LEBT Design Studies for ESS

J. Pozimski, P. Groß, R. Dölling, K. Reidelbach and H. Klein
Institut für Angewandte Physik der Johann Wolfgang Goethe Universität,
Postfach 111932, D-60054 Frankfurt am Main, Germany.

Introduction

For new applications of accelerator physics like ESS, high perveance ion beams have to be transported from the ion source to the first accelerator (see fig. 1). The requirements for such a Low Energy Beam Transport (LEBT) are high transmisson and low emittance growth. The transport properties of the section will be influenced strongly by the space charge of the beam. This can not be avoided in an electrostatic LEBT [1,2,3] and defines a limit of transportable beam current. It also increases the beam diameter drastically and therefore emittance growth due to higher aberrations occurs. In opposite magnetic LEBT sections (i.g. with solenoids) where the space charge can be compensated by particles of opposite sign avoid this problems. The compensation particles are usually produced by interaction of beam ions and residual gas atoms. In absence of external electric fields they are trapped in the potential well of the beam itself and reduce the net charge density. In spite of the fact that space charge compensated beam transport is used quite often, the theoretical models do not allow precise forecasts of the transport properties and the emittence growth.

1. Space charge compensation

For a beam of negative ions three different stages of space charge compensation can be characterized (shown in fig. 2). The gas (or self-) focusing stage is similar (concerning the radial potential distribution and the net charge density distribution) to a compensated positive ion beam. Therefore considerable experimental experiences and computer codes are available [4, 5]. The lower pressure limit for self focusing can be calculated by

$$p_{limit} = k_b \, T_{RGA} \frac{v_{RGI}}{r_b \, \sigma_{RGI} \, v_{BI}} \qquad (1)$$

and is for the given ESS parameters below $1{*}10^{-3}$ Pa. For this pressure the losses by charge exchange and stripping in the LEBT can be calculated (see fig. 3) for a 1 m LEBT to be below 5%. This is suitable for an ESS application. The minimum rise time for compensation is given by

$$\tau = \frac{1}{N_{RGA} \, \sigma_{RGI} \, v_{BI}} \qquad (2)$$

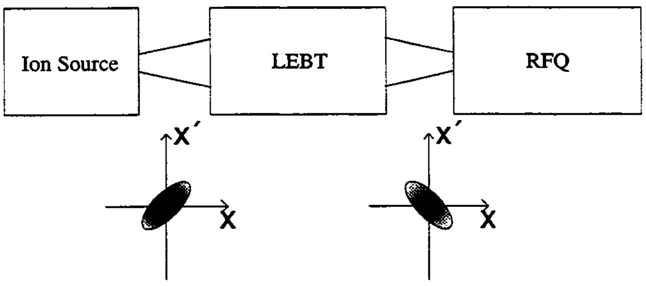


Fig. 1 : Schematic drawing of beam matching from ion source to first accelerator section (RFQ).

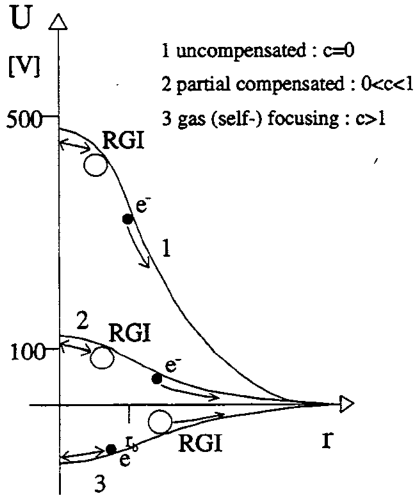


Fig. 2 : Schematic drawing of the three compensation stages for negative ion beams.

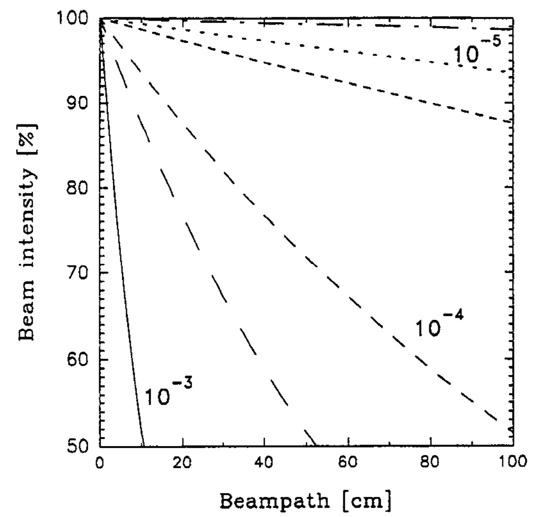


Fig. 3 : Transmission through LEBT as a function of LEBT lenght and residual gas pressure [hPa](H⁻, 50 keV in Ar).

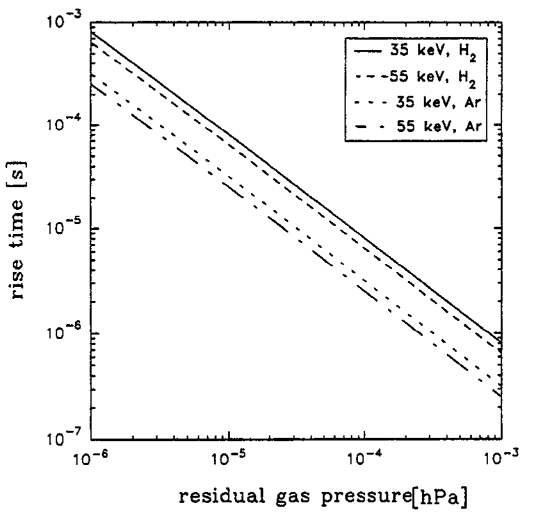


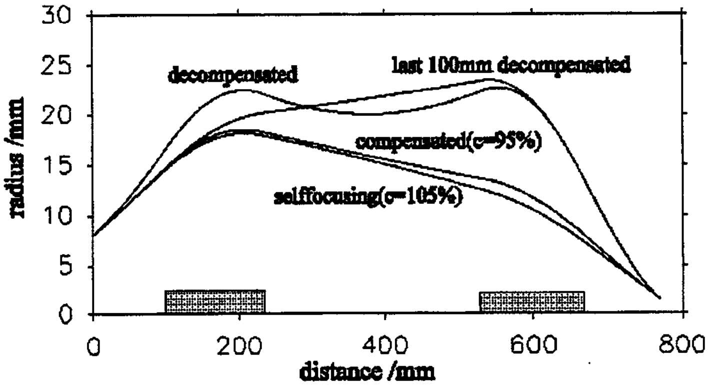
Fig. 4 : Minimum rise time of compensation as a function of residual gas pressure for different gases and ion energies.

For the lower pressure limit the rise time will be approx. 50 µs (see fig. 4). This seems to be appropriate for ESS application (pulse duration 1.2 ms). A simulation of different beam enveloppes for different degrees of compensation, where the magnetic field strength was altered for the same matching in parameters, is shown in fig. 5. Smaller beam radii are the clearly visible result of compensated transport. The influence of the RFQ fields are taken into account in one calculation (last 100 mm decompensated - worst case !).

2. Emittance growth

Two general sources of emittance growth can be determined. Aberrations of lenses (or other external devices) and the internal forces due to space charge. Both can be influenced by space charge compensation. Due to the lower inner fields the lens is filled to a lower degree by the beam and therefore the influence by the nonlineareties of the external fields on the beam is smaller. Numerical simulations [6] have shown that in drift regions the beam redistributes himself into a homogeneous net charge density distribution with minimum non linear field energy. Non linear field energy is transformed into non linear kinetic energy (emittance growth). Lower internal fields due to compensation of the space charge therefore directly influences the emittance growth. The final emittance after a drift region long enough to allow total redistribution can be calculated by

$$\varepsilon_{final} = \sqrt{\varepsilon^2_{initial} + \frac{K\langle x^2\rangle f}{2}} \qquad (3)$$



two solenoid match: 70mA,50keV H⁻

Fig. 5 : Calculation of beam enveloppe for different compensation degrees (and field strength from 0.3 to 0.6 T) in a two solenoid LEBT.

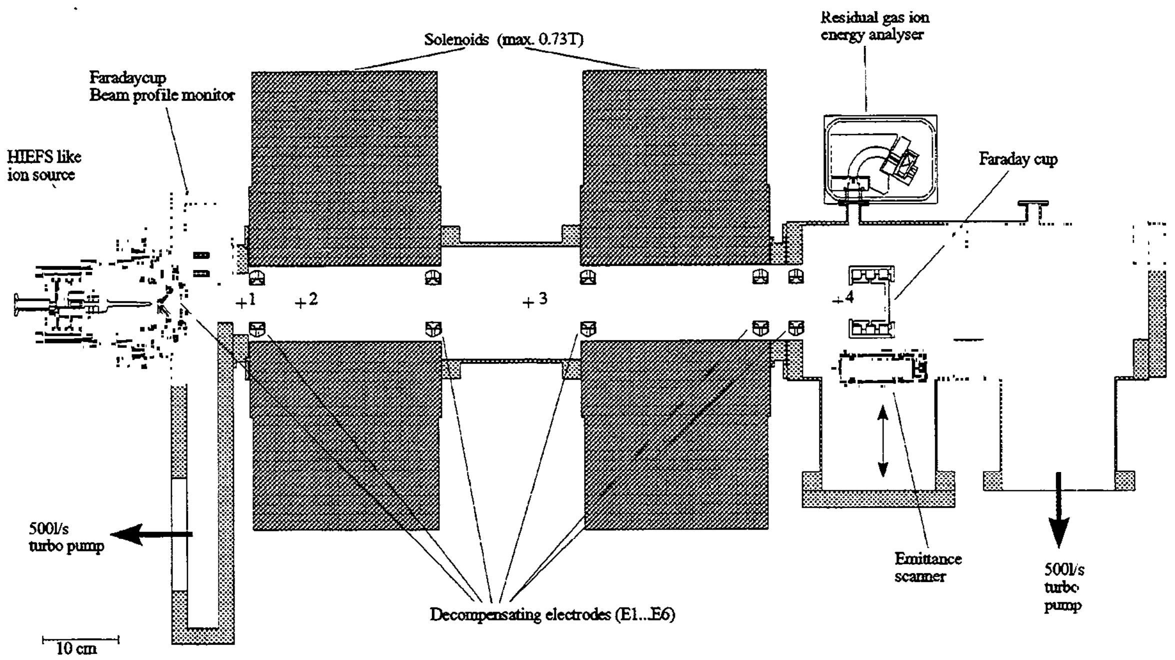


Fig. 6 : Schematic drawing of the experimental set up of the Frankfurt LEBT for ε growth measurements.

where K is the generalized perveance and f is the redistribution factor (0.0386 for Gauss into homogeneous). Whereas the perveance K is influenced positively by compensation, the Factor f might grow. A disadvantage of compensated transport is the fact that the net charge density distribution might change due to changing compensation degrees along z and therefore redistributions might occure more often. Also the unavoidable decompensation in front of the RFQ due to electric fields might add emittance growth. In the moment it is not possible to fully calculate the behavior of a compensated ion beam in a magnetic LEBT and therefore theoretical comparisons with other solutions are not possible, but the theoretical work might help to optimize an existing LEBT.

3. Experimental set up

In Frankfurt a magnetic LEBT similar to the proposed ESS LEBT (see fig. 6) has been set up. It consists of a HIEFS like ion source delivering a high perveance He$^+$ beam (comparable to the ESS perveance) with very low emittance (see fig. 7). This very low emittance yield high growth rates which is necessary to identify the sources of emittance growth [7] (aberrations and charge redistributions). Various cylindrical electrodes allow to influence the degreee of compensation

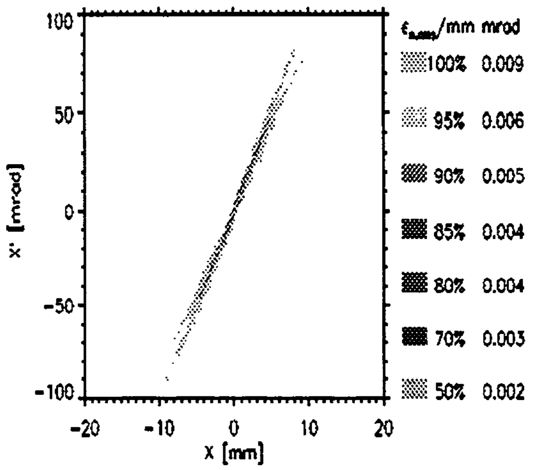


Fig. 7 : Initial emittance of a 10 keV, 2.5 mA He beam 11 cm behind extraction.

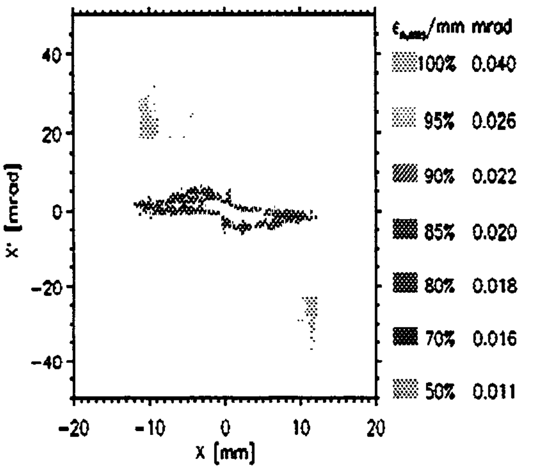


Fig. 8 : Emittance behind the LEBT for the same beam.

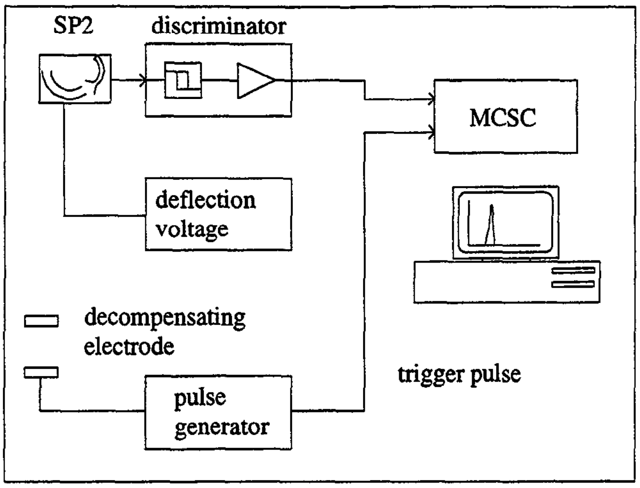


Fig. 9 : Schematic drawing of the experimental set up for measurements of the rise time.

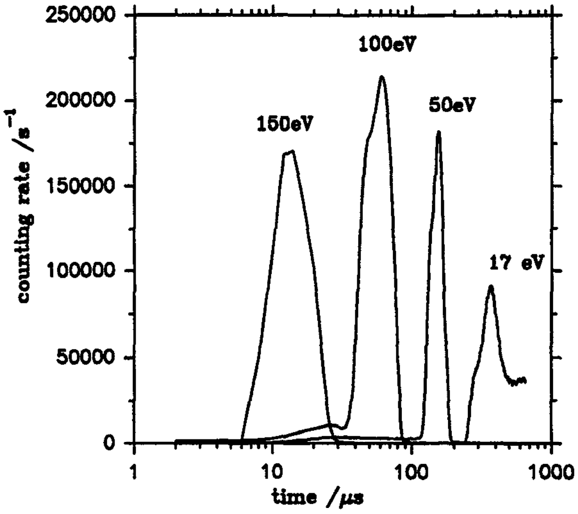


Fig. 10 : Time dependence of the occurence of certain RGI energies (t=0 start of compensation).

along the beampath. Fig. 8 shows the emittance behind the LEBT for fully compensated transport. The absolute growth of emittance is $\Delta\ \varepsilon = 0.017$ πmmmrad (90 %, RMS). For ESS (ε=0.1 πmmmrad) this would give an growth rate of appr. 20 % including the growth in front of the RFQ. Various measurements have shown that disturbance of compensation will result an enormous emittance growth and fluctuations in the beam.

To get more information concerning the behavior of a pulsed compensated ion beam a upgrade program for the beam diagnostics has been started. A time resolved residual gas ion (RGI) energy analyser is already in use. Fig. 9 shows the experimental set up. With a single particle detector a time resolution of 2 µs has been achieved. Fig. 10 shows a first result, from which the rise time of compensation can be derived. The first measurements [8] indicated rise times of compensation below the theoretical minimum rise time. This might be due to secondary electrons.

4. Conclusions

Space charge compensated transport has many advantages. The LEBT has to be designed very carefully and flexible to allow optimization. The LEBT should be kept short to keep the beamradius small and there should be no irritating external electric fields. Still there is no way to exactly predict the behavior of the beam because there is no model available to forecast the density distribution of the compensating particles in r and z (for cylindrical symmetry). For pulsed beams the dynamic of the rise of space charge compensation makes the problem even worse. If the rise time of compensation is in the range of the rise time of the beam pulse itself if does not influence the focus shift substantial. Otherwise active compensation by encasement of the compensating particles in a Gabor Plasma Lens [9] might improve the rise time. Nevertheless optimization of the LEBT including the final version of the ion source is absolutely necessary and might benefit from the existing experimental and theoretical knowledge.

5. Reference

[1] Anderson et. al. Pac 1987
[2] C. Allen et. al., LINAC 1990
[3] Guharay et. al. PAC 1991
[4] R. Dölling, Dissertation, IAP, Frankfurt, 1994
[5] J. Pozimski et. al. , Il Nuovo Cimento 106 A (1993), 1713
[6] P. Groß et. al., Il Nuovo Cimento 106 a (1993), 1657
[7] P. Groß et. al., LINAC 1994
[8] K. Reidelbach et. al., EPAC 1994
[9] J. Pozimski, GSI Annual Report 94, GSI-95-06, 32