

PERFORMANCE OF MBE-4, AN EXPERIMENTAL MULTIPLE BEAM INDUCTION LINEAR ACCELERATOR FOR HEAVY IONS*

A. I. Warwick, T. J. Fessenden, D. Keefe, C. H. Kim, and H. Meuth
Lawrence Berkeley Laboratory, Berkeley, CA 94720, U.S.A.

Abstract

An experimental induction linac, called MBE-4, has been constructed to demonstrate acceleration and current amplification of multiple heavy ion beams. This work is part of a program to study the use of such an accelerator as a driver for heavy ion inertial fusion. MBE-4 is 16m long and accelerates four space-charge-dominated beams of singly-charged cesium ions, in this case from 200 keV to 700 keV, amplifying the current in each beam from 10mA by a factor of nine. Construction of the experiment was completed late in 1987 and we present the results of detailed measurements of the longitudinal beam dynamics. Of particular interest is the contribution of acceleration errors to the growth of current fluctuations and to the longitudinal emittance. The effectiveness of the longitudinal focusing, accomplished by means of the controlled time dependence of the accelerating fields, is also discussed.

Introduction

If heavy ion beams ($A = 200$) are to be used to drive inertial fusion, a large current is required (several kA) at a kinetic energy per nucleon of about 50MeV/u. An induction linac could efficiently accelerate high current beams of heavy ions. Because the initial velocity would be non-relativistic ($\beta = 10^{-2}$), the head and tail of an initially long bunch (60 m) could be differentially accelerated by time-dependent accelerating pulses so that the current would be amplified during acceleration. The high beam current at low kinetic energy would be beyond the technological limits of transverse focusing if transported in a single channel. Multiple beams are required instead, individually focused by electrostatic lenses at first, then by magnets as the velocity increases. Longitudinal focusing must be provided by specially time-dependent accelerating fields which would accelerate the extreme ends of the bunch in such a way as to counteract the longitudinal space charge forces. These forces would otherwise elongate the bunch.

MBE-4 is an experiment to prove these principles on a small scale. It has four beams. This is the smallest reasonable number with which to demonstrate a multiple beam linac. Singly charged cesium ions are used because of the availability of high quality ion sources. The initial kinetic energy is 200keV and each beam bunch is injected with a current of 10 mA and a 2.5 μ s duration. The initial line charge density in each beam is thus $1.9 \times 10^{-8} \text{ cm}^{-1}$, about 14 times smaller than at the beginning of a fusion driver¹.

In order to avoid bunch lengthening, acceleration of the head of the bunch does not begin until the bunch is entirely inside

the linac. MBE-4 is 14 times longer than the initial beam bunch, the length of which is short (1 m) compared to that in a driver (60 m). The short bunch in MBE-4 means that a significant portion of a driver, several hundred meters of its length, can be modeled using a vigorous schedule of acceleration and current amplification in the 14 m length of the experiment. For a given increase of kinetic energy, the current amplification is greater in MBE-4 than in a driver. Furthermore, each pulser provides a much larger relative increase of the kinetic energy than in a driver, thus the subdivision of the acceleration is much coarser. MBE-4 is thus a stringent test of current amplification through application of controlled accelerating voltages.

Figure 1 shows the layout of MBE-4. After passing through eight matching quadrupoles, the four beams enter the accelerator where induction accelerator units provide shaped accelerating voltage pulses as the bunch passes through the accelerating gaps. Each fifth gap is a diagnostic station.

The transverse dynamics in MBE-4 has been described before^{2,3}. Here we report on the measured longitudinal dynamics under a vigorous schedule of acceleration and current amplification in which the current in each beam is increased from 10 mA to 90 mA, and the kinetic energy increases from 200 keV to 700 keV in the middle of the bunch. Table 1 compares this schedule with that in the first 400 m of a fusion driver.

Designing the accelerating voltage waveforms

The longitudinal dynamics within the bunch must be controlled explicitly by the designer. This is accomplished through the time dependence of the accelerating voltage waveforms at each gap. The waveforms on the first four gaps are increasing functions of time to provide the velocity difference between head and tail of the bunch at a given location, needed for current amplification. The extreme head and tail of the bunch must be accelerated in a particular way to provide intermittent focusing against the effects of the longitudinal space charge force. Acceleration errors must be kept to a minimum as they contribute significantly to the longitudinal emittance, especially at the beginning of the linac where the beam velocity is low.

We use a simple one-dimensional simulation³ with about 75 macro-particles to design the accelerating waveforms for each gap. This simulation uses a long wavelength approximation, in which the longitudinal space charge force is given by the expression:

$$E = - (g \partial \lambda / \partial z) / \gamma^2$$

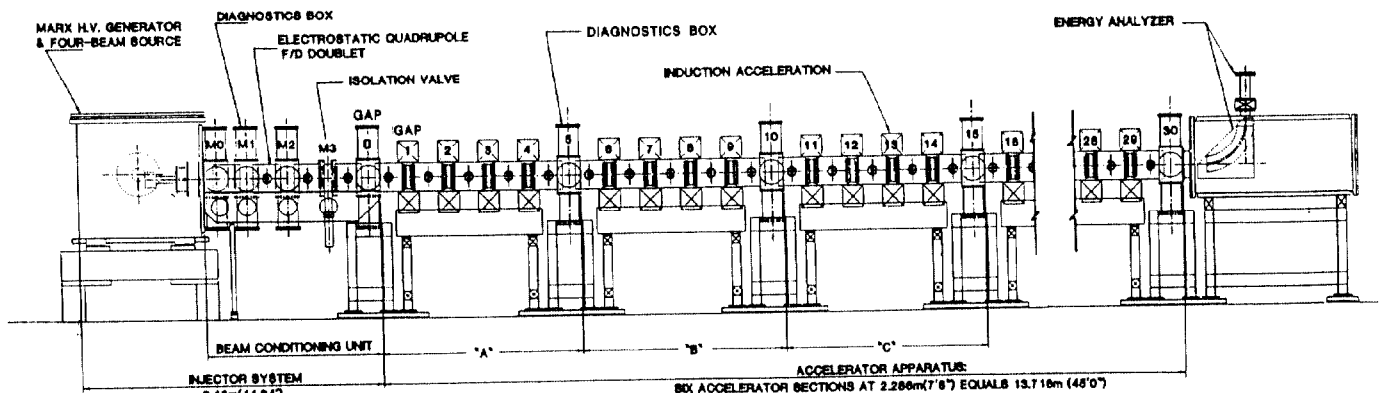


Figure 1. Schematic layout of the accelerator.

*This work was supported by the Office of Energy Research, Office of Basic Energy Sciences, Department of Energy under Contract No. DE-AC03-76SF00098.

Table 1
Comparison of the parameters of MBE-4
with the latest driver design.

longitudinal position (z)	MBE-4 z = 0m	MBE-4 z = 14m	DRIVER z = 0m	DRIVER z = 400m	DRIVER z = 4km
charge number	1	1	3	3	3
mass number	133	133	200	200	200
kinetic energy	0.2 MeV	0.7 MeV	10 MeV	100 MeV	10 GeV
β	1.8×10^{-3}	3.4×10^{-3}	10^{-2}	3.2×10^{-2}	3.2×10^{-1}
number of beams	4	4	64	16	16
current per beam	10 mA	†90 mA	0.78 A	15.6 A	625 A
line charge Cm^{-1}	1.9×10^{-8}	$†8.6 \times 10^{-8}$	2.6×10^{-7}	1.6×10^{-6}	6.5×10^{-6}
bunch length	1 m	0.42 m	60 m	38.4 m	9.6 m
bunch duration	2.5 μs	400 ns	20 μs	4 μs	100 ns
wave speed ms^{-1}	1.7×10^4	$†3.6 \times 10^4$	8.8×10^4	2.2×10^5	4.4×10^5

*The speed of a longitudinal space-charge wave in a frame moving with the bunch, using an empirically determined value of $4\pi\epsilon_0 g = 2.2$.
†Peak value.

where λ is the line charge density and g is a geometrical factor to be determined empirically and includes the shielding effect of the metal electrodes that surround the beam. As well as integrating the equations of motion, the simulations include an algorithm which will compute the accelerating voltage waveform required at each gap to maintain the shape of the beam current waveform (current self-replication)³. If these accelerating waveforms are realized the current pulse will remain approximately uniform, as it begins, see figure 2.

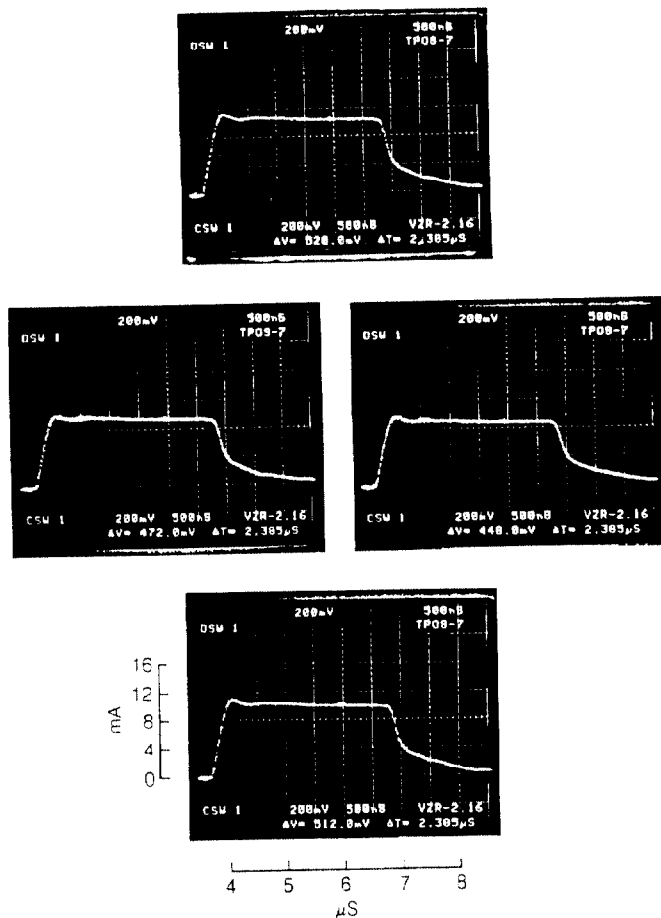


Figure 2. Current waveforms at the beginning of the linac.

Two types of induction pulsers have been built and the design waveforms are realized by summing two or three such pulsers, with varying parameters, on a single gap. Reference 3 includes an example of the synthesis of the design waveforms from these two generic shapes.

Longitudinal space charge waves

The long wavelength approximation for the longitudinal space-charge electric field, together with the equation of continuity, give rise to a simple wave equation:

$$\partial^2 \lambda_1 / \partial z^2 = [(m \gamma^2) / (\lambda_0 g q)] \partial^2 \lambda_1 / \partial t^2$$

where m and q are the ion mass and charge, and λ_1 is a small perturbation to the line charge density λ_0 .

There is no dispersion and the wave velocity in the frame moving with the bunch is:

$$c = [(\lambda_0 g q) / (m \gamma^2)]^{1/2}$$

The bunch at the beginning of MBE-4 has $\lambda_0 = 1.9 \times 10^{-8} \text{cm}^{-1}$ giving a wave velocity in the bunch frame:

$$c = 1.7 \text{ cm}/\mu\text{s}$$

As an example of the behaviour of longitudinal errors, we consider a typical acceleration error of 1kV at the beginning of MBE-4 where the kinetic energy is 200 keV. This gives a velocity perturbation in the bunch frame of:

$$v_1^{\text{bunch}} = (v_0^{\text{lab}}/2)(T_1^{\text{lab}}/T_0^{\text{lab}}) = 0.14 \text{ cm}/\mu\text{s}$$

where T is kinetic energy, v is velocity, the subscript denotes the perturbation or the unperturbed quantity and the superscript denotes the frame of reference.

Because the perturbation velocity in the bunch frame is significantly smaller than the wave velocity, acceleration errors propagate through the bunch as waves. However, at the extreme ends of the bunch where the charge density becomes small, the wave picture breaks down.

The amplitude of the charge fluctuation is related to the amplitude of the velocity fluctuation in the bunch frame by the expression:

$$\lambda_1 / \lambda_0 = v_1^{\text{bunch}} / c$$

so that a sinusoidal kinetic energy error with an amplitude of 1kV will produce a standing wave which, for constant λ_0 , will oscillate into a current fluctuation of 8% amplitude, with a frequency which depends on the wavelength of the error.

We consider a typical MBE-4 accelerating error at gap 1 with a frequency of 1MHz, giving a wavelength in the bunch frame of 0.5m. The resulting waves will oscillate while the line charge density changes only slowly. The current fluctuation will be at a maximum after one quarter period, about 7 μs , when the bunch is 1/3 of the way through the linac.

Tuning the longitudinal dynamics

In general, one cannot correct an arbitrary acceleration error after more than one quarter period of the wave oscillation. In practice, it is impossible to perfectly realize the design acceleration waveforms at every gap; small acceleration errors are inevitable and in MBE-4 they become readily visible as current fluctuations.

Figure 2 shows the current waveforms for all four beams at gap 0, before acceleration. Figure 3 shows the current waveforms at each diagnostic station through the linac. Current fluctuations are apparent once the error-waves have had time to oscillate one quarter period.

It is particularly interesting to see in figure 3 how the ends of the bunch behave under the application of longitudinal focusing. The first longitudinal focus force is at gap 4. It is an extra pulser which acts to speed up the tail of the bunch. The results are seen at gap 15, the tail is steepened and a small spike appears where the focus pulser has affected the interior of the bunch. Subsequently the tail slows and spreads under the longitudinal space charge force. The focus forces on the head of the bunch are at gaps six and seven. Here we modify the main pulsers to refrain from accelerating the head of the

bunch, causing the head to slow, and steepen at gap 20. Again a small spike appears where the focus force has intruded into the body of the bunch. Subsequently the head speeds up and spreads under the longitudinal space charge force. At gap 30 the bunch is ready for more longitudinal focusing.

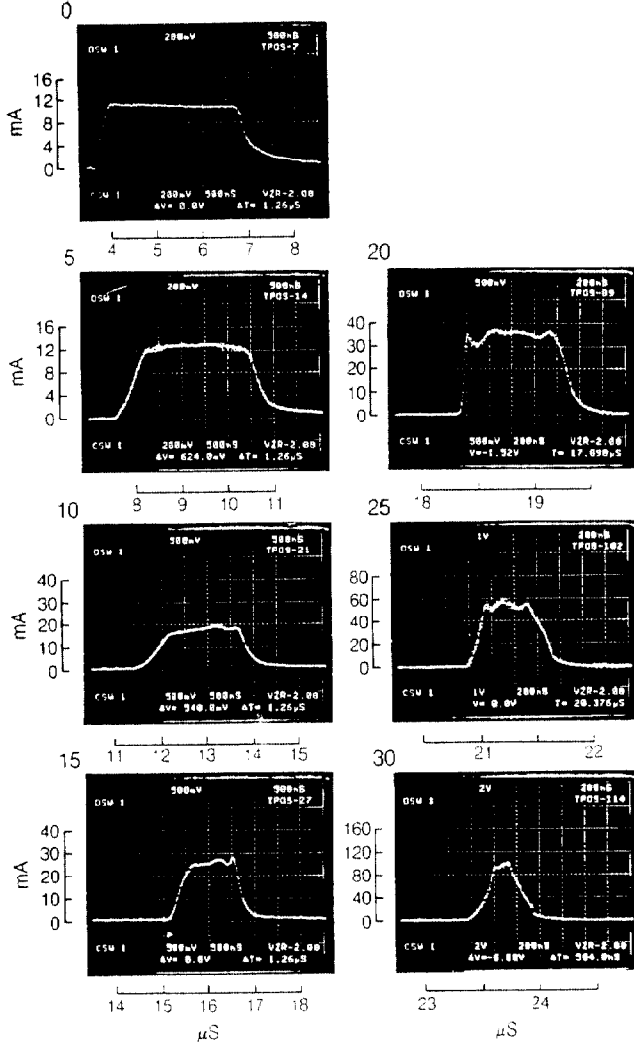


Figure 3. Current waveforms at each diagnostic gap.

Figure 4 shows our simple simulations tracking the bunch through MBE-4. These computations can follow the actual longitudinal dynamics quite well. The physical assumptions behind these calculations, namely one-dimensional dynamics in the long-wavelength approximation, are exactly those used to derive the one-dimensional wave equation above.

Figure 5 shows the measured longitudinal emittance, including shot-to-shot variations. The kinks in longitudinal phase space are systematic acceleration errors accumulated through the length of the linac. Particularly obvious is the poor control of the phase space distribution where the head of the bunch is longitudinally focussed by the leading edge of the accelerating waveform. The area of an enclosing ellipse is estimated to be:

$$\pi \epsilon_{\text{longitudinal}} = 4.0 \times 10^{-3} \pi \text{ eV s}$$

The higher beam velocity in a driver will reduce the contribution of a given error to the longitudinal emittance, in inverse proportion to the beam velocity. Current fluctuations at the beginning of a driver are further reduced by the square root of the line charge density, so that with acceleration errors the same size as in MBE-4 current fluctuations would be about 50 times smaller. Nevertheless the fluctuations observed here are unsatisfactorily large and more effort is planned to reduce acceleration errors through the linac before they oscillate into current fluctuations.

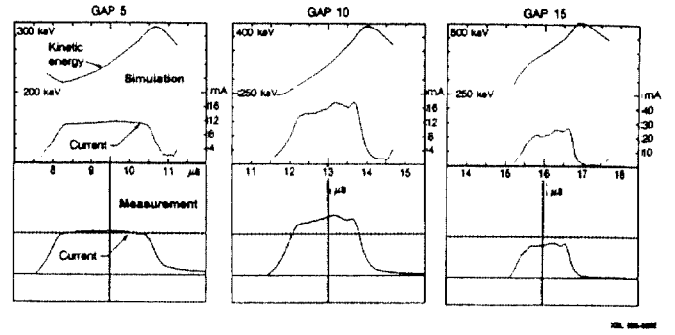


Figure 4. Comparison of simulation and measurements.

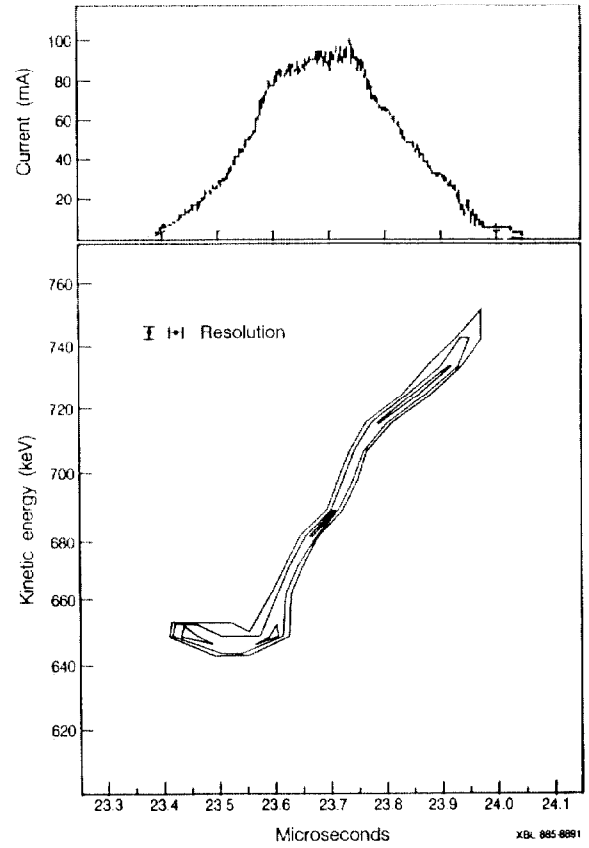


Figure 5. Measured longitudinal phase space distribution.

References

- [1] "Heavy Ion Accelerator Research, an Outline Plan", PUB-5178, Lawrence Berkeley Laboratory, Sept.1986.
- [2] T. J. Fessenden, D. Keefe, C. Kim, H. Meuth and A. I. Warwick, "The LBL Multiple Beam Experiments", Proc. IEEE Particle Accelerator Conf., Washington D.C., March 1987, IEEE cat.no.87CH2387-9, page 898. (1987)
- [3] T. J. Fessenden, D. L. Judd, D. Keefe, C. Kim, L.J. Laslett, L.Smith and A. I. Warwick, "Preliminary Results from MBE-4: A Four Beam Induction Linac for Heavy Ion Fusion Research", Proc. Int. Symposium on Heavy Ion Fusion, Washington D.C. 1986, AIP conf. proc. 152, page 145.
- [4] C. H. Kim, "Ion Induction Linac Design and Operation Codes INDEX/SLID Users Manual," private communication, and C. H. Kim and L. Smith, "A Design Procedure for Acceleration and Bunching in an Ion Induction Linac", Particle Accelerators 18 (1985) 101.