Space-Charge Compensation Using Electron Columns at IOTA

Ben Freemire & Chong Shik Park

HB2018

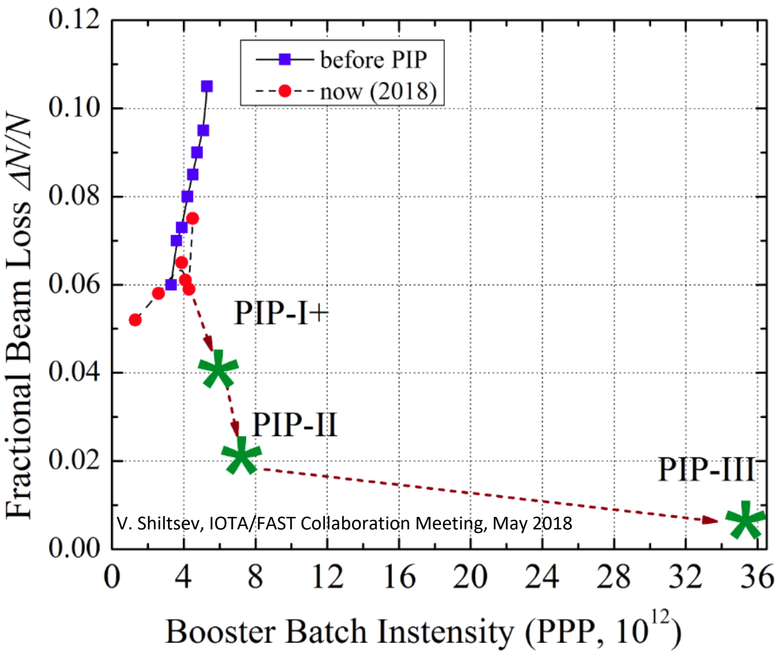
20 June 2018

Outline

- Motivation
- Space-Charge Compensation using an Electron Column
- IOTA
- Experimental Schedule
- Simulation Effort
- Summary

Motivation

- High intensity accelerators suffer from beam loss and component radioactivation due to the space-charge force within the beam
- Future proton accelerators and upgrades to existing machines will require better control of beam loss to prevent damage to components, minimize cost, and achieve desired beam power
- For example, at Fermilab, goal is for LBNF to provide 2+ MW beam power for the DUNE physics program
    - Requires upgrade of accelerator complex
- Space-charge compensation could drastically improve performance at Fermilab and elsewhere

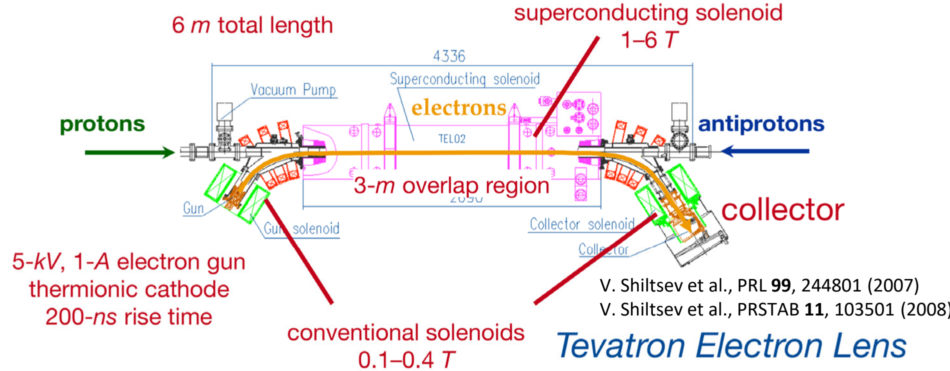


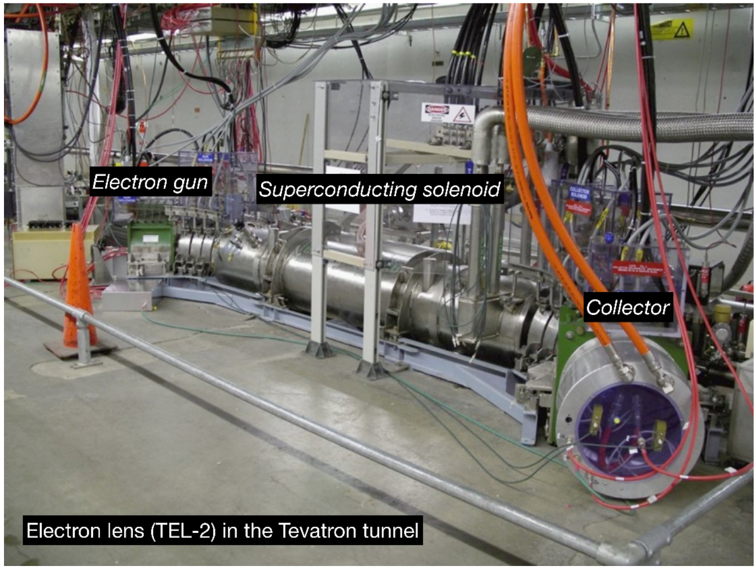
Space-Charge Compensation

- Undesirable effects of Coulomb repulsion can be mitigated by making beam pass through plasma column of opposite charge, with same charge distribution
  - Required total charge of plasma column decreases with beam energy
- This concept successfully applied to transport high current, low energy proton and H^- beams in the RFQs of linacs
- In circular machines, suppression of e-p instabilities can be achieved using a solenoidal magnetic field of sufficient strength

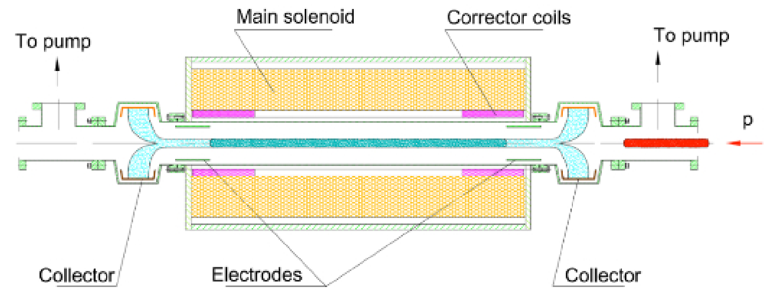
Electron Lenses

- Electron gun provides electrons that overlap with circulating proton beam for short region
- Strong solenoid magnet confines electrons and suppresses instabilities
- Electron transverse profile needs to be carefully matched to that of beam
- Additional magnets needed for injection and extraction
- Employed successfully at Tevatron and RHIC





Electron Columns



- Similar in concept to Electron Lenses
  - Electrons provide negative charge to compensate Coulomb repulsion
- Electrons produced by ionization of gas by beam in region of Column
- Electron transverse distribution matches beam intrinsically
- Solenoid magnet confines electrons transversely
  - Strength of field must be enough to suppress e-p instability, but weak enough to all plasma ions to escape
- Electrodes at either end provide longitudinal confinement
- Does not require electron gun, collector, or transport magnets
- Does require additional pumping to maintain vacuum in rest of ring

Electron Column Historical Context

- Successfully used for high current, low energy beams in linacs
- 1984 at Institute of Nuclear Physics, Novosibirsk – First attempt in circular machine
  - 1 MeV, 8 mA proton beam
  - Few mTorr hydrogen gas
  - No stabilizing magnetic field
  - Achieved 10x increase in beam current
  - Beam lifetime reduced
  - e-p instabilities significant
- 2007 V. Shiltsev proposes attempt using Electron Lens at Fermilab
  - Accumulation of negative charge observed
  - Vacuum and beam instabilities

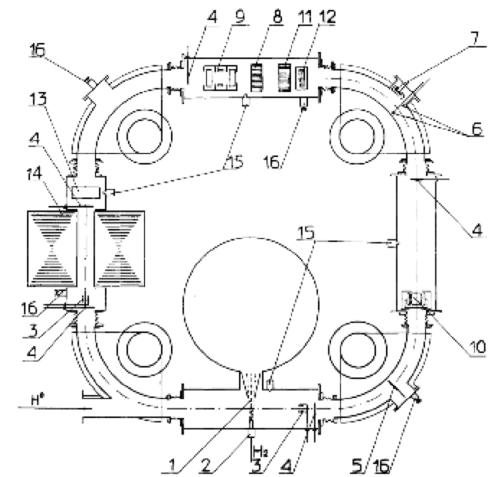
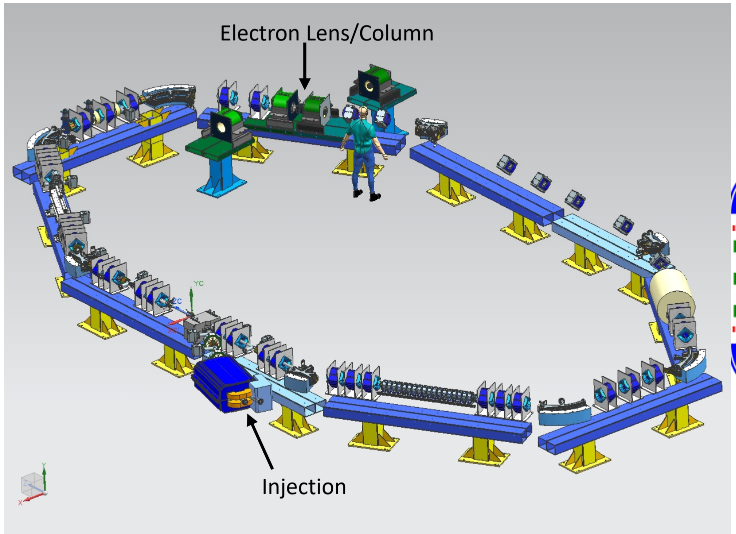
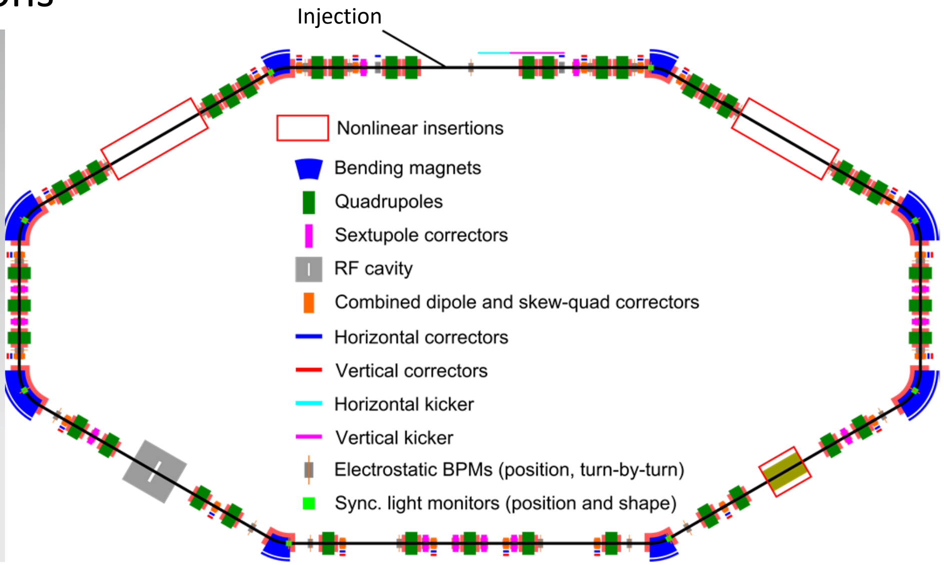


FIGURE 1 Layout of the proton storage ring. 1—secondary stripping gas target, 2—pulsed gas valve, 3—Faraday cups, 4—quartz screens, 5, 6—mobile targets, 7—ion collector, 8—Rogovsky coil, 9—"pick-up" station, 10—electrostatic transducer of quadrupole beam oscillations, 11—magneto-inductance transducer, 12—transducer of vertical beam losses with high time resolution, 13—device for measuring the secondary charged-particle concentration in the beam region, 14—betatron core, 15—electromagnetic gas valves of the system of pulsed gas leak-in, 16—microleaks of the system of stationary gas leak-in.

Integrable Optics Test Accelerator

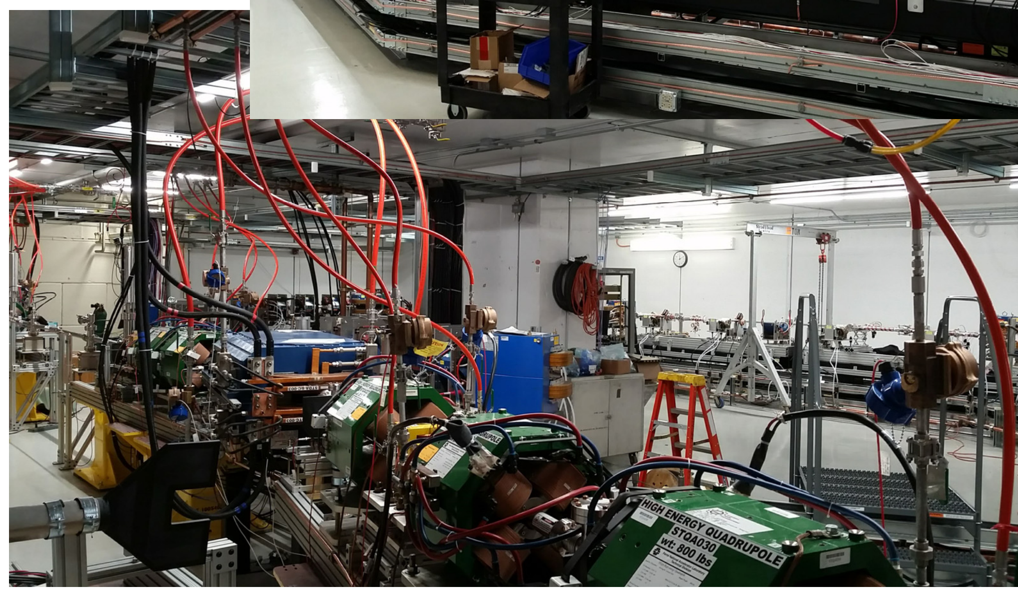
- Located at Fermilab's Accelerator and Science Technology (FAST) Facility
- Storage ring for advanced beam physics research
- Will operate with electrons or protons





Experimental Schedule

- Electron linac commissioned – 2017
- Construction of IOTA ring complete – August 2018
- Commissioning – August-September 2018
- First electron experiments – September-December 2018
- Proton RFQ installation – mid-2019
- Commissioning for protons in IOTA – late-2019



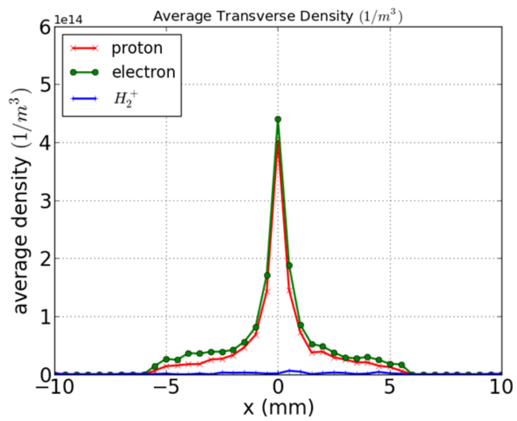
Electron Column Simulation / IOTA Parameters

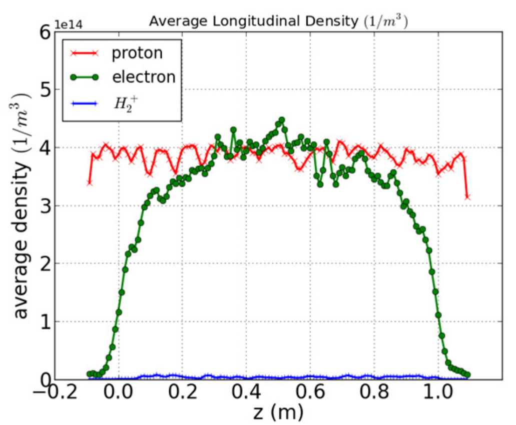
Beam Parameters	
Beam Species	Proton
Beam Energy	2.5 MeV (p = 68.5 MeV/c)
Beam Current	8 mA
Beam Pulse Length	1.77 µs
Beam Distribution	KV (transverse), Step function (longitudinal)

Hardware Parameters	
Column Length	1 m
Pipe Radius	2.54 cm
Electrode Positions	0, 100 cm
Electrode Strength	-5 V
Solenoid Field	0.1 T

Gas Parameters	
Gas Species	Hydrogen
Gas Density	1.65×10^{13} cm^{-3} (5×10^{-4} torr)
Ionization Process	$p + 2H_2 \rightarrow p + e + H_3^+ + H$
Ionization Cross Section	1.82×10^{-17} cm^2
Plasma Electron Energy, Spread	45 eV, 19 eV

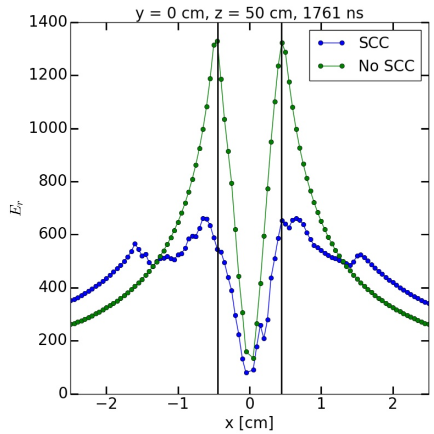
Numerical Parameters	
Particles Injected/Step	500
Grid Spacing, x,y,z	0.5, 0.5, 1.0 cm
Time Step	70 ps
Simulation length	1.83 µs
Number of Passes	2

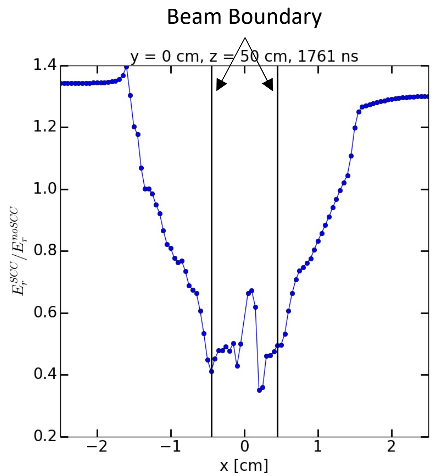




Previous Work / Updates

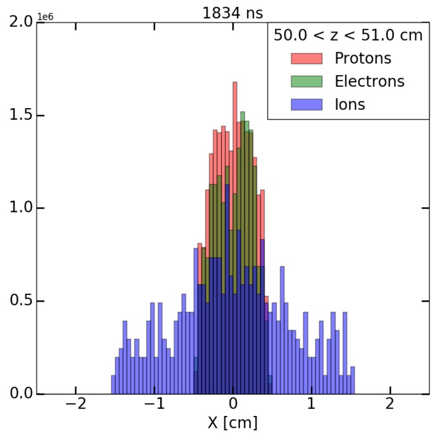
- Initial optimization of Column parameters (gas density, electrode potential, magnetic field) performed using constant beam
  - THA3CO04, NAPAC'16
- Work presented hereafter includes:
  - Expected emittance & beam size
  - Pulse length and revolution period
  - Plasma generation improvements
  - Two passes with plasma resulting from first pass

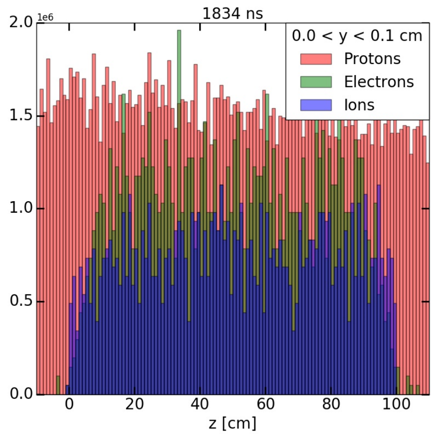




Space-Charge Compensation after First Pass

- To quantify effect of Space-Charge Compensation, simulations with ionization (SCC) and without ionization (no SCC) turned on
- Significant reduction in radial electric field within beam radius observed

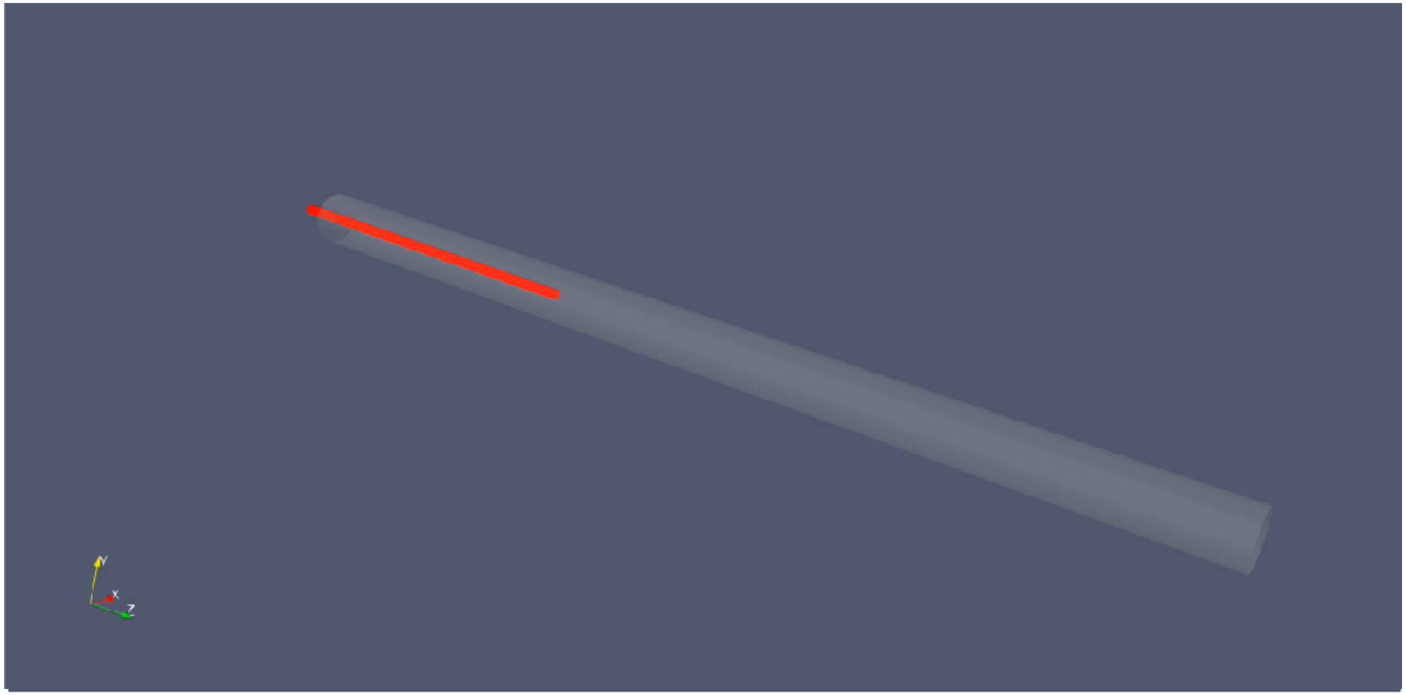


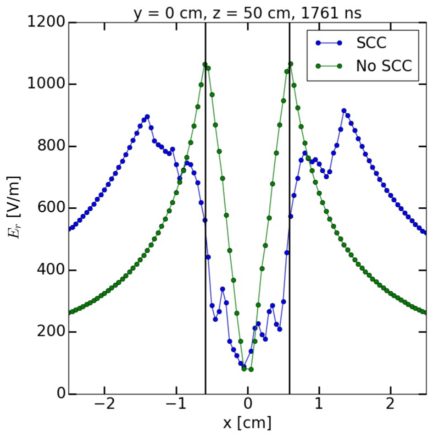


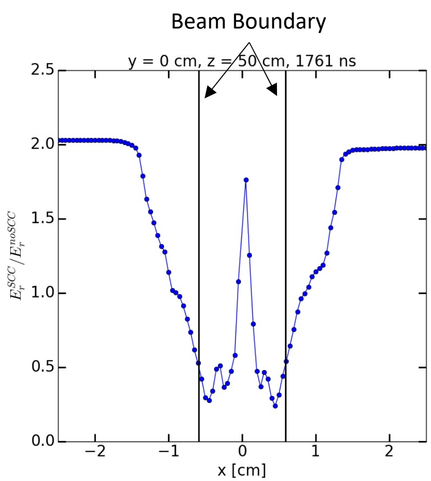
Distribution Match After First Pass

- Distributions taken at center of Column in z and y
- Transverse profile of plasma electrons at Column center and beam matched after first pass
- Density of electrons approaching that of beam
- Unwanted ions more homogeneously distributed

Animation of First Pass





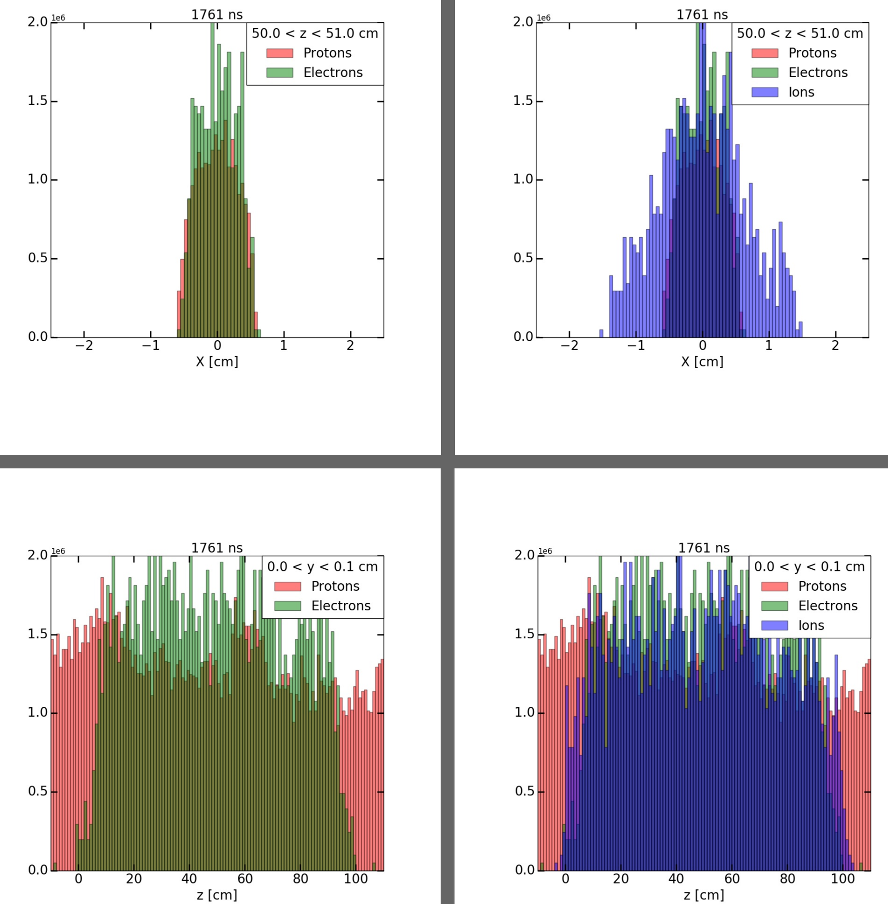


Space-Charge Compensation after Second Pass

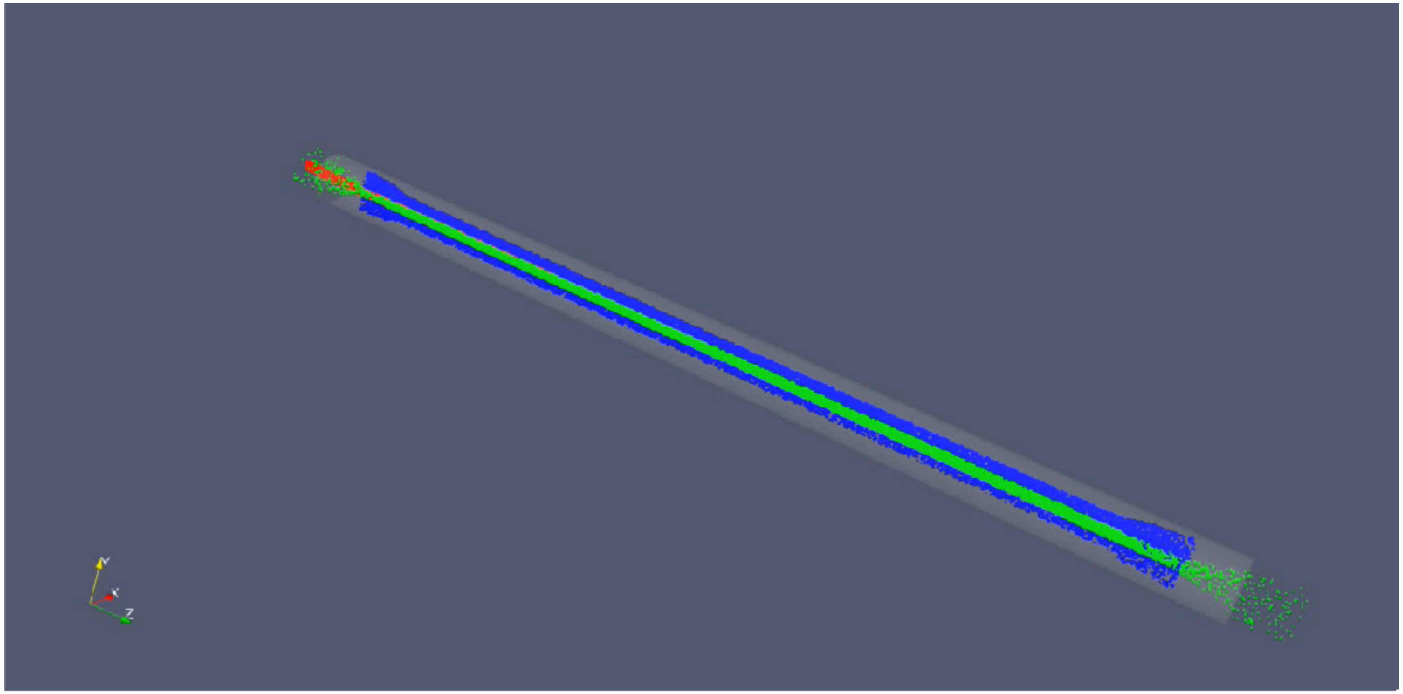
- Degree of space-charge compensation similar to first pass
  - Indicates full extent of compensation reached quickly
- Accumulation of positive ions along beam center observed
  - Undesirable – Counteracts compensation

Distribution after Second Pass

- Distributions taken at center of Column in z and y
- Transverse distribution of electrons still closely matched to that of beam
- Density of electrons now greater than beam density
  - Electron loss due to recombination neglected
- Ion density also surpasses beam density
  - Leads to reduction in space-charge compensation
  - Can be mitigated by reducing gas density and/or magnetic field strength



Second Pass Animation



Summary

- Space-Charge Compensation using an Electron Column offers the potential to decrease beam loss in circular machines
- Simulations of the space-charge compensation using an Electron Column in IOTA show a positive effect after a single pass
- After a second pass, reduction in the radial electric field ~50% observed
- Optimization required to minimize impact of plasma ions
- Additional plasma effects must be accounted for
  - Particle collisions
  - Recombination
- Evolution of beam phase space including rest of IOTA lattice to be studied
- Experimental program for protons in IOTA planned for 2019-2020

Acknowledgements

- The rest of the Electron Column group: Giulio Stancari, Gregg Penn, Chad Mitchell, & Moses Chung
- Thank you to all of the FAST/IOTA team, in particular Vladimir Shiltsev and Swapan Chattopadhyay
- This work is supported by the US DOE Office of HEP, and the General Accelerator Research and Development Program