SPACE CHARGE COMPENSATION USING ELECTRON COLUMNS AND ELECTRON LENSES AT IOTA *

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Abstract

The ability to transport a high current proton beam in a ring is ultimately limited by space charge effects. Two novel ways to overcome this limit in a proton ring are by adding low energy, externally matched electron beams (electron lens, e-lens), and by taking advantage of residual gas ionization induced neutralization to create an electron column (e-column). Theory predicts that an appropriately confined electrons can completely compensate the space charge through neutralization, both transversely and longitudinally. In this report, we will discuss the current status of the Fermilab's e-lens experiment for the space charge compensation. In addition, we will show how the IOTA e-column compensates space charge with the WARP simulations. The dynamics of proton beams inside of the e-column is understood by changing the magnetic field of a solenoid, the voltage on the electrodes, and the vacuum pressure, and by looking for electron accumulation, as well as by considering various beam dynamics in the IOTA ring.

INTRODUCTION

High intensity accelerators have been fundamentally limited to their intensities by various sources of instabilities, such as e-cloud, beam halo, space charge effects, etc [1]. There have been many challenges to mitigate the effects of space charge forces, by controlling the beam using solenoidal fields, scrapping the halos, or compensating with opposite charges [2].

The Space Charge Compensation (SCC) methods have been successfully applied to transport high current, low energy proton or H^- beam in linear accelerators. In addition, solenoid based compensations in RF photoinjectors are widely used in most of xFELs. However, SCC schemes in circular machines have not been actively implemented since charge neutralization over the entire circumference of the ring is not practical, and local compensation scheme results in high density profiles of electrons which would also cause another e-p instabilities.

The Integrable Optics Test Accelerator (IOTA) ring is being built at Fermilab to implement nonlinear integrable lattices, which will improve the beam stability to perturbations and mitigations of collective instabilities through Landau damping [3]. The IOTA ring will be also used to study space charge compensation in circular rings, and to demonstrate optical stochastic cooling system. Using newly built IOTA ring, two novel schemes have been planned to study space charge compensations in circular machines; electron lens and electron column.

For the SCC method with an electron lens, externally generated co-propagating beam of opposite charge collides with the proton beam inside a strong magnetic field, in result, it compensates the space charge tune shift of the proton beam. For an electron column method, however, electrons are generated from the ionization processes of the beam itself with the residual gas in a solenoidal field. Both methods of space charge compensations require to precisely control the density profile of magnetized electrons through propagating or trapping inside strong magnetic fields. In this report, we present these two novel experimental projects to mitigate instabilities induced by space charge effects using electron lens or electron column methods at Fermilab's IOTA ring.

ELECTRON LENS

In the electron lens, a pulsed, magnetically confined, and low energy electron beam interacts with circulating proton beam electromagnetically to mitigate space charge tune shifts [4]. There exists many applications of electron lenses including long-range beam-beam compensation, head-on beam-beam compensation, and halo-scrapping with hollow electron beams [5]. Figure 1 shows the schematic layout of the electron lens previously used in Tevatron.

In an electron lens scheme for the space charge compensation, the externally generated electron beam with matched transverse distributions collides with the circulating proton beam. The transverse density profile of the injected electron beam is shaped by the cathode of the RF photoinjector, and the stability of the electron beam is maintained by strong external solenoidal fields. The longitudinal profile of pulsed electron beam could also match to proton bunch profile, if needed.

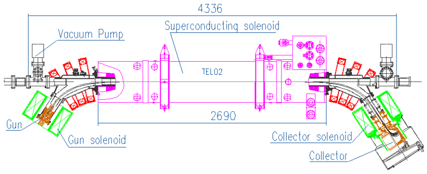

Figure 1: Schematic Layout of an Electron Lens Experimental Setup

We recycle components from the Tevatron electron lenses. Currently, vacuum tests of gun and collector are completed. We aim to assemble the e-lens in straight configuration for checkout by the end of 2018. The electron beam transport

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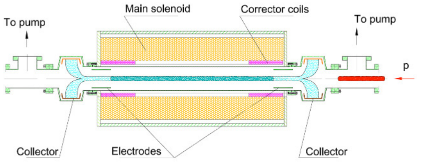


Figure 2: Schematic Layout of an Electron Column Experimental Setup

simulations in the e-lens at the IOTA ring has also been performed with field line mapping of solenoid fields, single particle tracking, and tracking with space charge forces. Several effects need to be accurately studies further, for example, 1) lattice deviations from ideal case, 2) impact of chromaticity-correction sextupoles on integrability, 3) azimuthal asymmetries in electron-lens kicks, 4) effect of fringe fields on ring optics, 5) perveance of electron gun and accuracy of beam profile, and 6) chromatic effects of the electron lens. These studies are based on numerical simulations and on experiments at the Fermilab electron lens test stand

ELECTRON COLUMN

The space charge compensation method using the electron column (Fig. 2, [6]) is to achieve intense and stable beams in circular accelerators through trapping and controlling of electrons, which are generated from beam-induced residual gas ionizations without external electron sources and optics. The primary advantage of the e-column lies in using the proton beam itself to generate electrons and match the proton beam profile. This scheme was tested with some successes before but the beam stabilities were not assured.

The optimal compensation conditions for the e-column method could be obtained if the distributions of electrons and circulating beam are matched transversely, moreover, longitudinally. This can be realized by trapping electrons transversely with a strong solenoid fields to a column, and using electrostatic electrodes to finely tune the densities. The strong external magnetic field also stabilizes the motion of electrons by keeping them in the column, and prevents coherent e-p instabilities. The field strength should also be weak enough to enable ions to escape easily from the column, and not to affect the processes of charge compensations between electrons and beam. It also requires that the neutralization time should be fast enough, so that it is shorter than the revolution time of the proton beam in the ring.

Simulation Setup

Our initial approaches are to simulate physical processes inside the electron column using the Warp code [7], and to understand the precise parameter ranges for the solenoidal magnetic field, voltages on electrodes, gas pressure in the column, etc. Table 1 shows beam, machine, and simulation parameters.

We consider that the dominant ionization processes in the column are $p + H_2 \rightarrow p + H_2^+ + e$ and $e + H_2 \rightarrow H_2^+ + 2e$ [8]. Therefore, protons ionize the residual H_2 gas and generated electrons also ionize the gas, too. The simulation time step is set to 15 *psec* which is less than the cyclotron period. The real to macro particle ratio is set to 7500. In each time step, 100 macro particles of the proton beam are injected.

Table 1: Electron Column Simulation Parameters

	Value	Unit
Beam Species	Proton	
Beam Current (average)	8	mA
Beam size (RMS)	5.5	mm
Beam Momentum	70	MeV/c
Cell Length	1	m
Solenoid Fields	$0 \sim 0.2$	T
Electrode Voltages	$0 \sim -200$	V
Vacuum Pressure	$10^{-3} \sim 10^{-5}$	$Torr$

We control the solenoidal magnetic field (0 to 0.1 T), gas pressure (10^{-3} to 10^{-5} $Torr$), and voltages on left and right electrodes (0 to -200 V). For given beam parameters, one can find that proton beam potential at the center is given by $\phi = 30I/\beta \approx 3.5V$. With 1 m length of an electron column and the circumference of ~ 40 m, we need about 140 V for full space charge compensation. At this stage, our study is limited to 1 m channel only. No ring is considered. This gives us a proper range of voltages on electrodes.

Simulation Results

Without external magnetic field and trapping voltage, simulation results show that the longitudinal density of electrons are lower than that of protons, i.e., under-compensation. If solenoid field and trapping voltages are turned on, electron densities are growing in time until the whole processes are neutralized. Figure 3 shows the comparison of the electron density variations in time for different control parameters as well as proton density. When voltages on electrodes are higher, the neutralization time is getting longer. Since the revolution time in the IOTA ring is ~ 1.8 μsec, the neutralization time for $V = -200$ V is not acceptable.

In addition, with high voltages on electrodes, more electrons tend to be trapped between two electrodes inside the column, therefore, densities of electrons exceed those of pro-

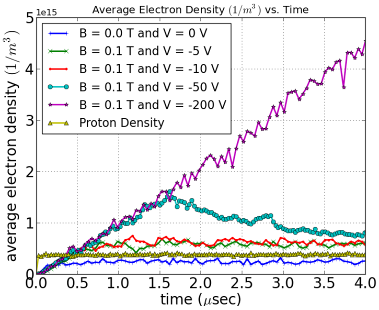
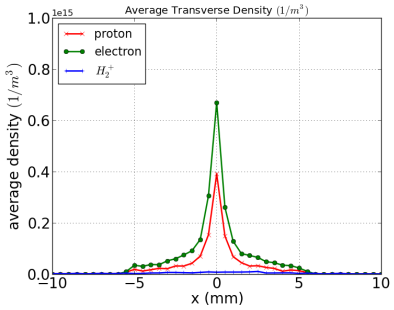
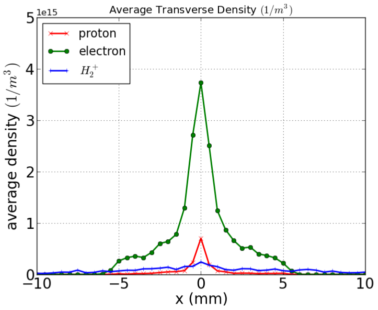


Figure 3: Neutralization time for various parameters



(a) $B = 0.1\ T$ and $V = -5\ V$



(b) $B = 0.1\ T$ and $V = -200\ V$

Figure 4: Transverse density profiles of protons, electrons, and H_2^+. The vacuum pressure is $10^{-3}\ Torr$.

tons. As shown in Fig. 4, transverse density profiles of electrons are closely matched to those of protons for $B = 0.1\ T$ and $V = -5\ V$ (Fig. 4(a)). However, simulations show that there are significant over-compensations for $B = 0.1\ T$ and $V = -200\ V$ (Fig. 4(b)). When applied voltages are higher, the densities of H_2^+ are also noticeably increased, so it could affect the physical processes between protons and electrons.

Moreover, the vacuum pressure of the electron column also plays an important role to control the density level of electrons. By lowering the vacuum pressure, the electron densities can be decreased with less ionization processes in the column. For $B = 0.1\ T$, $V = -5\ V$, and $P = 5 \times 10^{-4}\ Torr$, we achieved matched transverse and longitudinal distributions of electrons as shown in Fig. 5.

DISCUSSION

Space charge compensation (SCC) experiments with both e-lens and e-column are being pursued in IOTA ring at Fermilab. For the electron lens, external e-beam will be used to compensate circulating proton beam in IOTA ring. Experimental setup is being assembled by 2018. Simulation studies 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. Experiment will use the E-Lens setup. Practical issues such as ring dynamics of the primary proton beam with external focusing and multiple passes through the e-column in the IOTA ring will be investigated. We will also continue construction, tests, and installation of both IOTA e-lens and e-column.

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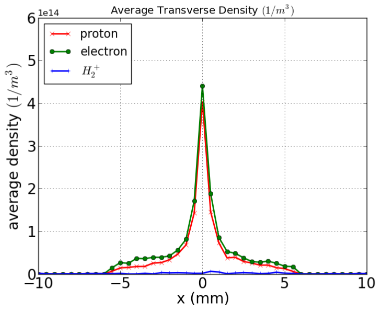
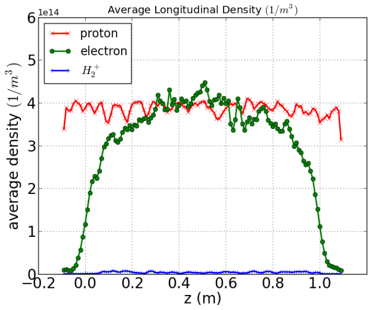


(a) Transverse density profile



(b) Longitudinal density profile

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