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# IOTA electron lens: nonlinear optics, cooling, and space-charge compensation

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*Fermilab*

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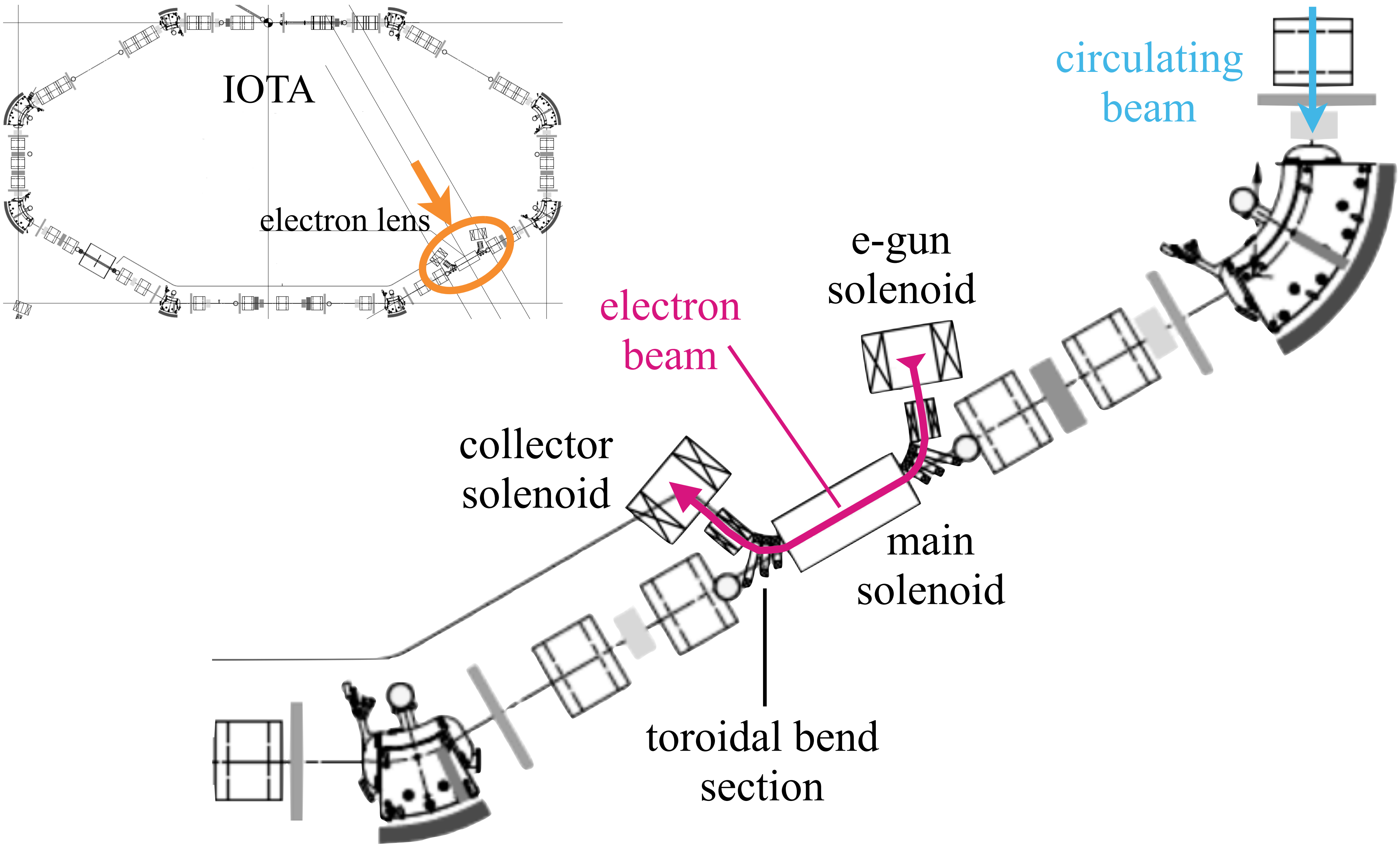
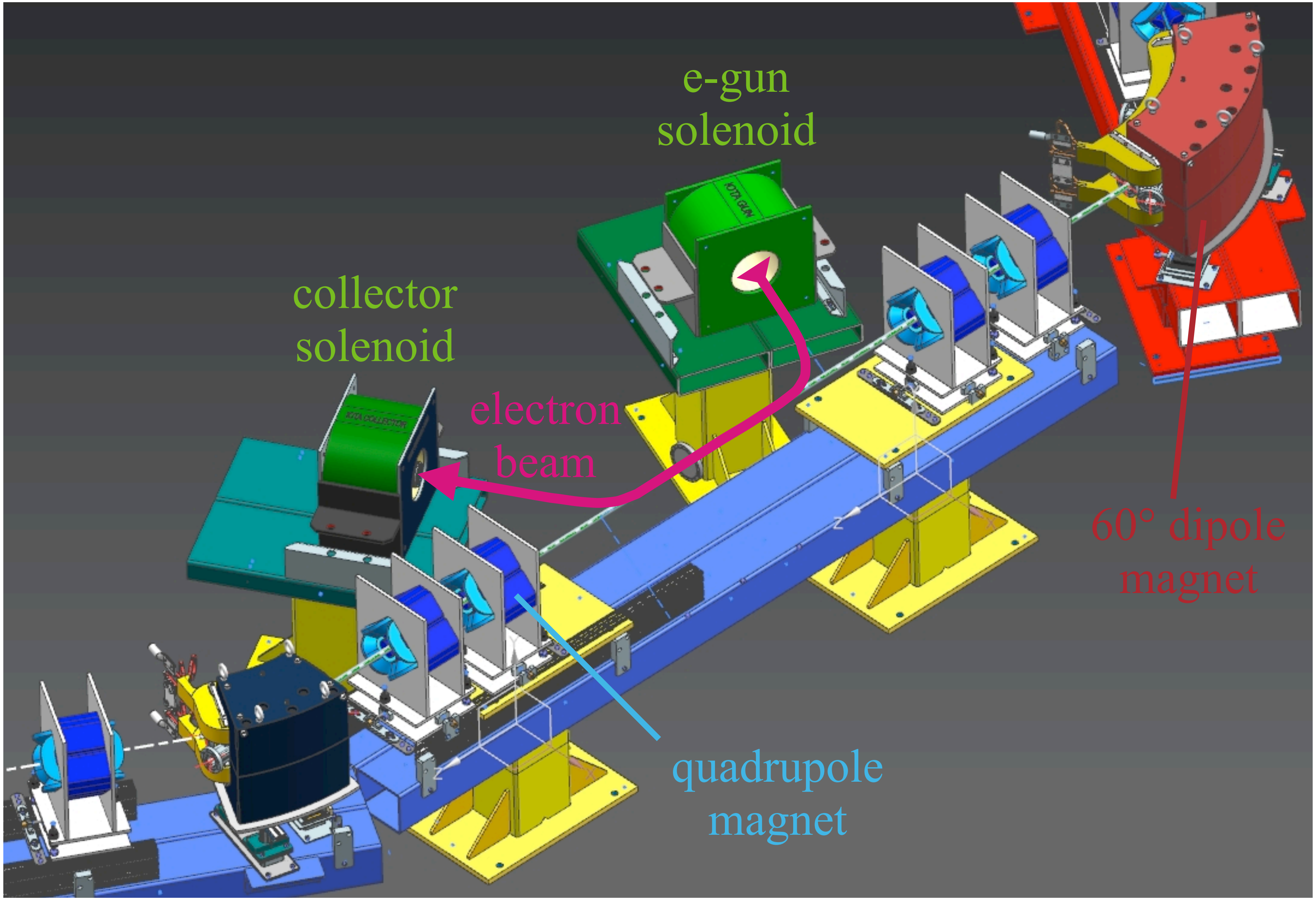
# Introduction

# Electron lens layout in IOTA (top view)



# Electron-lens layout in IOTA



# Roles of the IOTA electron lens

- **Nonlinear element for integrable optics**
  - thin McMillan lens
  - thick axially symmetric lens
- **Electron cooler**
  - extend range of proton emittances and lifetimes for experiments
  - new research on electron cooling reach in nonlinear lattice
- **Space-charge compensator for rings**
  - shaped beam from electron gun
  - trapped electron column from residual gas

[“Electron lens” = magnetically confined electrons acting on the circulating beam]

Antipov et al., JINST **12**, T03002 (2017)

# Typical e-lens parameters

| | |
|---|---|
| Cathode-anode voltage | 0.1 -- 10 kV |
| Electron beam current | 5 mA -- 5 A |
| Current density on axis | 0.1 -- 12 $A/cm^2$ |
| Main solenoid length | 0.7 m |
| Main solenoid field | 0.1 -- 0.8 T |
| Gun/collector solenoid fields | 0.1 -- 0.4 T |
| Max. cathode radius | 15 mm |
| Lattice amplitude function | 0.5 -- 10 m |
| Circulating beam size (rms), $e^-$ | 0.1 -- 0.5 mm |
| Circulating beam size (rms), p | 1 -- 5 mm |

# Electron lenses for nonlinear integrable optics

# Nonlinear integrable optics with electron lenses

Use the electromagnetic field generated by the electron distribution to provide the desired nonlinear field.

Linear focusing strength on axis ~ 1/m: $k_e = 2\pi \frac{j_0 L (1 \pm \beta_e \beta_z)}{(B\rho)\beta_e \beta_z c^2} \left( \frac{1}{4\pi\epsilon_0} \right).$

**1. Axially symmetric thin kick of McMillan type**

current density $j(r) = \frac{j_0 a^4}{(r^2 + a^2)^2}$

transverse kick $\theta(r) = \frac{k_e a^2 r}{r^2 + a^2}$

achievable tune spread $\sim \frac{\beta k_e}{4\pi}$

**Larger tune spreads in IOTA**

**More sensitive to kick shape**

**2. Axially symmetric kick in long solenoid**

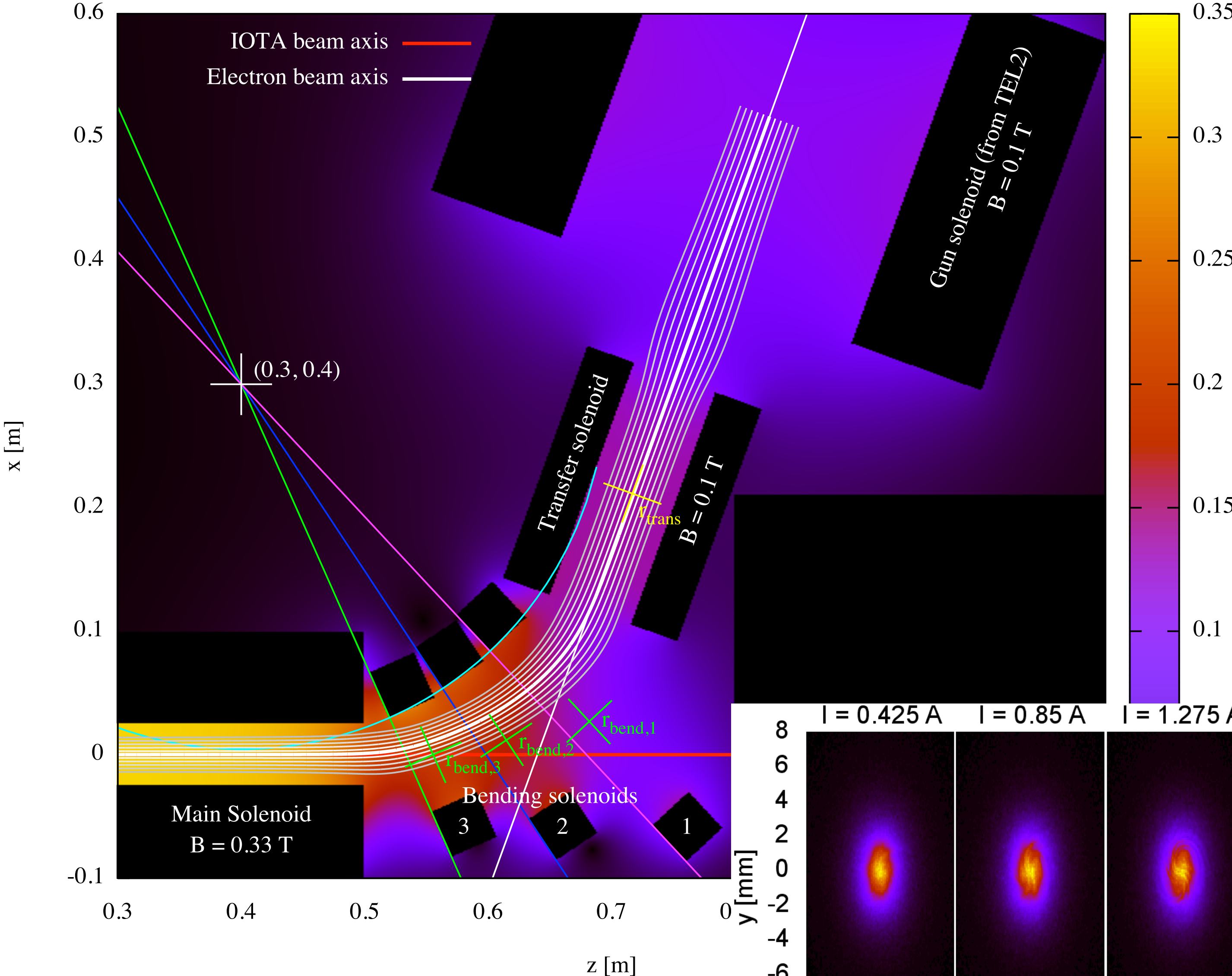
Any axially-symmetric current distribution

$$\sim \frac{L}{2\pi\beta} = \frac{L B_z}{4\pi(B\rho)}$$

**Smaller tune spreads in IOTA**

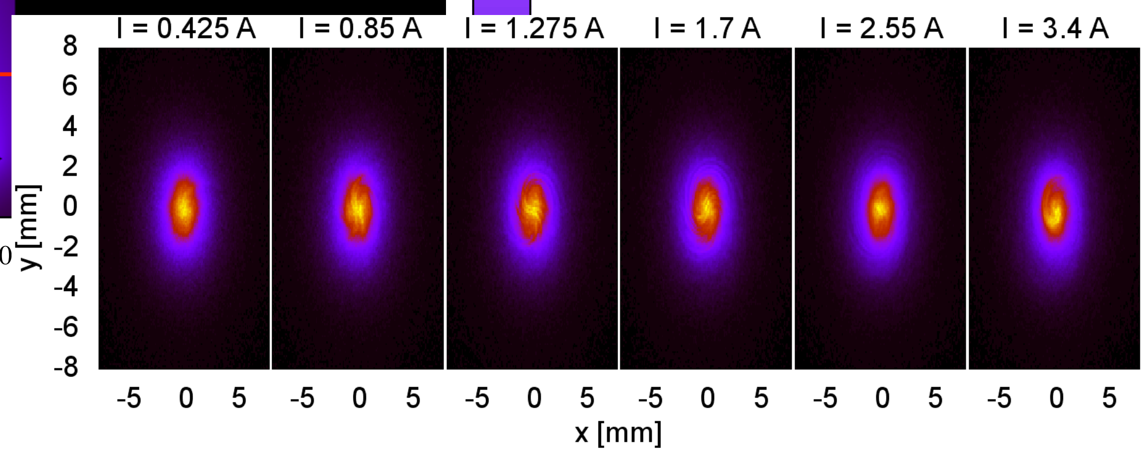
**More robust**

# Design of beam transport in electron lens




1. Field-line mapping
2. Single-particle tracking
3. Tracking with space charge

Noll and Stancari, FERMILAB-TM-2598-AD-APC; Noll, PhD Thesis (2016)




Minimize distortions

Provide input for tracking in ring

# Design of McMillan e-gun

Is it possible to generate the required current-density profile?

Contrasting requirements of high yield and peaked distribution

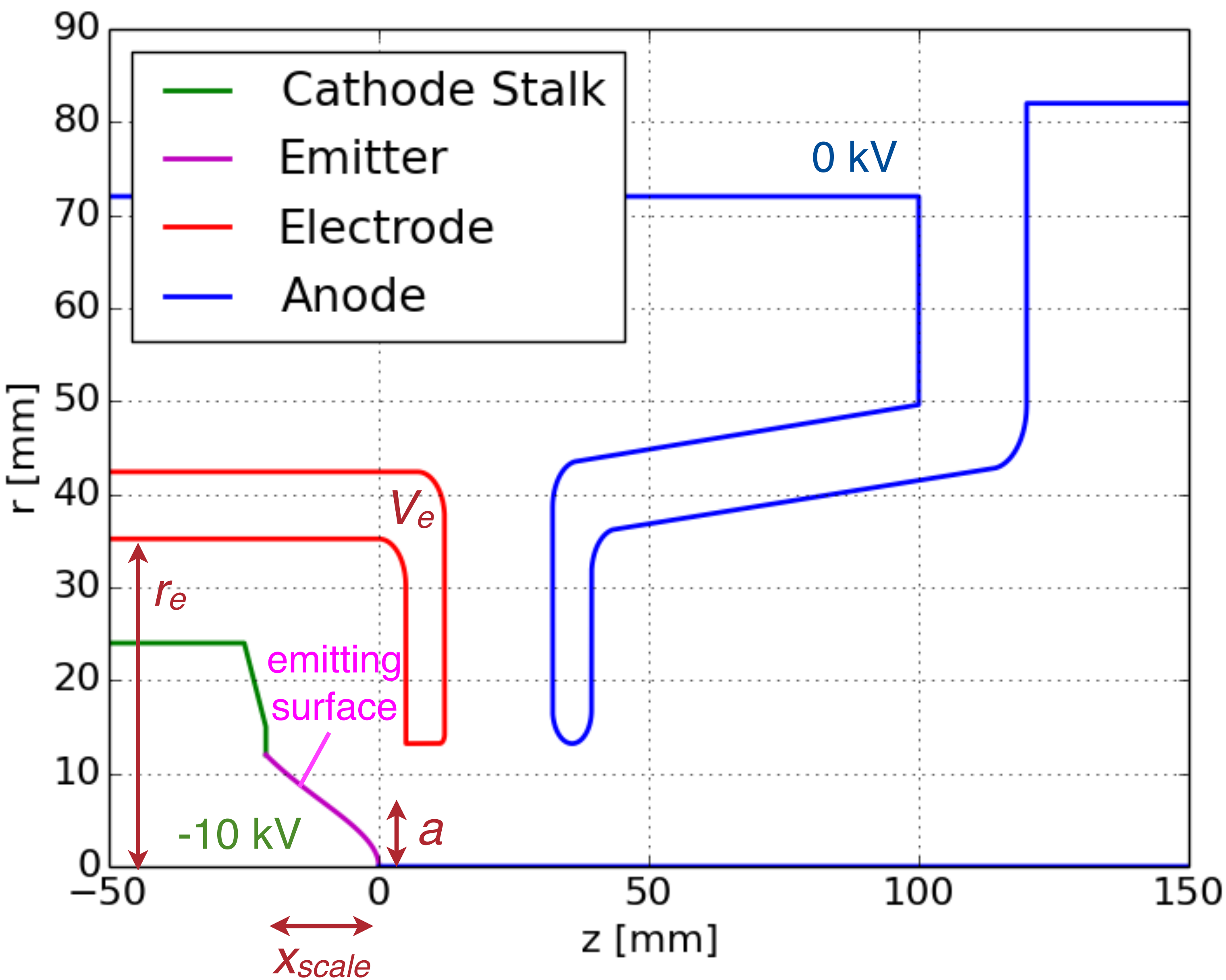
Optimization of the e-gun geometry to match the desired profile

$$j(r) = \frac{j_0 a^4}{\left(r^2 + a^2\right)^2}$$

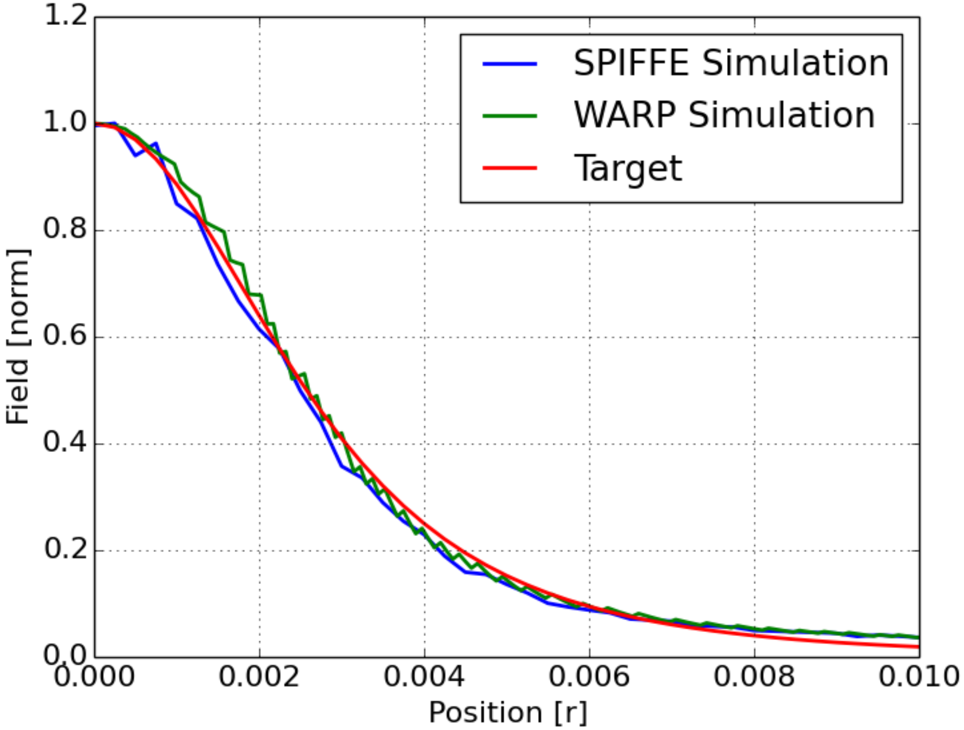
Space-charge-limited emission determined mostly by E-field at surface =>

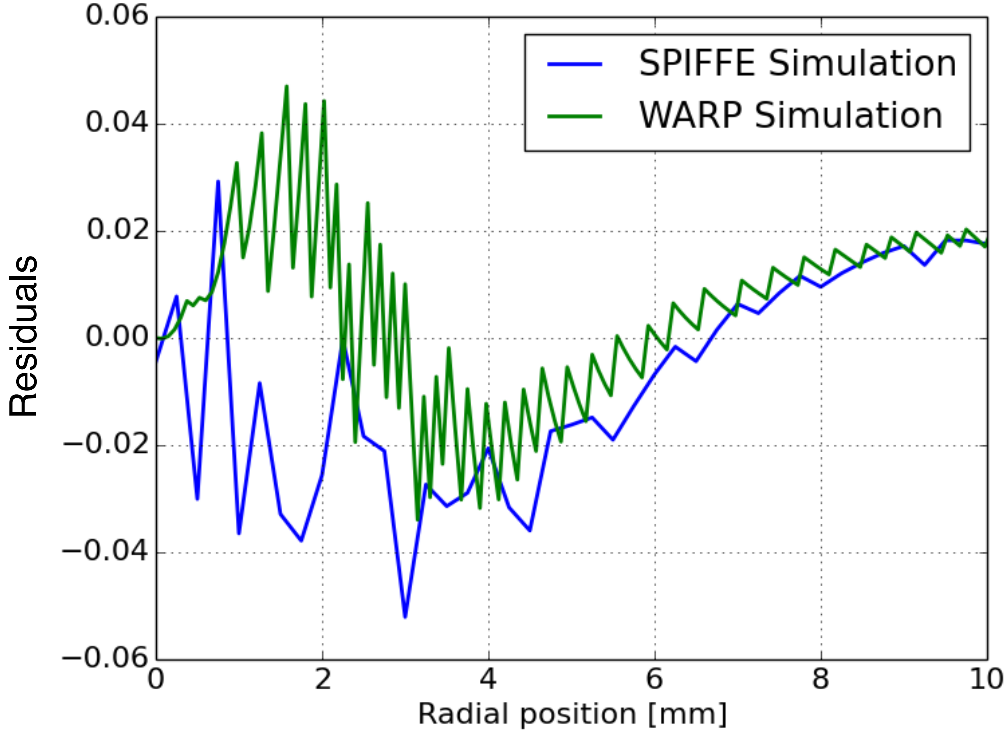
- optimize E-field first (fast)
- then, refine beam profile (slower), iterating calculation of space-charge-limited emission

# Electron gun parametric geometry



# Optimization of the electric field at the emitter

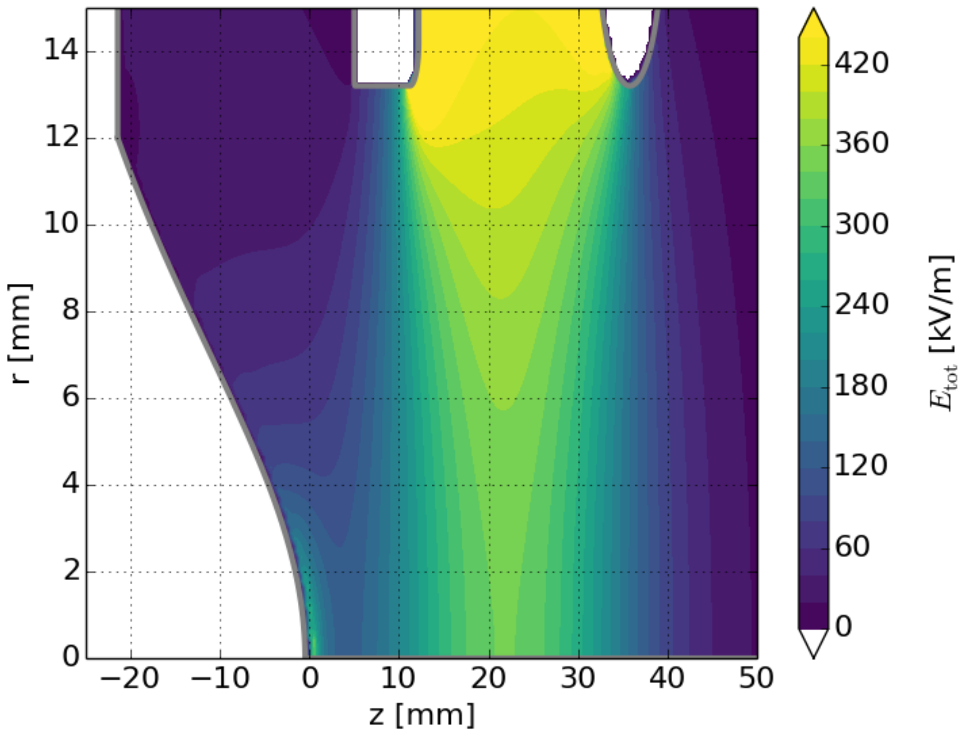


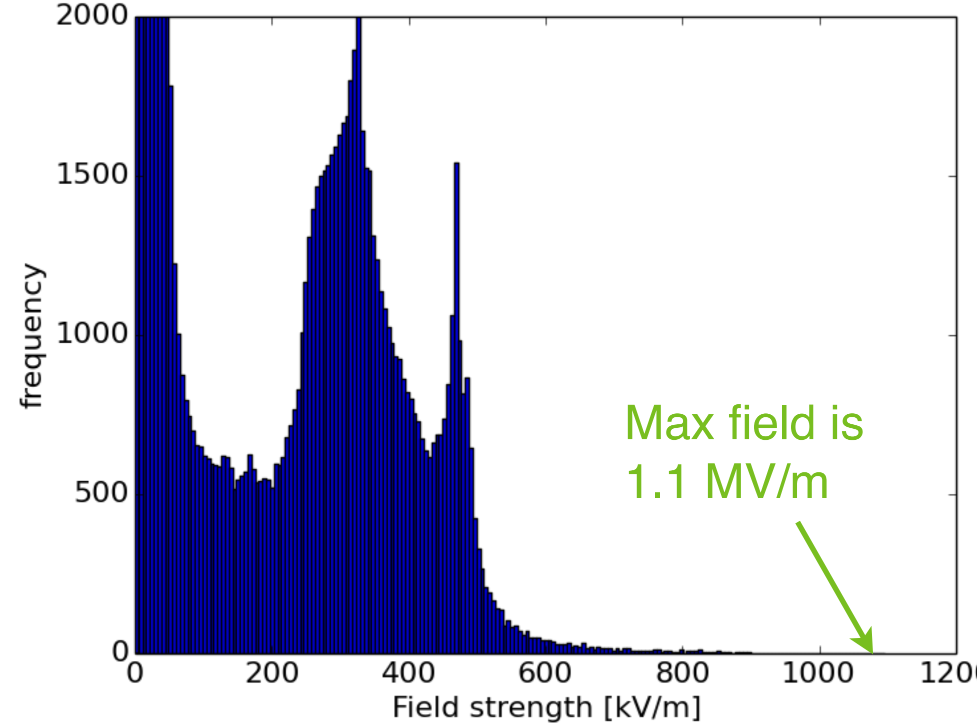

Deviations from target distribution < 5% of peak field

Comparable agreement between codes Spiffe and Warp

# Electric field distribution



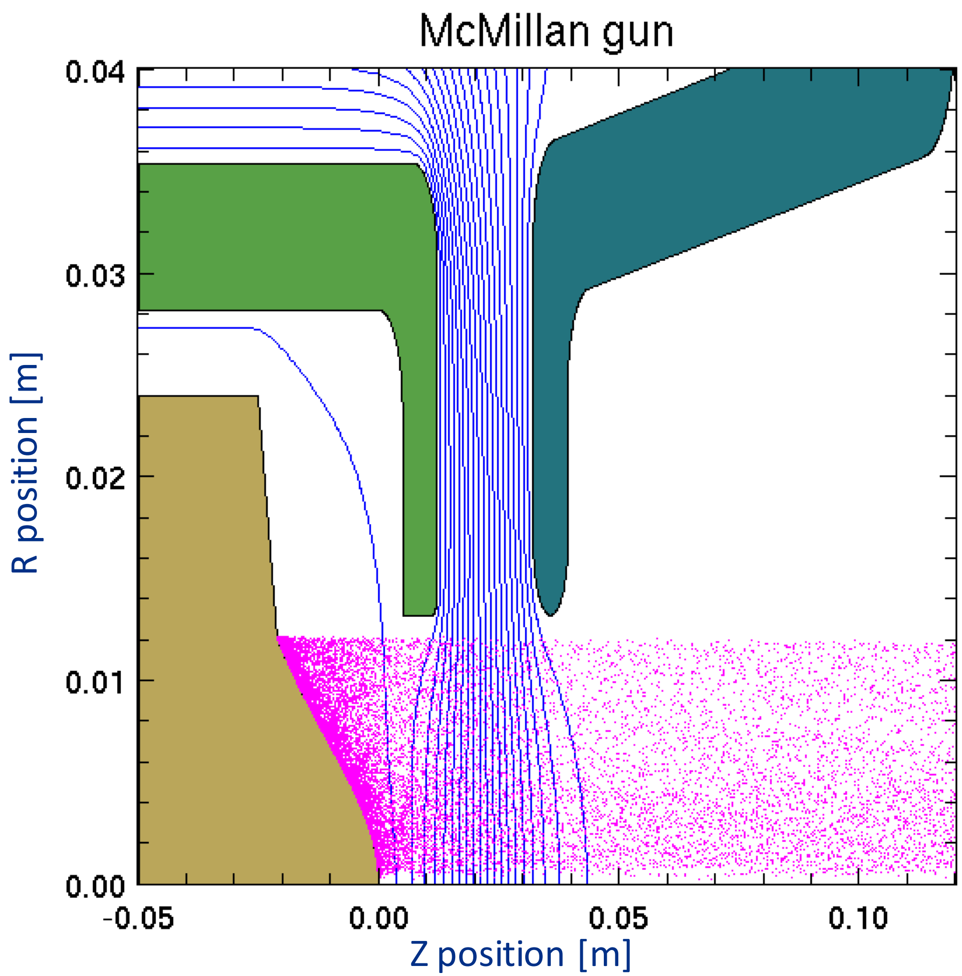

Histogram of electric field magnitude on simulation mesh

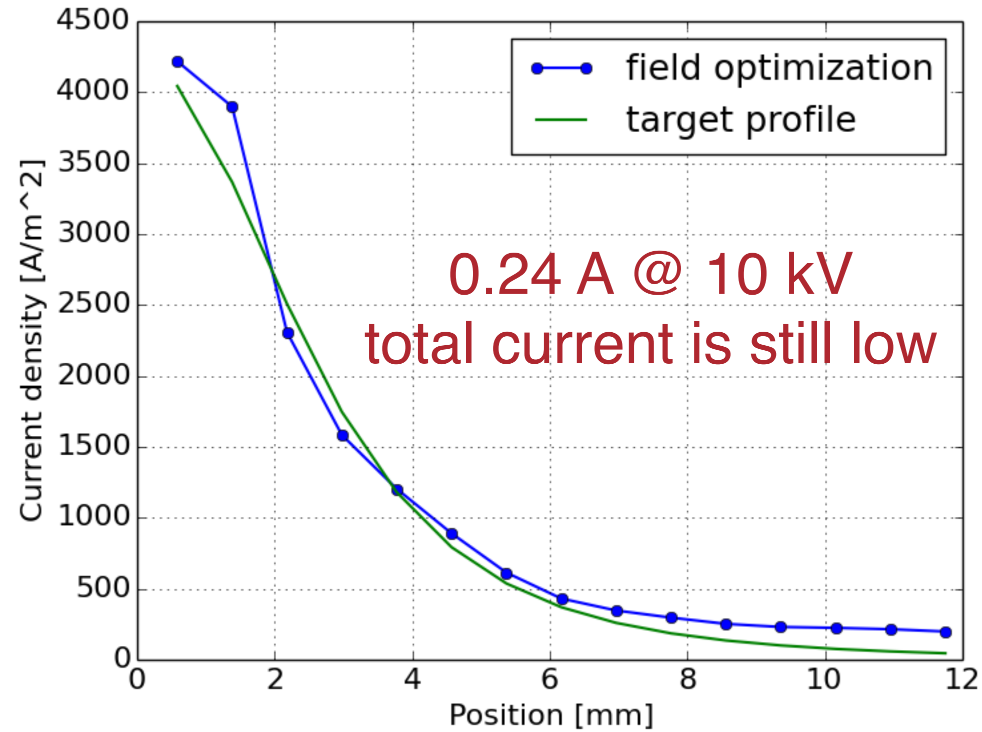



There is margin to decrease distances and increase perveance

# Current density distribution and sensitivity

## Space-charge-limited simulation of beam emission

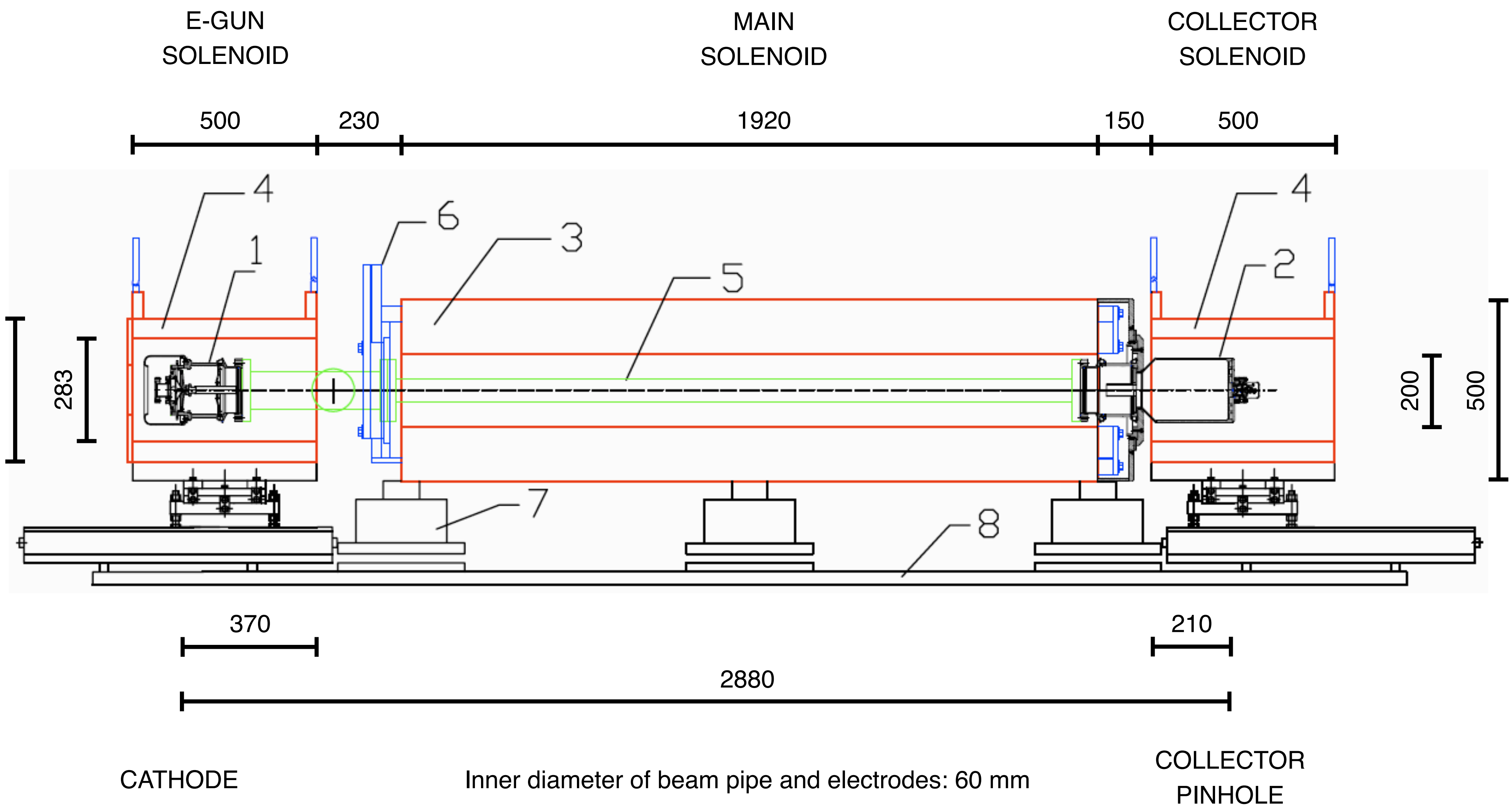



Field optimization provides good starting point for current-density optimization (within 10% of target)

# Fermilab electron-lens test stand

dimensions in mm




Inner diameter of beam pipe and electrodes: 60 mm

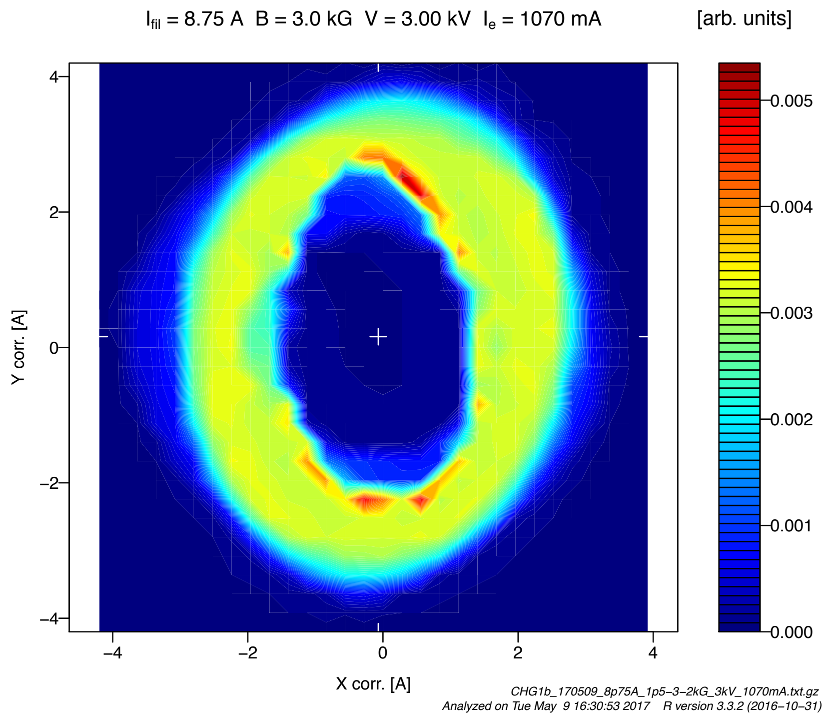
# Accuracy of profile measurements in e-lens test stand

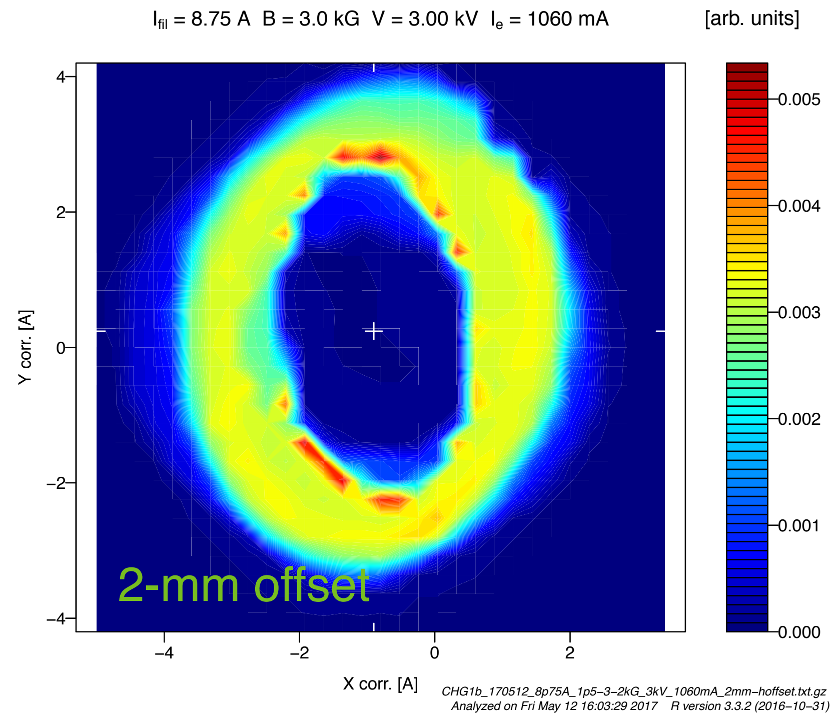
Current density measured with beam scans over collector pinhole

Very reproducible, but misalignments may introduce systematics

No observed effects due to repetition rate (ions, ...)

Recent studies done with a hollow beam (larger and more sensitive to distortions)




Can we also measure the velocity distribution vs. radius?

Charge density vs. current density

# Space-charge compensation

# Space-charge compensation in rings

Space-charge compensation routinely used in linacs, rf photoinjectors

In rings, it would enable higher intensities

A challenging subject: local correction of global effect?

Issues: high charge densities, lattice distortions, beam-plasma instabilities

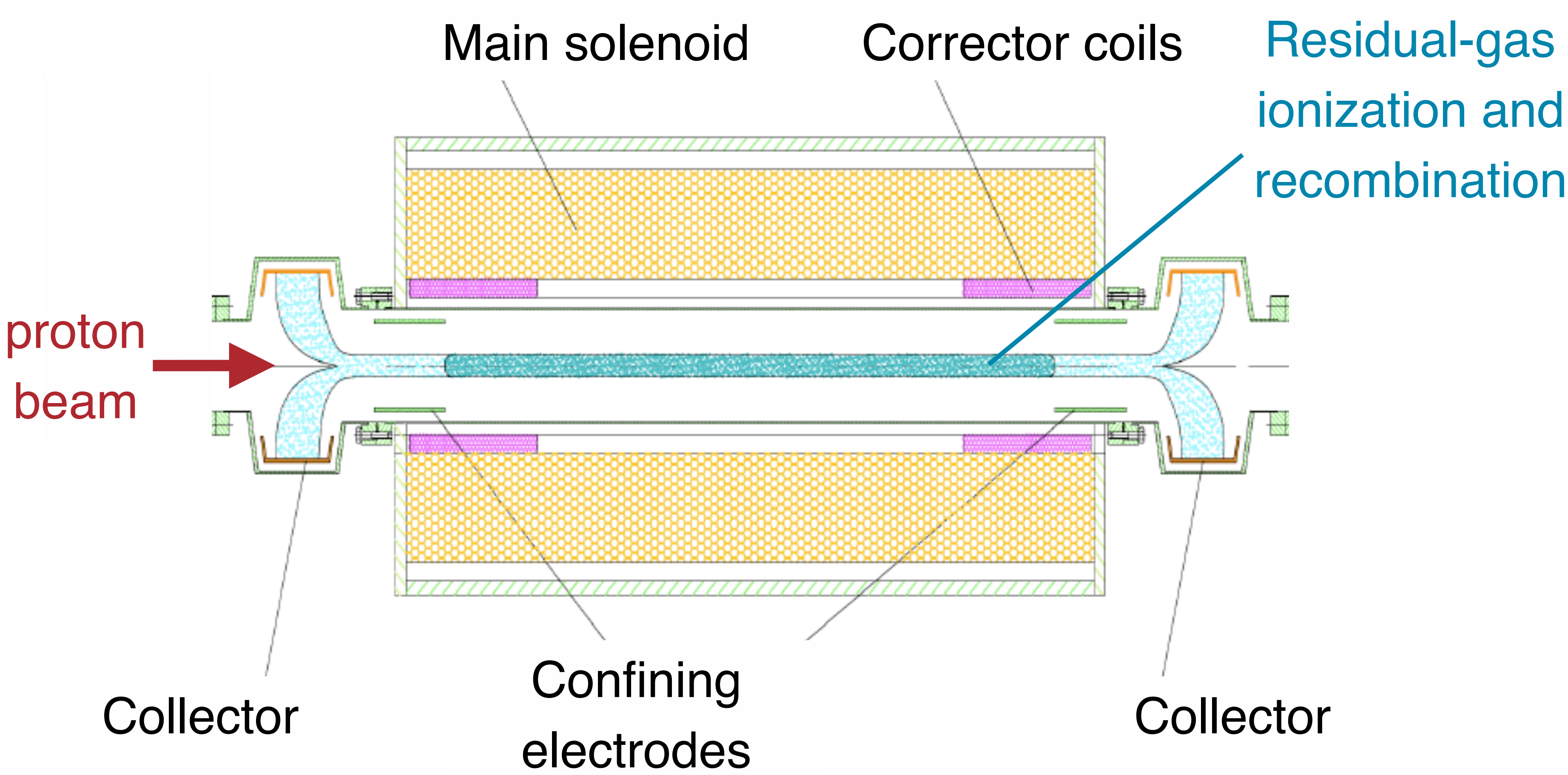
Implementation with electron lens has advantage of magnetic confinement for stability

Two concepts:

- given profile (transverse/longitudinal?) from electron gun <u>or</u>
- electrons from residual-gas ionization trapped in Penning-Malmberg configuration ("electron column")

Numerical simulation studies to guide experiments in IOTA

# Concept of electron column




In strong field, ionization electrons mirror transverse profile of protons

How does the e-column evolve?

# Electron-column simulations in IOTA with Warp

Trap configuration: 1 m length, [0 T, 0.2 T] solenoid, [0 V, -200 V] electrodes

Residual gas: $H_2$, [$10^{-3}$ torr, $10^{-5}$ torr] (to enhance ionization rates)

Protons: 2.5 MeV, 8 mA (~5 V on axis), various profiles and time structures

New protons injected in interaction volume (no ring circulation yet)

Ionization processes:

5.4 keV max.
most below 0.2 keV

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

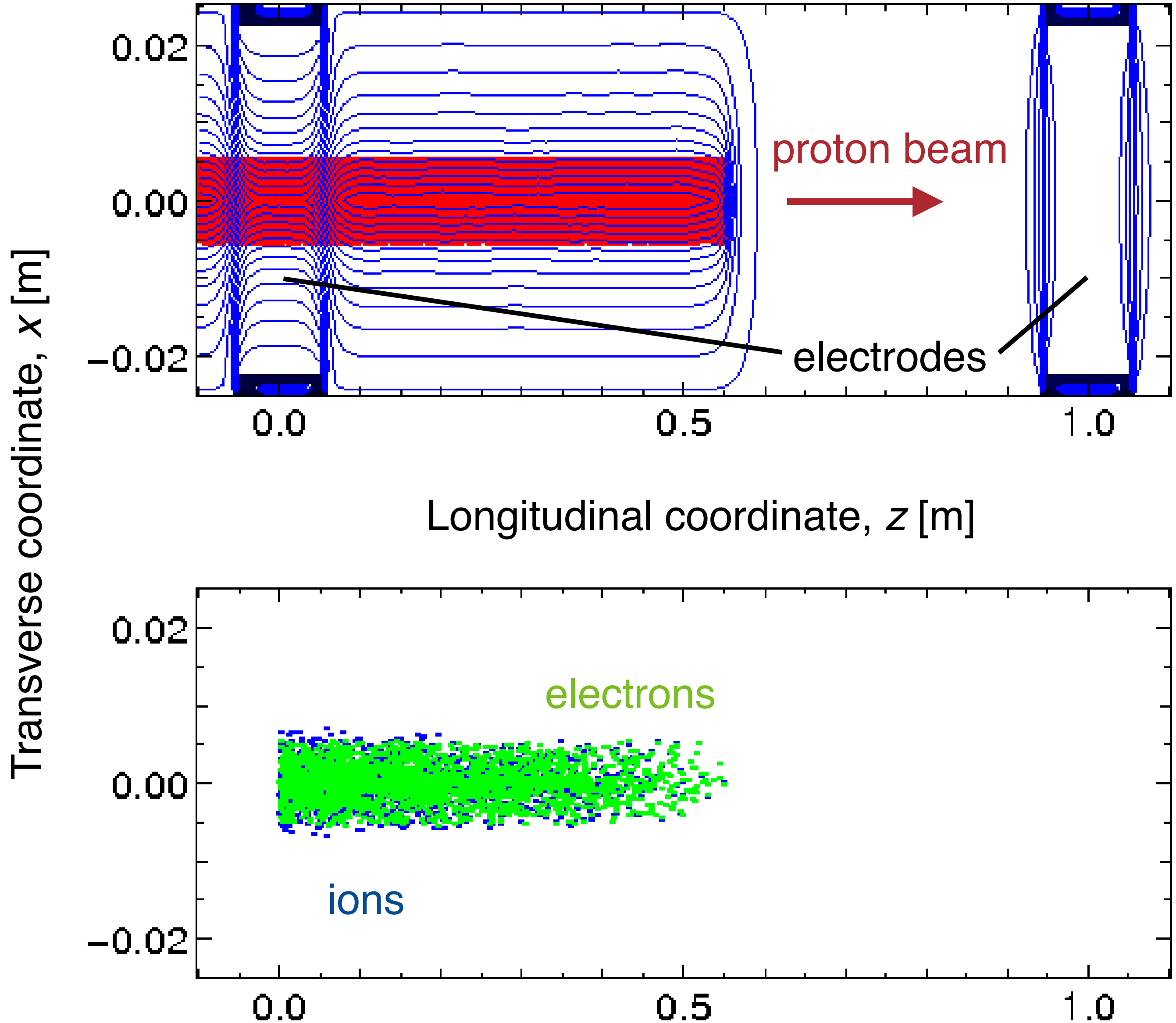
$\sigma = 1.5\times10^{-21}$ m$^2$

$$e^- + H_2 \rightarrow 2e^- + H_2^+$$

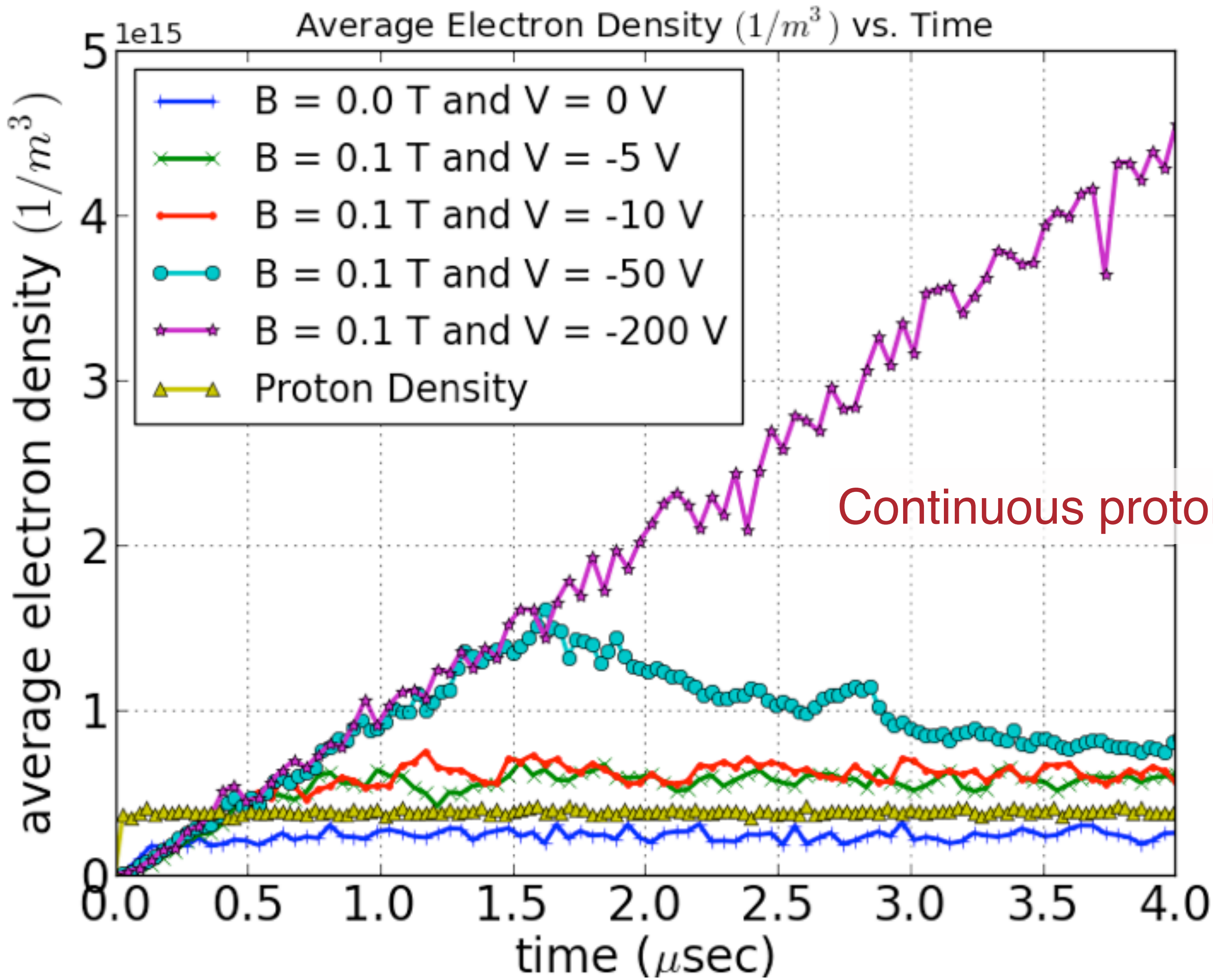
$\sigma = 1.3\times10^{-20}$ m$^2$

No recombination, double ionization, hydrogen clusters, ...

# Simulation layout



# Electron density buildup vs. electrode voltage



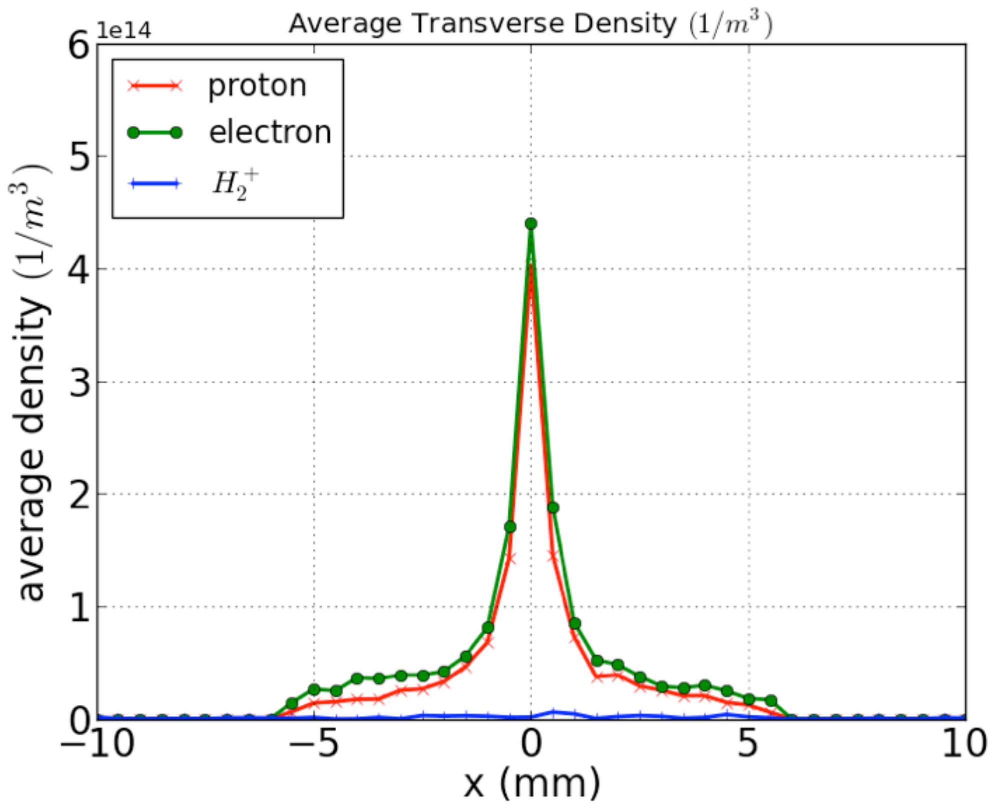

Continuous proton beam

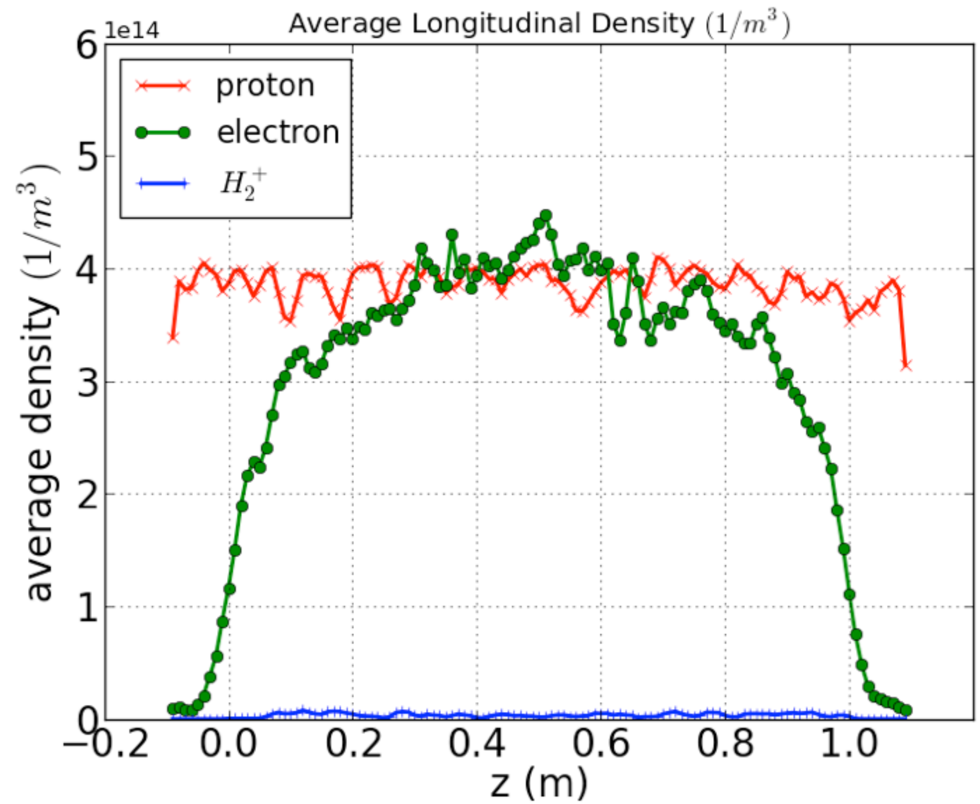
Park et al., NAPAC16

# Example of particle distributions

Continuous proton beam

$B$ = 0.1 T, $V$ = -5 V, $p$ = 5×10$^{-4}$ torr




Electrons reach equilibrium transverse distribution

They may have enough energy to escape longitudinally

# Numerical calculations with pulsed proton beam

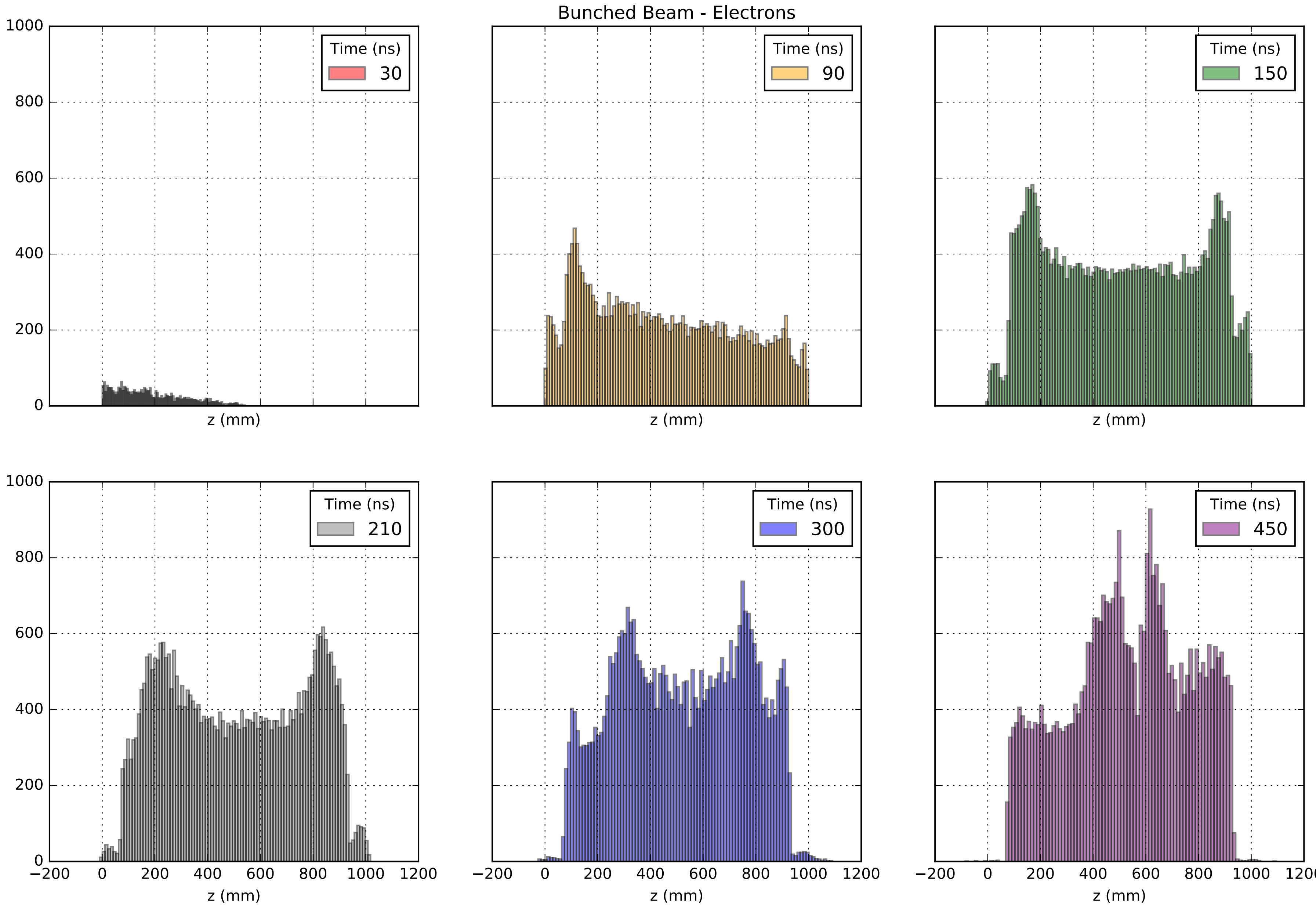
How does the electron column evolve after one proton beam traversal?

Protons on for 100 ns, then off for 900 ns (as an example)

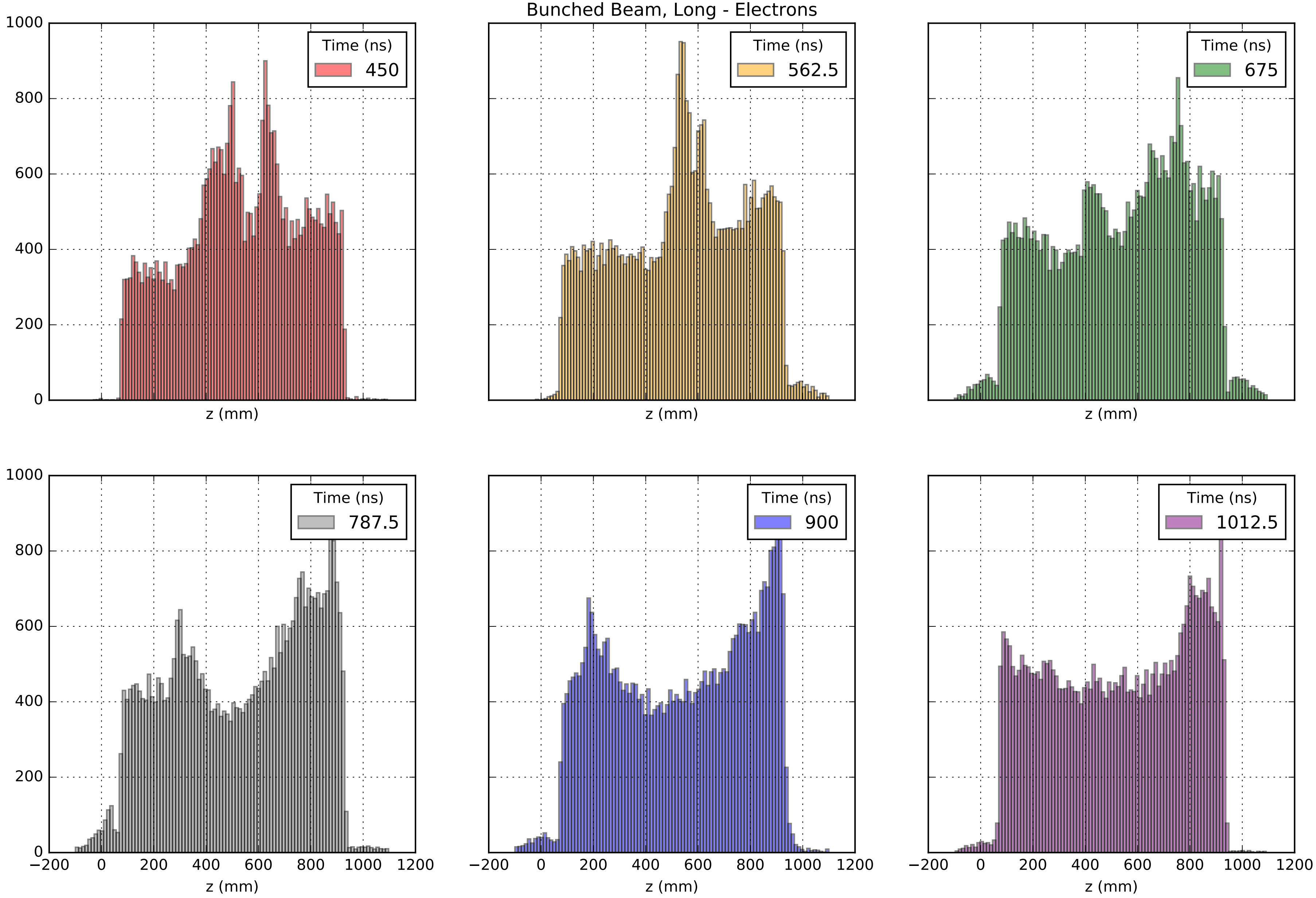
Transit time in e-column is 46 ns, revolution time in IOTA is 1.8 us

*link to animation*

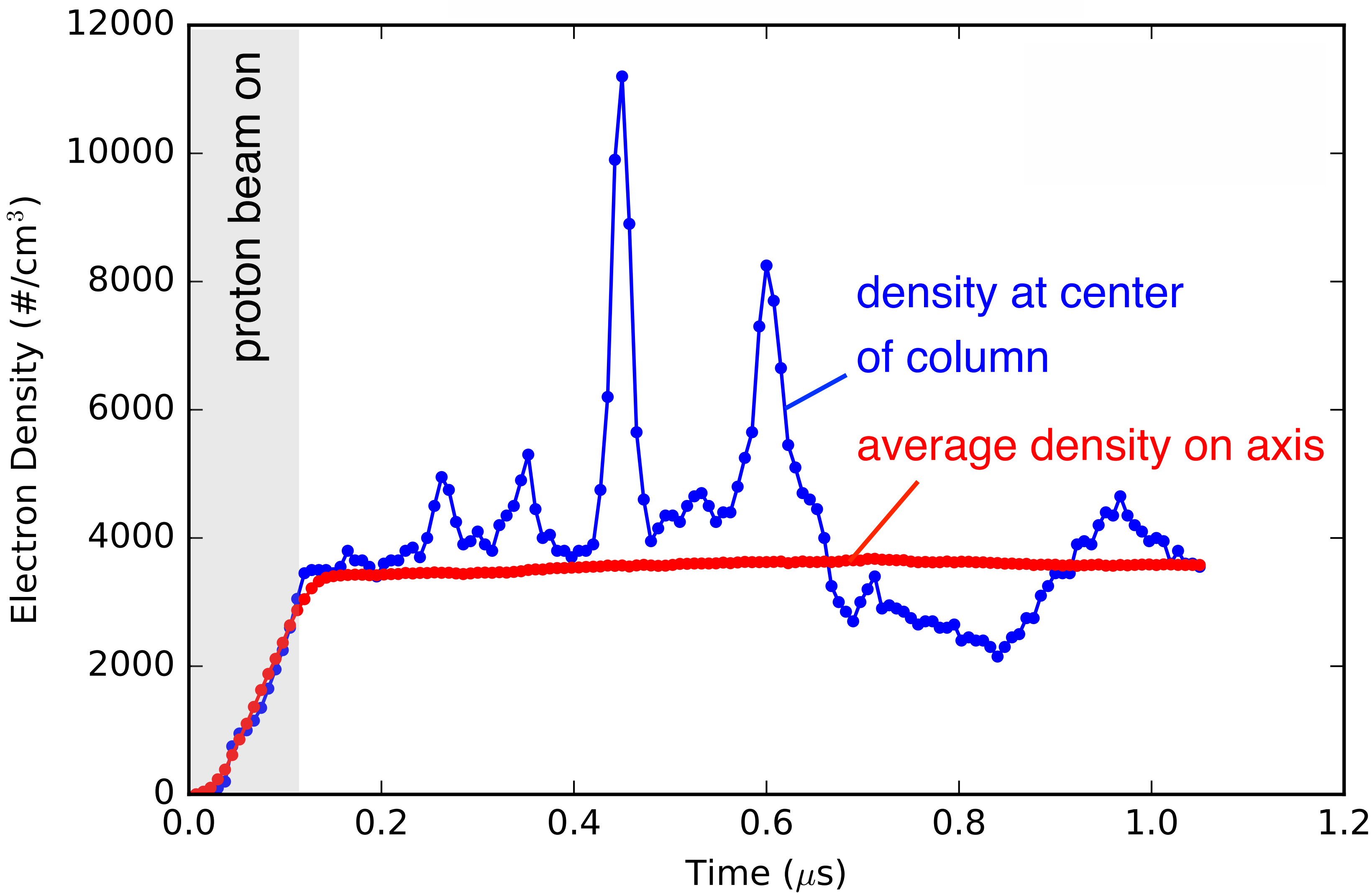
# Longitudinal electron density vs. time



# Longitudinal electron density vs. time



# Evolution of electron density



# Numerical calculations with pulsed proton beam

How does the electron column evolve after one proton beam traversal?

Protons on for 100 ns, then off for 900 ns

Electrons are confined transversely and oscillate longitudinally, with little loss

Ions are lost both transversely and longitudinally

Oscillations are determined by secondary electron velocity and by plasma frequency

Distributed electrode voltages can help shape the charge distribution

# Electron cooling

# Electron cooling

1.36-keV electrons match the velocity of 2.5-MeV protons

A wider range of proton lifetimes and brightnesses will be available for experiments

Cooling option determined the co-propagating configuration of the e-lens

Cooling rates of 0.1 s are achievable

Emittances can be reduced by a factor 10

Better models of magnetized cooling are needed for predictions

Does nonlinear integrable optics combined with cooling enable higher brightnesses?

Stancari et al., COOL15

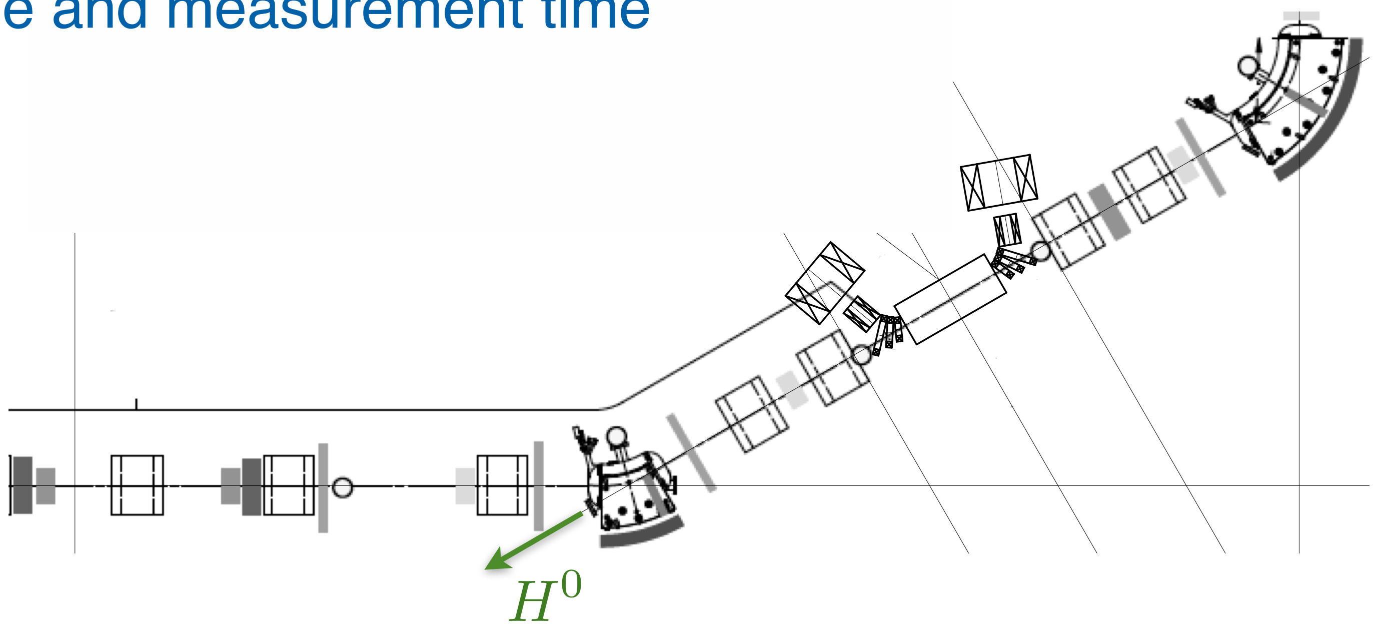
Antipov et al., JINST **12**, T03002 (2017)

# Proton beam diagnostics through recombination

Spontaneous recombination generates neutral hydrogen with distribution of Rydberg states, some of which are Lorentz-stripped in e-lens toroid and IOTA dipole

$$p + e^- \rightarrow H^0 + h\nu$$

Recombination rate at detector is ~ 50 kHz; good compromise between beam lifetime and measurement time




A critical diagnostic tool for cooling and proton beam evolution

Hardware options identified; needs final design

# Hardware status

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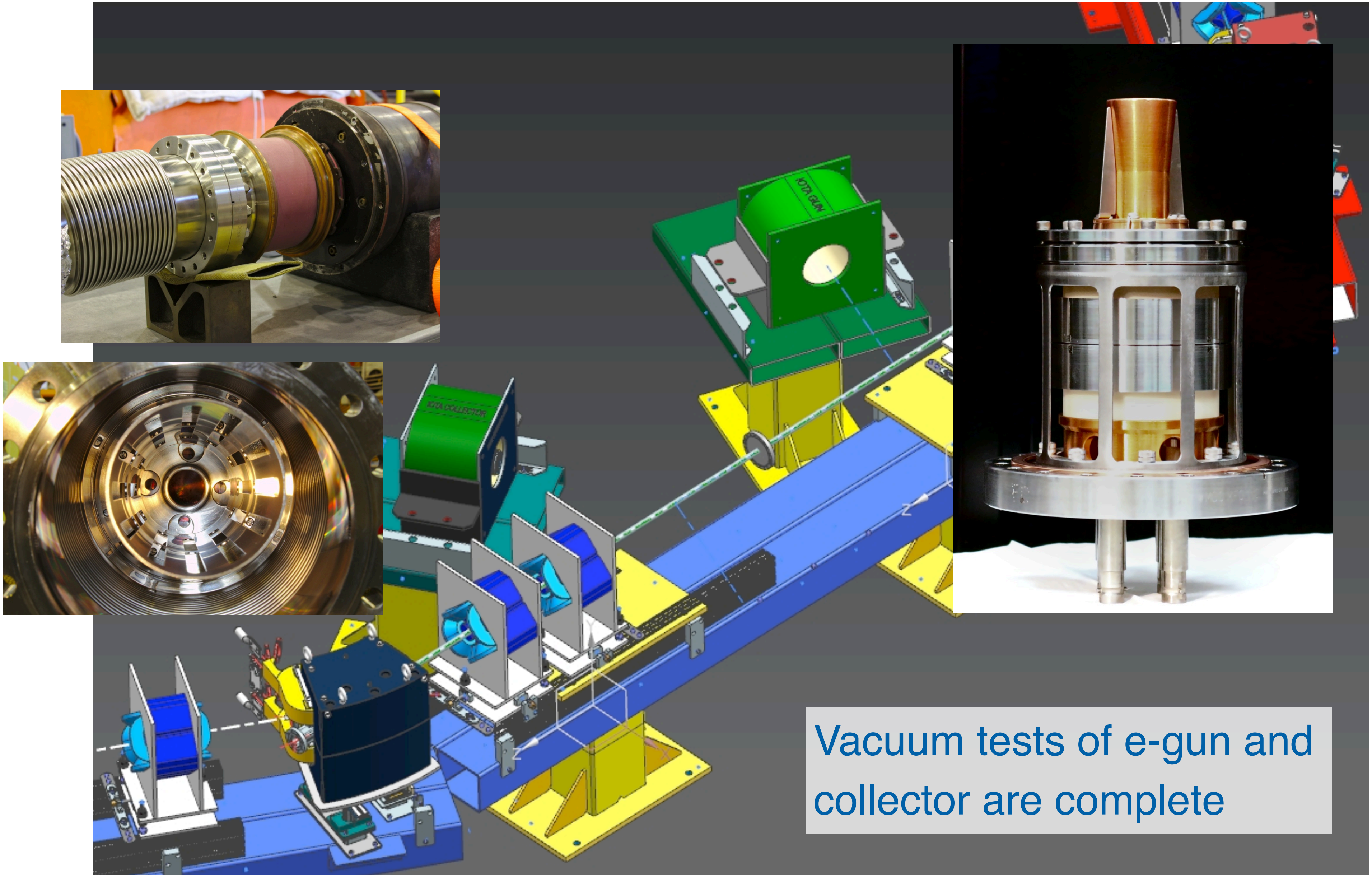
Gun and collector solenoids reused from Tevatron

Now awaiting for magnetic measurements

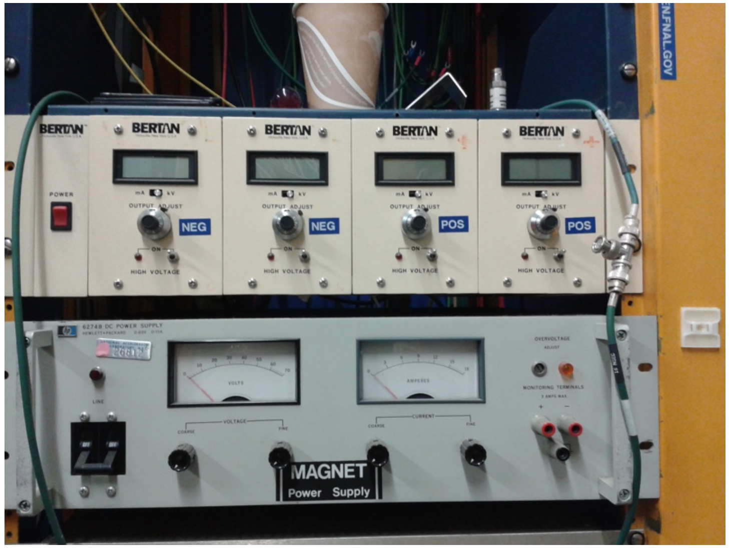
# Hardware status




Vacuum tests of e-gun and collector are complete

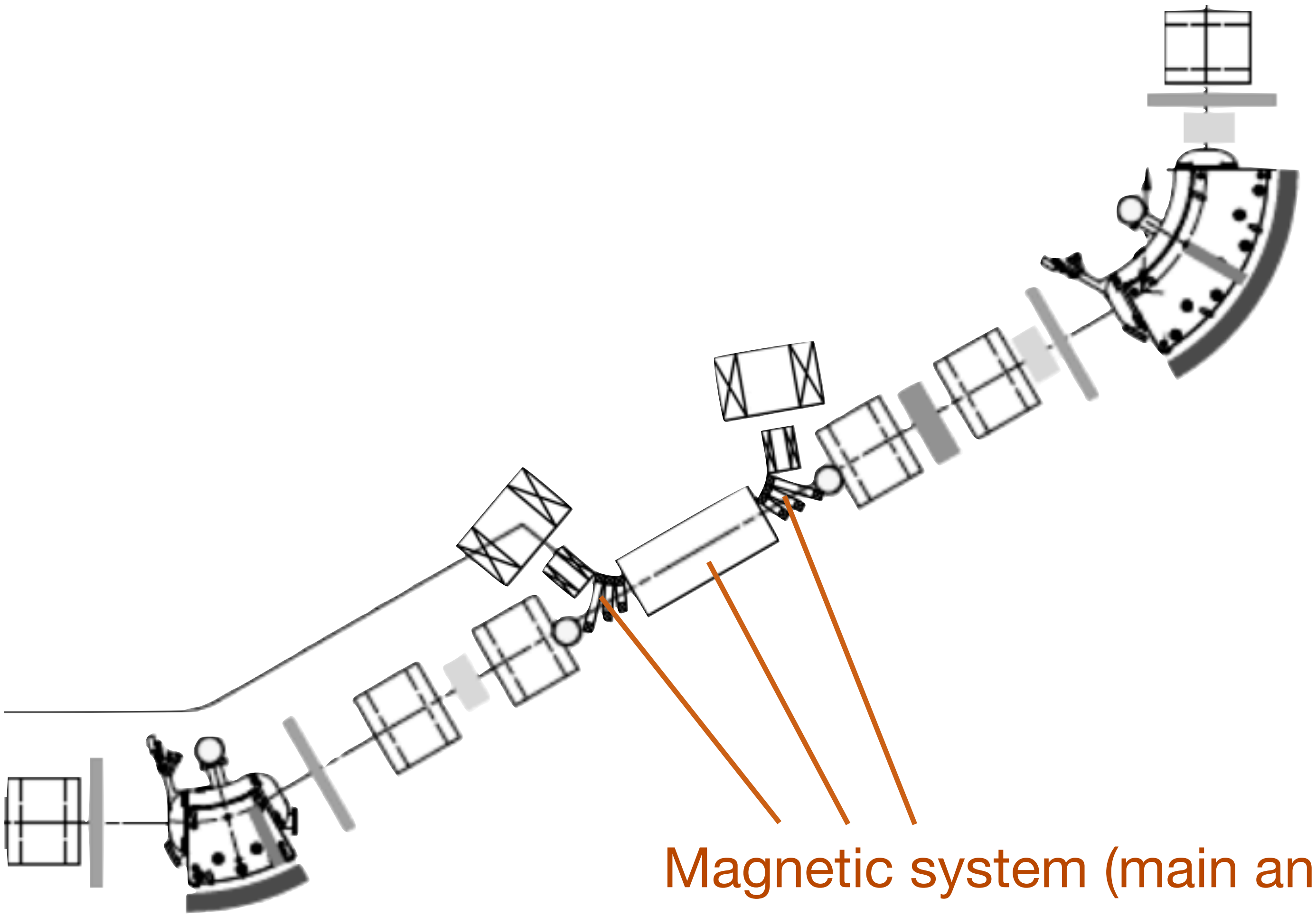
# Hardware status

Several Tevatron power supplies for magnets and HV can be reused



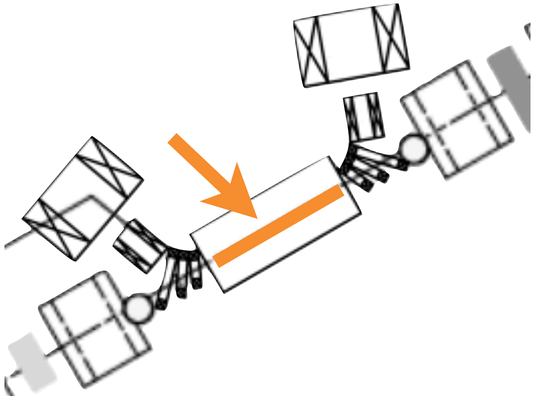


# Hardware status



Magnetic system (main and transport solenoids) is behind schedule, limited by resources

# Electrode and pickup structure



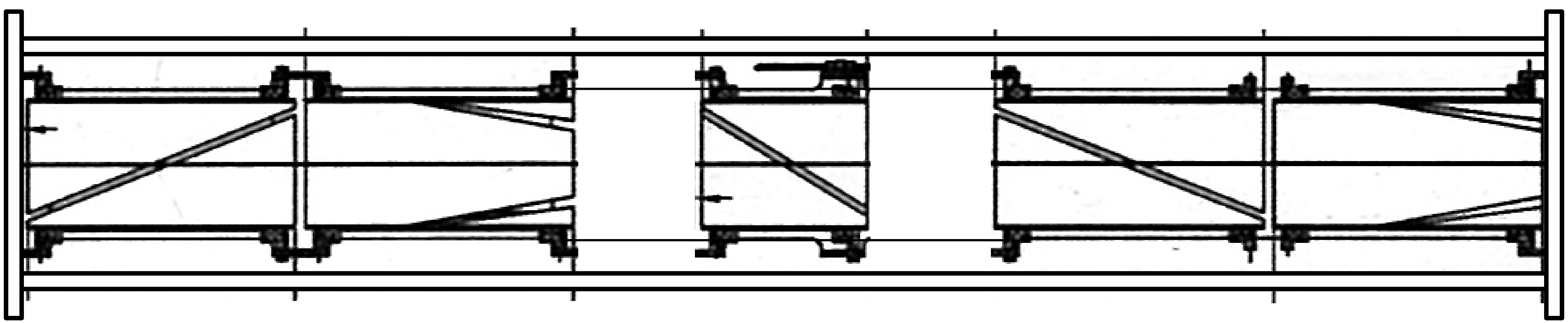
**Electrodes** will serve as

- beam-position monitors
- signal pickups for charge oscillations
- trapping/clearing electrodes

**Antenna** for high-frequency plasma and cyclotron osc.

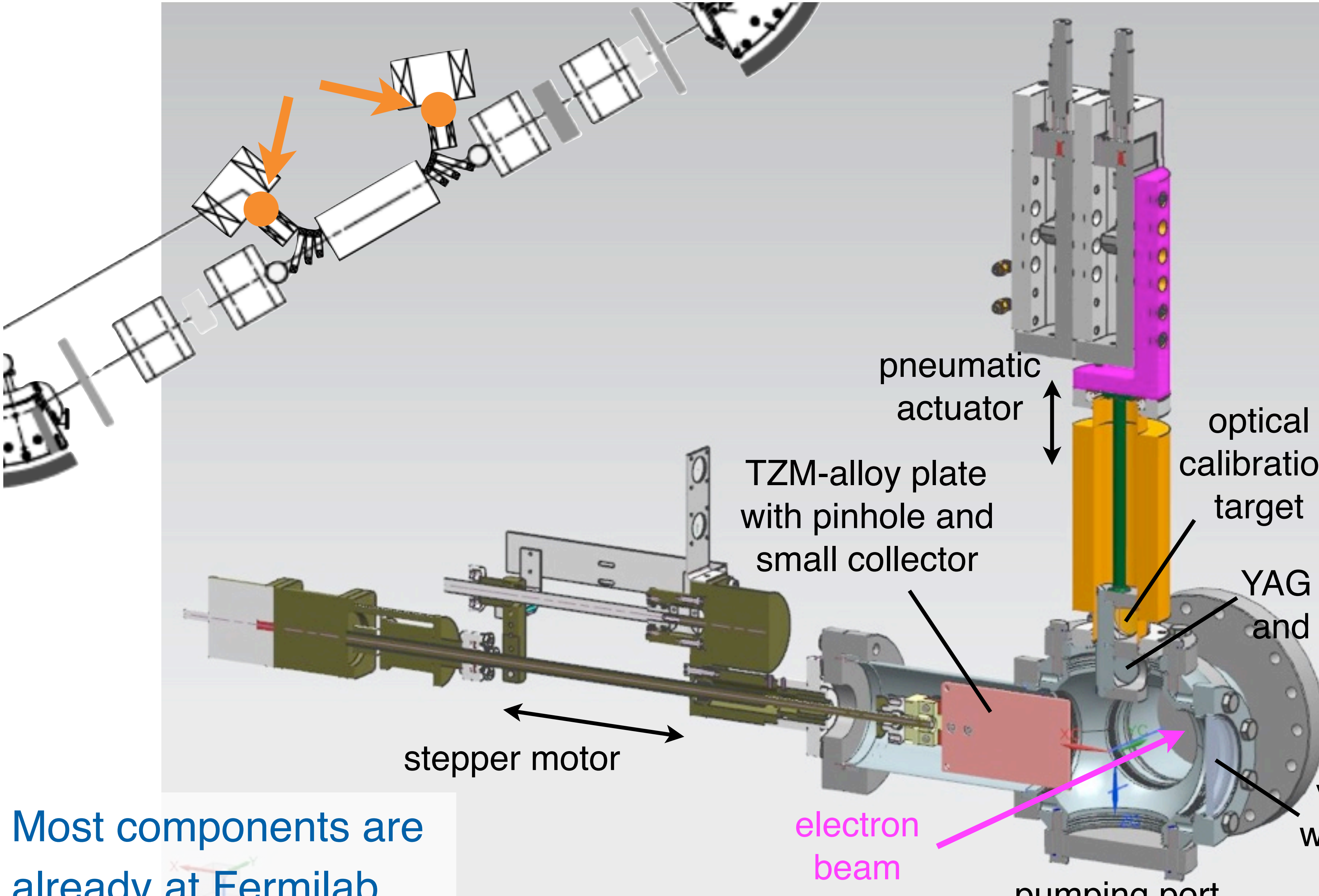
=> estimates of electron density and temperature

Need technical design, hardware, electronics



5 diagonally split cylinders or combined horiz./vert. striplines

# New diagnostic stations for e-beam current and profile




Most components are already at Fermilab

# Conclusions

# Conclusions

The electron lens in IOTA will enable new experiments in nonlinear optics, electron cooling, and space-charge compensation

Design challenges are related to the multiple functions and the limited physical space

The project is closely related to electron-lens applications in other machines, such as beam-beam compensation and hollow electron beam collimation

There are several opportunities for collaborators to make an impact: theory, numerical calculations, diagnostics, hardware, experiments

*Thank you for your attention!*