International MUON Collider Collaboration

MuCol

Muon Collider

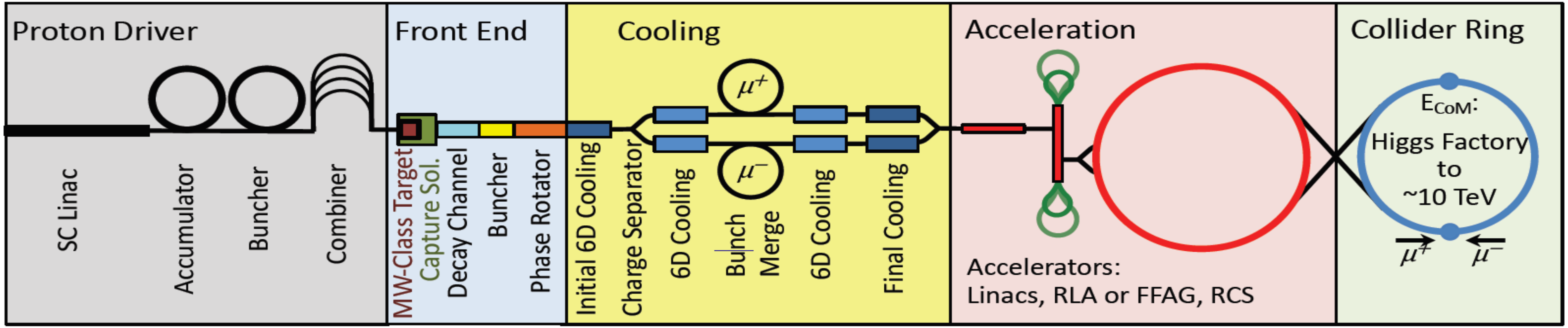
D. Schulte
On behalf of the International Muon Collider Collaboration

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.

Tokyo, July, 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

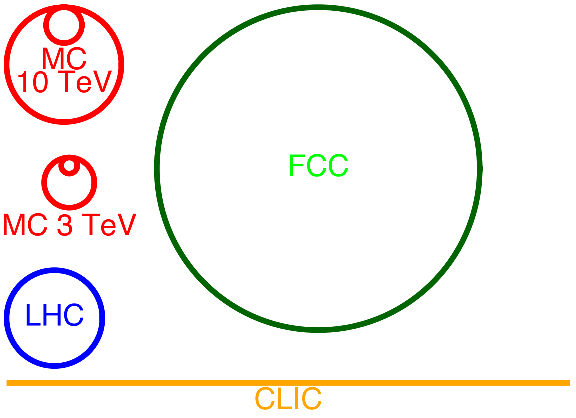
Protons produce pions which decay into muons
muons are captured

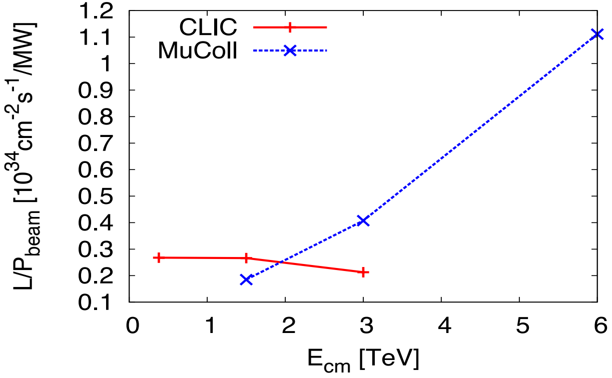
Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Muon Collider Promises





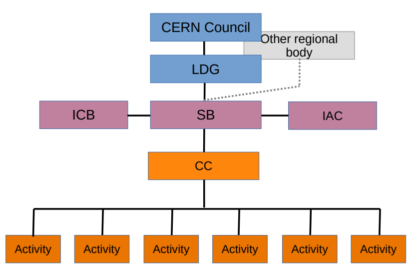
US Snowmass Implementation Task Force: Th. Roser, R. Brinkmann, S. Cousineau, D. Denisov, S. Gessner, S. Gourlay, Ph. Lebrun, M. Narain, K. Oide, T. Raubenheimer, J. Seeman, V. Shiltsev, J. Straight, M. Turner, L. Wang et al.

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

Judgement by ITF, take it *cum grano salis*

Muon Collider Community

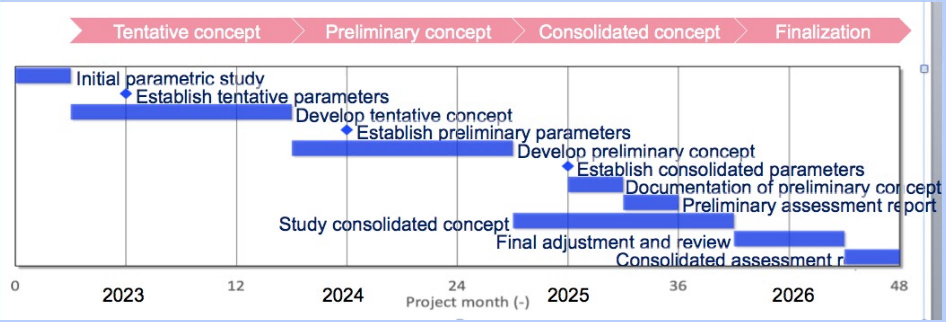
Formed **collaboration** hosted by CERN to implement R&D Roadmap for CERN Council



60+ partners, 50+ already signed MoC

EU Design Study

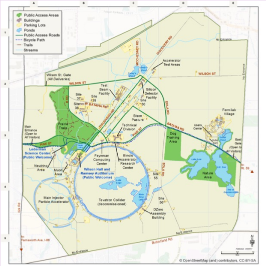
(EU+Switzerland+UK and partners)



US P5 has **strong support "Our Muon Shot"**

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

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



Develop the muon collider as option for Europe, the US and any other interested region

Continue to grow the collaboration and secure resources

MoC and MuCol Partners

MuCol

International MUON Collider Collaboration

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
	Pittsbergh PAC
India	***CHEP***

US	FNAL
	LBL
	JLAB
	BNL

Goals and Progress

Goal is to develop a staged high-energy muon collider concept

- Focus on 10 TeV
- First stage by 2050

Changes with respect to past studies:

- Focus on **highest energy**
- **Technology** and **design advances** in past years

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

Target integrated luminosities are based on physics
Increase as E_{cm}^2

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.

Reviews in Europe and US found **no unsurmountable obstacle**

- But less mature than other concepts (linear collider)

Global community developed **Accelerator R&D Roadmap**

Good progress in implementing Roadmap

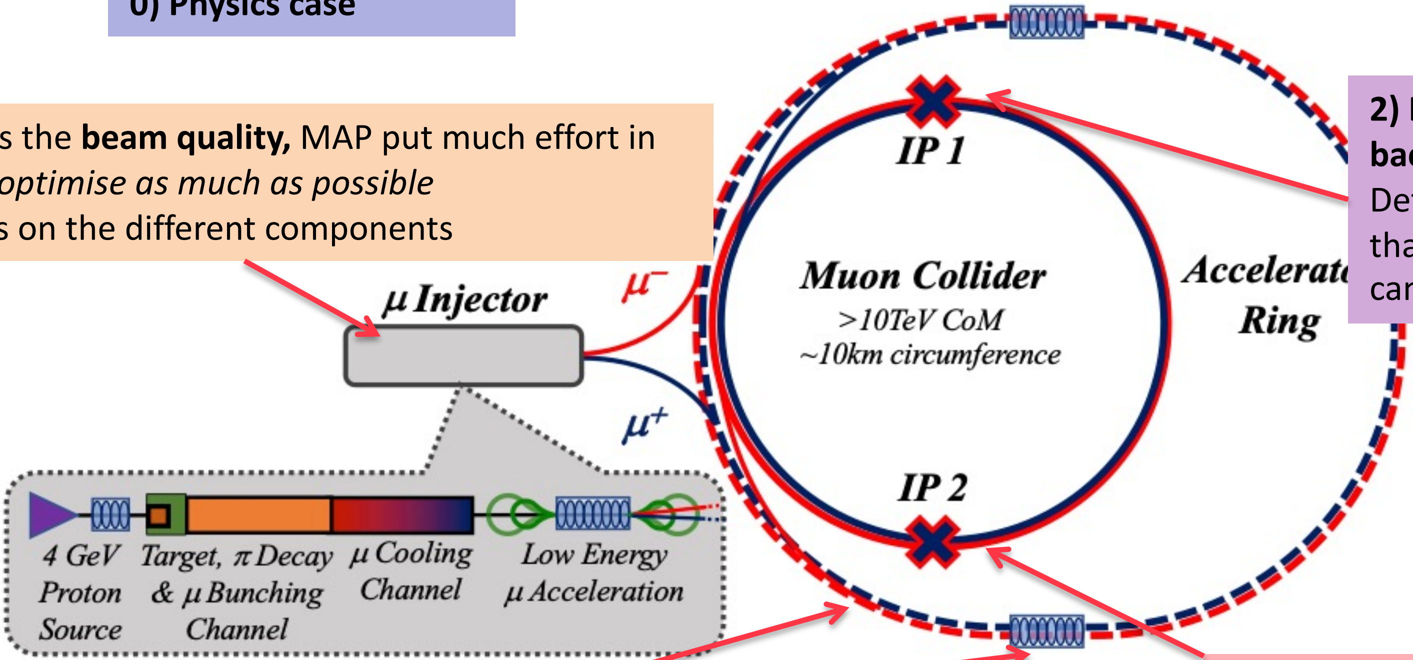
- But still budget limited

Key Challenges

0) Physics case

4) Drives the **beam quality,** MAP put much effort in design, *optimise as much as possible*
Progress on the different components

2) Beam-induced background
Detector studies show that important physics can be done



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

3) Cost and **power** consumption limit energy reach and **beam quality**
Good progress on key items

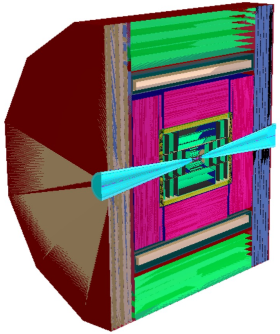
Important technical progress

But cannot cover it here

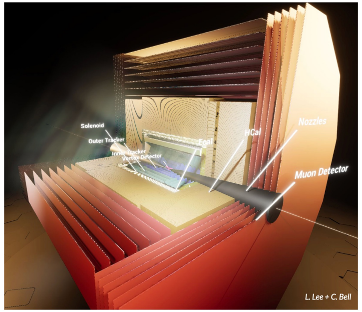
Physics and Detector Concepts

Two detector concepts are being developed

MUSIC
(MUon Smasher for Interesting Collisions)



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



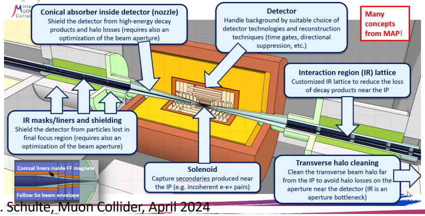
D. Schulte, Muon Collider, Birmingham, July 2024

MDI and beam-induced background

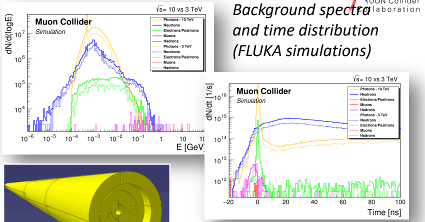
Activities in SY/STI:

- 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

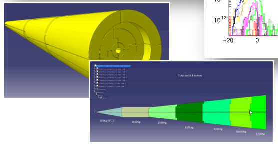
Integral approach for MDI design:



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)

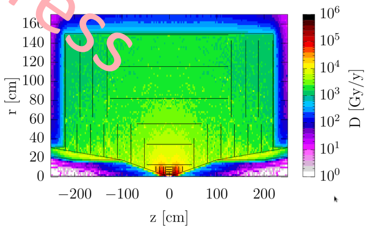
Main goals for ESPPU report:

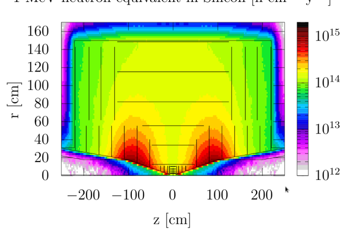
- Optimization of the nozzle, absorbers, shielding for 3 TeV and 10 TeV, respectively
- Continue 10 TeV IR lattice development
- Engineering considerations for nozzle and integration with detector and solenoid
- Study the permissible halo-induced background in the IR (derive specs for halo cleaning)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

Technical progress

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

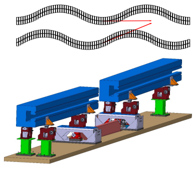
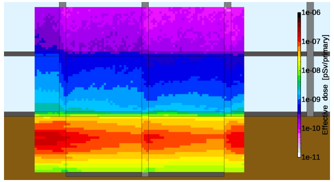
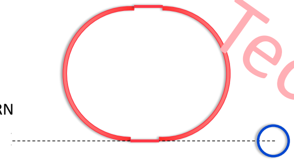


Fig. 7.23: Mock-up of the proposed magnet movement system.



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

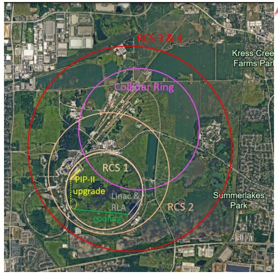


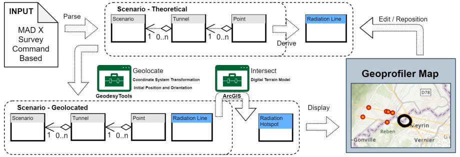
Site Studies

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

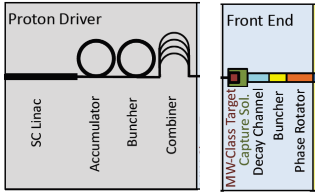




Potential site next to CERN identified
- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura
- Detailed studies required (280 m deep)

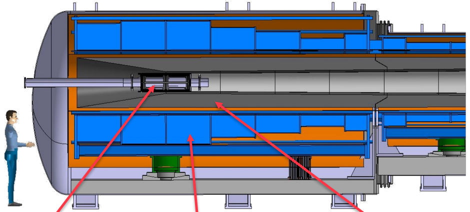
Technical progress

Proton Complex and Target



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

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

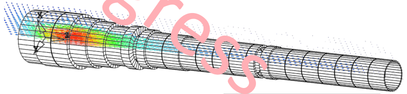


5 GeV proton beam, 2 MW = 400 kJ x 5 Hz
Power is at hand

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

Target Technologies

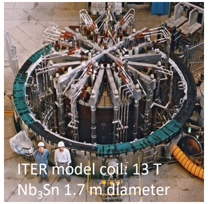
Target solenoid design ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert



HTS target solenoid: 20 T, 20 K

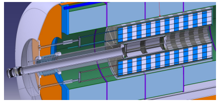
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

Our work is relevant for fusion



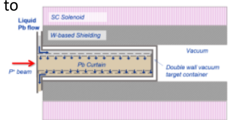
FLUKA studies:
2 MW target: stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

Integration

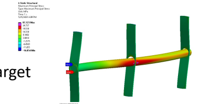


Cooling, vacuum, mechanics, …

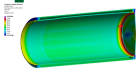
Liquid metal target
Serious alternative to graphite



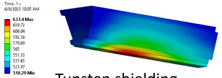
Target



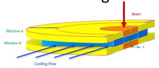
Vessel



Tunsten shielding

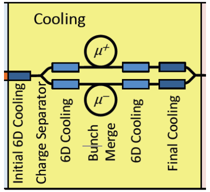


Window

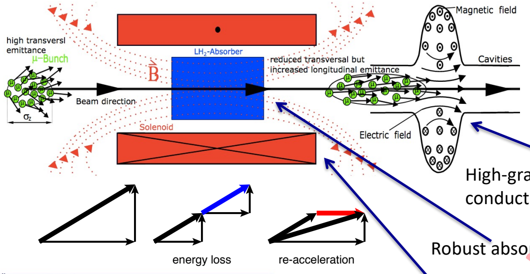


A. Lechner, D. et al.

Muon Cooling Principle



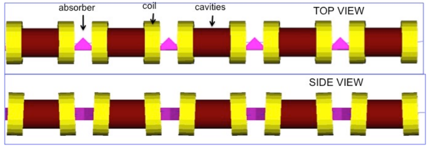
C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)



High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid



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

D. Schulte, Muon Collider, INFN, May 2024

37

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

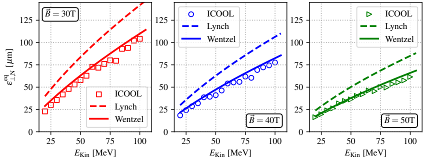
Benchmarking confirms validity

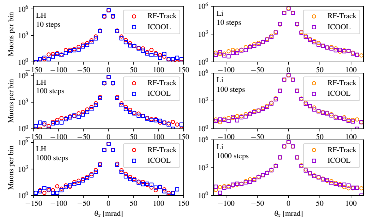
Recently discovered:

- Some bug in data extraction routine
- Step size dependence

Both seem to be solved by now

- But would like to review previous results

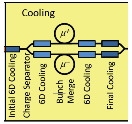


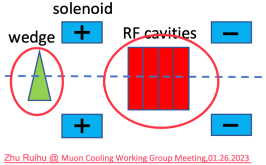


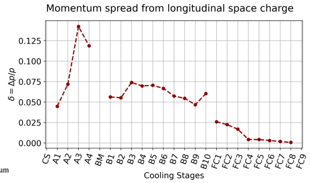
B. Stechauner, E. Fol, Taylor, A. Latina, P. Valdor et al.

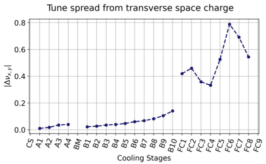
D. Schulte, Muon Collider, May 2024

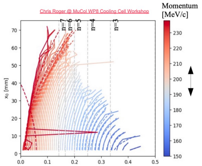
Collective Effects











Activity started recently

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

D. Schulte, Muon Collider, May 2024

Muon Cooling Performance

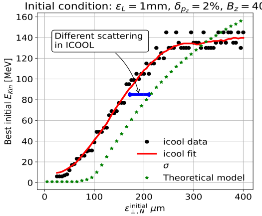
MAP design achieved 55 um based on achieved fields

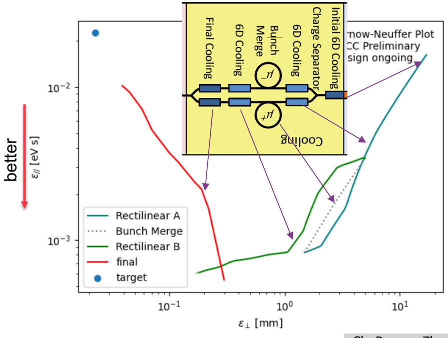
Currently in 30-40 um range

- Need careful checks

Identification of optimum energy for cooling as function of emittance

B. Stechauner at al.





better

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

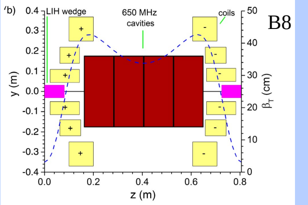
D. Schulte, Muon Collider, May 2024

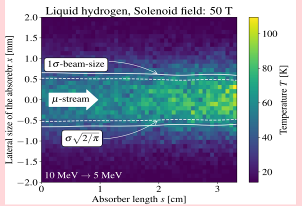
Cooling Cell Technology

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, …

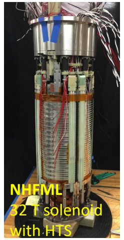
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

Final Cooling solenoid

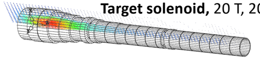
$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}$

σ_{max} = 600 MPa

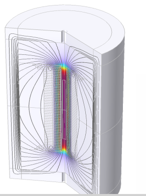
$B_{max} \approx$ 55 T

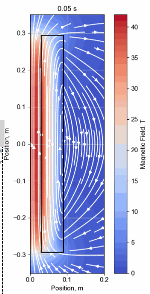


32 T LTS/HTS solenoid demonstrated

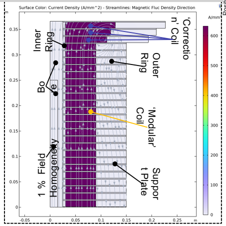


Target solenoid, 20 T, 20 K





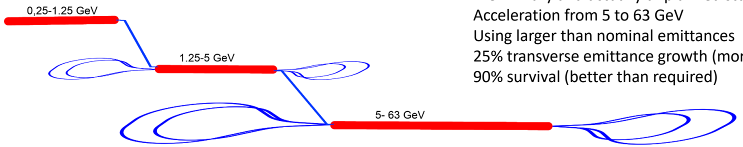
A. Dudarev, B. Bordini, T. Mulder, S. Fabbri



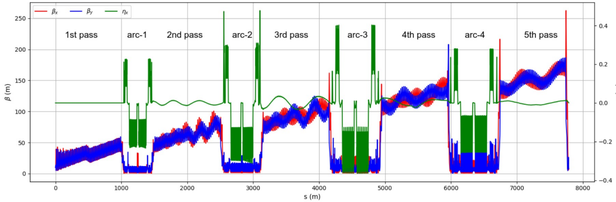
D. Schulte. Muon Collider. INFN. May 2024

40

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)

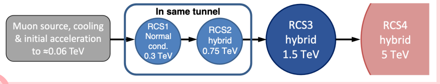


A. Aksoy

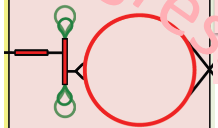
No more resources!
Avni left!

D. Schulte, Muon Collider, May 2024

Acceleration Complex



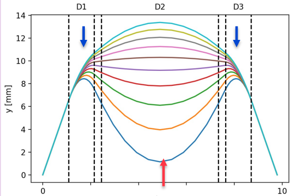
Acceleration



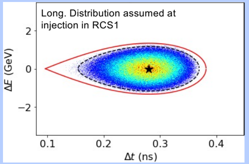
Accelerators:
Linacs, RLA or FFAG, RCS

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

41

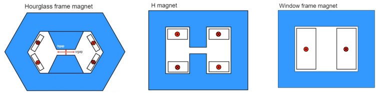
Fast-ramping Magnet System

MuCol

International UON Collider Collaboration

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

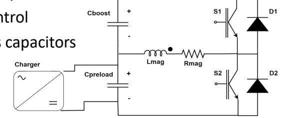
F. Boattini et al.

Differerent power converter options investigated

Commutated resonance (novel)

Attractive new option

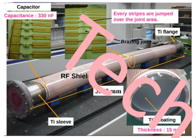
- Better control
- Much less capacitors



Beampipe study

Eddy currents vs impedance

Maybe ceramic chamber with stripes



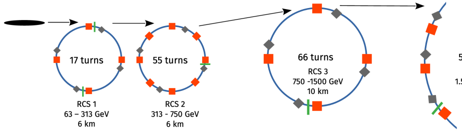
D. Schulte, Muon Collider, INFN, May 2024

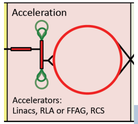
42

Collective Effects

MuCol

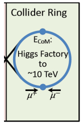
International UON Collider Collaboration

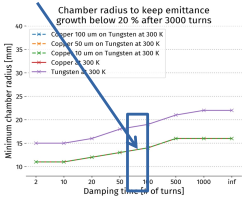




Impedance studies

Single beam instability limits OK with conservative feedback



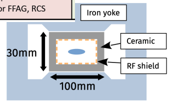


D. Schulte, Muon Collider, May 2024

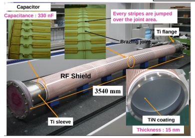
Beampipe study

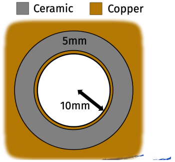
Eddy currents vs impedance

Maybe ceramic chamber with stripes



Impedance model





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

Collider Ring

MuCol

International UON Collider Collaboration

High performance 10 TeV challenges:

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

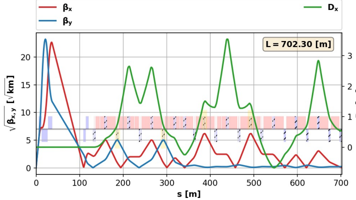
3 TeV:

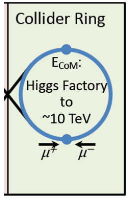
MAP developed 4.5 km ring with Nb_3Sn

- 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



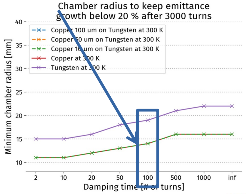


K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas

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

Impedance studies

Single beam instability limits OK with conservative feedback



D. Schulte, Muon Collider, INFN, May 2024

43

Collider Ring Technologies

MuCol

International

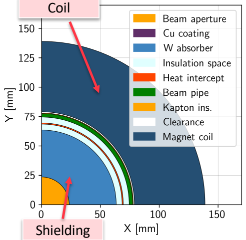
Power loss due to muon decay 500 W/m

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.

Different **cooling scenarios** studied

< 25 MW power for cooling possible

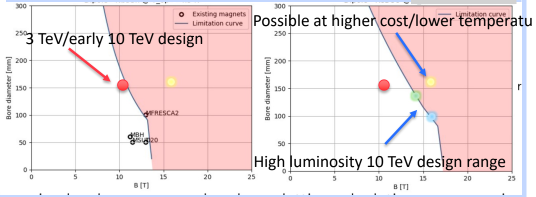
Shield with CO_2 at 250 K (preferred) or water

Support of shield is important for heat transfer

Discussion on options for magnet cooling

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

20

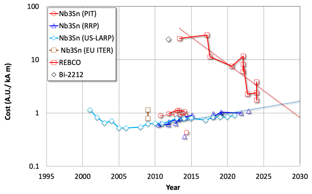
Dipole Cost

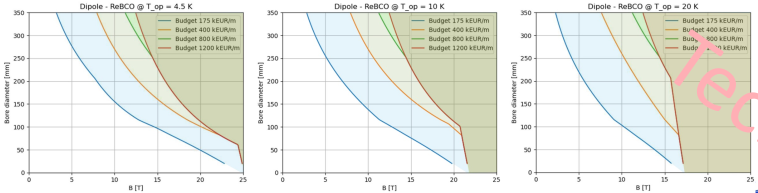
Key cost drivers are based on sound models
- E.g. RCS with trade-off between RF and magnet cost

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



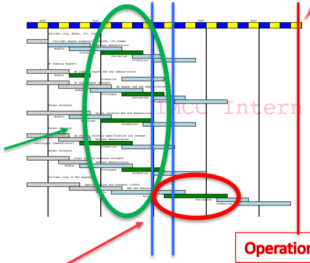


Magnet Roadmap

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**

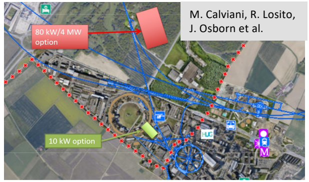


Strategy:
- HTS solenoids
- Nb_3Sn accelerator magnets
- HTS accelerator magnets

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

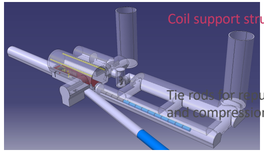


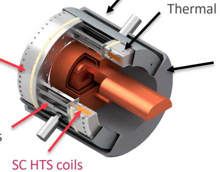
Cooling demonstrator is a key facility
- look for an existing proton beam with significant power

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

With cryostat

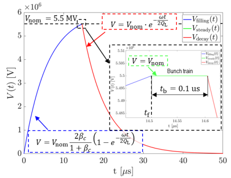


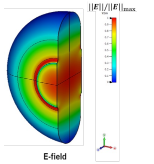


704 MHz cavity for the Muon Cooling (MC) Demonstrator

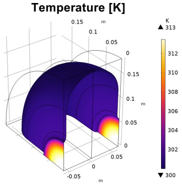
RF design and coupler RF-thermo-mechanical simulations

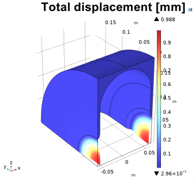
- RF simulations in CST Studio Suite®
  - Calculation of the pulse shape
  - Computation of the main RF figure of merits
  - Optimization of the cavity shape





- 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





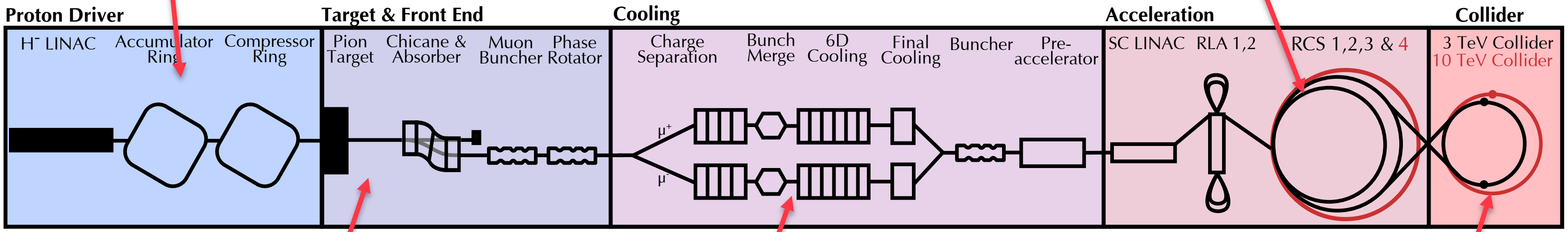
Some Progress Examples

Systematic approach to magnet performance expectations
Target magnet similar to fusion reactor magnets
Engineering design of muon cooling cells started

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

Proton complex similar to SPL
Work on main challenge (compressor ring) ongoing

Detailed studies of fast-ramping magnets, power converter and RF



2 MW graphite tarket basically done
4 MW as alternative started
Liquid metal or fluidized tunsten

Progress in performance of muon cooling

Lattice design advancing, some improvement of energy acceptance required and imperfection studies

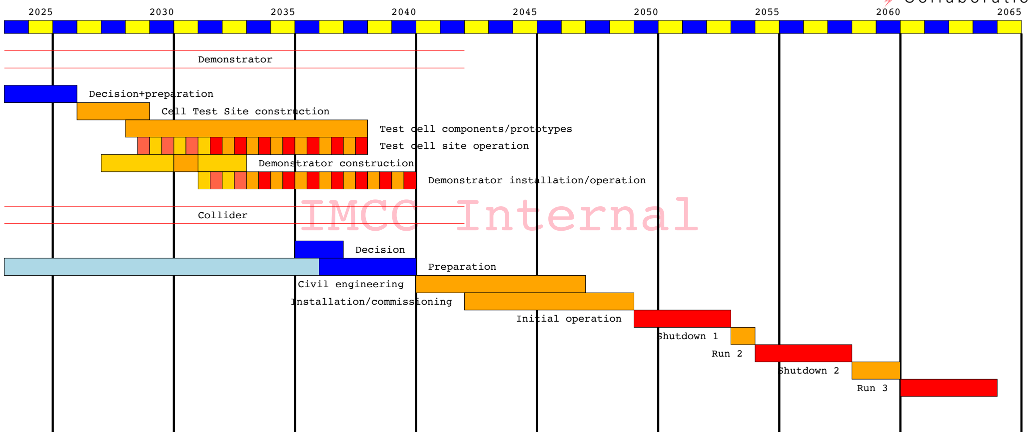
MuCol

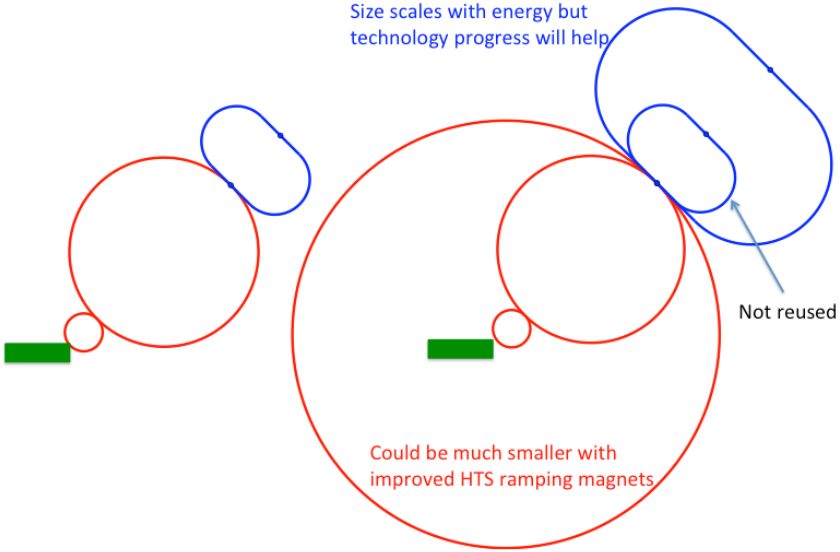
International MUON Collider Collaboration

Timeline and Staging

Exploring timeline with first stage operational by 2050, main technical drivers:

- Muon cooling technology
- Magnets
- Detector





Energy staging

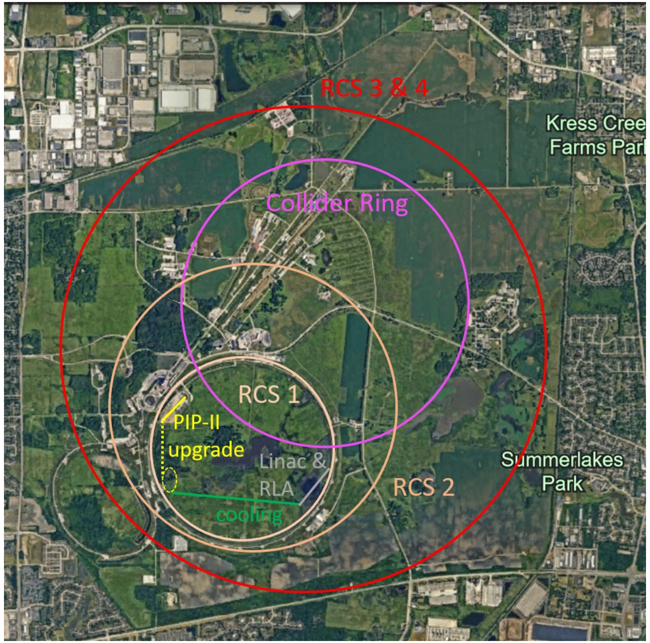
- Start at lower energy
- Current 3 TeV, design takes lower performance into account
- Splits cost, little increase in integrated cost

Luminosity staging

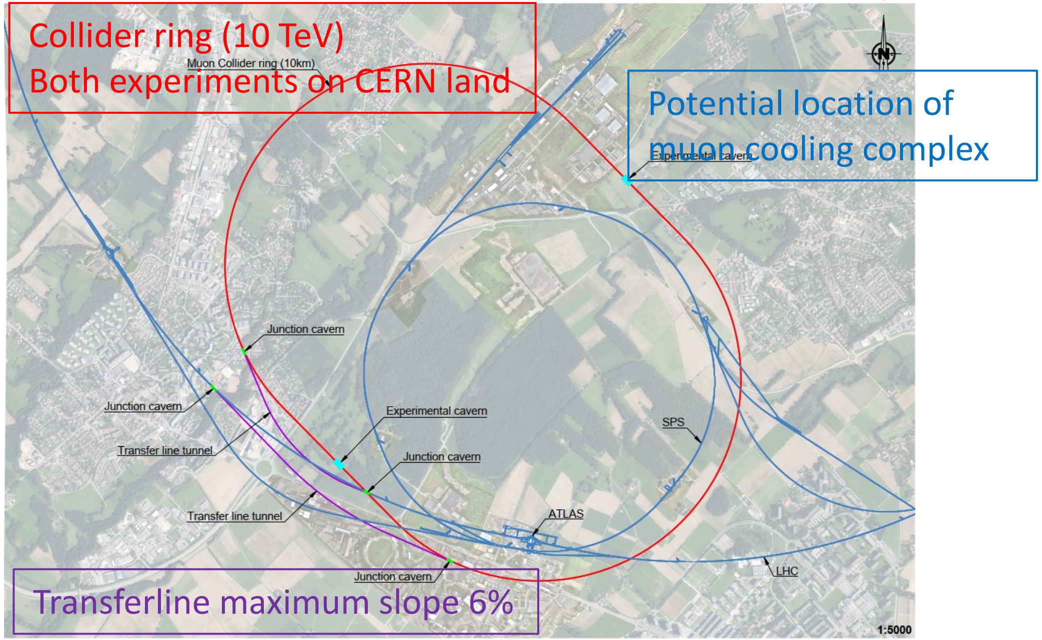
- Start at with full energy, but lower luminosity
- Main luminosity loss sources are arcs and interaction region
  - Can later upgrade interaction region (as in HL-LHC)

Site Studies

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



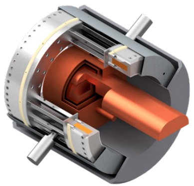
Exploration at FNAL started
Collider and accelerator complex could fit on site
Demonstrator as well

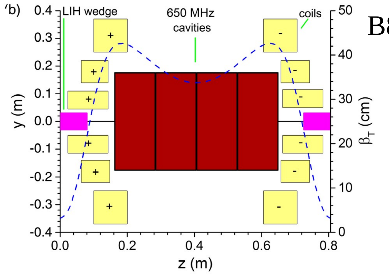


Exploration at CERN started
Re-using LHC and SPS tunnels, new collider ring
Collider and accelerator complex could fit on CERN land
More detailed studies required

R&D Programme

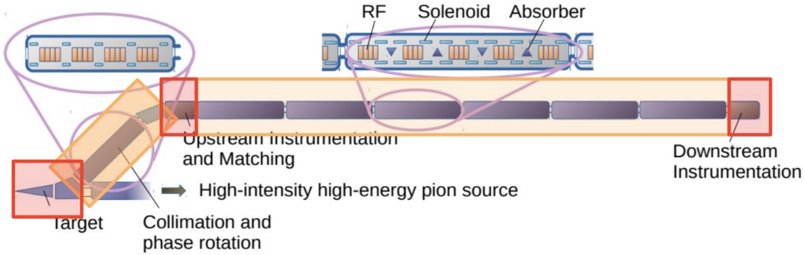
Broad R&D programme can be distributed world-wide





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

Conclusion

R&D progress is increasing confidence that the collider is a unique, sustainable path to the future
P5 strongly supports this view

- Plan to increase collaboration with the US

Started exploring the implementation at CERN and FNAL using existing infrastructure

Cost scale estimate has started

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

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

Need to continue ramping up the momentum

Many thanks to the collaboration for all the work

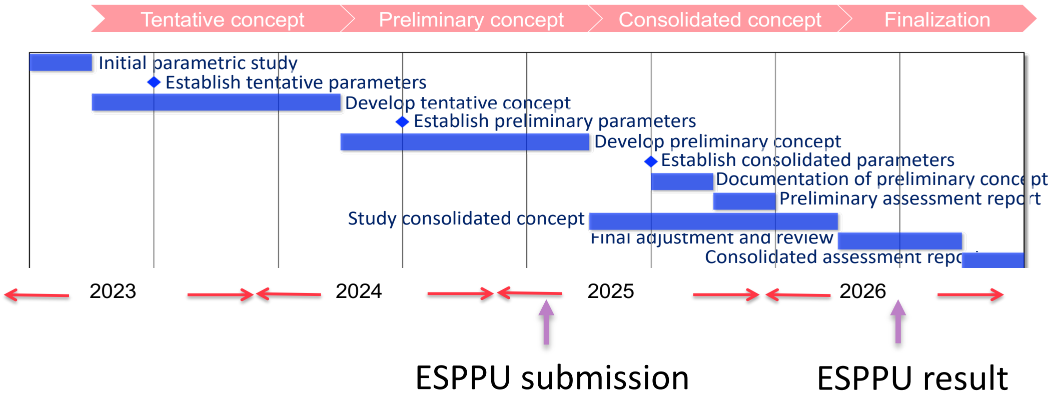
To join contact muon.collider.secretariat@cern.ch

Reserve

IMCC Plans

For the **ESPPU,** will deliver

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



After ESPPU submission:

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

Continue together to develop green field concept

- Avoid becoming site specific before funding agencies put the resources on the table
- Develop site specific versions as derived approaches

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

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

Power and Environment

The compact footprint, limited cost and power consumption are intrinsic features that motivate the muon collider study in the first place. Reuse of existing infrastructure is further reducing the impact on the environnement.

Specific studies address the key power consumers:

- Superconducting magnets, fast-ramping magnets, normal- and superconducting RF systems, cooling of the components and their shielding

Can give some numbers on CO_2, where common database is available

Neutrino flux mitigation is being studied

Tentative Staged Target Parameters

Target integrated luminosities

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

Need to spell out scenarios

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

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

Examples as discussion basis
numbers will change

IMCC Organisation

Collaboration Board (ICB)

- Elected chair: **Nadia Pastrone**
- **50 full members, 60+ total**

Steering Board (ISB)

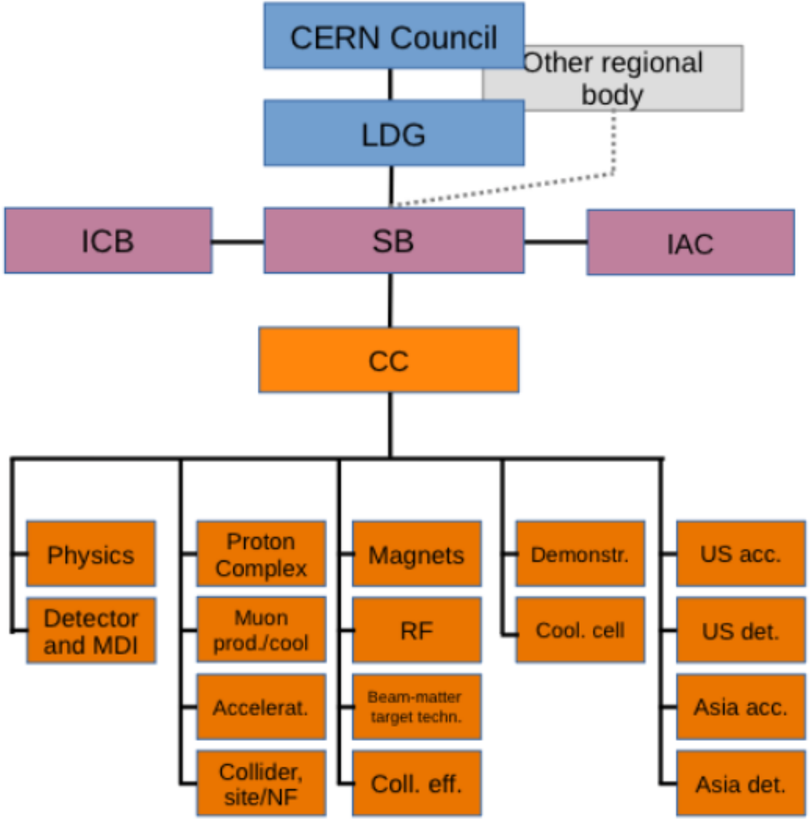
- Chair **Steinar Stapnes**
- CERN members: Mike Lamont, Gianluigi Arduini
- ICB members: Dave Newbold (STFC), Mats Lindroos (ESS), Pierre Vedrine (CEA), N. Pastrone (INFN), Beate Heinemann (DESY)
- Study members: SL and deputies

Advisory Committee

Coordination committee (CC)

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

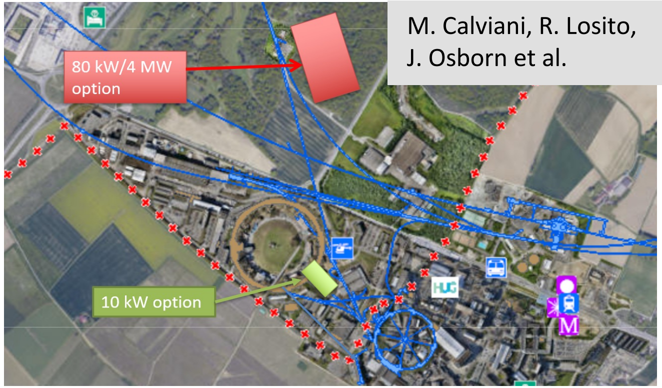
Will integrated the US also in the leadership



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

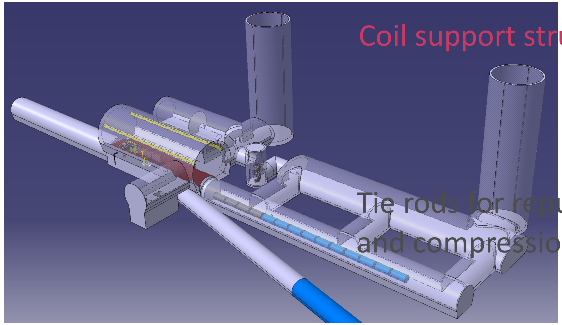
- look for an existing proton beam with significant power

Different sites are being considered

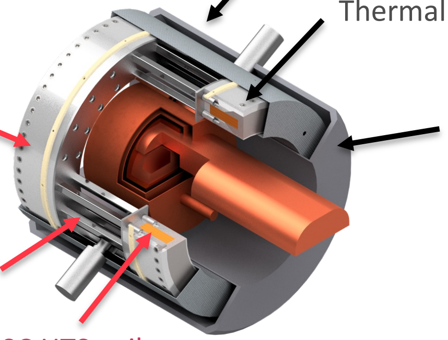
- CERN, FNAL, ESS …
- Two site options at CERN

Muon cooling module test is important

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



With cryostat



US P5: The Muon Shot

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

US ambition:

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

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

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

IMCC prepares options for Europe and for the US in parallel