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STUDIES OF HEAVY ION BEAM TRANSPORT IN A MAGNETIC QUADRUPOLE CHANNEL

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Summary

In connection with the West German Heavy Ion Fusion Program the first stage (six periods) of a magnetic quadrupole channel (FODO type) to study the transport of intense ion beams was built at GSI. Different ion beams can be used and the variation of the brightness of these beams (hence of the tune depression σ/σ_0) is sufficiently large that regions of theoretically predicted instabilities can be covered. The initial studies are being carried out with a high-brightness beam of 190 keV Ar+ ions and currents of a few mA. Since the pulse length is > 0.5 ms and the pressure is between 10^{-6} and 10^{-7} torr partial space charge neutralization occurs. Clearing electrodes can be used to remove the electrons from the beam. Results of theoretical studies, measurements of charge neutralization effects and first results of transport experiments will be reported.

Introduction

The acceleration and transport of intense ion beams is of great current interest for a variety of applications. In particular, the proposed use of heavy ions for inertial fusion triggered new theoretical studies of the particle beam physics in the presence of high space charge forces. New computational results and general formulas for the maximum beam current that can be transported or accelerated through a particular periodic system under ideal conditions were obtained.[1,2,3] Analytical and computer simulation studies showed that instabilities caused by the interaction between the space-charge forces and the external periodic forces could result in a severe reduction of these ideal maximum current values due to transverse emittance growth.[4] Some of these instabilities, in particular modes of third and higher order, depend on the particle distribution function in phase space and it is an open question to what extent actual laboratory beams are affected by these modes. Furthermore, other effects such as mismatch, nonlinear external forces (e.g. spherical aberrations), misalignments or field errors, and (in bunched beams) coupling between longitudinal and transverse forces may also produce emittance growth. No systematic experimental study has been made so far to check theoretical predictions and to determine quantitatively the relative importance of various sources of emittance growth. For this reason experimental projects were started at the University of Maryland (in collaboration with the Rutherford Laboratory)[5], at the Lawrence Berkeley Laboratory[6], and now also at GSI. The Maryland experiment uses an electron beam in a periodic array of solenoid lenses. The Berkeley group studies an electric quadrupole channel with a Cs+ ion beam. At GSI, the first stage (six periods) of a magnetic quadrupole channel for intense heavy ion beams was put into operation several months ago. In the following sections of the paper we present design parameters, a description of the facility, and preliminary results of the studies made so far.

Theoretical Considerations and Design Parameters

For practical reasons a quadrupole channel of the FODO type with unequal drift sections between lenses was selected. The larger of the two drift sections in each period is being used for insertion of beam diagnostics. Fig. 1 shows the measured variation of the magnetic field gradient versus distance and the "hard-edge" approximation.

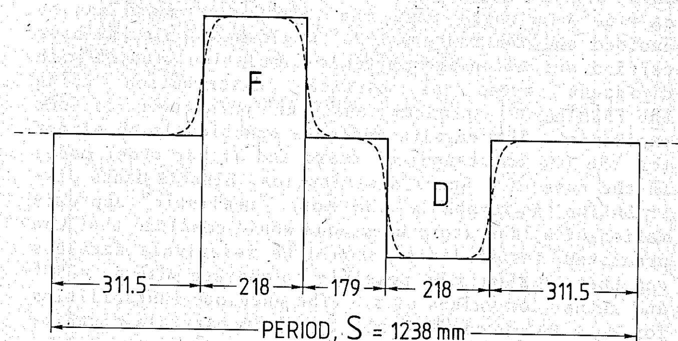

Fig. 1: Magnetic gradient variation in one period Hard-edge model(——) and measured curve (---).

Several types of ion sources with varying brightness are available at GSI. For the initial experiments the ELSIRE source[7] and an Ar+ beam was chosen. By variation of the source operating parameters the output current I and the emittance ε can be changed to obtain a sufficiently large range of values for the tune depression σ/σ_0.

Typical Ar+ beam energies are 190 keV, the current is in the range of a few mA, and the unnormalized emittance ε can vary between 5 and 50 mm mrad depending on the operating conditions. According to the smooth approximation theory[3], the relation for the beam current under matched conditions may be written in the form

$$I = 1/2\, I_0\, \beta^3\gamma^3 \quad (\sigma_0\varepsilon/S)\ (1-\sigma^2/\sigma_0{}^2)/(\sigma/\sigma_0),$$

where $I_0 = 3.1 \times 10^7$ A/Z amperes, A = particle mass number, Z = charge number, $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$, ε = emittance, and the relation $\varepsilon/\alpha = \sigma/\sigma_0$ has been used (α = acceptance).

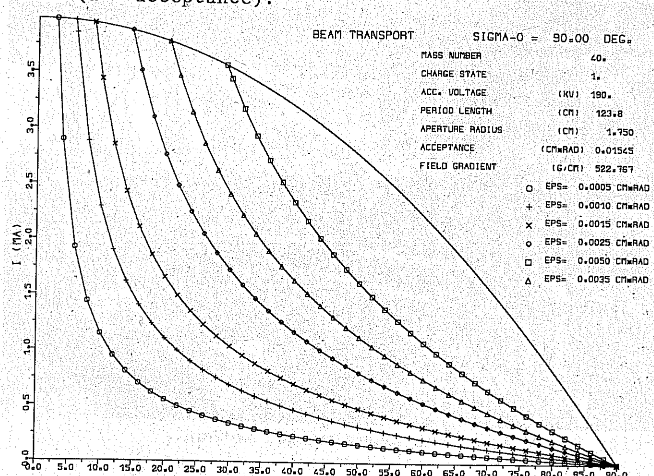

Fig. 2: Ar+ beam current vs. depressed phase advance σ for different values of emittance.

Fig. 2 shows a working diagram for one channel with 190 keV Ar+. It is based on the above relations and assumes a zero-current phase advance of $\sigma_0 = 90°$, and a maximum beam envelope radius (or aperture) of a = 1.75 cm. The parabolic outer curve of I vs σ represents the maximum acceptable current for each val-

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ue of σ. The labelled curves represent constant values of emittance. For a given emittance, the current can be increased until one reaches the maximum value on the parabola. (Below that maximum, the beam radius is smaller than 1.75 cm.) In a long channel with many periods, the theoretically studied instabilities could limit the operation to values of σ above a certain threshold. A beam with a K-V distribution, for instance, was found theoretically to be unstable[4] for values of $\sigma \leq 57^0$ when $\sigma_0 = 90^0$. It would be better to operate with $\sigma_0 = 60^0$ in which case the third-order modes can be avoided and the range $\sigma \geq 24^0$ would be stable. We have carried out extensive particle simulation studies with different types of particle distribution using the PARMILA-GSI program and the parameters of our experiment. The results indicate practically no effect (on the RMS emittance) of third and higher order modes in the case of a Gauss distribution. Since a Gauss distribution is probably the most "realistic" approximation of a laboratory beam, one would conclude that the predicted instabilities should be relatively harmless and that it should be possible to operate with $\sigma_0 = 90^0$ and rather low values of σ. (The envelope instabilities for $\sigma_0 > 90^0$ occur for all types of particle distribution so that σ_0 should be limited to values of 90^0 or less.) However, the final answer to this question must come from the experimental studies on high-current beam transport. A difficult problem affecting our studies at GSI is charge neutralization by electrons. The beam pulse is rather long (> 0.5 ms), and at a vacuum pressure of 10^{-7} to 10^{-6} torr, we have a high degree of fractional neutralization due to ionizing collisions with the background gas. Thus clearing electrodes along the beam line will be necessary to remove the electrons from the ion beam. Another possibility under consideration is to reduce the pulse length by use of a chopper to the range of ~ 10 µs where collisional ionization effects are negligible. Since space-charge neutralization is important in all high current beam transport lines (e.g. between the ion source and the linear accelerator), we are devoting some of our efforts to a study of this problem, as will be reported below.

Description of Apparatus

Fig. 3 shows a view of the experimental set-up, Fig. 4 gives detailed information on the arrangement of the components. For injection in the periodic beam transport channel a new installed high current beam line at the GSI 300 kV accelerator is used. For the first experiments Ar+ ions were extracted from the GSI high current source ELSIRE. The single-aperture three electrode extraction system and the geometry of the accelerating column provide for a well focused high intensity beam. A large-aperture magnetic triplet serves to match the beam to the FODO channel. A collimating system can also be used for defining of the input emittance of the channel. 12 identical magnetic quadrupole singlets form the nonsymmetric FODO channel. Due to the maximum field gradient of 3 kG/cm, the whole range of the phase advance σ from 0 to 180^0 can be obtained. At appropriate positions along the beam line different diagnostic elements are installed (see Fig. 4).

Emittance growth in the channel can be measured by computer-controlled slit-collector systems at the entrance and exit of the channel. The emittance measurement can be started at different times within the beam pulse except the first 300 µs interval, which is used for electronic adjustment of the current amplifiers. A minimum time window of 200 µs can be selected. Along the beam line clearing electrodes are installed to eliminate the electrons from the beam. A special device for beam potential measurements has been developed at the University of Frankfurt (Institut für Kernphysik). It measures the energy of the residual gas ions diffusing out of the beam.[8]

Initial Experimental Results

The first experiments have been started with an Ar+ beam at the energy of 190 keV. The current available at the entrance of the FODO channel was varied in the range from 0.04 mA to a maximum level of 3 mA. The input emittance was varied between ε = 3 mm mrad and 15 mm mrad. For evaluation of our experiments the knowledge of the degree of space charge neutralization is very important. We measured the expansion of the beam envelope over a drift length of 1.2 m downstream of the triplet (from the position of emittance measurement device to the diagnostics box at the end of the first magnet period; the magnetic field of the quadrupoles was switched off in these experiments). It was found that the beam in this drift region is partially neutralized. By using the clearing electrodes shown in fig. 4 with potentials ≥ + 100 V this neutralization effect could be reduced. This was demonstrated by the expansion of the beam cross section which, at the end of the 1.2 m drift section, exceeded the widths of the profile grids.
The electronics of the profile measurement device integrates the current over the entire beam pulse. Therefore variations of the space charge potential within the beam pulse cannot be detected. As mentioned before, the emittance measurement device starts the data taking 300 µs from the beginning of the beam pulse. Therefore the degree of the space charge neutralization at the end of the pulse must be known.

Fig. 5 shows the energy spectrum of the residual gas ions diffusing out of the Ar+ beam measured with the ion detector mentioned above. The lower curve represents the ion energy spectrum within a 200 µs-window at the beginning of the pulse. The upper curve is the energy spectrum at the end of the pulse. These measurements

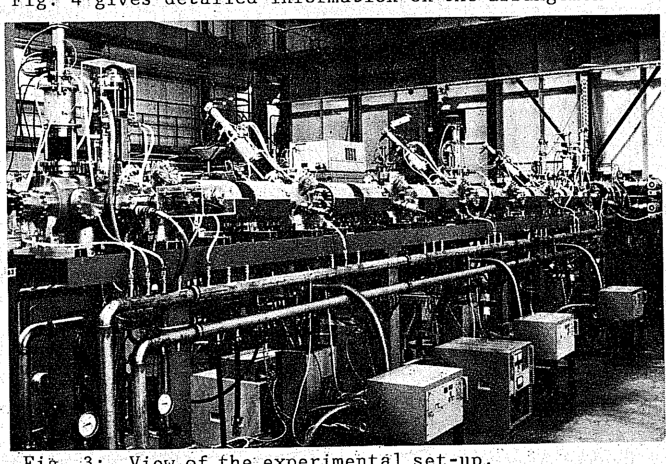
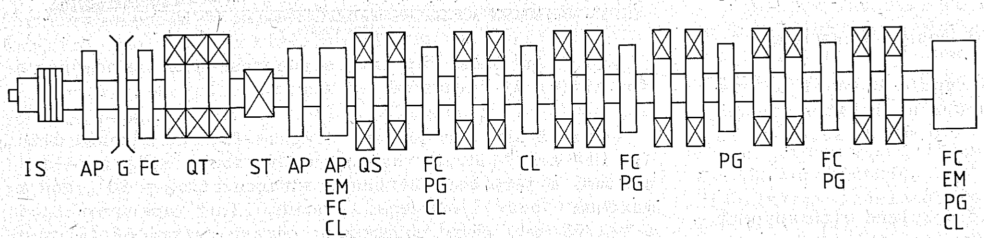


Fig. 3: View of the experimental set-up.



IS Ion Source with Extraction
AP Aperture (variable)
G DC Accelerating Gap
FC Faraday Cup
PG Profile Grid
EM Emittance Measurement Device
CL Clearing Electrode
QT Quadrupole Triplet
QS Quadrupole Singlet
ST Steering Coil

Fig. 4: Schematic drawing of the apparatus.

demonstrate that the ion beam space charge potential and thus the amount of neutralization varies within the pulse. Measurements with a 50 μs-window (fig. 6) indicate that after about 300 μs from the beginning of the pulse the space charge potential reaches a minimum value, i.e. the amount of neutralization remains constant. In ref. 9 it was shown theoretically that due to the energy spread of the electron distribution formed by ionizing collisions in the residual gas a pulsed ion beam cannot be fully neutralized. The measurements also show that it was not possible to obtain complete deneutralization of the beam by using only the clearing electrodes at the entrance of the channel. Apparently one needs clearing electrodes along the entire length of the beam at suitably small intervalls.

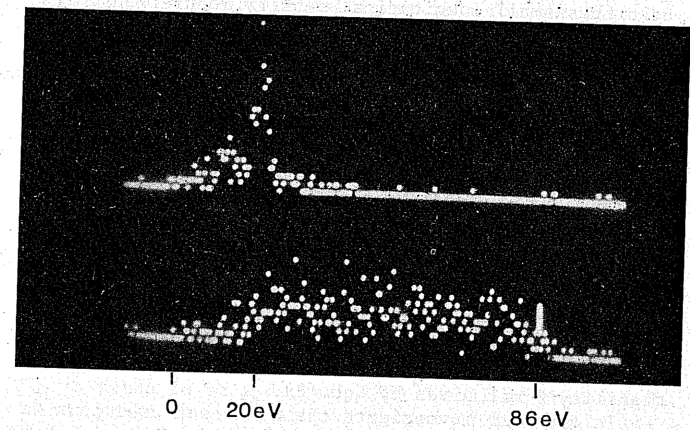


Fig. 5: Energy spectrum of residual gas ions. (Top: Last 200 μs of 1 ms pulse; Bottom: First 200 μs of 1 ms pulse.)

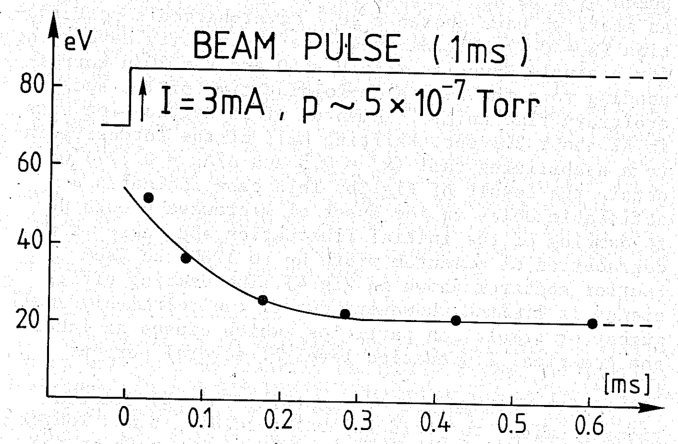


Fig. 6: Energy of peak intensity of residual gas ions vs. time within the pulse (50 μs time window).

In another series of experiments we studied the transport of the partially neutralized beam through the six periods of the channel. Fig. 7 shows a typical result of emittance measurements at a high current level (1 mA) and a magnetic field corresponding to $\sigma_o = 90^0$. Phase space deterioration and a rather large emittance growth effect are evident in this figure. The emittance growth at different current levels versus σ_o is shown in fig. 8. A strong dependence on the beam current was found. This emittance growth cannot be explained so far in general. The rapid growth above $\sigma_o = 90^0$ for the high-current cases may be indicative of the presence of envelope instabilities even though the beam is partially neutralized by electrons. Future experiments with unneutralized beams should show to which extent the emittance growth seen in the present measurements may be attributed to the effects of electrons.

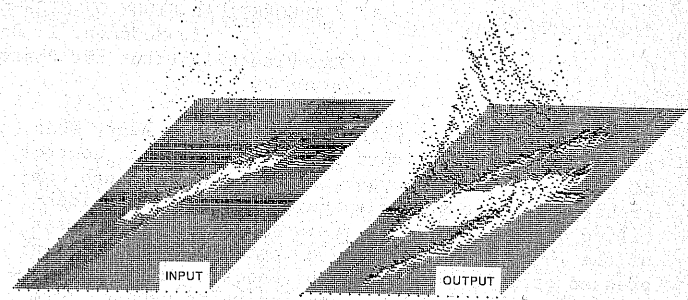


Fig. 7: Measured emittance ($\sigma_o = 90^0$, I = 1 mA).

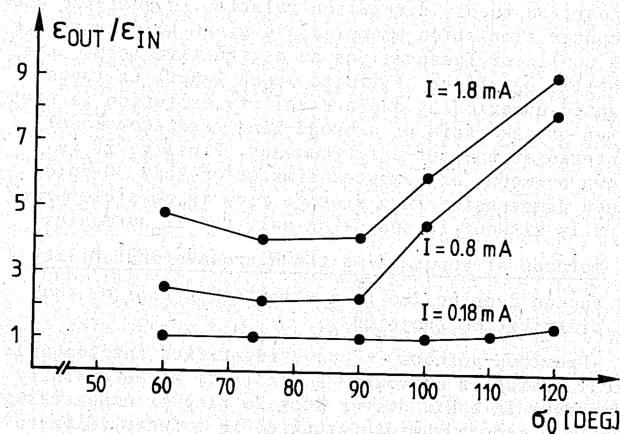


Fig. 8: Emittance growth versus σ_o for different currents (90 % of the total emittance are compared).

Conclusions

Numerical simulation studies indicate that third and higher order mode instabilities as predicted for K-V or waterbag distributions do not occur for a more realistic Gaussian beam. Therefore it should be possible to operate a long periodic transport channel with $\sigma_o = 90^0$ and low values of σ.

In our first transport experiment an enormous emittance growth was measured over a wide range of the phase advance σ_o. These results cannot be explained so far since the degree and spatical variation of the space charge neutralization inside the magnetic channel is not known. The rapid increase of the emittance growth above $\sigma_o = 90^0$ could indicate that theoretically predicted envelope instabilities are present even though the beam is not unneutralized.

In future experiments space charge compensation has to be avoided. Improvement of vacuum, more efficient clearing electrodes and shorter beam pulses are under consideration to achieve this goal. A low current ion beam probe will be installed soon.

Acknowledgement

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