# Muon Collider

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On behalf of the International Muon Collider Collaboration

LDG Review, February, 2025

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.

# Overall Goals and Roadmap Deliverables

IMCC, International Muon Collider Collaboration
- Currently hosted at CERN

**Collaboration goal:**

Develop high-energy muon collider as option for particle physics:
- Focus on **10 TeV feasibility**
- **Initial stage as option by ~2050** as strongly recommended by Steering Board and Advisory Committee, with required compromises
- Could later consider other energies

**LDG Roadmap deliverables**:
- A **Project Evaluation Report** that assesses the muon collider potential as input to the next ESPPU;
- An **R&D Plan** that describes a path towards the collider;
- An **Interim Report** by the end of 2023 that documents progress and allows the wider community to update their view of the concept and to give feedback to the collaboration (**has been delivered**)

Will deliver **tentative Project Evaluation Report** and **R&D Plan on March 31, 2025**

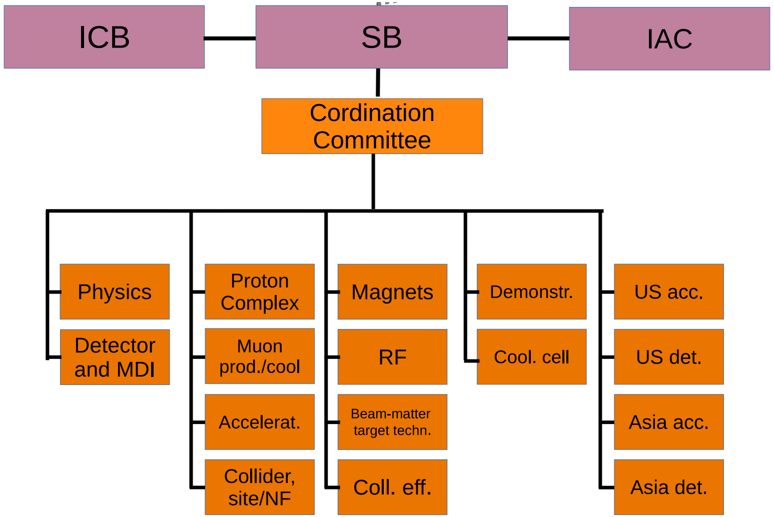
Final versions at the end of MuCol February 2027

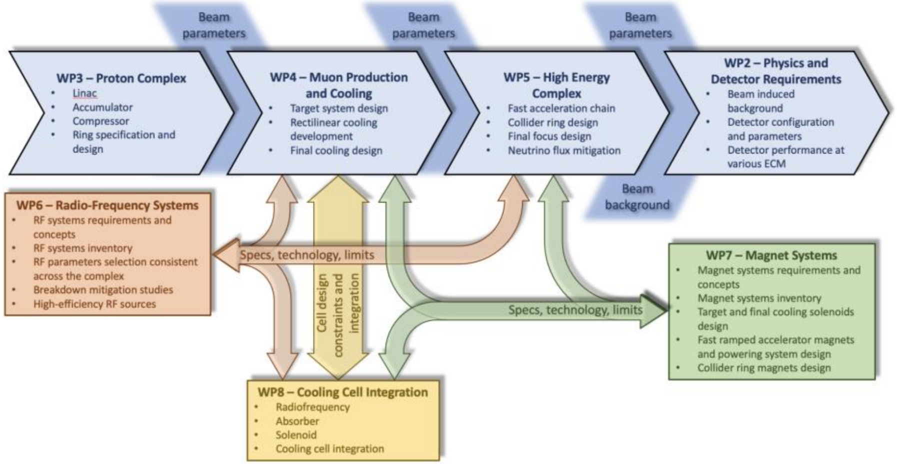
# IMCC Organisation

**Resources**
- Contributions of the partners
- EU co-funding via MuCol
- US contributed through P5 and now starts contributing
    - Addendum to CERN-DoE agreement in preparation

Roughly reaching minimal programme of LDG Roadmap

**IMCC reports to**
- The members and other contributors
- LDG
- CERN
- European Union because they co-fund MuCol





# Critical Technology Elements from Roadmap

| **Accelerator area** | **Critical Technology Elements (CTE)** |
|---|---|
| Proton complex | Proton driver bunch compression |
| Target | Graphite target<br>Target solenoid |
| Muon cooling | Muon cooling design<br>6D cooling solenoids<br>6D cooling RF cavities<br>Final cooling solenoids<br>Final cooling absorbers* |
| RCS system | Pulsed magnets and power converters<br>RCS RF system |
| Collider ring | Collider ring dipoles<br>Final focus quadrupoles |

*Identified during the Roadmap execution

# IMCC Workpackages

| **Acronym** | **Workpackage** | **Leader/comment** |
|---|---|---|
| SITE | Site considerations and layout | Christian Carli, Claudia Ahdida, John Osborn |
| NF | Neutrino flux mitigation system | Roberto Losito, Christian Carli |
| MDI | Machine-detector interface | Anton Lechner |
| ACC | Accelerator design | Natalia Milas (proton complex), Chris Rogers (muon production and cooling), Antoine Chance (RCS), Christian Carli (collider ring), Elias Metral (collective effects), Heiko Damerau (longitudinal beam dynamics in acceleration) |
| HFM | High-field magnet technology | Luca Bottura |
| FR | Fast-ramping magnet technology | Fulvio Boattini |
| RF | Radio frequency technologies | Alexej Grudiev, Dario Giove |
| TAR | Target facility and technology | Chris Rogers |
| MOD | Muon cooling cell module technologies | Lucio Rossi |
| DEM | Muon cooling demonstrator | Roberto Losito |
| INT | Integration | John Osborn, Carlo Rossi, Daniel Schulte |

Additional CC members:
Andrea Wulzer (deputy/physics), Donatella Luccesi (deputy/detector), Chris Rogers (deputy/machine)
Diktys Stratakis, Sergo Jindiariani, Mark Palmer, Steinar Stapnes (SB chair), Nadia Pastron (ICB chair)

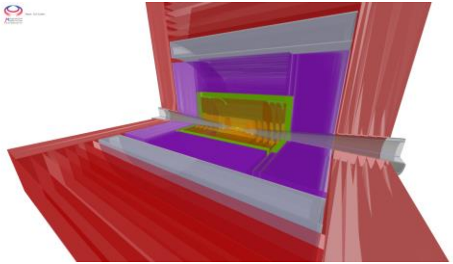
# Beam-induced Background (MDI)

**Goal**:
Develop tools and provide required input for detector background studies and improve mask

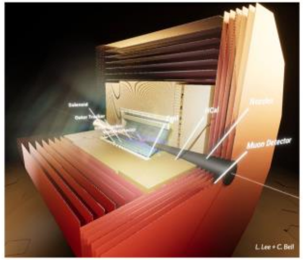
**Achieved:**
All software tools are in place, mask optimized and background data delivered to experiment, now iterating with detector experts

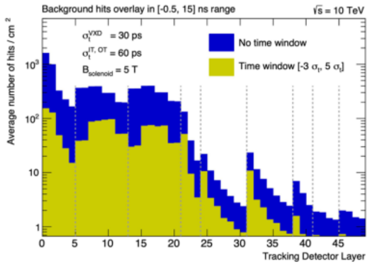
**Key conclusions**:
Can do the important physics with near-term technology also thanks to HL-LHC developments
Radiation levels similar to HL-LHC

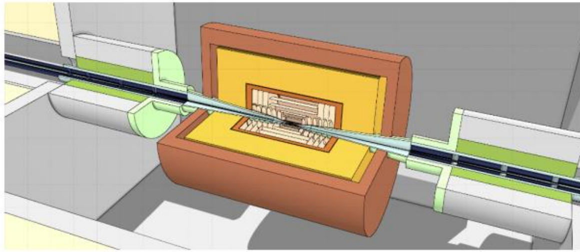
**MUSIC**
(MUon System for Interesting Collisions)

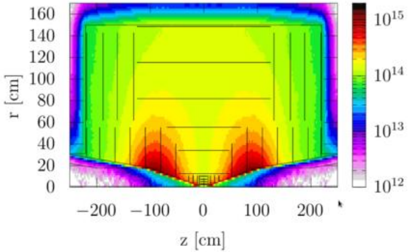


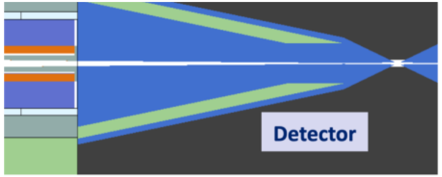
**MAIA**
(Muon Accelerator Instrumented Aperatus)









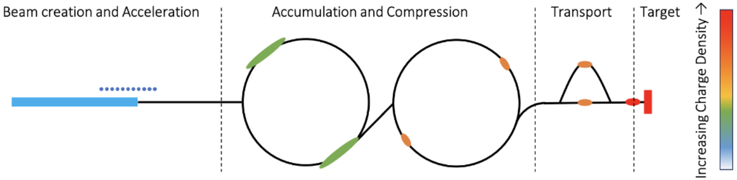


# Proton Complex (ACC)

**Goal:**
Design proton pulse combination complex (accumulator and compressor rings)

**Achieved:**
Lattices exist for accumulator and combiner rings, first collective effects studies

**Key conclusions:**
2 MW 5 GeV proton beam can be compressed to two 2 ns bunches, need to merge the two bunches
4 MW will require to increase beam energy to 10 GeV



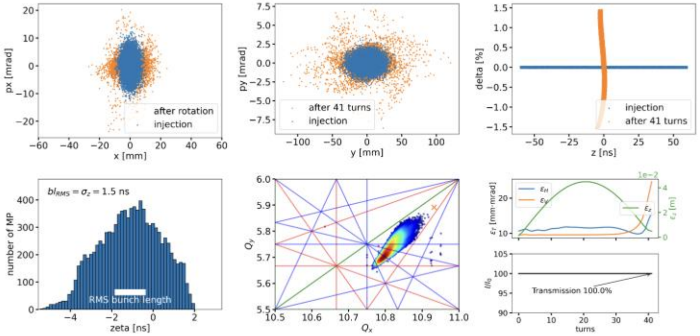


Fig. 5.1.8: Simulation of the full compression for one bunch at 5 GeV. Since this requires a 2 bunch
ll intensity shown in Table 5.1.1. Notice that at the end of
blow up that need still to be addressed.

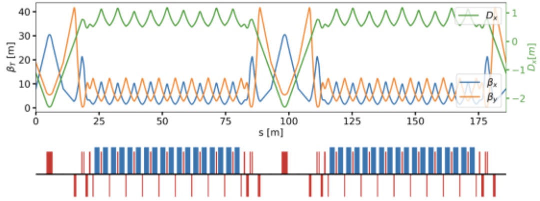
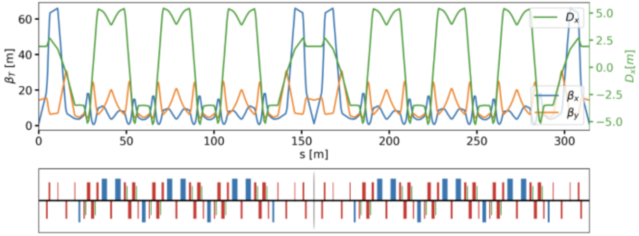


**Fig. 5.1.4:** The 5 GeV Accumulator lattice is shown. Dipoles are represented by blue blocks, while quadrupoles are represented by red blocks. Focusing quadrupoles are placed above the reference line, and defocusing quadrupoles are placed below the reference line.



# Target (TAR/HFM)

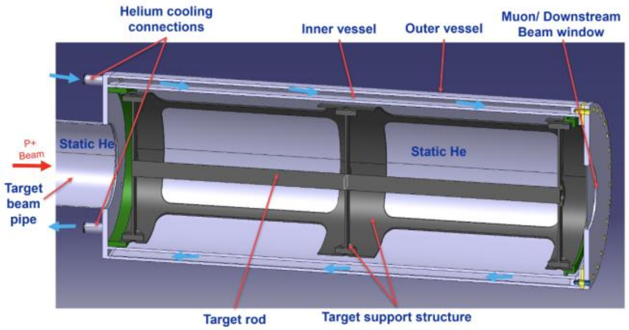
**Goal:** Assessment of feasibility of 2 MW graphite target

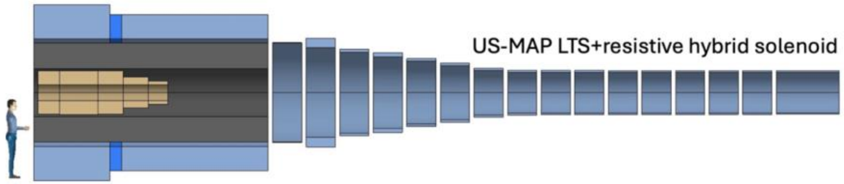
**Achieved:** 2 MW Target concept exists including

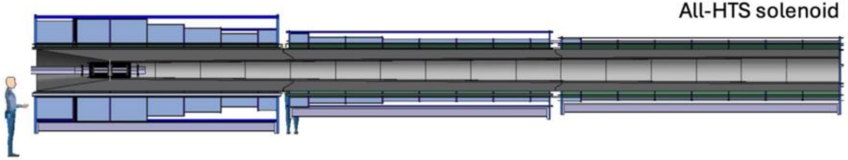
- Graphite target can be used instead of mercury
- Losses and shielding design
- Superconducting solenoid concept

**Key conclusions**: Components survive 2 MW beam

Spent beam remains to be investigated







| Inner radius of the magnet coils | Shielding thickness around the target | DPA/year [$10^{-3}$] | Dose [MGy/year] |
|---|---|---|---|
| 60 cm | W 31.2 cm + $H_2O$ 2 cm + $B_4C$ 0.5 cm + W 1 cm | $1.70 \pm 0.02$ | $10.0 \pm 0.3$ |
| 65 cm | W 36.2 cm + $H_2O$ 2 cm + $B_4C$ 0.5 cm + W 1 cm | $0.90 \pm 0.02$ | $5.6 \pm 0.2$ |
| 70 cm | W 41.2 cm + $H_2O$ 2 cm + $B_4C$ 0.5 cm + W 1 cm | $0.49 \pm 0.01$ | $3.1 \pm 0.1$ |
| 75 cm | W 46.2 cm + $H_2O$ 2 cm + $B_4C$ 0.5 cm + W 1 cm | $0.29 \pm 0.01$ | $1.9 \pm 0.1$ |
| 80 cm | W 51.2 cm + $H_2O$ 2 cm + $B_4C$ 0.5 cm + W 1 cm | $0.16 \pm 0.01$ | $1.0 \pm 0.1$ |
| 85 cm | W 56.2 cm + $H_2O$ 2 cm + $B_4C$ 0.5 cm + W 1 cm | $0.09 \pm 0.01$ | $0.6 \pm 0.1$ |

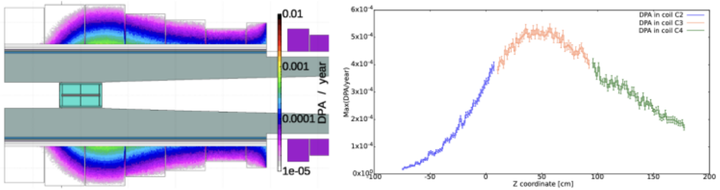


**Fig. 6.5.1:** 2D map of the displacement per atom (DPA) in the superconducting magnets of the target area (left) and the peak DPA in the coils most exposed to radiation (right).

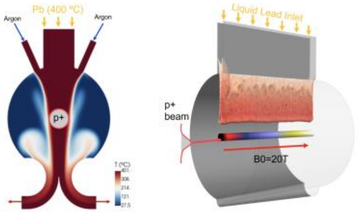


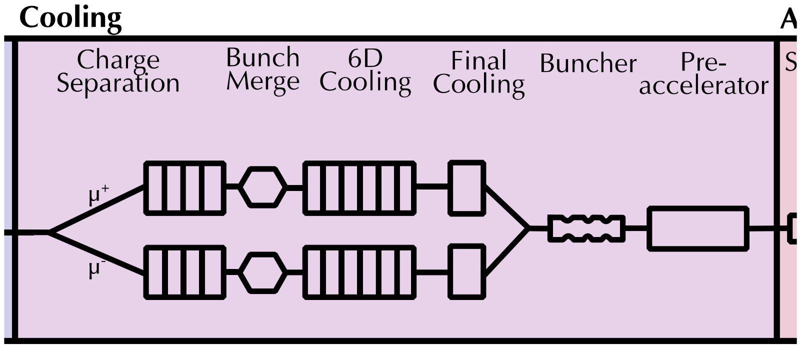
**Fig. 6.4.4:** Liquid lead target curtain concept.

# Muon Cooling (ACC)

**Goal:**
Improve the muon cooling design
Improve the final muon cooling design

**Achieved:**
Improved 6D cooling lattice developed
Two improved final cooling lattices have been developed

- One is conservativeOne focuses on overall optimisation



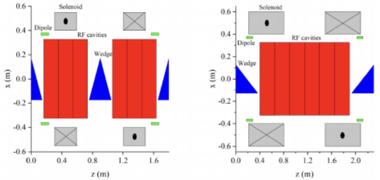
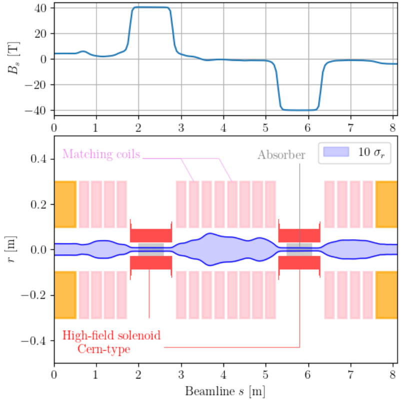
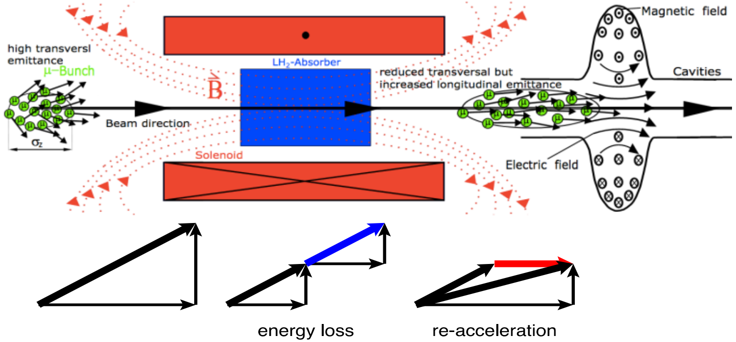
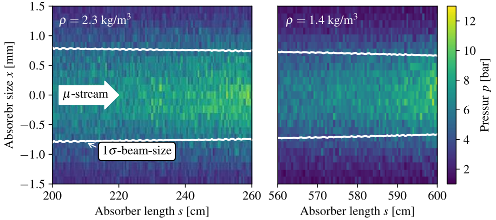


Fig. 5.2.4: Schematic of the (left) A-type and (right) B-type cooling cell layout.







# Muon Cooling (ACC)

**Key conclusions:**

6D cooling achieves much smaller transverse emittance for similar longitudinal emittance

Final cooling comes close to the goal

Transmission in cooling too low, but mostly compensated by overachieving in high-energy complex

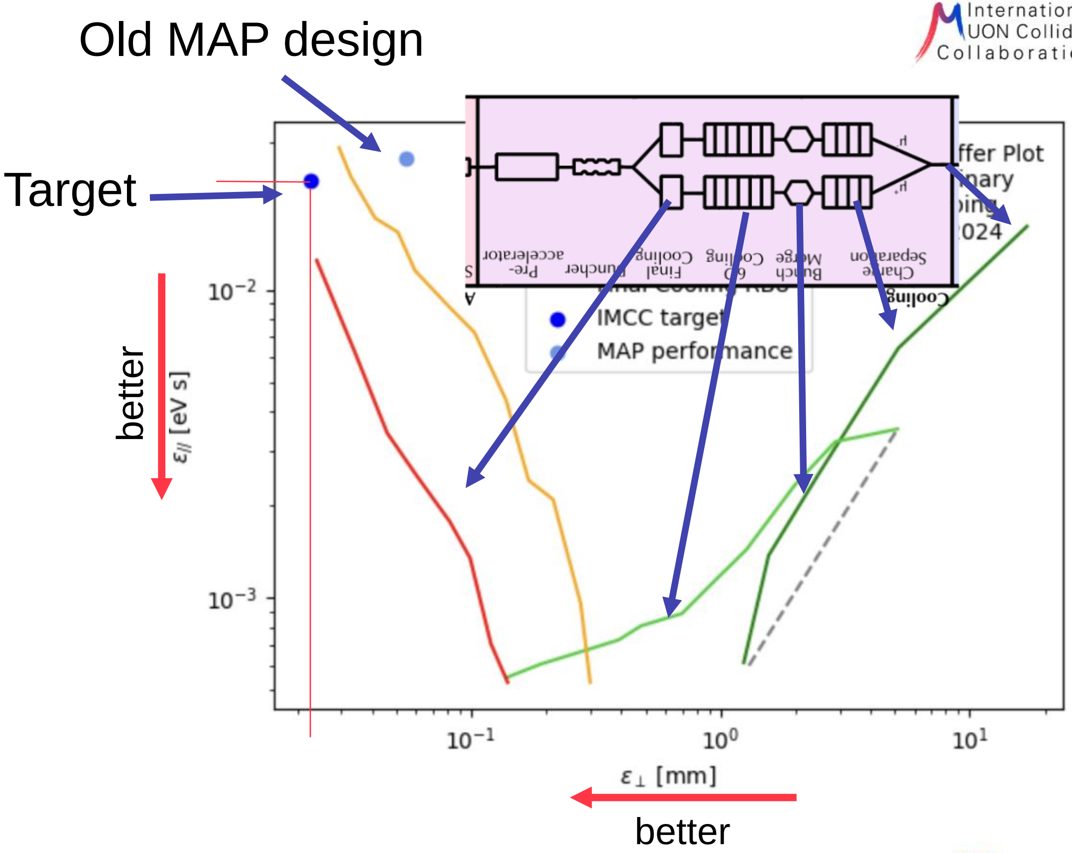
Identified muon beam density in absorber as a critical issue, solved by using hydrogen gas

Need to include collective effects

Beam loading/space charge in initial cooling cells needs to be addressed in detail

Negative muons transmission [$10^{12}$]

| System | goal | estim. |
|---|---|---|
| Front end | | 45 |
| End of cooling | 4 | 2.8 |
| Collider | 1.8 | 1.5 |

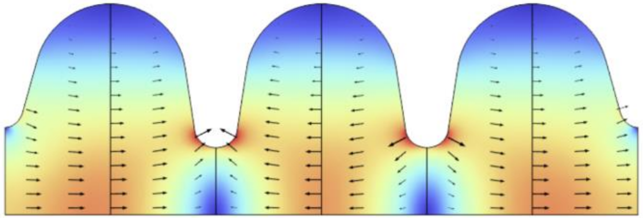


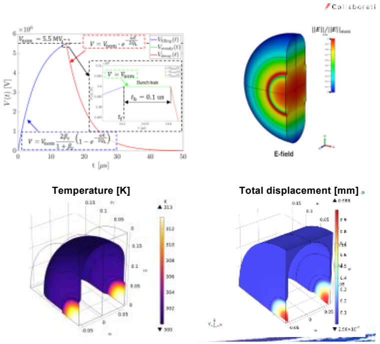
# Muon Cooling RF Technology (RF/MOD)

**Goal:**
A concept for the normal-conducting accelerating cavities of the muon cooling complex considering beam loading

**Achieved:**
Frequency selected
Two RF cavity designs are being developed (magnetic and electric coupling)
Parameters along cooling complex defined
Cavity design for cooling module test exists and is being updated

**Key conclusions:**
High-field RF gradients in a solenoid field have been demonstrated at FNAL, but test stand no longer exists
Need new RF test stand urgently
Test stand in ASP programme is not funded,
SLAC is preparing test stand for 3 to 1.3 GHz
This needs urgent funding





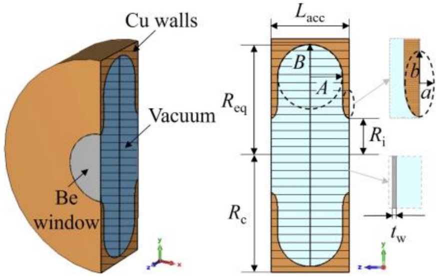


**Fig. 6.3.1:** Design of the 704 MHz cavity for muon cooling.

# Muon Cooling Solenoids (HFM)

**Goal:**

Establish realistic performance goals for the different 6D muon cooling solenoids

40+ T small aperture solenoid concept for final cooling

**Achieved:**

Developed tool to generate 6D cooling solenoid configurations (based on HTS)

- Used in beam dynamics

A concept for the final HTS-based cooling solenoid has been developed, reaching 40 T (used in design)

**Key conclusions:**

6D cooling lattice design uses realistic solenoid performances, slightly high in final cells

40 T final cooling solenoid appears feasible (32 T has been demonstrated in the past)

(Note: Ultimate limit may be 55 T)

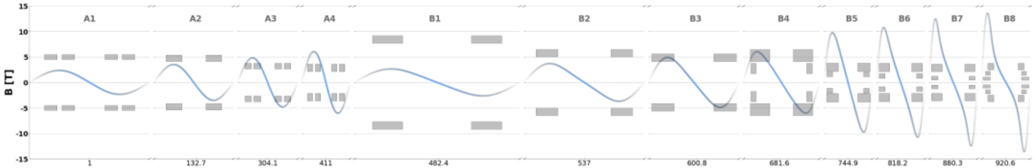


**Fig. 6.1.5:** Condensed schematic of the 12 types of cooling cells (A1 to B8) of a muon collider from the MAP configuration [300], with solenoid cross sections and the on-axis $B_z$ field assuming each cell is in a lattice of neighboring cells of the same type. z-axis values shown correspond to the the middle of the first cell of each type.

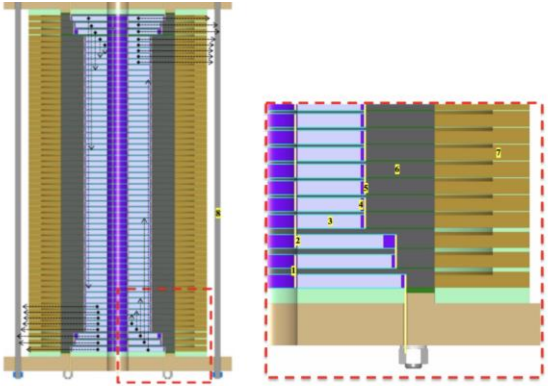


**Fig. 6.1.7:** Cross-section of the 40 T solenoid; the arrows indicate the axial and radial Lorentz forces acting on each pancake. The lengths of the radial arrows have been scaled down by a factor of 3.

# Muon 6D Cooling Cell (MOD)

**Goal:**
Assess the engineering challenges of an integrated 6D cooling cell

**Achieved:**
Preliminary design of a cooling cell

- Solenoid
- Cavity
- Integrated model

Challenges identified

**Key conclusions**:
Key challenge is force from magnetic field
Iterations to improve overall and components design also considering beam dynamics is required/ongoing

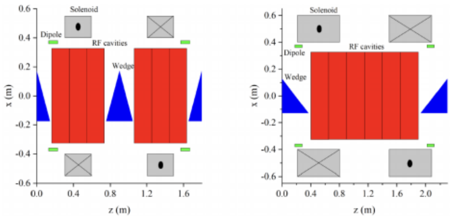


Fig. 5.2.4: Schematic of the (left) A-type and (right) B-type cooling cell layout.

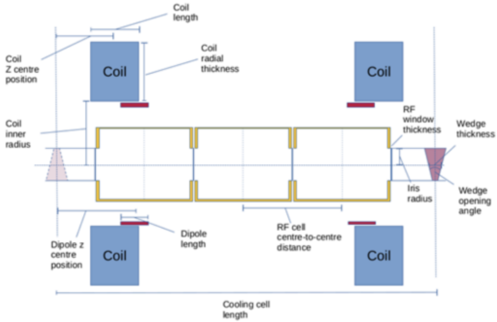


Fig. 6.6.1: Schematics of the MuCol Cooling cell

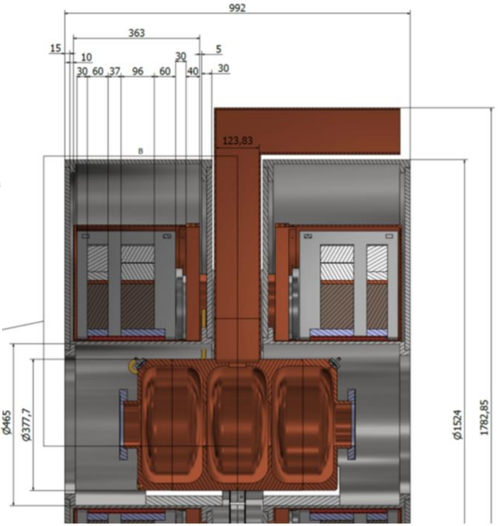


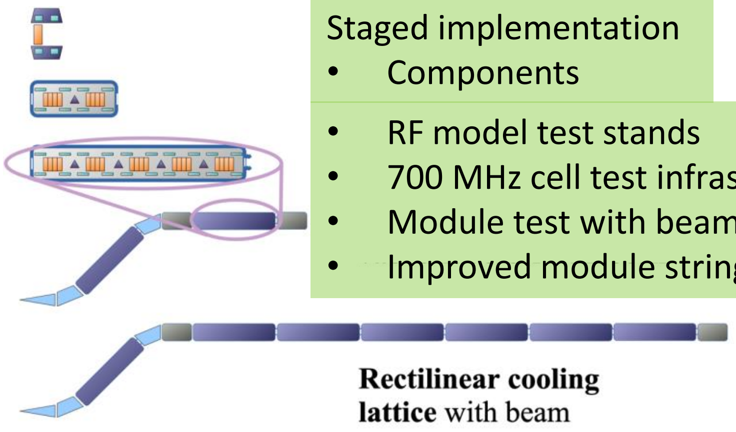
Fig. 6.6.2: Preliminary design of the MuCol Cooling cell

# Muon Cooling Demonstrator (DEM)

**Goal:**
Identify scope and potential location of facility to demonstrate cooling cell technology with beam

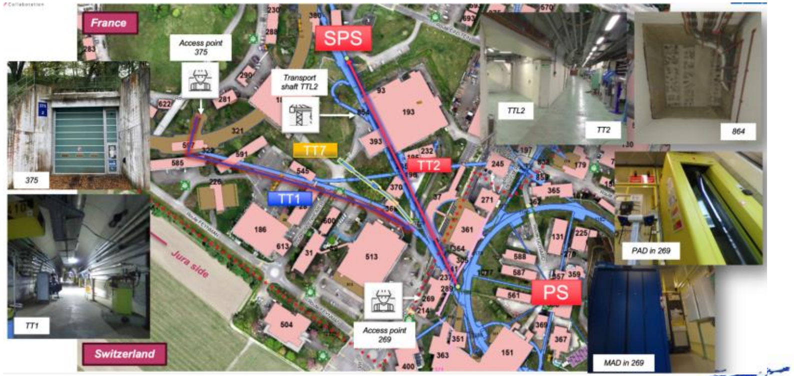
**Achieved:**
Defined the scope and concept, made initial cost estimate, investigated three promising locations at CERN, funding for study of demonstrator at FNAL exists.
Staged timeline to implement demonstrator

**Key conclusions:**
Two locations at CERN appear possible with limited cost, identified hardware needs for demonstrator
RF test stand is critical to verify cavity performance in time
High-power 704 MHz klystron needs to be developed now



Staged implementation
- Components
- RF model test stands
- 700 MHz cell test infrastructure
- Module test with beam
- Improved module string

**Rectilinear cooling lattice** with beam

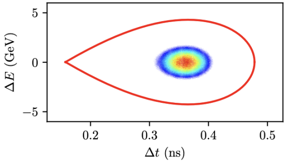


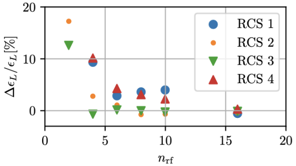
# RCS Design (ACC)

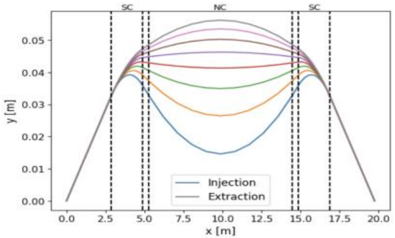
**Goal:**
Design concept for RCS
Choice of RF configuration

**Achieved:**
Lattices for all site independent RCSs exist
Longitudinal beam dynamics studied in each RCS

**Key conclusions**:
1.3 GHz TESLA-type cavities could be used
Dimensions of magnet apertures know







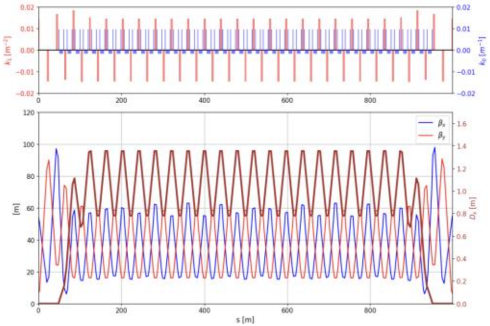
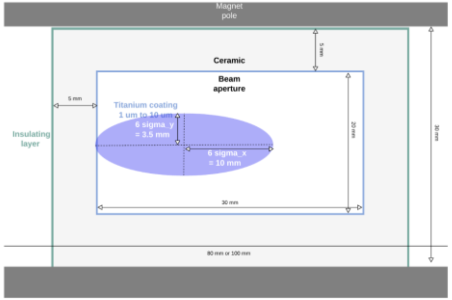


**Fig. 5.3.7:** Normalized strength of the dipoles (top, in blue) and quadrupoles (top, in red) and betatron functions (bottom, in blue and red) and dispersion function (in dark red) in one out of 6 arcs of RCS2.

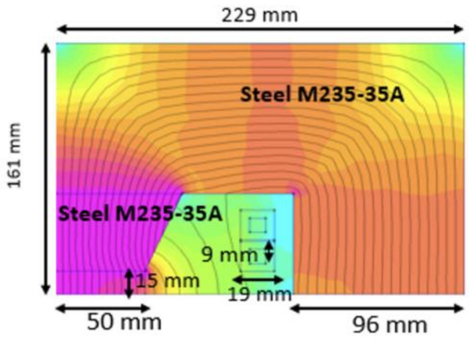


# Fast-ramping RCD Dipoles (FR)

**Goal:**
RCS dipoles and power converter (PC) concept
In some RCS direction of magnetic field/voltage has to change

**Achieved:**
Best solution picked from several magnet concepts and PC concept developed
Power converter concept developed that does not require to switch capacitor voltage to switch PC voltage
Optimisation tool to match magnet and RF ramp for minimal cost

**Key conclusions**:
Energy in dipole about 6 kJ/m (200 MJ in total)
System reaches 99% recovery efficiency for single direction PC
Around 95% for switching direction
Key cost in magnetic material and power stacks, could be improved



$T_{pulse}$= 4.5 ms
$\sigma_{rms}$= 4.6 A/mm2
mmf= 48374 At

$E_{lossIron}$= 56.2 J/m/pulse
$E_{losscu}$= 424.9 J/m/pulse
$NRG_{stored}$= 6263 J/m

ult of CAPEX+OPEX optimization on the dipole

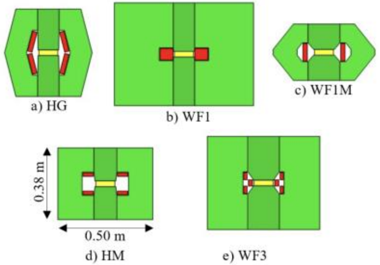


**Fig. 6.1.18:** Summary of the optimized geometries (the cross sections are to scale): a) Hourglass, J = 10 A/mm2, b) Window-frame WF#1, J = 10 A/mm2, c) Window-frame WF#1M, J = 20 A/mm2, d) H-type HM, J = 20 A/mm2; e) Window-frame WF#3, J = 20 A/mm2.

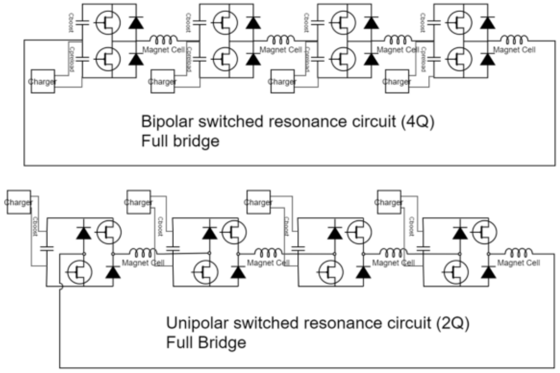


**Fig. 6.1.14:** Bipolar and Unipolar switched reluctance circuits

# Collider Ring (ACC)

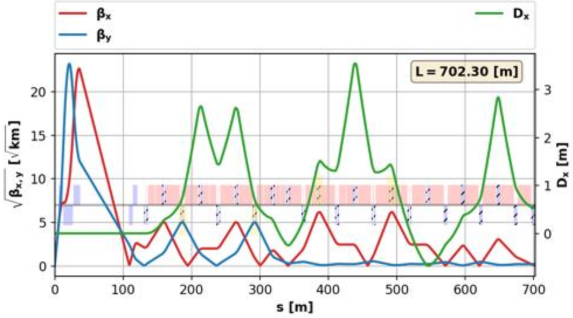
**Goal:**
Design concept collider ring lattice

**Achieved:**
Apertures defined based on magnet protection from muon decay debris
Lattice reaches target beta-functions but not yet target energy acceptance

**Key conclusions**:
Need to further improve energy acceptance

- Factor 2-3 for current baseline parameters
- 1.5 for new reduced longitudinal emittance beam from final cooling
- If we could not improve would loose 40% of luminosity

Slight adjustment to new magnet performance specifications is required
Need to address the impact of the neutrino flux mitigation movers on beam operation



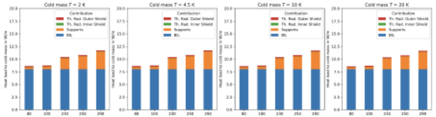
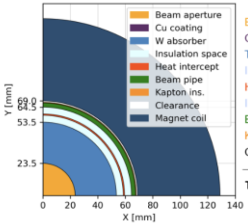
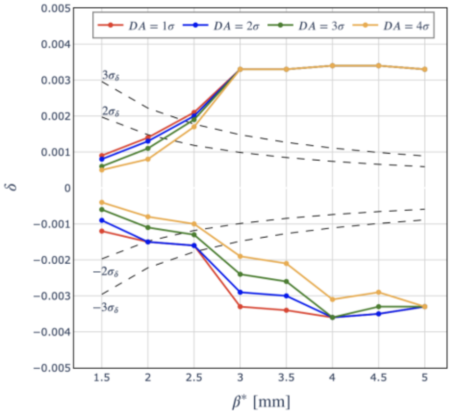


**Fig. 6.7.2:** Estimated heat load deposited on the cold mass in W/m, as a function of absorber temperature, for an absorber thickness of 30 mm, for nominal magnet operating temperatures of 2 K, 4.5 K, 10 K and 20 K (from [351]). The thermal shields (inner shield between absorber and coil, and outer shield) are assumed to be at 80 K. In the legend, "BIL" stands for "beam-induced losses".



| | $\Delta r$ |
|---|---|
| Beam aperture (5σ) | 23.49 mm |
| Cu layer beam screen | 0.01 mm |
| Tungsten absorber | 20-40 mm |
| Insulation space | 5 mm |
| Heat intercept | 1 mm |
| Insulation space | 5 mm |
| Beam pipe | 3 mm |
| Kapton insulation | 0.5 mm |
| Clearance to coils | 1 mm |
| **Total magnet aperture** | **118-158 mm (diameter)** |



# Collider Ring Magnets (HFM)

**Goal:**
Define realistic target parameters for the collider ring magnets

**Achieved:** New method developed to identify magnetic field limit depending on technology, cost, aperture considering current, stress and protection (quadrupoles, dipoles, combined function magnets)
Two conceptual dipole design ongoing

**Key conclusions**:
Some limited adjustment to initial magnet performance specifications required
Magnets appear feasible:

- NbTi dipoles at 4 K, 4.5 T, 16 cm aperture
- Nb3Sn at 4, 11 T, 16 cm aperture
- HTS at 20 K, 14 T, 14 cm aperture

Experimental programme is now essential

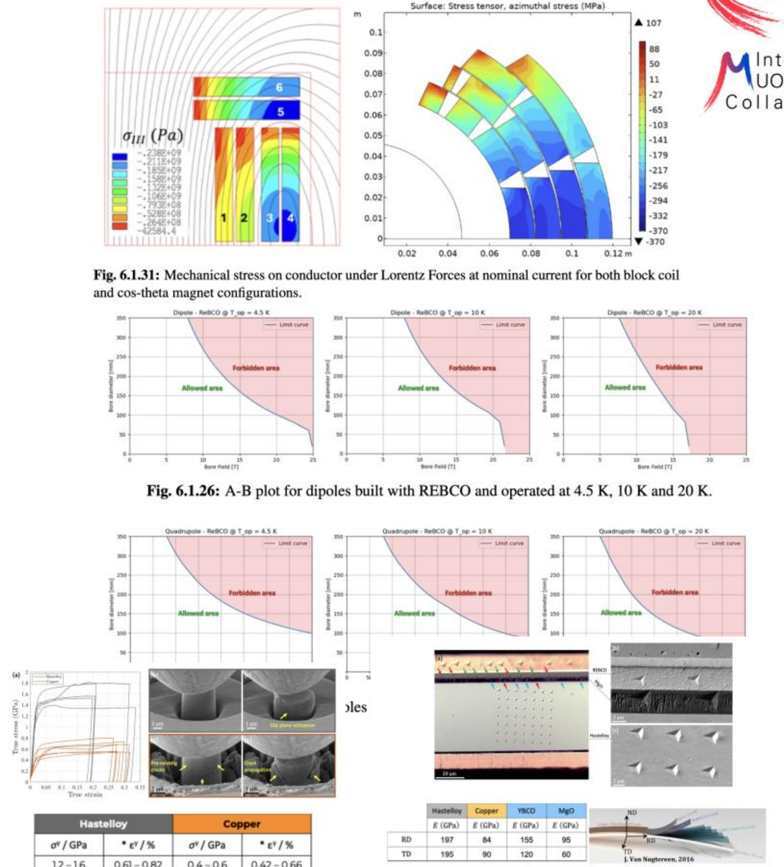


Fig. 6.1.31: Mechanical stress on conductor under Lorentz Forces at nominal current for both block coil and cos-theta magnet configurations.

Fig. 6.1.26: A-B plot for dipoles built with REBCO and operated at 4.5 K, 10 K and 20 K.

| Hastelloy | | Copper | |
|---|---|---|---|
| $\sigma^Y$ / GPa | * $\varepsilon^Y$ / % | $\sigma^Y$ / GPa | * $\varepsilon^Y$ / % |
| 1.2 – 1.6 | 0.61 – 0.82 | 0.4 – 0.6 | 0.42 – 0.66 |

Fig. 6.1.10: (a) True stress-strain curves of Hastelloy and copper layers obtained by micropillar compression. (b)-(c) SEM images of a representative Hastelloy pillar before and after compression, respectively. (d)-(e) SEM images of a representative copper pillar before and after compression, respectively. The measured values are summarized in the table.

| | Hastelloy | Copper | YBCO | MgO |
|---|---|---|---|---|
| | E (GPa) | E (GPa) | E (GPa) | E (GPa) |
| RD | 197 | 84 | 155 | 95 |
| TD | 195 | 90 | 120 | 60 |

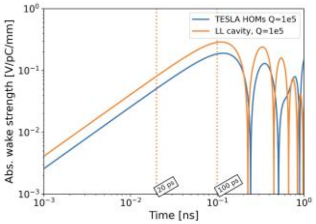
Fig. 6.1.9: (a) Optical image of the residual indentation imprints in the Hastelloy, copper, MgO (blue arrows) and REBCO (green arrows) layers. Red arrows indicate tests rejected due to being too close to other layers because of poor targeting. (b) SEM images of the residual indentation imprints in the REBCO and MgO layers. (c) SEM images of the residual indentation imprints in the Hastelloy layer. The measured values are summarized in the table.

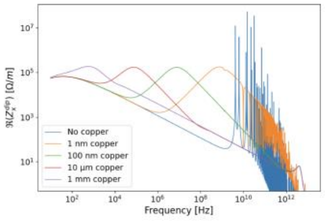
# Collective Effects (ACC)

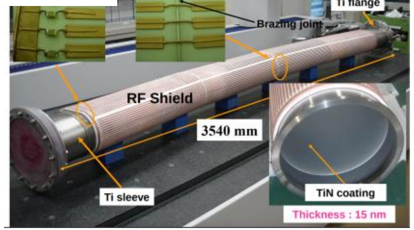
**Goal:**
Identify collective effects intensity bottlenecks

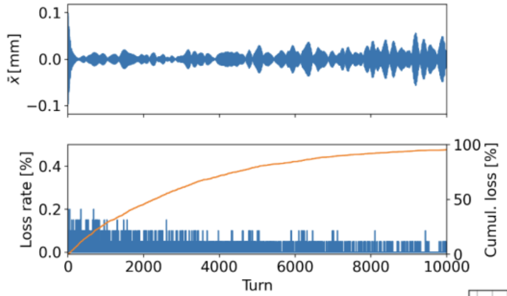
**Achieved:**
Impedances (beam screen and cavities) assessed for RCSs and collider ring
Counterrotating beam impedance studied
Key bottlenecks identified

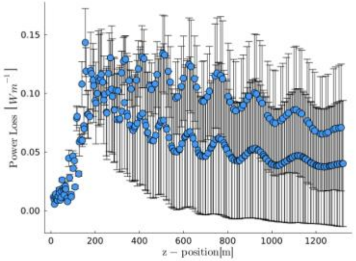
**Key conclusions:**
Impedances in high-energy complex can be taken care of by design
Beam-beam can be handled by 20 turn feedback
Resistive wall in muon cooling is OK
Identified that detailed studies and optimization is required for beam loading, longitudinal and transverse space charge in 6D cooling
Impedance of cooling absorbers require detailed study



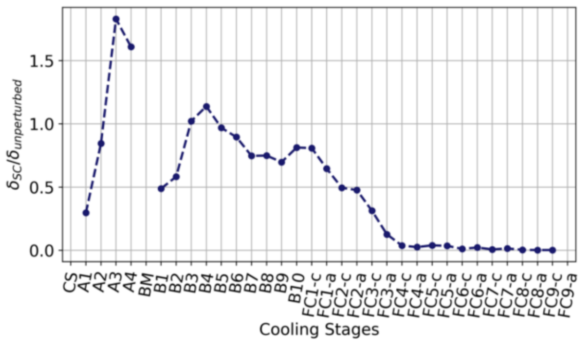








Chamber radius to keep emittance

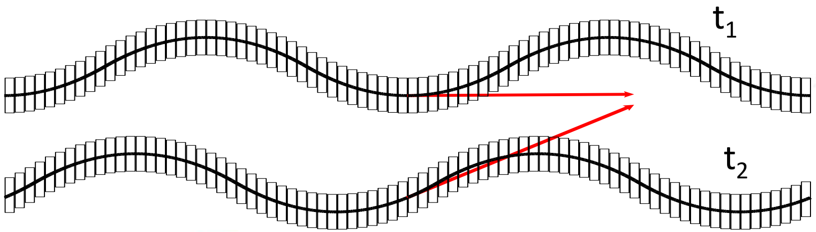


# Site (SITE/NF/INT)

**Goal:**
Assess wether collider ring can be implemented at CERN or elsewhere, in particular regarding neutrino flux

**Achieved:**
Developed RP tools with FLUKA
Develop CV placement tool
Specifications for mechanical mover system against dense neutrino flux
Identified first site and orientation of ring to retire risk from experimental insertion neutrino flux

**Key conclusions**:
Experimental straights are OK if we can get two sites on a downhill slope in the Jura
Neutrino flux from arcs is very likely negligible for 3 TeV
Can be approved for higher energies, more work needed to make it negligible



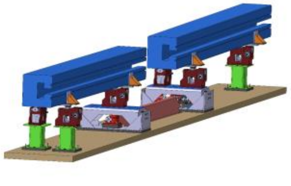


Fig. 7.23: Mock-up of the proposed magnet movement system.

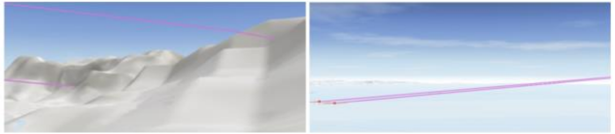
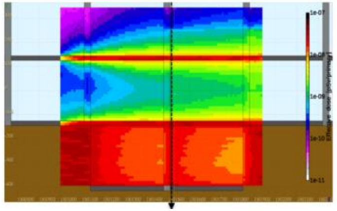
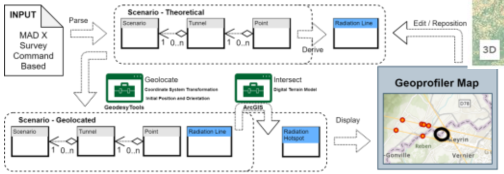


Fig. 6.11.5: 3D visualization of the exit points in the mountainous non-built area (left) and the sea (right) of the potential collider placement option in the local CERN area.





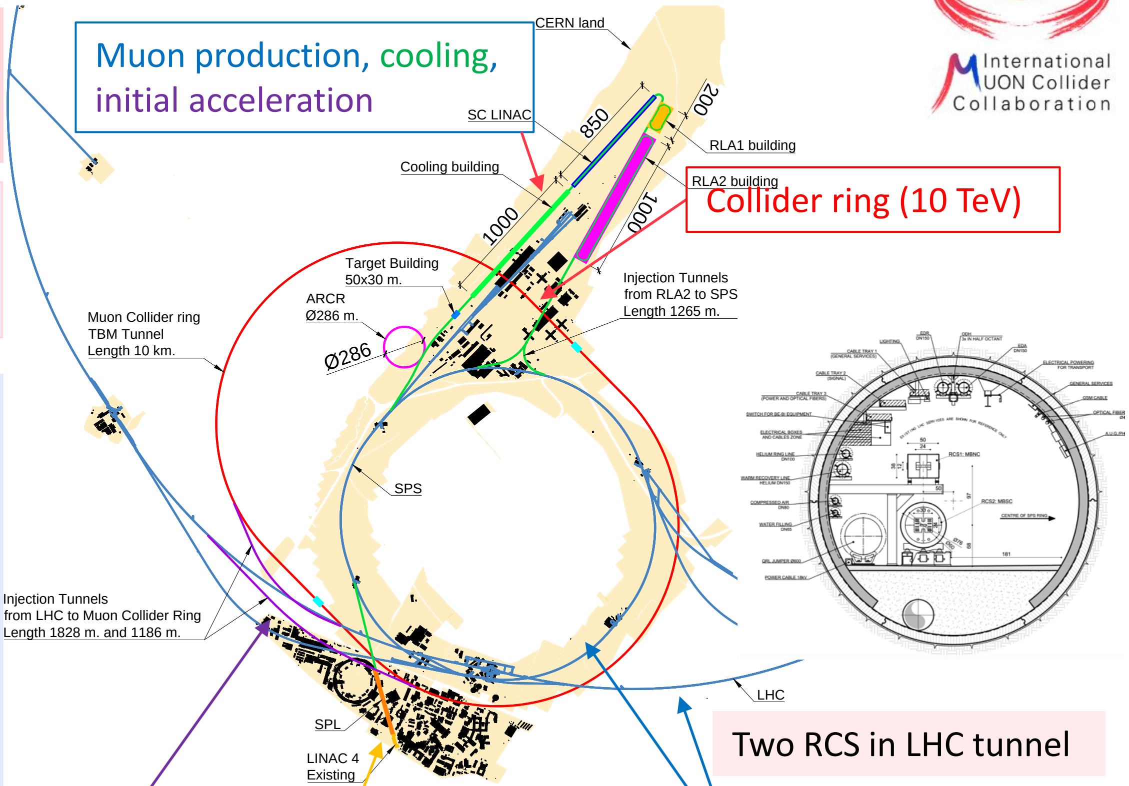
# Site (SITE/INT)

**Goal:**
Assess wether collider could be implemented at CERN

**Achieved:**
Tentative assessment of parameters and layout using SPS and LHC tunnels

**Key conclusions**:
Collider ring could be connected to LHC
Potential RCSs (tentative):
- SPS-1 (normal conducting) normal RCS
- LHC-1 1.6 TeV, normal RCS
- LHC-2 3.8 TeV, hybrid RCS

LHC tunnel should be large enough
Construction almost exclusively on CERN land
**Detailed study required!**



Muon production, cooling, initial acceleration

Collider ring (10 TeV)

Two RCS in LHC tunnel

Injector similar to SPL

SPS and LHC used for RCSs

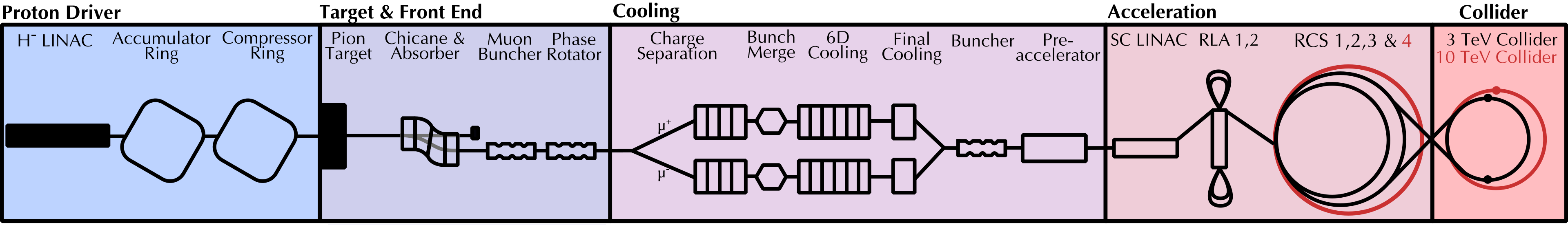
Transferline maximum slope 6%

# Summary

To be done …

# For Reference: Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is τ = γ x 2.2 μs (e.g. average 3100 turns in collider ring)



Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

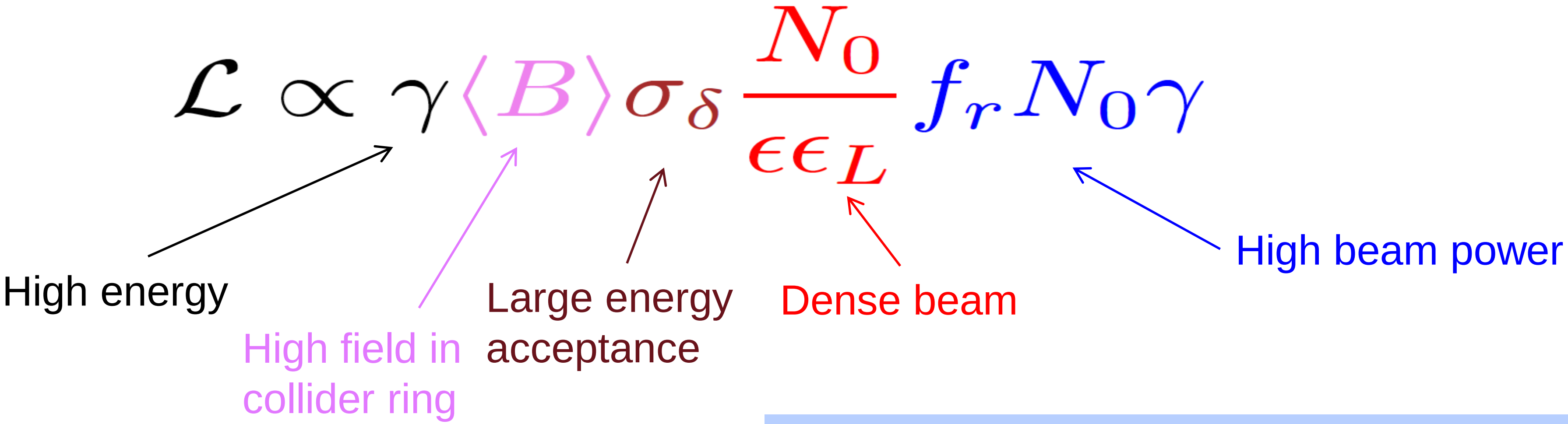
Acceleration to collision energy

Collision

# Risks, Energy

| Risk | Impact | Comment | Mitigation |
|---|---|---|---|
| Fast-ramping dipoles do not reach field | Energy | Protoype will verify value | Larger RCS, if tunnel is not fixed |
| Static RCS dipoles do not reach field | Energy | Protoype will verify value | Larger RCS, if tunnel is not fiexed |
| Collider ring dipoles cannot reach field | Energy | Protoype will verify value | Larger collider ring if tunnel is not fixed |

# Risks, Luminosity



$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

Luminosity per power increases with energy
Provided technologies can be made available

Constant current for required luminosity scaling

# Risks, Luminosity (Emittances)

| Risk | Impact | Comment | Mitigation |
|---|---|---|---|
| Muon 6D cooling cell does not reach specifications | Luminosity (emittance) | | Demonstrate integrated module with specified performance<br>Redesign lattice to optimise muon number/emittance trade-off |
| Muon final cooling solenoids do not achieve field | Luminosity (emittance) | Expect solenoids to reach field | Demonstrate solenoid<br>Redesign lattice to optimise muon number/emittance trade-off (last cells suffer more than initial cells from weaker solenoid) |
| Muon cooling lattice cannot be improved | Luminosity (emittance) | Emittances are close to the target values (30% in longitudinal, 10-20% in transverse) | Increase solenoid strength if possible |
| Emittance growth above target | Luminosity (emittance) | Initial studies did not show strong effects | Improve tuning, reduce imperfections |
| Collider ring dipoles cannot reach field | Before construction: reduced luminosity;<br>Otherwise reduced energy | Protoype should establish exact number | Larger collider ring |
| Collider ring lattice energy acceptance cannot be improved | Luminosity (energy spread) | Aim require a factor 2-3 improvement; | Reduced energy spread along the chain and increased collider ring bunchlength and IP betafunction. |

# Risks, Luminosity (Muon Number)

| Risk | Impact | Comment | Mitigation |
|---|---|---|---|
| Proton beam intensity cannot be reached | Luminosity (Reduced muon number) | Studies look promising | Higher proton energy, improved design, combination of beams |
| Target solenoid field cannot be achieved | Luminosity (reduced muon number) | Loss would in the 20% range for 15 T | Higher power target |
| Spent beam cannot be extracted sufficiently | Luminosity (reduced muon number) | | Reduce target power, redesign target for lower losses |
| Muon transmission not sufficient | Luminosity (reduced muon number) | Muon capture efficiency, lower 6D cooling cell gradient, slower magnets ramps, injection/extraction losses; unlikely to reduce muon number by more than O(10%) | Higher power target; design of muon capture; improvement of transmission in other systems to compensate |
| Collective effects limit muon number | Luminosity (reduced muon number) | Full study required, mainly a concern for the muon cooling (beam loading, absorbers) | Increased aperture, reduced impedances, stabilisation methods, … |
| Density limit of absorbers | Luminosity (reduced muon number) | Use of H2 gas to reduce pressure rise<br>Need to verify windows experimentally | |
| Neutrino flux too high | Luminosity (reduced repetition rate) | Studies indicate that close to OK for collider ring, need to further detail and inclusion of RCSs and transfer lines | Larger mover range, improved collider ring positioning, larger bunch charge, work with authorities |

# Key Power Drivers

| **Risk** | **Impact** | **Comment** | **Improvement potential** |
|---|---|---|---|
| Proton complex | Power | Detailed estimate based on other linacs available | |
| Target | Power | Power loss in the solenoid is known and acceptable | |
| Muon cooling cells | Power | RF power estimate exists; may need extra power to compensate beam loading | Efficient klystrons; consider other cavitiy technologies |
| Initial linacs RF | Power | Estimate for last linac exists | Reduce injection energy for first RCS<br>Optimise design for cost |
| Fast-ramping RCS magnet systems | Power | Estimates exist | |
| Static superconducting RCS magnets | Power | Estimate exists<br>Upper estimate for beam loss exists | Design collimation/protection system<br>Design shower absorber system |
| RCS RF | Power | Estimate exists<br>Upper estimate for beam loss exists | Design collimation/protection system<br>Design shower absorber system |
| Collider ring magnets | Power | Estimate exists | |

# Risks, Cost

| Risk | Impact | Comment | Mitigation |
|---|---|---|---|
| Proton complex | Cost | Well known based on other linacs | |
| Muon cooling cells | Cost | Need dedicated effort for cost reduction | Demonstration of module reaching performance specifications<br>Cost optimisation including beam dynamics |
| Initial linacs RF | Cost | | Reduce injection energy for first RCS<br>Optimise design for cost |
| Fast-ramping RCS magnet systems | Cost | | Design, prototype |
| Static superconducting RCS magnets | Cost | | Design, prototype |
| RCS RF | Cost | | |
| Collider ring magnets | Cost | | |
| Implementation at CERN or other site | Cost | Civil engineering/re-use of infrastructure | Detailed study |

# Risks, Schedule

| Risk | Impact | Comment | Mitigation |
|---|---|---|---|
| R&D programme | Schedule | The investment into the R&D programme is key for the schedule<br>Technical problems could lengthen the R&D programme | Intense R&D programme with sufficient funding<br>Sufficient margin and R&D on alternatives can reduce this risk |
| Implementation at CERN or other site | Schedule | Civil engineering/re-use of infrastructure | Detailed study |
| Removel of components in existing infrastructure | Schedule | | |
| Civil engineering | Schedule | | |
| Production | Schedule | All components that are required in large numbers or have challenging specifications | Prototype/preseries development of the challenging components |
| Installation | Schedule | | |

# Staging (CERN-specific)

Expect to be ready for implementation in 15 years

- **Detector**
- **Muon cooling technology**
- **HTS solenoid technology**
- **NbTi or Nb3Sn collider ring magnets**

Likely need longer for

- HTS collider ring magnets
- Fast-ramping HTS RCS magnets

Aim for 3.2 TeV and later 10 TeV
Or 7.6 TeV in one step

| **Parameter** | **Unit** | **3 TeV (GF)** | **10 TeV (GF)** | **3.2 TeV (1)** | **7.6 TeV (2)** | **10 TeV (1)** |
|---|---|---|---|---|---|---|
| **L** | **$10^{34}$ cm$^{-2}$s$^{-1}$** | **1.8** | **18.75** | **0.74** | **7.9** | **18** |
| N | $10^{12}$ | 2.2 | 1.8 | 2.2 | 1.8 | 1.8 |
| $f_r$ | Hz | 5 | 5 | 5 | 5 | 5 |
| **$P_{beam}$** | **MW** | **5.3** | **14.4** | **5.3** | **11** | **14.4** |
| C | km | 4.5 | 10.7 | 11 | 11 | 11 |
| $B_{dipole}$ | T | 11 | 15 | 4.8 | 11 | 14.5 |
| Collider techn. | | Nb3Sn | HTS | NbTi | Nb3Sn | HTS |
| Last RCS techn. | | normal | normal | normal | normal | HTS |

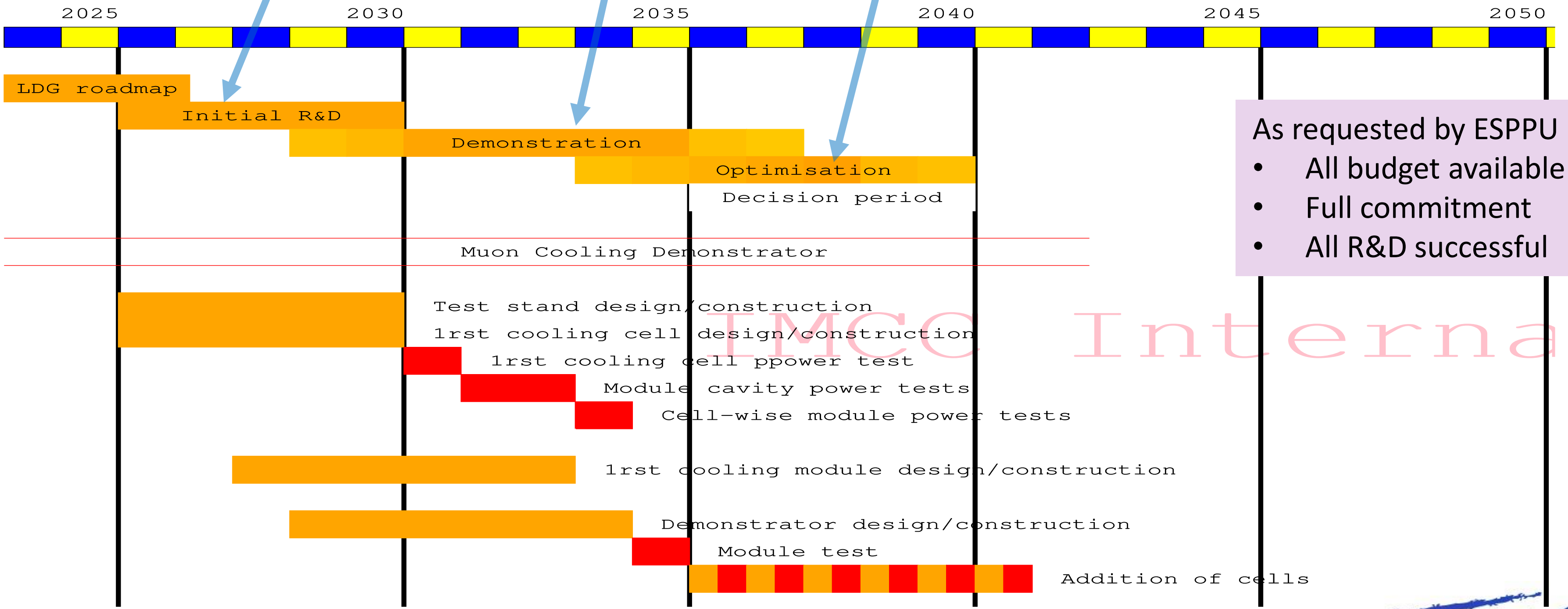
Take with a grain of salt, this is to motivate the studies

# Technically Limited Timeline for Development Phase

Initial programme to keep potential for ambitious starting point

R&D required to prepare approval and launch of project

Decision process and further optimization/project preparation



As requested by ESPPU
- All budget available
- Full commitment
- All R&D successful

# RF Technology

- A concept for the normal-conducting accelerating cavities of the muon cooling complex, in particular choices for the frequencies and shapes along the cooling chain. These have to balance beam loading effects and RF power requirements. Initially, they would be based on the two cavities that have been tested in the past. (MIN)
- A concept for the longitudinal beam dynamics and the RF systems in the high-energy muon beam acceleration complex, which uses superconducting cavities. The very high bunch charge and short bunch length require mitigation of single bunch beamloading effects. The RF has to be synchronised with the fast-ramping magnet system with due consideration of the lattice limitations. The study will link to measurements of the achievable gradients in superconducting cavities within the RF R&D Programme and world-wide. (MIN)

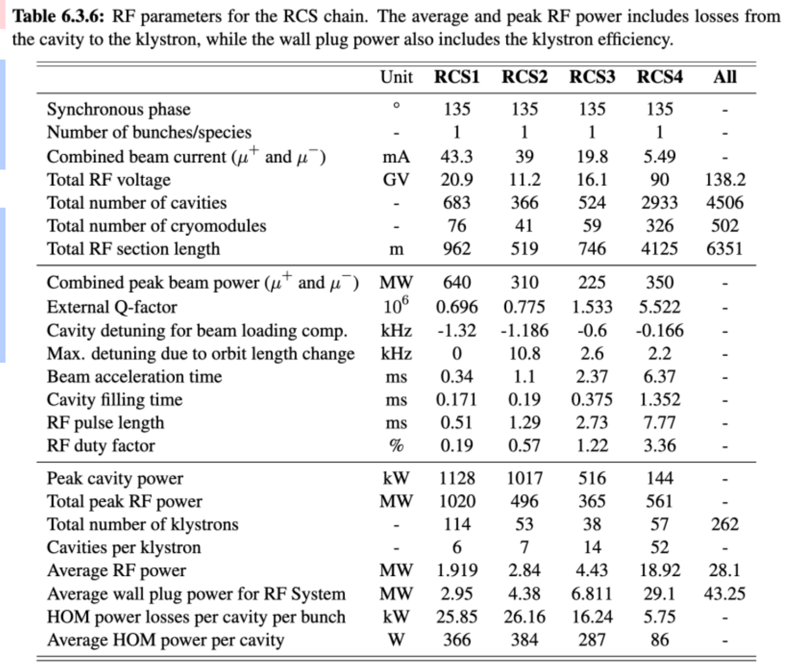
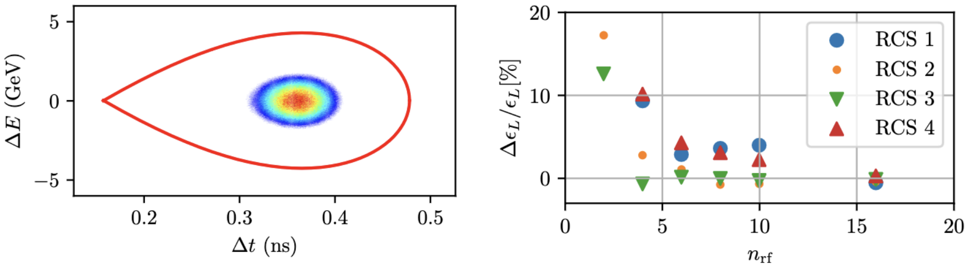


**Table 6.3.6:** RF parameters for the RCS chain. The average and peak RF power includes losses from the cavity to the klystron, while the wall plug power also includes the klystron efficiency.

| | Unit | RCS1 | RCS2 | RCS3 | RCS4 | All |
|---|---|---|---|---|---|---|
| Synchronous phase | ° | 135 | 135 | 135 | 135 | - |
| Number of bunches/species | - | 1 | 1 | 1 | 1 | - |
| Combined beam current ($\mu^+$ and $\mu^-$) | mA | 43.3 | 39 | 19.8 | 5.49 | - |
| Total RF voltage | GV | 20.9 | 11.2 | 16.1 | 90 | 138.2 |
| Total number of cavities | - | 683 | 366 | 524 | 2933 | 4506 |
| Total number of cryomodules | - | 76 | 41 | 59 | 326 | 502 |
| Total RF section length | m | 962 | 519 | 746 | 4125 | 6351 |
| Combined peak beam power ($\mu^+$ and $\mu^-$) | MW | 640 | 310 | 225 | 350 | - |
| External Q-factor | $10^6$ | 0.696 | 0.775 | 1.533 | 5.522 | - |
| Cavity detuning for beam loading comp. | kHz | -1.32 | -1.186 | -0.6 | -0.166 | - |
| Max. detuning due to orbit length change | kHz | 0 | 10.8 | 2.6 | 2.2 | - |
| Beam acceleration time | ms | 0.34 | 1.1 | 2.37 | 6.37 | - |
| Cavity filling time | ms | 0.171 | 0.19 | 0.375 | 1.352 | - |
| RF pulse length | ms | 0.51 | 1.29 | 2.73 | 7.77 | - |
| RF duty factor | % | 0.19 | 0.57 | 1.22 | 3.36 | - |
| Peak cavity power | kW | 1128 | 1017 | 516 | 144 | - |
| Total peak RF power | MW | 1020 | 496 | 365 | 561 | - |
| Total number of klystrons | - | 114 | 53 | 38 | 57 | 262 |
| Cavities per klystron | - | 6 | 7 | 14 | 52 | - |
| Average RF power | MW | 1.919 | 2.84 | 4.43 | 18.92 | 28.1 |
| Average wall plug power for RF System | MW | 2.95 | 4.38 | 6.811 | 29.1 | 43.25 |
| HOM power losses per cavity per bunch | kW | 25.85 | 26.16 | 16.24 | 5.75 | - |
| Average HOM power per cavity | W | 366 | 384 | 287 | 86 | - |

and an initial cavity design concept exists. Beam loading studies need
/ design.

RCSs have been performed and indicate that 1.3 GHz cavities could
fast-ramping magnets has been studied. The integration of the RCS



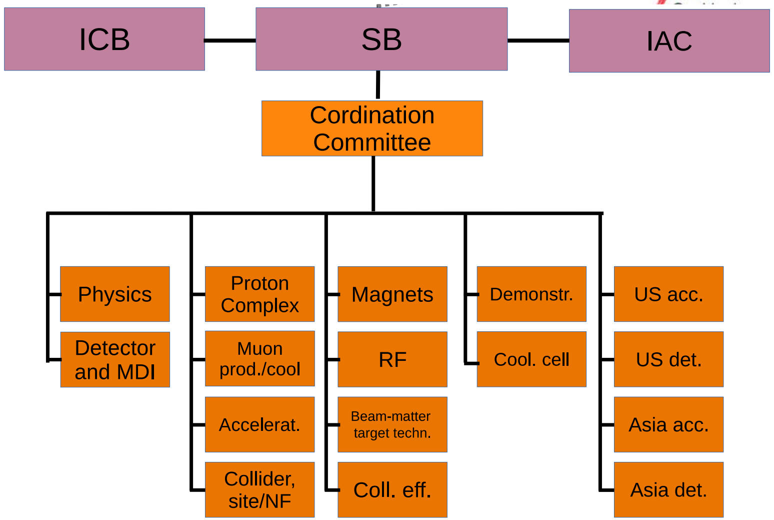
# For Reference: Organisation

IMCC, International Muon Collider Collaboration
- Can be joined by signing MoC
- Currently hosted at CERN, but can be modified

Resources
- Voluntary contributions of the partners
- The European Union via MuCol and iFast
- Non-member contributions

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

- Addendum to CERN-DoE agreement in preparation
  - Actually, collaboration is already starting in practice
  - Will revise organization once US is fully joining



ICB

SB

IAC

Cordination Committee

Physics

Detector and MDI

Proton Complex

Muon prod./cool

Accelerat.

Collider, site/NF

Magnets

RF

Beam-matter target techn.

Coll. eff.

Demonstr.

Cool. cell

US acc.

US det.

Asia acc.

Asia det.

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

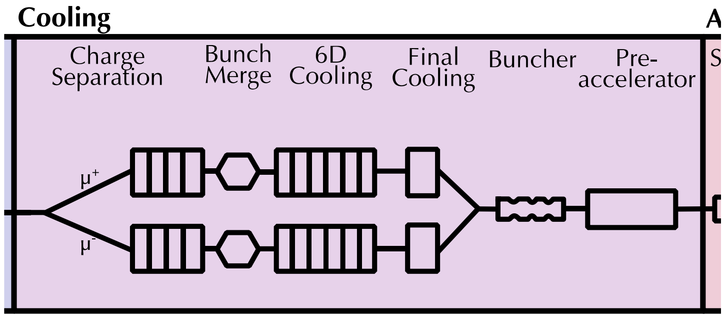
**Coordination committee (CC)**
- Study Leader: **Daniel Schulte**
- Deputies: **Andrea Wulzer, Donatella Lucchesi, Chris Rogers**

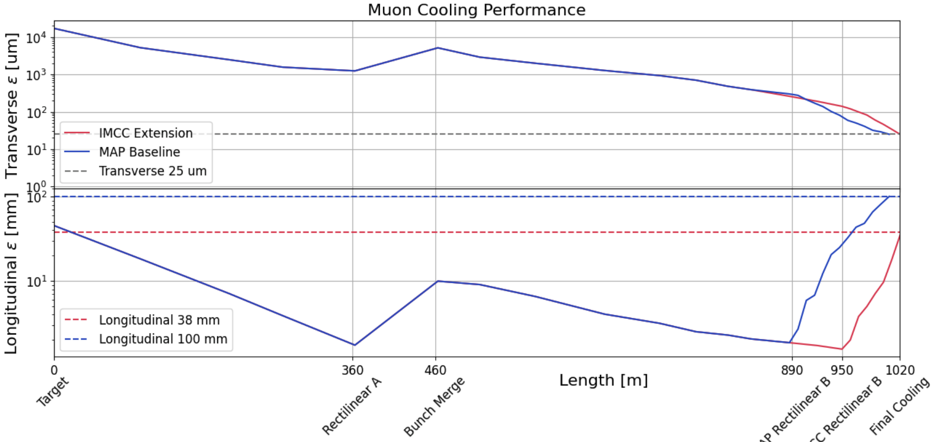
# Final Muon Cooling (ACC)

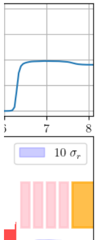
**Goal:**
Improve the final muon cooling design

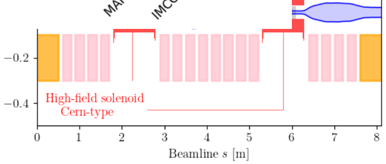
**Achieved:**
Two improved final cooling lattices have been developed
- One is conservative, fully taking hardware into account
- One focuses on overall optimisation

**Key conclusions:**
Factor two better than MAP, almost reaching the target
Identified muon beam density in absorber as a critical issue, solved by using gas
Need to include collective effects









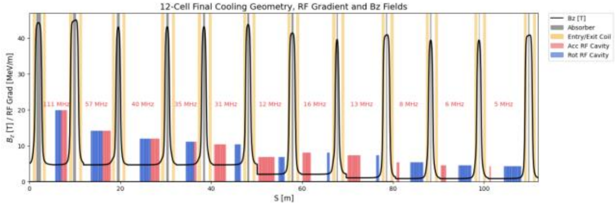
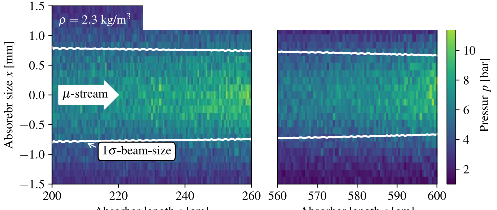


**Fig. 5.2.5:** Final cooling lattice diagram from Rectilinear Stage B8



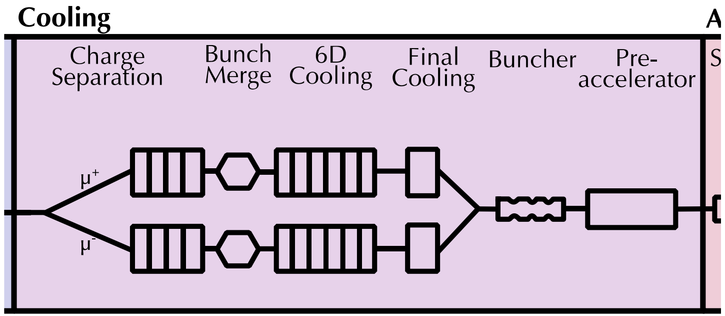
# Muon Cooling (ACC)

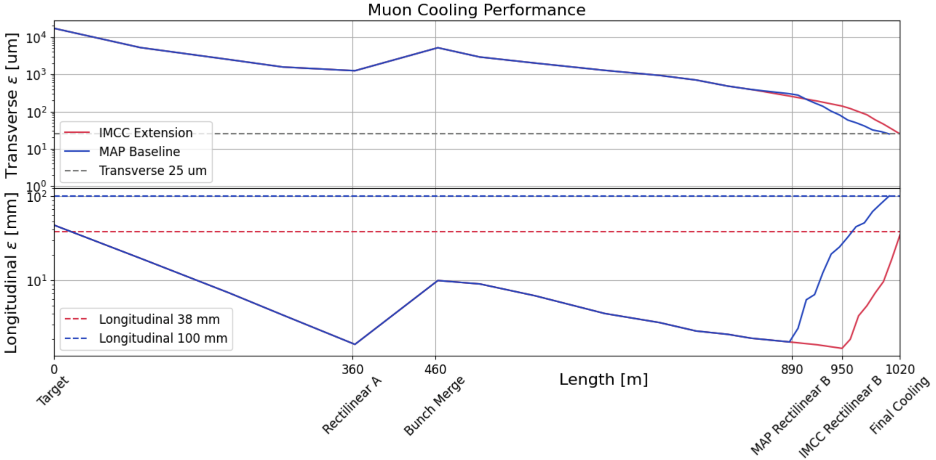
**Goal:**
Improve the final muon cooling design

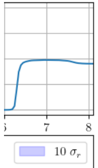
**Achieved:**
Two improved final cooling lattices have been developed

- One is conservative, fully taking hardware into account
- One focuses on overall optimisation

**Key conclusions:**
Factor two better than MAP, almost reaching the target
Identified muon beam density in absorber as a critical issue, solved by using gas
Need to include collective effects







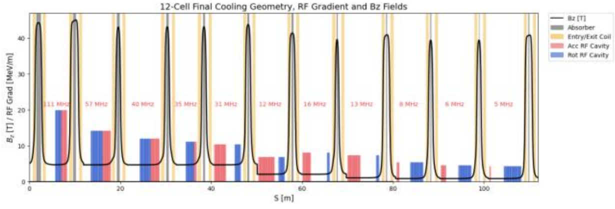


**Fig. 5.2.5:** Final cooling lattice diagram from Rectilinear Stage B8