Cyclotrons 2013

Space Charge Compensation Measurements in the Injector Beam Lines of the NSCL Coupled Cyclotron Facility

Daniel Winklehner

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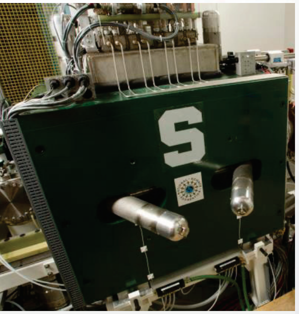
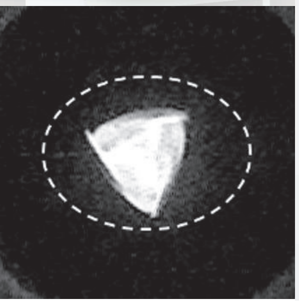
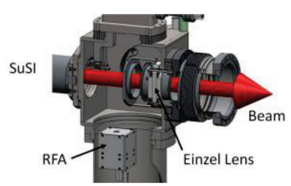
Vancouver – September 18th, 2013







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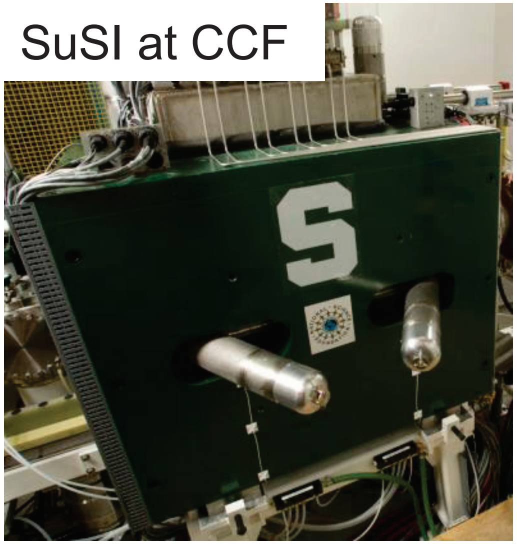
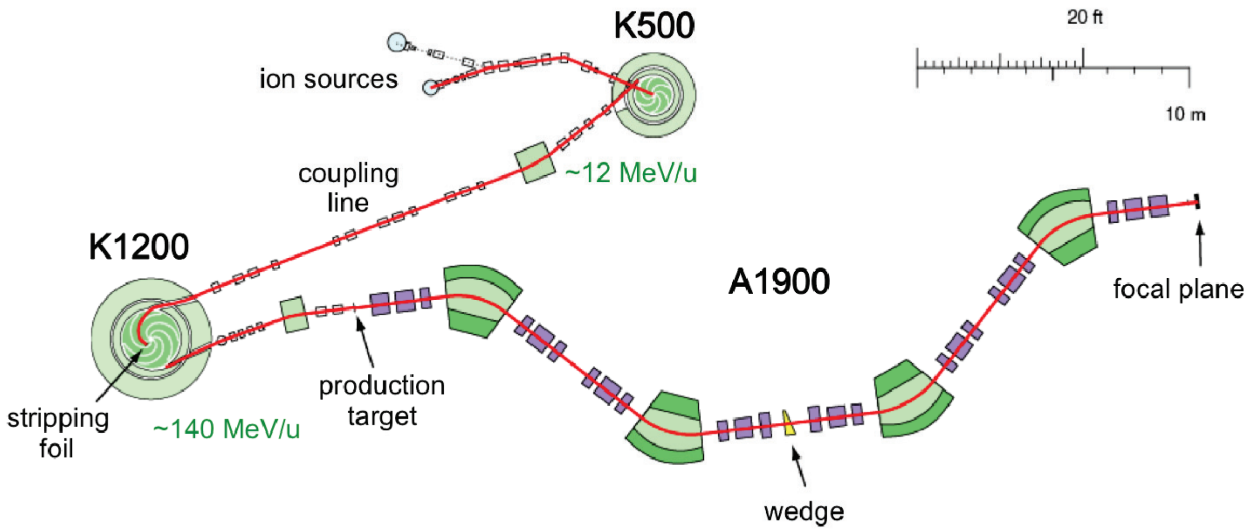
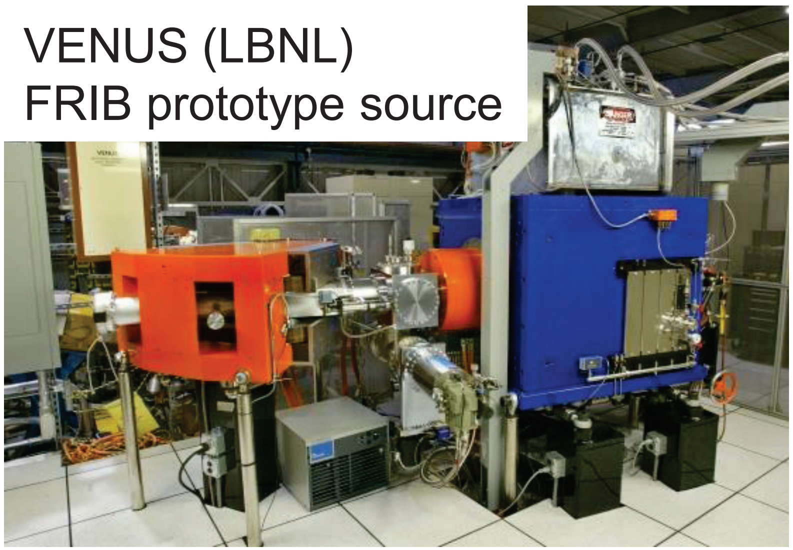
ECRIS as Injector Sources for Cyclotrons

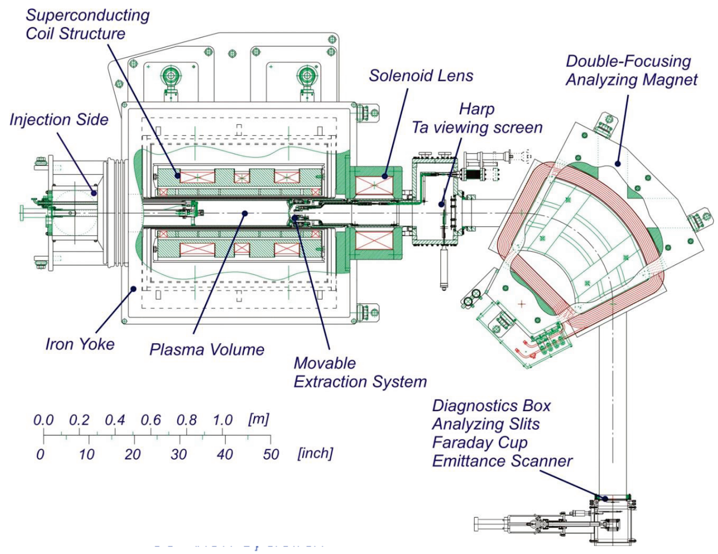
SuSI at CCF





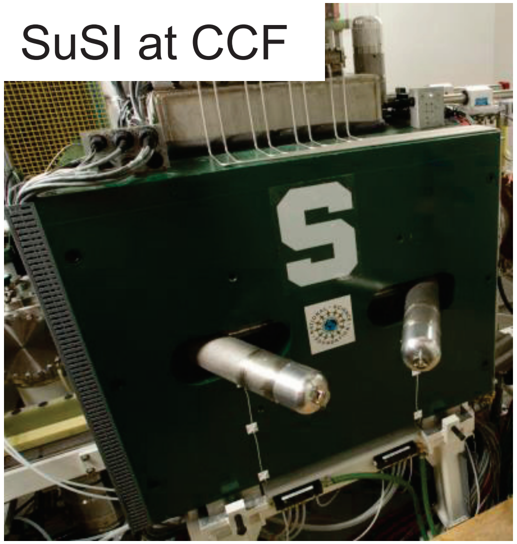
VENUS (LBNL)
FRIB prototype source

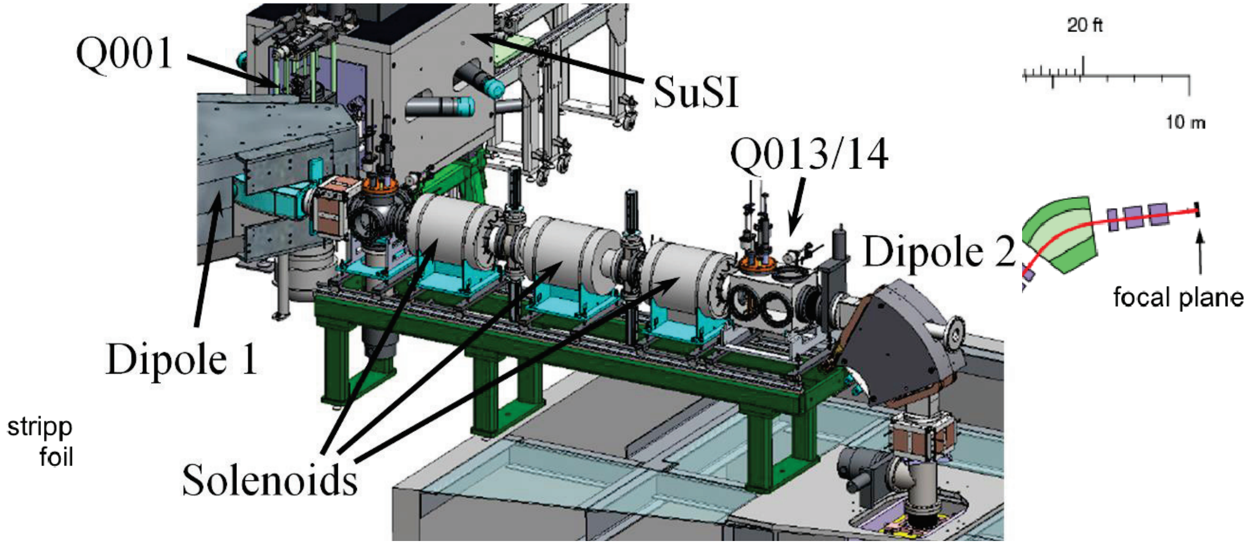




ECRIS as Injector Sources for Cyclotrons

SuSI at CCF





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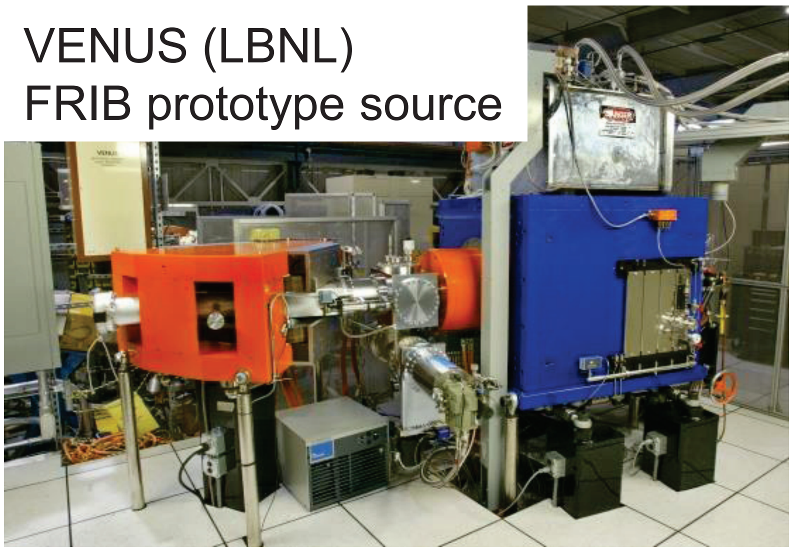
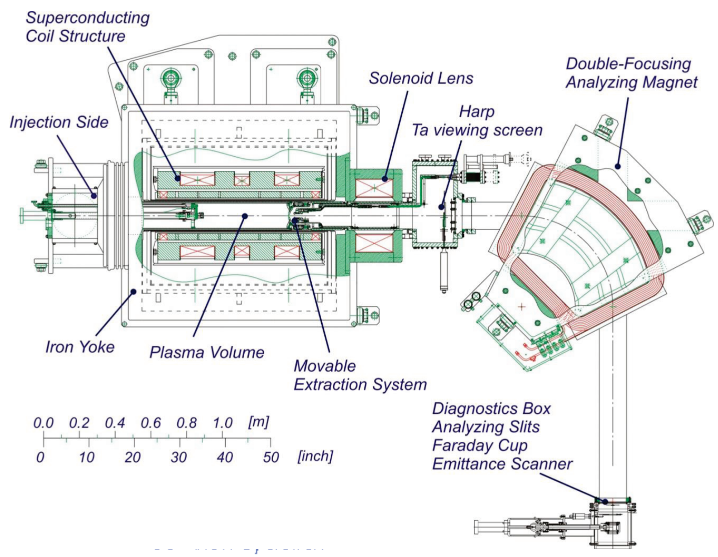
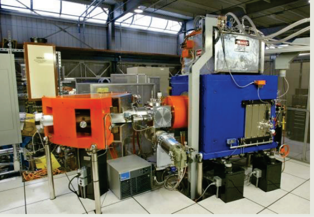
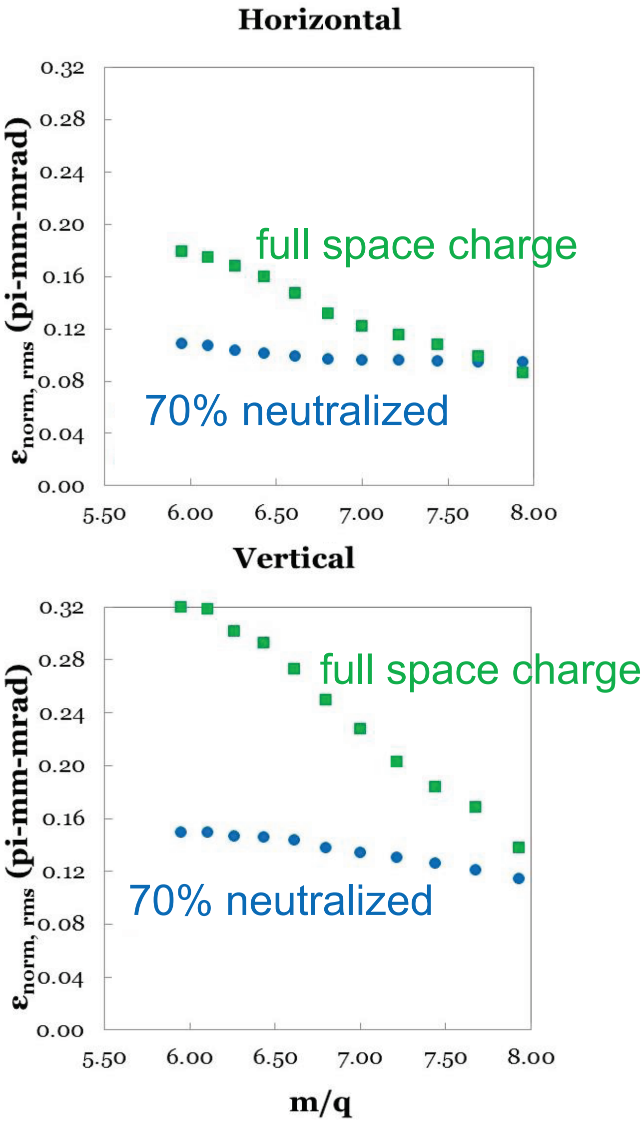
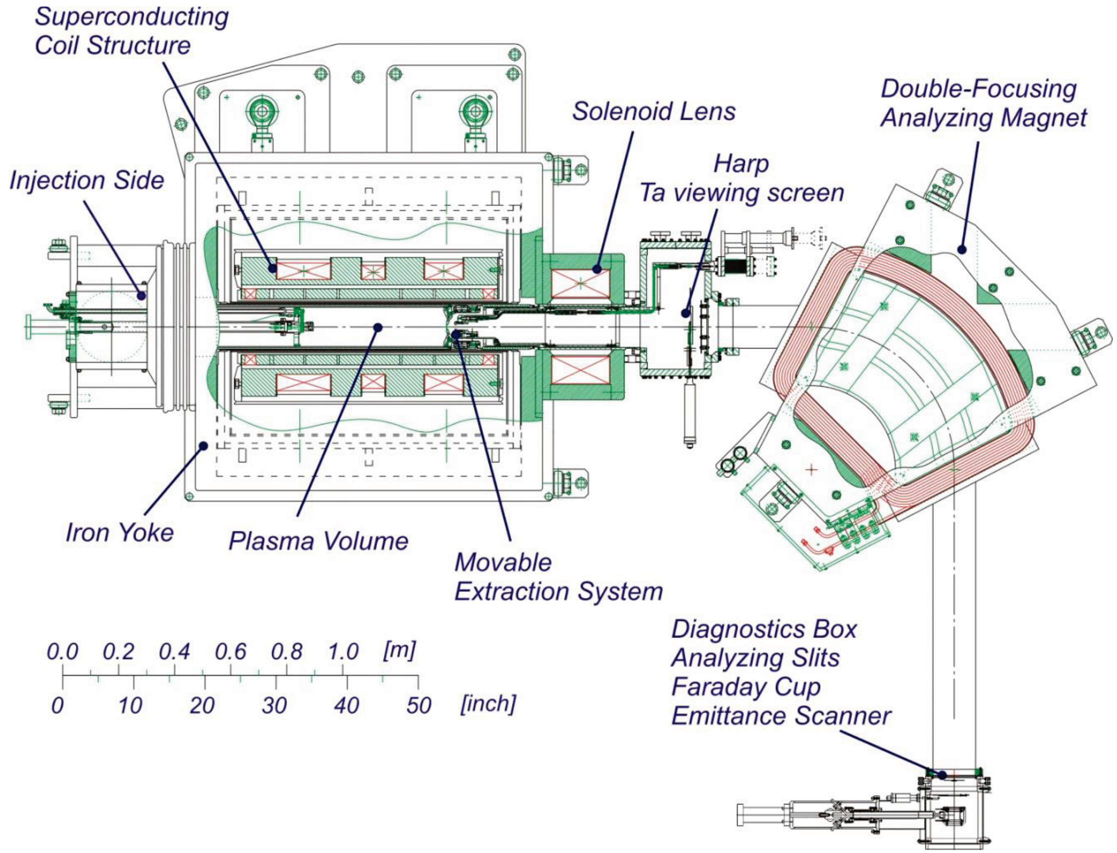






1.6 mA Uranium - Neutralization





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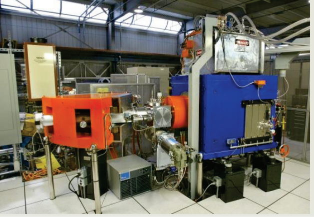
D. Winklehner et al., RSI, Volume 83, Issue 2, pp. 02B706-02B706-3 (2012).



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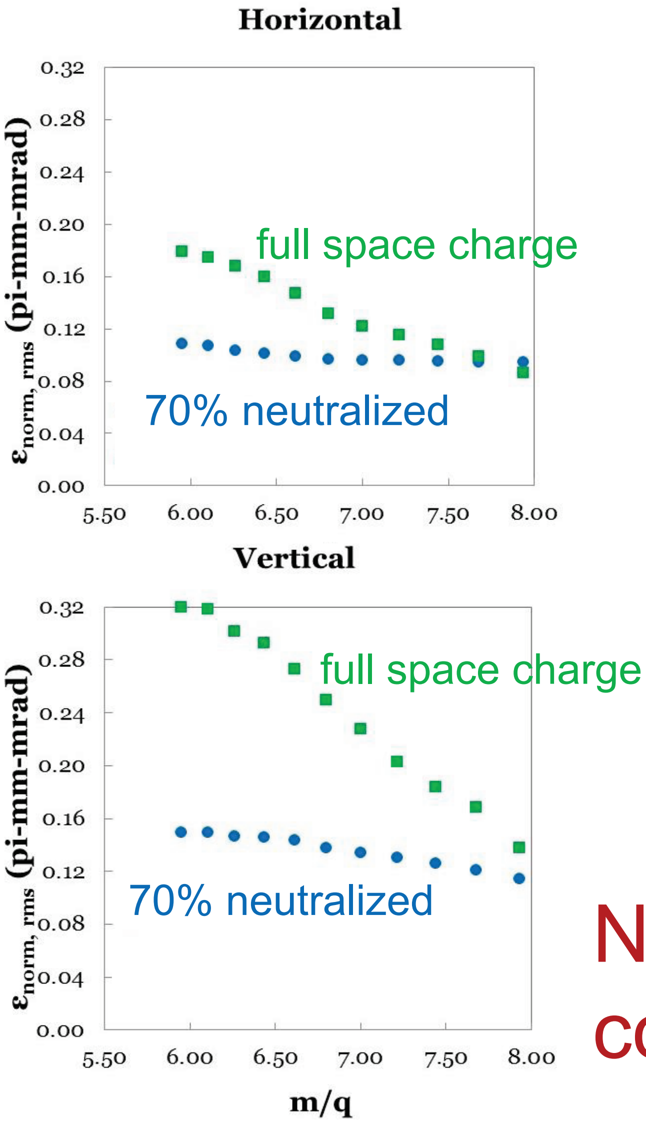
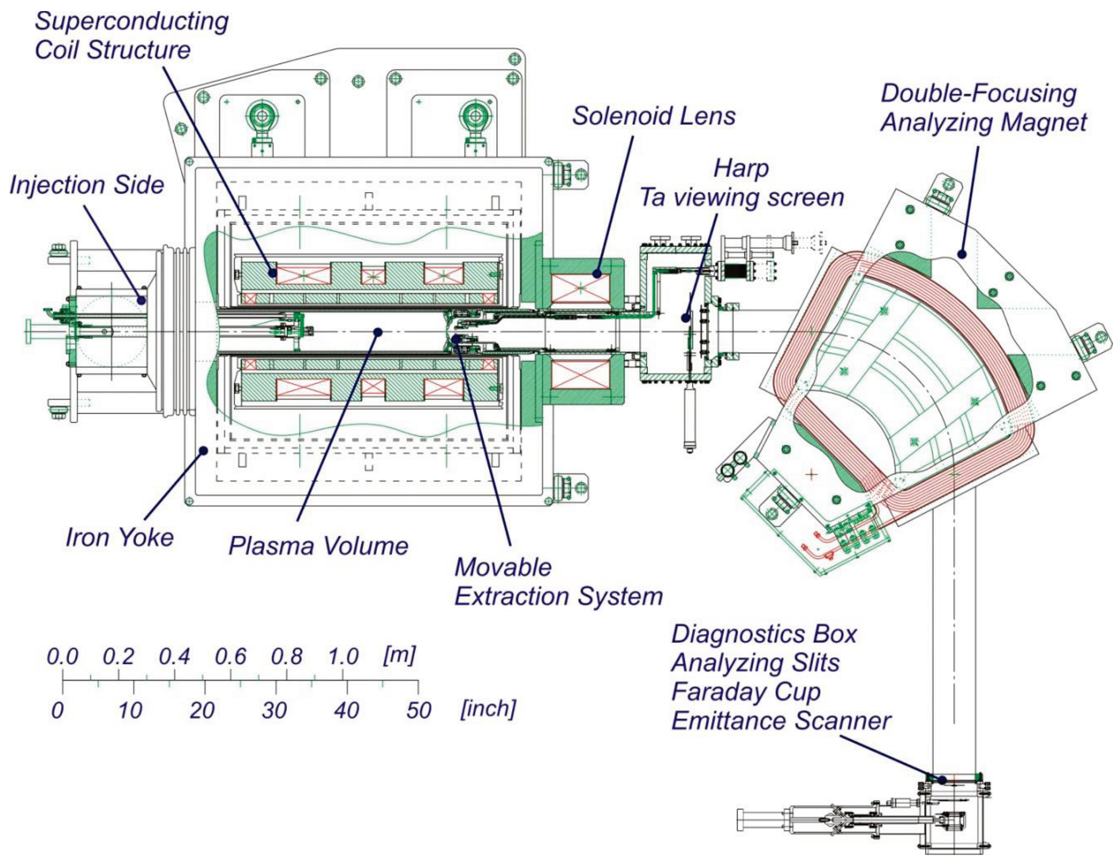




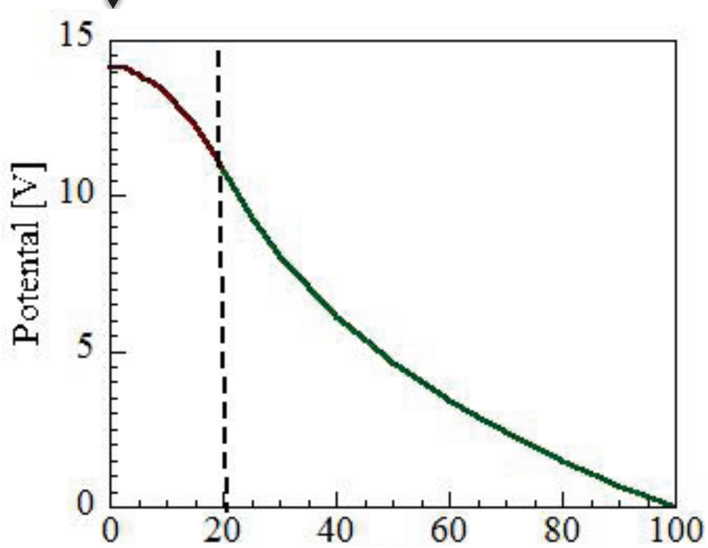
Need to determine the space charge compensation (neutralization)!

D. Winklehner et al., RSI, Volume 83, Issue 2, pp. 02B706-02B706-3 (2012).

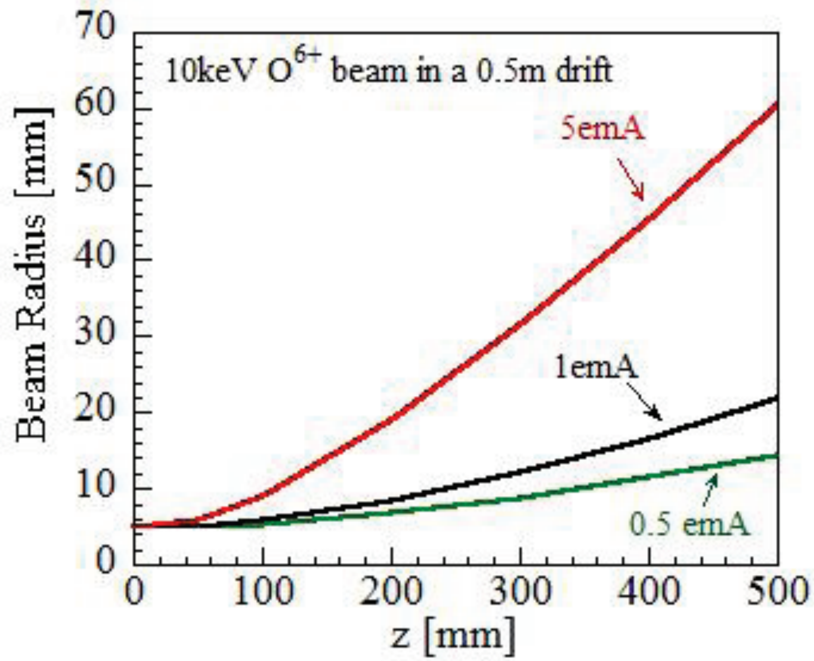
Space Charge

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

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



r [mm]



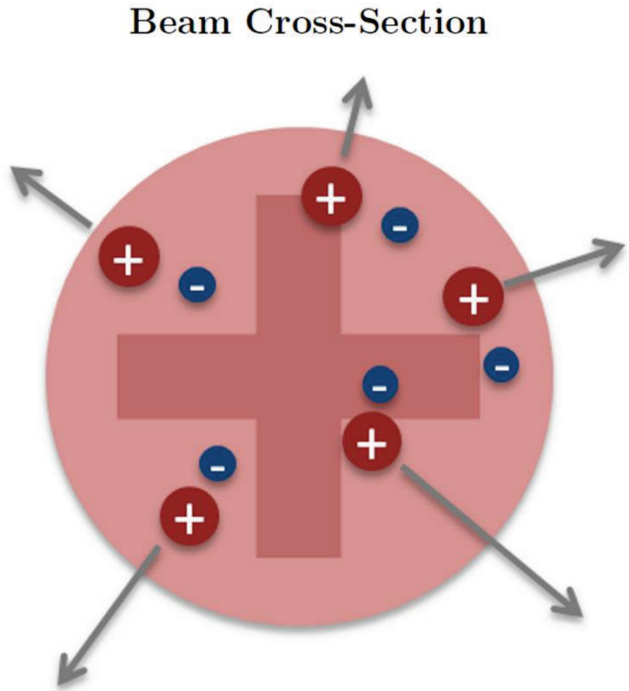
- Acts defocusing on the beam → need to counteract with beam optics elements

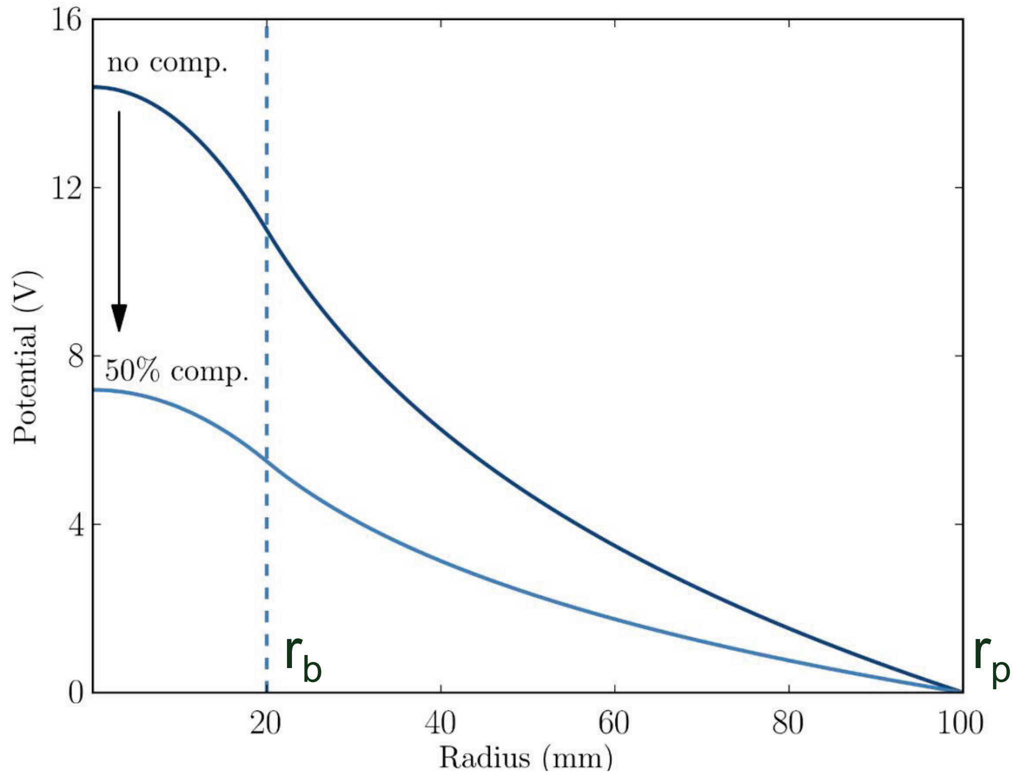
Space Charge Compensation (Neutralization)

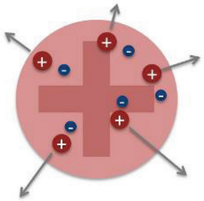
- Beam interacts with residual gas

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

$$\Delta\phi_{meas} = \Delta\phi_I(1 - fe)$$







Space Charge 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

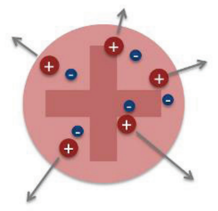
- Major contributions to cross sections:

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

- 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 $n_e = q \cdot n_b + n_i$

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

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



How can this model be applied to ECRIS?

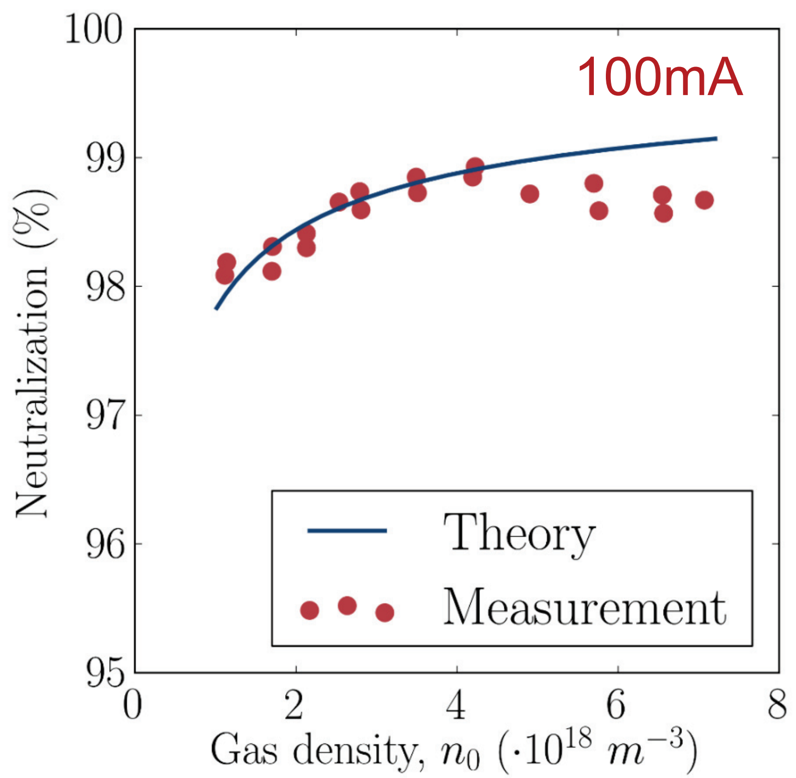
- Pressure in ECR transport line are as low as possible to reduce charge exchange (therefore low production of electrons)
- ECR beams are probably far from neutralized

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

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

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

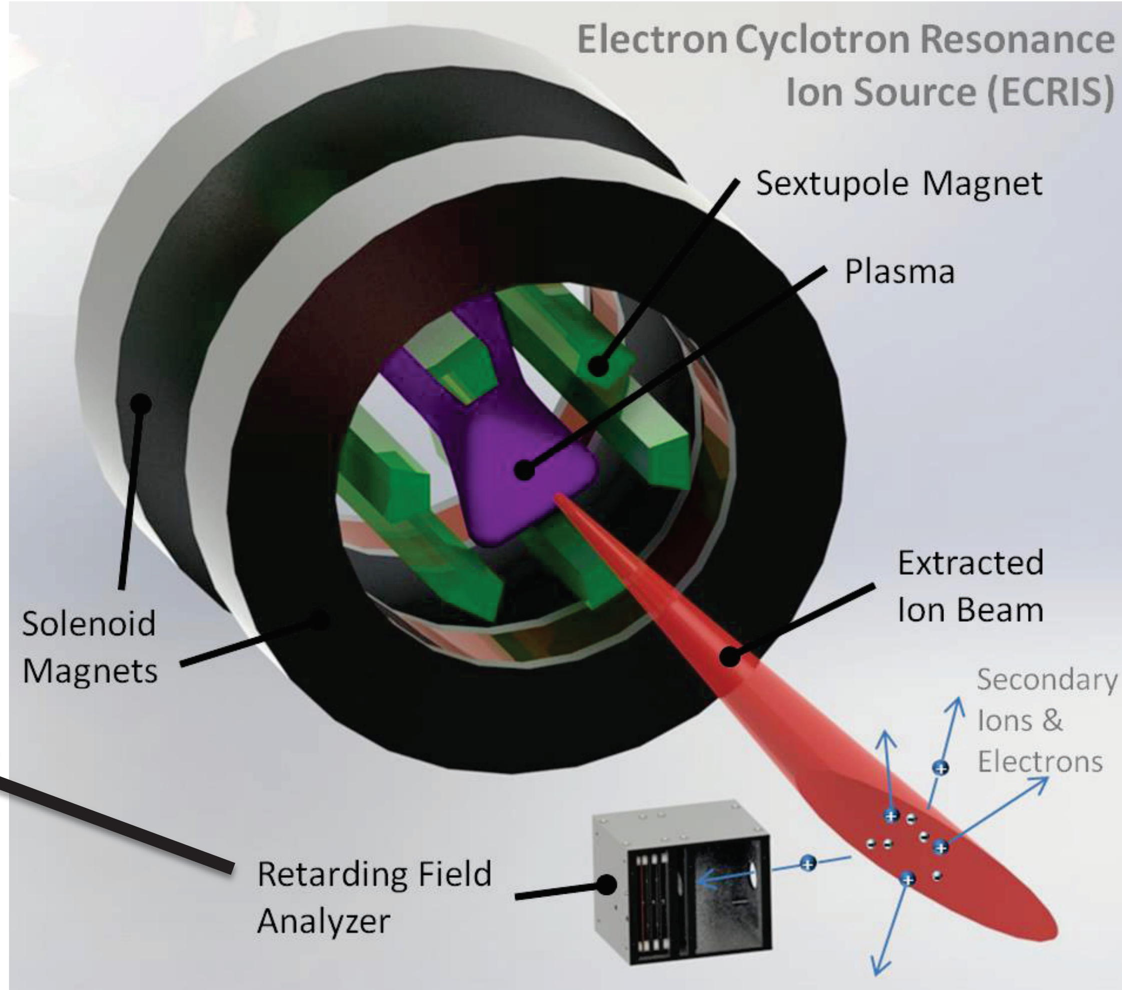
$$f_e = 1 + \frac{\chi^2}{2} - \frac{\chi}{2}\sqrt{\chi^2 + 4}$$



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

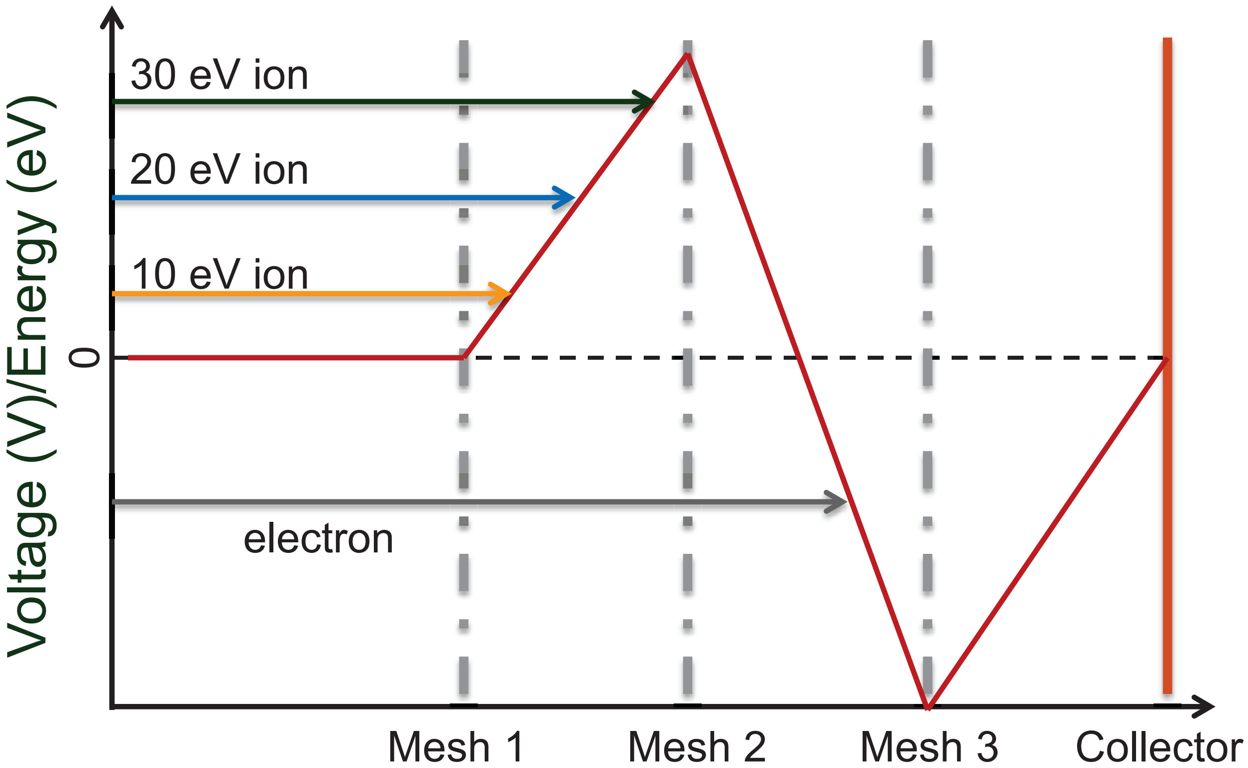
Measuring Space Charge Compensation with a Retarding Field Analyzer

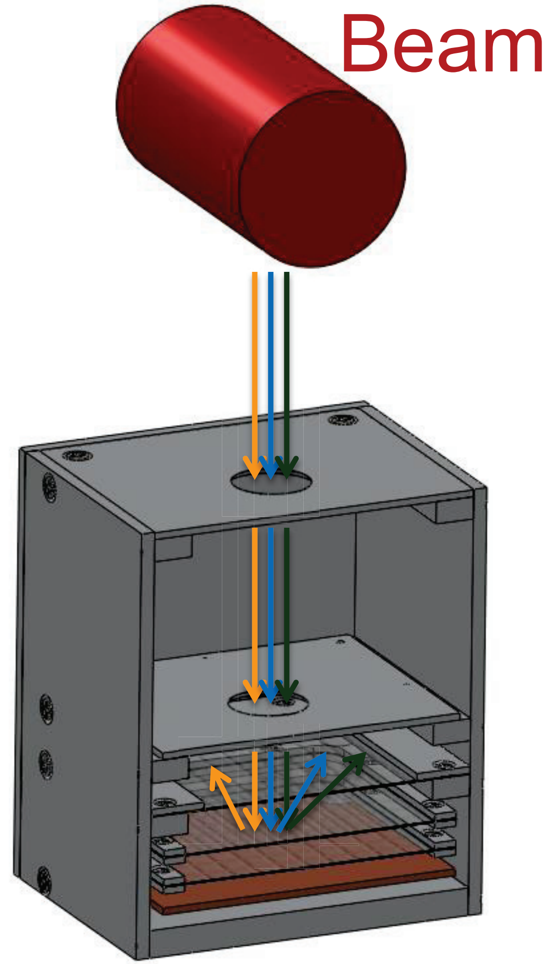
- Measure secondary ion energy distribution → compensated beam potential
- Compare to full (uncomp.) beam potential → f_e



Retarding Field Analyzer (RFA)

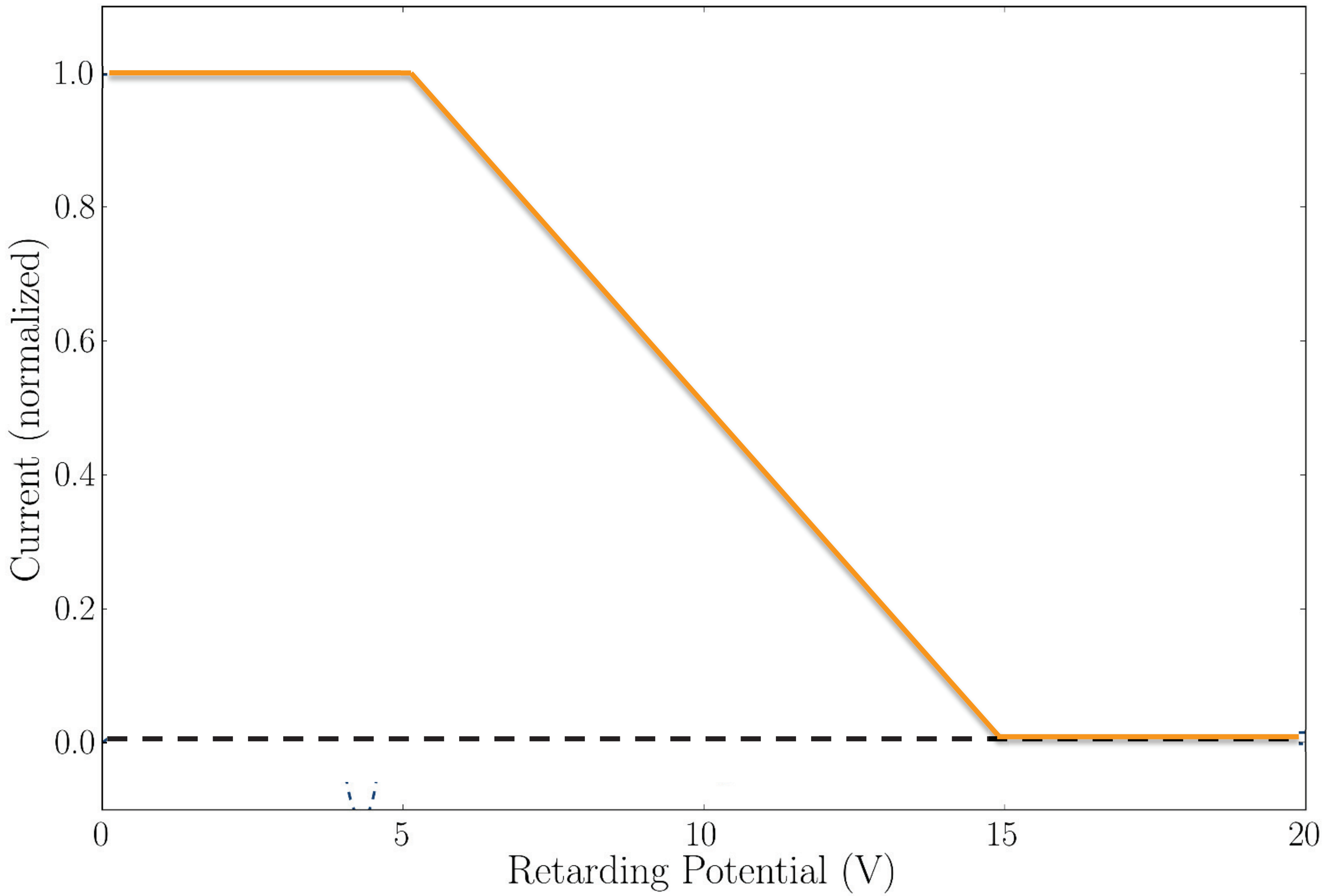
- Mesh 1 voltage = 0 V
- Mesh 2 voltage = 35 V
- Mesh 3 voltage = - 150 V



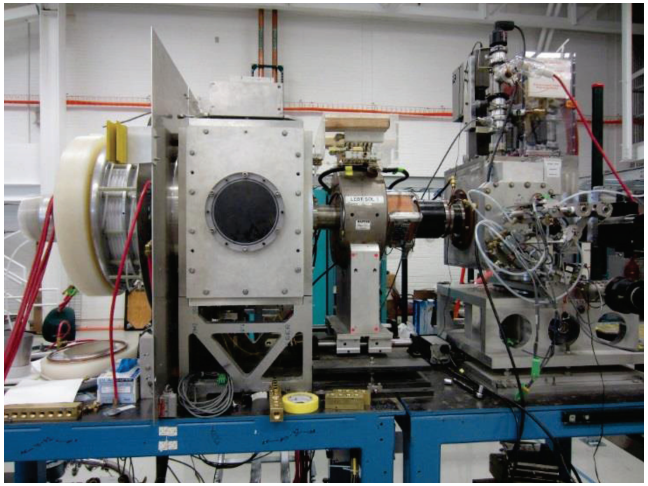


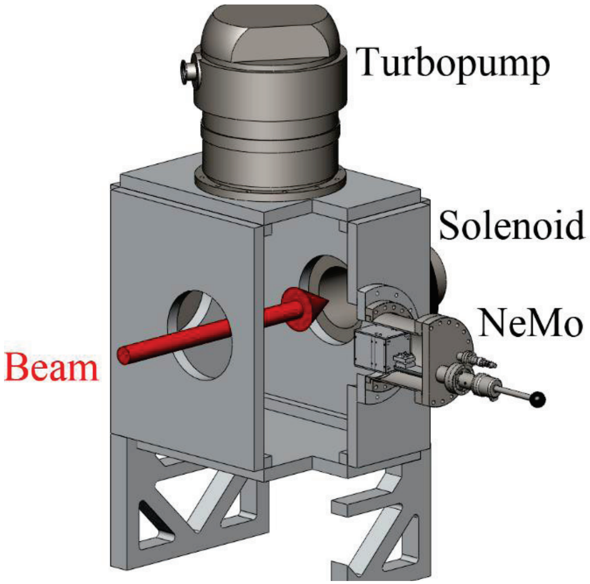
RFA Spectrum

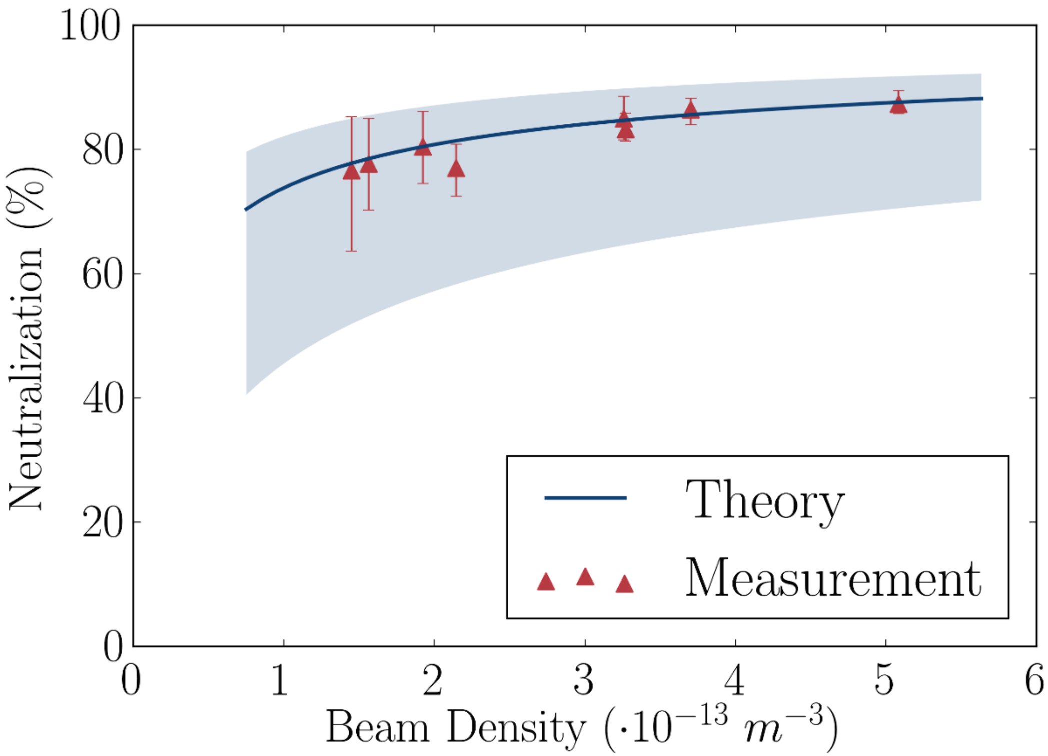
- “Perfect” spectrum
- Typical spectrum in LEDA injector source
- In Theory:
  -dI/dV corresponds to secondary ion energy distribution
  f(E) → Δφ
- Reality:
  Obtain Δφ by fitting detector signal to theoretical f(E) folded with detector transmission



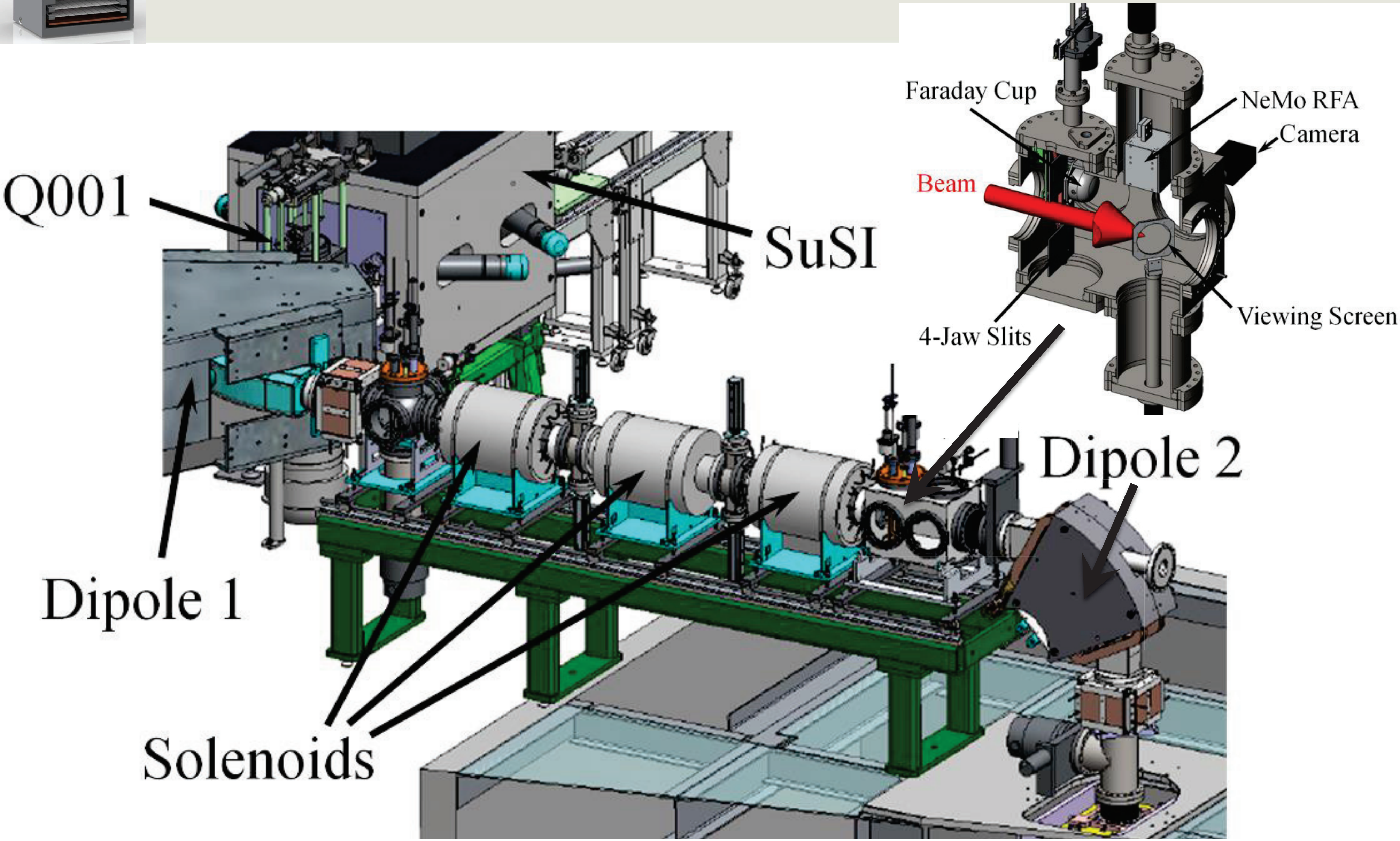
LEDA Injector Source (Microwave) SCC Measurements (3-10 mA)



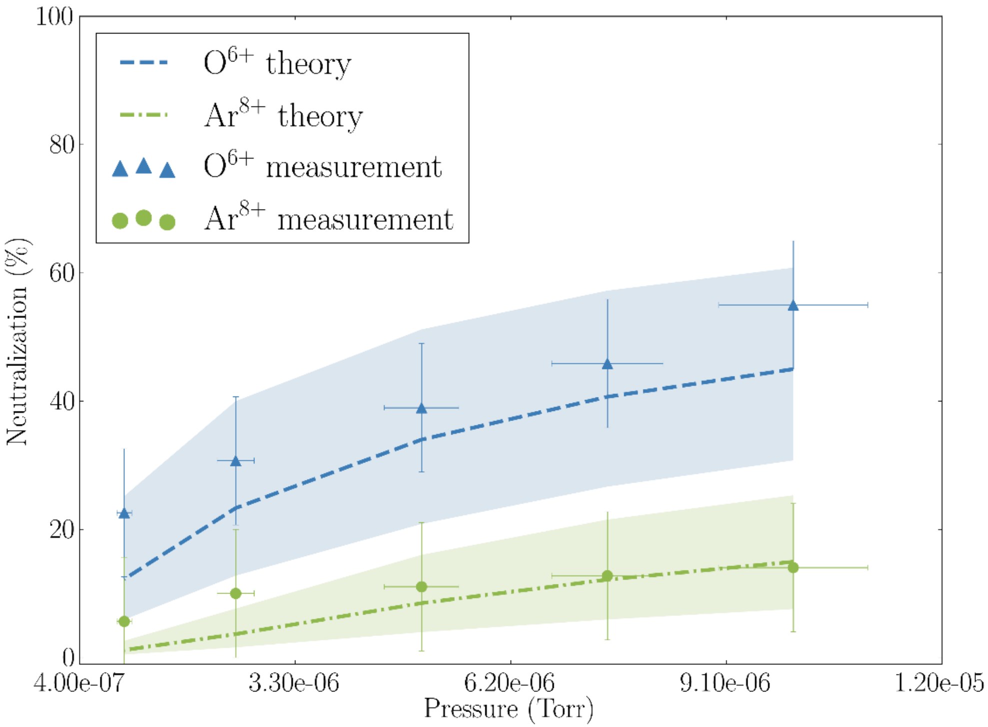


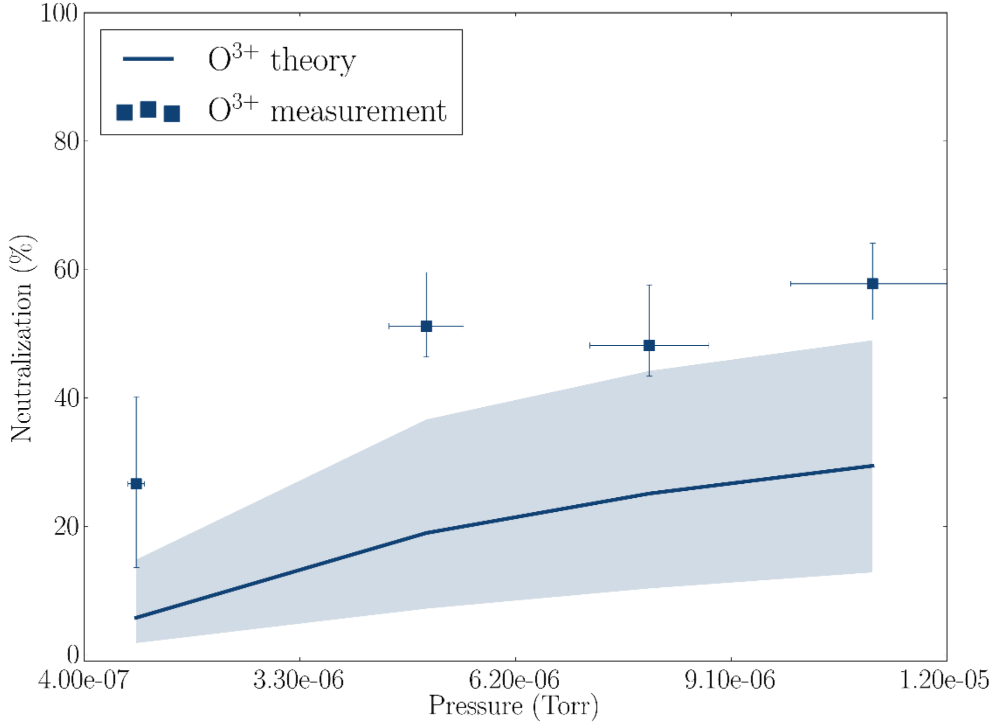


SuSI Low Energy Beam Transport Line



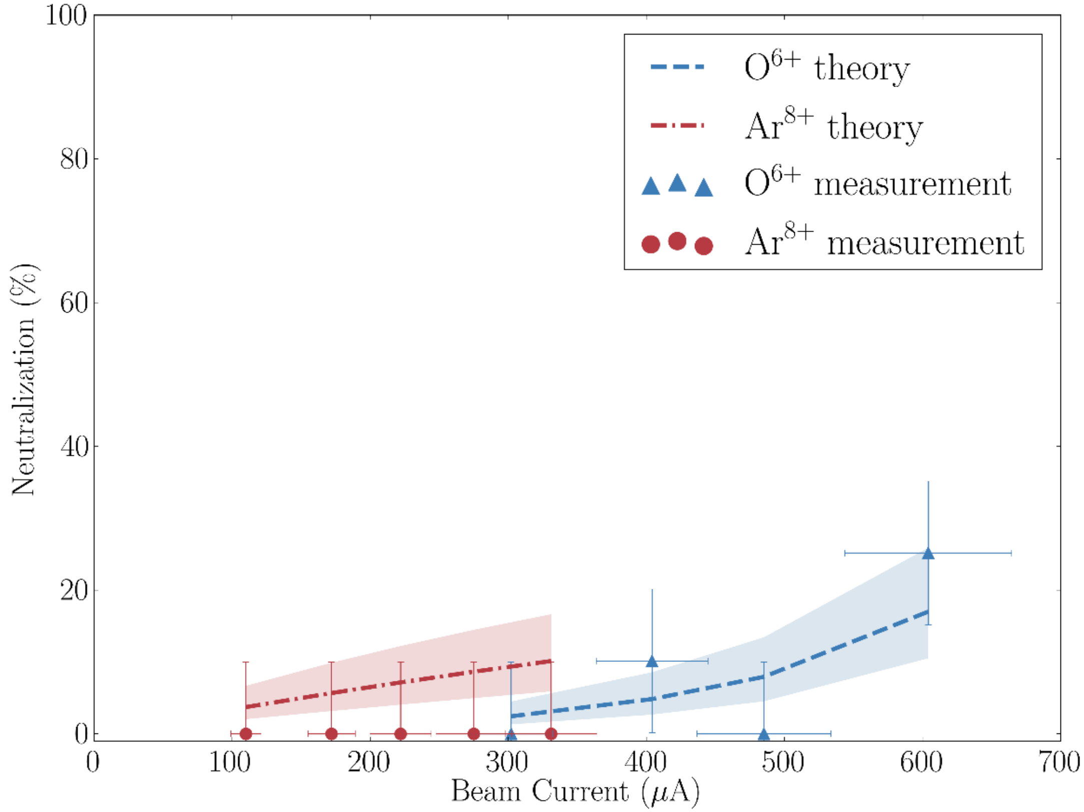
SCC – SuSI Beam Line Pressure Variation



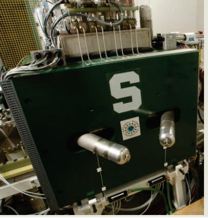


- O^{6+} and Ar^{8+} agree quite well.
- O^{3+} theory underestimates neutralization.
- Possible reasons:
  - Beam size (lowest current of all measurements, on Quartz, not KBr)
  - Cross sections

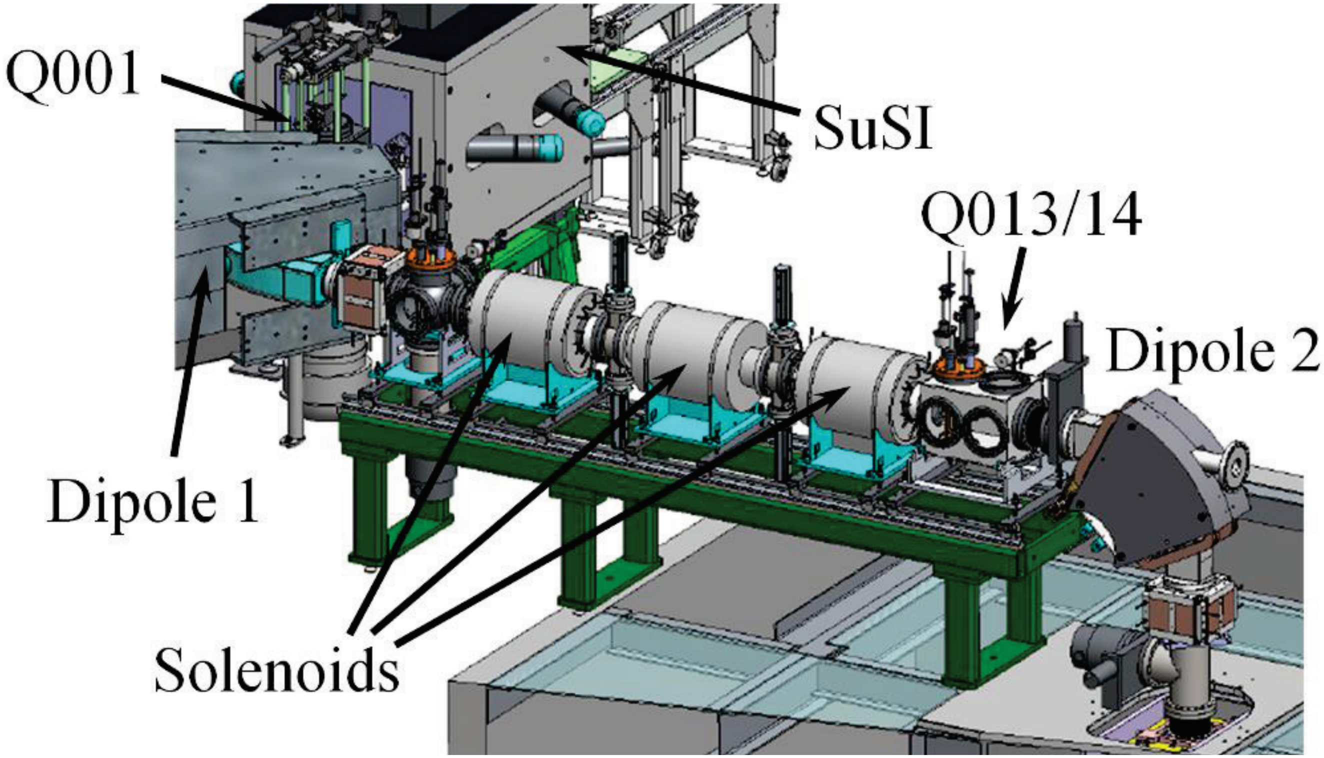
SCC – SuSI Beam Current Variation



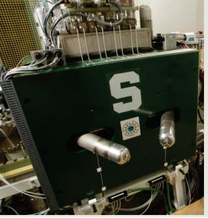
- O^{6+} and Ar^{8+}, 5.0e-6 Torr
- Neutralization very low
- Agrees well with theoretical prediction.



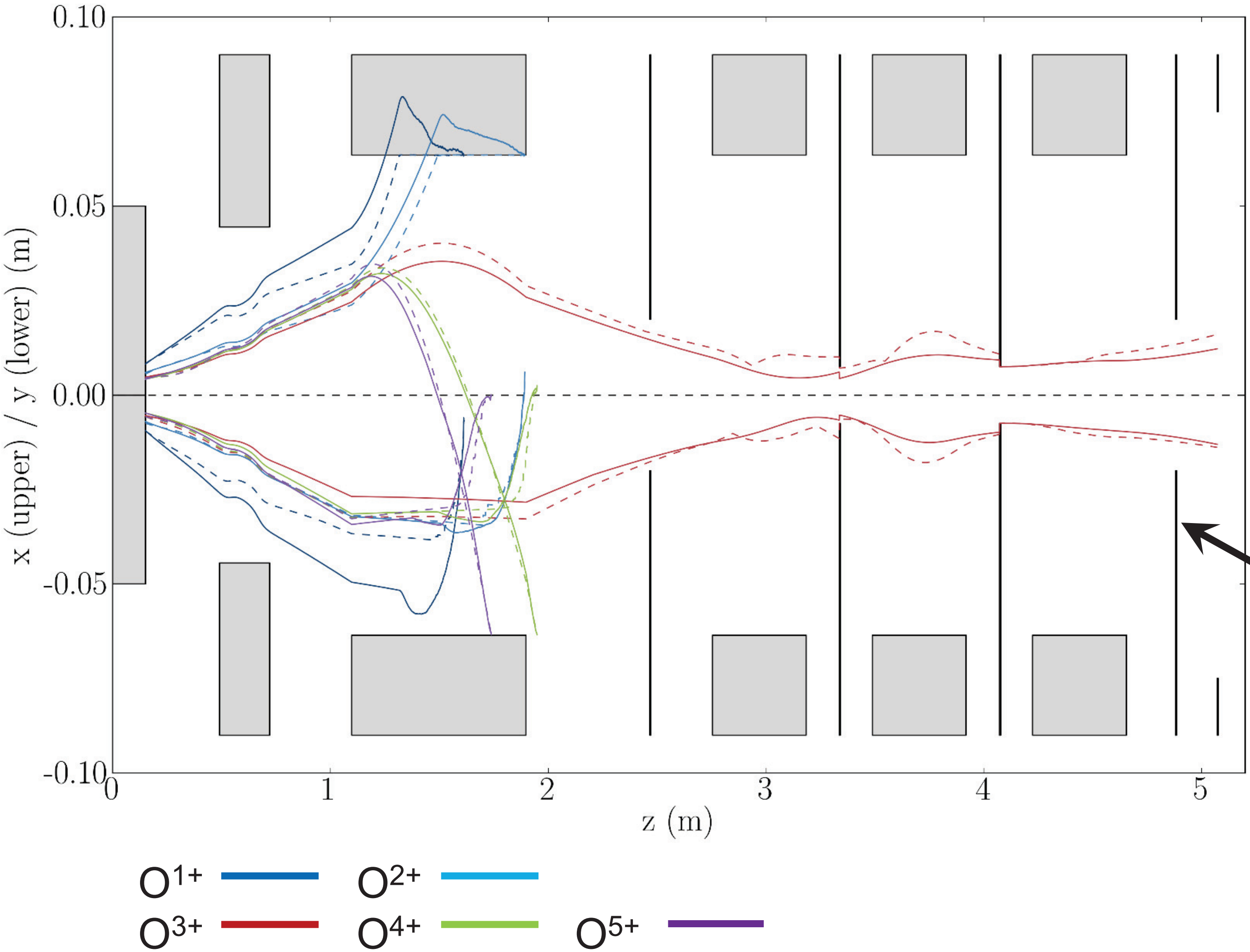
Neutralization model was included into WARP Simulation of SuSI Beam Line

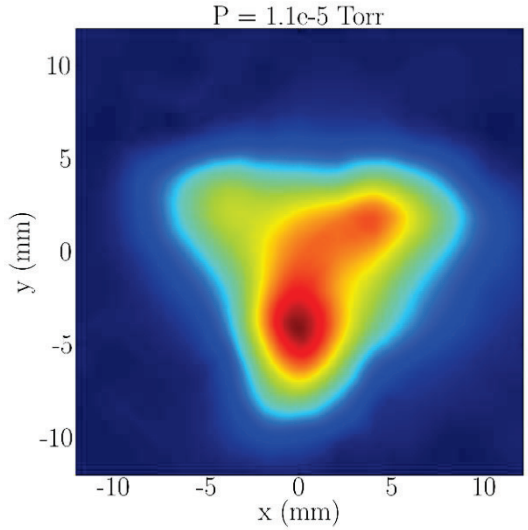


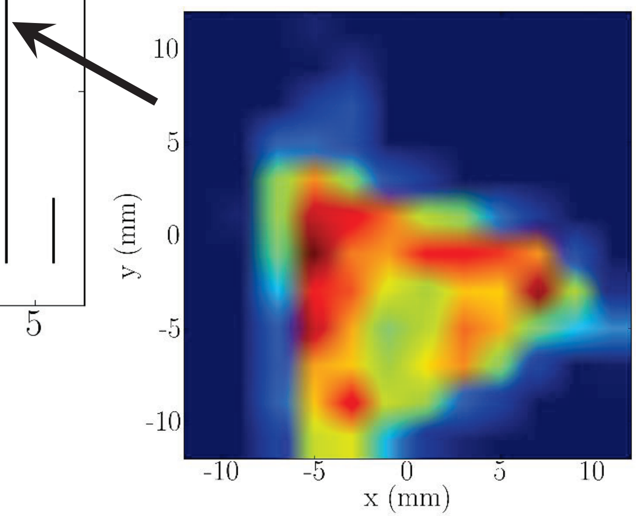
- User sets initial parameters:
  - cross-sections for ion and electron production
  - gas pressure
- At each step:
  - get 2σ beam radius
  - get beam current
- Calculate multispecies neutralization assuming same radius for each species
- Use new neutralization in next step of calculation

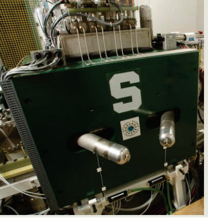


SuSI Beam Line, O^{3+}, 1.1e-5 Torr

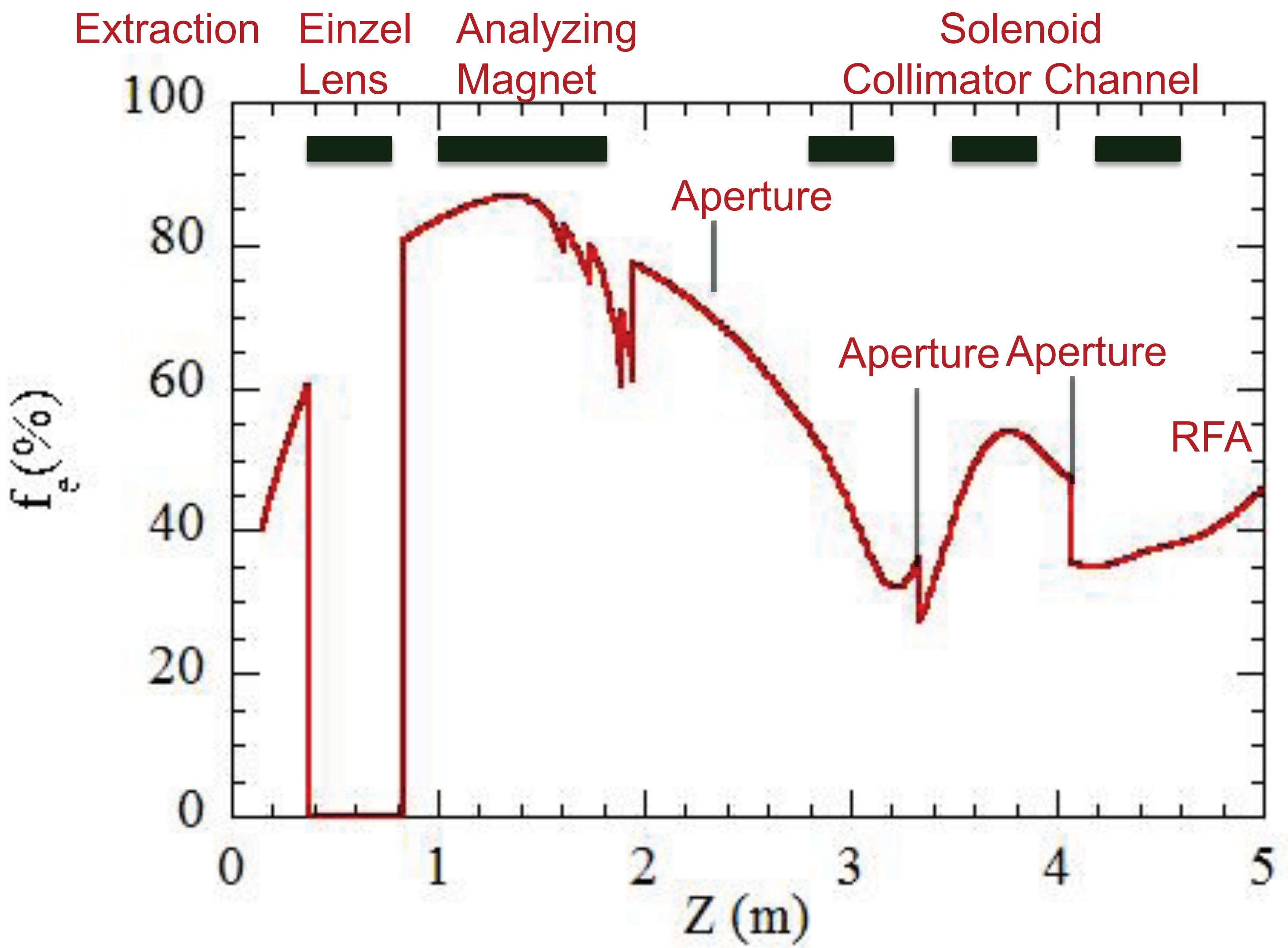








SuSI Neutralization Along Beam Line



$f_{meas} = 57\%$

$f_{sim} = 48\%$

Conclusion & Outlook

- A relatively low neutralization factor (0-60%) in ECRIS beam transport lines was measured for typical operational conditions (low beam line pressure, a few 100eμA)
- The neutralization factors depend on: beam line pressure, the transported beam current, and beam radius.
- Good agreement was found between measurements and a simple beam plasma model (adapted from Gabovich et al.).
- The simplified beam plasma model was incorporated in beam line simulations. Good agreement was found between the measured and simulated beam profiles and the neutralization factor.
- Outlook:
  - Improvements on detector
  - Measure in other locations (multispecies beams, but complicated!)
  - Include Pressure profile in simulations

Acknowledgements

- NSCL/MSU:
  - Daniela Leitner
  - ECR Group: Guillaume Machicoane, Dallas Cole, Larry Tobos, Alain Lapierre
  - NSCL Machine Shop: Jay Pline, Susan LeCureux
  - NSCL Electronics Department: Ghulam Mujtaba
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  - Dave Grote, Damon Todd, Alberto Lemut

…And thank you for your attention!