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Heavy-Ion Fusion Accelerator Research

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Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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1.

HEAVY-ION FUSION ACCELERATOR RESEARCH

EXPERIMENTAL SUCCESSES INDICATE THAT THE TECHNOLOGY being studied by AFRD's Heavy-Ion Fusion Accelerator Research (HIFAR) group—the induction linac—is a prime candidate for further technology development toward the long-range goal of an inertial-confinement fusion driver. The 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 economy 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.

The experimental program at MBE-4, the Multiple-Beam Experiment, was completed in April 1991. The HIFAR Group is developing a concept called ILSE, the Induction Linac Systems Experiments. ILSE will address

R. Bangerter *(group leader)*
T.J. Fessenden *(deputy group leader)*

W.W. Chupp''
E. Close''
R.D. Edwards
S. Eylon
W. Fawley
A. Faltens'
C. Fong'
M. Fong
T. Garvey
W.B. Ghiorso'
W. Greenway'
K. Hahn
E. Henestroza
R.R. Hipple*
C. Houston*
R.M. Johnson''
D. Judd
L.J. Laslett''
E. Lee
H.-J. Lee
C. Lionberger'
H. Meyer*
S. Mukherjee'
J. Perez'
C.D. Pike'
J. Pruyn'
T.J. Purtell'
L. Reginato'
J. Rice, Jr.'
H.L. Rutkowski
L. Smith''
G.E. Stoker'
W. Tiffany'
D. Vanecek'
G. West'

Students
F. Algol
M. Gross
K. La Mon
B. Lipps
M. Nathwani

Administrative Support
J. Kono
D. Morris
A. Tidwell
O. Wong

' Engineering Division
'' Information and Computing Sciences Division
* Lawrence Livermore National Laboratory
'' Retired

most of the remaining beam-control and beam-manipulation issues at approximately 1/10 of a driver's scale in several key parameters, such as the number of focusing elements and latt: .e periods. Moreover, the line charge density and consequently the size of the ILSE beams will be at full driver scale.

A theory group closely integrated with the experimental groups continues to support present-day work and also to look ahead toward larger experiments and the eventual driver. Much of the theory group's effort in both areas during 1990 and 1991 focused on studies of longitudinal instability. The resistive and inductive components of acceleration-module impedances can lead to beam instabilities that would become significant at the high-current end of a driver. Because the heavy ions would be subrelativistic even at the high-energy end of a driver, these longitudinal instabilities would be much more severe than for, say, electron beams. (Most of today's experience base with high currents has been obtained with electron beams. Because of the low mass of the electron, they behave relativistically, and thus become immune to these instabilities, even at low energies.) Therefore, we must learn how to reduce and suppress these instabilities effectively and economically. The theory group has also published a new technique for calculating electric fields in complicated three-dimensional geometries, which agrees well with measurements of the effective length of quadrupoles and the strength of dodecapole fields in MBE-4.

Research with MBE-4

Our group concentrates on the multiple-beam induction linac incorporating current amplification as well as acceleration, a concept that we consider to be a leading candidate for an inertial-fusion driver. The ultimate beam characteristics (including energy, power, pulse length, and various measures of quality such as transverse and longitudinal emittance) are established by the needs of the inertial-fusion target, so it is important to control the lengths of the beam bunches precisely, with minimal degradation, throughout acceleration. The accelerating waveforms must be shaped carefully in order to shorten the bunch length (thus amplifying current) and to control longitudinal space-charge forces. Small errors, especially in the low-energy end of the system, can lead to current spikes and beam spill and/or to unacceptable increases in emittance. The focusing and transport system faces demanding requirements as well; the speed of the beams increases by as much as 20% during the length of a pulse. The six-year MBE-4 program, which concluded in 1991, provided abundant data toward an experimental understanding of these phenomena and constraints.

Selected Highlights of the MBE-4 Program

In MBE-4 (Figure 1-1), cesium ions are injected into each of the four beamlines at 200 keV. Another energy boost of up to 30 keV is given at each of 24 accelerating gaps for a final kinetic energy of 920 keV. Current is amplified by increasing the speed (through acceleration) and the line density of the charged particles. The line charge density is increased through pulse compression, which is achieved by accelerating the rear particles in the bunch more than the front ones.

The parameters of MBE-4 gave beam dynamics similar to those expected in the lower-energy, electrostatic-focusing end of a driver. In the first three years (during which MBE-4 provided useful data even at partial stages of completion), longitudinal beam dynamics and control were studied; in the last three years, using the complete machine, we concentrated on transverse beam control and the study of emittance growth during acceleration.

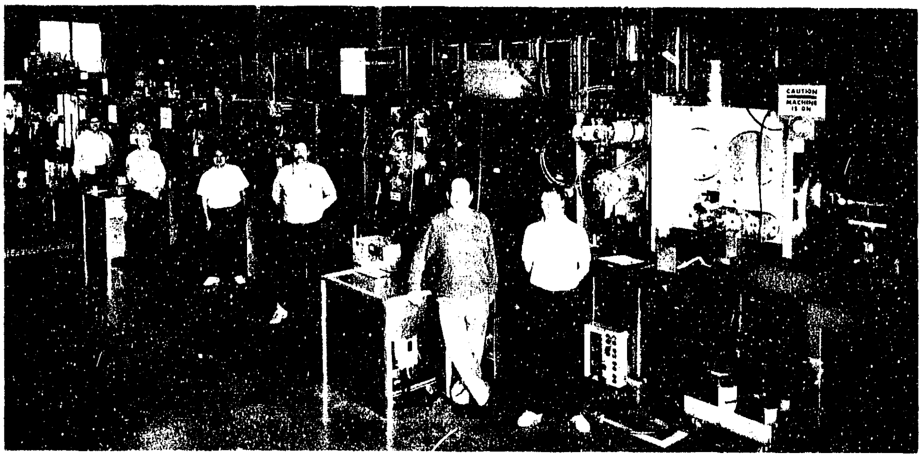

Figure 1-1. The MBE-4 apparatus, now idle, has supported a highly productive experimental program for the past several years. It has been used to study acceleration of multiple beams in a single induction core, amplification of current through pulse compression, and issues related to transverse and longitudinal emittance.

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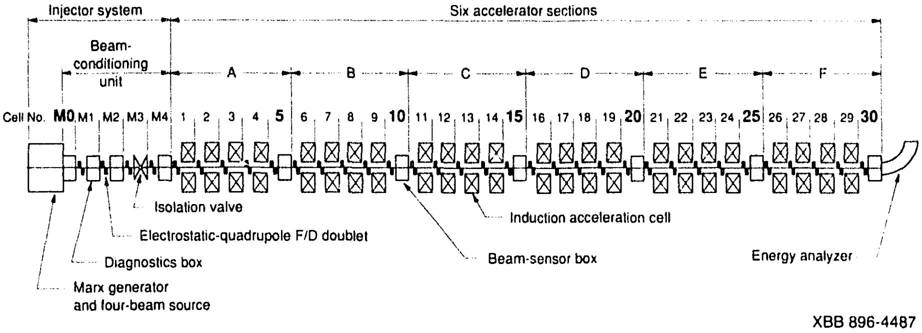

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Longitudinal Beam Dynamics

The charge distribution along the length of a bunch generates a longitudinal electric field that will lengthen the bunch unless the accelerating voltages compensate for it. One of the important results of the MBE-4 effort was the development of a scheme for devising the proper waveforms. This scheme was embodied in a computer program called SLID (Study of Longitudinal Ion Dynamics) and its extended version SLIDE, which accounts for particles overtaking one another during current amplification. SLID was used iteratively during the design of the pulsers. The upstream (low-energy) pulsers were designed according to the ideal waveforms from SLID; then, to compensate for their nonideality, actual measurements were fed into SLID to design subsequent pulsers. Theoretical studies of the effects and propagation of errors were also conducted.

Transverse Beam Dynamics and Current Amplification

The latter parts of the MBE-4 program concentrated on understanding the forces that affect the beam transversely—particularly the problem of accelerating the beam and amplifying its current without spoiling its normalized transverse emittance. In the earlier experiments, we had found that the normalized emittance tended to increase and that measurements varied by as much as twofold over long periods (a matter of months). The transverse-emittance increases appear to be caused in part by improper centering, matching, and alignment. The beam radius is comparable to the aperture, so without care in these matters, the outer portions of the beam may be outside the linear, "good-field" region. There they encounter dodecapole nonlinearities in the focusing fields, and the effect of image charges on the focusing electrodes is also exacerbated.

Studying emittance growth in experiment (and, with excellent qualitative agreement, in simulation), we found that the rms emittance varies rapidly along the length of the accelerator. It appeared to be modulated at a wavelength corresponding to 2.3 lattice periods and also oscillated about the accelerator aperture by 4–5 mm, or nearly 20% of the aperture. These variations were a consequence of a focusing imperfection that kicked the beam off axis, causing it to oscillate back and forth in the transport channel. The most recent experiments have concentrated on carefully matching and centering very "cold" beams in the channel to demonstrate current amplification at constant normalized emittance. As expected, when the beam was properly centered, the normalized emittance was preserved under drift or acceleration.

The Lessons of MBE-4

In conclusion, MBE-4 was both a successful experiment and a harbinger of the work yet to be done. It quickly relieved an initial concern that the multiple beams might interact with each other; this happened only at low energy in the injector, where the beams "see" each other's radial space-charge electric fields for some distance. (At higher energies, magnetic interactions play a stronger role, and some periodic coupling phenomena might conceivably arise.) MBE-4 also showed that current amplification is possible and that longitudinal control can be exerted over the beam by tailoring the pulser waveforms, although pulsers more versatile than the thyratron-based units in MBE-4 will be required.

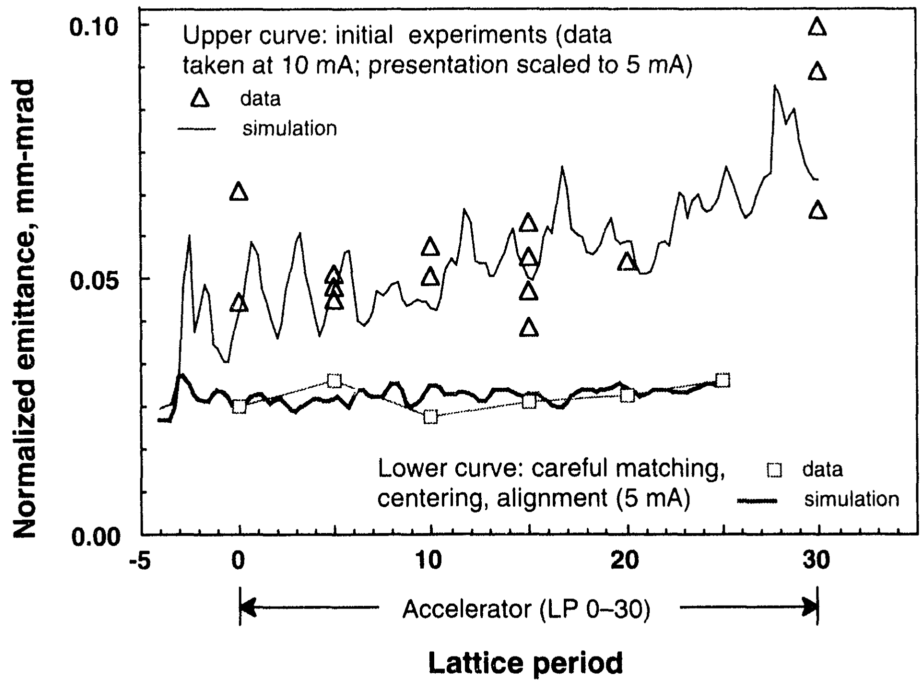
Preservation of low emittance continues to be an important issue in our experiments and scaling exercises. Acceleration errors can be partially corrected downstream of the point where they occur (the closer the better). Although these corrections contribute to longitudinal emittance, extrapolations from MBE-4 data lead us to believe that this emittance growth might not unduly compromise the final focusing of the beam onto the target. The admittedly long extrapolation to a driver showed a momentum spread ($\Delta p/p$) of 1×10^{-3}, which is considerably better than the 1×10^{-2} limit suggested by theoretical final-focus studies.

Figure 1-2 compares emittance growth in MBE-4, both in experiment and in numerical simulation, under two sets of circumstances. In both cases, the beams injected into the accelerator were very "cold," that is, the initial emittance was near its minimum possible value.* With great care in matching and centering of the beam, we accelerated it without increasing the normalized transverse emittance, the value of which was slightly below 0.03 mm-milliradian. In initial experiments without such painstaking matching and centering, the emittance had increased, but not to a very high value. We are now exploring this phenomenon in longer devices, such as a driver, through numerical simulation and extrapolation.

We speculate that over the length of a driver, emittance will reach an asymptote, hopefully at an acceptable level. Thus a driver might not need the great care we had to take in matching, centering, and alignment; the beams would center and match themselves, and the accompanying increase in emittance may be affordable. Obviously, much more research is needed, especially

* An ion source has a minimum intrinsic emittance determined by the radius of the source and the random thermal energy of the emitted ions.

Figure 1-2. Emittance growth in MBE-4 has been extensively studied both in experiments and in numerical simulations. With great care in matching and centering of the beam, we accelerated it without incurring a net increase in the normalized transverse emittance. Without such care, the emittance increased by a factor ranging up to 2×. We are now exploring this phenomenon in longer devices, such as a driver, through numerical simulation and extrapolation.



considering the extent of the extrapolation and the paucity of experimental knowledge about long induction ion linacs. This will be among the issues explored in the additional steps between MBE-4 and a driver.

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 would be required (on a larger scale) 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 space-charge-dominated ion beams.*
- *Amplifying current by "drift compression."*
- *Focusing ion beams precisely onto a small spot.*

Conceptual studies of the apparatus are in progress, and it will be proposed for a construction start in fiscal year 1994.

ILSE Physics Point Design

The original ILSE conceptual design, published in 1988, called for 16 beams to be accelerated and electrostatically focused, then combined into four beams (thus providing data on a key driver feature). The beams are further accelerated, this time with magnetic focusing—another important driver feature. Then three beams are dumped and the fourth is used for experiments in drift compression and final focus.

In light of the knowledge gained from MBE-4, as well as developments elsewhere in the heavy-ion fusion community, we have begun redesigning

ILSE. The new configuration, shown in Figure 1-3, starts with four beams and combines them into one. This cost-reducing simplification was made possible by the success of MBE-4 and by some prototype assembly work of components for the first ILSE design; multiple-beam induction cores and other components proved to be more straightforward than we had expected. The new configuration is otherwise similar to the original.

The design has been improved in a variety of ways. It takes advantage of recent technology developments, including better Metglas induction-core material, commercially available alignment systems that can achieve 0.001-inch precision, and better control and data-acquisition systems.

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. Other parameters (Table 1-1) are scaled down compared to those of a driver. Another important change 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 considerably less expensive than the nonrecirculating induction linacs that we have been envisioning. However, much less is known about the physics of recirculating induction ion accelerators. Various schemes are being studied to possibly extend the ILSE sequence of experiments to cover the essentials of the recirculating approach, assuming that theoretical studies confirm the desirability of performing these experiments in ILSE.

The result of the physics design effort, which is still underway, will be a "point design" — a self-consistent design, selected from a broad continuum of possibilities, that best addresses our experimental needs within our funding prospects. Later we plan to prepare a Conceptual Design Report. Construction of the accelerator would start in fiscal 1994 under the current proposal.

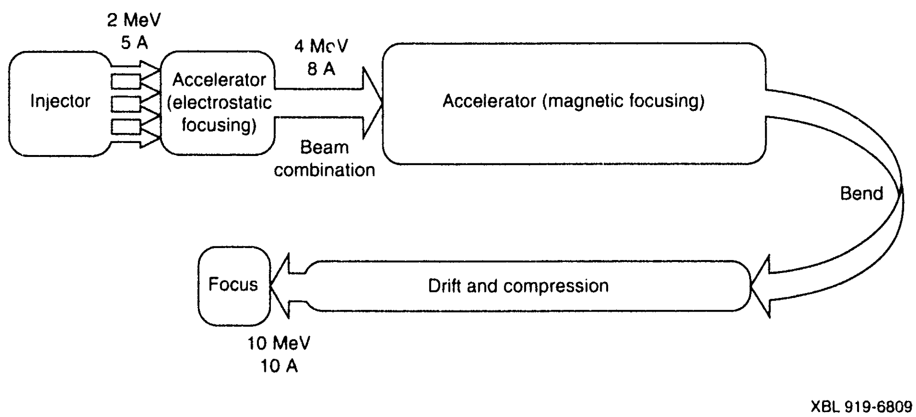


Figure 1-3. ILSE, the Induction Linac Systems Experiments, is the next step in our experimental program. Originally proposed in 1988, ILSE is now being redesigned in anticipation of a construction start in fiscal 1994.

Table 1-1. Key parameters of HIFAR experiments and a postulated driver.

	SBTE	MBE-4	ILSE (1988)	ILSE (1991)	Postulated driver
Ion species	Cs^+	Cs^+	C^+	Ne^+	Bi^{3+} or Hg^{3+}
Number of beams	1	4	16→4	4→1	64→16
Injection voltage (MV)	0.16	0.2	2	2	3
Final voltage (MV)	0.16	1	10	10	3300
Final current per beam (A)	0.023	0.24	4	10	6000
Final beam energy (J)	0.07	0.08	55	87	3×10^6
Final ion velocity/*c*	0.0016	0.004	0.04	0.03	0.3
Accelerating gradient (MV/m)	n/a	0.07	0.22	0.22	0.8
Bunch length (m)	8.0	1.1→0.25	5.6→4.4	8.8→8.8*	70→10*
Pulse width (μs)	20	2→0.4	1→0.35	2→1	24→0.1

* 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.

Meanwhile, the search for an ILSE site continues. The leading candidate, whose dimensional constraints are being assumed in the point design, is Building 58 (Figure 1-4), which currently houses MBE-4 . However, we are also weighing the merits of other possible locations on the LBL grounds.

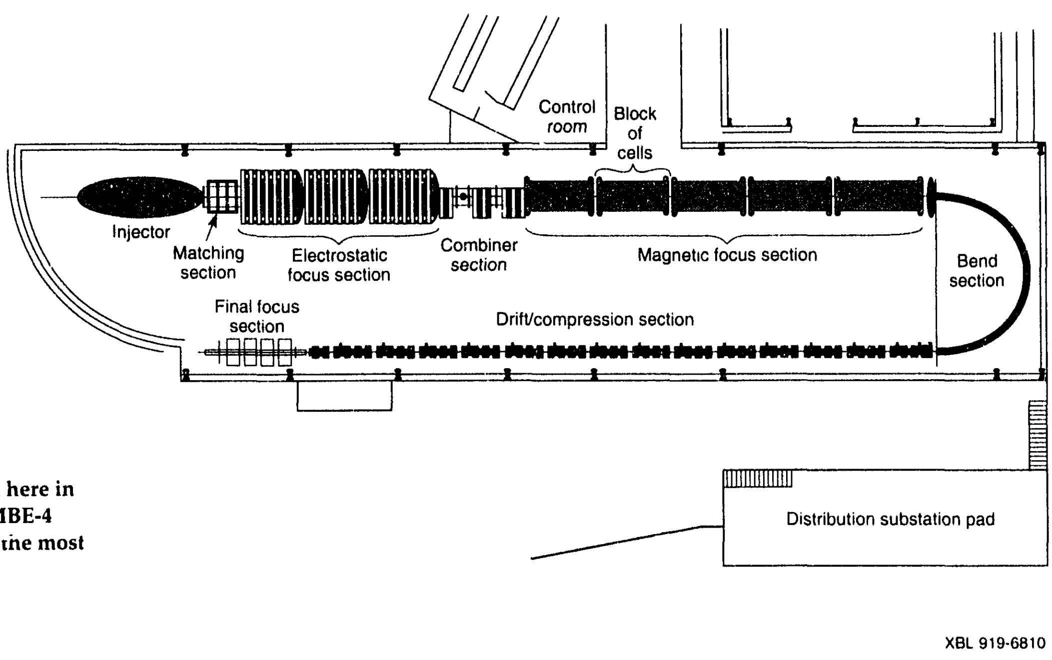


Figure 1-4. ILSE is shown here in Building 58 (the current MBE-4 site), which appears to be the most probable location.

Ion-Source and Injector Development

Until 1991, most of the ILSE ion-source effort concentrated upon a carbon-vacuum-arc device that turned on and came up to full current rapidly, based on a prototype developed by a group from the University of New Mexico. It was used in conjunction with an electrostatic plasma confinement device, or "plasma switch," which allowed beams to be extracted not from the noisy stream of plasma from the cathode spot, but rather from a layer of ions captured by space-charge forces near the grid of the plasma switch. While studying ways to optimize the performance of the carbon-arc source and plasma switch, we used it for tests of the 944-kV first-half column of the 16-beam injector.

The source has also successfully produced long pulses (about 50 μs) at a current of 210–230 mA, which was limited by the extraction geometry used in this test. It was encouraging to see that such long pulses could be transported reliably at the full voltage of the half-column. Despite considerable efforts, though, it appeared that the emittance of this source would exceed ILSE's tolerances. Accordingly, we began R&D on other ion-source approaches.

The new ILSE point design uses a 25-cm-diameter rf-powered source in which the plasma is confined by a multicusp magnetic field, much like the Magnetic Fusion Energy Group sources described in Chapter 2 of the *AFRD Summary of Activities*. The very 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. The choice of ion species is a complex issue (*sidebar*); the physics point design assumes that ILSE will accelerate Ne^+. Backup work on thermionic Cs^+ and K^+ sources is also being continued.

Selecting an Ion

ILSE could accelerate a range of elements at various charge states. Choosing the best one for a particular experiment 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 energy. In ILSE, a 5-MeV beam of an ion species of moderate mass, such as C^+ or Ne^+, will allow approximation of the beam physics of 85-MeV U^+.

Also important are the ease and reliability with which multiampere quantities of the ion can be produced in the desired charge state. The rf-driven sources from the MFE Group readily produce high currents of the gaseous elements with reasonable transverse emittance.

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, Ne^+ was chosen for the ILSE physics point design. Ar^+, which, within the ILSE parameters, requires magnetic focusing forces that are stronger by about the square root of two, is also being considered. (The rf-driven ion sources are quite flexible.)

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, which helps avoid high-current instabilities. Economic considerations also come into play; doubling the current would double 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— probably in a charge state as high as +3, with the +1 and +2 ions magnetically separated—are promising candidates.

Long-Range Research and Development

Although present-day and near-future research programs occupy most of our attention, we also engage in various experimental and conceptual efforts (ourselves and in collaboration with colleagues in the inertial fusion energy community) that look further down the road to a driver.

Model Driver Core

As part of our program to evaluate longitudinal instability at driver parameters, we fabricated a model of an induction-accelerator core at nearly full scale. The model duplicates the rf properties of an actual acceleration module from a driver. Data from these rf studies will be 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 to fully test these instabilities.

The model core, shown in Figure 1-5, is quite large, 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. This allows us to test the core at 20 kV rather than 200 kV and also provides a way to probe voltages and currents at various points within.

The Road Ahead

Figure 1-6 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, at least one intermediate step will be needed, probably at an energy of about 10–100 kJ. This will allow us to understand two key areas of physics that cannot be addressed at a smaller scale.

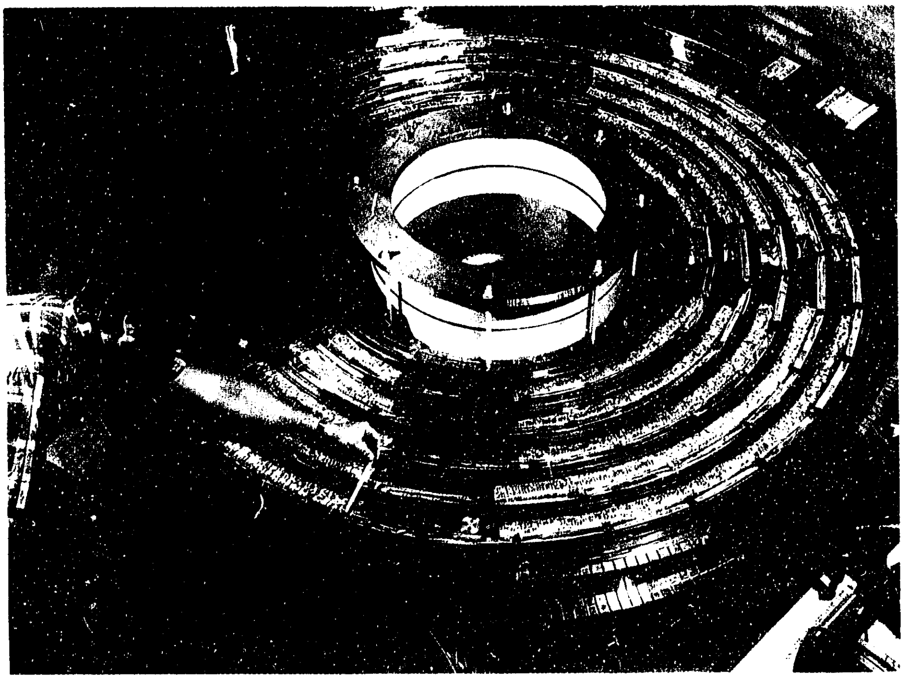


Figure 1-5. In an early look at some characteristics of a driver, we are experimenting with this model of a driver-sized induction core. It is only 10% filled with ferromagnetic material, so we can experiment at about 10% of a driver's voltage. The aluminum ducting helps model the capacitance of a driver core, overcoming the effects of the partial filling.

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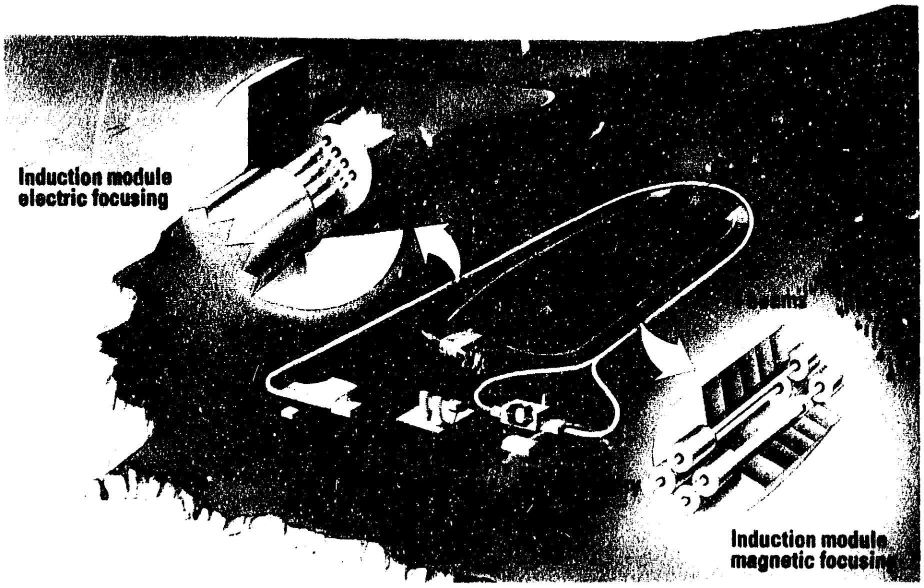

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Figure 1-6. A conceptual drawing shows the scale and some postulated technical details of a power plant that uses heavy-ion induction linacs as drivers for inertial fusion energy. (LLNL illustration)

The first key physics area that would be explored 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. The second key physics area is the interaction of high-power ion beams with a high-temperature, solid-density plasma (at a temperature of approximately 100 eV, as compared with the 200–250 eV needed in a power-plant target).* By proceeding directly from the "front end" of ILSE rather than building the two projects in strict serial order, 10-kJ results could arrive before the year 2000. (The front ends of both machines are similar; the difference comes further downstream, where many more accelerating units are needed to reach 10 kJ.)

It may prove to be prudent to have another experiment at about the 200-kJ level: a few times more energy than is currently produced by the Nova laser at LLNL, but at an accelerator's rate of pulses per second rather than the pulses per day of present laser technology (*sidebar*). This apparatus, which could conduct target experiments at some 200 eV in plasma temperature, would validate the final driver technology at a satisfactorily large scale. From this level onwards, the approach would be to build hardware large enough to re-use as part of a full-scale driver (implying that design work on megajoule heavy-ion facilities should be getting underway).

* The 10-to-100-kJ target will not resemble an actual deuterium-tritium power-plant "pellet," which might be either a one- or two-stage direct-drive ablative target or an indirect-drive target of the currently classified type used in thermonuclear weapons. Thus the research could be conducted in an open environment. ILSE will be a beam-manipulation apparatus that will not involve a pellet.

Meanwhile, research in other areas will have begun at other laboratories. The critical technologies of inertial-confinement fusion—driver, target pellet, mass-production pellet factory, and reactor—are all equally necessary, like the four legs of a stool. There has been strong support in major review committees for a facility that would use 1- to 2-MJ lasers to explore pellet implosion physics in the ignition regine 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 pellet-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 the Engineering Test Reactor (ETR). The ETR would bring together the essential new pieces of an ICF power plant: the reaction chamber from the new reactor-studies program; targets designed in the LMF program and mass-produced in the pellet factory; and heavy-ion driver experience from the 10-kJ-plus test facilities. We define the ETR as a full-scale test of everything involved in a reactor except conversion of fusion energy into electricity and recovery of tritium. Given adequate support, the ETR could be operational in the 2015-2020 period.

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

- Power.
- Repetition rate (a few pulses per second, mandated by the thermal equilibrium of the reactor chamber).
- 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 presently have low repetition rates because of the time needed for the glass to cool between "shots." The cooling restriction may be less severe for gas lasers. However, like glass lasers, they are currently 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 10. Because target gain (the ratio of reaction energy to driving energy) 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 should nonetheless be 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.

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