

International
Muon Collider
Collaboration



MuCol

Progress Towards a Muon Collider

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On behalf of the International Muon Collider Collaboration

IPAC26, Deauville, May 18, 2026

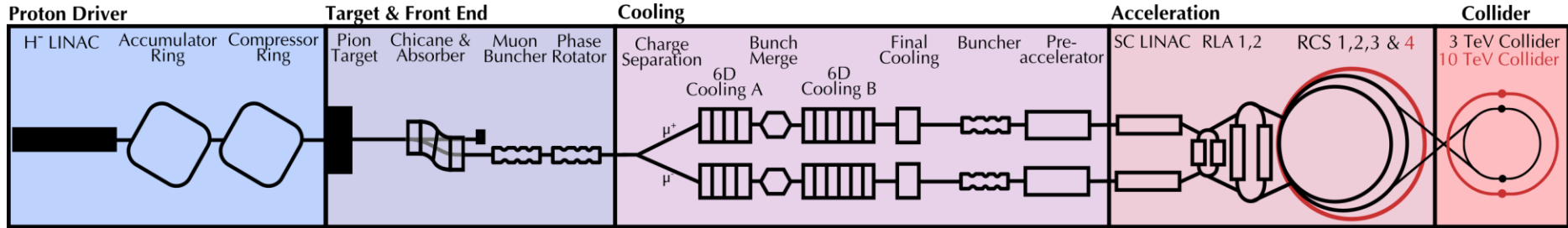


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Muon Collider Concept

A muon collider combines the physics advantages of an **electron-positron** and a **proton-proton collider** — **10 TeV collisions** in a compact facility

The main challenge is the short muon lifetime $\tau = \gamma \times 2.2 \mu\text{s}$



Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muons in matter

Acceleration to collision energy

Collision

IMCC

International Muon Collider Collaboration



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

- Implement globally defined accelerator R&D roadmap to justify CDR phase
- Mid-term roadmap review found 75% of goal achieved

Focus on feasibility of **10 TeV with 10 ab⁻¹** (site independent)

- Explore **initial stage by around 2050**, maybe with 3 TeV with 1 ab⁻¹ or lower luminosity 10 TeV

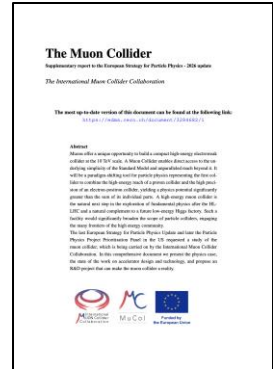
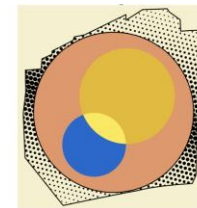
Explore implementation at specific sites reusing infrastructure

Provided ESPPU with

- **Assessment of the muon collider**
- **An R&D plan** for the next 10 years
- **Implementation considerations** (including site, timeline)
- **Back-up document** (406p, 450 signatories)

In US the National Lab Accelerator Study Group for the Muon Collider identifies how the US labs can best engage

Param.	Unit	3 TeV	10 TeV
L/IP	10 ³⁴ cm ⁻² s ⁻¹	2.1	18
N	10 ¹²	2.2	1.8
f _r	Hz	5	5
C	km	4.5	11.4
B _{dipole}	T	11	14
Collider dipole techn.		Nb3Sn	HTS



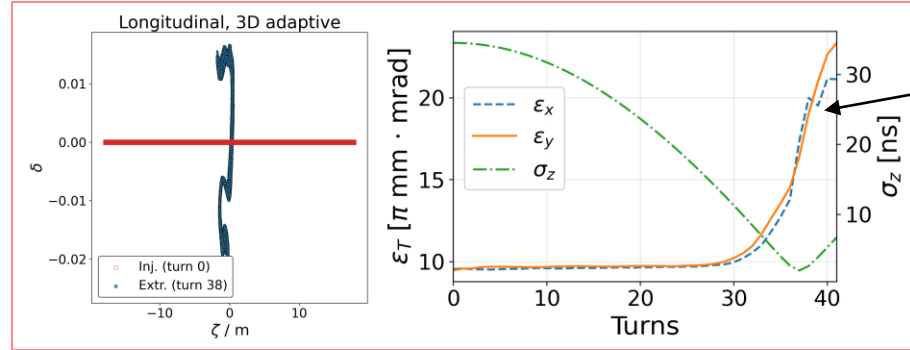
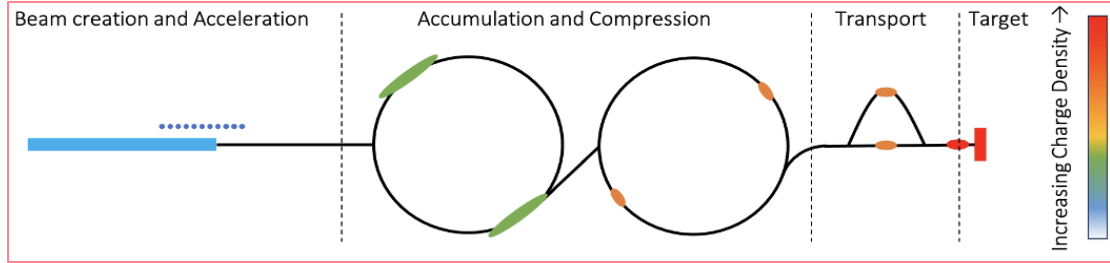
Proton Complex

Challenge:

- 2 MW, 5 GeV, 5 Hz
- 5×10^{14} protons in a 2 ns pulse

Achieved:

- A preliminary design for the whole complex
- Two compression schemes studied: **baseline** (accumulator + compressor with RF rotation) and an **energy chirp-based scheme**
- Improved space-charge modelling



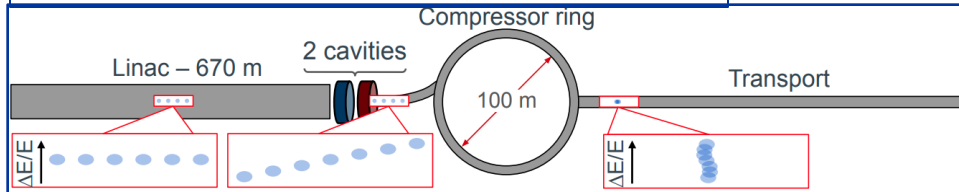
Baseline: RF rotation

SC amplified 4th order resonance

WEP5116

THP4042

Alternative: Compression with an Energy Chirp



Key conclusions:

- Can compress 2 MW, 5 GeV proton beam to 2 ns for the baseline compressor design; chirp scheme not reaching the target yet
- Compression instabilities under investigation
- CERN and SNS bunch compression experiments ongoing

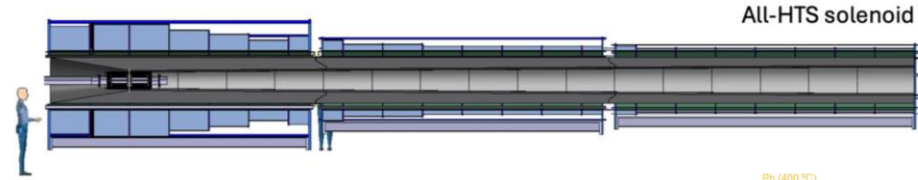
Target

Challenges:

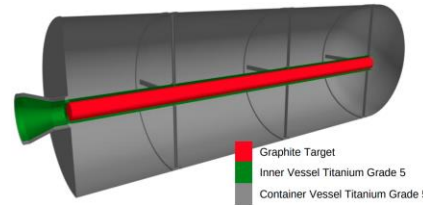
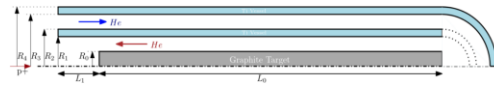
- 2 MW, 5 Hz, 400 MJ/pulse target
- Spent beam extraction

Achieved:

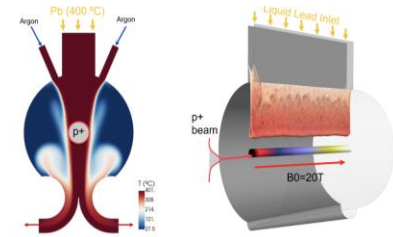
- 2 MW graphite target conceptual design, optimised yield
- Explored design options for a 4 MW, 10 GeV beam: graphite & liquid lead studies
- Advanced proton extraction studies



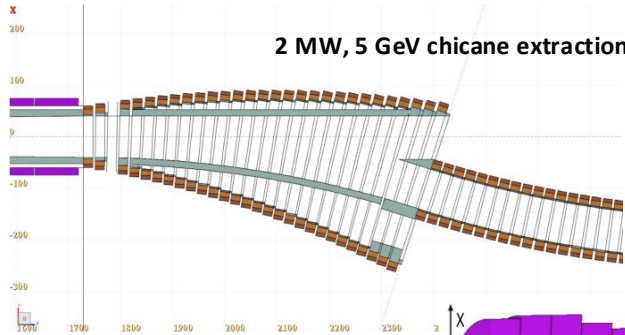
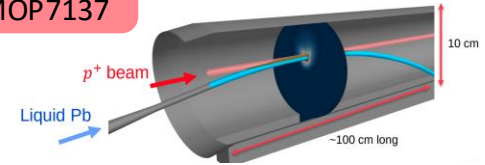
All-HTS solenoid



Graphite Target
Inner Vessel Titanium Grade 5
Container Vessel Titanium Grade 5

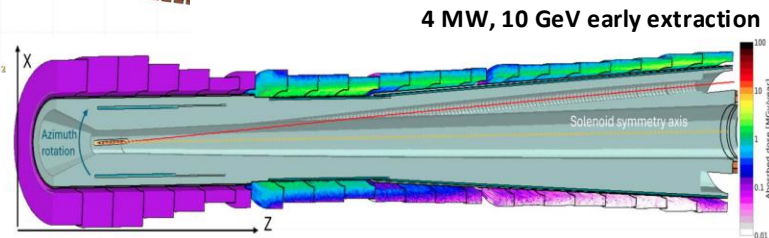


MOP7137



2 MW, 5 GeV chicane extraction

WEP1012



4 MW, 10 GeV early extraction

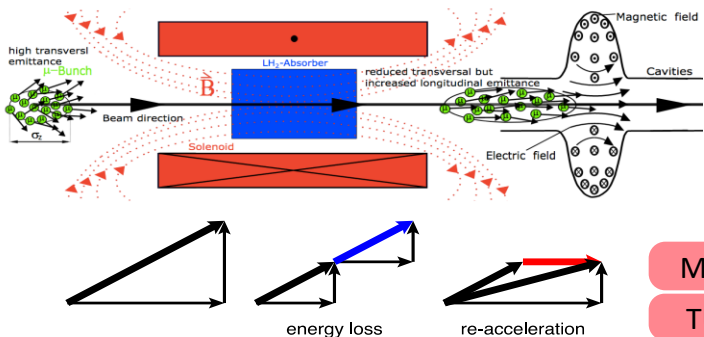
Key conclusions:

- 2 MW: Yield, magnet shielding, target stresses, cooling, radiation are OK
- 4 MW alternatives require further study
 - Graphite, liquid lead
- Good progress on proton extraction, further investigations required

Muon Cooling Lattice Design

Challenge:

Novel, complex lattice with RF cavities and absorbers in high-field solenoids

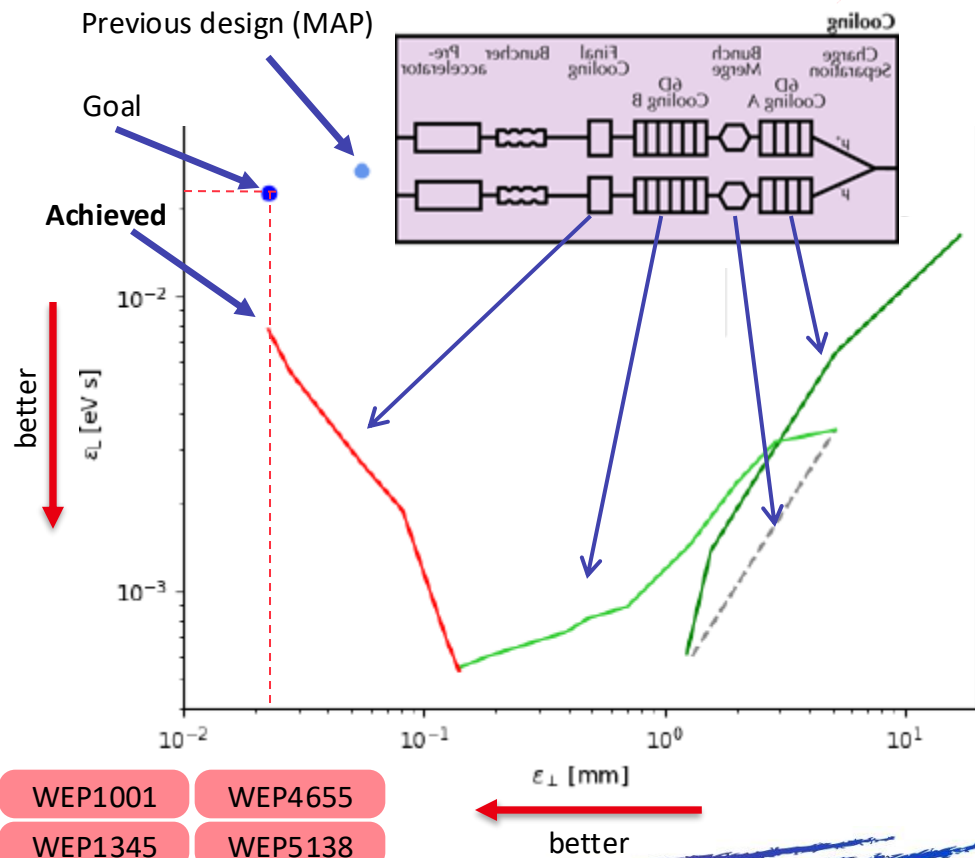


Achieved:

- Much improved lattice design, both 6D and Final Cooling
- Improved simulation tools: BDSIM and RFtrack
- Refined lattices, incorporated hardware feedback, started collective effects modelling, explored alternatives

Key conclusions:

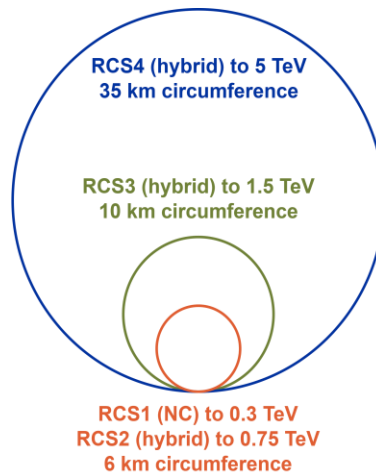
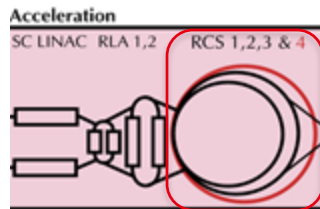
- Current performance exceeds target
- Much improved longitudinal, may be useful for collider ring
- Study of collective effects ongoing



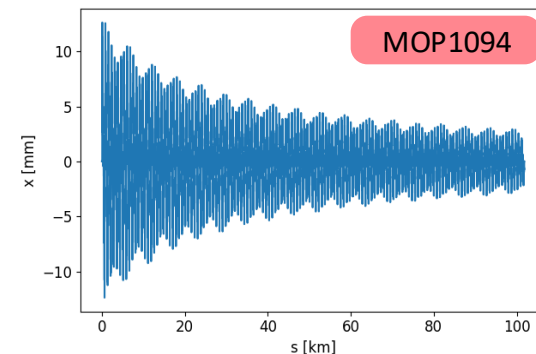
RCS Design

Challenges:

- 5 Hz pulses of O(1-10ms)
- Fast-pulsed magnets
- Energy efficient acceleration
- High bunch charge
- Maintain beam quality



Horizontal trajectory oscillations for the entire acceleration in RCS1

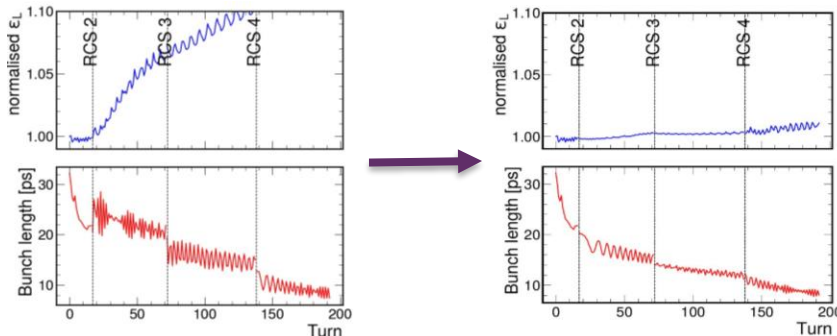


Achieved:

- Lattices for all site independent RCSs
- Beam energy/ramped magnet field mismatch studied
- Inter-RCS matching optimised
- Upgraded simulation codes
- Extended modelling of intensity effects from counter-rotating beams

THP4038

MOP1121



Key conclusions:

- Emittance growth due to energy – field mismatch to be controlled with RF systems distributed over many sections
- Improved longitudinal emittance transport

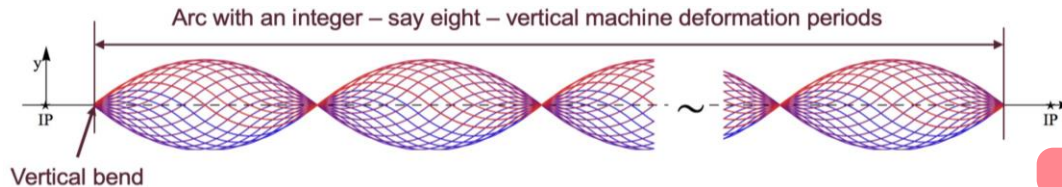
Collider Ring

Challenges:

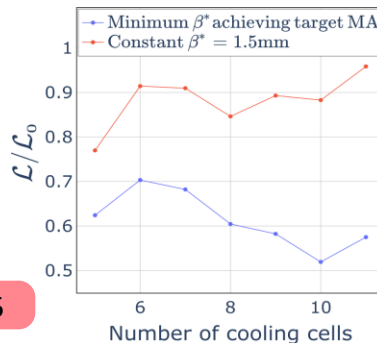
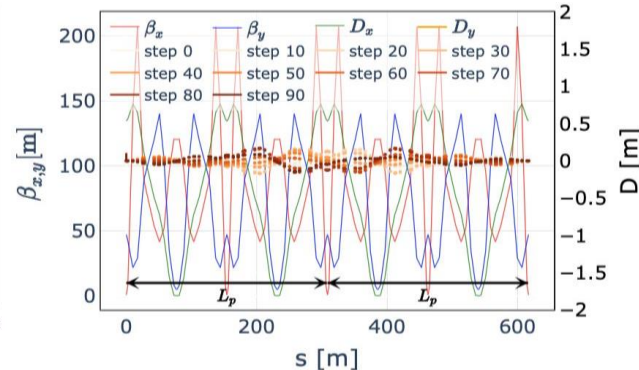
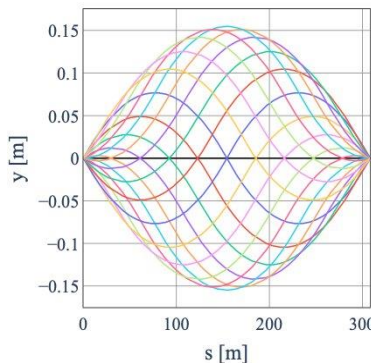
- Small β^* (1.5-5 mm), 0.1% beam energy spread \rightarrow strong chromatic effects
- Short muon lifetime (circumference, shielding, BIB), neutrino flux mitigation
- Magnet field strength, quality
- Maintain a short bunch length

Achieved:

- Vertical periodic machine deformation in the regular arc regions (VIPER)
- First joint optimization of the ionization cooling and the collider ring design
- More realistic constraints in the interaction region design



MOP1045



MOP1025

Key conclusions:

- VIPER in regular arcs: **negligible performance impact**; feasibility in more challenging sections to be studied
- Shorter cooling system: **potential luminosity gain**; further optimization needed

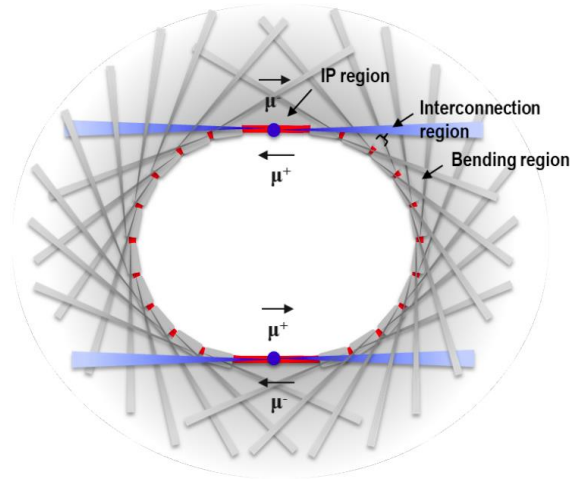
Placement

Challenge:

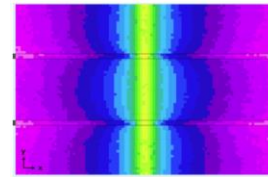
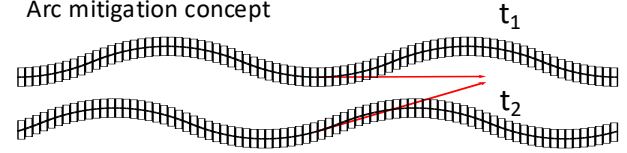
Obtain negligible neutrino flux

Achieved:

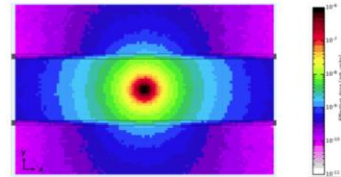
- Detailed modelling – GeoProfiler and placement optimization tools
- Radiation protection studies in FLUKA
- First viable orientation identified
- Mover system concept
- First characterisation of forward neutrino beams



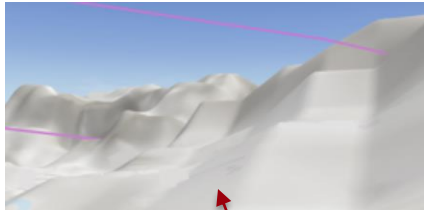
Arc mitigation concept



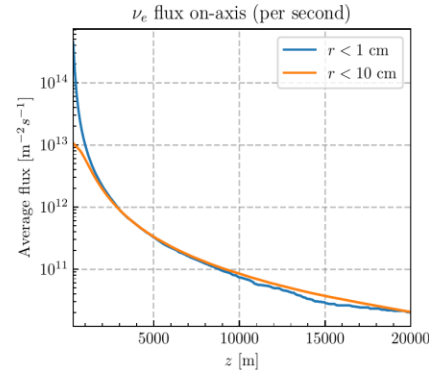
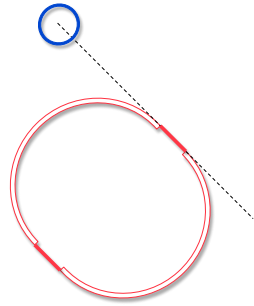
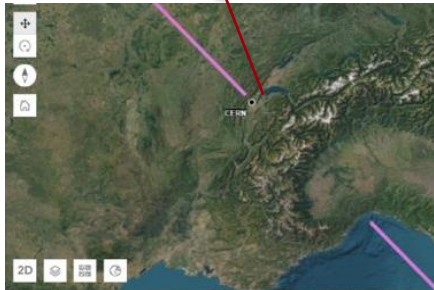
Movers



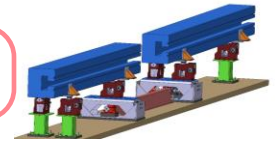
No movers



Site study at CERN for experimental insertion



Mover system



Key conclusions:

- Converging on a placement solution, optimization ongoing
- Arcs impact similar to current CERN impact

Collective Effects

Goal:

Model and quantify collective effects across the complex

THP4038

WEP1001

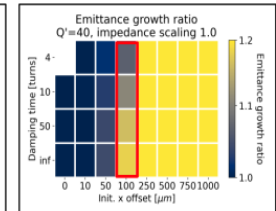
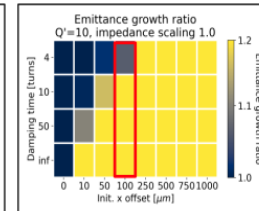
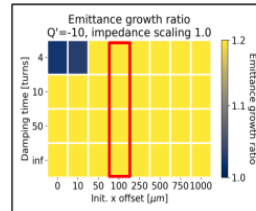
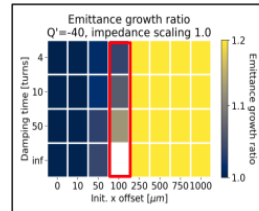
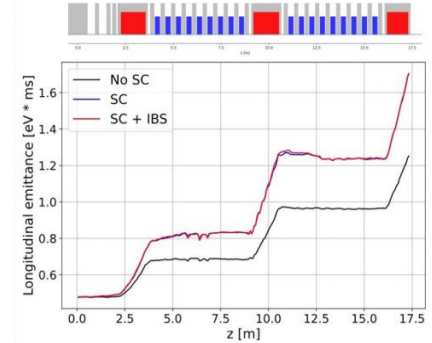
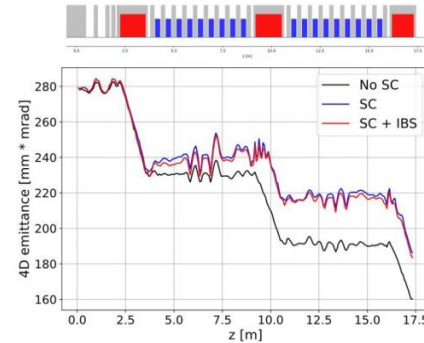
MOP1100

Achieved:

- **Proton driver:** improved space-charge (SC) modelling in the compressor ring
- **Cooling:** First intra-beam scattering + SC study in the final cooling lattice; beam loading analysed for cooling cavities
- **RCS chain:** Assessed mitigation strategies for impedance-driven transverse instability; counter-rotating multi-turn wakefields modelled across the chain

Key conclusions:

- SC + IBS cause emittance growth in final cooling; study to be extended to entire lattice
- Transverse beam emittance in RCS chain can be preserved
- Beam loading compensation in cooling cavities requires an increase in RF voltage



R&D Programme



Accelerator design

- Complete **start-to-end design** to validate and optimize performance, cost, power and risk

Muon cooling technology

- Implementation in steps important for timeline
- Need hardware**
 - Cooling RF tech. requires **urgent test infrastructure**
- New detector technologies** useful for instrumentation

Detector

- Strong potential to further **improve physics potential** with **technologies, AI and ML**

Magnet programme

- Produced conceptual designs, need hardware
- HTS solenoids have important **synergy with society** (e.g. fusion, power generators for windmills, ...)
 - Industry** is ready to invest
 - Must seize the **opportunity**

Innovation is essential, ideal for **early career researchers**

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

The International Advisory Committee Review supports the R&D programme proposal with suggestions for minor improvements

The IAC		Invited experts	
Giorgio Apollinari	Mauro Mezzetto	Sergey Belomestnykh	Alessandro Gallo
Ursula	Maurizio Vretena	Barbara Dalena	Steve Gourlay
Bassler (chair)	r	Pantaleo Raimondi	Mike Lamont
Stewart Boogert	Akira Yamamoto	Lyn Evans	Mike Seidel
Sarah Demers	Hongwei Zhao	Pierre Vedrine	

Muon 6D Cooling Cell

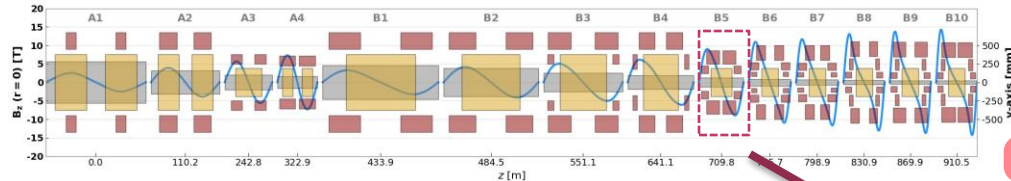


Challenges:

- Integration of 6D cooling cell (HTS solenoid, RF, absorbers) in tight space
- Compact HTS solenoid concept
- Remote-handling for cell beam pipe inter connections

Achieved:

- Full design of demonstrator 6D cooling cell
- First design of cooling module with suitable end force management
- Designed a reduced diameter (250 mm ID) HTS solenoid for 3 GHz RF test stand
- Remote-handling concept down-selected
- RF test stands preparation (INFN, SLAC)



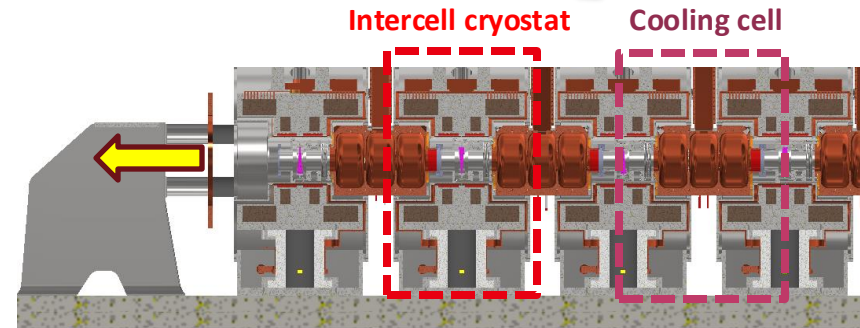
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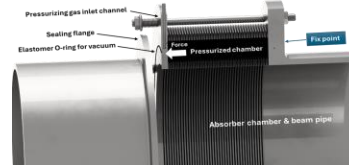
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WEP1011



Test stand for RF material qualification using magnetic fields up to 1.2 T and pulsed voltages

Remote handling beam pipe connection (pillow seal)



Key conclusions:

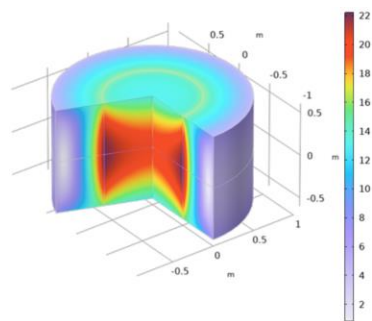
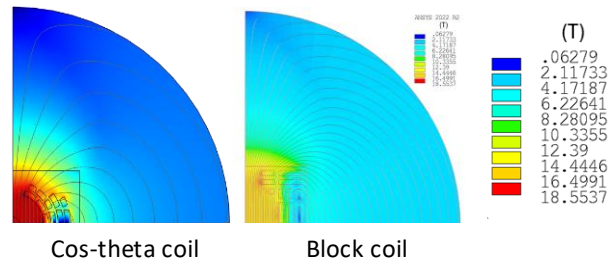
- **Solid cell design** meets **mature optics** specs; feasible maintenance for the collider system
- First force management solution for module testing; promising solutions for operation with beam in progress
- **Ready to ramp-up prototyping and testing**

Magnets

Achieved:

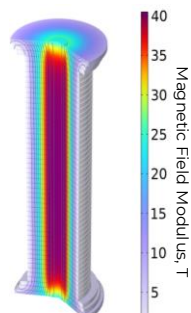
- HTS solenoid designs (target, 6D cooling, final cooling)
- Normal-conducting fast-pulsed dipoles
- Progressing conceptual designs for the collider dipoles
- Planned dedicated experimental activities to validate design choices

Collider Dipoles E.M. layout



Target solenoid

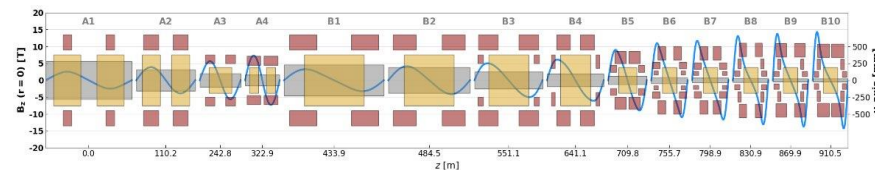
No showstoppers identified



Final cooling solenoids

73 cm height – 5 cm bore aperture, 46 modular single ReBCO pancakes + 6 pancakes for the heads

Intense measurement campaign to validate technology



6D cooling solenoids

Key conclusions:

- Comprehensive design work mostly completed
- HTS solenoids have strong synergy with fusion reactors

Conclusions

The muon collider: a novel and unique path to high-energy physics

Strong technical progress across the complex is increasing confidence in the concept

- Consolidated the baseline parameters at 10 TeV (post ESPPU submission)
- Improved, evolving design – no showstoppers identified, but further work required

R&D path forward

- Developed an R&D programme proposal
- Hardware development and validation a priority
 - Staged muon cooling demonstrator programme
 - HTS solenoids and other magnet technologies
- Strong societal synergies (HTS magnets → fusion, MRI, power generators) and industrial interest
- Funding is now the critical enabler

Innovation is essential

Many thanks to the collaborators for all the work

Our web page:

<http://muoncollider.web.cern.ch>

If you want to join:

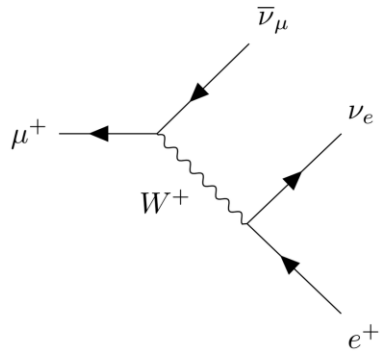
muon.collider.secretariat@cern.ch

Back-up

Physics and Detector Concepts

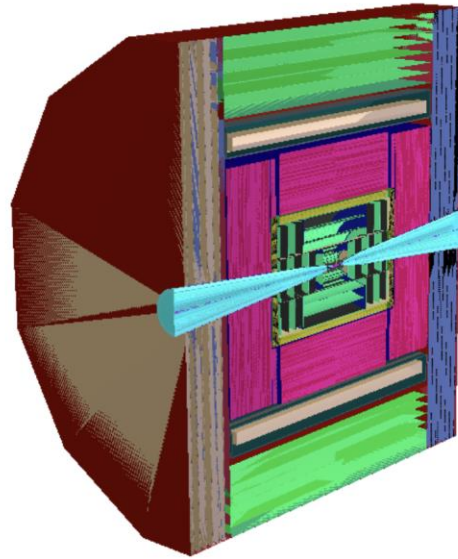
Challenges:

Background from muon decay



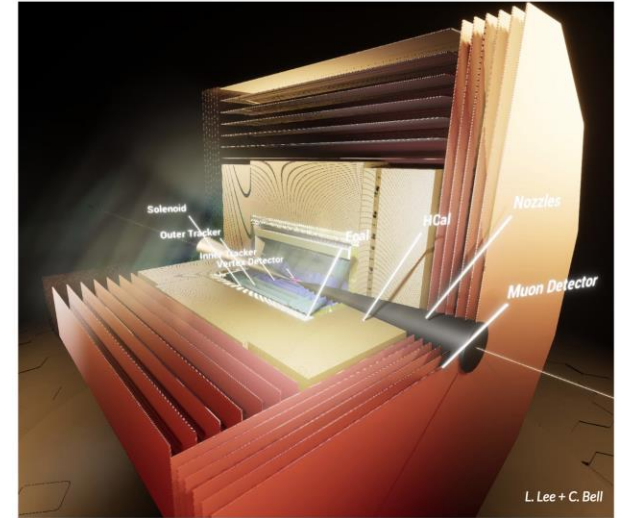
MUSIC

(MUon Smasher for Interesting Collisions)



MAIA

(Muon Accelerator Instrumented Apparatus)



Two detector concepts are being developed

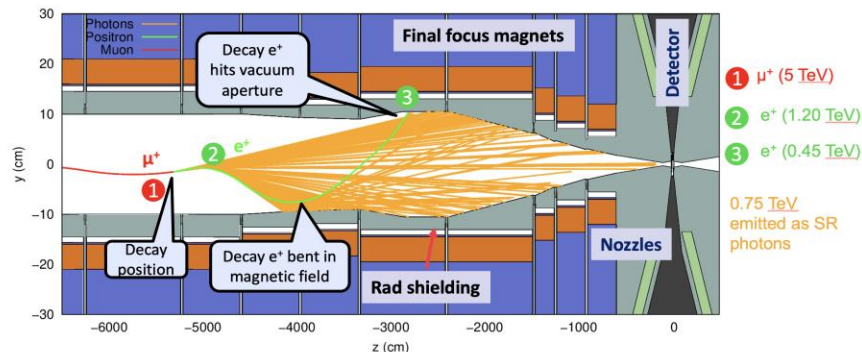
Beam-induced Background

Challenges:

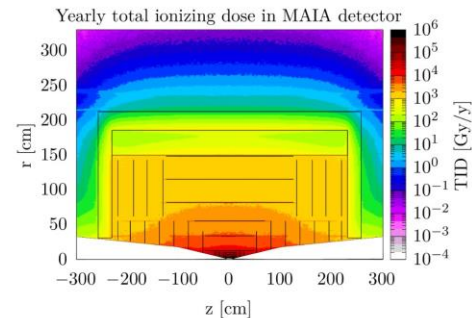
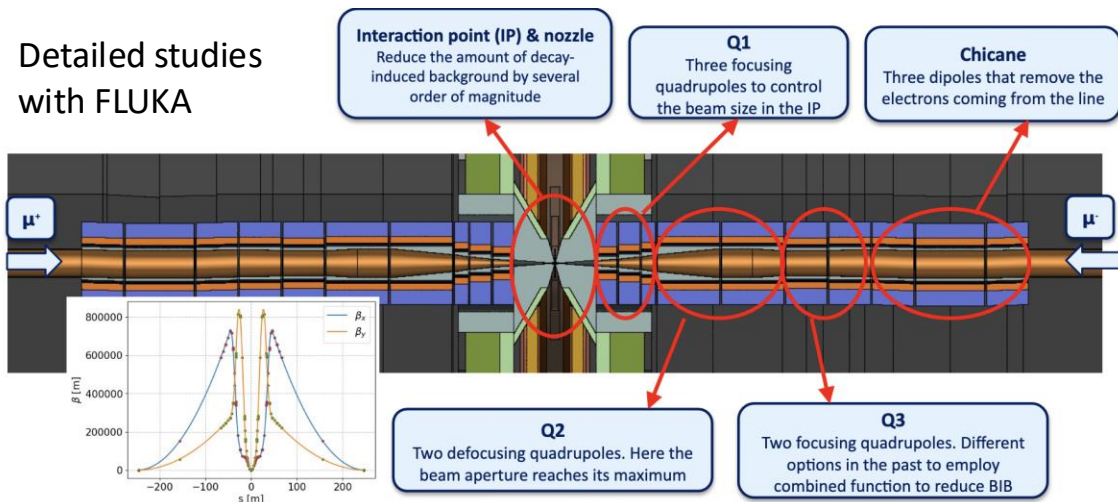
Background from muon decay

Achievements:

- Two conceptual detector designs
- IR lattice and nozzle optimized to reduce BIB impact
- Decay induced background simulated with different IR lattices
- Improved description of incoherent pair production at 10 TeV



Detailed studies with FLUKA



Conclusions:

- Long term radiation damage compatible with detector operations
- Radiation level similar to HL-LHC