International MUON Collider Collaboration

MuCol

# Muon Collider

D. Schulte
On behalf of the International Muon Collider Collaboration

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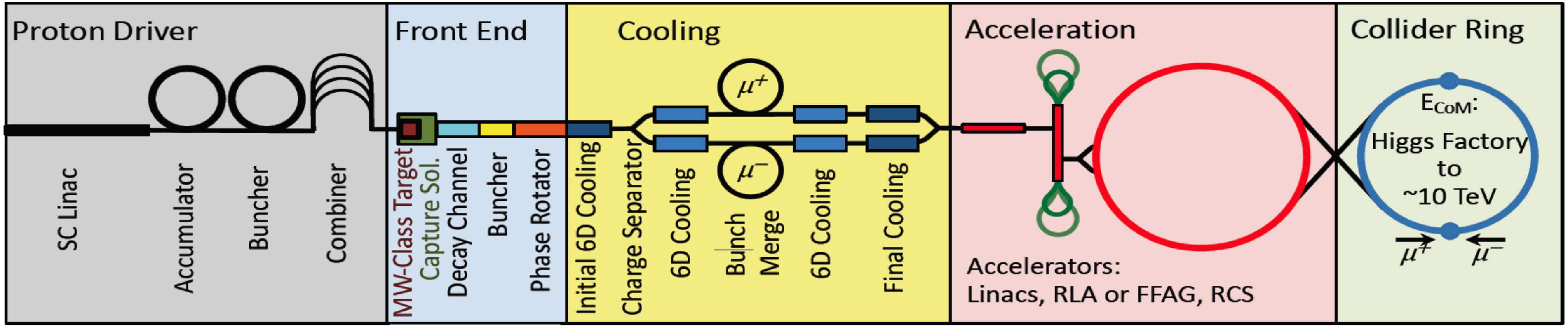
FNAL, October, 2024

# 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

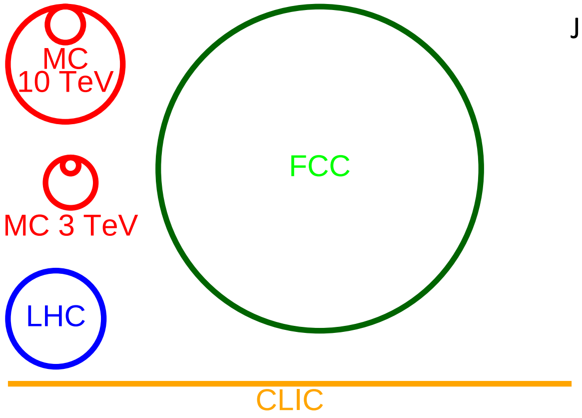
Ionisation cooling of muon in matter

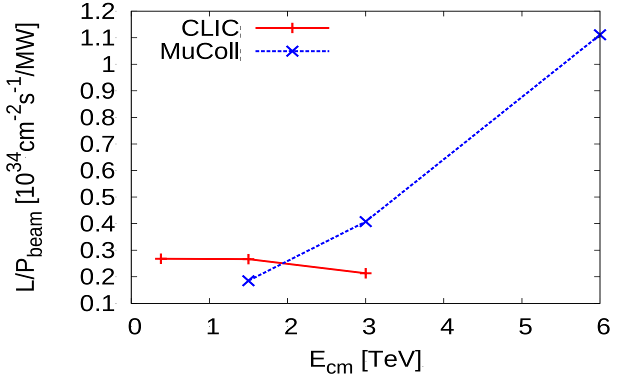
Acceleration to collision energy

Collision

# Muon Collider Promises

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




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

Judgement by ITF, take it *cum grano salis*

# IMCC

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

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

Current accelerator R&D Roadmap identifies the required work

- Has been developed with the global community

IMCC Goals

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

IMCC: International Muon Collider Collaboration

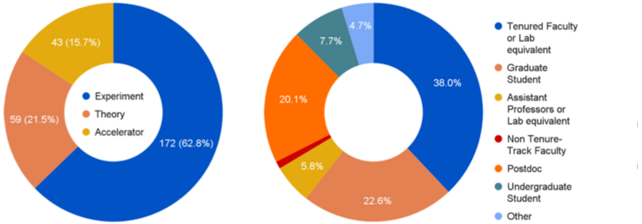
| Label | Begin | End | Description | Aspirational [FTEy] | Aspirational [kCHF] | Minimal [FTEy] | Minimal [kCHF] |
|---|---|---|---|---|---|---|---|
| MC.SITE | 2021 | 2025 | Site and layout | 15.5 | 300 | 13.5 | 300 |
| MC.NF | 2022 | 2026 | Neutrino flux mitigation system | 22.5 | 250 | 0 | 0 |
| 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 |

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

http://arxiv.org/abs/2201.07895

# US Progress

- In early August, held an open meeting of the US community
  - 274 (+25 virtual) participants




US Muon Collider Inauguration Meeting beginning of August at FNAL showed the strong interest (again)

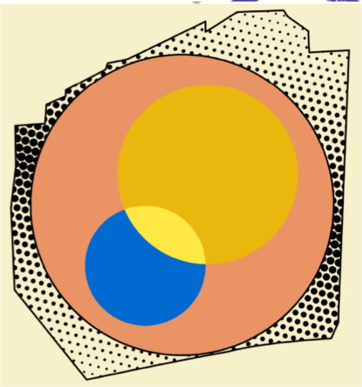
Full integration with US planned and started
CERN-DoE agreement in preparation

Need to move forward with US, while US is getting organised
In particular R&D plan has to be common plan

Use Organization Committee of FNAL with some additional members as de facto US organisation, providing members for

- Editorial Board
- Authors of ESPPU report
- Cost estimate
- Next annual meeting programme committee

**“Open” publications rules are now very important during the transition**
Anyone can send papers to IMCC-PSC@cern.ch for IMCC endorsement



Michael Begel (BNL)
Pushpa Bhat (Fermilab)
Philip Chang (University of Florida)
Sarah Cousineau (ORNL)
Nathaniel Craig (University of California, Santa Barbara)
Sridhara Dasu (University of Wisconsin)
Karri DiPetrillo (University of Chicago)
Spencer Gessner (SLAC)
Tova Holmes (University of Tennessee)
Walter Hopkins (ANL)
Sergo Jindariani (Fermilab)
Donatella Lucchesi (University of Padova/INFN)
Patrick Meade (Stony Brook University)
Isobel Ojalvo (Princeton University)
Simone Pagan Griso (LBNL)
Diktys Stratakis (Fermilab)

And Mark Palmer, Stephen Gourlay, Kevin Black, Lawrence Lee

# IMCC Partners

| | |
|---|---|
| IEIO | **CERN** |
| FR | **CEA-IRFU** |
| | CNRS-LNCMI |
| | ***Mines St-Etienne*** |
| 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** |
| | **University of Birmingham** |
| | ***University of Cambridge*** |

| | |
|---|---|
| IT | **INFN** |
| | **INFN, Univ., Polit. Torino** |
| | **INFN, Univ. Milano Biocca** |
| | **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** |
| PT | **LIP** |

**Signed MoC, *requested MoC***, contributor

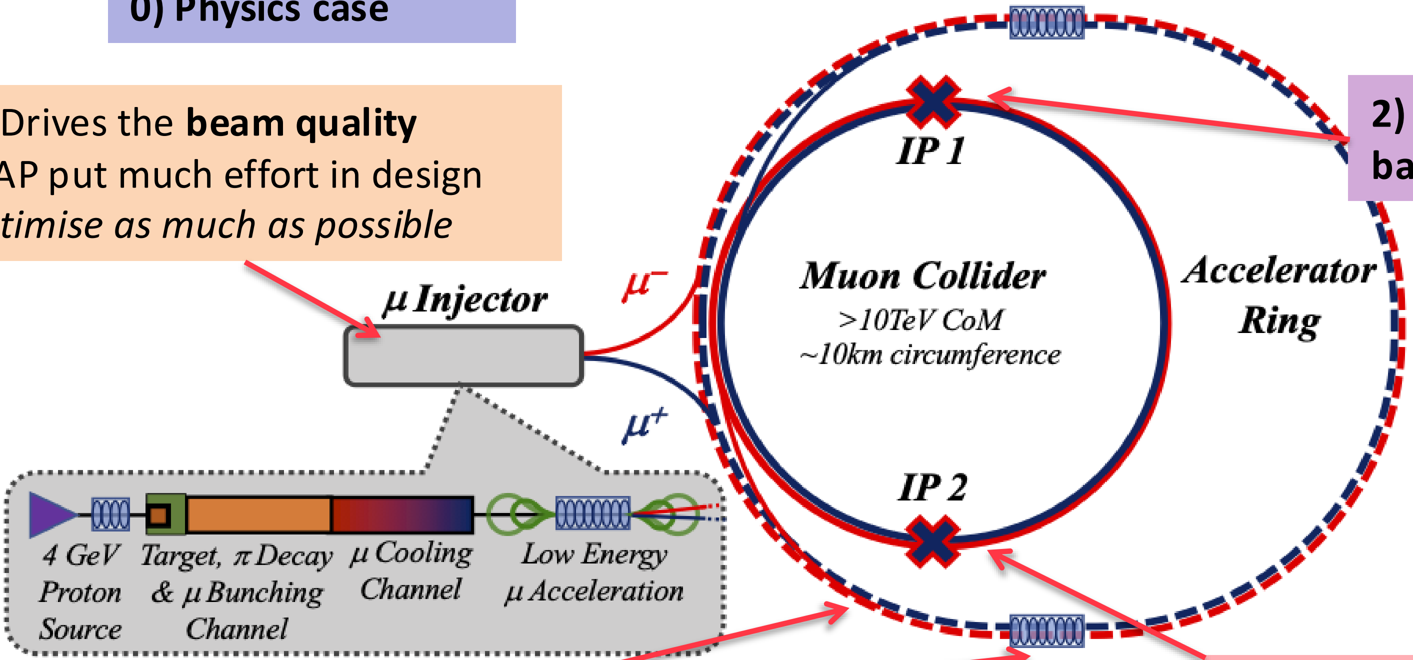
| | |
|---|---|
| SE | **ESS** |
| | **University of Uppsala** |
| NL | **University of Twente** |
| FI | **Tampere University** |
| LAT | **Riga Technical University** |
| CH | **PSI** |
| | **University of Geneva** |
| | EPFL |
| BE | **Univ. Louvain** |
| AU | **HEPHY** |
| | ***TU Wien*** |
| ES | **I3M** |
| | ***CIEMAT*** |
| | **ICMAB** |
| China | ***Sun Yat-sen University*** |
| | **IHEP** |
| | **Peking University** |
| | **Inst. Of Mod. Physics, CAS** |
| KO | **Kyungpook National University** |
| | **Yonsei University** |
| | ***Seoul National University*** |
| India | ***CHEP*** |

| | |
|---|---|
| US | **Iowa State University** |
| | **University of Iowa** |
| | **Wisconsin-Madison** |
| | ***University of Pittsburgh*** |
| | **Old Dominion** |
| | **Chicago University** |
| | **Florida State University** |
| | **RICE University** |
| | **Tennessee University** |
| | ***MIT Plasma science center*** |
| | **Pittsburgh PAC** |
| | Yale |
| | ***Princeton*** |
| | ***Stony Brook*** |
| | Stanford/SLAC |
| | … |
| DoE labs | FNAL |
| | LBNL |
| | JLAB |
| | BNL |
| Brazil | ***CNPEM*** |

# 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**

Important technical progress

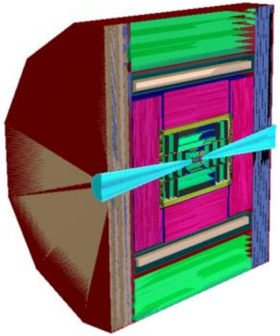
But cannot cover it here



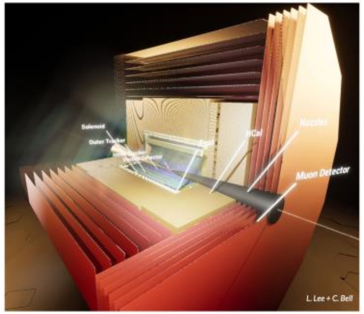
## Physics and Detector Concepts

Two detector concepts are being developed

MUSIC
(MUon Smasher for Interesting Collisions)



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



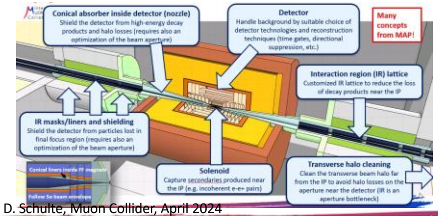

D. Schulte, Muon Collider, Birmingham, July 2024

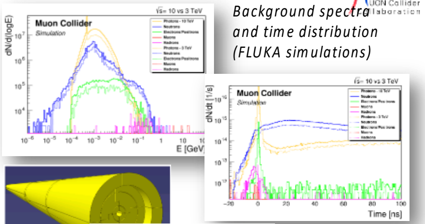
## MDI and beam-induced background

**Activities in SY/STI:**

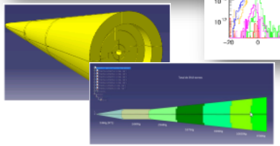
- Detailed simulation of detector background and radiation damage by means of FLUKA
- Optimization of MDI (nozzle, shielding) and IR for 10 TeV collider ongoing,
- First engineering considerations for nozzle

*Integral approach for MDI design:*




*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:**

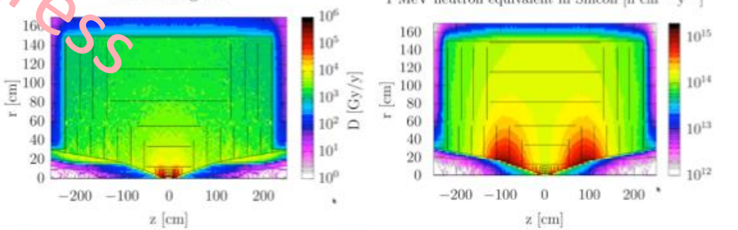
- Optimization of the nozzle, absorbers, shielding for 3 TeV and 10 TeV, respectively
- Continue 10 TeV IR lattice development
- Engineering considerations for nozzle and integration with detector and solenoid
- Study the permissible halo-induced background in the IR (derive specs for halo cleaning)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

D. Schulte, Muon Collider, April 2024

## 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 | $3\times10^{14}$ n/cm$^2$ |
| Inner tracker | 10 kGy | $1\times10^{15}$ n/cm$^2$ |
| ECAL | 2 kGy | $1\times10^{14}$ 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

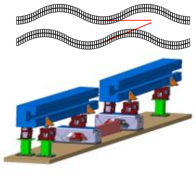
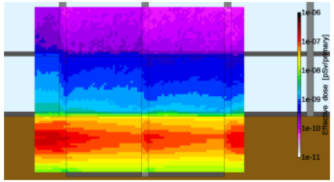
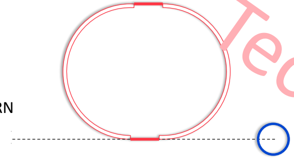


Fig. 7.23: Mock-up of the proposed magnet movement system.




**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



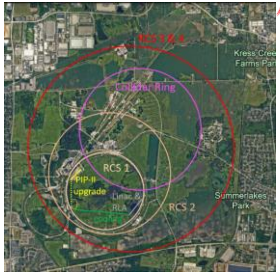


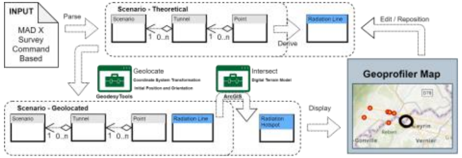
# Site Studies

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

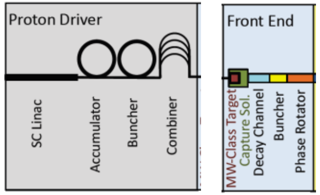



**Potential site next to CERN identified**
- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura
- Detailed studies required (280 m deep)



# Proton Complex and Target




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

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

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

Graphite **Target**

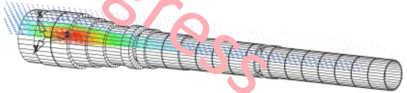
20 T **solenoid**
to guide pions and muons

**Tunsten shielding**
To protect magnet



# Target Technologies

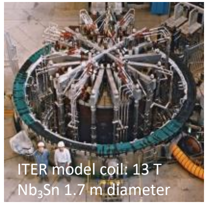
**Target solenoid design** ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert



**HTS target solenoid:** 20 T, 20 K

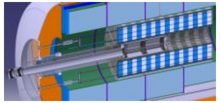
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

**Our work is relevant for fusion**



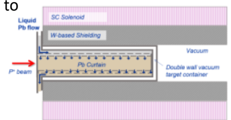

**FLUKA studies:**
**2 MW target:** stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

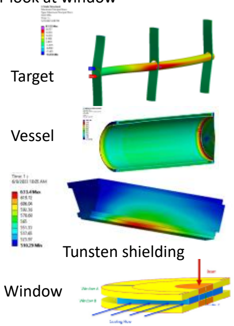
**Integration**



Cooling, vacuum, mechanics, …

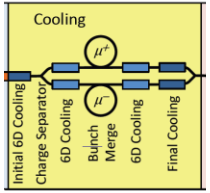
**Liquid metal target**
Serious alternative to graphite



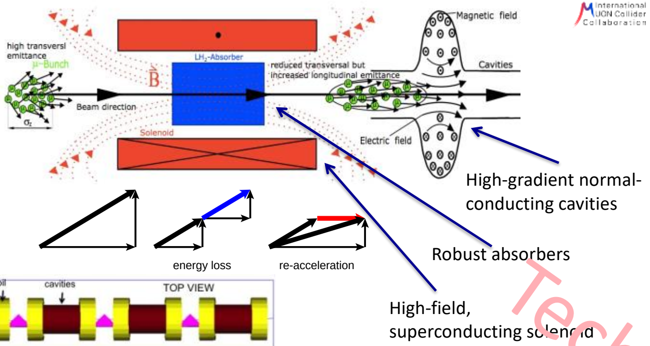



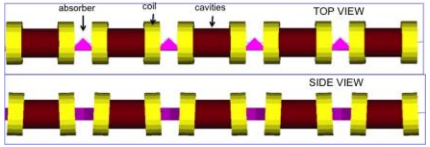

A. Lechner, D. et al.

## Muon Cooling Principle




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




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

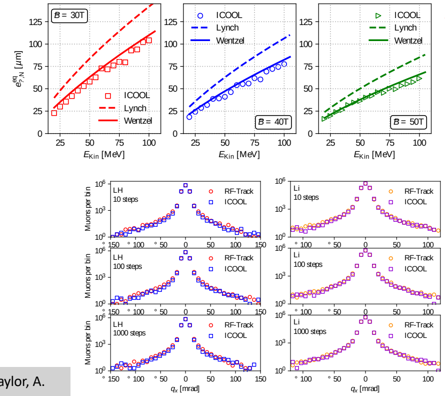
Benchmarking confirms validity

Recently discovered:

- Some bug in data extraction routine
- Step size dependence

Both seem to be solved by now

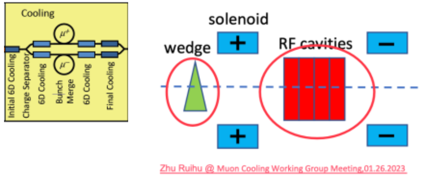
- But would like to review previous results

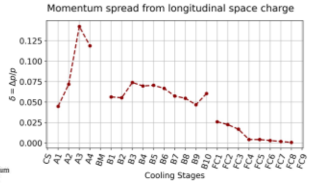


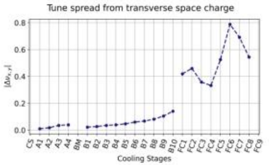

B. Stechauner, E. Fol, Taylor, A. Latina, P. Valdor et al.

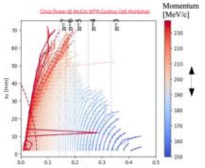


## Collective Effects




Activity started recently

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



## Muon Cooling Performance

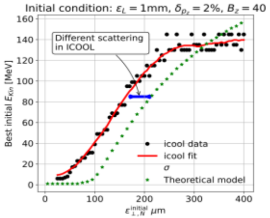
MAP design achieved 55 um based on achieved fields

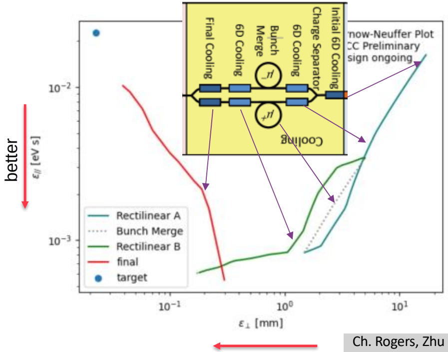
Currently in 30-40 um range

- Need careful checks

Identification of optimum energy for cooling as function of emittance

B. Stechauner at al.



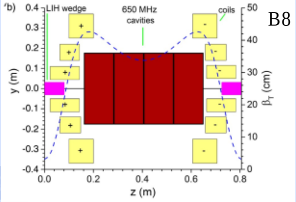

Ch. Rogers, Zhu Ruihu, R. Taylor, B. Stechauner, E. Vol et al.

# Cooling Cell Technology

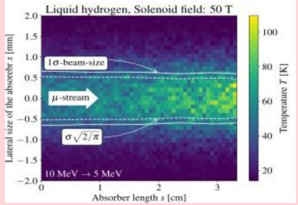
L. Rossi et al. (INFN, Milano, STFC, CERN),
J. Ferreira Somoza et al.

**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



Technical progress

# Solenoid R&D

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

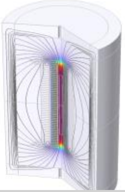
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

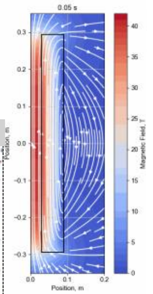
**Final Cooling solenoid**

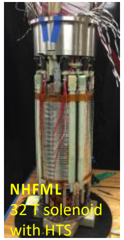
$$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}$$

$s_{max}$ = 600 MPa

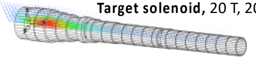
$B_{max} \approx$ 55 T





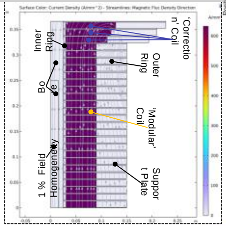



32 T LTS/HTS solenoid demonstrated



**Target solenoid**, 20 T, 20 K

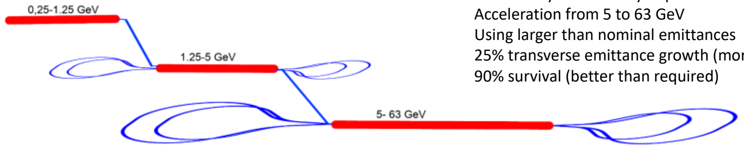

A. Dudarev, B. Bordini, T. Mulder, S. Fabbri



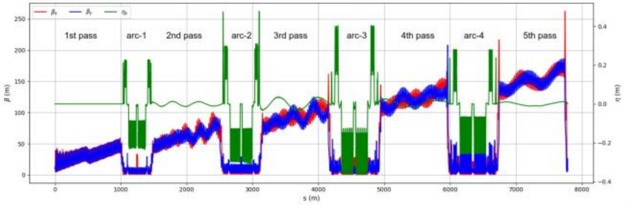




# Muon Initial Acceleration




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)

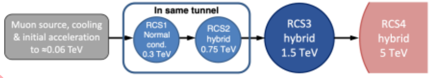


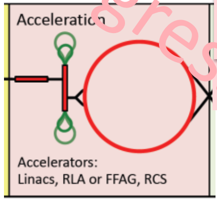

A. Aksoy

No more resources!
Avni left!



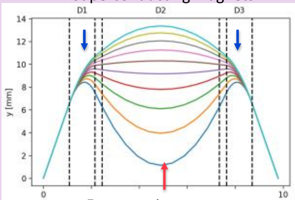
# Acceleration Complex



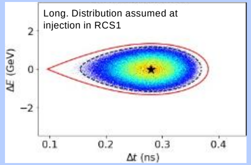




Core is sequence of pulsed synchrotron (0.4-11 ms)
Alternative FFA

Superconducting magnets




Fast-ramping magnets




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

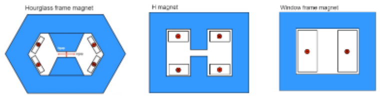
**Lattice:**
**Hybrid design works**
**Can spread RF in the arcs**

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)

# Fast-ramping Magnet System

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

Synchronisation of magnets and RF for power and cost




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

**FNAL** 300 T/s HTS magnet

Could consider using HTS dipoles for largest ring

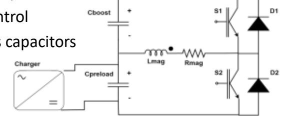
*Simple* HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

**Commutated resonance (novel)**

Attractive new option

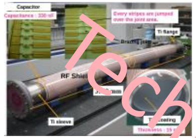
- Better control
- Much less capacitors




**Beampipe study**

Eddy currents vs impedance

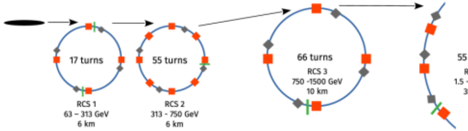
Maybe ceramic chamber with stripes

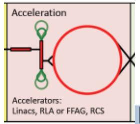


F. Boattini et al.



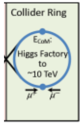
# Collective Effects

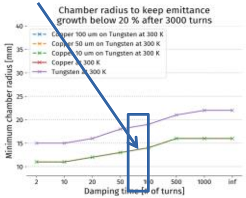



**Impedance studies**

Single beam instability limits OK with conservative feedback

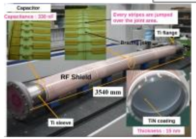


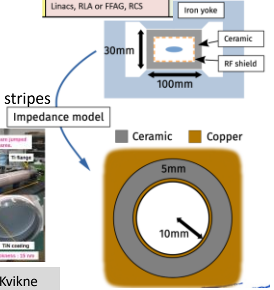




**Beampipe study**

Eddy currents vs impedance

Maybe ceramic chamber with stripes






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



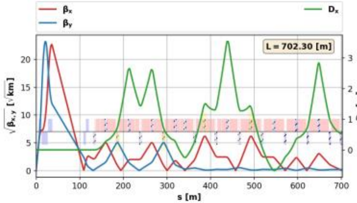
# Collider Ring

High performance 10 TeV challenges:

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

**10 TeV collider ring** in progress:

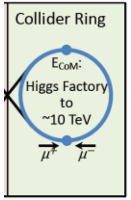
- around 16 T HTS dipoles or lower $Nb_3Sn$
- final focus based on HTS
- Need to further improve the energy acceptance by small factor




**3 TeV:**

MAP developed 4.5 km ring with $Nb_3Sn$

- magnet specifications in the HL-LHC range
- 5 mm beta-function

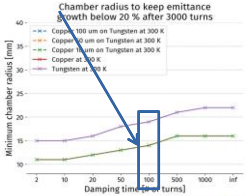



K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas

**Impedance studies**

Single beam instability limits OK with conservative feedback

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






# Collider Ring Technologies

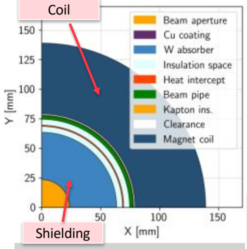
Power loss due to muon decay 500 W/m

FLUKA simulation of required **shielding:**

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

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

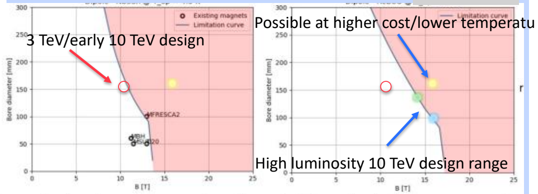
Þ Magnet coil radius 59-79 mm




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



Technical progress

D. Schulte, Muon Collider, Demonstrator Workshop, FNAL, October 2024

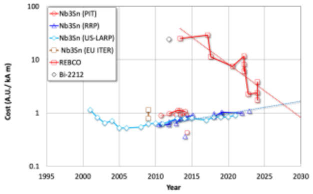
# Dipole Cost

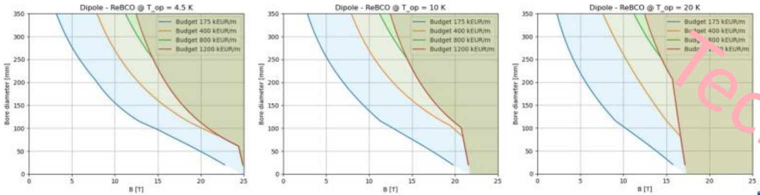
Key cost drivers are based on sound models
- E.g. RCS with trade-off between RF and magnet cost

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



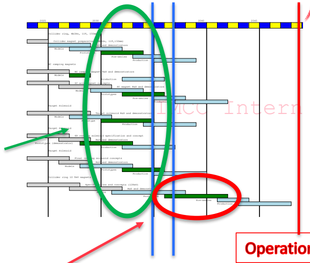

D. Schulte, Muon Collider, Birmingham, July 2024

# 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



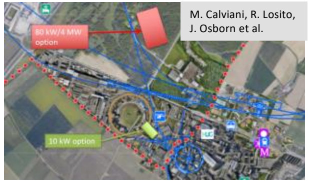
# CDR Phase, R&D and Demonstrator Facility

**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

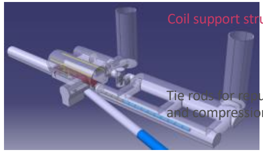
Different sites are being considered
- CERN, FNAL, ESS …
- Two site options at CERN

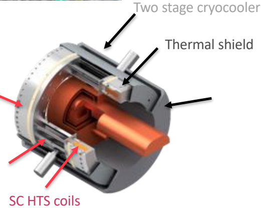
Muon cooling module test is important
- INFN is driving the work
- Could test it at CERN with proton beam




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

With cryostat



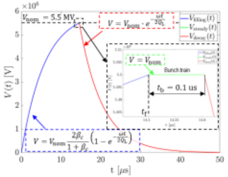

D. Schulte, Muon Collider, INFN, May 2024

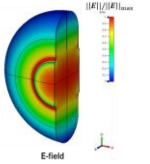


# 704 MHz cavity for the Muon Cooling (MC) Demonstrator

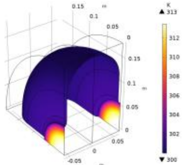
*RF design and coupler RF-thermo-mechanical simulations*

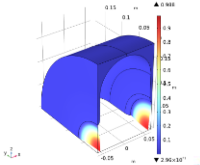
- RF simulations in CST Studio Suite®
  - Calculation of the pulse shape
  - Computation of the main RF figure of merits
  - Optimization of the cavity shape




- 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





D. Schulte, Muon Collider, Demonstrator Workshop, FNAL, October 2024

# Interim Report (144 pages)

https://arxiv.org/abs/2407.12450

**Executive Summary**

**Implementation Considerations**

**Physics Potential**

**Physics, Detector and Accelerator Interface**

**Detector**

**Accelerator design**

**Accelerator technologies**

**Synergies**

**R&D programme development**

**Collaboration Development**

arXiv > physics > arXiv:2407.12450

Search...

Help | Advan

**Physics > Accelerator Physics**

*[Submitted on 17 Jul 2024]*

## Interim report for the International Muon Collider Collaboration (IMCC)

C. Accettura, S. Adrian, R. Agarwal, C. Ahdida, C. Aimé, A. Aksoy, G. L. Alberghi, S. Alden, N. Amapane, D. Amorim, P. Andreetto, F. Anulli, R. Appleby, A. Apresyan, P. Asadi, M. Attia Mahmoud, B. Auchmann, J. Back, A. Badea, K. J. Bae, E. J. Bahng, L. Balconi, F. Balli, L. Bandiera, C. Barbagallo, R. Barlow, C. Bartoli, N. Bartosik, E. Barzi, F. Batsch, M. Bauce, M. Begel, J. S. Berg, A. Bersani, A. Bertarelli, F. Bertinelli, A. Bertolin, P. Bhat, C. Bianchi, M. Bianco, W. Bishop, K. Black, F. Boattini, A. Bogacz, M. Bonesini, B. Bordini, P. Borges de Sousa, S. Bottaro, L. Bottura, S. Boyd, M. Breschi, F. Broggi, M. Brunoldi, X. Buffat, L. Buonincontri, P. N. Burrows, G. C. Burt, D. Buttazzo, B. Caiffi, S. Calatroni, M. Calviani, S. Calzaferri, D. Calzolari, C. Cantone, R. Capdevilla, C. Carli, C. Carrelli, F. Casaburo, M. Casarsa, L. Castelli, M. G. Catanesi, L. Cavallucci, G. Cavoto, F. G. Celiberto, L. Celona, A. Cemmi, S. Ceravolo, A. Cerri, F. Cerutti, G. Cesarini, C. Cesarotti, A. Chancé, N. Charitonidis, M. Chiesa, P. Chiggiato, V. L. Ciccarella, P. Cioli Puviani, A. Colaleo, F. Colao, F. Collamati, M. Costa, N. Craig, D. Curtin, L. D'Angelo, G. Da Molin, H. Damerau, S. Dasu, J. de Blas, S. De Curtis, H. De Gersem et al. (287 additional authors not shown)

The International Muon Collider Collaboration (IMCC) [1] was established in 2020 following the recommendations of the European Strategy for Particle Physics (ESPP) and the implementation of the European Strategy for Particle Physics–Accelerator R&D Roadmap by the Laboratory Directors Group [2], hereinafter referred to as the the European LDG roadmap. The Muon Collider Study (MuC) covers the accelerator complex, detectors and physics for a future muon collider. In 2023, European Commission support was obtained for a design study of a muon collider (MuCol) [3]. This project started on 1st March 2023, with work-packages aligned with the overall muon collider studies. In preparation of and during the 2021-22 U.S. Snowmass process, the muon collider project parameters, technical studies and physics performance studies were performed and presented in great detail. Recently, the P5 panel [4] in the U.S. recommended a muon collider R&D, proposed to join the IMCC and envisages that the U.S. should prepare to host a muon collider, calling this their "muon shot". In the past, the U.S. Muon Accelerator Programme (MAP) [5] has been instrumental in studies of concepts and technologies for a muon collider.

# 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 O(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**

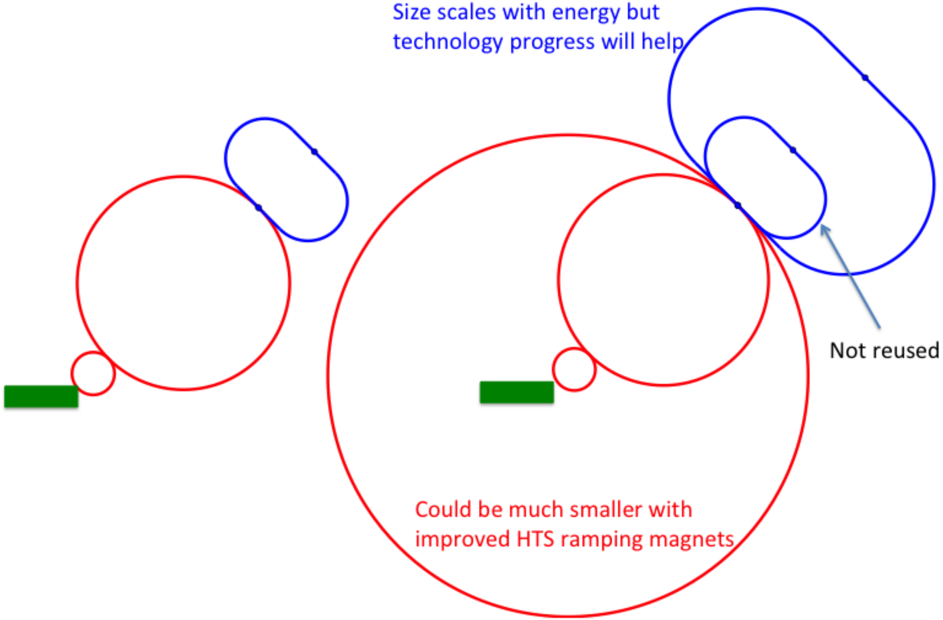
- Start at lower energy
- Current 3 TeV, design takes lower performance into account
- Splits cost, little increase in integrated cost

**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)

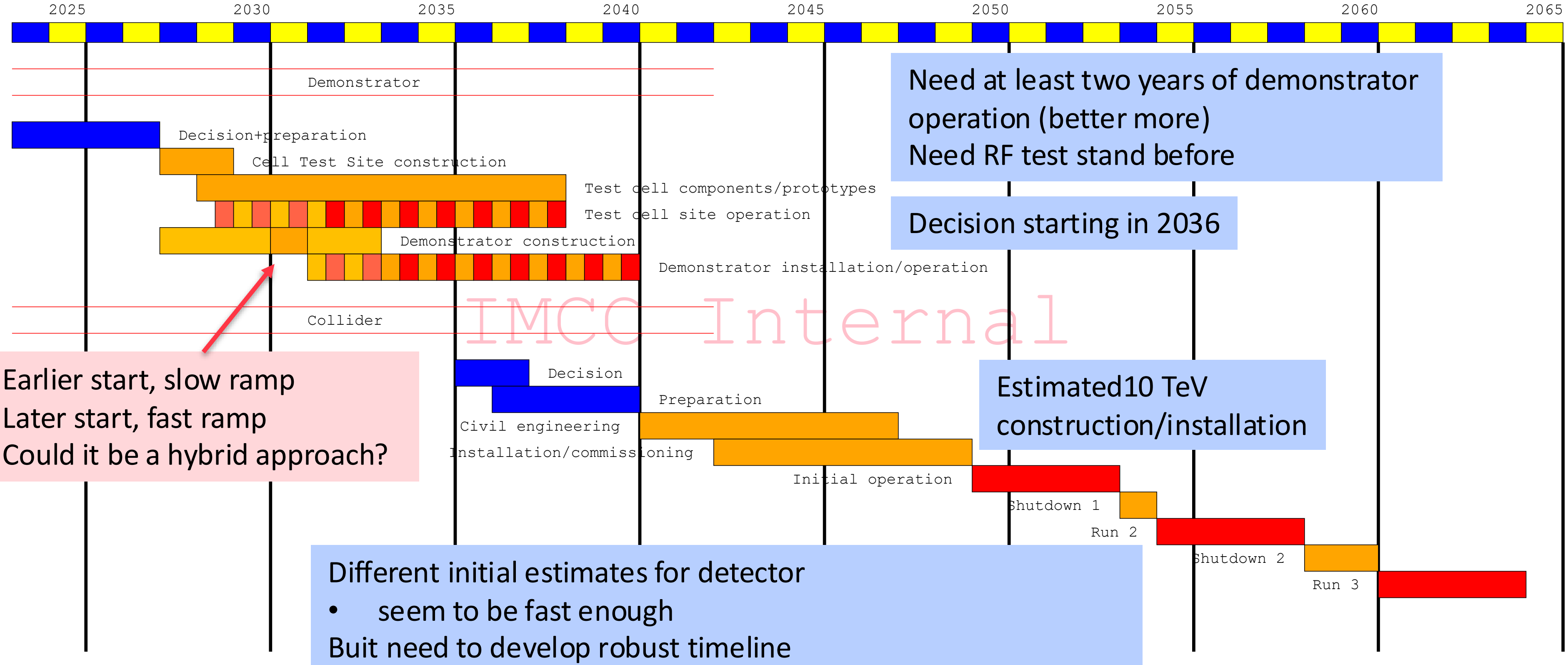
Start considering reuse of existing infrastructures

- But maintain green field



# Tentative Timeline (Fast-track 10 TeV)

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

Earlier start, slow ramp
Later start, fast ramp
Could it be a hybrid approach?

Estimated10 TeV construction/installation

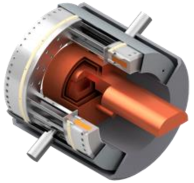
Different initial estimates for detector

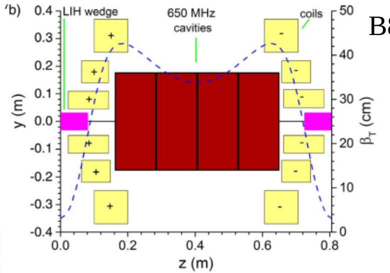
- seem to be fast enough

Buit need to develop robust timeline

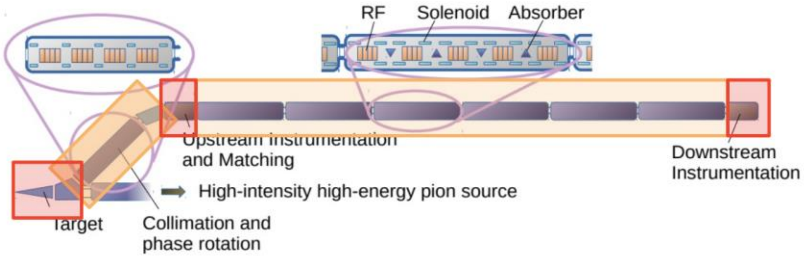
# R&D Programme

**Broad R&D programme** can be distributed world-wide






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




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

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

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

Training of **young people**

Strong synergy with HFM Roadmap and RF efforts

# 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 provide report to fulfill **EU contract (February 2027)**
- Will provide the required input to the **US process (2027?),** recommended by P5 (Reference Design?)
- Will provide input to any other processes

# ESPPU Input

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


**Preparatory Group**
Prepares Briefing Book
Two members from the Americas

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

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

IMCC Report timeline
- 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**

Formed **editorial teams**
- Regular meetings
- Active role in writing
    - And pushing the other authors

# Plan for ESPPU

**March 2025** deliver promised ESPPU report containing

- **Assessment**, including tentative cost and power consumption scale
- **R&D plan**, including scenarios and timelines
    - **The muon cooling technology and test facility is critical for this**
- **Implementation considerations**

In **Assessment**:

Present **green field** designs and technologies

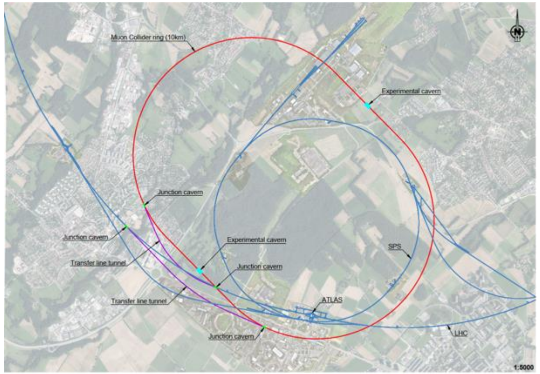
- International collaboration
- Parameters, lattice designs, component designs, beam dynamics, cost, …

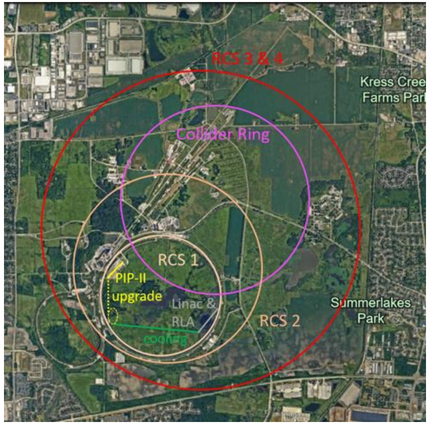
In **Implementation Considerations:**

**Civil engineering studies/considerations**

- for CERN and if possible for FNAL
- Provide parameter tables for these implementations, scaled from green field
    - Do not have resources/time to redo detailed lattice designs for ESPPU

**Schedule** (strongly linked to R&D Plan)



# R&D Plan and Schedule

**Will submit the R&D plan to ESPPU** and later other funding agencies

- Allows to maintain momentum during and after the process
- Aims at 5 and 10 years
- Demonstrator programme is a key part of the plan, need to consider sites (R. Losito et al. for CERN, D. Stratakis et al. for FNAL, others welcome)

**A common plan agreed with the US and other regions**

- Depending on funding agencies we will share the work

**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

**Critical to agree on common technically limited timeline**

- Implementation in the different regions may
- E.g. political developments, budgets, other projects, strategy decisions, …

# 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 started integrating the US at eye level

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

Then preparation of US process
- Other processes that need input?

Many thanks to the collaboration for all the work

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

# Reserve

# 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

**Contents**



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# Magnet Roadmap

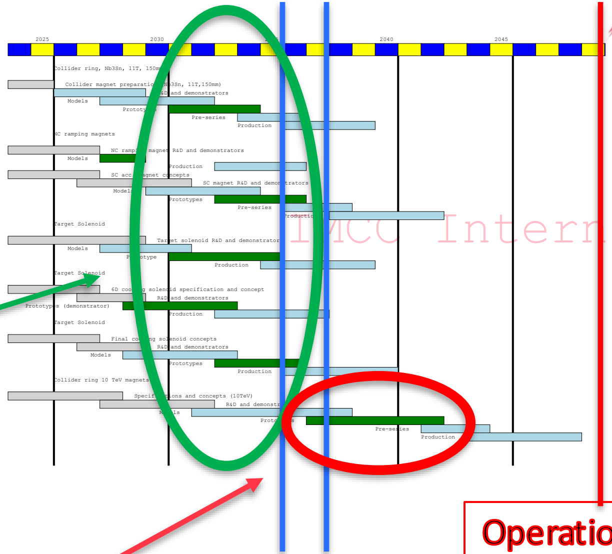
Assume: Need prototype of magnets by decision process

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

# IMCC

International Muon Collider Collaboration

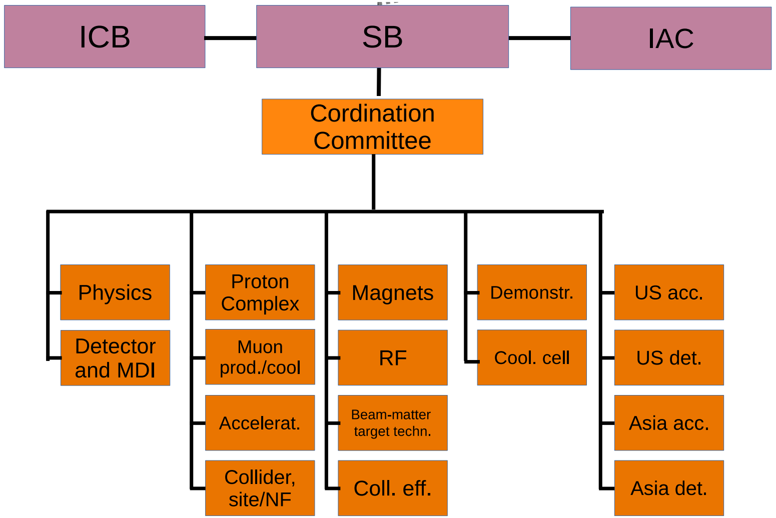
- Can be joined by signing MoC (58 signed)
- Currently hosted at CERN, but can be modified

Resources

- Voluntary contributions of the partners
- The European Union
- Non-member contributions (70+ total partners)

Study reports to

- The members and other contributors
- CERN Council (represents European Particle Physics)
  - Via Lab Directors Group (LDG)
  - Via ESPPU
- European Union because they co-fund MuCol
- Hopefully soon DoE
  - Acutally, did already through collaboration during Snowmass




**Collaboration Board (ICB),** elected chair: **Nadia Pastrone**
**Steering Board (ISB),** Chair **Steinar Stapnes**
**International Advisory Committee (IAC),** Chair **Ursula Basler**

**Coordination committee (CC)**

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