

PROGRESS ON BEAM-PLASMA EFFECT SIMULATIONS IN MUON IONIZATION COOLING LATTICES*

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Abstract

New computational tools are essential for accurate modeling and simulation of the next generation of muon-based accelerators. One of the crucial physics processes specific to muon accelerators that has not yet been simulated in detail is beam-induced plasma effect in liquid, solid, and gaseous absorbers. We report here on the progress of developing the required simulation tools and applying them to study the properties of plasma and its effects on the beam in muon ionization cooling channels.

INTRODUCTION

Though muon accelerator simulation codes have been steadily improving over the years, there is still much room for improvement. Many single-particle processes and collective effects in vacuum and matter, such as space charge, beam-beam effects, plasma effects from ionized electrons and ions have not been implemented in any current code. These effects have to be either deemed negligible or taken into account to ensure the proper accuracy of simulations.

Ionization cooling (principle illustrated in Fig. 1) is a method by which the emittance of a muon beam can be reduced. A beam is sent through a material, losing momentum through multiple scattering and ionization processes, and reducing its emittance. By re-accelerating the beam through RF cavities, the longitudinal momentum is restored, and any lost energy is regained so that the process can be repeated.



Figure 1: Principle of ionization cooling: 1) The overall momentum is reduced through ionization where $\langle \frac{dE}{dx} \rangle$ is the mean energy loss of the muons. 2) Transverse momentum increases through multiple scattering. 3) Through re-acceleration, longitudinal momentum is regained.

The evolution of the normalized transverse emittance can be described by the following equation:

$$\frac{d\epsilon_n}{dz} \approx -\frac{1}{\beta^2} \left\langle \frac{dE_\mu}{dz} \right\rangle \frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta_\perp E_s^2}{2E_\mu mc^2 X_0},$$

where ϵ_n is the normalized emittance, z is the path length, E_μ is the muon beam energy, $\beta = v/c$, X_0 is the radiation length of the absorber material, β_\perp is the betatron function, and E_s is the characteristic scattering energy [1]. Here, two

competing effects can be seen: the first term is the cooling (reduction of phase space beam size) component from ionization energy loss and the second term is the heating (increase of phase space beam size) term from multiple scattering. For minimizing heating, a small betatron function from a strong magnetic field and a large radiation length are needed. To maximize cooling, a large stopping power is needed, $\left\langle \frac{dE_\mu}{dz} \right\rangle$. Hydrogen seems to give the best balance between a large radiation length and a large stopping power.

Muons will ionize material as they travel through absorbers. This will generate a plasma, and it is the interaction of the muon beam with the generated plasma that is studied here. Beam-plasma interaction is not taken into account currently in a majority of muon accelerator simulation codes. This interaction is especially important when simulating ionization cooling in the hybrid cooling channels with medium-to-high pressure gas-filled RF cavities (Fig. 2).

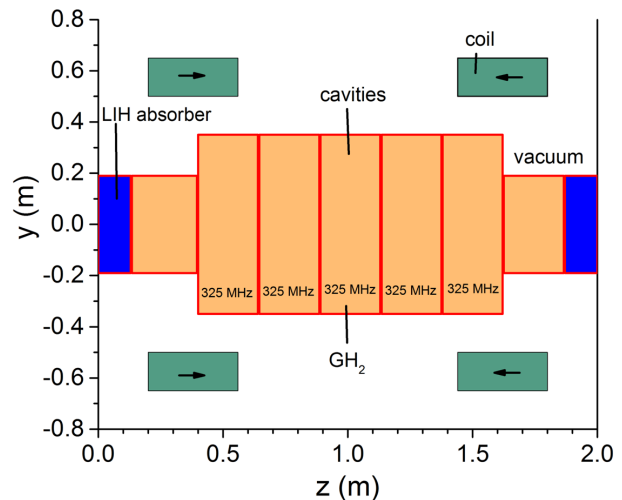


Figure 2: Example of a matter-dominated hybrid cooling channel with gas-filled RF cavities, nearly all the cell length has material: either medium-pressure gaseous hydrogen or LiH absorber. (Image courtesy of D. Stratakis)

The plasma effects have been studied by plasma physicists, but have not been studied extensively from a beam physics point of view. The plasma has been shown not to disrupt the beam or make it blow up dramatically [2], however, for ionization cooling purposes beam-plasma effects may have a large impact on the cooling rates for both charges of muons. Essentially, the head of a bunch sees a material with different properties than the tail of the bunch and whole bunches may see materials with different properties than the previous bunches. Ionization rates vary from material to material so

* Work supported by the U.S. Department of Energy.

the effects may be more prominent in some materials than others.

SIMULATIONS

After several simulation packages were considered, the one found to best suit our needs was WARP [3]. WARP is an actively developed particle-in-cell (PIC) simulation code designed to simulate particle beams with high space-charge intensity.

Several ionization models were considered to generate the plasma including multiple ways to introduce the plasma manually, but ultimately the ionization module contained within WARP was used. Given an ionization cross section,

$$\sigma = \left\langle \frac{dE}{dx} \right\rangle \frac{1}{W_i} \frac{\rho}{\rho_n},$$

WARP will generate the plasma on its own. Here, $\left\langle \frac{dE}{dx} \right\rangle$ is the mean rate of energy loss by the muons, W_i is the average energy to produce an ion pair, and ρ and ρ_n are the mass and atomic densities of the medium, respectively.

In the proof-of-concept simulations with an highly dense muon beam, it was seen that beam-plasma effects can significantly alter the simulation. The bunch shape varied drastically when comparing the simulation results with and without plasma effects [4]. WARP proved to calculate the desired effects fairly efficiently, with a factor of six slow down when plasma effects were included.

The main result of the beam-plasma interaction is the effect of charge neutralization. Consider a bunch of positive muons ionizing a material. Due to space charge effects, muons will tend to spread out. When the plasma is created, the plasma electrons are mobile, while the ions are not. The electrons are attracted to and move towards the center of the bunch, lowering the net charge and reducing the repelling space charge force felt by the muons. Overall then, the spread in the bunch tail is less than the spread in the bunch head.

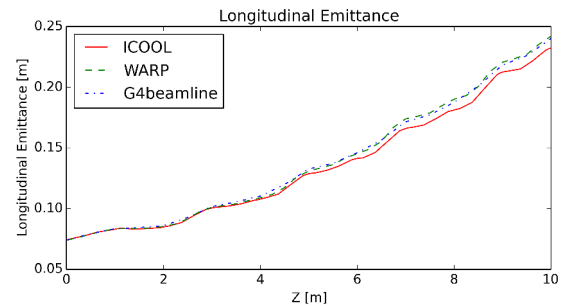
PROGRESS ON SIMULATIONS

Beam-plasma effects have been shown to potentially have a significant impact on the shape of a muon bunch. This impact needs to be quantified, and the effect on cooling rates needs to be studied. To do this, a section of a realistic cooling channel has to be simulated.

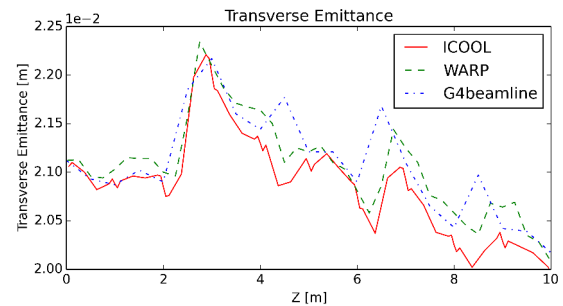
In the previous simulations, scattering and straggling have not been taken into account due to the lack of these features in WARP. Subsequently, a WARP-ICOOL wrapper has been used [5], incorporating into WARP the scattering and straggling processes from ICOOL [6]. At the end of each step inside the material, WARP calls the relevant ICOOL processes and applies them to the particles in the simulation.

A complete cooling cell based on the first stage of the current version of the rectilinear cooling channel has been modeled with the layout similar to Figure 2. This cell consists of four solenoidal coils producing a maximum magnetic field of 2.36 T, six 325 MHz RF cavities with a maximum

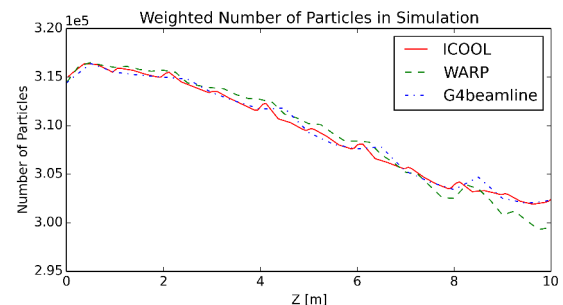
gradient of 22 MV/m and accelerating phase of 14° , and 10.5 cm of liquid Hydrogen absorber between solenoids. Due to current limitations, flat absorbers are used in place of wedge absorbers and magnetic coils are not tilted. This channel was simulated in WARP, ICOOL, and G4beamline [7], with all stochastic effects taken into account but ionization. Due to the input differences between the simulations, the initial beam was loaded into WARP and ran for one cell with no material, with the results at 2 m used as input for the other simulations. Results were compared using Ecalc9 [8] and are summarized in Figure 3. Since all three codes agree for the case with no ionization, moving forward we limit ourselves to comparing only the WARP simulations with ionization effects on and off.



(a) longitudinal emittance



(b) transverse emittance



(c) particle transmission

Figure 3: Comparison of ICOOL (red), WARP (green), and G4beamline (blue) simulations through 5 cells (10 m) of the first stage of the rectilinear cooling channel.

Since only WARP was used, there were no input differences between codes, allowing the beam to start centered at 0 m. Results were again gathered and compared using

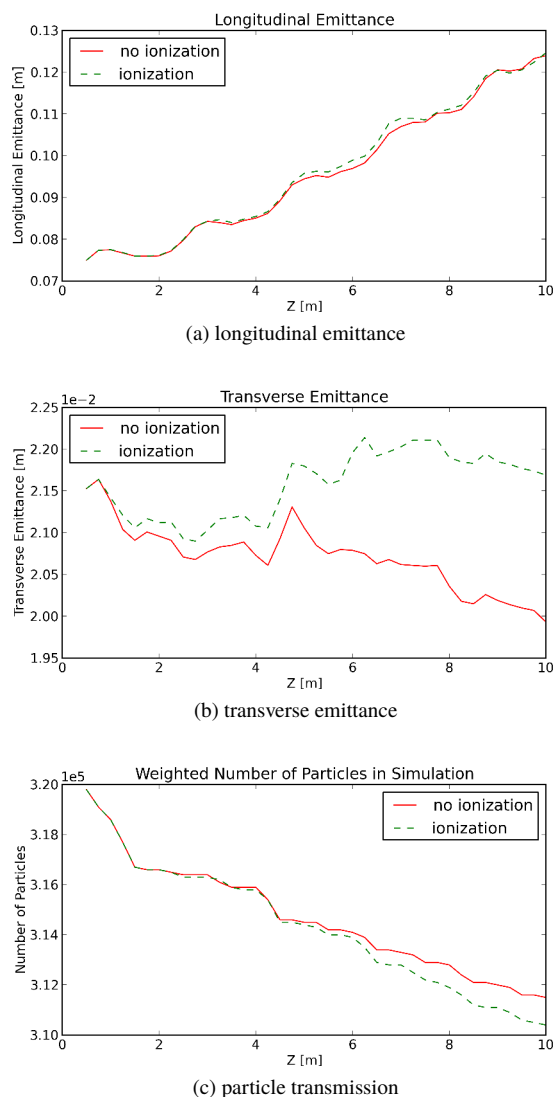


Figure 4: Comparison of WARP simulation with (green) and without (red) ionization through 5 cells (10 m) of the first stage of the rectilinear cooling channel. Data starts at the first virtual detector.

Ecalc9 and are summarized in Figure 4. The difference in the particle transmission (Fig. 4(c)) after 5 cells is 0.35%.

The most notable feature of the simulation is an 8% increase in the transverse emittance (Fig. 4(b)) compared to the case with no ionization, and a difference of this magnitude shows that beam-induced plasma effects should not be neglected for muon accelerators.

CURRENT CHALLENGES

The results shown here are from a model based on the first stage of the proposed rectilinear cooling channel. The muon beam and electromagnetic fields will be much stronger in the later stages. It is expected the beam-induced plasma effects will be more dramatic.

The plasma's behavior during and after generation are being improved upon.

With a large number of particles to be tracked when plasma is generated, resource needs have expanded. Due to memory and speed concerns, especially for longer runs, the simulations are being benchmarked and adapted for optimum running time and resources needed, including running simulations in increments.

A few real world experiments have been identified to potentially model with WARP. This could provide us with verification of our models.

ACKNOWLEDGMENT

Authors would like to thank Alvin Tollestrup, Ben Freemire, and Katsuya Yonehara for many fruitful discussions, along with David Grote and Jean-Luc Vay for assistance with the WARP simulation package they (and others) developed.

This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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