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Space Charge Compensation Using Electron Columns and Electron Lenses at IOTA

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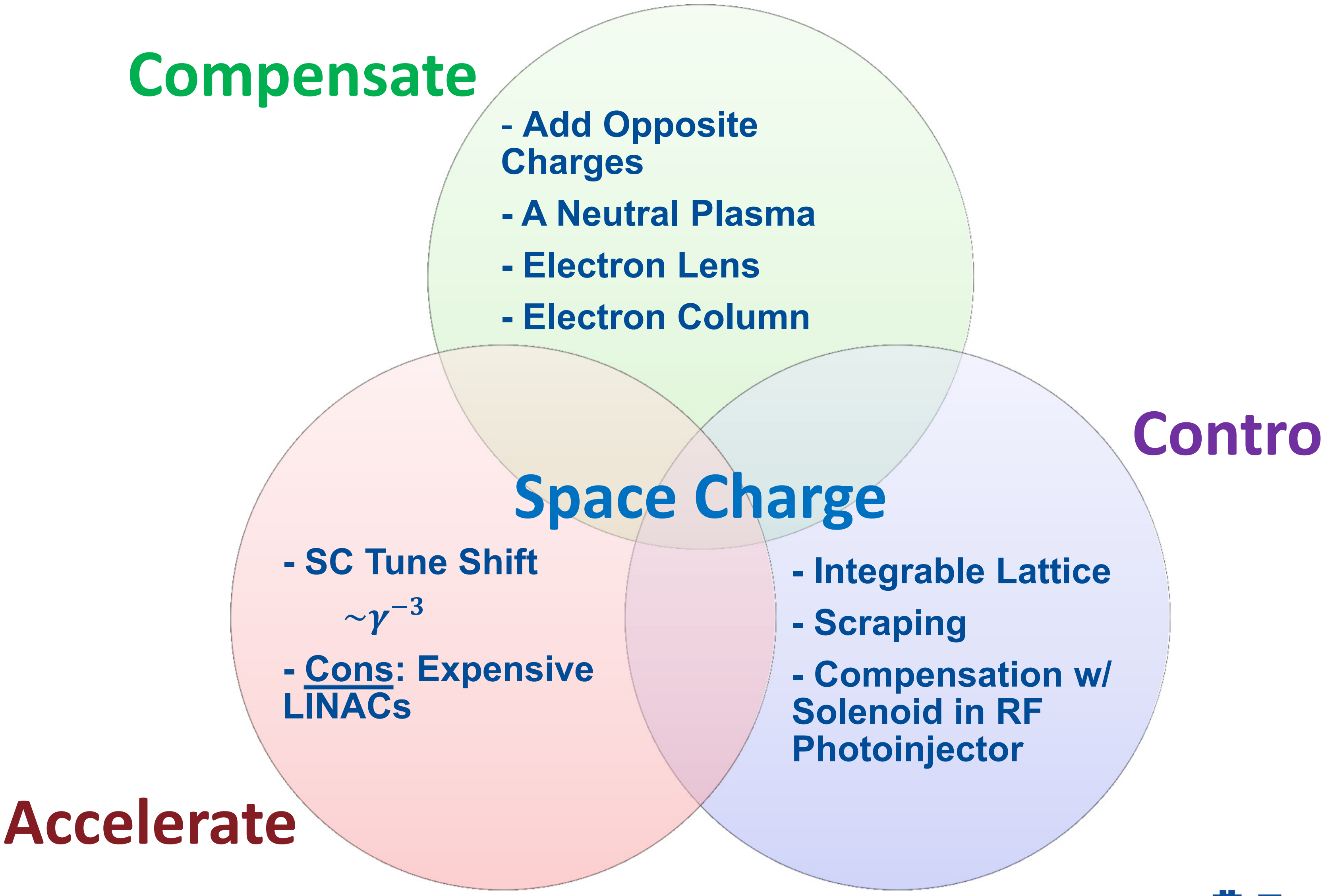
Outline and Acknowledgments

- **Space Charge Compensation (SCC)**
- **Electron Lens**
  - Main features and current status
- **Electron Column**
  - Concept and simulation studies
- **Summary**

- Acknowledgments
  - Team: V. Shiltsev, G. Stancari, J.C.T. Thangaraj, and D. Milana
  - FAST-IOTA Group at Fermilab

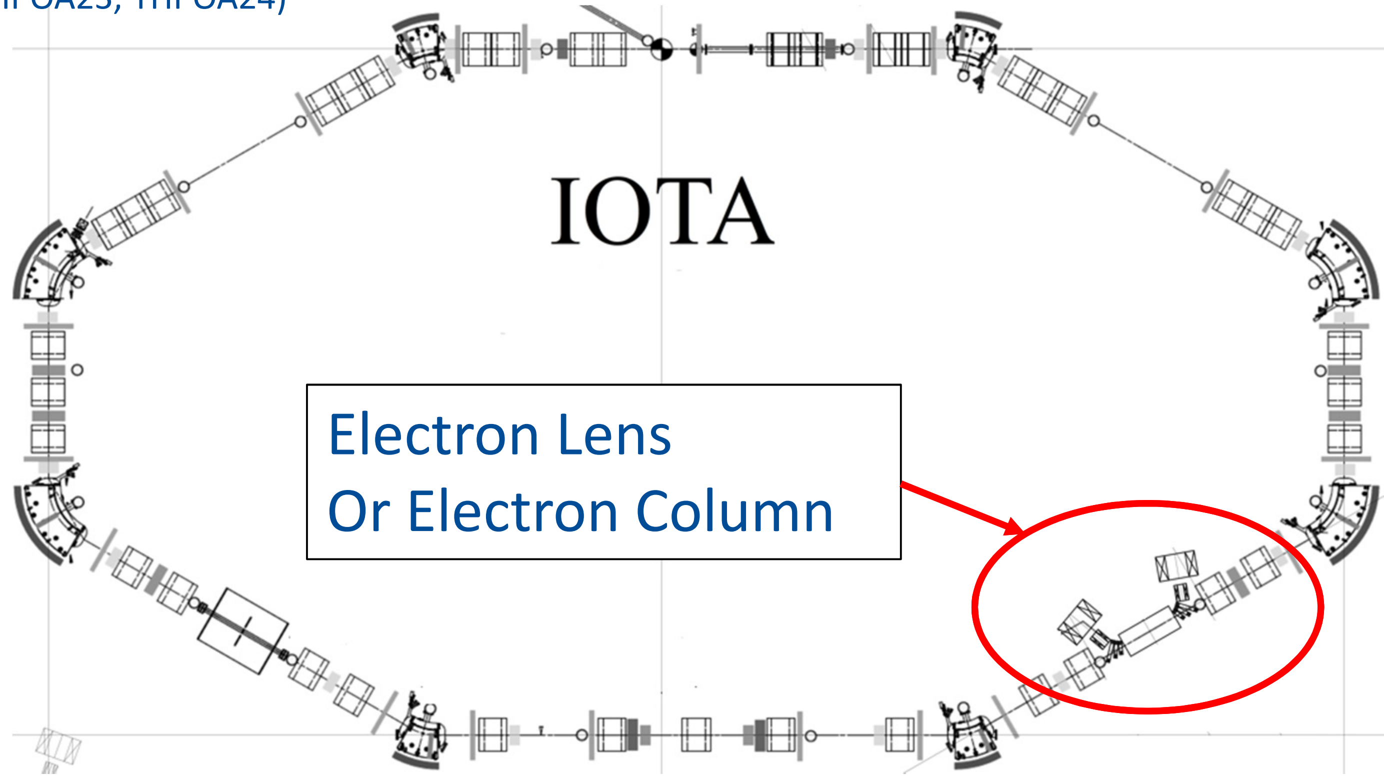
Space Charge Compensation

Space Charge (SC) – Crucial Challenge at High Intensity



Integrable Optics Test Accelerator (IOTA) Ring at Fermilab

- The IOTA ring is being built at Fermilab to study Space Charge Compensation.
  - D. Edstrom (TUPOA19), D. Bruhwiler (WEA2IO02), C. Hall (WEA4CO02), N. Cook (WEPOA31), A. Romanov (THPOA23, THPOA24)



Circumference = 40 m, 70 MeV/c proton beam

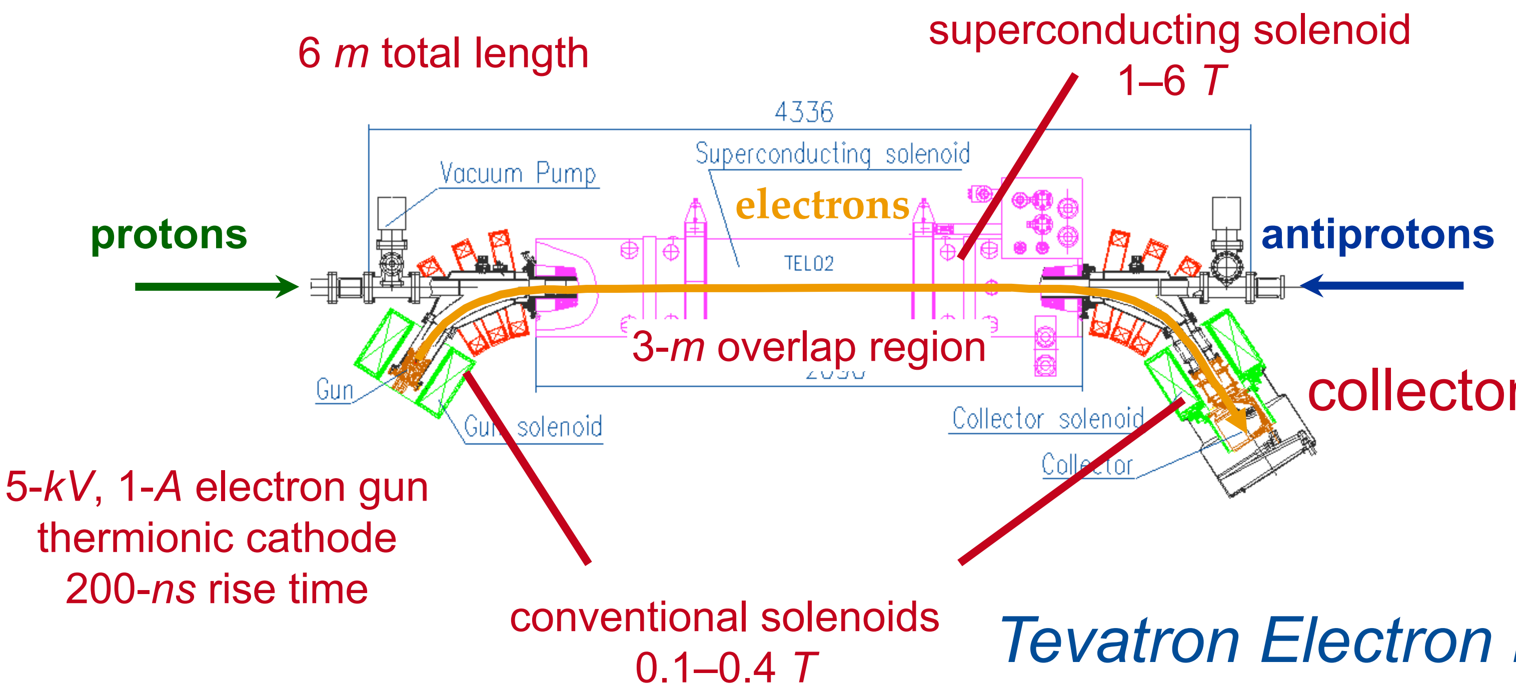
Space Charge Compensation at IOTA Ring

- Two ways of compensation are being done 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.
  - Passive compensation of the proton beam (electron column)
    - Self-ignition: Use protons to ionize the vacuum 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.

Electron Lens

What's an Electron Lens?

- Magnetically confined, low-energy electron beam, pulsed if needed.
- Circulating proton beam is affected by electromagnetic fields generated by electrons
- Transverse stability provided by strong axial magnetic fields

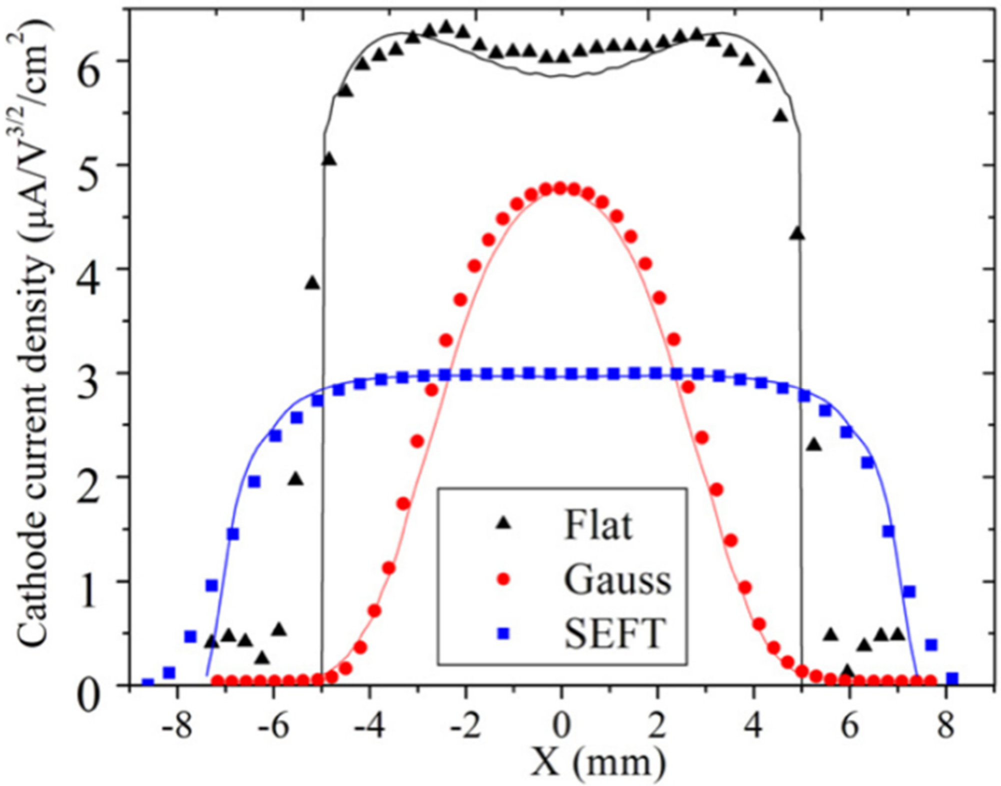


Tevatron Electron Lens

V. Shiltsev et al., PRL **99**, 244801 (2007)
V. Shiltsev et al., PRST-AB **11**, 103501 (2008)

E-Lens: Control of Transverse Electron Beam Profile

Transverse density profile of electron beam is shaped by cathode and electrode geometry, and maintained by strong solenoidal fields.



Gaussian profile for compensation of nonlinear beam-beam forces

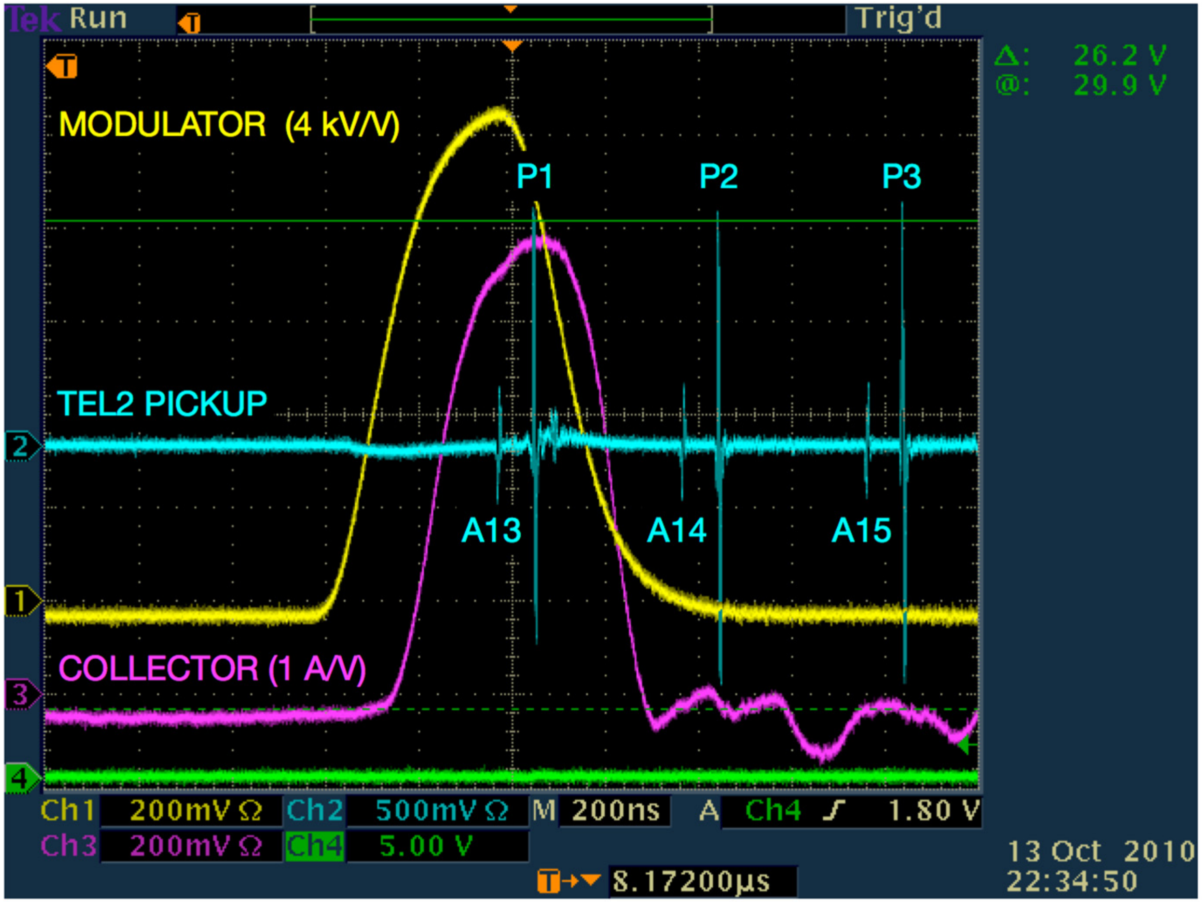
Flat profiles for bunch-by-bunch betatron tune correction

E-Lens: Control of Longitudinal Electron Beam Profile

Pulsed electron profile could match to proton bunch profile, if needed.

- V.N. Litvinenko et al, Phys. Rev. ST Accel. Beams. **17**, 114401 (2014)

Beam synchronization in the Tevatron



Status of Electron Lens Experiment Setup at IOTA Ring

- **Hardware**
  - We recycle components from the Tevatron electron lenses
  - Vacuum tests of gun and collector completed
  - Girders and supports are being designed and fabricated
  - Aim to assemble e-lens in straight configuration for checkout by the end of 2018

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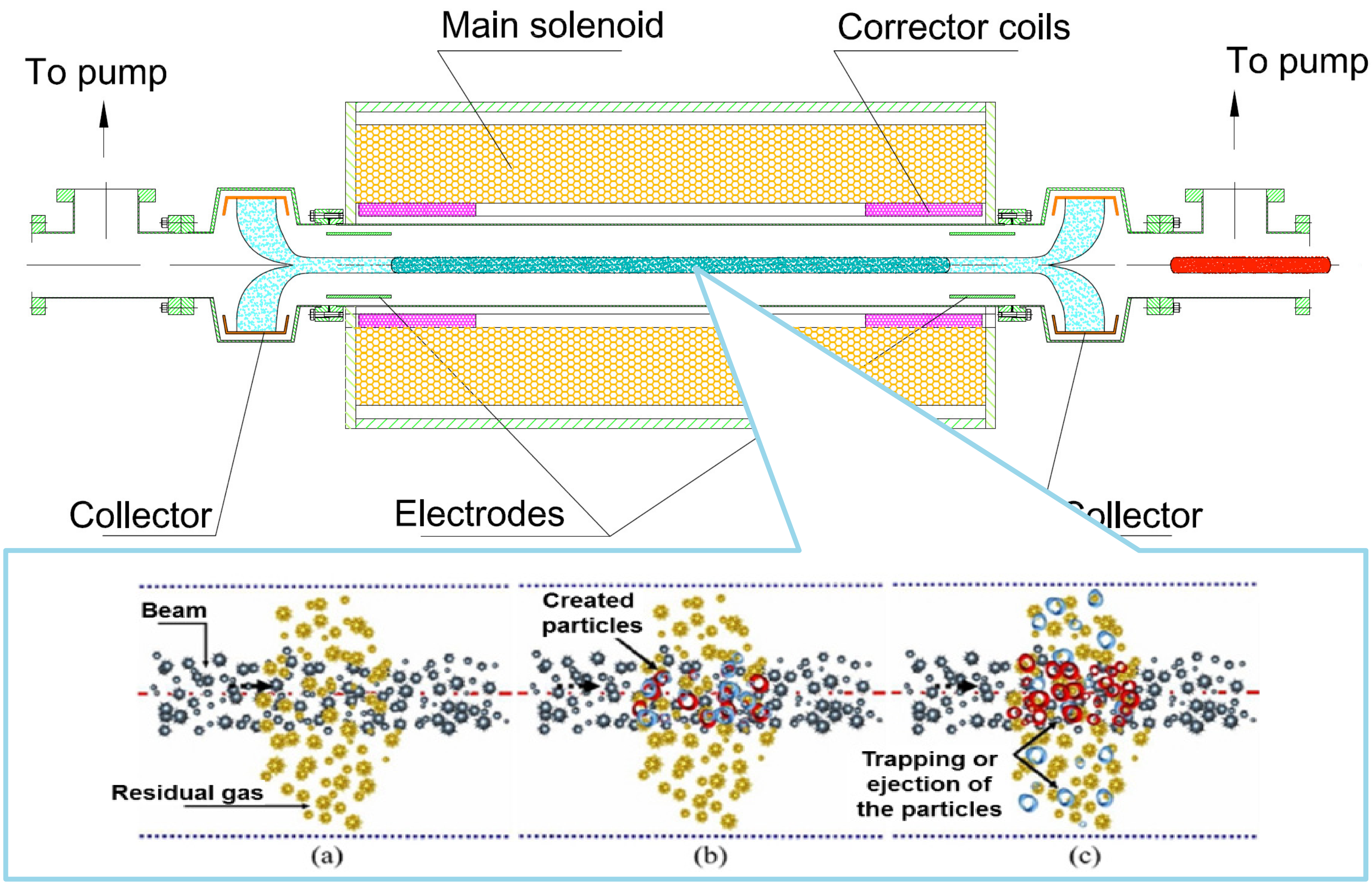
- **Several effects are being studied, for instance:**
  - lattice deviations from ideal case and misalignments
  - impact of chromaticity-correction sextupoles on integrability
  - azimuthal asymmetries in electron lens kicks due to bending sections
  - effect of fringe fields on ring optics
  - perveance of electron gun and accuracy of beam profile
  - chromatic effects of the electron lens
  - These studies involve numerical simulations and experiments at the Fermilab electron-lens test stand

Electron Column

Proposed the Experimental Setup for Electron Column - V. Shiltsev (2007)*



[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)

Historical Success and Challenges

- Several experimental attempts have been made
  - Linacs:
    - In linear machines, successfully applied to transport high-current low energy proton and H^- beam (gas focusing), Gabor lens, etc.
  - Circular machines
    - Novosibirsk PSR, *G. I. Dimov, V. E. Chupriyanov (1984)*
      - Conditions: few $mTorr$, H_2 gas, 1 MeV protons, 100 turns, 6.8 m
      - Cons: No stabilizing B-field, e-p instabilities a major obstacle
    - At Fermilab, M. Chung (2014) used WARP 3D code to test the idea of e-column in IOTA Ring.
      - Conclusion: Over-compensations - too much electron accumulations.

Our Approach to Space Charge Compensation using E-Column at IOTA Ring

- Strong magnetic field stabilizes the e-column, and prevents e-p instabilities
- In IOTA, we will use e-lens central solenoid for e-column operation.
- Match/control the transverse profile with B-field, voltages on electrodes, and vacuum pressure.
  - Investigate dynamics of electrons and ions in E and B fields
  - Primary proton beam considered as stable.
  - WARP-3D simulations have been performed on the Fermilab Wilson Cluster

WARP 3D Simulation Parameters

IOTA Beam parameters:	
Beam species	Proton
Beam energy	2.5 *MeV* (p = 70 *MeV/c*)
Average beam current	8 *mA*
RMS beam size	5.5 *mm*
Beam distribution	-Uniform in longitudinal direction -Gaussian in transverse direction (for initial test)

Apparatus parameters:	
Length	1 *m*
Electrode size	0.1 *m*
Wall radius	25 *mm*
Solenoid field	0 ~ 0.2 *T*
Voltages on Electrodes	-200 ~ 0 *V*

Gas parameters:	
Main gas species	H_2
Pressure	10^{-3} – 10^{-5} *Torr*
Neutralization time	0.86 μs (for 10^{-3} *Torr*)
Processes considered	$p + \mathrm{H}_2 \rightarrow p + \mathrm{H}_2^+ + e$ $e + \mathrm{H}_2 \rightarrow \mathrm{H}_2^+ + 2e$

Numerical parameters:	
Particle injection/step	100 (~7500)
Time step (< $2\pi/\omega_{ce}$)	15 *psec*
Boundary conditions	Absorbing boundaries for particles

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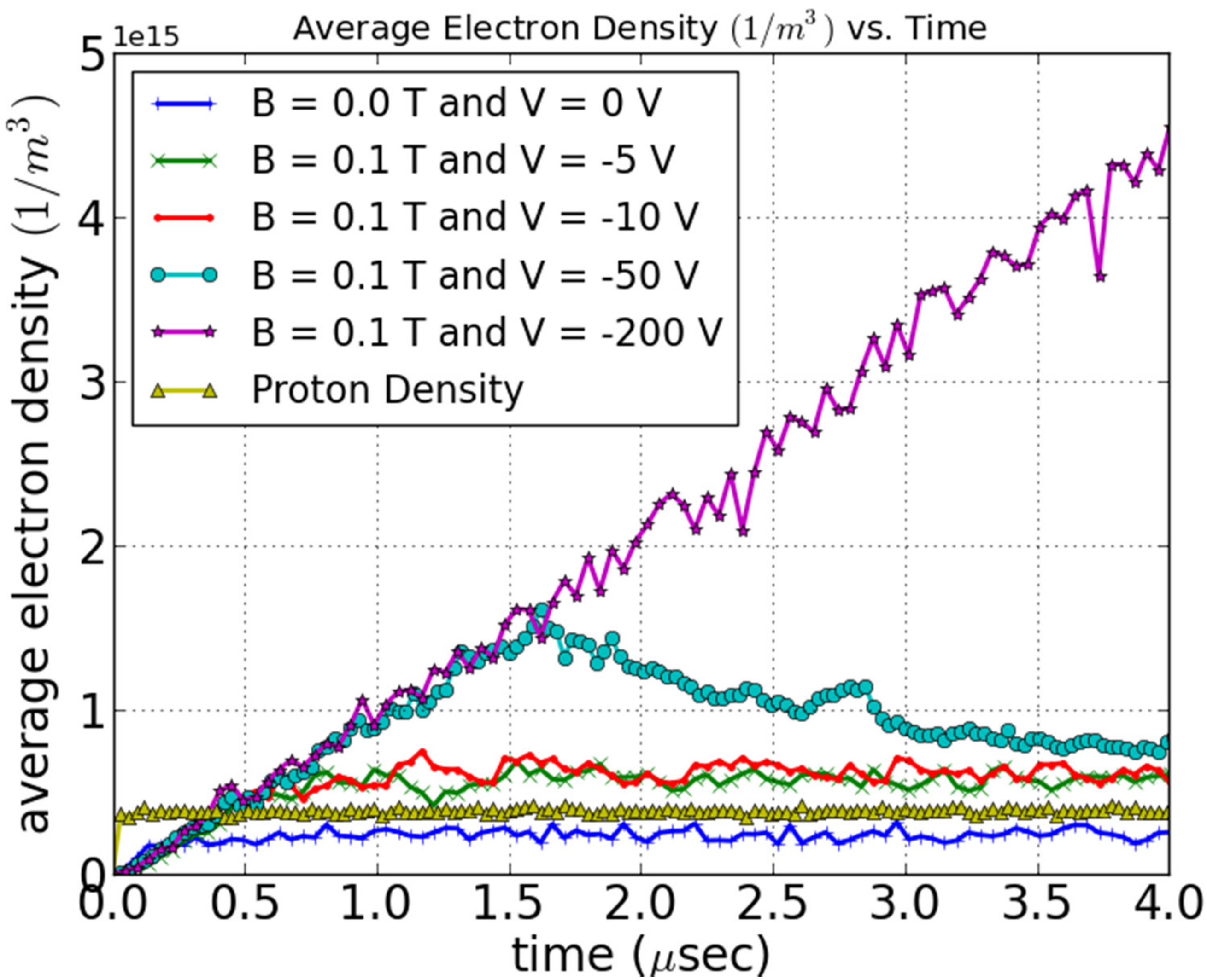
Some Practical Numbers and Limits

- Proton beam potential at the center is given by $\phi = \frac{30I}{\beta} = \frac{30 \times 8\, mA}{0.07} \sim 3.5\, V$
- If e-column length is 1 *m* and the circumference is ~ 40 *m*, we need about 3.5 *V* X 40 = 140 *V* for full space charge compensation. *At this stage, our study is limited to 1-m channel only. No ring is considered (no circulation).*
- Larmor radius (for 100 *eV*, 0.1 *T*) < 0.5 *mm*, $r_L = 3.37\, [\mu m] \frac{\sqrt{T_L\, [eV]}}{B\, [T]}$

  << proton beam radius

- Our goal is three-fold
  - Match transversely ['resistive' solenoid field and electrodes]
  - Compensate longitudinally [electrodes]
  - Neutralize quickly i.e. neutralization time should not be too long may few turns at max. Revolution time is ~ 1.8 μs

Neutralization Time for Various Parameters



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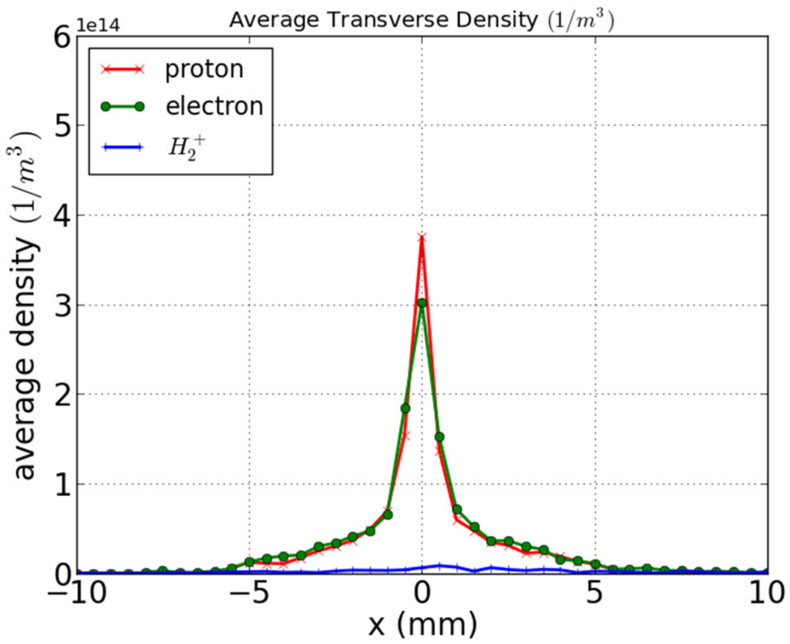
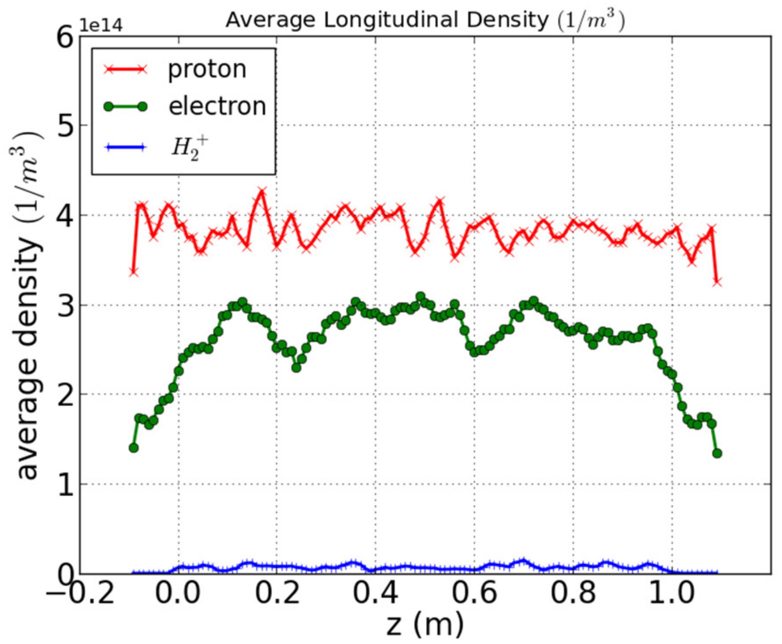
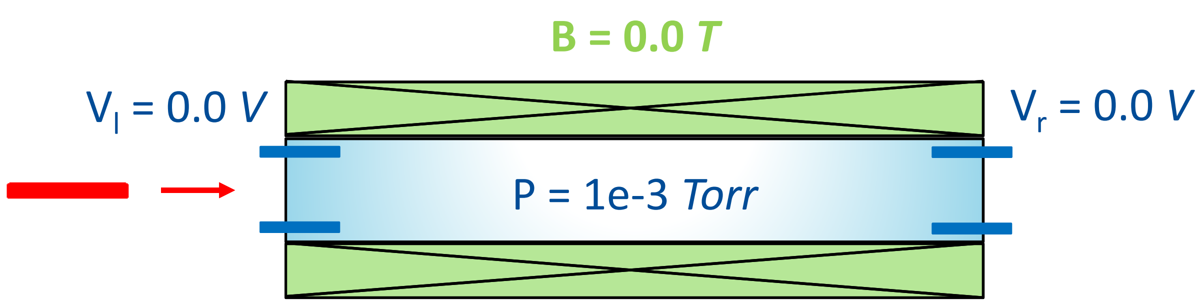
Under Compensation



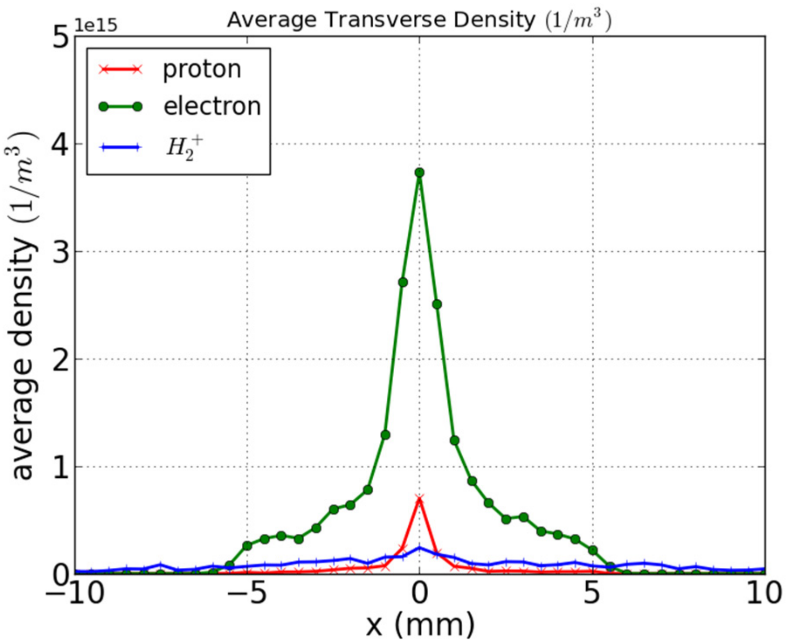
Transverse Density Profile

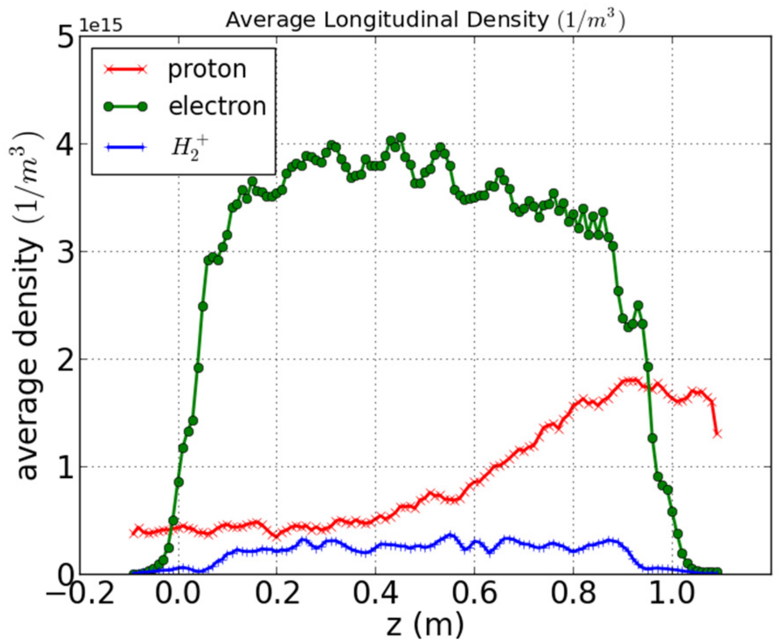


Longitudinal Density Profile



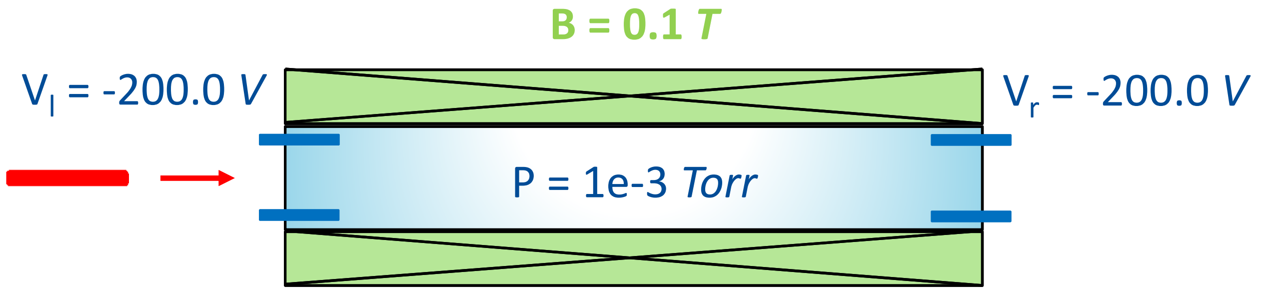
Over Compensation



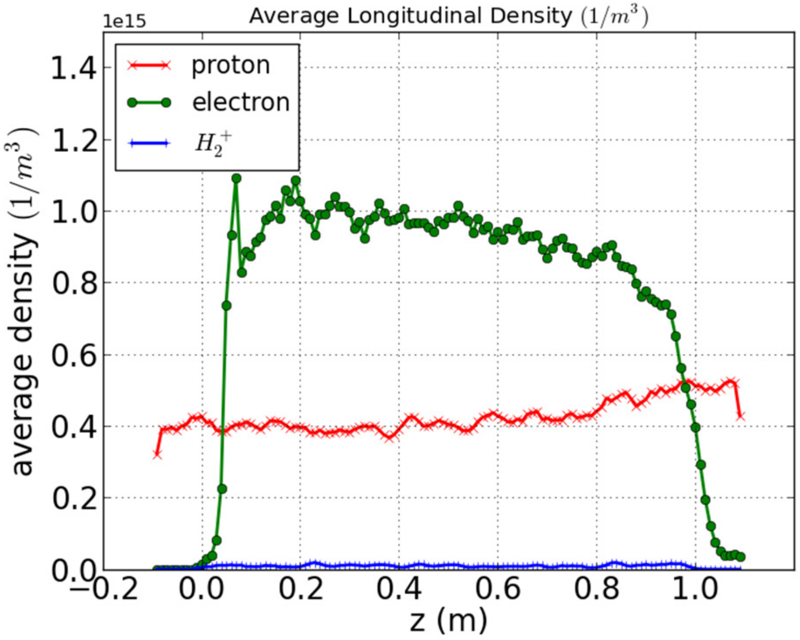


Transverse Density Profile

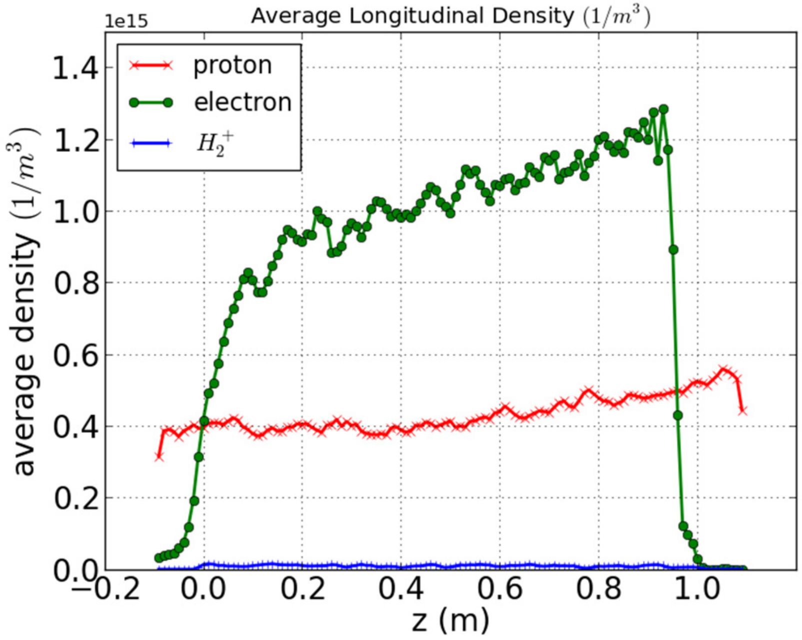
Longitudinal Density Profile



Asymmetric Voltages on Electrodes



V_l = -50 *V* and V_r = -5 *V*



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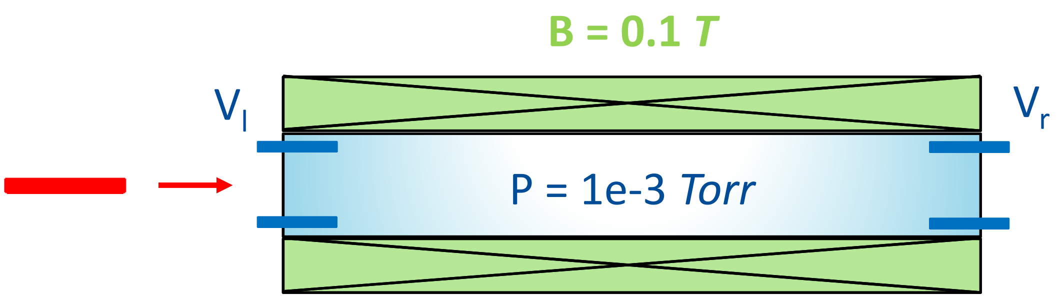
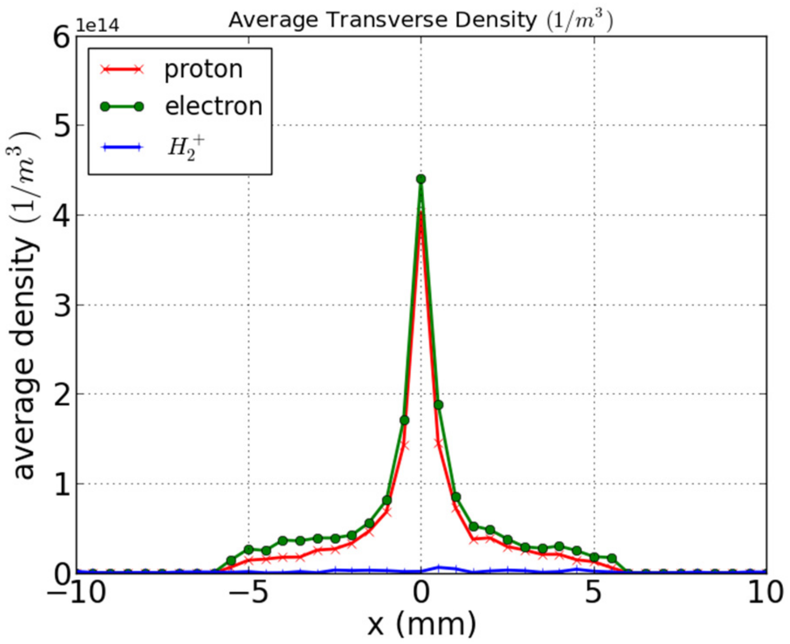
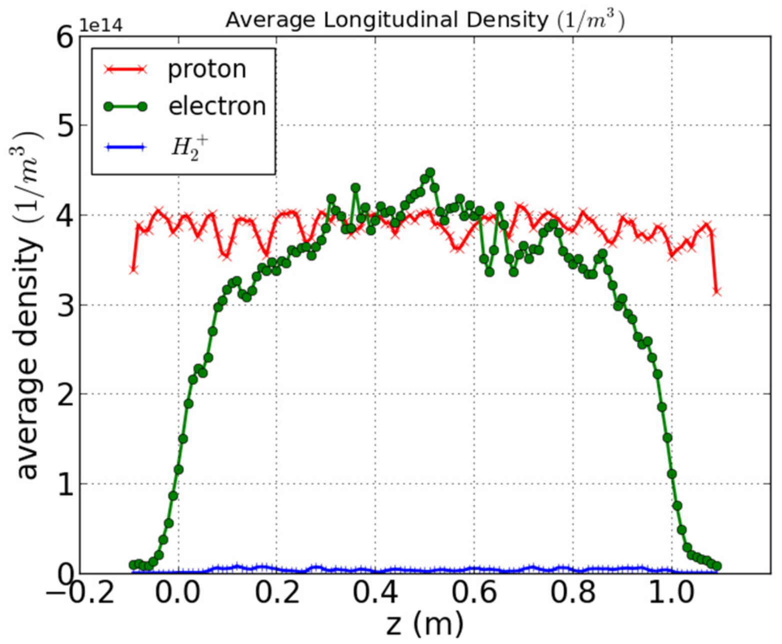


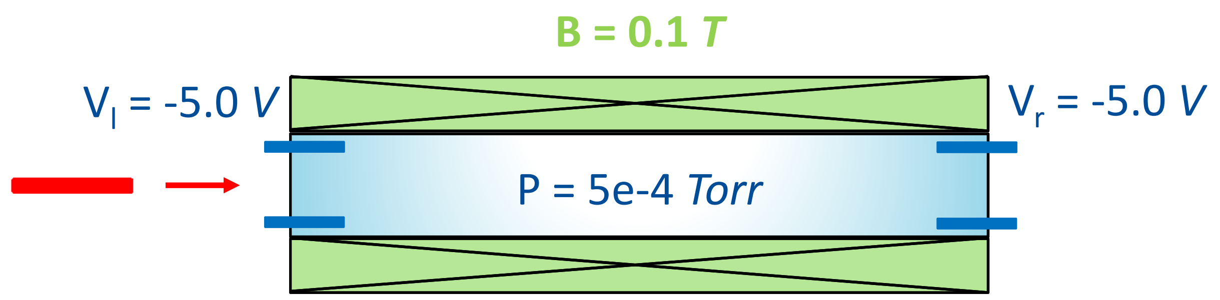
Vacuum:
Knob to Control the Degree of SC Compensation



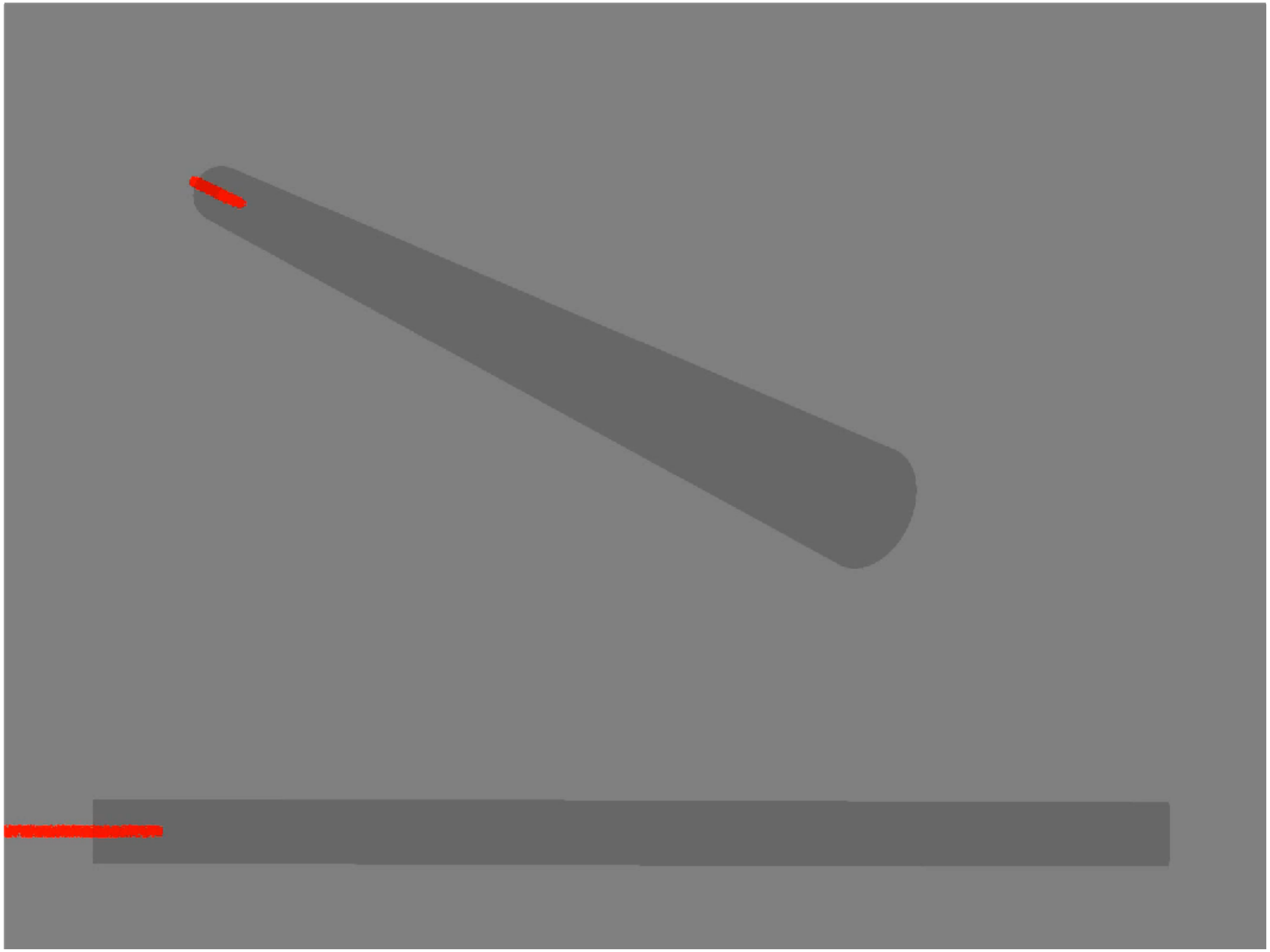
Transverse Density Profile



Longitudinal Density Profile



Evolution of Particles inside the Electron Column



B = 0.1 *T*, V = -5.0 *V*, and P = 5x10^{-4} *Torr*

D. Milana (2016)

Summary

- Space Charge Compensation (SCC) experiments with both e-lens and e-column are being pursued in IOTA ring at Fermilab.

- **E-Lens**:
  - External e-beam will be used to match and SCC circulating proton beam in IOTA ring. Experimental setup is being assembled.

- **E-Column**:
  - Simulations 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.

- **NEXT STEPS**:
  - Simulate circulating proton beam with external focusing and multiple passes through the e-column in IOTA.
  - Continue construction, tests, and installation of both IOTA e-lens and e-column.