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HIGH CURRENT BEAM TRANSPORT EXPERIMENTS AT GSI

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Summary

The status of the high current ion beam transport experiment is reported. 190 keV Ar^{1+} ions were injected into six periods of a magnetic quadrupole channel. Since the pulse length is > 0.5 ms partial space charge neutralization occurs. In our experiments, the behavior of unneutralized and partially space charge compensated beams is compared. With an unneutralized beam, emittance growth has been measured for high intensities even in case of the zero-current phase advance $\sigma_0 < 90°$. This initial emittance growth at high tune depression we attribute to the homogenization effect of the space charge density. An analytical formula based on this assumption describes the emittance growth very well. Furthermore the predicted envelope instabilities for $\sigma_0 > 90°$ were observed even after 6 periods. In agreement with the theory, unstable beam transport was also experimentally found if a beam with different emittances in the two transverse phase planes was injected into the transport channel. Although the space charge force is reduced for a partially neutralized beam a deterioration of the beam quality was measured in a certain range of beam parameters. Only in the range where an unneutralized beam shows the initial emittance growth, the partial neutralization reduces this effect, otherwise the partially neutralized beam is more unstable.

Introduction

In recent years there has been a considerable interest in the problems of transporting high current ion beams. Transport systems have been studied in connection with heavy ions used as a driver for thermonuclear fusion by inertial confinement. But the problem is of wider interest. New projects for high intensity linear accelerators require operation close to the space charge limit. Especially for the injection into a high-current radio frequency linear accelerator the beam transport from the ion source to the accelerator must be understood in order to avoid a loss of beam brightness. The role of space charge compensation in such low energy transport systems is of special interest. This topic has been often studied, many effects have been reported, but they are very dependent on the special situation. A general theory does not exist. In our transport experiment we are confronted with both, unneutralized and partial neutralized beam. The first experiments, reported in Ref.1, have dealt with a partial neutralized beam. Although the space charge force is reduced for a wide range of beam parameters an unexpected high emittance growth occurs. At that time, measurements could not be carried out with an unneutralized beam. In a second stage of experiments (Ref.2), the behavior of an unneutralized beam has been studied. At high tune depression an emittance growth was measured somewhat higher than with an equivalent partially space charge compensated beam. From these measurements we concluded that in very high intense ion beams the compensating electrons are not the main source of emittance growth. In the following we will report measurements at a wider range of beam parameters. The measurements have been devoted to unneutralized and partial neutralized beams.

Experimental Apparatus

A more detailed description was given in earlier publications[1,2]. The transport channel consists of twelve identical magnetic quadrupoles forming six periods of a FODO type channel, the cell length is 123.8 cm (effective quadrupole length 21.8 cm, drift space 17.9 cm and 62.3 cm). Ar^{1+} ions are extracted from a CORDIS source[3]. The discharge is of multipole-reflex type, the extraction system consists of a single aperture triode system. The pulse length was 2 ms at a repetition frequency of 50 Hz. After a drift space of 0.5 m, a single gap accelerates the ions to the energy of 190 keV (β = 0.0032). Four lenses are provided for matching into the periodic transport channel. The maximum pulse current available at the entrance of the channel was ≈ 6 mA sufficiently above the calculated space charge limit. A wide range of beam parameters (current 0.1 to 6 mA, unnormalized marginal emittance 2-30 π mm mrad) is obtained by variation of the ion source parameters, different ratios of the extraction and acceleration voltage, and a variable slit system at beginning of the channel. The emittance can be measured by a conventional slit-collector system, positioned at entrance and exit of the channel. The device is computer-controlled, the data collection takes ≈ 50 s for one emittance scan, including storage of the emittance data on a file for later evaluation. The degree of space charge compensation was estimated from the energy spectrum of the ionized background gas ions diffusing radially out of the beam. Fig.1 shows the variation of the energy of gas ions along the beam pulse. A sketch of the used device is also shown in Fig.1. The ion current has been measured as function of the applied deceleration voltage.

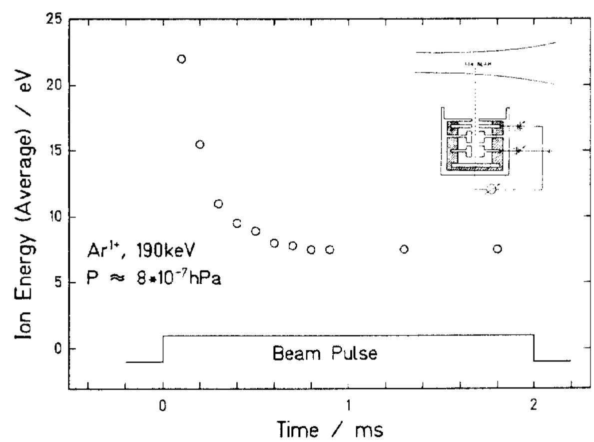

Fig. 1: Mean energy of background gas ions along the beam pulse, and schematic drawing of the ion spectrometer.

Experimental Results

Unneutralized Beam

At the different quadrupole settings, corresponding to σ_0 = 60°, 90°, 120°, the beam behavior was studied over a wide range of tune depression. Fig.2 demonstrates, that for σ_0 = 60° an rms emittance growth starts at σ ≈ 15°. Above this value no loss of beam brightness was observed. But the increase of the emittance below 15° is considerable.

In simulation studies a rapid emittance growth for non-KV distributions occured significantly at high

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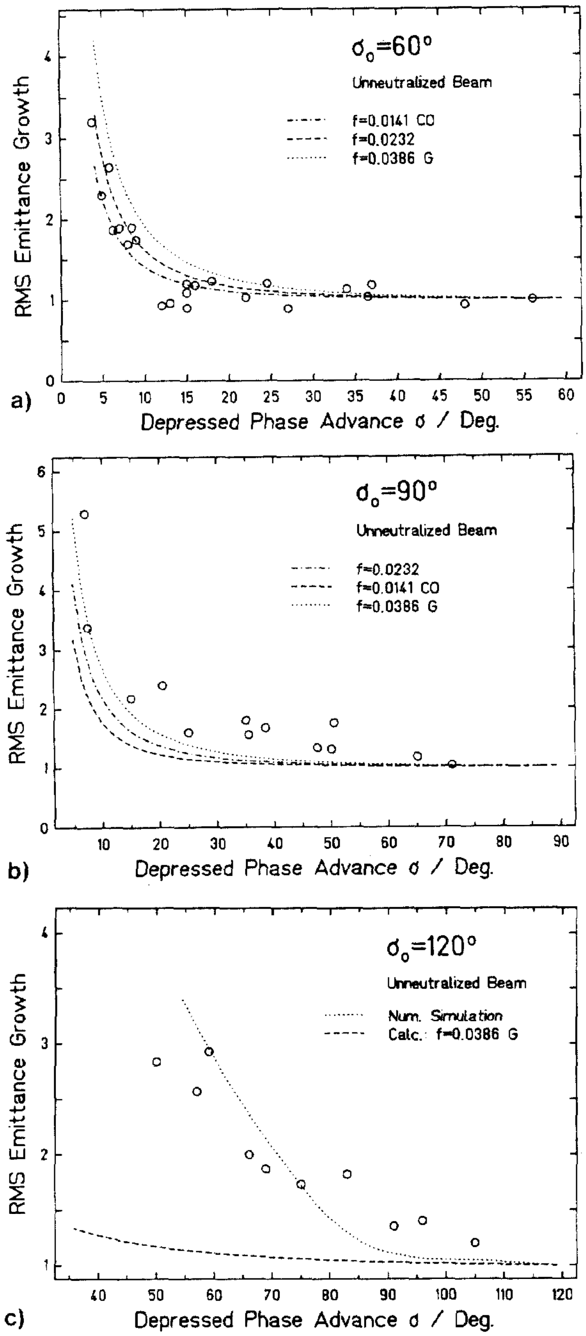

Fig. 2: Rms emittance growth for an unneutralized beam at $\sigma_0 = 60°$, $90°$, $120°$ and different tune depressions.

beam intensities even when the beam passes through one period. The source of this growth was attributed to a homogenization of the space charge density. If we assume a transfer of space charge energy into transverse kinetic energy, one obtains for the initial emittance growth[4]

$$\varepsilon_{out}/\varepsilon_{in} = \sqrt{1+2f(\sigma_0^{\ 2}/\sigma^2-1)} \qquad (1).$$

The factor f expresses the difference in field energy between a non-uniform and a KV distribution. The simulation results are in good agreement with the analytical formula. The emittance growth was calculated for a Gaussian (f=0.0386) and for a conical distribution (f=0.0141). Fig.2a shows the good qualitative agreement between measurements and calculations. With f = 0.0232 the best fit to the experimental data was obtained. The enormous increase of emittance growth for high tune depression was also found for $\sigma_0 = 90°$ (Fig.2b). By comparison with the above given formula and the same f-values as in Fig.2a, the emittance growth of the beam already tends to start at larger σ-values. More pronounced is this behavior for $\sigma_0 = 120°$ (Fig.2c). Here we attribute the measured emittance growth to the onset of envelope instabilities predicted by the theory and confirmed by numerical simulations. The upper curve was calculated with a semi-Gaussian distribution.

For the above discussed measurements the input emittances in both transverse phase planes had the same size within a few percent. Fig.3 shows the result when anisotropic input emittances were injected into the channel. The emittance growth already starts to occur at relatively small differences in emittance size, growth rates up to a factor 3-4 can be seen in the diagram for highly anisotropic input distributions. For the measurements shown in Fig.3, the minimum tune depression for one plane was not extremely high, about $\sigma/\sigma_0 \approx 0.35$. At higher tune depression, the effect of anisotropy was amplified, growth rates up to a factor of 6 have been observed. These experiments were also confirmed by numerical simulations. The best agreement was obtained with a semi-Gaussian distribution at input. The instabilities due to equipartitioning of initial anisotropy were theoretically predicted[5].

Another characteristic result with unneutralized beams is shown in Fig.4. Different input emittances at nearly the same current were adjusted by variation of the ion source parameters and the slit positions. The measured points for the corresponding output emittances are placed above the equal-emittance line. For decreasing input emittances the output emittances go toward a lower limit, the emittance growth rates then increases considerably. This experimental result is also in excellent agreement with theoretical considerations discussed above and computer simulations. Again with f = 0.0232 the best description of the experiments was achieved. M. Reiser derived an analytical formula for the lower limit based on the described physical model.[6] The calculated values indicate a very good agreement with our experiments and simulation runs. T.P. Wangler derived a more general equation for rms emittance growth due to the field energy of space charge distributions. By solving the emittance equation in an approximation, he obtained our formula (1).

An indication of the existence of a lower limit we observed in earlier measurements reported in a previous paper[2]. The lower limit for the output emittance was found even in the case of nearly constant tune depression with decreasing input emittances. There we also reported measurements of emittance growth over a drift space, the growth rate for small input emittances was remarkably high.

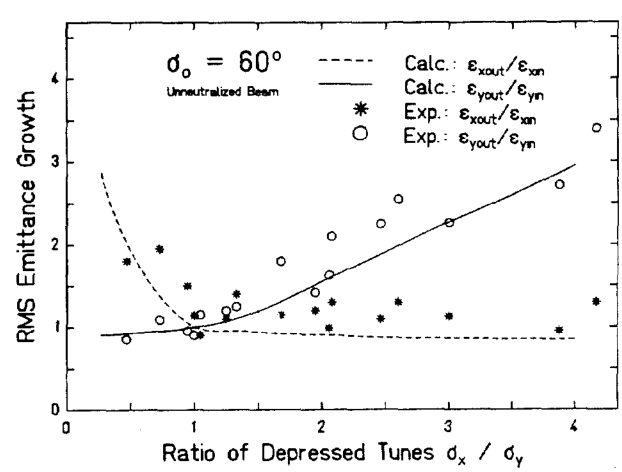

Fig. 3: Rms emittance growth at anisotropic distributions of the transverse phase planes.

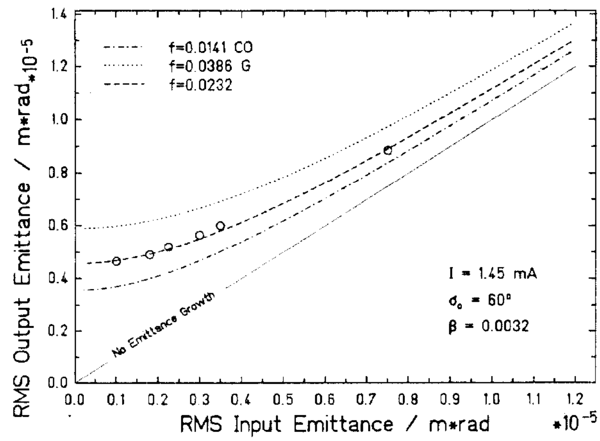

Fig.4 : Rms output emittances versus different input emittances at constant beam current.

Partial neutralized beam

As shown in Fig.1 the space charge potential decreases along the beam pulse and reaches a saturated level after about 0.5 ms. The emittance growth rates measured at the end of a 2 ms pulse are shown in Fig.5 for $\sigma_0 = 60°$ and $90°$. For a better comparison , the growth rates are assigned to tune depressions calculated from beam parameters without space charge compensation. The degree of compensation was in the range from 65 to 95% measured in different drift spaces. For the evaluation of our experimental results we should take into account the variation of space charge compensation along the channel. Possible sources are: variation of vacuum pressure along the channel, variable beam pipe diameter, magnetic fields of quadrupoles etc. From Fig.5 we can see that for a certain range of beam parameters the emittance growth is higher than measured for the corresponding unneutralized beam. The drawn line represents the behavior of an unneutralized beam, it was calculated from the emittance growth formula with f = 0.0232 (see Fig.2). At low values of σ, the emittance growth is smaller in comparison to an unneutralized beam. In this regime the unneutralized beam experiences the high initial emittance growth as discussed before. As also shown in Fig.5, in a limited range of σ the beam behaves particularly unstable ($\sigma \approx 10° - 25°$ for $\sigma_0 = 60°$ and $\sigma \approx 30° - 45°$ for $\sigma_0 = 90°$).

The behavior of a partially neutralized beam cannot be explained so far in general. More experimental and theoretical work is needed to identify sources of the effects. We are planning experiments with well defined boundary conditions, e.g. constant vacuum pressure, constant diameter of beam tubes, defined composition of background gas, etc.

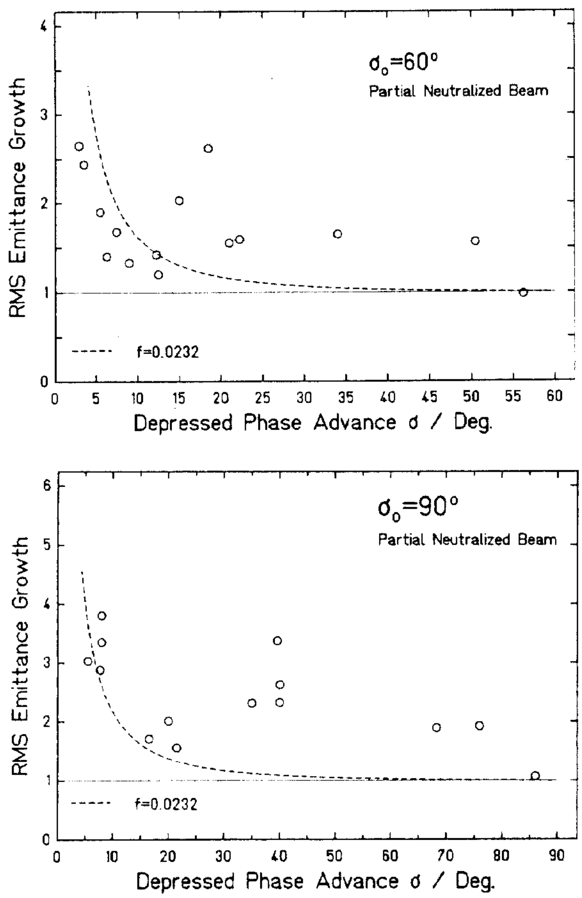

Fig. 5: Rms emittance growth for partially neutralized beam at $\sigma_0 = 60°$, $90°$ and different time depression

Conclusions

Emittance growth has been measured in high-brightness beams. Computer simulation and an analytical formula confirm the experimental data. A lower limit of the output emittance has been found experimentally. The source for these effects we attribute to the homogenization effect of the particle distribution, at least in cases where no instabilities occured. Even after 6 periods, the predicted envelope instabilities at $\sigma_0 = 120°$ have been observed. Also emittance growth for anisotropic input distribution in the transverse phase planes has been measured.

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. The behavior of a partial neutralized beam is not fully understood, knowledge and experience are still limited. For many applications, especially for the planned GSI high current injector, a better insight is of great importance. Further experiments are planned at GSI in collaboration with the University of Frankfurt.

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