CHART
Swiss Accelerator Research and Technology

CHART Scientific Report

Muon Collider Feasibility Studies: Collective effects and muon cooling

(**Muon Colliders Feasibility Studies**)

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1. Introduction / Original goals of this project

Muon colliders have emerged as one of the most promising concepts for advancing the energy frontier in particle physics. Their ability to accelerate point-like particles to multi-TeV energies in circular machines—without the severe synchrotron-radiation limitations faced by electrons—offers the potential for unprecedented precision measurements and discovery reach. Within the framework of the International Muon Collider Collaboration (IMCC), a 10 TeV centre-of-mass muon collider is currently being developed as a long-term facility for next-generation high-energy physics.

Reaching the luminosity targets required for such a collider relies on the production and preservation of two intense, low-emittance μ^+ and μ^- bunches. The machine complex includes a high-power proton driver, a target and capture system producing pions which decay into muons, a 6D ionization-cooling channel that reduces the beam emittance by nearly three orders of magnitude, and a rapid acceleration chain composed of Recirculating Linacs (RLAs) and Rapid Cycling Synchrotrons (RCSs). The beams are then injected into a 10 TeV collider ring operating at a repetition rate of 5 Hz.

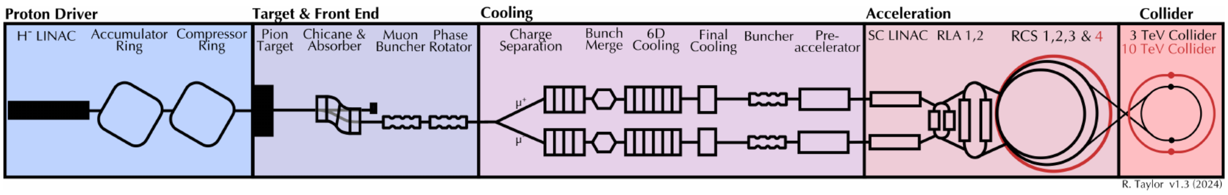

Figure 1: Layout of the Muon Collider facility

These demanding performance requirements push the bunch intensities into the range of 10^{12}–10^{13} muons, where several collective effects become potentially limiting. Impedance-driven instabilities, direct space-charge forces, beam break-up and head–tail modes, beam–beam interactions between the counter-rotating muon beams, and wakefields generated inside absorber materials during ionization cooling all have the potential to degrade emittance, induce beam loss, or restrict the achievable luminosity. Understanding, modelling, and mitigating these effects is therefore a central requirement for establishing the feasibility of the muon collider concept.

In this context, the objectives of the present project were defined as follows. First, to develop realistic impedance and wakefield models for all major accelerator subsystems, including the RCS chain and the collider ring. Second, to analyse collective instabilities arising both during ionization cooling and throughout the acceleration process. Third, to extend and develop multi-stage tracking tools capable of impedance-aware simulations across the full machine complex. Fourth, to study and propose mitigation strategies such as chromaticity correction, transverse damping, and optimised vacuum-chamber designs. Fifth, to carry out initial beam–beam studies for the 10 TeV collider ring. Sixth, to compare analytical approaches for modelling direct space-charge forces in the proton driver and to identify reliable formulations for design studies. Finally, the project aimed to provide design-relevant results and modelling capabilities that contribute directly to the IMCC baseline concept and to the broader assessment of muon-collider feasibility.

2. Realisation

The project addressed the above goals through a coordinated programme of analytical studies, numerical modelling, and simulation-tool development.

Acceleration Chain and Collider Ring

- Comprehensive impedance models were developed for the four-stage RCS system and the 10 TeV collider ring, covering RF cavities, resistive-wall effects, and complex vacuum-chamber geometries.
- Multi-stage particle-tracking tools were implemented to simulate beam evolution from the start of the acceleration chain through four consecutive machines.

Cooling Channel and Wakefield Effects

- Wakefield models were extended to include electromagnetic fields generated inside matter such as absorbers and gas-filled RF structures used in ionization cooling.
- New models describing ionization-induced charge production, recombination, motion in magnetic fields, and interaction with the beam were incorporated.

Mitigation and Design Support

- Stability-enhancement techniques (e.g., sextupoles, dampers) were evaluated and integrated into the RCS design.
- RCS vacuum-chamber design was refined through impedance and eddy-current analysis, supporting the adoption of a ceramic chamber with metallic stripes.

Tool Development and Collaboration

- A dedicated RCS-parameter optimisation package was developed in collaboration with RF, powering, and optics teams.
- All impedance and beam-dynamics tools are now available to the IMCC community via CERN GitLab.

The outcomes provide both a theoretical foundation and practical tools supporting the IMCC baseline design effort.

3. Results / Conclusions / Deliverables

The project delivered a broad set of technical results, analytical advances, and software tools that collectively strengthen the beam-dynamics foundations required for a future multi-TeV muon collider. A complete set of impedance and wakefield models was produced for the four-stage RCS acceleration chain and for the 10 TeV collider ring. These models quantify the influence of RF cavities, resistive-wall effects, and vacuum-chamber geometry on transverse coherent stability, and they guided several key design decisions in the IMCC, including the RF-cavity layout and the choice of vacuum-chamber materials and geometries. All impedance models and simulation tools are publicly accessible through the repository at https://gitlab.cern.ch/muon-collider-bd/muc-impedance.

Stability studies showed that sextupoles providing chromaticity control and a transverse feedback damper both play an essential role in stabilising RCS beams under strong wakefield forces. The work also supported the selection of a ceramic vacuum chamber with metallic stripes for the RCS, which reduces both eddy-current heating and transverse impedance during fast magnetic cycling. Complementing these studies, new simulation capabilities were developed to describe electromagnetic wakefields generated inside matter, including absorbers and gas-filled RF cavities used during ionization cooling. These extensions enabled the first detailed exploration of collective effects unique to cooling channels, where dense materials, moderate relativistic velocities, and extremely high bunch charges must be considered together.

A major scientific achievement of this project is the derivation of analytic expressions for the beam-coupling impedance of a relativistic point charge travelling inside a cylindrical multilayer beam pipe where the beam passage region is filled with an arbitrary linear, homogeneous, and isotropic medium. This work generalises the classical field-matching formalism developed by Mounet, Zotter, and Burov & Lebedev by retaining the full complex permittivity and permeability of the material throughout the derivation. By expanding the electromagnetic fields in azimuthal harmonics, expressing their radial dependence in terms of modified Bessel functions, and applying field-matching conditions at the source radius and at each cylindrical interface, closed-form expressions were obtained for both longitudinal and transverse impedances. The usual vacuum results are recovered when the product of the material permittivity and permeability approaches unity. This extended formalism is especially relevant to muon ionization cooling, where muons travel at $\beta \approx 0.6$–0.9 through dense absorber materials such as liquid hydrogen or lithium hydride. Under these conditions, material properties strongly affect space-charge forces, and the new model provides, for the first time, impedance predictions that include these medium effects. Applications to realistic ionization-cooling parameters demonstrated that the method captures space-charge and wall contributions under conditions that cannot be treated using vacuum-based impedance formulas. This work will be published in a dedicated article.

In parallel, first beam–beam simulations for the 10 TeV collider ring were performed, establishing initial expectations for beam–beam tune shifts, luminosity reach, and sensitivity to key parameters. The acceleration chain design also benefited from the development of a

Python-based RCS optimisation tool, created in collaboration with the RF, powering, and optics teams. This tool allows automated exploration of RF voltage profiles, ramp rates, optics functions, and magnet powering. It is available at https://gitlab.cern.ch/muon-collider-bd/rcsparameters, with a web interface at https://rcsparameters.web.cern.ch.

For the proton driver, a detailed benchmarking study compared several analytical approaches for estimating transverse coherent direct space charge. This work clarified the regimes of validity of each method and identified key differences relevant to the proton-driver design. The results were published in D. Amorim et al., "Transverse coherent direct space charge: comparison between several approaches", IPAC 2025, and were presented at the MuCol Proton Complex Meeting.

Finally, new multi-stage tracking tools were developed at CERN, enabling impedance-aware simulations from the end of the cooling channel through the full acceleration chain and up to collider-ring injection. These tools are now being integrated into IMCC workflows and support consistent, end-to-end modelling of collective effects across the entire machine complex.

Taken together, these results provide crucial modelling capabilities, validated theoretical methods, and practical simulation tools that directly support the design, optimisation, and feasibility assessment of a multi-TeV muon collider. They now form part of the technical foundation used across the IMCC for decisions related to cooling, acceleration, and collider-ring performance.

4. Publications and Outreach

Peer-Reviewed / Conference Publications

- D. Amorim et al., *"Transverse coherent direct space charge: comparison between several approaches"*, Proceedings of IPAC 2025.
- Accettura, Carlotta, et al. "The Muon Collider." No journal information, Apr. 2025. https://doi.org/10.48550/arXiv.2504.21417
- Accettura, C., Adrian, S., Agarwal, R., Ahdida, C., Aime', C., Aksoy, A., Alberghi, G. L., Alden, S., Alfonso, L., Ali, M., Altamura, A. R., Amapane, N., Amm, K., Amorim, D., Andreetto, P., Anulli, F., Bella, L. A., Appleby, R., Apresyan, A., ... Zurita, J. F. (2025). The Muon Collider - Supplementary report to the European Strategy for Particle Physics - 2026 update.
- Amorim D., Batsch F., Carli, C., Chance, A., Damerau H., Kvikne E., Métral E., Pieloni T., Schulte D., PoS10.22323/1.476.0838 838 ICHEP2024 2025 2025

Presentations and Internal Outreach

- Presentation at the **MuCol Proton Complex Meeting**, covering space-charge modelling and implications for proton-driver design.
- Contributions to IMCC beam-dynamics working-group meetings and design-study reviews.

Open-Source Tools and Repositories

- Impedance models and simulations: gitlab.cern.ch/muon-collider-bd/muc-impedance

- RCS parameter optimization package: gitlab.cern.ch/muon-collider-bd/rcsparameters
- RCS optimisation web tool: rcsparameters.web.cern.ch

More detailed scientific reports are published at https://chart.ch/reports/