SPACE-CHARGE LIMITATIONS ON THE FINAL STAGES OF A MUON COLLIDER COOLING CHANNEL*

D. P. Grote#, Lawrence Livermore National Laboratory, Livermore, CA, USA
D. Stratakis, R. B. Palmer, J. S. Berg, Brookhaven National Laboratory, Upton, NY, USA

Abstract
Muon Colliders use ionization cooling to reduce the emittance of the muon beam prior to acceleration. At the last stages of the cooling channel, the bunch has 4×10^{12} muons, an average momentum of 200 MeV/c, and an rms bunch of 2 cm. With this beam intensity and relatively low momentum, we expect space charge effects to have a significant impact on beam dynamics. Here, with the aid of the particle-in-cell code Warp, a 3D model is developed to examine space-charge for muon cooling lattices and some recent results are presented. The model includes 6D cooling with wedge shaped absorbers. We show that space-charge under certain conditions can cause a notable particle loss. Furthermore, we discuss some potential space-charge compensation mechanisms.

INTRODUCTION

A complete scheme for cooling a muon beam sufficiently for use in a muon collider has been previously described [1]. This scheme uses separate 6D ionization cooling channels for the two signs of the particle charge. In each, a channel first reduces the emittance of a train of muon bunches until they can be injected into a bunch-merging system. The single muon bunches, one of each sign, are then sent through a second tapered 6D cooling channel where the transverse emittance is reduced as much as possible and the longitudinal emittance is cooled to a value below that needed for the collider. The beam can then be recombined and sent through a final cooling channel using high-field solenoids that cools the transverse emittance to the required values for the collider. The baseline cooling requirement for cooling is shown in Fig. 1.

Theoretical estimates predict that at the last stages of the post-bunch-merge 6D cooling channel the rms bunch length is just 2 cm and contains 4×10^{12} muons. Thus, the peak current becomes ~4 kA at a ~200 MeV/c momentum. Due to this large current, space-charge forces can be present and thus, there is cause for concern that the existing 6D cooling lattice design may not work so well. Recent studies [2] with the Warp PIC code [3] confirmed this fact since it was shown that longitudinal space-charge can oppose cooling while simultaneously it causes severe particle losses. To reduce the space charge effects, the overall lattice was redesigned with a higher longitudinal emittance target, increased from 1.5 to 2.0. We note that those previous studies were assuming a matrix for longitudinal cooling and thus, the effect of a real absorber wedge was not taken into account. This paper will present results from recent studies on simulating full 3D space-charge effects on muon cooling lattices with more realistic wedge shaped absorbers.

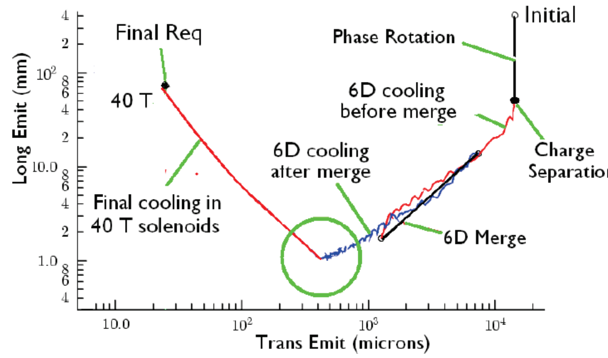

Figure 1: Baseline cooling requirement for the Muon Collider.

LATTICE DESIGN

In order to cool towards the micron scale emittances required for a Muon Collider a 16-stage tapering channel has been proposed. A detailed description of this lattice can be found elsewhere [4]. In this scheme, we apply the concept of tapering [5] where parameters such as cell length, focusing and radius of curvature progressively change from stage to stage based on the emittance reduction rate and transmission.

A segment of one stage of our proposed cooling system is shown in Fig. 2(a). Each stage consists of straight section with a number of identical cells like the one shown in Fig. 2(b) and Fig. 2(c). The coils (yellow) are

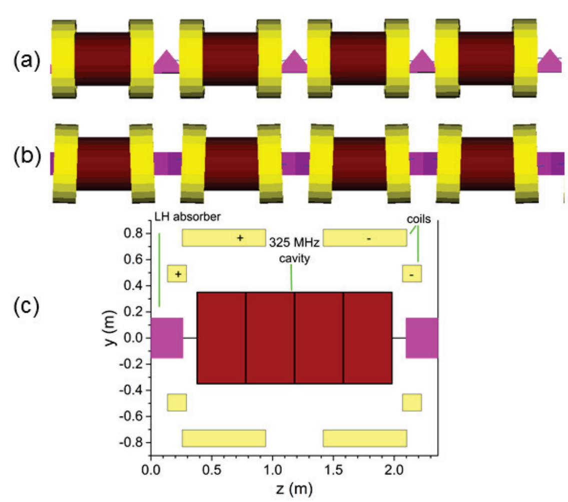

Figure 2: Cooling scheme for the Muon Collider. Fig. (c) depicts one lattice cell. The tilts of the magnets are not shown.

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#dpgrote@lbl.gov

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not evenly spaced and in order to produce dispersion, they are tilted by 1.1-1.3^0. The liquid hydrogen absorber (magenta) is wedge shaped so that higher momentum particles go through the thicker part. Each lattice cell contains the same number of rf cavities (dark red) which, depending on the stage, can be 4, 5, or 6. We use only two sets of rf frequencies, namely 325 MHz and 650 MHz. The choice of 325 MHz is made in order to match with the initial linac of Project X. The cavity window material is Be.

SIMULATION RESULTS

The input beam in the simulations has a normalized transverse emittance of 3.63 mm and a normalized longitudinal emittance of 10.17 mm, while the average longitudinal momentum is 218 MeV/c. Note that those parameters closely resemble the baseline distribution of a muon beam before the final 6D cooling sequence of a Muon Collider [1]. We tracked 100,000 particles and included decay of muons. We generated 3D field maps for each of the stages by superimposing the fields from all the solenoids in the cell and its neighbour cells, including the solenoid tilts. The rf cavities were modelled using cylindrical pillboxes running in the TM010 mode.

Space-charge effects were studied by using the particle-in-cell code Warp. Warp was originally developed to simulate space-charge-dominated beam dynamics in induction accelerators for heavy-ion fusion (HIF). The code now has an international user base and is being applied to projects both within and far removed from the HIF community. A layer was added to Warp to read in and parse ICOOL input files allowing identical problem setup. Note though that Warp operates with time as the independent variable whereas ICOOL uses *s*, so there are small numerical differences in the calculations. During the calculation, Warp handles all operations except for the interaction with the material in the wedge absorber, which is handled by calls to the appropriate ICOOL routines.

The lattice as seen in the Warp simulation is shown in Fig. 3. This is a cell in the first stage of cooling. The simulation incorporates all aspects relevant to the beam motion, including the 3D solenoid field map, RF cavities with absorbing Be windows, and the wedge absorbers and windows. The wedges and RF cavity windows both act as

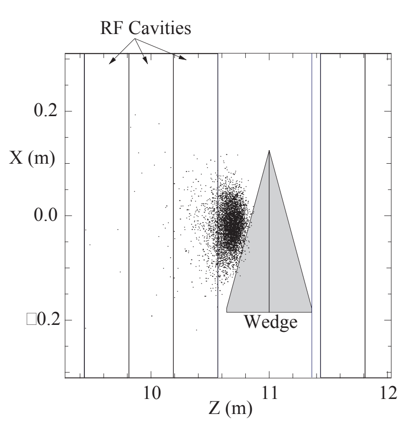

Figure 3: Lattice as known by the Warp simulation.

perfectly conducting internal boundary conditions on the electrostatic potential. The beam macro-particles were generated with an initially Gaussian distribution in physical and velocity space.

Before examining the effects of space charge, checks were carried out comparing ICOOL and Warp simulations without space-charge to check correctness of the models. The resulting emittance and particle numbers are shown in Fig. 4. Four cases are shown, ICOOL and Warp with and without muon decay. As can be seen, good agreement was obtained.

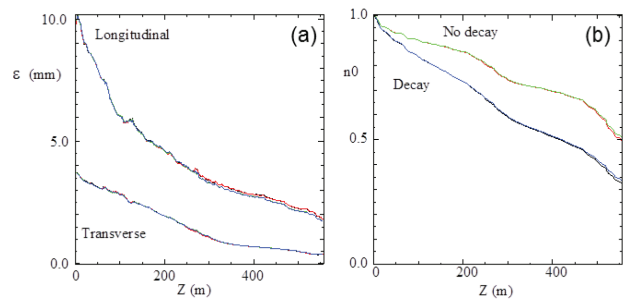

Figure 4: ICOOL and Warp cross-check without space charge (a) emittance, and (b) number of muons. Simulations are carried with and without muon decay using both codes.

In these initial simulations, the electrostatic self-field model was used. The resulting fields from the beam are significant, of order several MV/m, as can be seen Fig. 5. However, this is small compared to RF gradient, which is typically between 17 and 27 MV/m. Note the sharp cut off of the field at the RF cavity windows.

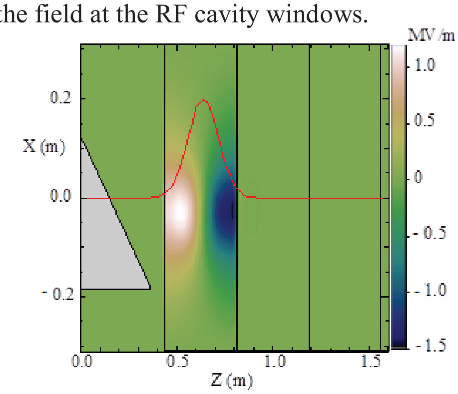

Figure 5: Longitudinal electric self-field. The red curve shows the scale current to show the location of the beam bunch.

The electrostatic potential was calculated on a 3D grid with an initially 2 cm transverse and 1 cm longitudinal cell sizes. As the simulation progresses and the lattice dimensions decreased, the grid cell sizes were correspondingly reduced. The simulations are significant, requiring on the order of a day of wall clock time, depending on the number of processors, because of the large number of time steps, > 500,000, to traverse the cooling channel. Note that the time step size is driven by the need to resolve the variations in the applied fields and not by the space-charge calculation.

The results of the simulations with space charge are shown in Figs. 6, 7 and 8. The main effect of the space charge is to increase the particle loss. Little difference is seen in the emittances. There is a reduction in the longitudinal emittance, but it is associated with the increased particle loss. Most of the particle loss is longitudinal – the increase in the loss is not unexpected since the space charge increases the length of the pulse, pushing more particles out of the RF bucket. The increase in bunch length is shown in Fig. 8. The transverse size is unaffected.

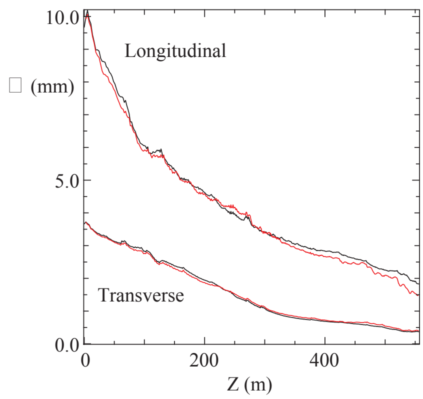

Figure 6: Beam normalized rms emittances along the channel with (red) and without (black) space-charge.

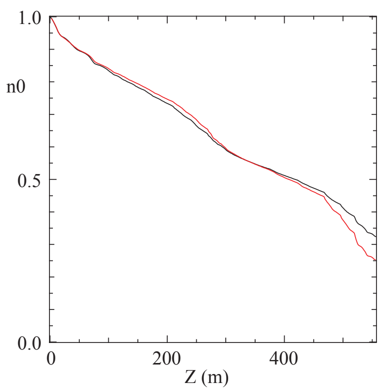

Figure 7: Fraction of beam remaining with (red) and without (black) space-charge.

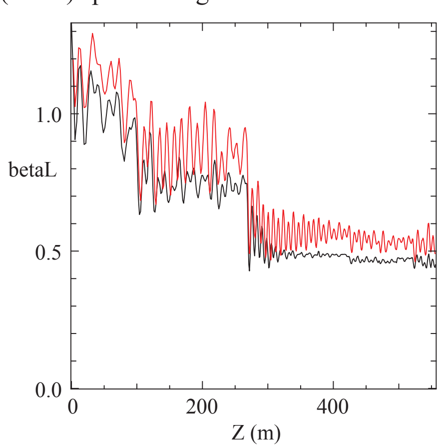

Figure 8: Longitudinal beta function with (red) and without (black) space-charge.

One possible method to reduce the particle loss is to increase the RF gradient, which increases the depth of the bucket. In the previous work [2], this was found to be effective. However, in the current lattice design, increasing the gradient was ineffective. Figure 9 shows the resulting emittances and particle losses with the gradient increased by steps of 1.5 MV/m in the last 8 stages. Note that the red line shows the default value of 26 MV/m while the yellow line corresponds to 46 MV/m which is the maximum gradient simulated. It is possible to obtain better performances if the beam is matched for each gradient accordingly. This will be investigated in more detail in a future study.

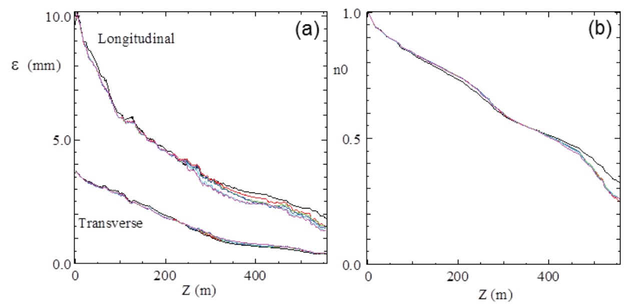

Figure 9: Emittances with varying RF gradients. The emittance is reduced with each 1.5 MV/m increment. The black curve, without space charge, is for reference. (b) Fraction of beam remaining for varying RF gradients. The black curve, without space charge, is for reference.

CONCLUSIONS

Towards the end of the cooling channel, the density of the muon bunch becomes significant enough that space charge effects can become important. A simulation campaign has been carried out, using the Warp code, to examine the effects. Warp uses a fully self-consistent PIC model to include space charge. The simulations show that there is little effect on the emittance, but an increase in the particle loss. Most of the particle loss is longitudinal, out the tail of the bunch. Unfortunately, the simple remediation of increasing the RF cavity gradient was not effective. Work examining other techniques to reduce particle loss will continue.

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REFERENCES

[1] R. B. Palmer, Proc. of PAC 2007, Albuquerque NM, p. 1222 (2007).
[2] D. Stratakis et al., Proc. of IPAC 2013, Shanghai, China, p. 1553 (2013).
[3] J.-L. Vay, D. P. Grote, R. H. Cohen, A. Friedman, Comput. Sci. Disc. **5** (2012) 014019.
[4] D. Stratakis et al., Proc. of NA-PAC 2013, Pasadena CA, THPHO12.
[5] D. Stratakis et al., Phys. Rev. ST Accel. Beams **16**, (2013) 091001.

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