HIGH CURRENT BEAM TRANSPORT EXPERIMENTS IN A MAGNETIC QUADRUPOLE CHANNEL AT GSI

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Summary

The transport of a high intensity ion beam in a magnetic quadrupole channel consisting of twelve lenses has been studied. The experiments are being carried out with a high brightness beam of 190 keV Ar^{1+} ions and currents of a few mA. The tune depression can be varied in a wide range by varying the beam parameters before the channel entrance. Due to the minimum beam pulse length of 0.5 ms and the vacuum pressure between 10^{-6} and 10^{-7} torr, partial space charge neutralization occurs. The space charge potential varies along the beam pulse. At the front end of the beam pulse no space charge compensation was measured. Emittance growth measurements for different intervals along the beam pulse indicate that partial neutralization reduces the growth rates.

Introduction

The beam transport experiment is intended to investigate the behavior of high intensity ion beams. Analytical and computer simulation studies showed that beam instabilities caused by the interaction between the space charge forces and the external periodic forces could result in a severe deterioration of beam quality. High intensity and high brightness beams are required for various applications, e.g. for accelerator drivers for inertial confinement fusion systems. Beam transport experiments were started at different laboratories. At the University of Maryland an electron beam is transported in a periodic array of solenoid lenses[1]. The Berkeley group uses electric quadrupoles for a Cs^{1+} ion beam[2]. The GSI transport channel consists of twelve magnetic quadrupoles forming a FODO type channel of six periods. Ar^{1+} ions are injected with an energy of 190 keV.

The main objectives of the transport experiments are to explore the stability thresholds and the theoretically predicted instability modes in a long transport channel consisting of at least 40 periods. However, computer simulation studies[3,4,5] show that many space charge effects should be observable in as few as six periods of a transport channel. Envelope instabilities at the single particle phase advance per focusing period above $\sigma_0 = 90^0$ occur very fast. The homogenization of the particle density in real space takes place within the first cell. This leads to an initial growth of the r.m.s. emittance. In the simulations the type of the particle distribution assumed at the channel entrance is important for this effect. The experimental examination of this issue with real beams is of importance.

A special problem affecting our studies is space charge neutralization by electrons. Due to the pulse length of ≥ 0.5 ms and the vacuum pressure between 10^{-6} and 10^{-7} torr, space charge neutralization effects influence the behavior of the ion beam. The amount of neutralization varies along the beam pulse. The influence on the emittance growth needs to be studied experimentally.

The first transport experiments reported in Ref.6 were devoted to a study of partially neutralized ion beams. Experimental work on unneutralized and partially neutralized ion beams will be reported in the following sections of the paper.

Experimental set-up

A more complete description of the apparatus can be found in our earlier publication[6]. Twelve identical magnetic quadrupole lenses (aperture radius 2 cm, maximum field gradient 3 kG/cm) form the periodic transport channel of FODO type. For practical reasons the drift sections between the quadrupoles differ (17.9 and 62.3 cm). The larger of the drift sections in each period is used for insertion of beam diagnosis elements. With the effective length of 21.8 cm of one lens the total length of each period amounts to 123.8 cm.

The high current ion source CORDIS[7] developed at GSI was used to provide high brightness, high current Ar^{1+} ion beams for the experiments. The extraction voltage of the single aperture extraction system was varied in a range of 20 to 40 kV to change the beam current. After a short distance of 0.5 m the final energy of 190 keV was achieved by a single gap DC-accelerator.

Four large aperture magnetic singlets were installed for matching to the periodic channel. Clearing electrodes were positioned at the entrance of the channel to remove the electrons from the beam. For input emittance variation a collimating system was also installed at this position. The beam current could be measured by Faraday cups at different positions of the beam line. For emittance growth measurements computer controlled slit-collector-systems were installed at the entrance and exit of the periodic channel. In our first experiments (see Ref. 6) the data acquisition could be started at different times within the beam pulse with a minimum time window of 200µs, except in the first 300µs interval. For the emittance measurements described below the control electronics were changed. It is now possible to start the measurement at the front end of the beam pulse where the beam is expected to be unneutralized.

Experimental Results

The first emittance growth measurements reported in Ref.6 were caried out only in the partially neutralized part of the beam pulse. An enormous deterioration of the beam brightness depending on the tune σ_0 and the current was measured as shown in Fig.1.

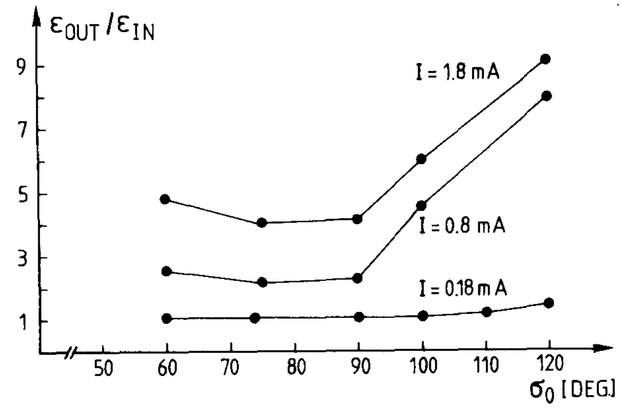

Fig.1: r.m.s. emittance growth versus σ_0 for an partially neutralized beam.

The rapid increase of emittance growth above $\sigma_0 = 90^o$ indicates the envelope instabilities as predicted by the theory and computer simulations even though the beam is partially neutralized. The current used for the computer calculation was 40 - 60% of the measured value. The measured emittance growth below $\sigma_0 = 90^o$ could not be explained. It was not clear to which extent the growth may be attributed to the effects of electrons.
The space charge potential within the beam pulse was measured by different methods. The energy of the residual gas ions diffusing out of the beam was measured by a device developed at the University of Frankfurt[8]. The measuring device was positioned behind the first channel period. At the vacuum pressure of 10^{-6} torr the beam potential decreases after ≈ 200 µs to a saturated level.

These measurements were confirmed by beam transport experiments through one magnetic quadrupole doublet. The emittance along the beam pulse was measured before and behind the doublet. Using the measured input emittance for the beam simulation code the best agreement between measured and computed output emittances was attained for the front end of the beam pulse if the full beam current was introduced in the simulation program. Over this time period then the beam is unneutralized. At the center of the beam pulse the effective current has to be decreased

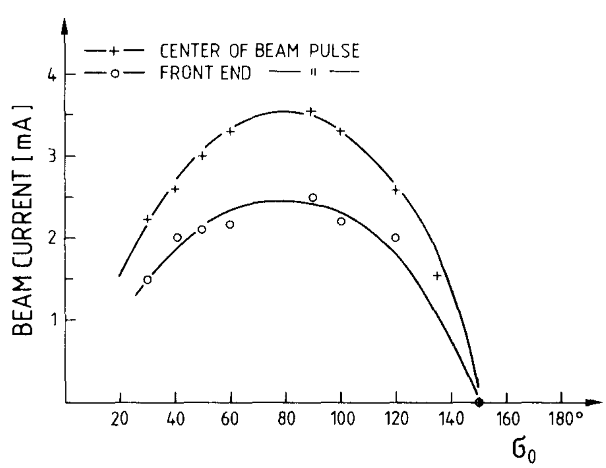

Fig.2: Output current as function of σ_0 for the front end and center of beam pulse

by a factor of 0.6 - 0.4, depending on the vacuum pressure. For these measurements the clearing electrodes at the entrance were biased by a positive voltage.

In another series of experiments the FODO channel was illuminated with a large emittance, high current beam. The intensity was far above the expected current limit of the transport channel.
Fig.2 shows the output current for different zero-current phase advance values σ_0. The output current for the front end of the beam pulse is clearly below the current measured at the center of the pulse. For each σ_0 the difference in transmitted current through the six periods of the channel expresses the variation of the space charge forces along the beam pulse.

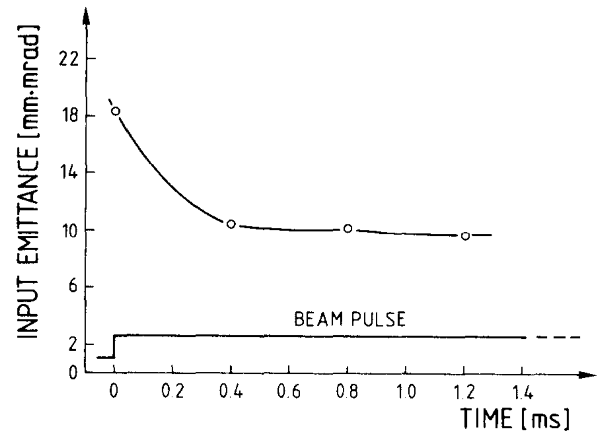

Fig.3: Variation of the beam emittance area along the beam pulse

Another peculiarity was found in our measurements. In Fig.3 the emittance variation at the channel input is shown along the beam pulse. At the front end of the beam pulse the emittance area is up to a factor 2 larger than at the center of the pulse. This effect may be attributed also to the variation of the space charge forces along the pulse. It is not quite clear to which extent the ion source itself is responsible for this effect. Further experimental work is needed to clarify the problem. It can have important implications for transport and acceleration of long beam pulses.

The experimental studies concerning the behavior of the unneutralized and partial neutralized ion beam are summarized in Fig.4.
At the phase advances $\sigma_0 = 60^o, 90^o$ and 120^o, the emittance growth factor for the front end and the center of the beam pulse is shown. The emittance size was varied by a collimating system in front of the channel. The beam current was adjusted to a value at which the tune depression is nearly the same for the corresponding σ_0-value. The tune depression is $\sigma/\sigma_0 = 0.15$ at $\sigma_0 = 60^o$ and $\sigma_0 = 90^o$; at $\sigma_0 = 120^o$ the tune depression is smaller ($\sigma/\sigma_0 = 0.25$).

Beam matching was accomplished experimentally by varying the gradients of the four quadrupoles before the FODO channel until maximum current transmission was obtained.

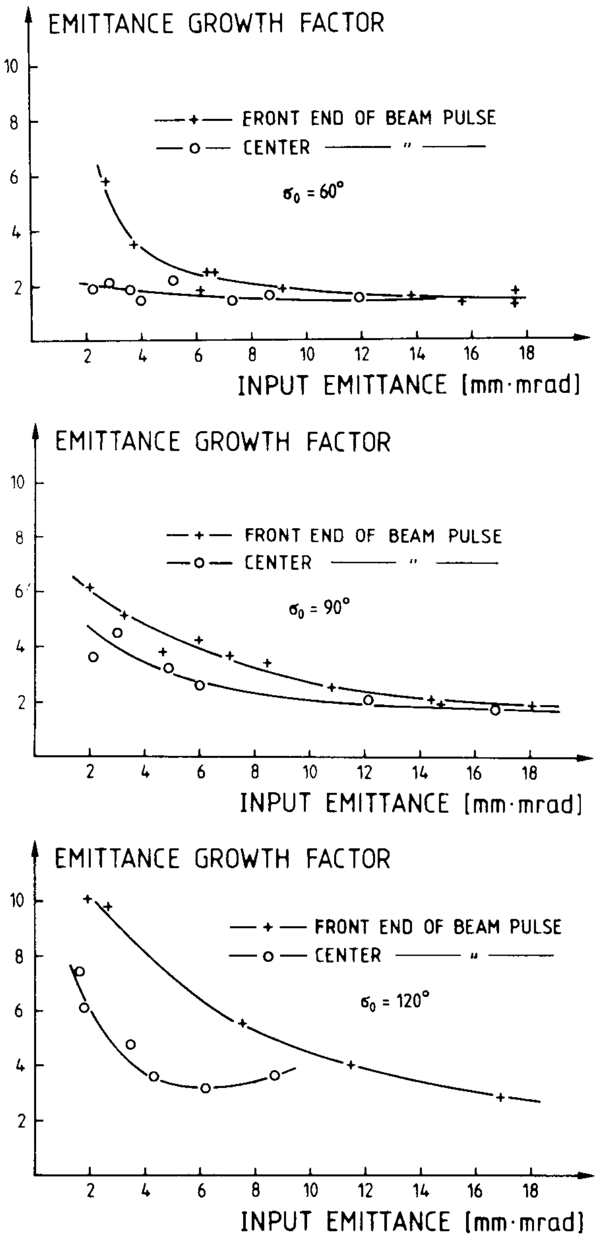

Fig.4: Emittance growth factors for different zero-current tune depressions σ_0 and different input emittances.
$\sigma/\sigma_0 = 0.15$ for $\sigma_0 = 60^0, 90^0$
$\sigma/\sigma_0 = 0.25$ for $\sigma_0 = 120^0$

For a certain value of the input emittance, the emittance growth factor of the unneutralized beam is above the growth factor measured at the center part of the beam pulse where the beam is partially neutralized. The difference in emittance growth is more pronounced at a smaller input emittance. Summarizing the experimental results, shown in Fig.4, the emittance growth occurs also for a unneutralized beam. We conclude that the emittance growth measured in our experiments cannot be explained by partial neutralization of the beam by electrons.

The dependence of the emittance growth on the input emittance, also shown in Fig.4, needs further study. This effect did not occur in computer simulations with K-V and Gaussian distribution if we start with an r.m.s. matched beam. In our measurements the particle distribution function at the beginning of the channel is similar to a semi-Gaussian distribution however significant distortions are present.
Starting with the experimental distribution the computer simulations confirm qualitativly the emittance growth as function of size of the input emittance. Similar results were obtained for beam transport over a drift space as shown in Fig.5. We conclude therefore that the distorted input distribution present in our measurements is a source of this effect.

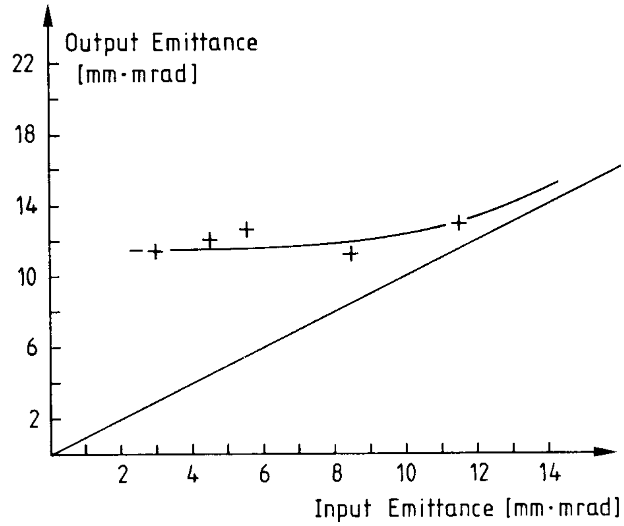

Fig.5: Output emittance versus input emittance after a drift (1m)

Conclusions

The deterioration of the beam brigthness in our transport channel cannot be attributed to the effects of electrons. The presence of neutralization electrons in fact reduces the emittance growth. The present measurements cannot explain the large emittance growth for σ_0 below 90^0. Distortions in the input phase space and mismatching to the beam channel may be major contributors to this growth and need to be investigated. Higher quality He beams directly extracted from the ion source and transported through the FODO channel will be used for further experiments.

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