SPACE CHARGE COMPENSATION MEASUREMENTS IN THE INJECTOR BEAM LINES OF THE NSCL COUPLED CYCLOTRON FACILITY*

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Abstract

In this contribution we report on measurements of space charge compensation (alternatively called “neutralization” here) in one of the injector beam lines of the Coupled Cyclotron Facility (CCF) at the National Superconducting Cyclotron Laboratory (NSCL) using a retarding field analyzer (RFA). The beams were produced by the superconducting electron cyclotron resonance ion source (ECRIS) SuSI. The measured neutralization values were between 0% and 60% and agreed reasonably well with a theoretical prediction using an adaptation of the formula presented by Gabovich et al. [1]. A dependence on beam intensity, radius and pressure could be observed.

INTRODUCTION

Space charge compensation is a well-known phenomenon for high current injector beam lines. For beam lines using mostly magnetic focusing elements and for pressures above 10^{-6} Torr, compensation up to 98% has been observed [2]. However, due to the low pressures required for the efficient transport of high charge state ions, ion beams in ECR injector lines are typically only partly neutralized and space charge effects are present. Current state-of-the-art Electron Cyclotron Resonance Ion Sources (ECRIS) are able to produce many emA of total extracted beam and several hundred eμA in a single species. Thus, realistic beam transport simulations, which are important to meet the acceptance criteria of subsequent accelerator systems, have to include non-linear effects from space charge, but also space charge compensation. In general, the self-electric field of the beam arising from the space charge of the collective of beam particles acts as a defocusing field on the beam.

Space Charge Compensation

Space charge compensation (for positively charged ions) takes place when slow electrons created by the interaction of the beam ions with the residual gas of the beam line accumulate inside the beam envelope (attracted by the positive space charge potential of the beam), thereby lowering the effective potential. The two main processes contributing to the creation of secondary ions and electrons are charge-exchange and ionization. To first order, electrons are created only through ionization. In both cases, slow secondary ions are created which are expelled by the beam potential. By measuring the energy distribution of these secondary ions, the beam potential can be found. By comparison the measured value with the calculated potential of an uncompensated beam, the neutralization factor f_e can be derived.

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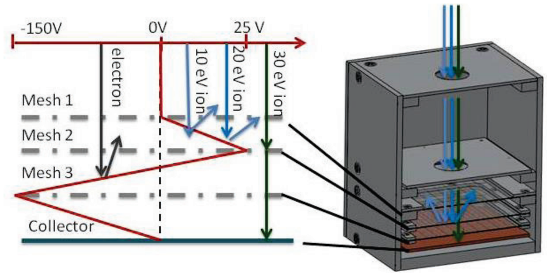

Figure 1: 3D CAD model of the RFA is shown on the right. The picture on the left depicts the working principle of the RFA. The retarding grid is biased at 25 V, the electron suppressor is biased at -150 V. Two 5 mm diameter apertures collimate the incoming secondary ions.

Theoretical Prediction

Following the derivation in [1], the potential difference between the beam center and beam edge ($\Delta\phi = \phi_{center} - \phi_{edge}$) for a compensated beam can be expressed in SI units as:

$$(\Delta\phi)^2 = 3\mathcal{L}\left(\frac{M}{m_e}\right)\left(\frac{\varphi_i}{V_0}\right)\frac{n_b q e^2}{(4\pi\varepsilon_0)^2}\left(\frac{q}{n_g\sigma_e}+\frac{v_b\sigma_i r_b}{2v_i\sigma_e}\right) \quad (1)$$

with $\mathcal{L}$ a Coulomb logarithm, M the beam ion mass, φ_i the gas ionization potential, V_0 the source voltage, v_i the plasma ion velocity, n_b the ion beam density, n_g the residual gas density, σ_i the total ion production cross-section, σ_e the electron production cross-section, and r_b the ion beam radius. From this, f_e can be calculated using:

$$f_e = 1 - \frac{\Delta\phi}{\Delta\phi_{full}} \quad (2) \qquad \text{where:} \quad \Delta\phi_{full} = \frac{I}{4\pi\cdot\varepsilon_0\cdot\beta c} \quad (3)$$

with $\Delta\phi_{full}$ the full potential drop in an uncompensated beam, ε_0 the vacuum permittivity and βc the beam velocity. The theoretical predictions presented here are using an adaptation of this model for lower neutralization by replacing the quasi-neutrality of the beam plasma (beam ions + secondary ions = e^-) with a simple non-neutral condition for the electron density [3], changing Eq. 2:

$$f_e = 1 - \sqrt{f_e}\cdot\frac{\Delta\phi}{\Delta\phi_{full}} \quad (4)$$

MEASUREMENT SETUP

Retarding Field Analyzer (RFA)

The RFA used in this work is a three grid device with a two aperture collimation system at the entrance. Both apertures have a diameter of 10 mm. The three grids are highly transparent (90%) copper meshes (with a combined theoretical transparency of ~73%). A CAD model of the RFA is shown in Fig. 1, as well as a cartoon of the working principle. The three meshes are

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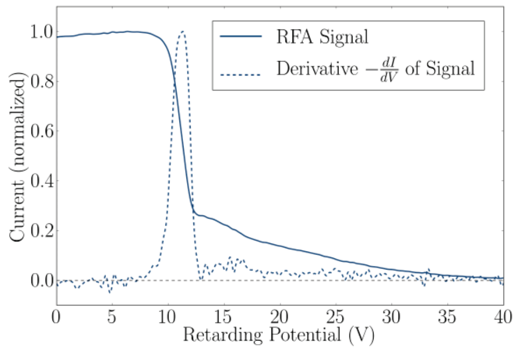

Figure 2: Typical RFA spectrum obtained with SuSI (solid line) and the first derivative (dashed line) which corresponds to the secondary ion energy distribution.

biased as follows: Mesh 1 is at ground potential, there to insure a uniform retarding field. Mesh 2 can be swept from -100 to +200 V while measuring the current on the collector plate. Mesh 3 is at a negative voltage (typically -150 to -450 V) to suppress electrons from the outside as well as electrons created upon impact of the measured ions on the collector plate. By sweeping the voltage on mesh 2, more and more ions are reflected and a spectrum is obtained by plotting the retarding voltage versus the measured collector current. Such a spectrum can be seen in Fig. 2.

Measurement Locations

The RFA was tested in the low energy beam transport line (LEBT) of the LEDA injector source [4], which was set up at the NSCL at MSU in 2012. The LEDA injector source is a microwave plasma ion source with a solenoid mirror field for confinement. The absence of a sextupole magnet (as compared to an ECRIS) leads to axially symmetric 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 [4]. The RFA was mounted perpendicular to the beam (to measure the radially expelled secondary ions) at a position approximately 50 cm downstream of the extraction aperture.

Systematic measurements were then performed in the LEBT of the superconducting ECRIS SuSI [5], one of the injector sources of the CCF. In this context, it should be noted, that the sextupole magnet usually used in ECRIS for radial confinement and plasma stability imposes a unique triangular structure on the beam [6, 7] which has to be taken into account in the analysis of the RFA data. The RFA was installed ~5.1 m downstream of the extraction aperture in a diagnostic box, together with a faraday cup, slit scanner, viewing screen, leak valve, and ion gauge (see Fig. 3). This position is after the analyzing magnet, where essentially only one ion species is present in the beam. With the leak valve the pressure at the measurement location could be adjusted from 10^{-7} Torr to 10^{-5} Torr.

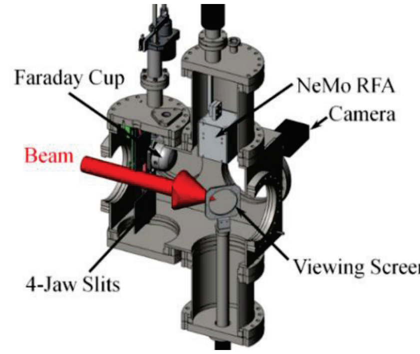

Figure 3: Diagnostic box in the SuSI LEBT with RFA and beam imaging devices.

ANALYSIS METHODS

Realistic Mesh Effects

Due to the finite size of the wires, the distance between wires, and the potential difference between neighboring not straight and influence the measured spectrum as well as the transmission through the wires [3,8,9].

The following effects must be taken into account when the spectra are analyzed:

- Formation of an effective potential between the wires of the mesh, which is lower than the applied voltage and depends on the distances and voltages of the neighboring meshes [8]. This effect shifts the spectrum towards higher potential, but does not influence the measurement of the beam potential.
- The lens effect from the potential depressions between the wires can change the measured ions' trajectories and thus the transmission. This introduces an energy spread that leads to a finite detector resolution [9].
- Depending on the potentials on grid 2 and 3, the ion energies, and whether or not a negative bias is applied to the collector ('faraday cup') plate, ions can be reflected back from the collector after making it past the retarding field grid.

In addition to mesh effects, in the present of magnetic fields the transmission into the detector can be reduced due to the combination of slightly curved trajectories and the two-aperture collimator system. This makes the transmission energy dependent and must be considered as well.

Data Analysis

In order to account for mesh effects (and in the LEDA case for residual magnetic fields), high resolution simulations were performed with SIMION 8.1 [10] to obtain a set of normalized detector transmission curves depending on secondary ion energy and the bias voltage applied to mesh 3 (electron suppression). The spectra were analyzed in a least squares fit method by generating secondary ion energy distributions f(E) and folding them with the detector transmission curves. For the round LEDA beams and also for some of the SuSI beams which were tuned for axisymmetry at the measurement location,

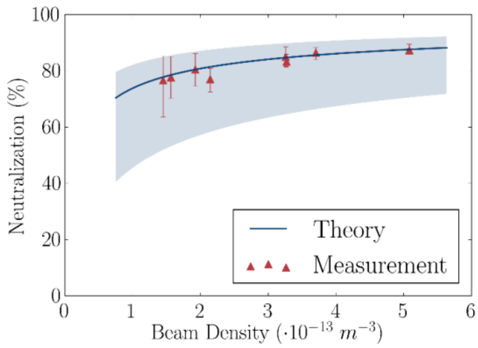

Figure 4: Neutralization factors of a proton beam for different beam densities in the LEBT of the LEDA injector source. The solid line indicates the model prediction and the shaded area the uncertainty due to the not well known cross sections and uncertainties in the pressure measurement.

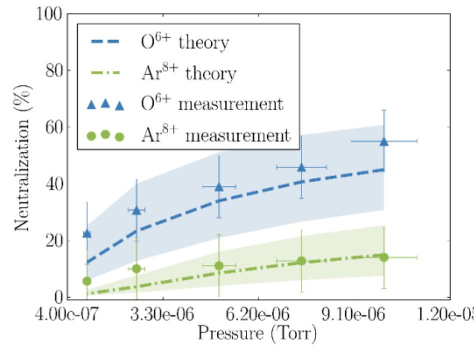

Figure 5: Neutralization factors of a 200 eμA Ar^{8+} and a 700 eμA O^{6+} beam at different vacuum pressures in the LEBT of the SuSI source at NSCL. The dashed lines indicate the model description with the shaded areas being the uncertainty due to the not well known cross sections.

f(E) was obtained from the theoretical distribution of a uniform round beam (with one or two beam components). For the more complicated triangular shapes of the SuSI measurements, a more complex method was introduced. As seen in Fig. 3, a (4-jaw) slit scanner and a beam viewer were present at the measurement location. The obtained beam profiles were used in SIMION to generate a charge distribution according to the respective beam. The beam potential was calculated with the new Poisson-solver in SIMION 8.1, and f(E) was obtained for each measurement by particle tracking from the beam envelope to the RFA.

It should be noted that with these methods, structures on the low energy side of the spectra could be reproduced very well. The high energy tail seen in Fig. 2, which was present in all SuSI measurements, unfortunately, could not be explained so far. A background function had to be introduced, which in turn increased the error bars seen in Figs. 4 and 5. The analysis methods are described in detail in [3].

MEASUREMENT RESULTS

LEDA Injector Source

In Fig. 4, the resulting neutralization values of a proton beam extracted from the LEDA injector source are shown. Beam currents from 2.9 mA to 9.4 mA were used in a pressure regime around $2.4 \cdot 10^{-6}$ Torr. The residual gas in the beam line was composed mostly of H_2, with some intermixture of H_2O and N_2. A general trend of increasing neutralization with increasing beam density can be seen. The measurements agree well with the theoretical prediction (solid line) discussed in the introduction, as well as previous measurements with the same source by Ferdinand et al. [2].

SuSI Beam Line

Neutralization was measured for various beams (Ar^{8+}, O^{3+}, and O^{6+}) in dependence of the beam line pressure and the beam current. A sample is shown in Fig. 5 (pressure series for Ar^{8+}, and O^{6+}). Again an increase in neutralization can be seen, this time with increasing pressure. The other sets showed similar trends, albeit not always with the same agreement to theory, which can be attributed to uncertainties about the beam size at the location of the measurement and the cross-sections for secondary ion and electron production.

SUMMARY

Measurements of space charge compensation, performed in the LEBTs of two different ion sources (LEDA and SuSI) using an RFA were presented. The compensation factors showed expected trends of increasing with pressure, beam radius and beam current, and agreed reasonably well with previous measurements [2], and a theoretical prediction using an extension of the model presented by Gabovich et al. [1].

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