MITIGATION OF SPACE CHARGE EFFECTS USING ELECTRON COLUMN AT IOTA RING

C.S. Park*, Korea University Sejong Campus, Sejong, South Korea
B. Freemire, Euclid Techlabs LLC, Bolingbrook, IL USA
E. Stern, Fermi National Accelerator Laboratory, Batavia, USA
C.E. Mitchell, Lawrence Berkeley National Laboratory, Berkeley, USA

Abstract

We investigate a novel method to mitigate space charge effects of high intensity proton beams propagating in circular accelerators by means of trapping and controlling electrons generated from beam- induced residual gas ionization. This compensation method uses Coulomb repulsion force between a proton beam and electrons to mitigate self-space charge effects of the beam if it passes through a plasma column. The transverse electron-proton (e-p) instability in the plasma column is well controlled by the longitudinal magnetic field of a solenoid magnet and the bias voltages on electrodes. In this report, we will show simulation results how to control distributions of electrons and ions as well as that of the proton beam inside the column.

INTRODUCTION

Mitigation of space charge effects is a crucial challenge in high intensity hadron accelerators. In order to mitigate these effects, various techniques have been implemented such as by adding opposite charges (e.g., electron lens and electron column), by accelerating beam rapidly, by scraping beam halos, and by using solenoidal fields [1–3]

At Fermilab, the Integrable Optics Test Accelerator (IOTA) ring is built to enable accelerator researchers to study the frontiers of accelerator science, and is designed to explore and improve the particle beams and machines for the future high intensity accelerators [4]. IOTA is being commissioned to investigate a novel technique called nonlinear integrable optics. The IOTA ring will be also used to study the space charge compensation (SCC) using both electron lens and electron column.

The SCC method with an electron lens uses co-propagating beams of opposite charge (electron beam) to collide with proton beams inside the strong magnetic field by a solenoid. This results in the compensation of proton beams' space charge tune shift. This method requires a precise control of transverse profile of e-beam. It is experimentally mature "Swiss Knife," and has been employed in Tevatron, RHIC, and now LHC [5]. However, the space charge compensation with an electron column utilizes proton beam itself to ionize residual gas and to generate electrons. Electrons are approximately at rest longitudinally compared to co-moving electrons in the electron lens scheme. Electrons are trapped, matched, and controlled using external solenoid and electrodes. In this report we present recent simulation results to mitigate space charge effects using electron column method at Fermilab's IOTA ring.

* kuphy@korea.ac.kr

EXPERIMENTAL SETUP

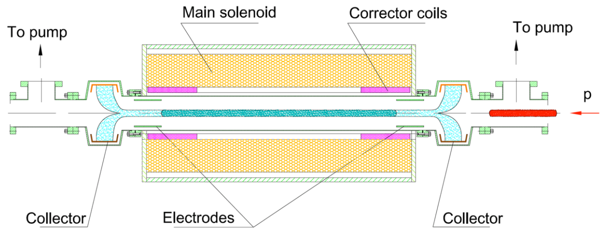


Figure 1: Schematic Layout of an Electron Column Experimental Setup

Space charge effects can be compensated by making proton beam pass through plasma column of opposite charge with matched distribution. In linear machines, this concept was successfully applied to transport high-current low energy proton and H^{-} beam (gas focusing), Gabor lens, etc [6]. In circular machines, e-p instabilities can be suppressed using an external magnetic field of sufficient strength.

Electrons are generated from the beam-induced ionization of residual gas without an external electron source. Then their density profile is matched to that of proton beam by using external magnetic field and precisely controlled by using electrostatic electrodes. The schematic drawing of the experimental setup is in Figure 1. The magnetic field should be strong enough to stabilize electrons' motion inside the column, so that coherent e-p instabilities should be mitigated. However, it also needs to be weak enough to allow ions escape the column easily.

In IOTA, we will use e-lens' central solenoid for e-column operation. Ionization rate of residual gas by proton beam can be controlled with the vacuum pressure, therefore it also plays an important role to control the electron distribution.

SIMULATION SETUP

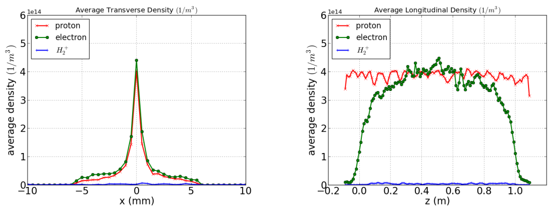
We investigate the dynamics of proton beam, electrons, and ions with external E and B fields using Warp3D code [8]. The goal of the simulation is first to find matching conditions of the transverse electron profile with B-field, voltages on electrodes, and vacuum pressure. With these conditions, a pulsed proton bunch is injected and passed through the column. Density distributions of electrons and ions right after the proton beam passed the column are recorded during

Table 1: Beam and IOTA ring simulation parameters

Parameter	Value	Units
Beam Species	proton	
Beam Energy	2.5	MeV
Beam Current	8	mA
Beam Pulse Length	1.77	μs
Column Length	1	m
Revolution Period	1.83	μs
Gas Species	Hydrogen	
Macroparticle/step	500	
Grid Spacing (x,y,z)	5, 5, 10	mm
Timestep	70	ps

one revolution period. Then, the second proton beam is injected into the column with these preserved distributions. Table 1 shows IOTA and SCC simulation parameters.

MATCHING CONDITION



(a) Transverse density profile (b) Longitudinal density profile

Figure 2: Transverse and longitudinal density profiles when $B = 0.1\ T$, $V = -5\ V$, and $P = 5 \times 10^{-4}\ Torr$.

To find matching conditions, initial optimization of the column parameters (gas density, electrode potential, and magnetic field) are performed using a coasting proton beam. For given beam parameters, one can find the proton beam potential at the center, which is given by $\phi = 30I/\beta \approx 3.5\ V$, where I is the beam current and β is the relativistic velocity of the beam. With this estimation, we could estimate the optimal voltage on the electrodes. In addition, the vacuum pressure also plays an important role to control the electron density level. As a result, for $B = 0.1\ T$, $V = -5\ V$, and $P = 5 \times 10^{-4}\ Torr$, matched transverse and longitudinal distributions of electrons are achieved as shown in Figure 2.

SCC AFTER FIRST PASS

For the proton bunched beam, the KV distribution is used in the transverse direction, while the uniform, step function is used in the longitudinal direction. In order to quantify SCC effects, simulations with ionization (SCC) and without ionization (no SCC) are compared. Figure 3 shows the radial electric field along the x direction at the center of the column for both cases (left) and their ratio (SCC to no SCC, right). There are significant reduction in the radial electric field by a factor of 2 inside the beam with the space charge compensation.

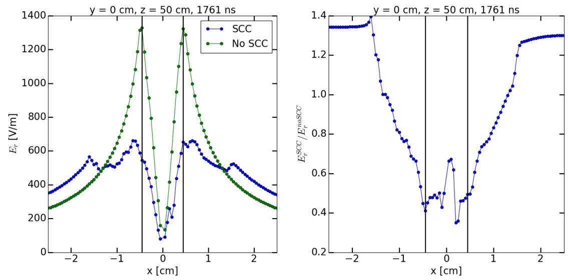


Figure 3: Radial electric fields along x at the center of the column for no SCC (green) and SCC (blue) at the end of the first pass of the beam through the Electron Column (left) and ratio of radial electric fields (SCC to no SCC, right). Vertical black lines indicates the boundary of the proton beam.

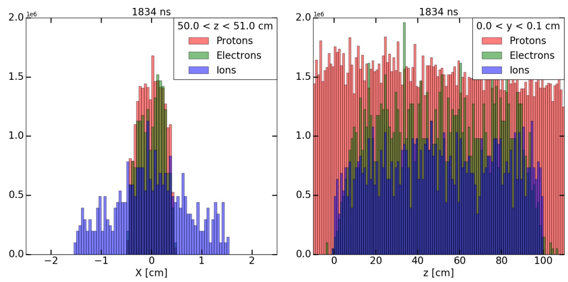


Figure 4: Distribution along x for the beam (red), electrons (green), and ions (blue) at the center of the Electron Column in z just before the beam would reenter the Column for a second pass - top. Note the beam distribution plotted is for the last time step that the beam is in the Column, for reference. 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.

Figure 4 shows the density profiles (left: transverse and right: longitudinal) of the proton beam, electrons, and ions after the beam passes the column. The density distributions of electrons are not perfectly matched to those of proton beam for both directions. These under-compensation can be precisely controlled by increasing the electrode voltage or by increasing the vacuum pressure. The ions are are not strongly confined by the magnetic field, so that they are more homogeneously distributed.

SCC AFTER SECOND PASS

Figure 5 shows the radial electric field along the x direction at the center of the column for both cases (left) and their ratio (SCC to no SCC, right) after the second pass of the proton beam. After the second pass, the transverse distribution of electrons are still closely matched to that of the proton beam. Therefore, there is still significant reduction of the radial electric field within the beam. However, as shown in Figure 6, there is a huge build up of ions near the beam, and ion density surpasses the proton beam density. This will lead to significant reduction in space charge compensation.

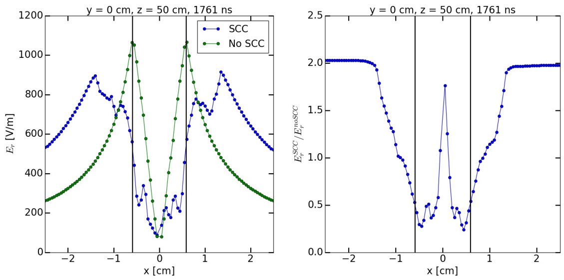


Figure 5: Same at Fig. 3, but at the end of the second pass of the beam through the Column.

This could be mitigated by reducing the gas density and/or magnetic field strength.

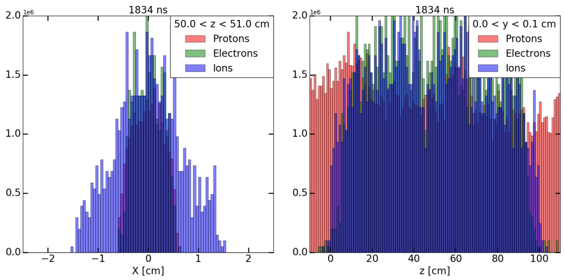


Figure 6: Same as Fig. 4, but just before the beam would reenter the Column for a third pass.

CONCLUSION

Simulations results show that the density profile of e-column can be tuned with axial B-field, electrode voltages, and vacuum pressure for (partial/full/over) SCC in the IOTA ring. Simulations of the Space Charge Compensation using an Electron Column shows positive effects to reduce radial electric fields inside the pulsed beam. However, these reduction is about 50 % after the first and second pass. Additional optimization is required to find suitable settings for E and B fields as well as gas pressure for each turn. Electron and ion distributions for each turn need to be monitored precisely. Longer period (multiple passes throughout the ring) of simulations are to be investigated. Evolution of tune foot print and phase space are also to be studied.

REFERENCES

[1] V. D. Shiltsev, *et al.*, in *Proc. PAC'13*, Pasadena, CA, USA, Sep. 2013, pp. 99-101.

[2] A. W. Chao and M. Tigner, (Eds), Handbook of Accelerator Physics and Engineering, 2013, p. 395.

[3] O. Meusel *et al*, "Beam transport and space charge compensation strategies," *Rev. Sci. Instr.*, vol. 87, 02B937 (2016).

[4] K. Schulte *et al*, in *in Proc. HB'14*, East Lansing, MI, USA, Nov. 2014, pp 67-69.

[5] S. Antipov *et al.*, "IOTA (Integrable Optics Test Accelerator): facility and experimental beam physics program", *J. Inst.*, vol. 12, T03002, Mar. 2017.

[6] G. D. Stancari *et al.*, in *in Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 46-48.

[7] G.I. Dimov and V.E. Chupriyanov, "Compensated Proton-Beam Production in an Accelerating Ring at a Current Above the Space-Charge Limit", *Part. Accel.*, vol. 14, pp. 155-184, 1984.

[8] A. Friedman *et al.*, "Computational Methods in the Warp Code Framework for Kinetic Simulations of Particle Beams and Plasmas", *IEEE Trans. Plasma Sci.*, vol. 42, no. 5, p. 1321, May 2014.