10/26-9295①
5

LBL-31943
UC-415

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Heavy Ion Fusion Accelerator Research (HIFAR)

Year-End Report

April 1, 1991–September 30, 1991

Heavy Ion Fusion Staff

September 1991

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

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.

**This report has been reproduced directly
from the best available copy.**

**Available to DOE and DOE Contractors
from the Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401**

**Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, VA 22161**

Lawrence Berkeley Laboratory is an equal opportunity employer.

LBL--31943

DE92 013762

**HEAVY ION FUSION ACCELERATOR RESEARCH (HIFAR)
YEAR-END REPORT***

April 1, 1991 - September 30, 1991

Heavy Ion Fusion Staff
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

September 1991

Attention: This document is provided for DOE "Official Use". Distribution to other interested parties is made with the understanding that no information or experimental results given herein will be quoted without first obtaining the authors' permission, or until such information or results have appeared in the open literature.

* This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

Highlights.....	1
R. Bangerter	
Ion Source for the Final Focusing Scaling Experiment	3
E. Henestroza and S. Eylon	
Reference ILSE Physics Design	5
T. J. Fessenden	
Injector and Ion Source Development	7
H. L. Rutkowski	
The Injector Matching Section.....	8
A. Faltens and E. Henestroza	
Beam Merging in ILSE.....	10
K. Hahn	
Short Quadrupole Magnet Design.....	11
W. Fawley and L. J. Laslett	
ILSE Concept Induction Cell Studies	12
L. Reginato and C. Fong	
Fast Split-Harp Emittance Measurements Using a Multichannel Waveform Analyzer.....	14
E. Eylon and C. Lionberger	
HIFAR Staff Roster	15
Publications and Internal Notes	16
Distribution List.....	21

HIGHLIGHTS

The HIFAR Program made excellent progress during the last six months. The design and development of the ILSE concept have been our major activities during this time period. The physics design for the ILSE accelerator is described in the section by T. J. Fessenden and progress on ion sources, injectors, matching, merging are described in the papers by H. Rutkowski, A. Faltens and E. Henestroza, and K. Hahn.

W. Fawley and L. J. Laslett have designed short quadrupole magnets that are compatible with either normal or superconducting technology, and that have interestingly large dynamic apertures. Short quadrupoles are necessary to minimize the cost and maximize the efficiency of heavy ion drivers; however, there has been some concern that short quadrupoles would lead to excessive emittance growth.

For several years we have believed that we would either have to use expensive, cobalt-based magnetic materials for induction cores or develop insulating materials that could withstand the high-temperature annealing thought to be needed for inexpensive iron-based materials. It now appears that the iron-based materials will not require annealing. Moreover, extremely thin insulation is now available which allows us to fabricate compact, inexpensive, efficient induction cores. This work is described in the section by L. Reginato and C. Fong.

Emittance measurements were very time-consuming on MBE-4, and we are examining alternative approaches for ILSE. S. Eylon and C. Lionberger have developed a new diagnostics system that reduces the time required to measure emittance by more than a factor of 30. The article on page 14 describes the new system.

In addition to our work on ILSE, the ion source for the final focus experiment (to be performed in collaboration with AccSys Corporation), has been designed and built and is now operational. Beam uniformity, current density, and emittance are already good but will be improved by employing a new heater design for the ion source. This work is described on page 3.

Ion source for the Final Focus Scaling Experiment

E. Henestroza and S. Eylon

A Final Focus Scaling Experiment is being performed with AccSys Corporation with support from a SBIR grant. It will be performed on the Single Beam Transport Experiment (SBTE) using a modified Cs^+ source injector. The experiment requires a beam with the following characteristics:

- A waist that is less than 1" in diameter at the entrance to the final focus transport system.
- A waist location that does not change as the current is charged.
- A current that scales as the square of the beam radius.

In order to meet these requirements the SBTE ion source layout has been redesigned using the EGUN code to obtain a converging, uniform current density at the end of the diode. This has been done by repositioning the extraction electrodes as well as the Pierce electrode. A set of currents can be obtained by a set of circular apertures located at the beam waist.

Fig. 1 shows the beam trajectories and equipotential lines obtained by the EGUN code (Ref 1). The simulation predicts that the source will deliver 10 mA of converging, uniform Cs^+ beam within an aperture of 12.5 mm radius at the end of the diode. The energy of this beam is 120 keV.

The SBTE injector was modified and assembled following the above design, an improved source was installed, and measurements were taken to characterize the injector performance.

The dependence of beam total current on the injector voltage, i.e. beam energy, is shown in Fig. 2 and found to be consistent with the Child-Langmuir space-charge limited emission law.

The current density profile measured using a 1 mm pinhole aperture to scan the beam horizontally along the diameter showed a uniform current density of about 2.1 mA/cm^2 . This result is consistent with the linear dependence of the measured apertured beam current v.s. the aperture area shown in Fig. 3.

Emittance measurements were taken with a two slit scanner. The first slit is about 1/2" from the injector output electrode (close to the predicted beam waist position). This measurement resulted in an unnormalized beam emittance of $5/\pi \text{ mm-mr}$, a beam divergence angle of 2 mr, and a beam radius of 11.2 mm. Fig. 5 shows the phase space plot, i.e., beam divergence angle X' v.s. beam radius X , obtained from the above emittance measurement. The total beam current measured at an energy of 120 keV is about 90% of the current predicted by the EGUN simulations. This difference may be due to a relative low emitting surface temperature caused by a low source heater efficiency. A source with a new improved heater design and increased emission will be available in the near future.

The source performance is consistent with the requirements for the Final Focus Scaling Experiment.

Fig. 1 Beam trajectories and equipotential lines obtained by the EGUN code.

Fig. 2 Child-Langmuir law.

Fig. 3 Apertured beam current.

Fig. 2 Contour plots of the measured beam distribution in (x, x') phase space at beam waist.

REFERENCES

- [1] E. Henestroza, "Ion source simulations for the Final Focus Scaling Experiment", HIFAR-298.

Reference ILSE Physics Design T. J. Fessenden

Introduction

Since the original design was generated, the approach to the ILSE experiments has changed. The present plan is for the accelerator to be constructed as a project with the experimental program to follow. This strategy should minimize both the risk associated with the project and the total project cost. The project would be justified as providing the facility for the research program. We estimate that the research program could start in approximately five years under the assumptions of two years of Research and Development Associated with Construction (RDAC) beginning in the spring of 92 and a three year construction project beginning in FY 94. This plan evolved in a workshop held at the San Damiano Retreat on August 12-14, 1991.

To design the ILSE components, we have focused on the maximum parameters that ILSE should address in modeling the behavior of beams in a driver. A reference physics design was developed that accelerates Ne^+ from 2 to 10 MV with amplification of the total current from 4.3 to 10 amps over a length of approximately 40 m. The design of the magnetic-focus section was done so that it could ultimately transport all the expected beam current following 4:1 beam combining. Each of four beams in the electric-focus section carries the line density considered optimum for a fusion driver and, therefore, the beams in ILSE and those of a fusion driver will be of similar size.

ILSE Layout

Figure 1 is a layout of the accelerator and experiments combining, beam bending, drift compression, and focussing. Table 1 contains parameters of the reference physics design. Four beams at driver line-charge densities will be obtained from a 2-MV injector. The nominal pulse width of this reference ILSE design is 1.3 μs . The injector is followed by a matching section that transforms the round beams produced by the injector to an "A-G" profile and "squeezes" them together for insertion into the electric-focused linac. To amplify the current, the linac imparts a velocity shear or "tilt" to the beams as it accelerates the beams to 4.5 MV. During the experimental program, the four beams will be combined to one in the 18 half-lattice-periods (HLPs) of the combining

section. During the project phase, one of the four beams will be transferred to the system axis and the other three discarded. The magnetic-focus accelerator will continue current amplification while accelerating the beam to 10 MV. Both the electric and magnetic focused sections of ILSE contain 32 accelerating cells which are grouped into blocks of 8. The cell blocks are separated by two HLPs which provide diagnostic access to the beams. Along the machine, as the focusing system becomes more efficient, the HLP increases from 33 cm in the first three blocks, to 41 cm in the fourth cell block, to 50 cm from the beginning of the combining section to the end of the accelerator.

Table 1 Parameters of the reference physics design

Initial kinetic energy	=	2.0 MeV
Electric beam-aperture	=	3.5 cm (radius)
Magnetic beam-aperture	=	6.5 cm (radius)
Initial current	=	4.4 Amp Total
Initial pulse duration	=	1.3 μs
Initial pulse length	=	5.7 meters
Initial line density	=	0.25 $\mu\text{C} / \text{m} / \text{beam}$
Final kinetic energy	=	10.1 MeV
Final current	=	10.1 A
Final pulse duration	=	0.56 μs
Final pulse length	=	5.4 meters
Final line density	=	1.06 $\mu\text{C} / \text{m} / \text{beam}$
Final beam energy	=	57.30 Joules
Length of the Linac	=	41.2 meters
# of acceleration gaps	=	64
Final velocity tilt	=	6.0 %

Summary of the planned ILSE experiments

The first experiments will measure the parameters of the 4 beams delivered by the 2 MV injector and match the beams for insertion into the induction accelerator. Achievement of the full ILSE parameters requires beams from the injector with line charge densities of 0.25 $\mu\text{C}/\text{m}$ (Neon $^+$ or Potassium $^+$). These beams will be equal in size and line density to those needed for a fusion driver.

Fig 1. Layout of the ILSE experiments

Next will come the operation of the electrostatically focused induction linac which takes the beams to 4.5 MV. This portion of the accelerator can be operated both at constant current (requires flat acceleration pulses) or as a buncher to impart a velocity tilt to the beam that will permit current amplification in the last 5-6 MV of the accelerator. The transport aperture and the electric quadrupole focusing voltages will be equal to those in a driver.

Dynamic steering experiments are planned for the region between the electric-focused accelerator and the combiner. The positions and directions of the four beams in the transport channel will be adjusted to be as near and parallel to the axis as possible using time-dependent steering.

Combiner experiments will be an important new contribution to the physics and technology of heavy ion linacs. The experiments will be done both with and without a velocity tilt to the beams. The key finding will be the emittance dilution that will occur as the 4 beams are combined to 1. These measurements will be compared with theory to complete our understanding and evaluation of the practicality of beam-combining in heavy ion inertial fusion drivers. Our present combiner designs use linear focusing elements but a wide variety of experiments may be possible that use nonlinear elements to reduce the emittance growth.

Further acceleration of the 4 beams to 10 MV in a magnetically-focused induction linac will demonstrate our ability to make the transition from an electrostatic to magnetic transport system. Of continued interest will be the evolution of the transverse and longitudinal emittances of the beams. The use of a light "heavy ion" allows the ILSE beam to be transported magnetically at greatly reduced energy and therefore cost than will be encountered in a driver. Because more space is available in the magnetic transport section, beam steering using frequent time-independent steering dipoles will be studied.

The experiments on bending of space charge-dominated beams through large angles are very important. Results (e.g., emittance preservation, chromatic effects) from these experiments will be compared with theory and simulation. Most HIF driver designs do require some beam bending between the accelerator and final focus.

An important concept in a heavy ion driver is the factor of about 10 current amplification that occurs in the drift-compression section from the end of the linac to the final focus lens. The beam enters this section with an axial velocity tilt thus causing it to bunch longitudinally. As the beam line charge density increases, the axial space charge force grows until the compression is stopped. Ideally, the axial position of velocity tilt reversal is identical for all beam ions; at this position, the beam can be focused without chromatic aberration. Because the line charge densities in the ILSE beams are near driver scale, we will be able to address the important features of this manipulation, e.g. transverse and longitudinal emittance growth, at relevant scale.

Accurate focusing to a small focal spot is required for high target gain; therefore, final focusing experiments are an essential part of the ILSE experimental program. In these experiments the beam will be focused by magnetic quadrupole lens to a small spot. Of interest are: pulse to pulse reproducibility of the size and location of the focal spot; methods of partially neutralizing the ion beam that reduce space charge repulsion allowing a smaller spot; potential filamentation or two-stream instabilities which could be important in a reactor or perhaps the corona of a fusion target; and the material temperature achieved at the focal spot. The use of dipole, sextupole, and octopole elements to correct chromatic and geometric aberrations are potentially important experiments. Using preformed plasma channels to guide the beam across the reactor to the target would lead to very attractive reactor concepts. This type of plasma guiding can be studied using the ILSE beams.

If physics and engineering studies continue to be favorable, the ILSE linac could be operated as an injector to a recirculating accelerator which would continue accelerating the ions to energies approaching 100 MeV as sketched in Fig. 2. Although the decision to perform these experiments will be made at a later date, space at the end of the linac has been retained for recirculation. According to present studies, recirculation has potential for reducing the cost of heavy-ion driver by more than a factor of two; thus, recirculation experiments are important in their own right. Moreover, the higher kinetic energy available from a ring would enhance the focusability of the ILSE beams. The ring could also provide the long transport distances that are required for some studies of longitudinal dynamics.

Fig 2 Sketch of a recirculator experiment

Injector and Ion Source Development

H. L. Rutkowski

At the present time, the injector program is changing direction. New source and acceleration structure options are being explored, partly stimulated by new requirements from the ILSE design effort. Experiments to study beam behavior in the existing injector continue.

The high voltage generator of the present injector uses an inductively graded Marx circuit. The coils in this circuit are gradually deteriorating and will have to be replaced eventually. Some experiments involving low voltage pulsing of the existing column were performed in the last period that indicated it may be possible to use a faster rise pulse than that provided by the existing generator. L. Reginato is designing an alternate Marx composed of PFN stages rather than single L-C stages that should provide an ~ 5 μ sec flat voltage with ~ 2 μ sec rise time. This system would have less stored energy than the existing system and would be designed to operate at repetition rates as high as ~ 1 Hz. Further calculations of the implications of this system for the beam optics must be done.

The ion source program has taken a new direction. Because of the lifetime and emittance limitations with the carbon arc source, an RF cusp field source is being developed to provide quiet plasma, essentially infinite lifetime, and capability to supply any gaseous species. During the last review period a 10" dia., 8" long cylindrical cusp field chamber using 16 neodymium iron magnet bars was constructed. The geometry and strength of the magnet bars was calculated using the POISSON code. The number of multipoles and chamber diameters was chosen to create a 4" diameter zone in the center which is essentially field free ($B < 20$ gauss) for extraction of large beams. The chamber contains a porcelain coated copper antenna which serves as a source of ionizing electrons. A hot tungsten wire filament in the center of the antenna serves as a source of initiating electrons to start the pulsed discharge. We have also acquired a commercial, pulsed R.F. oscillator-amplifier-matching network to power the source. It is capable of generating up to 70 kw average power in 100 μ sec bursts with a 1 Hz rep rate. The amplifier tubes are operable in the 80 psig atmosphere of the injector vessel. Also, the entire package is very compact so that it will fit easily into the injector high voltage dome structure. The power level was deliberately chosen to be higher

than the ~ 6 KW required for the test stand source so that it would run a multi-beam large source in the injector. Experiments are now underway to characterize the emission of the source using neon as the fill gas. Experiments using constant flow will be used to find a suitable operating point. At that point, a commercial piezo-electric puff valve or a combination of several valves will be used to reproduce the fill pressure in a pulsed fashion thus reducing the gas load damped into the column for each beam pulse. Initial experiments indicated that a single puff valve cannot provide sufficient gas fill.

Another source concept being pursued is the hot surface contact ionization source. Such sources are well known in the field of ion space propulsion where the technology is well developed for cesium ions emitted from hot tungsten surfaces. In our case, a lighter ion is desired. It is feasible to get high ionization efficiencies for potassium from iridium surfaces. The difference between ionization potential and work function for this material pair is ~ 1 eV. The disadvantages of this type of source is that high temperatures must be used ($\sim 1000^\circ\text{C}$) and the flow of alkali vapor must be strictly matched to the beam extraction rate. The former condition requires a large power source in the dome and the downstream electrodes must be cooled to prevent warping. The latter condition comes from the fact that surface coverage greater than 2% of a monolayer by the alkali species reduces the surface work function rapidly and unwanted neutral emission occurs. S. Eylon is in contact with commercial suppliers of porous tungsten sources in an effort to purchase a suitable source for characterizing a 1" diameter porous iridium source. Of course there are engineering uncertainties related to building a larger aperture source such as thermal uniformity and cracking. However, the 1" source will allow convenient study of the physics of source operation and lifetime of the porous plug. This source type is well known to provide very low emittance due to its low ion temperature and it also provides a fixed ion emission surface which obviates the need for a plasma switch such as that used with the carbon arc and the cusp field sources.

The Injector Matching Section

A. Falters and E. Henestroza

The injector and the matching section are intimately related and neither can be treated separately. The function of the matching section is to take the round beams with a small, azimuthally symmetric divergence emerging from the injector and transform them to match the alternating-gradient (A-G) focusing lattice in the first part of ILSE. The maximum beam envelopes in the AG lattice are about half as great as those required within the injector, and their spacing is less than half as great. In the matching process, however, the beam envelopes and separations must at first be increased, and then decreased. In this process the interference between beams and focusing elements is a major constraint. To facilitate the required operations, the beams within the injector are launched with a slightly convergent angle, thereby reducing their divergence at the exit, and the beams are aimed along non-parallel individual axes which lead to a desired larger separation between beams in the matching section. Some of these non-standard operations are a result of the limitations in size of ceramic insulator columns, and of the desire to maximize the current in four beams. The matching section also includes diagnostics to measure the beam parameters, and provision for adjusting the required steering angles.

The initial beam matching problem is, from a technical point of view, similar to the beam merging problem. Within the injector it is economical to pack in as many large beams as possible in order to get the greatest total output current. At the exit of the injector the beams are round and spaced so closely that it is difficult to find room for the required transport elements. These beams must eventually be matched and steered into four parallel channels at a much smaller separation than in the injector, but first it is necessary to expand the beams and their separations. The first matching quadrupole makes a diverging envelope in one plane which reaches a maximum within the second quad. Whenever the envelope is large in one plane, the corresponding thermal angles are small, from conservation of emittance, which makes the beam particularly sensitive to aberrations in that plane. The field nonlinearities, on the other hand, tend to be largest near the focusing electrodes. One solution to the resulting requirement of nearly perfect quadrupole field is to use circular electrodes whose radius is 1.146 times the aperture radius, thereby closely approximating the ideal hyperbolic profile for 2-D fields. The electrostatic quads are long enough in most locations, compared to their apertures, to be treated as 2-D, whereas this is more difficult with magnetic quads. Because the electric quads are chosen to provide good fields, the beams in the matching section are allowed within one centimeter of the electrodes. The close proximity is aided by the expectation that the beams are well centered in the injector channels and that large oscillations due to random quadrupole misalignments have not had time to develop. The required bends from tightly spaced beams at the exit of the injector to widely separated beams are easier than the inverse problem in the combiner

because the beams are well centered and practically monoenergetic.

Adopting the "large quad" solution, it is straightforward to calculate the array size and minimum beam separations for the various computer-generated single channel matching solutions. A common characteristic of such solutions is that the beam envelopes expand to 1.5-2 times their initial sizes, depending on exit angle divergences, and it is convenient to defer the largest beam sizes and focusing element to a location about a meter downstream. This is accomplished by the first quad doublet which is reentrant into the injector column and has very limited room. Shortly after the large amplitude location, the beams reduce down to their matched values for the downstream lattice, with about a 2 cm radius. These small beams are bent back towards each other and straightened out, again as in the combiner, but at a larger separation than in the combiner. At the injector end of the matching section there is an incentive to start the matching process as early as possible because the space charge of the beams increases the divergence; there is no similar incentive after the beams are matched, and the beams are brought together gradually and smoothly.

The focusing and bending throughout the matching section are accomplished by electrostatic quadrupoles. In an ideal quadrupole, the electric field gradient is constant over the aperture, and any point within it may be considered as a new origin which has an ideal quadrupole and two bends centered on it. By displacing the quadrupole electrodes as a rigid unit, we obtain the desired bending angles. In most instances the required displacement is small compared to the beam aperture. Occasionally the suggestion has been made that individual electrodes be moved instead of all of the electrodes as a unit, but this leads to unwanted multipoles in the fields. The displaced quads may be thought of as combined function elements, and are of two types which we designate as fixed and independent. The fixed quads share common electrodes with more than one beam, and once built can not be easily changed. The independent quads have no common electrodes shared by more than one beam. The fixed quads are used immediately after the injector, and near the end of the matching section. The independent quads are used in the intervening region, and are used for steering adjustments between the injector and the accelerator.

Beam diagnostics are located after the first doublet, which is the earliest conveniently accessible location. The beam emerging from the injector has an exit size and divergence angle which change throughout the drift distance to the first diagnostics station. For the nominal beam parameters, the divergence increases by about 1/4 mr/cm from space charge. The beam parameters at the entrance to the matching section would be determined by measuring them about 50 cm downstream and correcting them for this drift distance.

For design purposes, the ideal geometry is very nearly given by

$$r_e = r_{\text{electrode}} = \frac{8}{7} r_a = \frac{8}{7} r_{\text{aperture}}$$

and by our clearance prescription,

$$r_a = r_b + 1 = r_{\text{beam}} + 1$$

For four beams (Fig. 1), the beam centroid, r_c , is

$$r_c = \frac{15}{7} (r_b + 1)$$

Fig. 1 Quadrupole array.

For the example solution shown in Fig. 2, the maximum beam radii are 5.7 cm in Q2 and 7 cm in Q3. From Eq. 3, $r_c = 14.36$ cm for Q2 and 17.14 cm for Q3. We seek solutions for the axis of the beamlines, with four-fold symmetry in the overall geometry, of the form

$$x = x_0 + m_x z$$

$$y = y_0 + m_y z$$

for the centroids of the sources within the injector at $r_c = 12.5$ cm, and an exit constriction of $r_c = 13.5$ cm for a ~ 4.5 cm radius beam.

Choosing $z = 0$ as the exit plane of the injector, and orienting the axes so that

$$x_0 = 0$$

$$y_0 = 13.5$$

$$\text{at } z = 0$$

$$r^2 = x^2 + y^2 = (x_0 + m_x z)^2 + (y_0 + m_y z)^2$$

may be solved for $r = 12.5$ cm at $z = -50$ cm and $r = 14.5$ cm at $z = +20$ cm to yield $m_x = 103$, $m_y = 0423$.

These give $x = 10.3$ cm, $y = 17.7$ cm, and $r_c = 20.5$ cm in the third quad, which means that the second quad forms the limiting constriction and we may start bending the beams back towards a common axis after the second quad. The orientation of all of the quadrupole electrodes is determined by their orientation in the second quad, where the focusing electrode should be in the radial direction of a coordinate system centered on the injector. At the center of Q2, $z = 45$ cm and

$$x = 4.64 \text{ cm}$$

$$y = 15.4 \text{ cm}$$

$$\theta_r \approx 70 \text{ mr}$$

$$\theta_\theta \approx -86 \text{ mr}$$

This choice minimizes the required array size and angles for the present example, and may be considered as determining the origin of a new coordinate system, with the new required bend angles being 70 mr in x and 86 mr in y . At Q3 and subsequent quads the bends may start to be reversed.

The attainable bends are

$$\Delta \theta = \frac{E' \Delta(x, y) d}{2 T} = \frac{(E')(1 \text{ cm})(40 \text{ cm})}{(4)(10^6)}$$

per centimeter of displacement in the matching quads, and

$$\Delta \theta = \frac{(E')(24 \text{ cm})}{(4)(10^6)}$$

per centimeter of displacement in the AG transport quads:

$$\Delta \theta_3 = 25.73 \text{ mr/cm}$$

$$\Delta \theta_4 = 27.4 \text{ mr/cm}$$

$$\Delta \theta_5 = 29.6 \text{ mr/cm}$$

$$\Delta \theta_6 = 35.0 \text{ mr/cm},$$

and $\Delta \theta = 53.76 \text{ mr/cm}$ displacement in the standard lattice.

The solution given depends on the column design details and the detailed geometry of the first few quads, and will continue to be refined during the design process and, after operations begin, experimentally. There is also an ongoing effort to design alternatives to the present injector and matching section solution, such as strong focusing columns, conventional columns, parallel independent columns, larger diameter columns, etc., therefore the present design should be viewed only as an attempt to get the desired line charge density beams out of existing hardware.

Fig. 2 Matching section beam envelopes.

Beam Merging in ILSE and Transverse Emittance Growth

K. Hahn

In the currently proposed ILSE design, four beamlets are brought together in the combiner and matched into the magnetic transport channel. The interaction between the beamlets after combining is known to increase the transverse velocity spread. The resultant normalized emittance growth can be estimated using the emittance equation¹ for a matched beam of mean radius a :

$$\delta[\epsilon_n^2] = 2 Q a^2 \delta f$$

where $Q = \frac{Nq^2}{\gamma mc^2}$, N = line number density, a = the downstream envelope radius, and δf is a dimensionless profile factor depending on the beamlet arrangement and spacing.

For ILSE parameters after the combiner we have $Q \approx 4.5 \times 10^{-7}$, $a \approx 0.04$ m, and the profile factor $\delta f \sim 0.06$ for a symmetric initial configuration where four round beamlets are spaced 8 mm apart and the upstream beamlet envelope radius is 20.2 mm. This gives a normalized emittance increase of $\delta\epsilon_n \sim 10$ mm·mr which is much larger than the initial geometric emittance dilution typically a few times the emittance of a single beamlet upstream (~ 1 mm·mr).

A matching section is introduced to prevent further emittance increase. An initial convergence angle among the beamlets can be introduced to reduce the beam envelope at the matching section. The dynamics of the beam in a symmetric configuration with and without a convergence angle have been calculated using the particle-in-cell code SHIFT-XY. This is a sequel to the previous calculation for the 1988 ILSE parameters² where both the symmetric and "stonehenge" configurations were considered along with a head-to-tail velocity tilt. The initial beamlet emittance is assumed to be negligible. The quadrupoles of the matching section are assumed to be ideal with effective length of 25 cm and bore radius of 8 cm. The half period is 50 cm. The axial spacing between the combiner and the first quadrupole is 12.5 cm.

Figure 1 shows the time history of the normalized emittance for the converging beamlets in a symmetric configuration. The initial emittance of 5×10^{-6} mm-mrad is due to the converging angle of 9.6 mrad per beamlet, which has a rather small influence on the final emittance. The final normalized emittance will be inversely proportional to the square root of the ion mass as can be seen from above equation. For example, the ion mass number $A = 200$ ion would have $\sqrt{10}$ times smaller normalized emittance than $A = 20$ used in this calculation. Due to the small bore radius and rather violent beam dynamics at the matching section, a moderate fraction ($\sim 7\%$) of the particles were lost.

Figure 2 shows the same calculation without the convergence angle. Even though the initial emittance is very small, the final emittance approaches that in Figure 1 and no particle loss is observed.

Figure 1. Time history of the normalized emittance. Initial convergence angle is 9.6 mrad per beamlet.

Figure 2. Time history of the emittance for non-converging beamlets.

1. K. Hahn and L. Smith, 2-D Emittance Equation with Accelerator and Compression," LBL-26167, HIFAN-415.
2. K. Hahn, "Beam Dynamics in the Matching Section after the 4-Beam Combiner in ILSE," HIFAR Note-207, Aug. 1988.

Short Quadrupole Magnet Design

W. Fawley and L. J. Laslett

An important issue in the design of heavy ion fusion drivers is the dynamic aperture a of short period magnetic quadrupoles. The reason for this is that if the undepressed phase advance σ_0 can be kept constant (by raising B_{peak}) as the half-period L decreases, the maximum transportable current within the lattice scales as $(a/L)^2$. However, as the aspect ratio (L/a) of a magnetic quad decreases, a number of phenomena (e.g. fringe fields, azimuthal harmonic components) can degrade the field quality. We have started a new design effort to examine the minimum allowable aspect ratio, concentrating on direct applicability to ILSE. Our design philosophy for ILSE quadrupole magnets has been to maximize those features which are expected to be present in an HIF driver while simultaneously being aware of cost and complexity tradeoffs. Some of these features include:

- a) Small aspect ratio design to maximize the current which can be transported stably for a given phase advance per lattice period.
- b) Elimination in a z -integral sense and minimization locally of higher order harmonic components (e.g. dodecapole) of the magnetic field.
- c) Choosing a magnet design that in theory could be made out of superconductor components and, in particular, does not violate existing superconductor cable limitations. For example, the minimum radius of curvature must not be too small (> 1 cm) and the maximum magnetic field at any particular winding must not be too high relative to the average quadrupole field component to prevent quenching. Furthermore, "air-core" magnet designs are to be preferred to those which use iron to suppress and control fringe fields.

We have also considered some ILSE-specific constraints and "wishes" in guiding us in the magnet design such as:

- a) A dynamic aperture large enough to transport space-charge dominated Ne^+ (or alternatively, K^+) beams of approximately $1\mu\text{C/m}$ line charge density with an undepressed phase advance of 72 degrees per lattice period ($2L=1.0$ m).
- b) A peak magnetic field no greater than 2T. If iron is used, it will be at radii a few cm greater than that of the conductors by which point the magnetic field has dropped 30% or greater.
- c) A maximum winding length in each quadrupole no greater than 30 cm in order to retain space for induction core gaps, pumping ports, and diagnostic access.
- d) A magnet design which is compatible with the inclusion of low field dipole steering/correction magnets. Some steering algorithms require one set of such magnets for each transverse plane per lattice period.

A few years ago, Laslett, Brady, and Celata did some detailed design on ILSE short period quadrupoles that concentrated on current windings whose geometry included abrupt, 90° turns. In the present effort, we have begun examining designs employing gently curving ends. The design process includes 1) choosing an algebraic formulation for the winding geometry 2) using a code such as MAFCO to compute the magnetic field components at a number of (r,z) locations 3) decomposing the field into quadrupole, dodecapole, etc. components as a function of z 4) using a particle simulation code (HIFI) to calculate the dynamic aperture in a transport lattice made of such magnets. HIFI was especially designed to be a fast-running (< 4 Cray CPU minutes for ILSE-like parameters) by treating the beam space charge as being that due to a uniformly charged 2-D ellipse. The external focusing fields are treated in far greater detail, including z -resolved fringe and azimuthal harmonic fields.

With all of the above constraints and wishes in mind, we have settled on an initial design for the quadrupole magnets for the 4.5-10 MeV portion of ILSE. This design will continually evolve over the next year or so as different aspects of the problem are examined more closely. Fortunately, there appears to be a reasonably wide range of designs that appear to work for ILSE and our tentative design was favored mainly because of the small L/a aspect ratio.

One particular design has two layers of windings centered on a radius of 7.0 cm and a maximum winding length of 21 cm. Hence, L/a can be considered to be 3. If this short a magnet can be constructed with the good transport properties, this would be significantly good news for HIF driver design. However, the effective length of the magnet, 16.5 cm, is significantly shorter and leads to a required peak quadrupole field at the windings of approximately 1.5 Tesla to focus a 4-MeV Neon beam with $1.0\mu\text{C/m}$ line charge density. Each winding layer is composed of eight wires whose azimuthal angles are chosen so that the z -integrated harmonics (specifically, the $\cos(4l+2)\phi$ dependencies for $l=1,2,3,4,5$) are zero within each quarter lattice period. The required pulsed current per winding is close to 5 kA. The dissipated heat over the expected 10-ms duration of the magnet current pulse is expected to be quite small presuming no greater than a 1-Hz repetition rate for ILSE operation.

According to preliminary HIFI code results, the useful dynamic aperture of these magnets is about 5.2 cm. This aperture is limited more by particle loss to the beam pipe walls than by emittance growth. More detailed particle simulation runs must be done in order to take into account effects of image charges on the beam pipe and higher-order multipole-induced deviation of the beam from a uniform ellipsoid. We expect to use the SHIFT-XY code and, possibly, an improved version of HIFI to study these effects.

ILSE Concept Induction Cell Studies

Lou Reginato and Craig Fong

Amorphous Material Selection

One of the most important components of an induction linac is the ferromagnetic material used in the induction cores. The accelerating voltage and the pulse duration establish the size of these cores. For ILSE, a gradient of 300 to 400 kV/m and a duration 1 to 2 μ s will require cores 1 to 2 meters in diameter. The material quantities required for ILSE are modest compared to that of a full scale heavy ion fusion driver where material cost will be a crucial factor.

Considerable effort has already been invested in the investigation of the magnetic materials which are appropriate for ILSE.¹ The material must have a high flux swing (ΔB) and low magnetizing current (Δi) under high rates of magnetization (dB/dt). The Allied 2605 series of amorphous material seems to be a very good match to our requirements. This material can be mass produced in usable width as thin ribbon (15 to 20 microns thick) with high resistivity and a total flux swing of 2 to 3 Tesla.

The insulation required between layers is a function of the rate of magnetization, ribbon thickness and width. For ILSE, the insulation must withstand 10 to 20 volts/turn. Previous efforts have concentrated on finding interlaminar insulation that allows annealing after the material is wound into a core. Annealing is essential in cores used at lower frequency (≈ 60 Hz) since it results in considerable increase in flux swing and reduction in magnetization losses. For our applications where dB/dt is between 2 and 4 Tesla/micros, the eddy current losses will dominate, hence the magnetizing currents will be determined strictly by the rate of magnetization and the material thickness. For ILSE, the "as-cast" material should be quite acceptable and the requirement that the insulation withstand annealing temperatures is not necessary.

We are presently fabricating induction cores that utilize 2 inch wide material with a 2.5 μ m type C Mylar as interlaminar insulation. A test core was wound with a packing factor of 0.78 using 25 μ m thick 2605-S3A. Other materials such as 2605-S2 will be wound into a full size core and tested at the full rate of magnetization before a final selection is made. Preliminary studies indicate that the 2605-SC or S2 will provide a nearly optimum solution in terms of energy loss and cost effectiveness. Core losses for several 2605 alloys at different rates of magnetization are shown in Figure 1.

Fig. 1 Core losses at different rates of magnetization

ILSE Accelerator Cell Design

Figure 2 is a side view of the electrostatic acceleration section. To maximize transportable beam current, the half lattice period of the beam transport quadrupoles must be varied from 33 to 50 centimeters. Each acceleration cell is segmented into three radial cores. A 2 inch wide material was chosen to minimize the interlaminar voltage levels and provide optimal radial packing factors. This keeps the maximum voltage in each core to a nominal 11.1 kV, or a gap voltage of 33.3 kV which avoids the need for dielectric fluids or insulating gases in either the cell or the pulse modulator. Moreover, core segmentation allows a more uniform magnetizing current and avoids saturation on the inside portion of the core and permits thyratrons to be used as the pulse forming network modulator switching device.

Another requirement is the need for a well aligned beam transport system. Early estimates call for alignment errors that errors not exceed 100 microns in the electric focus section. Quadrupoles will be independently supported and articulated relative to a straight line reference system isolated from the beamline vacuum vessel. Axial space shared with the core modules along the longitudinal axis is used for the quadrupole high voltage leads, articulation and straight line reference alignment interfaces, vacuum ports, and diagnostics leads. The core design is modular which allows stacking of the core modules as the half lattice period grows thereby maintaining the acceleration gradient.

The acceleration schedule for ILSE will require careful tailoring of the voltage waveform at each gap in order to provide energy gain, and current amplification with adequate

¹A. Faltens and S. Rosenblum, Appl. Phys. 57 (1), 15 April, 1985.

Fig. 2 Induction module for electrostatic focusing section

longitudinal control. The 2 to 4 MeV electrostatic acceleration section requires waveforms which are initially triangular in time with a 1.3 microsecond duration. The waveforms become rectangular in shape and decrease in duration from 2 microsec to 500 nanosec. To satisfy these requirements we envision building modulators with pulse forming networks (PFNs) switched by a thyratron. These pulsers are expected to produce the desired waveform with a maximum error of $\pm 5\%$. Since the waveshape must be controlled to better than 1% and must be capable of fast correction at the leading and trailing edges, we tentatively plan to employ an active hard-tube modulator in a feedback system to achieve the desired accuracy. The bulk of the acceleration voltages will therefore be provided by fixed PFN modulators while the fast correction will be provided by a few of these more expensive modulators. Figure 3 is a simplified schematic of a switched PFN modulator which uses the Blumlein type of circuit to generate a ramped voltage waveform. A resonant circuit is used to provide reset current to the induction cells during the charge cycle. The fast correction modulator has not been designed. However, it will employ some type of hard tube which can operate in the linear mode or as an on-off switch. Correction voltage "ears" will also be generated by means of line type modulator.

Fig. 3 A simplified resonant charging circuit and switched pulse forming network is shown here.

Fast Split-Harp Emittance Measurements Using A Multichannel Waveform Analyzer

S. Eylon and C. Lionberger

Emittance measurements, using two slit scanners, in MBE-4 and SBTE required about 1000 machine pulses, which at the rate of one pulse every 5 seconds took more than one hour. A fast emittance measurement system is suggested for the ILSE experiment. The system uses a slit-harp scanner to minimize the scan time. All the angular data (X' in Fig. 1), is gathered by the harp in a single machine pulse at a given slit position X and measured by a fast multichannel waveform analyzer. This will reduce the number of machine pulses on ILSE to about 20-30, i.e. an emittance scan will take about 1.5 minutes at the above rate. A profile measurement, i. e. beam current density profile, size and position, using a single coarse harp will only require a single machine pulse.

Fig. 1 The slit-harp and the double slit methods.

The fast emittance diagnostic setup is shown in Fig. 2. SBTE harp scanners were modified to enhance the harp time response and reduce beam and electrical "crosstalk" between channels. Miniature coaxial insulated cables were used to connect the harp wires, and a positive bias plate was placed behind (down stream from) the harp wires at a distance of 1mm. The bias plate collects the approximately 10 electrons ejected from a harp wire when struck by one beam ion thus increasing the wire current signal by about 10. The ejected electrons follow the electric field lines defined by the bias potential thus eliminating stray electrons and reducing the "crosstalk" between the harp wires. Signal conditioning systems using commercially available instrumentation amplifier modules have been installed as close as possible to the harp scanner outputs to increase the signal to noise ratio along the transmission cables to the main control rack.

Fig. 2 The fast slit-harp emittance measuring setup.

During the report period an expandable sixteen-channel fast waveform digitizer was purchased after evaluating several brands of such digitizers. The analyzer is capable 512 samples at a sample rate of 125 MS / sec i.e. pulse duration up to 4 ms with a rise time of about 12 nsec. Several of the MBE-4 data acquisition and analysis software programs required changes to support the new system. The program CONFIG was upgraded to support a slit-harp probe with variable dimensions. The PHASE program, used to define the region in phase space that will be scanned during the measurement, was given the capability to present the results of the sixteen channels after each exploratory firing of the beam. The SCAN program which does the emittance scan is now capable of a sequence consisting of positioning the slit and the harp, taking up to sixteen channels of data, and then moving to the next position; in addition the harp can be moved to intermediate positions for a given slit position to increase the angular resolution. The program DISPLAY, which presents results computed from the scan data, has been modified to pre-process the equal-wire-distance harp data format into the equal-angle format used in the remainder of the program. These modified programs still perform as before with old data files and the various diagnostic probes and digitizers already in use.

The fast slit harp emittance diagnostics system has been assembled and installed in the SBTE, and a complete emittance measurement has been performed on the single beam.

HIFAR STAFF ROSTER

Roger Bangerter

Warren Chupp
Robert D. Edwards
Shmuel Eylon
Andris Faltens
Thomas J. Fessenden
Craig Fong
Terence Garvey
William B. Ghiorso
Wayne Greenway
Ralph Hipple
Cai Houston
Rudin Johnson
Heon-Ju Lee
Carl Lionberger
Sam Mukherjee
Harry Meyer
Joseph Perez
Chester D. Pike
John Pruyn
Thomas Purtell
James Rice, Jr.
Henry L. Rutkowski
Gerald L. Stoker
William Tiffany
David Vanecek
Gerald West

Lloyd Smith

Elon Close
William Fawley
Kyoung Hahn
Enrique Henestroza
David L. Judd
L. Jackson Laslett
Edward P. Lee

Clerical Staff

Joy Kono
Diana Morris
Alline Tidwell
Olivia Wong

LLNL

Louis L. Reginato

Students

Eric Agol
Miguel Nathwani
Dan Keeney

PUBLICATIONS AND INTERNAL NOTES

<p>HIFAN-502
Fessenden
03/18/91</p>	Report on the International Symposium held at Monterey, California, December 3-6, 1990, "Heavy Ion Inertial Fusion," Thomas J. Fessenden, LBL; Alex Friedman, LLNL, Nuclear Fusion, Vol. <u>32</u>, No. 8, pg. 1567 (1991).
<p>HIFAN-506
LBL-30839a
Fong</p>	C. G. Fong and L. Reginato, "Investigation of Induction Cells and Modulator Design for Heavy Ion Accelerators," presented to the 14th Symposium on Fusion Engineering, IEEE/NPSS, General Atomics, Fusion Group, San Diego, CA, September 30-October 3, 1991.
<p>HIFAN-507
Bangerter</p>	R. O. Bangerter, "Field Task Proposal Presentation for Heavy Ion Fusion Accelerator Research," Presented to Office of Fusion Energy, Division of Applied Plasma Physics, Germantown, MD, April 9, 1991.
<p>HIFAN-509
HIFAR Staff</p>	HIFAR Staff, "Half-Year Report," LBL-30748, October 1, 1991 - March 31, 1991.
<p>HIFAN-510
LBL-30891a
Bangerter</p>	R. O. Bangerter, "ICF Drivers and Targets," presented to the 14th Symposium on Fusion Engineering, IEEE/NPSS, General Atomics, Fusion Group, San Diego, CA, September 30-October 3, 1991, LBL-30891a.
<p>HIFAN-512
Bieri</p>	R. Bieri, "Inertial Confinement Fusion Driver Enhancements: Final Focusing Systems and Compact Heavy-Ion Driver Designs," June 13, 1991.
<p>HIFAN-513
LBL-31037a
Lee</p>	E. P. Lee, "Longitudinal Instability of Induction Linear Accelerators for Heavy Ion Driven Inertial Confinement Fusion," LBL-31037a, Invited abstract submitted to <i>Bulletin of the American Physical Society</i>, July 12, 1991.
<p>HIFAN-514
LBL-31036a
Eylon</p>	S. Eylon, "The Diagnostics Systems for MBE-4, a Multiple Ion Beam Linear Induction Accelerators," Abstract submitted to the 1991 Accelerator Instrumentation Workshop, October 28-31, 1991 at the Continuous Electron Beam Accelerator Facility, Newport News, Virginia.
<p>HIFAN-515
Fessenden</p>	T. J. Fessenden, "Heavy Ion Fusion Accelerator Research" HIFAR material for AEP book, July 19, 1991

HIFAN-516 Bangerter	R. O. Bangerter, "Heavy Ion Accelerators," Invited abstract submitted to the Thirty-Third Annual Meeting Division of Plasma Physics, November 4-8, 1991, Tampa, Florida
HIFAN-517 Bangerter	R. O. Bangerter, HIF Program Overview -- Division Review, July 26, 1991, Talk #09.
HIFAN-518 Fessenden	T. J. Fessenden, HIF Program Overview -- Division Review, July 26, 1991.
HIFAN-519 Fong	C. G. Fong, HIF Program Overview -- Division Review, July 26, 1991.
HIFAN-520 Fessenden	T. J. Fessenden, et al, "The ILSE Advance." San Damiano Retreat, Danville, CA, August 12-14, 1991
HIFAN-521 Fessenden	T. J. Fessenden, "MBE-4 Experiments with Bright Cesium ⁺ Beams," to be published in the American Institute of Physics for the Symposium on High-Brightness Beams for Advanced Accelerator Applications.
HIFAN-522 Fessenden	T. J. Fessenden, Inertial Fusion Energy, Visit of Congressman George Brown, August 26, 1991.
HIFAN-524 Fessenden	T. J. Fessenden and HIFAR Staff, "New ILSE Physics Design," September 30, 1991.
HIFAN-525 LBL-29863	E. P. Lee and J. Hovingh, "High current Heavy Ion Beams for Inertial Confinement Fusion," prepared for the 1989 Particle Accelerator Summer School, Brookhaven National Laboratory.
HIFAN-526 LBL-31248 UC-421 Lee	E. P. Lee, "Heavy Ion Driven LMF Design Concept" October 7, 1991
HIFAN-527 HIFAR Staff	HIFAR Staff, Photograph of attendees at San Diamo Retreat, Danville, CA, August 12-14, 1991,
HIFAN-528 LBL-31412 Fawley	W. M. Fawely, "ILSE: The Next Step in Heavy Ion Fusion Research," Proceedings of the Fusion Power Associates Symposium in Journal of Fusion Energy, Princeton, NJ, June 1991

HIFAN-529
LBL-31427
Eylon

S. Eylon, "The Diagnostics System for the Multiple Heavy Ion Beams Induction Linac Experiment, MBE-4," presented at the 1991 Accelerator Instrumentation Workshop, Continuous Electron Beam Accelerators Facility Center, Newport News, VA, October 28-31, 1991.

HIFAN-530
Fessenden

T. J. Fessenden, "Summary of New ILSE Physics Design," November 13, 1991, sent to Committee Members of ILSE Review.

HIFAN-531
HIFAR Staff

HIFAR Staff, "Technical Review of the Physics Design of the ILSE Accelerator Construction Project," November 18-19, 1991, DOE Review, Director's Conference Room, Bldg. 50.

HIFAN-532
LBL-30994a
Eylon

S. Eylon and E. Henestroza, "Cs⁺ Source for the Heavy Ion Fusion Final focusing Experiment," LBL-30994a, presented at the APS, Tampa, Florida, October 17, 1991.

HIFAR NOTES (Internal and Informal)

HIFAR Note-302 Johnson	R. Johnson, New Optical Survey Equipment for MBE-4, June 26, 1990
HIFAR Note-303	AIP Physics and Astronomy Classification Scheme-1990.
HIFAR Note-304 Lionberger	C. Lionberger, The HIFAR Database PC July 2, 1991
HIFAR Note-305	HIFAR Organizational Charts, 1991
HIFAR Note-306 Close	E. Close, Unsupported Numerical Software, July 8, 1991
HIFAR Note 307 Fong	C. Fong, Letter to Dr. Wayne Meier, W.J. Schafer Associates, Inc., Subject: Linac Cost Data and Work Breakdown Structure,
HIFAR Note-308 Lee	E. Lee, Possibility of Achromatic Steering, August 17, 1991.
HIFAR Note-309	Physics Design Words and Sketches Needed by September 20, 1991 Tentative Division of Labor, August 29, 1991.
HIFAR Note-310 Shay	H. Shay, "Scaling Laws for Drift Compression," September 3, 1991 in preparation for ILSE CDR.
HIFAR Note-311 Lee	E. Lee, ILSE Combiner Concept, July 19, 1991
HIFAR Note-312	The Conventional Column Option (Addendum to HIFAR Note 114 on High Gradient Column). Sept. 6, 1991
HIFAR Note-313 Lee	E. Lee, ILSE Transfer Line, August 16, 1991
HIFAR Note-314 Lee	E. Lee, ILSE 180° Bend Layout, September 20, 1991
HIFAR Note-315 Lee	E. Lee and D. Judd, Combiner Studies, September 23, 1991
HIFAR Note 316 Eylon	S. Eylon, ILSE Position Sensor Feasibility Experiment, October 17, 1991.
HIFAR Note-317 Eylon	S. Eylon, K ⁺ Ion Hot Plat Source Preliminary Study, October 22, 1991.
HIFAR Note-318 Eylon	S. Eylon and J. Stoker, SBTE Marx output (System Divider) Calibration, October 22, 1991.

HIFAR Note 319 Eylon	S. Eylon, ILSE Position Sensor Feasibility Experiment, October 25, 1991.
HIFAR Note-320 Faltens	A. Faltens, Na and K Emission Test, November 7, 1991.
HIFAR Note-321 Faltens	A. Faltens, Worst-Case Injector Option, December 9, 1991.

HALF-YEAR/YEAR-END REPORT: DISTRIBUTION LIST

Allied Chemical Corporation

C. Smith

Argonne National Laboratory

R. Martin

Batelle

J. Hartman

BMD/ATC/SDC

M. Hawie
B. Strickland

Brookhaven National Laboratory

E. Courant

C.E.A. Bruyeres-le-Chatel

R. Dei-Cas

CEBAF

J. Bisognano
H. Grunder
G. Krafft
C. Leemann
M. Tiefenback

CERN

C. Rubbia, Director-General
E. Picasso, EP
D. Möhl

University of Calif., Irvine

N. Rostoker

Cornell University

D. Hammer
J. Nation
R. N. Sudan

DARPA

H. Lee Buchanan

Department of Defense (SDIO)

M. Toole

Department of Energy

DP-OIE

S. L. Kahalas (DP-DIF)
M. Sluyter (DP)
R.A. Jones (DP-DIF)

ER

D. Crandall, ER-54
A. Davies, ER-50
J. Decker, ER-2
W. Dove, ER-543
G. Peters, ER-224
W. Polansky, ER-16
D. Priester, ER-543
R. Rader, ER-33
D. F. Sutter, ER-224
M. Wilson, ER-543

DOE San Office

D. Neely
J. Krupa

E.P.R.I.

R. Scott

Fermi National Accelerator Lab.

F. T. Cole
F. Mills
L. Teng

F.O.M. Amsterdam

F. Siebenlist

Fusion Power Associates

S. Dean

GANIL

P. Lapostolle

GE

J. Lucek

GHG Associates

G.H. Gillespie

GSI

R. Bock
D. Boehne
D. Hoffmann
I. Hofmann
R. Muller

University of Illinois

G. Miley

Institut fuer Kernphysik

H. Meuth

Institute for Nuclear Study

Y. Hirao
T. Katayama

Kanazawa University

S. Kawasaki

Lawrence Berkeley Laboratory

J. Alonso, 50/149
D. Attwood, 2/400
R. Bangerter, 47/112
K. Berkner, 50/149
D. Brodzik, 47/112
C. Celata, 64/121
W. Chupp, 47/112
J. Chew, 50/149
S. Chattopadhyay, 71/259
T. Elioff, 47/112
S. Eylon, 47/112
A. Faltens, 47/112
W. Fawley, 47/112
T. Fessenden, 47/112
C. Fong, 47/112
R. Fulton, 90/2148
A. Garren, 90/4040
R. Gough, 50/149
K. Hahn, 47/112
R. Johnson, 47/112
D. Judd, 47/112
C. Kim, 71-259
M. Krebs, 50A/4112
W. Kunkel, 4/230
G. Lambertson, 47/112
L.J. Laslett, 47/112
E.P. Lee, 47/112
C. Lionberger, 47/112
E. Lofgren, 47/112
J. Marx, 46/161
J. Meneghetti, 46/161
S. Mukherjee, 47/112
P. Oddone, 47/112
C. Pike, 47/112
L. Reginato, 47/112

Lawrence Berkeley Laboratory (Con't)

H. Rutkowski, 47/112
A. Sessler, 71/259
C. Shank, Director, 50A/4133
L. Smith, 47/112
C. Taylor, 46/161
D. Vanecek, 58/101
A. Warwick, 2/400

Lawrence Livermore Laboratory

W. Barletta, L-626
J. Barnard, L-626
A. Friedman, L-630
A. Glass, L-1
D. Hewitt, L-472
D. Ho, L-477
W. Kruer, L-472
W. Krupke, L-488
B. Langdon, L-472
J. Lindl, L-477
M. Newton, L-627
J. Nuckolls, Director, L-295
H. Shay, L-626
E. Storm, L-481
D. Prosnitz, L-626
S. Yu, L-626

Legnardo Laboratory

R.A. Ricci

Lockheed

J. Siambis

Los Alamos National Laboratory

I. Bohachevsky
R. Cooper
R. Jameson
T. McDonald
R. B. Perkins
R. Morse
R. Stokes
T.-S. Wang
D. Wilson

L'Université Paris-SUD

Terence Garvey

University of Maryland

M. Reiser
D. Tidman

Max Planck Inst. fur
Plasma Physik Garching

A. Schluter

Max-Planck-Inst. fur
Quantenoptik

J. Meyer-Ter-Vehn

Maxwell Laboratories

Library

McDonnell Douglas

Les Waganer

University of Nagaoka

K. Yatsui

University of Naples

G. Vaccaro

Naval Research Laboratory

S. Bodner
T. Coffey, Director
T. Godlove
I. Haber
P. Sprangle
M. Lampe

Osaka University, Institute of Laser
Engineering

T. Mochizuki
S. Nakai, Director
C. Yamanaka

University of Padova

G. Ricci
A. Pascolini
M. Pusterla

University of Paris at Orsay

C. Deutsch

Physics International

Library

Pulse Sciences, Inc.

S. Putnam
I. Smith

RAFAEL

J. Shiloh

Rutherford Laboratory

J. D. Lawson
C. Pryor
G. Rees

Sandia Laboratories

E. H. Beckner
M. Clauser
D. Cook
G. Kuswa
T. Martin
C.L. Olson
K. Prestwich
J.J. Ramirez
J.P. VanDevender
G. Yonas

Schafer Associates

M. Monsler

SLAC

D. Gough, Bin 49
W. Herrmannsfeldt, Bin 26
B. Richter, Director, Bin 7

Soka University

T. Saito

SOREQ Nuclear Research Center

A. Sternlieb

SSC

R.J. Briggs

SURA

W. Wallenmeyer, President

University of TRIESTE

M. Puglisi

TRW

J. Gordon
Z. Guiragossian
J. Maniscalco
A.W. Maschke
W. Steele

UCSD

K. Brueckner
M. Rosenbluth

University of Texas at Austin

T. Tajima

URA

E. Knapp

Varian

S.S. Rosenblum

University of Wisconsin

G. Kulcinski
G. Moses
R. Peterson

Other

J.E. Leiss

END

**DATE
FILMED**

6/17/92