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SIMULATIONS OF THE ELECTRON COLUMN IN IOTA*

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Abstract

Future high current proton accelerators will need to minimize beam loss due to space-charge in order to achieve safe operation while achieving the desired physics goals. One method of space-charge compensation to be tested at the Integrable Optics Test Accelerator (IOTA) at Fermilab is the Electron Column. The concept for this device is to allow a circulating beam to ionize a small region of relatively high pressure residual gas, while using electric and magnetic fields to confine and shape the resulting plasma electrons. If the profile of the electrons is matched to the beam profile transversely and longitudinally, the electrons should counteract the space-charge force of the proton beam. Simulations of the IOTA proton beam circulating through the electron column have been performed, with the evolution of the electron plasma and its effect on the beam studied.

INTRODUCTION

Space-charge forces lead to beam loss in high current accelerators, which activates and damages beamline components [1]. Additionally, if superconducting cavities or magnets are involved, losses may result in quenching these devices. In future high current accelerators, or upgrades to existing accelerators, these losses must be kept to a minumum - see, e.g. Ref. [2].

One method of Space-Charge Compensation (SCC) that is applicable to proton rings is the Electron Column [3,4]. The Electron Column is similar to an Electron Lens (such as those operated at Fermilab's Tevatron) in that it employs electrons with a distribution matched to that of the circulating beam to compensate space charge [5]. As opposed to the Electron Lens, which creates an external beam of electrons, shapes and injects them into the beam path of the protons, and then extracts the electrons, the Electron Column relies on a short section of relatively high gas density as the source of electrons [6]. The beam passing through the gas will ionize it, with the distribution of the resulting plasma electrons being matched to that of the beam using external electric and magnetic fields. Figure 1 shows a schematic of what the Electron Column would look like.

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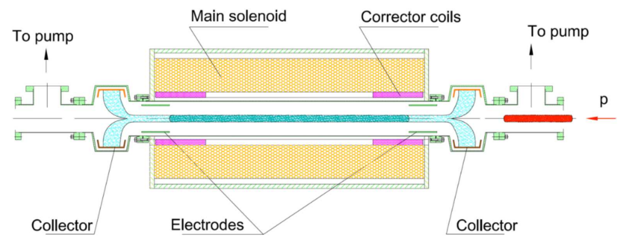

Figure 1: Schematic layout of the Electron Column experiment. The solenoid provides the magnetic field, while the electrodes provide the electric field.

The Integrable Optics Test Accelerator (IOTA) at the Fermilab Accelerator Science and Technology (FAST) Facility is under construction, and will be home to a 2.5-MeV proton source and storage ring to host experiments for research and development of technology for the next generation of particle accelerators [7, 8]. Space-charge compensation using an electron column is one such planned experiment.

Because the plasma electrons are relatively stationary with respect to the beam, the electron charge needed to compensate the proton charge is reduced by a factor of γ^2, where γ is the relativistic factor of the beam. Another benefit of the Electron Column is that full compensation need not be achieved in one device, which would lead to e-p instabilities. A number of columns may be interspersed around the ring to provide full compensation on average, with smaller densities of electrons locally. For example, in the Fermilab Recycler or Main Injector, where $\gamma \approx 8.94$, only about 1.2% of the ring circumference would be needed for complete compensation. The plasma ions, however, need to be considered as well, as they work to counteract the effect of the electrons. For this reason, the magnetic field used to confine the electrons transversely must be weak enough to allow the ions to diffuse out radially.

Simulations of the Electron Column to be studied in IOTA have been carried out using the code Warp, which includes the effects of space-charge [9].

SIMULATION PARAMETERS

A single pass of the IOTA proton beam through the Electron Column has been simulated, improving upon results reported previously in Ref. [10] by using a more complete

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ionization process and a pulsed proton beam with a longitudinally uniform distribution, rather than a coasting beam.

The simulation domain was a cylinder 120 cm long and 2.54 cm in radius. The center 100 cm was filled with hydrogen gas of density $1.65 \times 10^{13}\,\mathrm{cm}^{-3}$ (5×10^{-4} torr at 293 K). For a beam current of 8 mA and relativistic beta of 0.0728, the potential as the beam center is ~ 3.5 V. Given that the Column length is 1/40 that of the ring circumference, a potential of ~ 140 V would be needed for full compensation. Previous simulations of the Electron Column [10] have shown that potentials as high as 200 V result in significant over compensation, while 5 V resulted in the best match between beam and electron distributions. Therefore, electrodes with an inner radius of 2.286 cm and length of 10 cm were centered at z = 0 & 100 cm (the longitudinal direction), and given a potential of -5 V. An external 0.1 T solenoidal magnetic field was applied, which is strong enough to confine the plasma electrons and weak enough to allow the plasma ions to diffuse radially.

Protons of 2.5 MeV kinetic energy were injected with a Gaussian distribution of $\sigma_x = \sigma_y = 4.47$ mm, 10 cm upstream of the Column. The ionization process was

$$p + 2\mathrm{H}_2 \rightarrow p + e + \mathrm{H}_3^+ + \mathrm{H}\,. \qquad (1)$$

(H_2^+ tends to react with H_2 rather quickly to form H_3^+. This process was assumed to happen instantaneously for simplification here. The only significant difference is that the outward drift of H_3^+ due to the space-charge force would be slower given the same initial momentum.) The cross section for ionization was set to $1.82 \times 10^{-17}\,\mathrm{cm}^2$, based on experimental results from Ref. [11]. Plasma electrons were given an average initial energy of 45 eV, with $\sigma = 19$ eV, based on calculations done using experimental data reported in Ref. [12].

The time step was set to 70 ps in order to resolve the ~350 ps cyclotron period. A beam current of 8 mA was injected for 1.77 µs, followed by 60 ns with no beam, given the 1.83-µs revolution period in IOTA.

RESULTS

Transverse distributions of the beam, plasma electrons, and plasma ions at the center of the Column longitudinally at times corresponding to 1/4, 1/2 and the end of the beam pulse are shown in Fig. 2. Additionally shown is the ratio of the radial component of the electric field with ionization turned on (i.e. SCC) to that without ionization (i.e. no SCC) along x at the center of the column in y and z.

It can be seen from the top row of Fig. 2 that the plasma electrons are well confined by the magnetic field, and build with time so their profile closely matches that of the beam after one full pass of the beam through the Column. Halfway through the beam pulse, the electron peak is ~60% that of the beam, while at the end of the pulse, the value is closer to 85%.

The ions, shown in the second row of Fig. 2, also build with time, however are not as well confined by the magnetic field, and broaden out more so that their density is less in the center of the column, and larger than the electrons or beam at larger radii.

Table 1: The ratio of the radial component of the electric field with ionization turned on (SCC) to the case without ionization (no SCC), averaged over the diameter of the Electron Column, for times 1/4, 1/2, at the end of the beam pulse.

Time [µs]	Average E_r^{SCC}/E_r^{noSCC}
0.44	0.967
0.88	0.914
1.76	0.947

The degree of Space-Charge Compensation can be estimated from the reduction in the radial electric field within the Column. As can be seen in the third row of Fig. 2, the radial component of the electric field that results from the beam and plasma is less than the field from the beam alone. At r (= x) = 0 (the center of the column) the contribution from the beam and ions outweighs that of the electrons, causing the spikes seen in the figure. However, this quickly falls off at larger radii, as the ion density is smaller than that of the electrons. At the end of the beam pulse, the radial electric field has been reduced by 20–30% for much of the beam radius. The average electric field over the diameter of the Column, i.e. $(1/d)\int E_r\,dx$, where d is the diameter, indicates that the average radial electric field is reduced by 3–8% over a single pass of the beam through the Electron Column. The values for three different times are given in Table 1.

The plasma electrons and ions were allowed to evolve during the time the beam is not present in the Column. Their distributions at the center of the Column are shown in the fourth row of Fig. 2. The electron distribution is still well-matched to that of the beam, while the ions have diffused out somewhat by this time.

CONCLUSION

Simulations of the Electron Column experiment planned for IOTA indicate the profile of the plasma electrons in the Column can be matched reasonably well to the beam profile after only one beam revolution. Furthermore, the effect of Space-Charge Compensation can be seen in a $\sim 5\%$ reduction in the radial component of the electric field. Future work will involve studies of the evolution plasma and phase space of the beam for multiple passes through the Column, and the effect of electric and magnetic field strengths on under- and over-compensation of space-charge.

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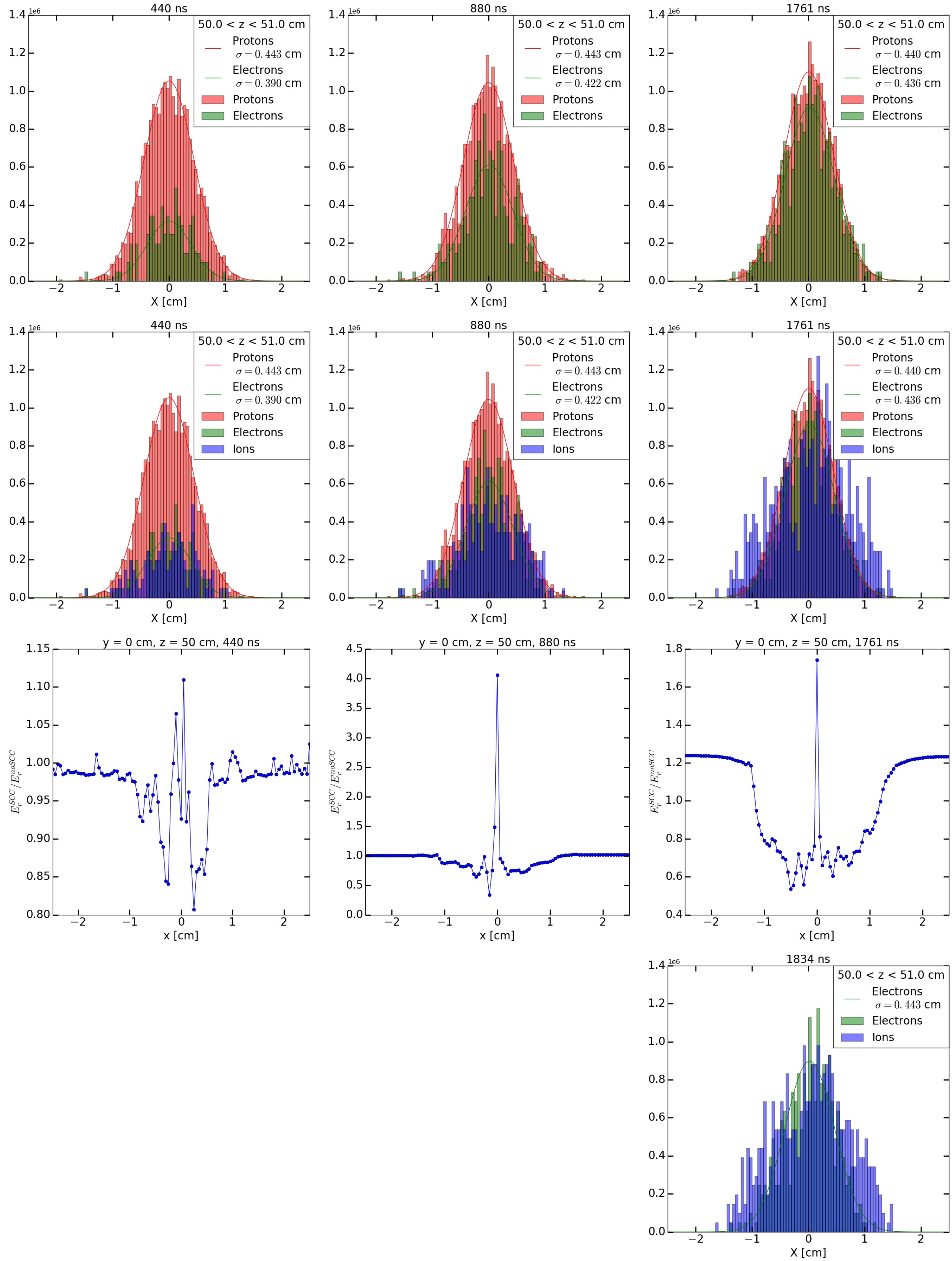

Figure 2: Simulation results for three different times during the beam pulse, left to right - 0.44, 0.88, and 1.761 µs. The top row shows the transverse distribution of protons and electrons along x at the center of the column. The second row is a reproduction of the top row, with the ion distribution added. The third row is the ratio of the radial component of the electric field with ionization turned on to that without ionization. The fourth row shows the transverse distribution of electrons and ions at the center of the column just before the beam re-enters.

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