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Heavy-Ion Fusion Accelerator Research 1987

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April 1988

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

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Heavy-Ion Fusion Accelerator Research

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Reprinted from *Accelerator and Fusion Research Division: 1987 Summary of Activities*
LBL-24670, April 1988

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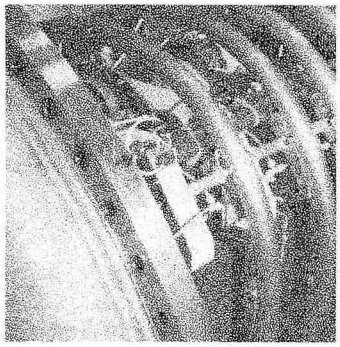
Foreword

The objective of the Heavy-Ion Fusion Accelerator Research program is, ultimately, to assess the suitability of heavy-ion accelerators as "drivers" for electric power plants based on inertial-confinement fusion. These drivers would serve to compress tiny pellets of fuel to the point that energy-producing thermonuclear reactions would occur. (Alternative driver technologies, such as light-ion accelerators and lasers, are being explored elsewhere.) In our program, a specific accelerator technology, namely, the use of induction linacs to accelerate multiple beams of heavy ions, is being studied, and we are now only a few years from being able to assess its promise with reasonable confidence.

The HIFAR program strategy is to attack the practical issues of induction linacs in a series of experiments of increasing scale and sophistication. The first of these was the single-beam transport experiment, in which we explored beam-current limits in a long, linear, alternating-gradient transport system. The results allowed us to use safe design values for beam transport in a long induction linac without suffering degradation in either beam current or optical quality. The following pages describe progress on the fabrication of the second of the HIFAR experiments—the multiple-beam experiment, MBE-4—as well as some encouraging interim experimental results. In addition, we briefly outline our current thinking regarding the next proposed experiment, the Induction Linac System Experiment, which would test at a reduced scale many of the systems and beam manipulations that would be required in a full-scale fusion driver.

Increasing attention is now being given to heavy-ion fusion, and we are encouraged to hope that a vigorous program will go forward in the coming years, allowing us soon to make a sensible appraisal of the induction linac as a practical driver for commercial fusion power.

Denis Keefe
HIFAR Group Leader
March 23, 1988



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HEAVY-ION FUSION ACCELERATOR RESEARCH

. . . as the culmination of this research program, ILSE would address the main driver issues for a full-size heavy-ion fusion reactor . . .

TWO SCHEMES ARE HELD to have the greatest promise for harnessing the near-limitless potential of fusion energy. The more widely known is magnetic-confinement fusion (see pages 71–83), in which strong magnetic fields are used to contain a continuously burning tritium-deuterium plasma. By contrast, inertial-confinement fusion (ICF) depends on the inertia of a small fuel pellet to keep the deuterium and tritium together for the fraction of a nanosecond it takes them to burn. By repeating this process a few times per second, enough heat can be produced to drive the generators of an electric power plant. ICF therefore relies on a pulsed process, analogous to the repeated mini-explosions in an automobile engine. To provide the intense focused energy necessary to compress and ignite the fuel pellet, two types of ICF "driver" are under active consideration. Laser drivers would use powerful beams of short-wavelength light to heat and "ablate" the pellet surface, leading in turn to compression and ignition of the fuel. The alternative, ion-beam drivers, would rely on high-energy beams of ions, which would deposit their kinetic energy in the pellet and thereby compress it. The thrust of our effort at LBL is to explore the practical possibilities of heavy-ion accelerators, which offer several advantages over lasers as fusion drivers.

The means for this exploration is a series of increasingly sophisticated experiments. The first, which began in 1982, was the single-beam transport experiment. In it we studied in detail the physics of a single high-current heavy-ion beam. Second is the multiple-beam experiment MBE-4, in which four independent high-current beams are transported and accelerated through a multigap accelerating structure. A unique feature of this second experiment is that the ion current is continually amplified during the acceleration process. The past year was highlighted by completion of the apparatus for this proof-of-principle experiment. Finally, as the culmination of this research program, we have proposed a much larger Induc-

Experiment

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tion Linac System Experiment, which would address the main physics and technology issues of a driver for a full-size heavy-ion fusion reactor.

Underlying the promise of this research, and the promise of heavy-ion fusion generally, are the results of a comprehensive feasibility study known as the Heavy Ion Fusion Systems Assessment. This multilaboratory study, sponsored by the DOE and the Electric Power Research Institute and coordinated by the Los Alamos National Laboratory, was completed in 1986. Among its results, it found that the estimated cost of electricity generated by a heavy-ion fusion power plant (see Fig. 23) compares favorably with the estimates obtained in analogous magnetic fusion studies.

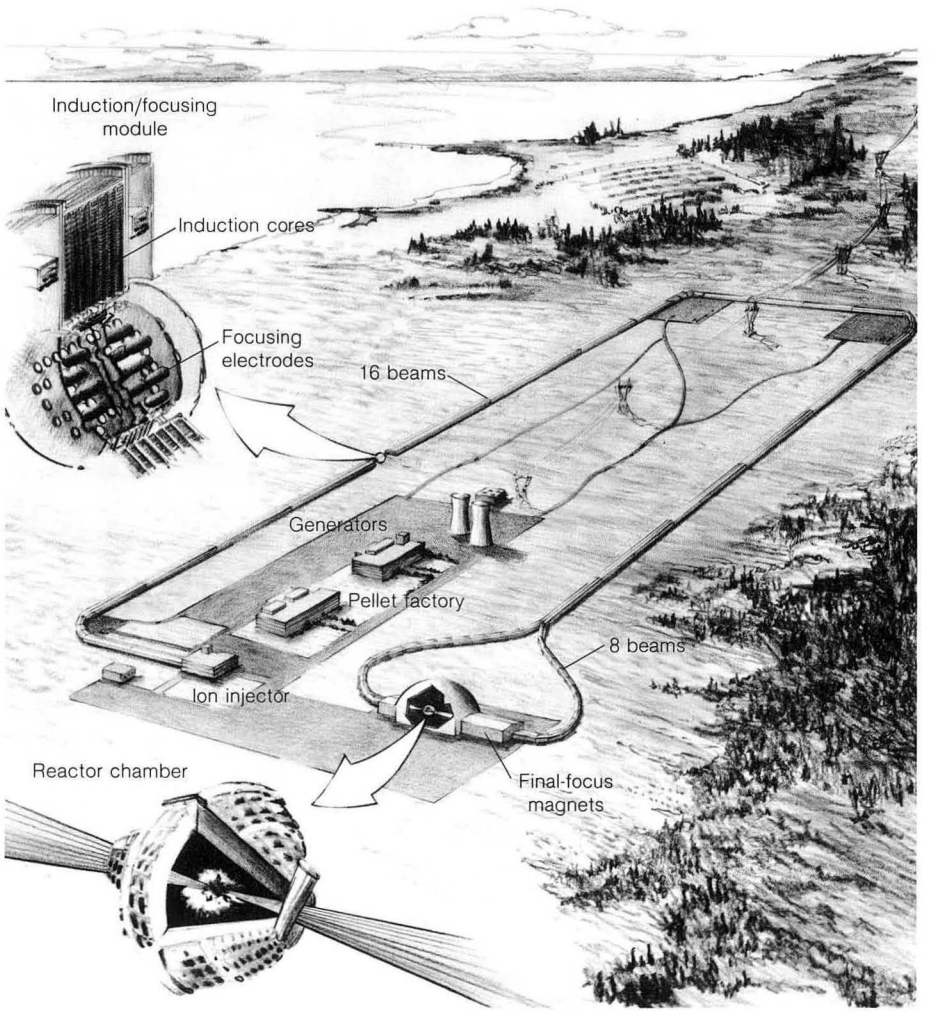

Figure 23. An artist's drawing of an inertial fusion power plant based on a 16-beam heavy-ion induction linear accelerator. The system shown here uses the Cascade reactor chamber design developed at the Lawrence Livermore National Laboratory—one of several concepts that have been studied. In this design, the inner wall of the chamber, which must absorb the punishing effects of x-ray and debris bombardment, is a thick layer of ceramic granules, kept in place by rotating the chamber. The granules are cycled through a heat exchanger, which uses helium as a secondary medium. Except for the pellet factory, the remainder of the plant—primarily steam turbines and generators—relies on conventional technology.

Multiple-Beam Experiment

The highlight of fiscal 1987 was the completion of the apparatus for MBE-4. One of the features of this experiment is its modular design, which has allowed us to conduct a series of studies over the past two years. Long before the apparatus was complete, therefore, we had successfully demonstrated significant amplification in beam current, achieved by suitably shaping the accelerating voltage pulses so as to actually shorten the duration of the ion pulse during acceleration. With all of the hardware in place, we can now pursue in earnest our aim of modeling several of the phenomena we expect to encounter in any eventual heavy-ion driver—especially the consequences of approaching stability limits imposed by space charge (the mutually repulsive charges in a high-current ion beam) and the effects on the optical quality of the beams caused by voltage- and current-amplification manipulations.

MBE-4 Design Concept

Since 1983 heavy-ion fusion driver research in the U.S. has concentrated on the multiple-beam induction linac, which can be visualized as a structure comprising many closely packed channels of beam-focusing lenses in which parallel "beamlets" of heavy ions are transported. Surrounding this structure is a series of ferromagnetic cores, along with the pulser circuitry needed to apply a succession of long-duration, high-voltage accelerating pulses to the beamlets. In MBE-4 four beams of positive cesium ions are accelerated through six accelerator sections (designated A through F), each containing four induction units. Along the entire length of the accelerator, the beams are focused by electrostatic quadrupole lenses, identical in concept to those that might be used in a full-scale driver. In a driver, these would be followed by superconducting magnetic quadrupole lenses, which are effective only at higher ion energies.

One major attraction of the induction linac method, and an important underlying justification for MBE-4, is the relative ease with which the physics and technology of a large driver can be scaled down to a laboratory setting. This benefit arises from the fundamental properties of particle beams dominated by internal space-charge forces. The disruptive effects of space charge are, in fact, somewhat worse in a 10-mA beam at 0.2 MeV than in a 1000-amp beam in a 10-GeV driver. This scaling property allows accurate predictions to be made for the beam physics in a driver, once the behavior of a small accelerator is well-understood. The carefully scaled design of MBE-4, therefore, will allow us to assess the consequences of errors in accelerating voltages, to investigate beam-beam coupling phenomena, and to gain relevant practical experience in accelerating and controlling parallel, space-charge-dominated beams.

Components and Fabrication

During the past year, a major milestone was reached when the final components were installed on MBE-4. Figure 24 shows the completed apparatus. By the end of the year, the 35 focusing elements were aligned to within ±5 mils (rms) over the entire 17-meter-long accelerator, in preparation for resuming the experimental program.

The final phase of fabrication entailed installation of the four section D accelerator cores, installation of the section E cores and transport sections, and the fabrication and installation of all section F components. During this final period of fabrication and assembly, a small electrostatic energy analyzer was built, similar to the large energy analyzer at the end of the apparatus. This smaller version can be inserted in any of the diagnostics boxes of MBE-4, though it cannot be used at beam energies much above 300 keV, owing to voltage breakdown limitations. It will therefore be most useful for determining the beam energy at the entrance to the accelerator, downstream of section A, and perhaps downstream of section B. The analyzer consists of two coaxial cylindrical electrodes with a radial spacing of 1 cm and a mean radius of 10 cm. In preliminary measurements, we determined

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Figure 24. The completed apparatus for the multiple-beam experiment MBE-4. The injector is at the far end; the rectangular enclosures house the 24 accelerating cores.

the energy dispersion of the beam at two points between the ion source and the first accelerator section. Good agreement was found between the results and those obtained with the larger analyzer during an early phase of MBE-4 fabrication.

Experimental Results

The modular design of MBE-4 allowed us to perform experiments at several early stages in the fabrication. During early fiscal 1987, for example, experiments were conducted with four transport sections and three accelerator sections in place.

Any eventual heavy-ion fusion driver must deliver beams of extraordinarily high power to the target. This translates more or less directly into a requirement for high-current beams. As a consequence, one of the fundamental aims of MBE-4 is to demonstrate current amplification in an induction linac. In the absence of special measures, the physical length of an accelerated ion bunch grows in direct proportion to its velocity, whereby the current remains constant. Therefore, if we are to amplify the current, the electrical pulses applied to the cores must be specially shaped so as to accelerate the tails of the beam pulses more than the front ends. The duration of the beam pulses, as measured at different points along the accelerator, thus decreases as the ions are accelerated.

During the past year, we conducted experiments with the first 12 accelerating cores (that is, sections A, B, and C) in place. The necessary voltage waveforms were derived iteratively by numerically following the longitudinal motion of the beam particles through the accelerator, taking account of the effects of space charge and the finite gap width. They were generated by a computer code (SLID), such that the resulting current waveform retains a self-similar rectangular shape as the beam is accelerated. Since it is not possible to synthesize exactly the ideal voltage waveforms, we also used SLID to solve for slightly modified downstream waveforms that corrected for upstream errors. In addition, the accelerating voltages at the fourth, eighth, and ninth gaps contained components to control the longitudinal space-charge spreading of the beams, as well as to accelerate them.

A typical experimental result is shown in Fig. 25, which depicts oscillograms for one of the four accelerated beams at the entrance of the accelerator and at the ends of the first three accelerator sections. By electronically integrating traces

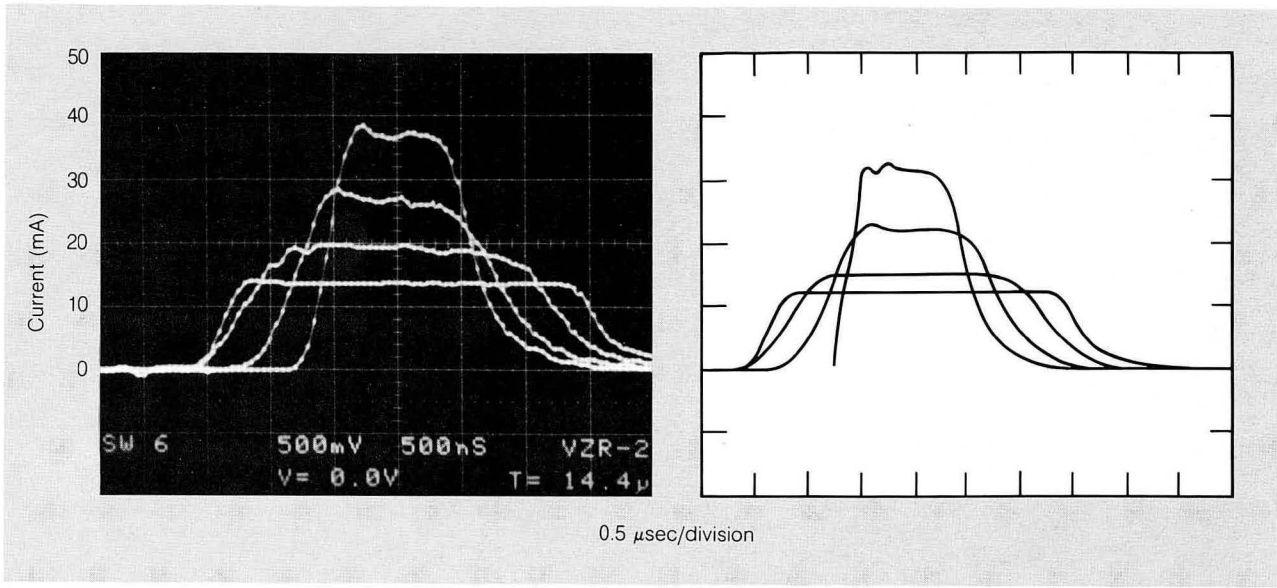

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Figure 25. Measured and computed waveforms for one of the four beams in MBE-4 at diagnostic stations 0, 5, 10, and 15. The data were taken when only 12 of the 24 cores were in operation. The computed waveforms were obtained by the SLID code, given as input the initial beam energy and current, and the accelerating voltage waveforms.

such as these for all four beams, we determined that the charge contained in each beam at any given station varies by no more than 5%. Further, for a given beam, the charge varies by less than 3% along the length of the accelerator. Also shown in Fig. 25 are the current waveforms computed by SLID, given as input the accelerating voltage waveforms and the beam current and energy at the entrance to the accelerator. A graphic illustration of the longitudinal dynamics of the beam is shown in Fig. 26, a plot of the head, tail, and midpoint energies along the first three accelerator sections. The result is a "velocity shear" that allows the beam tail to keep pace with the head.

The transverse dynamics of the beams in MBE-4 is also of critical importance. Indeed, two of the reasons for doing the experiments are to assess the effects of space charge and to examine possible interactions among the beams as they are transported in parallel channels. A crucial diagnostic parameter is therefore the emittance, a measure of the transverse beam size and its divergence. In our

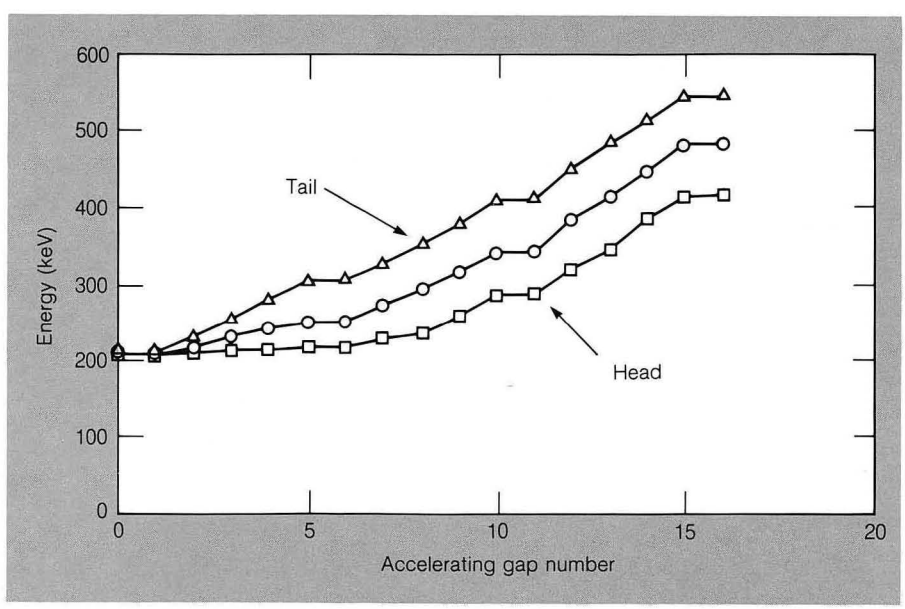

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Figure 26. A plot of head, tail, and midpoint energies of an ion beam in the first three sections of MBE-4. The energy, hence velocity, difference between the head and tail (referred to as velocity shear) is a prerequisite for current amplification.

experiments, emittance measurements are made using a "two-slit method," the apparatus for which is shown schematically in Fig. 27. By scanning the Faraday cup detectors, measurements are obtained of the rms beam size, its mean angle of travel with respect to the ideal axis, its mean position in the focusing channel, and the random transverse velocity of the beam particles. A typical emittance measurement is also shown in Fig. 27. Values for the normalized emittance, calculated from plots such as this, show essentially no emittance growth in the first three accelerator sections of MBE-4.

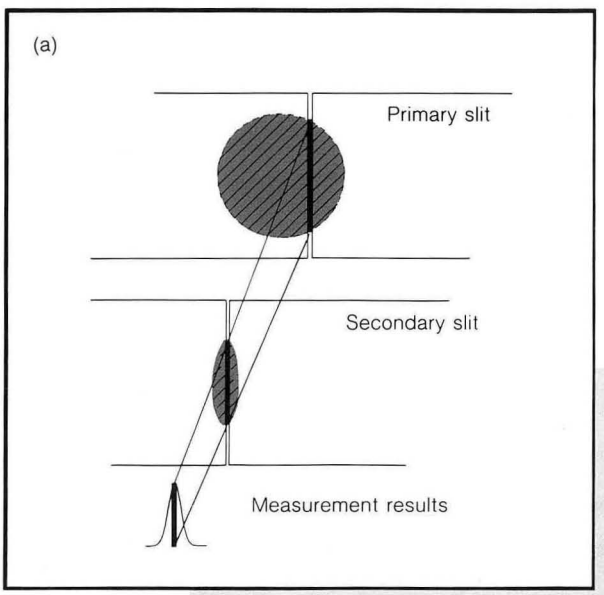

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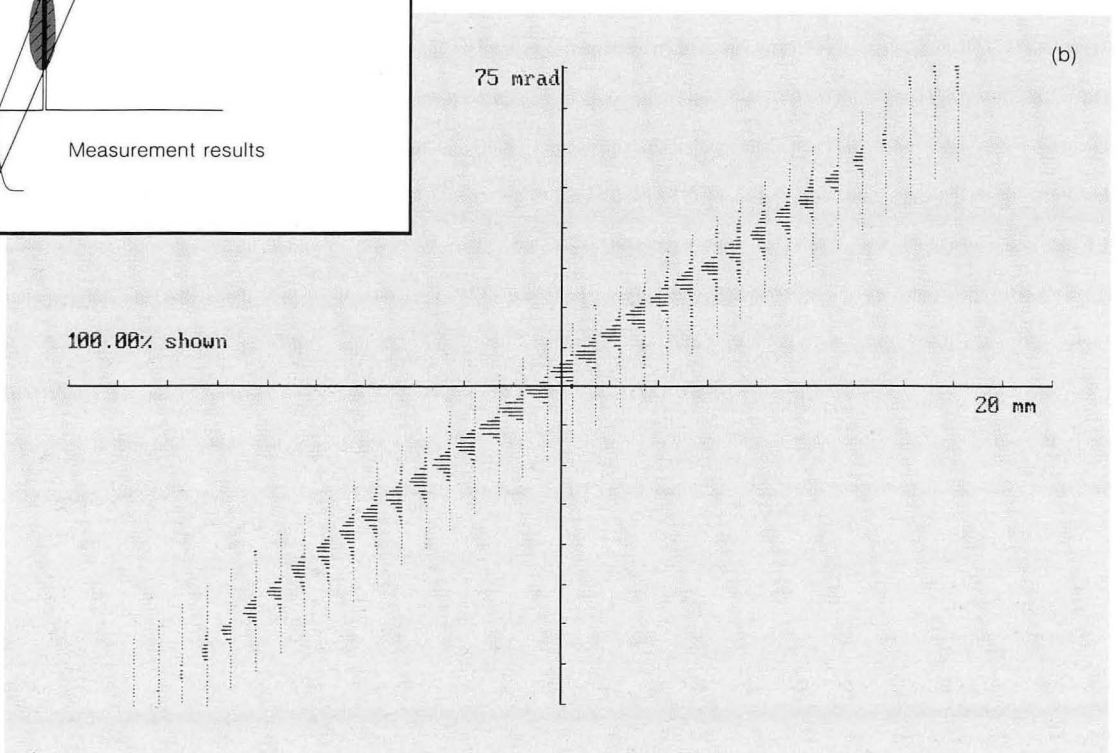
Figure 27. (a) A schematic illustration of the two-slit emittance-measuring concept. For a given position of the primary slit, the secondary slit passes into the detector only those particles with a well-defined transverse velocity. The two-slit apparatus yields measurements of rms beam size, its mean direction of travel, its mean position in the beam channel, and the random transverse velocity of the beam particles. (b) Data from typical emittance measurement. The horizontal axis reflects different positions of the primary slit; the vertical axis, different positions of the secondary slit.



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Injector Development

In looking beyond MBE-4, certain challenges become especially evident. One such challenge is the development of a high-current multiple-beam injector for an experiment that lies a step closer to a full-scale driver. Accordingly, a 16-beam, 2-MV injector (Fig. 28) has been under development for the past few years at the Los Alamos National Laboratory. During the last half of fiscal 1987, this project was in the process of being moved to LBL. Several components arrived, and others were shipped. In preparation, the Marx generator system was redesigned, and space was prepared for assembly of the injector. In addition, the 200-kV injector for the single-beam transport experiment was used as a test bed for the carbon arc source intended for use in the 2-MV injector.

Over the past year, there were three main areas of progress on the 2-MV injector that would form the basis for the next step in the HIFAR program (see ILSE, below). Much of the work was done at Los Alamos, where this project began, but several steps were taken at LBL in preparation for further development here. At Los Alamos, the ceramic insulators in which the accelerator column will reside were subjected to a series of acid treatments to remove fillets remaining from the brazing process. Also, a prototype clamp ring for the electrodes was designed and successfully tested. A trial assembly of the insulator column and its external hardware was successful. At LBL meanwhile, the 750-kV pulsed power system was redesigned to reduce trigger jitter and to make possible the conversion of the originally specified conventional Marx generator to an inductively graded Marx.

The ion source for the 2-MV injector is to be a carbon arc source, which has been developed by S. Humphries at the University of New Mexico. During the past year, a duplicate of the New Mexico source was fabricated and installed on the single-beam transport experiment. The source operates by generating a plasma at a carbon arc, then confining it by means of a pair of biased grids. An ion pulse is then extracted by applying a voltage between the second of the grids and the grounded extractor plate. Experiments on this source were aimed at optimizing a number of operational parameters and evaluating the properties of the extracted beam. Perhaps most significant was an observed maximum current density equivalent to 24.5 mA/cm^2, essentially meeting the requirements for a 16-beam, 8-amp injector. Continuing work aims at improving the trigger lifetime and stability.

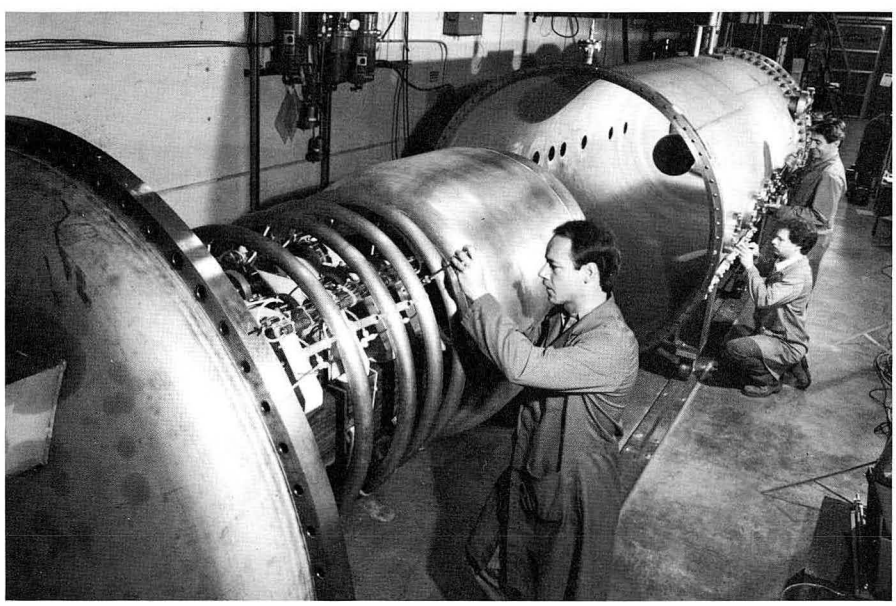

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Figure 28. Components of the 16-beam, 2-MV injector partially fabricated at LANL and now being completed at LBL. High voltage is generated at the large terminal in the center of the photograph by the Marx generator in the foreground. Ions produced at the terminal voltage will then be accelerated through a column, yet to be fabricated, attached to the far side of the terminal. The entire injector will operate within the pressure vessel seen in the background. During the past year, responsibility for the development of this injector has been transferred to LBL.

Induction Linac System Experiment

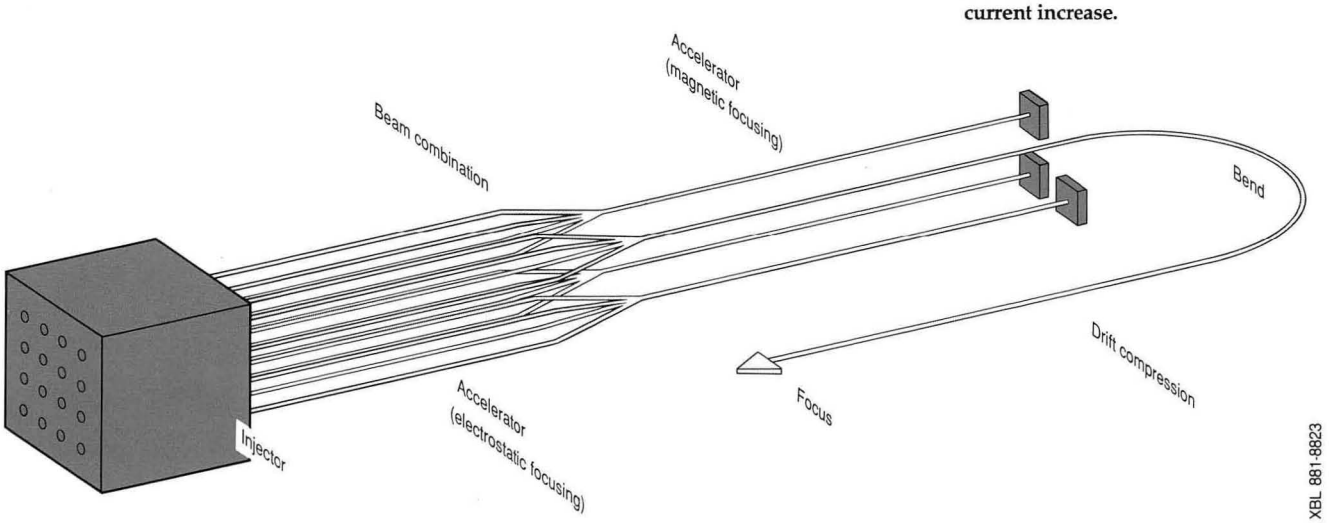
To complete the validation of induction linacs for inertial-confinement fusion, LBL has proposed the Induction Linac System Experiment (ILSE), which would demonstrate, in a scaled model accelerator, the physics and technology of a large driver. The system would include the 16-beam, 2-MV injector now being constructed here, an electrostatic focusing section that accelerates all 16 beams to an intermediate energy, a beam-combining system to merge the 16 beams into 4, a magnetic focusing section that accelerates the resulting beams to a final energy, and a section in which a single beam is bent, then longitudinally compressed and focused onto a small target. At the end of 1987, a basic physics design for ILSE was near completion. Particular effort was devoted to understanding the physics of the combining section and to designing the necessary electrostatic and magnetic focusing and bending elements for such a section.

Conceptual Basis

ILSE was conceived to address several of the yet-untested concepts that must be embodied in any practical heavy-ion fusion driver: the transverse combination of space-charge-dominated ion beams, the transition from an electrostatic to a magnetic beam-transport system, the magnetic bending of ion beams that are both space-charge dominated and increasing in energy, current amplification by "drift compression," and the focusing of intense ion beams to a 2-mm-diameter spot. A schematic for a system in which these various beam manipulations could be attempted is shown in Fig. 29.

Current amplification in ILSE would be achieved by means of the same type of pulse shaping already demonstrated with MBE-4. However, the injected beam currents would be considerably higher, owing to the design of the new injector. Likewise, the peak power in the beam on target would be more than a 1000 times that of MBE-4. The parametric design of ILSE was based on a careful cost-benefit analysis of the physics and technology issues still to be addressed by the HIFAR program. We estimate that the fabrication of ILSE would cost an additional $28 million (fiscal 1987 dollars), spread over four years.

Figure 29. A schematic diagram of the proposed Induction Linac System Experiment, conceived to address remaining issues crucial to the concept of heavy-ion inertial fusion. As the experiment is now visualized, an initial total current of 8 amps would be amplified to about 18 amps at the end of the magnetic-focusing accelerator section; one of the four beams (with 4.5 amps) would then be further compressed longitudinally to achieve an additional threefold current increase.



Beam Combination

Physics Designs. In a full-scale inertial fusion driver, the required power on target would demand intractably long bunches at the low-energy end of the accelerator, unless beams are combined, perhaps several times, somewhere along the length of the machine. During the past year, we examined the physics designs of several candidate beam combiners, each of which has its distinct set of advantages and disadvantages. Until recently, the alternatives being considered consisted of a short series of electrostatic quadrupoles and electric or magnetic bends. Each of four beams would be deflected through a bend, followed by a reverse bend, after which all four beams would emerge into a common channel, separated by only a few centimeters. Such systems can be relatively short and inexpensive, but they are not intrinsically achromatic. That is, because of the head-to-tail "velocity tilt" of the ion beam, different parts of the beam would follow different trajectories. A challenging, but possible, solution is to ramp the fields of the bending elements (and possibly the focusing elements as well) during the passage of the beam. The difficulty of this approach, however, has prompted us to examine inherently achromatic combiner designs.

A variety of preliminary achromatic designs has now been examined. The shortest such systems are the most complex in that they involve both electrostatic and magnetic bends with relatively high fields. Longer combiners can be made entirely with electrostatic bends and quadrupoles. One such all-electrostatic system contains six full focal periods and requires only two very weak bends, in addition to the quadrupoles. It may even be possible that the bending and focusing functions could be combined in the same elements. We shall continue to study these preliminary physics designs in the coming year.

Beam Dynamics. Emittance growth during beam combination occurs for two reasons. First, the betatron motion of the particles causes them to fill the "holes" present between beams when they first emerge into the common focusing channel. This phenomenon, called geometric emittance dilution, has been extensively studied in the context of "stacking" in storage rings. Second, space-charge forces cause beams to expand into the available spaces; the changes in electrostatic field energy become manifest as transverse kinetic energy. During the past two years, we have looked carefully at the extent to which these two effects cause emittance growth during four-to-one beam combination at an energy of 100–500 MeV. (In assessing our findings, it is important to note that a transverse emittance increase of about a hundredfold is permissible along the entire length of a fusion driver.) In both analytical and particle simulation studies, we assumed that four identical beams of uniform density emerge from a combiner into a common channel defined by a round conducting pipe.

For beam parameters such as those we expect in ILSE, two analytical results are of particular interest. First, not surprisingly, transverse emittance growth due to space charge dominates that caused by geometric dilution. Second, the total effect is approximately an eightfold increase in emittance, judged to be an acceptably small value. (During a four-to-one combination, a twofold increase is the minimum possible.) Particle simulation results are consistent with this finding. Figure 30 shows the emittance of a combined beam over 50 periods downstream of the combiner, assuming an asymmetric geometry for the initial beam configuration (see inset).

Bending and Focusing Elements. The emittance studies reported above assumed a beam-beam separation of only 3 mm in the common channel just downstream of the beam combiner. Innovative hardware designs will be needed if this is to prove a realistic assumption. On the other hand, beam merging will take place after only 40 focusing elements, suggesting a negligible 0.5-mm transverse misalignment in the beams, assuming typical tolerances. It thus seems plausible to get the beams very close together by using thin bending and focusing elements, then to scrape off any beam halo. Along these lines, we have investigated two new

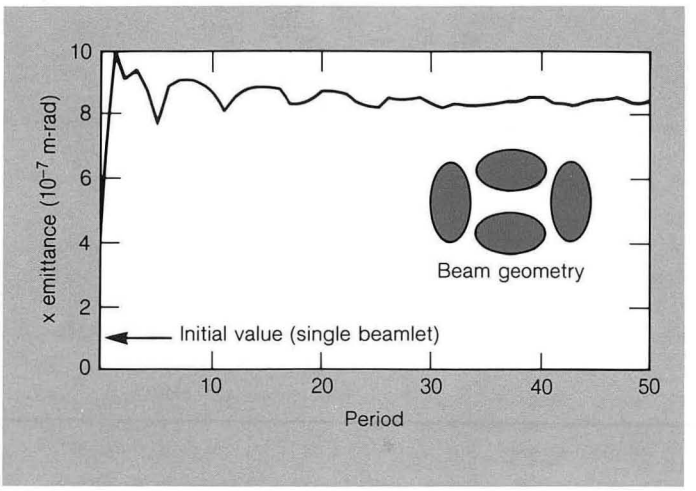


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Figure 30. Plot of horizontal normalized rms emittance over 50 lattice periods downstream of a beam combiner, as computed by the particle simulation code SHIFTXY. The inset illustrates the assumed asymmetric geometry of the beams as they enter the common channel. In agreement with analytic studies, these results indicate that the fourfold increase in current resulting from the combining is accompanied by an eightfold increase in transverse emittance, an acceptably small change. Significant also is the fact that the emittance increase occurs within a few periods of the beam combiner.

types of final combining elements: multielectrode "squirrel cages" for electric dipoles and quadrupoles, and multiwire current distributions with iron boundaries for magnetic dipoles and quadrupoles.

The electric elements are more suitable for beam-merging scenarios in which it is necessary to change the fields significantly during the 1-μsec beam pulse, but they also entail the risk of electrical breakdown. The magnetic elements are better matched to achromatic systems (see previous page), though they could be pulsed on a millisecond time scale, allowing the use of small, uncooled conductors carrying several hundred amperes of current. A magnetic quadrupole array is shown schematically in Fig. 31.

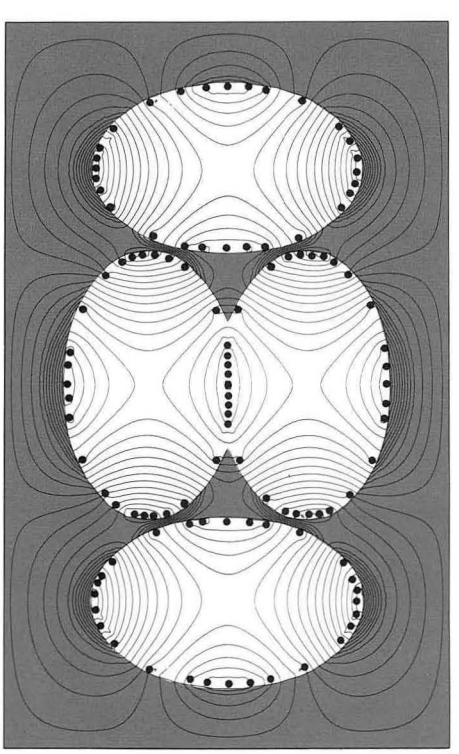

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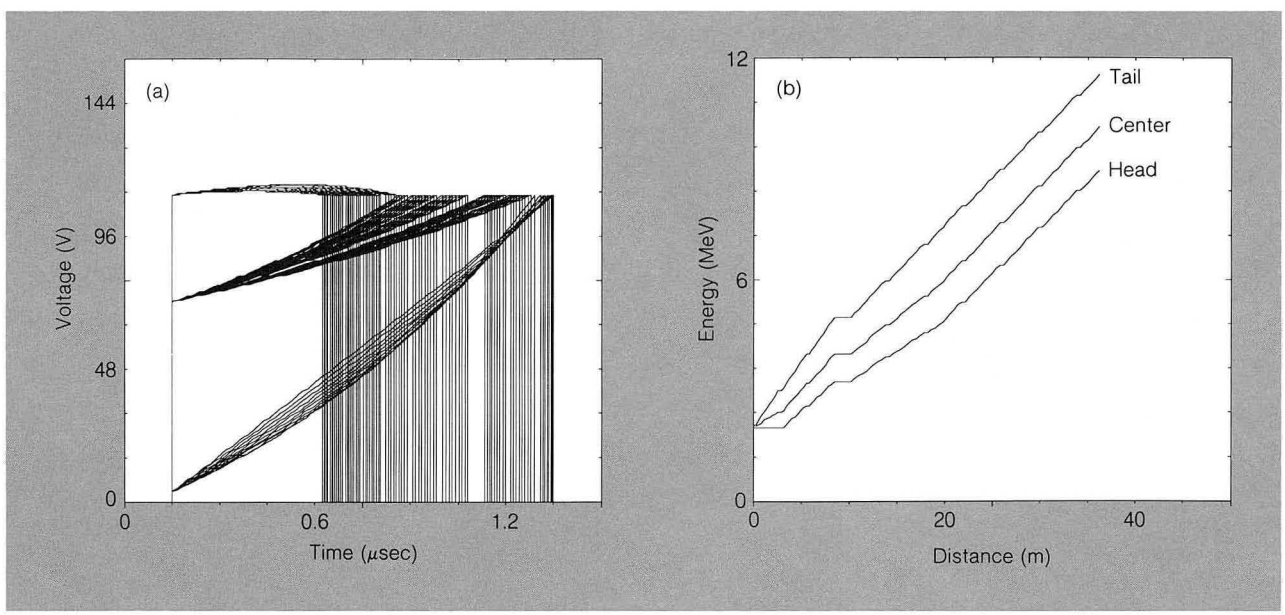
Figure 31. Computed field lines in a four-beam quadrupole array designed to be used as the last element in the merging section of ILSE. The conductors shown, each about 1 mm in diameter, represent the minimum number needed to give acceptable fields over the beams, which would nearly fill the apertures. A very thin iron septum between beams is sufficient to redirect the external field from one aperture to the next.

Other Design Considerations

Quadrupoles Magnets. Several quadrupole magnet designs for ILSE have been considered over the past years, including both dc-powered and pulsed systems. Standard dc designs were considered first, but the cross-sectional area of the required conductor led to an undesirably large interbeam spacing, which translated in turn into a larger and more expensive induction accelerator. An iron-dominated pulsed design was also considered, but the present preferred option is a current-dominated design that uses a large number of small conductors, cooled by conduction to the outside. Among other things, this option is preferable for correctly treating the quadrupole end effects.

Waveforms and Longitudinal Beam Parameters. ILSE poses several difficult design problems with regard to a proposed "accelerating schedule." The first stems from the length of the bunch entering the accelerator from the 2-MV injector. This length, 6.8 meters, is about one-fifth the length of the entire accelerator, making it difficult to achieve significant bunch shortening without appealing to very high values of the velocity shear. (For comparison, MBE-4 is 18 times the length of the initial bunch.) This, in turn, leads to a second problem, namely, the constraints on the velocity shear that must be observed at the beam combiners and at the 180° bend at the exit of the accelerator. A reference design that solves all of these problems is illustrated in Fig. 32, which shows both the accelerating voltage waveforms and the energy of the ion bunch (head, middle, and tail) as a function of distance along the accelerator.

Figure 32. (a) Voltage waveforms for a reference ILSE accelerating schedule and (b) a plot of the resulting head, tail, and midpoint energies, as functions of distance along the accelerator. Note that the bunch head is not accelerated until $z = 3$ meters and that no acceleration occurs at the combiner (between $z = 8$ and $z = 10$) or at the short diagnostics sections.



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XBL 8712-5052A

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