Title
Heavy Ion Fusion Accelerator Research 1992

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Publication Date
1993-06-01

LBL-34254
UC-421

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Reprinted from *Accelerator and Fusion Research Division 1992 Summary of Activities*, LBL-33377 (December 1992).

This work was supported principally by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Support came from the Director, Office of Energy Research, through the Office of Fusion Energy.

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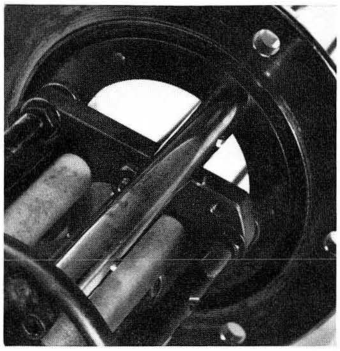

1.

HEAVY-ION FUSION ACCELERATOR RESEARCH

THE HEAVY-ION FUSION ACCELERATOR RESEARCH (HIFAR) program in AFRD has the long-range goal of developing accelerators for fusion-energy production. Heavy-ion fusion, like laser fusion, uses intense beams to implode and ignite, or "drive," small targets containing thermonuclear fuel. This creates a burst of energy that can be contained in a target chamber or reactor. The beams from the driver (a particle accelerator or laser) 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, called inertial fusion energy (IFE), the fuel "burns" in pulses that take place so rapidly the reactants are confined by their own inertia. This may be contrasted with the other main approach to fusion, magnetic fusion energy (MFE), in which the fuel is confined by magnetic fields and burns in long pulses or continuously.

The *National Energy Strategy*, published by the Department of Energy in 1992, calls for a demonstration IFE power plant by the year 2025. The cornerstone of the plan to meet this ambitious goal is research and development for heavy-ion driver technology. A series of successes indicates that the technology being studied by the HIFAR Group—the induction accelerator—is a prime candidate for further technology development toward this long-range goal.

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The emphasis on heavy-ion drivers is readily understandable. For engineering and economic feasibility, drivers must be both reliable and efficient. They must also have a high pulse repetition rate (several pulses per second) and long life (about 30 years). Existing drivers—lasers and light-ion accelerators—are excellent for near-term research, but they have been designed for a low repetition rate, typically a few shots per day. Therefore, new drivers must be developed for power production. During the last decade, nearly all high-level DOE and Congressionally mandated committees have identified heavy-ion accelerators as the most promising drivers for actual power plants.

The HIFAR program addresses the generation of high-power, high-brightness beams of heavy ions; the understanding of the scaling laws that apply in this hitherto little-explored physics regime; and the validation of new, potentially more economical accelerator strategies. (The strategy-validation issue is especially important because an inertial-fusion power plant will have to be a success not only in physics and engineering, but also in commerce.) Key specific elements to be addressed include:

- Fundamental physical limits of transverse and longitudinal beam quality.
- Development of induction modules for accelerators, along with multiple-beam hardware, at reasonable cost.
- Acceleration of multiple beams, merging of the beams, and amplification of current without significant dilution of beam quality.
- Final bunching, transport, and focusing onto a small target.

In 1992, the HIFAR Program was concerned principally with the next step toward a driver: the design of ILSE, the Induction Linac Systems Experiments. ILSE will address most of the remaining beam-control and beam-manipulation issues at partial driver scale. A few parameters—most importantly, the line charge density and consequently the size of the ILSE beams—will be at full driver scale. This will allow us to model some particularly important beam behaviors, which were not addressed by the earlier experiments, at energies much lower than those of a driver. The ILSE proposal was well received, and the DOE responded with a Determination of Need, the first "key decision" on the way to authorization of a construction start.

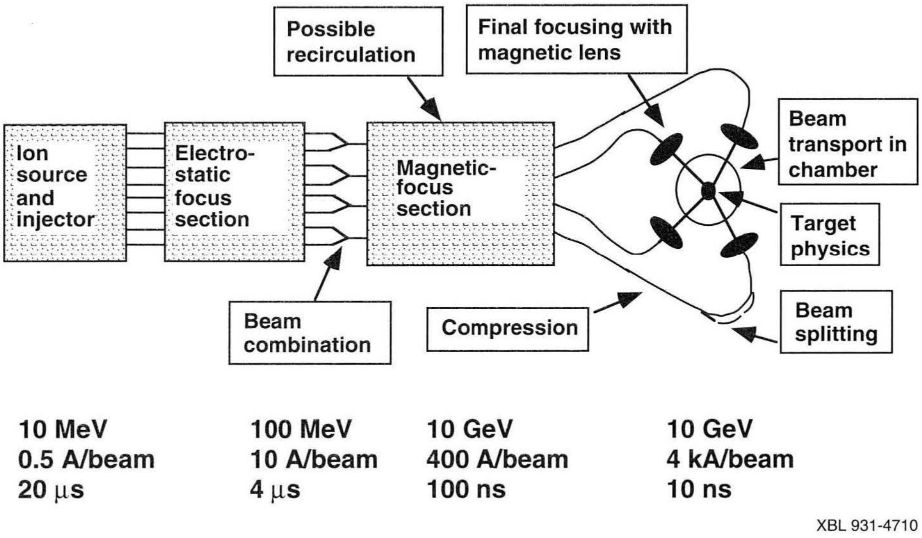

Figure 1-1. The accelerator systems and beam manipulations found in typical heavy-ion driver designs are represented by boxes. A highly accurate alignment system, not shown, will be used throughout. The shaded boxes represent systems that have been tested in past experiments (AccSys Technologies is planning a small-scale focusing experiment on LBL's existing SBTE apparatus). The remaining issues, except target physics, will be tested in ILSE and its anticipated experimental program. Typical driver values of energy, current, and pulse length are shown at various stages.

A theory group closely integrated with the experimental groups continues supporting present-day work and looking ahead toward larger experiments and the eventual driver. Much of the group's effort in both areas during 1992 was of course focused on ILSE, but long-range theoretical and experimental research continued. Highlights of this long-range, driver-oriented research included continued investigations of longitudinal instability and some new insights into scaled experiments with which we might examine hard-to-calculate beam-dynamics phenomena.

Induction Linac Systems Experiments

The next logical step on the road to a driver is ILSE, the Induction Linac Systems Experiments. The multi-beam apparatus will provide the first data on several significant capabilities that will be necessary or at least economically desirable in a driver. They include:

- *Combining parallel ion beams dominated by space charge.*
- *Making the transition from an electrostatic to a magnetic beam-transport system.*
- *Magnetic bending of intense, space-charge-dominated ion beams.*
- *Amplifying current by "drift compression."*
- *Focusing ion beams precisely onto a small spot.*

A new design for the apparatus was developed in 1992, and a Conceptual Design Report, or proposal, was prepared in April. The design has since been undergoing improvements and will be proposed in fiscal year 1993 for a construction start in FY95.

ILSE Physics Design

In the ILSE conceptual design (Figure 1-2), four beams are accelerated and electrostatically focused, then combined into one, thus providing data on a possible driver feature.[*] The beams are further accelerated in a subsequent section, this time with magnetic focusing. In both the electrostatic-focus and the magnetic-focus sections, the beam is compressed—another important feature. Then the beam is used for experiments in drift compression and final focus.

The new ILSE also has the same line charge density, in beampipes of the same diameter, as the electrostatically focused section of a postulated driver. ILSE will thus allow us to test this driver parameter at full scale. (Most ILSE parameters, as shown in Table 1-1, are scaled down from those of a driver.) Another aspect of ILSE that may turn out to be highly relevant to a driver is a set of provisions for recirculating acceleration.

Economic studies of recirculating induction ion accelerators, performed at Lawrence Livermore National Laboratory (LLNL) in collaboration with our group, have indicated that such a driver might be less expensive than a linear induction accelerator. However, much less is known about the physics of recirculating induction ion accelerators. Various schemes are being

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[*] Beam combination appears to be a good way to increase the current of the beams without greatly increasing the length of the accelerator (which, in a driver, will be some hundreds of meters). This would be economically attractive. However, it would not be strictly necessary should experiments show that it is not feasible to combine driverlike beams without spoiling the beam quality.

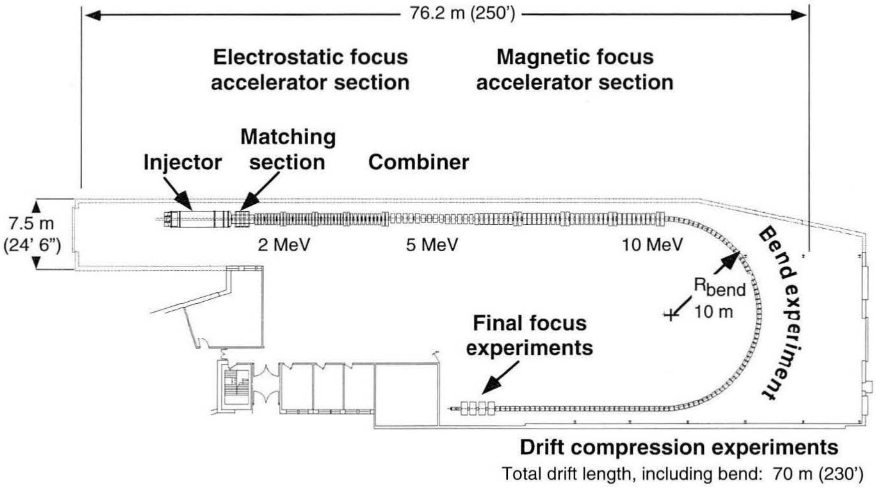

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Figure 1-2. This diagram shows the physics design of the ILSE accelerator and a possible arrangement of some of the experiments. The 2-MeV injector provides four beams of Ne^+ or K^+ in 1-μs pulses at driver line-charge densities. A matching section transforms the round beams to an alternating gradient profile and "squeezes" them together for insertion into the electrostatically focused linac. To amplify the current, the electrostatic-focus induction linac imparts a velocity shear or "tilt" to the beams as it accelerates them to 4.5 MV. A subsequent magnetic-focus induction linac, which also amplifies current, takes one of the beams to 10 MeV. A later phase of ILSE will combine the four beams into one for injection into the magnetic-focus linac.

studied for extending the ILSE sequence of experiments to cover the essentials of the recirculating approach in case theoretical work indicates the desirability of these experiments.

The result of the physics design effort is a "point design" — a self-consistent design, selected from a broad continuum of possibilities, that best addresses our experimental needs within our space and funding prospects. The engineering design that builds upon the physics point design was completed in 1992 and is being refined to best fulfill our experimental needs within realistic funding prospects.

ILSE will be constructed in two phases. During the initial "project" phase, the electrostatic-focus section (which accelerates the beams from 2 to about 5 MeV) and the later magnetic-focus section (5 to 10 MeV) will be connected by a transfer line. The transfer line will contain diagnostics and

Table 1-1. Key parameters of HIFAR experiments and an example driver.

	SBTE	MBE-4	ILSE	LMF-based example
Ion species	Cs^+	Cs^+	K^+	Kr^+
Number of beams	1	4	4→1	20→4†
Final voltage (MV)	0.15	1	10	25 000
Total final energy (J)	0.07	0.08	60	5×10^6
Final ion velocity/c	0.0016	0.004	0.03	0.25
Bunch length (m)	8.0	1.1→0.25	8.8→8.8*	70→10*†
Pulse width (μs)	20	2→0.4	2→1†	24→0.1†

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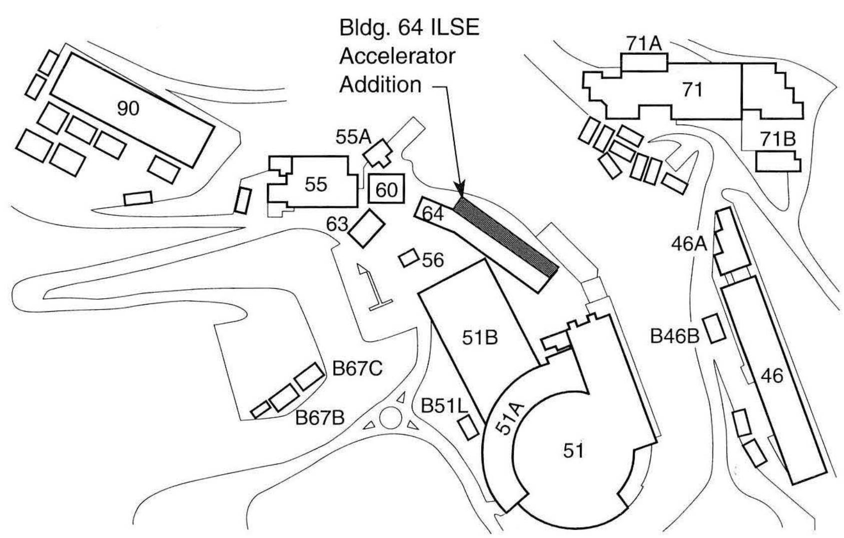
[*] These pulse lengths are given at the end of the accelerator section. In a driver, drift compression would further shorten the pulse. Note also that smaller, less-intense beams can be compressed further.

[†] The bunch lengths and pulse widths specified here, with their beam-compression implications, are hypothetical driver values, not calculated LMF values.

will introduce an offset that couples one of the four beams into the magnetic-focus section. During this phase, the other three beams will not be accelerated in the magnetic-focus section.

Later, during the experimental program, we will remove the transfer line to provide space for combiner experiments that merge the four beams to make one beam of higher current. The magnetic-focus accelerator will continue current amplification* while accelerating the beam to 10 MV. Construction would start in fiscal 1995 under the proposal that we plan to submit in 1993; various parts of the experimental program would follow successive intermediate stages of construction. A variety of siting options are being evaluated, a decision process that is being coordinated with the probable decommissioning of the Bevatron. Figure 1-3 shows the option that was described in the 1992 *Conceptual Design Report,*



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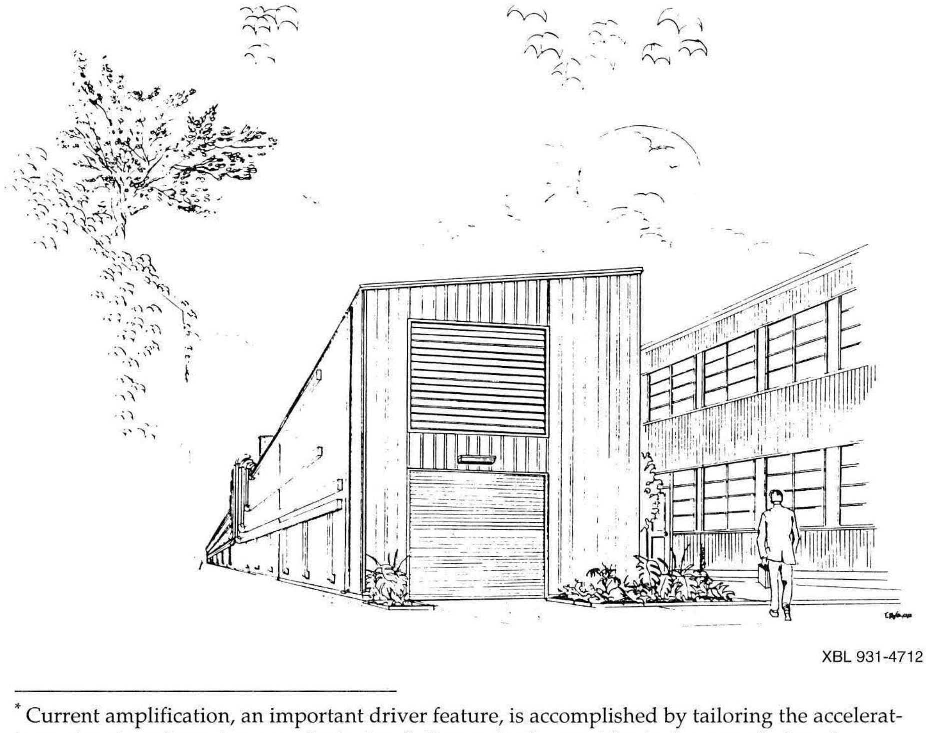

Figure 1-3. The 1992 proposal specified an ILSE site in is an area behind Building 64 near the Bevatron accelerator. ILSE would be housed largely in a new two-story addition to Building 64. Other possibilities are being examined, including part of the site of the Bevatron itself, which was recently scheduled for shutdown and decommissioning.

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[*] Current amplification, an important driver feature, is accomplished by tailoring the accelerating pulses in order to impart a "velocity tilt," or make the particles in the rear of a bunch go faster than the ones in the front. This presents a number of challenges in technology and operations, but its basic feasibility was demonstrated in our earlier MBE-4 experiment. In the "experiment" phase of ILSE, we may test drift compression after the accelerator—another driver feature in which the last acceleration modules give the tail of the bunch one last kick, creating a velocity tilt that has its beam-compression effect on the way to the target.

which was written before the news of the Bevatron's 1993 closure was received: an addition behind Building 64 near the Bevatron. The External Particle Beam hall (user area) of the Bevatron now looks like the most attractive site: it is a large high-bay building with infrastructure items of suitable capacity, such as electrical utilities.

A broad R&D program is being conducted to develop ILSE components and systems, including the ion source and injector, the induction cores, and beam instrumentation. Theoretical work has also been done on the methods and effects of transverse beam combination in ILSE and in a driver. A conceptual design study of the ILSE combiner is in progress.

Ion-Source and Injector Development

Progress toward an injection system for ILSE continued on several fronts in 1992. An existing carbon-arc source and 1-MeV injector were used for various experiments with transient C^+ pulses. A study group examined possible approaches to the injection system, recommending a 1-MV electrostatic aperture accelerator feeding an electrostatic-quadrupole accelerator. Subsequently a scaled experiment was performed on the SBTE, Single-Beam Transport Experiment (the principal HIFAR apparatus from the early 1980s, which has been brought out of mothballs several times for beam-transport and focusing studies). Meanwhile, development and evaluation of various candidate ion sources continued; it now looks as though we will use a hot-surface alkali-metal source. We also began design work on a major modification of the 2-MV Marx generator; the new design, which will not have to supply long pulses, should offer much lower impedance.

The study group, composed of personnel from LBL and Lawrence Livermore National Laboratory (which has collaborated with us extensively on ILSE), along with other experts, was established to study the injection needs of ILSE. Information was gathered from other laboratories that have built high-voltage injectors; this was followed by a large theory effort to model the candidate injectors in two and three dimensions. Two candidates were examined: the electrostatic aperture column (ESAC) accelerator—which in our case would be a diode, a single-gap accelerator, operated at 0.5 to 1 MV—and the electrostatic-quadrupole-focused column accelerator (ESQ). Each proved to have its strengths and weaknesses. The ESAC approach entailed increased risk of insulator breakdown as the total voltage increased. The ESQ could cause emittance growth because of the "energy effect," a phenomenon in which different energies are imparted to particles at different radial positions in the quadrupole apertures even if their axial positions are the same.

The study culminated in a design workshop that recommended a combination of the two approaches, each in its most appropriate role: an 0.5-1 MeV ESAC feeding an ESQ that takes the beam to the full injection energy of 2 MeV. This technology is similar in concept to an accelerator being developed by AFRD's Magnetic Fusion Energy group, which has collaborated with us extensively during the ion-source and injector efforts. We plan to build a single-beam prototype in 1993.

The injector will obtain K^+ from a surface-conversion ion source in which K or another alkali metal is embedded in an aluminosilicate (zeolite) carrier. (Zeolite can be infused with a great deal of carried material, which gives it a variety of industrial and scientific uses; in this case, the benefit is long source lifetime.) An injector with an ESAC first stage might require a source with a diameter of about 22.4 cm and a current density of about 2 mA/cm^2. Zeolite sources can definitely meet the ILSE requirements, which are a total current of about 790 mA of K^+ with a normalized transverse emittance of a fractional π mm-mrad. After considerable applied research, we have developed a new potassium-implantation technique that combines long life and the required performance: tests of a 2.5-cm-diameter prototype (Figure 1-4) on SBTE indicated a current density of 19.5 mA/cm^2 (limited by the optics of the extraction diode, not by the source's capabilities), a normalized transverse emittance of 0.2 π mm-mrad, and a lifetime of some months in the ILSE duty cycle. We are now extending R&D efforts to sources with diameters in the 10-cm range.

Another approach that was studied for possible use in ILSE was an rf-powered source in which the plasma is confined by a multicusp magnetic field, much like the ion sources developed by AFRD's magnetic fusion energy program and described in Chapter 2 of the *AFRD Summary of Activities.* The low ion temperatures reported for these sources should permit development of flexible, low-emittance sources suitable for our needs. The higher line charge density of these beams also supports the goal of modeling some characteristics of a driver. Finally, these sources can provide a variety of ion species, including various noble gases, which is interesting because ILSE can be operated with ion species ranging in mass from carbon to potassium.

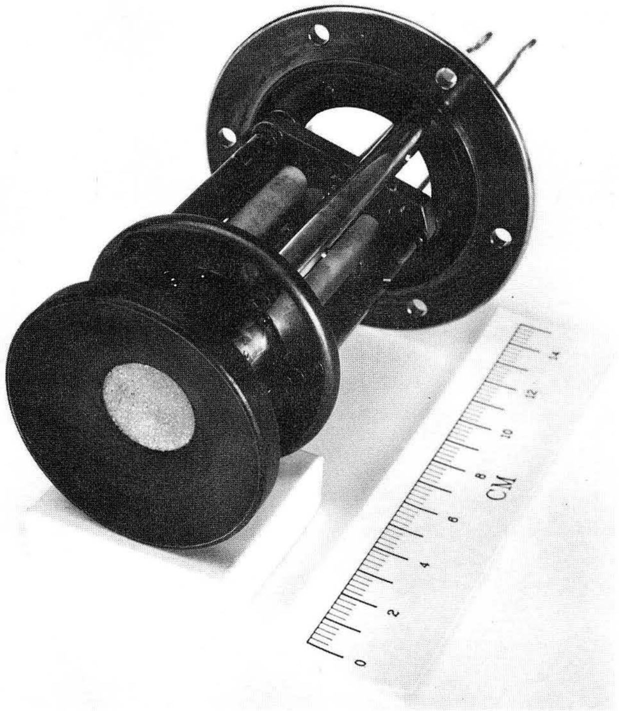

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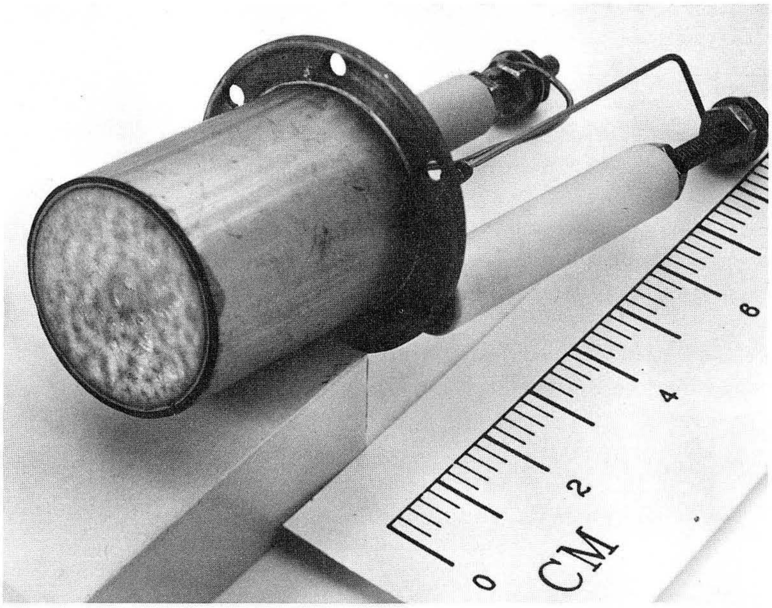
Figure 1-4. This one-inch experimental ion source incorporates two LBL-developed improvements to an existing technology: artificial zeolites incorporating the desired ion species, which in this case is potassium. The two innovations are applying the zeolite to a porous tungsten plate and heat-treating it between 1400 and 1700° C. In this range, crystals a fraction of a millimeter in length, similar to the mineral cristobalite, are formed. Lower temperatures, as in previous attempts to use zeolite, sinter the material, compromising its mechanical integrity, and higher temperatures would vitrify it. The use of porous tungsten helps keep the zeolite coating from puddling into nonuniformities on the curved surface, a defect that would show up in the extraction optics, and also contributes to mechanical strength. The result is a source that meets ILSE's severe requirements for low beam "temperature" and shows no physical or performance degradation in one month of simulated ILSE duty. Shown here are the zeolite in its heat shield, as well as a complete ion source in Pierce geometry.



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The choice of ion species is a complex issue (*sidebar*); the 1991 physics point design assumed that ILSE would accelerate Ne^+. However, the new point design uses K^+, a species readily available from the zeolite source, and the extraction of short pulses from plasma sources (which were designed as part of a program that deals primarily with long pulses) can be problematic. (If the use of small extraction apertures proved feasible, we could use higher ion temperatures and therefore obtain shorter pulses without compromising the source brightness.) The multicusp source remains promising as a "fallback position" or as a source of nonmetallic ion species for experiments that have not yet been conceived.

ILSE Transport Physics Studies on SBTE

In preparation for using an ESQ stage in the ILSE injector, we have been performing an ESQ physics experiment on SBTE. The apparatus was equipped with one of the aluminosilicate K^+ ion sources, and the accelerating column was modified into a single diode with a 3.3-cm gap to accelerate the beam to 27 kV. The three electrostatic quadrupoles from the SBTE matching section were turned into an accelerating ESQ by reconnecting their power supplies; this ESQ accelerates the beam to 54 kV. With this configuration, we are studying the beam dynamics along the ESQ section. These experiments search for a subtle emittance growth due to the "energy effect," as mentioned earlier. This potential problem, which was predicted by various studies, including simulations with the particle-in-cell code Argus, affects beams whose longitudinal energy is large in proportion to the quadrupole voltage and whose envelopes are large enough to approach the quadrupoles. The phase-space profile in the vertical direction, the emittance growth along the ESQ, and the amount of the beam hitting the quadrupoles were found to be consistent with the Argus results and with Faraday-cup measurements of total beam current at various points. Similar horizontal measurements are next on the agenda. We also plan to reconfigure SBTE for a scaled injector-diode-and-ESQ experiment that will examine the transverse beam dynamics in the ESQ, and we will experiment with a quadrupole correction scheme that should eliminate the predicted growth in transverse emittance.

Selecting an Ion

ILSE could accelerate a range of elements at various charge states. Choosing the best one for the experimental program is subtle and complex.

In ILSE, the capabilities of the magnetic beam-transport section will play a major role in the decision, as they will in subsequent systems. The force that can be exerted by a given magnetic field depends on the velocity, and thus the energy, of the ion beam. The heavier the ion, the bigger and more expensive the accelerator required for a given velocity. In ILSE, a few-MeV beam of an ion species of moderate mass will allow approximation of the beam physics of a very heavy ion species at many tens of MeV. Also important are the ease and reliability with which multi-ampere quantities of the ion can be produced in the desired charge state.

In principle, higher charge states are desirable because they multiply the force that a given electric or magnetic field can exert upon the ion. (The charge of an ion is the "handle" by which it is manipulated.) In practice, however, sources capable of higher charge states tend to put out the lower ones as well. Separating the undesired species does not appear practical for the purposes of ILSE. Another factor, more significant for future experiments than for ILSE, is that the actual beam current is likewise multiplied, possibly crossing into a region of high-current instability for the energy in question.

Subject to these considerations, K^+ has been chosen for the 1992 ILSE physics point design.

As heavy-ion IFE progresses to target shots, the desired power deposition in the target will become an important factor. The driving beams have to deposit roughly 10^{15} W cm^{-2} in the outer shell of the target over a period of about 10^{-8} s. To achieve the correct combination of power and range, heavier ions need higher energies but correspondingly lower currents, an advantage that helps avoid high-current instabilities. Economic considerations also come into play; doubling the current would increase the risk of high-current instabilities (and the required strength of the focusing fields) but would also halve the length of the accelerator. Studies indicate that Bi and Hg— possibly in a charge state as high as +3, with the +1 and +2 ions magnetically separated—are promising candidates.

Induction Core R&D

Induction-accelerator designers have a variety of magnetic materials at their disposal for the acceleration cells. In an induction accelerator for HIF, the ion current will typically be a small fraction of the magnetizing current at the beginning of the acceleration cycle. The magnetic material chosen sets the current drive required from the modulator. Hence the choice of materials is determined by the combined cost of the material and the modulator driving it, as well as by the performance requirements. The logical choice for ILSE is Metglas, a "metallic glass" magnetic alloy, available in various formulations, that is used in large volumes for 60-Hz power applications. Because of its intrinsic properties (high resistivity and high capability to respond to time-varying magnetic-field gradients) and a method of fabrication that leads to very thin ribbon, Metglas is also well suited for the ILSE application, which requires rates of magnetization of 1-5 T/μs.

Some research and development was required in order to learn how the power industry's materials and practices might apply to a short-pulse induction accelerator. At 60 Hz, the metallic glass is annealed to maximize ΔB. At 60 Hz, only a few millivolts of potential difference is induced between adjacent turns of ribbon, so surface oxides and resistivity provide sufficient insulation. However, the high magnetization rates in ILSE, the voltage induced per turn will be closer to 10 V. Coatings that could withstand the annealing temperatures and would not adversely affect the magnetic properties are available, but would add considerably to the cost of the cores, so we began experimenting with unannealed Metglas on our induction-core test stand (Figure 1-5).

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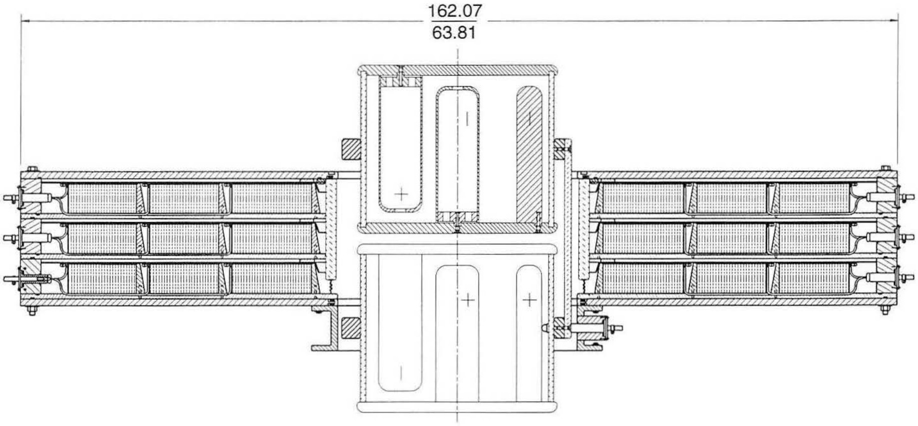

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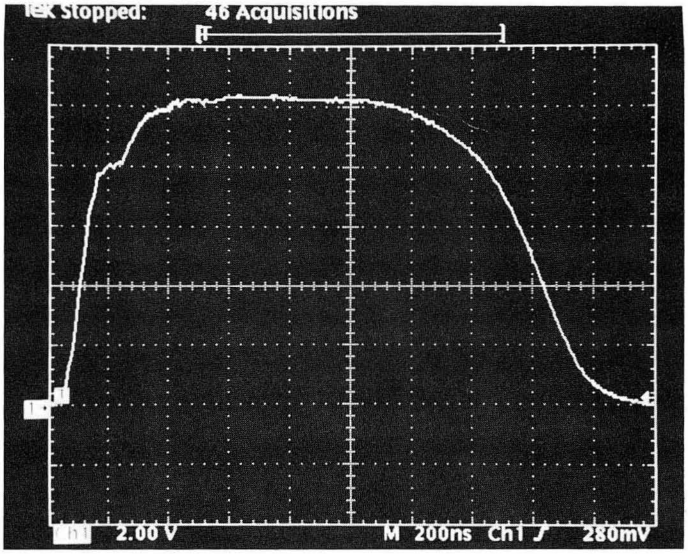
Figure 1-5. A test stand enables us to make a great many measurements, without beam but otherwise under realistic conditions, of prototype ILSE induction cores. A cross section of a typical three-core cell from the electrostatic-focus accelerator section is shown in the line drawing.

The tests were conducted using two cores made with 2605 SC Metglas, the alloy with the optimum properties for ILSE. One core was wound by our technicians, the other by Allied-Signal Corp., the supplier of the material. The results (Figure 1-6) confirm that the unannealed material is quite acceptable for ILSE. Our 1993 plans include constructing enough cores with this optimum material to make up one 33-cm lattice half-period of ILSE for further development of pulsed power supplies and waveform correction systems.



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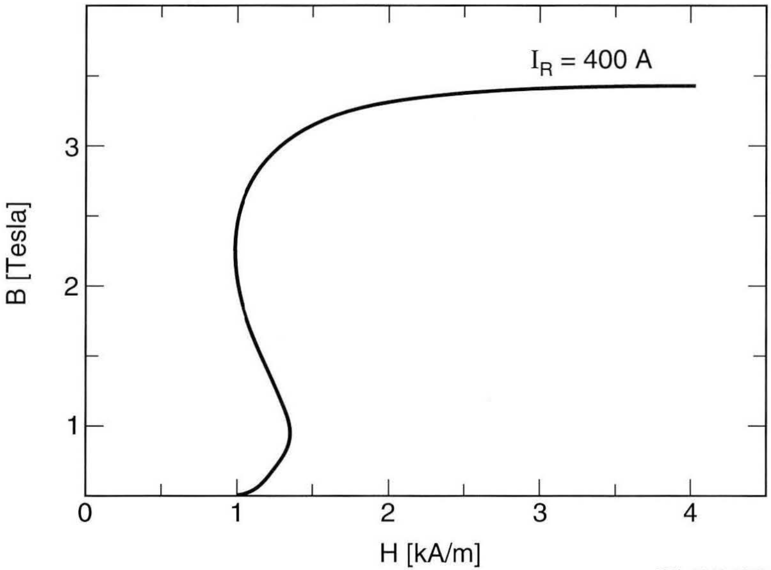

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Figure 1-6. Results from the test stand show that the performance of "as cast" (unannealed) 2605 SC Metglas will be sufficient for ILSE, both in magnetic properties and in its turn-to-turn insulation. These illustrations show that the core responded to a fast pulse (*photo*) with a flux swing of 3 T at an acceptable magnetization rate. This is good news because insulation materials that could withstand the annealing process and would not degrade the magnetic properties would add considerably to the cost of ILSE. The performance of unannealed 2605 SC, by contrast, will make the cost of the cores lower than we had anticipated early in 1992.

Magnet Design

An important factor in the design of ILSE (and subsequent accelerators for heavy-ion fusion) is the maximum beam current that can be transported through the quadrupoles of the magnetic-focusing accelerator section. The greater the current per beam, the fewer the beams and therefore the lower the cost. Using numerical particle simulation we have studied this problem in terms of preserving beam quality during transport (that is, minimizing emittance growth) and determining the maximum dynamic aperture that can be achieved.

In 1992 our magnet design work concentrated on large magnets whose radius is a significant fraction of the accelerator's lattice half-period. In such magnets the anharmonic "fringe fields" that extend longitudinally beyond the winding become increasingly important. As an aid in this effort, we improved our simulation code HIFI to account accurately for the way ILSE's space-charge-dominated beams* respond to nonlinear external focusing fields. One of the candidate designs that resulted has no azimuthal multipoles whatsoever apart from the desired quadrupole field.

However, the effects of higher-order components are not necessarily adverse. We began a study, using analytical methods and transport simulation codes, of the effect that nonlinear transverse and longitudinal fringe fields exert upon emittance growth. It could be that judicious introduction of an octupole field (a technique used in many final-focus magnet designs) will be able to significantly reduce the emittance growth that stems from these fringe fields.

Also underway is a study of dynamic aperture (the cross-sectional area beyond which oscillations are no longer coherent and particles are lost to nonlinear-dynamic processes) as a function of phase advance per cell and the relationship of this range to the maximum transportable current. It appears that the maximum transportable current is nearly invariant for phase advances of 10-45° even though the corresponding beam size varies by more than a factor of two over this range—a finding that promises considerable latitude in this parameter when a driver is designed.

The "LMF driver" is a point design for a heavy-ion driver that was studied on behalf of the Laboratory Microfusion Facility, a possible weapons-physics and weapons-effects facility that has been discussed in recent years. An IFE power-plant driver is expected to be similar to the LMF driver.

Long-Range Research and Development

Although present-day and near-future research programs such as ILSE occupy much of our attention, we also engage in various experimental and conceptual efforts (by ourselves and in collaboration with colleagues from other institutions such as LLNL) that look further down the road to a driver.

Longitudinal Instability Studies

Studies have indicated that a driver of the kind we are studying—an induction linac accelerating high-current pulses of heavy ions at subrelativistic velocities—may be subject to a slow-growing instability: the unstable growth of current fluctuations. The unstable mode is caused when the beam induces an electromotive force in the induction cores of the accelerator; this "back-EMF" affects the beam. The net effect is a growing wave that moves forward in the accelerator but does so more slowly than the beam and thus moves backward in each pulse. This effect is closely related to various phenomena that have to be avoided or controlled in other accelerators, such as the transverse beam-breakup mode in electron linacs and an instability that affects cold beams of either ions or electrons in storage rings.

In the late 1980s, as driver concepts became better defined, we and others realized that the drivers' parameters, including the use of multiple beams, pushed the predicted growth length of the instability into the 50-500 m

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* The ion beams in a driver and in ILSE are strongly space-charge-dominated rather than emittance-dominated. That is, the beam size in the focusing channel is essentially determined by the charge of a bunch of particles (which all have the same charge sign, positive in this case, and therefore repel each other) rather than by the beam's emittance, or the thermal motion of the individual particles.

range. This permits considerable growth over the several-kilometer length of a driver. Consequently there has been a vigorous effort at several laboratories to understand the nature and control of this instability. While we and others search for means of direct experimental investigation, the instability has been studied with one- and two-dimensional particle-in-cell simulations, examinations of feedforward control, impedance-model calculations, and a variety of other theoretical approaches. We have also performed experiments with a scaled driver module (Figure 1-7).

The model duplicates the rf properties of an actual acceleration module from a driver. Data from these rf studies were used to validate our computer models of how the ion beam in a driver would react with the accelerating units at frequencies relevant to the longitudinal instabilities. ILSE will not be long enough for a complete test of these instabilities, although some driverlike beam-dynamics experiments will be possible.

The model core is nearly driverlike in size with an inner diameter of 1 m and an outer diameter of 2 m. The area between would be filled with ferromagnetic material in a real core. In this model, about 1 out of every 10 cm along the radius is filled with Metglas 2605 CO ferromagnetic tape; the rest is filled with aluminum ducting to maintain the approximate capacitance of a real core. (The capacitance plays an important role in the frequency response of the coupling impedance that describes the interaction between the beam and the core.) The 1-in-10 filling allows us to test the core at 20 kV rather than 200 kV and makes it convenient to probe voltages and currents within.

A February 1992 workshop on longitudinal instability took recent information from various laboratories into account. It seems that growth length of low-frequency disturbances ("low-frequency" in comparison to the

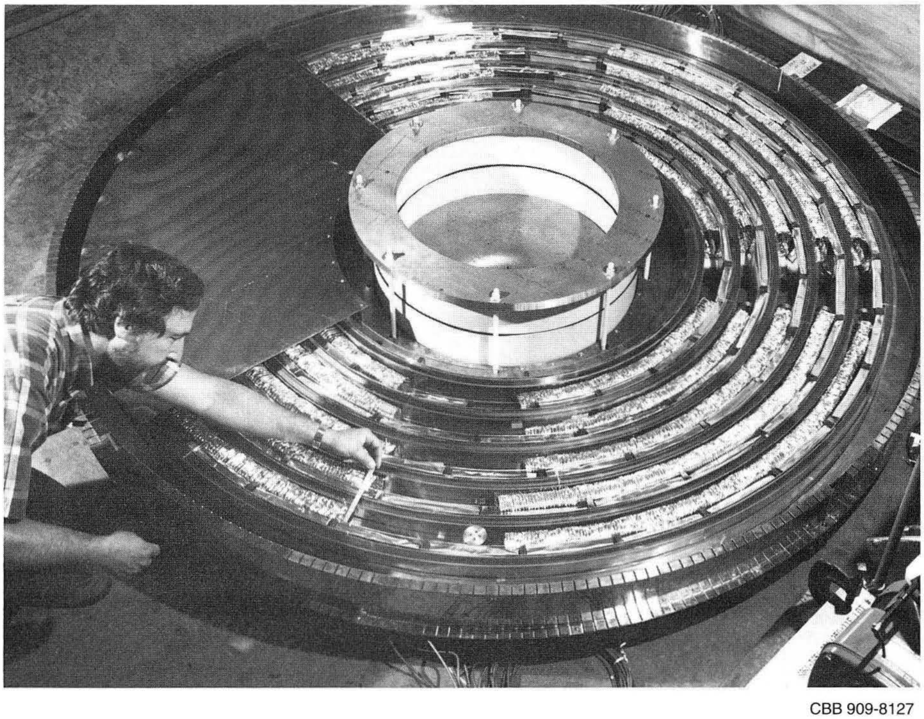

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Figure 1-7. In an early look at some characteristics of a driver, we are experimenting with this model of a driver-sized induction core. It is only 10% filled with ferromagnetic material, so we can experiment at about 10% of a driver's voltage. The aluminum ducting helps model the capacitance of a driver core, overcoming the effects of the partial filling.

frequencies corresponding to typical 500-ns pulse widths) can be increased toward the hundreds-of-meters end of the range of possibilities, and that these disturbances can probably be countered with feedforward control systems, which would be necessary in any case. At high frequencies (tens of megahertz), the low quality factors at resonance of the induction cores should allow the expected momentum spreads to effectively damp resonant instabilities. Work continues on these longitudinal instabilities, but it seems likely that the unstable modes can be predicted and either avoided or controlled.

The Road Ahead

Figure 1-8 shows an artist's conception of an inertial-confinement power plant based on a heavy-ion driver. Obviously this installation will be much larger than the present-day experimental systems. Between ILSE and a driver (*sidebar*) at least one intermediate step will be needed, probably at an energy in the range of 10-100 kJ. This "Intermediate Driver Facility," or IDF, will allow us to understand two key areas of physics that cannot be addressed at a smaller scale.

One key physics area that would be explored with the IDF is cost-effective avoidance or control of possible high-current instabilities; such research can be done with good confidence only in an experimental test at this scale. Another key area is the interaction of high-power ion beams with the high-temperature, solid-density matter[*] of a target that is being compressed.

Meanwhile, research in other areas will have continued at various laboratories. The critical technologies of inertial-confinement fusion—driver, target, mass-production target factory, and reactor—are all equally necessary, like the four legs of a stool. There has been strong support in major

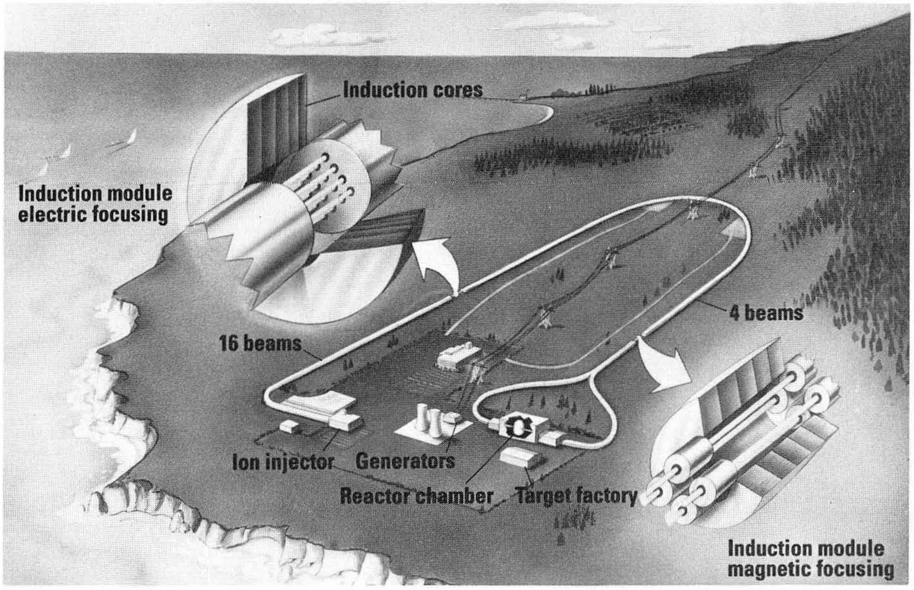

Figure 1-8. A conceptual drawing shows the scale and some postulated technical details of a power plant that uses heavy-ion induction linacs as drivers for inertial fusion energy.

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[*] This matter has few electrons per cubic Debye length and therefore cannot be called a "plasma," but is similar in some respects.

review committees for a facility that would use 1- to 2-MJ lasers to explore target-implosion physics in the ignition regime with significant gain. Preliminary planning for such a facility is beginning at several DOE laboratories.

Reactor ideas have also been investigated at several laboratories and industrial firms worldwide. It would be appropriate to begin their further development in earnest as the target-implosion results become available.

The decision point for extending driver development to the megajoule level is at least 15 years in the future, and will depend on two main factors: results from the target experiments and the national need to move forward to an Engineering Test Reactor (ETR). An ETR would bring together the essential new pieces of an IFE power plant: the reaction chamber, the target design; the means for mass production of the targets; and heavy-ion driver experience from the IDF. It could support a full-scale test of all devices and processes involved in a reactor except conversion of fusion energy into electricity and recovery of tritium.

Driver Candidates

There are a variety of ways to "drive" a deuterium-tritium target, or impart sufficient energy to it (about 10^{15} W) to cause fusion. LBL is investigating one of these approaches—the heavy-ion induction linac. Other laboratories are studying and experimenting with lasers and beams of lighter ions (to date, ranging from protons through lithium), and the German laboratory GSI is pursuing rf-accelerator options for heavy-ion drivers. The requirements for a driver are quite stringent; they include

- Cost, if IFE is to be an attractive power-plant option.
- Power sufficient to drive the target.
- Repetition rate (a few pulses per second; the lower limit is set by the maximum size of explosion the reaction chamber can handle in each shot, and the upper limit is set by the chamber's ability to prepare for the next shot).
- Shot-to-shot reliability combined with long lifetime.
- And, because a power plant must have a very substantial net output, efficiency.

Lasers, such as Nova at LLNL, have been investigated for some time in the context of inertial-confinement fusion. Glass lasers like Nova can be made quite powerful, but at this time, pending further R&D on cooling techniques, they have low repetition rates because of the time needed for the glass to cool between "shots." Also, today's lasers are only a few percent efficient, whereas heavy-ion drivers are projected to achieve operating efficiencies of 30% or more.

For an economical power plant, the product of driver efficiency and target gain will have to be greater than about 10. Because target gain (the energy produced in the fusion reactions, divided by the energy put in by the driver) is expected to be on the order of 100, driver efficiency is a stringent criterion. Lasers definitely have a place in inertial-confinement fusion and in defense research as the most-advanced drivers for target experiments, but their candidacy as power-plant drivers will remain uncertain until the efficiency and repetition-rate issues are resolved.

Light-ion diode accelerators are also being studied for this purpose, notably at Sandia National Laboratories. The disadvantage of light ions is that much greater beam current is needed to achieve sufficient power at the proper energy. The proper energy, in turn, is a function of the necessary range of target penetration. For heavy ions, the energy is higher (a few GeV versus tens of MeV) but attainable. The beam current, a more troublesome parameter, is lower for heavy ions (kA versus MA), suggesting that collective effects might be much less severe. Both the Fusion Policy Advisory Committee and a National Academy of Sciences panel have recommended that the heavy-ion approach be developed further.

Publications and Presentations

J.J. Barnard, A.L. Brooks, J.P. Clay, F.E. Coffield, E.J. Deadrick, L.V. Griffith, A.R. Harvey, D.L. Judd, H.C. Kirbie, V.K. Neil, M.A. Newton, A.C. Paul, L.L. Reginato, G.E. Russell, W.M. Sharp, H.D. Shay, J.H. Wilson, and S.S. Yu, "Study of recirculating induction accelerators as drivers for heavy ion fusion," Lawrence Livermore National Laboratory report UCRL-LR-108095 (1991).

S. Caspi, M. Helm, L.J. Laslett, W.M. Fawley, and M. Berz, "The use of numerical methods and differential algebra in magnetic field computation," abstract for the Spring Meeting of the American Physical Society (Washington, DC, 1992).

E. Close, C. Fong, and E. Lee, "The HILDA program," LBL-31917 (1991).

T. Fessenden and C. Fong, editors, *Induction Linac Systems Experiments Conceptual Design Report*, LBL document PUB-5324 (limited distribution, 1992).

S. Eylon and E. Henestroza, "C^+ source for the heavy ion fusion final focusing experiment," abstract for the 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (Seattle, WA, 1991); LBL-30994a (1991).

S. Eylon and E. Henestroza, "K^+ source for the heavy ion fusion final focusing experiment," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (Seattle, WA, 1991); LBL-32604a (1991).

S. Eylon, E. Henestroza, W. Chupp, and H. Rutkowski, "Low emittance K^+ ion source for heavy ion fusion linear induction accelerators," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (Seattle, WA, 1991); LBL-32605a (1991).

W. Fawley, "Design of large aperture ratio magnetic quadrupoles for transport of heavy-ion fusion beams," Spring Meeting of the American Physical Society (Washington, DC, 1992); LBL-31699a (1992).

William M. Fawley, "ILSE: The next step in heavy ion fusion research," Journal of Fusion Energy **10**, 297-298 (1991); LBL-31412 (1991).

T. Fessenden, R.O. Bangerter, D. Berners, J. Chew, S. Eylon, A. Faltens, F. Deadrick, and A. Friedman, "ILSE: the next step toward a heavy ion induction accelerator for inertial fusion energy," in *Proceedings* of the 14th International Conference on Plasma Physics and Controlled Nuclear Fusion Research (Würzburg, Germany, 1992); LBL-32213 (1992).

E. Henestroza, S. Eylon, W. Chupp, and H. Rutkowski, "High brightness K^+ ion source for heavy ion fusion linear induction accelerators," in *Proceedings* of the 1992 IEEE International Conference on Plasma Science (Tampa, Florida, 1992); LBL-32039a (1992).

William B. Herrmannsfeldt, Roger O. Bangerter, Rudolf Bock, William J. Hogan, and John D. Lindl, "Inertially confined fusion using heavy ion drivers," 15th Congress of the World Energy Council (Madrid, Spain, 1992); Stanford Linear Accelerator Center report SLAC-PUB-5457 (1992).

Dennis W. Hewett, William L. Kruer, and Roger O. Bangerter, "Corona physics of heavy ion fusion targets," invited talk for the European Research Conference on Nuclear Physics: Prospects for Heavy Ion Fusion (Aghia Pelaghia, Crete, Greece, 1992).

HIFAR Staff, "Heavy Ion Fusion Accelerator Research (HIFAR) year-end report, April 11, 1991-September 30, 1991," LBL-31943 (1991).

William J. Hogan, Roger Bangerter, and Gerald L. Kulcinski, "Energy from inertial fusion," Physics Today **42**, 9 (September 1992) pp. 42-50.

Hugh C. Kirbie, George J. Caporaso, Mark A. Newton, and Simon S. Yu, "Evolution of high-repetition-rate induction accelerators through advancements in switching," 16th International Linac Conference (Ottawa, Ontario, Canada, 1992).

E.P. Lee, "Beam dynamics and longitudinal instabilities in heavy-ion-fusion induction linacs," 16th International Linac Conference (Ottawa, Ontario, Canada, 1992); LBL-32813 (1992).

Edward P. Lee, "Heavy ion driven LMF design concept," Journal of Defense Research **21**, 2 (May 1992); also in the Laboratory Microfusion Capability Study, Phase II report, to the U.S. Department of Energy (InterScience, Inc., 1993; LBL-31248 (1991).

E. Lee, "Longitudinal instability in accelerators for heavy ion driven inertial fusion energy," 32nd Annual Meeting of the American Physical Society, Division of

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