SIMULATIONS OF SPACE CHARGE NEUTRALIZATION IN A MAGNETIZED ELECTRON COOLER

James Gerity, Peter M. McIntyre, Texas A&M University, College Station, Texas
David Leslie Bruhwiler, Christopher Hall, RadiaSoft LLC, Boulder, Colorado
Vince Jan Moens, EPFL, Lausanne, Chong Shik Park, Giulio Stancari, Fermilab, Batavia, Illinois

Abstract

Magnetized electron cooling at relativistic energies and Ampere scale current is essential to achieve the proposed ion luminosities in a future electron-ion collider (EIC). Neutralization of the space charge in such a cooler can significantly increase the magnetized dynamic friction and, hence, the cooling rate. The Warp framework is being used to simulate magnetized electron beam dynamics during and after the build-up of neutralizing ions, via ionization of residual gas in the cooler. The design follows previous experiments at Fermilab as a verification case. We also discuss the relevance to EIC designs.

INTRODUCTION

The nuclear physics community has identified the construction and operation of a high-luminosity polarized electron-ion collider (EIC) as a top priority in answering pressing questions about the structure of nuclear matter [1]. In the United States, the design of both Jefferson Lab's JLEIC [2] and Brookhaven's eRHIC [3] rely on electron cooling to reach their target luminosity. The novel strategies these projects employ for high-energy cooling (bunched cooling and coherent cooling, respectively) are promising, but also represent substantial R&D risk, motivating detailed study of possible improvements to DC electron cooling at intermediate energies. In particular, strong magnetization of the electron beam enhances cooling [4] by transverse confinement of electrons, so that the Coulomb interactions with the ion beam effectively only see the longitudinal degree of freedom. This enhancement is useful up to a "drift velocity" stability limit that shears the beam apart due to the combined effects of magnetization and strong space-charge, which scales with $\vec{E}_{s.c.} \times \vec{B}$. If the electron beam space charge is neutralized, this limit can be removed, enabling the use of stronger magnetization and higher electron beam current. A previous proposal [5] makes the case for using an intense beam of neutralized and magnetized electrons for cooling in an EIC.

IONIZATION

Warp includes an Ionization class that handles ionization interactions between arbitrary species, producing arbitrary secondaries. The implementation in the most recent version uses the total ionization cross-section when randomly deciding if an ionization occurs between particles on any particular check. A full treatment of these interactions necessitates the use of differential cross-incident and emitted species as well as the angle of emission, as described in [6] and [7].

To this end, an extended Ionization class has been developed as part of rswarp [8] to allow for this more complete description of ionization physics. The extended class allows the user to specify the energy distribution of emitted species as arbitrary functions of incidence parameters. Also included is an implementation for sampling the differential cross-section described in [6, 7] using an algorithm originally developed for XOOPIC [9]. Several of the solvers included with Warp do not include native routines for exporting particle and field data for offline analysis, and the rswarp module also includes classes for exporting these data in a format compliant with the OpenPMD standard [10].

PRELIMINARY RESULTS

A validation case* was simulated in the form of a 10 mA beam of 116 keV electrons traveling over a 1 m drift with a periodic field constraint on the longitudinal boundaries. The beam was generated with a transverse KV distribution and Gaussian velocity distribution with $\Delta p/p = 1\text{e-}3$. The electron beam spatial profile is shown in Fig. 1. All species were absorbed at the boundaries of the computational domain.

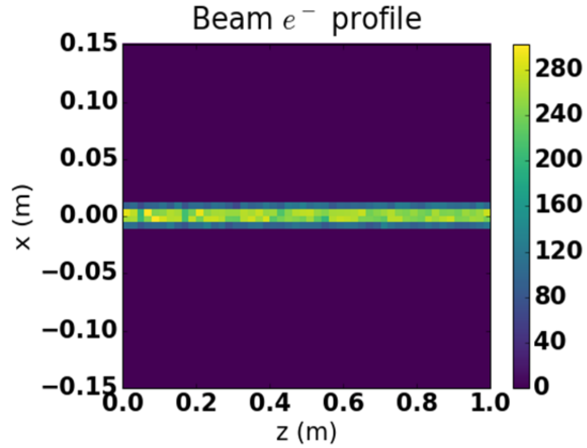

Figure 1: Beam profile at 0.5 μs, binned by macroparticle count. The single-pass beam is not noticeably disrupted by its interaction with the background gas.

The beam was simulated both with and without ionization of a background H_2 gas enabled, and the resulting beam self-fields were compared to assess the neutralizing effect of the ionized gas (see Fig. 2). Ionization caused by emitted secondary electrons was not considered in the interest of simulation runtime. As shown in Fig. 3, fast

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* Full source code for this simulation is freely available as part of the rscooler repository [11]. See the *10mA_DC_ionization* example.

equilibration of emitted electrons was observed, consistent with this exclusion. The onset of neutralization of the beam was observed, with the ions suppressing the electron self-field by ~10% at the longitudinal center of the domain (see Fig. 4). The results shown here do not include the effect of an imposed solenoidal magnetic field, which was sufficiently resolved in separate dedicated simulations.

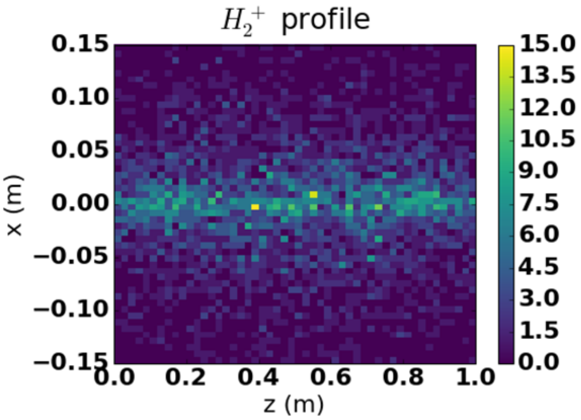

Figure 2: Ion profile at 0.5 μs, binned by macroparticle count.

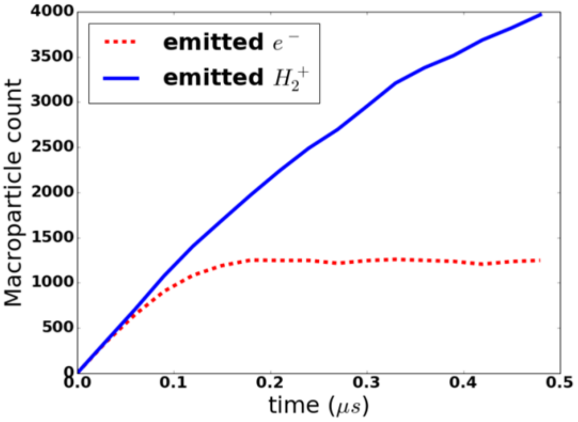

Figure 3: Particle population during a simulation including ionization of residual gas. The emitted electrons rapidly reach equilibrium, owing to their lower mass.

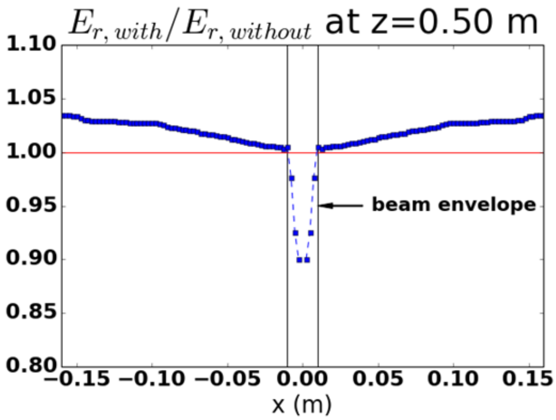

Figure 4: Ratio of radial self-field observed with and without ionization of residual gas, showing reduction in field strength in the beam core when ions are present.

FUTURE WORK

Continuation of this work will involving scaling these simulations to Ampere currents and replicating prior Fermilab cooling experiments involving a magnetized, neutralized beam [4, 12]. Of particular interest is verifying the presence of the "electron wind" instability seen in these experiments. It is likely that these larger-scale simulations will be conducted with supercomputing resources from e.g. NERSC.

Once these experiments can be reproduced with good fidelity, a greater degree of beam magnetization can be studied. In doing so, we will study the matching a beam 'born' in a magnetic field into a cooling solenoid, as described in [13]. Simulations of single-pass interaction with an ion beam will be conducted in order to assess the enhancement in cooling rate that strong magnetization and neutralization provide. With this information in hand, the benefits such a cooler can provide for beam quality and lifetime at an EIC can be quantified by detailed study of a circulating ion beam with continuous cooling.

CONCLUSION

The neutralizing effect of residual gas ionization in a simulated beam has been successfully observed. A fuller understanding of the beam instabilities that may develop in a strongly magnetized and neutralized cooler will be necessary to the design of a system based on this premise. Once this validation case is in hand and the dynamics responsible for these instabilities can be adequately resolved, we will begin simulation of a beam as envisioned for cooling at intermediate energies at a future electron-ion collider, with the goal of developing a robust estimate of the cooling rate for use in many-turn cooling studies of these proposed machines.

ACKNOWLEDGMENT

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