Investigations of Space Charge Compensation of Pulsed Ion Beams*

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Abstract

Space charge compensation (SCC) is necessary for the transport of high perveance ion beams in many cases. Its rise time assuming electron production by residual gas ionization amounts up to several ms, depending on residual gas pressure and ionization cross sections. This is of special interest for pulsed ion beams, with a pulse length close to or below that range. To study this compensation process, we developed a time-resolving residual gas ion energy spectrometer with single particle detection. First experiences and results of measurements in a low energy beam transport line (LEBT) are presented.

1. Introduction

Interactions between beam ions and residual gas mainly produce electrons and slow residual gas ions (RGI) by ionization and charge exchange. The electrons are trapped in the beam potential and compensate the space charge of the beam. The RGI are expelled radially by the electric self field of the space charge and leave the beam. Their kinetic energy is given by the potential at the origin point, their start energy is in most cases negligible. The energy distribution of the RGI contains information about the beam potential distribution and therefore about the degree of compensation.

2. Theory

The degree of compensation of an ion beam is not defined in general. A possible definition, based on the line charge is:

$$K = \frac{Q'_c}{Q'_{dc}}, \tag{1}$$

where Q'_c is the line charge of the compensated beam and Q'_{dc} that of the decompensated beam. An estimate calculation of the minimum compensation rise time can be deduced from (1) with the admit, that only beam ions and compensating electrons are considered and electron losses are negligible as well as the space charge of the RGI:

$$\tau = \frac{1}{N\,\sigma_e v_b}, \tag{2}$$

where N is the residual gas density, σ_e the total cross section for the creation of electrons ($5.5*10^{-17}$ cm^2 at 10 keV $He^+ \rightarrow He$) [1]. The definition (1) is unsuitable for practical use with a RGI energy analyser, because the absolute line charge cannot be measured directly. A more practical definition of the degree of compensation is

$$K = \frac{\Phi_{dc} - \Phi_c}{\Phi_{dc}}, \tag{3}$$

where Φ_c is the potential difference (between beam radius and beam axis) th within e compensated beam and Φ_{dc} within a decompensated beam. These potentials can be measured directly with a RGI energy spectrometer. The maximum RGI energy is determined by the space charge potential on the beam axis, the minimum is given by the potential at the beam radius. Another advantage is, that K does not depend on beam and drift tube radius. So (3) is very suitable, if the beam ion density distribution does not change with rising compensation, which is unfortunately usually not satisfied for high perveance beams. Although a direct measurement of K is not possible, spectrometer measurements allow examination of the rise time of compensation.

3. Experimental Setup

Fig. 1 shows a schematic drawing of the experimental setup used for our first experiments. They were performed at our LEBT, consisting of an ion source and two Solenoids for beam formation. Behind the solenoids a drift region follows enclosed by negatively biased cylindrical electrodes to reduce the influence of secondary electrons produced outside. An additional electrode within the drift section allows variable decompensation of the ion beam.
For diagnostics two Hughes Rojanskij type spectrometers and a beam profile monitor are mounted in a plane perpendicular to the beam axis.

Fig 2 shows a schematic drawing of the spectrometer measurements. One is provided with a Faraday cup for analog operation mode, the other can be used either in analog or single particle mode with a Faraday cup or a channeltron detector. In single particle mode the deflection voltage for the spectrometer is generated by amplification of the linear output ramp of a multichannel scaling card (MCSC). The channeltron pulses pass a dicriminator and are registered by the MCSC.

*Work supported by BMFT under contract no. 06 OF 351 I

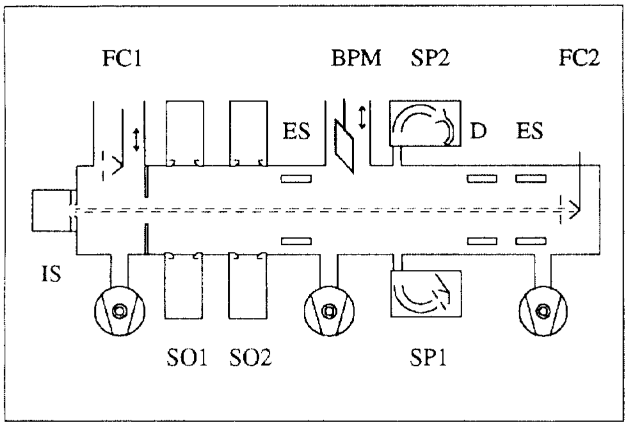

Fig. 1. Schematic drawing of the experimental setup.

IS:	ion source
FC:	Faraday cup
SO:	solenoid
ES:	electron suppression electrode
BPM:	beam profile monitor
SP:	spectrometer
D:	decompensating electrode

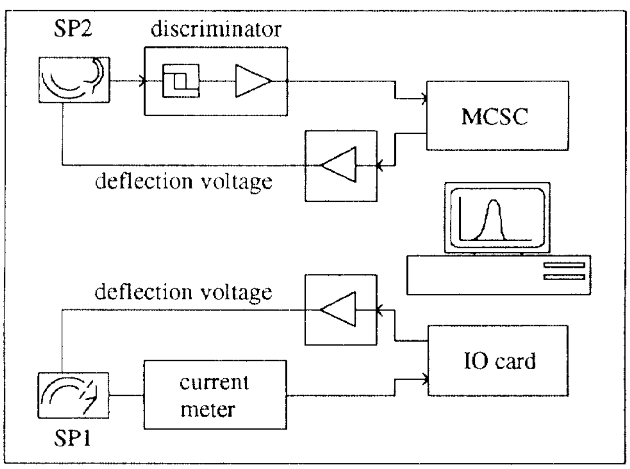

Fig. 2. Schematic drawing of the spectrometer setup for single particle and analog operation.

The first measurements were performed to compare the results of the different spectrometer versions for varying decompensating voltages. In fig. 3 the energy spectra for 50V were taken with both spectrometers in analog mode and for the compensated beam in analog and single particle mode. The energy shift of the low energy spectra might be caused by a deflection voltage offset, an unsymmetrical compensated beam plasma or residual magnetic fields. Besides this effect, the results are in acceptable agreement.

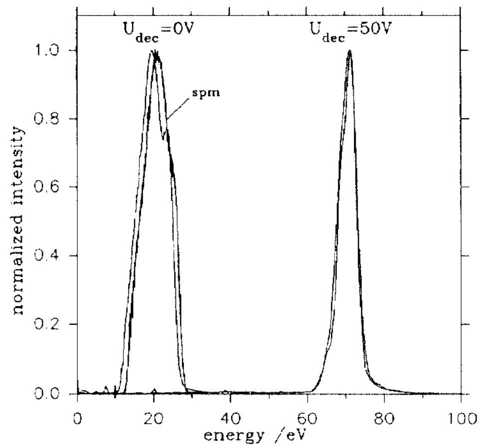

Fig. 3. Comparison of energy spectra taken with different energy analysers for compensated and partly decompensated beams (3,1 mA He^{+}, 10.7 keV). For 50 V decompensating voltage both measurements were performed in analog mode, for the compensated beam one spectrometer was in single particle mode (spm).

Instead of pulsing the ion source for examination of the rise of space charge compensation the voltage of the decompensating electrode is pulsed (typically 300V, 40Hz, rectangle) which can be done with a very short rise time.
The deflection voltage is fixed at a certain value and the MCSC registers counts as a function of time, triggered by the falling edge of the decompensating voltage electrode. The time resolution is 2μs, which is the shortest possible MCSC dwell time.

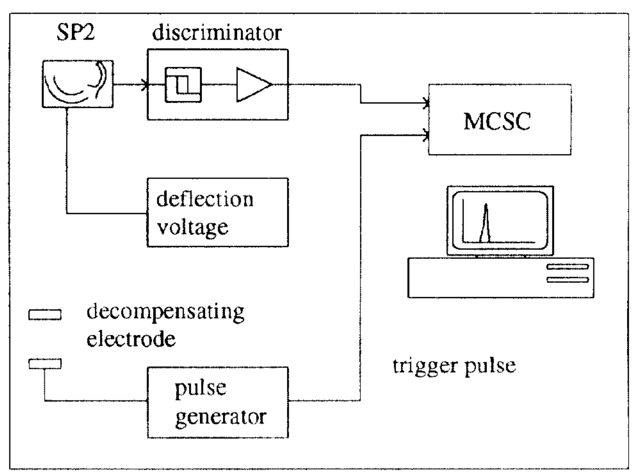

Fig. 4. Spectrometer setup for the examination of the rise time of compensation.

The high energy RGI only appear for a certain time while the beam becomes compensated. For the low energies the counting rate keeps constant after a while corresponding to the value of the RGI energy spectrum of the compensated beam.

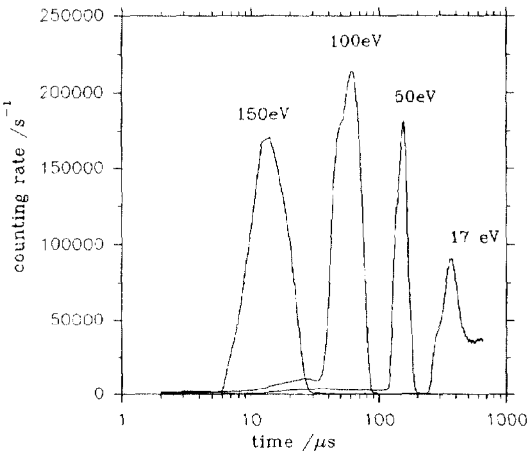

Fig. 5. Some typical counting rate spectra for specific residual gas ion energies during the rise of compensation of a 10,7 keV He^+ beam, residual gas pressure $8.3 \cdot 10^{-6}$ hPa. RGI with energies above 30 eV only appear during the rise time of compensation, while the counting rate for lower energy RGI keeps constant at a nonzero value after the compensation has build up.

4. Experimental Results

For a detailed investigation of the time dependence of space charge compensation and the degree of compensation as defined in (2), it is necessary to know the combined time and energy spectrum of the RGI, which requires a large amount of measurements, which will be performed in the next step. Since high residual gas ion energies appear only during the rise of compensation, their first appearance gives a good hint for the time dependence of the build up of SSC.

In a first approximation (fig. 6) there is an exponential decrease at the beginning. For varying residual gas pressures measurements proof that an increasing residual gas density leads to a faster compensation of the beam as expected from (2). This result implicates that the compensating electrons are mainly created by residual gas ionization.

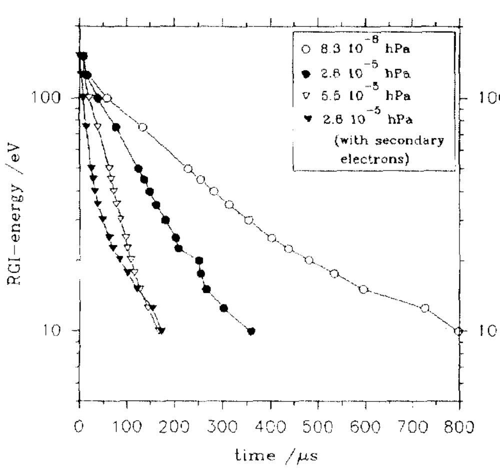

Fig. 6. The RGI energy versus the first time of their appearance for varying residual gas pressures.

For a comparison fig. 6 also shows the time dependence for the case that there is no secondary electron suppression at beginning and end of the drift region. As expected, the beam needs less time to compensate.

We have assumed an exponential decay and calculated the time constant. The results are presented in fig. 7. The values are in a range estimated from (2), but for a detailed understanding more data have to be taken into account.

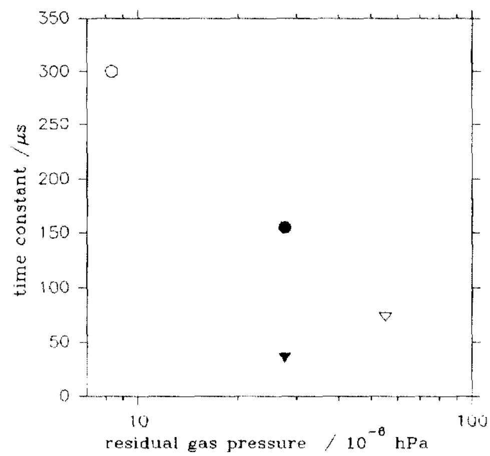

Fig. 7. Time constants calculated from the data of fig. 6 based on the nearly exponential part of the energy vs. time function.

5. Conclusion

The use of a time resolving RGI energy spectrometer allows a detailed examination of the rise of space charge compensation. With our present setup (time resolution 2 µs) diagnostic of macro pulses is possible and will be performed as a next step.

Special attention will be payed to the theoretical understanding and the enhanced understanding of beam transport. In parallel we want to improve the time resolution of our diagnostics for the examination of SCC of bunched beams, which is of major interest for high energy and high intensity accelerators.

6. References

[1] P.K. Janer, W.D. Langer, K. Evans Jr., De Post Jr. , Elementary Processes in Hydrogen-Helium-Plasmas, Springer, Berlin Heidelberg, 1987