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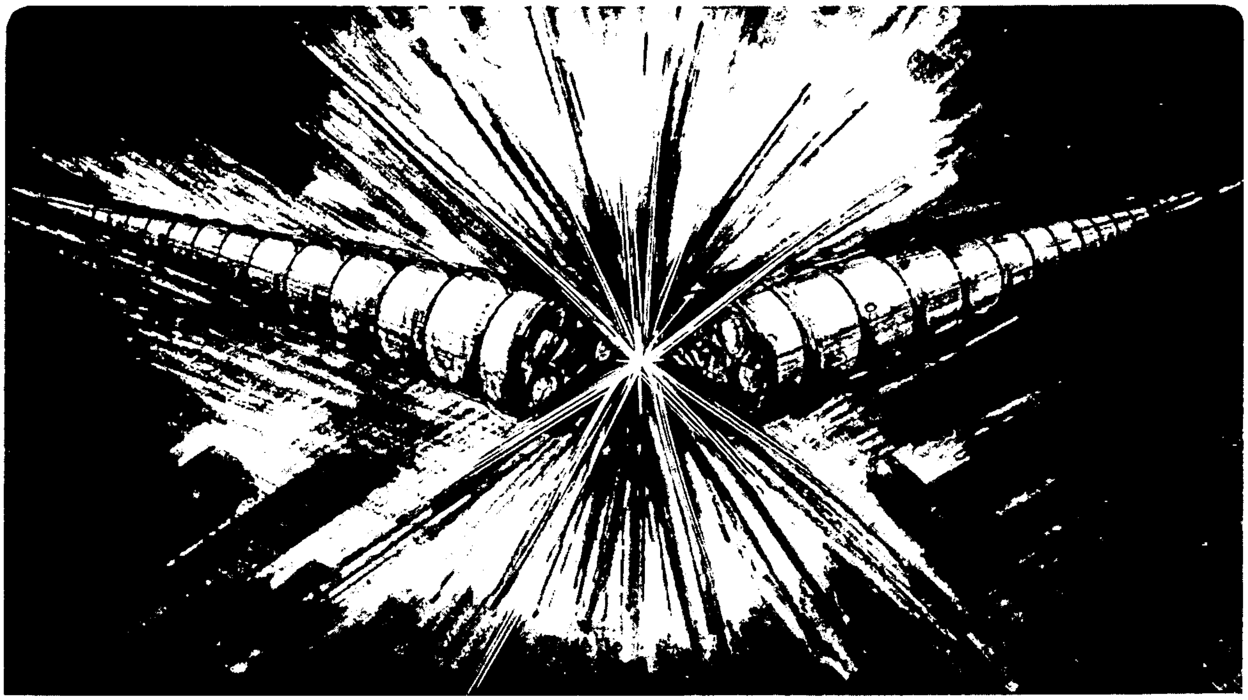

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ILSE: THE NEXT STEP TOWARD A HEAVY ION INDUCTION ACCELERATOR FOR INERTIAL FUSION ENERGY*

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LBL and LLNL propose to build, at LBL, the Induction Linac Systems Experiments (ILSE), the next logical step towards the eventual goal of a heavy-ion induction accelerator powerful enough to implode or "drive" inertial-confinement fusion targets. ILSE , although much smaller than a driver, will be the first experiment at full driver scale in several important parameters. Most notable among these are line charge density and beam cross section. Many other accelerator components and beam manipulations needed for an inertial fusion energy (IFE) driver will be tested. The ILSE accelerator and research program will permit experimental study of those beam manipulations required of an induction linac inertial fusion driver which have not been tested sufficiently in previous experiments (see Table I), and will provide a step toward driver technology.

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1. INTRODUCTION

Research programs throughout the world using high-power lasers and light-ion accelerators, along with the Halite/Centurion program conducted at the U.S. Nevada Test Site using nuclear explosives, have already put to rest fundamental questions about the basic feasibility of achieving high gain with inertial fusion targets. However, the efficiency and cost goals that mark the difference between laboratory science and economically competitive power plants must also be achieved. It now appears possible to develop and build a demonstration IFE power plant for energy production by the year 2025. Plans for this development are outlined in the newly formulated U.S. National Energy Strategy. A multi-gap heavy-ion accelerator has unique advantages as an IFE driver because it is simultaneously high in repetition rate, electrical efficiency, reliability, and lifetime. Thus it has become the leading driver candidate for commercial IFE, as recommended by the Fusion Policy Advisory Panel [1] and described in the National Energy Strategy [2].

The fundamental requirements for an HIF driver are to produce a short beam pulse (about 10 ns) with an instantaneous power of more than 10^{14} W and enough quality to be focused to a spot with a radius of ≈ 3 mm. To minimize the space-charge forces and other collective effects associated with high currents, it is desirable to achieve the required beam power by maximizing ion kinetic energy (voltage) while minimizing beam current. An upper limit on ion kinetic energy is set by the desired target penetration. For the target to achieve high energy gain, ion range must be limited to ≈ 0.1 g/cm^2. For light ions such as protons, this requirement limits the kinetic energy to about 10 MeV and a total beam current of 40 MA would be required to produce 4×10^{14} W on target. For heavy ions, the limit determined by ion range is about 10 GeV, leading to a current requirement of about 40 kA. Consequently, the space-charge forces and collective effects are much smaller and the beams more manageable.

A schematic diagram of a generic induction accelerator designed to produce 40 kA of 10-GeV ions is shown in Figure 1. To achieve this current, 40 beams, initially at a current of ≈ 0.5 A apiece, are electrostatically focused and accelerated to an energy where magnetic focusing becomes preferable (≈ 100 MeV). The 40 beams are combined transversely to 10 beams and accelerated to 10 GeV. During acceleration the total current within the accelerator is amplified from 40 to 4000 A by increasing the beam velocity (by a factor of ≈ 30) and decreasing bunch length (by a factor of ≈ 4). Downstream from the accelerator, power increases by an additional factor of ten, reaching 4×10^{14} W, because the "velocity tilt" imparted in the accelerator causes additional compression in the drift distance from accelerator to target.

Since 1984, the US Heavy-Ion Fusion Accelerator Research (HIFAR) Program at LBL and LLNL has been concentrating on the multiple-beam induction accelerator. (A parallel program in Europe is exploring rf linacs and storage rings.) A series of increasingly sophisticated experiments has explored, in scaled parameters, the accelerator physics of the induction approach; developed relevant accelerator technology; and estimated the capital costs and potential economics of induction drivers.

Early HIFAR experiments investigated fundamental aspects of ion-induction accelerators. One of the first experiments demonstrated that ion sources of adequate intensity and beam quality could be fabricated [3]. A Single-Beam Transport Experiment showed that it was easy to transport intense ion beams at the brightness needed [4]. The recently completed four-beam accelerator experiment, MBE-4, demonstrated that it is possible to amplify the current of ion beams during acceleration—an important driver feature—without appreciably degrading them [5]. In order to study most of the other beam manipulations required of a driver, we have proposed an accelerator and sequence of experiments collectively called the Induction Linac Systems Experiments, or ILSE.

2. ILSE PHYSICS DESIGN

A principal design criterion is that the beams must be of the same line charge density expected in a full-scale driver. As a consequence, the size of the beams and the strengths of the focusing fields in the accelerator will be directly relevant to the low-energy end of a driver. Thus, the ILSE accelerator and experimental program will allow realistic experimental investigation of many key issues, providing the base of knowledge needed for the next step.

Figure 2 presents a block diagram of the physics design of the ILSE accelerator and a possible arrangement of some of the experiments. Four beams from a 2-MV injector are matched to an electrostatic transport system and accelerated to 5.0 MV. The four beams are then combined into one and matched into a magnetically focused linac for further acceleration to 10 MV. A relatively light ion, potassium, is used to permit magnetically focused beam transport at energies approximately 20 times lower than those in a driver and therefore at a fraction of the cost. The electrostatic- and magnetic-focus accelerator sections of ILSE each contain 32 accelerating cells, which are physically grouped into blocks of eight. Each cell block is separated from the next by a full lattice period, which provides diagnostic access to the beams. Along the machine, as the focusing system becomes more efficient with increasing ion velocity, the length of the focusing lattice period increases from 66 cm in the first three blocks, to 82 cm in the fourth block, and then to 1 m from the beginning of the combining section to the end of the accelerator.

Amplification of current and control of longitudinal bunch length through the accelerator are essential components of our studies of induction linacs for HIF. These aspects require the use of carefully shaped accelerating-voltage waveforms. One method of finding waveforms for accelerating the beams, ignoring longitudinal space-charge effects, has been described by Kim and Smith [6]. In this self-replicating scheme, the profile of current versus time at a fixed location is preserved throughout the accelerator, and the magnitude increases as the bunch shortens in time. We adopted this scheme for the ILSE physics design. Solutions for the current and the accelerating waveforms at every accelerating gap can be constructed easily.

3. ISSUES TO BE ADDRESSED EXPERIMENTALLY WITH ILSE

By building and commissioning ILSE itself, and by subsequently performing an experimental program, we will examine most driver issues either directly or in scaled form. While ILSE will initially use ions in the range of neon to potassium, the results will be scaleable to ions with different charge-to-mass ratios, such as the mass 100–200 ions typical of a driver. We list here 10 experiments and systemwide issues in the ILSE Program and comment on the comparable features as incorporated in a driver.

3.1. Experiments within the linear accelerator

1. *Performance of the 4-beam, 2-MV injector.* Close in size to the injector needed for a driver, it will generate beams at full driver line charge density.

2. *Acceleration of four beams with electrostatic focusing.* This models the first 400 m of a driver and was investigated in MBE-4, but with smaller beams.

3. *Transverse beam combining or merging of four beams into one.* Studies show that this beam manipulation, although not essential, permits significant cost savings at driver scale.

4. *Acceleration of intense beams with magnetic focusing.* Acceleration of multiple beams with magnetic transport will be used in more than 90% of a driver. To date, acceleration of space-charge-dominated ion beams using magnetic quadrupole transport has not been studied experimentally.

5. *Pulse shaping and longitudinal control.* To achieve high gain, a fusion target requires a properly shaped pulse. ILSE will allow us to test various acceleration "schedules" to control pulse shape.

6. *Alignment and steering.* ILSE will allow us to examine the practical accelerator trade-offs between steering and alignment. Steering with time-dependent voltages will be investigated just after the electrostatic-focus accelerator, whereas steering with time-independent focusing will be studied in the magnetic-focus accelerator.

3.2. Experiments downstream from the accelerator

7. *Magnetic bending of an intense ion beam.* With most high-gain target designs, intense final beams that are dominated by space charge must be transported in bending magnets and turned through angles as large as 270°.

8. *Recirculating experiments.* The ILSE linac can be used as an injector for a recirculating-induction accelerator, a scheme that, in conceptual studies, has shown promise for reducing the cost of a heavy-ion driver. However, this type of accelerator is not as well understood as the induction linac. A more thorough examination of the physics of the recirculator is in progress. If successful, this device could increase the total beam energy of ILSE by a factor of ten.

9. *Drift-compression current amplification.* This manipulation amplifies the beam power just prior to the target. This is a fundamental and vital test of new beam physics in which the beam energy tilt is removed, rather precisely, by longitudinal collective accelerating forces at the beam head and decelerating forces at the tail. In other words, the velocity tilt causes beam compression over the drift distance, as previously mentioned, but eventually the space-charge forces remove the velocity tilt. The challenge is to arrive at the final focus with a highly compressed beam in which space-charge forces have zeroed the velocity tilt (thus avoiding chromatic problems in final focus) but have not yet caused beam blow-up. The ILSE beam will have enough line-charge density to remove an energy tilt of more than 10%, compared to an expected tilt of about 5% in a driver.

10. *Focusing, with or without neutralization, onto a small target spot.* Although there is extensive theory, relatively little is known experimentally about the behavior of space-charge-dominated beams in the target chamber. The higher perveance of the final ILSE beam will allow us to experiment under conditions more demanding than those in a driver.

3. PROSPECTS FOR ILSE

After receiving U.S. Department of Energy approval to begin construction, we would expect to build and commission ILSE within 5 years, at a total estimated cost of construction of roughly $60 million (1992 U.S. dollars).

In summary, ILSE represents a step beyond existing experimental facilities both in quantitative parameters and in the variety of the work that can be performed. It will have a highly flexible experimental capability with which we can address most of the remaining induction accelerator issues for inertial fusion.

4. REFERENCES

[1] Final Report, Fusion Policy Advisory Committee, U.S. Department of Energy Report DOE/S-0081 (September 1990).

[2] National Energy Strategy, First Edition 1991/1992, U.S. Department of Energy, Washington, D.C. (February 1991). Available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

[3] ABBOTT, S., CHUPP, W., FALTENS, A., HERRMANNSFELDT, W., HOYER, E., KEEFE, D., KIM, C., ROSENBLUM, S., SHILOH, J., "Large Aperture Contacts Cs +1 Ion Source for an Induction Linac," Lawrence Berkeley Laboratory Report LBL-8359 (March 1979).

[4] TIEFENBACK, M.G., KEEFE, D., "Minimum Steady-State Emittance to Current Ratio for Alternating Gradient Transport of Charged Particle Beams," IEEE Trans. Nucl. Sci. **NS-32**, pp. 2483-2485 (1985).

[5] FESSENDEN, T., "Emittance Variations in Current-Amplifying Ion Induction Linacs," Conference Record, 1991 IEEE Particle Accelerator Conference, **1**, p. 586, IEEE Catalog Number 91CH3038-7 (May 1991).

[6] KIM, C.H., SMITH, L., "A Design Procedure for Acceleration and Bunching in an Ion Induction Linac," Part. Accel. **85** (1986) 101–113.

TABLE I. HOW PAST LBL EXPERIMENTS COMPARE TO ILSE AND A DRIVER

	Line charge density	Initial current per beam	Final kinetic energy	Initial Tp	Final Tp
Cs ion source	0.5–1 μC/m	1 A	2 MeV	~0.1 eV	n/a
SBTE	0.03 μC/m	20 mA	200 keV	~0.1 eV	~0.1 eV
MBE-4	0.01 μC/m	~5–10 mA	1 MeV	~0.1 eV	~0.1 eV
ILSE	0.25 μC/m	~1 A	10 MeV	~0.1 eV	To be measured
Driver	~0.25 μC/m	~0.5 A	~10 GeV	~0.1 eV	<1 keV

T_p is the beam temperature perpendicular to the direction of beam propagation.

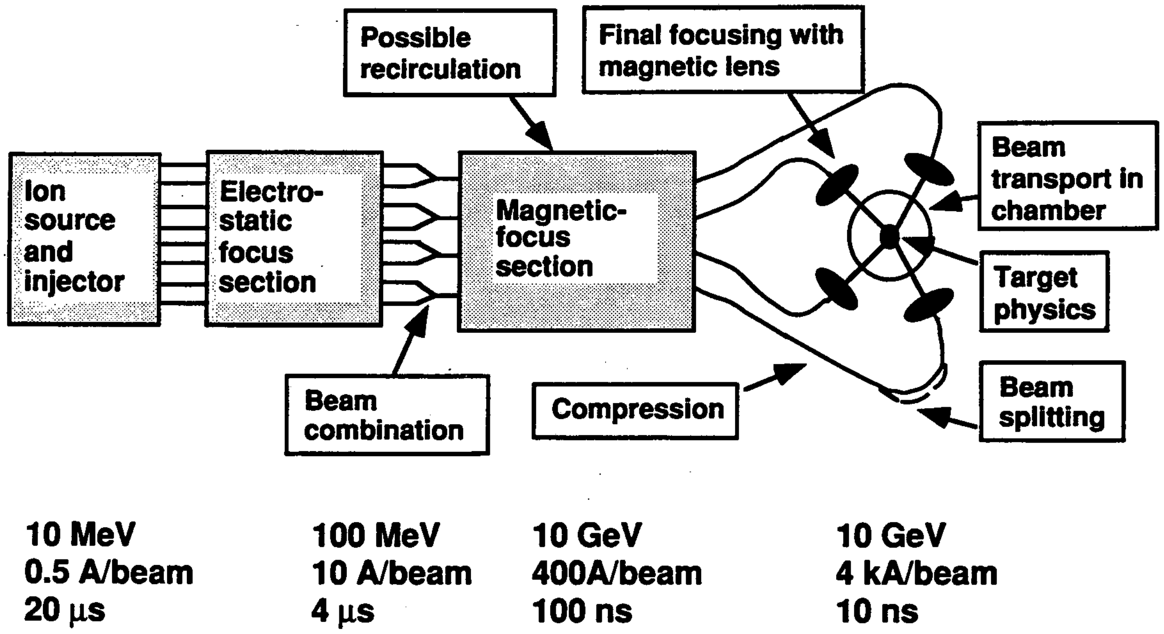

Figure 1. Schematic of a conceptual accelerator/driver that delivers 4×10^{14} W of heavy ions for 10 ns. The total length of the facility is expected to be 5–10 km.

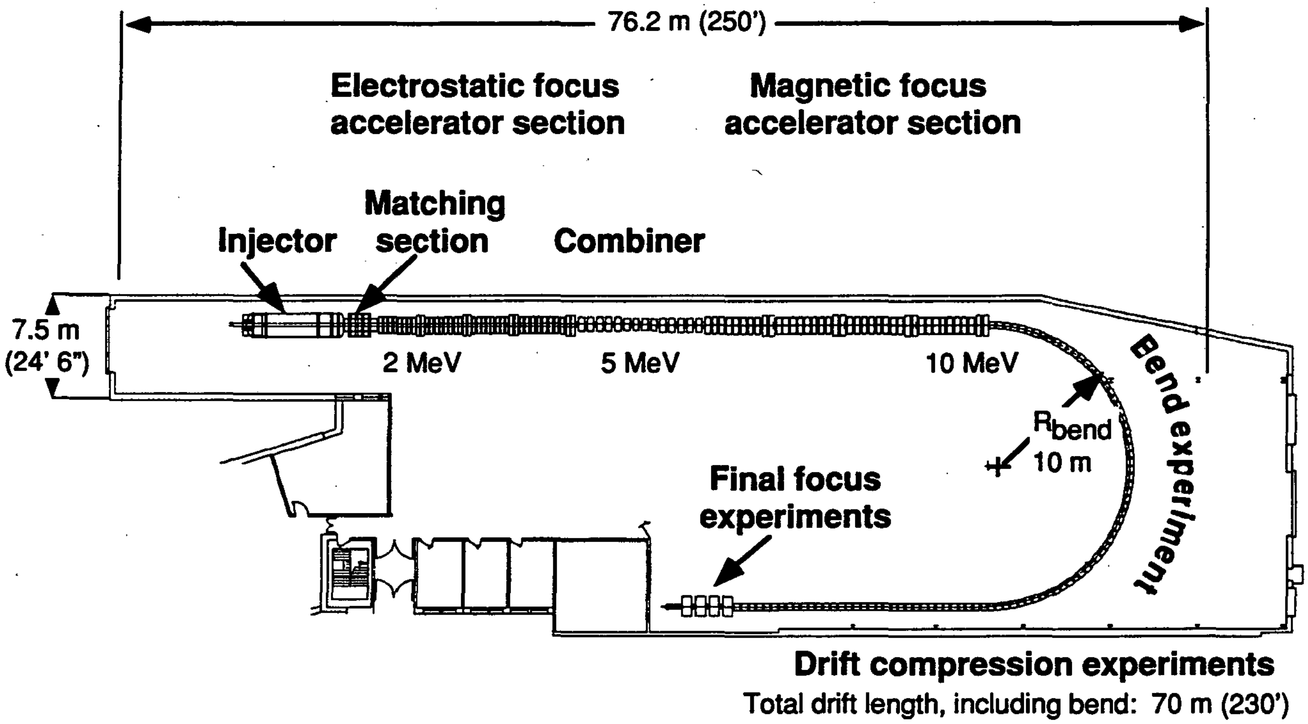

Figure 2. Diagram of the ILSE accelerator and principal experiments that will examine the induction linac approach to a driver.