LBL-19137
Preprint c.2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

RECEIVED
LAWRENCE
BERKELEY LABORATORY

MAY 16 1985

LIBRARY AND
DOCUMENTS SECTION

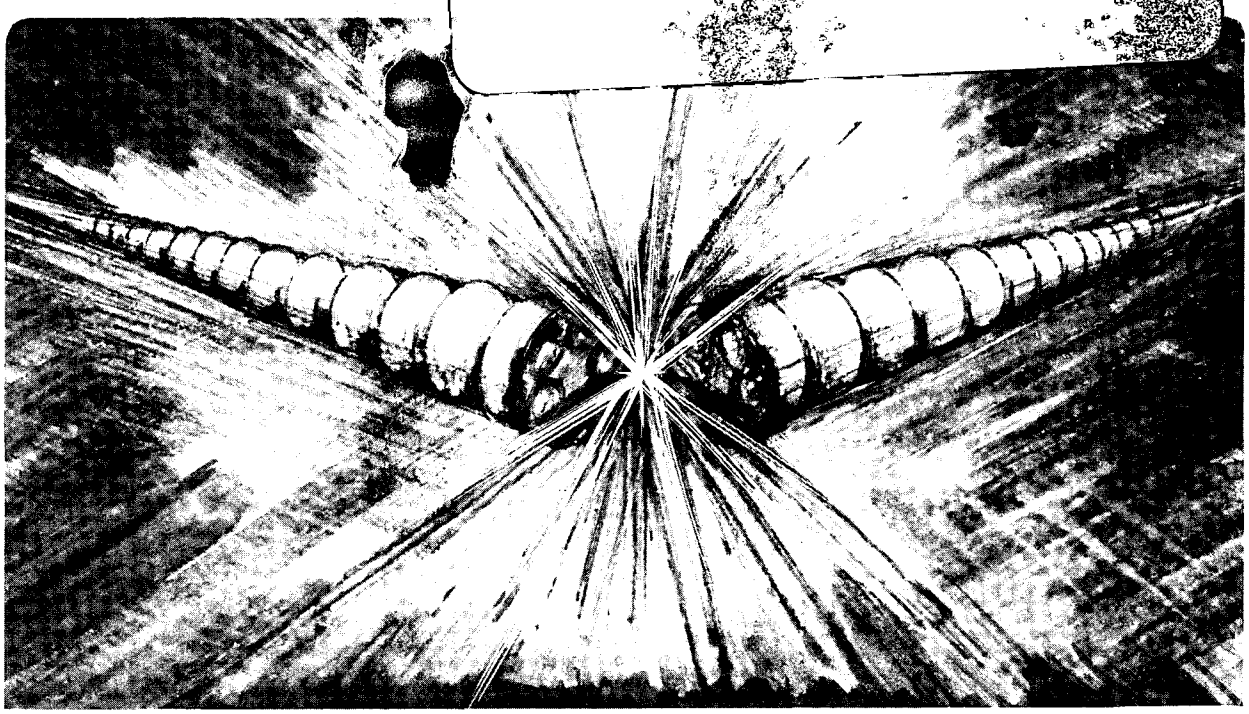
Submitted to Particle Accelerators

A DESIGN PROCEDURE FOR ACCELERATION AND BUNCHING IN AN ION INDUCTION LINAC

C.H. Kim and L. Smith

February 1985

TWO-WEEK LOAN COPY
This is a Library Circulating Copy
which may be borrowed for two weeks.



LBL-19137
c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-19137

A DESIGN PROCEDURE FOR ACCELERATION AND BUNCHING IN AN ION INDUCTION LINAC*

C.H. Kim and L. Smith

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

February 1985

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

A DESIGN PROCEDURE FOR ACCELERATION AND BUNCHING IN AN ION INDUCTION LINAC*

C.H. Kim and L. Smith
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

As a driver of an inertial confinement fusion system, an ion induction linac has to accelerate and longitudinally compress non-relativistic heavy ion beams whose current is by necessity close to the space charge limit of the transverse focusing system. This requires that the tail must be accelerated more than the head of the bunch in some programmed fashion which maintains the beam current close to the limit but at the same time minimize the longitudinal variation of line charge density, in order to minimize longitudinal space charge forces. Two such schemes, the current self-replicating scheme and the line charge density self-replicating scheme, are described. Longitudinal dynamics is first treated by disregarding longitudinal space charge effects, but satisfying the separately determined transverse space charge limits and other constraints of a practical nature. A design so generated is then tested with a computer code for its longitudinal dynamics, including space charge effects, deviations from ideal accelerating voltage waveforms, and module impedances. The results of this step are then used to make (usually minor) adjustments to the design. Finally, an application of the procedure to the planned "high temperature experiment" is described.

*This work is supported by the Office of Energy Research, Office of Basic Energy Sciences, US Department of Energy under Contract No. DE-AC03-76SF-00098.

I. INTRODUCTION

Inertial confinement fusion requires the delivery of several megajoules of energy in tens of nanoseconds to a D-T loaded target at a rate of several times a second if it is to succeed as a viable method of energy production. The behavior of a pellet is to a considerable extent independent of the means of supplying the driving energy and so the issue of a suitable driver can be examined without detailed knowledge of pellet physics. Prime candidates are laser beams, light ion beams (a few MeV and mega-amperes of current) and heavy ion beams (a few GeV and kilo-amperes of current). For heavy ions, the primary accelerator candidates are conventional rf linacs combined with numerous storage rings to accumulate the required number of ions and a not so conventional application of the linear induction accelerator, which would deliver the required number of ions in a single beam pulse and thus avoid many perilous beam manipulations.[1,2]

Since its development by N.C. Christofilos, et al.,[3] a number of induction linacs have been built to accelerate kiloamperes of electrons in short pulses -- microsecond and sub-microsecond pulses.[4,5] These machines are relatively simple in concept; the injected electrons are already relativistic and travel at close to the speed of light throughout the accelerator. Thus all accelerator modules are identical and modest solenoids suffice for transverse confinement. The emerging beam has the same time duration as the injected beam, with energy fluctuations in time given by the sum of module voltage fluctuations in time. In contrast, heavy ions would be injected at $v/c \sim 10^{-3} - 10^{-2}$ under space-charge dominated conditions, requiring an almost continuous strong focusing system for transverse containment (fig. 1). Since the bunch must be compressed in time for the ICF application and, if the capability of an induction accelerator to handle high currents is to be exploited, the modules must accelerate the tail more

than the head of the bunch in some programmed fashion[6]. The aim is to maintain the line charge density near to the transverse space charge limit but at the same time minimize the longitudinal variation of line charge density in order to minimize longitudinal space charge forces.

It is the purpose of this paper to present a procedure to design such a device. The longitudinal dynamics is first treated by disregarding longitudinal space charge effects, but satisfying the separately determined transverse space charge limits as well as other constraints of a practical nature. A design so generated is then tested with a computer code for its longitudinal dynamics, including module impedances, deviations from ideal voltage waveforms and longitudinal space charge effects. The results of this step are then used to make (usually minor) adjustments in the design. Finally in this paper, we present an application to the "high temperature experiment", a plan for an accelerator which would test the essential features of the driver concept and provide sufficient energy and power to heat a target to 50 - 100 eV temperature.[7,8,9]

II. SELF REPLICATION AND THE VELOCITY FUNCTIONS

There are two conceptually simple acceleration and bunching schemes which maintain the longitudinal integrity of the bunch; that is, prevent ions from overtaking their neighbors, which would create undesirable density fluctuations. They are: (1) the current self-replicating scheme, as it is called in this paper, and (2) the line charge density self-replicating scheme.

In the current self-replicating scheme, the functional form of the current as a function of time at a fixed location is preserved throughout the accelerator while the magnitude increases as the bunch shortens in time.

Exact solutions can be found for spatially discrete accelerators using this scheme; a spatially discrete accelerator is defined as one in which temporally continuous acceleration voltages can be applied at discrete locations. Consider the drift region between the n-th and the $(n+1)^{th}$ gap, in a spatially discrete accelerator (fig. 2a). The necessary and sufficient condition for current self-replication is that the trajectories of all the particles in the trapezoid in the (z, t) plane bounded by the two gaps are directed to a common focal spot (ζ, η) as illustrated in fig. 2a. This condition requires that the velocity of the particle located at (z,t) in this region be given by the velocity function;

$$v_n(z,t) = \frac{\zeta_n - z}{\eta_n - t} ; \qquad z_n < z < z_{n+1} \quad . \tag{1}$$

The velocity given by eq. (1) is, of course, the fluid velocity. It is assumed that the temperature of the beam at injection is negligible; a good design should keep it that way by preventing an irreversible mixing of particle trajectories.

The beam current, I(z,t), and the line charge density, $\lambda(z,t)$, can be found by considering charge conservation and the similarity of the triangles drawn by the tangents of the trajectories of two adjacent particles at subsequent locations z_n and z, (see fig. 2a);

$$I(z, \tau) = I_n(\tau) \frac{\zeta_n - z_n}{\zeta_n - z} ; \; z_n \leq z < z_{n+1} \quad , \tag{2}$$

$$\lambda(z, \tau) = I_n(\tau) \frac{\zeta_n - z_n}{[\zeta_n - z]^2} (\eta_n - t) \quad , \tag{3}$$

$$z_n \leq z < z_{n+1} \quad ,$$

where the current at the n-th gap, $I_n(\tau)$, is given by;

$$I_n(\tau) = I_1(\tau) \prod_{k=1}^{n-1} \frac{\zeta_k - z_k}{\zeta_k - z_{k+1}} , \quad n \geq 2 . \tag{4}$$

Here τ is the normalized time in the beam frame: $\tau = (t - t_h)/T_z$, and t, t_h, and T_z are the particle arrival time, bunch head arrival time and the pulse duration, respectively, at the location, z. As can be seen from eqs. (2) and (4), the initial pulse shape, $I_1(\tau)$, is reproduced throughout the accelerator, which is what we mean by current self-replication. Notice that $I(z, \tau)$ is a continuous function of z and τ, while an inspection of eq.(3) shows that at a fixed time the density has a sawtooth modulation between gaps given by the z dependence of the denominator and a long range tilt by the z dependence of $I_n(\tau)$.

In the line charge density self-replicating scheme, the functional form of the line charge density as a function of space at a fixed time is preserved throughout the accelerator while the magnitude increases as the bunch shortens in space. This scheme can be considered as a mirror image of the current self-replicating scheme with the current-density and the space-time variables interchanged. Exact solutions can be found for temporally discrete accelerators using this scheme; a temporally discrete accelerator is defined as one in which spatially continuous acceleration voltages can be applied at discrete time intervals. Obviously, it is not very practical to build a temporally discrete accelerator. Nevertheless, a comparison of the concepts helps one to gain some insight in understanding the nature of the problem. Consider the drift region between the m-th and (m+1)st acceleration times, in a temporally discrete accelerator (fig. 2b). The necessary and sufficient condition for line charge density self-replication is that the trajectories of all the particles in the trapezoid in the (z, t) plane bounded by the two

accelerating times are directed to a common focal spot (ζ, η) as illustrated in fig. 2b. This condition requires that the velocity of the particle located at (z,t) in this region be given by the following velocity function;

$$v_m(z,t) = \frac{\zeta_m - z}{\eta_m - t} \; ; \qquad t_m < t < t_{m+1} \tag{5}$$

Expressions for $I(z,\tau)$ and $\lambda(z,\tau)$ for this scheme, similar to eqs.(2) and (3), can be found in the same way.

Some years ago, L. J. Laslett, with S. Chattodadhyay, A. Faltens, and L. Smith,[10] and, more recently, L.J. Laslett and D. Judd[11] developed an acceleration and bunching scheme in which the line charge density is kept constant in space at a fixed time, thus avoiding the longitudinal force which is proportional to the spatial derivative of the line density. The acceleration is first assumed to be continuous in space, with the acceleration of a reference particle and the beam bunch length specified as functions of time along the linac. From this design z vs. t at the actual (discrete) gap locations can be calculated for various ions regularly situated along the beam, and the voltage wave forms (in time) at the discrete gap locations then adjusted so that the ions again follow this z vs. t dependence at each such gap.[12]

The sawtooth modulation of the line charge density in space at a fixed time is unavoidable in spatially discrete accelerators no matter what scheme is used. The resulting space charge force does work on particles. In order to estimate the magnitude of this energy perturbation, we assume that the space charge field is given by the long wavelength approximation;

$$E_s = - \frac{q}{4\pi\epsilon_0\gamma^2} \frac{\partial\lambda}{\partial z} \tag{6}$$

where $g = 1 + 2 \ln (b/a)$, b and a the pipe and the beam radius, and γ the usual relativistic parameter. The work done on a particle as it moves from gap number, n_1, to gap number, n_2, is calculated by integrating Eq. (6) along the particle trajectory. For the current self-replicating scheme with the line density given by Eq. (3), one can show that:

$$\Delta W = \frac{g}{4\pi\varepsilon_0\gamma^2} \sum_{n_1}^{n_2} \frac{I_n}{v_n^2} \left(2d \left(\frac{\partial v}{\partial z}\right)_n + \Delta v_{n+1} \right) \quad , \tag{7}$$

where I_n, v_n, and Δv_n are the current, velocity and the velocity increment at the n-th gap, respectively, d is the intergap distance. The value of $\left(\frac{\partial v}{\partial z}\right)_n$ is evaluated in the drift region right after the n-th gap.

Eq. (7) shows that the energy change due to self-forces per interval is proportional to the instantaneous beam current at the gap, a feature which is similar to that of conventional beam loading in an acceleration gap. In beam loading, the actual gap voltage is reduced from the applied value by an amount given by the beam current multiplied by the resistive part of the module impedance. The equivalent impedance of the self-force is the coefficient of I_n in Eq.(7), which decreases as v_n^{-3} as the beam is accelerated. The magnitude is comparable to a typical module impedance at the front end of the linac. Both effects can be easily corrected by a minor adjustment to the accelerating voltage, as discussed in section III.

III. VOLTAGE WAVEFORMS AND ACCELERATION-BUNCHING SCHEDULES

For any acceleration and bunching scheme, the required acceleration voltage at a gap is given by energy conservation at the gap, if the velocity functions before and after the gap are known. These velocity functions can be either one of the self replicating types or of some special types if one

wants to modify the pulse shape of the beam. For instance, such a need may occur as a result of unsatisfactory beam initial conditions, or at the end of the accelerator where a special pulse shaping may yield a better target performance. From here on we restrict the analysis to the current self-replicating scheme, from which results can be derived more easily.

For the current self-replicating scheme, the ideal gap voltage at the n-th gap is given by;

$$V_n(t) = \frac{m}{2e} \left\{ \left(\frac{\zeta_n - z_n}{\eta_n - t} \right)^2 - \left(\frac{\zeta_{n-1} - z_n}{\eta_{n-1} - t} \right)^2 \right\} . \tag{8}$$

The accelerating voltages at the head and tail of the beam are determined in compliance with various physics and technological constraints. Then, Eq. (8) is used as a recurrence formula to find all the values of ζ's and η's. The constraints dictated by beam dynamics are:

1) If the beam is not to increase in length on entering the accelerator, a situation which is difficult to overcome by subsequent manipulation of voltage wave forms, the head must not be accelerated before the tail has entered.

2) If the bunch length is to be held constant or shortened during acceleration to achieve additional current amplification, the velocity of the tail must be equal to or greater than the velocity of the head at fixed time. It follows that the velocity of the tail will necessarily be greater than the velocity of the head at fixed z. If the transverse focusing voltage or magnetic field at fixed z

is constant in time*, the tail experiences a weaker focusing strength than the head, which results in a larger beam radius at the tail. In the absence of experimental information on the consequences of this difference we somewhat arbitrarily impose a "$\delta\beta/\beta$ limit"; that is, that the tail-head velocity difference normalized to the central particle velocity at fixed z should not exceed a certain relative value.

This relative limit is encountered early in the accelerator, where β is small. Once free of the $\delta\beta/\beta$ limit, with beta continuing to increase, one can use up the available margin in $\delta\beta/\beta$ to initiate spatial compression of the bunch, by making the tail acceleration rate greater than that of the head at a fixed time. Most of the spatial compression actually occurs after the bunching region where the bunch length decreases linearly with time.

There are also technological constraints:

(1) Two important modifications for an ion induction accelerator from the existing electron accelerators are the need for a husky transverse focusing system and the need for voltage pulses much longer in time at the low energy end in order to accept the required number of ions. The flux change and thus the total amount of magnetic material needed in the accelerating units are proportional to the required volt-seconds at the accelerating gap; thus, more material per unit length than in an electron accelerator must be fitted into a space already restricted by focusing requirements. One can run into a limit on reasonable core size which can be expressed for design purposes as a limiting value on volt-seconds per meter.

*This condition seems to be the only reasonable one on a micro-second time scale.

(2) In common with electron accelerators is a voltage break-down limit, which can be expressed as a maximum allowable average accelerating field gradient.

Because of these constraints, an ion induction linac consists of five distinct parts: (1) beam entrance region, (2) $\delta\beta/\beta$ limit region, (3) bunching region, (4) flux limit region, and (5) field gradient limit region. To minimize accelerator length, it is desirable to reach region (5) as soon as possible. The procedure is best illustrated by an example, which is described in the following section.

In a practical accelerator, the ideal waveforms are synthesized either by superposing simple waveforms of several independent induction cores[13] or by using special pulse-forming-networks (PFN). The velocity functions actually realized are likely to be different from the ideal ones given by Eq. (1) due to imperfect waveform synthesis, to space charge forces, or to the module impedances. The resulting undesirable density fluctuations can cause transverse particle losses and (or) longitudinal emittance growth. These imperfections can be corrected down stream by employing a modified gap voltage waveform;

$$V_n(t) = \frac{m}{2e}\left\{\left(\frac{\zeta_n - z_n}{\eta_n - t}\right)^2 - v_{n-1}(z_n, t)^2\right\} , \qquad (9)$$

where $v_{n-1}(z_n, t)$ is the actually realized velocity function just before the n-th gap. This waveform will restore the current self-replicating feature, but not the original current waveform itself.

IV. THE HIGH TEMPERATURE EXPERIMENT (HTE)

One of the intermediate goals of the Heavy Ion Fusion Accelerator Research (HIFAR) program in the United States[7,8,9] is to develop an ion induction linac capable of depositing enough energy in a small target to heat it to a temperature of 50 to 100 electron volts. This installation, named the High Temperature Experiment (HTE), would test the essential features of the driver concept and provide information on energy deposition physics at high temperature. We shall now illustrate how the current self-replicating scheme described above can be applied to a design of the HTE. We shall use the same design parameters as in Ref. (11), which are listed below;

species	Na
initial current	0.3 Amp per beamlet
number of beamlets	16
initial pulse duration	6.1 micro-second
initial bunch length	25 meter
initial kinetic energy	2 MeV
final kinetic energy	125 MeV
final $\delta\beta/\beta$	0.04
max accelerating field	0.43 MV/m
max volt-second/meter	0.45 V-s/m
max $\delta\beta/\beta$	0.2
current amplification	20
module impedance	100 Ω/m x 16 beamlets

A computer code written to Study the Longitudinal Ion Dynamics (SLID) is used to determine the head and tail acceleration voltages at every gap. The bunch is assumed to have initially a constant energy of 2 MeV and uniform line density with parabolic bunch ends.[14] The acceleration gaps are assumed to be infinitesimally narrow and uniformly separated by 6.35 meters; in a real design, however, this distance will be shorter at the front end of the linac and increase with increasing energy. The acceleration-gap voltages as functions of time can now be calculated according to the procedure described in section III: the resulting voltage waveforms are shown in

Figs. 3a,b. Notice that the voltages applied to head and tail are the same at a given time, except in the buncher region. In the volt-second limited region, the acceleration rate is increased as the bunch length becomes shorter. The corresponding five characteristic regions are also denoted in the figure.

The calculated beam energy (head, center, and tail), $\delta\beta/\beta$, volt-second/meter, and the normalized bunch length as functions of z are shown in Figs. 4a,b,c,d. The normalized bunch length is calculated at the time when the head of the beam reaches the indicated values of z. The boundaries of the five characteristic regions are also denoted in these figures.

The longitudinal dynamics of the beam subjected to these acceleration fields are investigated by studying the behavior of a number of interacting test particles (typically 101 particles) which are initially equally spaced and have electric charges which are proportional to the line charge densities at the initial locations of the particles. The space charge field is given by Eq. (6). The line charge density at a subsequent time is proportional to the initial charge and inversely proportional to the inter-particle distance, at the location of interest. Longitudinal focussing fields are calculated as described by Eq. (9) and applied at regular intervals to prevent the bunch from distending due to the space charge forces at the ends. A comparison of this code with a more elaborate particle-in-cell code written by I. Haber[15] was made by studying the evolution of a drifting beam with a simple velocity perturbation; the results showed excellent agreement in describing the conversion of the perturbation into two space charge waves traveling in the opposite directions. In fact, the simple numerical model introduced less numerical noise than the one of Ref. (15). We conclude that this algorithm is adequate for design purposes even though it cannot deal with situations in which particles overtake one another and is

incorrect for perturbations of wavelength shorter than the pipe diameter.

The current waveforms at four typical locations (Figs. 5a,b,c,d) demonstrate the current self-replicating feature as the design called for. Notice that the current and the time scales are normalized with respect to the value of the current at the center of the bunch and the pulse duration at each location, respectively. Kinetic energy vs. time at these locations is also shown. The deviation of the kinetic energy from the ideal value is found to be accurately given by Eq. (7).

The line charge density and the velocity vs z at several fixed times (Fig. 6a,b,c,d) show the sawtooth modulation and the long range density tilt. These figures illustrate that the longitudinal beam dynamics appear to be satisfactory even in the presence of the sawtooth discontinuities and the long range tilt.

V. CONCLUSIONS

We have described a design procedure for acceleration and bunching in an ion induction linac using a current self-replicating scheme. The resulting longitudinal ion dynamics are quite satisfactory in spite of the sawtooth modulation and long range tilt of the line charge density, for the beam parameters relevant to the ICF application. We also have described a method to make adjustments to the acceleration voltage waveforms as they are necessary to maintain the current self-replication in the presence of the space-charge forces, module impedances, and imperfect waveform synthesis. The procedure can be used to optimize linac design with respect to the various constraints imposed by beam dynamics and presently available accelerator technologies.

The line charge density self-replicating scheme can be applied to spatially discrete accelerators in an approximate manner in which the long

range density tilt at a fixed time is replaced by a long time current tilt at a fixed location[12]. The sawtooth modulation is unavoidable in any spatially discrete accelerator. For the beam parameters of present interest, the longitudinal beam behavior for this scheme should be essentially the same as that of the current self-replicating scheme.

Finally, we have illustrated how the scheme can be used in designing the projected high temperature experiment.

The sensitivity of beam dynamics to imperfections of the synthesized voltage waveforms, the feasibility of downstream corrections for these imperfections, and the stability of the beam under realistic situations including finite module impedances are some of the topics which need to be studied in more detail.

The authors wish to acknowledge helpful discussions with and encouragement by Drs. J. Bisognano, D. Judd, T. Fessenden, D. Keefe, and L. J. Laslett, and to thank Mrs. O. Wong for typing the manuscript.

REFERENCES

A comprehensive review of heavy ion drivers can be found in references (1) and (2).

(1) D. Keefe, Ann. Rev. Nucl. Part. Sci., 32, 391(1982), and references therein.

(2) R. Bock, I. Hofmann, and R. Arnold, Nucl. Sci. Applications, 2, (1984) to be published, and reference therein.

(3) N.C. Christofilos, R.E. Hester, W.A.S. Lamb, D.D. Reagon, W.A. Sherwood, and R.A. Wright, Rev. Sci. Instr., 35, 886 (1964).

A comprehensive review of electron induction linacs can be found in refer- ences (4) and (5).

(4) R.J. Briggs, Proceedings of the Linear Accelerator Conference, Seeheim/Darmstadt, FRG, May 7-11, GSI-84-11, 507 (1984).

(5) J.E. Leiss, IEEE Trans. Nucl. Sci., NS-26, 3870 (1979).

(6) R.O. Bangerter, Ed., "Heavy Ion Fusion Accelerator Research (HIFAR) Program Plan for FY84 - FY89," Los Alamos National Laboratory Report LA-UR-83-1717, (1983)

(7) J.E. Leiss and T. Godlove, INS International Symposium on Heavy Ion Accelerators and their Application to Inertial Fusion, Tokyo, Japan, Jan 23 -27, 1984, p. 31.

(8) D. Keefe, ibid., p.299

(10) S. Chattopadhyay, A. Faltens, L.J. Laslett, and L. Smith, Proceedings of the Heavy Ion Fusion Workshop, Berkeley, California, Oct. 29 - Nov. 9, 1979, page 151, LBL-10301 (1980).

(11) L. J. Laslett, LBL HIF Group Report, HI-FAN-229, (1983), unpublished.

(12) L.J. Laslett, private communications (1984). *Discretization in the manner suggested in the text would be with the object of suppressing an overall tilt of density vs. z (at fixed t), although local saw-tooth variation will be unavoidable. A tilt in the velocity distribution, however, in general may be expected.*

(13) A. Faltens, INS International Symposium on Heavy Ion Accelerators and their Application to Inertial Fusion, Tokyo, Japan, Jan. 23 -27, 1984, p.313

(14) D. Neuffer, IEEE Trans. Nucl. Sci., NS-26, 3031(1979).

(15) J. Bisognano, I. Haber, L. Smith, and A. Sternlieb, IEEE Trans.Nucl. Sci., NS-28, 2513 (1981).

(16) D.L. Judd, Ed., "Multiple Beam Experiment Conceptual Design and Program Description," Lawrence Berkeley Laboratory Report, PUB-5123, October (1984), unpublished.

Figure Captions

Fig. 1 ; (a) A conceptual design of a low energy section of an ion induction linac, and (b) focussing elements and an acceleration gap for 16 beamlets individually focussed by electrostatic quadrupoles (from reference 16). An almost continous strong focussing for transverse containment of the space charge dominated beam and a relatively narrow acceleration gaps are shown.

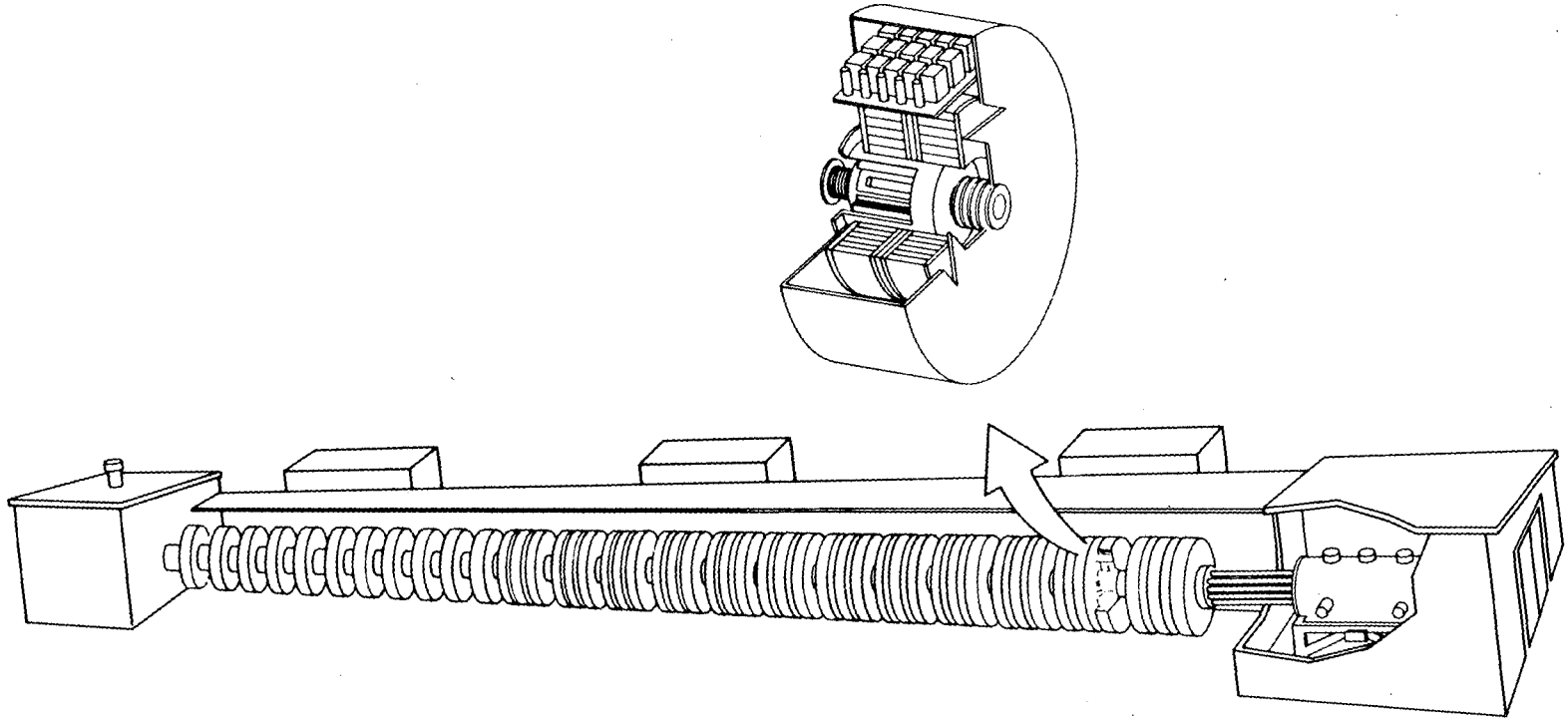
Fig. 2 ; Schematic diagrams illustrating: (a) the current self-replicating scheme for a spatially discrete accelerator, and (b) the line charge density self-replicating scheme for a temporally discrete accelerator. Charge conservation and the self similarity of the triangles drawn by the trajectories of any two particles in the bunch give the current and the line charge density waveforms.

Fig. 3 ; The gap voltage wave forms of HTE normalized to the intergap distance (6.35 m) calculated by using the current self-replicating scheme. The wave forms have different characteristic shapes for the five different regions of HTE. The five characteristic regions are; (I) beam entrance region, (II) $\delta\beta/\beta$ limited region, (III) buncher region, (IV) maximum volt-second limited region, and (V) maximum accelerating field limited region. τ_0 is defined as the beam time normalized to the initial pulse duration of 6.1 microseconds.

Fig. 4 ; (a) Kinetic energy of the head, center and tail of the beam, (b) $\delta\beta/\beta$, (c) volt-second/meter, and (d) the bunch length normalized to the initial bunch length (W) as functions of the location (z) along HTE. The normalized bunch length are calculated at the time when the head of the bunch arrives at the location. The five characteristic regions are the same as in fig. 3.

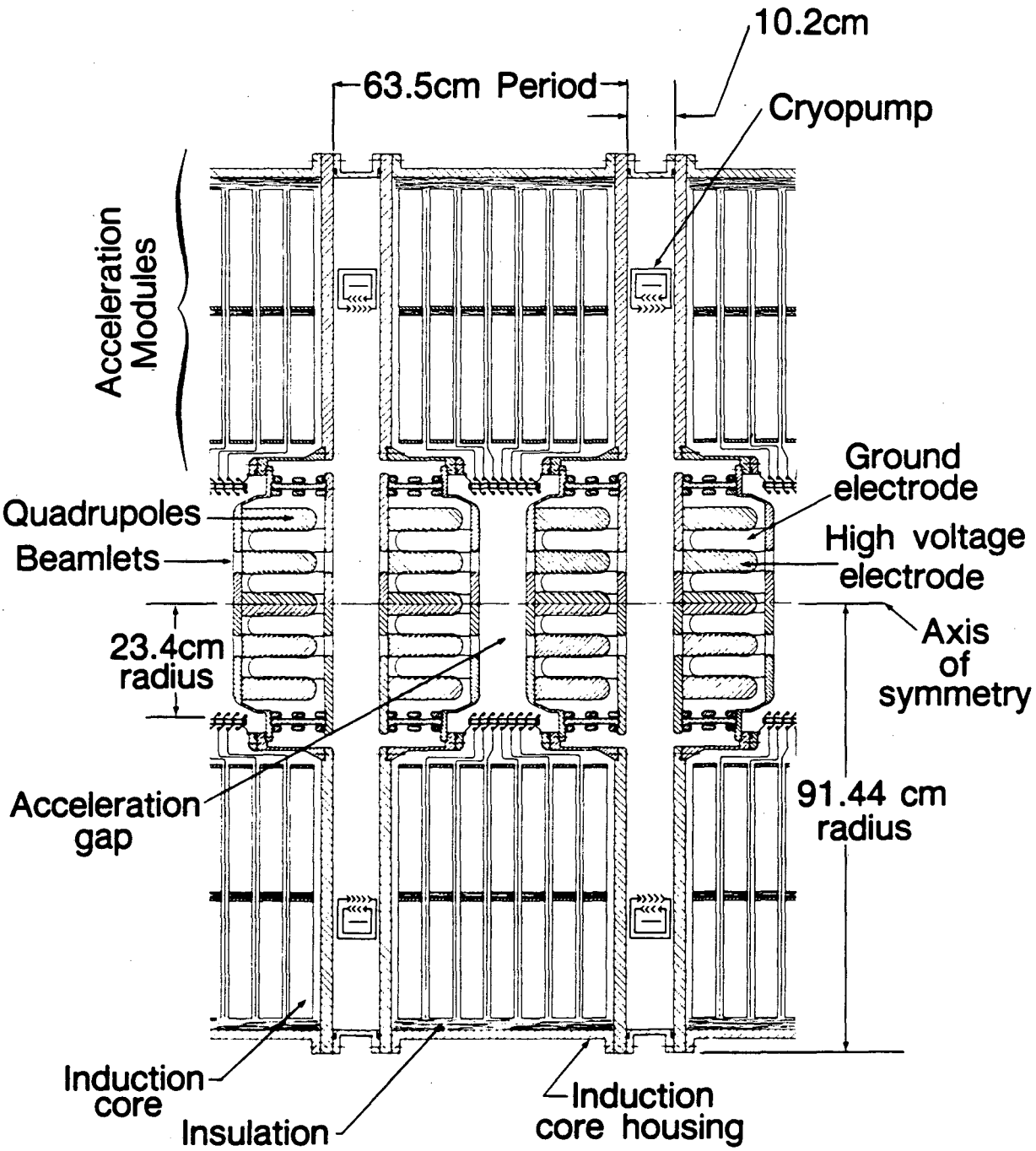
Fig. 5 ; The evolution of the kinetic energy and the current waveforms monitored at several locations of HTE demonstrate the current self-replication. τ is the beam time normalized by the beam duration at each of the locations.

Fig. 6 ; The evolution of the velocity and the line charge density waveforms shown at several times. The longitudinal temperature is assume to be negligible. Idealized focussing fields are applied to prevent a longitudinal distension of the bunch.



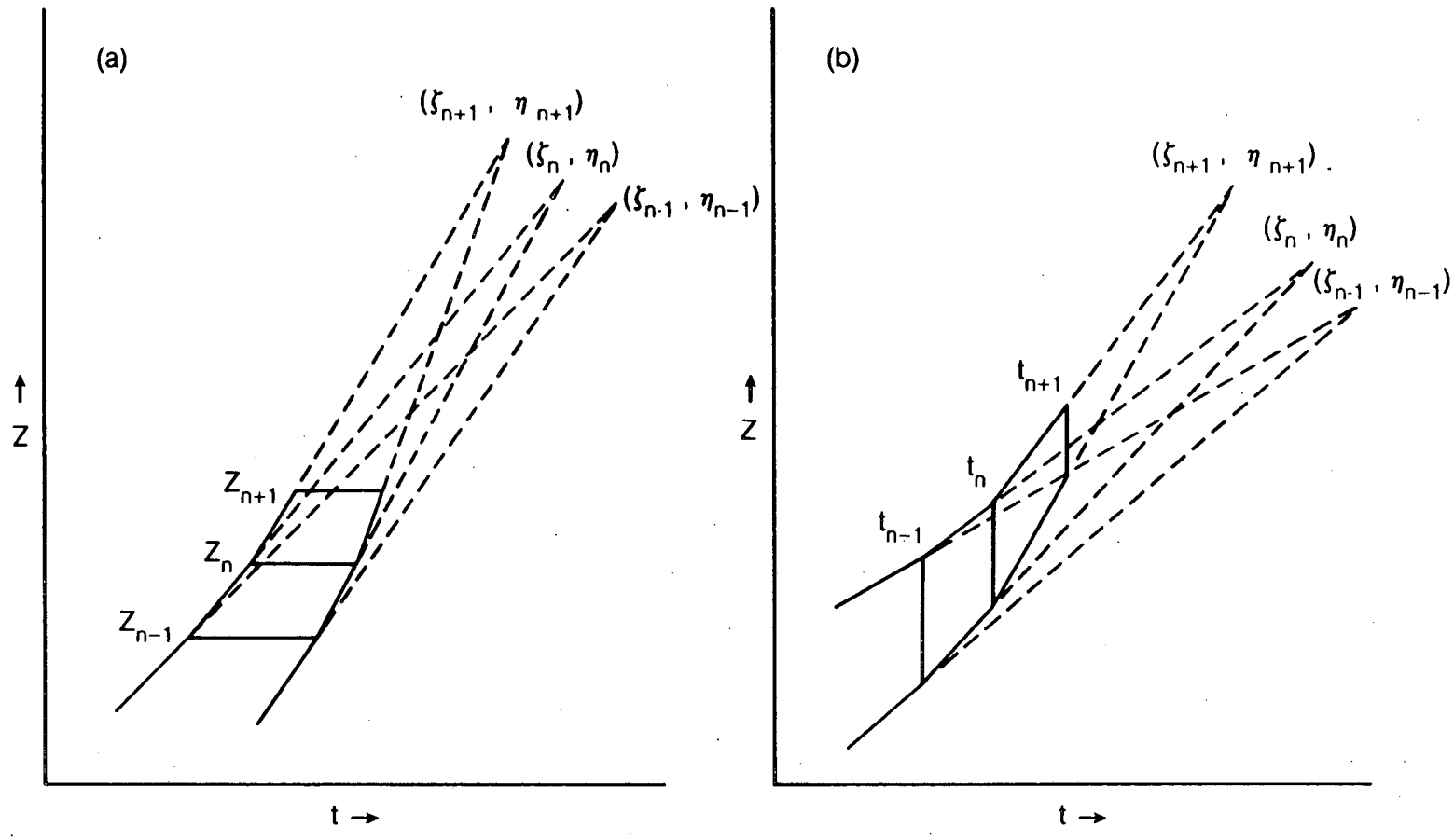
XBL 852-1273

Fig. 1a



XBL 852-1274

Fig. 1b


(a)
$(\zeta_{n+1}, \eta_{n+1})$
(ζ_n, η_n)
$(\zeta_{n-1}, \eta_{n-1})$
Z
Z_{n+1}
Z_n
Z_{n-1}
t →
(b)
$(\zeta_{n+1}, \eta_{n+1})$
(ζ_n, η_n)
$(\zeta_{n-1}, \eta_{n-1})$
Z
t_{n+1}
t_n
t_{n-1}
t →
XBL 8412-5966

(a) (b)

Fig. 2

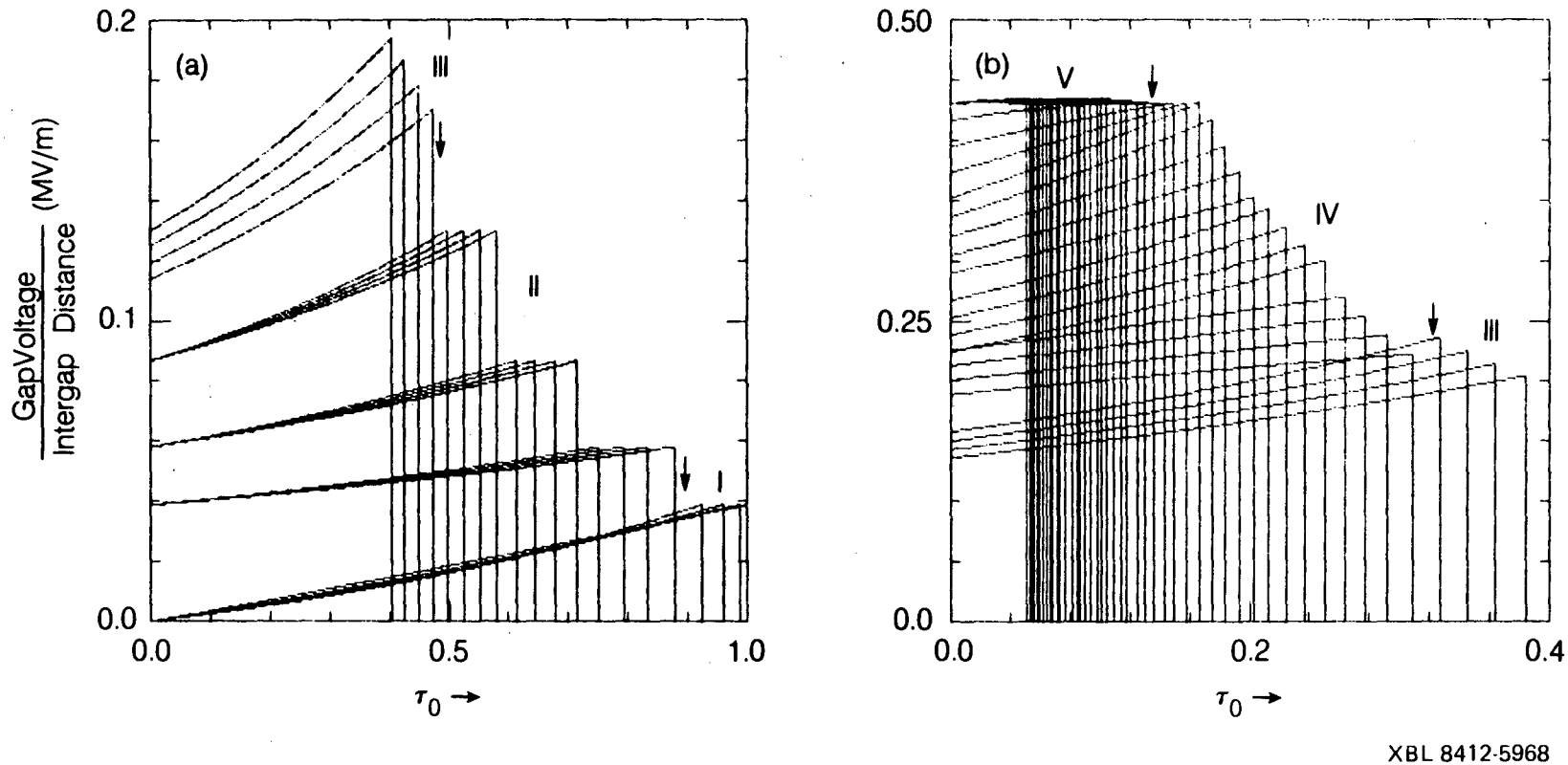
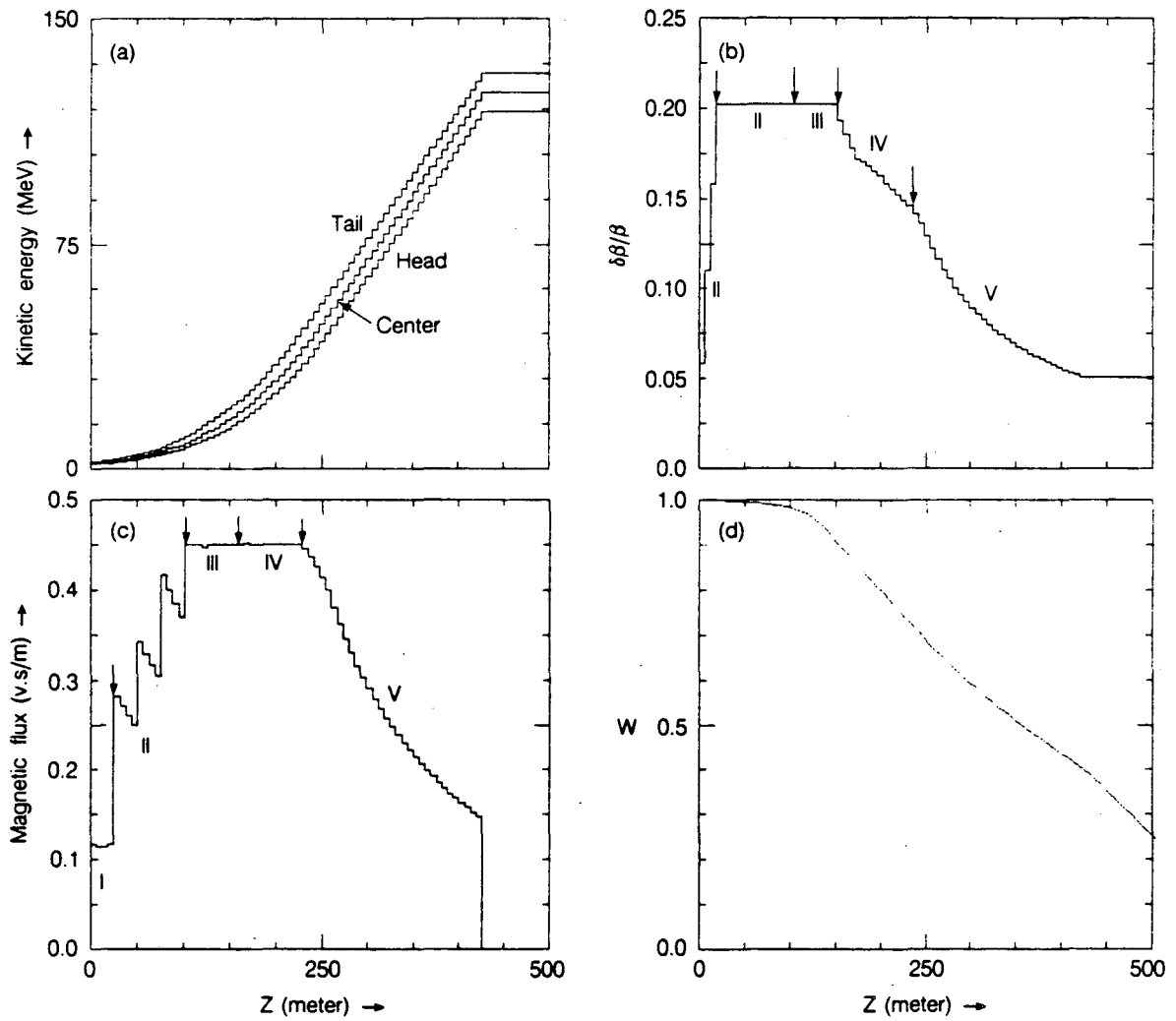
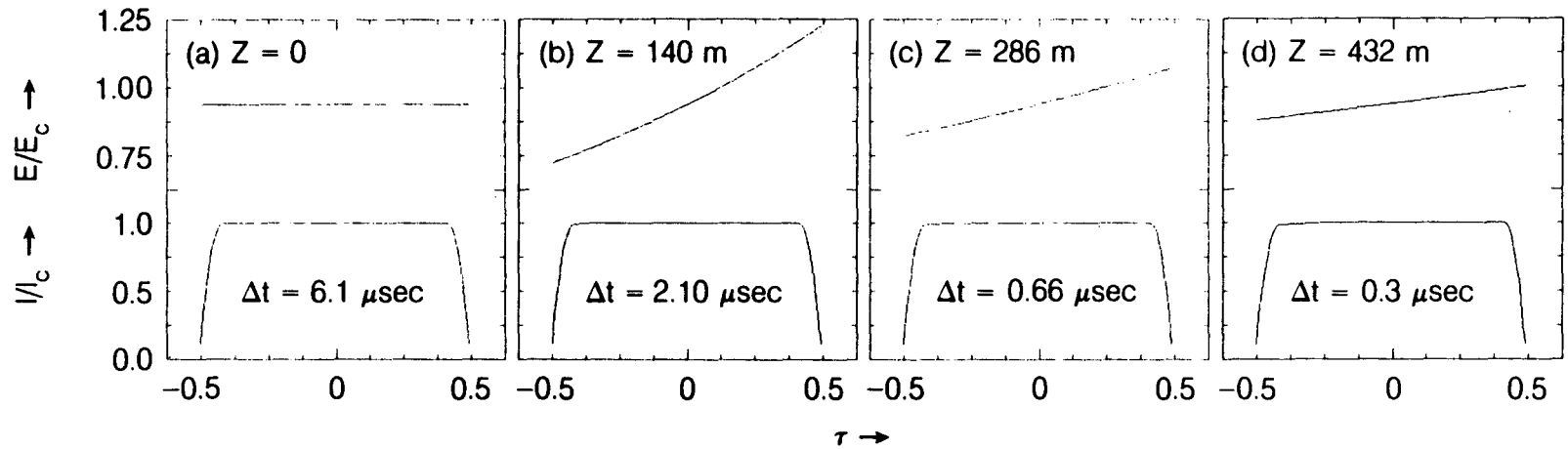

(a)
(b)
GapVoltage / Intergap Distance (MV/m)
0.2
0.1
0.0
0.50
0.25
0.0
0.5
1.0
0.2
0.4
I
II
III
IV
V
$\tau_0 \rightarrow$
XBL 8412-5968

Fig. 3



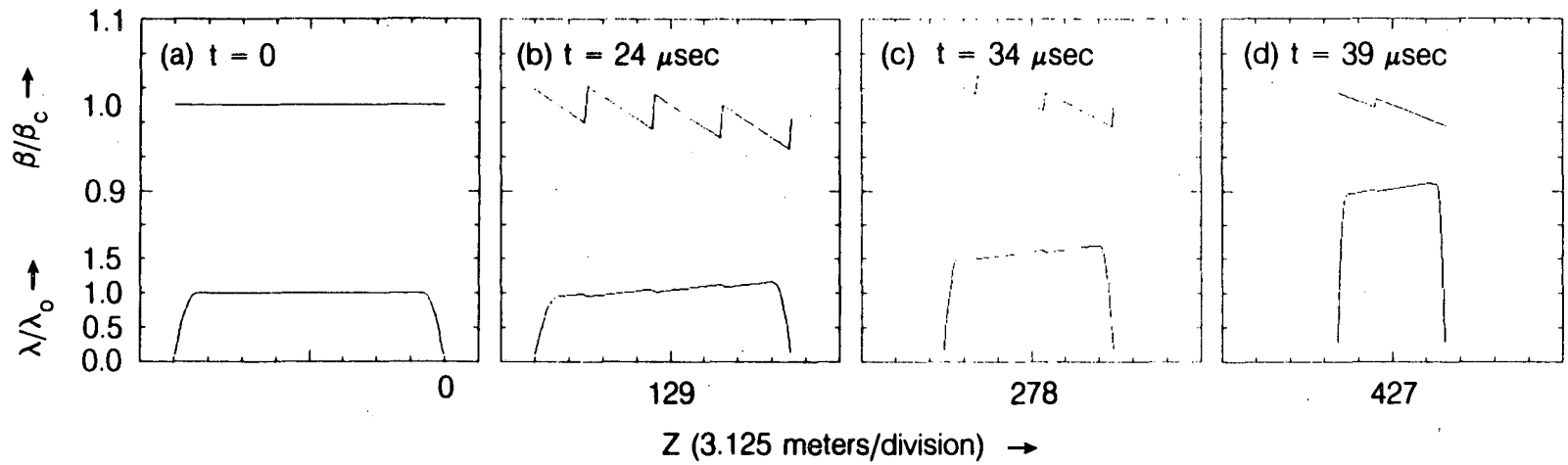
XBL 8412-5967

Fig. 4



XBL 8412-5969

Fig. 5



XBL 8412-5970

Fig. 6

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720