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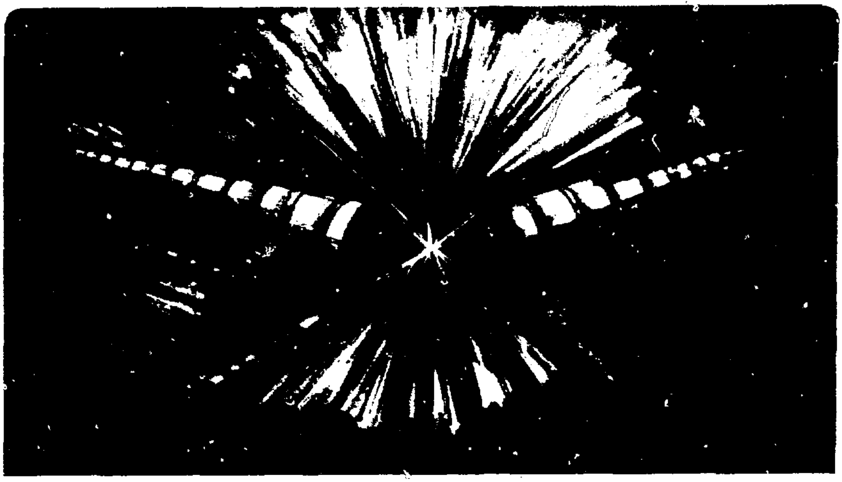

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QUADRUPOLE TRANSPORT EXPERIMENT WITH SPACE CHARGE DOMINATED CESIUM ION BEAM*

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1. Introduction

The purpose of the experiment is to investigate the beam current transport limit in a long quadrupole-focussed transport channel in the space charge dominated region where the space charge defocussing force is almost as large as the average focussing force of the channel. In this region, the total current and the beam size scale as[1]

$$I \sim \epsilon \frac{\sigma_0}{\sigma}\left[1-\left(\frac{\sigma}{\sigma_0}\right)^2\right], \qquad (1)$$

$$a^2 \sim \epsilon/\sigma$$

where symbols denote the total current (I), emittance (ϵ), the phase advance of the betatron oscillation per lattice period with (σ) and without (σ_0) the space charge, and the beam radius (a).

Various authors have proposed the permissible values of σ and σ_0 for stable beam transport. Historically, A. Maschke suggested that $\sigma/\sigma_0 > 0.7$ based on the then-available information. Theoretical calculations[2] based on the Kapchinskij-Vladimirskij (K-V) distribution function showed that $\sigma/\sigma_0 > 0.4$ may be safe but $\sigma_0 < 60^\circ$ to avoid the third order instability. Subsequent computer simulations[3] for the K-V distribution found that the instabilities are benign, i.e. particles redistribute themselves in the 4-D phase space, but the RMS emittance does not grow if $\sigma_0 < 60^\circ$, and $\sigma/\sigma_0 > 0.1$. Recent simulations[3] using the semi-Gaussian distribution showed a stable beam for σ/σ_0 down to a few percent which is only limited by the accuracy of the simulation at small values of σ/σ_0. A semi-Gaussian distribution, which is also called a thermal distribution, has a flat top distribution in configuration space and a Gaussian distribution in velocity space.

In the present experiment we have observed stable beam transport for $\sigma_0 = 60^\circ$ and $\sigma \geqslant 8^\circ$ which is the lowest value of σ accessible with the present ion source. Unstable beam transport is observed only when $\sigma_0 \geq 90^\circ$ and σ smaller than a threshold value which is dependent on σ_0; for $\sigma_0 = 120^\circ$, the observed threshold value is $\sigma \approx 90^\circ$.

2. Experimental Apparatus

The experimental setup is composed of the ion gun, matching section (5 electrostatic quadrupoles), transport section (82 electrostatic quadrupoles) and the diagnostics tank. The ranges of beam parameters are: Cs^+ beam; kinetic energy 120-160 keV; beam current 0.7-23 mA; normalized beam emittance 0.08-0.5 π mm mRad. Current-attenuating grids and emittance-varying biased grids are used to achieve these parameters.

The half lattice-period is 15.24 cm and the bore diameter is 5.08 cm. Because of the high voltages on the electro-static quadrupoles the placement of diagnostics is restricted to the mid-plane between any pair of quadrupoles. The phase ellipses in the xx' and yy' planes for a matched beam are similar in shape but tilted with equal and opposite angles (astigmatic), at this antisymmetrical point of the lattice. In phase space plots presented in this report $x' \rightarrow x' - \alpha x$ type coordinate transformation is performed to suppress these tilts.

The current is measured with a gridless deep Faraday cup at the end of the transport section and with a shallow gridded Faraday cup in between quadrupoles at the end of the matching section. The kinetic energy is measured by the time of the flight method and by measuring the Marx generator voltage using a capacitive divider. The beam emittance is measured with the conventional two slit scan method. The beam is about 10 μs long and pulsed every 5 seconds. More detailed description of the apparatus can be found in our earlier publication.[4]

3. Experimental Results

3.1 Beam Matching

Five quadrupoles in the matching section are used to match the beam from the injector to the transport section. Four quadrupoles are usually enough for matching. However, when the required quadrupole voltages are excessive, additional quadrupoles are required. The matching procedure is described in our earlier publications.[4] Guided by the RMS envelope equation we were able to construct a fairly periodic beam envelope. The degree of mismatch, measured by the amplitude of the envelope oscillation is about 5 percent of the beam radius.

3.2 Stability

We have measured the total current and the particle distribution in xx' and yy' planes, at several locations including the beginning and the end of the transport section. The beam is inferred to be unstable if current loss or emittance growth is detected. We have observed a stable beam propagation for $\sigma_0 = 60^\circ$ and $\sigma > 8^\circ$ where the 4th and higher order instabilities have been predicted by the K-V theory. Measured xx' distributions for $\sigma/\sigma_0 = 8^\circ/60^\circ$ at various locations in the transport section (Q4, Q35, Q59, Q80) are shown in Fig. 1. The current loss and the emittance growth is less than the experimental uncertainty.

For other values of σ_0, the lowest accessible values of σ/σ_0 scales proportionately as σ_0. Within these accessible parameter regions, we have observed unstable beams only when $\sigma_0 \geq 90^\circ$ and $\sigma < \sigma_{\text{threshold}}$. The threshold behavior of the instability at $\sigma_0 = 120^\circ$ is shown in Fig. 2. The value of σ is increased by increasing the RMS emittance using the biased grids. The measured onset of the instability at $\sigma < 90^\circ$ agrees with the theoretical prediction for the envelope instability.

3.3 Steady State Distributions

The distribution function at the ion source is approximately semi-Gaussian, which is somewhat distorted in the matching section probably due to the nonlinearities, but reaches a steady state in the transport section (Fig. 1).

The steady state distribution for the low space-charge stable beam is characteristically different

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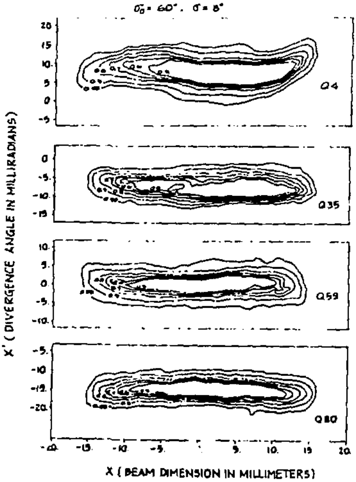

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Fig. 1. Phase space distribution of particles in xx' plane measured at various homologous locations in the channel. Coordinate transformation of x' → x' −αx are used to suppress the tilt. The numbers on the contour are the fraction of the total number of particles contained within the contour.

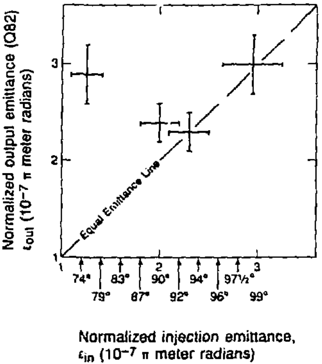

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Fig. 2. Measured output emittance 80 quadrupoles downstream from input emittance measurement for 3.45 mA Cs$^+$ beam at 160 kV with σ_0 ~ 120°. Approximate depressed tune (σ) values for injection emittance are shown on horizontal axis.

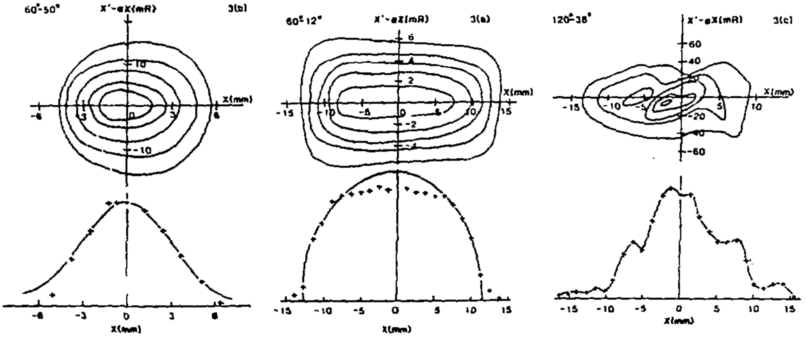

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Fig. 3. Three characteristic particle distributions: for a low space charge stable beam (a), a high space charge stable beam (b) and an unstable beam. Upper three figures show contours of 0.1, 0.3, 0.5, 0.7, and 0.9 of the peak value. Lower three figures show $\int jdy$. Expected current profiles for Gaussian (a) and semi-Gaussian (b) distributions are shown.

from that for the high space-charge stable beam. The contours in the xx' distribution is approximately circular and the current profile is approximately parabolic, for $\sigma/\sigma_0 = 50^\circ/60^\circ$. For $\sigma/\sigma_0 = 12^\circ/60^\circ$, the contour looks more squarish, and the current profile is much more flat. In both cases the distribution in the velocity space is observed to be Gaussian. A computer simulation using a PIC Code for the present experimental parameters shows a similar steady state distribution with an elliptical current profile (a flat distribution in xx'). The experimental current profile in Fig. 3b shows that the current density near the beam axis is somewhat depressed from the elliptical one observed in the simulation. We believe that the hollow formation is due to the nonlinearities of the focussing channel. The nonlinearities caused by the Bessel function (I_2), the nonparaxial particle trajectory, and the axial electric field doing work on particles cause the average focussing strength of the channel to be stronger as the radius is increased. A typical unstable distribution for $\sigma_0 = 120^\circ$ and $\sigma = 36^\circ$ is shown in Fig. 3c. A current loss of 40 percent at Q44 and a large emittance growth is observed for this case.

4. Conclusion

Stable beam transport with a steady state distribution has been observed for space-charge dominated beams whose space charge defocussing field is as large as $\sim$98 percent of the average focussing force of the transport channel, provided $\sigma_0 < 90^\circ$. Observed results agree very well with that of the PIC simulation. The K-V distribution has been the only known steady state distribution in the alternating-gradient focussing channel, but the present experiment and the computer simulation show that the semi-Gaussian distribution (with a somewhat smoothed beam edge) also preserves its form along the channel if the beam is intense enough.

Further experiments are required to demonstrate stable beam transport for smaller values of σ/σ_0. However, computer simulations indicate that there may be no physics limits. In the earlier designs of high current beam transport channel, the beam emittance and the values of σ/σ_0 and σ_0 were thought to play the crucial roles. In the absence of these limits, the total current is proportional to the cross-sectional area of the matched beam, and the current density is determined by the condition that the space charge defocussing force is equal to the average focussing force of the channel.

If the beam and the focussing elements are not aligned well enough, the beam emittance may grow even in the otherwise stable region, due to the coherent betatron oscillation and the image charge effects. More experimental and theoretical work is necessary to delineate this problem.

References

1. See, for example, J.D. Lawson, in these proceedings.

2. I. Hoffmann, L.J. Laslett, L. Smith, and I. Haber, Particle Accelerators, 13, 145 (1983).

3. I. Haber, Proceedings of the INS International Symposium on Heavy Ion Accelerators and Their Applications to Inertial Fusion, Institute for Nuclear Study, University of Tokyo, Tokyo, Japan, January 23-27, 1984.

4. W. Chupp, A. Faltens, E.C. Hartwig, D. Keefe, C.H. Kim, L.J. Laslett, R. Nemetz, C. Pike, S.S. Rosenblum, J. Shiloh, L. Smith, M. Tiefenback, and D. Vanecek, IEEE Trans. Nucl. Sci., NS-30, 2549 (1983).

5. C. Celata, I. Haber private communication (1984).