Simulations of the Electron Column in IOTA

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Electron Lens vs Column

- Electron Lenses successful in compensating beam-beam effects & increasing beam lifetime
  - Two operated at Tevatron with good effect
- Relies on external source of electrons, injection & extraction systems
- Simpler source of electrons is ionization of residual gas by beam
  - Ions must be contended with
- Electric & magnetic fields then used to shape plasma electrons

Space-Charge Force

- Start with Lorentz force equation

$$\vec{F} = q\left(\vec{E} + c\,\vec{\beta} \times \vec{B}\right)$$

- Radial component of force

$$F_r = q\left(E_r - \beta_z c B_\theta\right) = q E_r\left(1 - \beta^2\right) \propto \frac{n_p}{\gamma^2}$$

- Net space-charge force is repulsive, proportional to charge density and relativistic parameter
- The space-charge force of a proton beam can be compensated by accumulating electrons so that electron charge with respect to proton charge is

$$\langle\eta\rangle = \frac{1}{\gamma^2}$$

Space-Charge Compensation with Electron Columns

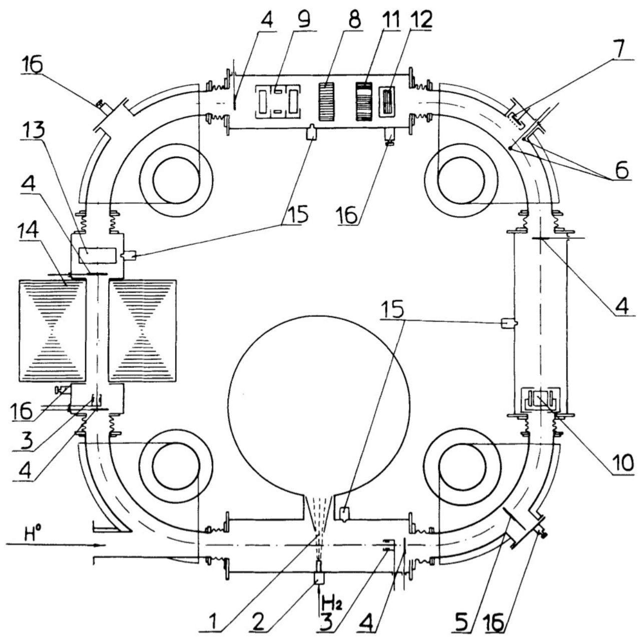
- Electron charge can be spread homogeneously around a ring, or more practically, in short sections
- Fraction of ring circumference needed for complete compensation

$$R = \eta = \frac{1}{\gamma^2}$$

- For 8 GeV Main Injector, R ≈ 1.2%
- For IOTA, R = 100%
  - Only 1 out of 40 m occupied by Electron Column → electron charge would have to be 40x proton charge for full compensation

Past Electron Column Experiment

- 1984, Institute of Nuclear Physics, Novosibirsk
- 1 MeV, 8 mA proton beam, >10^{-3} torr residual gas pressure

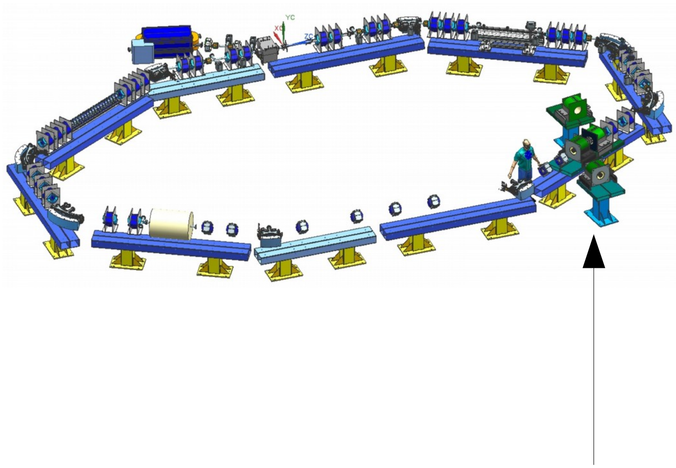


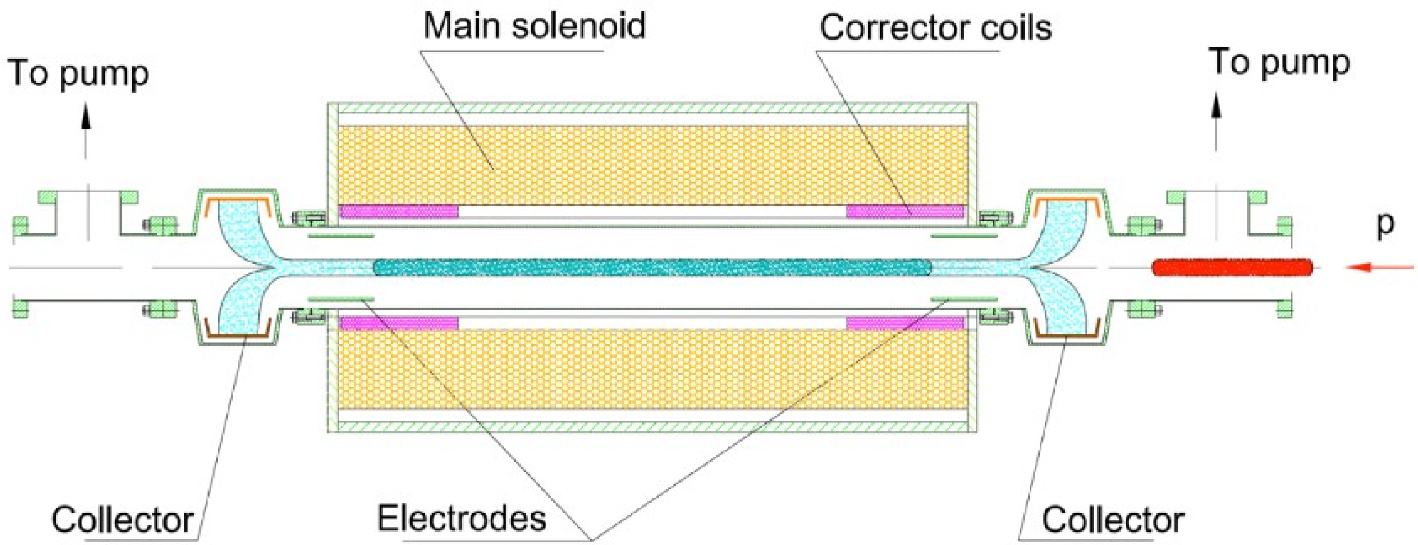
(Dimov & Chupriyanov, Part. Acc. 14, 1984)

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.

- Achieved ~10 increase in beam current vs. higher vacuum
- Beam lifetime very short & electron distributions not well controlled

Electron Column at IOTA





- Solenoid provides magnetic field
  - Strong enough to prevent electrons from escaping transversely, suppress e-p instabilities
  - Weak enough to allow ions to escape
- Electrodes provide electric field to prevent electrons from escaping longitudinally
- Plumbing and pumping to provide variable gas pressure in column region

Electron Column Generation

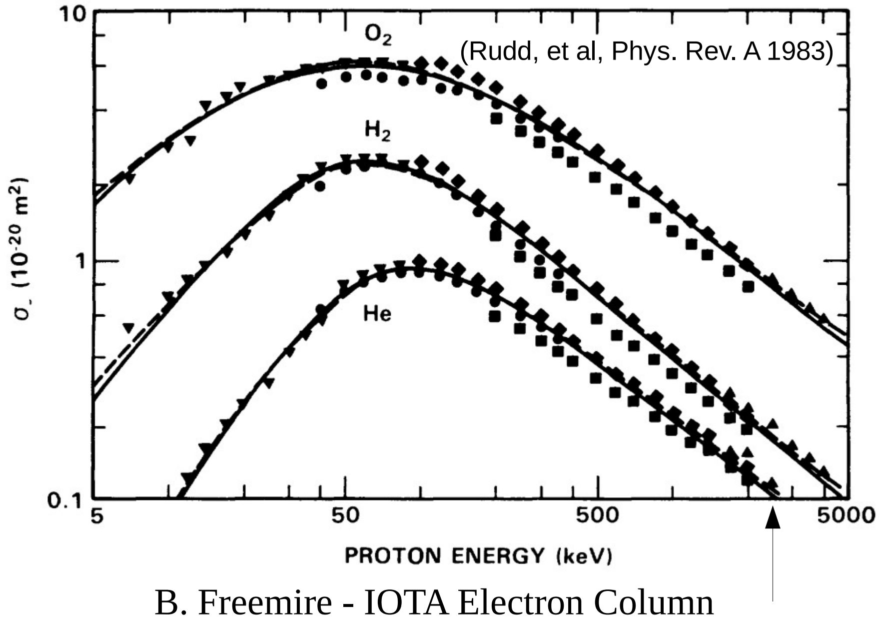
- Electrons are created through ionization

$$p + H_2 \rightarrow p + e^- + H_2^+$$

- Number of electrons (and ions) produced per beam particle dependent on ionization cross section, gas number density, & length of gas traversed

$$\tilde{N} = \sigma \, n_g \, l$$

- Secondary ionization by electrons possible as well



Hydrogen Cluster Formation

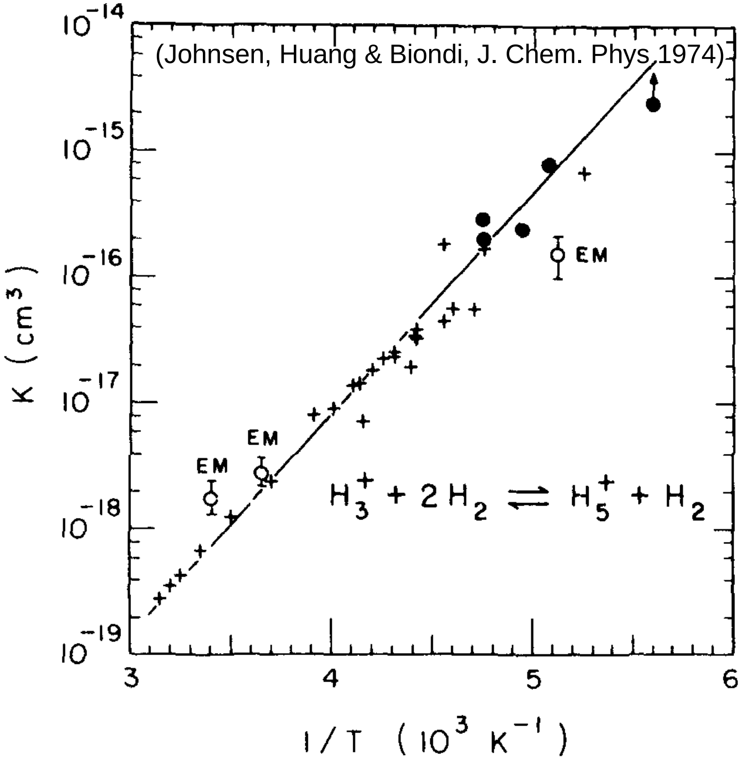
- Hydrogen ions quickly form clusters

$$H_2^+ + H_2 \rightarrow H_3^+ + H \qquad H_n^+ + 2H_2 \Leftrightarrow H_{n+2}^+ + H_2 \quad n = 3, 5, 7, \ldots$$

- Density of clusters comes into equilibrium with some constant, dependent on hydrogen density and temperature
- Density of H_3^+:

$$[H_3^+] = k\,[H_2^+]\,[H_2]$$

$k = forward\ reaction\ rate$



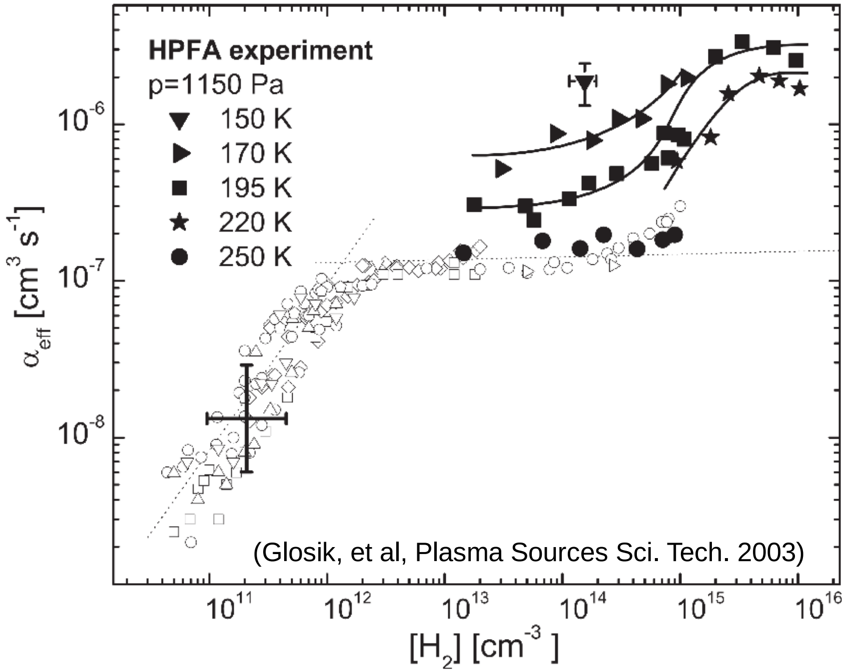
Recombination

- Electrons recombine with hydrogen ions

$$e^{-} + H_3^{+} + H_2 \rightarrow H_3 + H_2$$

$$e^{-} + H_3^{+} \rightarrow 3H \qquad e^{-} + H_3^{+} \rightarrow H_2 + H$$

- Recombination rate well known for H_3^+
- Limits density growth of plasma
  - Along with diffusion out of ends of Column
  - Ionization & recombination competing effects
- Density distribution of H_3^+ important
  - Electrons trapped by B-field, ions migrate out radially

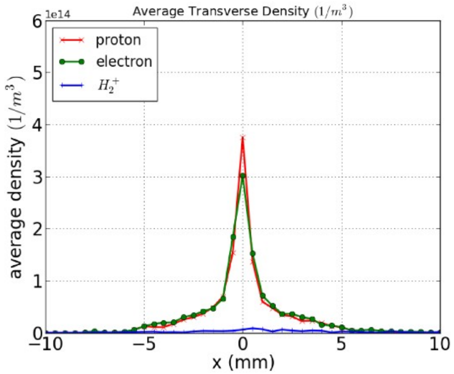


Simulations of the Electron Column

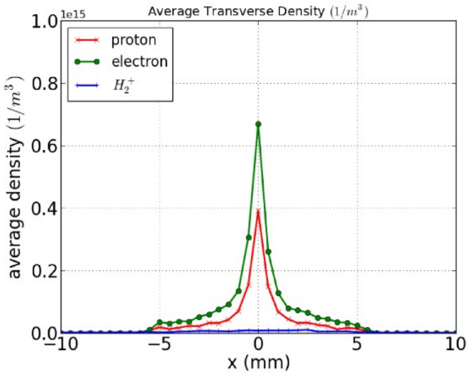
- PIC code Warp used for simulations
- Many effects to be included in an accurate simulation
  - Gas ionization
  - Forces on particles from
    - Beam EM fields
    - Plasma EM fields
    - External EM fields
  - Plasma oscillation
  - Electron-Ion Recombination
  - Plasma-gas scattering/collisions
- Many correlated effects
  - For example, gas density affects number of electrons produced, which affects strength of electrodes needed to ensure desired longitudinal distribution

Past Parameter Optimization

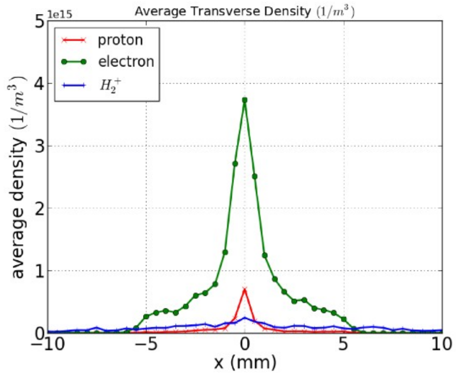
- Studies performed beginning with basic model, working toward "complete" model
- Strength of electric & magnetic fields studied



(a) $B = 0.0\ T$ and $V = 0.0\ V$



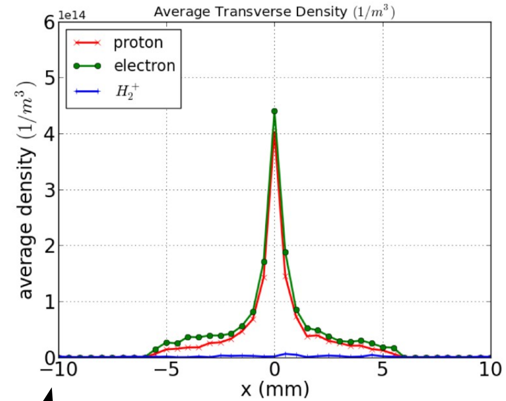
(b) $B = 0.1\ T$ and $V = -5.0\ V$



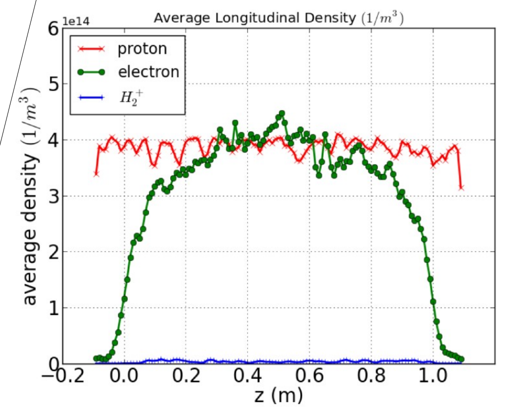
(c) $B = 0.1\ T$ and $V = -200.0\ V$

- Reasonable transverse profile match for $5\text{x}10^{-4}$ torr, -5 V, 0.1 T

Park, et al, NAPAC'16, THA3CO04



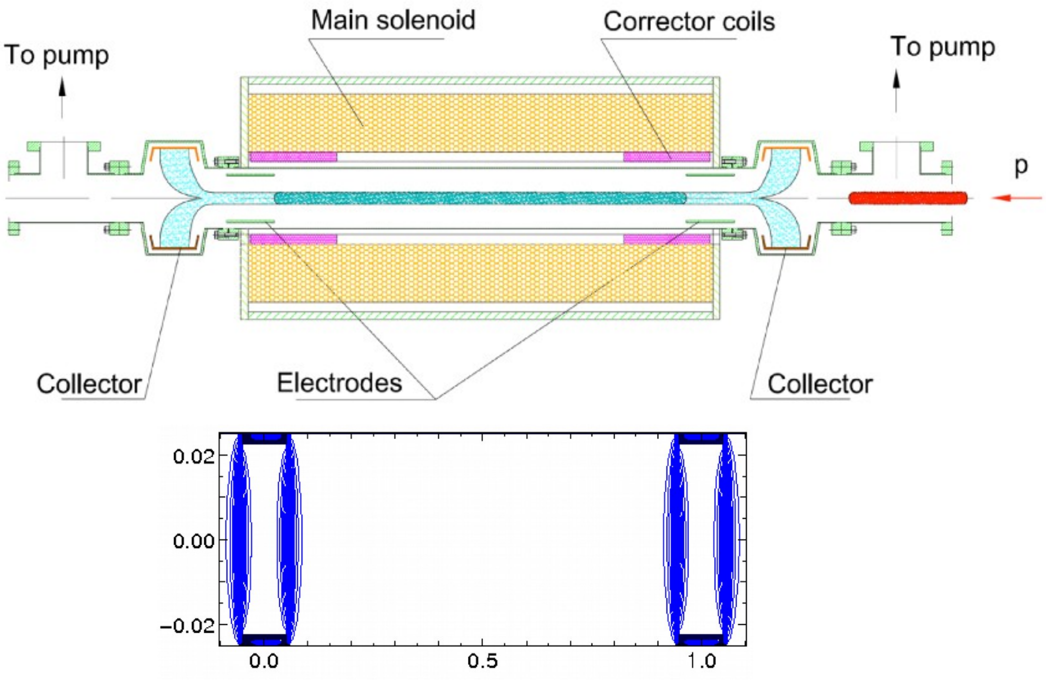
(a) Transverse density profile



(b) Longitudinal density profile

Current Simulation Parameters

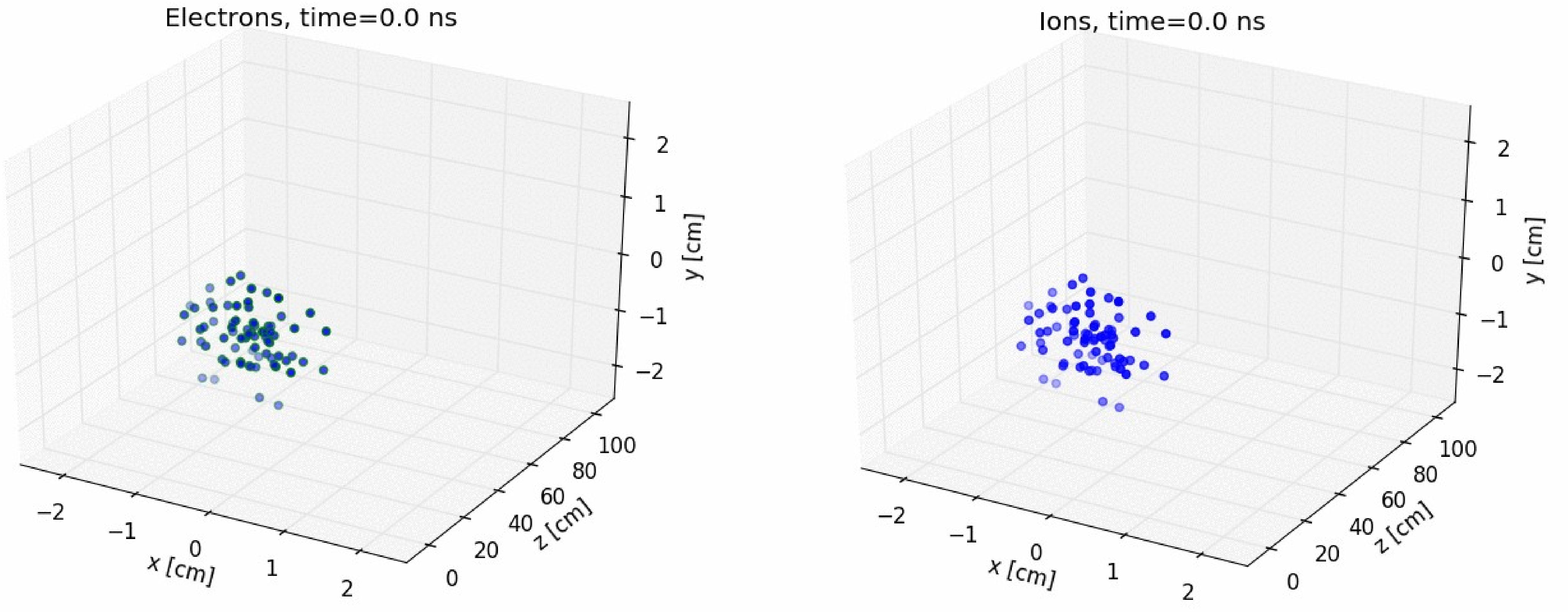
- 2.5 MeV protons
- 8 mA beam current, 8.85E10 protons
- Gaussian distribution with σ = 4.47 mm
- 1.77 μs beam pulse length
- 1.83 μs revolution period
- 100 cm column length
- 45.8 ns column traversal time
- 5 cm diameter beampipe
- Electrodes 10 cm long and 4.5 cm in diameter, -5 V bias
- 0.1 T solenoidal magnetic field
- Grid spacing 0.05 cm in x and y, 1.0 cm in z (100 x 100 x 120 grid)
- 500 macroparticle protons injected every time step (7,000 protons per macroparticle, 7 electrons or ions per macroparticle)
    - 10 cm upstream of column



Plasma Parameters

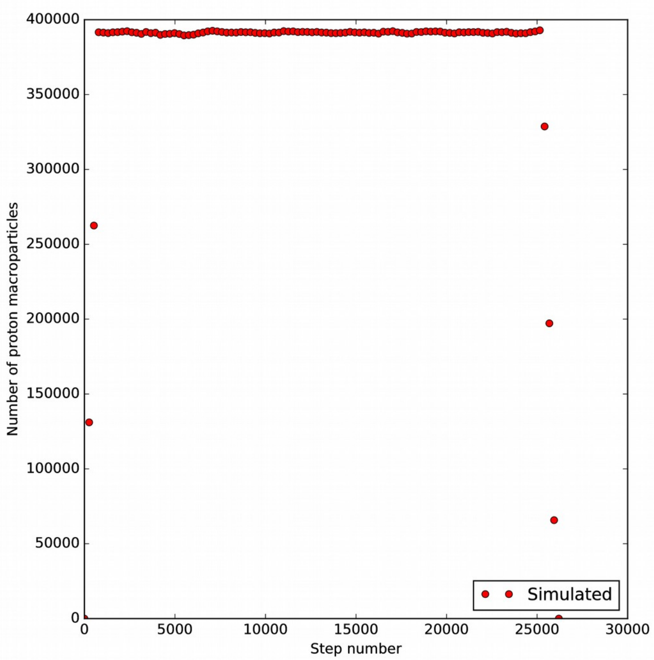
- Hydrogen gas density 1.65E13 cm^{-3} (5.0e-4 torr at 293 K)
- Plasma processes included
  - Single ionization of hydrogen by protons $p + 2H_2 \rightarrow p + H_3^+ + H + e^-$
- Proton on hydrogen cross section 1.82E-17 cm^2
- Electron energy 45 eV, energy spread 19 eV (ion energy 0)
- 54 ns plasma period assuming homogeneous electron density
- 0.46 ns z grid travel time for protons
- 0.36 ns cyclotron period
- 0.07 ns time step
- 0.15 cm traveled by beam in 1 time step
- 25,286 time steps for full beam pulse
- 26,200 time steps (1.834 μs) simulated

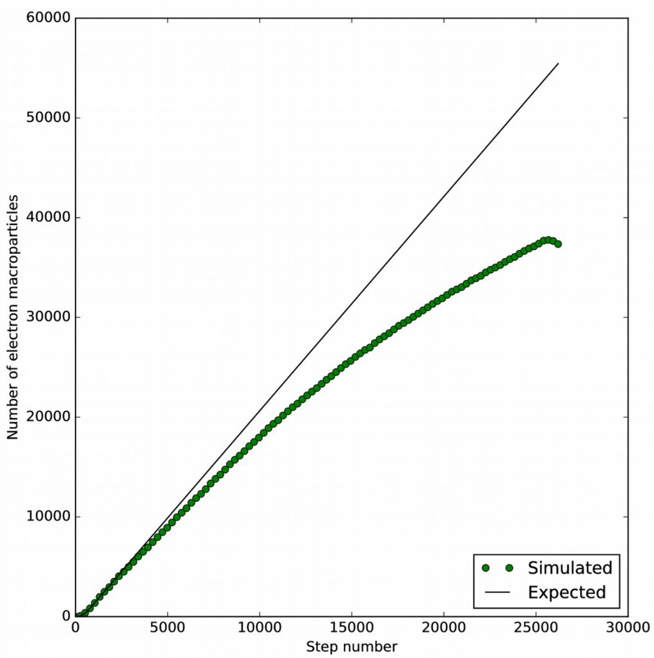
Plasma Animation

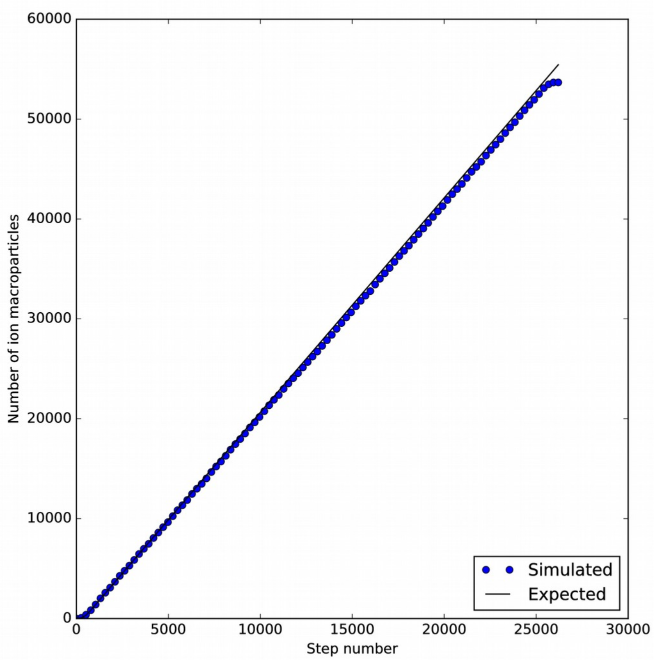


Number of Particles

- Number of macroparticles produced – black curve
- Number of macroparticles present – protons, electrons, ions

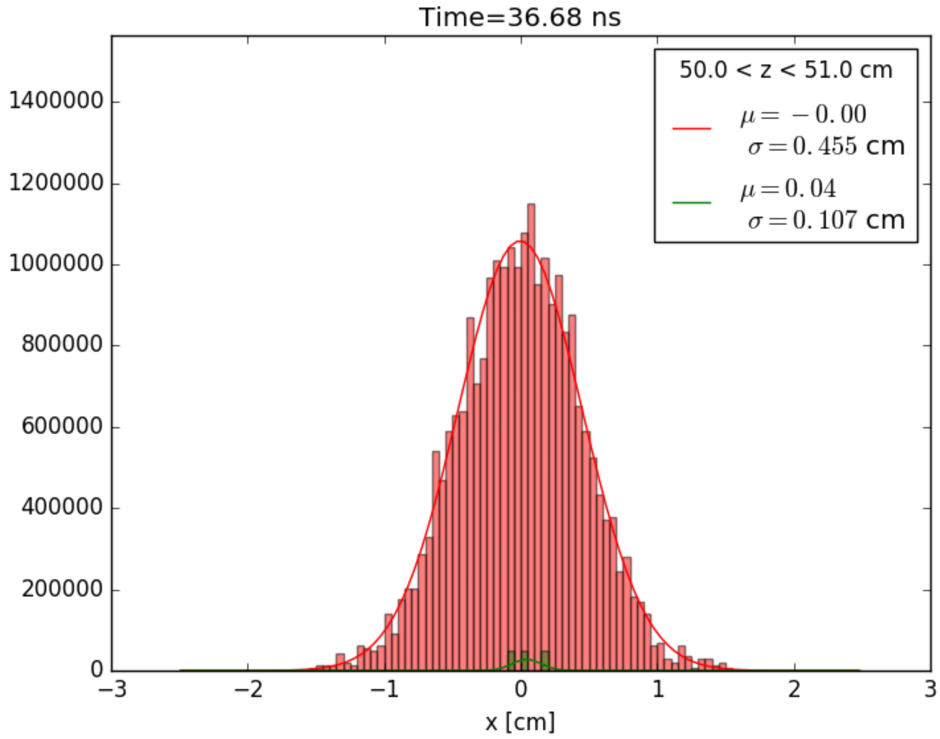


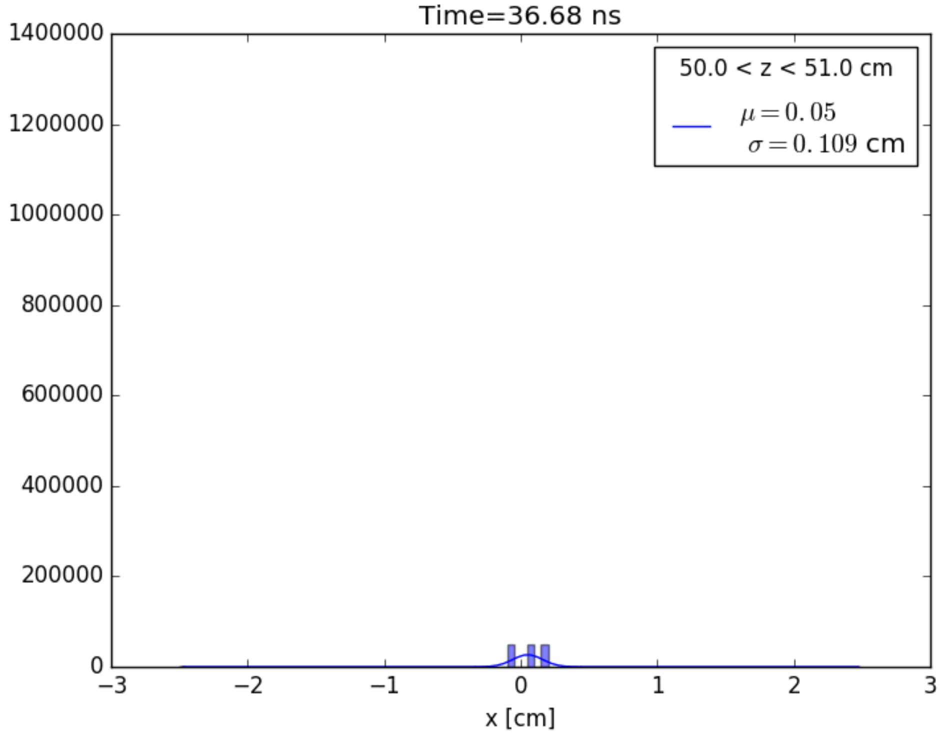




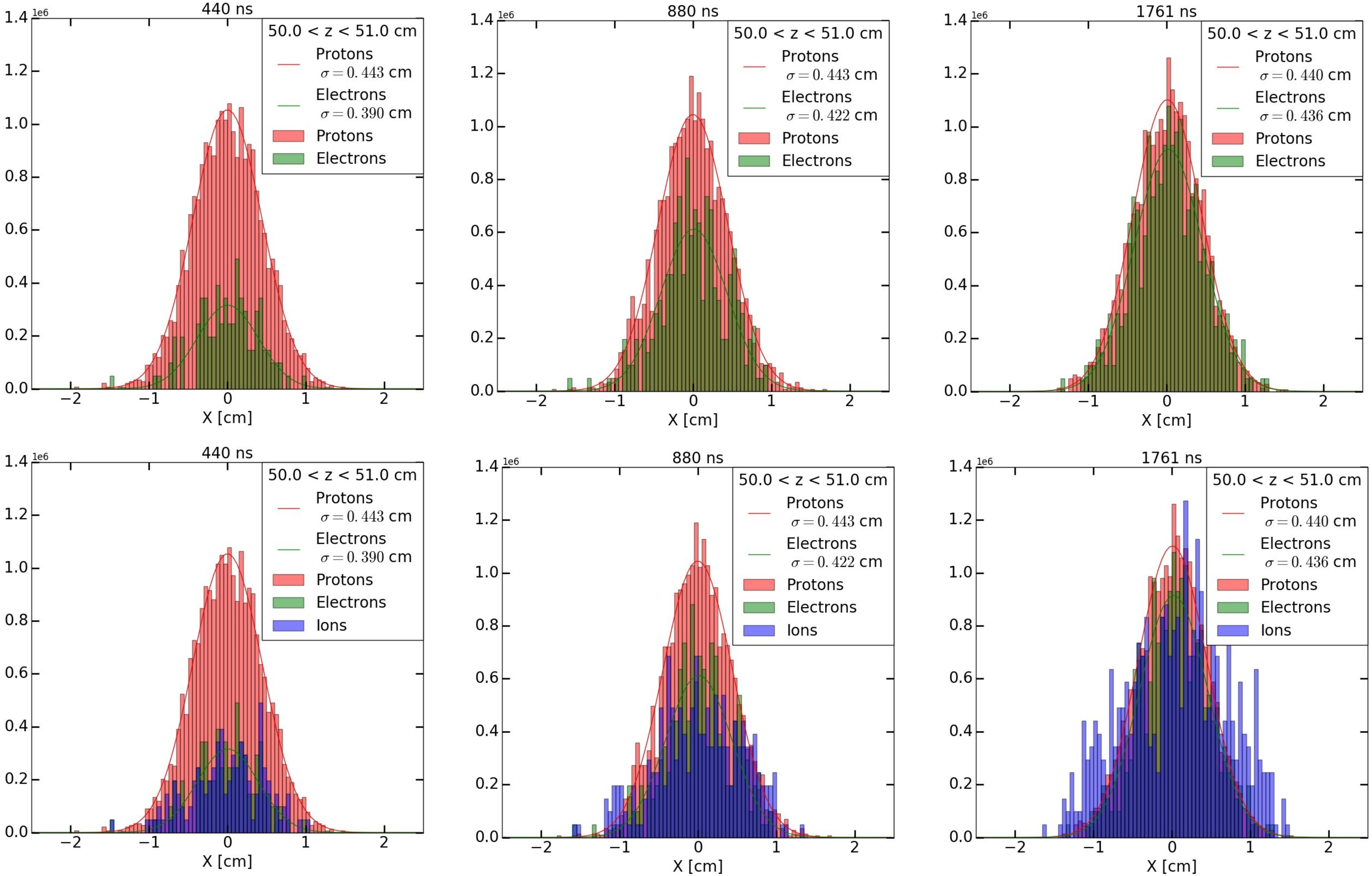
Transverse Profile Comparison

- Center of the column (z = 50 cm)
- Protons, electrons – left, ions – right

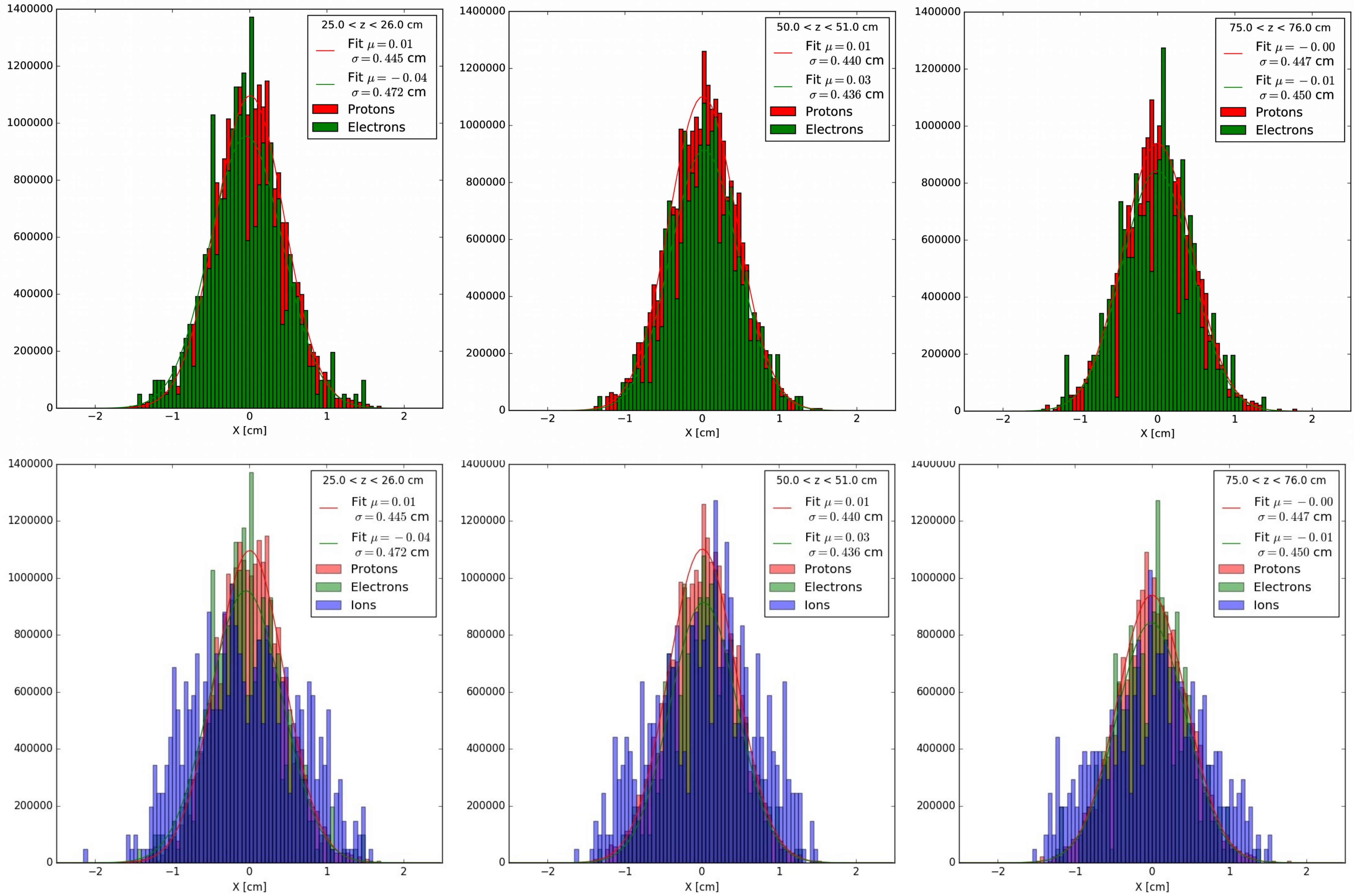




Transverse Profile Snapshots – Center

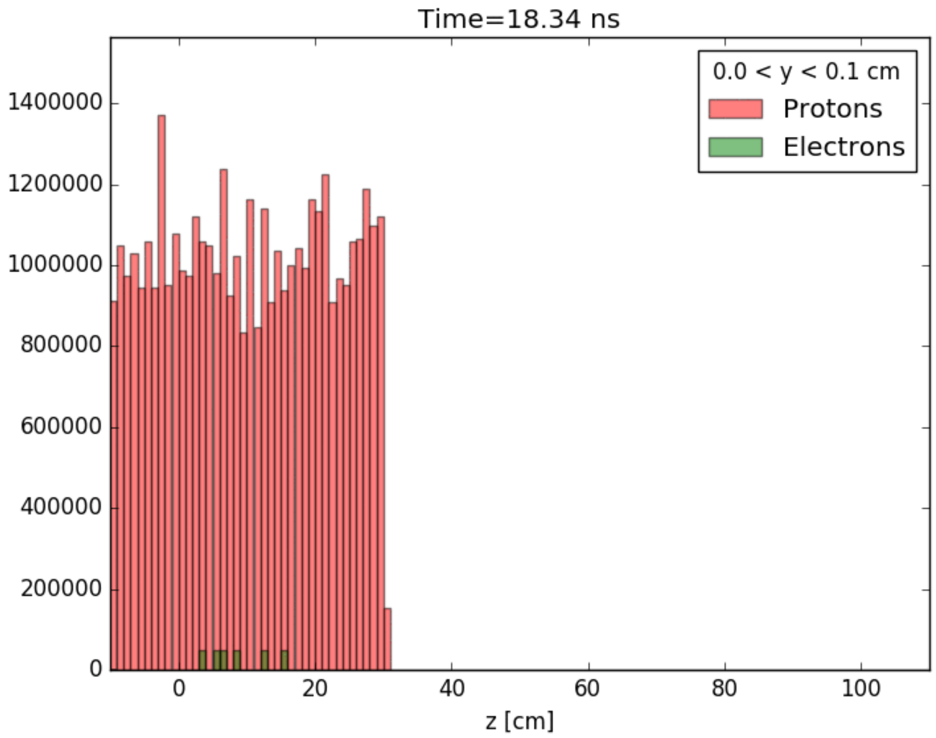


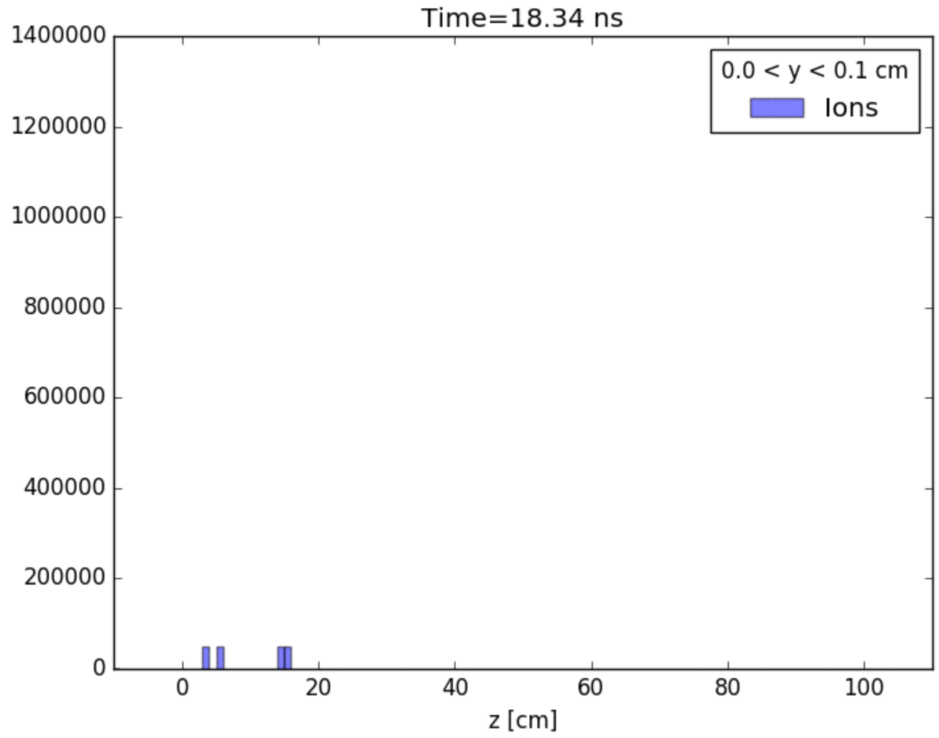
Transverse Profile Snapshots – 1.76 μs



Longitudinal Profile Comparison

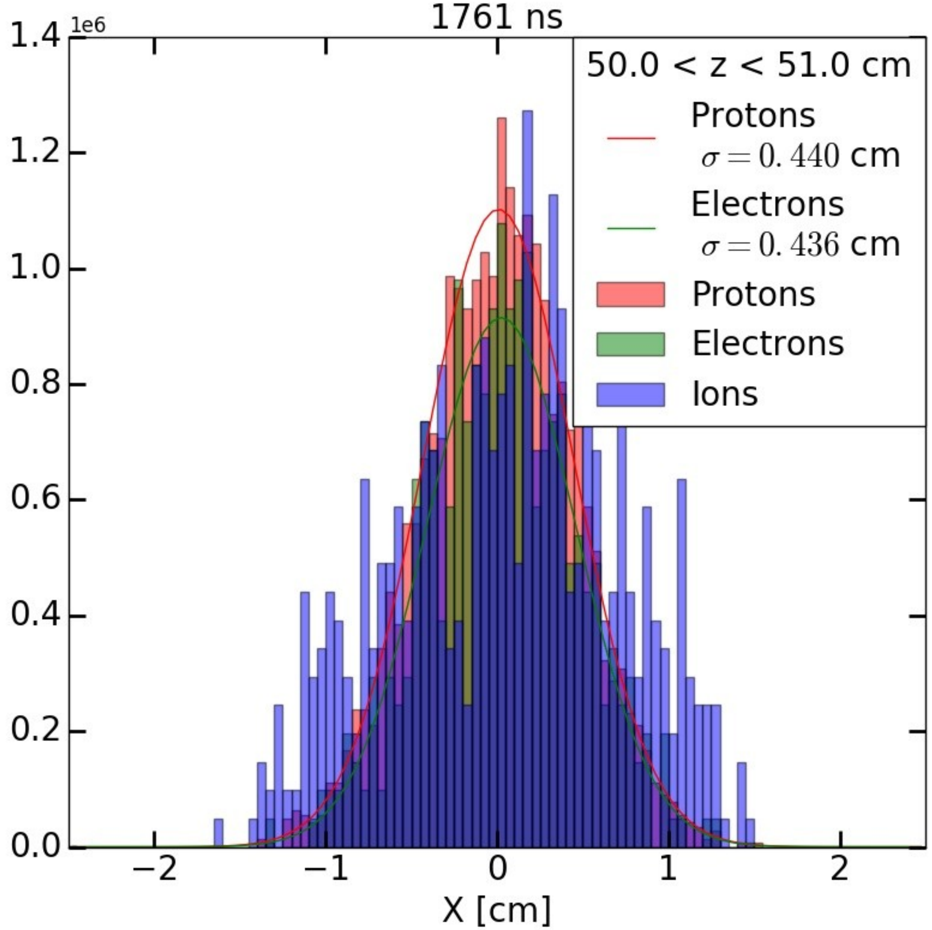
- Center of the column (y = 0 cm)
- Protons, electrons – left, ions – right

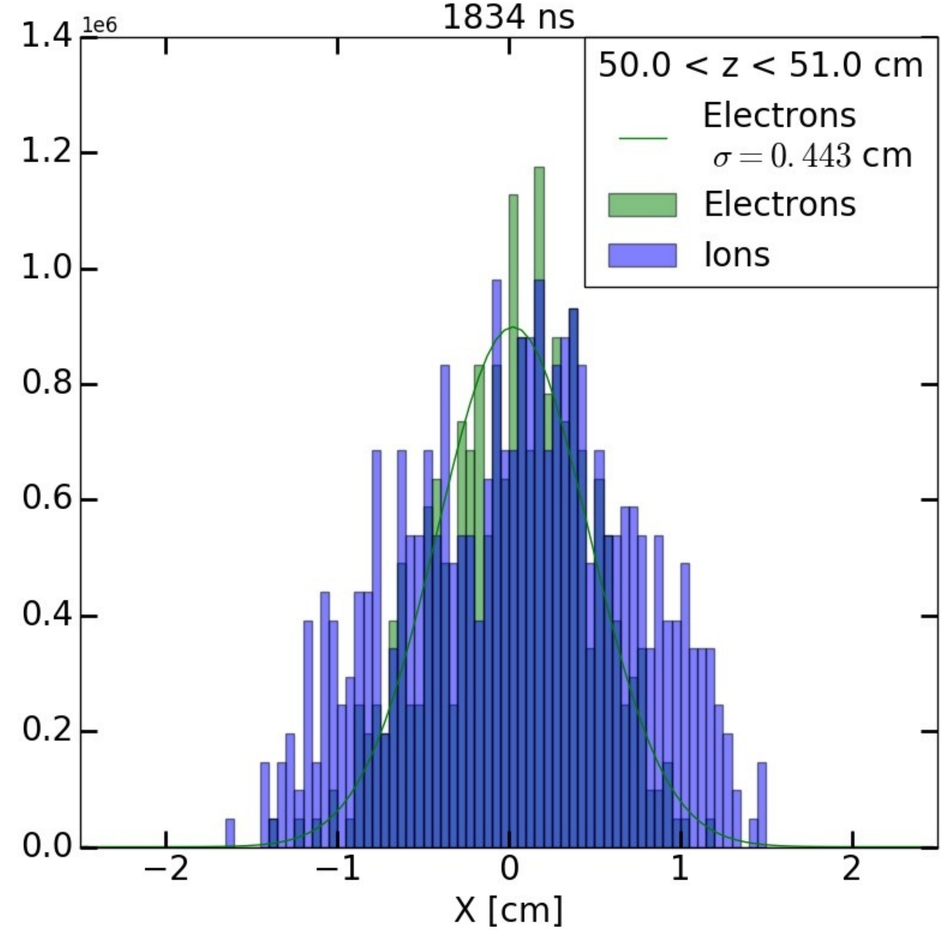




Distribution Before Next Beam Pulse

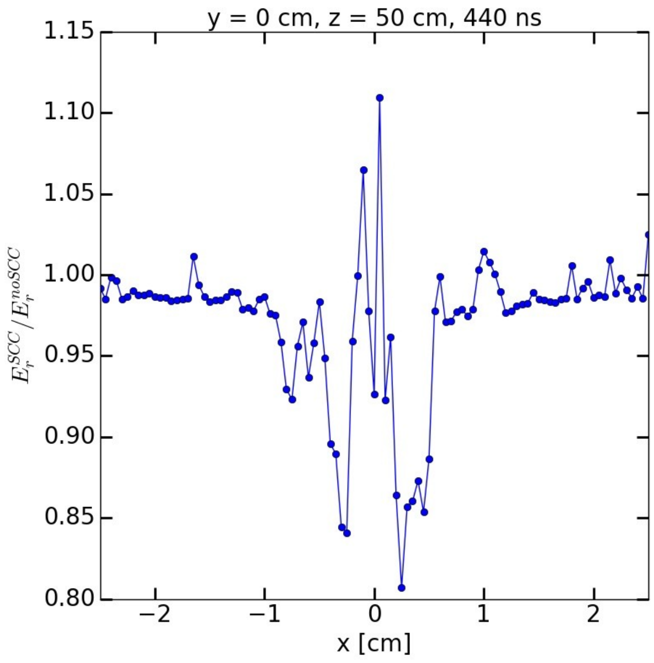
- Electrons still well matched to beam
- Ions diffuse radially slightly

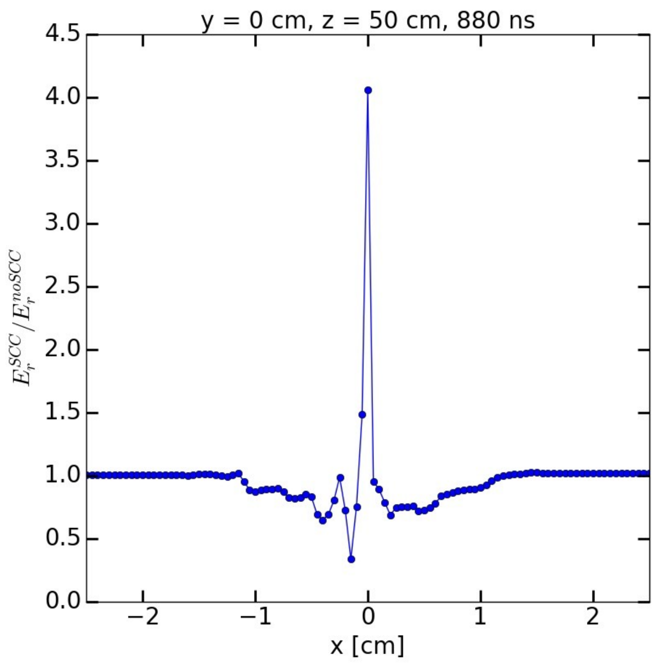


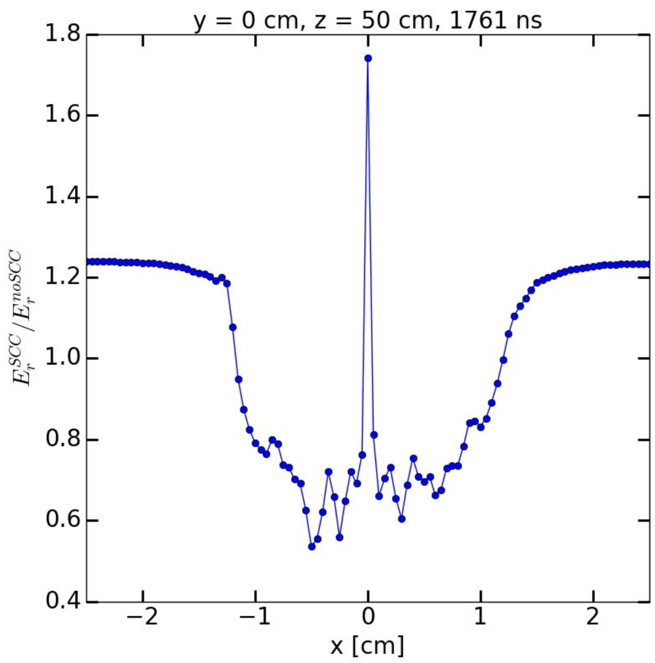


Space-Charge Compensation

- Radial component of electric field at center of column (y = 0, z = 50 cm)
  - With ionization (i.e. SCC) and without (i.e. no SCC)
- Ratio of field with SCC to without SCC plotted
- Average field over width of column shows reduction in space-charge force
  - ~5% at end of beam pulse







Beam Lifetime

- Low energy protons easy to kill
  - Not a concern for higher energy machines, but major consideration for IOTA
- Beam lifetime defined as time it takes to fall to 1/e of original population

$$N[t] = N_0 e^{\frac{-t}{\tau}}$$

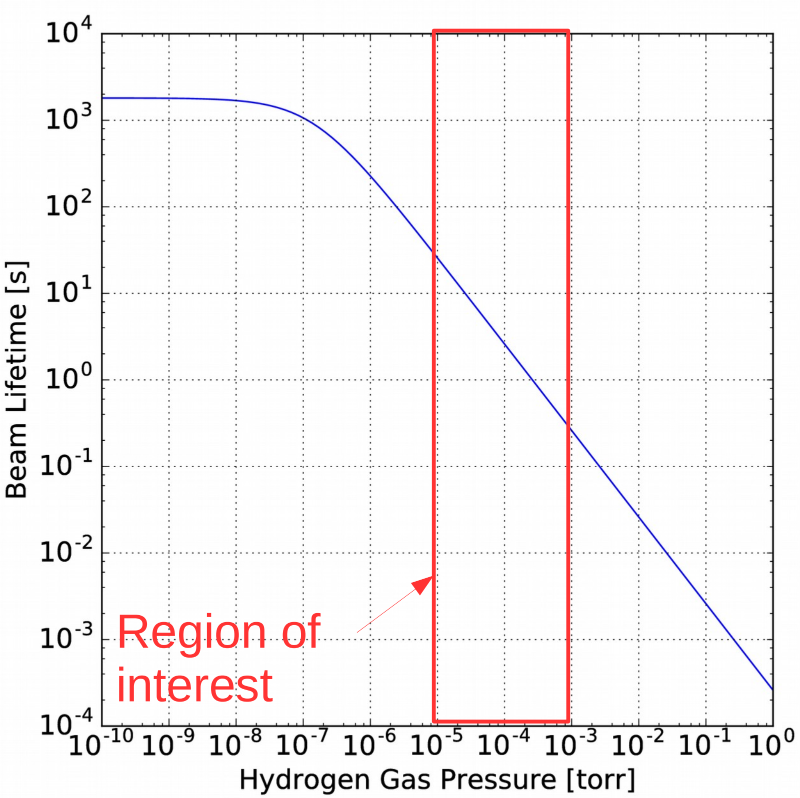
- Lifetime determined by Coulomb scattering, nuclear scattering, and intrabeam effects
  - Coulomb scattering dominant loss mechanism

$$\frac{1}{\tau} = \frac{1}{\tau_{CS}} + \frac{1}{\tau_{NS}} + \frac{1}{\tau_{IB}}$$

IOTA Proton Beam Lifetime

- Estimates for residual gas pressure ~1E-10 torr
  - Partial pressures in table
  - Baseline beam lifetime ~30 minutes
- Effect of hydrogen gas pressure in 1 m electron column on beam lifetime
- Lifetimes on the order of tenths to tens of seconds correspond to $10^5 – 10^7$ turns
- Sufficient for space-charge compensation studies

Gas	Pressure [10^{-11} torr]
H_2	4.6
H_2O	3.8
CO_2	1.8
CO	0.7
CH_4	0.17
Ar	0.023
Other	0.21



Summary / Future Work

- Electron profile matches beam profile reasonably well after 1 pass
- Radial electric field reduced by ~5% on average after *only 1 pass*

- Simulate multiple passes
  - Save beam & plasma distributions after one pass, reload beam at beginning of Column for second pass
  - Incorporate rest of IOTA lattice
- Tweak knobs for gas density, electrode strength

Backup Slides

Lifetime Contributions

- Lifetime from Coulomb scattering:

$$\frac{1}{\tau_{ES}} = \frac{\langle\beta\rangle}{\pi\,\beta\,c\,k_B\,T\,\epsilon_A}\left(\frac{q}{2\,\epsilon_0\,\gamma\,m\,\beta\,c}\right)^2 \sum_i P_i\,Q_i^2$$

$\gamma, \beta = \textit{relativistic factors}$
$c = \textit{speed of light}$
$k_B = \textit{Boltzmann's constant}$

$m = \textit{proton mass}$
$T = \textit{gas temperature}$
$\epsilon_0 = \textit{vacuum permittivity}$

$\langle\beta\rangle = \textit{average beta function}$
$\epsilon_A = \textit{ring acceptance}$

$q = \textit{electric charge}$
$P_i = \textit{pressure of ith gas species}$
$Q_i = \textit{atomic number of ith gas species}$

- Lifetime from intrabeam scattering (Touschek effect):

$$\frac{1}{\tau_{IB}} = \frac{r^2\,c\,N_b\,\lambda^3}{8\,\pi\,\gamma^2\,\sigma_x\,\sigma_y\,\sigma_z}\,D(\epsilon)$$

$r = \textit{classical proton radius}$
$N_b = \textit{number of beam particles}$
$\lambda = \textit{momentum acceptance}$
$\sigma_{x,y,z} = \textit{beam} ¿ x, y, z$
$D(\epsilon) = \textit{Touschek function}$