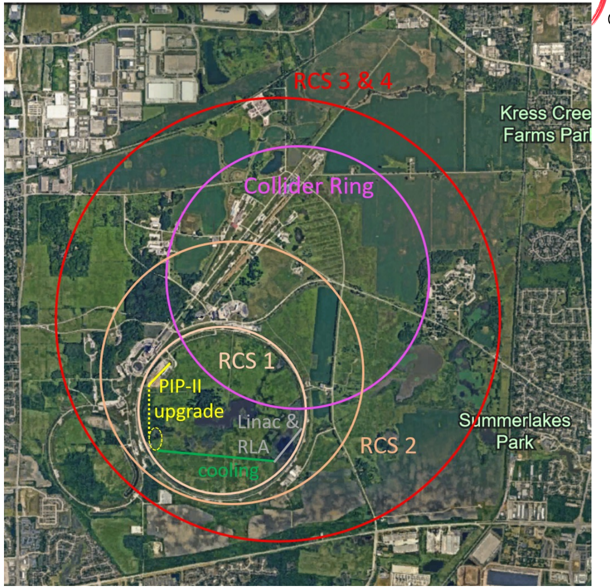
Candidate sites **CERN, FNAL,** potentially others **(**ESS, JPARC, …)

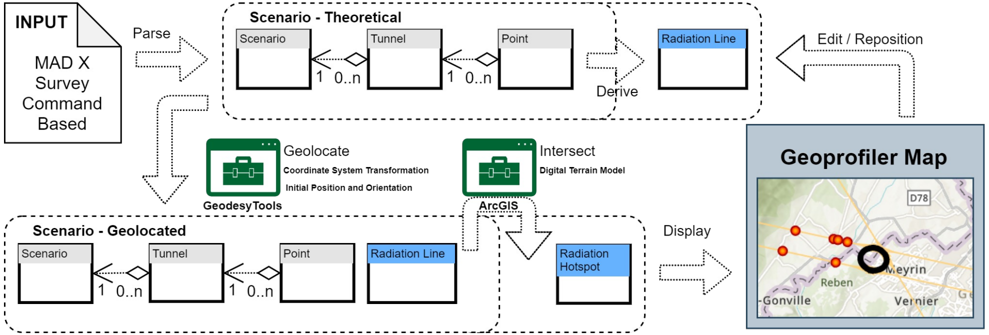
Study is mostly site independent

- 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)