

Emittance Variations in Current-Amplifying Ion Induction Linacs*

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I. SUMMARY

Since 1985 the Heavy Ion Fusion Accelerator Research program at the Lawrence Berkeley Laboratory has been studying current amplification and emittance variations in MBE-4, a four-cesium-beam induction linac. This experiment models much of the accelerator physics of the electrostatically focused section of a fusion driver. Four space-charge dominated Cs^+ beams, initially about one meter in length at currents of 5-10 mA, are focused by electrostatic quadrupoles and accelerated in parallel from approximately 200 keV up to one MeV by 24 accelerating gaps. Final currents of 20-40 mA per beam are typical. Recent experiments with extremely low emittance beams ($\epsilon_n = 0.03$ mm-mRad) have investigated variations of transverse and longitudinal normalized emittance for drifting and accelerating beams. These very strongly tune-depressed beams ($\sigma_0 = 72^\circ$, $\sigma = 6^\circ$) are difficult to match to the accelerator so as to avoid emittance growth during acceleration. During transport strong emittance fluctuations are observed in good qualitative agreement with simulations. Warmer beams with less tune depression exhibit little to no emittance growth, show smaller emittance fluctuations, and are much easier to match. A summary of findings from the MBE-4 studies is presented.

II. INTRODUCTION

The Heavy Ion Fusion Accelerator Research Program (HIFAR) at LBL is assessing the multiple-beam induction linac as a inertial fusion driver. In this concept multiple parallel beams of heavy ions are continually amplified in current and in voltage as they are accelerated to the parameters required to ignite an inertial fusion target (≈ 10 GeV, 500 TW, 10 ns).

Control of the lengths of the beam bunches during the acceleration process is one of the key beam dynamics issues of this approach to a fusion driver. The accelerating waveforms must be carefully shaped to shorten the bunch length and to control longitudinal space charge forces while accelerating the beams. Small acceleration errors, particularly troublesome at low beam energies, can lead to current spikes and beam spill and/or to unacceptable increases in beam emittance. A necessary consequence of current-amplifying acceleration is that the focusing system must transport beams whose speed at a focusing element increases by as much as 20% over the time of the pulse.

MBE-4 is a multiple-beam current-amplifying ion induction accelerator. It was built to develop an experimental understanding of this new type of accelerator. Longitudinal beam dynamics in this experiment are similar to those expected in the electrostatic-focused region of a heavy ion driver. Experiments began with the completion of the injector in 1985 and continued for approximately six years through April 1991. Of particular interest were possibilities of interactions between the multiple beams, longitudinal beam control, and the preservation of longitudinal and transverse normalized emittance during acceleration. The main thrust of the first three years of experimentation was longitudinal beam dynamics and control. The last three were mostly concerned with understanding transverse beam control and emittance growth during acceleration. MBE-4 has been very useful in understanding the physics of current-amplifying accelerators and in providing confidence that much larger ion induction linacs can be expected to operate satisfactorily. This paper will summarize our findings from MBE-4.

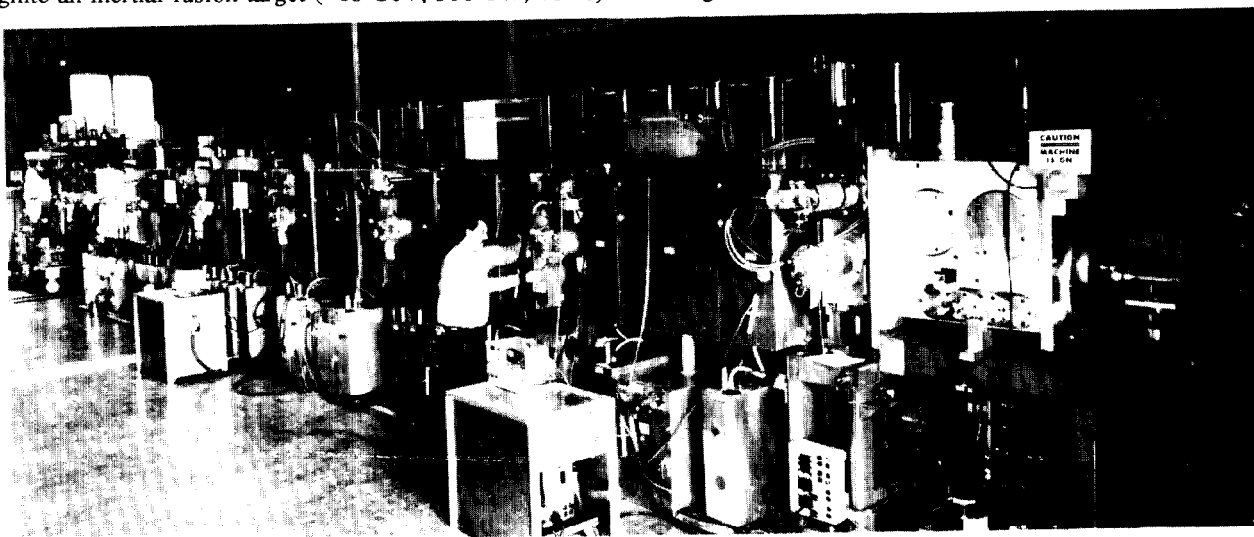


Fig 1 The MBE-4 multiple-beam ion accelerator (CBB 912-1174)

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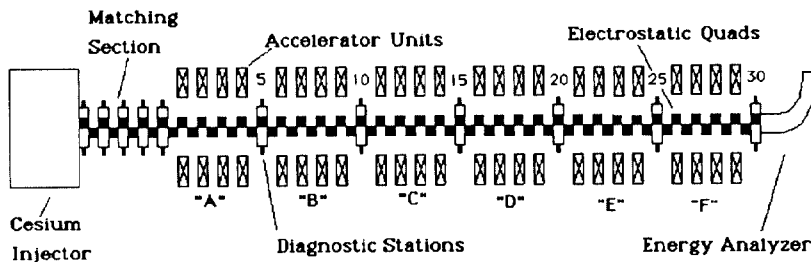


Fig. 2 Schematic of MBE-4.

III. DESCRIPTION

MBE-4 is an induction linac that accelerates four Cs⁺ beams from 200 keV at the injector to as much as 875 keV(head); 950 keV(tail) after 24 accelerator gaps with current amplifications as large as nine. Transverse focusing is supplied by four-beam arrays of electrostatic quadrupoles. The initial bunch length is 1.3 m with duration of 2.2 μ s. Fabrication of the apparatus was completed in September 1987. A picture of MBE-4 is presented in Fig. 1 and a schematic of the accelerator is given in Fig. 2. The accelerator is 30 periods long. Pumping and diagnostic access are provided at the ends and at each 5th focusing period. Our principal diagnostics are Faraday cups and two-slit scanners which reveal the beam size and emittance for current measurements at each of the diagnostic stations. An electrostatic energy analyzer at the end of the experiment is used to measure the final beam energy and obtain estimates of the longitudinal beam emittance. We also used a small electrostatic energy analyzer that could be inserted at the diagnostic stations to characterize the beam at the input and along the accelerator. During operation the apparatus is pulsed every five seconds. Each pulse is highly repeatable. Every waveform repeats to better than 1 %.

IV. LONGITUDINAL STUDIES AND FINDINGS

Current amplification and longitudinal bunch length control through the accelerator require the use of carefully shaped accelerating voltage waveforms. The method of finding waveforms for accelerating beams in ion induction linacs, was developed by C. Kim [1]. In this current self-replicating scheme, the functional form of the current versus time at a fixed location is preserved through the accelerator and the magnitude increases as the bunch shortens in time. Solutions for the current and the accelerating waveforms at every accelerating gap can be constructed. The charge distribution along the length of the beam bunch generates a longitudinal electric field E_z that will lengthen the bunch if not compensated by the accelerating voltages. The procedure for generating these waveforms including the effects of longitudinal space charge and the finite width of the accelerating gaps were incorporated into a code called SLID which runs on a small computer.

The SLID procedure has proved to be extremely valuable for engineering pulsers for MBE-4 and for understanding and interpreting the results of the experiments. An improved version of the procedure called SLIDE[2] which permits particle overtaking was recently developed by Henestroza. We have

found that the SLID and SLIDE calculations of the current and energy waveforms agree very well with experimental measurements [3,4].

To develop the pulsers for controlling and accelerating beams in MBE-4, ideal waveforms from the SLID procedure were first supplied to engineering. As the pulsers were fabricated, the outputs of the pulsers were measured and used as input to the SLID code to generate downstream waveform requests that tended to

compensate for unavoidable upstream synthesis errors. Our method of synthesizing waveforms was to add the outputs of several pulsers so as to generate the waveform asked for by the SLID procedure as well as possible. An example of this synthesis is presented in figure 3. Here the outputs of four pulsers are added at gap 11 to generate the waveform requested by the SLID procedure. As can be seen, small errors are inevitably generated as each pulser is energized. Waveforms to provide control of the bunch ends are not present at each accelerating gap but rather are provided at every five to seven gaps.

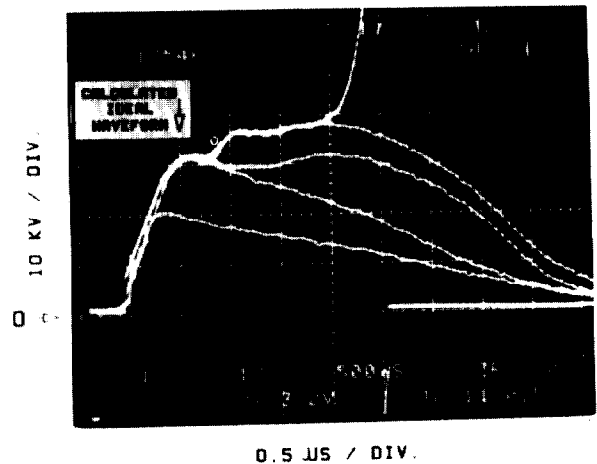


Fig. 3. Synthesis of MBE-4 accelerator wave forms. The outputs of four pulsers are added to produce an accelerating voltage close to that requested by the SLID acceleration procedure (XBB 872-1623)

Amplifying current waveforms obtained in MBE-4 are shown in Fig. 4. Here the current of each of the four beams increases from 10 mA at 0.2 MV at the accelerator input to over 90 mA at end of the accelerator. At exit the beam energy increases approximately linearly from 650 kV at the head to 750 kV at the tail. The effect of the acceleration errors can be seen in these waveforms.

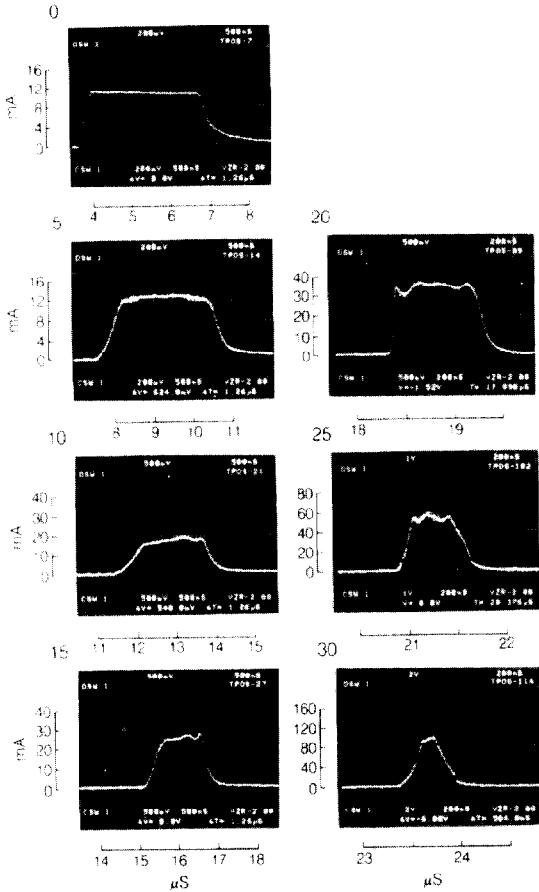


Fig 4. Current amplification from 10 to 90 mA/beam in MBE-4. Each oscillogram shows several pulses. (XBB 887-7123)

A better understanding of the effects of errors can be obtained by considering space charge waves on a heavy ion beam. According to Warwick[5] et al., space charge waves in the long-thin geometry of a heavy ion accelerator propagate without dispersion at a speed v_p in the beam frame of

$$v_p = g^{1/2}(\omega_p a/2) \quad (1)$$

where ω_p is the beam-plasma frequency, a is the beam radius and g is a factor (≈ 2) that depends weakly on geometry. For MBE-4 the space charge wave speed is a few percent of the beam speed which, relatively, is only three to ten times faster than in a driver. An acceleration error δV generates a space charge wave that separates into forward and backward traveling waves in the beam frame. These produce a current modulation if the waves are allowed to split as the beam travels through the accelerator. This current modulation[6] is given by

$$\delta I = \frac{I(v_0^2 - v_p^2)}{V 4 v_0 v_p} [\delta V(z - v_p t) - \delta V(z + v_p t)] \quad (2)$$

where v_0 is the beam speed, V is the kinetic beam voltage and I is the beam current. Corrections must be applied before the waves split and the error turns into a current modulation. This will occur in a distance L along the accelerator given approximately by

$$L \approx \frac{1 v_0^2 \Delta t}{4 v_p} \quad (3)$$

where Δt is the duration of the error which is assumed short compared with the pulse width. These phenomena are most troublesome at the front of an accelerator where the beam wave speed are lowest. For errors about one microsecond in duration this distance is 2.8 m in MBE-4 and 6 m toward the low end of a driver.

The energy analyzer at the end of MBE-4 is used to measure the beam energy versus time and to estimate the longitudinal emittance growth that has occurred during acceleration. The energy resolution of this instrument is better than 0.5 %. Because the current is amplifying, the beam energy at the end of MBE-4 increases from 650 kV at the head to 750 kV at the tail for the acceleration data presented in Fig. 4. The area of the ellipse that encloses this curve is approximately $4\pi \times 10^{-3} (V \text{ sec})$. These measurements when extrapolated to the final focus in a driver[7] yield an expected momentum spread of $\Delta p/p \approx 1.5 \times 10^{-3}$ -- well within the 1% permitted by target focusing considerations. This rather long extrapolation assumes that subsequent acceleration errors are not correlated and are similar in magnitude to those experienced in MBE-4.

V. TRANSVERSE STUDIES AND FINDINGS

Since approximately August of 1988, the preservation of normalized emittance with acceleration has been the principal issue studied with MBE-4. We had observed during the longitudinal experiments that the transverse emittance remained approximately constant or increased with drift or acceleration implying that the normalized emittance was increasing. Moreover, although each emittance measurement could be repeated to within about 5% if done immediately, measurements over long periods varied by factors of 1.5 to 2.

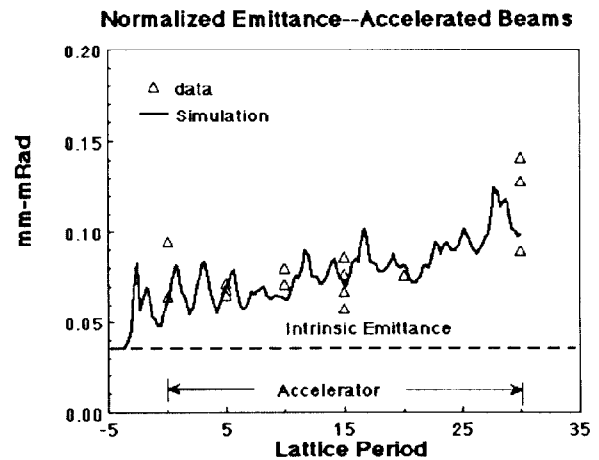


Fig. 5 Measurements and simulation of normalized emittance along MBE-4. The intrinsic emittance is that determined by the source temperature ($\approx 1000^\circ\text{C}$) and beam radius.

Figure 5 shows data collected from accelerated beams at an initial current of 10 mA per beam over a period of several months. Very similar emittance variations obtained from 2-D PIC simulations of strongly tune-depressed beams drifting in electric-quadrupole-focused transport systems had been reported previously by Celata[8]. These simulation studies were continued and extended to accelerating beams by K. Hahn. We define normalized emittance as $\epsilon_n = 4 \beta \gamma \epsilon_{rms}$ where ϵ_{rms} is given by

$$\epsilon_{rms} = \left[\frac{\langle x^2 \rangle \langle x'^2 \rangle}{\langle x x' \rangle^2} \right]^{1/2} \quad (4)$$

A simulation in which the measured beam in phase space at the output of the injector was used to load the code is also presented in Fig. 5. The intrinsic beam emittance as determined by the source radius r_s and the rms thermal velocity v_θ at a temperature of 0.1 eV was used at the start of the simulation. The initial emittance growth is due to a space-charge-driven re-arrangement of particles in the beam[9]. Diagnostic access and, consequently, emittance measurements are limited to every 5th lattice period. Because of the sparse sampling and the rapid fluctuations in emittance, the measured emittance can both increase and decrease along the accelerator.

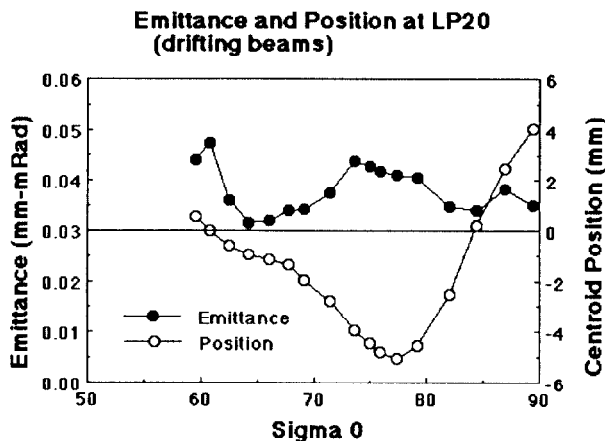


Fig. 6. Variations of beam position and emittance versus focusing strength at lattice point 20. By varying focus strength the beam fluctuations are brought to the point of diagnostic access.

To demonstrate that the rms emittance was rapidly varying along MBE-4, measurements of beam offset and emittance versus the strength of the focusing lattice (σ_0) at fixed position were performed. This technique (which was suggested by D. Keefe) showed that the beam was oscillating back and forth in the channel with an amplitude of 4 to 5 millimeters or nearly 20% of the channel aperture as shown in Fig. 6. This experiment also confirmed that the rms beam emittance was strongly modulated at what corresponds to 2.3 lattice periods in excellent qualitative agreement with the simulations.

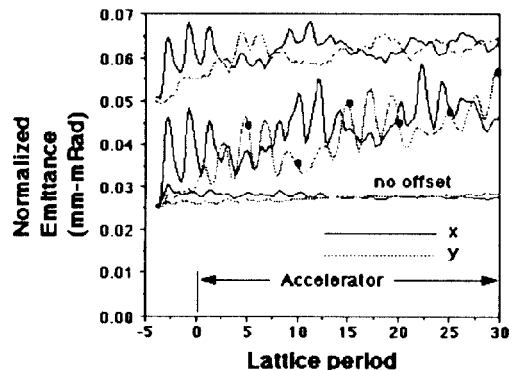


Fig. 7 Beam emittance variations in the x and y planes for offset beams drifted through MBE-4 obtained from code simulations.

Figure 7 shows the x and y normalized emittance versus z obtained from simulations of strongly tune-depressed beams in MBE-4. Except for the case of no offset, the beams were started 3 mm off axis, slightly more than 10% of the channel aperture, with equal x and y deflections. For the lower curves the simulations were started at the intrinsic beam emittance. The dots on the y emittance plot signify the emittance that might be measured at the points of diagnostic access. A simulation at twice the intrinsic emittance which is close to the final emittance of the first off-axis case is also given. These simulations suggest that strongly tune-depressed beams conserve normalized emittance if held to the system axis. Off-axis low-emittance beams exhibit large modulations in rms emittance and a net growth in passing through the transport system. At increased initial emittance, the modulations are less severe and the growth less significant. This behavior was experimentally checked[10] by approximately doubling the beam emittance at injection with a biased grid pair and measuring emittance growth through MBE-4. Reduced emittance growth was recorded as predicted by the simulation.

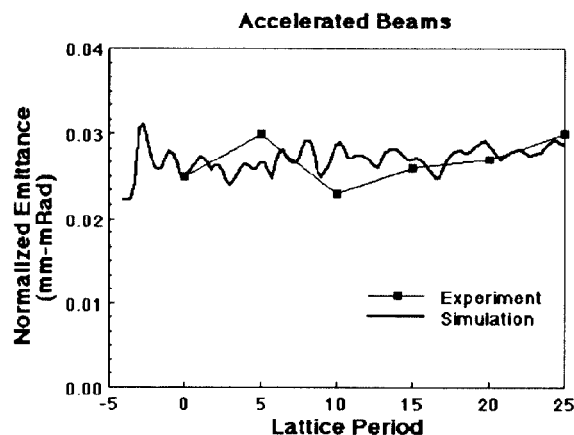


Fig. 8 Measurements and simulation of normalized emittance during acceleration through MBE-4. For these experiments the beams were very carefully matched, centered and aligned in the focusing channel.

Recent MBE-4 experiments have concentrated on carefully matching and centering the beams in the channel to demonstrate current amplification at constant normalized emittance. A second steering array was placed at the entrance to the accelerator that, with the first array at the injector output, centered and aligned the beam on axis. In our initial attempt[11], the beam was centered but not adequately matched. As a consequence, emittance growth was observed. Only after carefully matching, centering, and aligning the beams could these very cold beams be accelerated at constant normalized emittance. Figure 8 shows measurements of normalized beam emittance versus position and a comparison with simulation. Much more information on these experiments is presented in the paper[12] at this conference by T. Garvey et al.

VI. DISCUSSION

The MBE-4 experiments were performed to obtain practical experience with a current amplifying multiple-beam ion induction linac. One of the initial concerns was possible interactions between the beams as they were accelerated or transported through the accelerator. With the exception of a weak interaction in the injector where the beams are at low energy and "see" each other for some distance, no such effect was observed. At low energy the beams interact primarily through their radial space-charge electric fields. These are easily controlled by radial shorting planes along the accelerator which are present for other reasons. At high beam energy, magnetic interactions play a stronger role and some periodic beam coupling phenomena could conceivably arise. The major multiple-beam issue encountered in these experiments was the diagnostic complexity associated with working with many beams.

Current amplification in an induction linac is possible and the beams can be controlled longitudinally with the accelerating waveforms. However, longitudinal control in MBE-4 was more difficult than we anticipated. The accelerator pulsed used for MBE-4 are based on conventional thyatron-switched pulse forming lines. This type of pulser does not have adequate waveform flexibility to easily control the beams longitudinally. Future ion induction linacs will require more agile correction or compensating pulsers every few accelerating gaps—particularly at the low energy end.

Beam space charge greatly reduces the impact of longitudinal acceleration errors as can be seen from Eq. 3. At very low beam intensities the response to an error becomes large with time or drift length. The acceleration errors can be repaired or compensated downstream if corrections are made before the forward and backward space charge waves on the beams can split. Although these corrections contribute to the longitudinal temperature of the beams, the scaling formulas suggest that these will not unduly compromise the final focusing of the beam onto the target.

Transversely, very cold space-charge dominated ion beams can be accelerated at constant normalized emittance at least over the length of MBE-4 if great care is taken to match, center, and align these beams in the transport channel.

However, for long linacs or drivers, extreme care may not be required. These experiments and simulations suggest that for sufficiently long system, the beams will center and match themselves with an accompanying increase in emittance. This emittance growth may be affordable. Further study is required (experiments, theory, simulation) to determine if this so.

VII. ACKNOWLEDGEMENT

The work presented here is a summary of the efforts of much of the LBL HIFAR group since 1985. Notable among these are A. Warwick, and C. Kim who made major contributions to the design of MBE-4 and to the longitudinal studies; H. Meuth, S. Eylon, and T. Garvey who concentrated more on the transverse studies; K. Hahn, E. Henestroza, L. Smith, A. Faltens and more recently W. Fawley who provided the theoretical guidance and simulation backup; and last but far from least was D. Keefe who contributed in every conceivable way to the MBE-4 experimental program.

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