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SIMULATIONS OF THE LEDA LEBT WITH H^+, H_2^+, AND E^- PARTICLES*

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Abstract

The low-energy-beam transport (LEBT) system for the Low-Energy Demonstration Accelerator (LEDA) transports the beam from the ion-source plasma surface to the LEDA RFQ entrance. The code PARMELA performed these simulations of the beam transport through the LEBT. This code can simultaneously transport three particle types of different charge-to-mass ratio. Electrostatic fields, magnetic fields, and space charge influence the beam particles in this simulation. The electrostatic fields exist in the ion-source extractor. The magnetic field exists in the ion source and in the solenoid lenses. The e^- particles, introduced into the beam of H^+ and H_2^+, simulate the space charge neutralization by the residual gas in the LEBT. The H^+ and H_2^+ ions leaving the source emerge from a longitudinal magnetic field, which causes the beam to rotate.

INTRODUCTION

Ions of H^+ and H_2^+ originate on a curved plasma surface, which intersects the beam axis at z = 0. The ions accelerate through the electrostatic fields of the ion source's accelerating column[1]. Then the beam goes through the LEBT, which has two magnetic solenoid lenses, and arrives at the input of the RFQ[2].

Two other papers[3,4] at this conference describe details of the LEBT for LEDA. Extensive modifications of the computer code PARMELA[5] added the ability to track multiple particle types. This paper discusses simulations of the LEBT that exploited this new multiple-particle feature. PARMELA can now track simultaneously three different particle species, each one with a different charge-to-mass ratio. The code can create new particles in the beam (e^-, for example) at the location of another particle (H^+, for example). One of the input parameters in the code is the probability for creating a new particle. This feature simulates space-charge neutralization of the H^+ and H_2^+ beam by electrons. The physical process is ionization of the residual gas in the beam line. The residual gas is mostly hydrogen. The ionization process strips an electron from the hydrogen molecule producing an H_2^+ ion and an electron. The space-charge potential well traps the e^- and expels the H_2^+ ion. The simulation ignores the H_2^+ ions created in this manner to speed the calculation. Note the distinction between these H_2^+ ions created by ionization of the residual gas and those that emerge from the source. The code does not ignore the H_2^+ ions emerging from the ion source.

PARMELA

First, PARMELA simulated the emittance measuring unit(EMU)[6] to validate the techniques used in the code. PARMELA uses time as the independent variable in the beam-dynamics simulations. Even though the beam has no bunch structure, PARMELA measures the time steps in degrees of the 350-MHz RFQ frequency. The goal of the simulation is to construct the input phase-space distribution of H^+ particles at the RFQ entrance. Because the PARMELA simulation starts with no beam at all, we must inject a long enough stream of H^+ and H_2^+ ions to reach a steady-state condition. One problem is that the H_2^+ ions move slower than the H^+ ions. To reduce the number of time steps in the calculation, PARMELA advances time faster for the H_2^+ ions so they keep up with the faster H^+ ions. With this adjustment, the beam arriving at the end of the LEBT after 20 350-MHz RF periods has achieved a steady state. The simulation continues through 40 RF periods, and the code builds a phase-space distribution from periods 20 to 30.

The program POISSON[7] calculated the electrostatic field of the ion-source accelerating column, the magnetic field from the Helmholtz coils surrounding the source, and the magnetic field of the solenoid lenses in the LEBT. PARMELA reads these fields and uses them in the beam-dynamics calculation. For the magnet calculations, measured values of the coil currents fix the magnetic-field strengths. For the electrostatic calculation, the only unknown is the radius of curvature r_p of the plasma boundary in the ion-source-extraction aperture. With different values of r_p, PARMELA followed the beam to the EMU at z = 213.5 cm. A video camera at z = 43 cm measures the beam profile. The value r_p = 4.9 cm reproduces the beam diameter measured by the beam profile monitor.

The amount of beam neutralization also affects the beam size. We varied the beam neutralization by changing the probability of introducing electrons. At every time step for each H^+ particle, PARMELA creates electrons at random according to this probability. The electron has the coordinates of the H^+ particle, but zero kinetic energy. For too large a probability, too many electrons are added to the beam, causing the space-charge potential well to disappear. Without the potential well, the e^- particles leave the beam radially.

Modeling the space-charge neutralization by injecting electrons works well until the beam approaches the solenoid lens. Here, the lens strongly focuses the e^- beam. After a long enough time (>400 RF periods), the electrons would eventually reach equilibrium. However, this calculation would take at least 10 times more particles and about 10 times more time steps. Such a calculation would require >900 hours on today's fastest PC. To reduce computation time, we switch to a different model of the space-charge neutralization for particles beyond z = 40 cm. After this point, we drop electrons from the calculation and assign only 4% of the normal charge to the H^+ or H_2^+ ions in the space-charge calculation. The value

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of 4% is consistent with a measurement (95-99%) of the space-charge neutralization[8]. The 4% value comes from comparing the simulated distribution (Figure 1) at the EMU position with the measured distribution (Figure 2).

Figure 3 shows the beam and the accelerating column. The electron suppressor at −1.2 kV prevents electrons from flowing from the neutralized beam to the ion source. This figure shows that the beam is neutralized by electrons beyond about 3.3 cm from the source. Electrons created closer to the source than this accelerate toward the source.

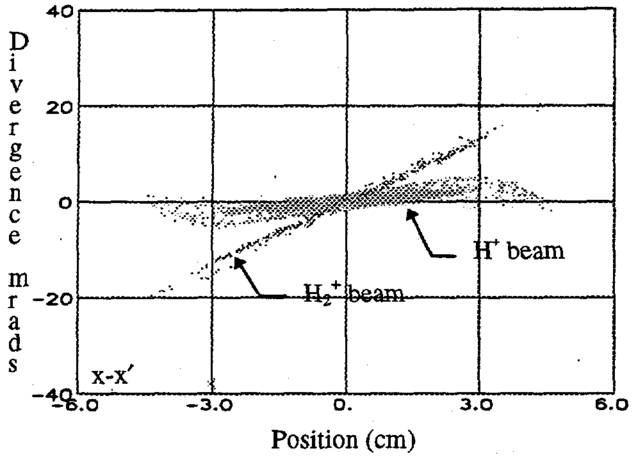

Figure 1. Simulated distribution of H^+ and H_2^+ at the position of the EMU. The solenoid lenses do not focus the H_2^+ beam as strongly as the H^+ beam, so the H_2^+ beam diverges more than the H^+ beam. This beam contains 118 mA of H^+ and 12 mA of H_2^+. The rms emittance of the simulated H^+ beam is 0.028 cm-mrad. (If viewing in color, H^+ ions are green and H_2^+ ions are red.)

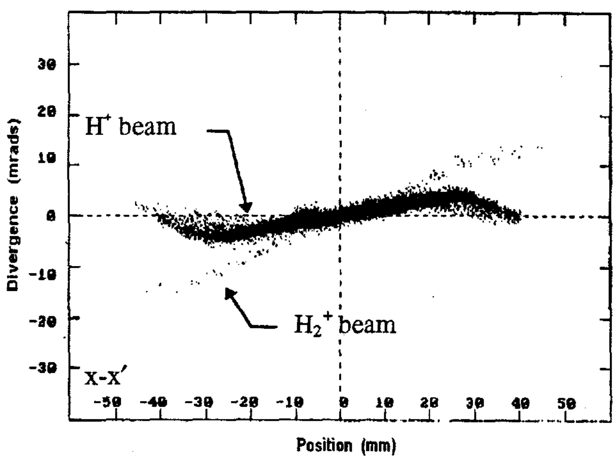

Figure 2. The measured beam distribution from the EMU. The rms emittance of this H^+ beam is 0.0207 cm-mrad.

Figure 4 shows equipotentials calculated by POISSON for the ion-source accelerating column. A comparison of electron locations in Figure 3 with the −954-Volt equipotential in Figure 4 shows that the electrons remain to the right of this equipotential.

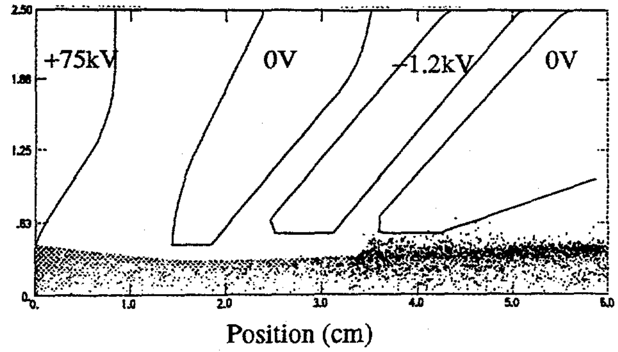

Figure 3. The ion-source accelerator column showing the simulated beam of H^+, H_2^+, and e^- particles. The −1.2-kV electrode suppresses the electron current flowing toward the ion source at 75kV. The dark black points are electrons. (If viewing in color, H^+ ions are green and H_2^+ ions are red.)

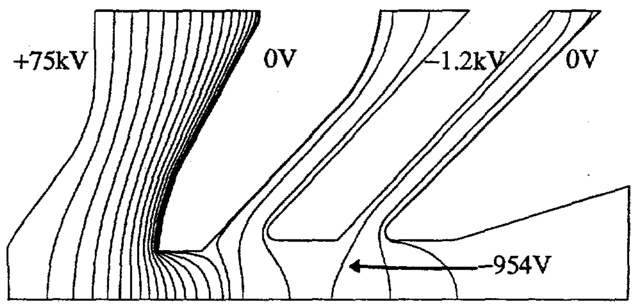

Figure 4. Equipotentials from the POISSON solution of the ion-source accelerating column. The equipotential spacing is dense near 0 Volts and sparse near 75 kV.

The best fit between the simulated beam size in Figure 5 and the measured beam size in Figure 6 occurred with a convex plasma surface with r_p = 4.9 cm at the ion-source extractor. The measured beam size depends on the ion-source parameters. The emittance scan data was taken Feb. 9, 1996 and the profile scan in Figure 6 was taken on Jan. 23, 1996. A simultaneous set of EMU data and profile data is not available.

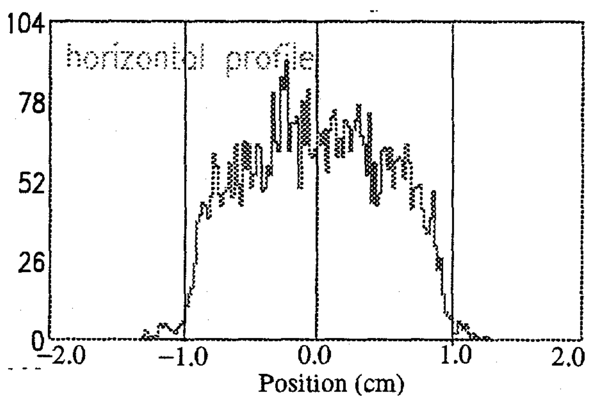

Figure 5. Simulated horizontal profile at 42.3 cm from ion source.

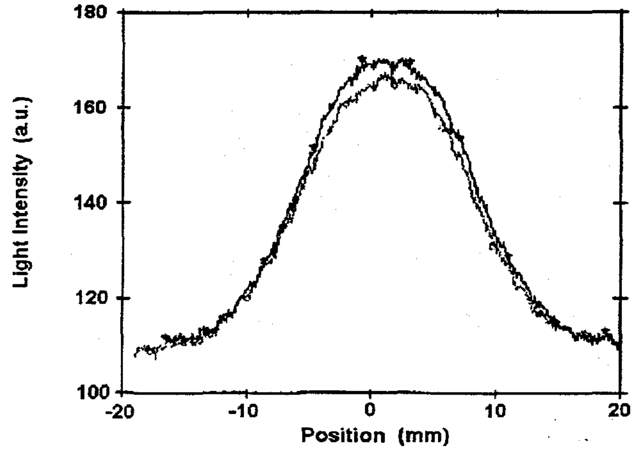

Figure 6. Representative profile from the video monitor at z = 43 cm. This profile was taken about 2 weeks earlier than the emittance scan shown in Figure 2.

The beam leaving the central part of the convex plasma diverges as shown in Figure 7. The outer part of the beam is focused strongly by the accelerating-column electrostatic fields. Because the plasma is in a strong longitudinal magnetic field (746 gauss), the beam begins to rotate as it leaves the magnetic field. Ions moving toward the axis in Figure 7 revolve around the axis, leaving a hole in the beam density near the axis beyond z = 15 cm. This hole persists throughout the EMU simulation.

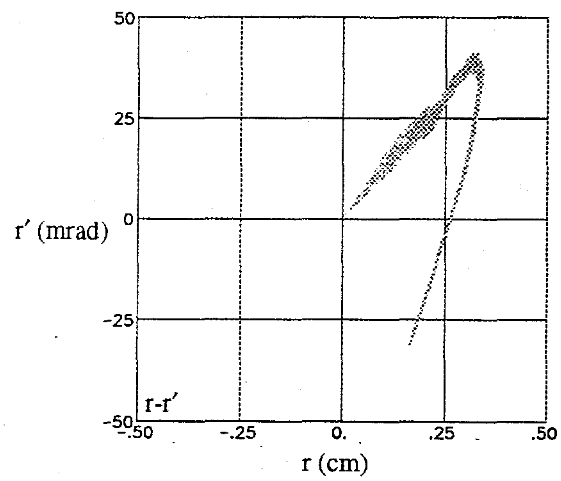

Figure 7. Plot of r versus r′ at 3.5 cm from ion-source extractor (near the point where the beam becomes neutralized). The convex plasma surface causes the center part of the beam to diverge. The shape of the electrodes focus the outer portion of the beam.

THE LEDA LEBT SIMULATION

PARMELA simulated the LEDA LEBT using the radius of the plasma surface determined from the simulation of the EMU. The space-charge neutralization factor of 4% used in the simulation of the EMU is also used in the simulation of the LEDA LEBT.

Initial simulations of the LEBT resulted in unsatisfactory input beam distributions to the LEDA RFQ. The transmission through the RFQ was less than the required 90%. Transmission is defined as the percentage of input beam that is accelerated through the RFQ. The radial aperture of the LEBT beam line through the last solenoid is 5 cm. Aberrations in the solenoid lenses focused the beam particles beyond 2.5 cm from the axis more strongly than the particles closer in. These beam particles at large radius are lost in the RFQ, spoiling the transmission. Installing 2.5-cm-radius apertures between the LEBT solenoid lenses removed particles from the beam that would later be lost in the RFQ. The RFQ transmission improved to 95%. Beam lost in the RFQ becomes H_2 gas. The RFQ vacuum system can pump the equivalent of 10 mA of H^+ and still maintain an adequate vacuum. In the LEBT, which is easier to pump, good vacuum is not as critical as it is in the RFQ. Therefore, using the apertures in the LEBT is desirable.

CONCLUSIONS

PARMELA simulations of the LEBT beam line showed that aberrations in the solenoid lenses reduced the RFQ transmission to unacceptable levels. One way to solve this problem is to install apertures in the LEBT. A better solution (not proven at present) might be to use solenoid lenses with less aberrations.

ACKNOWLEGEMENTS

I thank Joseph Sherman and Thomas Zaugg for Figures 2 and 5 that show typical data obtained from measurements on the beam from the LEDA ion source. I also thank Vernon Smith and Joseph Sherman for discussions on the properties of ion-source beams.

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