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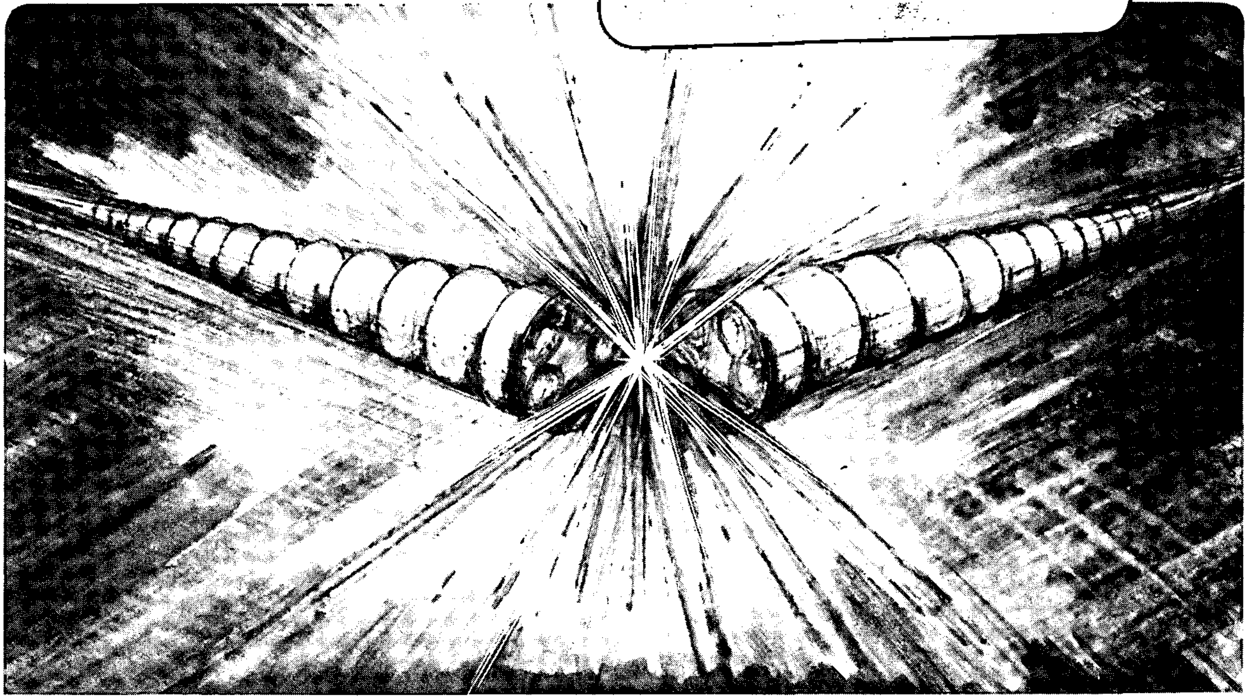

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Summary

At the low energy end of an induction linac HIF driver the beam current is limited by our ability to control space charge by a focusing system. As a consequence, HIF induction accelerator designs feature simultaneous acceleration of many beams in parallel within a single accelerator structure. As the speed of the beams increase, the focusing system changes from electrostatic to magnetic quadrupoles with a corresponding increase in the maximum allowable current. At that point the beams are merged thereby decreasing the cost of the subsequent accelerator structure.

The LBL group is developing an experiment to study the physics of merging and of focusing ion beams. In the design, parallel beams of ions (C^+, Al^+, or Al^{++}) are accelerated to several MV and merged transversely. The merged beams are then further accelerated and the growth in transverse and longitudinal emittance is determined for comparison with theory. The apparatus will then be used to study the problems associated with focusing ion beams to a small spot. Details of the accelerator design and considerations of the physics of combining beams are presented.

Introduction

In the induction linac driver concept, Fig 1., many beams (≈64) are accelerated in parallel at or near the current limit set by space charge. At low energies the beams are focused by arrays of electrostatic quadrupoles. As the beams gain energy and the particle speeds exceed a few percent of light speed, magnetic focusing becomes more effective and a transition to magnetic focusing is made. At this point the beams are combined to

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perhaps 16 for acceleration to the target. Further speed increases allow the beams to be compressed longitudinally. The current then increases faster than the speed of the beams. By the time the beams attain their final energy the total current in the accelerator has increased by a factor of several hundred and the pulse duration has decreased by the same factor. The beams exit the accelerator with an axial velocity tilt of 4%. A final power amplification of 10 is obtained in a drift-compression section just before the beams are focused onto the target. If the conditions are correctly adjusted, the longitudinal space charge forces will remove the axial velocity shear enabling the final lenses to focus all the beams onto the target with a minimum of chromatic aberration. A simulation of these compression physics is presented in reference (1).

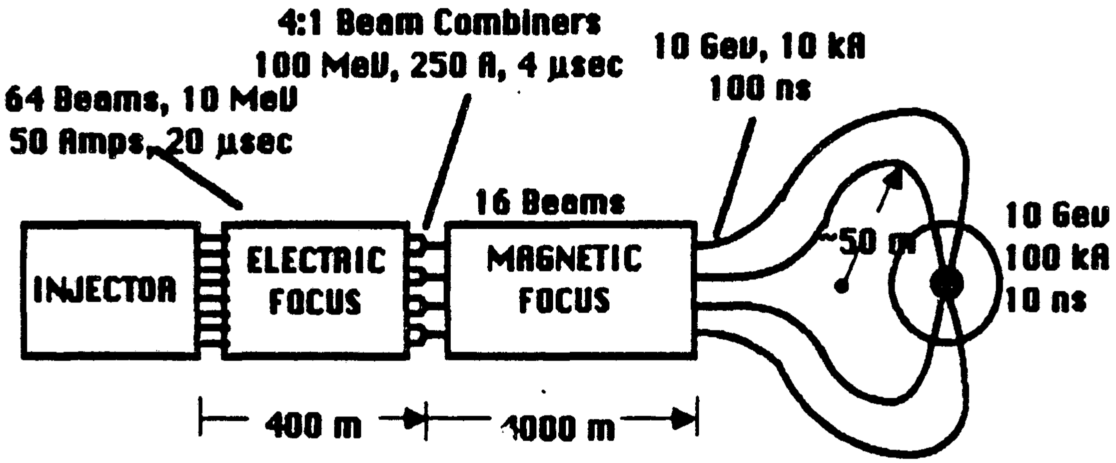

Fig. 1
Ion induction linac driver concept

The principal experiment of the HIFAR program at LBL is the four beam experiment MBE-4 (2) that is currently in progress. This experiment models the longitudinal acceleration physics of the electrostatic portion of a much longer ion induction linac. It accomplishes this by using low-voltage relatively heavy Cesium$^+$ ions so that the lengths of the beams are short compared to the length of the accelerator. There are several consequences of this approach: 1) the ion speed is low and magnetic focusing is impractical; 2) the energy carried by the beams is insufficient to assess the consequences of beam spill in high power linacs; and 3) the physics of the drift-compression power amplification and of the final focus onto the target can not be addressed.

In this paper we present a very preliminary physics design of an Induction Linac Systems Experiment, ILSE, that is intended to address many of the remaining accelerator physics issues that must be faced by an induction linac fusion driver.

ILSE Objectives

The ILSE was designed to address the following physics and engineering objectives;

1. Examine the physics of transversely combining space-charge dominated ion beams
2. Explore the transition from an electrostatic to a magnetic beam transport system.
3. Examine the physics of bending ion beams with intense space charge and with time dependent energy.
4. Study the physics of drift-compression current amplification.
5. Explore the focusing of intense ion beams to a 1-2 millimeter spot.

In addition ILSE will advance the technology of heavy ion multiple-beam induction linacs much closer to that needed for a driver. Magnetic focusing elements are used after the point where beams are combined to the final focal spot; hence the choice of 10 MV of acceleration and a relatively light ion to simulate a heavier ion at higher kinetic energy.

ILSE Description

A block diagram of a conceptual design for ILSE is presented in Fig. 2. Sixteen beams of singly or doubly charged ions at two MV from the LANL injector(3) are matched to an electrostatic transport system and accelerated to 4 MV by a multiple beam induction accelerator with a pulse duration of one microsecond. At this point the beams are combined to four, and matched to a magnetically focused linac for further acceleration to 10 MV. Three of the beams are then blanked off and the remaining beam is deflected through a large angle (90 or 180 degrees) by a bending magnet and longitudinally compressed in a transport section. The beam is then used in final focus experiments. The length from the source to the end of the accelerator is approximately 50 meters which is somewhat longer than the extra drift distance to the final focal spot.

A comparison of the parameters of the ILSE beams at the output of the accelerator with the parameters of MBE-4, and a fusion driver is presented in Table 1.

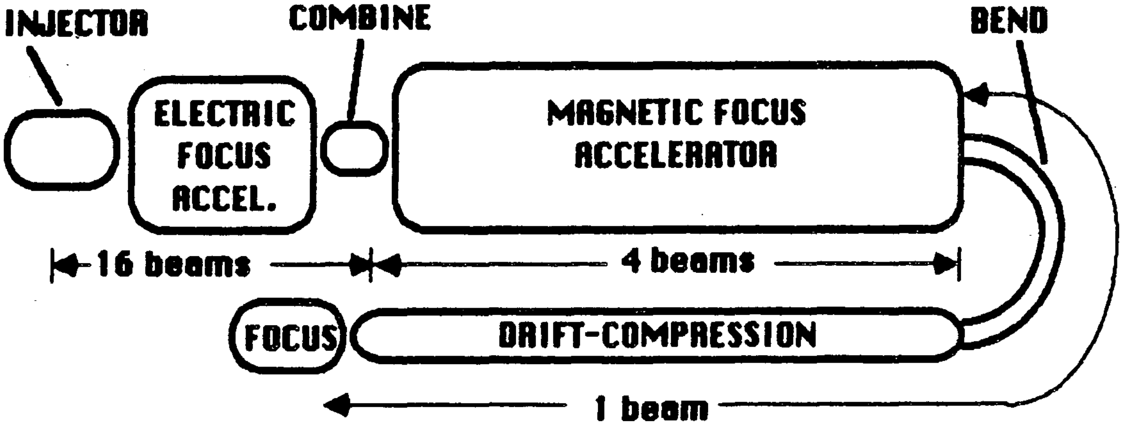

Fig. 2
Block Diagram of the ILSE Apparatus

Table 1
Beam parameters of MBE-4, ILSE, and a driver

Parameter	MBE-4	ILSE	Driver
Ion	Cs^+	C^+ (AL^{++})	200^{+++}
Inj. Volt. (MV)	0.2	2	3
Final Volt. (MV)	1.0	10	3300
Final Current(A)	0.1	30	60000
Beam Energy (J)	0.1	125	3 MJ
Ion Velocity/c	0.004	0.04	0.3
Accel Grad. (MV/m)	0.07	0.22	0.5
# Beams	4	16-4	64-16
Pulse Width (μs)	2-1	1-0.5	24-.1
Charge (μCoul.)	0.1	15	900
Init. bunch length (m)	1.1	5.6	70
Final Perv. (Norm.)	3.8×10^{-4}	3.6×10^{-4}	5.6×10^{-5}

The designed beamlet charge per meter and/or the beamlet current in the electrostatically focused portion of the accelerator are near the limit set by space charge. This limit is determined by the electric field strength that can be produced by the quadrupoles at the beam position that can be achieved without breakdown. For an array of dimensions similar to those used in MBE-4, this translates to a maximum voltage near 50 kV.

The initial design calculations are shown in Figs. 3 and 4. These were calculated using the approach developed by E. Lee (4).

Figure 3 shows calculations of the beamlet current as a function of the beam energy for parametric focus electrode voltages and phase advance per period. Because the system must operate near the limit of the electrode voltages, bunch length shortening in this section of the accelerator is impractical. In these calculations the beamlet charge per meter is 0.2 µC/m. At constant bunch length (constant charge per meter), the current increases as the beam speed. Thus, in accelerating from 2 to 4 MV, a 1.1 Amp carbon beam will increase to 1.6 Amps. This figure shows operating lines for both constant current and constant bunch length operation. The occupancy is the fraction of the lattice period occupied by the electrostatic quadrupoles. The aspect is the ratio of the lattice length to the clear aperture. The calculations are done for a beam that, at maximum size, fills 2/3 of the clear aperture.

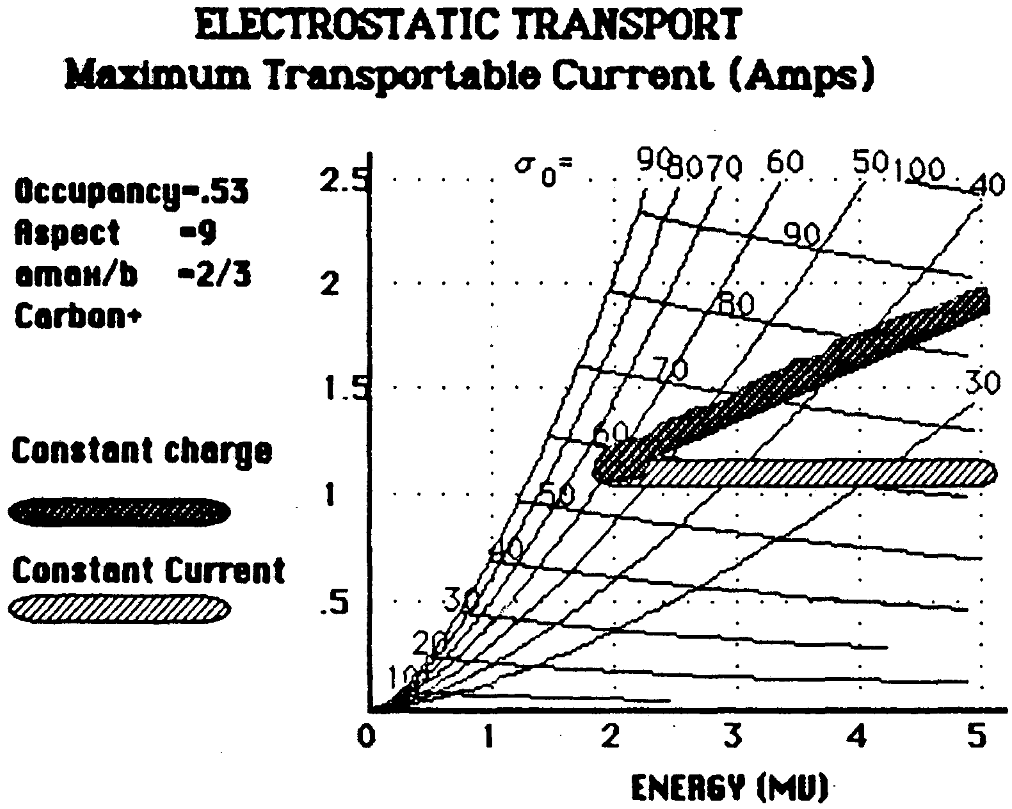
ELECTROSTATIC TRANSPORT
Maximum Transportable Current (Amps)

Fig. 3

Operating characteristics of the electrostatically focused accelerator.The ordinate is the beamlet current in Amps. The parametric lines are at constant phase advance per period (σ_0) in degrees and at constant voltage from a quadrupole to the beamlet axis in kilovolts.

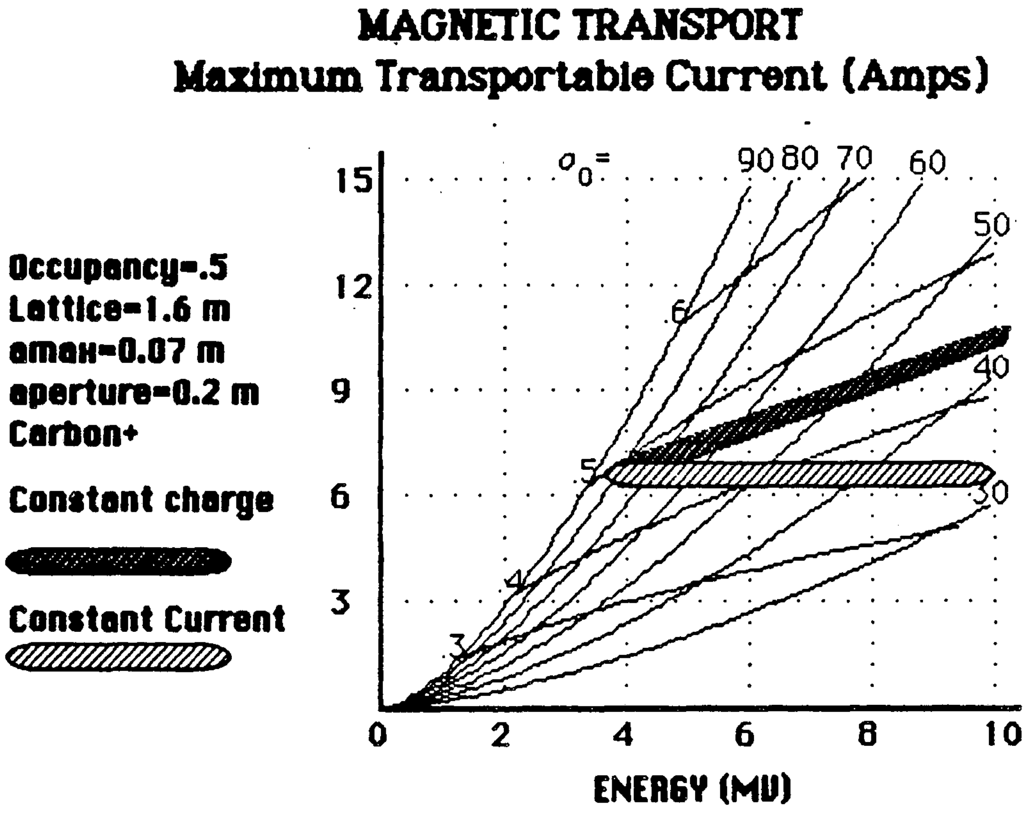

Fig. 4
Operating Characteristics of the magnetically focused accelerator after beam merging. The ordinate is beamlet current in amperes and the parametric lines are phase advance per period (σ_0) and magnetic pole tip field in Tesla.

Figure 4 shows the operating characteristics of the magnetically focused portion of the accelerator as a function of the beam energy for parametric pole tip magnetic fields and phase advance per period. The assumption is that a four to one beam combination occurs between the electrostatically focused and magnetically focused accelerators. Hence the larger currents in the magnetically focused accelerator.

ILSE Experiments

The ILSE experiments will address at a reduced scale all the particle beam manipulations required of a heavy ion fusion system. These experiments will be performed in several stages as the apparatus is assembled and will extend over the period of assembly as progress and budgets dictate. Our present estimate is that the experiments will extend over approximately five years.

The first experiments will measure the parameters of the 16 beams delivered by the 2 MV LANL injector and to match them for insertion into the induction accelerator. Achievement of the ILSE parameters requires beams of Carbon$^+$ and Carbon^{++} ions with line charge densities of 0.2 μC/m from the LANL source. Aluminum$^+$ and Aluminum^{++} are also candidate ions.

Next will come the operation of the electrostatically focused induction linac that will take the 16 beams to 4 MV. This portion of the accelerator will be operated both at constant current (requires flat acceleration pulses) or as a buncher to impart a velocity tilt to the beam that will permit current amplification in the last 6-7 MV acceleration. Operation of this portion of the accelerator will be similar to that of MBE-4.

The combining experiment will be an important new contribution to the physics and technology of heavy ion linacs. This study will be done both with and without a velocity tilt to the beam.

There is little previous practical experience by other workers to guide the design of systems for transversely combining intense space-charge-dominated beams. Practical experience exists for applications where minimization of transverse phase space dilution is of importance but only for low currents. Practical constraints on this process are under study, but no detailed designs have yet been generated. Each beam to be merged is contained upstream of the merging region by a periodic AG quadrupole transport line. The process may be described by its successive stages. First a beam emerges from its upstream line and enters a matching quadrupole lens system which produces some envelope convergence. Next it undergoes two successive small-angle bends of opposite curvatures which displace its axis toward that of the final merged single beam. While being bent, it is also subject to unbalanced radial space charge forces tending to increase its size. After being bent it finds itself able to "see" the other beams with which it is to be merged; all of these together enter the final transport line. During traversal of the first portion of this line considerable equilibration occurs among the constituent beams, leading to a single final distribution of the beam in phase space of a character comparable with that of an original beam but with larger emittance.

Transverse emittance growth during the combining of beams derives from two sources. First, the emittance is increased by the fact that empty spaces between the beams are filled by particles and add to the phase space occupied by the final beam. This might be called a "geometric" emittance dilution, and it gives the only emittance increase for low energy beams. In intense beams there is also a conversion of electrostatic field energy to transverse kinetic energy, as the density profile of the combined configuration of beams changes. It has been show by one of us (5) that this "space charge" dilution can be minimized by compressing the beams as described above. The beams will then be "hotter", so that the relative increase in the transverse kinetic energy caused by the conversion of electrostatic field energy to kinetic energy (and therefore the relative emittance increase) is small. With reasonable experimental parameters, it then appears (5) that the total emittance growth in one transverse dimension can be kept to about a factor of two. This is small enough to allow the combining to be done a few times in the length of a fusion driver without jeopardizing the ability to focus to a small spot at the target.

Further acceleration of the four beams to 10 MV in a magnetically focused induction linac will demonstrate our ability to make the transition from an electrostatic to magnetic transport system. Of continued interest will be the evolution of the transverse and longitudinal emittances of the beams.

An important experiment is the bending of a space charge dominated beam through a large angle. We are just beginning a theoretical study to investigate beam bending physics. Beam bending in the presence of space charge involves charge induced forces of two principal types which are being incorporated into a code model. First there is the well known direct force of the beam on itself which is readily treated by a standard formulation. The second force is that resulting from image charges in a surrounding tube located at finite radius. This force affects both the beam centroid and envelop and, in fact, couples their dynamics. Results from the experiment will be compared with results from theory and simulation to complete our picture of the influence of space charge in the bending of charged particle beams.

An important concept in a heavy ion driver is the factor of 10-20 current amplification that occurs in the drift-compression section from the end of the linac to the final focus lens. The beam enters this section with an axial velocity tilt causing the beam to bunch longitudinally. As the beam line charge density increases, the axial space charge force acts increasingly against the compression until the compression is reversed. Ideally, at the point of reversal the velocity shear will go to zero, all ions in the beam will have the same momentum, and it can be focused without chromatic aberration. In ILSE the current increase will be limited to a factor of a few. The physics of this beam manipulation will be examined experimentally in the transport section following the linac.

The final experiments in the ILSE sequence is an examination of the physics of final focus. In this experiment the beam will be focused by a conventional and/or a collective lens (6) to a one to two millimeter spot on solid material. Of interest are: pulse-to-pulse reproducibility of the size and location of the focal spot; methods of partially neutralizing the ion beam that reduce space charge repulsion allowing a smaller spot; potential filamentation or two-stream instabilities which could be important in the corona of a fusion target; and the material temperature achieved at the focal spot.

Comments and Conclusions

The successful completion of all these experiments will do much to prove the multiple-beam ion induction linac as a driver for inertial fusion. The step beyond these experiments will require the construction of a larger accelerator to develop technology at the proper scale.

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