Swiss Accelerator Research and Technology

Project:Muon Collider Feasibility Studies

Muon collider Feasibility Studies: Collective effects and muon cooling

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1.1 General Overview and goals

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.

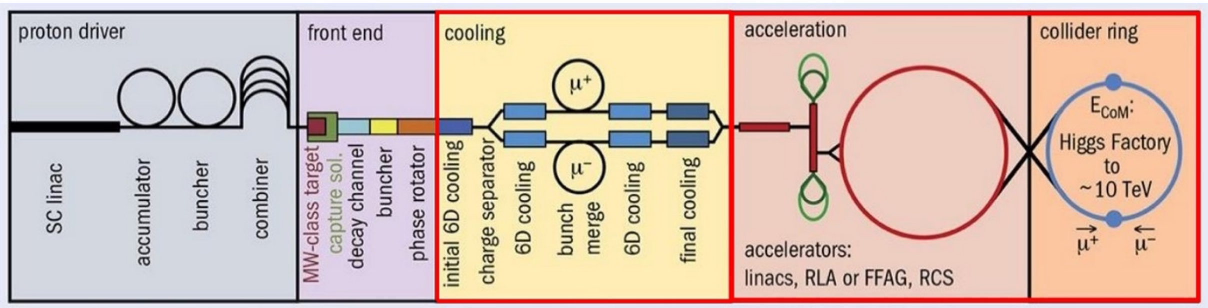

Figure 1: Proposed layout for a muon collider complex. Collective effects are investigated in the parts highlighted in red.

Collective effects are a major concern in the different stages of the muon collider complex. This project focuses in particular the project 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.
The project aims to check that collective effects are not a limitation to the machine performance and if necessary provide possible mitigation measures or limits to the machine system characteristics.

1.2 Research Activities and preliminary 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.

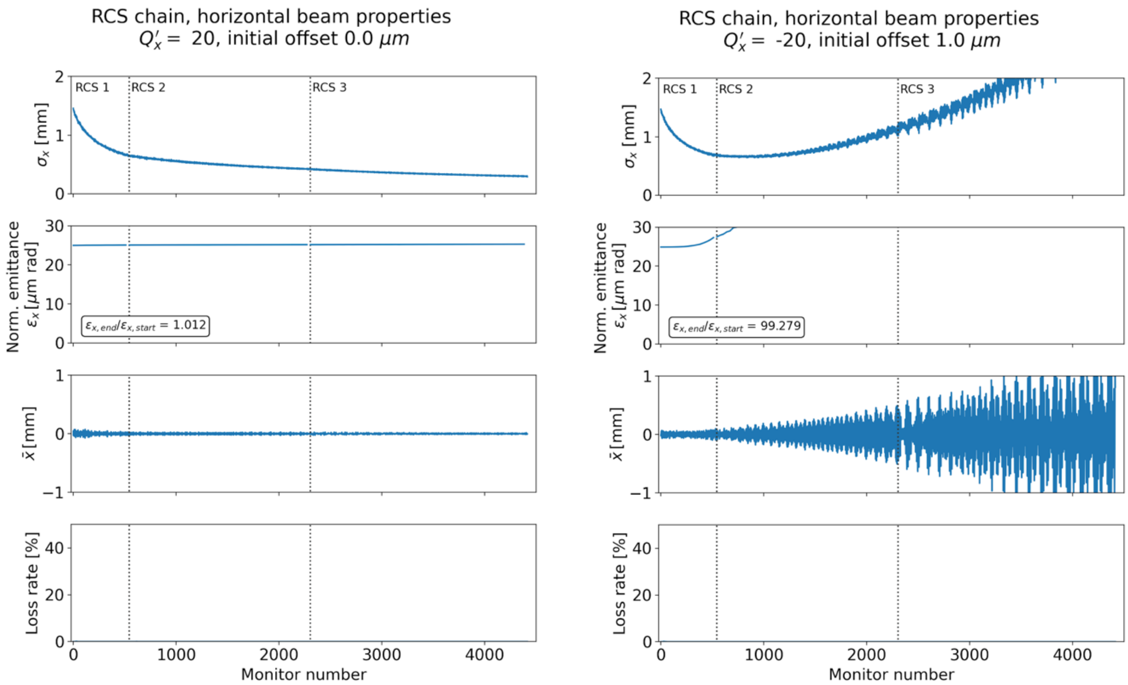

Figure 2: example of transverse beam stability simulations with collective effects performed with XSuite+PyHEADTAIL. The plots show the beam properties evolution over the three RCS (transverse size, horizontal emittance, centroid position, particle loss rate). Left image shows a stable configuration (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 refined to account for the latest development of the magnet radial build. The superconducting magnet coils must be protected from the muon decay debris (electrons and positrons) by a tungsten shielding inserted inside the cold bore. This shielding currently has an inner radius of 23.5 mm. To reduce impedance resistive wall impedance effects, a copper coating should be deposited on the inner surface of the tungsten shield seen by the beam.
Impedance models were generated with ImpedanceWake2D and the pywit framework for different copper coating thickness. With tracking simulations performed with PyHEADTAIL, it was found that a copper layer at least 1 um thick is required to shield the tungsten bulk. Together with the large 23.5 mm inner radius, simulations show that transverse beam stability is preserved for the muon bunch intensity of 1.8e12 planned at injection in the collider.
Because of the small β* at the collision points (β* = 1.5mm) and the large bunch intensity, beam-beam effects will also play an important role in the collider. Studies started to investigate the effects of 4D (horizontal and vertical) beam-beam interactions using XSuite and PyHEADTAIL. Figure 3 shows an example of simulations performed with the combination of the two tracking codes, for a chromaticity corrected to Q'=0. With the nominal bunch intensity at injection of 1.8e12 muons per bunch, the bunch is predicted to be stable, both without or with beam-beam effects. But bunch intensities higher than 2.0e12 can lead to instabilities when only one beam is considered. In simulations. adding head-on beam-beam effects appears to stabilize the bunch for higher intensities.

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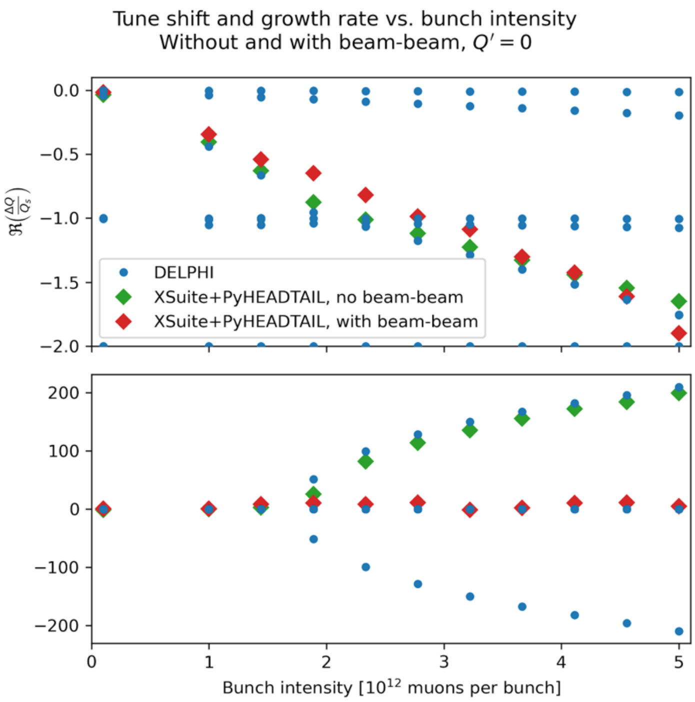

Figure 3: example of transverse beam stability simulations with collective effects performed with XSuite+PyHEADTAIL. The plots show the mode frequency shifts (top plot) and their growth rate (bottom plot) as a function of the single bunch intensity. Without beam-beam effects a strong instability appears 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.
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 RCS parameters computation and optimization tool 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

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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	$N_{\text{ej}}/N_{\text{inj}}$	-	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	$\dot{B}_{\text{NC}}$	[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

Together with Erik Kvikne, technical student at CERN who started under the supervision of David Amorim, the effects of eddy currents in the RCS vacuum chamber started to be investigated. In the RCS the normal conducting magnets ramping rate can be up to 4000 T/s, several orders of magnitude higher than existing RCS (for example J-PARC RCS has a maximum ramp rate of 55 T/s).

Because of these high ramping rates, eddy current and the subsequent induced heating could be a concern for the RCS vacuum chamber. Specific materials such as ceramic chambers with thin metallic shielding for the impedance are being considered. Still the eddy current that develops in the metallic shield should be estimated and the induced heating evaluated to confirm this solution. First analytic estimates have been made and confirm the necessity of having thin stripes of mettalic shielding instead of a bulk metallic chamber, even very thin (0.1mm). 3D electromagnetic simulations coupled with thermal simulations are currently ongoing to confirm the analytic estimates and provide inputs to the vacuum and magnets 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.

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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 an update presentation is expected at the 2024 IMCC annual meeting https://indico.cern.ch/event/1325963/overview.

1.2 Next steps

The next goal of the study is to model the ionization cooling chain. This will be the main activity of the newly hired EPFL PhD student J. Potdevin in October 2023. The first step is an estimate 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). Then 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 the PhD student will 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.

1.3 Publications and Presentations

List of presentations:

- 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/

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- 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/

List of publications:

- 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

List of references:

- RCS and Collider impedance and transverse beam dynamics codes: https://gitlab.cern.ch/muon-collider-bd/muc-impedance
- RCS chain parameter set generator: https://gitlab.cern.ch/muon-collider-bd/rcsparameters
- RF-Track https://abpcomputing.web.cern.ch/codes/codes_pages/RF-Track/