REDUCING EMITTANCE OF A H⁻ BEAM IN A SOLENOID-BASED LOW-ENERGY BEAM TRANSPORT THROUGH NUMERICAL MODELING*

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Abstract

A solenoid-based low-energy beam transport (LEBT) subsystem is under development for the H^- linac front end of the Spallation Neutron Source. The LEBT design includes MHz-frequency chopping of a partially neutralized H^- beam that can potentially lead to beam instabilities. We report results of numerical modeling using the parallel VSim [1] framework for 3D electrostatic particle-in-cell (PIC) to simulate H^- beam dynamics in the LEBT, over multiple chopping events. We detail how the addition of a positively biased potential barrier near the entrance of the chopper can improve LEBT performance by eliminating chopper-induced emittance increases over many chopping events.

INTRODUCTION

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory provides the most intense pulsed neutron beams in the world for scientific research and industrial development. It has been recently proposed to upgrade the power of the SNS by increasing the accelerated beam energy by 30%. Such upgrade entails increasing the H^- beam current that reaches the radio frequency quadrupole (RFQ) through the low-energy beam transport (LEBT) to 60 mA. The existing electrostatic LEBT operating with such high current is vulnerable to beam loss and sparking. Therefore, physicists at ORNL have proposed to replace the electrostatic LEBT by a two-solenoid magnetic LEBT [2, 3] which lacks of the sparking problem and can transport high-current space-charge neutral beams.

The LEBT includes a chopper that deflects the beam away from the RFQ at periodic intervals at MHz frequency rate, which is required for extracting the beam from an accumulator ring with minimum loss [4]. Also, the H^- beam in the solenoid-based LEBT includes positive ions created through collisions reactions between H^- and the neutral H_2 background gas. It has been suggested that the influence of the MHz chopper in the ions dynamics can ultimately lead instabilities in the H^- beam.

Here, we carry out simulation of the solenoid-based LEBT and analyze its performance. We use the VSim particle-in-cell framework that includes a variety of physical models for plasma simulation.

SIMULATION METHOD

The LEBT at the SNS connects the H^- ion source with a radio-frequency quadrupole (RFQ) accelerator. The details of the proposed solenoid-based LEBT, shown in Fig. 1, can be found in Ref. [4]. The magnetic LEBT features two solenoids and has an intermediate dipole magnet that allows for switching between two ion sources. Between the second solenoid and the RFQ there is a four-quadrant circular aperture electrical beam chopper use for steering of the H^- beam.

Our simulation domain begins 32 cm to the left of the second solenoid and includes the second solenoid fields, the chopper and the RFQ. The solenoid is assumed to have a radius of 7.2 mm and 13.5 cm length. Its field strength is tuned to achieve the desired beam focus. The beam is emitted from the left boundary of the simulation domain with a 2.1-cm radius at an angle of 10 mrad. The current is set to 47 mA and 60 mA in different simulations and the energy of the H^- ions is 65 keV.

To describe the relevant collisional processes, we use the Monte Carlo collision models implemented in VSim. The H^- beam, as it passes through the simulation domain, interacts with a uniform background H_2 gas, modeled here

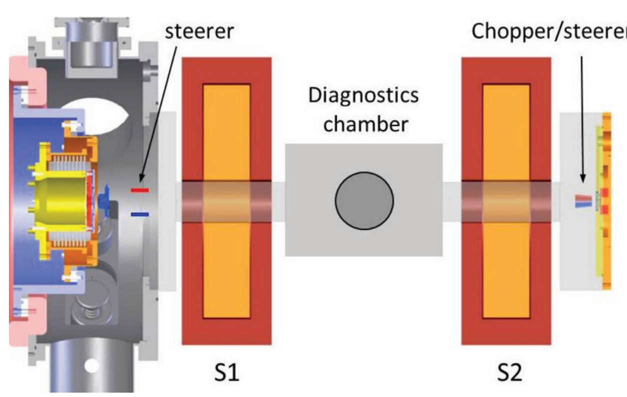

Figure 1: A schematic view of the 2-solenoid SNS LEBT. (Reprinted from Ref. [4].)

* This work is supported by the US DOE Office of Science, Office of Basic Energy Sciences, including grant No. DE-SC0000844. This research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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with a density of $n_{H_2} = 3.33 \times 10^{16}$ m^{-3}. These two species interact mainly through two collisional processes: the detachment of an electron from H$^-$, which produces H atoms, and the ionization of H_2, which produces H_2^+. The secondary species produced by these collisions interact with each other and with the primary species. Four other reactions are described in Ref. [5] including the secondary and primary species. These collisions have been implemented in Monte Carlo collision models of VSim which uses the relevant collision cross-section data from Evaluated Electron Data Library (EEDL) of the Lawrence Livermore National Laboratory [6].

Of all the species generated by the collisions, H_2^+ plays a key role in neutralizing the beam. In order to reach an equilibrium condition in shorter simulation times, the H$^-$ and H_2^+ are initialized following the method described in Ref. [7]. The H$^-$ beam is initialized so that it follows the trajectory of a neutralized beam that focusses in the RFQ and H_2^+ ions are distributed in order to neutralize the H$^-$ beam. To further accelerate the neutralization process the collisional cross-sections are enhanced by a factor of 50 for the first 17 μs of the simulation.

During the first microseconds of simulation time, the neutralization of the H$^-$ was monitored [7]. After 10 μs the neutralization reaches an equilibrium value of $\alpha = 0.5$. Here, $\alpha = 1 - \frac{|\Sigma\rho(t)|}{|\Sigma\rho_0^{H^-}|}$ where the numerator ρ is the net charge density of the H$^-$, H_2^+, and electrons in the RFQ entrance and the denominator $\rho_0^{H^-}$ is the equilibrium value of the charge density of an unneutralized H$^-$ beam in the LEBT.

During these first microseconds the emittance of the beam in the RFQ show clear oscillations about a mean value of $\tilde{\epsilon_n} = 0.33\ \pi$ mm-mrad. A Fourier analysis of the emittance signal shows a primary oscillation frequency of 1.7 MHz. This frequency falls in the range of relevant H_2^+ plasma and cyclotron frequencies which might explain the origin of these oscillations. Also, the 1 MHz chopping frequency also falls in the relevant range of plasma and cyclotron frequencies. Thus, our analysis suggest that the chopping mechanism might activate a resonant behavior which could affect the performance of the beam.

EFFECTS OF BEAM CHOPPING

The neutralization process and the chemical reactions lead, after roughly 20 μs, to steady distributions of H, H$^-$, H_2, H_2^+ and e^- (see Fig. 2). This is our starting point for the analysis of the dynamics associated with the chopping mechanism. The chopper bends the beam in four directions in the xy plane. The chops occur every 1 μs and last for 0.1 μs, i. e. with a 10% duty cycle. To analyze instabilities in the LEBT setup, different observables are measured at the RFQ region. Here we focus on the analysis of the current and emittance.

The H$^-$ particles are emitted at the left of the simulation volume. For the first simulations, we set the current of these emitted particles to be 47 mA and its normalized rms emittance to be 0.35 π mm-mrad. Note also that the minimum reached emittance during the chop depends on whether the chop is in the same axis as the measured emittance or it is perpendicular to the measured emittance. For example, the emittance measured in the x-v_x plane reaches a lower minimum if the beam is bent in the x direction than it is bent in the y.

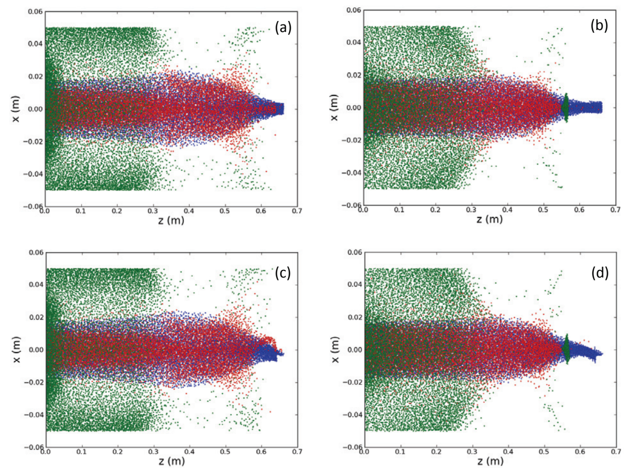

Figure 2: Snapshots of scatter plot of charged particles in 3D VSim simulation of SNS LEBT. (Red: H2+. Green: H-. Blue: electrons.) Left (Right) column figures correspond to a system in the absence (presence) of a positively biased potential barrier. Top (bottom) row shows snapshots when the chopper is off (on).

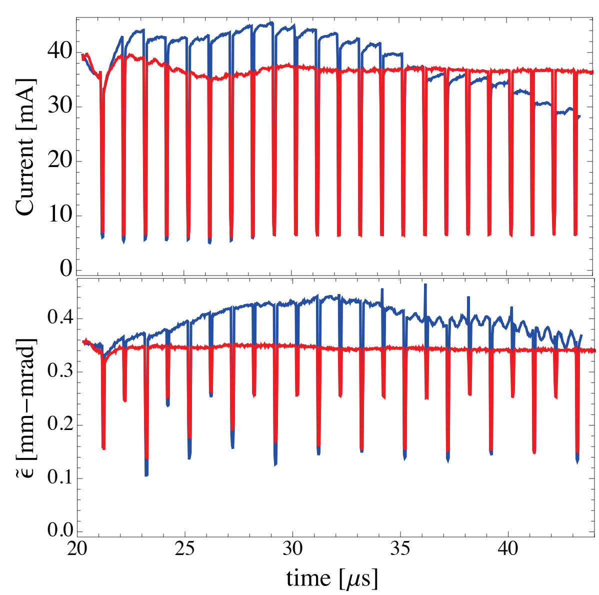

Figure 3: Evidence of improved stability in H- observables measured after the chopper. Blue curves represent results without the entrance aperture and red curves results with the entrance aperture included.

ISBN 978-3-95450-122-9

The results for the current and the emittance in the RFQ are presented as blue curves in Fig. 3. The emittance shows a clear initial increase most likely due to heating and then a decrease likely related to a decrease of the current. After several chopping events, oscillations appear in the emittance. The typical frequency of these oscillations is roughly 1.7 MHz which is similar to the oscillation frequency observed in the emittance at the beginning of the simulation. These frequencies fall within the range of typical H_2^+ cyclotron and plasma frequencies relevant to the system. Thus, it is likely that the chopping mechanism is activating either a plasma or cyclotron oscillations in the system. The blue curves in Fig. 3 illustrate the sort of instabilities produced by the chopping mechanism that would lead to a poor performance of the LEBT system.

To reduce these instabilities, we propose a new LEBT design that includes a 1kV entrance aperture 3 cm to the left of the chopper. The entrance aperture goal is to prevent H_2^+ particle from penetrating in the chopper region. The red curves in Fig. 3 correspond to results obtained with the entrance aperture. Since the entrance aperture is included after the equilibration process, there is initially a significant number of H_2^+ particles at the right of the entrance aperture. These particles are removed by the first chop. We can see that the current and emittance show a significantly more stable behavior in comparison with the simulation based on the original design.

The dynamics in the chopper region provides insight in the instabilities produced by the chopping mechanism (see Fig. 4). In the absence of an entrance aperture, the H_2^+ reenters in the chopper region affecting the H^- beam dynamics. Thus, the H_2^+ density in the chopper region grows roughly linearly with time between chopping events. In contrast, in the presence of an entrance aperture, the H_2^+ cannot reenter the chopper region after the first chop.

However, there is a second source of H_2^+ in the chopper region. Chemical reactions between H^- and H_2 lead to the formation of H_2^+ between chopping events. This process is also roughly linear with time between chopping events but is significantly slower than the reentering of the H_2^+ in the absence of an entrance aperture. Thus, the H_2^+ densities reached between chops does not affect substantially the H^- beam dynamics and the H^- beam dynamics is more stable.

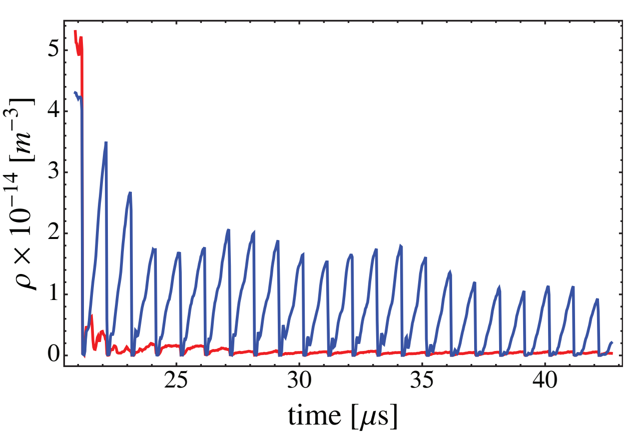

Figure 4: H_2^+ density at the center of the chopper region. Blue curves represent results without the entrance aperture and red curves results with the entrance aperture included.

The new design also improves other technical aspects of the LEBT performance. While the H^- particles are slightly steered by the chopper electric field, H_2^+ particles are displaced drastically hitting the chopper surface. This will eventually damage the chopper. By introducing the entrance aperture, the H_2^+ density in the chopper region is significantly reduced producing less damage to the chopper surface. This represents another clear advantage of the proposed design.

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