LBL--25998

DE89 012999

ENGINEERING STUDY OF A 10 MEV HEAVY ION LINEAR ACCELERATOR*

C. G. Fong, T. J. Fessenden, R. L. Fulton, and D. Keefe

Accelerator & Fusion Research Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

March 1989

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.

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

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ENGINEERING STUDY OF A 10 MEV HEAVY ION LINEAR ACCELERATOR*

C. G. Fong, T. J. Fessenden, R. L. Fulton, and D. Keefe
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

Abstract

LBL's Heavy Ion Fusion Accelerator Research group has completed the engineering study of the Induction Linac Systems Experiment (ILSE). ILSE will address nearly all accelerator physics issues of a scaled heavy ion induction linac inertial fusion pellet driver. Designed as a series of subsystem experiments, ILSE will accelerate 16 parallel carbon ion beams from a 2 MeV injector presently under development to 10 MeV at one µsec. This overview paper will present the physics and engineering requirements and describe conceptual design approaches for building ILSE. Major ILSE subsystems consist of electrostatic focusing quadrupole matching and accelerating sections, a 16 to 4 beam transverse combining section, a 4 beam magnetic focusing quadrupole accelerating section, a single beam 180 degree bend section, a drift compression section and a final focus and target chamber. These subsystems are the subject of accompanying papers. Also discussed are vacuum and alignment, diagnostics/data acquisition and controls, key conclusions and plans for further development.

Introduction

Commercial inertial fusion (IF) offers an attractive long-term solution to the problem of future energy supplies. Of the several approaches to a commercial fusion target driver, a multigap heavy-ion driver has unique advantages in simultaneously offering repetition rate, electrical efficiency, reliability, and long stand-off focusing. Since 1983, the U.S. Heavy Ion Fusion Accelerator Research Program (HIFAR) has been assessing the multiple-beam induction linac as an inertial fusion driver. The approach includes a series of increasingly sophisticated experiments to explore, in a scaled way, the accelerator physics of the induction linac approach to a driver, to encourage and develop relevant accelerator technology, and to estimate the capital costs and potential economics of induction linac driven fusion power plants. Earlier experiments[1] have yielded significant results on the transport limits of intense ion beams. At present, the multiple ion-beam accelerator experiment[2] MBE-4 is examining the longitudinal dynamics of the electric-focused portion of an induction linac driver. In order to complete the HIFAR data base we have designed a sequence of experiments that collectively are called the Induction Linac Systems Experiments or ILSE. The selection of experiments is derived from the requirements for a driver as developed in the recent HIFSA study[3] of induction linac driven IF for commercial energy production. While ILSE will initially use C^+ ions (Al^{++} may be used later), most of the results will be scalable to ions with different charge-to-mass ratio such as the mass 200 charge state +3 ions in the HIFSA driver. A report of the conceptual engineering study of the ILSE experiments is contained in reference 4.

ILSE Description and Design Development

A block diagram of the ILSE sequence of experiments is presented in Fig. 1. Sixteen C^+ beams from a 2-MV injector are matched to an electrostatic transport system and accelerated to 4 MeV. The beams are then combined to four, and matched to a magnetically focused linac for further acceleration to 10 MeV. This beam-combining experiment is one of the most important in the ILSE sequence and models the 64 to 16 combination in the HIFSA driver concept. Since acceleration of space-charge-dominated ion beams with magnetic focusing has not yet been performed within the HIFAR program, observations on the beam behavior in the magnetically focused parts of ILSE will represent new experience.

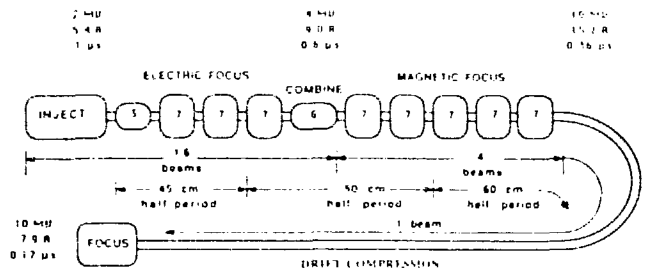

Fig. 1. ILSE block diagram

One of the 10 MeV ILSE beams will be deflected through 180 degrees by a series of bending magnets. In a driver, some 16 beams from the accelerator must be brought to bear and focused symmetrically onto the target--a process that will require bending stiff beams through large angles. The drift-compression power amplification experiment in ILSE (factor of 2 power increase) models a similar feature in a driver (factor of 10 power increase). Finally, the beam will be aimed toward a small spot and neutralized to study the analogous maneuver for a driver. Some of the ILSE parameters are contained in Table. 1.

Table 1 Some ILSE Parameters

Beam energy at injection	2 MeV
Initial current in 16 beams	5.4 A
Final beam current in 4 beams	5 A
Final beam energy	10 MeV
Total Accelerator length	37.5 m
Acceleration gradient	0.3 MV/m
Electrostatic Quad voltages to	± 35 kV
Magnetic Quad tip fields to	±1 T.
Bend Radius	4 m
Drift-Compression length	55 m
Target Current	8 A

This design was developed with the aid of the INDEX induction linac code.[5] From the initial beam parameters, this code applies the current amplifying acceleration theory[6] to calculate the accelerating voltages that will preserve a self-similar current waveform through the acceleration and transport sections of the experiment. In developing the design, the matched beam radius was limited to approximately one-half the quadrupole aperture to allow for envelope oscillations that may occur.

Figure 2 shows the entire ILSE facility within LBL's HIFAR experimental area. The length of ILSE from the source to the end of the accelerator is approximately 40 meters. The length (including the bend) from the end of the accelerator to the final focal spot is 55 meters.

The 2-MV 16 beam injector is a significant development which was begun at LANL and transferred to LBL in 1987. Carbon ions are provided by an arc source in which the plasma is kept from entering the extraction diode by an electrostatic plasma switch. The current pulse is injected into the column by a planar current valve diode that provides a 1µs current pulse. The acceleration voltage,

* Work supported by the Office of Energy Research, Office of Basic Energy Sciences, Advanced Energy Projects Division, U. S. Department of Energy under Contract DE-AC03-76SF00098.

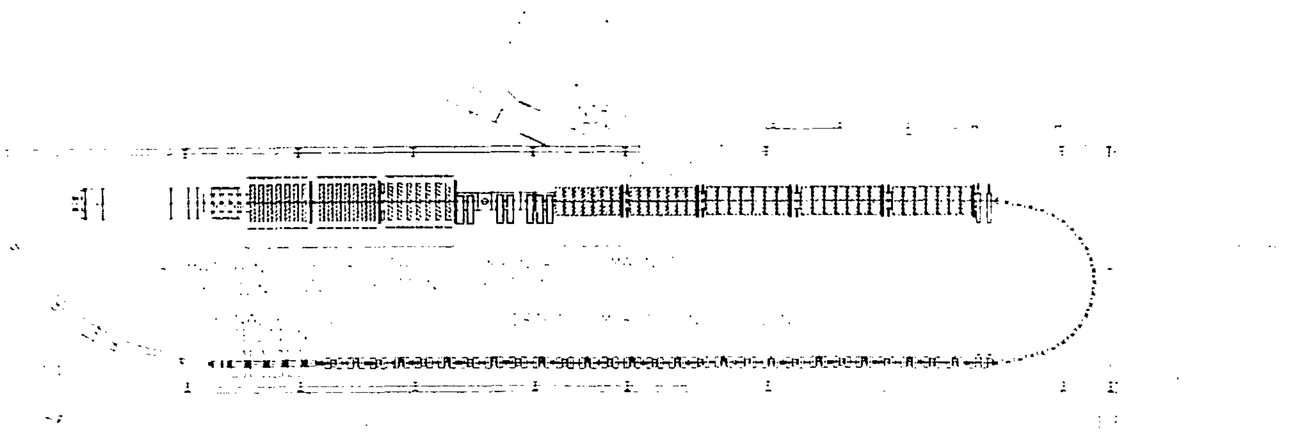

Fig. 2. ILSE plan view.

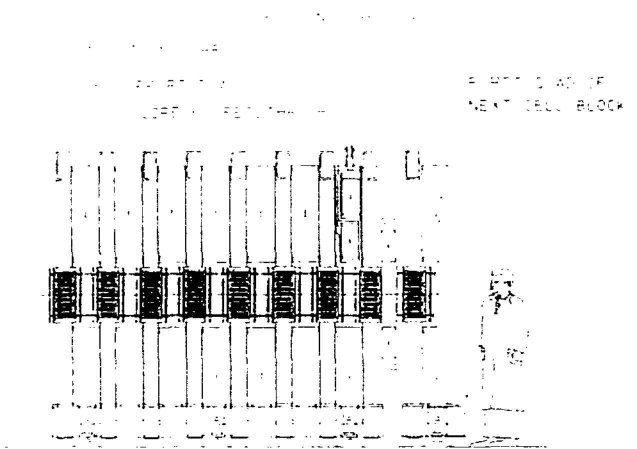

Fig. 3 One cell block of the electric focus acceleration section. The half-lattice-period is 45 cm.

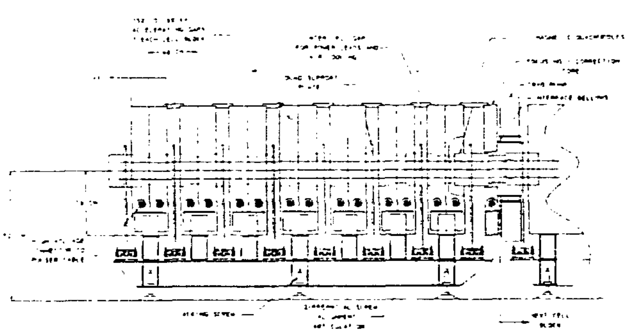

Fig. 4. One cell block of the magnetic focus acceleration section. Shown here is the 50 cm half-lattice-period section

which is generated by an inductively graded Marx bank, is applied to the column electrodes with a 34 μs rise time. An electron trap at the end of the column prevents electrons created by ionization of background gas from being accelerated toward the source. The acceleration column itself consists of a series of aperture lenses that focus the beam and help prevent backstreaming electrons from achieving high energy. The status of the development is the subject of the paper[7] by Rutkowski et al.

The 16 beams from the injector will be matched to the accelerator by an electric focus matching section consisting of five half-lattice-periods of 45 cm each. Dipole steering is used in two drift spaces to compensate for possible angular and position errors of each of the 16 beams at the output of the injector. The matching section will also contain a full complement of beam diagnostics to fully characterize injector performance.

The electric focused accelerator section of ILSE is arranged into three major cell blocks, each consisting of eight electric quadrupoles and seven accelerating cells spaced at half-lattice-periods from 45 to 50 cm as shown in Fig. 3. Each cell contains two induction cores stacked radially and driven by carefully shaped 150 kV pulses. The eighth half-lattice-period contains smaller cores for correction pulsers that compensate for unavoidable waveform synthesis errors and provide longitudinal bunch control. The magnetic focus accelerator section of ILSE consists of five accelerator cell blocks, each block contains eight quadrupole arrays and seven accelerator cells distributed over half-lattice- periods. The lattice half period ranges from 50 to 60 cm and space is available to allow two accelerator cores to be arranged axially . The eighth position of each cell block is used for vacuum pumping, current diagnostics and focus/correction core as in the electric focus accelerator. A typical 50 cm cell block is shown in Fig. 4. A full lattice period at the end of this section is used for diagnostic access. More complete details on the designs for the accelerator units is contained in the paper[8] of Faltens et al.

A key experiment in the ILSE sequence is the transverse beam combining or merging of 16 beams to 4. This is a step in complexity towards the 64-to-16 beam combiner in the HIFSA driver concept. Most important, however, it will be the first experiment of its kind ever undertaken with space-charge-dominated beams where collective phenomena play a decisive role. The paper[9] of Judd et al. details our physics and engineering designs of this experiment.

ILSE's bend experiment will model high current, high energy beam bending required for an ICF reactor configuration. In both ILSE and a driver the velocity of the bending beams increases by approximately 5% over the duration of the pulse. Morever, the perveance of the ILSE beam will be greater than that in a driver. The bend section, designed to operate without time changing fields, consists of 23 current dominated quadrupole and dipole magnets which focus and deflect the beam through a total of 180° with a bending radius of approximately 4.0 m.

Beam power amplification between the accelerator and the fusion target is an essential feature of the induction linac driver concept. At the end of the accelerator the beams will have a velocity tilt which compresses the bunch lengths resulting in current and power amplification during the drift to the target. The compression is opposed by the longitudinal space charge force which must remove the velocity spread at the final focus lens to within ±1%. For an ICF driver, drift compression is expected to amplify power by a factor of ten; in ILSE, beam power amplification will be approximately two.

A driver must provide high power beams focused to a radius of a few millimeters at the fuel pellet. To model this, the ILSE final focus section will expand and refocus the beam for the required angle of convergence of approximately 0.04 radians. The higher perveance of the final ILSE beam is a more severe test than for a driver.

Details of the conceptual design of the ILSE bend, drift-compression and final focus sections are presented in the paper[10] of Lee et al.

System Wide Considerations

To eliminate the need for downstream steering in ILSE requires that each electric quadrupole be aligned to ±0.1 mm. Since the beams are larger in the magnetic focus accelerator and downstream of the combiner, the positional tolerance of the magnetic quadrupoles could be set at ±0.25 mm. These tolerances were driven by the accurate beam positioning needed for a successful combiner experiment and by the beam positioning and emittance limits needed for a successful final focusing experiment. Our approaches to these accelerator alignment issues are detailed in the companion paper[8] of Faltens et al.

The vacuum requirements throughout ILSE were based on the charge exchange and stripping cross sections of carbon ions in gas. Cross section data and an experiment on SBTE indicated that vacuums less than 1×10^{-6} torr would limit the carbon beam loss in ILSE to less than 1%. This vacuum level can be achieved using elastomer vacuum seals and a pumping system consisting of turbo-molecular and cryopumps. Since ILSE will be sequentially built, a local vacuum system will be provided for each experimental section.

Diagnostic instruments for measuring the key parameters of ILSE's ion beams will evolve from those that have been successfully developed for the SBTE and MBE-4 experiments. These include acceleration voltage monitors, two-slit emittance instruments, fine wire harps for beam size measurements, and ion-Faraday cups for current measurements. The higher currents that exist in ILSE permit the use of non-intercepting Rogowski loops located between cell blocks. ILSE's greater complexity (more beams, more diagnostic locations) provides incentives for improving the operation of individual instruments, and for developing a more efficient data gathering system. Data acquisition and reduction, as well as control and monitoring functions will be performed by highly distributed microprocessors based on the building block system currently being developed for the LBL Advanced Light Source (ALS) project.

Conclusions and Further Developments

Each step in the staged series of experiments that ILSE comprises requires some development and has an element of risk. In particular, the performance of the 2-MV injector that is presently under development determines the parameters of the beams that will be input to the accelerator. Final designs for the balance of the experiments cannot be completed until the performance of the injector is well characterized. Results from the beam-combining experiment may also influence designs of subsequent experiments.

The project plan assumes that certain key components will be developed and tested under the HIFAR program before the fabrication of the ILSE acceleration units can begin. Most important is an accelerator cell including core and pulser at parameters appropriate for ILSE. The 2-MV injector development is already a major component of the LBL HIFAR program. As soon as an evaluation of the injector and of the core and pulser development is available, the ILSE design will be reiterated.

For HIFAR, the ILSE sequence represents the logical next step beyond MBE-4. An anticipated start date of FY91 also coincides well with the development of the 2-MV injector and ongoing target chamber studies at LLNL. Presently planned for a four to five year span, the completion of the ILSE experiment will provide current data for HIFAR driver studies and constitute a minimal proof-of-principle experiment to test most remaining induction linac driver accelerator issues.

References

1. M. G. Tiefenback and D. Keefe, IEEE Trans. Nucl. Sci., NS-32, 2483 (1985).
2. H. Meuth, S. Eylon, D. E. Gough, D. Keefe, and A.I. Warwick, "An Experimental Small-Scale Ion Induction Linac for Heavy Ion Fusion," this conference (talk only).
3. D. J. Dudziak, guest editor, "HIFSA Heavy Ion Fusion Systems Assessment Project," Fusion Technology, 13, February 1988.
4. Lawrence Berkeley Laboratory, "Induction Linac Systems Experiments Conceptual Engineering Design Study," LBL Pub -5219, Lawrence Berkeley Laboratory, March 1989.
5. C. H. Kim, "Ion Induction Linac Design and Operating Codes,". Lawrence Berkeley Laboratory, unpublished.
6. C. H. Kim and L. Smith, Part. Accel. 18, pp. 101-113, (1985)
7. H. L. Rutkowski, D. Vanecek, D. Brodzik, A. Faltens, R.M. Johnson, and S. Humphries Jr.,"The Berkeley 2 MV Heavy Ion Fusion Injector," this Conference.
8. A. Faltens, V. Brady, D. Brodzik, L. Hansen, L. J. Laslett, S. Mukherjee, D. Bubp, D. Ravenscroft, and L. Reginato, "Acceleration Units for the Induction Linac Systems Experiment," this Conference
9. D. L. Judd, C. Celata, E. Close, A. Faltens, K. Hahn, K. La Mon, E.P. Lee, L. Smith, and W. Thur, "Concepts, Features and Design of a 16-to-4 Beam Combiner for ILSE," this Conference.
10. E. P. Lee, C. Fong, S. Mukherjee, and W. Thur, "Conceptual Design of Bend, Compression and Final Focus Components of ILSE," this Conference.