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June 1990

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Contents

1.

HEAVY-ION FUSION ACCELERATOR RESEARCH

. . . heavy-ion accelerators as igniters, or "drivers," for inertial-confinement fusion . . .

THE MISSION OF THE HEAVY-ION FUSION ACCELERATOR RESEARCH (HIFAR) group at the Laboratory is to assess the suitability of heavy-ion accelerators as igniters, or "drivers," for inertial-confinement fusion. A prototype power plant is decades away, but a series of experimental successes indicates that the specific technology being studied by the HIFAR group—the induction linear accelerator—is a prime candidate for the driver and that development of this technology should be pursued over the next several years.

The HIFAR program, over the past decade or so, has involved a series of ever larger and more-complex acceleration and beam-transport experiments. The first was a 1-A cesium source and drift-tube accelerator module. This was followed by SBTE, the Single-Beam Transport Experiment, designed for studying beam stability at high currents. SBTE became operational in 1983 and was superseded in 1987 by MBE-4, a Multiple Beam Experiment with which to explore acceleration. Table 1-1 shows how these experiments relate to each other and to a postulated driver.

Experiments with MBE-4 will continue into 1991. Meanwhile, the group is designing components for a proposed accelerator called ILSE—the Induction Linac Systems Experiment. ILSE will address most of the remaining beam-control and beam-manipulation issues on a scale large enough for assessment of practicality in a driver.

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

Parameter	SBTE	MBE-4	ILSE	Driver
Ion species	Cs^+	Cs^+	C^+	Bi^{3+} or Hg^{3+}
Number of beams	1	4	16→4	64→16
Injection voltage (MV)	0.16	0.2	2	3
Final voltage (MV)	0.16	1	10	3300
Final beam current (A)	0.023	0.24	15	6000
Final beam energy (J)	0.07	0.08	55	3×10^6
Final ion velocity/c	0.0016	0.004	0.04	0.3
Accelerating gradient (MV/m)	n/a	0.07	0.22	0.8
Initial bunch length (m)	8.0	1.1	5.6	70
Pulse width (μs)	20	2→0.4	1→0.35	24→0.1

Research with MBE-4

In 1989 experiments continued on MBE-4, providing data with which to model and study several of the phenomena we expect to encounter in a heavy-ion fusion driver. Amplification of voltage and current, if not done properly, can excessively degrade the quality of the beam. As we progressively scale up our studies toward the eventual goal of a driver, these effects will remain important, and their study and control will continue to be an essential part of the HIFAR program.

MBE-4: The Induction-Linac Approach

Since 1983, U.S. heavy-ion fusion accelerator efforts have been directed toward the induction linac. This device is conceptually simpler than the rf linac, whose fusion applications are being investigated in Western Europe, Japan, and the USSR. More importantly, at least for the goals of the HIFAR program, the parameters and properties of the induction linac can be scaled up more readily as experiments become progressively more complex and energetic. The MBE-4 design effort drew heavily upon our previous experience with SBTE, and, in turn, the MBE-4 experience is benefitting the ILSE program.

Figure 1-1 illustrates the concept behind MBE-4. 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.

Reaching the necessary power calls for amplification of beam current, which is a function of the speed and line density of the bunch of charged particles. The speed is determined by the accelerated energy and the ion mass; the density can be increased through pulse compression, which is achieved by accelerating the rear particles in the bunch more than the front ones. The parameters of the accelerator set the ability to change these factors.

This procedure has several known complications. For example, errors can cause the beam to wander as it moves down the accelerator. This loss of control can lead to a reduction of beam quality and thus affect interaction between beam and target in a driver, so it must be minimized.

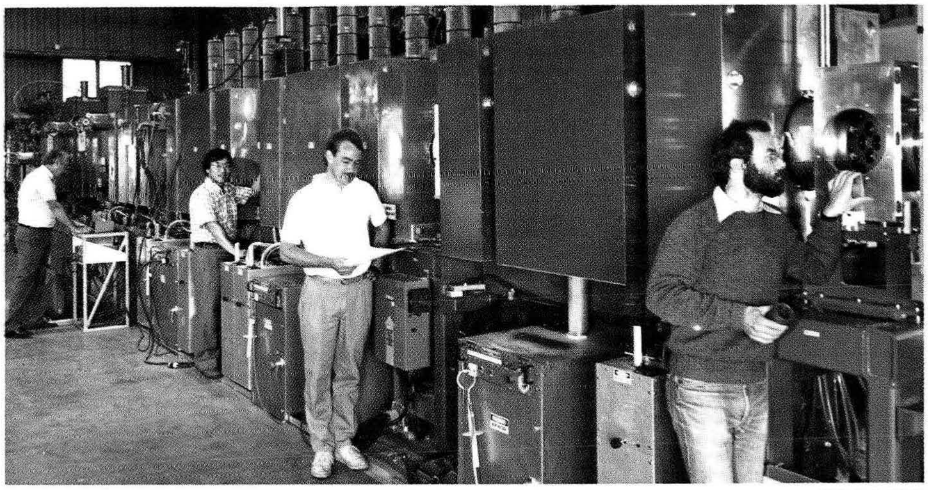

Figure 1-1. MBE-4, the four-channel Multiple-Beam Experiment, became fully operational late in 1987. (Its modular design had already permitted nearly three years of limited experimentation.) With MBE-4, we are studying the behavior of space-charge-dominated heavy-ion beams undergoing current amplification. The information gained will be useful in the design of any induction-linac heavy-ion fusion driver.

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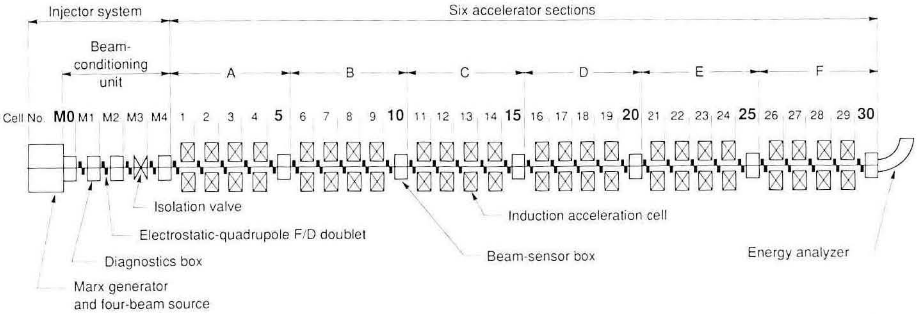

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Transverse Beam Dynamics and Current Amplification

The MBE-4 experiments have consistently shown that acceleration accompanied by current amplification causes a slow increase in the normalized emittance. There are a number of possible reasons for such an increase. For example, if the bunch length is compressed during acceleration, the energy carried by the beam's space-charge field is converted into emittance. In addition, if the beam is off axis and has very low emittance, it interacts with imperfections of the quadrupole focusing fields, and with "image" charges induced on the electrodes, in such a way as to cause the emittance to grow. For "warmer" (higher-emittance) beams, the relative emittance growth is smaller and more difficult to detect. The measurements are difficult to make, because the emittance is quite small even after current amplification—less than 0.1 mm-milliradian at the halfway point along the accelerator—and because, in this low energy regime, the effects of space charge dominate the beam's behavior.*

In addition to using better measurement apparatus, we modified the post-extraction geometry to select the more-uniform core of the 10-mA beam. This reduced the current to 5 mA, simultaneously halving the emittance and

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* Measurements reported in early 1987 gave emittance values in excess of 0.2 mm-mrad with no emittance growth during acceleration. However, at high emittance, it is difficult to detect relatively small values of emittance growth. With careful calibration procedures, such as checking of the single-particle betatron tune and correct matching at all observation points, we should be getting more-trustworthy data.

making the beam even more dominated by space charge. To provide a longer-term solution, we began working on an improved injection diode to make the 10-mA beam more uniform.

Attempts to reconcile the MBE-4 results with computer simulations led to further theoretical work because SHIFTXYA, our upgraded version of the SHIFTXY computer code, predicted a smaller increase in emittance. (The upgraded program takes current amplification into account; amplifying the current by compressing the beam increases the electrostatic beam energy because the positively charged particles are forced closer together.) The latest version of SHIFTXYA gives results that are closer to experimental values, as shown in Figure 1-2. We also developed an analytical theory of emittance growth, extending the familiar emittance formula to include the effects of acceleration and longitudinal beam compression. The analytical theory is in good agreement with recent numerical simulations; if further confirmed by MBE-4 measurements, it could be used to model transverse emittance growth in a fusion driver more confidently.

Scaling Up the Results

How might the MBE-4 results be interpreted in terms of an actual driver? As presently envisioned, each of the many beams in a driver would undergo current amplification by a factor of about 200. This results from a fiftyfold increase in velocity accompanied by compression of the beam to one-fourth its original length. After the accelerator, the beam would be compressed by a further factor of 10. The most "aggressive" current amplification trials in MBE-4 have involved a velocity increase of 2.1 × accompanied by a 3.8 × bunch-length reduction. The velocity increase of a real driver cannot even be approached in such a short accelerator (although the voltage is expected to

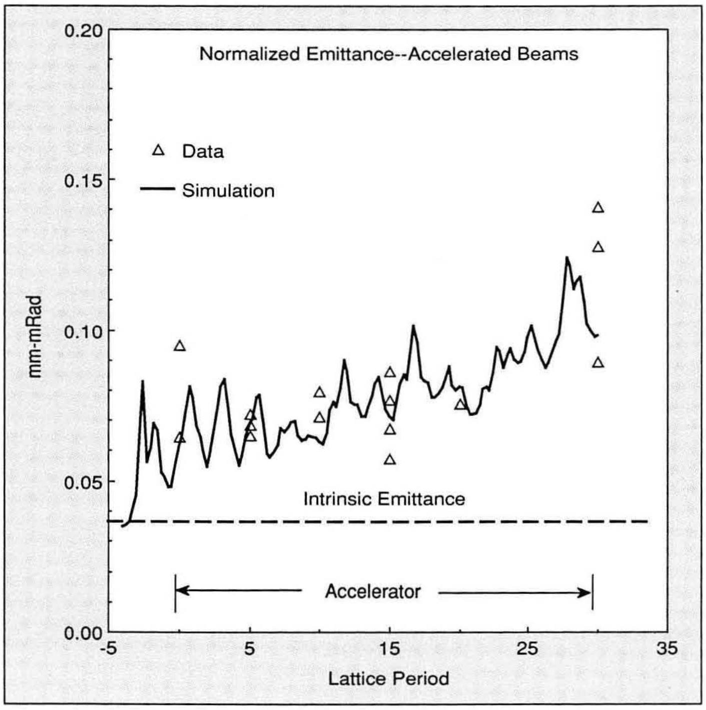

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Figure 1-2. A recent simulation with the latest version of the SHIFTXYA code, using an initial value close to the "intrinsic" beam emittance (the minimum value limited by radius and temperature of the ion source), gives a fairly accurate prediction of emittance growth along the accelerator. The simulation takes into account the behavior of 100% of the particles, whereas the analysis of experimental data only follows the 90% of the particles that comprise the main part of the beam, ignoring "halo." In the notation used here, the matching section of MBE-4 extends from Lattice Period -4 to LP 0, and the accelerator extends from LP 0 to LP 30. The nominal beam current in the simulations, as in most MBE-4 experiments, was 10 mA.

scale up straightforwardly). On the other hand, bunch-length manipulation is actually much more demanding in this short apparatus than it would be in a driver.

During aggressive current amplification, the final pulse shape in MBE-4 is dominated by rise-time effects: in a pulse whose initial width is about 2500 ns, rise-time effects account for 150–250 ns. A driver would initially use much longer pulses, typically 10 to 20 µs, and rise-time effects would not make up such a significant percentage of the pulse width (hence our rationale for working primarily with "gentler" acceleration, with amplifications on the order of 4 × and below).

Scaling of certain other parameters is similarly encouraging. The effects of space charge, for instance, should be proportionally less severe in a 10-GeV, 20-kA driver than in an MBE-4 beamline. However, one must be cautious in using the term "scaling." MBE-4 and ILSE are experiments, not scale models; we expect to continue learning as we progress toward a driver, and extrapolations must be qualified carefully.

Long-term stability of operation—i.e., shot-to-shot reproducibility—is important for effective gathering of data (and will be essential in a driver as well). We study this subject by taking data at various locations along the length of the apparatus; at each point we measure the beam position and angle coordinates and the density distribution in phase space. Acquiring such data is more difficult in MBE-4 than it was in SBTE. All these quantities must be measured as a function of time within each pulse. Furthermore, the energy and energy spread can be measured precisely only at the end of the accelerator (although a computer simulation tool, the SLIDE macroparticle code,* usually allows good inferences about the energy at other points). And, of course, each of these issues must be multiplied by four beams; ILSE, with 16 beams, will be even more complex. We continually improve and extend our beam-diagnostic capabilities to meet these challenges.

Induction Linac Systems Experiment

As the HIFAR group continues its mission—evaluating and validating the concept of heavy-ion drivers based on induction linacs—a step beyond MBE-4 will soon be needed. Of the concepts envisioned thus far, the most promising is ILSE, the proposed Induction Linac Systems Experiment. At an incremental cost of about $40 million 1990 dollars spread out over five years, ILSE would provide more than a thousand times as much peak power on target as MBE-4. It would also introduce several significant new capabilities, thus far untested, 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-ransport system*
- *Magnetically bending space-charge-dominated ion beams*
- *Amplifying current by "drift compression"*
- *Focusing ion beams precisely onto a small spot*

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* SLIDE stands for Study of Longitudinal Ion Dynamics—Extended; it is an enhanced version of the AFRD-developed particle-in-cell code SLID. SLIDE allows particles to overtake one another and is optimized for short machines and low currents.

Figure 1-3 illustrates the ILSE concept. Sixteen beams are produced in the 2-MV injector now being developed. Then the beams are accelerated to 4 MeV, and their current is amplified, as in MBE-4 but on a larger scale. The 16 beams are combined into 4, then accelerated to 10 MeV, with magnetic focusing rather than the electrostatic focusing employed in earlier stages. Finally, one beam is bent, subjected to further longitudinal compression for current amplification, and focused onto a pea-sized simulated fusion target.

Through ILSE to a Driver

The basic requirements for ILSE were defined in 1988 in the course of the ILSE Conceptual Engineering Design Study. In 1989 we built on this foundation by designing and developing suitable hardware, including the injection system and accelerator components such as induction cells and electrostatic and magnetic devices. The effort has been aided not only by a strong team of mechanical and electrical engineers from LBL, but also by the part-time participation of engineers from the Beam Research Group at Lawrence Livermore National Laboratory who have extensive experience in building electron induction linacs.

Meanwhile, our HIFAR Theory section, looking both toward ILSE and an eventual driver, analyzed the way perturbations in the beam current can be amplified by interaction with the resistive component of the impedance of the accelerating modules.

Ion-Source and Injector Development

As we move from today's apparatus toward a full-scale driver, the energy and current requirements placed upon the ion injector become greater. ILSE calls for a 16-beam, 2-MeV injector that can provide currents of several amperes. Constraints in the first parts of the accelerator will limit the current to 5.4 A in actual ILSE operation, but a current of 8 A is the goal for a stand-alone test of the injector (planned for early 1990). Additionally, ILSE will use carbon ions instead of the cesium ions in MBE-4, so the 16 high-current beams must be derived from a fundamentally different kind of ion source. (The lighter carbon ions will allow us to incorporate magnetic focusing in the experiments at energies as low as 4 MeV.) In earlier years, a collaborative effort with other institutions had produced a satisfactory carbon-arc ion source; we are now working to improve its operating characteristics, and then we must make 16 of these sources function within the 2-MV injector.

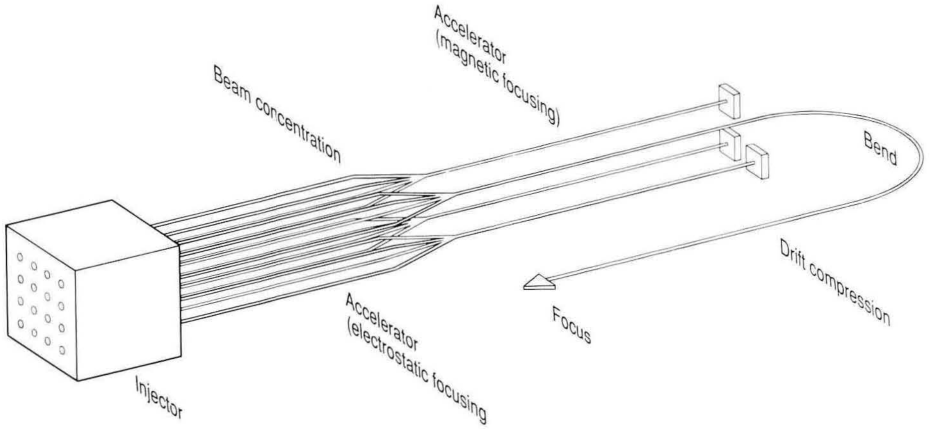

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Figure 1-3. In ILSE, sixteen C^+ beams will be accelerated, current-amplified, and combined into four beams, which will then be accelerated further. Finally, one of the four will be bent, subjected to additional current amplification, and focused onto a simulated target. (Carrying only one of the four beams through the final stages helps control costs while still providing the desired data.) The ILSE specifications call for a kinetic energy of 10.2 MeV and a current of 3.8 A in each of the four final beams, with a final pulse length of 4.4 m (0.355 μs).

The ILSE ion source (Figure 1-4) is a carbon-arc device that turns on and comes up to full current rapidly, based on a prototype developed by S. Humphries of the University of New Mexico. The source has proven its performance in terms of current density and beam quality. Present work is focused on improving its lifetime and reliability. Three areas are being explored simultaneously: small modifications of the design geometry; substitution of different materials (in the trigger electrode, for instance); and means of refurbishing a faulty source without dismantling the apparatus, such as glow-discharge cleaning. Early tests show a mean interval between failures of about 10 000 shots, where failure is defined as a drop in shot-to-shot reliability to about 90%, as compared to the usual 99% or better.

Until July 1989 we used a three-arc design that typically lasted about 10 000 shots before the cathode eroded into the blast shield and repair was needed. Since then we have been using a single-arc design, hoping that a single massive cathode would last longer than three slender ones. The performance picture (*sidebar*) is complicated and not yet well understood, but we have determined that the single-arc source runs at a good-shot rate of better than 99.5%, with a cathode lifetime on the order of 30 000 shots.

The carbon-arc source will be incorporated into the 2-MV, 16-beam injector that will be used for ILSE (Figure 1-5). The 1989 work was highlighted by a significant confirmation of the high-voltage system's basic geometry: an open-circuit "ring-up" of the inductively graded Marx generator to a full 2 MV without breakdown from the dome to the wall. That test was conducted with ten trays in place; later tests with all 18 trays achieved 1.3 MV by the end of 1989. Further work involves the design of inductors that are more resistant to damage; reduction of the effects of transients; and improvement of the triggering circuitry. Progress was also made on construction and test of the 16-beam electrostatic accelerating column.

Testing for Reliability

Characterizing the reliability and performance of the carbon-arc source has been complicated. The source is not as simple as, for example, an electron tube, which either works from the outset or falls victim to "infant mortality." A more physically complex device, the ion source undergoes an early conditioning period—we "burn it in" with several hundred shots before taking data—and then settles into a long period of satisfactory operation. Later, it sometimes degrades for a time, then undergoes some change, not immediately apparent, that resurrects its performance.

We performed emittance scans downstream from a double slit during a long series of shots. Each scan lasted for 900 shots, and the beam's variation in phase space brought it into the scanned area during about 300 shots. This procedure measured the consistency of the beam's size in phase space (emittance) in the long term, yet it also revealed detail, since the pulse shape of an individual shot depends on localized beam behavior. During the other 600 or so shots, we could detect malfunctions by observing a misfire of the arc-discharge pulse or by reading an out-of-range emittance signal.

The object of such lifetime studies is to obtain statistical data on the source's reliability and life cycle: the number and distribution of true failures as a function of the cumulative number of shots. Then we hypothesize about the causes of the failures and modify the source accordingly. The source's life history since the conversion to a single cathode can be thought of in four parts.

Run I: 0–9580 shots. Very reliable operation, with a good-shot rate of 99.6%, except for one less-successful scan (97.5%) in the middle, after which the source recovered spontaneously. At the end of the run, the plasma switch grid was replaced with a new unit of the same design.

Run II: 9580–27 600 shots. Similar to Run I.

Run III: 27 600–34 200 shots. Less successful (90%). Replacement of the plasma switch grid and then of the exit grid did not improve performance.

Run IV: 34 200–36 000 shots. Back to 99.7% after manual cleaning of the flashover trigger surface.

Subsequently we performed large-aperture Faraday-cup measurements to check the total beam current, then returned to the emittance scans for an additional 3600 shots. However, the good-shot rate had dropped below 90%.

This history is actually a confirmation of success and a foundation for further work. The single-arc source lasted three times as long as the best of its three-arc predecessors, and between discrete, major problems, it gave thousands of shots at an average good-shot rate of better than 99.5%. Component aging effects have been identified and can be studied further. Work is in progress on a new version of the source that uses tantalum rather than copper for the trigger wires, and planned investigations include ways of cleaning the trigger without removing or dismantling the source.

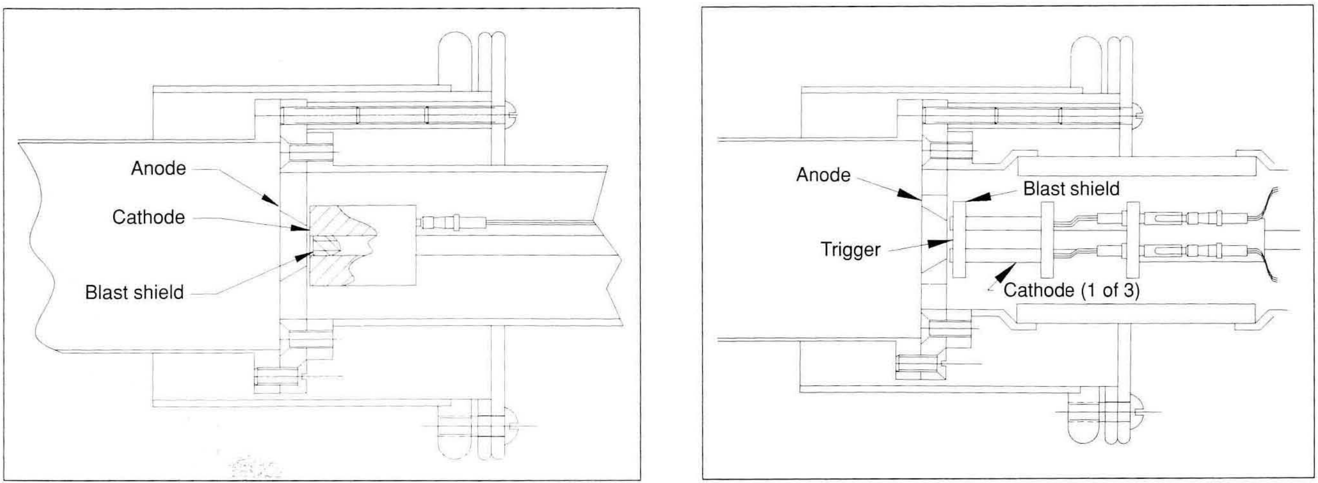

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Figure 1-4. ILSE reaches into an energy realm where cesium beams become impractical due to contamination, so a carbon source has been developed over a period of several years. It generates a plasma in a carbon arc, then confines it behind an electrically biased grid. To extract a beam pulse, a positive voltage is applied between the grid and the grounded extractor plate. The 1989 work focused on improving the lifetime and reliability of the source; after a single robust cathode replaced three slender ones, the lifetime went from 10 000 pulses to more than 30 000.

These tests were conducted using the original input-power concept: a 3.5-kW alternator inside the dome, driven by a Lucite shaft running the length of the Marx generator. This driveshaft scheme was supplanted in late 1989 by a hydraulic drive, and results to date have been very encouraging.

Work is underway to adapt a modular, distributed control system, which is becoming an AFRD standard, for use in the injector and on ILSE generally.* The system (Figure 1-6) uses computer cards called Intelligent Local Controllers to perform much of the processing at the controlled equipment. A personal computer and commercially available software form the user interface.

We plan to bring these injector components together in 1990 for a single-beam test at 1 MV before integration of the full 16-beam hardware.

Accelerator Component Research and Development

In the matching, electrostatic-acceleration, and beam-combining sections of ILSE, the beam will be focused by electrostatic quadrupoles, as shown in Figure 1-7. Precise beam control requires dimensional tolerances of ± 0.002 inch in this unit as assembled. Because tolerances might "stack up" during assembly, the individual parts have to be fabricated to nearly ±0.0001 inch.

One approach to achieving such precision would be plastic forming of titanium-alloy sheets. This new technology could elegantly and accurately form the electrodes and quad plate as one monolithic piece, but since ILSE will need only 32 such assemblies, the initial tooling costs could not be justified. We found that fabrication of individual parts using conventional computerized numeric control machining, followed by careful assembly in a cleanroom, could give the needed precision. The first prototype was completed in 1989, and, after dimensional verification by a metrology specialist, was used for high-voltage tests in vacuum.

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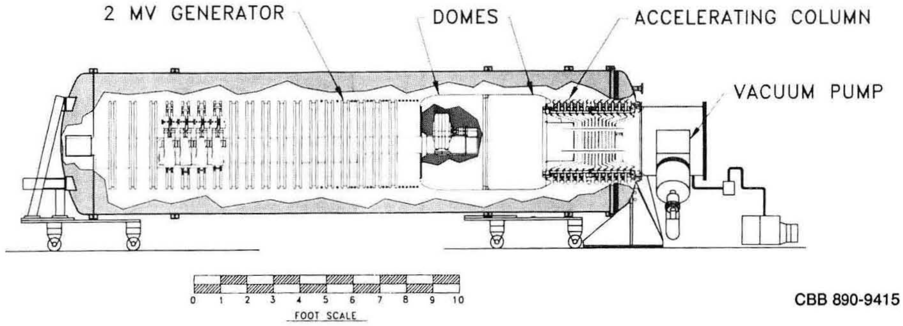
* The basic design was originated in the early 1980s for the Uranium Beams project at the Bevalac, a heavy-ion synchrotron. A refined version is being set up at the Advanced Light Source and will be copied for the infrared free-electron laser at the proposed Chemical Dynamics Research Laboratory.

Figure 1-5. In the ILSE injector, a 16-beam electrostatic accelerator powered by an inductively graded Marx generator will accelerate ions from the carbon-arc source. The design goals for the injection system are an energy of 2 MeV and a current of 8 A in stand-alone testing (the system is required to deliver 2 MeV, 5.4 A for injection into ILSE). A successful open-circuit "ring-up" to 2 MV with 10 of the 18 inductor trays installed was among the 1989 highlights.



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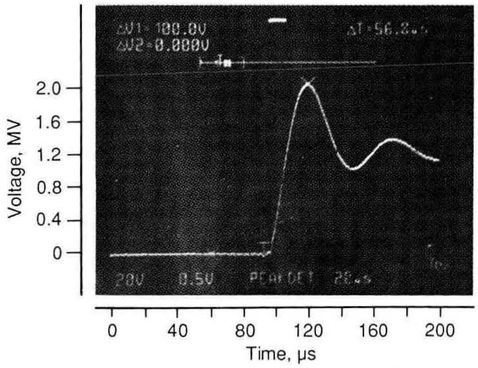

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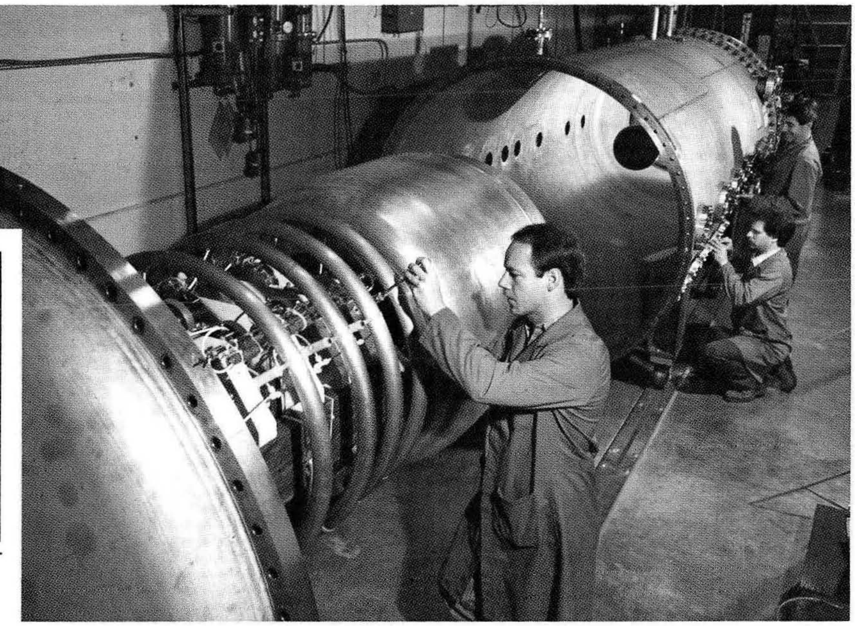

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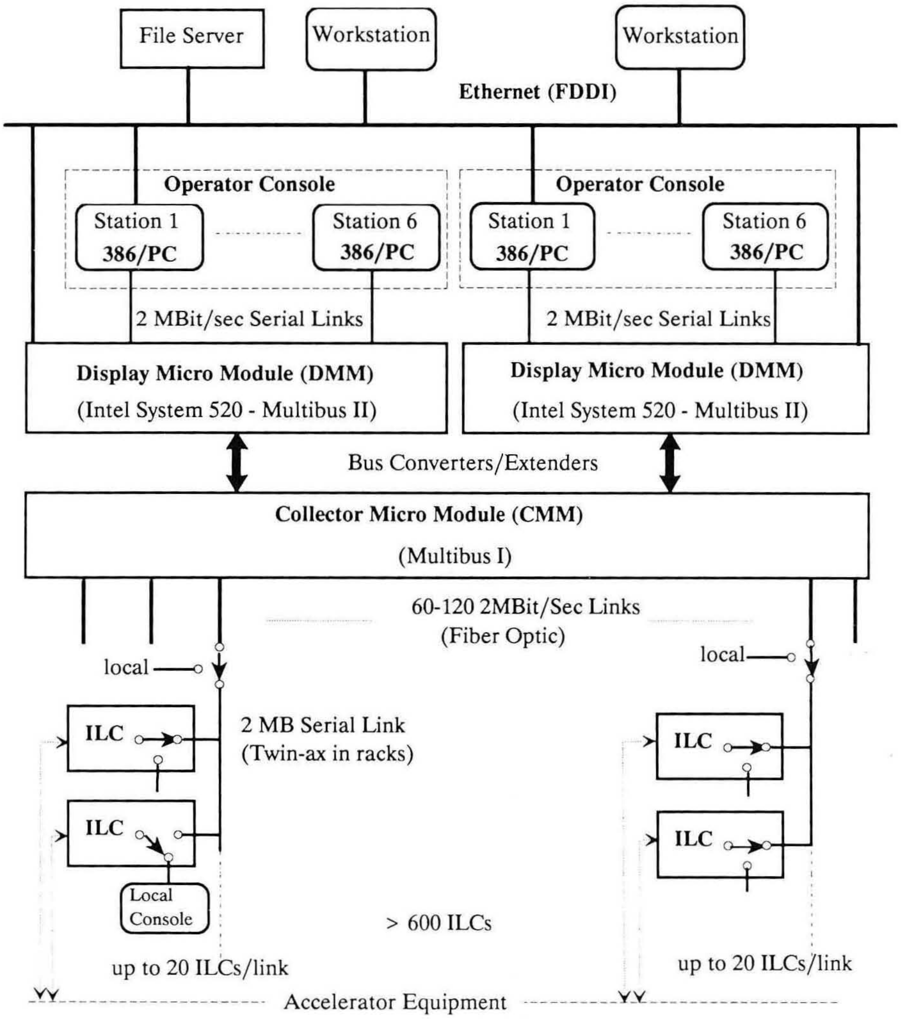
Beyond the beam combiner, the energies are higher and it becomes more sensible to use magnetic focusing. The challenging component development tasks identified in the ILSE Design Study last year included the design and fabrication of quadrupole magnets, including combined-function dipole/ quadrupole magnets that perform bending as well as focusing. The magnets must have great field uniformity; this permits the beam to occupy a large amount of the field area, so the bends can be made sharper. It is also desirable to use "current-dominated" magnets, avoiding the usual iron pole pieces, so that quadrupole windings can be layered atop the dipole windings and controlled separately without affecting the dipole field. A current-dominated magnet also allows a much more densely packed matrix, an essential quality in a multiple-beam accelerator.

To meet these requirements, we chose the basic design shown in Figure 1-8. The basic cosine-θ pattern of the outer (quadrupole) windings is modified slightly, compensating for the fact that their effective length, as seen by the beam, is slightly longer than that of the dipole windings. An iron yoke returns flux outside the beam aperture.

The next step will be the fabrication of one or two prototypes. Attention will also have to be paid to manufacturability. Each pole consists of 24 turns



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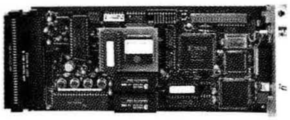

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Figure 1-6. **The computerized control system for the 2-MV injector uses a highly distributed architecture, with intelligent local controllers (ILCs) doing most of the processing at the controlled equipment. The control system is patterned closely on that of the Advanced Light Source, a 1–2 GeV synchrotron radiation facilit now being built at LBL.**

of wire placed within ± 0.003 inch of their ideal positions. The manufacturing method should require as little labor as possible and should locate the windings with inherent, reproducible accuracy. It might not be feasible to form the stiff 2-mm copper wire onto cast-resin wire forms with such accuracy, so alternative methods are being investigated. They include chemical milling of thin-wall copper tubes, five-axis numerically controlled machining of solid copper, laser cutting, electrodeposition, lamination of thin copper on Kapton substrates (like a flexible printed circuit board), and resin casting of many fine wires connected in parallel.

Nineteen eighty-nine also saw the beginning of design work on the induction accelerator cells for ILSE. The beams will be accelerated from 2 to 10 MeV as they pass through 56 of these cells. The basic 16-beam cell configuration will have two nested Metglas accelerator-core packages driven by two 90-kV pulsers in parallel.

Taking the long view toward heavy-ion drivers that will need 1000 or so induction cores apiece, we have been thinking not only about the scientific

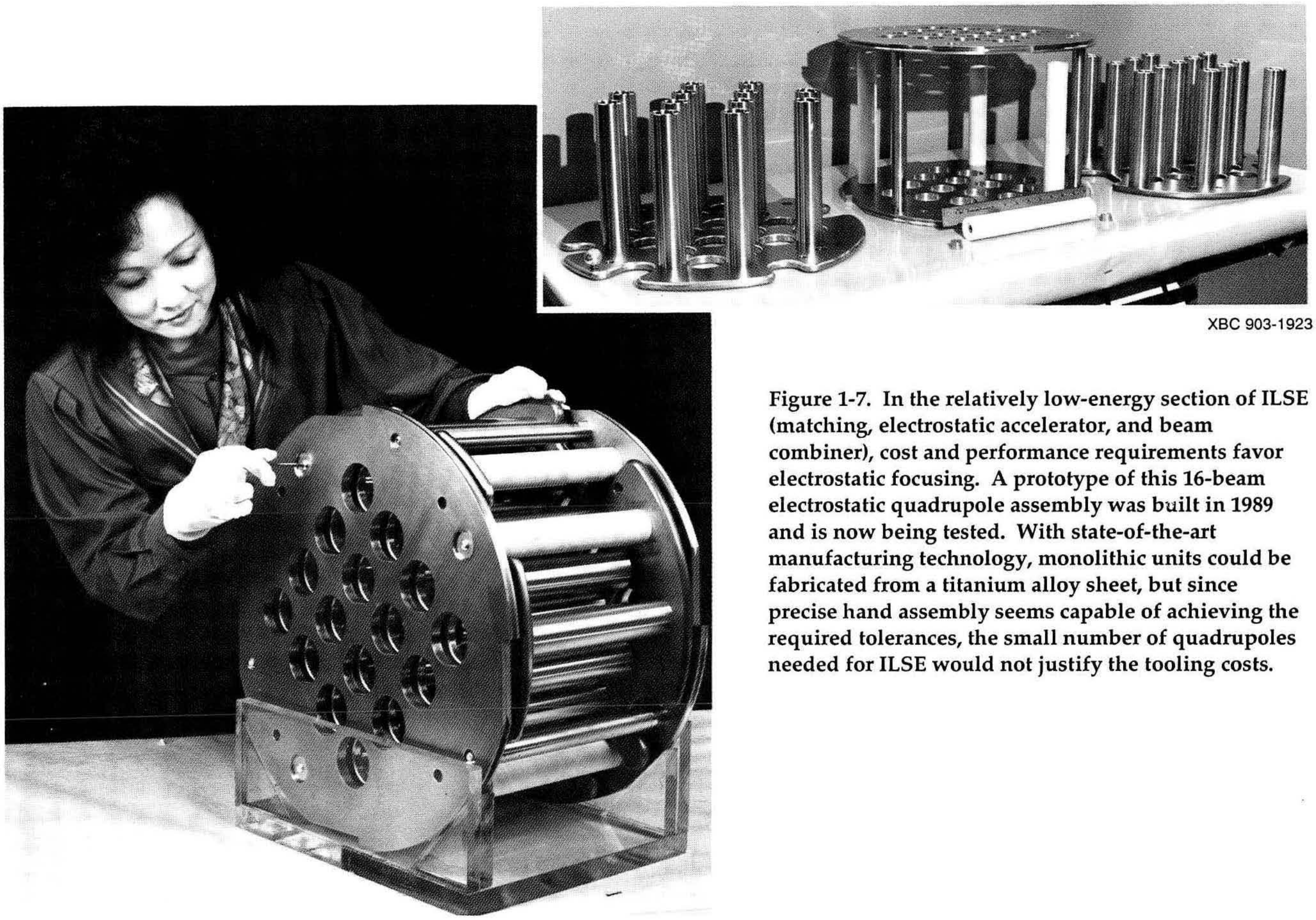

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Figure 1-7. In the relatively low-energy section of ILSE (matching, electrostatic accelerator, and beam combiner), cost and performance requirements favor electrostatic focusing. A prototype of this 16-beam electrostatic quadrupole assembly was built in 1989 and is now being tested. With state-of-the-art manufacturing technology, monolithic units could be fabricated from a titanium alloy sheet, but since precise hand assembly seems capable of achieving the required tolerances, the small number of quadrupoles needed for ILSE would not justify the tooling costs.

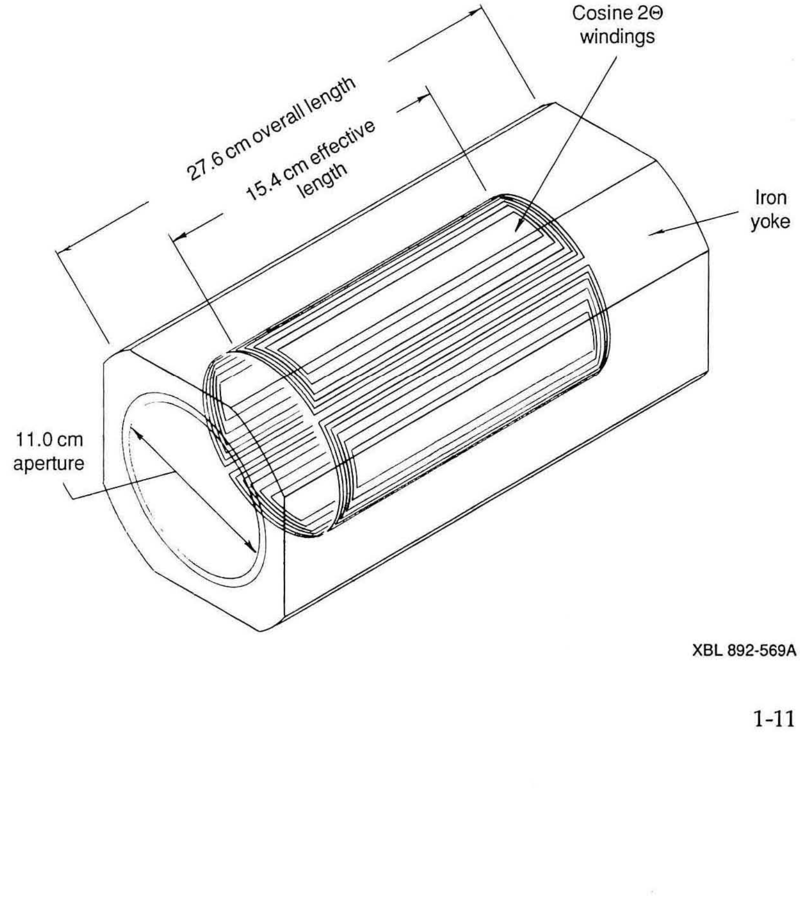

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Figure 1-8. The magnet planned for use in the ILSE bend section combines dipole windings that bend the beam and quadrupole windings that focus it. (The dipole windings, not shown here, would be layered outside the quadrupole windings.) Work has begun to find a cost-effective means of fabricating such a magnet with the required degree of precision.

performance needs of ILSE but also about engineering issues such as materials cost, manufacturability, and failure modes and long-term reliability. For example, the ILSE cores will be backfilled with a fluorocarbon dielectric fluid rather than, for instance, transformer oil; thus any leaks into the beamline would be much easier to clean up. The mechanical design makes leaks into the air more probable than leaks into the beamline in the event of most breakdowns, and structural factors such as handling and seismic loads are being considered. We are also working with industry on insulating laminates (which separate the Metglas layers) that would provide good efficiency, keep costs low, and survive the annealing process.

Publications and Presentations

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