BEAM TRANSPORT WITH SPACE CHARGE COMPENSATION

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Summary

High intense ion beam pulses have been investigated in a magnetic quadrupole transport line. Due to the pulse length of 2 ms space charge compensation ocurred. After a certain build-up time a saturated level of partial compensation was measured. Although the space charge forces are reduced, a considerable deterioration of beam quality was observed. In a certain parameter range of beam intensity and vacuum pressure the emittance growth was higher than it was measured with an equivalent fully space charge dominated beam. The degree of compensation was measured under different experimental conditions. The measurements will be compared with results of theoretical considerations.

Introduction

The transport of intense ion beams have been studied at GSI. The transport channel consists of twelve identical magnetic quadrupoles forming six periods of a FODO type channel. Ar^{1+} ions are extracted from a CORDIS source and accelerated to 190 keV by a DC accelerator. A detailed description of the complete experimental apparatus and the results of measurements are given in earlier publications[1,2,3]. The experiments have dealt with both unneutralized and partially space charge compensated beams. The beam pulse is rather long (> 0.5 ms), and at a vacuum pressure of 10^{-7} to 10^{-5} hPa a fractional neutralization due to ionizing collisions with background gas occurs. At the beginning of the pulse, the beam is expected to be unneutralized. Emittances were measured at the entrance and the exit of the transport channel. The data aquisition of the emittance scan can be started at different times within the beam pulse with a short time window.

The emittance measurements with the uncompensated part of the beam pulse are summarized as follows. At different quadrupole settings, corresponding to σ_o = 60°, 90°, 120°, the beam behavior was studied over a wide range of tune depressions. Stable beam transport is possible for $\sigma_o \leq 90°$. At high tune depressions an emittance growth ocurred. The source of this growth was attributed to a homogenization of the space charge density. This was confirmed by theoretical work and also by computer simulation studies. The predicted envelope instability for a space charge dominated beam was also measured at $\sigma_o > 90°$.

The experiments with partially neutralized beams indicate unstable behavior in a wide range of beam parameters. Emittance growth was measured even in cases where an equivalent unneutralized beam did not exhibit instabilities[3]. In the following, the effects of space charge compensation on beam transport will be reported for a wider parameter range. Especially, the influence of the vacuum pressure on the compensation degree at different levels of transported beams will be reported below.

Beam Potential Measurements and Analysis

Due to the ionization of the residual gas atoms, electrons and slow ions will be created inside the beam. The electrons are trapped by the space charge potential of the beam. The slow ions are repelled radially outward of the beam. So the space charge is gradually reduced until it reaches a stationary degree of compensation. The resulting potential drop inside the beam depends on the ion energy, ion current, and the residual gas pressure.

The energy spectrum of the ions diffusing out of the beam is used as a measure of the compensation degree. In Fig.1 a schematic drawing of the used ion spectrometer is shown. The ions are decelerated by positive potential, the current is measured as function of the retarding voltage.

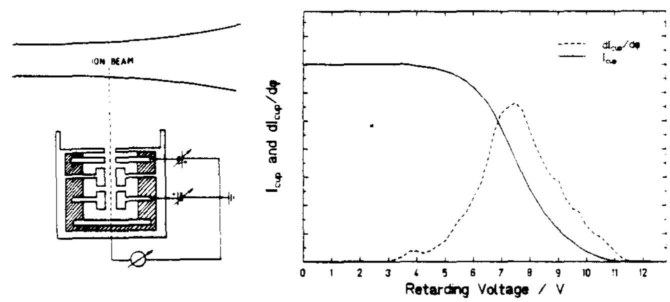

Fig.1: Schematic drawing of the energy spectrometer and an example of a measured energy spectrum.

Also in Fig.1 an example of a measured energy spectrum is given. The differential energy spectrum is obtained by differentiation of the integral curve.

The following definition of the compensation degree is used:

$$f = 1 - \phi_r(a)/\phi_{unc}(a) \quad .$$

$\phi_r(a)$ is the measured beam potential at the beam edge, $\phi_{unc}(a)$ is the calculated Potential at the edge, if the beam is uncompensated. This definition is independent of the density distribution of the electrons and ions inside the beam.

The potential at the beam edge cannot be measured by the energy spectrometer. The potential at the maximum of the differential energy distribution ϕ_{max} will be used for calculating the compensation degree. The theoretically calculated energy spectra for different distributions are shown in Fig.2. A round beam was assumed. For the homogeneous KV distribution, the intensity maximum appears at the beam edge. With increasing inhomogenity a shift away from the beam edge appears.

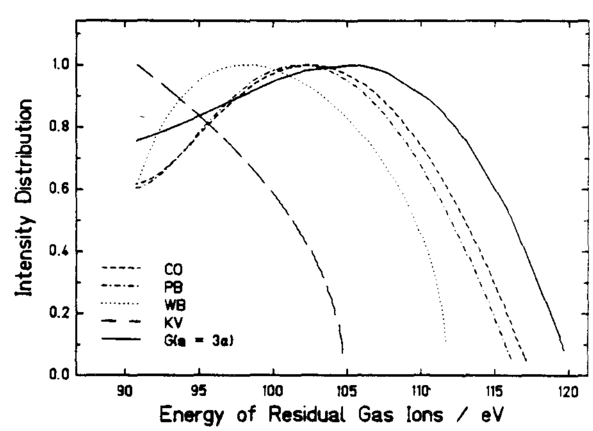

Fig.2: Calculated energy spectra of residual gas ions for different density distributions.
Beam parameters: Ar^{1+}, 190 keV, I = 1.5 mA, beam radius 5 mm, pipe radius 12.5 cm, P = $5*10^{-6}$ hPa.

The influence of the beam radius a and the beam pipe radius r_p on the ratio $\phi(a)/\phi_{max}$ is shown in Fig.3 for different density distributions. The shown ratio

$\phi(a)/\phi_{max}$ is only a function of the beam radius and beam pipe radius. It is independent on the beam energy and current.

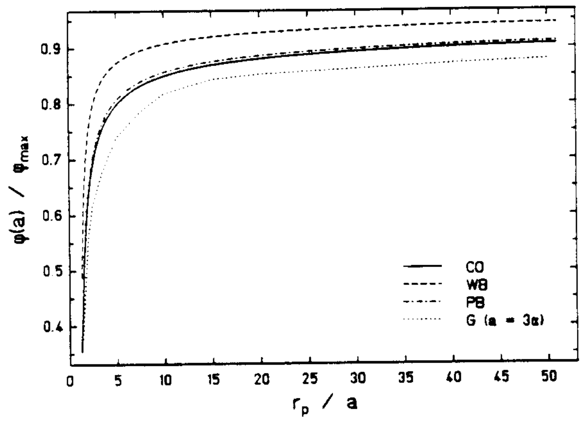

Fig.3: $\phi(a)/\phi_{max}$ as function of the ratio r_p/a for different density distributions (a - beam radius, r_p - beam pipe radius, ϕ_{max} = energy at intensity maximum).

This diagramm can be used for evaluation of the measured ϕ_{max} to obtain $\phi(a)$ and therefore the degree of compensation, if the intensity distribution of the beam is known.
Measured beam profiles and the measured energy spectra of the residual gas ions indicate parabolic or Gaussian density distributions. Therefore, the conical distribution (see Fig.3) will be used for the correction of ϕ_{max}. This leads to an inaccuracy of less than 10 % for the compensation degree.

Measurements of the Compensation Degree

In Fig.4 the measured energies of the residual gas ions at the intensity maximum as function of the beam current are shown. The resulting compensation degrees are plotted in Fig.5.

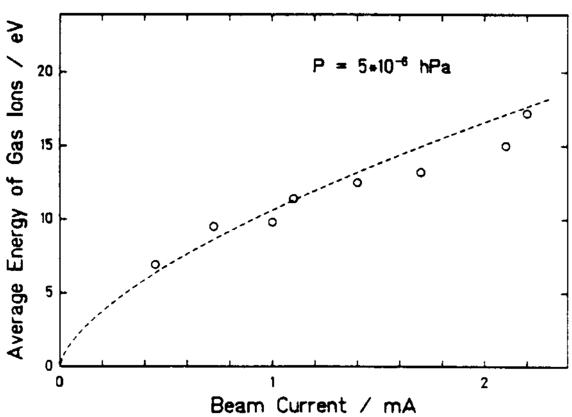

Fig.4: Potential at the maximum of the energy spectrum versus beam current, P = $5{*}10^{-6}$ hPa.

Holmes[4] derived a formula for the potential drop at the beam axis for a given gas pressure, beam density, and ion energy. The formula does not describe the measurements quantitatively. After introducing a scaling factor the theory describes the measurements very well. The measurements show that in our beam experiment full space charge compensation does not occur at the given gas pressure of P = $5{*}10^{-6}$ hPa.
The dependence of the compensation degree on the gas pressure is shown in Fig.6 and Fig.7. Again, the theory by Holmes describes the measurements very well qualitatively. A high compensation degree will be reached at high gas pressures. But at high gas pressures, the transport of high current beams is not realistic. Due to charge exchange processes beam loss will occur. Emittance growth by gas scattering has to be taken into account.

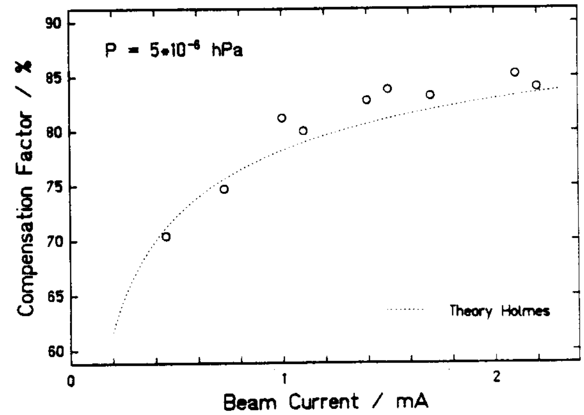

Fig.5: Compensation degree calculated from measuring points in Fig.4.

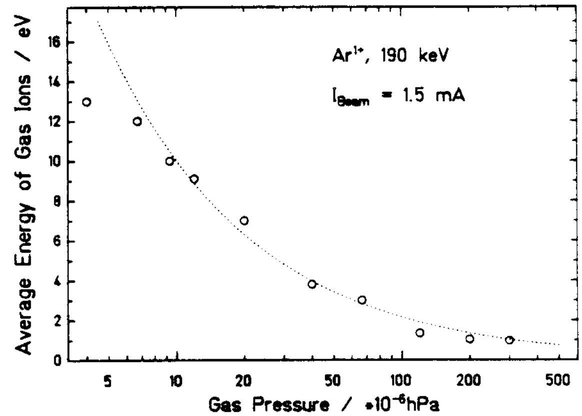

Fig.6: Potential at the maximum of the energy spectrum versus gas pressure, I = 1.5 mA.

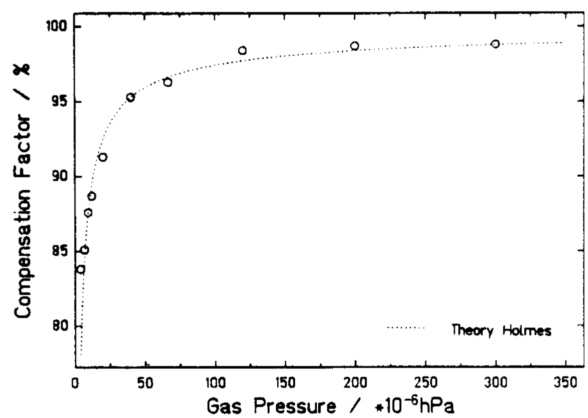

Fig.7: Compensation degree calculated from measuring points in Fig.6.

Transport of a Partially Compensated Ion Beam

Measurements on partially compensated ion beams at the GSI transport experiment were published in Ref.3. Fig.8 shoes the rms emittance growth for σ_o = 60°.
The growth rates are assigned to tune depressions calculated from beam parameters without space charge compensation. The measured compensation degree for beam

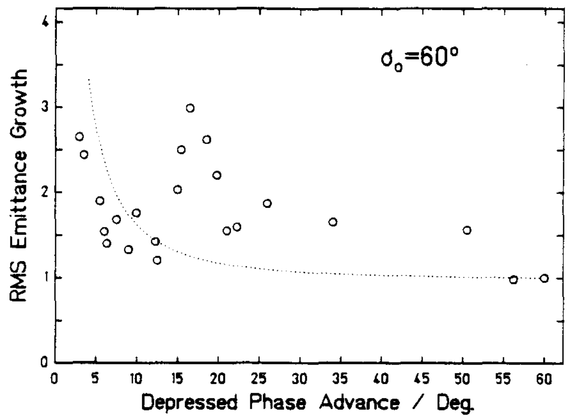

Fig.8: Rms emitance growth for partially compensated beams at $\sigma_0 = 60°$.

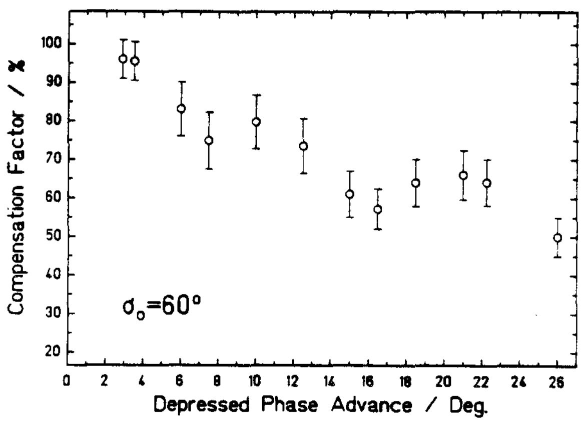

Fig.9: Compensation degree at different tune depressions σ_{unc}.

parameters of Fig.8 are shown in Fig.9. Even though the beam is partially neutralized, emittance growth was measured where an equivalent uncompensated beam did not show instabilities. The curve in Fig.8 describes the behavior of an uncompensated beam (see Ref.3). In a limited range of σ_{unc} (10° - 25°), the beam behaves particularly unstable. In this region the compensation degree was in the range of 60 - 80 % as shown in Fig.9. The reduction of the compensation degree with increasing σ_{unc} comes from decreasing ion current (see also Fig.5).

In order to increase the compensation degree at a certain current level, the gas pressure was varied. In Fig.10 the brilliance loss factor for four typical measuring points from Fig.9 - characterized by the tune depression σ_{unc} - is shown in dependence of the gas pressure.

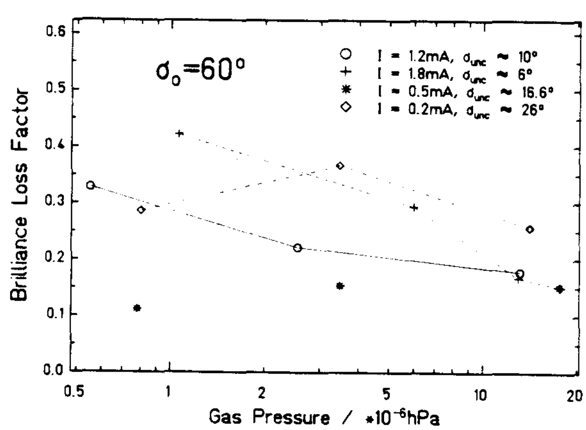

Fig.10: Brilliance loss as a function of gas pressure.

For the low current beam (I = 0.2 - 0.5 mA) the compensation degree increases from about 50 % to about 90 % with increasing gas pressure as shown in Fig.11. A slightly improved brilliance results.

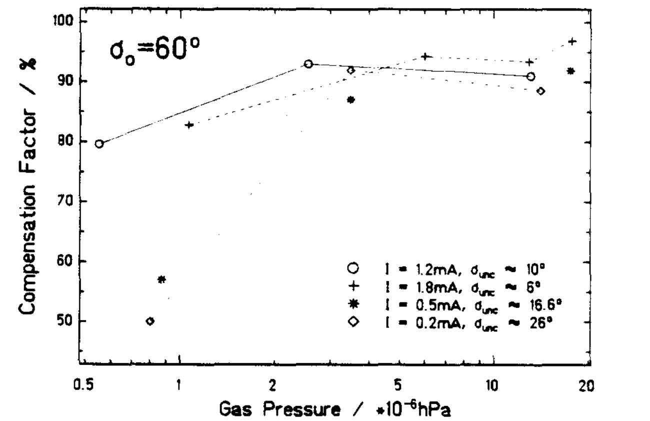

Fig.11: Compensation degree as function of gas pressure for the measuring points in Fig.10.

For higher currents (I > 1 mA), a continously decreasing beam brilliance with increasing gas pressure was measured.

Conclusions

Experiments with partially neutralized beams indicate unstable behaviour in a wide range of beam parameters. The emittance growth cannot be explained in general. More theoretical work is needed. Computer simulation codes have to be developed to handle the two-component beams. Work on this field will be continued at GSI in collaboration with Frankfurt University.

As a consequence of our measurements, the transport lines should be designed for unneutralized beams, electrostatic quadrupoles could be used. However, much stronger focusing strengths would be required.

References

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