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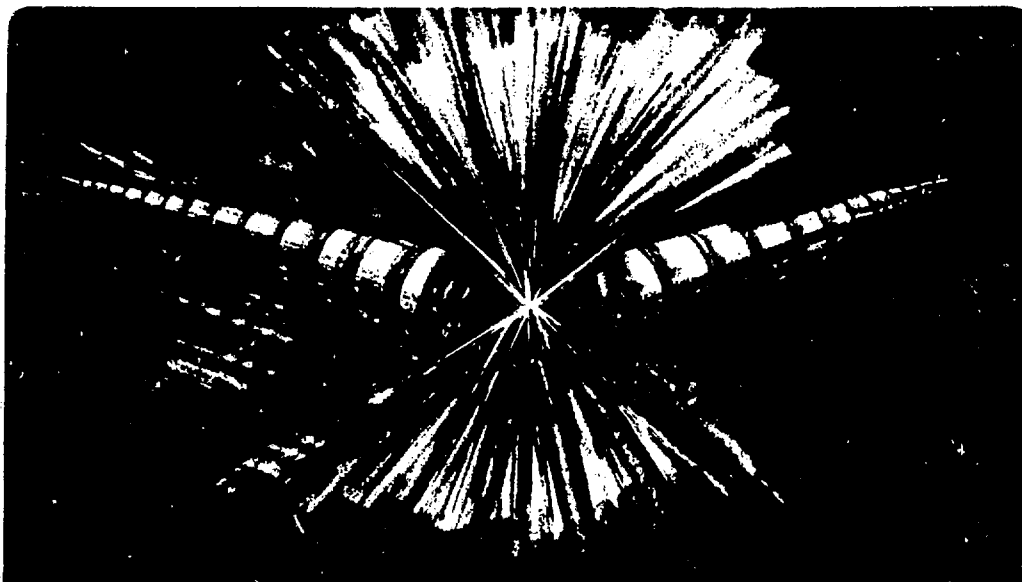
Accelerator & Fusion Research Division

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Summary

The multiple-beam induction linac approach to a heavy ion driver for inertial confinement fusion features continuous current amplification along the accelerator and a minimum of beam manipulations from source to pellet. Current amplification and bunch length control require careful shaping of the accelerating voltages.

MBE-4 is designed as a four-beam induction linac that models much of the accelerator physics of the electrostatically focused section of a significantly longer induction accelerator. Four space-charge-dominated Cs^+ beams, initially about one meter in length at a current of 13 mA, are focused by electrostatic quadrupoles and accelerated in parallel from 200 to nearly 600 keV. The energy will reach approximately one MeV when the accelerator is complete. Experiments have proceeded in parallel with the construction of the apparatus which began in FY 85 and is now more that half complete. The results show a current amplification, so far, by a factor of 2.8 in good agreement with the longitudinal acceleration calculations.

Introduction

The multiple beam induction accelerator experiment MBE-4 was designed to model the longitudinal physics of the electrostatically focused section of a much longer induction linac. The length of the beam bunches are short compared with the length of the accelerator and longitudinal space charge spreading must be controlled. In the completed accelerator, the current of each beam will increase by a factor of four to six and the beam energy will increase by nearly five-times. Thus the increase in beam power (V×I) will be a factor of 20 to 30. MBE-4 will demonstrate current magnification resulting largely from an increase in particle speed, but also from some shortening of the length of the beam bunch. As a percentage of beam energy, the acceleration voltages in MBE-4 are much larger than will be used in a driver. Therefore, the consequences of errors in acceleration voltages will be more apparent and more easily assessed.

Four beams are used to investigate potential effects caused by beam-beam coupling and to get practical experience in difficulties associated with accelerating and transversely controlling parallel beams. In examining the scaling with injection energy and with quadrupole size, we have been careful to preserve space-charge domination of the beams both transversely (depends on beam current density) and longitudinally (depends on line density of charge). Measured in units of initial-bunch-length, MBE-4 is comparable in length to the electrostatically focused portion of a fusion driver. In this paper we present the results of experiments with the first half of the accelerator.

An essential element in both the synthesis of the MBE-4 accelerating waveforms and the analysis of the experiments is the longitudinal acceleration procedure developed by C. Kim with help from L. Smith [1]. This method follows the longitudinal motion of the beam particles through the accelerator and includes the effects produced by beam space charge and finite gap width; it is incorporated into the computer code, SLID, which runs on a small computer. We use this code to find the accelerating waveforms at each gap in the accelerator that will produce the desired current waveforms at any position in the accelerator. For the MBE-4 design, we have chosen to specify a rectangular current pulse which remains self-similar as the current amplifies along the accelerator. Accelerating waveforms calculated by SLID are used as the initial specification for the engineering design of the accelerator pulsers [2]. Since it is not possible to synthesize exactly the ideal waveforms, we use the code to solve for slightly modified downstream accelerating waveforms that can correct for upstream errors.

Description of the MBE-4 Apparatus

Much of the mechanical design of the apparatus was presented at the IEEE Particle Accelerator Conference in Vancouver in 1985 [3]. A schematic diagram of the experiment is presented in Fig. 1. The experiment uses four beams of singly charged cesium obtained from four thermionic alumino-silicate sources. These are accelerated
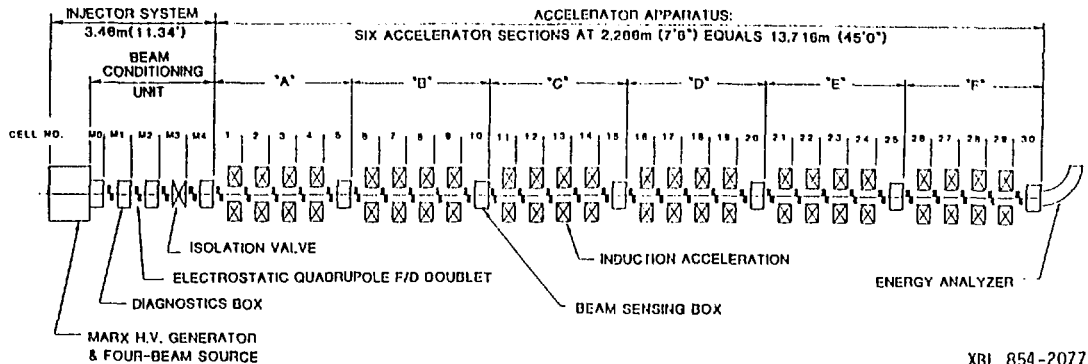
Fig. 1. Schematic Diagram of MBE-4.

to 0.2 MV in a single gap injector [4]. The initial pulse duration is 2.5 μs which will shorten to 0.6 μs at the end of the accelerator. The four beams are focused by arrays of electrostatic quadrupoles, each consisting of nine electrodes. A photograph of a quadrupole array is shown in Fig. 2. The beam-to-beam spacing is 6.67 cm (between centers) and the clear aperture diameter is 5.41 cm. The diameters of the electrodes are 4.02 cm. The electrodes occupy approximately one half the lattice period (45.7 cm). Each of the four beams is axi-symmetric at the exit of the injector, and has its envelope carefully adjusted in a electrostatic quadrupole beam matching section to the proper form for acceptance by the FODO transport system in the accelerator. The beams, each approximately one meter in length, will be accelerated to nearly 1.0 MV by 24 linear induction modules in a total length of 17.2 m. The voltage waveforms on the early accelerator gaps are nearly triangular so as to impart an axial velocity shear, or tilt, to the beam by accelerating the tail of the beam more than the head. A report [5] on the status of the development of pulsers for MBE-4 is being presented at this conference. After the tail of the beam has entered the accelerator, the head of the beam can be accelerated as well; thereafter, the waveforms on the downstream gaps can be almost flat-topped. The apparatus will be completed in the fall of 1987. The experiment has been completed through section "C" as shown in the photograph presented in Fig. 3. At this writing we are in the process of installing sections "D" and "E" and expect to begin experiments with these sections in place in May 1987.

Diagnostics

As shown in Fig. 1, the induction accelerator units are placed in groups of four, followed by a station that allows pumping and diagnostic access to the beams. The

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Fig. 2. Photograph of a four-beam electrostatic quadrupole array.

accelerating voltages are monitored with a resistive divider placed across each accelerating gap. Our primary beam diagnostics are arrays of four biased Faraday cups for current measurements. These have rise times less than 0.1 μs and are remotely inserted into the beams as required. We also use arrays of four capacitive pickups which measure the line charge density of the beams and have the advantage of being non-intercepting. The rise time of these is limited by the transit time of the beam through the pickup which, for cesium, can be as long as 0.3 μs. Emittance measurements employ the two-slit method; the detectors are small Faraday cups placed behind the downstream slits. Beam size measurements are made with parallel wire arrays called "Harps" that emit secondary electrons when struck by the cesium beam. The wires are .25 mm wide and are located .5 mm apart. Finally, at the end of the system, an electrostatic energy analyser is set up to analyse the right-hand beam. The analyser has an energy resolution of 0.5% and can be seen in the photograph of Fig. 3. As more of the MBE-4 apparatus is progressively assembled, the analyzer is moved downstream.

Data are collected by digitizing oscilloscopes that are interfaced to a small computer. The computer transfers data to and from the oscilloscopes and, in addition, runs the SLID program for analysis and interpretation of the experiments. The computer also controls the voltage on the electrostatic energy analyzer during measurements of beam energy, and positions the slits during measurements of beam emittance.

Experimental Results

Experiments on MBE-4 have proceeded one section at a time as the apparatus has been assembled. The status of the experiments was last reported at the Heavy Ion Inertial Fusion Symposium [5] in May 1986 and at the "Beams 86" conference [6] in Kobe, Japan in June 1986. At present the major experimental thrust is to study a so-called "acceleration schedule" in which the current is amplified as $\beta^{2.5}$. The accelerating waveforms that are used in the first twelve gaps are shown in Fig. 4. These were obtained by using the SLID code, experimental observation, and iteration procedure detailed above. Accelerating voltages at gaps 4, 9, and 11 contain components to control the longitudinal space-charge spreading of the beams as well as to accelerate the beams. The waveforms in section "C" (gaps 11-14) were synthesized in such a way that the accelerating voltage seen by beams passing through adjacent gaps was of the correct form to retain the desired self-similar current waveforms. That is, waveforms on adjacent gaps, as opposed to individual gaps, were required to synthesize the self-similar current amplifying acceleration schedule.

Oscillograms of each of the four cesium beams at the entrance to the accelerator and at diagnostic stations 5, 10, and 15 are presented in Fig. 5. These were obtained using four arrays of four Faraday cups. There are some variations in calibration among the 16 cups. By electronically
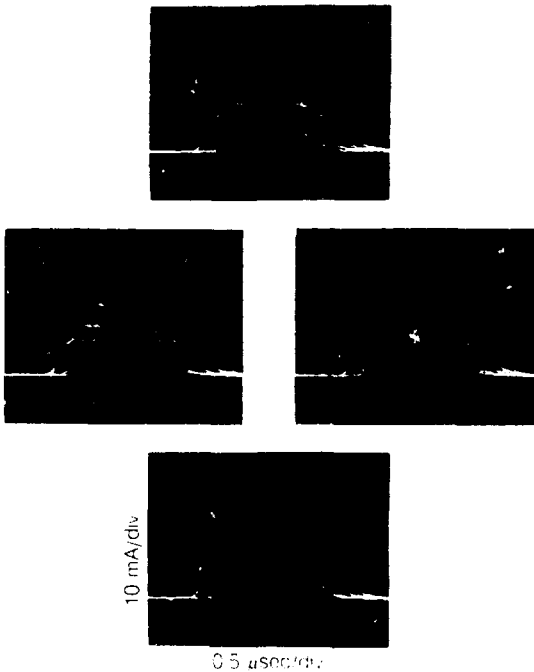

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Fig. 3. Photograph of MBE-4 taken in Nov. 1986.

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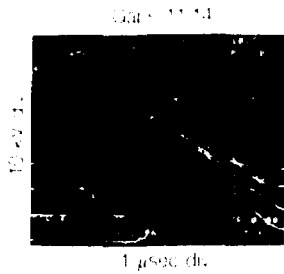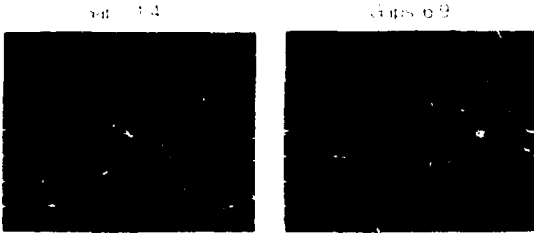
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Fig. 4. Oscillograms of the waveforms used in the first 12 accelerating gaps of MBE-4.
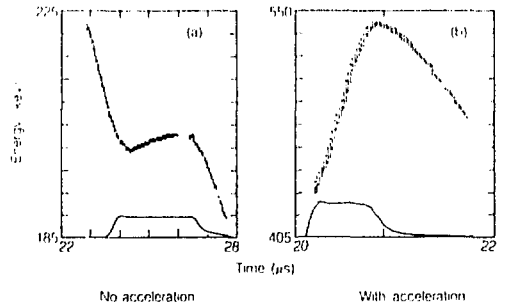

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Fig. 5. Cesium beam current wave forms at stations 0, 5, 10, and 15.

integrating the 16 current traces, we determined that the measured charge contained in each beam at each station varies by no more than 5%. For a given beam the charge varies by less that 3% along the length of the apparatus.

These variations are of the same order as our experimental error. The small peak on the top beam at station 15 is an artifact due to faulty operation of that particular Faraday cup.

Measurements of the time dependence of the energy of the right hand beam are shown in Fig. 6. In taking these data the analyser was located after section "D" which contained no acceleration. With each firing of the machine, the computer raised the electrostatic analyzing voltage in steps corresponding to approximately one percent of the energy range being scanned. To obtain a beam energy measurement requires the better part of one hour. After recording the data the computer calculates the mean and standard deviations of the detected signal to obtain the beam energy versus time.

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Fig. 6 Measurements of the Beam energy versus time at Station 20. a) Without acceleration, b) With acceleration.

Figure 6a shows the energy variation versus time for a beam drifted through the accelerator from the injector to the analyser without acceleration. As a result, the longitudinal space charge fields at the bunch ends were not compensated and the particles at the beam head gain energy from the bunch while the trailing particles lose energy. (An analysis of this physics was done by Faltens, Lee and Rosenblum [7] using experimental data taken from the Single Beam Transport Experiment [8].) The energy of the beam in the main body of the pulse is not exactly constant but shows a slight ramp of about 1.5%.

Figure 6b shows the energy of the MBE-4 beam accelerated by the waveforms in Fig. 4 to an average energy near 500 keV. The normalized beam velocity shear ($\Delta\beta/\beta$) is approximately 10% from head to tail. The down-turn in energy at later times occurs after the main body of the pulse and is associated with particles trailing behind that constitute a small fraction of the total. An aperture located at station 15 was used to greatly reduce the beam current and longitudinal space-charge effects as the beam passed through the drift section "D". However, for the accelerated beam, the beam velocity tilt at the end of the accelerator results in additional pulse shortening and current amplification before the beam energy is measured.

The SLID code was used to calculate the expected current and energy profiles at stations 0, 5, 10, and 15, where the diagnostics are located The results of these calculations are presented in Fig. 7. The SLID code was run in the analysis mode wherein the measured accelerator waveforms presented in Fig. 4 and the beam current and energy at the entrance to the accelerator were provided as inputs. SLID calculations of the energy at the position of the energy analyser are included in Fig. 6 for comparison.
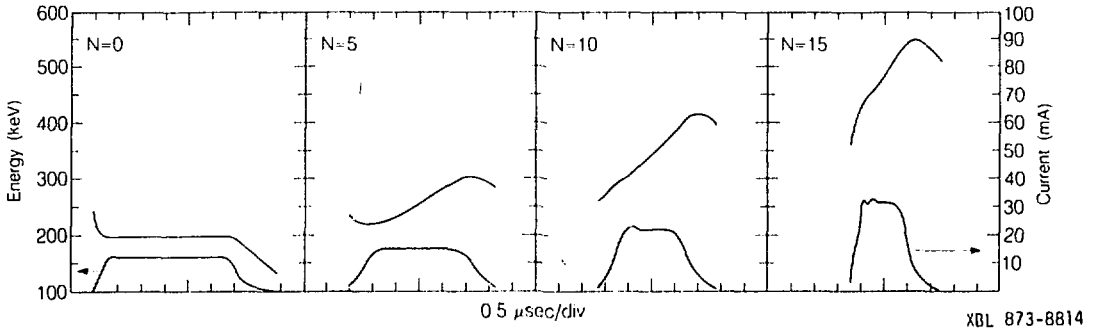
Fig 7. SLID Calculations of the MBE-4 current waveforms and energy at stations 0, 5, 10, and 15.
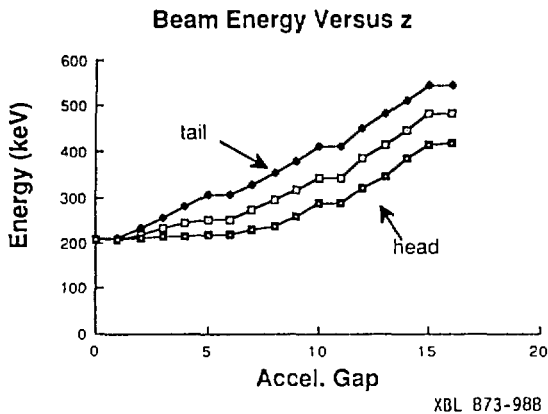
Beam Energy Versus z

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Fig. 8 Plots of the tail, center, and head energy of the MBE-4 beams as calculated by the SLID code from experimental data.
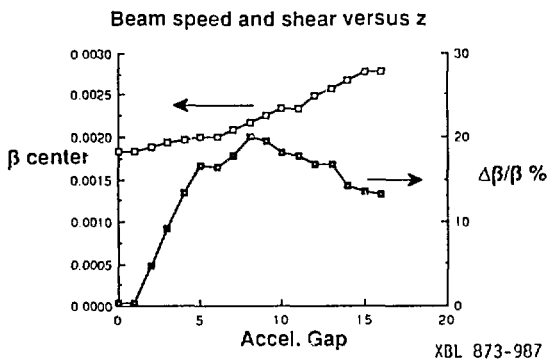
Beam speed and shear versus z

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Fig. 9 Beam speed at pulse center and normalized velocity shear of the MBE-4 beams in the accelerator.

Further analysis of the experimental operation of MBE-4 obtained with the SLID code is presented in Figs. 8 and 9. Figure 8 shows calculations of the energy of the beam tail, center, and head for the above experimental conditions. The energy variation at station 15 can be compared with the measurements of beam energy shown in

Fig. 6. Figure 9 shows the variation of the beam speed and the velocity shear, $\Delta\beta/\beta$, along the accelerator. The velocity shear peaks at 20% at period 7 then falls to 13% at the end of the present apparatus. The absence of acceleration in gaps 5, 10, and 15 is reflected by flat spots on the curves of beam energy versus z in Fig. 8 and beam speed in Fig. 9 at these locations.

Several experiments were performed to study the evolution of the beam emittance with time under acceleration. We measured the emittance of the bottom beam at station 15 at times near the head, center, and tail of the pulse. We also measured the beam emittance at pulse center at the gun exit (M1) and at station 15 with the accelerator turned off. The time window of the measurement is 60-70 ns. Figure 10 shows a plot of the bottom cesium beam in horizontal phase space at station 15. The contours are selected on the basis of amplitude and enclose all points that are greater than, respectively, 5, 10, 20, and 50% of the maximum signal. These data were taken at the time center of the pulse at the instant that the beam energy was approximately 500 keV.

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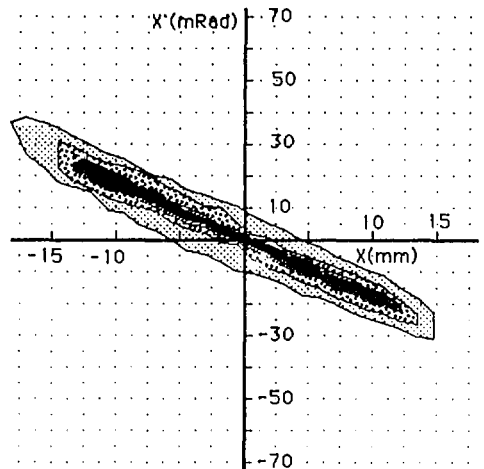
Fig. 10. The bottom cesium beam at station 15 in horizontal phase space. Mean $x = -1.4$ mm; rms $x = 7.6$mm; Mean $x' = 2.6$ mR; Rms $x' = 13.9$ mR; beam offset, 1.4 mm in x, 2.6 mR in x;. Rms emittance = 20.1 mm-mR with 95% of the particles.

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The computer code EPLOT is used to calculate the r.m.s. emittance. We define the rms emittance as

$$\epsilon_{rms} = \left(\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2 \right)^{1/2} \qquad (1)$$

where $\langle x \rangle$ and $\langle x' \rangle$ are, respectively, the r.m.s. beam size and the r.m.s. transverse velocity normalized to the parallel velocity. The parameter $\langle xx' \rangle$ is the rms mean product of the beam size and normalized parallel velocity. The normalized emittance is defined as $4\beta\epsilon_{rms}$ in the computations reported here.

Results are presented in Table 1. The experimental error in these data is considerable due to electrical noise generated by the pulsers firing and the data is not believed accurate to better than 20%. These results suggest that the normalized emittance remains constant under acceleration as expected and that there is no evidence of transverse emittance growth. Nevertheless, more experiments are required before we can be confident of this conclusion. We are in the process of developing the coding that will enable us to measure beam emittance simultaneously at several positions within the pulse instead of at one time; this will greatly shorten the required experimental time.

Table 1
Beam Emittance Measurements

pulse	Energy (keV)	rms Emit. (mm-mR)	norm. Emit. (mm-mR)	Comment
center	200	31	0.22	M1 Gun exit
center	200	29	0.21	15 Accel. off
head	450	26	0.28	15 Accel. on
center	500	20	0.23	15 Accel. on
center	500	21	0.24	15 Accel. on
tail	550	21	0.25	15 Accel. on

Discussion

We have accelerated four parallel space-charge dominated cesium ion beams from 0.2 MV to nearly 0.6 MV with a current amplification of 2.8 in the partially complete MBE-4 apparatus. The experiments are in excellent agreement with our theoretical acceleration model.

The acceleration schedule is one in which the current waveforms grow in amplitude and decrease in pulse duration in a self-similar or self-replicating way with acceleration distance. Aside from small fluctuations, generated by small errors in the acceleration waveforms, the experimental current waveforms are self-replicating. The acceleration errors are mostly corrected by "trim" pulsers located at approximately every fourth accelerating gap. These are also used to control space charge spreading of the ends of the beam bunches. Comparisons of the measurements with those calculated theoretically are used to derive small corrections to the design of the pulsers that provide the accelerating waveforms for subsequent gaps.

Preliminary measurements of the beam emittance versus position in the pulse, after acceleration of the cesium beams from 200 keV to nearly 600 keV, have revealed no unpleasant surprises. The normalized emittance appears to remain constant as expected. A more thorough experimental study will be made when the MBE-4 apparatus is completed.

Current amplification with acceleration in a linac is only possible for beams moving non-relativistically. In order to overcome the effects of space charge and control the bunch length within the accelerator, one must precisely control of the longitudinal acceleration fields seen by the beam. Small acceleration errors, if uncorrected, lead to growing current fluctuations that result in beam spill or momentum spread. We have been successful in controlling the consequences of unavoidable small errors with the use of the Kim-Smith longitudinal acceleration model as incorporated into the SLID computer code. Future experiments will give a clearer picture of the importance of current fluctuations in the operation of an ion induction linac and how effectively they may be controlled.

References

[1] C.H. Kim and L. Smith, Part. Accel. 85, pp. 101-113, (1985).

[2] C.H. Kim, V.O. Brady, T.J. Fessenden, D.L. Judd, and L.J. Laslett, IEEE Trans. on Nuc. Sci., NS-32, p. 3190, (1985).

[3] R.1. Avery, C.S. Chavis, T.J. Fessenden, D.E. Gough, T.F. Henderson, D. Keefe, J.R. Meneghetti, C.D. Pike, D.L. Vanecek, and A.I. Warwick, IEEE Trans. on Nuc. Sci., NS-32, p. 3187, (1985).

[4] A.I. Warwick, D. Vanecek, and D. Fredriksson, IEEE Trans. on Nuc. Sci., NS-32, p. 3196, (1985).

[5] D. Gough, D. Brodzik, A. Faltens, C. Pike, and J. Stoker, "Pulsers for the Induction Linac Experiment, MBE-4", this conference.

[6] T.J. Fessenden, D.L. Judd, D. Keefe, C. Kim, L.J. Laslett, L. Smith, and A.I. Warwick, AIP Conf. Proc. 152, Heavy Ion Inertial Fusion, Wash. D.C., p. 145, (1986).

[7] T.J. Fessenden, R.T. Avery, D.A. Brodzik, C.S. Chavis, A. Faltens, D.E. Gough, T.F. Henderson, D.L. Judd, D. Keefe, C. Kim, L.J. Laslett, J.R. Meneghetti, C.D. Pike, L. Smith, D.L. Vanecek, and A.I. Warwick, "MBE-4: An Induction Linac Experiment for Heavy Ion Fusion", Sixth International Conference on High-Power Particle Beams, Kobe, Japan, June 9-12, 1986.

[8] A. Faltens, E.P. Lee, and S.S. Rosenblum, "Beam End Erosion", Submitted to J.A.P. also LBL report LBL-19508 January 1986.

[9] W. Chupp, A. Faltens, E.C. Hartwig, D. Keefe, C.H. Kim, L.J. Laslett, R. Nemetz, C. Pike, S.S. Rosenblum, J. Shiloh, L. Smith, M. Tiefenback, and D. Vanecek, IEEE Trans. Nucl. Sci., NS-30, 2549 (1983).