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EMITTANCE DEGRADATION OF INTENSE AND PARTIALLY SPACE CHARGE NEUTRALIZED ION BEAMS†

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Severe transverse emittance growth of intense low-energy ion beams in magnetic transport lines has been observed at different laboratories in the case of a partially space charge neutralized beam. This is unfavorable since magnetic systems are the commonly used transfer lines for the transport of high-perveance beams, as are required for heavy ion inertial fusion drivers.

Rearrangement of the transverse charge density of the ion beam towards a uniform distribution is a known mechanism which leads to initial emittance increase at the front end of a transport system. In the presence of space-charge-compensating electrons, the rearrangement of charge density affects ions and electrons as well, and the finite electron temperature, together with beam envelope and residual-gas pressure variations along the beam line, is believed to cause continuous emittance increase.

Calculations using the tracking code PARMILA TRANSPORT, including the influence of compensating background electrons, have been carried out. First results will be reported and compared to experimental results obtained using a 10-keV, 1.5-mA He^+ beam in a magnetic transfer line.

1 INTRODUCTION

Especially at ion source extraction energies the HIBALL scenario[1] requires high-current (high-perveance) beams. They cannot be transported in low-energy beam transport lines (LEBTs) without an appropriate reduction of space-charge forces by means of space-charge neutralization, and it is strongly recommended that special attention is placed on the low-energy injector part to keep the overall emittance growth low.

A positive-ion beam passing through residual gas ionizes the neutral gas atoms. The produced electrons accumulate in the beam region, thus lowering the acting space charge forces significantly. The positive residual-gas ions (also created by charge exchange) are expelled from the beam. Several attempts have been made by different authors to calculate the distribution of compensating electrons and residual gas ions in the beam plasma by solving the Poisson equation containing the densities of beam ions, compensating electrons and residual gas ions using one-dimensional fluid equations for cold plasmas[2,3,4] or kinetic equations for the residual gas ion behavior.[5] Although the agreement has been excellent in specific cases, general predictions are not reliable and the aid of supporting measurements is still necessary.

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2 EMITTANCE DEGRADATION OF INTENSE BEAMS

Sources of transverse rms emittance growth in high current LEBT lines have been clearly identified[6,7], namely, nonlinear external focusing forces, and nonlinear internal space-charge fields of the beam itself causing a redistribution of the ion-beam transverse density towards a homogeneous one, 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 emittance along the beam path z is governed by the following equation:[6]

$$\frac{d}{dz}\,\varepsilon_{\mathrm{rms}} = -K\langle r^2\rangle \frac{d}{dz}\,\frac{W - W_u}{w_0}, \tag{1}$$

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

At first sight this looks quite favorable for a compensated beam because K and $\langle r^2\rangle$ in Equation (1) are drastically reduced. Compensated beam transport experiments at GSI[8] using a periodic structure of magnetic quadrupoles, however, have shown a severe increase of the rms transverse emittance. Compared to the experiments with an uncompensated transport, emittance growth occurred even in the low current region and could not be explained by rearrangement of the initial beam density distribution.

Charge density redistribution in the case of a partially compensated beam however means rearrangement of both ions and electrons (and even residual gas ions) towards a more linear internal self-field of the beam. The more or less thermal behavior of the compensating electrons (collisions with each other) and the dynamic equilibrium of heating of the trapped electrons by beam ion collisions and radial and longitudinal losses easily cause broader electron densities in space compared to the ion distribution. Measurements with a transverse electron beam probe indeed have shown that there is a region of net negative charge density outside the beam.[9] This process is not adiabatic in the sense that the total energy of the system is not necessarily constant. Therefore, rearrangement of the ion beam density distribution for a compensated beam does not necessarily end up in a homogeneous distribution. Variations of residual gas pressure, ion energy or beam radii change the relations of the charge distributions of all participating species and cause the beam distribution to react continuously to the varying situations.

3 EXPERIMENTAL AND NUMERICAL INVESTIGATIONS

We have set up a small-scale transport experiment in Frankfurt to investigate the beam behavior of uncompensated and compensated ion beams at ion-source extraction energy.[10] A 1.5-mA He^+ beam at 10 keV could be transported with full transmission through a short transport line with one solenoid. With the aid of a collimator behind the ion source extraction region an almost constant transverse beam profile could be obtained. The degree of compensation (80–90%) has been evaluated with residual gas ion spectrometers[11] at moderate beam sizes in front and downstream of the solenoid at operating pressures of approximately 10^{-5} mbar. Figure 1 summarizes the measured degrees of neutralization near and at beam waist position behind the magnetic lens. The measured energy of the residual gas ions expelled from the beam provide information on the total space charge potential $\Delta\varphi_1$ between beam axis and outer wall and on the beam potential $\Delta\varphi_2$ inside the beam. Measurements at beam waist position showed that the beam potential $\Delta\varphi_2$ is almost unneutralized, whereas the lowering of the total potential $\Delta\varphi_1$ remains constant and independent of beam size (Figure 1). The different degrees of compensation f_1 and f_2 are defined via

$$f_{1,2} = 1 - \frac{\Delta\varphi_{1,2}(\text{partially compensated})}{\Delta\varphi_{1,2}(\text{uncompensated})}. \qquad (2)$$

It is worthwhile to mention that the values of f_2 correspond to the degree of compensation inside the beam, telling us to what amount the internal space charge forces are reduced. The overall high values of f_1, however, show that even at the waist position the amount of electrons is approximately the same as anywhere else in the transport line and that most of the electrons stay outside the beam volume. Solving the Poisson equation with kinetic residual gas ions directly confirms this result numerically if the electron temperature is kept constant. Transverse rms emittance growth has been observed in the case of decreasing compensation obtained

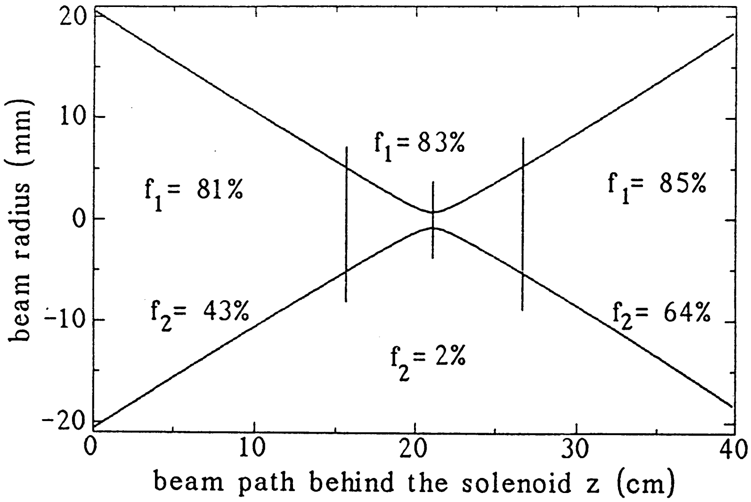

FIGURE 1 Beam envelope downstream of the solenoid versus path length. f_1 and f_2 refer to the different definitions of the degree of compensation (see text).

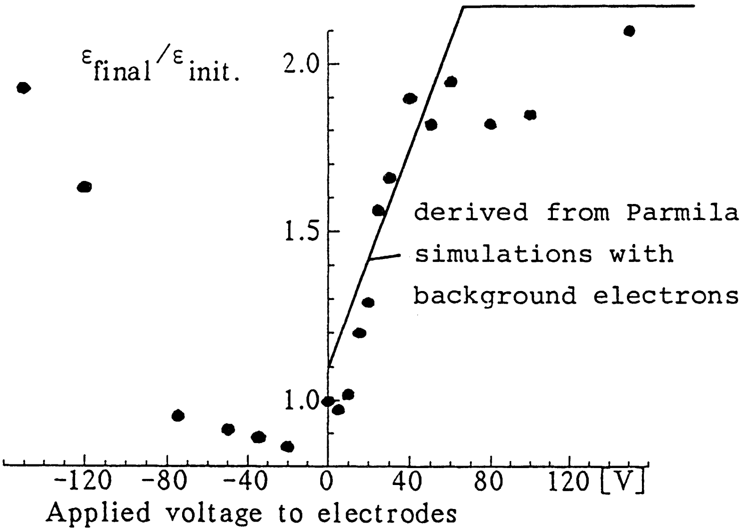

FIGURE 2 Ratio of final and initial transverse emittance versus decompensating electrode voltages.

by biasing cylindrical electrodes in the beam line to positive and negative potentials (Figure 2).

Numerical simulations with the GSI version of PARMILA TRANSPORT, including the coupling of both transverse planes and the consideration of the spherical aberration properties of the lens, were totally inconsistent with the experimental results. In these calculations the reduction of the acting space-charge forces is considered only by the variation of the ion current in the space-charge routine of the code.

Based on the numerical solution of the Poisson equation using kinetic residual gas ion behavior (Figure 3), the PARMILA code has been extended in a first step to allow for the creation of compensating background electrons. The electron distribution $n_e(r)$ is created with Gaussian shape (line 3 in Figure 3) and adapted to the second moment of the ion distribution $\langle r^2 \rangle$

$$n_e(r) = n_{e0} * \exp(-\alpha r^2/2\langle r^2 \rangle). \tag{3}$$

The factor α used in Equation (3) has been evaluated to be $\alpha = 1.33$ to give an acceptable agreement with the calculated electron distribution (line 2 in Figure 3). The numerical results obtained for various degrees of neutralization explain qualitatively as well as quantitatively the experimental results. The numerical derived evolution of the rms emittance along the beam path shows a slight increase during the initial drift, then an enhanced increase in the lens due to the large lens aberrations, followed by a decrease of the emittance beyond the lens.

4 CONCLUSION

Experimental as well as numerical studies have shown that space charge neutralization is necessary to keep the emittance degradation small in a system with large lens

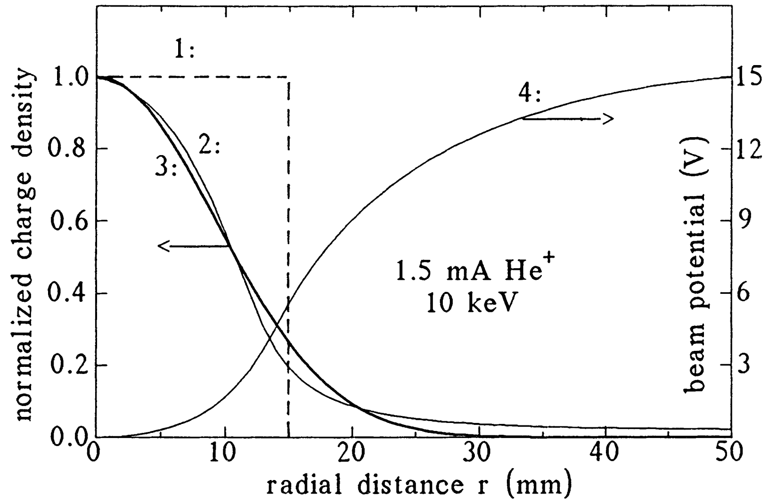

FIGURE 3 Calculated normalized charge densities for the ions (line 1), the electrons (line 2 (calculated) and 3 (adapted Gaussian shape)) and beam potential (line 4) versus distance r from the axis.

aberrations. This is due to the reduced beam radii in the aberrative elements. The experimental, theoretical and numerical studies, however, also indicate that, after an initial density redistribution, uncompensated beam transport in the absence of nonlinearities caused by the focusing system is the only way to avoid further emittance degradation.

Electrostatic focusing seems to be a way out, but the limited current capability of such "full perveance" systems restricts the transportable current in one channel to unacceptable values with respect to inertial confinement fusion requirements. Space-charge-neutralized transport is therefore the right track to follow, and the task for the future is keeping the emittance growth caused by the neutralization process as low as possible. To do this the following recommendations can be made: degrees of compensation as high as possible to achieve small remaining beam perveances (Equation (1)); strong focusing to keep the mean beam radii small (Equation (1)); and avoidance of large envelope variations or large beam-tube cross sections, which should be adapted as closely as possible to the actual beam radius.

The measurements will be repeated using a new transport line with low-aberration solenoids. The obtained experimental results will be used to extend the PARMILA code to a more sophisticated consideration of background electrons. An optimization of the compensated beam transport with respect to low emittance increase is one of our major goals.

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REFERENCES

1. HIBALL II, Kernforschungszentrum Karlsruhe, *Report KfK* **3840** (1985).
2. E. B. Hooper *et al.*, *Phys. Fluids* **22**, 2334 (1979).
3. D. S. Lemons *et al.*, *J. Appl. Phys.* **57**, 4962 (1985).
4. M. Reiser *et al.*, SPIE 873, Microwave and Particle Beam Sources and Propagation 172 (1988).
5. A. J. T. Holmes, *Phys. Rev. A* **19**, 389 (1979).
6. I. Hofmann *et al.*, *Part. Acc.* **21**, 69 (1987).
7. T. Wangler *et al.*, *IEEE Trans. Nucl. Sci.* NS-32, 2196 (1985).
8. J. Klabunde *et al.*, Proc. 1986 Lin. Acc. Conf., *SLAC-Report* **303**, 296 (1986).
9. P. Gross *et al.*, *Proc. 1990 Europ. Part Acc. Conf.*, Editions Frontieres, Gif-sur-Yvette, France 806 (1990).
10. T. Weis *et al.*, *ibid.* 809 (1990).
11. T. Weis *et al.*, this conference.