Mitigation of Space Charge Effects Using Electron Column at IOTA Ring

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ICFA mini-Workshop on Mitigation of Coherent Beam Instabilities in particle accelerators

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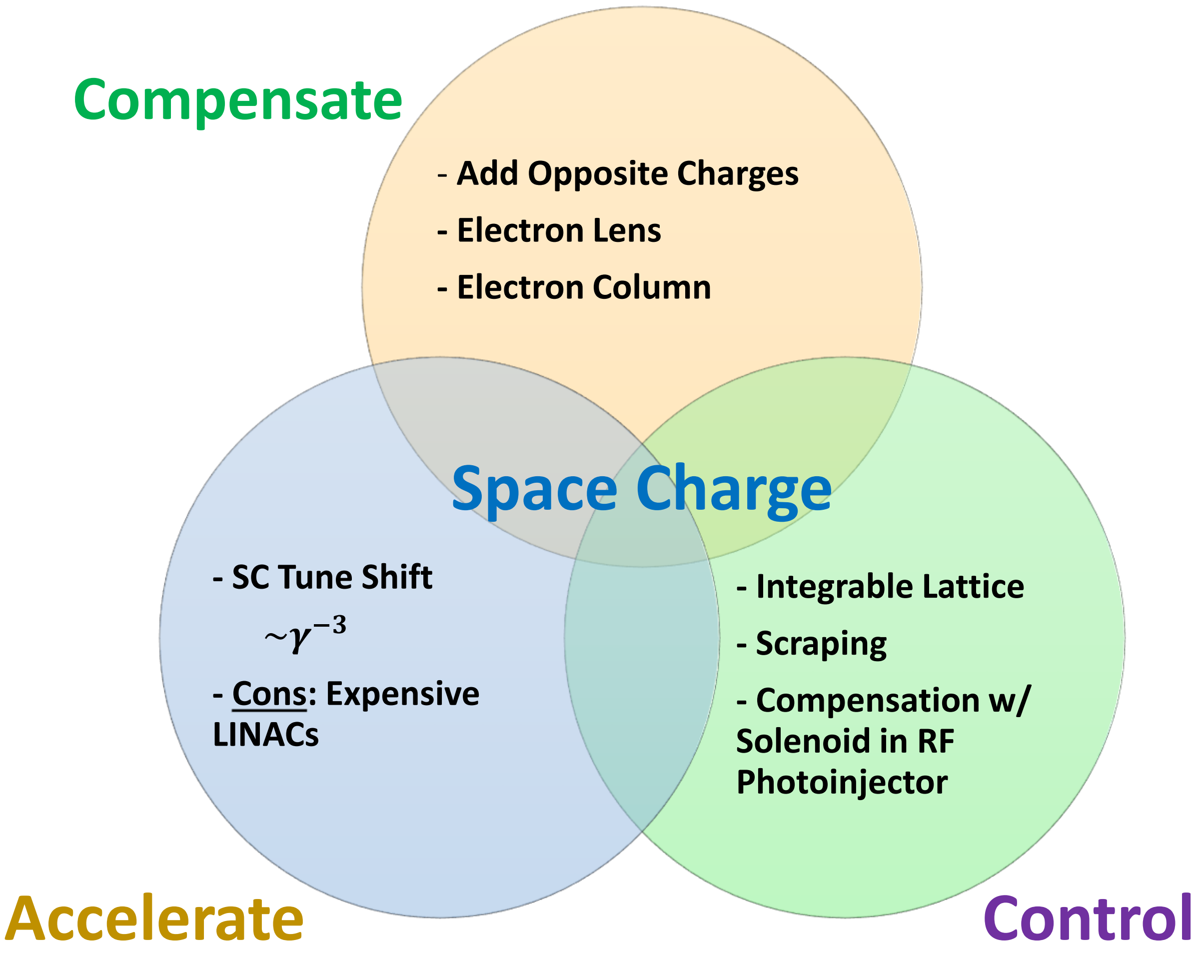
Outline

- Motivation
- Space Charge Compensation at IOTA Ring
- Simulation Methods
- Early Works
- Multi-Pass SCC Results
- Conclusion

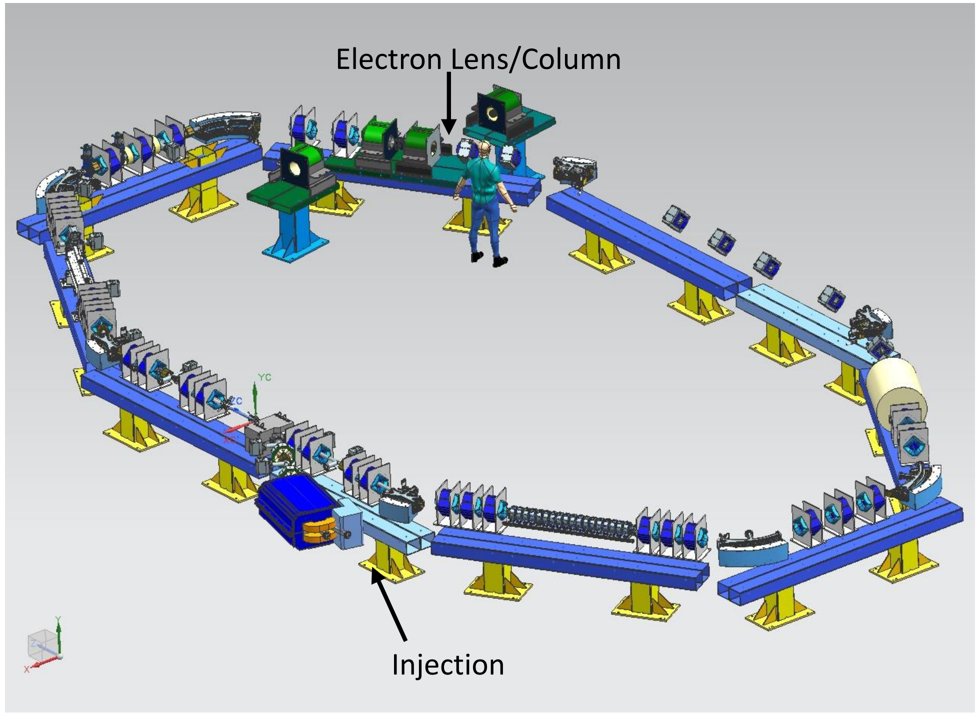
* Acknowledgement: **B. Freemire**, C. Mitchell, E. Stern, and V. Shiltsev

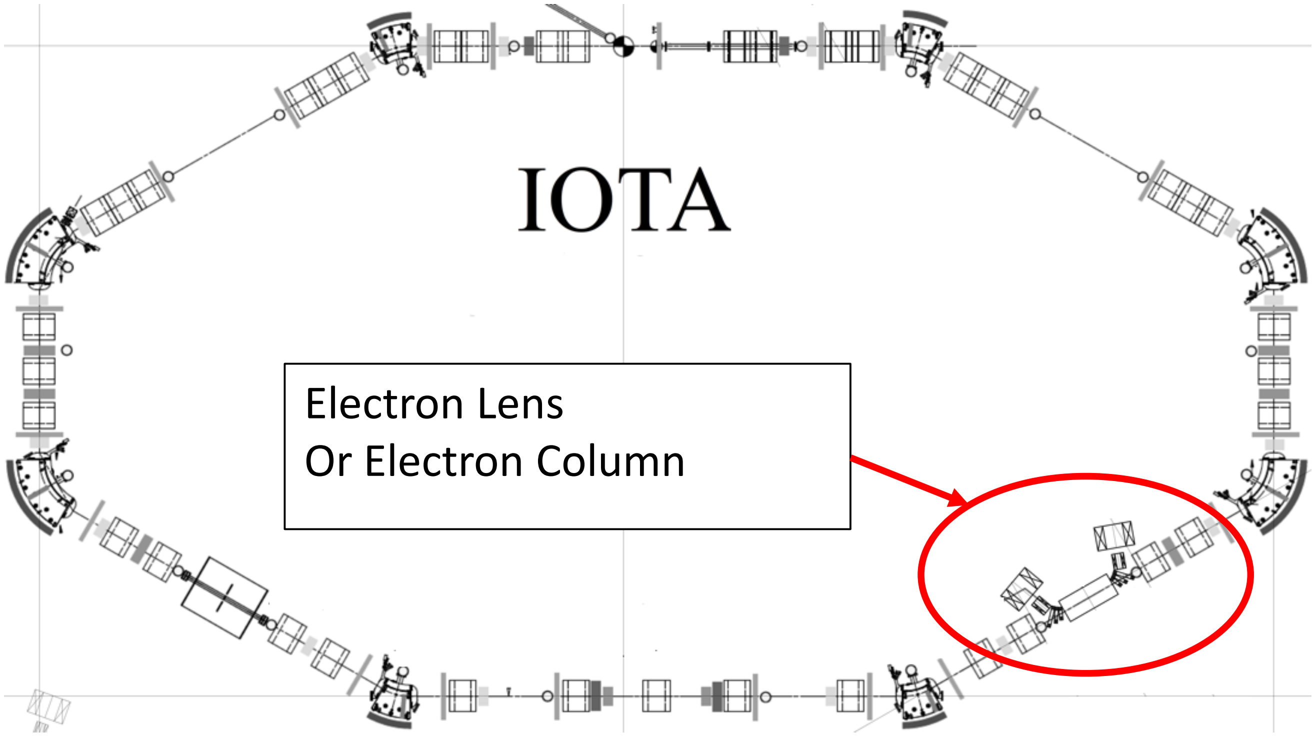
Space Charge: Crucial Challenge at High Intensity

Mitigation of Space Charge Effects



Integrable Optics Test Accelerator (IOTA) Ring at Fermilab





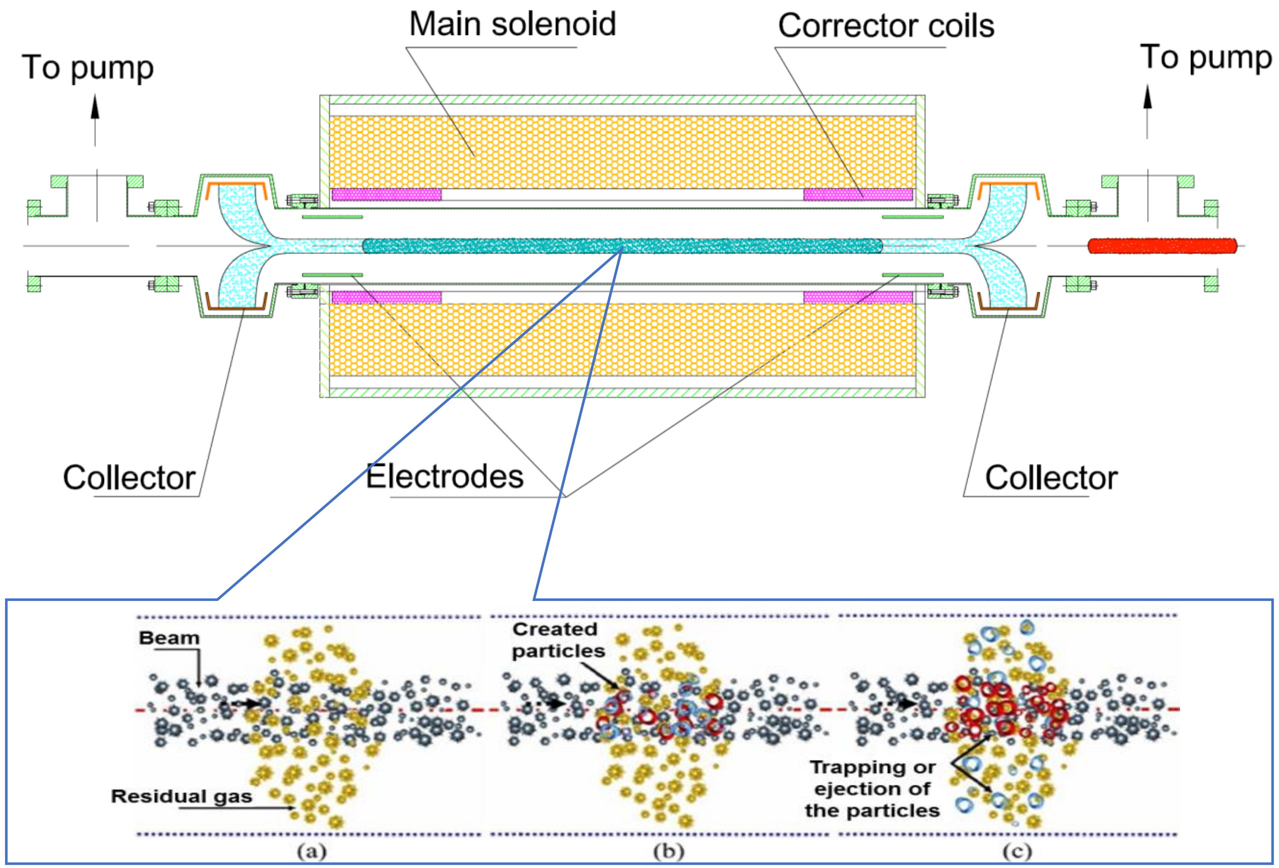
Circumference = 40 m, 70 MeV/c proton beam

Space Charge Compensation (SCC) at IOTA Ring

- Two ways of SCC are being studied at IOTA
  - Co-propagating beam of opposite charge (electron lens)
    - Robust, precise control of transverse profile of the e-beam
    - Experimentally mature "Swiss Knife," employed in Tevatron, RHIC, and now LHC.
    - Y. Alexahin's talk (Tuesday Morning)
  - Passive compensation of the proton beam (electron column)
    - Self-ignition: Use protons to ionize residual gas and to generate electrons
    - Electrons are approximately rest longitudinally compared to co-moving electrons in electron lens
    - Trap/Match/Control the electrons and their profile – solenoid and electrodes.

Proposed Experimental Setup for Electron Column

- 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.
- In circular machines, e-p instabilities can be suppressed using an external magnetic field of sufficient strength



[Courtesy of N. Chauvin, ICIS'11]

* V. Shiltsev et al. The Use of Ionization Electron Columns for Space-Charge Compensation in High Intensity Proton Accelerators AIP Conf. Proc. 1086, 649 (2009)

Our Approach to Space Charge Compensation Using Electron Column at IOTA Ring

- In IOTA, we will use e-lens' central solenoid for e-column operation.
  - Plasma column with electrons compensates Coulomb repulsion of proton beam
- Ionization of residual gas by proton beam inside the column
  - Vacuum pressure also plays an important role to control the electron distribution
- Magnetic field stabilizes the e-column, and prevents e-p instabilities
  - Confines electrons transversely
  - Strong enough to suppress e-p instabilities
  - Weak enough to make positive ions escape
- Requires Electrodes to longitudinally confine electrons inside the column
- Investigate dynamics of electrons and ions with external E and B fields
  - Use Warp3D code for beam dynamics simulations inside of E-Column
  - Use Synergia code for beam dynamics simulations in the rest of the ring
- Goal: Match/control the transverse profile of electrons with B-field, voltages on electrodes, and vacuum pressure for multi-turn through IOTA ring
  - Match transversely with solenoid field and electrodes
  - Compensate longitudinally with electrodes
  - Multi-turn simulations in IOTA ring with pulsed beam

IOTA and SCC Simulation Parameters

Beam Parameters	
Beam Species	Proton
Beam Energy	2.5 MeV (p = 70 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

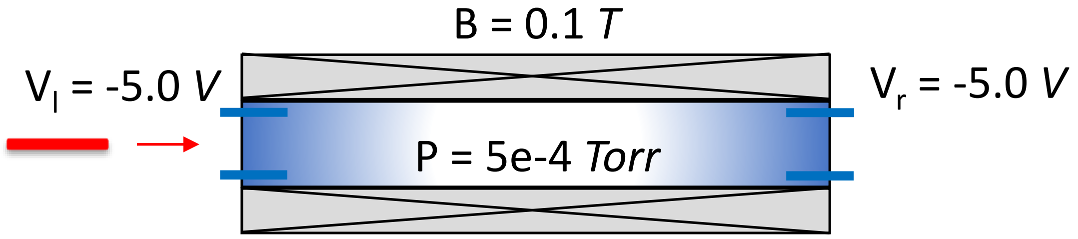
Gas Parameters	
Gas Species	Hydrogen
Gas Density	1.65×10^{13} cm^{-3} (5×10^{-4} torr)
Ionization Process	$p + 2H_2 \rightarrow p + e + H_3^+ + H$
Ionization Cross Section	1.82×10^{-17} cm^2
Plasma Electron Energy, Spread	45 eV, 19 eV

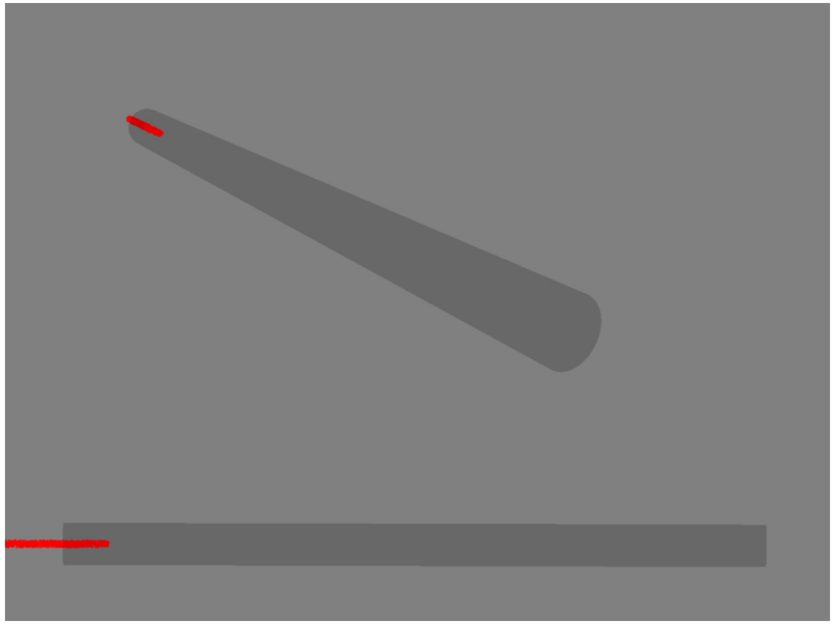
Numerical Parameters	
Particles Injected/Step	500
Grid Spacing, x,y,z	0.5, 0.5, 1.0 cm
Time Step	70 ps
Simulation length	1.83 µs
Number of Passes	2

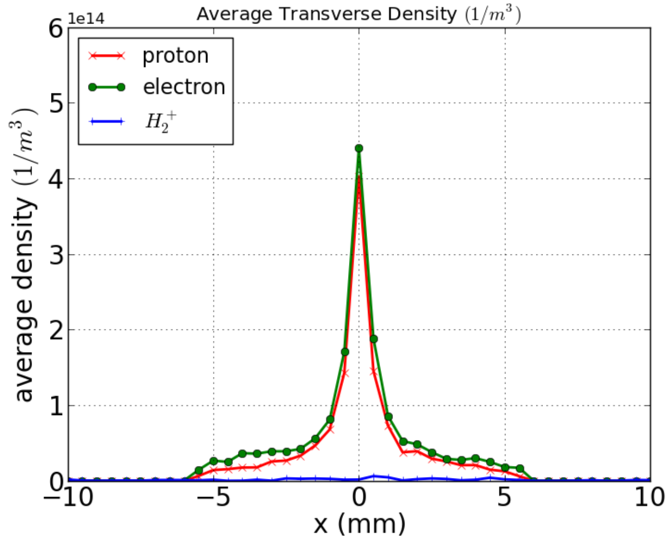
Early Results

Gaussian (Transverse) and Uniform and Coasting (Longitudinal) Beam

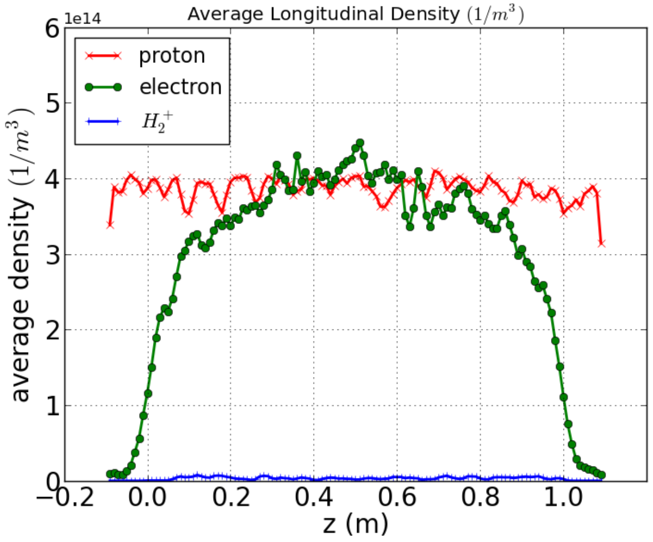
- Initial optimization of Column parameters (gas density, electrode potential, magnetic field) performed using constant beam







Transverse Density Profile



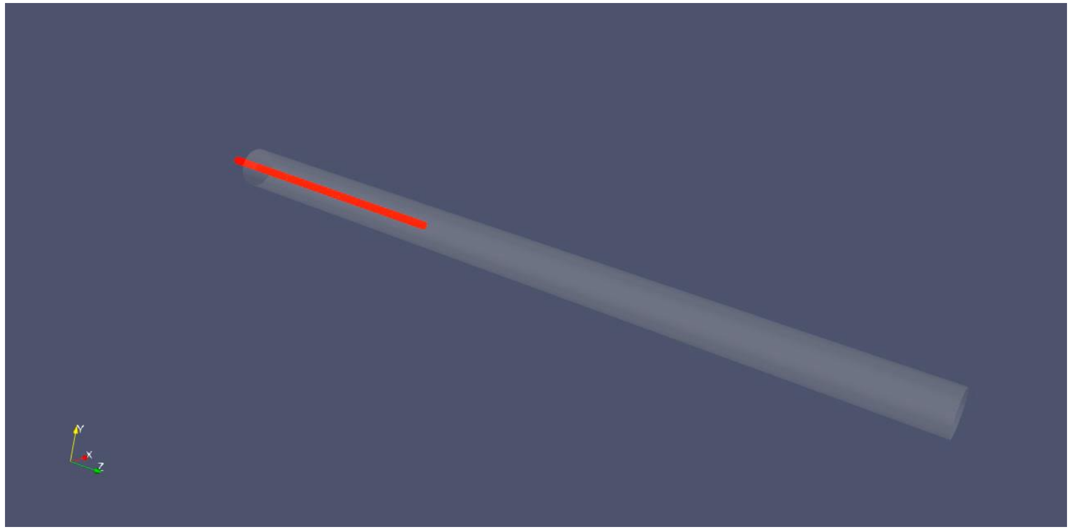
Longitudinal Density Profile

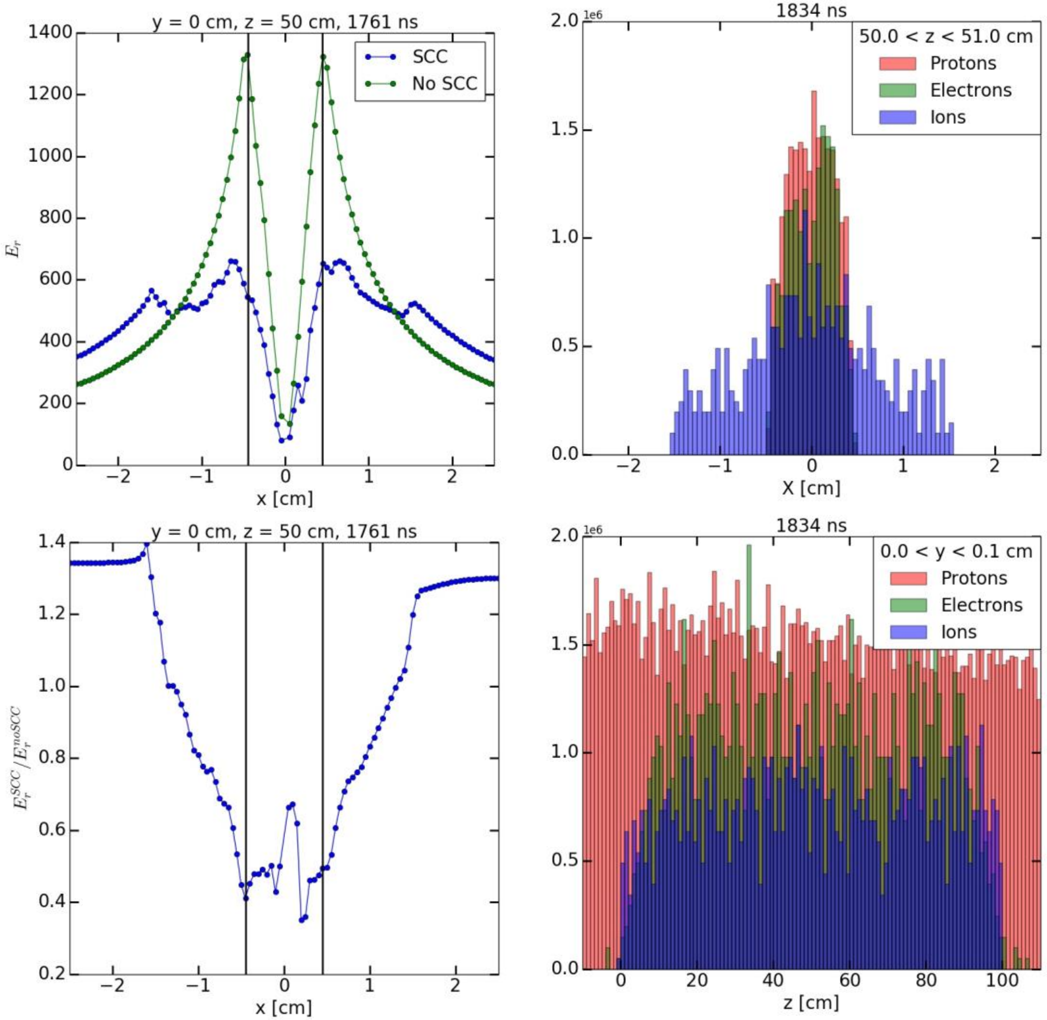
C.S. Park et al, NAPAC2016

Space Charge Compensation after First Pass

KV (Transverse) and Step Function (Longitudinal) Beam

- To quantify effects 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
- Density of electrons approaching that of beam
- Unwanted ions more homogeneously distributed

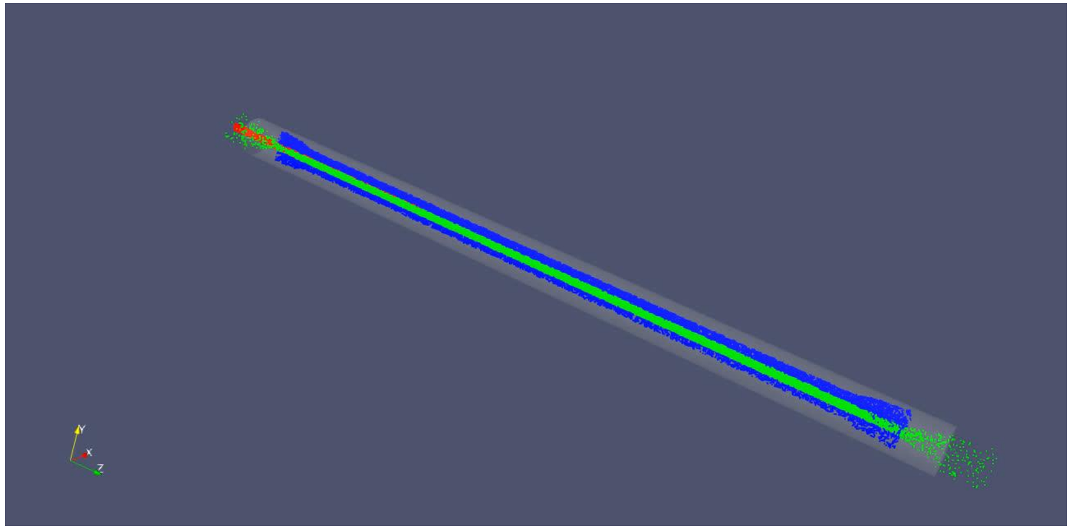


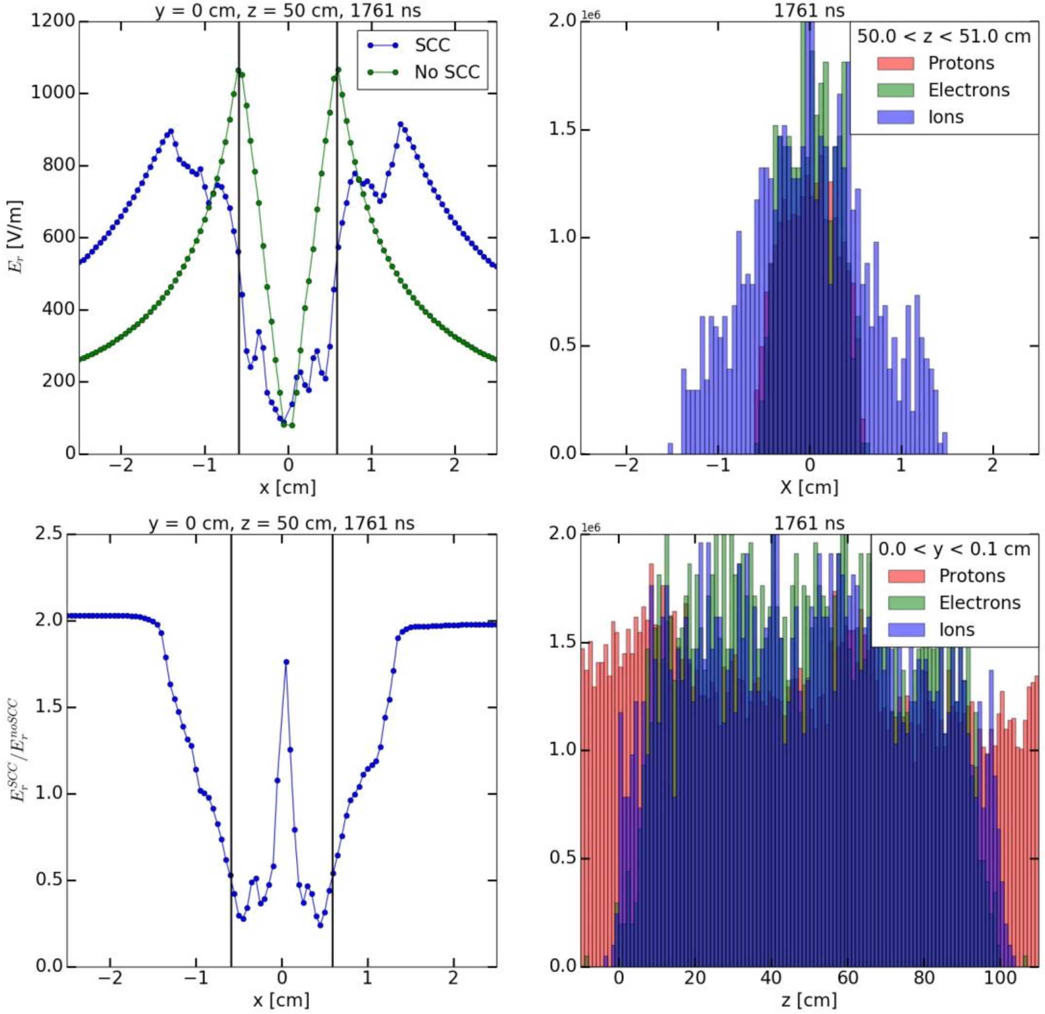


B. Freemire et al, HB2018

Space Charge Compensation after Second Pass

- Distributions taken at center of Column in z and y
- Transverse distribution of electrons still closely matched to that of beam
- 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





B. Freemire et al, HB2018

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.
- 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 second pass
- Additional optimization 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 to be investigated.
- Evolution of tune foot print and phase space to be studied.

Thank you for your attention!