Heavy-Ion Fusion Accelerator Research

LBL--27002

DE90 000169

1988

Accelerator and Fusion Research Division
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Berkeley, California 97420

May 1989

*Reprinted from Accelerator and Fusion Research Division: 1988 Summary of Activities,
LBL-27000, May 1989*

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences,
Advanced Energy Projects Division, of the U.S. Department of Energy under Contract
No. DE-AC03-76SF00098

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1.

HEAVY-ION FUSION ACCELERATOR RESEARCH

*... a series of ever larger
and more-complex
experiments ...*

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. The inertial-confinement power plants that have been envisioned would use a number of beams of heavy ions from the drivers; each beam would impinge upon the target (a deuterium-tritium fuel pellet) from a different direction with great symmetry of timing and positioning. A prototype power plant is decades away, but recent experimental successes indicate 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 approach has involved a series of ever larger and more-complex acceleration and beam-transport experiments over the past decade or so. 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 SBTE became operational in 1983 and was superseded in 1987 by MBE-4, a Multiple Beam Experiment with which to explore acceleration. Experiments with MBE-4 are now in progress. Meanwhile, the group is designing a research program called ILSE—the Induction Linac Systems Experiment—whose purpose is to 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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Nineteen eighty-eight was highlighted by experiments with the newly completed MBE-4, a Multiple Beam Experiment that accelerates four beams in parallel. The modular design of MBE-4 has allowed a series of productive studies over the past three years. Now the apparatus is fully assembled, and we have begun using it in earnest for the experiments it was meant to perform: modeling and studying several of the phenomena we expect to encounter in a full-scale heavy-ion fusion driver. For example, any accelerator has a theoretical stability limit imposed by the space charge; violation of this limit leads to increased beam emittance (diminished beam quality). 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.

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, an older design 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, is benefitting the ILSE program.

Figure 1-1 illustrates the concept behind MBE-4. Ions are injected into each of the four beamlines at 200 keV. Another 30-keV energy boost is given at each of 24 accelerating gaps for a final kinetic energy of 920 keV.

The preliminary design of MBE-4 called for a final kinetic energy of 920 keV and current amplification by a factor of 4.5. Halfway through 1988, MBE-4 had already exceeded those specifications, reaching a top kinetic energy of 950 keV and a maximum current amplification factor of approximately 9.0.

Reaching the necessary power calls for amplification of beam current, which in turn is determined by the speed and line density of the bunch of charged particles.

Research with MBE-4

MBE-4: The Induction-Linac Approach

Current Amplification and Acceleration Schedules

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.

The speed is determined by the beam 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 ability to change any of these factors is determined by the parameters of the accelerator.

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, so it must be minimized.

Given MBE-4's length and operating parameters, achieving an amplification factor of 8 or more requires an aggressive acceleration schedule—radical compression of the pulses to achieve high current amplification. After the initial experiments, we began a detailed study involving a gentler acceleration schedule in which the current was increased by a factor of 3.5. This more closely simulated the acceleration schedule of the 400-m electrostatically focused section in a full-scale driver.

Figure 1-2 shows the progress of a pulse through the seven diagnostic gaps in MBE-4 during both the aggressive and the gentle acceleration schedules. In the second (gentle) round of experiments, six of the accelerating gaps were devoted to small corrective voltage pulses. These corrections kept small deviations from causing current oscillation and also helped hold the ends of the bunch together against the dispersive influence of the space-charge force.

Emittance and Current Amplification

One of the questions arising from current amplification is whether normalized emittance grows or remains constant during the procedure. Several recent MBE-4 experiments have given conflicting results; perhaps current amplification intrinsically raises emittance for reasons we have not yet discovered, or perhaps the apparent increase was an artifact of instrumentation problems such as poor impedance matching or magnetic-lens misalignment. In search of a theoretical benchmark for use in further analysis, we modified the SHIFTX computer code to account for acceleration and current amplification in MBE-4. Thus far, the modified code, called SHIFTXA, has revealed some intrinsic growth in emittance, but not as much as we observed experimentally. We are improving the diagnostic instrumentation for further study of this phenomenon.

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 would undergo current amplification by a factor of about 200—a velocity term of 50, multiplied by a length term for bunch contraction of 4. The most aggressive MBE-4 trials involved a velocity factor of 2.1 and a length factor of 3.8. The velocity factor of a real driver cannot even be approached in such a short accelerator (though the voltage is expected to scale up straightforwardly). On the other hand, length-factor manipulation is actually much more demanding in such a 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 μ s, and rise-time effects would not make up such a significant percentage of the pulse width (hence our rationale for working with gentler acceleration schedules).

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 steps along the road to a full-scale driver, but they are experiments, not scale models, 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

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Figure 1-2. The changing shape of a pulse as it goes through the seven diagnostic gaps in MBE-4 shows the differing effects of aggressive (top) and gentle (bottom) acceleration schedules. In the second, gentle round of experiments, six of the accelerating gaps were devoted to small corrective voltage pulses, which kept small deviations from causing current oscillation and also helped hold the ends of the bunch together against dispersive space-charge forces.

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 (though a computer simulation tool, the SLID 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.

Ion-Source and Injector Development

As we move 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, high-current injector. Constraints in the first parts of the accelerator limit the current to 5.4 A, 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. (Because of its low work function, cesium is easy to use for high-current ion sources, but it tends to contaminate components downstream, lowering their breakdown voltage and thus limiting their acceleration capability.) A collaborative effort with other institutions has produced a satisfactory carbon-arc ion source; the next steps will be to improve its operating characteristics and to get 16 of these sources to function within the 2-MV injector.

Progress on the Carbon-Arc Source

During the past two years, ion-source work has been focused on a carbon-arc source 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 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.

Early on, this source was able to provide satisfactory current density. Ongoing work involves lowering its emittance (which, averaged over a thousand shots, is four times larger than we had hoped) and improving its shot-to-shot repeatability.

The repeatability was greatly improved by changing to a more closely spaced plasma mesh. (Increases in plasma density raise the Debye shielding effect of the mesh, making the electric field less effective in shutting off plasma flow. The resulting random leaks through the mesh cause random variation in the output parameters.) We are now measuring lower emittance, less variation from shot to shot, and plasma shutoff at lower voltages.

A significant event in ion-source development was the completion of a 200-kV test stand. (Previously, we had been using the otherwise-idle SBTE to test the injector.) In addition to the usual complement of extracted-beam diagnostics for current and emittance measurement, the new test stand has a channel-plate diagnostic system that lets us take a "snapshot" of emittance at a particular time during a pulse.

Injector Development

The carbon-arc source will be incorporated into the 2-MV, 16-beam injector that will eventually be used for ILSE. After receiving the parts for the injector from Los Alamos National Laboratory in September 1987, we assembled them in the previously tested 750-kV configuration. LBL now has responsibility for further development of this injector. In 1988 we changed the design (see Figure 1-3) from a pure Marx generator to an inductively graded one. We found that some parts had to be replaced to improve reliability; after that, we successfully tested it with 50 consecutive shots at the 1-MV level.

Figure 1-3. The 16-beam inductively graded Marx generator that will accelerate ions from the carbon-arc source. The design goals 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).

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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 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 \$37 million 1988 dollars spread out over five years, ILSE would provide more than a thousand times more peak power on target than 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-transport system
- Magnetically bending space-charge-dominated ion beams while increasing their energy
- Amplifying current by “drift compression”
- Focusing ion beams precisely onto a small spot

Induction Linac Systems Experiment

Figure 1-4 illustrates the ILSE concept. Sixteen beams are produced in the 2-MV injector now being developed. Then they are accelerated to 4 MeV, and their current is amplified, as in MBE-4 but on a larger scale. The sixteen beams are combined into four, which are accelerated to 10 MeV, but 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.

Progress towards an ILSE Design

In 1988 we began moving from a "physics design" of ILSE—a basic understanding of the needed components and how they would work—to a "conceptual engineering design" in greater mechanical and electrical detail. 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.

This design exercise has elucidated several important tradeoffs. The physics design naturally emphasizes a short lattice period; this allows higher current and, because there is an accelerating gap at every half-period, a higher gradient (more acceleration per meter). However, the three fundamental subsystems—focusing elements, accelerating elements, and vacuum apparatus—take up axial space, thereby increasing the lattice period. The technical challenge is to find the best compromise among these conflicting requirements. Table 1-1 lists the most significant parameters of the final ILSE physics design alongside the corresponding parameters of MBE-4 and SBTE. Those interested in the conceptual engineering design study of ILSE should consult Lawrence Berkeley Laboratory report PUB-5219 (March 1989).

Making these tradeoffs provided an excellent learning opportunity because the ILSE designers faced the same problems that would present the greatest difficulties in a driver. (In particular, the low-energy end of a driver is where focusing elements take up the greatest percentage of the length—as much as 50%. Through most of the remainder, they would take up less than 10% of the length, greatly alleviating the problems.)

Beam Combination

In a driver design, money might be saved by combining beams at a relatively low kinetic energy (10–100 MeV). To test this process, and also to increase the beam power, ILSE will combine 16 beams into 4 at the 4-MeV point. Until recently, all the proposed beam-combiner designs involved putting the beams through an S-curve so that they came out in the proper sequence. However, because the particles in a bunch are not all traveling at quite the same velocity, different parts of the resulting beam would take different trajectories, a problem analogous to chromatic aberration in a lens.

Figure 1-4. In ILSE, sixteen C^+ beams will be accelerated, current-amplified, and combined into four large beams, which will then be accelerated further. Finally, one of the four beams 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 μ s).

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

Parameter	1982	1983-4	1985	1986
Ion species	C ⁶⁺	C ⁶⁺	C ⁶⁺	Bi ²⁰⁸⁺
Number of bunches	1	4	10-20	10-100
Injection voltage (kV)	0.15	0.2	3	3
Final voltage (MV)	0.16	1	20	200
Final beam current (A)	0.023	0.20	10	100
Final beam energy (J)	0.07	0.08	20	200
Final ion velocity	0.0046	0.004	0.04	0.4
Accelerating gradient (MV/m)	0.6	0.07	0.03	0.03
Initial bunch length (ps)	0.8	1.1	0.1	0.1
Pulse width (ps)	20	2-10.4	1-10.15	0.1-10

It appeared forbiddingly complex to cure this problem with pulsed bends, so instead we found a new solution for the optics of the beam-combining section. In ILSE, electrostatic and electromagnetic elements will be used to bend and focus the beam in such a way that the dynamics are achromatic through the first order despite the velocity variations. This system has been translated into a conceptual engineering layout.

Other ongoing ILSE work centers on the magnetically focused accelerator section. A special difficulty arises from 3-D nonlinearities at the ends of the magnetic lenses; we have addressed this problem with a conductor-winding pattern that nulls the dodecapole (12-pole) component, which is usually the most disruptive. Particle-in-cell simulations to determine the effectiveness of this solution are underway.

Working with a reference case derived from the earlier Heavy Ion Fusion Systems Assessment (HIFSA) study, we have extended our research on the effects that component misalignments and changes in the half-period have on acceleration.

Numerical study indicates that longitudinal placement of quadrupoles is not extraordinarily critical; the required tolerances can be achieved through ordinary good practice in engineering and construction. But the transverse placement of the focusing elements must be very accurate. For example, in a driver that does not incorporate a mechanism for making steering corrections, the quadrupole magnets used for focusing must typically be placed within 25 μm of their intended transverse positions. If they are not positioned correctly, the beam undergoes transverse coherent oscillations that displace it radially and skew its path away from the beamline axis. However, if such a displacement can be sensed with sufficient accuracy, it can be corrected with appropriate transverse "kicks" (though additional diagnostic and steering devices are required).

This principle of sensing the displacement and applying a corrective kick, which is fairly straightforward in many types of accelerators, is not easily applied to a current-amplifying induction linac. Because of the current amplification, the head and tail of a bunch have substantially different velocities (the difference could be as great as 30% at the low-energy end of a driver). Therefore both the magnitude and the phase of the oscillations vary from one end of the bunch to the other. These factors twist the beam into a corkscrew; straightening it is a difficult, time-dependent problem. At the high-energy end of a driver, the "velocity tilt" would not be as great. However, the correction problem would still be severe; the kicks would have to be much harder and would have to be accomplished in less than 1 μs .

The HIFAR Theory group has studied the alignment problem with simulation in order to determine whether correction is actually necessary. Figure 1-5 shows the

Focusing-System Alignment Tolerances

Figure 1-5. To study the effects of transverse misalignment of accelerator components, we numerically modeled a 4-MJ, 3-GV driver with about 1500 focusing periods, operating at charge state +3. In this figure, the ratio of expected amplitude of coherent transverse beam oscillations to component misalignments (in an assumed uniform distribution of errors) is plotted as a function of cumulative accelerating voltage. The 60 MV point would be about 400 m down the driver; the 3-GV point would be at approximately 3.6 km.) This calculation indicates a need for highly precise transverse alignment, with rms tolerances on the order of 10 μm . This requirement can be relaxed through the use of a time-dependent steering system to correct the oscillations.

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growth of cumulative errors as a displaced beam travels down a driver. The conclusion: it is desirable not only to perform the correction, but also to minimize the oscillations by aligning the driver as accurately as possible. (The latest alignment techniques, developed for large laser systems and colliding-beam accelerators, have pointed the way toward transverse precision on the order of several μm .)

We performed a beam-steering experiment in MRE-4 using two pulsed electric dipoles, spaced $3/4 \lambda$ apart, to correct both angle and displacement. These dipoles reduced the effects of the oscillations from 4 mm to 0.5 mm in position, with negligible errors in the angle. To deal with comparable alignment problems in ILSE, our mechanical engineers have devised a kinematic mounting system for the 16-beam electrostatic-focusing array (Figure 1-6). The system, which uses a laser beam as a survey reference, can meet the ILSE requirements and appears to be a promising approach for a driver.

Figure 1-6. The kinematic mounting system designed for the ILSE electrostatic focusing array (left) uses a laser as a survey reference. The ILSE mounting design (right) features separate supports for the electrode arrays, vacuum wall, and induction cores, since they all have different positional-tolerance requirements. The support for the focusing-electrode arrays is shown at right. These mounting systems give precise alignment (a tolerance of $\pm 0.1 \text{ mm}$ is required for the electrode arrays) without extreme precision in machining. They also provide kinematic adjustment. The significance of such developments extends beyond ILSE; precision and kinematic adjustability would be important in a power-plant driver, which must operate consistently over the long term with low maintenance.

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