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SPACE-CHARGE COMPENSATION USING ELECTRON COLUMNS AT IOTA*

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Abstract

Beam loss due to space-charge is a major problem at current and future high intensity particle accelerators. The space-charge force can be compensated for proton or ion beams by creating a column of electrons with a charge distribution matched to that of the beam, while maintaining electron-proton stability. The column is created by the beam ionizing short sections of high pressure gas. The ionization electrons are then shaped appropriately using external electric and magnetic fields. The Integrable Optics Test Accelerator (IOTA) ring at Fermilab is a test bed for mitigation techniques for beam loss and instabilities. A 2.5 MeV proton beamline is under construction in IOTA, to be used to study space-charge compensation using an Electron Column and Electron Lens for a space-charge dominated beam. Simulations using the particle-in-cell code, Warp, have been made to track the evolution of both the electron column and the beam over multiple passes.

INTRODUCTION

Coulomb repulsion, known as the space-charge force within a beam of particles, results in beam loss and component radioactivation in high intensity accelerators. Future proton or ion accelerators and upgrades to existing machines will require better control of beam loss in order to prevent damage to components, minimize cost, and achieve the desired beam power. Compensation of the effects of space-charge by accumulating and trapping electrons through ionization of gas along the beam trajectory has been tested experimentally with limited results, and plans exist for a detailed study of a so-called Electron Column in the Integrable Optics Test Accelerator, currently under construction at Fermilab.

An Electron Column (EC) is similar to an Electron Lens (EL) in that the space-charge force is negated by matching the transverse (and preferably longitudinal) distribution of electrons to that of the beam. In the case of the Electron Column, electrons are obtained by maintaining a short section of beam pipe at a relatively high gas pressure, and capturing and shaping the electrons created by ionization of the gas by the beam using electrodes at the ends of the Column, and a solenoidal magnetic field. This eliminates the need for the electron gun and collector required by the Electron Lens. The total charge of electrons needed to achieve complete space-charge compensation (SCC) of the beam in the EC is reduced by a factor of (the relativistic) γ^2.

The plasma ions generated in the Electron Column negatively impact space-charge compensation, and so the magnetic field used to confine the electrons transversely must be weak enough to allow the ions to escape over time. However, the magnetic field must be strong enough to suppress electron-proton instabilities observed in EC experiments in the past [1, 2].

PRIOR SPACE-CHARGE COMPENSATION EXPERIMENTS

Space-charge compensation has successfully been implemented in high current, low energy beams in linacs. Experiments of SCC in circular machines have been performed in the past with limited results.

Institute of Nuclear Physics

Space-charge compensation in a ring was first attempted in 1983 at the Institute of Nuclear Physics in Novosibirsk using a 1 MeV, 8 mA proton beam with a few mTorr of hydrogen gas. There was no stabalizing magnetic field, and so while an increase of nearly an order of magnitude was observed in the beam current, there beam lifetime was reduced and e-p instabilities were significant [1].

Fermilab Tevatron

Two Electron Lenses, the concept on which the Electron Column is based, were operated successfully in the Tevatron at Fermilab [3, 4]. A Lens was modified to operate as a Column by turning off the electron gun and collector and using electrodes and a 3 T longitudinal magnetic field to trap electrons created by ionization of residual gas [5]. Using the 150 GeV proton beam and allowing the vacuum to degrade to about 50 nTorr, accumulation of charge within the Column and a positive tune shift was observed [2]. However, significant vacuum instability was observed, which resulted in beam instability and emittance growth or beam loss.

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SPACE-CHARGE COMPENSATION EXPERIMENT AT IOTA

The Integrable Optics Test Accelerator (IOTA) is under construction at Fermilab and will host experiments for research and development for technology to be used in the next generation of particle accelerator [6]. Electron Lens and Column experiments are planned, which will allow for testing space-charge compensation schemes using a 2.5 MeV proton beam and a range of parameters in gas density and electrode and magnet field strengths. Construction of the IOTA ring is expected to be complete in August of 2018, with commissioning and the first electron experiments to take place through 2018 and 2019. Installation of the proton RFQ and commissioning of IOTA with protons is expected to take place in late 2019 and early 2020. A schematic of what the Electron Column will look like when installed in IOTA is shown in Figure 1.

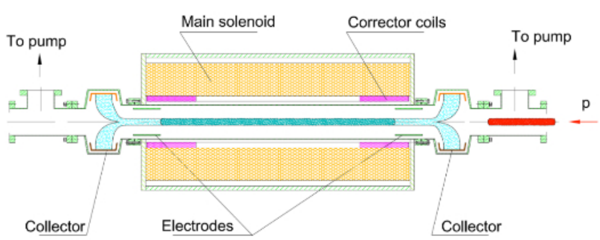

Figure 1: Schematic of the Electron Column in IOTA.

A simulation effort is underway with the goal of studying the evolution of the plasma in the Electron Column and the degree of space-charge compensation expected for varying conditions.

ELECTRON COLUMN SIMULATION PARAMETERS

Simulations of the Electron Column in IOTA have been done using Warp [7]. The results reported here will cover the proton beam in IOTA making two passes through the EC, and the resulting degree of space-charge compensation. Table 1 lists the relevant simulation parameters. Other simulation specifications have been reported elsewhere [8].

A KV beam with the expected proton beam emittance coming from the RFQ was injected at the beginning of the column and the distribution recorded after exiting the column. The plasma distribution after one revolution period (1.83 µs, compared the the 1.77 µs beam pulse length) was also recorded. The plasma was then loaded at the beginning of the second pass, and the saved beam particles loaded with the appropriate position and temporal coordinates. Finally, the beam and plasma distributions after the second revolution period were recorded. In this way, two passes of the beam through the EC were simulated, although the rest of the IOTA lattice was not taken into account.

Table 1: Simulation Parameters for the Electron Column in IOTA

Parameter	Value	Unit
Beam species	Proton	
Beam energy	2.5	MeV
Beam current	8	mA
Beam pulse length	1.77	µs
Gas species	Hydrogen	
Gas density	1.65×10^{13}	cm^{-3}
Ionization cross section	1.82×10^{-17}	cm^2
Plasma energy (spread)	45 (19)	eV (eV)
Column length	1	m
Beampipe radius	2.54	cm
Electrode positions (z)	0, 100	cm
Electrode strength	-5	V
Solenoid field	0.1	T
Macroparticle/timestep	500	
Grid spacing (x,y,z)	(0.5, 0.5, 1.0)	cm
Timestep	70	ps
Simulation length	1.83	µs

SIMULATION RESULTS

The results showing the degree of space-charge compensation at the center of the Electron Column after the first beam pass are shown in Figure 2. The top plot shows the radial electric field along the x transverse dimension for two cases: the beam only, and the beam with SCC (i.e. ionization of the gas). The bottom plot shows the ratio of the electric field with SCC to that without SCC (beam only). It can be seen that the radial electric field within the beam diameter (vertical lines on the plots) is reduced by a factor of ≈ 2 when SCC is turned on.

Figure 3 shows the distributions of the beam, electrons, and ions at the end of the first pass. The top plot shows the transverse distribution at the center of the Column in the longitudinal dimension, and the bottom plot shows the longitudinal distribution at the center of the Column in the transverse dimension. The distribution of electrons is well matched to the beam (protons) transversely, however the density is not yet matched. The ions, which are not as strongly confined by the magnetic field, have diffused radially and are not as dense in the center of the Column. Longitudinally, electrons are being lost out the ends of the Column as can be seen by their existence outside of the 0-100 cm boundary of the EC, while the ions are less mobile and therefore more well-confined.

Figure 4 shows the radial electric fields and ratio of electric fields for SCC and no SCC at the end of the second pass. Within the beam diameter there is a slight reduction in electric field compared to the first pass, however the build up of ions at the center of the column results in a degredation of SCC for small radii (x values). This can be seen in Figure 5, which shows the transverse and longitudinal distribution of particles at the end of the second pass.

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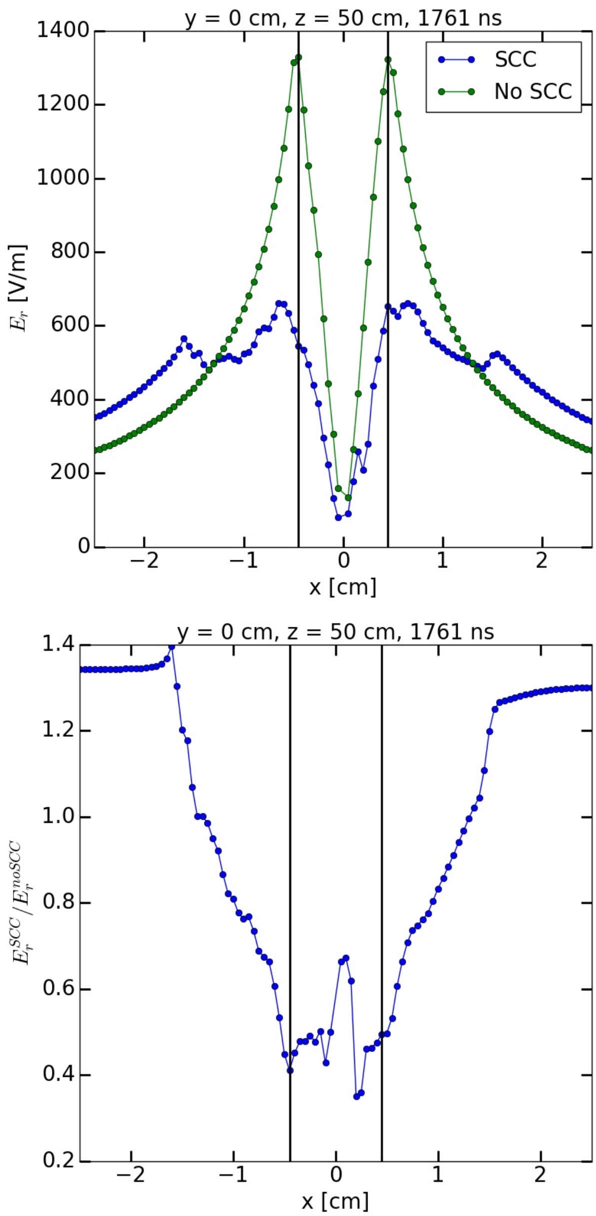

Figure 2: Radial electric field along x in the center of the column in y and z for beam alone (green) and with space-charge compensation (blue) at the end of the first pass of the beam through the Electron Column - top. Ratio of the two electric fields from the top plot - bottom. The vertical lines in both plots denote the boundary of the beam.

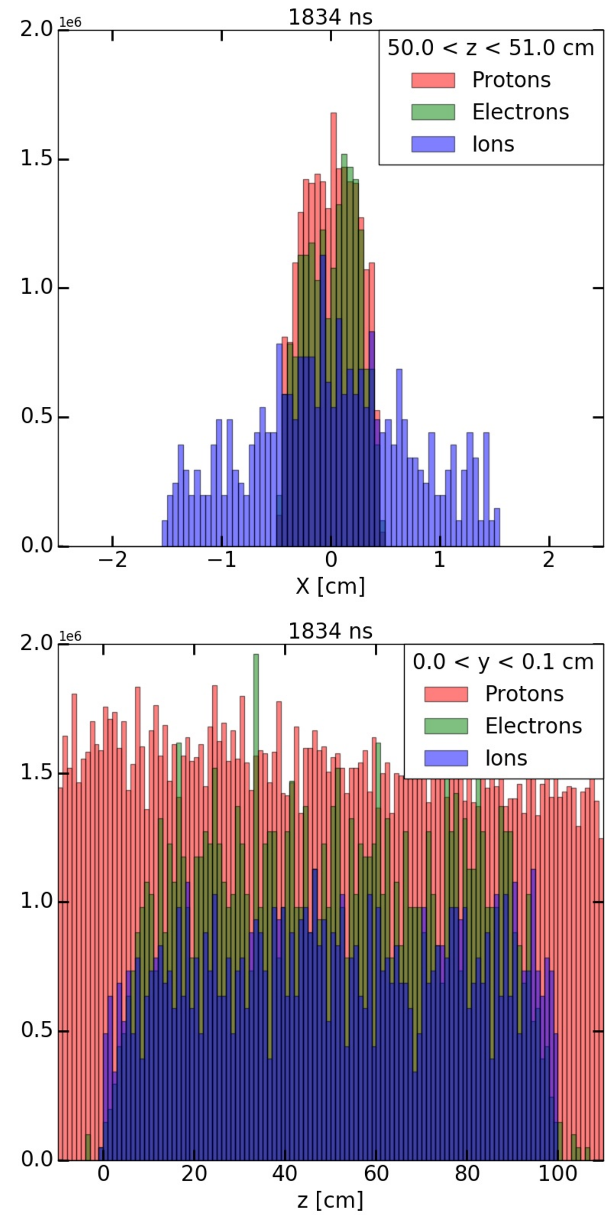

Figure 3: Distribution along x for the beam (red), electrons (green), and ions (blue) at the center of the Electron Column in z just before the beam would reenter the Column for a second pass - top. Note the beam distribution plotted is for the last time step that the beam is in the Column, for reference. Bottom - same as the top, but plotted along z at the center of the Column in y. The bin widths correspond to the simulation grid spacing.

At the end of the second pass, the distribution of electrons is still well matched to that of the beam, however the density is now greater. The density of ions is also greater, resulting in the reduction in SCC at the center of the beam seen in Figure 4. This over compensation of electrons, and corresponding increased density of ions can be countered by decreasing the gas density and/or magnetic field strength. Decreasing the gas density is preferable, as this will not affect suppression of e-p instability, however this will increase the length of time it takes the EC to reach full compensation.

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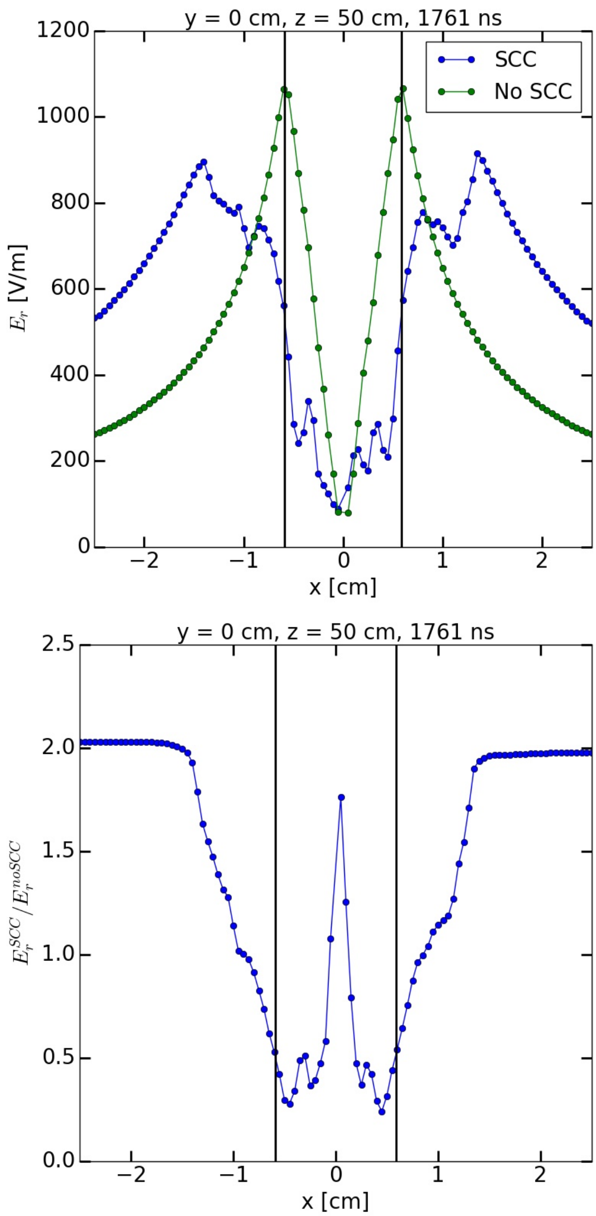

Figure 4: Same at Fig. 2, but at the end of the second pass of the beam through the Column.

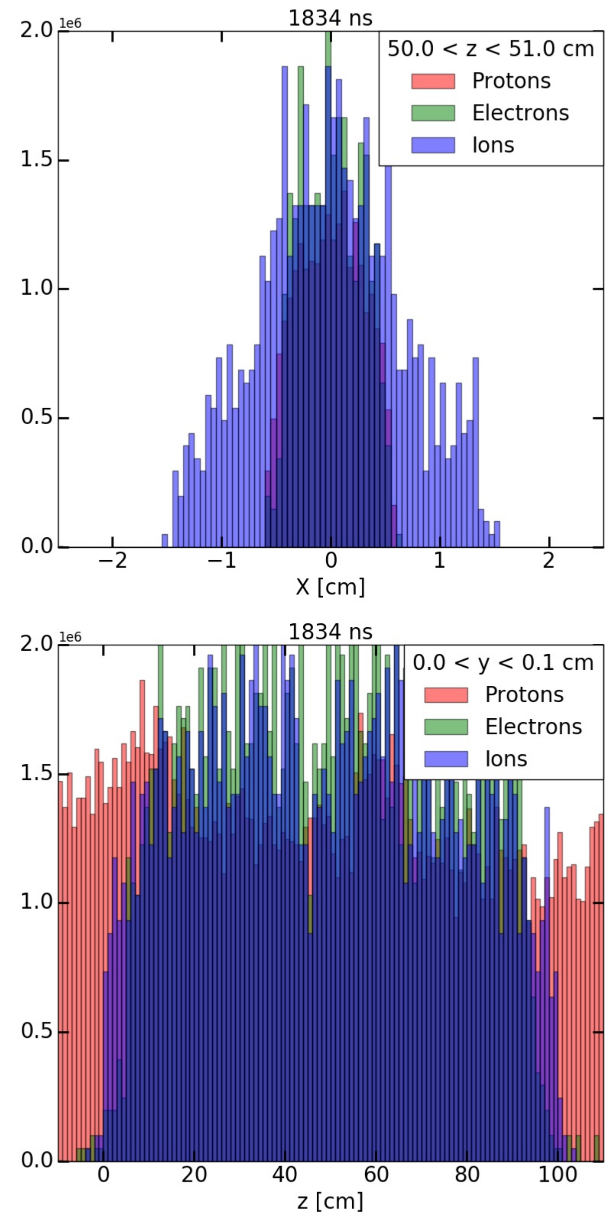

Figure 5: Same as Fig. 3, but just before the beam would reenter the Column for a third pass.

It should be noted that a number of important plasma processes are not implemented in these simulations. The first is collisions and therefore energy loss of plasma particles with the surrounding gas. The second is recombination of electrons with ions in the plasma. Both of these effects will contribute to the evolution of the number (and therefore density) of plasma particles.

Nonetheless, these intial simulations indicate that final level of space-charge compensation (whether it be complete compensation or some partial compensation) can be reached within a small number of turns of the beam in IOTA. Additionally, it appears that the gas density can be decreased, which will have a positive impact on the lifetime of the 2.5 MeV proton beam.

CONCLUSION

Space-charge compensation using an Electron Column is planned for the proton experimental program in IOTA. Simulations of two passes of the beam through the Electron Column indicate a significant degree of space-charge compensation can be achieved within a small number of passes. Future plans include incorporating the rest of the IOTA lattice into simulations, and studying the affect on space-charge compensation of varying the parameters, such as gas density and electrode strength, of the Electron Column.

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