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EMITTANCE GROWTH IN A MAGNETIC TRANSFER LINE CAUSED BY THE VARIATION OF BEAM NEUTRALIZATION*

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Abstract

A beam transfer line has been set up to investigate the influence of varying space charge neutralization on transverse beam emittance. The system consists of a plasma beam ion source with triode extraction system (10 keV, He^+, 3 mA) followed by a solenoidal magnetic lens. The beam emittance could be measured in front and behind the magnetic lens. Using a series of independently biased cylindrical electrodes we were able to vary the beam space charge potential at different locations in the beam line. The total decompensation of the beam e. g. results in an emittance growth by at least a factor of two. The experimental results will be summarized and a comparison with numerical simulation and emittance growth theory will be given.

Introduction

Emittance degradation and particle losses in the low energy part of an accelerator system is a crucial point. Since the major emittance growth occurs in the accelerator injection system special attention is strongly recommended to keep the loss of beam quality small[1]. The rms emittance (for definition see below) is highly affected by all kinds of nonlinearities of applied external fields and self fields of the beam[2]. If we stick to the LEBT section a careful design of the LEBT elements and probably the use of only a fraction of the available aperture is requested. A source of transverse rms emittance increase due to beam self fields has been clearly identified[3,4]. A space charge density distribution which is not homogeneous necessarily produces a nonlinear space charge field causing the charge density to redistribute towards a more or less constant density profile, thus converting nonlinear field energy into transverse kinetic energy.

Charge density redistribution in partly space charge compensated beams means rearrangement of both ions and trapped electrons (for positive ion beams) to give a linear internal self field. The electron velocity distribution is heated by ion - electron collisions[5]. Therefore the electrons are not cold enough to be exactly pinned to the ion distribution easily causing "broader" distributions compared to the ion density distribution.

The rearrangement of ions under space charge compensation does not necessarily end up in a homogeneous distribution. Moreover the process is not adiabatic, because the creation and loss of electrons is a dynamic process and highly affected by energy exchange between external fields and the beam plasma. The variation of neutralization rate, caused by changing of residual gas pressure or only by variing beam radii is a continuous source for emittance increase. Measurements at GSI with a partly compensated Ar^+ beam indeed have shown significant increase of emittance[6].

Experimental Set Up

The properties of our magnetic transfer line have been reported previously[7]. The system (see fig. 1) contains a modified duoplasmatron ion source with a triode extraction system and a solenoidal lens and is equipped with two emittance measuring devices, two residual gas ion spectrometers (RGI 1, RGI 2) to evaluate the space charge potential depth inside the beam and four cylindrical electrodes (E1-E4). The electrodes can be biased independently to positive or negative potentials and allow for the variation of the degree of neutralization.

We were able to extract more than 3 mA of He^+ at 10 kV extraction voltage, which is equivalent to a beam perveance given by a 50 keV proton beam of 65 mA. The residual gas pressure at source operation was $2*10^{-5}$ mbar.

Unfortunately we were not able to obtain full beam transmission throughout the system. After the insertion of a collimator in front of the diagnosis box, a 100% transmission of a 1.5 mA beam has been reached.

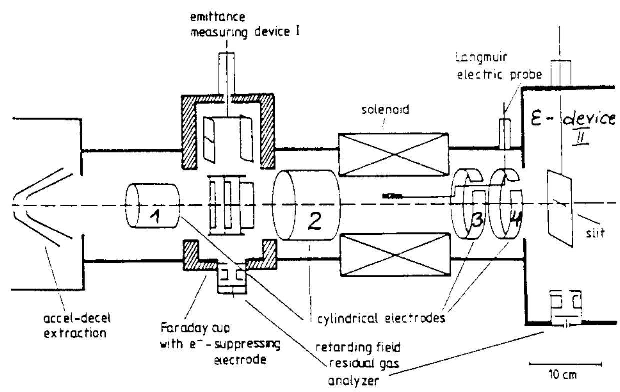

Fig. 1: Schematic layout of the experimental set up

Experimental Results

The evaluation of the beam emittance right after the collimator by inspection of the phase space pattern turned out to be difficult. The emittance is highly affected by some tens percent of neutral particles still present in the beam. Since most of these atoms have been neutralized in the region of high pressure in the first part of the extraction system, a few of them have slightly greater divergence angles compared to the beam ions, thus enlarging the measured phase space area behind the collimator. Moreover the distance between slit and grid of the emittance measuring device I allow only a few wires of the grid to be hit by the beam, leading to a reduced resolution of the system. Measurements of the ion source emittance with the large device II state that the normalized 90% rms emittance ($4*\sqrt{<x^2><x'^2>-<xx'>^2}$) is 0.35 π*mm*mrad. A reduction of the emittance pattern due to the geometry of the collimator gives a normalized emittance $\varepsilon_{n,rms}$(90%) of appr. 0.16 π*mm*mrad and 42 mrad divergence half angle.

The degree of compensation has been evaluated using the spectrometer RGI 1, giving 84% in the neutralized case, corresponding to 3.3 V potential depth in the beam (fig. 2). Roughly 80 V are necessary to decompensate the beam with

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electrode E 1 (20 V total potential depth)[7]. The theoretical value for a beam with homogeneous density and 1.5 mA can be calculated to 19.4 V. This indicates that the ion beam density behind the collimator is almost constant.

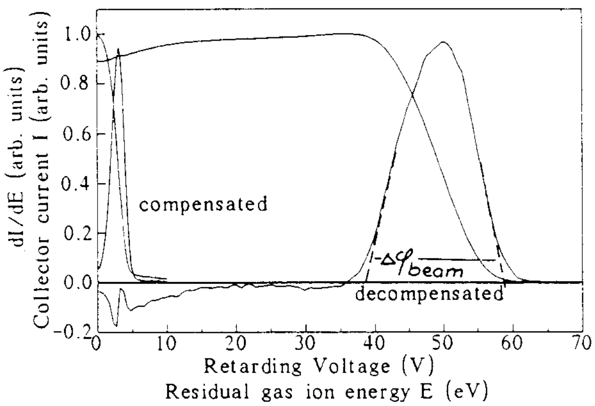

Fig. 2: Measured integral and differential residual gas ion currents versus retarding voltage V and ion energy E for the compensated and decompensated beam (1.5 mA, He^{+}, 10 keV)

The emittance and orientation of the beam has been measured behind the magnetic lens for different focusing strengths under space charge neutralized conditions. As an example fig. 3 shows the obtained transverse emittance pattern. The observed emittances for different lens strengths showed only slight deviations. Numerical enveloppe calculations gave a good agreement with the experimental results only, if a highly compensated beam is assumed[7].

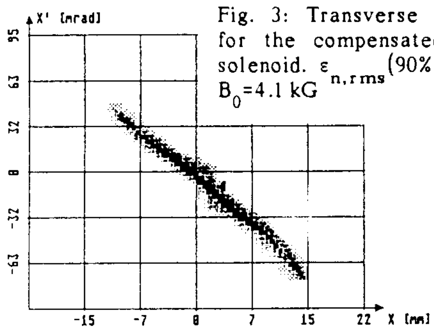

Fig. 3: Transverse emittance pattern for the compensated beam behind the solenoid. $\varepsilon_{n,rms}(90\%) = 0.18\ \pi*mm*mrad$, B_0=4.1 kG

Transverse emittance growth has been observed in the case of a partially and totally decompensated beam (see fig. 4 e.g.). Positive as well as negative voltages have been applied to the electrodes E 1-E 4 in this case. Fig. 5 shows a linear increase of the emittance ratio $\varepsilon_{final}/\varepsilon_{initial}$ (90% values) with the applied positive voltage. Here $\varepsilon_{initial}$ corresponds to the emittance for neutralized transport. The slope levels off at appr. 40 V electrode bias (maximum potential depth between beam axis and outer wall) and stays constant for increasing voltage. Calculations have shown that the electric fields of the electrodes have negligable influence on the particle trajectories, thus acting only via the decompensating process. Even high negative voltage bias showed increasing emittance, due to the fact that only a displacement of compensating electrons in and near the electrodes takes place. A slight reduction of the emittance as well as a reduction of small aberrations near the beam axis (see fig. 3) has been observed for small negative voltage bias. Enhanced trapping of electrons inside the magnetic lens together with a probably more linear space charge field could be an explanation.

Measurements with the spectrometers RGI 1 and 2 showed, that the degree of compensation in front of the solenoid is unchanged if electrode E 3 is set to 150 V and vice versa, indicating that the beam is still neutralized in the lens region.

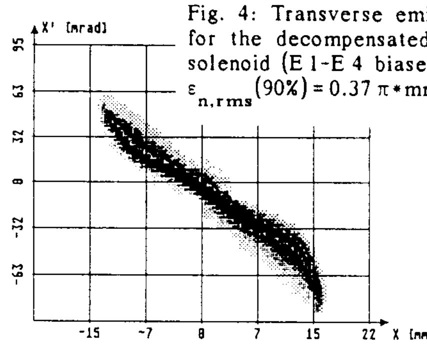

Fig. 4: Transverse emittance pattern for the decompensated beam behind the solenoid (E 1-E 4 biased to 150V). B_0=4.1 kG $\varepsilon_{n,rms}(90\%) = 0.37\ \pi*mm*mrad$

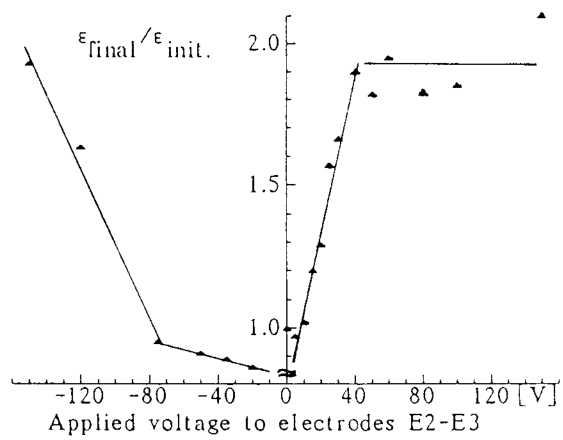

Fig. 5: Ratio of final and initial transverse emittance versus electrode voltage. For explanation see text.

Numerical and Theoretical Studies

As stated earlier in this paper emittance increase is caused by the nonlinearities of external and internal self fields. Therefore the nonlinearity of the acting space charge forces as well as existing sperical aberrations of the solenoid has to be taken into account to explain the observed results.

Measurements at the two-gap iron capsulated lens with 80 mm aperture diameter have been carried out with a pencil beam to evaluate the aberration properties[8]. The existing GSI-version of the particle code PARMILA TRANSPORT (Parmtra) has been extended to allow for the correct particle transformation in the solenoidal lens including spherical aberrations.

Numerical calculations with the code using peaked initial density distributions show emittance increase due to density redistribution under decompensated conditions (aberrations in the lens are neglected) and a drop of the emittance behind the lens, a result stated earlier by R. J. Noble[9].

Calculations with a constant initial density profile, as it is the case in our experiment, and different degrees of compensation gave totally inconsistent results compared to the experiment. In these calculations the reduction of the acting space charge is considered only by the variation of the ion current in the space charge routine of the code.

As mentioned earlier even a constant ion density profile does not necessarily mean that the acting space charge forces are linear under partly neutralized conditions. For a thermal velocity distribution of compensating electrons, Holmes[5] has shown that a Gaussian density distribution of ions and electrons is a selfconsistent solution of the beam plasma, the electron distribution having a more "narrow" shape than the ion distribution:

$$n_i(r) = n_{i0} * e^{-r^2/2<r^2>};\ n_e(r) = n_{e0} * e^{-1.33\, r^2/2<r^2>} \quad (1a,b)$$

Here n_i, n_{i0}, n_e, n_{e0} are the density of ions and electrons as a function of the distance r from the beam axis and the values at the beam center respectively. $<r^2>$ denotes the second moment of the ion distribution. For operating residual gas pressures lower than $5*10^{-5}$ mbar the influence of the residual gas ions can be neglected and n_{i0} equals n_{e0}. Experiments carried out at Culham Laboratory were in good agreement with the theoretical assumptions[5].

Assumed that the consideration of a thermal electron velocity distribution is still valid in the case of a beam with constant density profile, the selfconsisting space charge potential can easily be derived by numerical methods from the Poisson equation including the Boltzmann distribution of thermal electrons (fig. 6). The electron temperature kT has been chosen to 4.2 eV. The resulting potential depth in the beam comes out to be 5 V, which is in the order of our experimental value of 3.3 V. According to equation (1b) the Gaussian density profile of the electrons is also shown in fig. 6, indicating that this solution is a good approximation also in the case of a beam with homogeneous density.

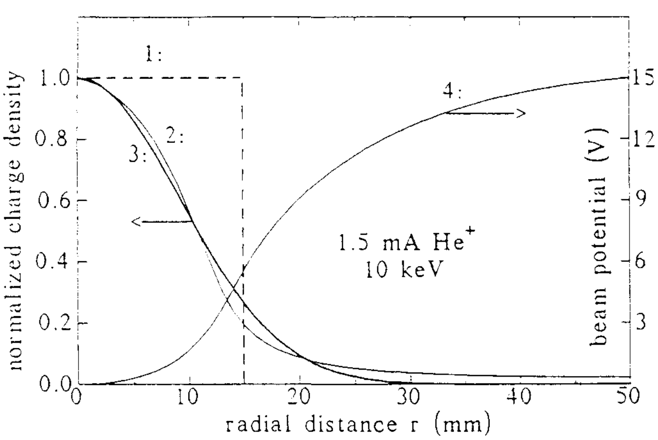

Fig. 6: Calculated normalized charge densities for the ions (line 1), the electrons (line 2 (calculated) and 3 (Gaussian shape)) and calculated beam potential (line 4) versus the radial distance r from the axis. For explanation see text.

The generation of a Gaussian shaped distribution of background electrons have been installed in the Parmtra code. The adaption to the variing beam radii and ion beam density profiles is done via the second moment $<r^2>$ of the ion distribution equivalent to eq. (1b).

The numerical results obtained for various degrees of compensation explain qualitatively as well as quantitatively the experimental results obtained from experiment (see fig. 7a,b) and indicate that the more or less estimated input emittance of $\varepsilon_{n,rms}(90\%) = 0.16\ \pi*mm*mrad$ is quite right.

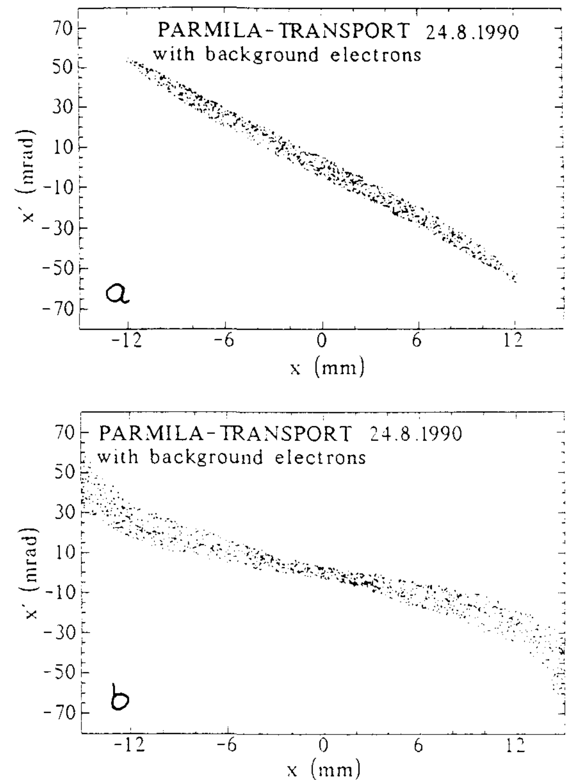

Fig. 7: Numerically derived emittance patterns for the compensated (a) and decompensated (b) beam according to fig 3,4. $\varepsilon_{n,rms}(90\%)$ is 0.175 (a) and 0.350 $\pi*mm*mrad$ (b).

The numerical derived evolution of the rms emittance along the beam path shows a slight increase during the initial drift, an enhanced increase in the lens due to the lens aberrations followed by a decrease of the emittance behind the lens.

Summary

We have shown that space charge neutralization is necessary to keep emittance degradation in a system with large lens aberrations small. This is in this case due to the reduced beam radii in the aberrative focusing element. The experimental, theoretical and numerical results however also indicate that after an initial density redistribution the uncompensated beam transport in the absence of aberrative elements is the only way to avoid further emittance degradation. Unfortunately the field nonlinearities in our magnetic transfer line are dominated mainly by the aberrations of the lens. The argumentation that emittance growth in partly compensated beams is due to the finite electron temperature and a Gaussian shape of the electron distribution causing field unlinearities can therefore only be preliminary.

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