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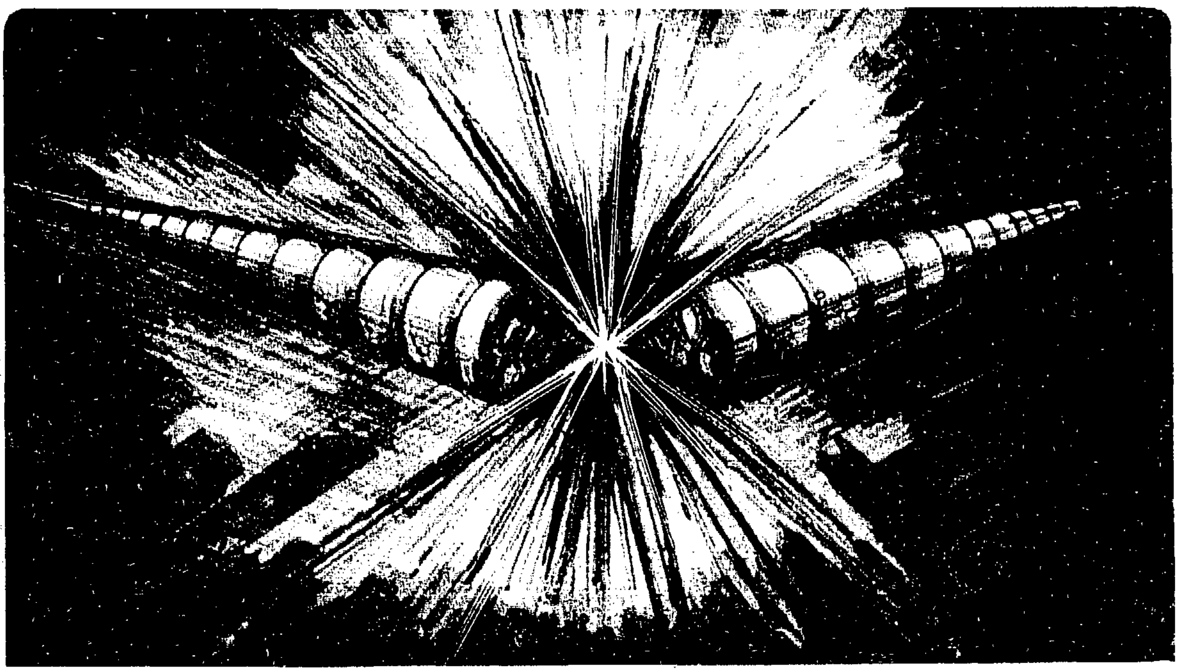

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EXPERIMENTAL MEASUREMENT OF EMITTANCE GROWTH IN MISMATCHED SPACE-CHARGE-DOMINATED BEAMS*

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Abstract

Using the Single Beam Transport Experiment (SBTE) at LBL, we have measured the emittance of a well-matched 4.6-mA beam of 122-keV Cs^+ to be conserved from injection into through exit from an 80-lens segment of the AG focussing channel. We then mismatched the beam into the same channel such that the maximum (minimum) radius of the beam at the midplane between lenses was about 1.5 (0.5) times the former value. We caused mismatches in the envelope of the beam in both transverse dimensions (labeled a and b) in modes both symmetric ($\delta a = \delta b$) and antisymmetric ($\delta a = -\delta b$). We found the mismatch amplitude to decay during the beam transit through the channel for both modes of mismatch, although more so for the antisymmetric mode. We also found the emittance of the symmetrically mismatched beam to be the same as for the matched beam, while the emittance of the antisymmetrically mismatched beam grew by as much as a factor of four over that for the matched beam.

Introduction

Because of the inevitable spread in betatron frequency of the particles in a beam, the particles will eventually "phase-mix" and forget their original neighbors in betatron phase. In the zero-current limit, for a beam that is either misaligned or mismatched within its channel, the beam will eventually diffuse so that its radius is equal to the maximum excursion of the particles of which it is composed.

We expect the same phenomenon to occur within space-charge-dominated beams, although the final radius of the beam will not be determined solely by the initial mismatch or misalignment amplitude, but also by the space-charge self-energy of the beam.

From perturbation of the equations for the envelope of a beam in two transverse dimensions (see, for example, refs. 1 and 2, which we label a and b), we obtain in the limit of continuous focussing, we obtain the following phase advance rates ("wave-numbers," in essence) for the eigenmodes of oscillation:

$$k_\pm^2 = \begin{cases} 2\sigma_0^2 + 2\sigma^2, & \delta a = \delta b \\ \sigma_0^2 + 3\sigma^2, & \delta a = -\delta b \end{cases} \qquad (1)$$

where σ_0 is the phase advance per arbitrary length for a single particle in the channel and σ is the net phase advance for a particle under the influence of the self-field of a beam. In the low-temperature limit ($\sigma \to 0$) we see that $k_+ \to \sqrt{2}\sigma_0$ (symmetric mismatch) and $k_- \to \sigma_0$ (antisymmetric mismatch). The symmetric mode frequency is the higher of the two because the space-charge density is affected by this oscillation and not by the antisymmetric mode. We will compare these values with our data below.

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Method

We used a 4.6-mA beam of 122-keV Cs^+ ions with a normalized emittance of $0.7\times10^{-7}\ \pi$ meter radians for our measurements. We matched the beam into the quadrupole channel of the SBTE by tuning the first five lenses of the channel (M1--M5) [3,4]. The channel was set so that $\sigma_0 = 60°$ (per focussing period), which resulted in a matched beam radius at the midplane between lenses of R_0 = 10 mm. We also tuned the matching lenses to mismatch the beam in the succeeding FODO lattice. In one experiment, the adjustment caused a purely symmetric mismatch. In the other a purely antisymmetric mismatch was created. In each case the maximum (minimum) radius between quadrupoles reached 1.5 R_0 (0.5 R_0).

Our emittance measurements were made using pairs of 0.010-inch-wide slits spaced 6 inches apart longitudinally. We have defined our "emittance" in terms of the measured phase space distribution in the following way: We delete the low-level measurements until the beam current represented by the sum of the remaining points drops to 95% of the original total. The emittance is then $4\beta\gamma$ times the RMS emittance of the subset of the data:

$$\epsilon = 4\beta\gamma \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}\ .$$

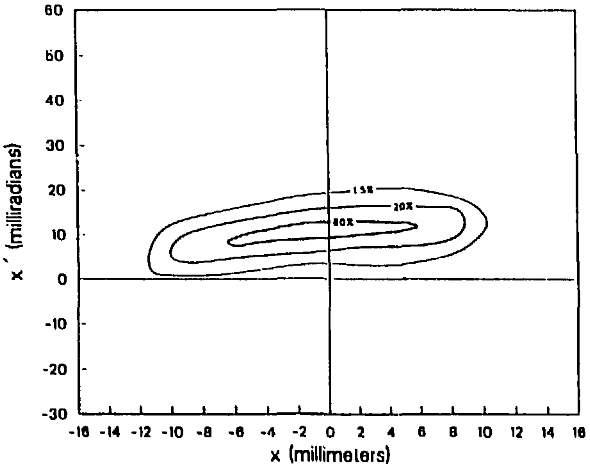
Results

The beam radius (defined as twice the RMS radius of the beam) near the injection and exit of the periodic channel is shown in Table 1 for these three sets of initial conditions.

For the beam parameters given above and for σ_0 = 60° we calculate $\sigma = 8°$ from the solution to the envelope equations. Thus $k_+ \approx 86°$ and $k_- \approx 62°$. The envelope data for the symmetric mode show that the minimum occurs

Table 1: Summary of beam radius data (in mm) for an approximately matched beam (Case I), a symmetrically mismatched beam (Case II), and an antisymetrically mismatched beam (Case III). In the two mismatched cases, the maximum amplitude of the beam was about 16 mm.

	Case I		Case II		Case III	
	R_V	R_H	R_V	R_H	R_V	R_H
M5	10.5	11.9	14.2	14.6	9.2	13.8
Q1	9.4	12.2	~ 14	14.8	3.8	15.3
Q5	10.0	8.1	5.2	6.8	15.1	6.5
Q7	11.9	10.7	12.9	12.1	15.8	4.0
Q9	10.3	10.7	13.6	15.0	9.8	9.2
Q73	10.8	9.4	11.5	11.5	12.0	10.7
Q75	10.0	9.7	10.2	11.3	9.9	11.3
Q77	8.6	9.0	7.33	7.7	10.2	11.8
Q79	-	9.9	-	9.9	-	11.7



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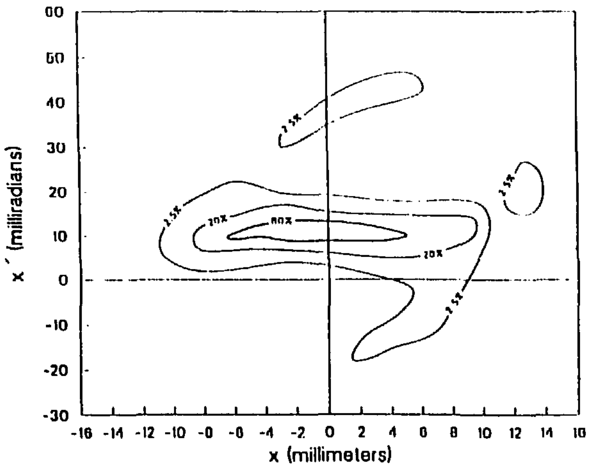
1A



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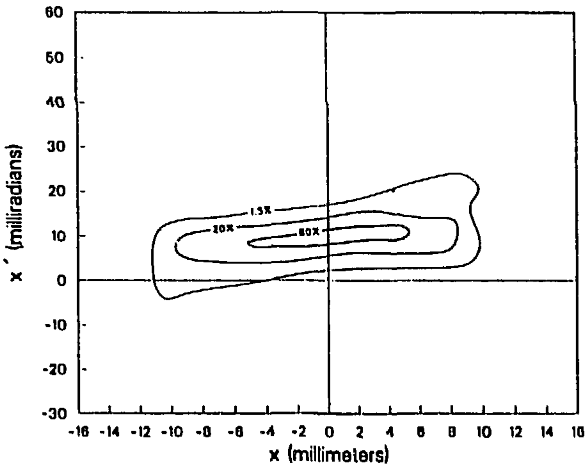

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1B

Fig. 1. Phase space contours for A) the matched beam, B) the symmetrically mismatched beam, and C) the antisymmetrically mismatched beam, transformed to suppress the overall focussing of the beam and make the phase ellipses approximately upright. The contour levels for A) and B) are for 1.5%, 20%, and 80% of the peak density at the center of the beam. The lowest contour level for C) was chosen as 2.5% of the peak level in order to show the gradient in phase space density and give a sense of the direction of particle diffusion in phase space. At the 1.5% level, the clockwise-pointed tails in phase space have encircled the body of the distribution, enclosing two regions of very low particle density. We expect that the 4-dimensional phase space density is conserved, while the 2-dimensional projected density measured experimentally is not conserved.

Table 2: Emittances of the beam for the various cases at the end of the transport channel (Q80) and for the most intense 95% of the distribution (to eliminate low-level data points and avoid heavy weighting of the distribution tails by the RMS emittance calculation).

Case I	Case II	Case III
0.67×10^{-7}	0.68×10^{-7}	2.94×10^{-7}

about 2 periods (4 lenses) after the maximum, so we would estimate $k_+ \approx 90°$. Similarly, the antisymmetric mode shows an interchange of radius values over 3 periods, so we measure $k_- \approx 60°$. These numbers are in close agreement with the values calculated from Eq. (1). The amplitudes of oscillation damp between injection (Q1) and exit (Q80), although the damping is less pronounced for the symmetrically mismatched beam. The measured emittance of the beam at Q80 (80 lenses downstream from the matching lenses, shown in Table 2) is unchanged for the symmetric mismatch with respect to the matched beam, but the emittance of the antisymmetrically mismatched beam is 4 times as great as for the matched beam.

The phase space contours shown in Figs. 1A)-C) show the marked difference between the antisymmetrically mismatched beam and the others. The matched beam in A) and the symmetrically mismatched beam in B) are very much alike in distribution. In contrast, a very extensive, but low-level, halo has formed around the beam core in phase space for the antisymmetrically mismatched beam. The lowest contour level in C) was chosen as 2.5% rather than 1.5% to show the gradient in density from the ends of the distribution. It is as if particles are being ejected from the ends of the distribution and wrapping clockwise around the beam. The contour at the 1.5% level (not shown) actually reconnects with the body of the distribution, enclosing void areas. Recall that the 4-d transverse phase space density $\rho(x,y,x',y')$ is expected to be conserved here, while the projected density need not be conserved under the influence of non-linear fields.

We also compare the peak signal level for the three cases to separate the effect of the tails of the distribution on the emittance from that of changes in the core of the distribution. The average of the three adjacent highest values in the distributions was highest for the matched beam, falling to about 95% for the symmetric and 77% for the antisymmetric mismatches. The change in emittance is thus not due solely to the extensive tails of the distribution shown in Fig. 1C.)

We note that the extensive tails of the distribution are only at the level of 2-3% of the peak intensity in the antisymetrically mismatched beam. We measured the phase space distribution at Q35 and found the same structure as that shown in Fig. 3 (including enclosed voids), but the halo was at the level of 1-2% of the peak and the voids were much cleaner. [Up to this point, the antisymetric mismatch had been generated from the configuration for the matched beam by raising the strength of lens M5 to about 20% above its nominal value. To check the dependence of the emittance growth on the mismatch amplitude, we then set this lens to about 14% above the value for the matched beam, expecting to have an antisymetrically mismatched beam with mismatch amplitude about 2/3 of the original value. When we measured the emittance at Q35 and Q80, we found that the same structure was present as before, but only at the level of 0.5-1% of the peak. The emittance at Q80 was reduced to $1.75\times10^{-7}\,\pi$ meter radian, but still well above the value for the matched beam, and the peak intensity was 82% of that for the matched beam.]

Interpretation of the Data

The ideal beam dynamics of the K-V distribution depends delicately upon the linear nature of the beam self-field. Real beams are not so smooth as mathematical beams, and if a space-charge-dominated beam is focused into a very eccentric profile (long in the x-dimension, say), this clumpiness can manifest itself in a large variation of the electric self-field component E_y as a function of x. In the severe antisymetric mismatch we caused in Case III, the beam is very ribbon-like, having an aspect ratio of approximately 4:1. In the case of the symmetric mismatch, the maximum beam aspect ratio remains near the value given by the AG flutter, which is about 1.5:1 for $\sigma_0 = 60°$.

This observation could well explain certain problems in beam matching encountered in the extensive SBTE survey reported elsewhere [3]. There it was noted that it became more difficult to match the beam cleanly to the FODO lattice the further the beam aspect ratio departed from unity.

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