IMPACT OF INTRABEAM SCATTERING AND SPACE-CHARGE IN THE FIRST THREE CELLS OF THE MUON COLLIDER FINAL COOLING CHANNEL[*,†]

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Abstract

The cooling process is one of the most critical challenges for the future Muon Collider, as muons are initially produced with a very large emittance that must be significantly reduced before acceleration. This cooling must occur rapidly, well within the muon lifetime. At low energies, collective effects such as space charge and intrabeam scattering can strongly influence emittance growth and must therefore be considered in the lattice design, which is currently under development. This work presents studies of space charge and intrabeam scattering effects within the first three cells of the latest Muon Collider final cooling lattice design, evaluating their impact on emittance growth using the tracking code RF-Track.

INTRODUCTION

The Muon Collider is a leading candidate for a future high-energy lepton collider [1]. Owing to the large muon mass, synchrotron radiation is strongly suppressed, enabling a compact multi-TeV circular design. However, the short muon lifetime imposes strict constraints on beam manipulation and acceleration.

Muons are produced as tertiary particles from proton–target interactions, followed by pion decay, resulting in beams with large emittances. Therefore, emittance reduction is required to achieve the target luminosity. Since most of the conventional cooling techniques are incompatible with the muon lifetime, ionization cooling is adopted [2]. In this method, muons loose momentum in low-Z absorbers (in this specific design, liquid hydrogen), while RF cavities restore the longitudinal component. High-field solenoids provide strong transverse focusing to mitigate multiple Coulomb scattering and enable net transverse cooling. The present work addresses the first three cells of the final cooling stage.

In the final cooling stage, the muon kinetic energy decreases from approximately 120 MeV to about 10 MeV in the last cells. Under these conditions, space charge (SC) and intrabeam scattering (IBS) are expected to play a significant role along the entire channel, with increasing impact at lower energies. These collective effects can drive emittance growth and may ultimately limit the achievable cooling performance. A quantitative evaluation of their impact is therefore required and constitutes the main objective of this study.

Collective effects may induce modifications of the beam phase space, including transverse emittance growth, bunch lengthening, and an increase in energy spread. Since the lattice was originally designed without accounting for these effects, a re-matching of the optical parameters may be required to preserve the intended cooling performance. In this context, the present study focuses on the first three cells of the channel, where the onset of such effects is expected and where early deviations from the nominal matching conditions can already be identified.

Simulations have been performed using RF-Track [3], a tracking code developed at CERN. The code allows self-consistent modeling of SC, multiple Coulomb scattering in matter (important for the absorbers), wakefields, beam loading, modeling of non-ultrarelativistic muons and muon decay within a time-integration framework that supports overlapping elements, such as absorbers embedded in solenoids. In addition, it was recenly equipped with a novel methodology to simulate IBS [4], making RF-Track a very suitable tool for the simulation of the final cooling channel.

The lattice considered in this study corresponds to one of the latest baseline design [5], which is described in detail in the next section. Alternative final cooling concepts have also been proposed at CERN, including machine-learning-optimized lattices [6, 7].

More recently, within the framework of the European Strategy for Particle Physics Update [1], an alternative design for the final cooling channel has been introduced [8]. Preliminary investigations of space charge (SC) effects for this scheme have been performed using Geant4Beamline [9],

Table 1: Muon Beam Characterization at the Entrance of the Final Cooling Section

Particle	μ^+
Number of muons	$5.3 \cdot 10^{12}$
Kinetic energy (MeV)	123.61
Norm. trans. emittance $\epsilon_\perp$ (mm· mrad)	299.48
Long. emittance $\epsilon_\parallel$ (eV· ms)	0.5244
Bunch length σ_t (mm/c)	29.14
Energy spread σ_E (MeV)	5.3948
Number of macroparticles	10000
Number of cells (SC and IBS algorithms)	32 × 32 × 32

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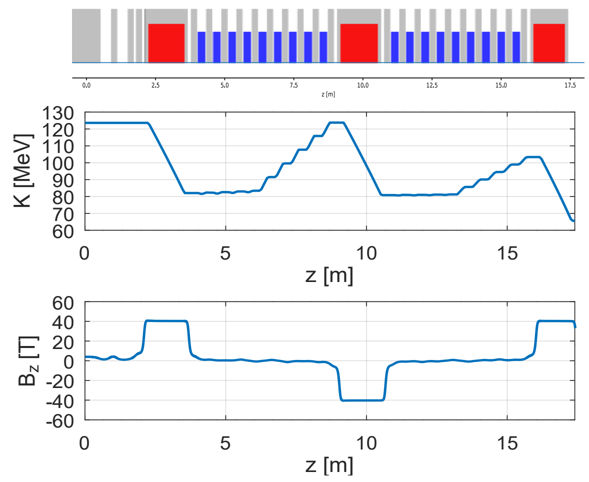

Figure 1: First three cells of the final cooling lattice [5]. Top: lattice layout (absorbers in red, RF cavities in blue, solenoids in grey). Middle: kinetic energy evolution. Bottom: longitudinal magnetic field profile.

following recent developments enabling SC modeling in this code, which has been used for lattice design studies in both configurations.

All current designs remain subject to ongoing revision. In particular, collective effects have not yet been fully incorporated into the design optimization, and the achievement of the required solenoidal magnetic fields relies on further developments in high-temperature superconducting (HTS) technology.

SIMULATION SETUP

The initial muon beam parameters used in this study are summarized in Table 1. These values correspond to the expected beam properties at the end of the 6D cooling stage, as defined in [1], i.e., immediately upstream of the final cooling section.

The cooling lattice is based on the design reported in [5], and consists of high-field solenoids, low-Z absorbers, and RF cavities. A field-flip solenoid configuration is employed to optimize the final transverse emittance [2].

A scheme of the first three cells of the Final Cooling (i.e. the lattice in this work) together with the magnetic field profile and kinetic energy evolution, is shown in Fig. 1. It can be seen that the beam dynamics along the lattice follows the ionization cooling scheme described in the introduction. The kinetic energy evolution reflects the alternating energy loss in the absorbers and re-acceleration in some of the RF cavities. Finally, Fig. 1 shows the required solenoidal magnetic field, reaching values of up to 40 T. Such fields, combined with the large apertures required for the beam, exceed the capabilities of present magnet technology and rely on further developments in high-temperature superconducting (HTS) conductors.

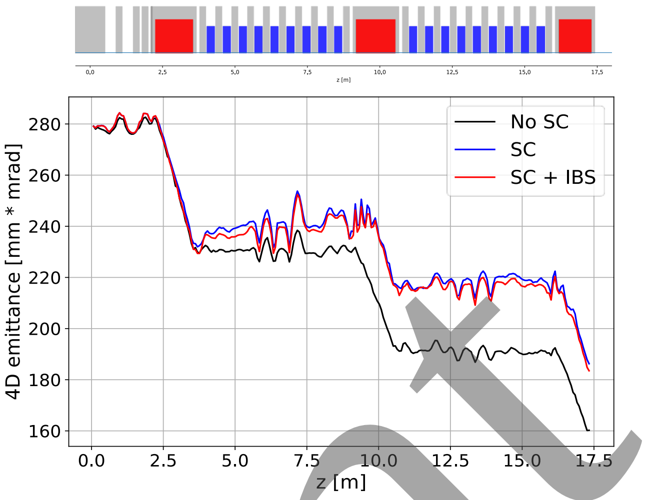

Figure 2: Transverse normalized emittance along the lattice.

RESULTS

The first three cells of the final cooling have been simulated with RF-Track, firstly without any collective effect, later with SC and finally with SC and IBS together. The muon decay has been taken into account.

The first task was to analyze the emittance growth due to SC and IBS, as it is the most important parameter to be controlled during the cooling. The emittances have been calculated using a 3σ cut. Figure 2 shows that, by the end of the third cell, space charge (SC) increases the final 4D normalized emittance by approximately 14%. In addition, SC induces a mismatch between the first two absorbers, indicating that the lattice matching conditions are already violated at an early stage of the channel.

Finally, small irregularities in the emittance evolution are observed even in the absence of SC and IBS (see Fig. 2). These effects may partly arise from the use of projected emittances, which are sensitive to distortions of the full 6D phase-space distribution. In the present lattice, the combination of strong short solenoids, RF cavities, and absorbers introduces momentum-dependent transport, nonlinear fringe-field effects, and stochastic scattering, all of which can perturb the projected phase-space distribution and produce small fluctuations in the calculated emittances. Alternatively, part of the observed irregularity may result from finite macro-particle statistics (see Table 1). A significantly stronger impact is observed in the longitudinal plane, where SC results in an increase of about 48% in the longitudinal emittance, as it can be seen in Fig. 3. This pronounced degradation motivates a more detailed analysis of the longitudinal phase space evolution.

Key parameters of the longitudinal emittance (the bunch length and the energy spread) have been further investigated. In particular, a significant increase in energy spread would require a re-optimization of the RF cavities, with potential impact on the overall lattice design. These results are summarized in Fig. 4, which compares the beam parameters at the end of each of the three cells with SC and IBS, with only

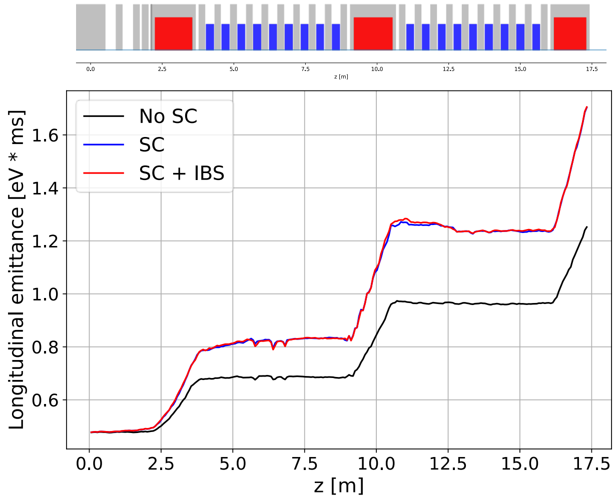

Figure 3: Longitudinal emittance along the lattice.

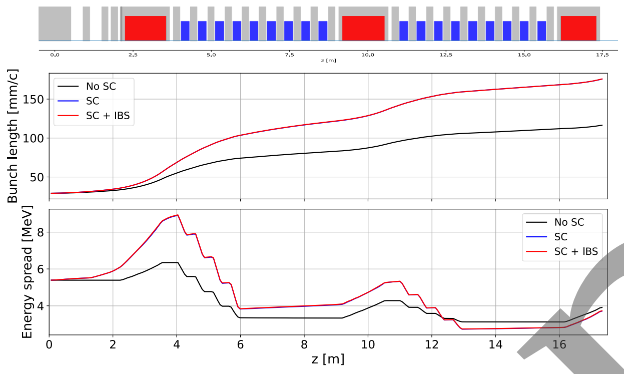

Figure 4: Bunch length (above) and energy spread (below) along the lattice.

SC and without any of the effects. Figure 4 shows that SC leads to a significant increase in the bunch length, which is likely the main driver of the observed growth in longitudinal emittance, as shown in Fig. 3. Regarding the energy spread, while the SC effect is comparatively reduced at the end of the third cell, a pronounced effect is observed in the first cell. This behavior suggests the possible presence of an early-stage mismatch, which should be further investigated in relation to the lattice matching conditions, even if later is smoothed.

As in Fig. 3, in Fig. 4 the curves including SC and SC together with IBS can barely be distinguished, allowing to conclude that the effect of IBS in these first three cells is still not relevant, but not discarding its possible importance in the next cells.

The effect of collective effects in the kinetic energy along the lattice was also analyzed, but their effect was negligible, obtaining a kinetic energy almost identical to the one without collective effects that could be seen in Fig. 1. In addition, the beam transmission was also studied, showing that the collective effects only made it a 0.2% lower. However, local mismatches may still develop in the following cells, potentially leading to increased particle losses. For this reason, a re-optimization of the lattice matching is recommended, even though no significant degradation of transmission is observed at this stage.

CONCLUSIONS AND FUTURE WORK

The present study has investigated the impact of Space-Charge and Intrabeam Scattering in the initial section of the final cooling channel. The results indicate a non-negligible increase in the emittances in both transverse and longitudinal planes already in the first cells due to SC, which motivates a more systematic analysis along the full channel.

As a first extension, future work will consider the entire final cooling section, including the remaining seven cells. As the beam energy decreases along the channel, both SC and IBS are expected to become increasingly relevant. At the same time, variations in beam intensity along the cooling process will also modify the relative strength of these effects, and therefore need to be consistently taken into account. It is also proposed to study the effect of other collective effects such as the presence of wakefields and beam loading.

Further studies will focus on possible coupling between the horizontal and vertical planes, as well as on the origin of the emittance peaks observed in the evolution of the 4D emittance. In particular, the influence of the statistical cut applied in the beam distribution will be reassessed, including alternative definitions of the truncation procedure.

The results also suggest that space charge may introduce lattice mismatches, especially in the early stages of the channel. A dedicated re-optimization of the lattice including Space-Charge and Intrabeam Scattering effects is therefore recommended. In this context, a global optimisation of the cooling channel that consistently includes both SC and IBS represents a natural continuation of this work.

Given the strong impact of space charge already observed in the first cell, it is also relevant to extend the analysis to the previous 6D cooling stages, where the beam energy is lower and collective effects may be enhanced. In addition, the subsequent early-acceleration stage foreseen in a short linac could also be affected, and the present simulation framework could be directly applied to study this regime.

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