IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

SYNTHESIS OF MBE-4 ACCELERATING WAVEFORMS*

C.H. Kim, V.O. Brady, T.J. Fessenden, D.L. Judd, and L.J.Laslett
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

An ion induction linac for HIF must operate near the space charge current limit along most of its length. Small errors in the voltages applied to the accelerating gaps can readily produce local unwanted beam bunching and consequent beam loss. Uncompensated space charge forces will generate current loss from longitudinal beam spreading. In the design of the MBE-4 ideal acceleration voltages were developed that assure self-similar amplifying current waveforms at each position along the accelerator. These were approximately synthesized by adding waveforms that can be obtained from realizable electrical pulsers. A code is used to study effects produced by the imperfect synthesis on the longitudinal ion dynamics and beam current waveforms in the presence of space-charge forces.

Introduction

In order to realize the necessary current amplification in an ion induction linac for HIF applications, the modules should accelerate the tail more than the head of bunch in a carefully programmed fashion. The purpose is to keep the current near the transverse space charge limit in order to exploit the capability of linear induction accelerators to handle high currents, but at the same time to minimize the current fluctuations in order to prevent consequent particle losses and emittance growth.

We used a procedure described in detail in Ref. 1 based on the current self-replicating scheme. The scheme assures self-similar amplifying current waveforms at each position along the linac. In this scheme, all the particles emerging from an accelerating gap are headed toward a common focal spot in z-t space, which is different for each gap. These common focal spots are determined by a number of constraints that depend both on physics and technology. The physics constraints are imposed by transverse and longitudinal beam dynamics. The bunch length should be compressed, but sufficiently gently so that the line charge density does not exceed the space charge limit. In the beam entrance region the head must not be accelerated before the tail has entered. At a given location the velocity variation from head to tail of the bunch ($\Delta\beta/\beta$) should not exceed a certain limit set by the ability of the transport system to focus beams with time-varying momentum. The technological constraints are: The size of the module -- or Volt-seconds per meter of the core material -- should not exceed a certain limit determined by cost. The average accelerating voltage per meter should not exceed the breakdown limit.

In this numerical design study, we calculated the "ideal" kinetic energy for the current self-replicating scheme by calculating the common focal spot for each gap in compliance with the various constraints. We also calculated the kinetic energies of a number of test particles, subjected to realistic accelerating voltages and space charge forces, as functions of time and space. The difference between the ideal kinetic energy just after a given gap and the realized kinetic energy just before the same accelerating gap gave the desired accelerating-gap voltage waveform for the gap. The desired waveform was then synthesized by adding elementary waveforms similar to those observed in development tests.

MBE-4 Design Parameters

MBE-4 has 30 FODO lattice periods (cells), 24 of which have an accelerating gap. Every 5-th cell is used for diagnostic access [2]. The design parameters used in this study are:

species	cesium +1
input energy	200 keV
No. of beamlets	4
input current	20 mA (4 beamlets)
output current	60 mA (4 beamlets)
$\Delta\beta/\beta$	0.2
Gap Voltage (max)	30 kV / gap
Core Size (max)	0.1V-s / gap
Output energy	
Head	770 keV
Center	820 keV
Tail	880 keV
bunch compression	0.6 x initial length

The ideal accelerating voltage waveforms for all 24 accelerating gaps are shown in Fig.1. The pulse duration becomes shorter as the bunch is compressed in time along the linac. The ideal accelerating voltage waveforms of MBE-4 have roughly one of the following typical shapes: (1) a triangular shape in the beam entrance region, (2) a trapezoidal shape in the beam dynamics ($\Delta\beta/\beta$) limited and volt-second limited regions, and (3) a flat-top shape in the breakdown limited region. The breakdown limit region should comprise most of the linac.

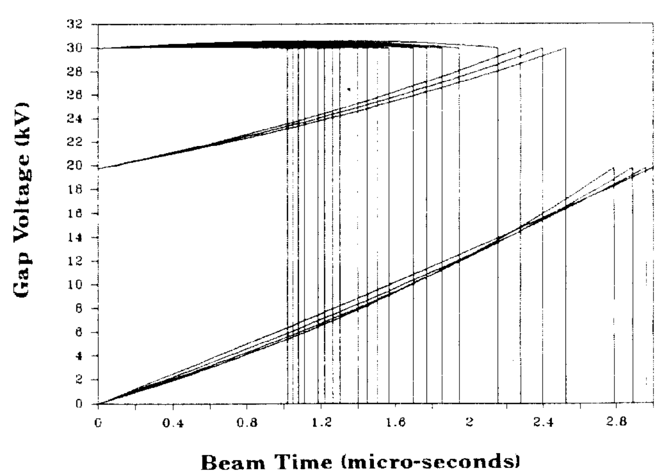


Fig. 1 Ideal accelerating voltage waveforms for all 24 gaps of MBE-4. Every 5-th cell is used for diagnostic access, and thus does not have any acceleration voltage. Pulse duration decreases monotonically along the linac. No space charge effects are included here.

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

Synthesis of Accelerating Waveforms

Errors in the accelerating voltages produce current fluctuations as the beam passes down the accelerator. Since the beam is already near the space charge limit, the fluctuations can cause beam loss. Although the longitudinal space charge forces tend to smooth out these fluctuations, particular precautions were taken to avoid discontinuous first derivatives and high frequency errors in the synthesized waveforms. In this way, klystron-like bunching was largely avoided.

Three generic types of elementary waveforms similar to those observed in the development tests [3], [4] were used in synthesizing the accelerating waveforms. We modeled the elementary waveforms by the following three functions.

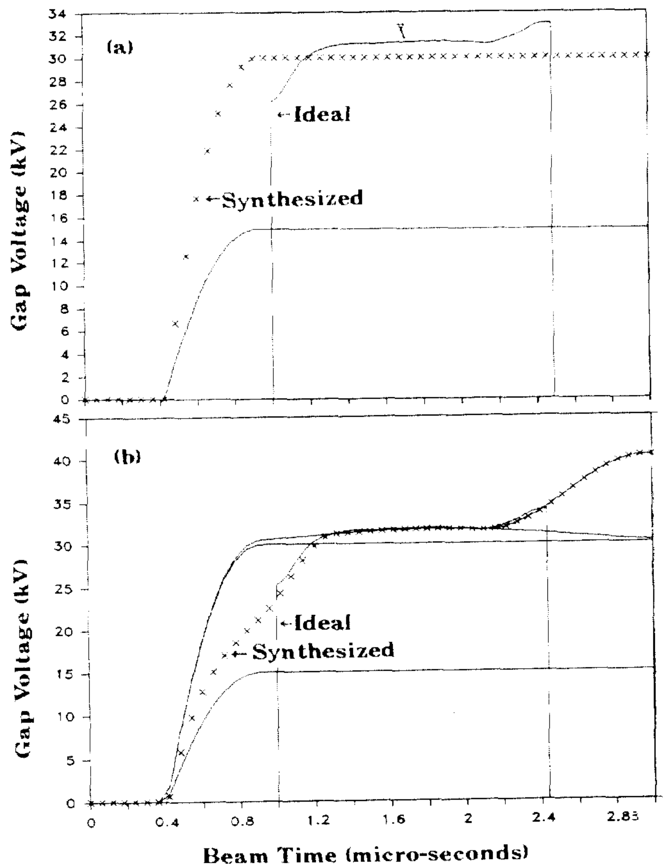
$$V = V_0 \quad \text{(fast rise to a constant voltage)} \qquad (1)$$
$$V = V_0 \ (2x - x^2) \quad ; 0 < x < 1 \qquad (2)$$
$$V = V_0 \ (1 - \cos(\pi x)) \ ; 0 < x < 2 \qquad (3)$$

where x is the normalized time, $(t - t_0)/t_r$, and t_0 and t_r are respectively the turn-on time and the time to reach the peak voltage. The type (3) functions are used not only to accelerate the beam but also to compensate for the space charge forces at the ends of the bunch, where the current was assumed to fall parabolically. The last half ($1 < x < 2$) of type (3) functions with negative values of V_0 are used to compensate for space charge expansion of the bunch head. The first half ($0 < x < 1$) of type (3) functions with positive values of V_0 are used for the tail of bunch.

The waveforms were synthesized modularly in groups of 4 cells preceding each diagnostic cell. The first three waveforms are synthesized in the simplest way possible. The errors due to the imperfect synthesis and the space charge forces are left to accumulate and then corrected with trimming pulsers at the 4-th cell. Thus a trimming cell is located just before each diagnostic cell. As an illustration, synthesized waveforms just before and at a trimming cell are shown in Figs. 2a and b. Seventy-one pulsers were used in this MBE-4 design study. Their waveforms fall into 18 different shapes which are summarized in table I. The first 10 of them are main pulsers and the remaining 8 are the trimming pulsers. The largest number of pulsers (40) generate a square pulse of from 1.3 to 3 μsec duration. In order to reduce the required number of power supplies the value of t_r rather than the value of V_0 was varied when a choice was possible.

Table I MBE-4 Pulsers

Type	V_0(kV)	t_r(us)	# Req'd
1	15.0	--	34
1	10.0	--	6
2	15.0	5.0	1
2	15.0	6.0	3
2	15.0	6.5	1
2	15.0	7.0	1
3	7.5	4.2	1
3	7.5	6.0	4
3	5.0	3.0	1
3	5.0	.0	2
3	3.0	0.9	5
3	5.0	0.9	2
3	3.0	0.5	3
3	0.3	0.6	1
3	1.2	1.3	1
3	0.7	1.5	2
3	0.45	0.5	1
3	5.0	0.5	2



XBL 855-2341

Fig. 2 Typical synthesized waveforms at (a) a cell just before a trimming cell and (b) at a trimming cell. The desired waveforms include corrections for the accumulated errors due to imperfect synthesis and space charge forces in the previous cells. Other solid lines show various stages of adding individual pulsers. Final synthesized waveforms are marked with "x".

Physics Performance

Judgment of the quality of the synthesized waveforms and the beam bunch is somewhat subjective. For HIF applications, current and kinetic energy fluctuations at the accelerator exit are limited by the passband of the final transport system of containment, bending, and focusing elements. Current and energy fluctuations which are reproducible from shot to shot can be corrected in principle to an arbitrary accuracy; however, fluctuations due to timing and voltage jitters can not be corrected easily. The effects of jitters depend not only on the magnitudes of the jitters but also on the way the waveforms are synthesized.

In order to evaluate the present design, the behavior of the beam subjected to the synthesized waveforms and space charge forces was studied numerically. Trajectories of a number (typically 101) of interacting test particles were calculated using a computer code similar to the one used in Ref. 1. The particles were equally spaced initially with charges weighted proportionally to the initial line charge density, which was assumed to be uniform (2μsec) with parabolic bunch ends (0.5 μsec for each end). The line charge density at a later time is inversely proportional to the inter-particle distance and proportional to the initial weighted charge. Although this method does not allow particles to overtake their neighbors, it appears to be adequate for the present design study. The calculated amplification of the beam current in MBE-4 is shown in Fig.3 for one of the four beamlets. The beam current at a given location is calculated at the time the center of the beam passes the location. A factor of 2 in current amplification is due to the increase in kinetic energy and a factor of 1.5 due to the spatial compression. Our transverse focusing system will be adequate to handle the 3-fold current amplification.

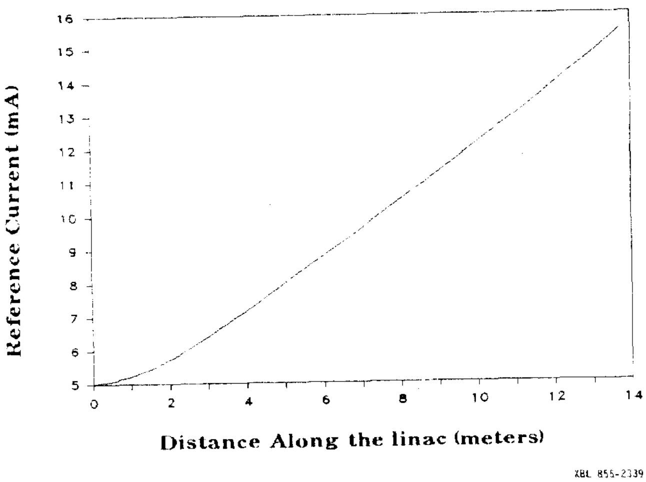


Fig. 3 Current amplification in MBE-4. The value of current at a given location is calculated at the time when the center of the bunch passes the location.

The calculated kinetic energy, the current waveform, and the energy fluctuation -- the deviation of the kinetic energy from the "ideal" value -- are shown in Figs. 4a, b, and c, at the linac exit. Notice that the current fluctuations in the flat portion of the beam are less than 2% and the energy fluctuations are less than 500 eV for most of the bunch except at the bunch ends. The magnitude of the current fluctuations depended on the accuracy of waveform synthesis over a distance along the accelerator. However, the magnitude of the energy fluctuations was mostly dependent upon the accuracy of the corrections made at the last trimming cell. As the beam is accelerated, the fractional energy fluctuations decrease.

We also studied the effects of random timing jitter on the magnitude of the current fluctuation. We found that timing jitters of the individual pulsers on the order 30 nsec introduced current fluctuations of no more than 2%. The magnitude of the fluctuations scaled linearly with the timing jitter.

Conclusions

Several properties of accelerating voltage waveforms needed to accelerate and compress ion bunches in an induction linac have been revealed or illustrated in this study. We have found that waveform components having both signs of curvature are needed for synthesizing some waveforms acceptably. Slope discontinuities of synthesized waveforms are to be avoided because they produce current spikes further downstream. Errors in ion kinetic energy along a bunch, which have accumulated from waveform errors at several preceding gaps, can be corrected by trimming pulsers at a single gap; however, errors in current distribution along a bunch cannot be repaired at a single gap. From this study we have demonstrated that waveforms for accelerating bunches in the MBE-4 can be synthesized acceptably by superposing realizable waveform components having shapes already demonstrated in laboratory tests.

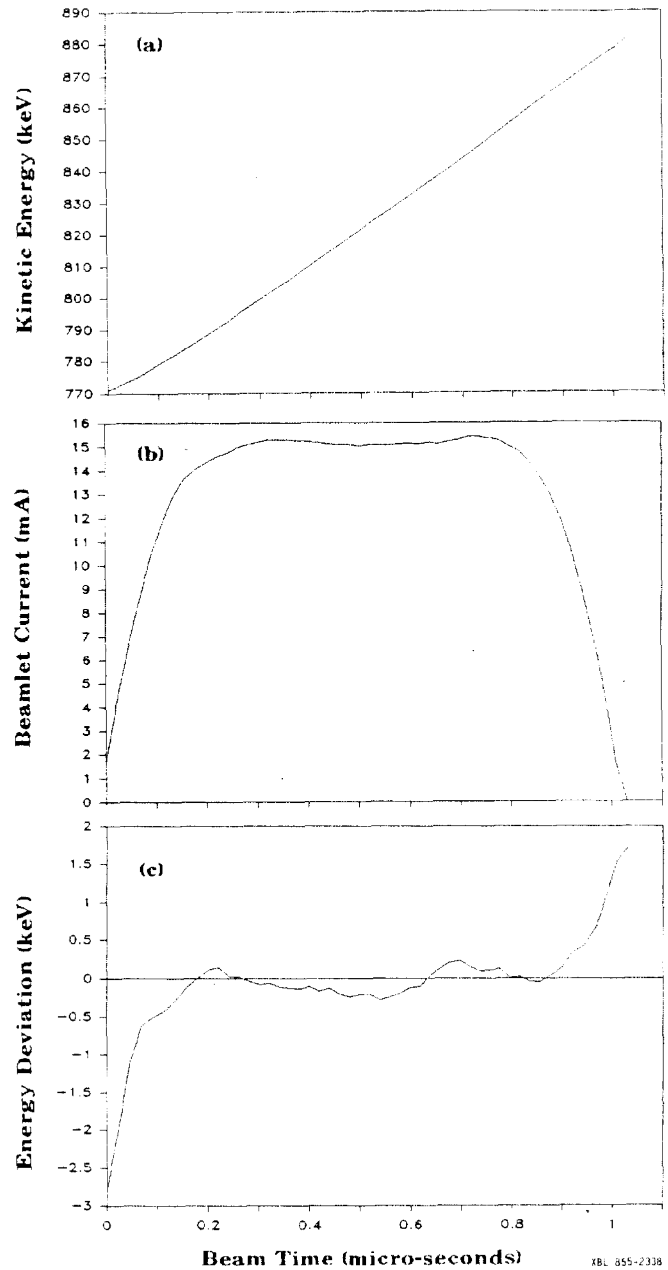


Fig. 4 (a) Kinetic energy of the bunch, (b) Current, and (c) Energy Deviation - compared to the "ideal values" -- as functions of beam time at the exit end of MBE-4. Input current is 5 mA per beamlet at 200 keV.

Authors wish to acknowledge helpful discussions with Drs. D. Keefe, L. Smith, and J. Bisognano.

References

1. C. Kim and L. Smith, Lawrence Berkeley Laboratory internal report, LBL-19137 (1985), submitted for publication in Particle Accelerators

2. A.T. 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, in these proceedings.

3. D. Gough, private communications (1985).

4. A. Faltens, M. Firth, S.S. Rosenblum, and D. Keefe, IEEE Trans. Nucl. Sci. NS-30, 3669(1983).