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STUDIES OF SPACE-CHARGE COMPENSATION OF POSITIVE IONS BY CREATING TIME-DEPENDENT SECONDARY ELECTRONS IN LOW-ENERGY BEAM TRANSPORT LINE

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Abstract

The space-charge neutralization of an ion beam by created electrons when the beam ionizes the gas is investigated using a three-dimensional electrostatic particle-in-cell code. Different kinds of injected gases are considered, and their space-charge compensation transient times are compared. The created secondary electrons by the beam collision with neutral gas along the beam trajectories are loaded in the simulation by a Monte Carlo generator, and their space charge contribution is added to the primary beam space charge densities. The injection and accumulation of secondaries are time-dependent and this process is continued until total space charge densities reach a steady state. In this study, a 2.4-meter LEBT line with two solenoid magnets is considered. Usually, the proton beam energy is 25 keV and the current level is around 10-15 mA. Additionally, beam extraction studies are conducted, and the extracted beam is used in both IBSimu and TraceWin codes for LEBT lines to validate the results.

INTRODUCTION

Space-charge compensation (SCC), or space-charge neutralization, occurs when a beam is propagating through the residual gas (or some injected gas) in the low-energy beam transport (LEBT) line and subsequently induces ionization of the molecules of this gas. In this case, the beam charge density may be varied along the trajectory, which affects beam parameters such as the transmission rate or the transverse phase space distribution.

In this study, to compensate for the beam potential of a positive ion beam, created electrons by different gases are introduced from outside. The electron creation rate is time-dependent and this progress continues until the space charge reaches steady state. Because of their different cross-sections, krypton, argon, and hydrogen gases produce different amounts of secondary particles in time, and their effects on proton beams are compared.

Two simulation codes are employed to model the low-energy part of the accelerator lattice. Specifically, IBSimu[1] is used for beam extraction from plasma and particle tracking, while TraceWin[2] is employed for particle tracking at low energy part to validate the results.

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KOMAC BTS LEBT LAYOUT

Korea Multi-purpose Accelerator Complex (KOMAC) Radio-Frequency Quadrupole (RFQ) Beam Test Stand (BTS) is a proton accelerator structure that accelerates the beam to 1 MeV/n. The RFQ BTS consists of a microwave ion source, an LEBT, an RFQ, and two beamlines, each with triple quadrupole magnets and a wire scanner. The layout of the ion source and LEBT is illustrated in Fig. 1.

The BTS LEBT line has been commissioned for proton ions generated from the microwave ion source of a 2.45 GHz magnetron. The proton beam is matched to RFQ by employing two solenoid magnets. To measure the phase space distribution of the beam in both vertical and horizontal directions, two Allison scanners are positioned approximately 1.2 meters downstream of the ion source. For measuring beam current, two Current Transformers (CTs) are located in the LEBT line, one just downstream of the ion source and the other in front of the RFQ.

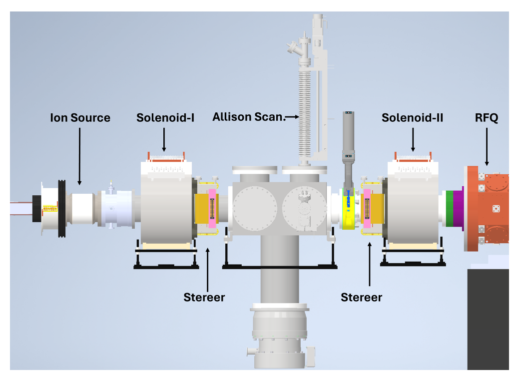

Figure 1: KOMAC BTS Ion source and LEBT line.

ION SOURCE EXTRACTION

KOMAC BTS ion source has a three-electrode extraction configuration. The plasma electrode with a 6 mm aperture is employed to extract a proton beam with an energy of 25 keV. Magnetic configuration and beam trajectories are simulated using the CST [3] and IBSimu, respectively. Figure 2 shows the magnetic field strength in axial direction. The plasma electrode is located a few mm downstream of the solenoid magnet and is shown with dashed line in the figure. The extraction configuration system is depicted in Fig. 3. The plasma electrode and secondary electrode are hold 25 kV and −2 kV, respectively, while the third electrode

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is grounded. The extracted beam current is 10-15 mA range and normalized emittance value is around 0.084 mm mrad.

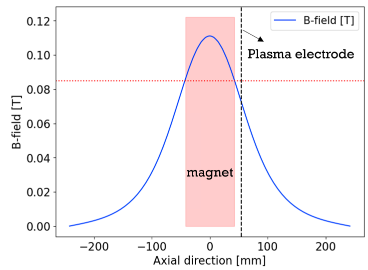

Figure 2: Magnetic field strength in axial direction. The position of the aperture of the plasma electrode is indicated by the dashed line.

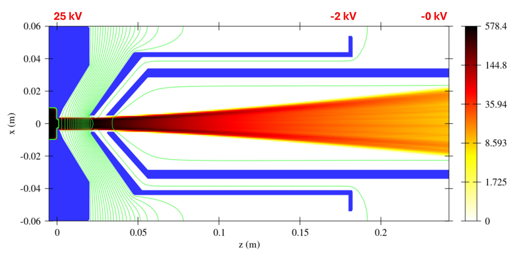

Figure 3: Particle density of extracted proton beam.

LEBT TRANSMISSION

In order to compare the two simulation tools, we tracked the same beam distribution through the LEBT with IBSimu and TraceWin.

Figure 4 and Figure 5 show the transmitted proton normalized emittance and the RMS size as a function of the LEBT distance, respectively. Since the imported particle distribution and magnetic file are the same, the results of both codes are consistent.

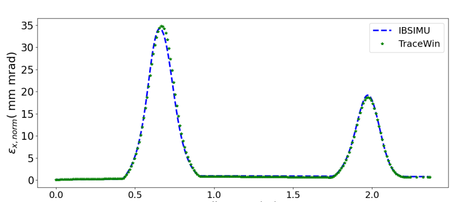

Figure 4: Normalized emittance evolution for both TraceWin and IBSimu codes of LEBT.

SPACE CHARGE COMPENSATION MODEL

The space charge compensation model is constructed in the ion optical code IBSimu which is capable of solving electric fields in one-dimensional, 2D (planar or cylindrical symmetry), or full 3D simulation geometries [1].

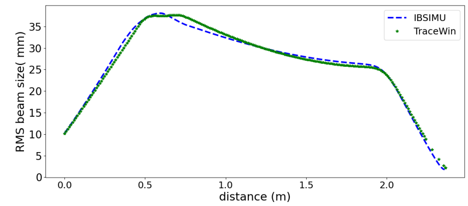

Figure 5: RMS beam size evolution for both TraceWin and IBSimu codes of LEBT.

Simulation Procedure

- Defining geometry and iterate primary particles: The almost 2.4 m total length of the LEBT line and the diameter of the chamber are introduced. The external magnetic fields coming from CST are imported. The primary particles are iterated, space charge is deposited, and the electrostatic potential is calculated until a convergent solution is obtained. The strength of the magnetic fields is adjusted to match the beam to RFQ. The evolutions of the beam size and emittance are shown in Fig. 5 and Fig. 4.
- Monte Carlo generator: Secondary particles are created randomly along the trajectories of the primary beam and are stepped in time. In every time step, the trajectory of these particles is saved for the next time step. As a result, the accumulation of charge density of secondary particles is increased until the total charge state reaches a steady state. The gas pressure is considered to be homogeneous in the beam line.
- Total charge densities of the beam and created secondaries are summed up and the beam is iterated under this charge density in time.

The cut view in the ***(z-x)*** plane of the space-charge potential of created electrons in the LEBT, when the space-charge compensation is transient time, is represented on Fig. 6. In this plot, the abscissa $z = 0$ represents the position of the exit of the ion extraction system, while $z = 2.365$ m is the RFQ entrance. The solenoids are respectively located at $z = 0.4$ m and $z = 1.7$ m. As seen in the figure the created electron potential is not uniform in space. It is higher in the solenoids regime because the electrons are confined by the magnetic field. We can evaluate the behavior of produced electron rate under the magnetic field. Figure 7 shows the created electron rate with and without of solenoid effect. In this figure, krypton gas is considered as a residual gas, and the vacuum level is 5×10^{-5} mbar in two situations, and here, the SCC is steady-state. In the absence of a B-field, the generated electron distribution is more uniform throughout the line; nevertheless, when a B-field is introduced in the simulation, electron densities are accumulated on the solenoid regime.

Beam Dynamics under SCC Effect

The extracted proton beam which is mentioned above is introduced before the SCC effect is introduced and transported along the LEBT beamline. In the LEBT, the baseline

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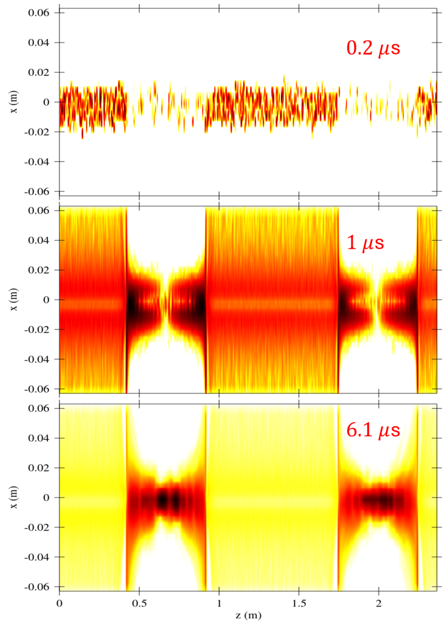

Figure 6: Electron densities at 0.2 μs (top), 1 μs (middle), and 6.1 μs (bottom).

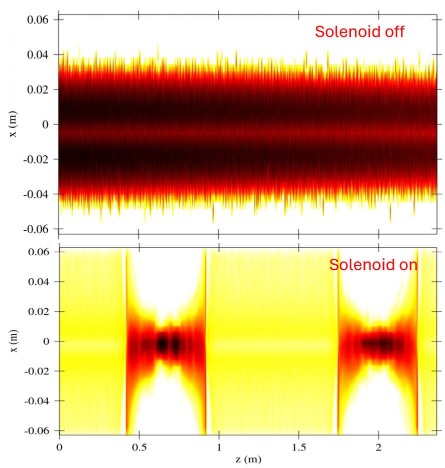

Figure 7: Electron creation without (top) and with (bottom) magnetic field.

pressure is around 5 $\times 10^{-7}$ mbar, and the beam parameters have been discussed previously.

Figure 8 shows the radial potential difference in compensated proton beam of 14 mA and 25 keV as a function of concentration of electrons created by krypton gas in time. It is noted that the calculation point is located around the middle of LEBT, approximately 1.2 meters downstream of the ion source. This point is where the Allison scanners are located. Here, the pressure level is 5 $\times 10^{-5}$ mbar and homogeneous along propagation. Here, the steady-state time is 6.1 μs and is consistent with the theoretical calculation. As seen in the figure, when SCC reaches the steady state beam is almost neutralized but not fully.

When different gases are injected their effects on the proton beam are compared. In this case, krypton, argon, and hydrogen are considered as injected gases. For comparison, the pressure level is adjusted 5 $\times 10^{-5}$ mbar for these three situations. The effect of these gases on the proton beam RMS size is then analyzed. The results showed that krypton had the strongest on the proton beam since it had the highest cross-section, followed by argon and finally hydrogen. Figure 9 gives the transient time of these three gases. The RMS beam size is reduced dramatically until SCC reaches a steady state. It is seen that the transient time of krypton is lower than the other two gases.

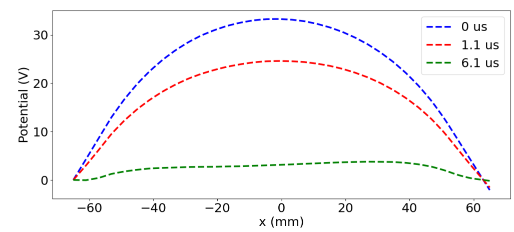

Figure 8: Dependence of beam potential along the radial axis on time for krypton gas. The beam current is 14 mA and the beam energy is 25 keV.

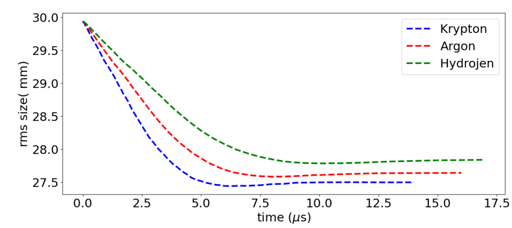

Figure 9: Proton beam RMS beam size evolution in time due to the SCC effect.

CONCLUSION

The RFQ test facility ion source extraction simulation is carried out to transfer the particle distribution to LEBT line. The simulations conducted by IBSimu and TraceWin showed that the LEBT has the capability to transport a proton beam of 14 mA while maintaining the beam transmission rate higher than 70%. Electron production is created in time considering certain pressure levels and different gases with different cross-sections and their space charge effects on the beam are simulated. A dramatic reduction of the RMS size of the beam is observed until the electron creation rate reaches a steady state.

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