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Heavy Ion Fusion Accelerator Research at the Lawrence Berkeley Laboratory

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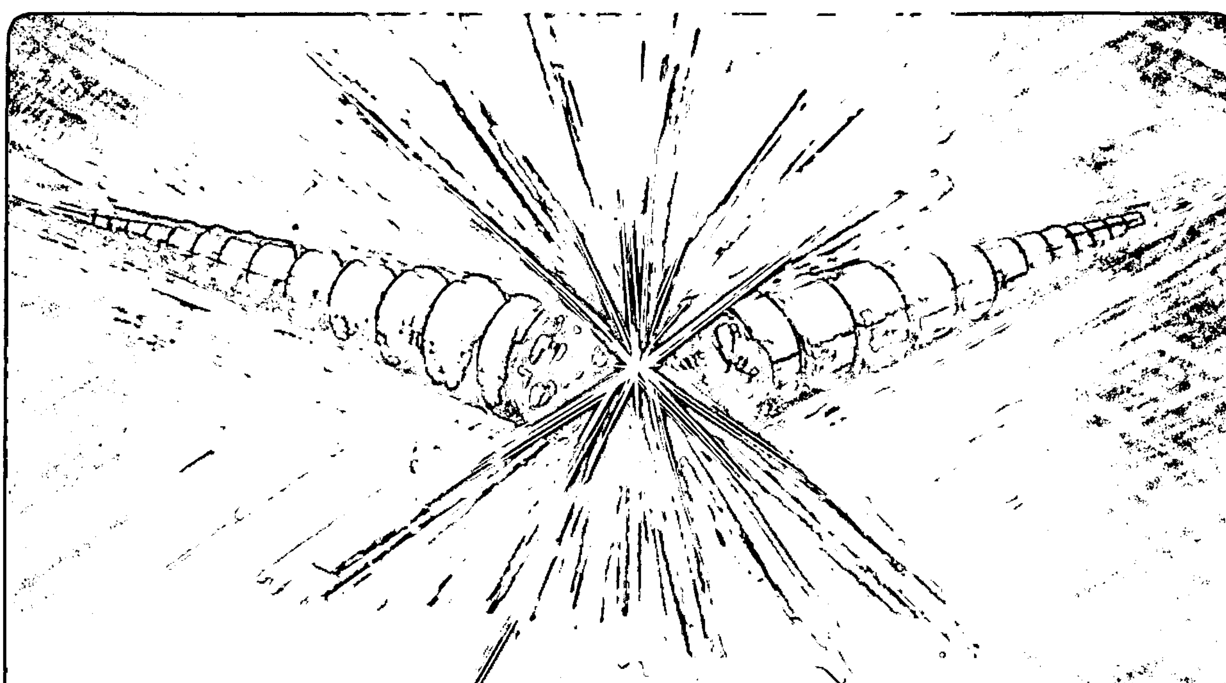

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HEAVY ION FUSION ACCELERATOR RESEARCH AT THE LAWRENCE BERKELEY LABORATORY

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HEAVY ION FUSION ACCELERATOR RESEARCH AT THE LAWRENCE BERKELEY LABORATORY*

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Abstract

Since 1983, U.S. research toward a heavy ion inertial fusion driver has concentrated on the multiple-beam ion-induction linac. This type of accelerator is unique in its ability to continuously amplify both the beam current and energy during the acceleration process. In a conceptual driver, many beams are accelerated in parallel through common induction cores in a linac that is 5-10 km long to final energies near 10 GeV in less than 0.2 msec. Past experiments at LBL have investigated the transport of intense ion beams in alternating gradient focusing structures and the acceleration of multiple ion beams with current amplification in an induction linac. At present our major project is the development of a pulsed, 2-MV injector that produces beams at full driver size and intensity. In addition, a major activity is the development of a physics and engineering design for a larger Induction Linac Systems Experiments (ILSE) to test in a scaled way almost all the manipulations needed in a full-scale driver. We hope to begin construction of this experiment near the beginning of 1995.

Introduction

The goal of the Heavy Ion Fusion Accelerator Research Program (HIFAR) is to develop accelerators for fusion energy production. Heavy-ion fusion, like laser fusion, uses intense beams to ignite small targets containing thermonuclear fuel. The "burning" fuel creates a burst of energy that can be contained in a target chamber or reactor. The beams from the particle accelerator or laser (the "driver") are focused onto the target, located at the center of the chamber, by lenses outside the chamber. (The targets typically would have a radius of a few millimeters and the target chamber would have a radius of a few meters.) In this scheme, which is called inertial fusion energy (IFE), the fuel burns so rapidly that it is confined by its own inertia. External confinement is not required, in contrast to the other main approach to fusion, magnetic fusion energy (MFE), in which the burning fuel is confined by magnetic fields. Research programs using the Nova and Omega lasers in the U.S. and the GEKKO XII laser in Japan, along with tests at the Nevada Test Site using nuclear explosives, have already put to rest fundamental questions about the feasibility of inertial fusion. It now appears possible to develop and build a demonstration power plant by the year 2025. Plans for this development are outlined in the National Energy Strategy[1]. The cornerstone of the Strategy's IFE plan is heavy-ion driver research.

Accelerator/drivers, designed to use the heavier ions such as xenon, cesium, or bismuth, are similar in many respects to the large accelerators that are used worldwide for basic research in high-energy physics. Many of the requirements for IFE have been demonstrated in existing accelerators. In particular, these accelerators usually have excellent reliability and long life. The new, additional requirement for fusion is the

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production of very high instantaneous beam power (greater than 10^{14} watts) in a beam that can be focused to hit a small target. There are two main methods of accelerating a heavy-ion beam in accordance with these requirements: induction and radio-frequency (rf) acceleration. Researchers in the US have chosen the induction accelerator because its relative simplicity and lower estimated cost appear to make it a more promising driver candidate. In Europe and elsewhere, the rf approach continues to be studied. Thus, the US program complements research in other parts of the world thereby assuring that the best heavy ion driver approach for IFE may ultimately be chosen.

Induction accelerator drivers for heavy ion fusion

A schematic diagram of a generic linear induction accelerator designed to produce 100 kA of cesium ions at the target at 4 GeV is shown in Figure 1. To achieve 100 kA, it uses several methods: multiple beams, beam combining, acceleration, and longitudinal bunching. Typical values of ion kinetic energy, beam current, and pulse length at various points in the accelerator are shown in the figure. Initially each of 64 beams has a current of 0.42 A at 2 MeV. The beams are accelerated to 100 MeV in an electrostatically focused accelerator. Thus, the velocity of each particle increases by about a factor of 7. At 100 MeV, the 64 beams are transversely combined in groups of four to form 16 beams. In the electrostatic-focus section, the physical length of the beams remains approximately constant; therefore, the combination of acceleration and merging increases the current of a single beam to $7 \times 4 \times 0.42 \text{ A} \approx 12 \text{ A}$. Acceleration to 4 GeV in the magnetically focused section produces an increase in velocity by a factor of 6.3 and would therefore give a current of 75 A per beam if the physical beam length remained constant. However, for economy and efficiency, it is desirable to compress the beam longitudinally by accelerating the tail to a slightly higher velocity than the head. In the example in Figure 1 a compression factor of 8 is assumed, leading to a current of 625 A/beam. As the beam leaves the accelerator, the head-to-tail "velocity tilt" is adjusted so that as the beam drifts toward the target, it is compressed by another factor of 10. This final compression gives 6250 A/beam, or, with 16 beams, the required power of 4×10^{14} W.

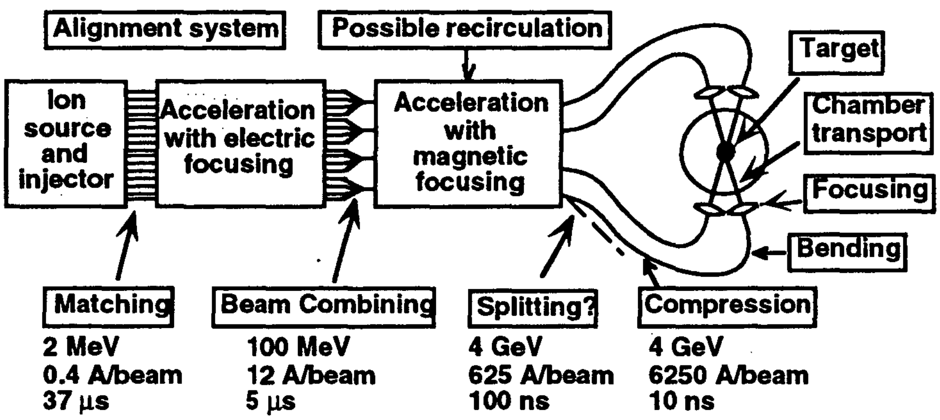

Figure 1. The accelerator systems and beam manipulations found in typical heavy-ion driver designs are represented by boxes. Typical values of energy, current, and pulse length are shown at various stages.

Recently, the HIFAR program at LLNL and at LBL has begun to investigate a recirculating induction accelerator. In this device several ion beams are accelerated in parallel in a relatively few turns in a series of circular induction accelerators. Figure 2 is a conceptual layout of a recirculating induction driver. Because the accelerator components are "reused" with each pass of the beams, significant cost saving should be possible. Pulsed magnetic dipoles of conventional construction are used to bend the beams around the ring during acceleration. The beams are focused by energy efficient superconducting magnetic quadrupoles that are not ramped. Because the beams remain in each accelerator for only 50 to 100 turns, acceleration of currents much larger than in conventional circular accelerators should be possible. An initial study [2] concluded that a 4-MJ driver with an efficiency of over 35% can be constructed for less than $0.5 billion. However, much less is known about the essential physics of this type of induction accelerator and experiments to model this type of experiment are still in the planning stage.

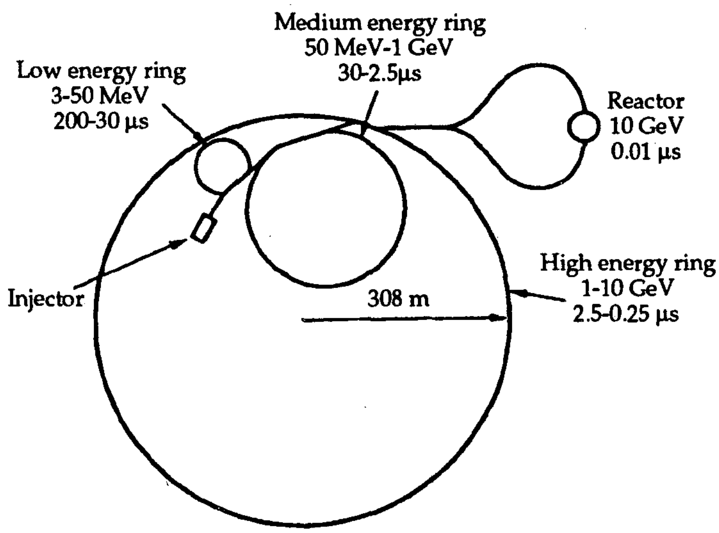

Fig. 2 Conceptual induction recirculating accelerator/driver for inertial fusion energy.

Past Experiments at LBL

Earlier experiments at LBL have addressed some important issues related to beam quality and the transport and acceleration of ion beams dominated by space charge rather than emittance. A high-brightness, 1-A cesium source was built and tested between 1977 and 1984. It gave a source temperature of 0.1 eV, about four orders of magnitude lower than the maximum value allowed at the final focus. The Single Beam Transport Experiment (SBTE), performed at LBL between 1981 and 1985, showed that it is possible to transport intense ion beams in an electrostatic-transport system without emittance growth [3]. In this experiment space-charge-dominated beams of Cesium^{+} were transported by 85 electrostatic quadrupoles with no measurable emittance growth provided the beam phase advance per period was less than approximately 85 degrees.

MBE-4, the first multiple-beam induction ion linac ever built, was used to investigate longitudinal and transverse beam control between 1985 and 1991. The fabrication of the major elements of the apparatus was completed in September 1987. The accelerator used low energy cesium ions to model the physics that is expected in the electrostatically focused section of a fusion driver but on a much smaller scale. Four parallel 10-mA beams of Cs+ at 200 kV were injected into a beam matching section, and accelerated to a little under 1 MV by 24 induction accelerator units. The four cesium beams were focused throughout by arrays of electrostatic quadrupole lenses. Each acceleration "section" had five quadrupole lattice periods, four induction units and one diagnostic/pumping station. The operation of the experiment required careful adjustment of the accelerating voltage waveforms to control the bunch length within the accelerator and to overcome longitudinal spreading due to space charge effects. Depending on the particular acceleration schedule, the total current increased from 40 mA to as much as 360 mA, by shortening the bunch within the accelerator from 1.3 m to 0.3 m and by increasing the ion speed by a factor of 2.2. The experiment was approximately 17 m long which is about 13 times as long as the initial bunch length.

The MBE-4 experimental program concluded [4] that current amplification in an induction linac is possible and the beams can be controlled longitudinally with the accelerating waveforms. However, even though beam space charge greatly reduces the impact of longitudinal acceleration errors, longitudinal control in MBE-4 was more difficult than we anticipated. The accelerator pulsers used for MBE-4 are based on conventional thyratron-switched pulse forming lines. This type of pulser does not have adequate waveform flexibility to easily control the beams longitudinally. Future ion induction linacs will require more agile correction or compensating pulsers every few accelerating gaps--particularly at the low energy end. Transversely, very cold space-charge dominated ion beams can be accelerated at constant normalized emittance if care is taken to match, center, and align these beams in the transport channel. However, for long linacs or drivers, extreme care may not be required. These experiments and simulations suggest that for sufficiently long systems, the beams will center and match themselves with an accompanying increase in emittance. This emittance growth may be affordable. Further study is required (experiments, theory, simulation) to determine if this so. The major multiple-beam issue encountered in these experiments was the diagnostic complexity associated with working with several beams.

ILSE

The next logical step towards the development of induction accelerator to drive inertial-confinement fusion targets is the Induction Linac Systems Experiments [5] (ILSE). The US HIFAR program has proposed to build this research facility starting in Oct. 1994 with experiments to begin in 1998. ILSE will be at full driver scale in several important parameters—most notably line charge density (a function of beam size), which was not explored in our earlier experiments. Nearly all other accelerator components and beam manipulations needed for an inertial fusion energy (IFE) driver will be tested, at full or partial scale, with ILSE. The goal of the program is to address all remaining issues in heavy-ion IFE except target physics, which is currently the responsibility of DOE Defense Programs, and the reactor chamber, thus providing a solid foundation of data for further progress toward a driver.

Figure 3 presents a block diagram of the physics design of the ILSE accelerator and a possible arrangement of some of the experiments. Four beams of K^+ at driver line-charge densities will be obtained from an injector at an energy of approximately 2 MeV. The nominal pulse width of the design is 1 µs. The injector is followed by a matching section that shapes the beams to the proper radius and "squeezes" them together for insertion into the electrostatically focused induction linac. To prepare the beams for current amplification, the electrostatic-focus section accelerates the tails of the beams more than the head. This causes the rear particles to catch up with the front ones, compressing the bunch and therefore increasing the current. The combiner, with 18 half lattice periods (HLPs), will merge the four beams together, a function that will be important in a driver. The magnetic-focus accelerator will continue current amplification while accelerating the beam to 10 MV.

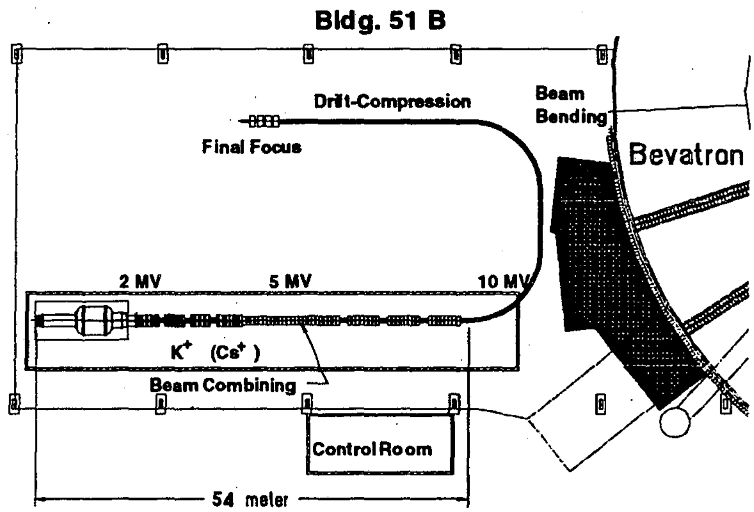

Fig. 3. Block diagram shows the accelerator and some of the initial ILSE experiments in the External Particle Beam (EPB) Hall of the recently shut-down Bevatron at LBL. The ILSE accelerator will later be used as the injector for an induction recirculating experiment.

The ILSE facility will enable experimental investigation of the following driver beam manipulations at significant scale. Within the linac we will examine:

Performance of the four-beam high-voltage injector;
Matching the beams to the accelerator;
Acceleration with electrostatic focusing;
Transverse beam combining;*
Acceleration with magnetic focusing;*
Beam pulse shaping and longitudinal control;
Alignment and steering.

Downstream of the accelerator we will study:
Magnetic bending of intense ion beams;*
Drift-compression current amplification*
Focusing with or without neutralization onto a small target spot;*
Beam storage and acceleration in an induction recirculator.*

Those items marked with an asterisk have not as yet been investigated experimentally at any scale within the HIFAR program. However, as will be described later, smaller experiments to study final focusing, beam merging, and induction recirculation are beginning or under study.

A summary and comparison of past LBL heavy ion fusion experiments with ILSE goals and with the requirements of an induction accelerator/driver for inertial fusion energy is presented in Table 2.

Table 2. Comparison of past experiments to ILSE and a driver (mass 200).

	Line charge density	Initial current	Final kinetic energy
Cs ion source	0.5–1 μC/m	1 A	2 MeV
SBTE	0.03 μC/m	20 mA	200 keV
MBE-4	0.01 μC/m	~5–10 mA	1 MeV
ILSE	0.25 μC/m	~1 A	10 MeV
Driver	0.25 μC/m	0.35A	~10 GeV

In addition to testing the remaining accelerator components and beam manipulations at meaningful scale, we have designed ILSE to meet long range programmatic objectives. To build a demonstration power plant by 2025, it will be necessary to begin design and construction of an accelerator at driver scale as soon as 2005. ILSE must be large enough to provide the data base and the justification for that facility.

Current Research at LBL

Injector Research

For several years the U.S. HIFAR program has been advancing the technology of high voltage, pulsed, heavy ion injectors. Past experiments [6] have studied injectors that employed a graded Pierce column at voltages up to one megavolt. Carbon ions were obtained from an arc source at an equivalent temperature of 2-5 eV. As a consequence, the emittances of the beams from the injector were too large for meaningful downstream heavy ion fusion experiments. In the fall of 1992, we concluded that potassium$^+$ from a zeolite at ≈0.1 eV would be a far better source of ions for use with ILSE. This source should permit the production of beams for the ILSE experiments at quite acceptable emittances. Modification of our existing injector hardware to provide a single potassium beam at full ILSE injector parameters of 2 MV and 0.8 A began in Oct. 1992. An added innovation was to use strong-focused acceleration for the injector between one and two MV. A second change was to switch to a low impedance MARX generator that provides a very square 4 μs pulse at 2-MV for the system. Fig. 4 contains a sketch of the new injector. At this writing the potassium source has been tested successfully and 0.8 A beams of potassium at one MV measured at the output of the diode. The strong-focused portion of the injector that will bring the beam to 2 MV is being assembled. Beam tests of the full system will begin in October.

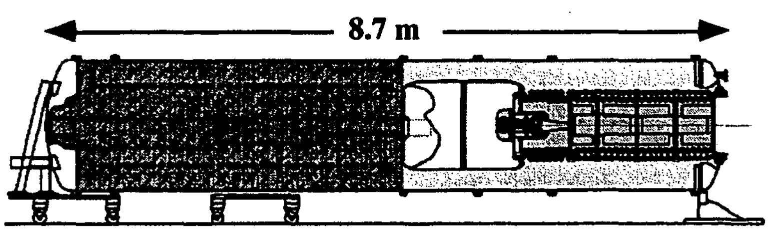

Fig . 4. Sketch of the 2-MV, 0.8 Amp K^+ Injector. This injector is a one-beam prototype for the ILSE injector.

Small HIFAR Experiments in progress

Final Focus

An experiment that models the effects of current variation on the focal spot in the target chamber is beginning on the SBTE apparatus. This experiment is being performed with AccSys Corp. of Pleasanton, California who proposed the experiment and constructed the focus magnet system.

Beam combining

We are initiating an experiment to study beam combining at scaled parameters using the MBE-4 injector. It requires a current of only 0.25 - 0.5 mA of Cs to obtain a perveance in MBE-4 (energy = 185 keV) equal to that of a driver beam. The resultant beams will have a major radius of 0.5 - 0.75 cm before combining, and approximately twice this after combining. These radii fit within the MBE-4 aperture, and therefore both the combined and uncombined beams can be focused by the MBE-4 electrostatic quadrupoles. A combiner is being designed, which will be inserted after the MBE-4 matching system. Fig. 5 presents a sketch of the experiment.

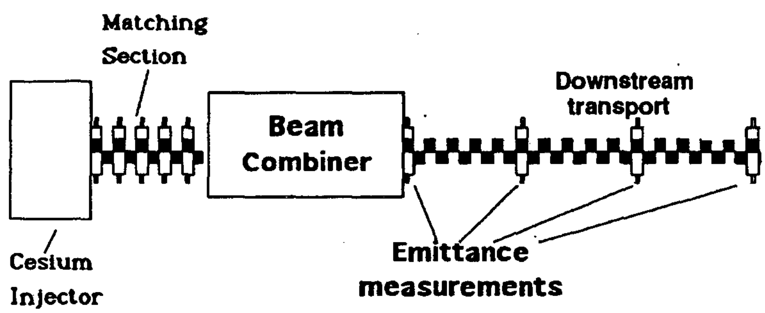

Fig. 5. Sketch of the beam combining experiment being installed on the MBE-4 apparatus.

This experiment will provide input to the ILSE combiner design by experimentally exploring the effect of misalignments, field aberrations, and the other beams on the passage of a beam through the achromatic combiner system. It will also measure the emittance growth due to beam bending and combining, providing data on the desirability of combining in a driver. It cannot explore the electrical engineering / physics issues inherent in combining at higher energy and charge-per-unit-length, such as arcing effects. Some of these issues will be addressed in ILSE, which has the same line-charge density as is presently planned for a driver.

Recirculating Induction Accelerator

Quite recently with our colleagues at the Lawrence Livermore National Laboratory, we have been investigating the possibility of fielding a small induction recirculator experiment at LLNL. A sketch of the experiment is presented in Fig. 6. The experiment would use beams of potassium at 80 kV from an injector similar to that used with the SBTE experiments. The beams would be injected into a ring with diameter near 4 meters. The beams will initially be focused in 5 cm channels by electric quadrupoles and bent in a circle by electric dipoles. Initial designs call for a total of 40 quadrupoles and dipoles around the ring. Eight induction accelerators placed symmetrically around the ring would control the longitudinal beam spreading and, within approximately 10 turns, accelerate the beams by a factor of 4 in energy to 320 kV. During acceleration, the K^+ ion current amplifies from 2 to 8 mA. This experiment can be performed economically in a relatively short time period Results from this experiment will be used to provide experimental physics input to the larger ILSE recirculator.

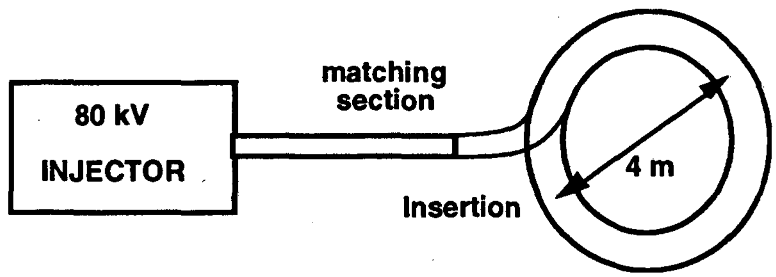

Fig. 6 An induction recirculator experiment planned at LLNL as part of the U.S. Heavy Ion Fusion Accelerator Research Program.

Summary

The US Heavy Ion Fusion Accelerator Research program is developing an induction accelerator/driver for inertial fusion energy production by 2025. Both the induction linac and the recirculating induction accelerator are being studied. Past experiments at LBL have demonstrated adequate sources, space-charge-dominated beam transport, and acceleration with current amplification. The ILSE research program has been defined and proposed to DOE sponsors for a 1995 construction start with beam experiments in 1998. A 2-MV potassium ion injector at the parameters needed for ILSE is nearing completion. Small experiments to investigate final focus, beam-combining, and induction recirculation are beginning at LBL and LLNL.

References

1. 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.

2 J.J. BARNARD. et al, "Study of Recirculating Induction Accelerators as Drivers for Heavy Ion Fusion", UCRL-LR-108095, LLNL, Sept. 1991.

3 M.G. TIEFENBACK and D. KEEFE, , "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).

4 T.J. FESSENDEN, "Emittance Variations in Current-Amplifying Ion Induction Linacs", Proc. of the 1991 IEEE Part. Accel. Conf., Vol. 1, p. 586, May 1991.

5 T.J. FESSENDEN et al, "ILSE, the Next Step toward a Heavy Ion Induction Accelerator for Inertial Fusion Energy". 14th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, Germany, Sept. 1992.

6 H.L. RUTKOWSKI et al., "The Berkeley Injector", Particle Accelerators, 37-38, pg.61, Feb. 1992.