Muon collider Feasibility Studies: Collective effects and muon cooling

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1. Introduction

The International Muon Collider Collaboration was started in 2021 to study a potential muon/anti-muon collider with a center-of-mass energy of 10 TeV. A 3 TeV center-of-mass collider is also planned as an intermediate step.

Generating high-intensity, low-emittance muon beams able to reach the luminosity targets would require a chain of new dedicated accelerators, as shown in Fig. 1.
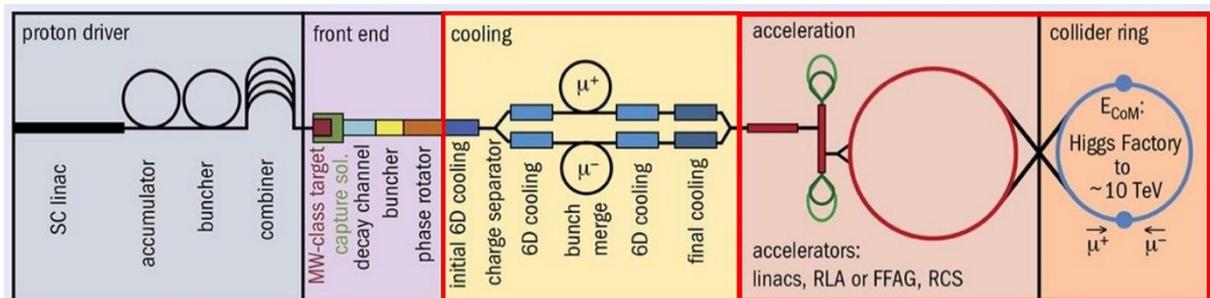

Figure 1: Proposed layout for a muon collider complex. Collective effects are investigated in the parts highlighted in red.

Collective effects are a major concern in the different stages of the muon collider complex. This project focuses in particular on two parts of the complex represented in Fig. 1. During the process of ionization cooling, the high-intensity muon beams will generate wakefields in the absorbers that could disrupt the bunch and lead to unwanted losses. In the acceleration chain, which comprises two recirculation linacs (RLAs) and four rapid cycling synchrotrons (RCS) to reach 5 TeV, the many RF cavities required to provide the large acceleration gradients will generate strong resonant wakefields that could create emittance growth or beam losses. In the collider ring, the beam chamber radius must be as small as possible to reach a high dipole field. This will create strong resistive-wall impedance that must be either mitigated by low resistivity materials or stabilization mechanisms such as chromaticity or a transverse feedback.

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2. Research Goal

This project focuses on addressing collective effects and instabilities in the development of a future muon collider. One major goal is to develop a realistic impedance model of the machine, primarily centered on the RF cavities and resistive-wall impedance, to ensure the preservation of longitudinal and transverse emittances necessary for achieving the desired collider luminosity and stable beam orbits. Managing the interaction of two high-charge muon bunches with opposite signs, while ensuring fast acceleration via the RF cavities, is critical. The unique conditions at beam-beam collision points and the influence of wake fields from distributed RF cavities in the ring will also be analyzed to understand their impact on beam stability and overall collider operation.

In parallel, the project aims to study collective effects and limitations within the muon cooling system. This includes developing models to describe electromagnetic wake fields generated by beams passing through matter and analyzing the dynamics of ionization-induced charges, their interactions with external magnetic fields, and the beam. Special attention will be given to identifying potential instabilities during ionization cooling, with comparisons made between different cooling concepts using existing computational tools. New numerical methods may also be developed to enhance the performance evaluation of the cooling systems.

3. Results

Start-to-end simulations in the Rapid Cycling Synchrotrons

Using [XSuite](), start-to-end simulations were developed for the RCS chain. For the 3 TeV collider stage, three RCS are needed, with varying parameters: for example, the acceleration in the first RCS is performed in 0.34 ms with 700 TESLA type RF cavities, whereas acceleration in the third RCS takes 2.4 ms and requires 540 cavities. Tracking simulations allow to check that the beam transmission is optimal between each stage, checking for example the RF bucket matching between machines.
The effect of the wake fields generated by High-Order Modes (HOMs) of the RF cavities was also included in the simulations by linking XSuite with [PyHEADTAIL](). A range of parameters can be scanned such as the chromaticity, the damper location and strength or the impedance model used. The effect of an initial transverse offset in each ring can also be modelled, to ensure that the beam remains stable even when injection errors occur.

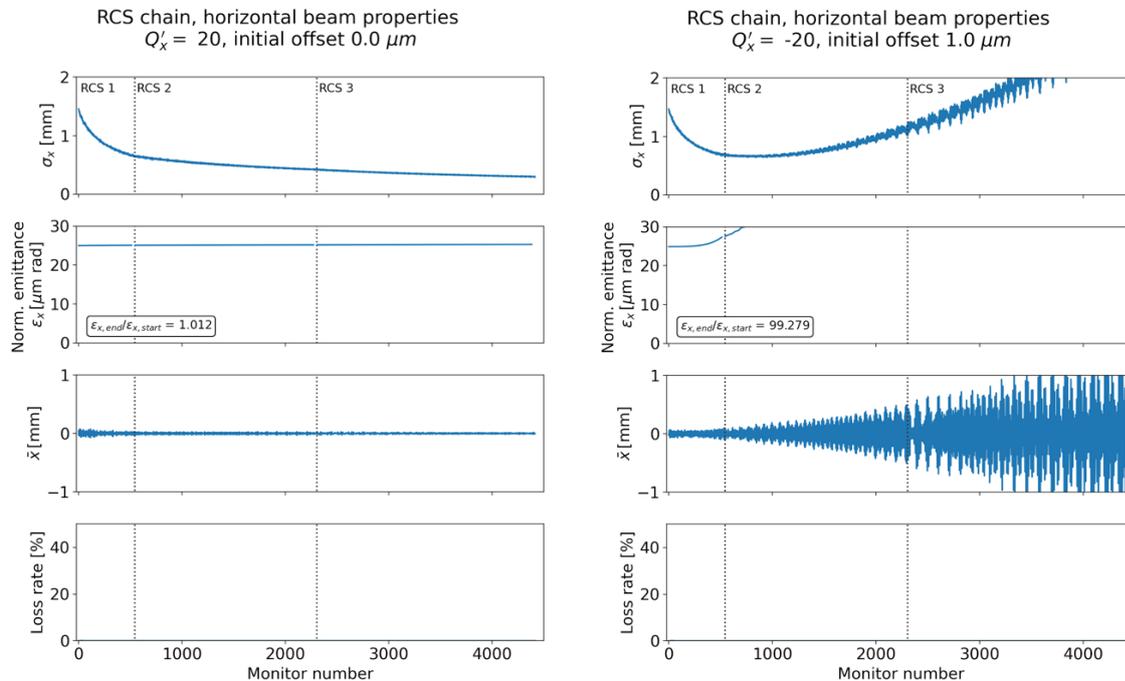# CHART Scientific Report (Final Report for Phase 2)

Figure 2: example of transverse beam stability simulations with collective effects performed with XSuite+PyHEADTAIL. The plots show the beam properties evolution over the three RCS (transverse size, horizontal emittance, centroid position, particle loss rate). Left image shows a stable configuration (positive chromaticity and transverse feedback activated), whereas the right image shows an unstable configuration (negative chromaticity, no transverse feedback, initial transverse beam offset).

This allows us to investigate the coherent beam stability limits and specify the mitigation measures needed. A positive chromaticity of at least Q'=15, together with a transverse feedback system with at least a 50-turn gain would be required to preserve transverse beam quality. The presence of a transverse feedback also allows to damp a transverse offset up to 100 um that could be created by beam injection errors and jitter.

Extension of the simulations to the fourth RCS, which would accelerate the muon beams from 3 TeV to 5 TeV, is underway now that the baseline parameters for the 5th RCS have been set.

Refinement of the collider impedance and coherent beam stability model

The transverse beam coupling impedance model for the 10 TeV collider has been updated based on the latest magnet design, incorporating a tungsten shield to protect the superconducting magnets from muon decay debris. To reduce resistive wall impedance, a copper coating is needed on the shield's inner surface. Simulations indicate that a 1 µm thick copper layer is sufficient to preserve beam stability with the large 23.5 mm inner radius for the planned muon intensity.

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Beam-beam effects were also studied using simulations, specifically looking at 4D horizontal and vertical interactions. Figure 3 shows simulations conducted with XSuite and PyHEADTAIL, where chromaticity was corrected to Q' = 0. The results show that at the nominal muon bunch intensity of 1.8e12, the beam is stable, both with and without beam-beam effects. However, when intensities exceed 2.0e12, instabilities may arise unless head-on beam-beam effects are included, which seem to stabilize the beam at higher intensities.
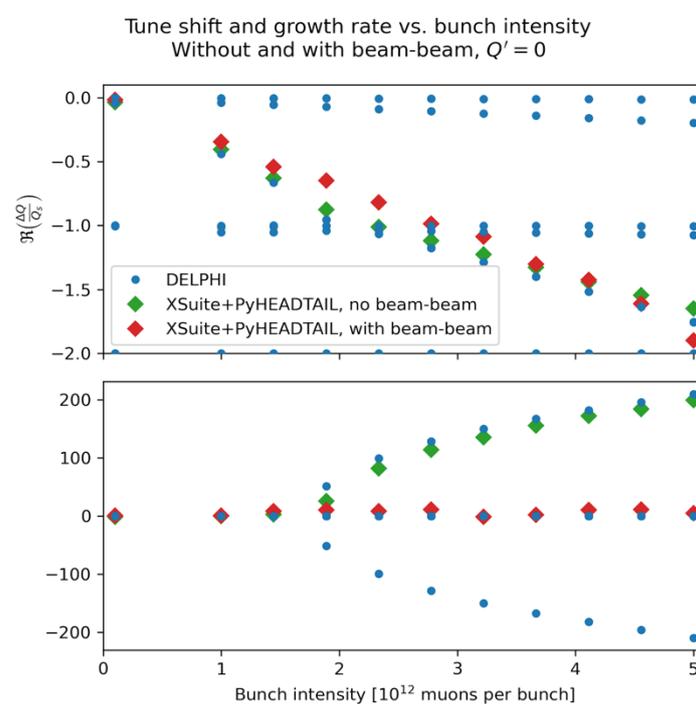

Figure 3: example of transverse beam stability simulations with collective effects performed with XSuite+PyHEADTAIL. The plots show the mode frequency shifts (top plot) and their growth rate (bottom plot) as a function of the single bunch intensity. Without beam-beam effects a strong instability appears at an intensity of 2e12 muons per bunch. Including beam-beam effects

Investigating these effects will help better understand the limitations and mitigation strategies required for the collider ring. The study of transverse collective effects with no RF voltage in the ring (as the optics design aims to generate a momentum compaction factor equal to zero) is also underway.

Development of the RCS chain parametrization and optimization tools

The current RCS parameters (available at https://muoncollider.web.cern.ch/node/262) inherit directly from the US Muon Accelerator Program (MAP) study done between 2010 and 2017.

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But a more optimal set of injection/ejection energies and muon decay rate might help reduce the magnet ramping rate and required total RF voltage, while keeping a similar overall muon decay rate over the RCS chain.

Development of a tool for computation and optimization of the RCS parameters has started in collaboration with the RF and magnets working groups. Written in Python, the package provides a simple interface to simply recompute the whole set of characteristics for the RCS chain (such as the required RF voltage, number of RF cavities, number of power converters for magnets…), given a few input parameters like the injection energy or the muon transmission rate in each RCS. The package is available on CERN Gitlab at the address https://gitlab.cern.ch/muon-collider-bd/rcsparameters

Parameter	Symbol	Unit	RCS1	RCS2	RCS3	RCS4	RCS 5
Injection energy	E_{inj}	[eV/u]	63.0G	350.0G	644.1G	1.3T	3.5T
Ejection energy	E_{ej}	[eV/u]	350.0G	644.1G	1.3T	3.5T	5.0T
Survival rate	N_{ej}/N_{inj}	-	0.89	0.90	0.95	0.96	0.89
Acceleration time	τ_{acc}	[s]	392.6u	1.1m	1.0m	2.0m	10.0m
Average RF gradient	G_{avg}	[V/m]	2.4M	883.6k	2.3M	3.7M	496.4k
Ramp rate	$\dot{B}_{NC}$	[T/s]	3.8k	3.2k	3.6k	1.8k	359.8
Circumference	$2\pi R$	[m]	6.9k	6.9k	10.7k	26.7k	26.7k

Table1: example of a parameter table obtained with the RCS chain parameter optimization tool (this parameter set is given as an example only).

This development already allows to optimize high level parameters of the RCS chain such as each synchrotron injection and ejection energy or the normal conducting magnet ramping rate by distributing the allowed muon decay rate over each machine differently. Table 1 shows an example of a possible optimization that would use a chain of 5 RCS instead of 4, with the largest rings fitting in CERN LHC tunnels.

Investigation of eddy current effects in the RCS vacuum chamber

Investigations into the effects of eddy currents in the RCS vacuum chamber have begun, prompted by the high ramping rates of the normal conducting magnets, which can reach up to 4000 T/s—several orders of magnitude higher than those in existing RCS systems, such as J-PARC, with a maximum ramp rate of 55 T/s. Due to these high ramping rates, eddy currents and the resulting induced heating pose potential concerns for the RCS vacuum chamber.

To mitigate this, materials such as ceramic chambers with thin metallic shielding for impedance control are being considered. However, it is essential to estimate the eddy currents generated in

the metallic shield and assess the associated heating to validate this approach. Initial analytic estimates indicate the need for thin stripes of metallic shielding rather than a bulk metallic chamber, even if the latter is very thin (0.1 mm). Currently, 3D electromagnetic simulations, coupled with thermal analysis, are underway to confirm these estimates and provide crucial input for both the vacuum and magnet working groups.

Study of collective effects during ionization cooling

The ionization cooling of the muon beam is a critical process happening at low energy and high intensity. The large sized muon beam produced goes through a series of absorbers and RF cavities to reduce the transverse and longitudinal emittances while being focused by solenoid magnets.

The MICE experiment demonstrated the validity of the ionization cooling of a muon. Moreover, the WP8 cooling demonstrator workshop aims at building a cooling cell capable of reducing the size of an actual muon beam.

Collective effects at this stage; such as space charge effects, beam loading and beam break-up effects, resistive-wall impedance, wake field and plasma produced in absorbers; may cause beam instabilities and losses and must be mitigated.

The study of those collective effects during this process has started and preliminary studies have been presented at the 2024 IMCC annual meeting. First estimates of the ionization cooling chain has been presented. These first estimates have been obtained using simplified analytical tools of the intensity limitations from the different collective effects involved in this part of the muon collider complex (mainly space charge, beam break up, high order modes impact). In addition, first modelling of the collider collective effects has been started. A summary of the International Muon Collider Collaboration (IMCC) progress and status of the Muon Collider R&D programme has been presented in a report.

The next goal of the study is to model the ionization cooling chain. This will be the main activity of the post-doc D. Amorim. A detail numerical model of the accelerating-cooling chain will be built around an existing software called RF-Track. This software will allow to track muons through radio frequency cavities, external wake fields taking into account relativistic effects. The model will need to be extended to account for wake fields in matter (the absorbers present in the cooling design). With this complete model it will be possible to characterize and study the impact on the beam dynamics. Intensity limitations from this new type of interactions will be estimated and possible counter actions will be proposed.

4. List of Presentations

- J. Potdevin, "Plans for the study of collective effects in the ionisation cooling system", IMCC Annual Meeting 2024, March 2024.

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- D. Amorim, "Update on transverse collective effect studies for the 10 TeV collider ring", Muon Collider Accelerator Design meeting, June 2023, https://indico.cern.ch/event/1283569
- D. Amorim, "Études d'instabilités transverses des faisceaux pour un projet de collisionneur muons anti-muons", contributed oral invitation, General Congress of the French Physics Society, July 2023, https://indico.ijclab.in2p3.fr/event/8021/sessions/4500/#20230705
- D. Amorim, "Status of the collective effects in the RCS", presentation at the IMCC annual meeting 2023, June 2023, https://indico.cern.ch/event/1250075/contributions/5350200/
- D. Amorim, "Status of the collective effects in the collider ring", presentation at the IMCC annual meeting 2023, June 2023, https://indico.cern.ch/event/1250075/contributions/5349692/
- E. Kvikne, "Eddy current effects in the RCS vacuum chamber", presentation at the 22nd HEMAC meeting, December 2023, https://indico.cern.ch/event/1346948/

5. List of Publications:

- Interim report for the International Muon Collider Collaboration (IMCC), C Accettura, et al. arXiv preprint arXiv:2407.12450, 2024.

- D. Amorim et al., "Transverse impedance and beam stability studies for the muon collider ring", Proceedings of IPAC 2023, May 2023, WEPL185, https://accelconf.web.cern.ch/ipac2023/doi/jacow-ipac2023-wepl185/
- D. Amorim et al., "Transverse impedance and beam stability studies for the muon collider Rapid Cycling Synchrotrons", May 2023, Proceedings of IPAC 2023, WEPL186, https://accelconf.web.cern.ch/ipac2023/doi/jacow-ipac2023-wepl186/
- D. Amorim et al., "Transverse Coherent Instability Studies for the High-Energy Part of the Muon Collider Complex", Proceedings of HB 2023, October 2023, THBP17, https://hb2023.vrws.de/papers/thbp17.pdf