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 accelerator experiments. One of the crucial physics processes specific to muon accelerators that has not yet been implemented in any current simulation code 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 a any current code. In order to ensure proper accuracy of simulations, these effects have to be either deemed negligible or taken into account.

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 the process can be repeated.

Figure 1: Principle of ionization cooling: 1) The overall momentum is reduced through ionization where $\left\langle \frac{dE}{dx} \right\rangle$ 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, $\beta_\perp$ 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).

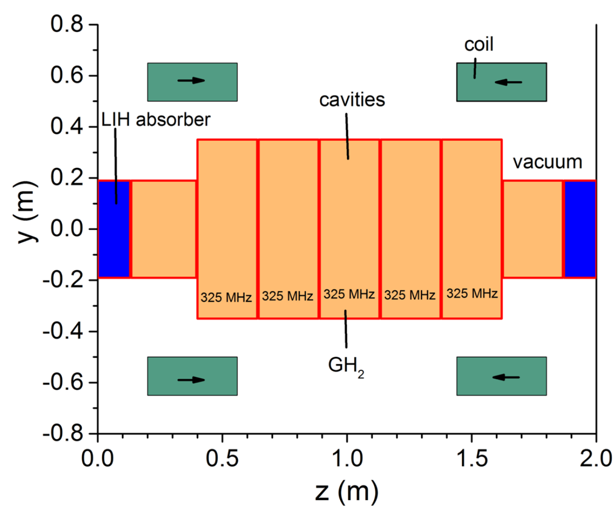

Figure 2: Example of a matter-dominated hybrid cooling channel with gas-filled RF cavities, nearly all the cell length has material: either medium-pressure gaseous hydrogen or LiH absorber.

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 to not disrupt the beam or make it blow up [2], however for ionization cooling purposes, beam-plasma effects may have a large impact on the cooling rates for both charges of muon. 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.

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Ionization rates vary from material to material so the effects may be more prominent in some materials than others.

QUALITATIVE 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. A dense Gaussian beam of muons ($N = 10^{12}$, $p = 200$ MeV/c) was sent through a solenoidal magnetic field ($B = 5.46$ T) and hydrogen gas (180 atm) with ionization and space-charge effects turned on only (multiple scattering and energy straggling were not implemented).

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, WARP will generate the plasma on its own where the cross section σ is given by

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

where $\left\langle \frac{dE}{dx} \right\rangle$ 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.

It was seen that beam-plasma effects can significantly alter the simulation. The bunch shape varied drastically when comparing the simulation with and without plasma effects [4]. WARP can calculate the desired effects fairly efficiently. In these simulations, there was a factor of six slowdown when including plasma, which was not prohibitive.

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 an accurate 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 been neglected, due to the lack of these features in WARP. Recently, 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 material, WARP calls the relevant ICOOL processes and applies them to the particles in the simulation.

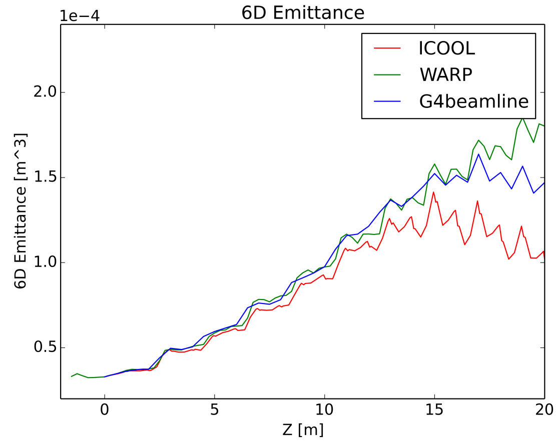

Figure 3: Comparison of ICOOL (red), WARP (green), and G4beamline (blue) simulations through 10 cells of the first stage of the rectilinear cooling channel: 6D emittance.

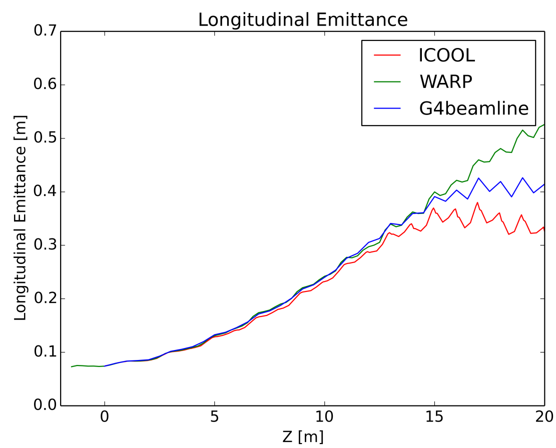

Figure 4: Comparison of ICOOL (red), WARP (green), and G4beamline (blue) simulations through 10 cells of the first stage of the rectilinear cooling channel: longitudinal emittance.

A complete cooling cell based on the first stage of the current version of the rectilinear cooling channel has been modeled [7, 8], similar to 2. This cell consist 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 21 cm blocks 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 has been simulated in WARP, ICOOL, and G4beamline [9], with all effects 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 gathered and compared using Ecalc9 [10] and are summarized in Figures 3–6.

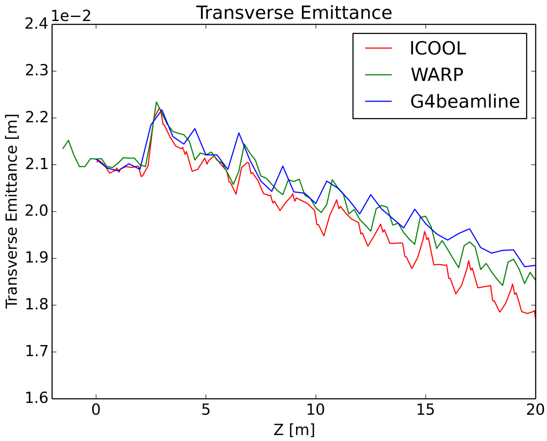

Figure 5: Comparison of ICOOL (red), WARP (green), and G4beamline (blue) simulations through 10 cells of the first stage of the rectilinear cooling channel: transverse emittance.

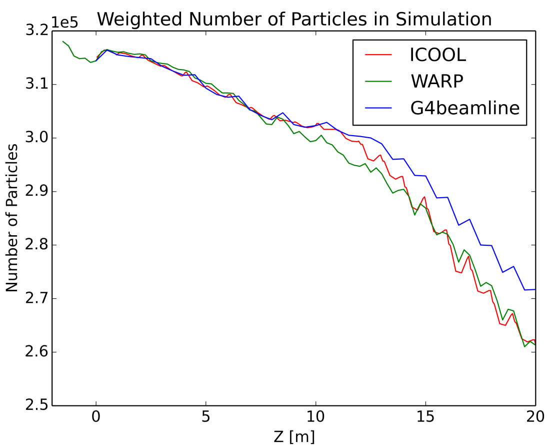

Figure 6: Comparison of ICOOL (red), WARP (green), and G4beamline (blue) simulations through 10 cells of the first stage of the rectilinear cooling channel: particle transmission.

CURRENT CHALLENGES

Thorough quantitative studies are underway with plasma effects included. Unlike the qualitative trials, a detailed simulation requires many more particles and computing power. Macroparticles are used in lieu of individual particles, and this must be balanced properly between the beam muons and plasma electrons.

As seen in Figure 3, after around five cells (10 m), the 3 simulations without plasma start to diverge. There are several possible causes, including edge effects from field maps that accumulate and coarseness of grid spacing. ICOOL and G4beamline step forward in z, while WARP steps forward in time. Due to this, particle collection on virtual detectors and particle scraping are handled differently. All of these issues are currently being investigated.

Due to the large number of particles that need to be tracked when plasma is generated, resource needs have expanded. Simulations are now being run mainly at NERSC (National Energy Research Scientific Computing Center) on its two main supercomputers: Cori and Edison. Due to memory and speed concerns, especially for longer runs, the simulations are being benchmarked and adapted for optimum running time and resources needed.

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

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