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BEAM ACCELERATION EXPERIMENTS ON A HEAVY ION LINEAR INDUCTION ACCELERATOR

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The evolution of the noramlized rms transverse emittance of heavy ion beams in induction linacs depends on many factors, including envelope matching, details of the acceleration waveforms, and beam misalignments within the focusing system. Present acceleration experiments on MBE-4 confirm the difficulty of fully resolving the explicit dependence of the emittance on these and other parameters. In this paper we discuss the most recent acceleration experiments on MBE-4. These experiments utilize a beam of smaller current (5 mA) and smaller emittance (0.03 mm-mrad normalized K-V) than was used in previous MBE-4 studies. As before, we find that acceleration is accompanied by more transverse emittance growth than predicted by our theoretical models.

1 INTRODUCTION

The induction linac approach to inertial confinement fusion requires a current amplification of the accelerated beam while minimizing growth of the normalized rms transverse emittance. Current amplification is achieved by a process of differential acceleration between the head and tail of the non-relativistic ion bunch, leading to longitudinal compression of the bunch. The Multiple Beam Experiment (MBE-4) was built as a proof-of-principle device to demonstrate longitudinal compression and control of such beams[1]. Previous experiments on MBE-4 have resulted in a demonstration of current amplification during acceleration; however, this was accompanied by a doubling of the transverse emittance[2]. This was in contrast to the drifting-beam results, which showed constant emittance. Several possible causes of the emittance growth have been advanced, although, taken together, they account for no more than 30% of the measured growth. Prominent among the causes of emittance growth is the effect of longitudinal compression, which leads to a change in the self-field electrostatic energy of the beam, resulting in transverse heating[3]. In this paper we discuss the most recent studies of the transverse emittance growth for one of the MBE-4 beams.

2 MBE-4 Source Characteristics

Reference 1 describes the MBE-4 apparatus, so we limit ourselves here to a discussion of an important change in the source geometry between the experiments described in this paper and those reported previously. Early experiments on MBE-4 were performed with a 10-mA beam extracted from a thermionic source. It was apparent, however, that the diode optics contained aberrations, which resulted in overfocusing of the outermost rays of the beam. This resulted in a hollow current density distribution and filamentation of the phase space profile. In order to remove the outermost rays of the beam, a current-limiting aperture stop was installed in the experiment just downstream of the extraction region. This results in a more uniform current distribution and greatly improved beam distribution in phase space. The transmitted current, however, is reduced from 10 mA to nominally 5 mA. This reduction in current is accompanied by a normalized emittance reduction in both planes from 0.08 mm-mrad to 0.03 mm-mmrad, resulting in an overall increase in beam brightness and tune depression ($\sigma_0/\sigma = 10$, as opposed to 5 previously). The maximum beam envelope radius is also reduced from 14 mm to 10 mm and so the fraction of the quadrupole aperture occupied by the beam is halved (27 mm bore radius). Consequently the beam is less likely to experience the nonlinear field regions of the quadrupoles. Before proceeding with acceleration we investigated the emittance of the drifting 5 mA beam. This work is described in reference 4; to summarize, we find that if the beam is properly matched to the MBE-4 lattice and if beam centroid displacements are kept small (< 1.5 mm), then the measured emittance along the linac is constant to within $\pm 10\%$. However, if the beam centroid has a large coherent betatron oscillation amplitude, then the emittance varies greatly ($\pm 25\%$). These emittance fluctuations in displaced beams are especially pronounced for beams with large tune depression[4].

3 Longitudinal Dynamics

Due to the lower beam current now employed in MBE-4, the acceleration schedule (i.e. the timings and amplitudes) of accelerating waveforms used previously is no longer appropriate to compensate for the beam space-charge forces. To determine a new schedule we employed our existing longitudinal dynamics code, SLID, and an upgraded version, SLIDE[5]. The longitudinal space-charge field is given by $E_z = g\lambda'/4\pi\varepsilon_0$, where λ' is the gradient of the line charge density and g is a geometry-dependent shielding factor which also has to be determined for the 5 mA beam. We determined the value of g appropriate to the 5 mA beam empirically by running SLIDE calculations for a drift beam using various values of g and comparing the output with measured beam parameters[6]. Figure 1 shows the measured temporal variation of current and energy at the input to the linac. These were used as input data to SLIDE. Figure 2 shows both the measured and calculated current and energy distributions after allowing the beam to drift to the end of the machine. Although the simulation results are insensitive to variations in g between 2.5 and 4.0, we found the best agreement between the calculation and measurements is for $g = 2.8$

In determining a new acceleration schedule we have not attempted to produce new pulser waveforms; rather, we have used the existing waveforms to provide current amplification while maintaining a reasonably flat, sharp-edged current pulse profile throughout the machine. In this respect we are using SLIDE as a simulation code rather

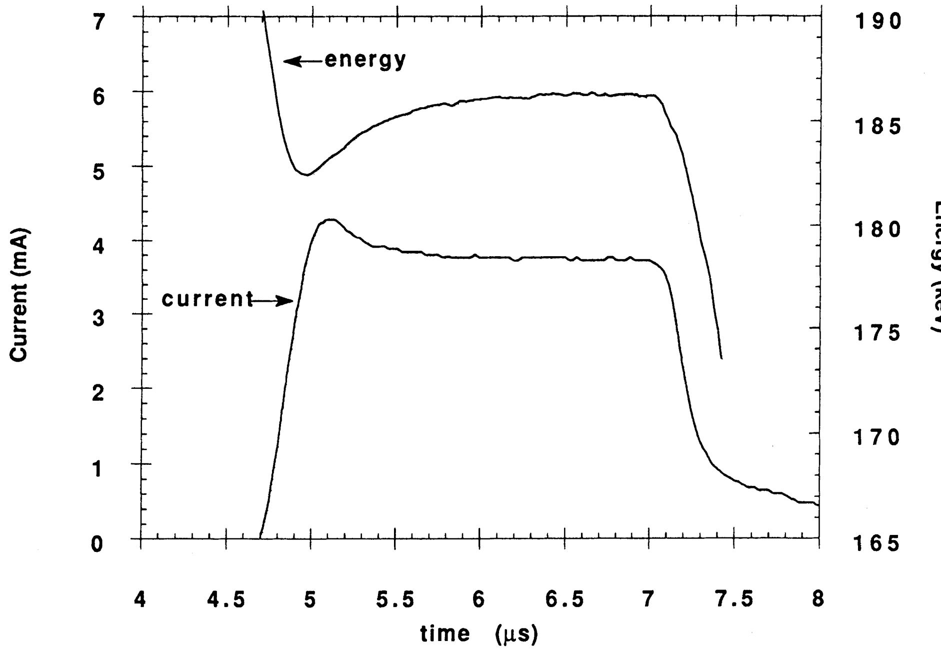

FIGURE 1 Initial distribution of beam current and energy at the entrance to the linac.

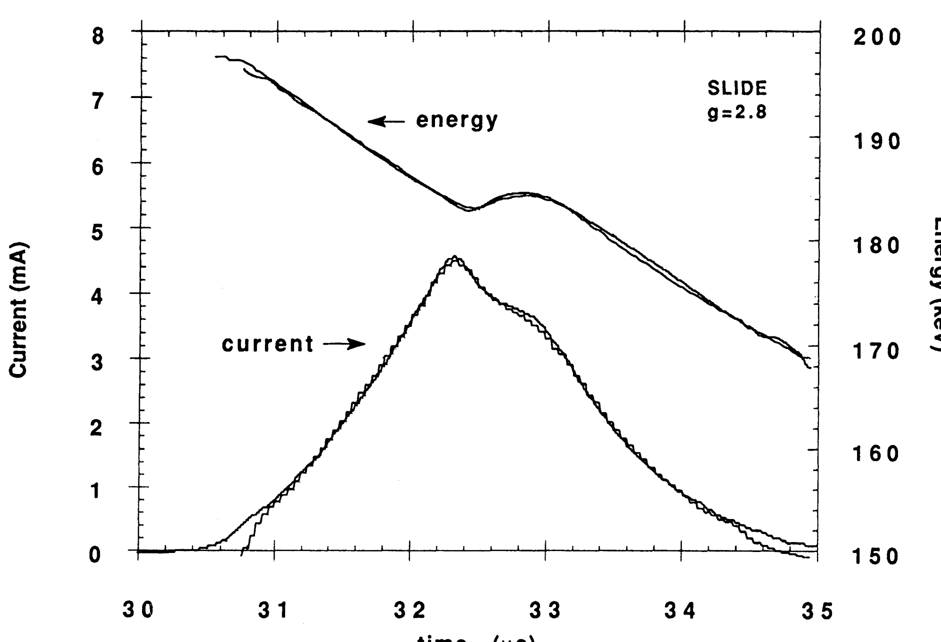

FIGURE 2 Comparison of the measured and computed current and energy of the beam after drifting to the end of the linac. Note the erosion of the beam head and tail due to space-charge effects.

than as a design tool. SLIDE is more appropriate than SLID for this work as it allows particle overtaking to occur. Such overtaking is inevitable due to acceleration errors resulting from real waveforms which depart from those ideally required, and this may represent another contribution to emittance growth in MBE-4 experiments.

4 Transverse Emittance

The intrinsic normalised emittance ε_n of a thermionic ion source of temperature T and radius b is given by, $\varepsilon_n = 0.65\mathrm{b}(\mathrm{T/A})^{1/2}$, where b is in centimeters, T is in electron-volts, A is the ion atomic mass and ε_n is in mm-mrad. For the MBE-4 source this gives an intrinsic emittance of 0.03 mm-mrad. Although in practice the achieved emittance is larger (by about a factor of 2) than the intrinsic value, the measured emittance of that part of the MBE-4 beam which passes the current-limiting aperture and the beam envelope matching section is close to the intrinsic source value.

In order to prevent unwanted emittance growth, it is necessary to maintain the beam on-axis. To achieve this we have installed an array of steering elements at the input to the linac to control injection errors. In addition, an extensive survey of the alignment of the focusing elements shows that they are aligned to within ± 0.13 mm. Smith and Hahn[7] give the maximum betatron oscillation amplitude A_m for a beam drifting through N lattice periods with randomly misaligned elements of peak displacement Δ to be

$$A_m = \Delta N^{1/2} F(\sigma_0, \eta)$$

where $F(\sigma_0, \eta)$ is a function of the zero-current tune and the lattice occupancy. For the 30 lattice periods of MBE-4 we expect a maximum displacement of 2 mm, which is consistent with our observation of $A_m = 1.5$ mm for the drifting MBE-4 beam.

Recently we have measured the emittance along MBE-4 of a 3.8 mA beam accelerated with our new schedule. The reduced current is due to a source problem and results in mismatch errors at injection (MBE-4 has a matching section between the source and the main linac that is currently optimized for 5 mA beams). The variation of the measured current at the diagnostic stations and the corresponding computed energies (using SLID) are shown in Table 1. The current amplification up to lattice period 20 is 4.5 which is intermediate to the values used in the early MBE-4

TABLE I
Variation of the Beam Current and Energy at the Diagnostic Stations.

Lattice period	Current (mA)	Energy (keV)
0	3.8	185
5	4.4	208
10	6.3	274
15	9.6	352
20	16.9	444

experiments where emittance growth was observed. The emittance variation along the linac is shown in Figure 3, where the measured values quoted correspond to 80% of the full current. This percentage is chosen to exclude electrical noise signals originating from the acceleration pulsers (see Reference 2 for a discussion of the data-aquisition and reduction procedures). The full curve shows the emittance of the drifted 3.8 mA beam and is seen to be constant up to lattice period 20. The accelerated beam, however, begins to show some growth at lattice period 15, and by the time the beam has reached lattice period 20 the normalized emittance has increased by a factor of 2.5. Beyond lattice period 20 no data is shown, as it is found that even the drift-beam emittance begins to increase (in contrast to our earlier 5 mA results), presumably due to the effects of the injection mismatch.

5 DISCUSSION

In order to resolve the contributions of mismatch and compression towards emittance growth, further measurements are required with more-careful matching of the beam from the injector to the main linac. The emittance growth observed during acceleration in the experiments discussed here is greater than that seen in previous MBE-4 studies. However one should note that these beams are extremely "cold," with initial emittances as much as 3 to 7 times smaller than in earlier studies[2,6]. This is consistent with the results of our drift beam studies which have shown us that low-emittance (high-tune-depression) beams are inherently more susceptible to growth[3]. Indeed, we have recently obtained some tentative evidence that the 3.8 mA beam can be accelerated, using the same acceleration schedule (and hence current amplification), with only ~20% emittance growth when the emittance is abruptly doubled at lattice period 5 by external means. Further experiments are required to confirm this finding.

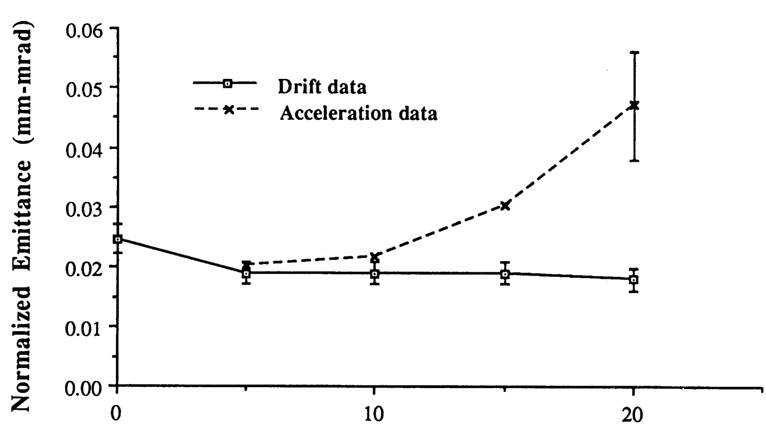

FIGURE 3 Measured emittance for drifting and accelerating beams at the various diagnostic stations. The observed growth in the emittance of the accelerated beam is due to mismatch errors at injection.

6 CONCLUSIONS

We have improved the quality of the beam extracted from our thermionic source and we have succeeded in controlling the beam centroid motion as it travels through the linac. Despite this we continue to observe a growth in the transverse emittance of accelerated beams in MBE-4. It is not possible to fully resolve the contribution of compression to emittance growth until we have.eliminated the detrimental effects of injection mismatch. Definite conclusions about emittance growth must await the outcome of further experiments to support the preliminary data presented above. Forthcoming experiments on MBE-4 will continue to address these issues.

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