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U.S. DEPARTMENT OF ENERGY

USPAS - Fundamentals of Ion Sources
14. Space Charge

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Outline

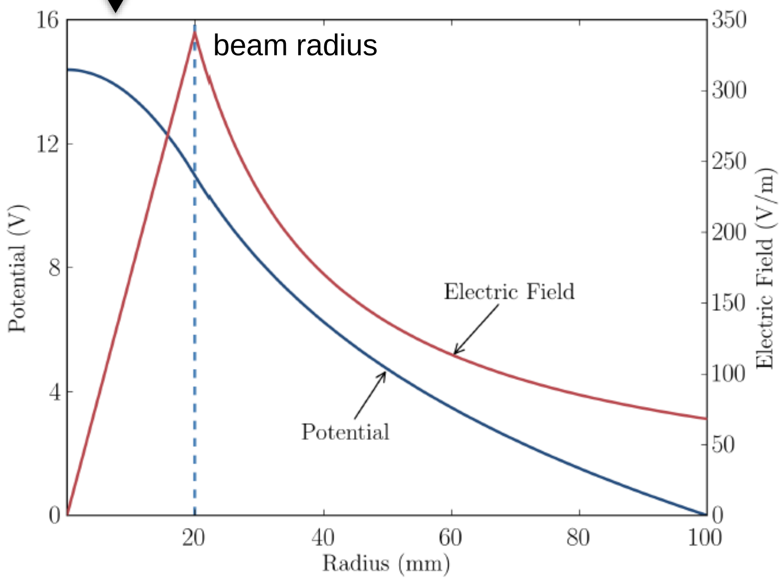
Main focus on LEBT and Design/Simulations thereof

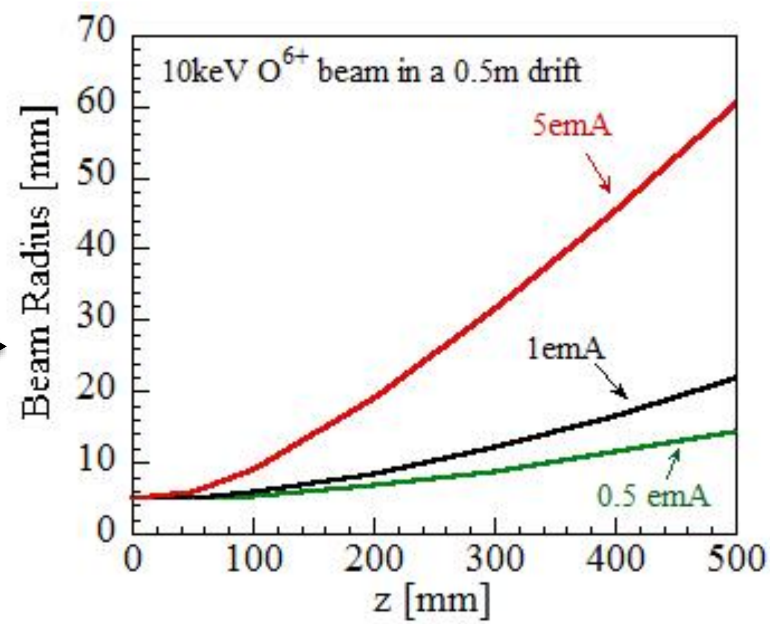
- General Introduction
- SC in the envelope equation *(Following N. Chauvin, CERN Accelerator School)*
- Generalized Perveance *(Following N. Chauvin, CERN Accelerator School)*
- Space Charge Compensation
- Space Charge Compensation in Simulations
- Measuring Space Charge Compensation
- Examples

Space Charge

- Space charge potential of a uniform and round beam with beam radius r_b in a grounded beam pipe r_p:

$$\phi(r) = \begin{cases} \Delta\phi \left(1 + 2\ln\frac{r_p}{r_b} - \frac{r^2}{r_b^2}\right) & \text{for } r \leq r_b \\ \Delta\phi \; 2\ln\frac{r_p}{r} & \text{for } r_b \leq r \leq r_p \end{cases} \qquad \Delta\phi = \frac{I}{4\pi\epsilon_0 v_b}$$





- Acts defocusing on the beam → need to counteract with beam optics elements

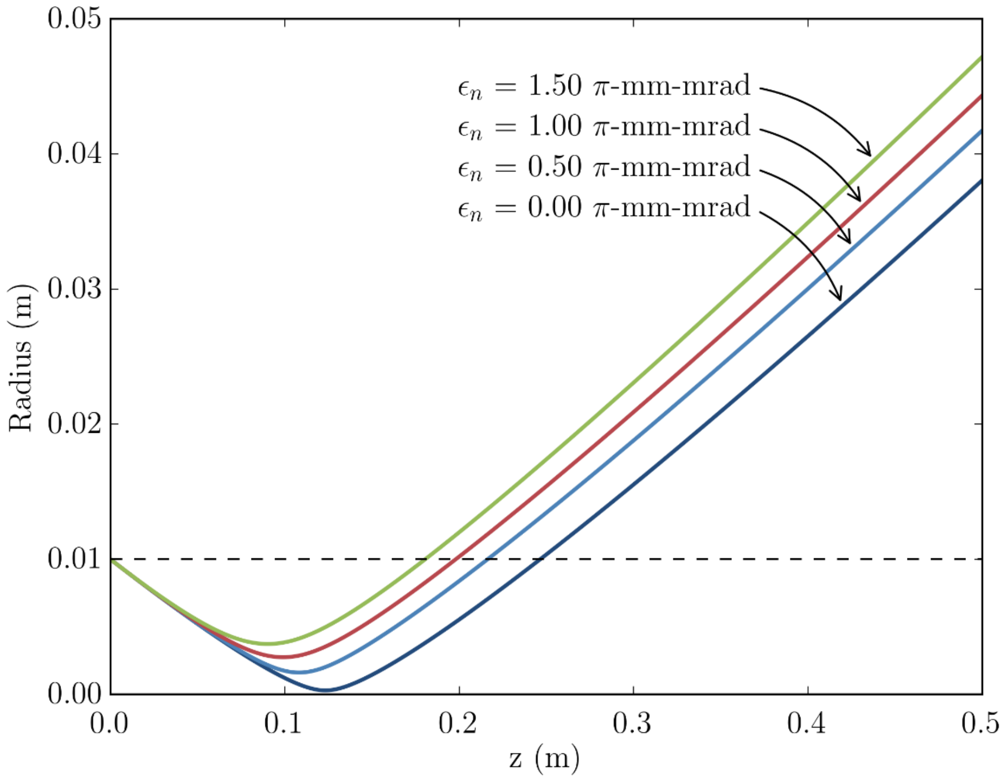
How does Emittance influence Beam Dynamics?

Courant-Snyder form of envelope equation:

$$x_m'' + \kappa x_m - \frac{\epsilon_x^2}{x_m^3} = 0$$

Emittance works against focusing…

…What about Space Charge?



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How does Space Charge influence Beam Dynamics?

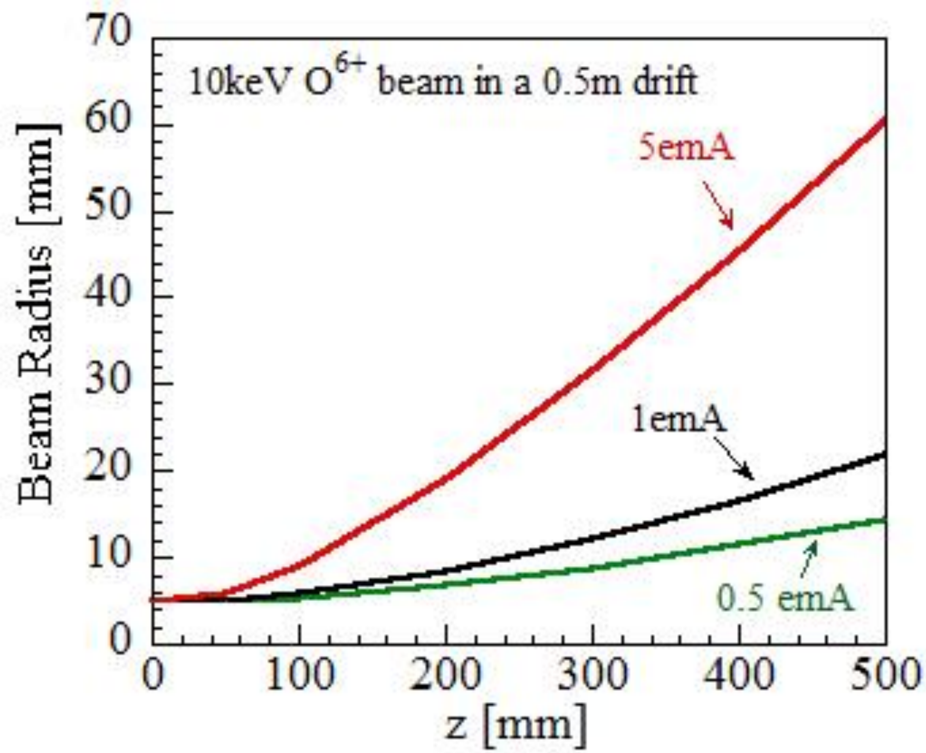
- Envelope equations with SC for elliptical beam:

$$x_m'' + \kappa_x x_m - \frac{\epsilon_x^2}{x_m^3} - \frac{K}{2(x_m+y_m)} = 0$$

$$y_m'' + \kappa_y y_m - \frac{\epsilon_y^2}{y_m^3} - \frac{2K}{2(x_m+y_m)} = 0$$

x_m, y_m, ϵ now the rms values

- Space Charge works against focusing!



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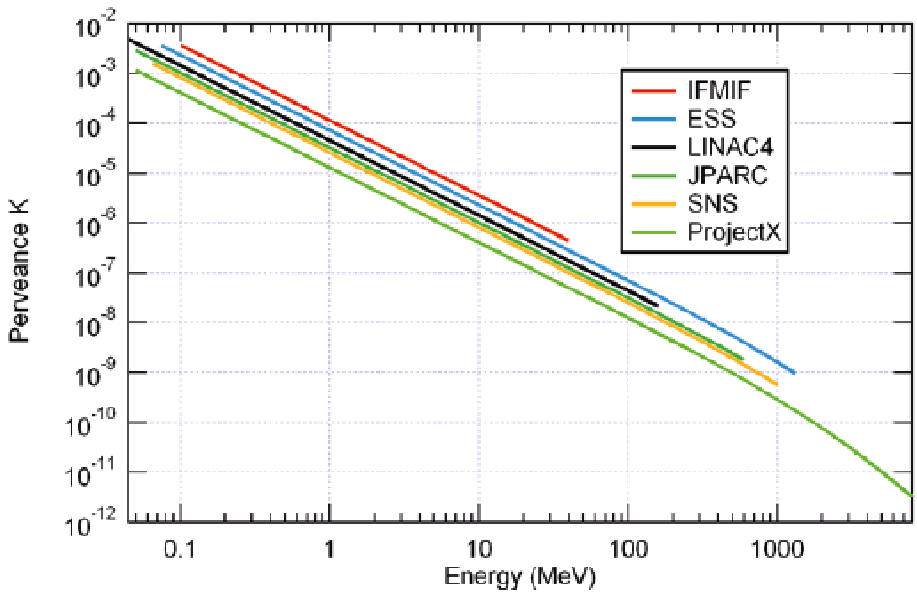
Generalized Perveance

Generalized Perveance: $K = \frac{qI}{2\pi\epsilon_0 m_0 c^3 \beta^3 \gamma^3}$



With Space Charge Compensation: $K = \frac{qI(1-\gamma^2 f_e)}{2\pi\epsilon_0 m_0 c^3 \beta^3 \gamma^3}$

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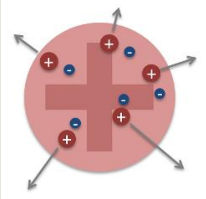


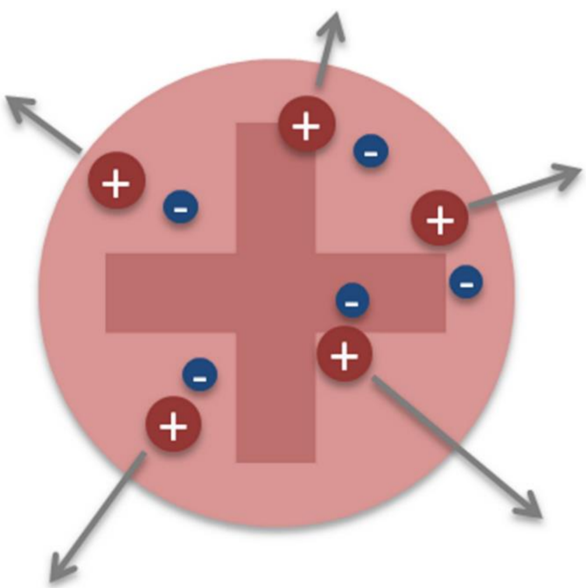
Space Charge Compensation (Neutralization)

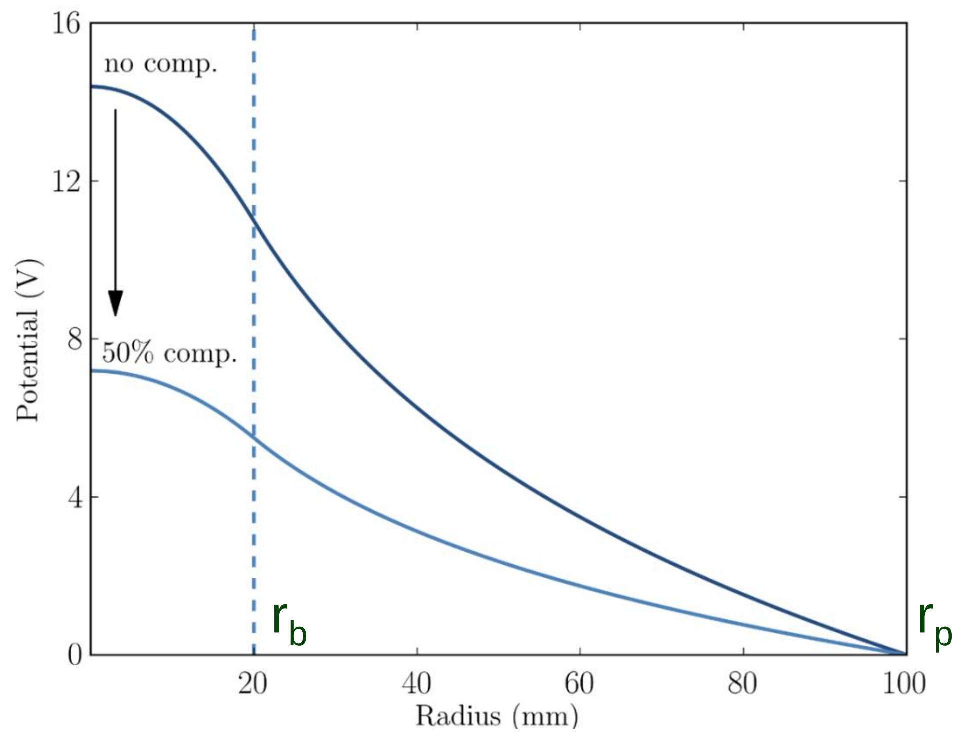
- Beam interacts with residual gas

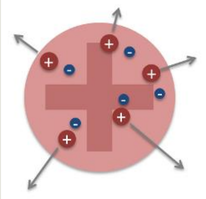
$$A^{q+} + X^0 \rightarrow A^{(q-1)+} + X^+ \qquad \text{(charge-exchange)}$$
$$A^{q+} + X^0 \rightarrow A^{q+} + X^+ + e^- \qquad \text{(ionization)}$$

$$\Delta\phi = \frac{I \cdot (1 - f_e)}{4\pi\epsilon_0 v_b}$$

Beam Cross-Section







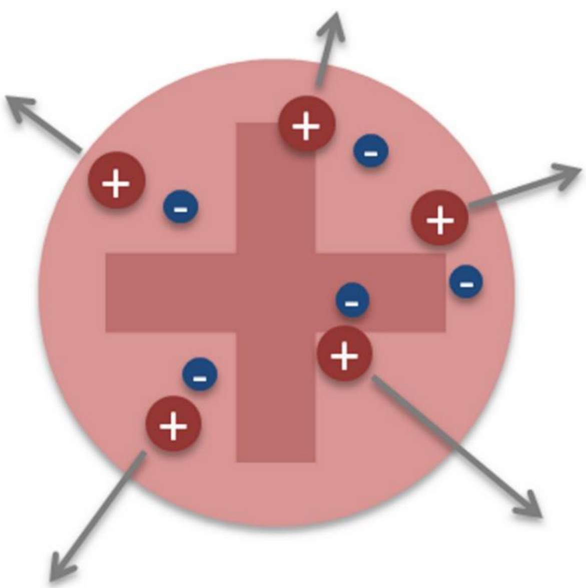
Space Charge Compensation (Neutralization)

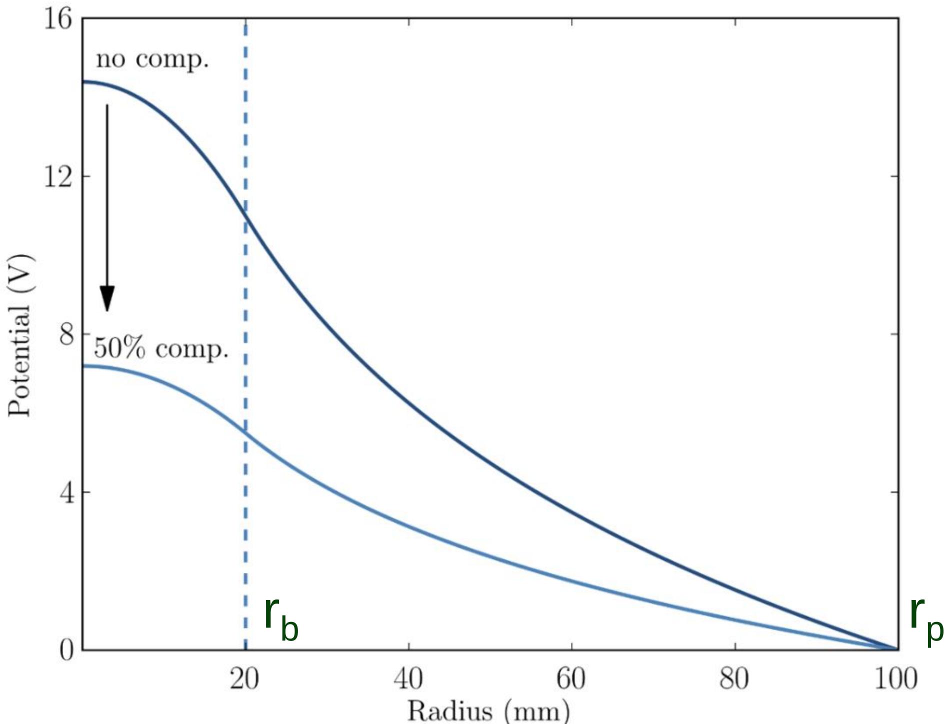
- Beam interacts with residual gas

$$\sigma_e = \sigma_{ionization}$$
$$\sigma_i = \sigma_{charge-exchange} + \sigma_{ionization}$$

$$\Delta\phi = \frac{I \cdot (1 - f_e)}{4\pi\epsilon_0 v_b}$$

Beam Cross-Section





Time to Compensation

- In absence of factors that reduce space charge compensation:

$$\tau_{\text{scc}} = \frac{1}{\sigma_{\text{ioniz}} n_{\text{g}} \beta_{\text{B}} c},$$

- However, collisions of the beam with the secondary electrons change the dynamics and this time increases a little.
- Also, no ‘full’ compensation can be reached in most cases.

Inclusion into Simulations

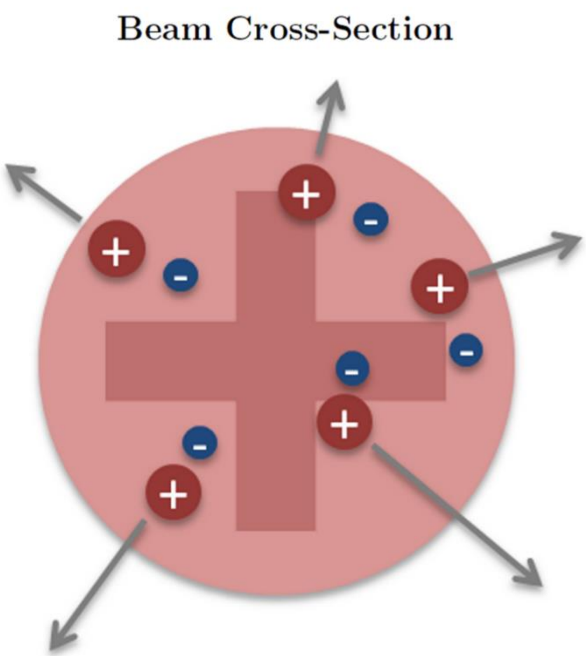
- Space Charge is included in PIC codes.
- What about Space Charge Compensation?
- 2 Methods: Self-consistently or semi-analytically.
- Self-Consistently: PIC codes include secondary ions and electrons and collisions/Coulomb interaction of beam ions with secondaries and neutrals.
- Semi-Analytically: Can try to find an expression for f_e for simplified beam.
- Let's start with the latter and then look at examples of both…

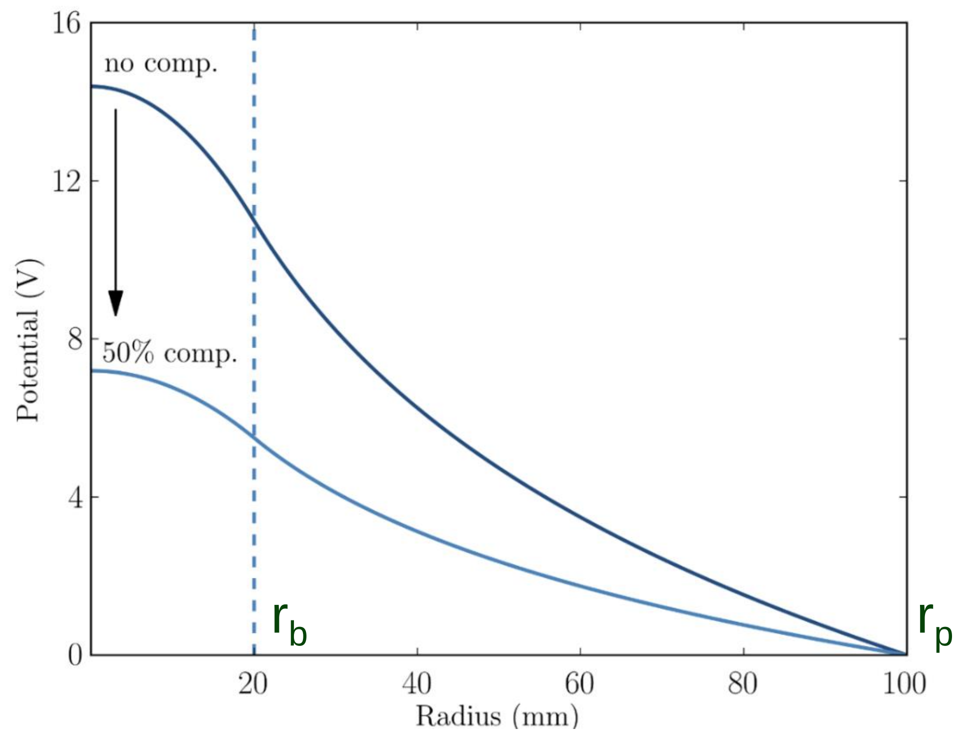
Space Charge Compensation (Neutralization)

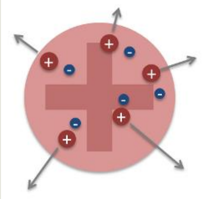
- Beam interacts with residual gas

$$\sigma_e = \sigma_{ionization}$$
$$\sigma_i = \sigma_{charge-exchange} + \sigma_{ionization}$$

$$\Delta\phi = \frac{I \cdot (1 - f_e)}{4\pi\epsilon_0 v_b}$$







Space Charge (De)Compensation - A Simple Theoretical Model

- 1975: Gabovich model for f_e, uses:
  - Secondary electron energy balance:

Steady state: energy transferred to electrons through Coulomb collisions = energy necessary to leave beam envelope

$$(\Delta\varphi_{neut})^2 = 3\mathcal{L} \cdot \frac{m_b}{m_e} \cdot \frac{\Phi_i}{U_0} \frac{n_b q e^2}{(4\pi\epsilon_0)^2} \left(\frac{q}{n_0 \sigma_e} + \frac{v_b \sigma_i r_b}{2\bar{v}_i \sigma_e} \right)$$

$$f_e = 1 - \frac{\Delta\varphi_{neut}}{\Delta\varphi_{full}}$$

$$\Delta\varphi_{full} = \frac{I}{4\pi\epsilon_0 v_b} \qquad \mathcal{L} = 4\pi \ln \left(4\pi\epsilon_0^{3/2} \frac{m_e^{3/2} v_b^3}{q e^3 n_e^{1/2}} \right)$$

M. Gabovich, L. Katsubo, and I. Soloshenko, "*Selfdecompensation of a stable quasineutral ion beam due to coulomb collisions*", **Fiz. Plazmy, vol. 1**, pp. 304-309, 1975.

Discussion

- Major contributions to cross sections:

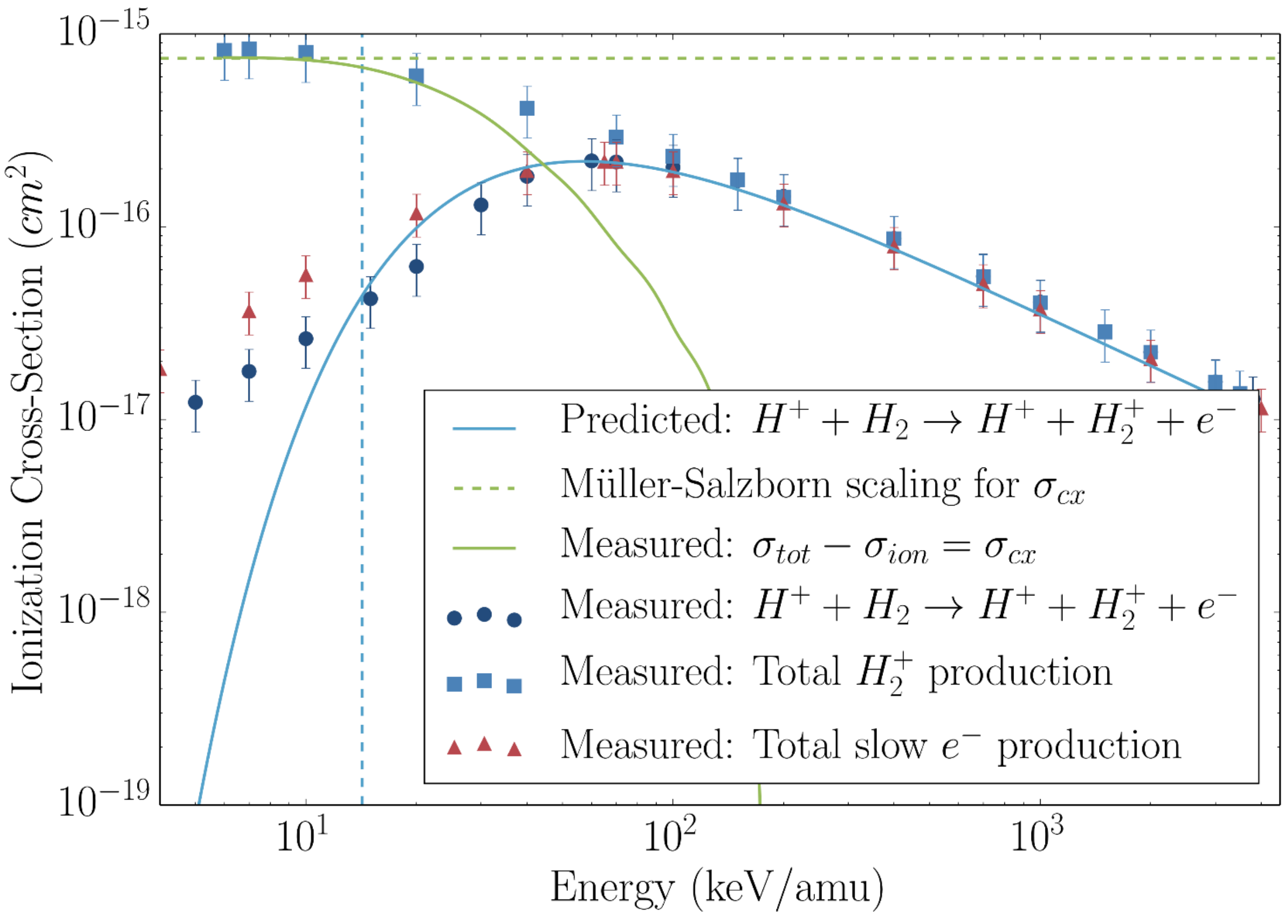
$$\begin{aligned}\sigma_e &= \sigma_{ionization} \\ \sigma_i &= \sigma_{charge-exchange} + \sigma_{ionization}\end{aligned}$$

- Large uncertainties in available cross-section data!
- Other simplifications:
  - Round, uniform beam
  - Secondary ions: simple balance of produced ions = leaving ions
  - Quasineutrality of the beam plasma $n_e = q \cdot n_b + n_i$

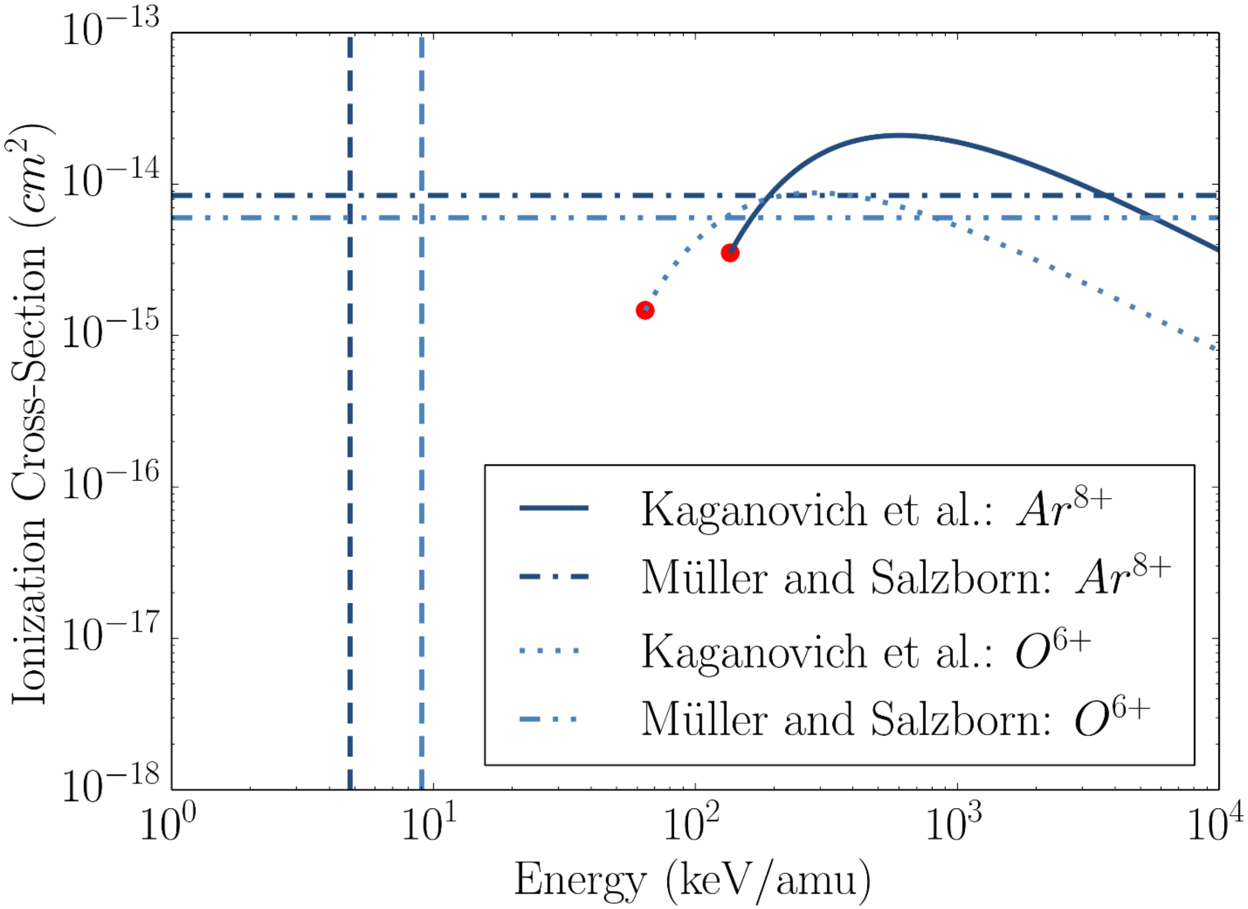
$$(\Delta\varphi_{neut})^2 = 3\mathcal{L} \cdot \frac{m_b}{m_e} \cdot \frac{\Phi_i}{U_0} \frac{n_b q e^2}{(4\pi\epsilon_0)^2} \left(\frac{q}{n_0 \sigma_e} + \frac{v_b \sigma_i r_b}{2\bar{v}_i \sigma_e} \right)$$

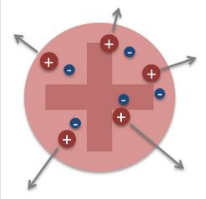
$$f_e = 1 - \frac{\Delta\varphi_{neut}}{\Delta\varphi_{full}}$$

Cross-Sections?



Cross-Sections?





How can this model be applied to ECRIS?

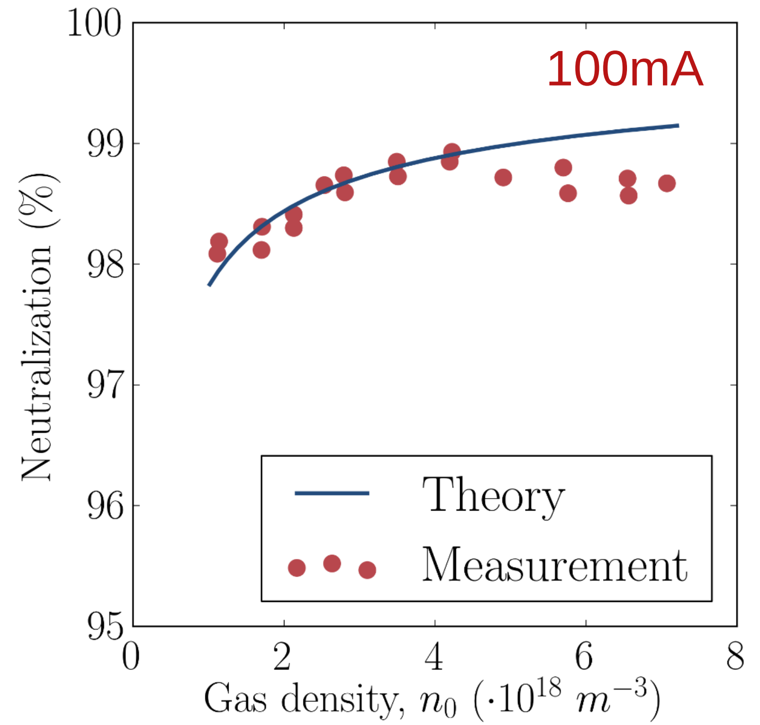
- Pressure in ECR transport line are as low as possible to reduce charge exchange (therefore low production of electrons)
- ECR beams are probably far from neutralized

$$n_e = q \cdot n_b + n_i \longrightarrow n_e = f_e \cdot (q \cdot n_b + n_i)$$

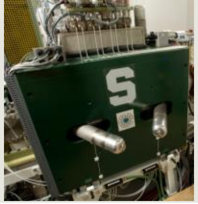
$$f_e = 1 - \sqrt{f_e} \cdot \frac{\Delta\varphi_{neut,Gabovich}}{\Delta\varphi_{full}}$$

$$\chi = \frac{\Delta\varphi_{neut,Gabovich}}{\Delta\varphi_{full}}$$

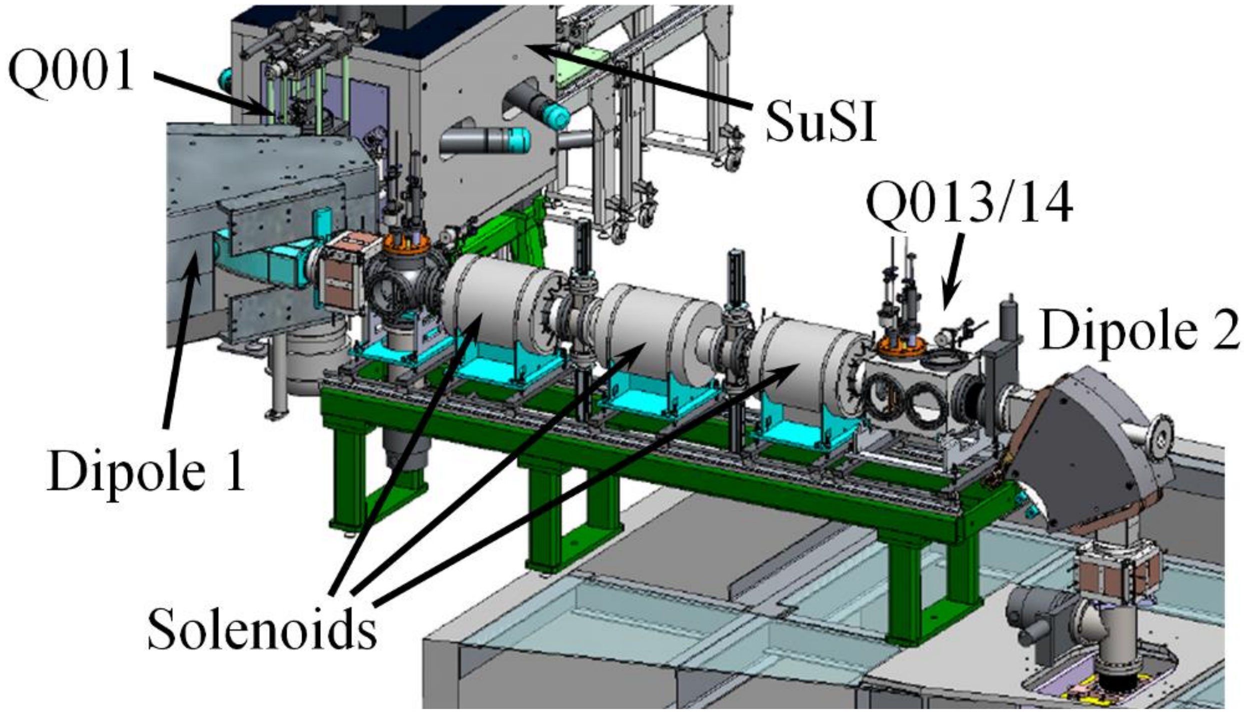
$$f_e = 1 + \frac{\chi^2}{2} - \frac{\chi}{2}\sqrt{\chi^2 + 4}$$



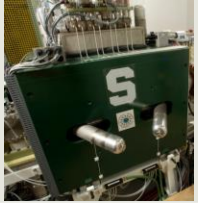
R. Ferdinand et al., Proceedings of the 1997 PAC, vol. 3, pp. 2723-2725, IEEE, 1997.



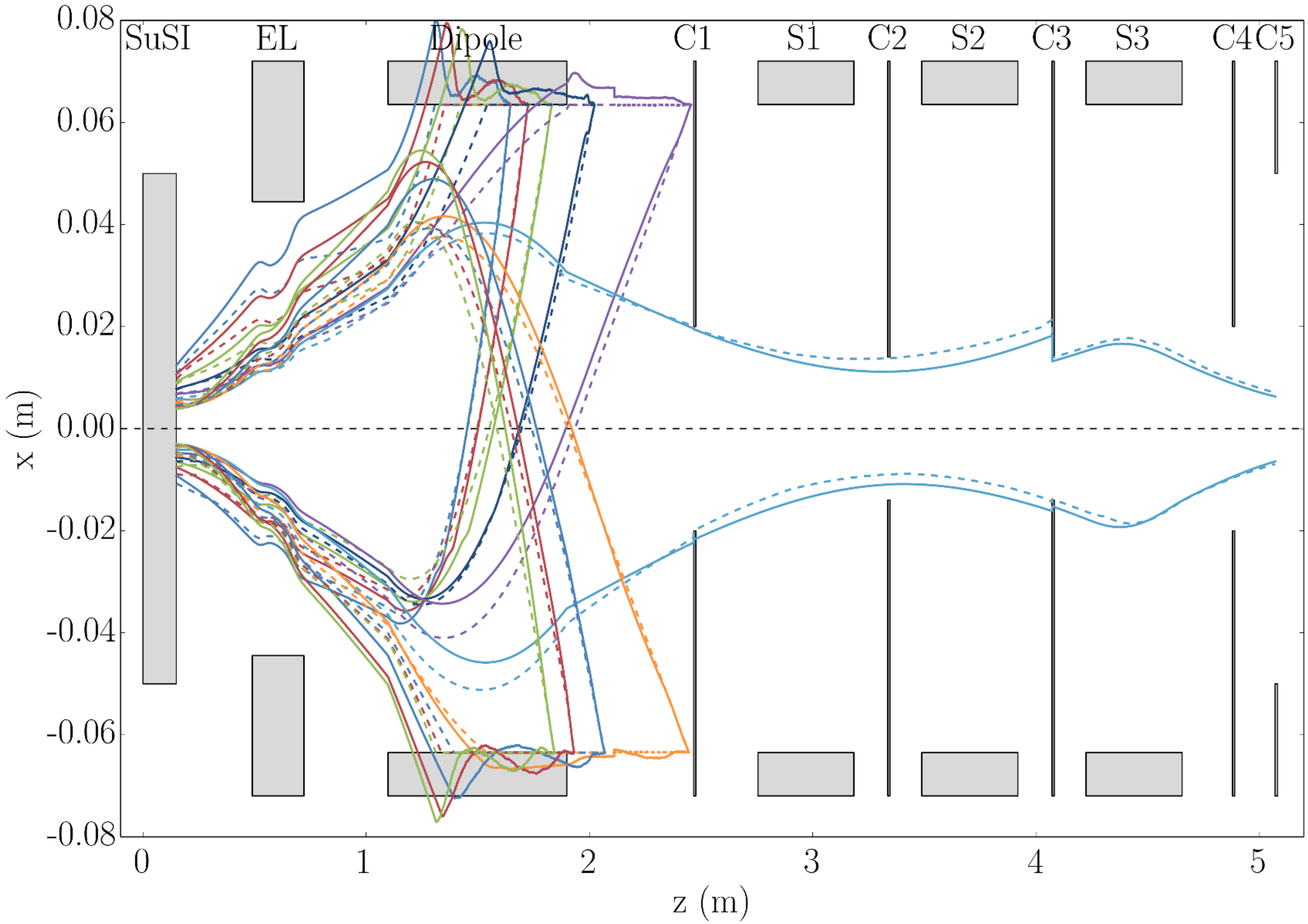
Neutralization model was included into WARP Simulation of SuSI Beam Line



- User sets initial parameters:
  - cross-sections for ion and electron production
  - gas pressure
- At each step:
  - get 2σ beam radius
  - get beam current
- Calculate multispecies neutralization assuming same radius for each species
- Use new neutralization in next step of calculation

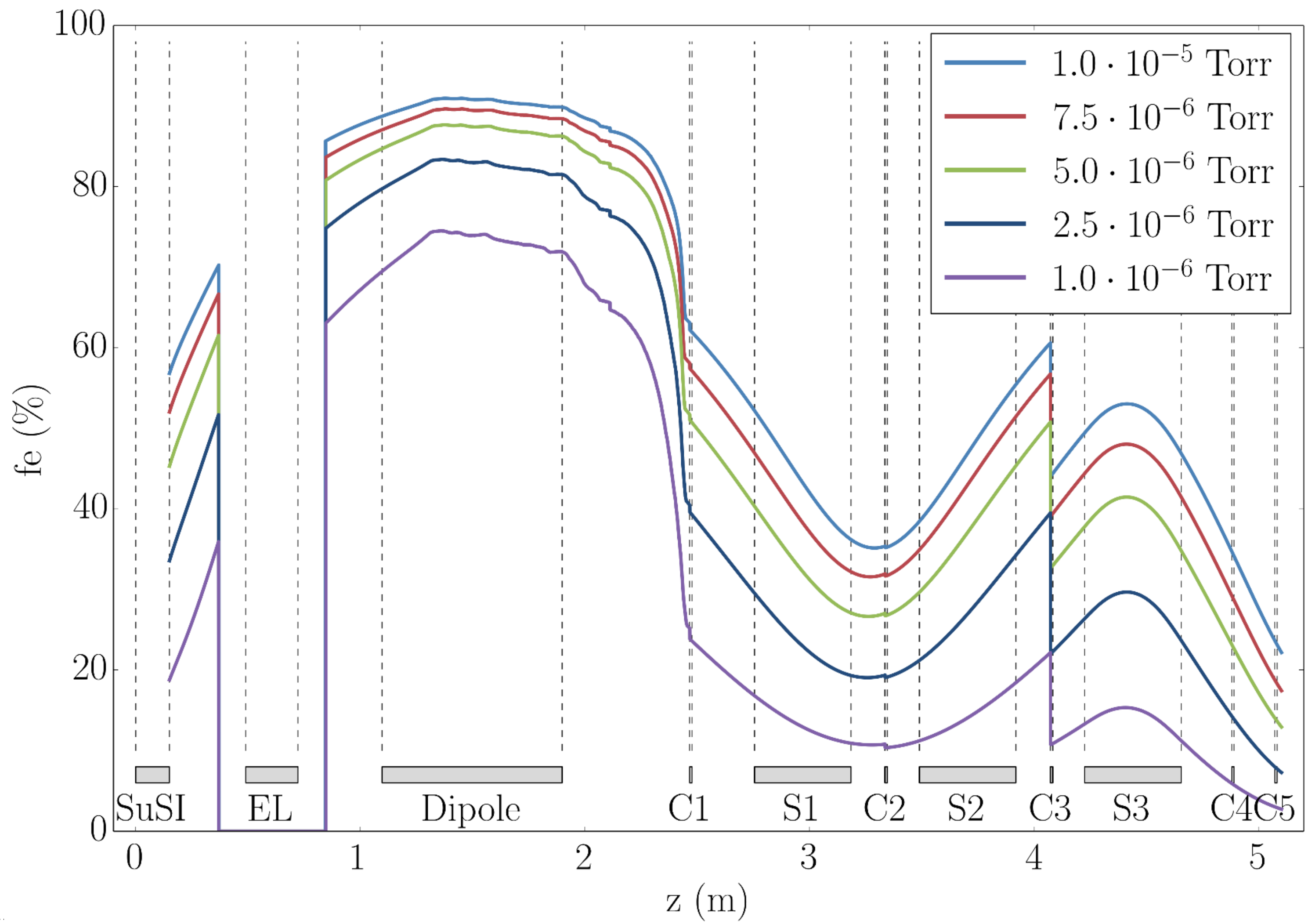


SuSI Beam Line, Ar^{8+}, 1.0e-6 Torr

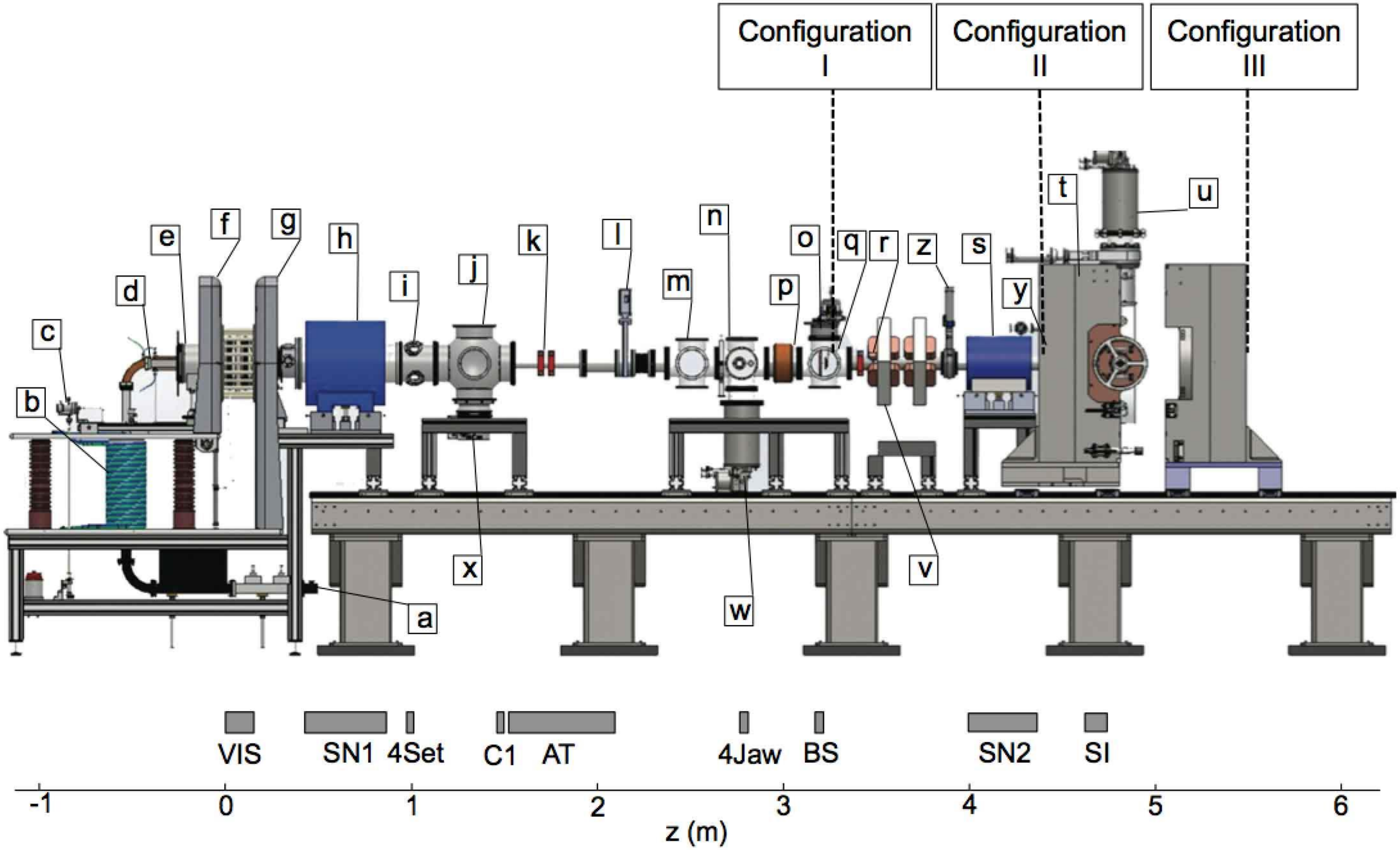


O1
O3

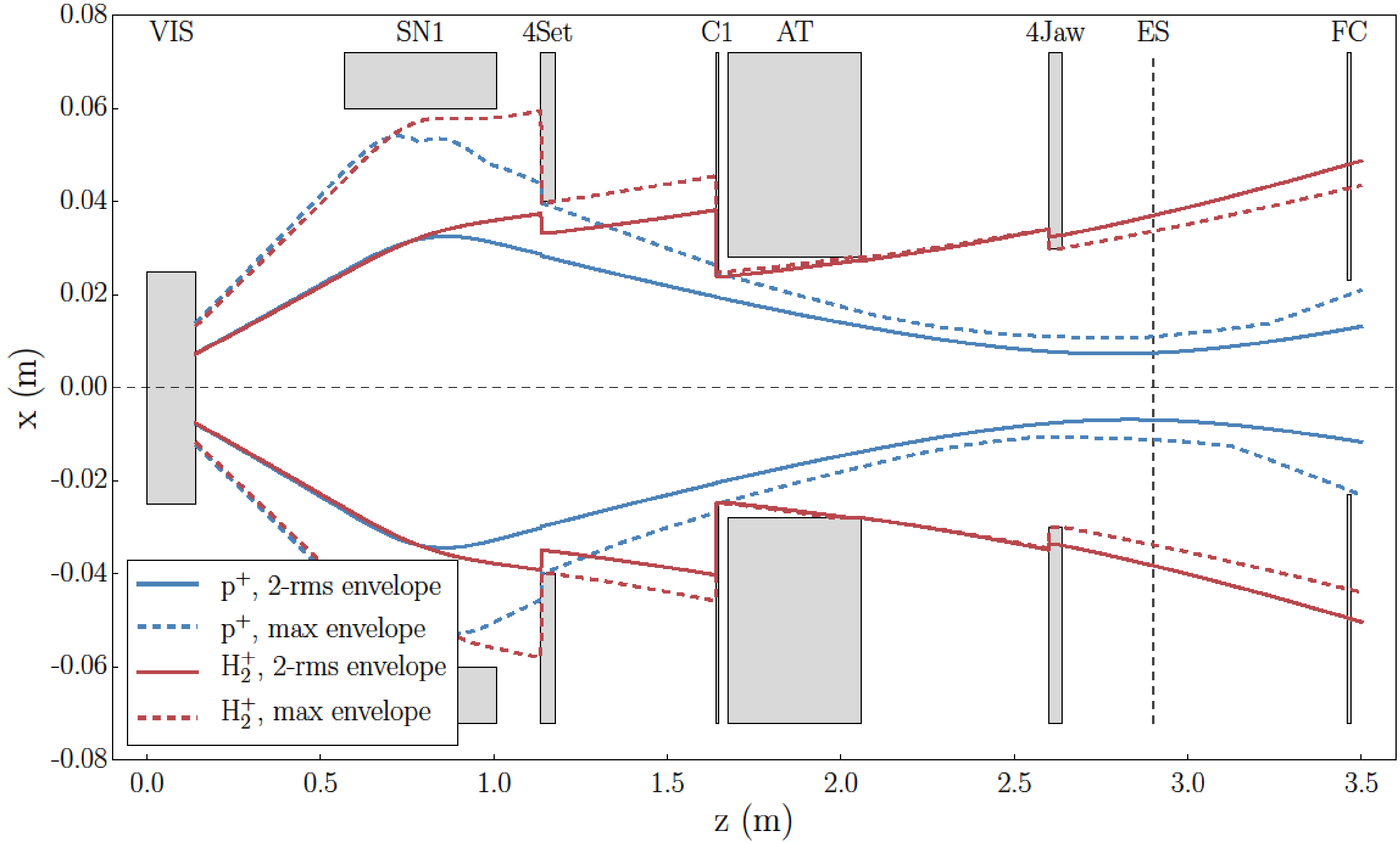
Space Charge Compensation



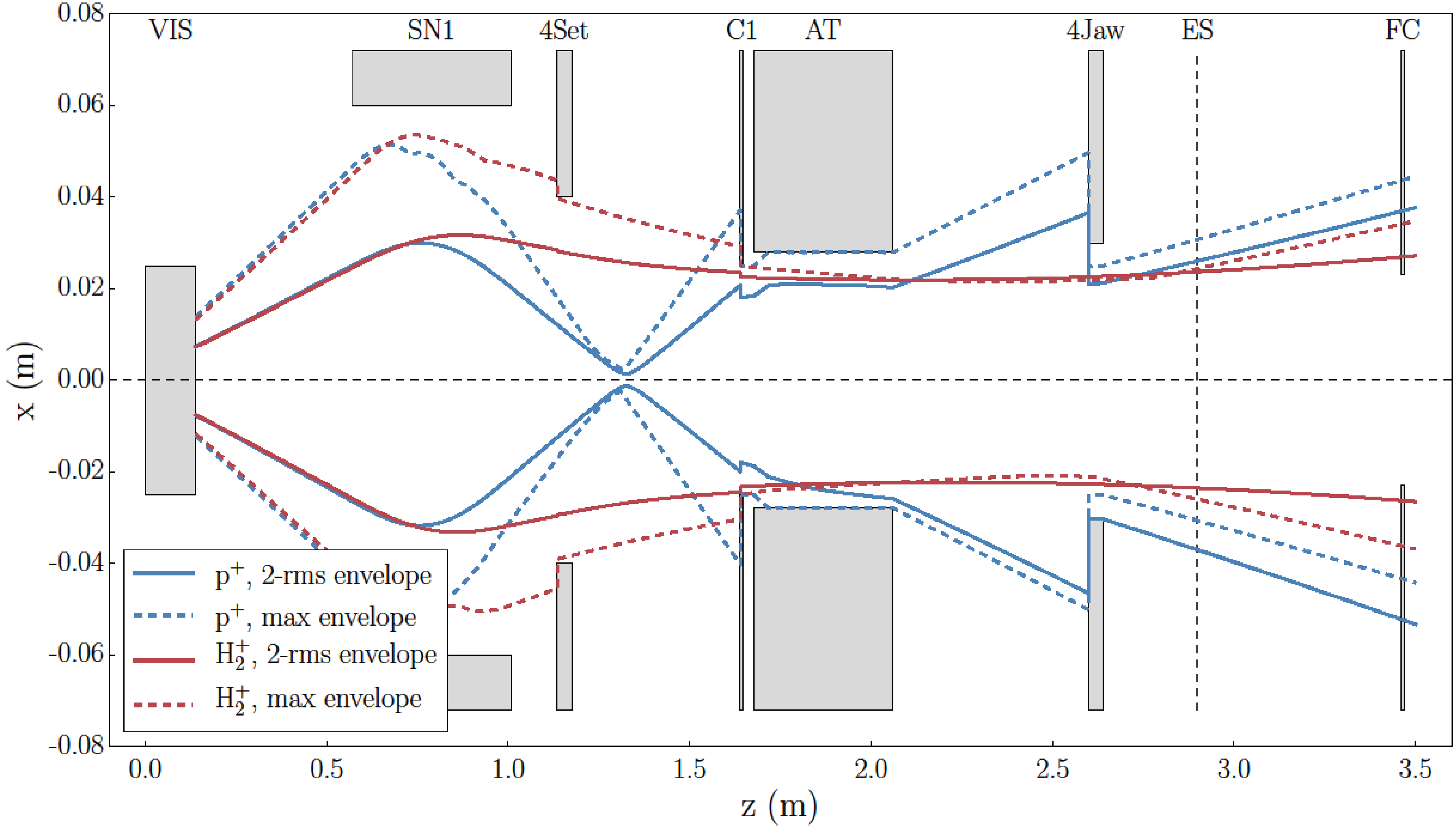
IsoDAR LEBT Measurements/Simulations



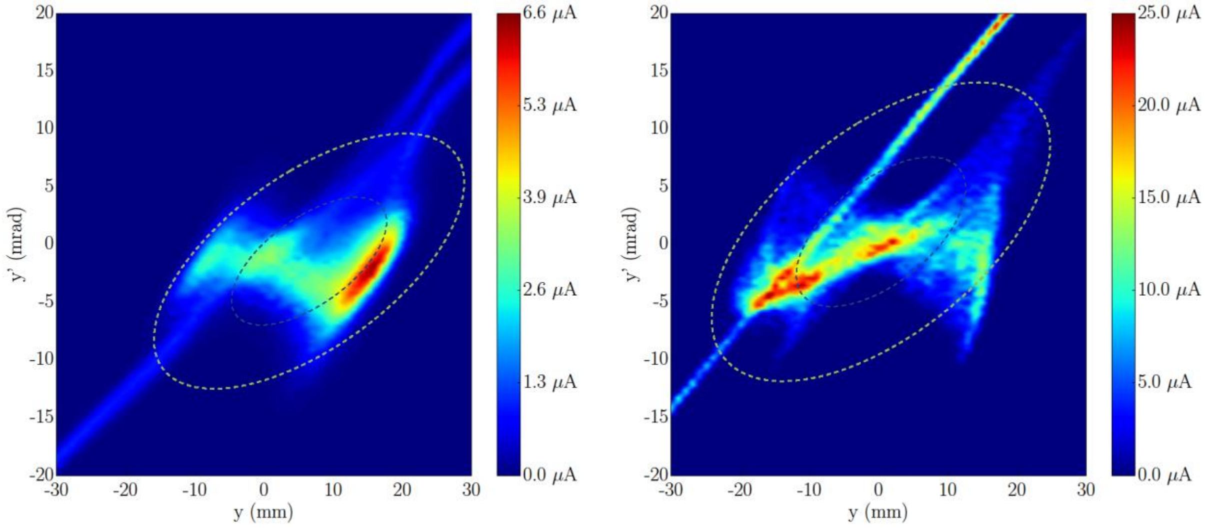
Beam Envelopes I

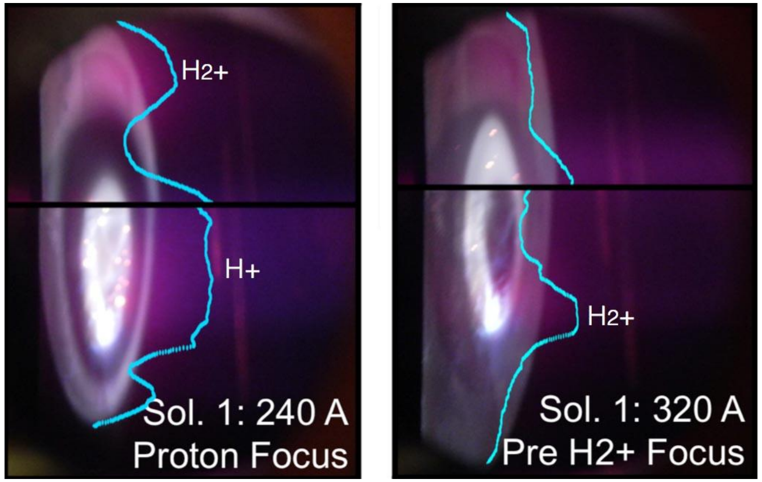


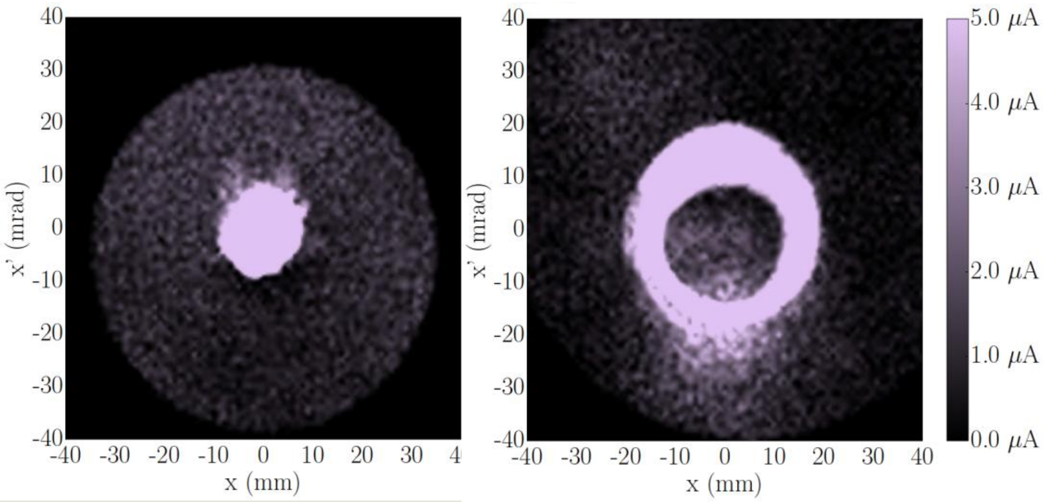
Beam Envelopes II



IsoDAR LEBT Measurements/Simulations

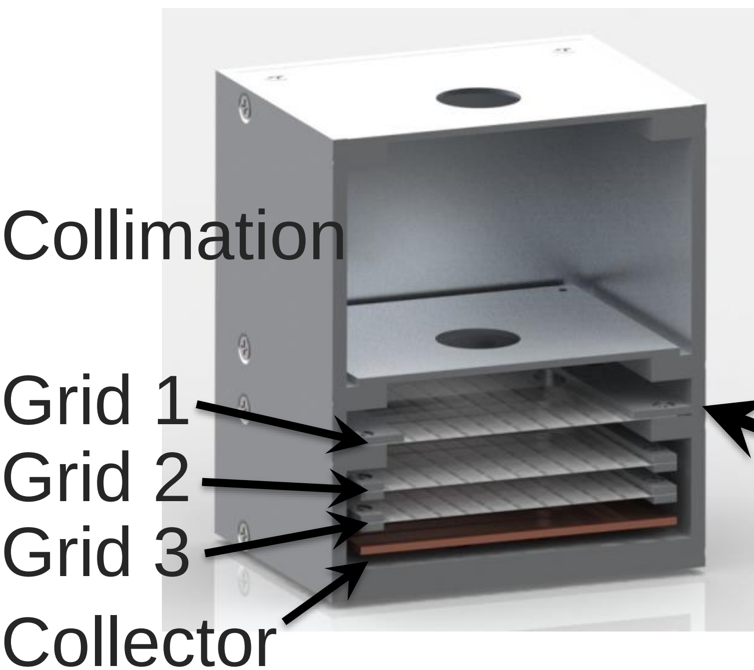


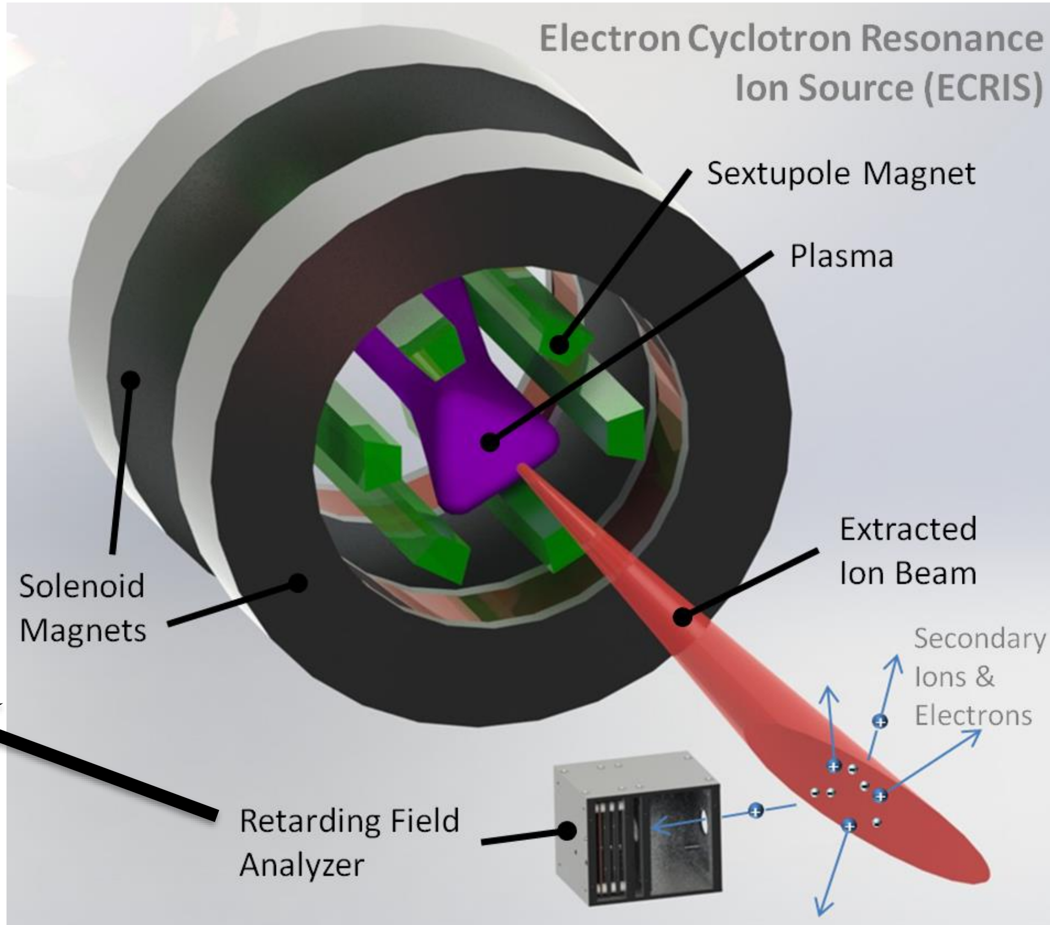




Measuring Space Charge Compensation with a Retarding Field Analyzer

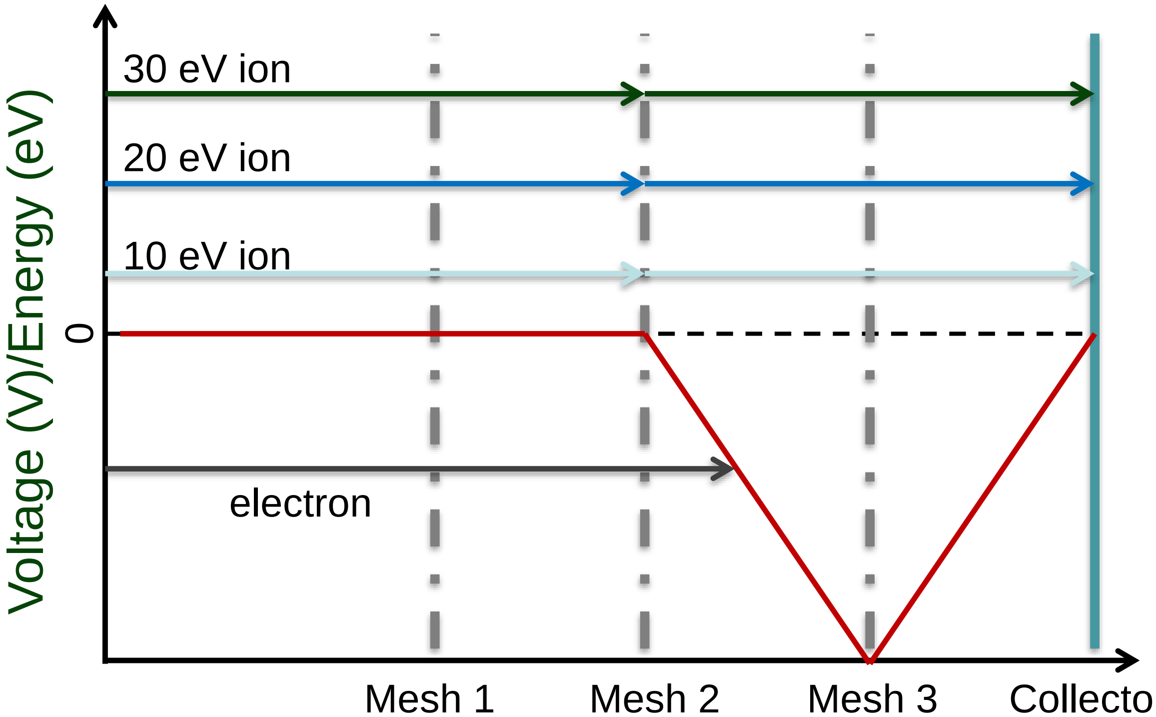
- Measure secondary ion energy distribution → compensated beam potential
- Compare to full (uncomp.) beam potential → f_e

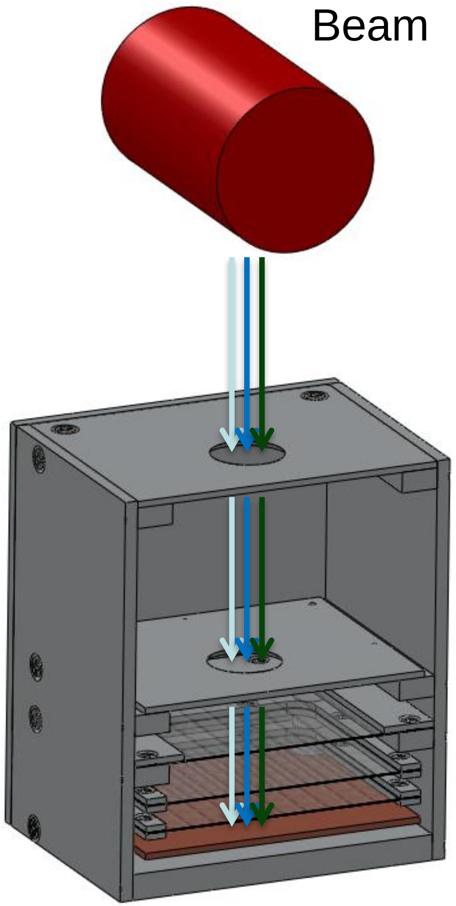




Retarding Field Analyzer (RFA)

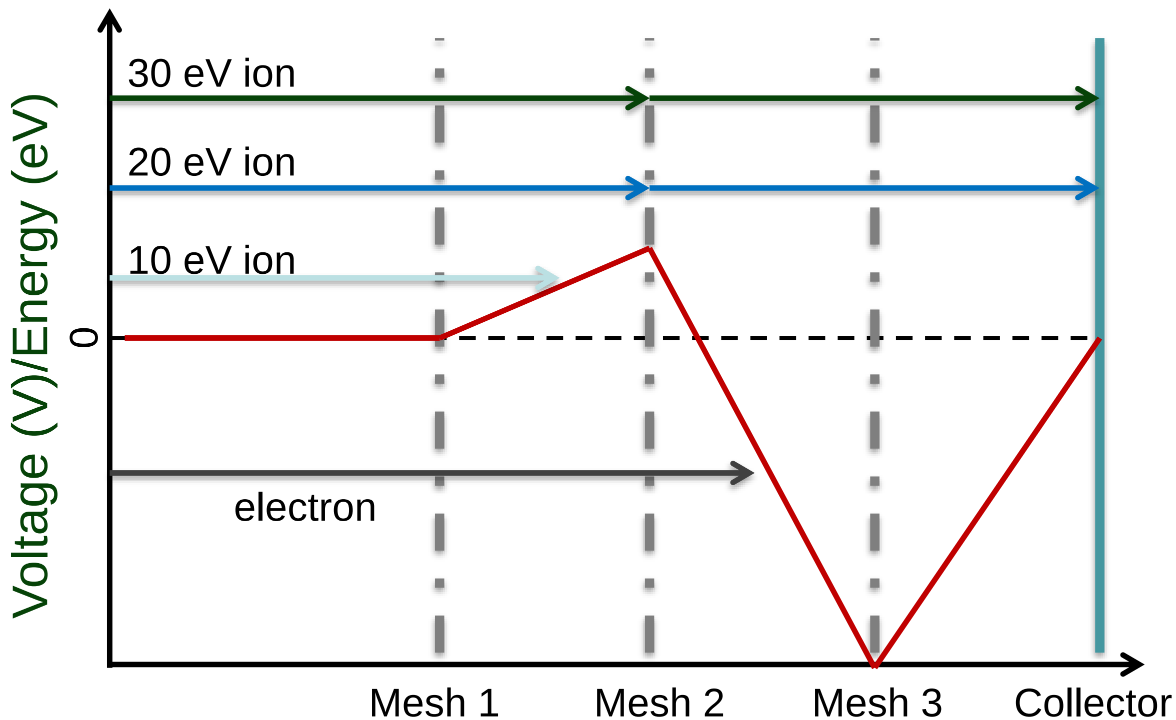
- Mesh 1 voltage = 0 V
- Mesh 2 voltage = 0 V
- Mesh 3 voltage = - 150 V

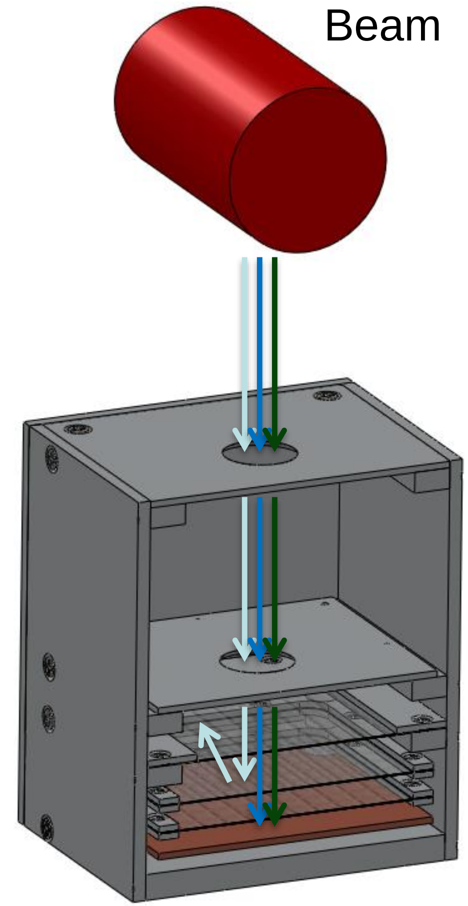




Retarding Field Analyzer (RFA)

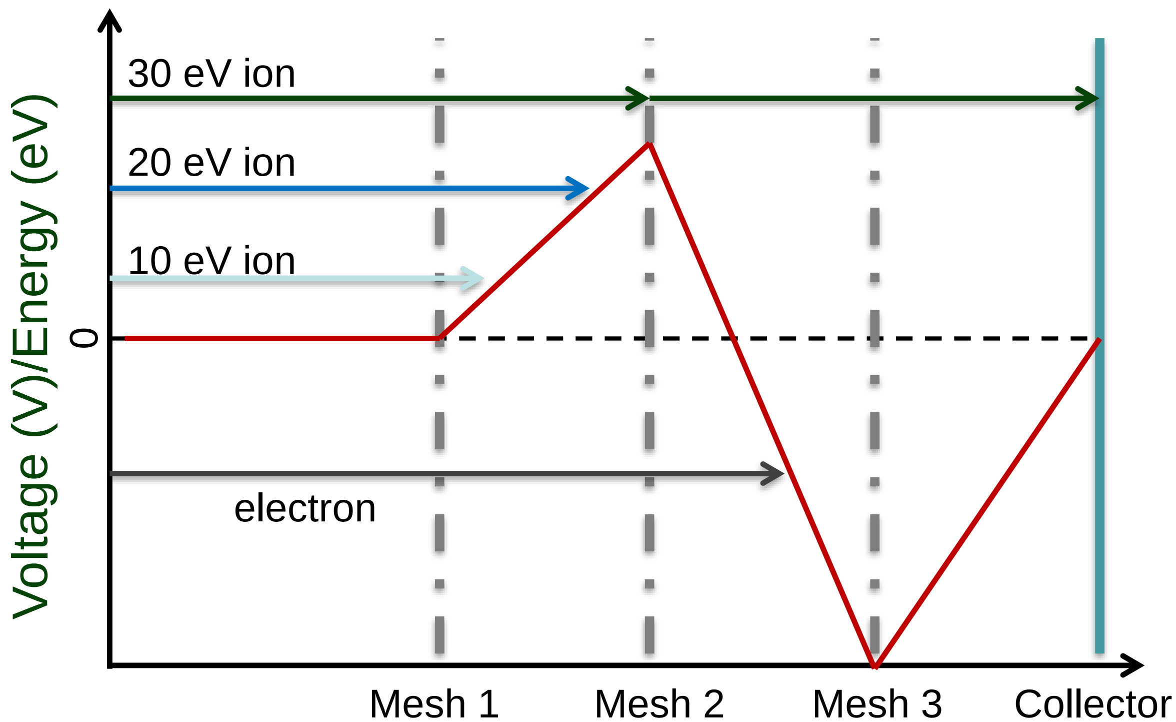
- Mesh 1 voltage = 0 V
- Mesh 2 voltage = 15 V
- Mesh 3 voltage = - 150 V

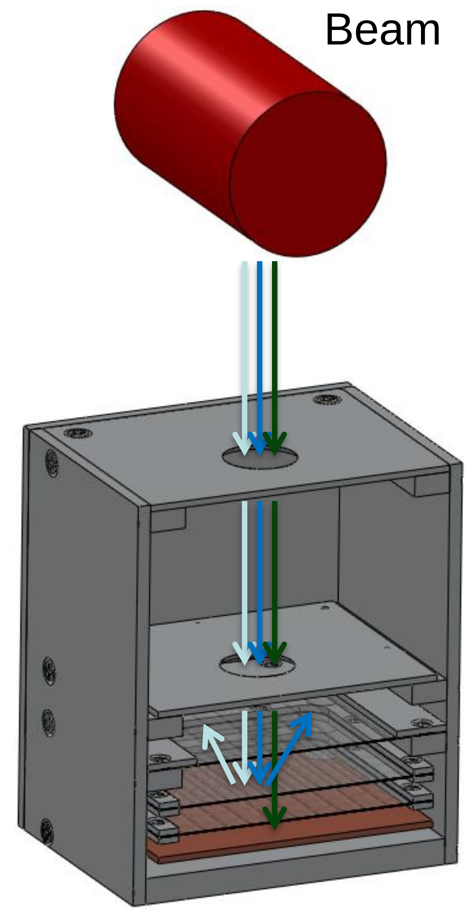




Retarding Field Analyzer (RFA)

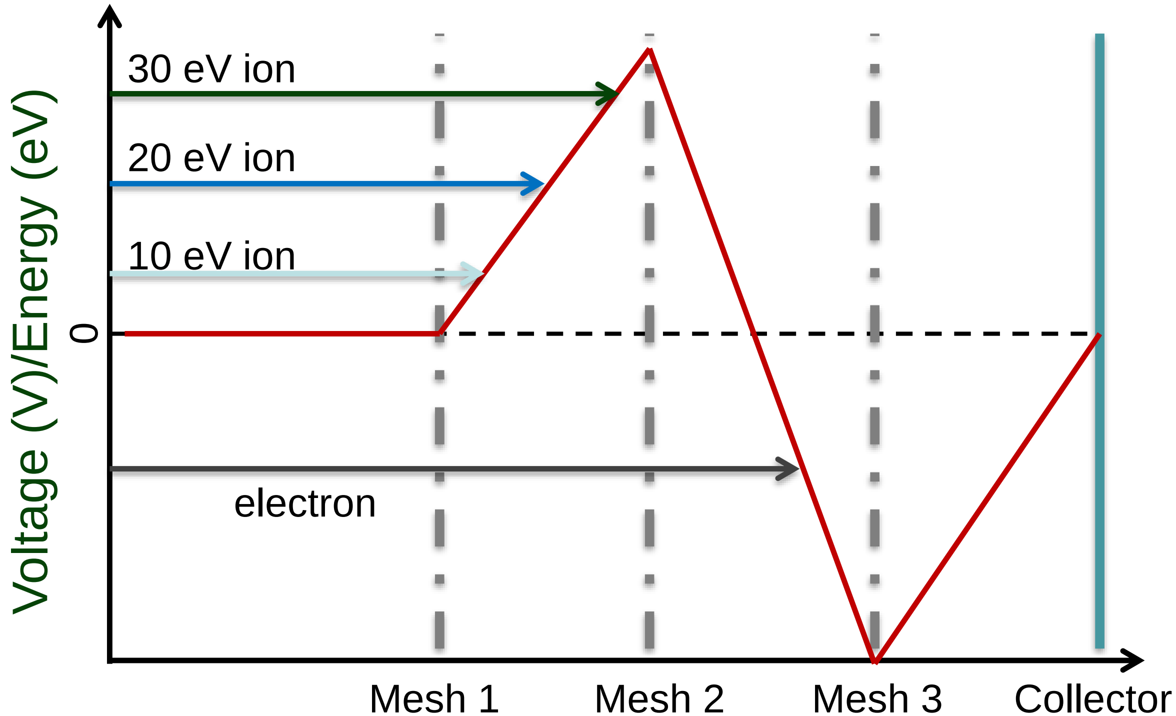
- Mesh 1 voltage = 0 V
- Mesh 2 voltage = 25 V
- Mesh 3 voltage = - 150 V

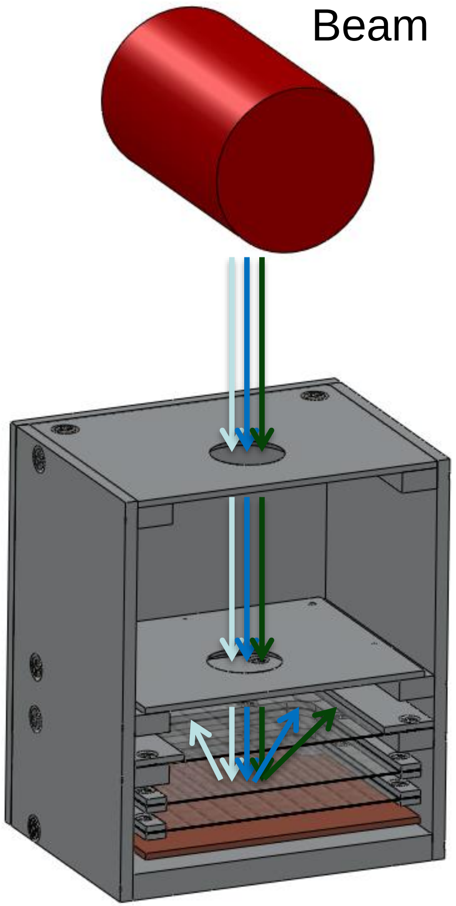




Retarding Field Analyzer (RFA)

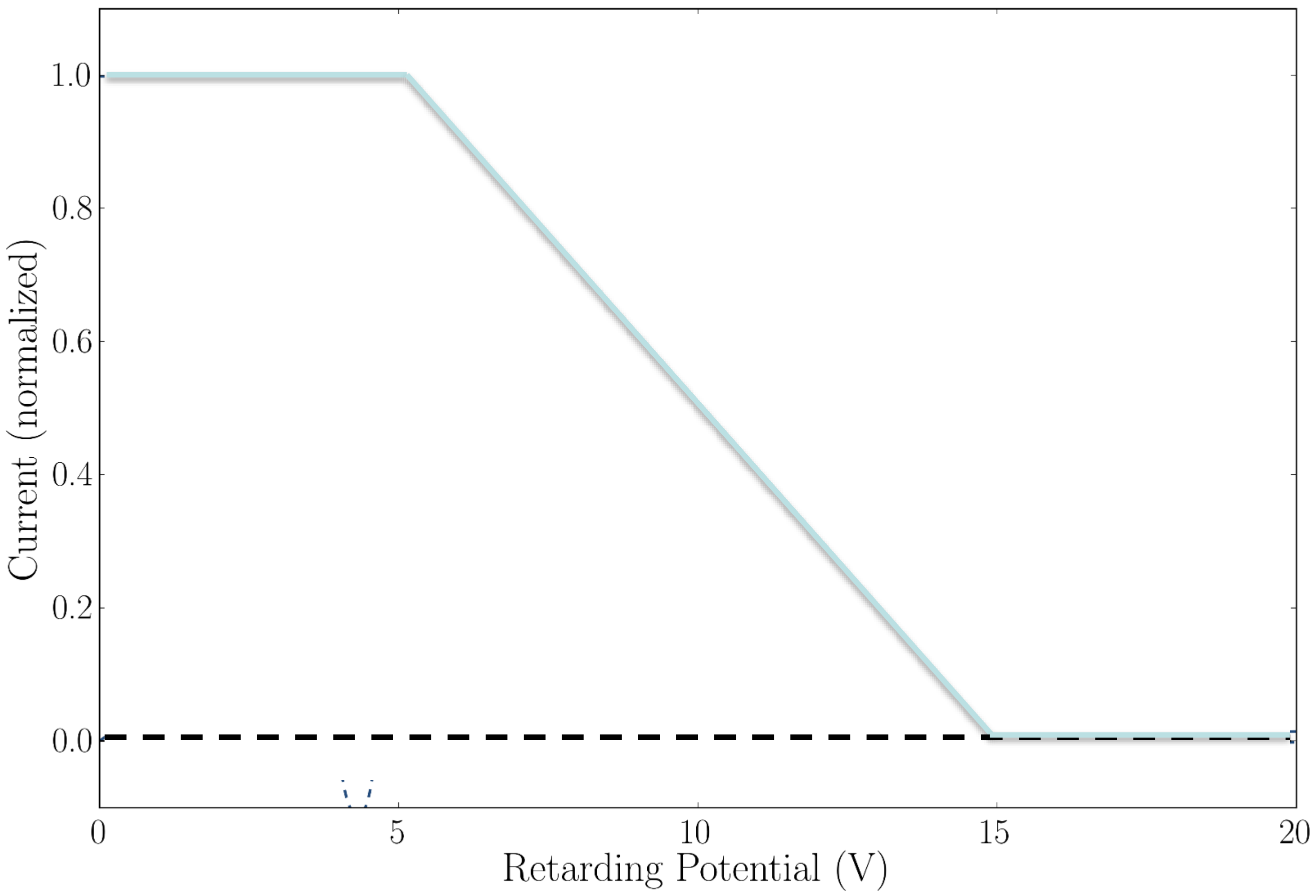
- Mesh 1 voltage = 0 V
- Mesh 2 voltage = 35 V
- Mesh 3 voltage = - 150 V





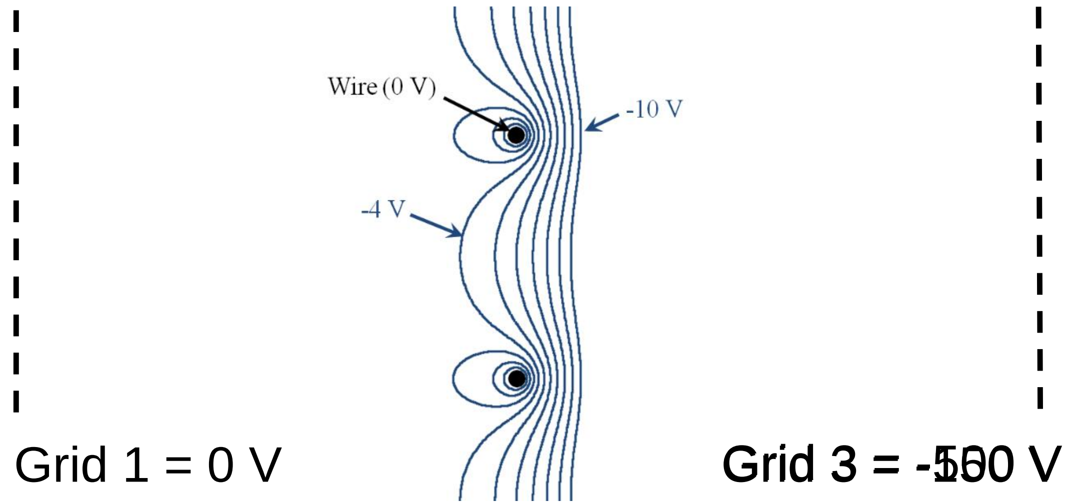
RFA Spectrum

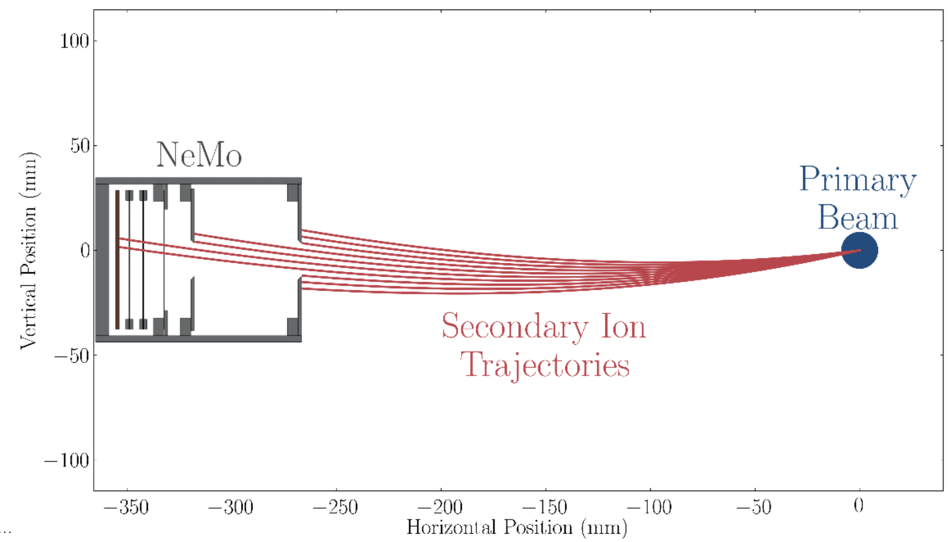
- “Perfect” spectrum
- Typical spectrum in LEDA injector source
- In Theory:
  -dI/dV corresponds to secondary ion energy distribution f(E) → Δφ
- Reality:
  Obtain Δφ by fitting detector signal to theoretical f(E) folded with detector transmission



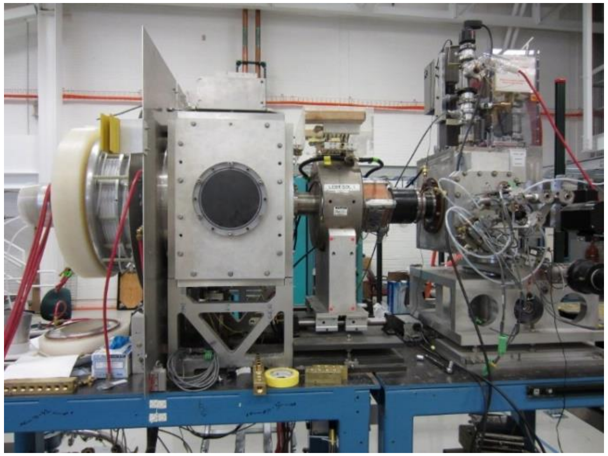
RFA @ Low Energies/Low Currents

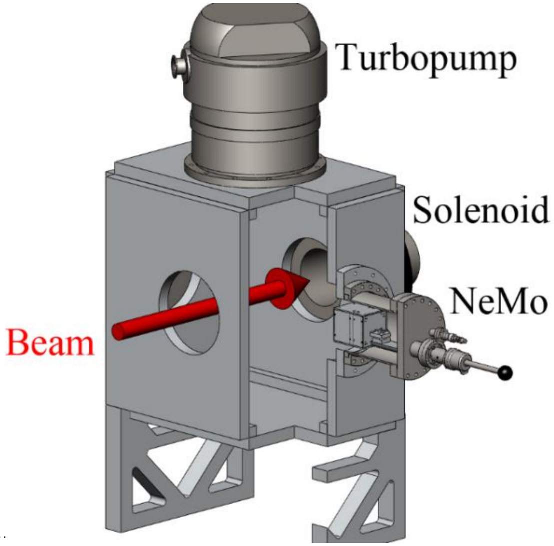
- Mesh Effect 1: Effective Potential
- Mesh Effect 2: Trajectories Through Mesh
- Collimator + External Magnetic Field → Energy Dependent Transmission
- Data analysis: Calculate Detector Transmission Curves with SIMION (µm resolution)

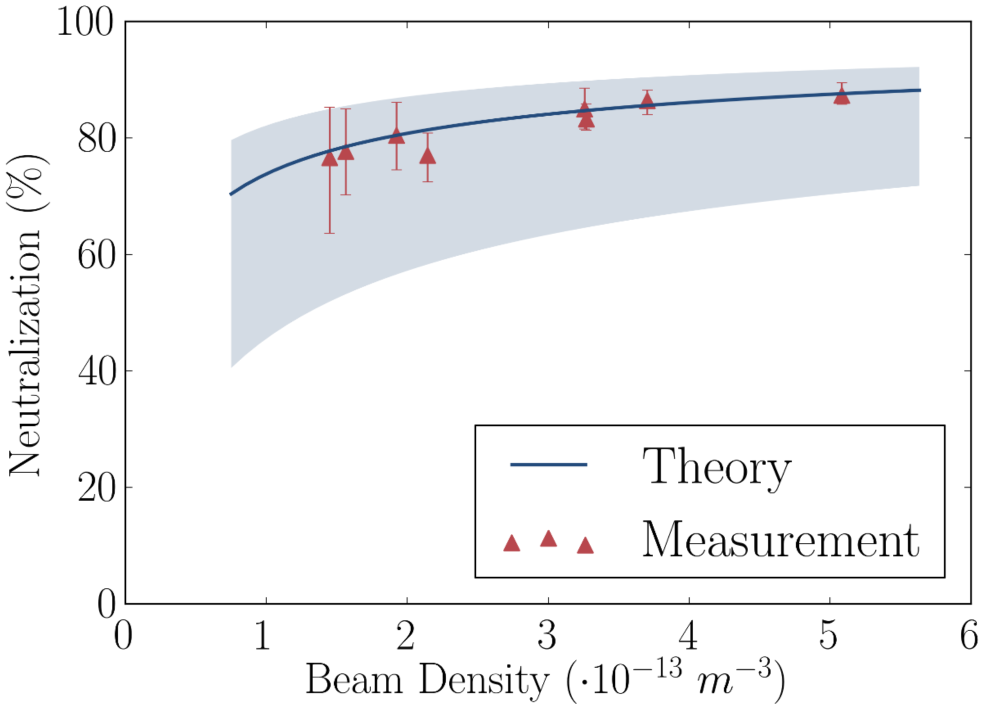




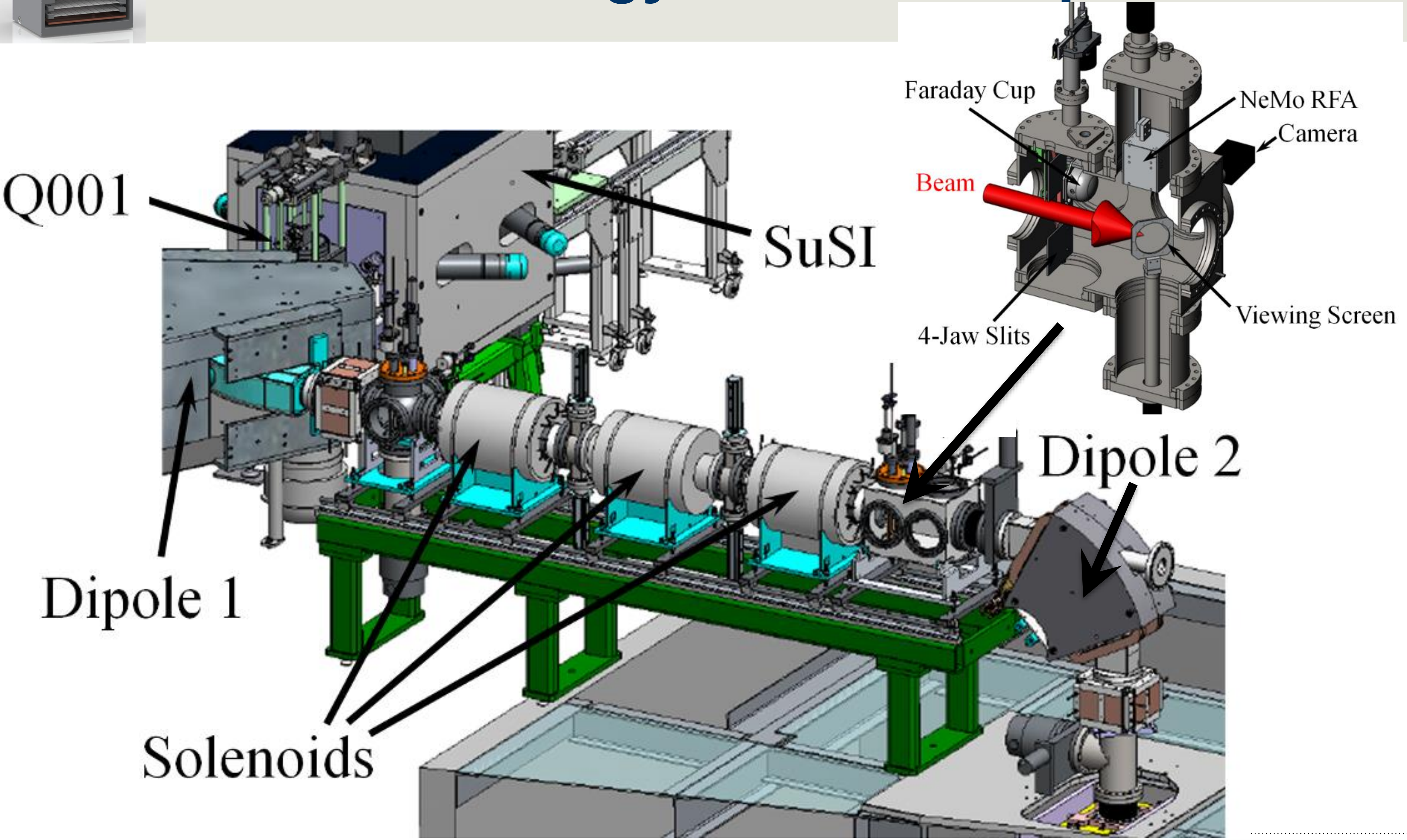
LEDA injector Source – SCC Measurements



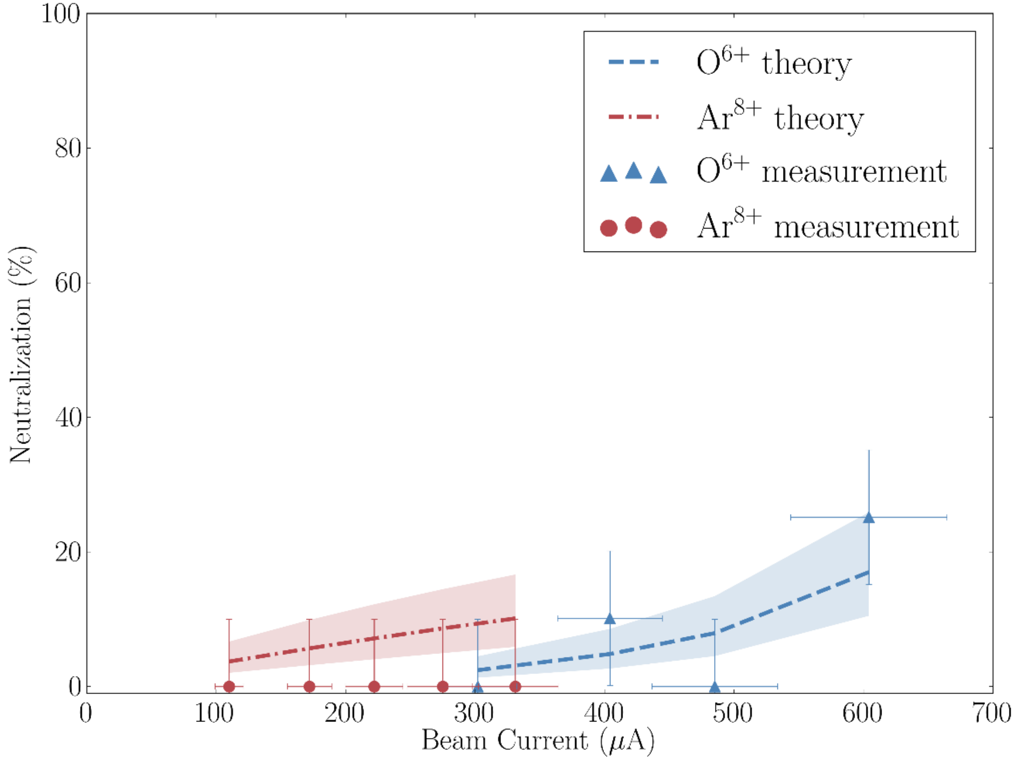




SuSI Low Energy Beam Transport Line

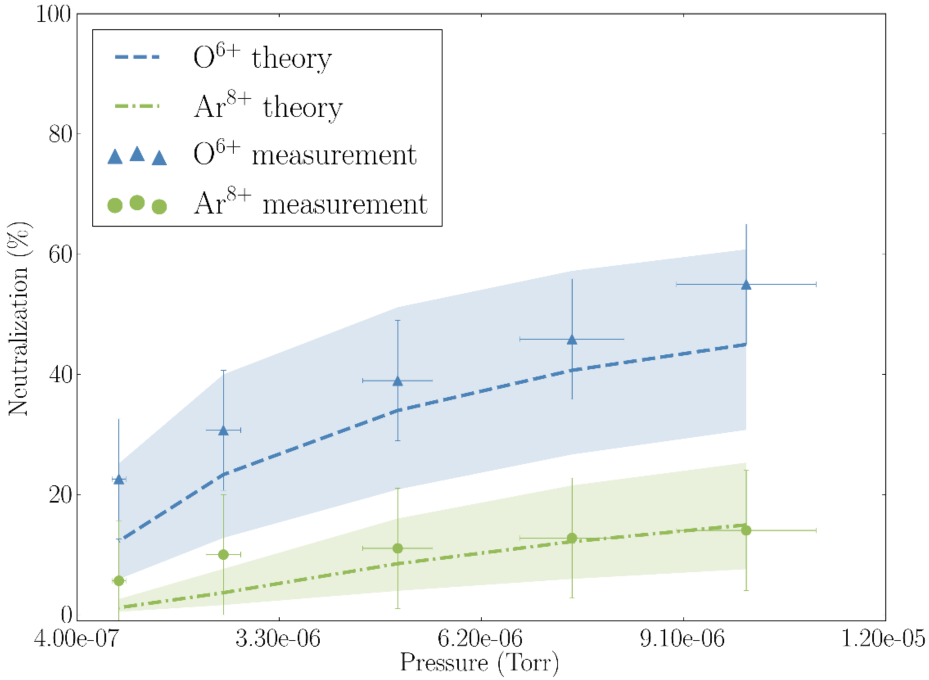


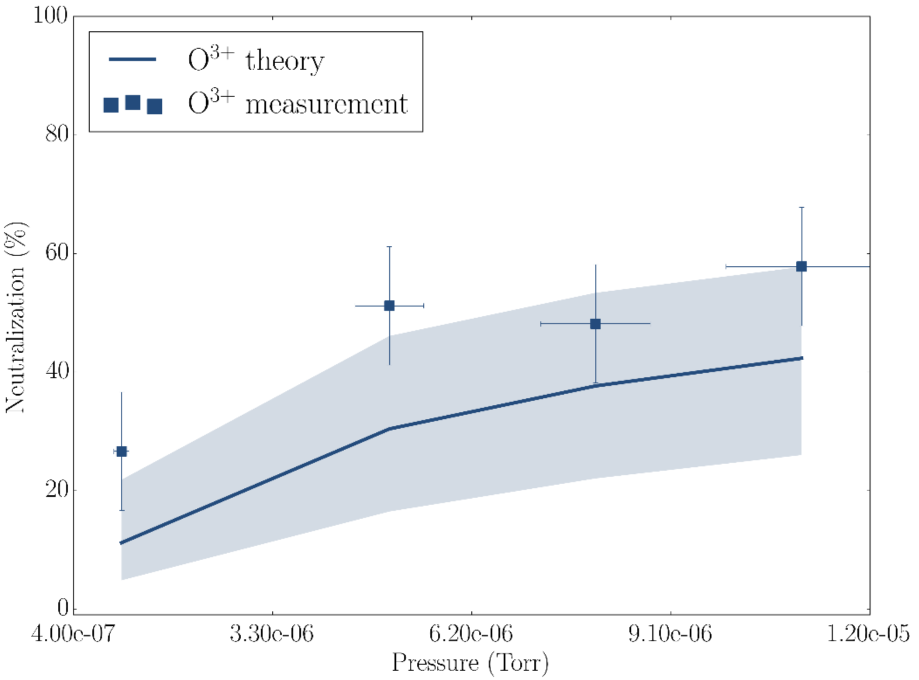
SCC – SuSI Beam Current Variation



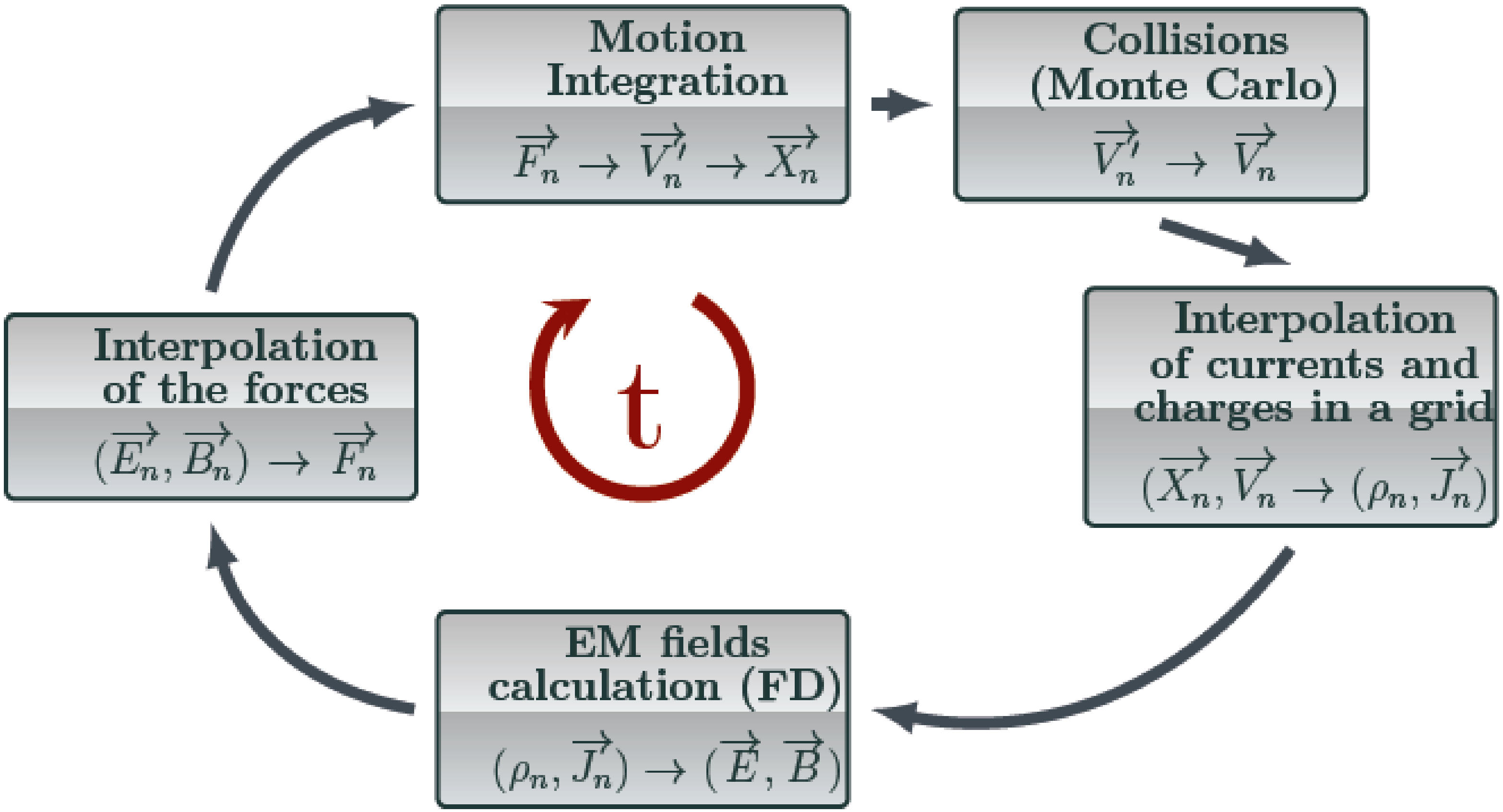
- O^{6+} and Ar^{8+}, 5.0e-6 Torr
- Neutralization very low
- Agrees well with theoretical prediction.

SCC – SuSI Beam Line Pressure Variation



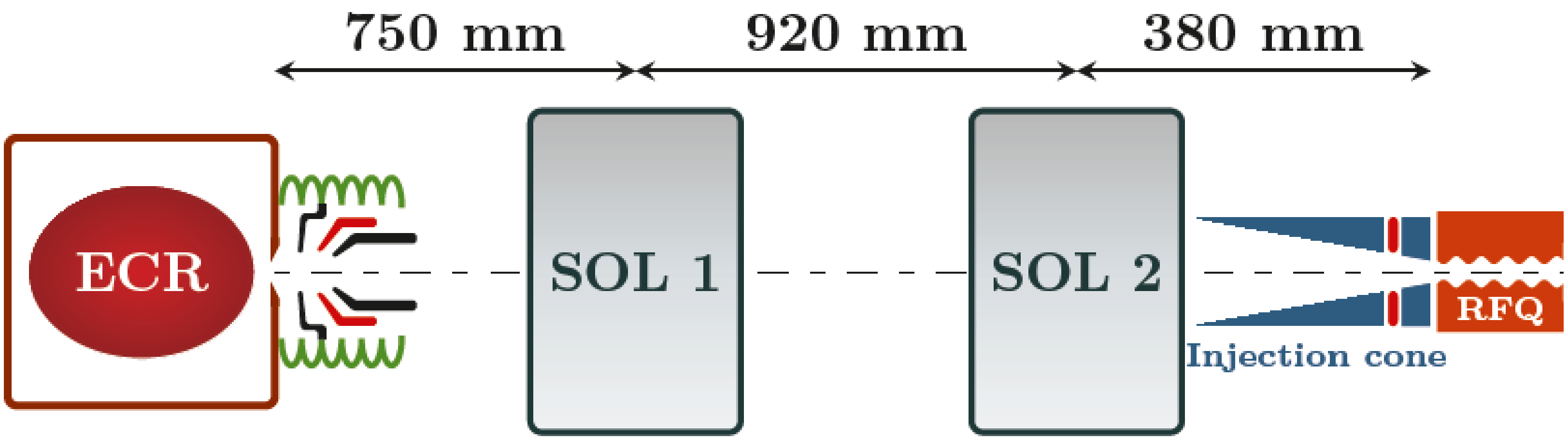


Example for PIC Code: SolMaxP

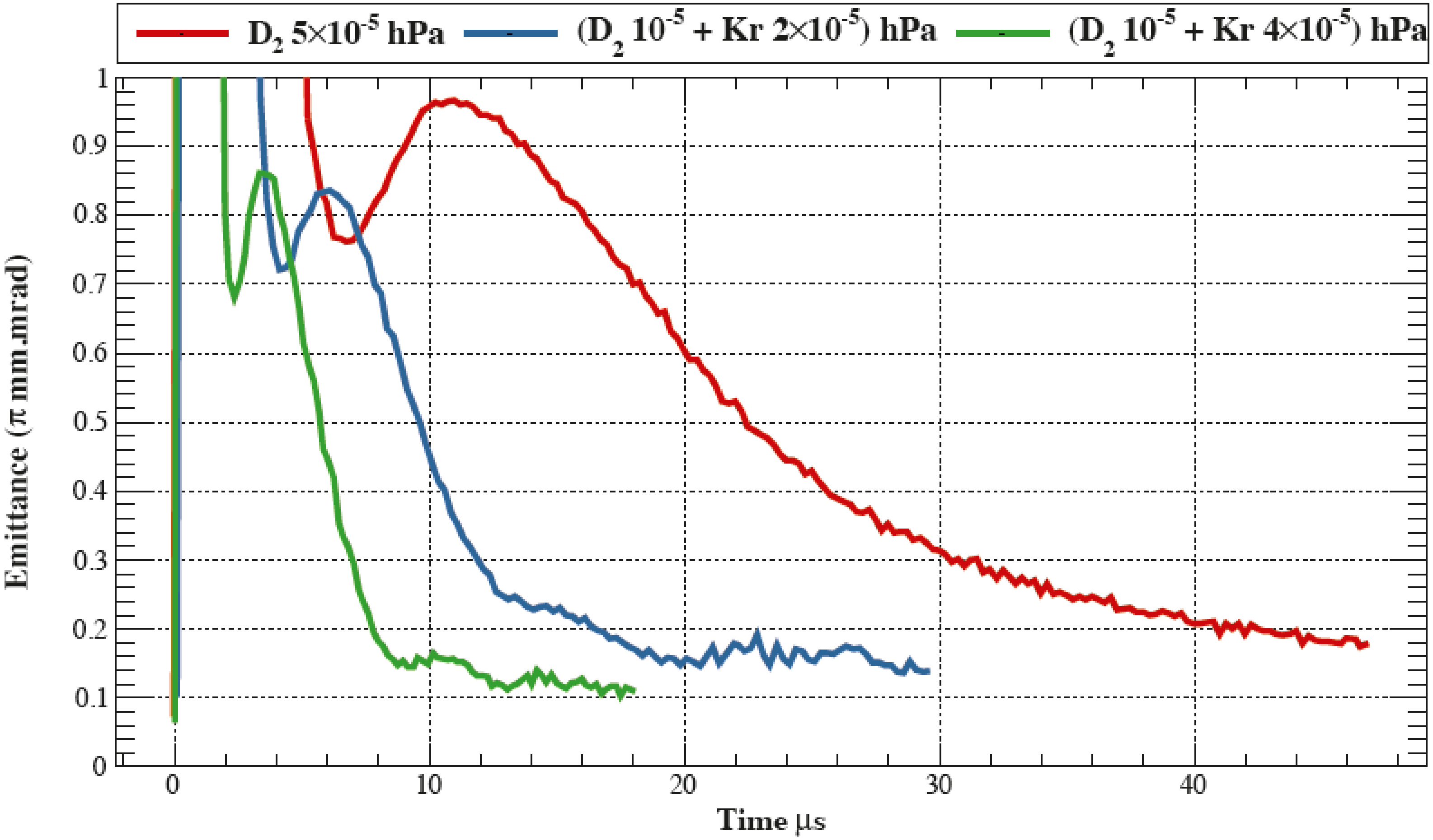


SolMaxP Example: IFMIF/IVEDA

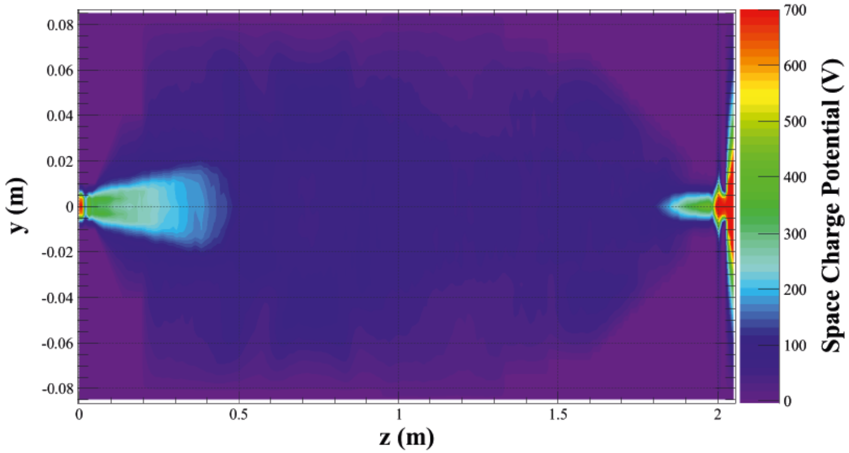
140 mA, 100 keV cw D+ beams.

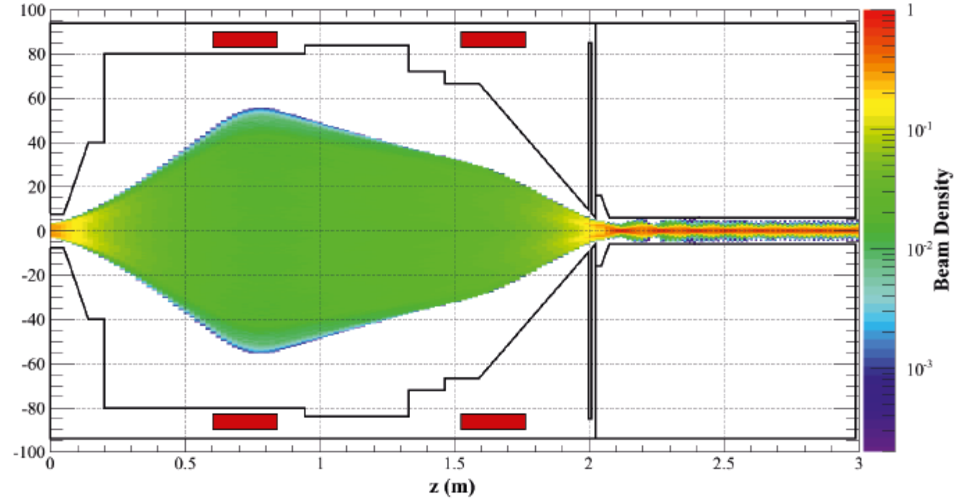


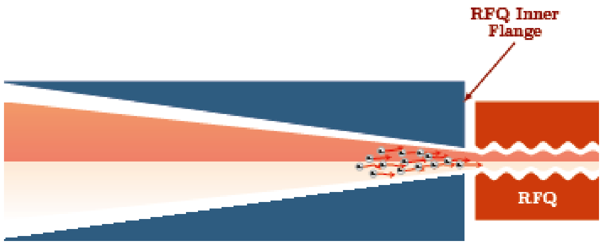
SolMaxP Example: IFMIF/IVEDA

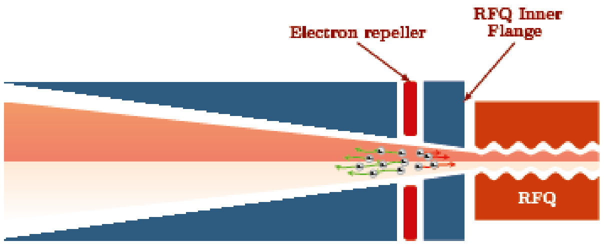


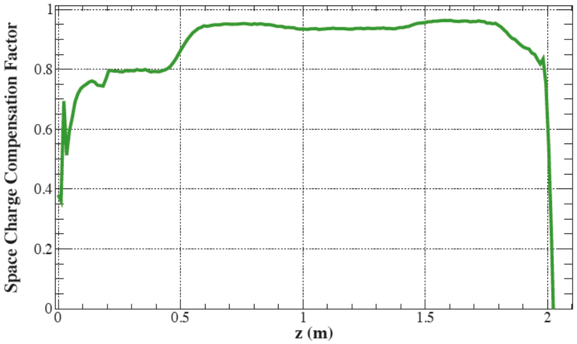
SolMaxP Example: IFMIF/IVEDA











Some Discussion

- Electrostatic devices in the beamline destroy space charge compensation.
- High gas pressure improves SCC, but may reduce beam current due to beam-residual gas interaction, charge-exchange, etc.
- Not fully understood: SCC inside Dipole magnets.
- When dealing with high intensity beams (10 mA and up) one has to be very careful about the design.
- In ECRIS and EBIS, the multitude of species may lead to a high intensity beam even if < 1 mA ends up at the accelerator…