EVALUATION OF SPACE CHARGE NEUTRALIZATION IN A HIGH PERVEANCE INJECTION SYSTEM WITH SOLENOIDS*

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Abstract

High perveance ion beams are of main interest for injection into RFQ-systems e.g. and commonly used magnetic low energy transport systems allow plasma build-up, which results in a highly space charge compensated beam. A system has been set up using a duoplasmatron type source (10 keV He^+, 3mA) followed by a solenoid system. The space charge potential of the beam is evaluated by residual gas ion analyzers outside the magnetic lens and by analyzing emittance measurements. With a series of cylindrical electrodes we were able to decompensate the beam partly or totally at different locations, causing transverse emittance growth. Experimental results and preliminary theoretical descriptions will be given.

Introduction

Magnetic focusing elements like quadrupoles, solenoids and magnetic beam manipulating devices such as dipoles, kickers and steering magnets are commonly used in high current beam transport systems.

At normal operating gas pressures ranging from 10^{-3} to 10^{-6} mbar the beam space charge potential of a positive ion beam is significantly lowered by trapping of low energy electrons, created via Coulomb collisions of beam ions with the residual gas atoms. The ionized gas atoms are expelled from the beam. Depending on the ionization cross section σ_i (10^{-16}-10^{-15} cm^2), the beam velocity v and the density of the residual gas atoms n, the lower limit of the neutralization rise time τ is given by $\tau = 1/(vn\sigma_i)$, which is in the order of µsec to msec for keV beams.

The space charge potential of a positive dc ion beam can be derived easily by solving the Poisson equation, giving

$$\Delta\Phi_{total} = \Delta\Phi_{beam} \cdot (1 + 2 \ln R/a) \quad \text{and}$$

$$\Delta\Phi_{beam} = N \cdot \frac{I}{4\pi\varepsilon_0 v} . \qquad (1)$$

Here $\Delta\Phi_{total}$ is the potential difference between beam axis and beam pipe with radius R, $\Delta\Phi_{beam}$ the inner beam potential and a the beam radius. $\Delta\Phi_{beam}$ depends on the ion current I and the beam velocity v. N is a function of the charge density distribution [1]. N equals 1 for a homogenious density and increases for peaked distributions (N = 57/30 for a conical distribution e.g.).

Heating of the trapped electrons and the non zero creation energy cause a significant increase of τ and necessarily a full compensation cannot be reached [2,3]. Estimations of achievable degrees of compensation have been given by Holmes [2] and Gabovich[4].

For dc beams at ion source extraction energy high compensation rates (even 90-99%) can be obtained, thus reducing the beam perveance drastically. Although the neutralization process is quite helpful to reduce necessary focusing strengths or even allows focused transport of very high intensities at all, the transverse rms emittance is highly affected [5].

Sources of transverse rms emittance growth have been clearly identified [6,7], namely aberrations caused by nonlinear fields of the transport channel and charge density redistribution of the beam, thus minimizing the internal field energy of the ions in their own space charge field. For a constant or periodic focusing of a round beam the increase of the transverse rms emittance ε_{rms} (see below for definition) along the beam path z is given by [8]

$$\frac{d}{dz}\varepsilon_{rms} = -2K < r^2 > \frac{d}{dz}\frac{W-W_u}{w_0} , \qquad (2)$$

where K is the beam perveance, $<r^2>$ the square of the rms beam size. $(W-W_u)/w_0$ is a normalized dimensionless parameter, which relates the nonlinear field energy to different beam profiles. The redistribution of beam charge density causes an energy transfer from field energy to transverse kinetic energy, thus increasing the rms emittance. This process is adiabatic in the case of an unneutralized beam and occurs once (after extraction), if only linear external fields exist.

At first sight this looks quite favorable in the neutralized beam case. First, the perveance and therefore the nonlinear field energy is much smaller and second, smaller mean beam radii can be achieved. On the other hand, charge density redistribution in partly compensated beams means rearrangement of both ions and electrons to give a linear selfconsisting space charge field. Unfortunately the electrons are not cold enough to be pinned directly to the ions. The thermal velocity distribution of the electrons can easily cause broader electron distributions in space compared to the ion distribution, resulting in a net negative charge density outside the beam. This has been demonstrated in Frankfurt using an electron beam probe [9]. Rearrangement of the space charge distribution therefore does not necessarily end up in a homogenious distribution. Moreover the process is not adiabatic. The loss and the creation of electrons is a dynamic process and highly influenced by energy exchange between external fields and the beam. The variation of the space charge neutralization rate, caused by changing pressure or even only by variing beam radii, or the local decompensation due to electric fields is a continous source for emittance degradation. Measurements at GSI with a partly compensated 190 keV Ar^+ beam indeed have shown significant increase of emittance [10].

Experimental Set Up

A beam transport experiment has been set up (fig. 1), using a plasma beam ion source [11]. The source is based on a duoplasmatron plasma generator and an additional magnetic solenoid for further plasma compression and is able to produce a hydrogen beam with a fraction of more than 90% of H^+. Instead of hydrogen we extracted Helium to obtain a beam containing He^+ ions only in order to avoid an ion mixed beam and different focal lengths of the adjacent magnetic line. With a common single gap accel/decel extraction system we were able to extract more than 3 mA at 10 kV extraction voltage.

The low extraction voltage has been chosen to obtain a short focal length and a small beam waist behind the used magnetic solenoid. Nevertheless the beam perveance is rather high and e.g. equivalent to a hydrogen beam of more than 65 mA at 50 keV.

To allow for current and emittance measurements behind the source and in front of the solenoid, the magnetic lens is located appr. 40 cm downstream. Measurements of current and emittance could also be done behind the solenoid. The solenoid is based on a two gap- and totally iron capsulated construction and has been especially designed for low aberration transport [12]. The solenoid provides a maximum field on axis of 8.5 kG at 72 kAturns (effective length 80 mm).

The emittance measurements (vertical plane only) have

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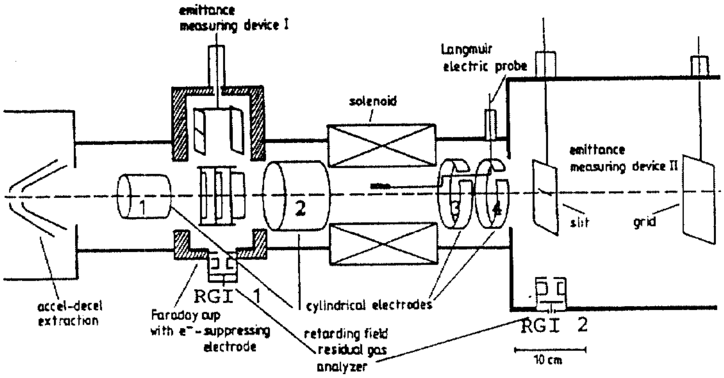

Fig. 1: Schematic drawing of the experimental set up

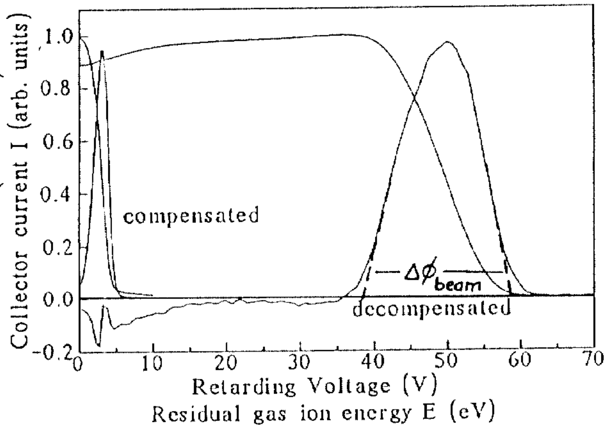

Fig. 2: Measured integral and differential residual gas ion currents versus retarding voltage V and ion energy E for the compensated and decompensated beam (1.5 mA, He,$^+$ 10 keV)

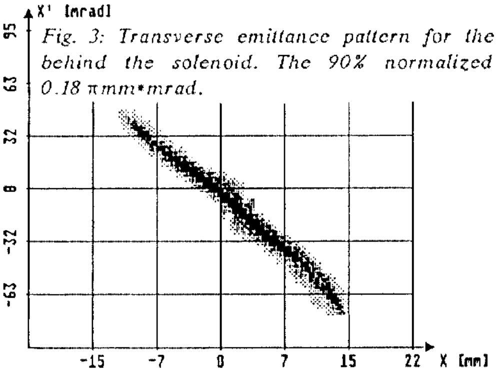

*Fig. 3: Transverse emittance pattern for the compensated beam behind the solenoid. The 90% normalized rms emittance is 0.18 π mm*mrad.*

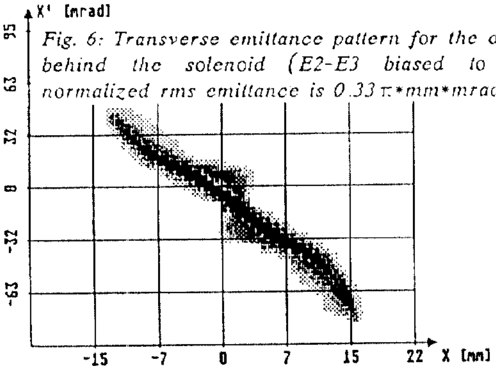

*Fig. 6: Transverse emittance pattern for the decompensated beam behind the solenoid (E2-E3 biased to +50V). The 90% normalized rms emittance is 0.33 π*mm*mrad.*

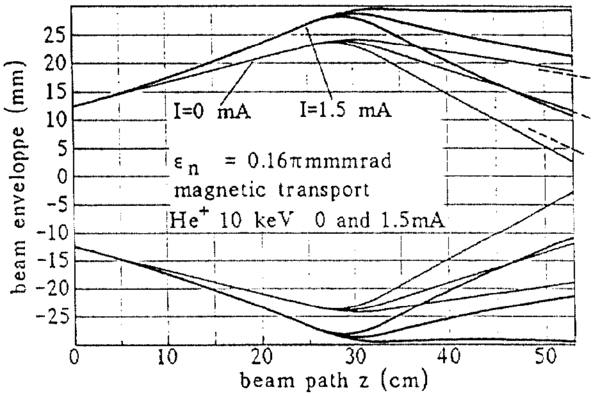

Fig. 4: Beam enveloppes in the transport line for 1.5mA and zero current and three different focusing strengths (B_0 = 3.4, 4.1, 4.9 kG). The dashed lines mark the experimental values obtained from emittance measurements.

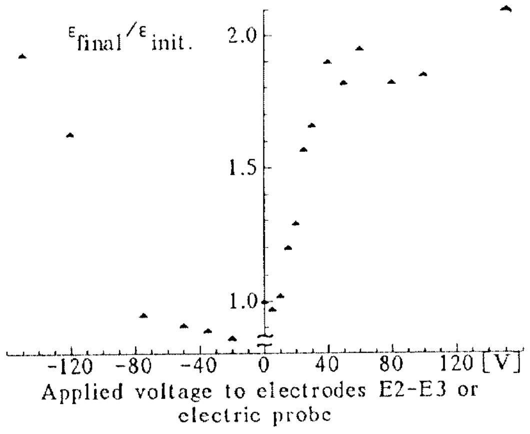

Fig. 7: Ratio of final and initial transverse emittance versus electrode and probe bias voltage. For explanation see text.

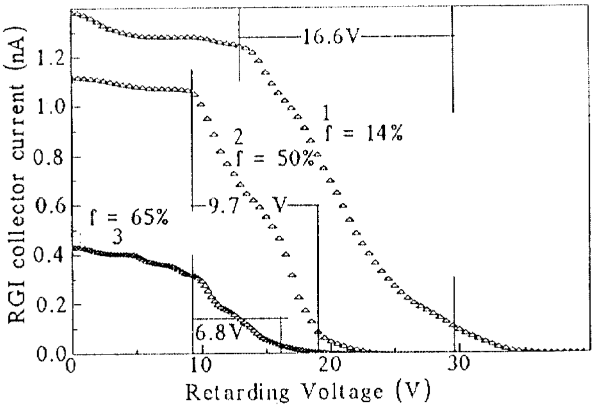

Fig. 5: Residual gas ion current versus retarding voltage of the spectrometer and resulting degrees of compensation f. Curve 1: beam waist position, beam diameter 2 mm. Curve 2: 5 cm in front of waist, beam diameter 8 mm. Curve 3: 5 cm behind waist position, beam diameter 10 cm

been carried out and analyzed with a microprocessor controlled slit/grid system [14].

Two retarding field residual gas ion analyzers have been installed in order to evaluate the energy distribution of the expelled ions produced by beam interaction with the background gas [1,13]. The spectrometers include an electrostatic einzellens (negatively biased) to reject incoming electrons and to optimize the ion beam transport to the grounded collector plate. The ion current is in the order of pA to nA. A Langmuir electric probe has been located inside the lens.

The degree of neutralization could be varied by four (E 1 - E 4) cylindrical electrodes placed in the beam line. The electrodes could be biased independently. The potential of the screening electrode of the extraction system has been set to -1 kV, to prevent electron backstreaming into the source and to allow for beam compensation right after extraction.

The residual gas pressure at source operation was in the order of 10^{-5} mbar.

Experimental Results

Measurements with Space Charge Neutralization

Measurements of the ion source emittance have been reported previously [11] giving a normalized 90% rms emittance of $0.7\pi*mm*mrad$ for protons and $0.35\pi*mm*mrad$ for the He^{+} beam. Here the rms emittance is defined by $4*\sqrt{\langle x \rangle\langle x' \rangle-\langle xx'\rangle}$. We were not able to transport the full beam through the whole line, the main losses occuring in the magnetic lens (aperture diameter 80mm). After the insertion of a collimator in front of the diagnosis box, a 100% transmission of a 1.5 mA beam could be obtained. Measurements with our short-built slit/grid emittance device I were not very accurate due to the small distance between entrance slit and grid wires. Comparable measurements with the large device state, that the divergence half angle is 42 mrad at a normalized emittance $\varepsilon_{n,rms}$ (90%) of $0.16\pi*mm*mrad$ for the collimated beam.

The energy of the residual gas ions expelled from the beam have been measured with the spectrometer RGI 1 (see fig.2). The minimum space charge potential in the beam was 3.3 V, compared to 20 V in the decompensated case with the cylindrical electrode 1 biased to +80 V. The degree of compensation f is given by

$$f = 1 - \Delta\Phi_{beam,compensated} / \Delta\Phi_{beam,uncompensated}.$$

The space charge compensation right after the ion source is as high as 84%. The theoretical value for $\Delta\Phi_{beam}$ and N=1 (see above) is 19.4 V at a current of 1.5 mA, indicating that the beam density after collimation is really homogenious.

The emittance behind the solenoid has been measured at different focusing strengths with the device II. As an example fig.3 shows the transverse emittance, giving $\varepsilon_{n,rms}(90\%) = 0.182\,\pi*mm*mrad$. Numerical enveloppe calculations show a good agreement with the experiment results only, if a highly compensated beam is assumed (fig.4).

Since the charge density is almost homogenious due to the collimation and the beam is neutralized, the transverse emittance growth is rather small. From inspection of the emittance pattern (fig.3) we deduce only small aberrations.

Special attention has been given to the determination of the beam neutralization rate in and near the beam waist behind the lens. Naturally the overall space charge potential depth between axis and beam pipe of a small sized beam is larger compared to a beam with bigger size, which results in a longitudinal potential distribution collecting electrons near the beam waist. Of course the electrons have the same temperature as oustide the waist region, thus a great amount of electrons stay outside the beam and do not contribute to the neutralization of the space charge inside the beam. By variing the focusing strength of the lens, we were able to measure with the spectrometer RGI 2 at and near the focal spot. Measured spectra are shown in fig.5 together with values for the degree of compensation (here an uncompensated $\Delta\Phi_{beam}$ of 19.4 V has been assumed).

Holmes [2] gave a theoretically derived evaluation for the beam potential well $\Delta\Phi_{beam}$, stating that $\Delta\Phi_{beam}$ is proportional to $n_b^{2/3}$ with n_b the ion density. $\Delta\Phi_{beam}$ therefore increases with $(1/a)^{2/3}$, qualitatively explaining the measured poor degrees of neutralization near the focal spot. Large variations of a beam enveloppe in a transport line cause a significant change in the degree of compensation. Exact numerical calculation of the beam behaviour in a given system are therefore not possible.

We also tried to evaluate the space charge potential in the lens itself by using a Langmuir type electric probe. This method has been successfully used in the absence of magnetic fields [13] and has given quite accurate values compared to the spectrometer measurements. Although we made a great effort to understand the complicated electron current characteristics at positive probe voltages in the operating lens, the results were quite poor.

Measurements with Decompensating Electrodes

Transverse emittance growth ocurred in the case of a partially or totally decompensated beam. Positive and negative voltages have been applied to the cylindrical electrodes E2 and E3, resulting in an emittance increase up to a factor of 2 (see fig. 6 e.g). A corresponding increase could be obtained by charging the electric probe. Fig. 7 gives a survey on obtained data for the ratio of final and initial 90% rms emittances. Calculations have shown, that the electrode electric fields have negligable influence on the particle trajectories, thus acting only via the decompensating process.

Even negative voltage bias show increasing emittance, due to the fact, that a displacement of neutralizing electrons in and near the electrodes takes place. A slight reduction of the emittance as well as a reduction of aberrations have been observed for E2-E3 biased to -50 V. Enhanced trapping of the electrons inside the lens and altered optical properties of the lens together with the remaining, probably more linear space charge field, could be an explanation.

Measurements with the spectrometer RGI1 showed, that the degree of compensation in front of the solenoid remains unchanged for an applied voltage of +150 V of E3. The same is valid behind the magnetic lens (E2 biased to +150 V) indicating that the beam is still neutralized in the lens region.

The observed high emittance degradation given in fig. 7 cannot totally be explained by equation (2). The transition of the beam from the unneutralized state to a compensated state in the lens and vice versa and the charge density redistribution correlated to such a tremendous variation of the neutralization rate seems to be the source for additional emittance increase.

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