Determination of Radial Ion Beam Profile from the Energy Spectrum of Residual Gas Ions Accelerated in the Beam Potential

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Abstract

Residual gas ions (RGI) created from collisions of positive beam ions (BI) with residual gas atoms are accelerated out of the ion beam by its space charge potential. It is demonstrated that with one-dimensional radial symmetry the radial distributions of BI density and space charge potential can be determined from the energy distribution of RGI radially leaving the beam tube. RGI energy spectra were taken with an electrostatic analyser of Hughes-Rojansky type on a 10 keV 1.5 mA He^+ beam. For comparison the radial BI density distribution was determined with a radial wire probe, an electron beam probe and a beam transport calculation based on an emittance measurement located downstream.

1 INFORMATION INCLUDED IN RGI ENERGY SPECTRA

1.1 Dependencies of BI number density, current and space potential

Cylindrical symmetry is assumed throughout. We start from a positive ion beam with radial distribution of number density $n_{BI}(r)$ inside a tube of radius r_{wall}. The space potential is defined to be zero at r_{wall}. The beam current inside radius r is given by

$$I_{BI}(r) = \frac{k\, q_{BI}}{\varepsilon_0} \int_{r'=0}^{r} n_{BI}(r')\, r'\, dr' \tag{1a}$$

with $k \equiv 2\pi\varepsilon_0 v_{BI}$ and q_{BI}, v_{BI} charge and velocity of BI. The total beam current is defined as $I_{BItot} \equiv I_{BI}(r_{wall})$.

The space potential follows from the Maxwell-Eq. as

$$\Phi(r) = \frac{1}{k} \int_{r'=r}^{r_{wall}} \frac{I_{BI}(r')}{r'}\, dr' . \tag{2a}$$

(It is assumed that the contribution of other particle species to the space potential is negligible. This is true for RGI if the residual gas density is low. For electrons this is valid as long as space-charge compensation does not occur or is suppressed.)

Differentiation of Eq. (2a) and looking at Φ instead of r as the independent variable yields the current from that part of the beam where the potential is higher than Φ:

$$I_{BI}(\Phi) = -k \frac{r(\Phi)}{\frac{dr(\Phi)}{d\Phi}} . \tag{3a}$$

In practice Eqs. (1a), (2a) and correlation of the results are sufficient to calculate $I_{BI}(\Phi)$ from $n_{BI}(r)$.

To perform the calculation in the opposite direction Eqs. (1a), (2a) are rewritten by differentiation as

$$n_{BI}(r) = \frac{\varepsilon_0}{q_{BI}\, k} \frac{1}{r} \frac{dI_{BI}(r)}{dr} \tag{1b}$$

$$I_{BI}(r) = -k\, r \frac{d\Phi(r)}{dr} \tag{2b}$$

and Eq. (3a) is rewritten by integration

$$-k \int_{\Phi'=0}^{\Phi} \frac{1}{I_{BI}(\Phi')}\, d\Phi' = \int_{\Phi'=0}^{\Phi} \frac{\frac{dr(\Phi')}{d\Phi'}}{r(\Phi')}\, d\Phi' = \ln \frac{r(\Phi)}{r_{wall}}$$

and expressing as the exponent

$$r(\Phi) = r_{wall}\, e^{-k \int_{\Phi'=0}^{\Phi} \frac{1}{I_{BI}(\Phi')} d\Phi'} . \tag{3b}$$

In practice Eq. (3b) and correlation of its results to $I_{BI}(\Phi)$ together with Eq. (1b) are sufficient to calculate $n_{BI}(r)$ from $I_{BI}(\Phi)$.

1.2 Energy spectrum of RGI at the beam tube wall

A residual gas present in the beam tube undergoes ionisation and charge exchange by the BI. RGI are produced at a local source strength

$$\dot{n}_{RGI}(r) = n_{BI}(r)\, n_{RGA}\, \sigma_{RGI}\, v_{BI} \tag{4}$$

with σ_{RGI} production cross section of RGI. (The number density of gas atoms n_{RGA} is assumed to be homogeneous. This holds as long as thinning of the background gas by the ionisation can be neglected. This is the case if

$$\frac{2\, I_{BItot}\, \sigma_{RGI}}{\pi\, r_{beam}\, q_{BI} \left\langle \left| v_{RGA} \right| \right\rangle} << 1 \tag{5}$$

with r_{beam} radius of the ion beam and v_{RGA} thermal velocities of gas atoms.)

From Eqs. (4), (1a) follows the line current (along the beam) of RGI produced inside radius r (or at potentials higher than $\Phi(r)$) as

$$I'_{\mathrm{RGI}}(r) = I_{\mathrm{BI}}(r)\,\frac{q_{\mathrm{RGI}}}{q_{\mathrm{BI}}}\,n_{\mathrm{RGA}}\,\sigma_{\mathrm{RGI}} \tag{6}$$

with q_{RGI} charge of RGI. The total line current is defined as $I'_{\mathrm{RGItot}} \equiv I'_{\mathrm{RGI}}(r_{\mathrm{wall}})$. Moreover is valid

$$I'_{\mathrm{RGI}}(r)/I'_{\mathrm{RGItot}} = I_{\mathrm{BI}}(r)/I_{\mathrm{BItot}}\,. \tag{7}$$

The RGI created by the beam are accelerated radially outwards by space-charge forces. The acceleration voltage Φ_{acc} a RGI has experienced when reaching the beam tube wall is determined by the space potential at the location of its creation:

$$\Phi_{\mathrm{acc}}(r) = \Phi(r) \tag{8}$$

It is assumed now that the kinetic energy of the RGI at the point of creation can be neglected. (For the case that the space-potential height is above 1 V this is true at least for monoatomic gases where the initial energy stems predominantly from the thermal movement of the gas atoms.) Therefore an "energy"-analyser (EA) located at the beam tube wall or outside the beam tube will just measure the acceleration voltage $\Phi_{\mathrm{acc}}(r)$ experienced by a RGI *due to the space potential*. ("energy" is set in quotation marks when acceleration voltage is meant.)

The integral "energy"-spectrum of the RGI at the beam tube wall $I'_{\mathrm{RGI}}(\Phi_{\mathrm{acc}})$ (i. e. the line current of RGI with acceleration voltages greater than $\Phi_{\mathrm{acc}}(r)$) is given by Eqs. (1a), (2a), (6), (8).

1.3 The opposite way: deduction of BI density distribution from RGI "energy"-spectrum

The combination of Eqs. (1b), (3b) with Eq. (7) yields

$$n_{\mathrm{BI}}(r) = \frac{\varepsilon_0\,I_{\mathrm{BItot}}}{q_{\mathrm{BI}}\,k}\,\frac{1}{r}\,\frac{d\left(I'_{\mathrm{RGI}}(r)/I'_{\mathrm{RGItot}}\right)}{dr} \tag{1c}$$

$$r(\Phi) = r_{\mathrm{wall}}\,\mathrm{e}^{-\frac{k}{I_{\mathrm{BItot}}}\int_{\Phi'=0}^{\Phi}\frac{1}{I'_{\mathrm{RGI}}(\Phi')/I'_{\mathrm{RGItot}}}\,d\Phi'}\,. \tag{3c}$$

By the use of Eqs. (8), (3c), (1c) the radial distributions of number density $n_{\mathrm{BI}}(r)$ and space potential $\Phi(r)$ can be deduced from an integral "energy"-spectrum $I'_{\mathrm{RGI}}(\Phi_{\mathrm{acc}})$ and the total beam current I_{BItot} (and of course q_{BI}, v_{BI}, r_{wall}). (It is possible to replace I_{BItot} via Eq. (6) by I'_{RGItot}, q_{RGI}, n_{RGA}, σ_{RGI}. Nevertheless this is not recommendable since n_{RGA} often cannot be measured with good accuracy at the position of the EA and the analyser efficiency sometimes is lower than theoretically expected for reasons partly not understood.)

1.4 Differential energy analyser

RGI leaving the beam tube by a window fell on the entrance slit of an electrostatic EA of Hughes-Rojansky type (corrected 127° segment of cylinder condensator) [1]. The amplitude of the differential "energy"-spectrum is given by (9)

$$-\frac{dI'_{\mathrm{RGI}}(\Phi_{\mathrm{acc}})}{d\Phi_{\mathrm{acc}}} = \frac{I_{\mathrm{det}}(\Phi_{\mathrm{acc}})}{\Phi_{\mathrm{acc}}\,\eta(\Phi_{\mathrm{acc}})}\,\frac{r_{\mathrm{ref}}}{d_{\mathrm{slit}}\,z_{\mathrm{EA}}\,\varphi_{\mathrm{EA}}/2\pi}$$

and the detected "energy" itself is given by

$$\Phi_{\mathrm{acc}} = \frac{U_{\mathrm{EA}}/2}{\ln\left(r_2/r_1\right)} \quad \text{with} \tag{10}$$

I_{det}	RGI current passing both slits of the EA
$r_{\mathrm{ref}} = \sqrt{r_2\,r_1}$	radius of reference path through EA
r_1, r_1	radii of inner and outer electrode of EA
d_{slit}	width of entrance and exit slits
z_{EA}, φ_{EA}	dimension of entrance aperture in axial and azimuthal direction (ref. to beam)
$\pm U_{\mathrm{EA}}/2$	voltages applied to outer and inner electrode.

The decrease of the detected RGI current due to the combined effect of the limited acceptance angle $\pm\alpha_{\max}$ of the EA (in one coordinate) together with the small angles of the incident RGI trajectories introduced by the initial thermal velocities of the newly born RGI (with mean kinetic energy W_{th}) is reflected by the factor

$$\eta(\Phi_{\mathrm{acc}}) = \mathrm{erf}\left(\sqrt{\frac{\Phi_{\mathrm{acc}}}{W_{\mathrm{th}}/q_{\mathrm{RGI}}}}\right)\sin\alpha_{\max}\,. \tag{11}$$

The differential "energy" spectrum is derived from the measured dependency $I_{\mathrm{det}}(U_{\mathrm{EA}})$. The integral "energy" spectrum follows as

$$I'_{\mathrm{RGI}}(\Phi_{\mathrm{acc}}) = \int_{\Phi'_{\mathrm{acc}}=\Phi_{\mathrm{acc}}}^{\Phi_{\mathrm{a}}}\frac{-\,dI'_{\mathrm{RGI}}(\Phi'_{\mathrm{acc}})}{d\Phi'_{\mathrm{acc}}}\,d\Phi'_{\mathrm{acc}}\,. \tag{12}$$

1.5 Combination with other information

In the problem under discussion from one of the functions $n_{\mathrm{BI}}(r)$, $\Phi(r)$, $I'_{\mathrm{RGI}}(\Phi_{\mathrm{acc}})$ the two others can be derived. (This holds even if a non-neglectable fraction of the space charge is provided by RGI because under the above assumptions the radial density distribution of RGI is fully determined.) In the presence of compensating electrons two of the dependencies $n_{\mathrm{CE}}(r)$, $n_{\mathrm{BI}}(r)$, $\Phi(r)$, $I'_{\mathrm{RGI}}(\Phi_{\mathrm{acc}})$ are needed to derive the others. It has been attempted to derive the radial density distribution $n_{\mathrm{CE}}(r)$ of compensating electrons or the total charge density (equivalent to $\Phi(r)$) in a partly space-charge compensated beam via the three 2-out-of-3 combinations of $n_{\mathrm{BI}}(r)$, $\Phi(r)$, $I'_{\mathrm{RGI}}(\Phi_{\mathrm{acc}})$ [2]. The success of this kind of combination was limited due to the accumulation of errors.

2 APPARATUS

Measurements were performed at a drifting rotational symmetric 10 keV 1.5 mA He^+ ion beam passing a cylindrical test chamber of 30 cm length and 10 cm diameter. In the central plane of the chamber the radial distribution of space potential was measured with an electron beam probe [3, 4], the RGI "energy" spectrum was taken with the EA and a radial wire probe (Ø 0.7 mm) could be moved radially through the beam. (The probe current was measured while the probe was biased to +200V in order to prevent secondary electron emission.) 30 cm downstream it was possible to measure beam emittance and profile. The beam current was measured with a Faraday-cup at the chamber entrance. An electrostatic einzel lens was used to focus the beam behind the ion source. Its strong aberrations resulted in a characteristic beam profile including a central peak and a thin halo. The halo was partly cut off by the entrance aperture of the test chamber and therefore had a sharp boundary inside the chamber. Space-charge compensation was prevented by a positively biased circular electrode following the entrance aperture. Negatively biased electrodes at both ends of the chamber prevented secondary electrons from entering. The background gas was helium with a pressure of $6.9 \cdot 10^{-5}$ hPa in the test chamber. A detailed description of the apparatus and the diagnostics is given in Refs. [2, 5].

3 EXPERIMENTAL RESULTS

The derivation of the radial density profile of the beam from a measured RGI "energy"-spectrum is depicted in Fig. 1. An indication of the good quality of the spectrum is its sharp edge at the high energy end. (a vertical drop is predicted from theory.) The sharp edge of the halo and details in the radial density profile are clearly visible. The height of the central peak depends on the sharpness of the edge of the spectrum and should not be taken too seriously at radii below 1 mm. The overall height and width of the density distribution is dependent on the value of the total beam current used in the derivation as demonstrated in Fig. 2.

For comparison the results of three independent diagnostics are shown in Fig. 3. The radial density distribution derived from the electron beam probe measurement is cut off due to the limited range of the impact parameter between electron and ion beam. The on-axis density is not shown due to the divergence of the inverse Abel-transformation at $r = 0$.

The beam profile derived from the downstream emittance measurement (Fig. 4 a) by a beam transport calculation (taking into account space-charge forces and boundary conditions) is cut off due to the limited area covered by the emittance scanner.

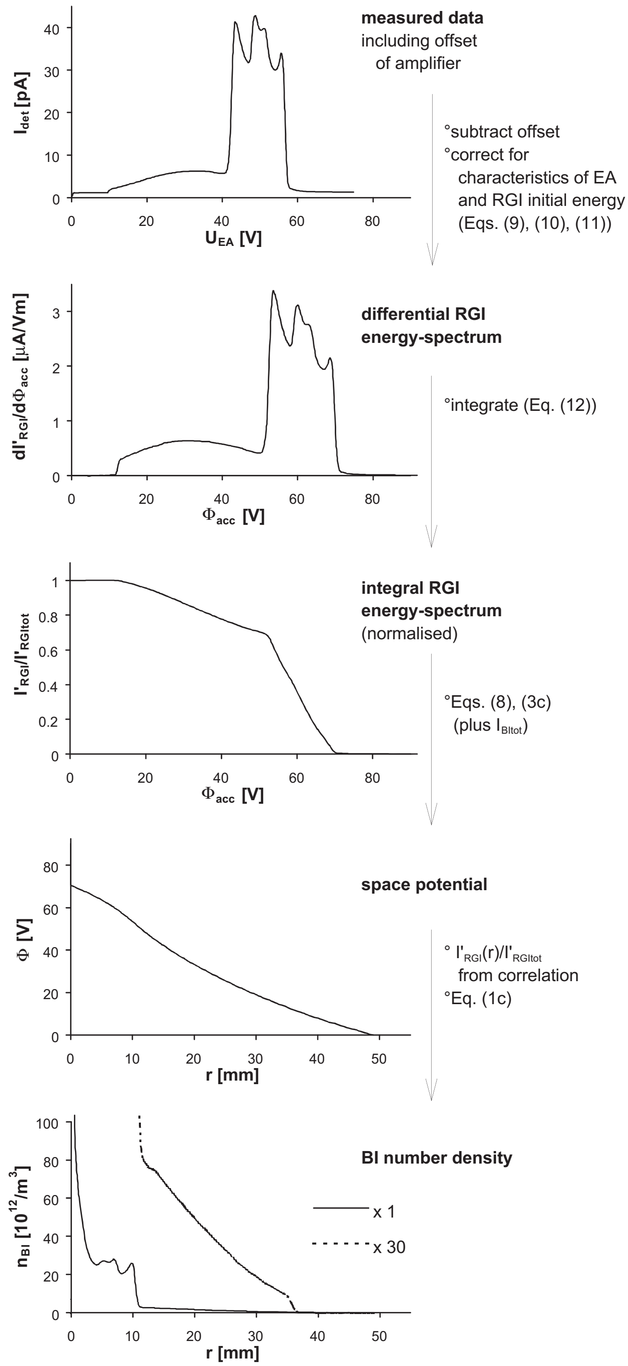

Figure 1: Derivation of radial beam profile.

Differentiation of the current to the radial wire probe with respect to the probe tip position again yields the beam profile. The edge of the halo is visible at the right end. Its position was reproducible although the measured data were very noisy and had to be smoothed. (Beam and probe position were adjusted within ±1 mm.)

The two-dimensional beam profile measured downstream is shown in Fig. 4 b, c for the beam decompensated (as in Figs. 1 to 3) and space-charge compensated in the test chamber. (Edge of halo outside scanned region in both cases.) The lower space-charge forces resulted in a higher central peak. In the center of the test chamber where the (difference of) space-charge forces have had an effect on the beam only along a short distance, the profile resembles Fig. 4 c for all degrees of compensation.

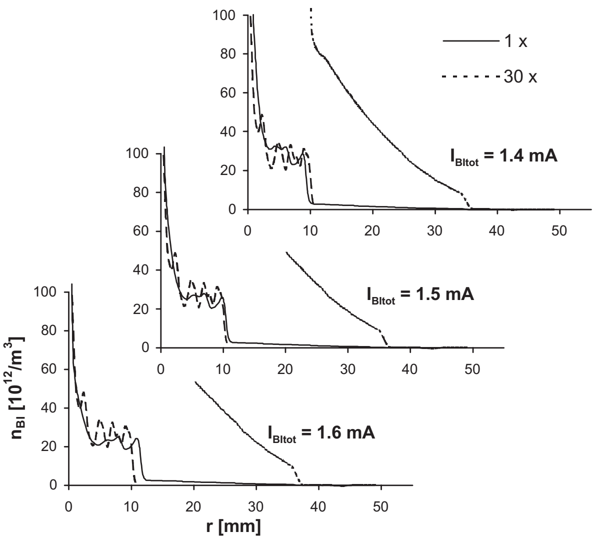

Figure 2: Dependency of derived beam profile on the assumed value of total beam current. (Measured current: 1.5 mA. For comparison, dashed line: beam profile derived from emittance measurement.)

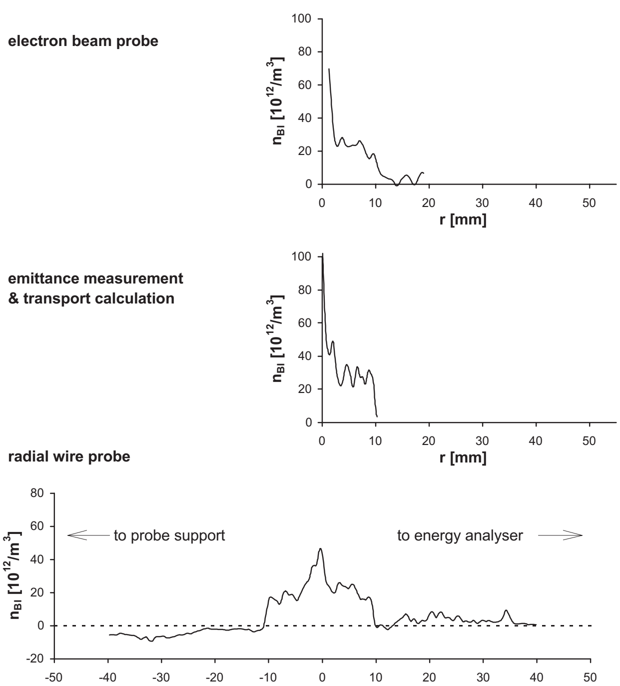

Figure 3: Results of three independent diagnostics at the same beam.

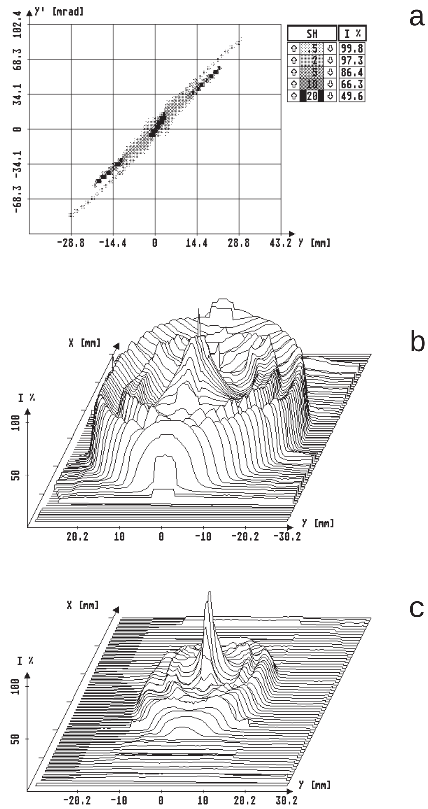

Figure 4: a, b: Emittance and beam profile of the decompensated beam measured downstream; c: beam profile of compensated beam.

Under the present well defined experimental conditions (cylindrical symmetry, low beam noise, no space-charge compensation, low electric and magnetic stray fields, no charging of isolated or dielectric surfaces) the derivation of the beam profile from the RGI "energy"-spectrum provides good spatial resolution without disturbing the beam.

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