SPACE CHARGE COMPENSATION MEASUREMENTS OF MULTI-CHARGED ION BEAMS EXTRACTED FROM ECR ION SOURCES

D. Winklehner#, D. Leitner, G. Machicoane, F. Marti, D. Cole, L. Tobos, NSCL/MSU, East Lansing, USA

Abstract

In this contribution, we present measurements of the beam potential performed after the extraction region of ECR ion sources in dependence of the base pressure in the beam line and other parameters, e.g. total extracted current, using a Retarding Field Analyzer (RFA). If the beam current and the beam profile are known, it is possible to infer the level of space-charge compensation from the measured beam potential distribution. Preliminary results are discussed and compared to simulations.

INTRODUCTION

Space-charge compensation in beam lines due to the interaction of the beam with residual gas molecules is a well-known phenomenon for high current injector beam lines. When the beam interacts with the residual gas in the beam line, electrons are separated from gas molecules by charge-exchange processes and accumulate inside the beam envelope, while the ions created in the process are expelled by the positive beam potential. This lowers the space-charge potential of the beam and is called space-charge compensation or - neutralization. In [1], Soloshenko investigates the simple case of space charge compensation for the stable stationary beam. A steady-state is defined for the beam, where the rates of electrons created/entering the beam and leaving the beam are equal. Electrons captured inside the beam may gain enough energy to leave through Coulomb collisions with the beam ions themselves and through collective processes. Considering also the energy balance of the electrons, Soloshenko arrives at the following expression for the potential difference of beam center and and beam edge ($\Delta\phi = \phi_{center} - \phi_{edge}$):

$$\Delta\phi = \sqrt{3\mathcal{L}}\left(\frac{M}{m}\right)^{1/2}\left(\frac{\varphi_i}{V_0}\right)^{1/2} n_+^{1/2}\left(\frac{1}{n_0\sigma_e}+\frac{v_+\sigma_i r_0}{2v_i\sigma_e}\right)^{1/2}\cdot e$$

Where $\mathcal{L} = 2\pi\Lambda$ with Λ a Coulomb logarithm, r_0 the beam radius, φ_i the gas ionization potential, M the beam ion mass, eV_0 the beam ion energy, $v_{i/+}$ the plasma ion/beam ion velocities, $\sigma_{i/e}$ the ion/electron originating cross-sections and $n_{0/+}$ the residual gas/beam ion densities. By investigating the balance of the two terms in the sum he concludes that for low pressures we can expect a decrease in $\Delta\phi$ with increasing pressure, whereas for high pressure, $\Delta\phi$ reaches its minimum and becomes essentially independent of the pressure (see [1] for more details).

winklehner@nscl.msu.edu

In addition, ions hitting apertures, charged electrodes, ion optics elements and beam line coatings can influence the creation and loss of compensation electrons greatly and have to be taken into consideration.

For beam lines using mostly magnetic focusing elements and for pressure around 10^{-5} Torr, almost full compensation has been predicted [1] and observed [2]. However, due to the low pressure (typically 10^{-7} to 10^{-8} Torr) required for the efficient transport of high charge state ions, ion beams in ECRIS injector lines may be only partly neutralized and space charge effects may be present. With the dramatic performance increase of the next generation Electron Cyclotron Resonance Ion Sources it is possible to extract tens of mA of beams from ECR plasmas [3]. In this high current regime, non-linear defocusing effects due to the space-charge potential of the beam become more and more important. In order to develop a realistic simulation model for low energy beam transport lines, it is important to estimate the degree of space charge compensation along the Low Energy Beam Line (LEBT).

HARDWARE

ECR Ion Sources

This type of ion source is described in great detail elsewhere [4]. One point to be made, though, is that the plasma from which the ions are extracted is confined by a strong magnetic field, which is usually a superposition of a solenoid field (longitudinal confinement) and a sextupole field (radial confinement). For special applications, however, (e.g. high currents of protons) it is preferable to use only the solenoid magnets (e.g. LEDA source, see below). In this context it is important to mention that the sextupole field has great influence on the shape and behavior of the extracted beam. While beams from sources using only solenoids are typically radially symmetric (uniform or Gaussian beam profile), ECR beams from sources using sextupoles exhibit a triangular or star-shaped cross-section [5, 6]. The triangular shape and intrinsic sextupole moment of the beam has been subject to research for many years now and has to be taken into account when designing the LEBT of an ECRIS. It might also influence the measurement of beam neutralization with an RFA as will be seen later.

SuSI

The Superconducting Source for Ions is one of the injector sources of the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. As the name suggests, the magnetic fields are provided by a set of superconducting

ISBN 978-3-95450-123-6

magnets. The position (about 46 cm downstream of the extraction aperture) at which the measurements have been conducted can be seen in figure 1. The Einzel Lens that is used to match the SuSI beams into the analyzing beam line section was turned off for these measurements. Oxygen and argon beams with total extracted currents of up to 3 mA were used in these measurements.

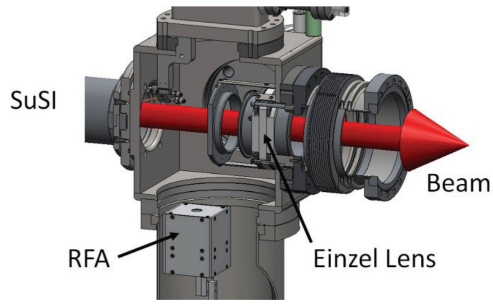

Figure 1: RFA in SuSI LEBT – diagnostic box 1. The Einzel Lens was turned off during measurements.

Artemis A

Artemis A is the second injector source used at the NSCL and is based on the design of the AECR-U source at Lawrence Berkeley National Laboratory [7]. The solenoid magnets are room temperature magnets and the radial confinement field is provided by a permanent magnet sextupole [8]. Oxygen and argon beams with total extracted currents of up to 2.8 mA were used in these measurements. The RFA was mounted in a 6-way cross in a vertical beam line between the source and the analyzing magnet, right after an electrostatic quadrupole doublet, looking at the beam from the side. The 6-way cross also held a faraday cup for measuring the beam current at that position and a turbo molecular pump as well as a needle valve for adjusting the beam-line pressure.

LEDA Source

Developed at Chalk River Laboratories, a high current proton source was extended as the Low-Energy Demonstration Accelerator (LEDA) injector source in Los Alamos and recently moved to the NSCL, where the presented measurements have been conducted. The LEDA source does not have a sextupole magnet and thus produces to first order round beams. Microwave powers of 500 to 700 W were used to produce 2-10 mA proton beams with a small contribution of H_2 ions. The ratio of H^+ to H_2^+ for this source is measured to be ~9:1 [9]. The RFA was mounted in a box approx. 50 cm after the plasma aperture looking at the beam from the side.

Retarding Field Analyzer (RFA)

The RFA consists of three parallel meshes housed in a grounded box with a set of two apertures for collimation of the secondary ions upon entering the detector (see figure 2). Mesh 1 is grounded at all times and helps providing a uniform retarding field together with mesh 2 which is set to the retarding potential (-100 V to +200 V). Mesh 3 is typically set to -450 V and acts as an electron repeller, both to keep electrons from the outside out and to turn back electrons produced upon impact of the measured ions on the collector. The collector is a copper plate.

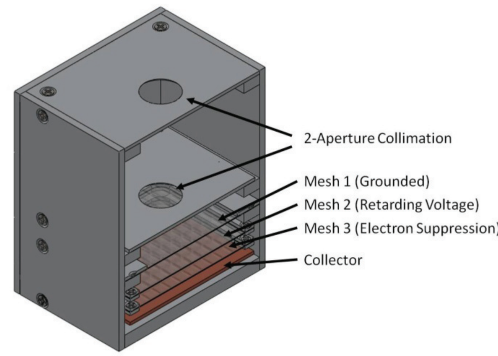

Figure 2: Cut isometric view of the RFA.

Extensive simulations using SIMION 8.1 [10] have been undertaken in order to determine the theoretical resolution of the device. In these simulations randomly generated monoenergetic particles filling the maximum acceptance of the detector were sent into the detector and the measured energy distribution was analyzed. The FWHM of the distributions were ~0.55 eV with a base width of 1.2 V. Together with a stability of the power supplies of better than 0.1 V a conservative estimation of the resolution of <1 eV can be made.

Alternative designs were considered, like giving the meshes a curvature to ensure maximum energy loss even for particles entering under an angle, but simulations showed negligible change in the resulting spectra.

Initial measurements without the double aperture system showed long tails on both, the high and the low energy side. Those could be mostly suppressed by adding the apertures, albeit thereby reducing the maximum current reaching the collector plate.

Data acquisition is managed by a computer program setting the voltage on mesh 3 and reading the current from an in-house fabricated BCM (beam current monitor) via EPICS/PLC communication.

MEASUREMENTS

Analysis Method

For the round beams from the LEDA source, we assume that the beam is a uniformly charged cylinder and the ions are created inside this cylinder through charge exchange processes. They are then expelled by the positive beam potential and carry a kinetic energy depending on the radial distance from the beam center at the time of their separation from the gas molecule. This is a good approximation, as has been seen in previous measurements with a similar device [2]. The potential difference between center and edge of the beam is then given by:

ISBN 978-3-95450-123-6

$$\Delta\phi = \frac{I\cdot(1-f)}{4\pi\cdot\varepsilon_0\cdot\beta c}$$

Where I is the total beam current, ε_0 the vacuum permittivity, βc the velocity of the beam, and f the neutralization factor between 0 and 1.

The potential difference Δϕ can be obtained from the RFA spectrum by taking the derivative dI/dV which yields the energy distribution of the ions. Δϕ is then given by the base width of the distribution (method 1) minus the base resolution of 1.2 V (method used in [2]). On the other hand, at the low currents that we are measuring, other effects like the initial random motion of the gas molecules, collisions, or the presence of a beam halo can add to the spectrum and round off the edges or even produce long tails. This widens the base of dI/dV. As a second method of analyzing the spectra, we suggest fitting with three straight lines and taking their crossing points as ϕ_{center} and ϕ_{edge} (method 2). An example of both methods for a typical spectrum can be seen in figure 3.

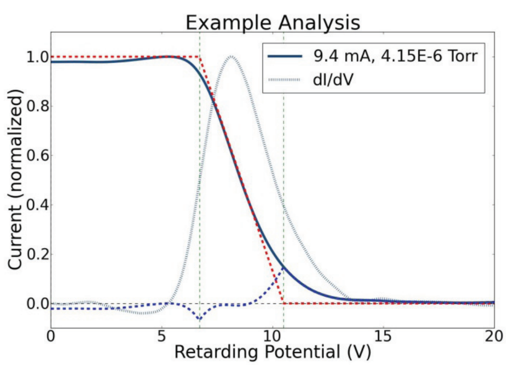

Figure 3: LEDA, Example Analysis of a LEDA ion source neutralization spectrum. The solid blue line is the normalized spectrum, the dotted line is dI/dV and the dashed red lines are the fit according to method 2. Method 1 would use the base width of dI/dV as Δϕ. $\Delta\phi_{meth.1}$ = 4.6 V, $\Delta\phi_{meth.2}$ = 3.8 V and f_{e1} = 78.4%; f_{e2} = 83.0%.

Measurements with Artemis A

The first measurements were obtained on the Artemis A line. In this setup, the RFA was operated with a larger aperture (r = 1.1 cm) and without the second collimation aperture. Following [2] we tried to relate the saturated RFA current $(I_{RFA})_s$ to theoretical predictions based on the 1-D continuity equation:

$$(I_{RFA})_s = \frac{{r_a}^2\cdot T\cdot I\cdot\left(\sum n_g\sigma_i\right)}{2d}$$

with r_a the RFA entrance aperture radius (1.1 cm), d the distance from aperture to beam axis (10 cm), σ_i the ion production cross-section, n_g the gas density, T the grid material transparency, and I the ion beam current. The σ_i were calculated for the different beam components (multi-species beam) individually according to an empirical formula [11]. Predictions compared to measurements can be found in figure 4. A transparency factor of T = 0.4 (40% transmission) gave good agreement.

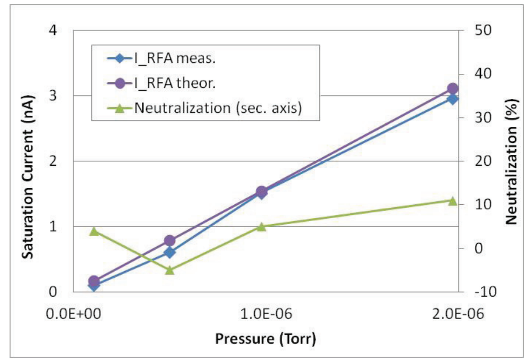

Figure 4: Artemis: Oxygen beam, pressure variation.

The neutralization values obtained with the aforementioned analysis method are also displayed in figure 4. They are distributed around 0 % with an overall tendency to increase slightly with pressure, indicating that in this region of the beamline no space charge compensation occurs. This might be due to the presence of the electrostatic quadrupole doublet, although the measurement was taken approx. 20 cm after the exit of the quadrupole. One of the values is slightly negative, stemming from the Δϕ in the spectrum being larger than the theoretical prediction for the completely uncompensated beam. See SuSI measurements below for a discussion.

Measurements with the LEDA Source

Measurements in the LEDA source were taken with both RFA apertures in place (as depicted in figure 2) and their radius decreased to 0.88 cm. The distance d is now 31.7 cm. The comparison of saturation current with theory is shown in figure 5. Here we had to decrease the transmission factor to T = 0.1 to match the experimental values. This is a factor 4 lower than for Artemis without the inner aperture. Several reasons are conceivable:

- A known misalignment of the LEDA beam.
- Longitudinal velocity components of the created ions (see *Measurements with SuSI* below for discussion).
- Aspect ratio of the ARTEMIS beam.
- Uncertainties of the absolute beam line gas pressure and composition.

But further investigation is necessary.

Despite the small collector currents, it was possible to obtain neutralization spectra for different beam currents (see figure 6) and different beam-line pressures (see figure 7). No significant change in neutralization with increasing current was observed. The neutralization for 3-10 mA lies between 60% and 80% (depending on the analysis method) at a pressure of 4.2E-6 Torr.

This is lower than the reported neutralization factors for high current operation with the LEDA source, but as shown in figure 8 the neutralization factor increases to 89% at higher beam line pressure (which are present at

ISBN 978-3-95450-123-6

high current operations). It has also been reported previously [2] that for lower currents the neutralization factor is dependent on total beam current and drops with current.

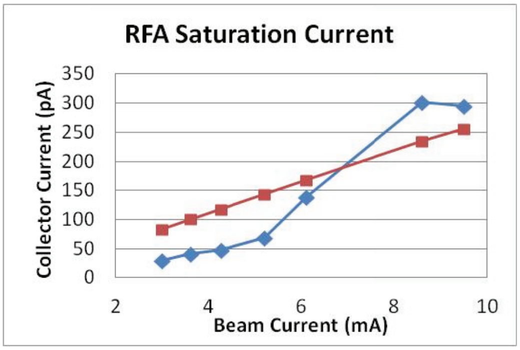

Figure 5: Blue diamonds: RFA saturation current on collector, red squares: Calculation with continuity equation using T = 0.1 (cf. Text).

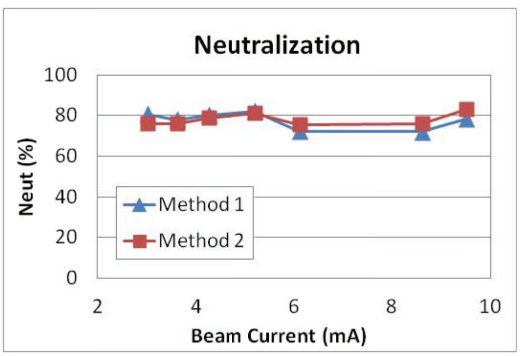

Figure 6: Neutralization level vs. beam current. The pressure in the beam line was 4.2E-6 Torr. For a description of methods 1&2 cf. text.

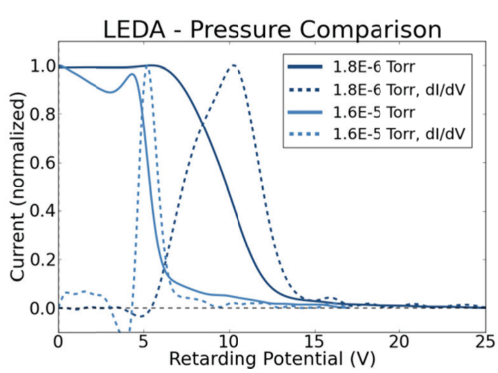

Figure 7: Measured beam potential for two different Ar pressures in the beam line. Beam current = 6.2 mA. The spectrum on the left was taken at the higher pressure. The neutralizations were about 64% for the lower pressure and 89% for the higher pressure.

Measurements with SuSI

When we apply the same analysis methods as in the LEDA source to the spectra obtained with the RFA positioned in the SuSI LEBT (as seen in figure 1), we immediately notice, that the simple assumptions are no longer valid. As an example, figure 8 shows saturation current and calculated neutralization factors as a function of pressure. Larger $\Delta\phi$ as theoretically predicted (with the simple model) for an uncompensated beam lead to slightly negative values for the neutralization at lower pressures. Obviously the round uniform beam approach is over-simplified. What we can conclude with these preliminary measurements, however, is that at this particular location of the SuSI beamline the space charge compensation is very low. We will continue the study, but are also planning to move the detector to a different location on the beam line in the near future.

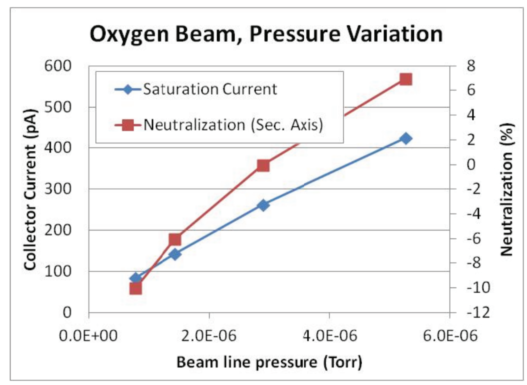

Figure 8: SuSI, oxygen beam, pressure variation. total beam current ~2 mA.

As a first step, the influence of the detector position perpendicular to the beam was investigated. For a round, centered beam, the saturation current should be symmetric about the center position and simulations showed that the neutralization obtained from the spectra should be more or less independent of the position. As can clearly be seen in figure 9, for the SuSI diagnostic box 1 this is not the case. The saturation current peaks at an offset of ~ -15 mm.

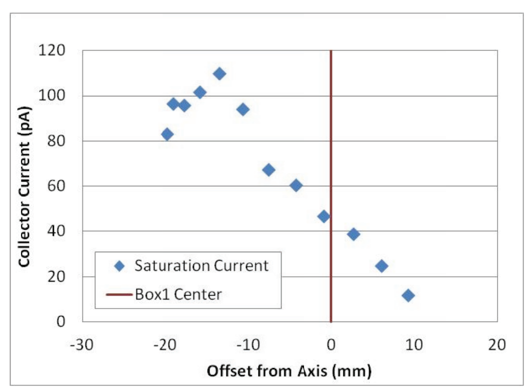

Figure 9: SuSI: RFA saturation current as a function of offset from the chamber center.

The situation in the diagnostic box right after SuSI's extraction system as it is seen in figure 1 is more complex as for the LEDA source. For one, there is a lot less space. Half of the box is filled with the first segment of an

ISBN 978-3-95450-123-6

Einzel Lens (the lens is switched off during the measurements). This changes the longitudinal space-charge potential distribution created by the beam. It actually has a maximum shortly after entering box 1, as can be seen in figure 10 in a potential map created with SIMION's Poisson-solver. This changes the expelled ion's trajectories and consequently the obtained signal.

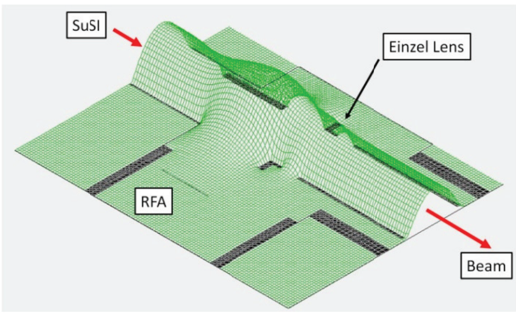

Figure 10: Potential map of beam space-charge potential. The cut is made vertically at the beam-line center.

On the other hand, as mentioned earlier, ECRIS beams from sources using a sextupole magnet have an intrinsic triangular structure and so great care has to be taken to determine whether or not the approximation of a uniformly charged cylinder can be made for these beams. Using SIMION's Poisson solver, a triangular charge distribution can easily be created and used as the beam's space-charge potential as experienced by the secondary ions. Figure 11 shows a simulated RFA spectrum for an oxygen beam with 2 mA total beam current and 25% neutralization as well as a round beam without neutralization compared to a measurement. The triangular beam seems to reproduce the shape of the spectrum better than the round one.

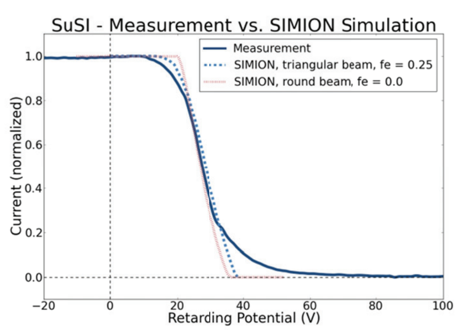

Figure 11: Comparison of a spectrum obtained with SuSI and SIMION simulations. Solid line: Measurement. Dashed line: Assuming triangular beam and 25% neutralization. Dotted line: Assuming round beam without neutralization. Both simulations used the same parameters otherwise.

Finding the right parameters (size, orientation of the triangle, neutralization factor), unfortunately, is a tedious and time-consuming work and we hope to come up with a simpler and faster method to analyze RFA spectra obtained in those problematic measuring locations.

CONCLUSION

Measurements of the beam space-charge compensation for ECR-type ion sources have been conducted using a newly-developed retarding field analyzer (RFA). These measurements have been performed at 3 different ECRIS low energy beam transport (LEBT) systems (ARTEMIS, LEDA, SuSI) for typical pressures and beam currents. The influence of a two-aperture collimation system for a more focused view of the beam on the saturation current $(I_{RFA})_s$ has to be investigated further, as it seems to reduce the $(I_{RFA})_s$ more than expected. Data obtained for a solenoid-only ECR source (LEDA injector source) agrees reasonably well with data presented in [2]. Data obtained for Artemis A and SuSI, the two injector sources of NSCL's coupled cyclotron facility indicate low to no neutralization at those particular measurement positions in the beam line. The influence of the beam shape (triangular) and intrinsic multi-component nature of ECR beams has been observed and will be subject to further investigation as well as it can have significant influence on the neutralization levels obtained from the data. In the future we are hoping to combine these measurements with beam cross-section measurements at the RFA location.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the excellent support from the NSCL's electronical engineering department and the machine shop.

D. Winklehner would also like to thank the Michigan Institute for Plasma Science and Engineering (MIPSE) for providing the MIPSE fellowship that made it possible for him to attend the ECRIS workshop this year.

This work was funded by the Michigan State University and the National Science Foundation.

REFERENCES

[1] I. A. Soloshenko, Rev. Sci. Instrum. 67(4) (1996).
[2] R. Ferdinand et al., PAC'97 (1997).
[3] D. Leitner et al., Cyclotrons'07, (2007).
[4] R. Geller, Electron Cyclotron Ion Sources and ECR Plasmas, (London, IOP Publishing, 1996).
[5] D. S. Todd et al., Rev. Sci. Instrum. 77 (2006).
[6] D. Winklehner et al., Rev. Sci. Instrum. 83 (2) (2012) 02B706.
[7] Z. Q. Xie, Rev. Sci. Instrum. 69 (1998) 625.
[9] J. D. Sherman, LINAC'96 (1996) THP23.
[10] SIMION® 8.1 Ion and Electron Optics Simulation Software http://www.sisweb.com/simion.htm
[11] A. Müller, E. Salzborn, Physics Letters 62A, 6 (1977).

ISBN 978-3-95450-123-6