**HEAVY-ION
ACCELERATOR RESEARCH
FOR
INERTIAL FUSION**

**LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA**

AUGUST 1987

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Thermonuclear fusion offers a most attractive long-term solution to the problem of future energy supplies: The fuel is virtually inexhaustible and the fusion reaction is notably free of long-lived radioactive by-products. Also, because the fuel is in the form of a plasma, there is no solid fuel core that could melt down. The DOE supports two major fusion research programs to exploit these virtues, one based on magnetic confinement and a second on inertial confinement. One part of the program aimed at inertial fusion is known as Heavy Ion Fusion Accelerator Research, or HIFAR. In these pages, our aim is to place this effort in the context of fusion research generally, to review the brief history of heavy-ion fusion, and to describe the current status of the HIFAR program.

MASTER

A simplified schematic shows eight laser or ion beams impinging on an ICF pellet; another eight beams would strike the pellet from the other side.

The principal fusion research programs can be classified according to the method used to confine the burning deuterium-tritium fuel. Magnetic confinement schemes, most commonly embodied in the Tokamak, use strong magnetic fields to contain the continuously burning hot D-T plasma. By contrast, inertial confinement fusion (ICF) depends on the inertia of a small D-T pellet to keep the fuel together long enough to burn. ICF therefore relies on a pulsed process, analogous to the repeated mini-explosions in an automobile engine. In the sun and the stars, yet another means of confinement is at work; there the gravitational force alone is strong enough to confine continuously-burning nuclear fuel.

ICF requires a "driver" to provide the intense focused energy necessary to compress and ignite the fuel pellet. Practical energy sources are of two types: laser drivers, which rely on powerful beams of short-wavelength light to compress the pellet, and ion-beam drivers, in which high-energy beams of ions deposit their kinetic energy in the pellet and thereby compress it.

In principle, ions of almost any mass can be used in an ion-beam driver. However, since most pellet designs require an ion deposition range of about 1 millimeter, the choice of ion mass determines the kinetic energy of the ion. Light ions such as lithium require an ion energy of around 50 MeV (million electron volts). Currently, so-called pulsed-power accelerators are used to generate light-ion beams and are especially suitable for single-shot experiments. Heavy ions such as bismuth or lead, on the other hand, require an ion energy of about 10 GeV (billion electron volts). Accordingly, since heavy ions carry far more energy per ion than do light ions, fewer are needed to deposit the required energy in the pellet. Thus beam currents, although high, are a few hundred times smaller than those needed with light ions. This means that reliable, more conventional methods can be used for transporting and focusing the beams. It also means that rapid-pulse accelerator systems can be used.

Building on pellet design research for laser-driven inertial fusion, which began in the 1960s, A.W. Maschke, then at Brookhaven National Laboratory (BNL), was first to recognize the advantages of using heavy-ion beams for ICF. This heavy-ion concept was then brought to the attention of ERDA (now DOE) in 1975. The following year, the Offices of Laser Fusion (later Inertial Fusion) and High Energy Physics sponsored a two-week summer study on the topic. Over 100 scientists participated, drawn from the fields of accelerator physics, fusion reactor design, and fusion pellet physics. Pellet designers from the ERDA weapons laboratories provided valuable input that helped guide the choice of accelerator requirements for heavy-ion fusion (HIF) applications.

While they emphasized the need for considerable research, scientists at the 1976 summer study concluded that prospects for HIF looked very encouraging. They examined three quite different accelerator methods and found no insurmountable problems. At the same time, they highlighted what was, and continues to be, the main design difficulty: how to reliably deliver extremely high beam currents (thousands of amperes) in a pulse having a duration of about 20 billionths of a second. The three accelerator methods put forward to overcome this difficulty were: (i) to sequentially fill several storage rings with ions from a single radio-frequency linear accelerator, then to deflect

the beams simultaneously onto the fusion pellet; (ii) to accelerate ions in a synchrotron, then either to use the beam bunches directly on a pellet or to use them to fill storage rings; and (iii) to use an induction linac, combined with special beam-bunching techniques.

In 1983 the DOE decided to concentrate on the induction method (proposed by LBL), primarily because of funding limitations, but also because this scheme promised simpler and less costly systems. Meanwhile, scientists in West Germany, the United Kingdom, Japan, and the Soviet Union continued with the rf linac/storage ring method, and several designs were published in 1984-86. In addition, Sandia National Laboratories continued their light-ion research efforts, which began with protons in 1979.

Selected Milestones

Research

- 1976** Summer study confirms and articulates advantages and critical issues.
- 1978** Detailed accelerator designs reviewed.
- 1981** Induction linac driver design completed; multiple beams emerge as economic advantage.
- 1984** LBL Single-Beam Transport Experiment produces high beam currents.
- 1984-85** German HIBALL, Japanese HIBLIC power plant designs completed.
- 1986** HIF Systems Assessment completed.
- 1987** LBL Multiple-Beam Experiment demonstrates current amplification in multiple-beam linac.

Management

- 1977** First federal funds from the Office of Inertial Fusion and the Office of High Energy Physics. Research begins at Argonne National Laboratory (ANL), BNL, LBL.
- 1983** U.S. concentrates on LBL induction method. Accelerator R&D transferred to Office of High Energy and Nuclear Physics. HIFAR program established.
- 1985** DOE HIFAR management consolidated in Office of Basic Energy Sciences, Division of Advanced Energy Projects.
- 1986** Funds approved for West German facility (GSI, Darmstadt) for heavy-ion nuclear physics and heavy-ion fusion.
- 1986** HIFAR reviewed by JASON panel.

To assess in detail the practical prospects for generating electric power by inertial fusion, and to guide future research, a comprehensive study known as the Heavy Ion Fusion Systems Assessment (HIFSA) was undertaken in 1984. This multilaboratory study, which was sponsored by the DOE and the Electric Power Research Institute, was coordinated by Los Alamos National Laboratory (LANL) and completed in 1986. McDonnell-Douglas Astronautics Co. provided system integration. Parameter variational methods were used not only for system optimization, but also to determine how sensitive the cost of electricity (COE) would be to changes in key parameters. Chamber designs and fusion pellet designs in the HIFSA were taken from ongoing studies at Lawrence Livermore National Laboratory (LLNL) and LANL.

The results of the HIFSA study are highly encouraging. The COE was estimated by using costing methods common for such studies, and it was found to compare favorably with results of magnetic fusion studies—as low as 5 cents per kilowatt-hour for 1000-megawatt designs. Moreover, a major conclusion of the study was that the COE is insensitive to variations in several key parameters, including ion mass (100–200), energy (3–12 GeV), repetition rate (3–10 hertz), and number of beams (10–30), provided that other parameters are suitably readjusted. This tolerance, primarily due to the high efficiency of particle accelerators, allows future system designers considerable flexibility.

HIFSA participants also concluded that the size and cost of the accelerator could be substantially reduced by designing the system around an ion with a charge state higher than +1. Specifically, a charge state of +3 was found to be a promising and viable choice. Difficulties in focusing the beam, especially in the region of the final focus onto the fusion pellet, will probably make still-higher charge states less attractive.

Heavy-Ion Fusion Power. An artist's drawing illustrates the basic components of an inertial fusion power plant based on a 16-beam heavy-ion induction linear accelerator. The system shown here uses the Cascade reactor chamber design developed at LLNL—one of several concepts that have been studied. In this design, the inner wall of the chamber, which must absorb the punishing effects of x-ray and debris bombardment, is a thick layer of ceramic granules, kept in

place by rotating the chamber. The granules are cycled through a heat exchanger, which uses helium as a secondary medium. Except for the pellet factory, the remainder of the plant—primarily steam turbines and generators—relies on conventional technology.

HIFAR AT LBL

Development of induction linac technology for intense electron beams began in the U.S. in the 1950s with the Astron accelerator at LLNL. Further development took place at LBL, then again at LLNL for their Advanced Test Accelerator. However, unlike electrons, slow-moving heavy ions required special designs to achieve high beam currents, including the innovative use of multiple beams in the accelerating structure.

One major attraction of the induction linac method is the relative ease with which the physics and technology of a large driver can be scaled down to a laboratory setting. This benefit arises from the fundamental properties of particle beams dominated by internal space-charge forces (the mutually repulsive forces between like-charged particles). The disruptive effects of space charge are, in fact, somewhat worse in a 10-milliamper beam at 0.2 MeV than in a 1000-amp beam in a full-scale 10-GeV driver. This scaling property allows accurate predictions to be made for the beam physics, once the behavior of a small accelerator is well understood, and it forms the basis for much of the planning in the HIFAR program.

Experimental Program at LBL	
Laboratory facility	Date of first results and principal purpose
Single-Beam Transport Experiment (SBTE)	1982 Determine stability and limits of high-current beams.
Multiple-Beam Experiment (MBE-4)	1986 Demonstrate induction acceleration, current amplification, and control of multiple ion beams.
Induction Linac System Experiment (ILSE)	1990 (proposed) Validate heavy-ion accelerators for inertial fusion by demonstrating a scaled system.
Other theoretical and experimental studies, beyond the scope of this brochure, have been conducted at ANL, BNL, LANL, LBL, LLNL, the Naval Research Laboratory, the Stanford Linear Accelerator Center, and the University of Maryland.

High-Current Beams. With the Single-Beam Transport Experiment (SBTE), LBL scientists demonstrated beam currents three times as high as those previously thought possible in beams dominated by their own space charge. Seen at the left are LBL-developed electrostatic lens elements, needed to hold the beams together. For scale, the outer vacuum chamber of the SBTE is about 30 inches wide. In addition to exciting broad interest among accelerator physicists, results from this experiment were used to design the MBE-4 facility and to dramatically reduce the estimated cost of a large driver.

Multiple Beams. The design of MBE-4 integrates both focusing and accelerating electrodes into a single structure and provides the basis for scaling to more beams. A technician, below, holds one electrostatic lens array of this innovative system. Arrays conceptually similar to this would be used in the first part of a full-scale driver. Magnetic lenses would be used in the remainder of the accelerator. Also shown below is the cross section of a full-scale 16-beam driver design, contrasted with that of MBE-4. Magnetic induction cores, which accelerate all of the beams as a unit, surround the lens arrays. The electrical pulses applied to the cores are specially shaped so as to accelerate the tails of the beams more than the front ends. Consequently, the duration of the beam pulses decreases as the pulses travel the length of the linac. This increases the current sixfold in MBE-4 (in a driver, current will be amplified by a factor of a few hundred). Using MBE-4, LBL scientists have demonstrated the pulse-shortening technique as well as the soundness of the multiple-beam design.

0 1
meter

LBL's proposed Induction Linac System Experiment (ILSE) is designed to complete the validation of induction linacs for ICF by demonstrating, in a scaled model accelerator, the physics and technology of a large driver. As suggested in the schematic below, the system includes a number of new and innovative features, each of which must be developed and tested. Among these are a 16-beam injector constructed at LANL, an electrostatic focusing section that accelerates all 16 beams to an intermediate energy, a beam-combining system to merge the 16 beams into 4, a magnetic focusing section that accelerates the resulting 4 beams to the final energy, and finally, a section in which a single beam is bent, then longitudinally compressed and focused onto a small target.

Current amplification throughout ILSE is achieved by means of the same type of pulse shaping already demonstrated at LBL. However, the injected beam currents are considerably higher than those in MBE-4, owing to the design of the new injector, which is near full scale. Likewise, the peak power in the beam on target, though too low for significant fusion pellet experiments, is more than a thousand times that of MBE-4. The ILSE design was based on a careful cost-benefit analysis of the physics and technology issues still to be addressed by the HIFAR program. LBL estimates that the fabrication of ILSE would cost an additional \$28 million (fiscal 1987 dollars), spread over four years.

Apart from driver issues, other research challenges remain for the inertial fusion method. These include demonstration of adequate pellet gain, development of mass production techniques for inexpensive pellets, resolution of reactor first-wall questions, development of adequate tritium-handling methods, and detailed assessments of system costs and acceptability. Some of these matters are being addressed by existing R&D activities. Others await, for example, further evolution of the national priorities in fusion. Meanwhile, HIFAR continues to progress on a well-defined path of research: to develop a definitive base of data and information on the possible use of heavy-ion induction accelerators for inertial confinement fusion. This base will enable the DOE to decide the role of the heavy-ion approach in the nation's future energy programs. That this role might be a major one was underscored recently by an independent panel of scientists (the JASON group), who concluded that, given suitable development, a heavy-ion accelerator "would probably be the driver of choice for commercial fusion power production."

Institutional Abbreviations

ANL	Argonne National Laboratory (Argonne, IL)
BNL	Brookhaven National Laboratory (Upton, Long Island, NY)
DOE	Department of Energy
ERDA	Energy Research and Development Administration (now DOE)
LANL	Los Alamos National Laboratory (Los Alamos, NM)
LBL	Lawrence Berkeley Laboratory (Berkeley, CA)
LLNL	Lawrence Livermore National Laboratory (Livermore, CA)
SNL	Sandia National Laboratories (Albuquerque, NM)

Other Abbreviations

COE	cost of electricity
D-T	deuterium-tritium
HIF	heavy-ion fusion
HIFAR	Heavy Ion Fusion Accelerator Research (program)
HIFSA	Heavy Ion Fusion Systems Assessment
ICF	inertial confinement fusion
ILSE	Induction Linac System Experiment
MBE-4	Multiple-Beam Experiment (4 beams)
rf	radio-frequency
SBTE	Single-Beam Transport Experiment

For Further Reading

1. M. Reiser, T. Godlove, and R. Bangerter, Eds., *Heavy Ion Inertial Fusion*, Proceedings of the 1986 International Symposium on Heavy Ion Inertial Fusion, Washington, DC, May 1986, *AIP Conf. Proc.* 152 (1986). This comprehensive volume contains 64 articles covering every aspect of heavy-ion fusion, including program reviews, technical reviews, and other contributions, on an international scale.

2. D. Hammer, C. Max, F. Perkins, and M. Rosenbluth, *Heavy Ion Fusion III*, JASON Report JSR-86-302 (Mitre Corp., McLean, VA, March 1987). Review of the DOE program by an independent panel of scientists. The JASON group also reviewed the program in 1977 and 1982.
3. LBL Heavy Ion Fusion Staff, *Heavy Ion Fusion Accelerator Research: An Outline Plan*, Lawrence Berkeley Laboratory PUB-5178 (Berkeley, CA, September 1986).
4. John H. Nuckolls, "The Feasibility of Inertial-Confinement Fusion," *Physics Today*, September 1982, p. 24. A comprehensive and readable description of ICF, which also includes a comparison of driver candidates and a discussion of global energy options.
5. D. Keefe, "Inertial Confinement Fusion," *Ann. Rev. Nucl. Part. Sci.* 32, 391 (1982). This review of ICF for the high-energy and nuclear physics community treats laser and light-ion methods as well as heavy-ion accelerators and gives a summary of pellet physics.
6. T.F. Godlove, "A Decade of Accelerator R&D for Heavy-Ion Fusion," in *Proceedings of the 1987 IEEE Particle Accelerator Conference*, Washington, DC, March 1987, IEEE Catalog No. 87CH2387-9. Accelerator research highlights.

Author	T.F. Godlove, with assistance from D. Keefe and D. Vaughan
Design and Layout	T. Ridge
Illustrations	M. Bailey and L. Geniesse
Text Processing	C. Silva

This document was prepared as an account of work sponsored by the United States Government. Neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California and shall not be used for advertising or product endorsement purposes.

Lawrence Berkeley Laboratory is an equal opportunity employer. Prepared for the U.S. Department of Energy under Contract DE-AC02-780P0086. PUB-5178-1