EXPERIMENTAL AND THEORETICAL INVESTIGATIONS OF EMITTANCE GROWTH OF SPACE CHARGE COMPENSATED BEAMS IN A MAGNETIC TRANSFER LINE *

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Abstract

We have set up a low energy beam transport (LEBT) line to investigate the influence of partial space charge compensation on the transverse beam emittance of space charge dominated beams. The line consists of an ion source with triode extraction system (typically 10 keV, 2.5 mA He^+), two solenoides, a series of independently supplied cylindrical electrodes for a variation of the space charge compensation at different locations in the beam line and an electric sweep scanner for high resolution emittance measurements. A severe emittance growth up to one order of magnitude due to charge redistribution and instabilities was observed.

Introduction

For many applications of accelerators minimization of emittance growth has become an important aspect. For high perveance beams space charge effects, especially in the low energy section, can contribute a large fraction to the total emittance growth. While decompensated electrostatic beam transport already can be optimized with existing numerical simulation codes this cannot be done for space charge compensated transport in a similar way since our knowledge of space charge compensation is not sufficient.

Theoretical Aspects

For decompensated beams it has been shown that a homogeneous charge density distribution of the beam ions has the minimum electric field energy of all rms-equivalent beams and that a homogenization of the charge density is coupled with decreasing the excess or so called nonlinear field energy $\Delta U(z)$ and a growth of the rms emittance [1, 2]:

$$\frac{d}{dz}\epsilon_{rms}^2 = -\frac{K}{2}\langle x^2\rangle \frac{d}{dz}\Delta U(z) \qquad (1)$$

with $\epsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$ and the generalized perveance $K = I\ e\ \zeta/(2\pi\epsilon_0\beta^3c^3\gamma^3 mA)$. The normalized nonlinear field energy ΔU has for e.g. a Gaussian shape a value of 0.0386.

Eq. 1 shows that charge reorganization becomes more critical with increasing perveance and beam size and allows a first estimate of the magnitude of possible emittance growth. For LEBT sections and beams with initially small emittance the time respectivly distance dependence of the rms emittance has to be taken into account, since the conversion of nonlinear field energy into nonlinear kinetic energy may be more or less reversible [3].

In the case of partly space charge compensated transport the beam ion distribution with minimum field energy cannot be defined in general. For positive ion beams and thermalized compensating electrons a Gaussian like distribution is favourable in principle, but in detail depends on parameters like e.g. beam radius, residual gas pressure, electron temperature and density as well as external field configuration. Numerical simulations based on a simplified model (e.g. neglecting residual gas ions) indicate that space charge compensated beams in drift regions behave similar to decompensated beams with the total charge density replacing the beam ion density [4].

Experiments

A schematic drawing of the experimental set-up is shown in fig. 1. The beam is generated by an HIEFS [5] like ion source developed in our institute with a short length triode extraction system optimized for low energies (≈10 keV) allowing decompensated beam transport without particle losses to the wall in the extraction channel. In a short box for diagnostics and differential pumping parts of the extraction system are integrated. Typical beam parameters at position 1 in fig. 1 are 2.5 mA He^+ at 10 keV with a normalized rms emittance of $\epsilon_{n,rms,80\%} \approx 4 \cdot 10^{-3}$ mm mrad and a Gaussian like density profile in the space charge compensated case. The residual gas pressure was typically $7 \cdot 10^{-5}$ hPa. Two solenoids (B_0=0.73 T, l_{eff}=13.48 cm, L=25.1 cm) separated by a 18.6 cm drift are used to focus the beam into the final diagnostics box. The space charge compensation can be influenced with six cylindrical electrodes at variable potentials.

Emittance measurements were performed with an electric sweep scanner [6, 7] successively with the set-up of the beamline because there was only one device available. Preceding measurements had shown that the beam parameters could be well reproduced, so systematic errors are assumed to be not too large (stepping from position 1 to 2 shows an emittance growth of ≈10%).

In the case of space charge compensated transport with a long drift section behind the first solenoid the emittance grows only by a factor of two, even with a focus between solenoid and the position of measurement (fig. 2a). The

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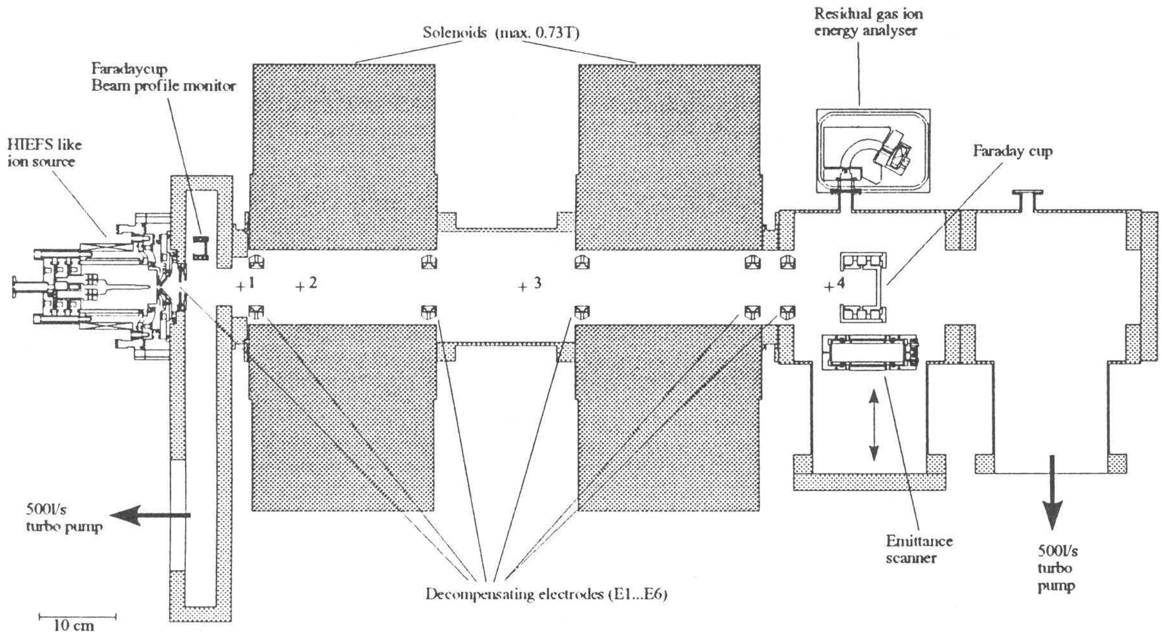

Fig. 1 Schematic drawing of the experimental set-up. Emittance measurements were performed successively with the set-up of the beamline at the positions 1..4.

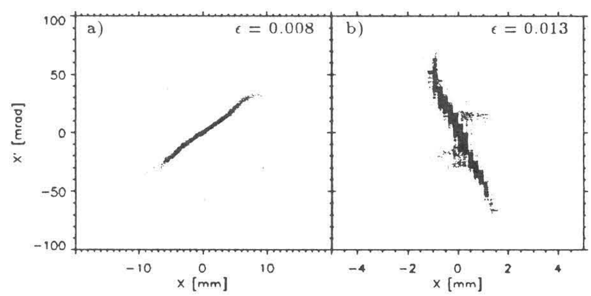

Fig. 2 Final emittance at pos. 4 for space charge compensated transport (E1...E6:0V) with the beam focused by the first solenoid (a) and both solenoids (b) (beam parameters see text, the emittance values given are $\epsilon_{n,rms,80\%}$/ mm mrad).

aberrations indicate a better compensation near the beam axis with increasing space charge forces towards the beam edge as expected from theory [8]. Focusing with both solenoids causes additional emittance growth of 50% with an '8'-shaped aberration near the center of the beam (fig. 2b). This type of aberration has previously been observed but not explained [9].

Usually a part of the last drift of a LEBT near the RFQ entrance is decompensated. This can be simulated by biasing the last electrode E6 positive. In this case the emittance plot (fig. 3b) shows slight 'S'-shaped aberrations as typically produced by charge homogenization of Gaussian type density distributions and a more intense '8'-shaped part. The corresponding beam profiles (fig. 3c,d) show the

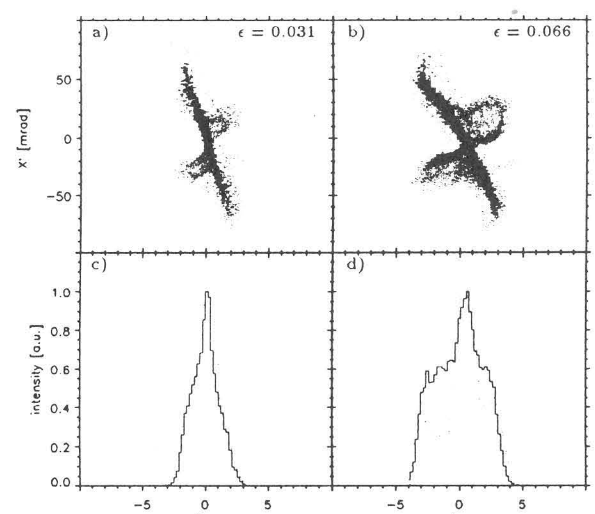

Fig. 3 Beam emittance and profile at pos. 4 for space charge compensated transport (a, c) and decompensated last drift (b,d; E6:400 V), focused by both solenoids.
The dotted lines in the profile plots are calculated via Abelinversion (assuming cylindrical symmetry) from the profiles and give an idea of the charge density vs. radius.

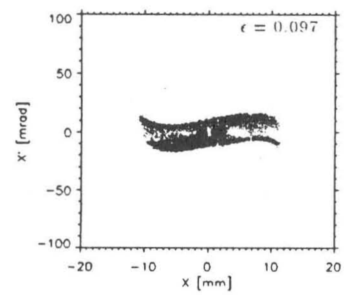

Fig. 4 Beam emittance at pos. 3 with E2 and E3 within the first solenoid at -200V.

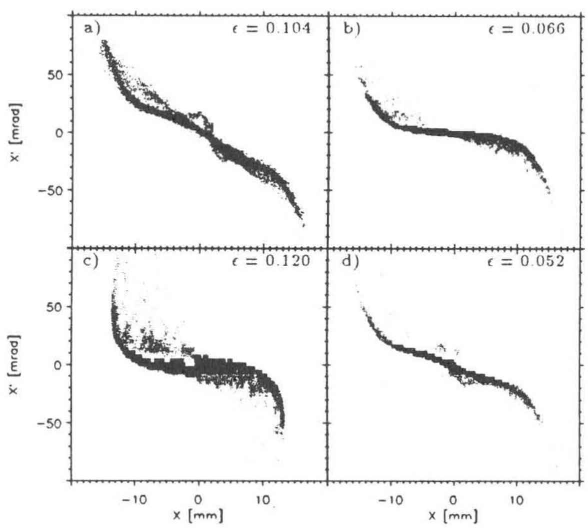

Fig. 5 a: Measured emittance at pos. 3 for E1:120V, E2, E3, E6:200V; b: Calculated emittance for decompensated initially diverging Gaussian beam focused by a perfect solenoid; c: as (b) but a real solenoid approximation; d: as (b) but additional homogeneous electron density near the axis.

tendency of charge homogenization for the partly decompensated beam.

We also have observed severe emittance growth for various combinations of magnetic field and electrode potentials where the emittance became 'noisy'. The corresponding faraday cup readings show modulations up to 5% with frequencies below 1MHz. An example is shown in fig. 4 where the two borderelectrodes of the first solenoid are supplied with -200V, a configuration for prevention of axial electron losses for compensation enhancement. This kind of emittance growth is not understood so far and the subject of further investigation.

If the risetime of space charge compensation is comparable to the length of the beam pulse, it may be helpful to avoid compensation at all. Measurements were realized at pos. 3, where transmission is near 100%, with all electrodes at positive potentials and therefore decompensating the beam as much as possible. They show an emittance with large mainly 'S'-shaped aberrations(fig. 5a) which can be originated by charge redistribution and/or nonlinear focusing forces.

Numerical Simulations

For our calculations we have extended the PARMILA TRANSPORT code to consider space charge compensation by thermalized electrons in drift regions, the measured magnetic field of the solenoids used in our experiments and an additional radius-depending radial force.

Since space charge compensation within the solenoids and instabilities cannot be modelled from our present knowledge, the calculations can only show the magnitude of emittance growth of decompensated DC-beams in realistic fields and types of aberrations of compensated beams.

In fig. 5b,c calculated emittances are presented for an initially Gaussian shaped divergent ion beam focused with a perfect lens and with a real solenoid approximation. The results support the assumption that in our experiments space charge effects are comparable to lens aberrations. An idea for understanding the 8-shaped aberrations in our LEBT may give fig. 5d. Here additional focusing by a homogeneous electron density with a small and constant radius was superimposed. Simulations and measurements show similar aberrations. Physically these electrons may be compensating electrons or secondary electrons, created at the front of the emittance scanner and not captured or stopped by the last cylindrical electrode.

Summary

We have performed emittance measurements at a magnetic LEBT and found that for intense ion beams emittance growth by charge redistribution and instabilities can dominate lens aberrations. Although we can understand some aberrations due to space charge effects in principle, further experimental and theoretical investigations are necessary for improving the modelling of space charge compensation to allow quantitative statements which permit prediction and therefrom optimization of space charge compensated transport.

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