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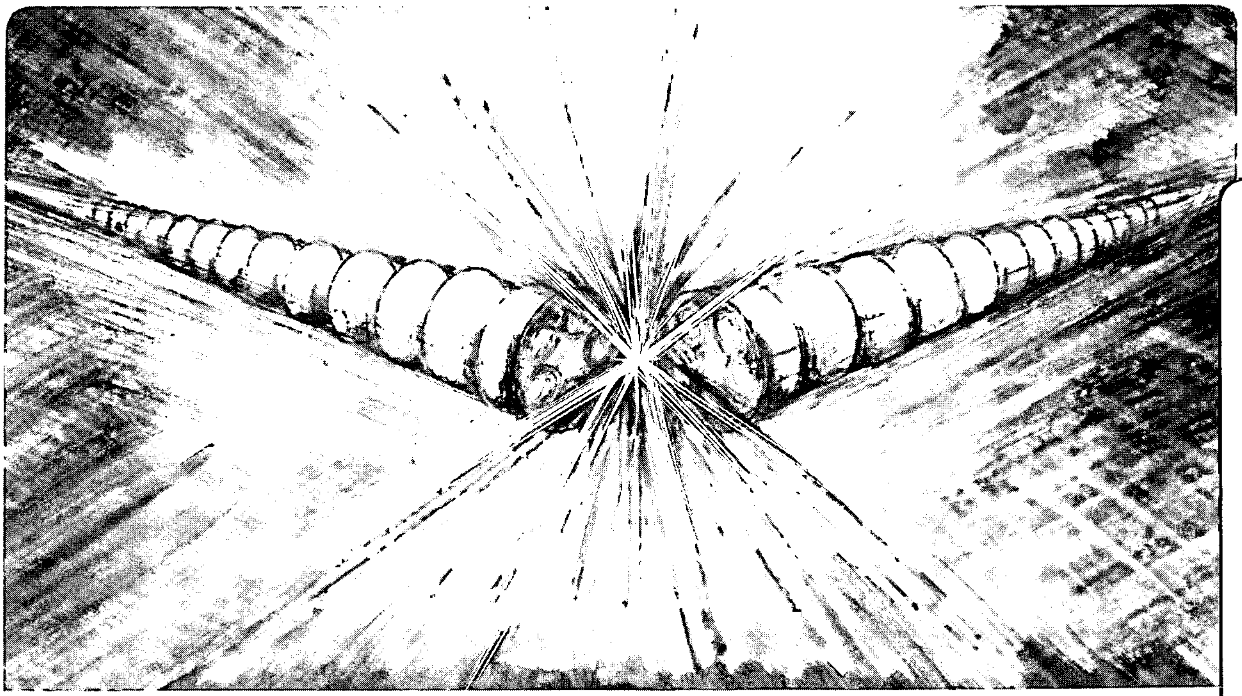

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Abstract

Current amplification of heavy ion beams is an integral feature of the induction linac approach to heavy ion fusion. As part of the Heavy Ion Fusion Accelerator Research program at LBL we have been studying the evolution of the transverse emittance of ion beams while they are undergoing current amplification, achieved by longitudinal bunch compression and acceleration. Experiments are conducted on MBE-4, a four beam Cs^+ induction linac. The space-charge dominated beams of MBE-4 are focused by electrostatic quadrupoles while they are accelerated from nominally 200 keV up to ~ 1 MeV by 24 accelerating gaps. Initially the beams have currents of typically 4 mA to 10 mA per beam. Early experimental results showed a growth of the normalized emittance by a factor of 2 while the beam current was amplified by up to 9 times its initial value. We will discuss the results of recent experiments in which a mild bunch length compression rate, more typical of that required by a fusion driver, has shown that the normalized emittance can be maintained at its injection value (0.03 mm-mr) during acceleration.

1. INTRODUCTION

The induction linac approach to heavy ion driven inertial fusion envisages a design in which multiple beams are employed at the low energy end of the driver with the beam current undergoing amplification as it is accelerated. Current amplification results both from the increase in particle velocity and also from longitudinal bunch compression. This compression is achieved by applying a velocity 'tilt' between the head and tail of the bunch, provided by tailored voltage waveforms applied at the accelerating gaps. MBE-4 is a four beam Cs^+ linac built to investigate longitudinal dynamics issues related to this concept. The linac is comprised of a 30 period, electrostatic, AG focusing lattice. Each doublet is followed by an accelerating gap with the exception of every fifth doublet where the gap is reserved for diagnostic access and vacuum pumping. Each lattice period (l.p.) is 45.7 cm long resulting in a linac of 13.7 metres.

Early experiments on MBE-4 concentrated on a demonstration of current amplification while maintaining control of the current profile and correcting for inevitable acceleration 'errors', which arose from the difference between ideal accelerating pulser waveforms and those waveforms achieved in practice. These experiments, in which the current was amplified from 4x10 mA to 4x90 mA and the energy increased from 200 keV (the injection value) to 900 keV, were accompanied by a growth in the normalised emittance by a factor of approximately two. This work has been reported previously and a review can be found elsewhere in these proceedings[1].

2. EXPERIMENTS

We have identified a number of mechanisms which may be responsible for emittance growth in MBE-4 including matching errors, rapid longitudinal compression (leading to a change in the space-charge electrostatic-field energy), and non-linear field effects (self-fields, image-fields, focus fields). The last of these mechanisms is particularly troublesome for off-axis beams where the edge of the beam may approach the non-linear field region of the quadrupoles[2]. For the experiments discussed here offsets are minimised by the use of steering elements at the entrance to the linac and by careful alignment of the accelerator. Proper matching of the beam phase-space to the lattice of the linac is performed by adjustment of a "matching section" consisting of eight electrostatic quadrupoles just downstream of the diode.

Recent experiments have involved the application of an acceleration schedule which results in a smaller increase in the beam line charge density between injection and full energy. In order to realise this we have reduced the extent of the applied velocity tilt in the early gaps of MBE-4 with the majority of the acceleration being provided by waveforms in which the voltage does not vary greatly during the passage of the beam pulse. The reduction in bunch compression in these experiments means that the beam pulse length is not sufficiently short for the final accelerating waveforms to completely straddle the beam pulse. Consequently the current waveforms observed in these experiments are poorer than those obtained in earlier studies, however the focus of these experiments is transverse beam dynamics.

In attempting to maintain a matched beam during acceleration we scale the strengths of the quadrupole focusing voltages, V_q, such as to keep them proportional to the beam line-charge density, λ, i.e. $V_q \sim \lambda \sim I / v$, where I and v are the beam current and velocity respectively. The beam currents and velocities used in calculating the required quadrupole voltages are determined approximately for any given acceleration schedule using a longitudinal dynamics simulation

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code (SLID) which uses the measured beam current and energy at injection as input. The available range of quadrupole voltages is limited by breakdown and such scaling would not have been possible in the early experiments where λ was increased by a factor of ~ 4.5

Diagnostics and Data Reduction

Transverse emittance measurements are made using the familiar double slit technique with a multi-shot scanning procedure to determine the signal strength as a function of the transverse (x,x') phase space position, the charge being collected in a Faraday cup behind the downstream slit. Measurements can be made in each transverse plane in turn with typically 400 shots required to obtain one value of emittance. The charge collected through both slits is recorded many times (20 to 50) during the pulse so as to provide a time resolved measurement of the emittance. The data collected can be reduced to yield other time resolved quantities of interest such as the beam size, centroid motion and current profile integrated along the direction of the slits. A typical set of data for the beam at injection is shown in Fig.1. The four traces show the beam current (top left), beam emittance (top right), r.m.s. beam size (bottom left, upper), centroid position (bottom left, lower), the r.m.s. slope of the beam (bottom right, upper) and the angular off-set of the centroid (bottom right, lower).

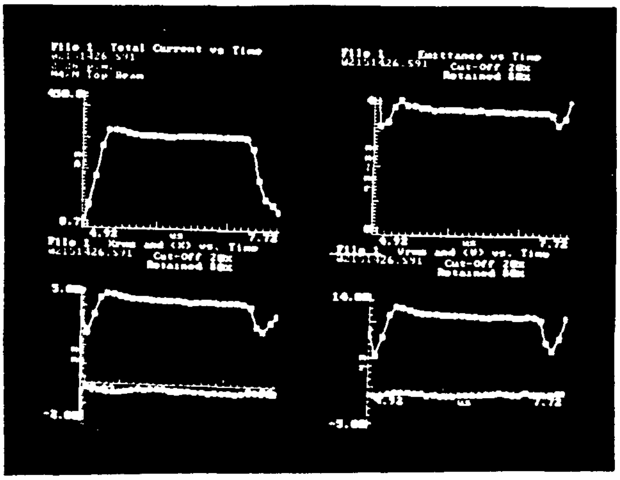

Figure 1. Time-resolved measurements of MBE-4 beam parameters. See text for explanation of traces.

Figure 2 shows a typical emittance plot at the entrance to the linac for a fixed time within the beam pulse.

In calculating the emittance we define the r.m.s. value ε_{rms} as,

$$\varepsilon_{rms}^2 = <(x - <x>)^2><(x' - <x'>)^2> - <(x - <x>)(x' - <x'>)^2 , \quad (1)$$

with the normalised emittance, ε_n, being defined as,

$$\pi\varepsilon_n = 4\pi\beta\varepsilon_{rms}. \quad (2)$$

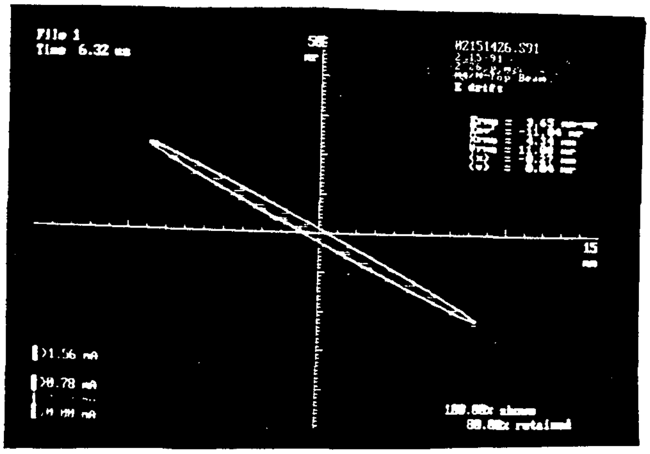

Figure 2. Phase space data at injection to the linac. The ellipse corresponds to a K-V beam of the same emittance as the measured beam.

During operation of the acceleration pulsers the signals obtained on the Faraday cups contain contributions from electrical noise which can be dominant at the edge of the phase space plots where the signal due to the beam is low. In order to exclude such effects we refer to the emittance contained in a given percentage, P, of the beam current where,

$$P = \Sigma_{i,j}\, S(x_i,x'_j,t)\, U(S(x_i,x'_j,t) - c) \,/\, \Sigma_{i,j}\, S(x_i,x'_j,t) \;, (3)$$

In equation (3) U is a unit-step function and the constant c is is a cut-off signal level determined by iteration to correspond to the desired P. The averages used in equation (1) are calculated using only signals above the cut-off value. Typically we find that 80% values are useful for quoting the emittances of accelerated beams while 90% is usable for drift beams. Figure 3 shows a plot of the calculated emittance as a function of P where it is quite apparent that the computed value increases non-linearly with P above P = 80%.

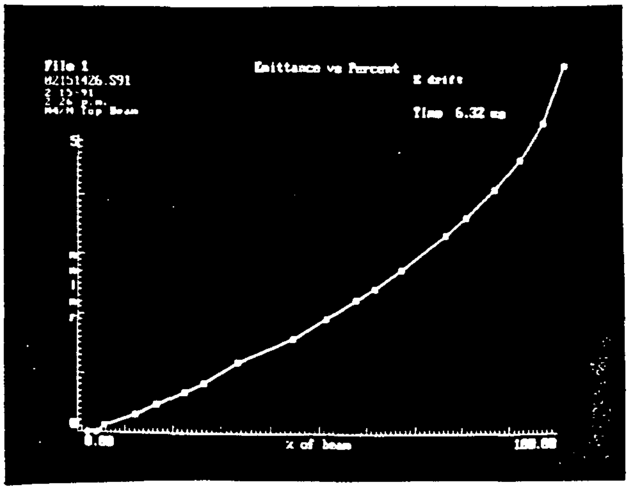

Figure 3. Emittance versus percentage of beam current.

3. RESULTS

Following the installation of a current limiting aperture we have been working with smaller beam currents (< 5 mA) which, at injection, typically have $\varepsilon_n = 0.03$ mm-mrad ($P = 90\%$) [3]. The aperture was employed to remove beam particles which were over-focused due to aberrations in the diode optics. The resulting beam radius is nominally 10 mm, propagating in a transport channel of 27 mm radius. For our 'mild' acceleration schedule the measured currents and computed energies at the diagnostic stations are given in Table 1. The corresponding emittances measured under both drift and acceleration in the horizontal plane are shown in Fig. 4 for $P = 80\%$. One can see that, within the limits of experimental error, the normalised emittance is conserved. For this schedule the energy is increased by a factor of 2.6 while λ is increased by only 18%. The 'missing' point for the acceleration data at l.p. 30 is due to faulty and irreproducible behaviour of the principal accelerating pulser in the last section of the machine.

Table 1.
Energy and current vs. l.p.

l.p.	Current (mA)	Energy (keV)
0	3.7	186
5	4.0	190
10	4.2	245
15	5.1	270
20	6.2	390
25	7.0	480

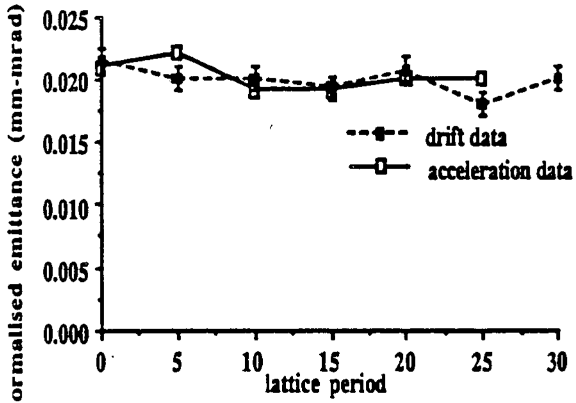

Fig. 4. Variation of horizontal emittance with l.p. for drift and acceleration.

4. DISCUSSION

We have previously reported emittance growth for our 3.7 mA beam under a stronger compression (x 3) but that data was complicated by poor matching from the injector (the matching section having been adjusted for the more usual current of 5 mA)[4]. For the data discussed in this paper the drift beam has been properly matched to the linac, however, it is apparent from measurements of the beam envelope under acceleration that the beam is becoming mismatched in the latter part of the machine. More careful matching under acceleration might require the use of accurately measured currents and energies, as opposed to the SLID calculated values, to determine the quadrupole voltages. An up-graded version of SLID (SLIDE) has been developed which gives improved agreement with the measured data and which might be used for better matching in future experiments on heavy ion induction linacs. Proper matching at injection is found to be neccessary however to minimise emittance growth for both drift and accelerated beams over the length of the linac.

Despite the mismatch under acceleration we find that, for well centered beams with sufficiently mild compression, the normalised emittance can be kept constant during acceleration. Our experiments, however, have not led us to an allowable limit for the rate of compression. Recently we have obtained data which shows that the line density can be doubled while the energy is increased by the same factor as above without much growth in the emittance. This is in contrast to early experimental data from MBE-4 where emittance growth of 75% was seen in another acceleration schedule which doubled the line density. The greater attention paid here to maintaining a well centered beam may be the beneficial factor in the new data. The maximum beam offset observed in our experiments is approximately 1.5 mm which is consistent with residual injection offsets and the limits of the alignment of the focus elements (±0.13 mm). The observed variations in emittance growth under different conditions of mis-match, beam offset and current amplification are found to be in reasonable agreement with the results of 2-D particle-in-cell simulations[1]. Thus we are confident that our computer code can accurately predict the expected growth of emittance in future induction linac designs.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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