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EMITTANCE VARIATIONS OF VERY COLD OFF-AXIS ION BEAMS DURING TRANSPORT THROUGH MBE-4†

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We have been studying the transverse emittance variations of very low emittance (0.03 mm-mrad normalized K-V)-Cs^+ beams drifting through the electrostatic quadrupole transport of the MBE-4 apparatus at the injection energy of 180 keV. Both experiment and simulation show that these strongly tune-depressed ($\sigma = 7°$) beams, when off-axis, interact with image charges and focus field nonlinearities to produce a modulated emittance that grows with distance. The modulations appear at frequencies of approximately $(\sqrt{2} + 1)\sigma_o$ where σ_o is the undepressed phase advance of the electrostatic focusing lattice. Experimentally, the extent of the emittance variation depends on the amplitude of coherent betatron oscillations induced by injection offsets and by transport alignment errors. At larger emittances and therefore less tune depression, the modulations and growth are reduced, suggesting that these effects may saturate with distance in a long transport system. Simulations, verified by experiments, indicate that on-axis beams exhibit essentially no emittance variation or growth with distance.

1 INTRODUCTION

In the heavy-ion approach to inertial confinement fusion the transverse emittance of the beam will determine how well the beam can be focused on the target. Therefore, an emittance "budget" for any particular scenario is defined by the requirements on emittance at the final focus and by the emittance practically achievable from the injector. Although the normalized emittance should be conserved for a beam subject only to ideal optics, one must envisage some emittance growth from aberrations, nonlinear space-charge effects, alignment errors, transport mismatches, etc. The subject of emittance growth in a heavy ion fusion driver is therefore of great concern. In this paper we report on measurements and theory of emittance growth in an electrostatically focused heavy ion (Cs^+) linac, MBE-4. The experiments are of relevance to the low energy end of a driver where electrostatic focusing is preferred over magnetic focusing due to the low velocity of the beam (0.0017c in MBE-4, typically 0.01c at the low-energy end of a driver).

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2 EXPERIMENTAL CONFIGURATION

The MBE-4 apparatus has been adequately described elsewhere[1] and here we give just a brief summary of the accelerator components relevant to the studies described in this paper. MBE-4 consists of a 200-keV injector followed by a short matching section, which adjusts the beam envelope parameters for injection into the main linac section. The main linac comprises a 30-period syncopated FODO lattice structure (45.72-cm unit cell length). Following each lattice period is an acceleration gap, with the exception that every fifth gap is reserved for diagnostic access and vacuum pumping. At the diagnostic ports, the transverse beam parameters, such as size, offset, emittance, etc., can be measured in either plane. Measurements are made using a multi-shot scanning system employing the familiar double-slit technique. Note that the parameters of the beam can be measured only at seven discrete locations throughout the linac. In a later section we will describe a technique that allows us to infer, from measurements made at the ports, values of the emittance, at locations intermediate to the diagnostic ports.

3 THEORY

We have been modelling the emittance development of drifting beams in MBE-4 using a particle-in-cell code (SHIFTXYA)[2]. This code assumes a 2-D geometry, but with varying boundary condition in the direction of beam propagation. Thus at places where there are no quadrupoles we replace the boundary condition by free space. The code includes the effect of nonlinear field components in the quadrupoles and the effects of induced image charges on them. These simulations were performed for the geometry and parameters of MBE-4, including the matching section, where envelope variations are large. Although we preserve the syncopated lattice structure the quadrupoles are treated as having hard edges. The beam has a nominal 5-mA current; 180-keV energy; 0.03 mm-mrad normalized K-V emittance; tune depression (σ_o/σ) of 10; and 10-mm envelope radius. Focusing is provided by electrostatic quadrupoles of bore radius 27 mm.

The principal results of the computations are illustrated in Figures 1 and 2. Figure 1 shows that if we include the effects of dodecapole field components and induced image charges, then a beam with initial transverse displacements dx and dy from the linac axis exhibits a continuous variation in emittance with an overall tendency to growth. It is found that the extent of these oscillations is sensitive to the size and direction of the initial displacement. If the effects of nonlinear fields are neglected, then even a displaced beam will travel through the linac without emittance growth. The frequency of the oscillations appears to be given by $(\sqrt{2}+1)\sigma_o$, suggesting the sum of the coherent betatron oscillation and plasma frequencies. In contrast, a beam that propagates on axis shows essentially no change in emittance. The observed emittance growth results from the excitation of coherent beam modes by non-linear forces. The emittance growth is amplitude-modulated by the coherent oscillation of the beam. In Figure 2 we observe that if the beam has an increased initial emittance

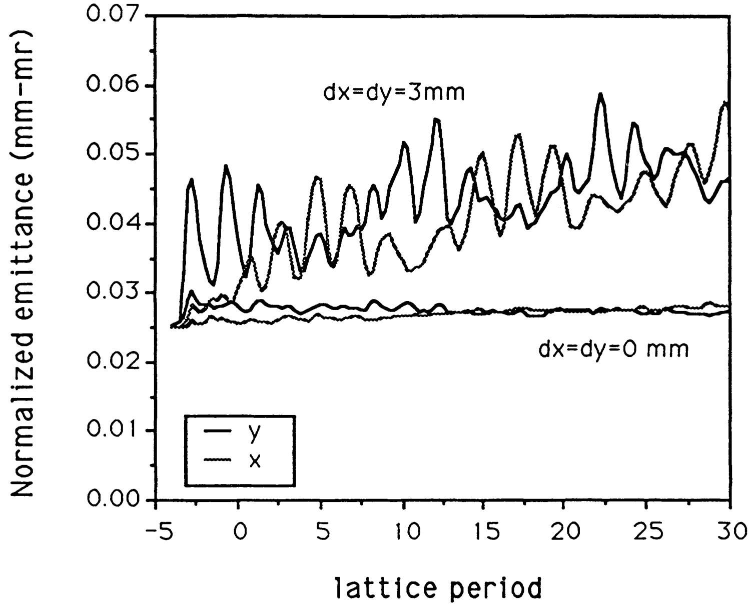

FIGURE 1 Simulation of the transverse emittance variations in MBE-4 for both off-axis and on-axis beams. The off-axis beam is displaced by 3 mm in both transverse planes (x and y).

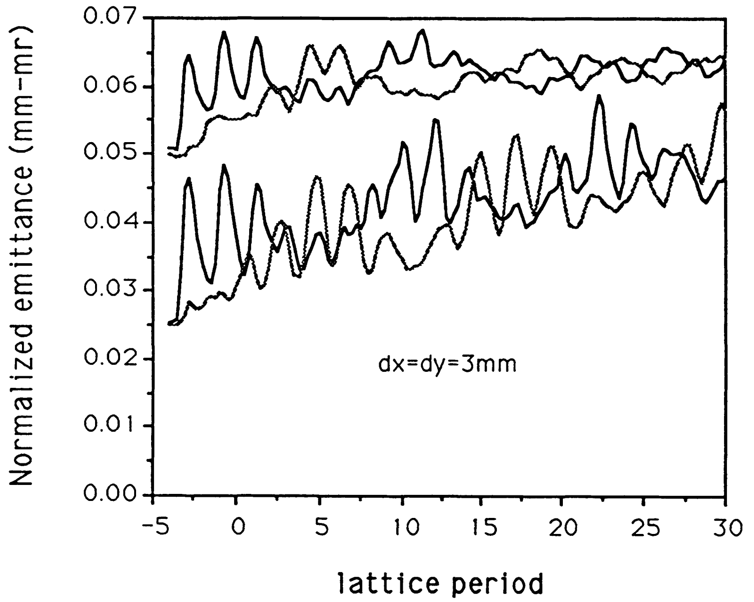

FIGURE 2 Emittance variations in MBE-4 for off-axis beams that have initial emittances of 0.025 and 0.05 mm-mrad.

(i.e., a decrease in the tune depression) then the emittance oscillations are less pronounced. We note that an earlier simulation of the drift of space-charge-dominated beams in a continuous electrostatic focusing lattice also revealed the presence of emittance oscillations[3].

4 EXPERIMENTS

It is clear that we cannot experimentally recover the high-frequency behavior of the simulated emittance oscillations by sampling the value at the sparsely distributed diagnostic ports. In order to effectively measure at locations upstream and downstream of the ports, we have employed the following technique[4]. The zero-current phase advance per cell (σ_0) is adjusted by varying the strength of the focusing quadrupoles, thus altering the total accumulated phase advance between injection and a fixed measurement location. This can be considered equivalent to changing the total number of periods traversed by a beam at the nominal σ_0. The permitted variation in the quadrupole strength was limited by beam envelope instability (high-voltage end) and by useful quadrupole aperture (low-voltage end). The coherent oscillation was induced by deliberately mis-steering the beam at injection using an electrostatic dipole.

5 RESULTS

Of the normalized emittance of the beam the variation with σ_0, as measured after drifting 25 lattice periods, is shown in Figure 3 for coherent amplitudes of ±4.5 mm

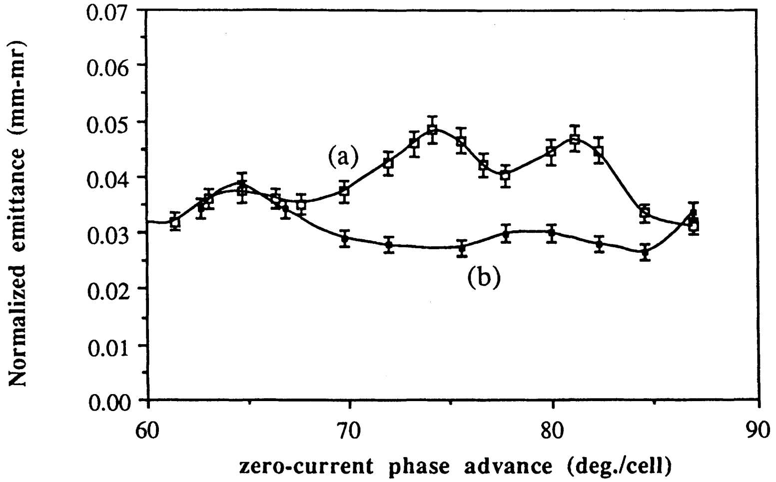

FIGURE 3 Measured emittance as a function of σ_0 at lattice period 25. The maximum beam amplitude displacements are (a) 4.5 mm and (b) 1.2 mm.

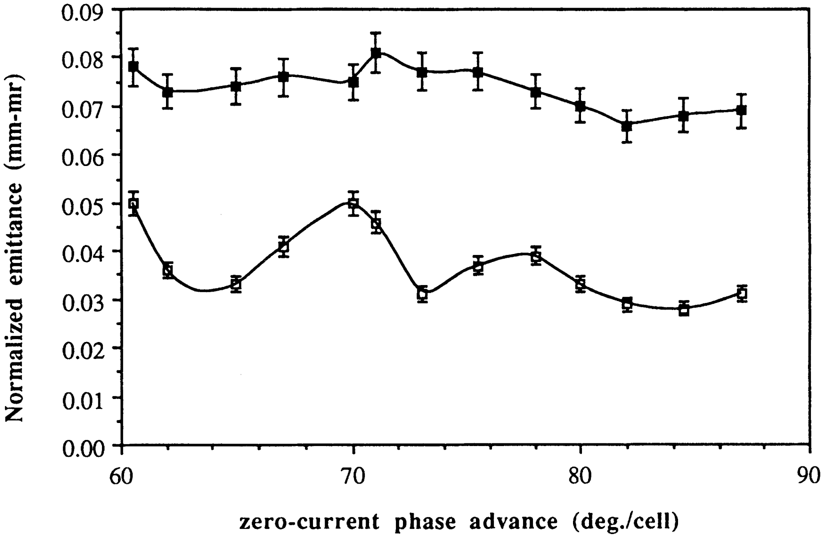

FIGURE 4 Measured emittance dependence on σ_0 at lattice period 25 for beams of initial emittances differing by ~2 (as measured at σ_0-71 deg./cell).

and ±1.2 mm. It should be understood that this corresponds to data that might be taken between periods 23 and 29 (if the diagnostics could be moved continuously through the linac) and is therefore representative of only a small part of the simulation result of Figure 1. However, there is good qualitative agreement between the simulation and the measurement in terms of the amplitude modulation and the frequency of the oscillations. As in the simulation one can see that the emittance variation for the reduced offset beam is much smaller than for the beam with a large offset. By placing a pair of wire grids, between which there is an electric field, in the path of the beam, we have been able to degrade the beam emittance. This occurs as the result of a net transverse impulse being imparted to the particles as they traverse the electric field[5]. In Figure 4 we compare the variation of the measured emittance with σ_0 for beams of initial emittances (or tune depressions) differing by a factor of two. Once again we see that, at least qualitatively, the simulation results are supported by our experimental results.

6 DISCUSSION AND CONCLUSIONS

We have obtained experimental evidence, supported by simulations, that strongly space-charge dominated beams propagating off-axis in electrostatic focus channels will exhibit growth and oscillation in the transverse emittance. Reducing the space charge depression reduces the emittance oscillation amplitude. This indicates that the growth of the emittance may ultimately saturate. The observed behavior of off-axis beams might have consequences for the low-energy end of a driver, as the need to minimize emittance growth may necessitate strict machining and alignment tolerances for the lattice elements. Alternatively, frequency trajectory correction could be applied to maintain a well-aligned beam, although such a measure will have its own cost implications.

ACKNOWLEDGEMENTS

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