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Transverse Collective Effects studies for a Muon Collider

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The International Muon Collider Collaboration (IMCC) is investigating the key challenges of a 10 TeV centre-of-mass muon collider ring, along with its injector complex and an intermediate 3 TeV collider stage. Muon and anti-muon bunches are produced via a proton driver complex and then undergo a process called 6D cooling. The bunches are then accelerated by a series of Linacs, Recirculating Linacs (RLA) and Rapid Cycling Synchrotrons (RCS) before entering the collider ring.

Collective effects are a concern due to the high charge of the muon bunches. The RCS require a significant number of RF cavities to rapidly accelerate the beams and keep a 90 % survival rate in each ring. The effect of the cavity high-order modes (HOMs) was evaluated using start-to-end simulations that included collective effects. The collider would be an isochronous ring to preserve a short bunch length. The study also examined the impact of this operation on transverse coherent stability, and potential methods for mitigating instabilities.

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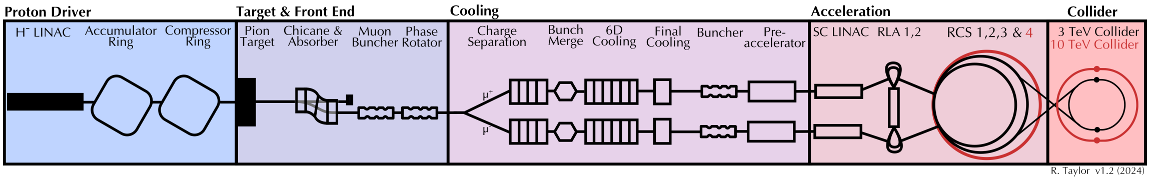

Figure 1: Schematic view of the proposed Muon Collider complex. Picture courtesy of R. Taylor.

1. Overview of the Muon Collider

First ideas of the Muon Collider were formulated in the 1960s [1, 2]. Between 2010 and 2016, the Muon Accelerator Program in the US studied a 3 TeV centre-of-mass (c.-o.-m) collider and its muon production and acceleration complex [3]. In 2021 the IMCC was formed to investigate a 3 TeV c.-o.-m. $\mu^+\mu^-$ collider, followed by a 10 TeV c.-o.-m. stage [4, 5]. In 2023 the MuCol European project followed to support the study effort [6].

Figure 1 shows a schematised depiction of the accelerator complex currently under study. A Linac creates and accelerates proton bunches which then hit a target. Pions are generated and decay into muons and anti-muons which are then bunched and separated. Afterwards the two bunches are 6D-cooled to reduce their transverse and longitudinal emittances. An acceleration complex comprising several Linacs, RLA and RCS brings the two bunches to 1.5 TeV in the first stage or 5 TeV in the second stage. The collider ring operates at fixed energy with two interaction points (IP) where the μ^+ and μ^- bunches collide.

Many challenges in terms of beam dynamics and accelerator engineering follow from the short muon lifetime, and are being investigated [7]. Among them are:

- The high power proton Linac, in the 1 MW to 4 MW range with an energy between 5 GeV and 10 GeV would be needed to yield enough muons.
- The target needs to withstand large thermal and radiation constraints, requiring careful study of the materials that would be used, and the global mechanical integration.
- The muon cooling which must reduce the transverse emittance of the bunches by a factor ~1000 to reach the required performance target. Ionisation cooling would be used and requires alternating cooling elements with RF cavities to re-accelerate longitudinally the particles. Transverse focusing is provided by a compact arrangement of solenoid magnets.
- The acceleration complex must accelerate quickly the two beams to the collider energy while preserving the bunch emittances. To reach the luminosity goal of the collider, less than 10 % of the bunch intensity can be lost inside each accelerator of the chain. This requires to accelerate the beams from 63 GeV to 5000 GeV in less than 10 ms in the four RCS.
- The collider ring must provide two high luminosity IP, and therefore uses strong final focusing magnets to reach $\beta^* = 1.5$ mm, thereby generating large chromatic effects in the lattice. Additionally the total length of straight sections must be minimised to reduce the neutrino flux that reach the ground surface.

2. Challenges in the acceleration chain and the collider ring

The acceleration chain of the Muon Collider complex starts after the muon cooling. Its goal is to accelerate the two μ^+ and μ^- bunches from 0.25 GeV to 1500 GeV or 5000 GeV for the 3 TeV and the 10 TeV collider respectively. The current IMCC baseline foresees a chain comprising a Linac and two RLA the beams from 0.25 GeV to 63 GeV. Three RCS then accelerate the beams from 63 GeV to 1.5 TeV and a fourth RCS accelerates from 1.5 TeV to 5 TeV. Some of the acceleration chain parameters are reported in Table 1, and more details can be found in Ref. [7].

	Linac	RLA1	RLA2	RCS1	RCS2	RCS3	RCS4
Circumference [m]		800	2430	5990	5990	10000	35000
Ejection energy [GeV]	1.25	5	63	314	750	1500	5000
Energy gain per turn/pass [GeV]	1.0	0.85	13.5	14.8	7.9	11.4	63.6
NC magnets ramp rate [T/s]	-	-	-	4200	3282	1519	565
Total RF voltage installed [GV]	-	-	-	20.9	11.2	16.1	90

Table 1: Overview of the muon acceleration chain machine parameters.

To minimise the beam intensity loss from muon decay, the accelerators must remain compact while providing the fastest acceleration possible. To ensure less than 10 % intensity loss in RCS1, the beam must be accelerated in less than 0.34 ms [5]. This requires a total accelerating voltage of 21 GV for this accelerator which would be provided by ~700 TESLA-type superconducting RF cavities [8, 9]. In the RCS2, 3 and 4, a total of respectively 370, 540 and 3000 of these cavities would be needed. The normal-conducting dipole magnets must have a ramping rate of 4200 T s^{-1} to follow the fast energy increase. Innovative magnet design and powering solutions are being studied to reach these target parameters [7].

To obtain the desired energy swing, RCS2, 3 and 4 would be hybrid machines: fast-ramping normal-conducting magnets would be interleaved with fixed-field superconducting magnets This allows to increase the average magnetic field at injection and extraction energy. Moreover the normal conducting magnets can ramp from −1.8 T at injection energy to 1.8 T at ejection energy, enabling a greater energy swing. However this scheme generates horizontal beam excursions in the magnets that must be accounted for in the lattice and magnet design [10, 11].

In the 10 TeV c.-o.-m collider ring, 16 T superconducting dipole magnets are needed to meet the 5 TeV energy per beam in a 10 km circumference. For better energy efficiency and to reach higher peak fields, high-temperature superconductors would be used for the magnet coils. These coils need to be protected from the heat load and radiation damage caused by the electrons generated by muon decay. A 4 cm thick cylindrical tungsten shield would be placed inside the magnet cold bore to intercept the electrons and positrons.

3. Transverse collective effect studies for the acceleration chain and the collider ring

As they travel through the accelerator, the charged particle beams generate an electromagnetic field. This field interacts with its surrounding environment (vacuum chamber, RF cavities, collimators, etc.) which in turns creates parasitic electromagnetic fields that can perturb the bunches

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transverse and longitudinal motions. Impedance and wakefield models are used to model these parasitic electromagnetic fields and their impact on coherent beam stability. They can be computed using analytical formulas or numerical calculations.

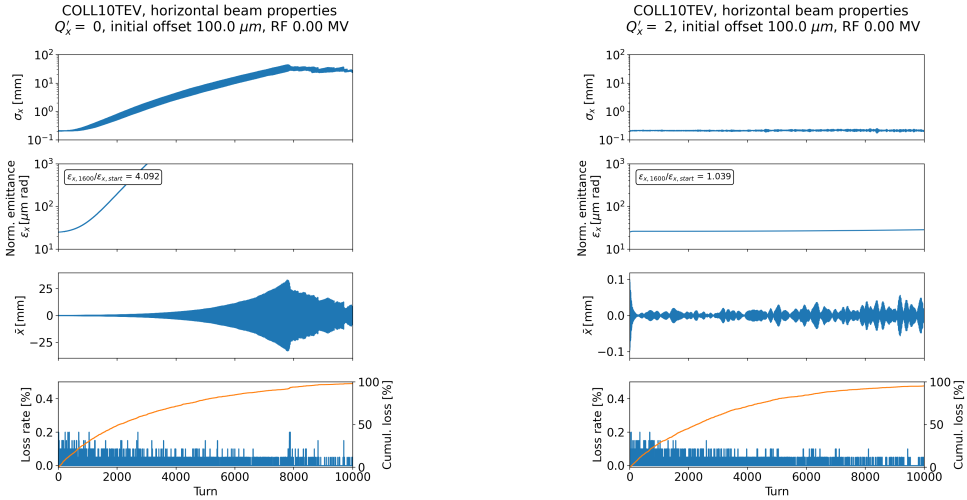
In the RCS, one of the main contributors to the impedance model is the large number of RF cavities needed to provide the required acceleration rate, as described in the previous section. The cavities have parasitic HOMs beside the fundamental accelerating mode that can perturb the beam motion, and lead to particle losses or emittance growth. TESLA type cavities at 1.3 GHz are the baseline choice, providing the high gradient needed (up to 30 MV m^{-1}). The second major contributor to the impedance would be the normal conducting magnet vacuum chambers. Because of the large ramping-rate in the magnets, large eddy currents would be generated in a fully metallic vacuum chamber, leading to large power losses and subsequent heating [12]. Ceramic chambers with a 10 µm Titanium Nitride metallic coating on the inner side and RF stripes on the outside are foreseen to alleviate the eddy current effects.

Macroparticle tracking simulations were performed with Xsuite [13] and PyHEADTAIL [14] to investigate the transverse coherent beam stability limitations that could be caused by the beam coupling impedance. The acceleration through the four RCS, with the subsequent change of parameters between machines, is simulated. Parametric scans of different mitigation measures such as chromaticity and transverse damper strength were performed. The effect of an initial transverse offset of the beam, that could be created by injection jitter, was also studied. Simulations found that a positive chromaticity is needed to preserve transverse beam stability, together with a 20-turn transverse damper [15]. In this case initial transverse offsets up to 100 µm can be accommodated without transverse emittance growth or abnormal bunch intensity loss.

In the collider, the first impedance source investigated is the resistive-wall from the dipole magnet vacuum chambers. In those magnets a tungsten shield must be inserted in the magnet cold bore to protect the superconducting magnet coils from muon decay-induced heating and radiation damage [16]. The inner radius of the shield is 23.5 mm and its surface would be copper-coated to reduce impedance. Macroparticle simulations were performed for a single bunch of the collider ring, including the effect of muon decay. At 5 TeV the muon half-life is $t_{1/2} = \ln(2)\gamma_{\text{Lorentz}}\tau_0 = \ln(2) \cdot 47323 \cdot 2.2\,\mu\text{s} = 72\,\text{ms}$, equivalent to ~2200 turns in the 10 km collider. These effects can help mitigate coherent instabilities as the bunch intensity quickly decreases after injection in the collider.

Figure 2 shows two examples of macroparticle simulations with the collider impedance model. These simulations do not include a transverse damper. On the left plot (Figure 2a) the chromaticity is corrected to $Q'_x = 0$. A transverse instability develops and large emittance growth occurs, together with additional beam losses when the particle distribution hits the chamber aperture at turn ~8000. Introducing a small amount of chromaticity $Q'_x = 2$ stabilises the beam as shown in Figure 2b.

The impact of chromaticity, transverse damper and initial beam offset on transverse beam stability was evaluated. With a chromaticity corrected to $Q' = 0$ the bunch is systematically unstable, even with small initial offset and strong transverse damper [17]. A slightly positive or negative chromaticity value such as $Q' = \pm 2$ is enough to stabilise the beams, even for large initial offset up to 100 µm and without a transverse damper. Pas studies showed that non-zero chromaticity might mitigate coherent instabilities by introducing a tune spread among the particles [18].



(a) Chromaticity corrected to $Q'_x = 0$ **(b)** Positive chromaticity $Q'_x = 2$

Figure 2: Example of the evolution of beam parameters over 10000 turns in the collider. From top to bottom: horizontal 1σ beam size, horizontal emittance, horizontal centroid position, particle loss rate per turn (in blue) and cumulative losses (in orange).

4. Conclusion

The Muon Collider presents many challenges in terms of accelerator design, RF and magnet engineering, powering, cooling, etc. Luminosity requirements for the collider interaction points have a strong impact on the beam dynamics in the acceleration complex and the collider ring. In the Rapid Cycling Synchrotrons, the impact on the transverse coherent stability of the beams of the RF cavities and magnet vacuum chambers have been investigated. Mitigation measures such as chromaticity and a transverse damper are required to preserve the beam emittance through the acceleration chain. In the collider ring, the impedance from the magnet shielding has been studied, and macroparticle simulations showed that some tune spread from chromaticity is required to mitigate the coherent beam instabilities. Additional effects relevant for transverse beam stability are being investigated, in particular two beam dynamic effects such as beam-beam effects at the interaction or crossing points in the RCS and the collider, and two-beam wakefields in the RF stations.

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