INDUCTION LINACS FOR HEAVY ION FUSION RESEARCH*

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Abstract

The new features of employing an induction linac as a driver for inertial fusion involve (1) transport of high-current low-emittance heavy ion beams. (2) multiple independently-focussed beams threading the same accelerator structure, and (3) synthesis of voltage waveforms to accomplish beam current amplification. A research program is underway at LBL to develop accelerators that test all these features with the final goal of producing an ion beam capable of heating matter to ~70 eV. This paper presents a discussion of some properties of induction linacs and how they may be used for HIF research. Physics designs of the High Temperature Experiment (HTE) and the Multiple Beam Experiment (MBE) accelerators are presented along with initial concepts of the MBE induction units.

Introduction

The objective of the Heavy Ion Fusion (HIF) research in the United States[1,2] is to develop the physics and technology of heavy ion accelerators to the point that a realistic assessment can be made of their potential as inertial fusion drivers for commercial electric power. Recently, it was decided[2] that the major thrust of the accelerator research in the United States would be toward the development of induction linacs (IL) for HIF. This decision was motivated by the observations that the IL method may be simpler than schemes employing r.f. accelerators with storage rings. Considerable experience[3] now exists in the United States on the acceleration of kiloampere beams of electrons with induction accelerators and the most serious technical issues concerning induction linacs for HIF can be addressed with small-to medium-sized accelerators.

The intermediate goal of IL research in the United States is to develop an accelerator capable of producing multiple ion beams that will heat matter to 50 or 100 electron volts. This experiment has been named the High Temperature Experiment (HTE). Material interaction physics suggests that this can be accomplished with 16 beams of Na^+ ions at 125 MeV carrying a total of 3.75 kJ of beam energy. Research at the Lawrence Berkeley Laboratory is directed toward the development of induction accelerators capable of transporting, accelerating, and focussing multiple beams of sodium or other ions of like mass. The Los Alamos National Laboratory is developing the ion source and 2 MeV injector for these accelerators. In addition, the research is receiving theoretical support and guidance from workers at the Stanford Linear Accelerator Center, the Naval Research Laboratory, and the Lawrence Livermore National Laboratory.

HIF accelerator research at LBL[4] is addressing the physics and engineering of the HTE accelerator. This work is proceeding along a number of parallel lines. Beam control, acceleration, and manipulation have been under intensive theoretical study for several years. Some specific components of induction linacs have been engineered and bench tested. Experimental studies of the transport and focussing of space charge dominated† cesium beams have been in progress on the Single Beam Transport Experiment (SBTE) for more than one year. These experiments are yielding important information on the practical amount of current that may be transported by FODO quadrupole focussing systems. At present we are engaged in the conceptual design of an experiment that will test our ability to transport, accelerate, and control 16 parallel ion beams and produce current amplification in the same accelerating structure. This Multiple Beam Experiment (MBE) should begin to produce data in 2-3 years.

Properties of Induction Linacs

Since its development[5] in the early 60s by Christofilos and co-workers at the Lawrence Livermore Lab, the induction linac has been used almost exclusively to accelerate electrons. Much of the history of the development of electron induction linacs in the United States is contained in the paper by R.J. Briggs[3] presented at this conference.

Compared with r.f. linacs, induction linacs are low impedance devices. They are at their best when accelerating currents in the hundreds to thousands of amperes. In this current range induction linacs promise electrical efficiencies of 50 percent or more and thus become candidates for economical HIF systems. However, accelerating gradients greater than 1 MeV/meter are difficult to achieve in induction accelerators. As a consequence, a HIF induction linac will be several kilometers long.

The operation of electron induction linacs is in several ways simpler than that of ion linacs. Electrons achieve essentially light-speed at the output of the injector or gun. Because the length of the electron bunch does not vary appreciably, the current through the accelerator is constant. The accelerating voltages are limited only by breakdown and not by the physics of the particle dynamics. The effect of time-varying accelerating voltages is to change the energy of the electrons within the bunch which can lead to beam control problems but not (directly) to current modulations. The beam gains both power and energy directly as the accelerating voltage. Space charge, if a problem at all, is most important at the gun output and at the low energy end of the accelerator. Because the lighter electrons respond rapidly to electric and magnetic fields and beam currents are large, collective beam instabilities tend to be important in electron linacs. The pulse duration of most electron linacs is considerably less than 1 μsec although a linac with a pulse width of 2 μsec has been built[6].

Ion induction accelerators are in many ways more complicated (or perhaps more interesting). The simple fact that ions travel much more slowly than electrons at the same voltage implies that the transportable ion current is reduced by the ratio of ion to electron speed and (since there is essentially no magnetic force cancellation for ions), by the square of the electron gamma. These factors add up to nearly 1800

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†A condition in which the beam envelope size is determined principally by space charge rather than emittance.

when sodium ions and electrons are compared in cylindrical geometry at 2 MeV. Thus, in order for the beam bunch to contain sufficient charge, the pulse must be much longer in time and in space at injection than at exit. It is likely that electrostatic focussing will be used in the initial stages of the accelerator. Because beams for HIF never reach relativistic speeds ($\beta \sim 0.3$), the current and bunch length of the beam can be changed as functions of position and time through the entire length of the accelerator. This can be done by differentially accelerating the beam head and tail. This implies, however, that the beam head and tail will focus differently (unless the focussing fields are suitably time dependent). Fortunately, there is no indication that collective accelerator instabilities will be a problem.

The acceleration of multiple ion beams in an induction linac all the way to the target has several interesting consequences for HIF. The ion source can consist of many small sources. The total beam current can be increased somewhat by using many small beams rather than one big beam. The electrostatic quadrupoles can operate at lower voltages and the magnetic quadrupoles can operate at lower fields. But perhaps most important, emittance growth and septum damage problems associated with the division of a beam containing megajoules before the final focus are conveniently avoided.

Since the total beam charge must be injected at the input to the accelerator, the current limit at lower energy forces the initial pulse duration to be many microseconds for HIF accelerators. This pulse must be shortened to a few tens of nanoseconds at the pellet. Although it appears possible[7] to obtain a factor of 10 pulse compression in the final transport of the beam to the pellet, much of the pulse shortening must occur in the accelerator. This requires the application of time dependent voltages to the accelerating gaps to reverse the longitudinal expansion of the bunch and to compress the bunch in time by a factor of 200 to 500 and in length by a factor of 2 to 5. Since the beam tail must be accelerated toward the head, the accelerating voltages should be applied after the beam tail is within the accelerator. Otherwise, the beam will elongate and the tail of the beam may not be able to catch up or keep pace. This tends to defeat the compression schedule or require that the bunching take place at higher energy at a considerable increase in the size and cost of the induction units. In our designs the beam acceleration and compression begin after the bunch is totally within the accelerator.

If an ion beam is accelerated at constant pulse length the beam head will be moving slower than the tail at any location along the accelerator. The focussing system which depends on the beam speed will act differently on the beam head and tail making it difficult to keep the beam matched over the length of the bunch. As a consequence the beam radius is expected to change along the length of the bunch. This effect is of most concern at the low energy end of the accelerator. Laslett[8] has calculated that a velocity change of 20 percent or less over the length of the bunch requires only a small increase in aperture to accommodate the changes in beam radius.

Single Beam Transport Results

Accurate information on the maximum current that can be transported by a long quadrupole transport system is required for even approximate designs of a fusion driver. In 1975 Maschke[9] proposed a transport limit based on a minimum σ/σ_0 of 0.7. Here σ and σ_0 are respectively the phase advance per lattice half period with and without space charge. Moreover, recent analytic calculations based on the Kapchinskij-Vladimirskij (K-V) distribution function have identified transversely unstable modes for $\sigma_0 = 90^\circ$ and for $\sigma_0 = 60^\circ$ but particle simulation results[10,11] suggest that modes at 60° are benign.

The Single Beam Transport Experiment (SBTE) was designed to study the transport of space charge dominated ion beams in an electrostatic focussing section and thereby provide experimental answers to the question of the current limits and transport instabilities in quadrupole focussing systems. The experiment is described in detail in Ref. (12). It consists of an ion source, injector, a matching section consisting of 5 quadrupoles, a transport section of 82 electrostatic quadrupoles, and a diagnostic tank.

A beam of Cs^+ is injected into the matching section from the source. The beam energy can be varied from 80-160 KeV, the beam current from 0.7-23 mA, and the beam emittance from $.8\text{-}5\times10^{-7}$ Rad-m. The transported current is measured with a gridless deep Faraday cup at the end of the transport section and with shallow gridded Faraday cups at the entrance to the transport section and at 3 places along the system. The kinetic energy is measured by time of flight. The beam emittance is measured by a two slit scan method.

At the recent HIF conference in Japan we reported[13] that the beam was stably transported at all experimental values of σ_0 less than 90° and for σ/σ_0 as low as 12°/60°. Recent experiments[14] have indicated stable transport for σ/σ_0 as low as 8°/60°. At this low value of depressed phase advance the beam size becomes essentially independent of emittance and the transportable current is proportional to the beam area. This is a more advantageous scaling relation than has been used for design calculations in the past. As a result it may be possible to increase the ion current at low velocity with impacts on the costs of induction linacs for HIF.

Induction Linac Designs

We at LBL are considering the designs of three different but related induction linacs that are on the path to the development of an accelerator for HIF. The parameters of these accelerators are presented in Table I. The first to be constructed is the MBE accelerator which should be producing data in 2-3 years. This experiment will study the production, acceleration, and control of multiple ion beams in an induction linac. The MBE components are being designed to be as representative as possible of those necessary for the HTE. Thus the MBE accelerator is expected to serve as the HTE prototype.

TABLE I

TENTATIVE PARAMETERS OF INDUCTION LINACS FOR HEAVY ION FUSION RESEARCH UNDER STUDY AT LBL

Parameters	MBE	HTE	Driver
Ion	Cs^+, Na^+	Na^+	e.g. Hg^+
Kinetic Energy	6-10 MeV	125 MeV	10 GeV
Beam Charge	2-5 μC	30 μC	300 μC
Pulse Energy	20-50 J	4 KJ	3 MJ
Beamlets	8-16	16	4-20
Pulse length			
Injection	3-8 m	25 m	?
Exit	2-7 m	10 m	20 m
Pulse Duration			
Injection	2 μs	6 μs	50 μs
Exit	1 μs	.3 μs	.1 μs
Current Gain	2	20	500
Length	30 m	500 m	?
Target Date	1986	1989	?
Cost Goal	~20 M$	60-80 M$	500 M$

At this writing we are in the midst of developing a conceptual design that includes all components of the MBE accelerator. This will be used as a guide to our likely costs and schedule. Some changes in the MBE parameters may result from this exercise.

In what follows we present the physics designs of the HTE and the MBE accelerators that are being used in the conceptual engineering design of the MBE. A study of a 3 megajoule heavy ion fusion driver was published[15] at the Palaiseau meeting in 1981.

The accelerator design procedure was developed by D.L. Judd and L.J. Laslett. They assumed that:

1. The charge density does not vary along the bunch;

2. The spread in bunch velocity at fixed z must not exceed 20 percent;

3. Electrostatic focussing is used until the beam exceeds .03 light speed;

4. The electrostatic half period was allowed to vary in HTE but was kept fixed at 31.75 cm in MBE.

The design procedure was to specify: 1) an acceleration field as a function of time on a reference particle; and 2) a bunching function for the beam. The parameters of the acceleration/ compression schedule could then be calculated. The procedure was then iterated until a design that satisfactorily satisfied all the constraints was obtained. The calculations were checked to insure that the accelerating gradient and the quadrupole voltages never became excessive.

A consequence of the assumptions of uniform charge density and limited velocity spread is that the acceleration schedule is limited by the following equation:

$$\left.\frac{\Delta v}{v}\right|_z = \frac{\ddot{z}\ell}{v^2} - \frac{1}{v}\frac{d\ell}{dt} \qquad (1)$$

Here ℓ is the bunch length, v is the beam speed, and $\ddot{z}$ is the acceleration of the beam center. This equation indicates that the initial acceleration of the ion beam must proceed slowly to control the velocity spread.

An acceleration/compression schedule for HTE is shown in fig. 1. This design achieves 125 MeV in 490 meters. The input consists of sixteen 300 mA sodium beams at 2 MeV injected for 6 μsec. The output is sixteen 6 Ampere beams at 125 MeV with a pulse width of 0.3 μsec. The initial pulse length is 25 m which remains approximately constant in the electrostatically focussed section, then shrinks in the magnetically focussed section to 10 m at the exit. At this point the velocity tilt from tail to head is approximately 5 percent.

The voltage waveforms required to achieve this acceleration schedule are presented in fig. 2. These are the waveforms that must be provided, when the beam is present, by the pulsed power sources at six example locations along the HTE accelerator.

Similar calculations have been carried out for the MBE accelerator. Figure 3 shows an acceleration/ compression schedule for MBE. The ion beams are similar to those used in the HTE design except that the pulse duration is shortened to 2 μsec which corresponds to 8.2 m for sodium at 2 MeV. The shorter pulse allows a more aggressive acceleration schedule and current gain of approximately two. The beam head will achieve 5.3 MeV and the beam tail 8.3 MeV with a velocity spread in the bunch of 20 percent. The current shown is calculated at beam center. Thus the expected current is 10 percent lower at the head and 10 percent higher at the tail.

The MBE voltage waveforms required to achieve this acceleration schedule are presented in fig. 4. These waveforms indicate the voltage that must be applied as the beam passes through the accelerating gaps. The actual voltage waveforms will be longer in duration than the beam pulse.

Finally it is interesting to compare the volt-seconds of magnetic material needed for the induction units of the two accelerators. These data are presented in fig. 5 as the volt-sec/m needed to provide the flux change that generates the acceleration voltages used in the acceleration schedules given above.

If possible, we will also experiment with Cs^+ in the MBE accelerator. Because a 2 μsec pulse of Cs^+ at 2 MeV is 3.3 m long, the MBE is nearly 10 bunch lengths long for Cs^+ instead of 3.7 bunch lengths for Na^+. Thus a greater current amplification should be possible allowing MBE to simulate better this feature of HTE.

The conceptual MBE design contains 16 parallel ion beams each having a nominal radius of one centimeter. These are focussed by an array of 21 electrostatic quadrupoles arranged as shown in fig. 6. Of these only the outer 16 will contain ion beams. The inner radius of the insulator is 25.4 cm and the outermost beam is just over 17 cm from the axis. This structure is considerably bigger than that used in the MEQALAC 1[16].

The quadrupoles are located within the induction units as shown in fig. 7. Each unit is 53.3 cm long and is separated from its neighbor by 10 cm. Thus the full lattice period of the quadrupole focussing system is 63.3 cm. The occupancy factor for the quadrupole lattice is 0.5. The quadrupoles will be biased by a DC power supply to a maximum voltage of approximately 80 kV giving a peak quadrupole focussing strength of 220 megavolts per square meter. The induction acceleration field passes through the insulator as shown. The peak voltage that this insulator must withstand in the MBE design is 175 kilovolts. The magnetic material will be metallic glass. The outside diameter of the accelerator units will be approximately 1.83 m (6 feet). These units will be similar in size to those used in the NBS accelerator[6].

The required waveforms to drive each MBE induction unit as shown in fig. 4 will be obtained from many distributed line pulsers[17] similar or identical to those developed for this application by Faltens et al.[18] These pulsers will generate a voltage of approximately 25 KV for typically 2 μsecs. Thus, by firing the pulsers at the proper relative times we believe that all the required MBE waveforms can be adequately synthesized.

Comments and Conclusions

The multiple beam experiment (MBE) will test many properties and parameters of the accelerator required for HTE. These include the transport and acceleration of multiple ion beams; any effects introduced by beam-beam coupling and their possible consequences; the tailoring of the accelerating waveforms; the engineering of the accelerator units; the performance of various ion sources; and the development of diagnostic techniques for ion induction accelerators. The size of the MBE induction units is only slightly less than those required for HTE.

The MBE accelerator will contain 300-400 individual voltage modules that must be fired at the correct instant to generate the tailored accelerating voltages. Even so, the theoretical voltage waveforms

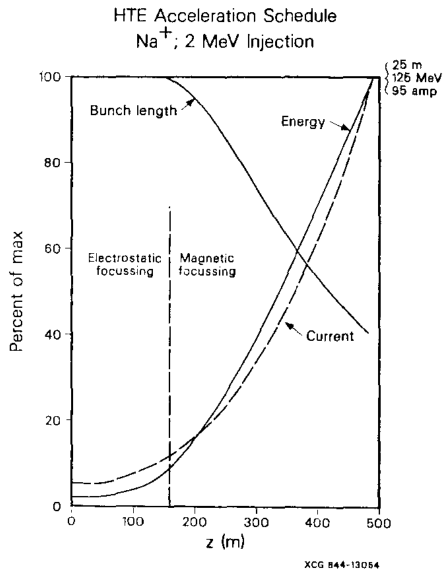

Fig. 1 Acceleration and compression schedule for the HTE accelerator.

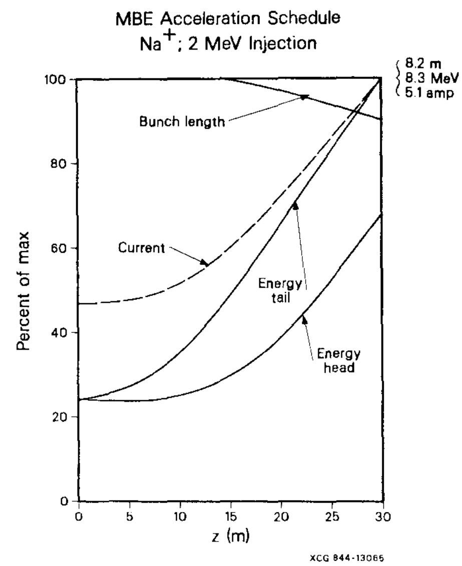

Fig. 3. Acceleration and compression schedule for the MBE accelerator.

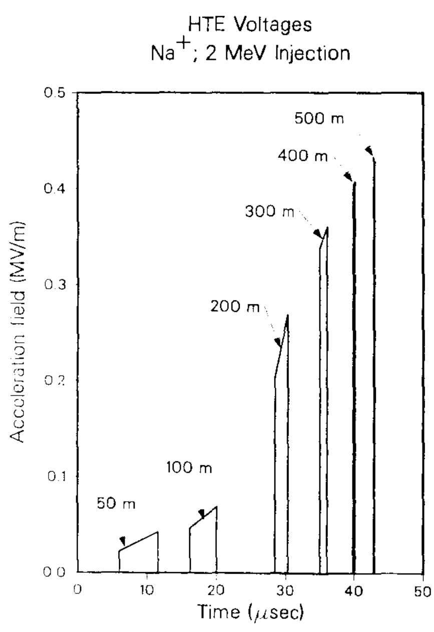

Fig. 2. Accelerating voltage waveforms at 50 m, 100 m, 200 m, 300 m, 400 m, and 500 m along the length of the HTE accelerator.

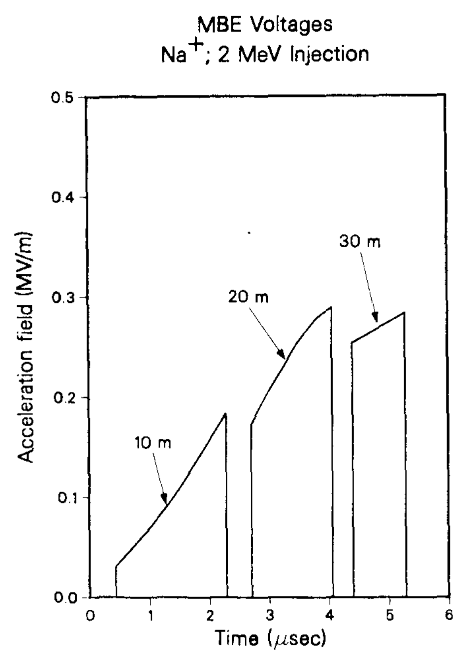

Fig. 4. Accelerating voltage waveforms at 10 m, 20 m, and 30 m, along the length of the MBE accelerator.

can only be approximated. Thus, an important experiment is to show that firing voltage transients and/or the statistical averaging of the voltages as performed by the MBE ion beam have no adverse effect on the beam properties.

Because the ion beam moves much slower than light, it should be possible to correct for acceleration errors caused by misfires of a few voltage modules by firing a few extra modules downstream. A correction technique such as this may affect the practicality of the induction linac as a fusion driver.

The Single Beam Transport Experiment is demonstrating that ion currents greater than once considered possible can be transported in an electrostatic quadrupole focussing system. These results will change our designs of heavy ion accelerators.

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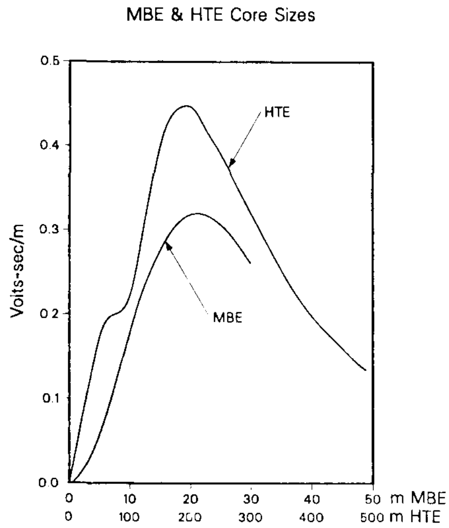

Fig. 5. Volt-sec/m needed for the HTE and MBE accelerators. The abscissa is 100 m/div for HTE and 10 m/div for MBE. The ordinate is 0.1 volt-sec/m for both.

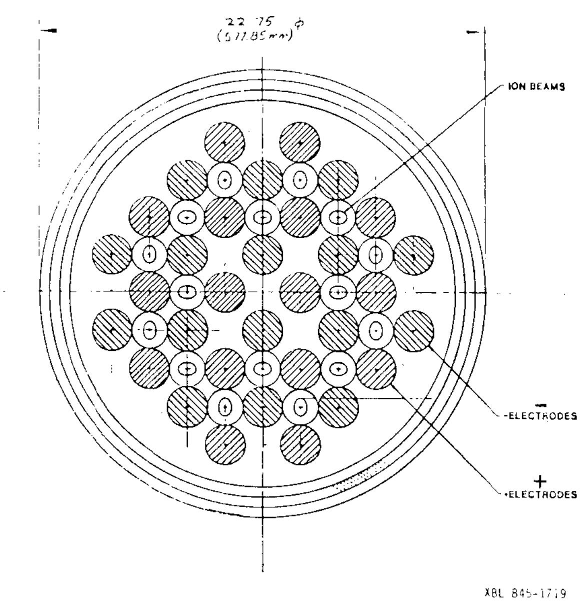

Fig. 6. Axial section of the MBE quadrupole focussing array.

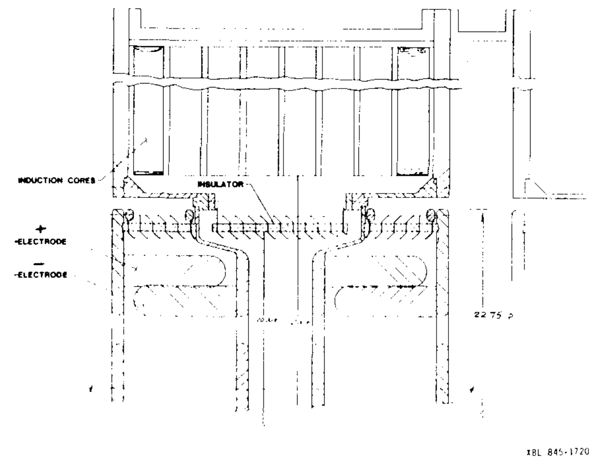

Fig. 7. Cross section of an MBE induction unit.

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