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

April 1, 1990 - September 30, 1990

Heavy Ion Fusion Staff
Accelerator and Fusion Research Division

Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

December 1990

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

The basic objective of the Heavy Ion Fusion Accelerator Research (HIFAR) program is to assess the suitability of heavy ion accelerators as igniters for Inertial Confinement Fusion (ICF). A specific accelerator technology, induction acceleration, is being studied at the Lawrence Berkeley Laboratory and at the Lawrence Livermore National Laboratory.

The HIFAR program addresses the generation of high-power, high-brightness beams of heavy ions, the understanding of the scaling laws in this novel physics regime, and the validation of new accelerator strategies to cut costs. Key elements to be addressed include: 1) Beam quality limits set by transverse and longitudinal beam physics; 2) Development of induction accelerating modules, and multiple-beam hardware, at affordable costs; 3) Acceleration of multiple beams with current amplification without significant dilution of the optical quality of the beams; 4) Final bunching, transport, and accurate focusing on a small target.
# TABLE OF CONTENTS

Highlights .................................................................................................................. 1

1. Centroid Motion and Transverse Emittance in MBE-4......................................... 4  
   (T. Garvey, S. Eylon, T.J. Fessenden, and E. Henestroza)

2. Transverse Emittance Studies with Artificially Increased Emittance............... 5  
   (E. Colby, T. Garvey and S. Eylon)

3. MBE-4, 5 mA Drift-Compressed Beam Studies.............................................. 6  
   (S. Eylon, T. Garvey, and E. Henestroza)

4. 2 MeV Injector and Source Development....................................................... 7  
   (H.L. Rutkowski)

5. LBL Contributions to the LLNL Recirculator Study....................................... 8  
   (D.L. Judd)

6. Asymptotic Analysis of the Longitudinal Instability....................................... 9  
   (E.P. Lee and L. Smith)

7. 1-D Time Domain Analysis of the Longitudinal Instability........................... 10  
   (K. Hahn and L. Smith)

8. Module Impedance Model............................................................................... 11  
   (E.P. Lee)

9. Scaled Driver Module..................................................................................... 12  
   (A. Faltens)

10. 3-D Multipole Decomposition of the MBE-4 Focussing Lattice Potential....... 13  
    (M. Berz, W.M. Fawley, K. Hahn)

11. HIF Beam Propagation in a "High" Pressure Reactor Environment............... 15  
    (W.M. Fawley)

12. The Development of a Compact Magnetic Quadrupole for ILSE.................... 16  
    (S. Mukherjee)

Publications and Internal Notes............................................................................. 18

H.I.F. Staff Roster.................................................................................................. 21

Distribution List...................................................................................................... 22
HIGHLIGHTS

1. During this reporting period, the National Academy of Sciences completed its review of the ICF Program and the Fusion Policy Advisory Committee (FPAC) reviewed both the ICF and MFE Programs. Significant effort went into the preparation of briefings and documents for these reviews. Both review panels made favorable comments about the scientific merit of heavy ion fusion. The FPAC recommended creation of a new Inertial Fusion Energy Program in the Office of Fusion Energy. The FPAC selected HIFAR as the cornerstone of this new program and specifically endorsed ILSE.

2. The 2-MeV injector was used for beam extraction for the first time at full design voltage for a half column, producing 212-232 mA C\(^+\) in a direct extraction mode for long pulses. The column seems to condition very well under beam loaded conditions.

3. A model of the longitudinal instability in induction linacs was developed which incorporated the contribution of module capacity to coupling impedance. Predicted growth rates are about an order of magnitude lower than previous estimates which did not include this feature.

4. Using an equivalent circuit model a more realistic, frequency-dependent model impedance has been implemented in the particle code SHIFTZ with the required causal condition. This enables us to simulate with increased accuracy the 1-D longitudinal beam dynamics of a driver, and in particular the longitudinal instability. With this tool we have verified predictions of reduced growth rates due to the reactive component of impedance.

5. A full-size induction accelerator test module was constructed for investigating the electromagnetic coupling impedance presented to the beam and for studying the pulse excitation transients. Improved diagnostic equipment is being acquired, and a test pulser is being refurbished. The module is fitted with enough diagnostic ports to measure the higher-order electromagnetic oscillation mode field distributions, both in the dielectric gap and induction core regions.
6. We have modified a two-dimensional, full E&M beam simulation code to study the physics of self-pinched ion propagation in low pressure (P ~ 1 Torr) gas reactor environments. Preliminary results suggest that the net currents are too weak to pinch the beam to the necessary 2-4 mm radius needed at the pellet. Other propagation modes such as discharge-assisted pinching will continue to be investigated.

7. In June 1990 a study group was formed at LLNL to consider the "recirculating induction linac" option for heavy-ion inertial-fusion drivers; it was hoped that by using the expensive accelerating units many times on a single beam pulse a system of lower cost could be developed to be competitive in cost with other proposed drivers. This study was staffed largely from LLNL's Beam Research Program, with some support from LLNL's X Division and LBL's HIFAR program. Understanding of high-current heavy-ion recirculators has been significantly advanced by the study; a good data base for future considerations is being assembled, and no fatal flaw in the concept has been discovered. Several individuals from LBL have contributed to this ongoing activity.

8. The amplitude of the beam centroid motion in MBE-4 has been reduced following correction of a mis-alignment error reported earlier. Subsequently, we have shown that the large variations in emittance observed previously in drifting beams are greatly diminished for the on-axis beam. In addition, experiments with beams whose emittance is deliberately "spoiled" by a pair of wire grids have demonstrated that higher emittance beams are less subject to emittance variations than beams of low emittance, in agreement with simulations.

Further experiments with drift-compressed beams were performed in MBE-4. Transverse emittance growth observed in these experiments supports the possibility that a previously observed emittance growth associated with acceleration is actually due to spatial bunch compression.
Construction of a cos(2θ) current-dominated, pulsed, magnetic quadrupole, which has a large bore to length ratio has been completed. The quadrupole was designed with ILSE parameters. The main challenge of this compact construction is to maintain dimensional accuracy and high voltage holding capacity. During the second phase of development those features will be tested.
Introduction
In the previous Half-Year Report we stated that the results of our studies of transverse emittance dependence on zero-current tune indicated that the r.m.s. emittance showed continuous variations as the tune was altered\(^1\). These variations were believed to be driven by a large coherent betatron oscillation amplitude (+/-4.5 mm) present on the beam. It was also reported that this coherent oscillation was primarily due to some mis-alignment of the linac focussing structure, resulting in a kick to the top beam of MBE-4 during its traversal through the linac\(^2\). The mis-alignment had been traced to section C with the most likely culprit being lattice period 11. Since that time we have endeavoured to remove the cause of the kick so allowing us to keep the beam on (or near) axis, thus making it possible to test the theory that the observed emittance variations were related to the large betatron oscillation amplitude\(^3\). This report summarises recent work in this area.

Centroid Motion
Having identified section C as being the location of the lattice imperfection we attempted to identify the specific quadrupole/electrode(s) which were responsible for the kick through a series of rather crude optical survey measurements. However, none of these succeeded in an unambiguous determination of the location of the problem. In order to allow us to continue with our beam experiments we removed section C and replaced it with section F, having first established the integrity of section F using the beam itself\(^2\). This allowed off-line measurements of section C to proceed in parallel with beam experiments on MBE-4. Measurements of the beam centroid at l.p. 20 (as a function of \(\sigma_0\)) both before and after the exchange of section F for section C are shown in Fig. 1. The coherent oscillation amplitude is seen to be reduced in the latter case and exhibits the expected sinusoidal pattern of the predicted period (one requires a change of \(180^\circ/\text{cell}\) to obtain a phase excursion of \(2\pi\) in the betatron oscillation). The residual amplitude is the result of injection offsets and has been further reduced by the use of an electrostatic steering element at the entrance to the accelerating structure.

The original section C has since been installed at the end of the linac. Still there is no firm identification of the misalignment and the section was rotated through \(90^\circ\) about the “beam” direction on installation, so that we are now using a different set of quadrupoles in this section for our experiments on the top beam of MBE-4. Further measurements of the beam centroid in the horizontal plane indicate that the beam is now centered to within +/-1.2 mm throughout the machine.

Emittance Measurements
Having succeeded in centering the beam we returned to the study of the r.m.s. emittance dependence on the zero-current tune. Measurements made at l.p. 25 with the centered beam are shown in Fig. 2. For comparison we also show data for the off-centered beam taken from the last Half-Year Report\(^1\).

The reduction in emittance variation in the new data as compared to the old is readily apparent and provides a striking experimental confirmation of the predictions, based on simulation, of Hahn and Smith\(^3\). Further work on this topic, showing that beams of higher initial emittance show reduced emittance growth (again in agreement with the results of simulation), are covered in a separate article by Colby et al. in this report\(^4\).

References

Fig. 1 Comparison of centroid variation with tune at l.p.20 (a) before and (b) after changing section F for C.

Fig.2 Emittance measured at l.p. 25 for coherent amplitudes of (a) 4.5 mm and (b) 1.2 mm.
TRANSVERSE EMITTANCE STUDIES WITH ARTIFICIALLY INCREASED EMITTANCE

E.R. Colby, T. Garvey, and S. Eylon

Introduction
Simulations of space-charge dominated beam transport by C.M. Celata and K. D. Hahn have demonstrated the existence of coherent emittance oscillations in the presence of nonlinear focussing forces.\textsuperscript{1,2} We report decreased emittance oscillation amplitude with increased initial emittance for offset beams, in concordance with the simulations. A pair of uniaxial wire grids held at ±18.1kV (Fig. 1) was used to increase the emittance by imparting a transverse impulse at lattice period five, thus raising the transverse ion temperature without altering the rms radius. Employing a measurement technique suggested by D. Keefe and refined by T. Garvey et al., the variation of the emittance along the length of the accelerator was examined by varying the quadrupole voltages in the accelerator sections downstream from the emittance spoiler, thus varying the total phase advance between the spoiler and the diagnostic station at which the emittance measurement was taken.

Experiment and Results
The experiment was performed with an unaccelerated beam of 185keV Cs\textsuperscript{+} ions using the top beam (5mA) of MBE-4. An electrostatic steerer was placed in the beam at lattice period zero with an applied potential of ±750V to move the beam centroid off center in angle by approximately 8.5±0.4 mrad as measured at l.p.5, the location of the spoiler grids. The focussing quadrupole voltages were varied in 0.5kV steps to vary the zero current tune (and thus the effective observation position downstream). No effort was made to readjust the matching section quadrupoles, so that in all cases the beam was mismatched on entry to the transport section. Previous experiments have demonstrated that the mismatch does not contribute in an appreciable way to the emittance growth.\textsuperscript{3}

![Fig. 1 Schematic of emittance spoiler](image)

Figure 2. Results of emittance measurements taken at l.p.25 with and without the emittance spoiler.

The effects of the spoiler are immediately apparent in the upper curve of figure 2, representing an increased initial emittance by a factor of ~1.4 (when measured at a phase advance of 70\textdegree). The emittance oscillations are visible on both curves superposed with a gentle overall emittance decrease with increasing $\sigma_0$.

Discussion
Figure 2 clearly shows a decrease in the amplitude (by a factor of ~1.5) of the emittance oscillations with the increase in the initial emittance, lending support to the numerical results of Celata and Hahn. In addition to the oscillations, an overall decrease in the emittance in each case is also visible. It has been suggested that the decrease is simply due to the functional dependence of the invariant amplitude on $\sigma_0$. Examination of the calculated emittance growth curve in Celata's paper shows that it is also possible that the measurements taken lie on a locally decreasing region of the computed curve. K. Hahn has suggested that a similar measurement be taken, but with the mean position carefully set to zero for each value of $\sigma_0$ and $<x>$ adjusted so that the invariant amplitude is kept constant, eliminating the overall decrease in the emittance. Indeed the amplitude difference is already apparent, and the significantly more time consuming experiment will not be completed in the near future.

References
In the course of studying the measured transverse emittance growth in the MBE-4 accelerated beam (ref. 1), a possible contribution to the growth associated with bunch compression in the beam was suggested. The bunch compression is obtained by applying an energy (velocity) tilt within the beam acceleration schedule. To explore this possibility a drift-compressed beam was investigated. An energy tilt was imposed on the beam when moving along section A, and was drift-compressed along sections B through F.

In this experiment the beam bunch compression is observed by measuring the current vs time using Faraday cups positioned along MBE-4. Fig. 1 shows a maximum current amplification (bunch compression) at lattice period (l.p.) 20 and later a reduction in the current at l.p. 25 following the increase in the beam current pulse duration (bunch expansion). The beam energy variation along the bunch, was measured using the small energy analyzer (ref. 2) at l.p. 5 through 25. Fig. 2 shows the energy tilt consistent with the beam compression as observed in the current waveform measured at l.p. 15. The energy and current were found to be in agreement with "SLIDE" (ref. 3) simulations. Transverse emittance measurements taken along the drift compressed beam (Fig. 3) showed a significant growth in the emittance along MBE-4. A reduction in the emittance growth was observed in beams accelerated under a more gentle compression schedule, i.e., a reduced energy tilt applied in section A.

Further analysis of the drift-compressed beam energy measurements showed an increase in the r.m.s energy spread (bars in Fig. 2) around the mean energy measured along the beam. The time jitter and voltage stability of the acceleration pulsers in section A were measured and found to be too small to account for the above observed energy spread. We are in the process of studying a possible correlation between the longitudinal energy spread in the beam and the spread in the r.m.s divergence angle observed in the beam phase space profile and associated with the emittance growth in the compressed beam.

References

The column for the first half of the injector (1 MeV particle energy) has remained assembled since the last program report. The column continues to operate quite well with no beam present. It has been opened to air several times for modifications of diagnostics and for source repair work. Each time some reconditioning has been necessary, but the structure can always be reconditioned up to approximately 980 kV.

When the system was first assembled, all of the electronics for the current valve pulser were included in the high voltage dome together with the source electronics. Various shakedown problems occurred. Special shielding was installed inside the dome to separate the dome halves electromagnetically because of noise triggering problems inside the HV dome. Even when the current valve pulser was made to run without noise triggering, a leakage current was found to occur in the column. This leakage current was due to electric field penetrating through the 90% transmitting grid at the output of the current valve from the first acceleration gap behind it. Because the accelerating voltage pulse applied to the column is a slow rise and fall pulse, ions are extracted directly from the plasma switch grid over a long period of time while the current valve gap has no voltage on it. In addition, the current valve pulse (13.6 kV, 1 μsec nominally), which was normal in the absence of plasma from the source, was severely distorted if the arc source was fired. We decided to remove the current valve from the injector and move it to the ion source test stand where its operation could be studied more easily than inside the injector itself. In the meantime, the injector gun was modified so that extraction directly from the plasma switch grid, which was now located in the aperture of the first column electrode, could be used to test the column optics. This involved transporting beams in the column at full design voltage (944 kV) but with much longer pulse durations. Also, because of the geometry and extraction field, less current would be produced.

When the current valve was installed on the ion source test stand, a gap behind the exit of the current valve was added; this gap had the same width as the first accelerating gap in the injector column. The electric field of the first accelerating gap could be reproduced in the test stand and the field penetration phenomenon could be studied. The leakage current from the source with the current valve turned on very rapidly, much faster than the 5 μsec rise time of the test stand Marx. However, the current magnitude was only about 2.5 mA into a 1" aperture Faraday cup. Attempts were made to eliminate the leakage current. First, a reverse biased electric field was applied to the current valve gap in order to cancel the penetrating E-field. This technique did not work, probably because the current valve gap is composed of grids and the cancelling field must go to the wires of the plasma switch grid. This allows the penetration field to affect the plasma between the wires. The second technique was to use multiple grids at the exit of the current valve gap to prevent the field penetration itself. Three grids were used:

1) single 70x70 90% transmitting mesh
2) double 70x70 90% mesh with 1/16" separation
3) triplet 70x70 90% mesh with 1/32" mesh to mesh separation.

No attenuation of leakage current could be found which could not be accounted for by the geometric absorption of the additional grids. The current valve impedance collapse problem was never observed in the controlled environment of the test stand. Once long pulse emittance measurements are completed on the injector the current valve will be reinstalled and retrieved. It is hoped that the low level of leakage current can be tolerated in the machine.

The injector was used to extract 212-232 mA in a single beam at 944 kV. The measurements were made with a 4" diameter aperture long Faraday cup. The system was run for about 120 shots under these conditions before shutting down to refit the diagnostics for emittance scanning. The range of current given above reflects the results for cup biases of 0 to ±3 kV on the collector and suppressor cylinder of the cup respectively. There were definite and reproducible electron effects in the cup which were functions of the bias voltage. The EGUN code predicts 300 mA in the column for these conditions. Now that the column operates reliably with beam at design voltage, emittance scans are underway.

A new diagnostic chamber has been installed which meets additional safety requirements for the system. The new chamber allows manned occupancy of the injector area while the vessel is at operating pressure. It will withstand the result of catastrophic failure of the insulator column when the system is pressurized to 80 psig. A gate valve to isolate the column from diagnostics is installed and a new cryopump has been installed on the new diagnostic chamber. The computer control system is assembled and functioning. The software for control of the injector driver beam profiling and emittance scans has been debugged and is operating well. The system is ready for automated emittance scans.

Experiments were performed on the ion source test stand to study the effect of plasma switch voltage modulation during extraction on source emittance. A modulator with rise time that matches the test stand Marx rise time has been tested and clean emittance scans were obtained. No effect was seen when the plasma switch voltage was reduced to -14 V. The plasma floating potential has kept the voltage from being depressed further with this device and the circuit is being modified.

(1) Heavy Ion Fusion Research Half Year Report (October 1, 1989-March 31, 1990), 8, LBL-29094.
The concept of a "recirculating induction linac" as a heavy-ion inertial-fusion driver was again considered about a year ago in a small-scale study by Godlove and Mako (FM Technologies, Inc.) and in a preliminary survey by Yu and Barnard (LLNL). Their ideas were reported at the DOE HIFAR Review on March 29, 1990 at LBL. The motivation for renewed interest was the hope that by recirculating the beams through the same accelerating elements many times the number and cost of these expensive units could be reduced enough to more than compensate for increases in other components associated with recirculation, so that less costly driver designs could be presented to compete with other proposed inertial-fusion power systems.

A more formal study was then initiated within the Beam Research Program at LLNL, with some support from X-Division at LLNL and the HIFAR group at LBL. The early work of this study was reported at one of the periodic joint LBL-LLNL meetings, on July 19, 1990. Since that time, the progress of the study is recorded primarily in the collections of transparencies shown by speakers at weekly meetings at LLNL starting Wednesday, July 25 and on every Wednesday thereafter. The present note outlines the character of the LBL contributions to the study and summarizes the progress toward its completion. A formal report on the study is now in progress at LLNL.

As LBL liaison I have attended the LLNL weekly meetings, summaries of which I have given in two monthly reports (HIFAR 278 and 284) intended to keep the LBL staff informed of the character of the study and its progress. In addition, I have participated actively in the Wednesday discussions. Other individuals from LBL have attended these meetings on occasion and offered comments and suggestions. Craig Fong (LBL) has worked with the LLNL cost-estimating staff with the aim of providing a degree of commonality with past (and probable future) LBL non-recirculating induction linac costing practices. Ed Lee (LBL) has made an interesting first step on the complex problem of possible beam emittance growth due to going around bent paths. Using an expansion in powers of beam path curvature, he has calculated to first order in $R^{-1}$ the electrostatic field of a round beam in a round (toroidal) conducting pipe. He finds a sextupole field, a uniform-field term suggesting an image-like effect, and a third term whose average over the beam profile vanishes.

I have emphasized the advantages of avoiding complexity when possible. One example is my suggestion of "circular" rather than "racetrack" geometry for recirculators. One motivation was to avoid need for four rearrangement operations per turn, that could in principle be replaced by a "twisted-circular" set of orbits which I showed, by an analysis in toroidal coordinates, to have particularly simple geometrical properties. Another motivation was to avoid longitudinal beam bunch spreading in the curved sections.

In trying to estimate cost differences between two different accelerator systems having the same purpose it is necessary to make conceptual designs of both systems at comparable levels of understanding of the physics problems and of hardware design; it has been clear from the outset that this condition was not possible to meet. With respect to the recirculators, a requirement is the existence of a specific point design whose cost may be studied. Studying sensitivity of its cost to the large inter-related collection of optimizing changes is another requirement, which is beyond the present scope and duration of the study. (Similar requirements apply to cost studies of straight-through induction linac drivers, and are also out of reach within a similar time frame.) Both systems are very large and complex, and contain features never yet demonstrated in practice. The understanding of high-current ion-beam recirculators has been significantly advanced by the present study, and a good data base for future considerations is being assembled.

In spite of much good work, a specific point design has not been specified as of this date. The lack of convergence to specific parameters thus far can be illustrated by comparing actively considered options as of March 29 with those considered near to October 1. In March: one ring or three, sixteen beams or four, and forty turns or twenty-seven. In October: four rings or three, four beams or two, and twenty-five turns or fifty. These variations represent searches for trends toward lower cost or more practical or even possible design choices in the light of new technical information being actively accumulated. Vacuum requirements have been restudied, motivated by the much longer ion residence time in a recirculator. The design of fast-pulsed bending magnets, and of kickers for injection and extraction, has been carefully examined. Systems for recovering much of the energy from them, and for pulsing the acceleration modules (induction cores), have been considered by LLNL staff having much relevant experience with electron induction linacs. The costs here are of greatest importance, but the energy losses in pulsed magnets are large and must be carefully minimized. Longitudinal instability considerations have been taken into account in considering design options. A sophisticated computer code has been adapted to bent orbits, and others are being planned and implemented. An interesting experiment on emittance growth around a bend is in progress, using an LBL-designed permanent-magnet bending and focusing system. The costs of conventional facilities are being estimated, based on LLNL construction experience.

An important result of the LLNL work thus far is that no fatal flaw in the concept of recirculation has been discovered, although careful attention has been paid to looking for such problems. Therefore this option must be seriously considered for intensive future study if the hoped-for cost advantage is unambiguously demonstrated.
Asymptotic Analysis of the Longitudinal Instability

E.P. Lee and Lloyd Smith

Recent theoretical work on the impedance seen by the beam in a typical driver module suggests that it resembles a lumped R-C circuit at low frequencies plus an R-L-C resonant circuit at about 100 MHz. In the absence of measurements on a real module, we have adopted this model for analytic and computational study. Simulations show that the capacitive element greatly reduces the virulence of the instability compared to a purely resistive impedance and that the resonant mode impedance has little effect. In this note we present a saddle point solution of the linearized cold fluid equations, neglecting the resonant impedance and the direct space charge force, proportional to the gradient of the line charge of the beamlets. The latter omission is appropriate to the case of many (-16) beamlets, since that force is proportional to beamlet current, while the interaction with the modules is proportional to the total current.

The equations to be solved are:

\[
\frac{\partial^2 \delta l}{\partial z^2} + \frac{\partial \delta E}{\partial \tau} = K^2 C \frac{\partial^2 \delta E}{\partial \tau^2} \tag{1}
\]

\[
\left(\alpha + \frac{\partial}{\partial \tau}\right) \delta E = -\frac{\delta l}{C} \tag{2}
\]

where \( \delta l \) and \( \delta E \) are the perturbed current and electric field,

\[
\alpha = \frac{1}{RC}, \quad K^2 = \frac{q d \lambda_0}{mv C} \quad \text{and} \quad \tau = t - \frac{z}{v_0}
\]

that is, the time after the head of the bunch has passed the longitudinal position, \( z \). The discrete modules are approximated by a continuous system with an \( R \) expressed in ohms/meter and \( C \) in farad-meters. This approximation is justified on the grounds that very little happens from one module to the next.

If the initial perturbation is a time dependent velocity error at \( z=0 \), the initial conditions for the equations are:

\[
\delta l(0,\tau) = 0, \quad \delta E(z,0) = 0 \quad \text{and} \quad \frac{\partial}{\partial z} \delta l(0,\tau) = \frac{\delta l_0}{v_0} \frac{\partial}{\partial \tau} \delta E(0,\tau) \tag{3}
\]

We solve (1) and (2) by a Laplace transform in \( \tau \):

\[
\hat{\delta l}(z,0,\Omega) = \int_0^\infty \delta l(0,\tau) e^{-i \Omega \tau} d\tau
\]

and

\[
(\delta l, \delta E) = \frac{1}{2\pi i} \int_c d\Omega e^{-i \Omega \tau} \hat{\delta l}(z,0,\Omega) \hat{\delta E}(z,0,\Omega)
\]

where the contour, \( c \), runs above any singularities in the \( \Omega \) plane.

As an example, consider the case of \( \delta v(0,\tau) \) to be a step-function in \( \tau \) of size \( \Delta v \), then

\[
\delta E = \frac{I_0}{2\pi v_0 C} \frac{\Delta v}{v_0} \int C \frac{d\Omega}{\Omega^2 - K^2 - \Omega^2 K^2} \tag{5}
\]

The integral can be evaluated analytically as an infinite series of spherical Bessel functions of \( K \) multiplied by coefficients dependent on \( z \) and \( \tau \). Its qualitative features can be obtained by using a saddle point method. The procedure is to set the derivative of the exponent equal to zero to find its saddle points in the complex plane and then integrate across these points, along an appropriate contour. To find the rate of exponentiation, it is sufficient just to locate the saddle points.

Sparing the reader the details of this process, we find that maximum growth occurs at \( \alpha \tau = (3/4 \sqrt{2}) K z \), where the exponent is \( K z/(2\sqrt{2}) \). To translate these results into meaningful numbers, we need specific parameters. For maximum efficiency, \( R \) should equal the average accelerating field divided by the beam current; we shall reduce it by a factor of three, which corresponds to about a 25% loss in efficiency. In order to minimize the energy flow from the pulsers needed to reach the required module voltage in a time short compared to the pulse length it would be desirable to have the time constant, \( \alpha^{-1} \), about 1/20 \( z \) pulse length; in this example we increase the capacity, and thus \( \alpha^{-1} \), to about 1/6 \( z \) pulse length. The specific numbers are given in Table 1. The perturbation then grows as \( \exp(2.6\zeta) \), where \( \zeta \) is given in kilometers, out to about 1.4 kilometers where \( \alpha \tau = 3/4 \sqrt{2} K z \). The exponentiating rate, \( K z/(2-\sqrt{2}) \), is what one would get from the simple dispersion relation for a sinusoidal velocity perturbation at a frequency of \( v = \alpha z/v_0 \sqrt{3} \sim 1 \) MHz, which is too low to appear on a 500 ns pulse. For a more reasonable 10 MHz perturbation, the exponentiation rate would be \( 0.64 \text{ km}^{-1} \) instead of \( 2.6 \text{ km}^{-1} \). Both of these growth rates are sufficiently smaller than earlier estimates that one might contemplate the use of feed-forward techniques to prevent serious growth.

References

1) E. Lee, elsewhere in this report
2) K. Hahn and L. Smith, elsewhere in this report.
3) For more details, see E.P. Lee and L. Smith, HIFAN 477 (LBL-29599), to be published in 1990 Linac Conference Proceedings.

Table I - Application to Heavy Ion Drivers

<table>
<thead>
<tr>
<th>Kinetic Energy ( T )</th>
<th>1000 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Mass ( M )</td>
<td>200 amu</td>
</tr>
<tr>
<td>Ion Charge State ( q )</td>
<td>+1</td>
</tr>
<tr>
<td>Module Capacity ( C )</td>
<td>( 3 \times 10^{-10} \text{ F-m} )</td>
</tr>
<tr>
<td>Module Resistance ( R )</td>
<td>300 ( \Omega \text{/m} )</td>
</tr>
<tr>
<td>Ion Velocity ( v_0 )</td>
<td>0.104 ( c )</td>
</tr>
<tr>
<td>Beam current ( I_0 )</td>
<td>1.0 kA</td>
</tr>
<tr>
<td>Pulse Length ( \tau )</td>
<td>500 ns</td>
</tr>
<tr>
<td>( K = (q e \lambda_0 / m v C)^{1/2} )</td>
<td>7.33 \times 10^{-3} \text{ m}^{-1}</td>
</tr>
<tr>
<td>( \alpha^{-1} = RC )</td>
<td>90 ns</td>
</tr>
<tr>
<td>Maximum growth point: (( \tau / \tau_p )) ( Z_{km} )</td>
<td>0.699</td>
</tr>
<tr>
<td>Amplitude at maximum growth point</td>
<td>( \exp(2.59 \ z_{km}) )</td>
</tr>
</tbody>
</table>
1-D time domain analysis of the longitudinal instability

K. Hahn and L. Smith

Although a heavy ion beam of interest to HIF has a velocity far less than speed of light, its longitudinal wake field falls off very sharply ahead of the bunch in about few radial dimensions. For a wave lengths longer than the radial dimension of the system, the beam coupling to the external structure prior to the arrival of the bunch head is small and the causal condition similar to that of a relativistic beam must be considered in order to insure the proper wake field. However the external response to the beam is conveniently described by the frequency dependent impedance $Z(\omega)$ at low frequency less than few 100 MHz. The usual Laplace transform to this type of problem with temporal boundary condition to a frequency response is possible but rather complicated. A simple alternative is the time domain analysis where the impedance is represented by an equivalent circuit which is integrated in time with a proper initial condition.

The construction of the equivalent circuit, though not exact, can be obtained by a linear combination of parallel RLC circuits; i.e.,

$$Z(\omega) = \sum \frac{Z_i(\omega)}{i} = \sum \frac{R_i}{1 - iQ_i(\omega - \omega_0)}$$

where $Q_i = \omega_0 R_i C_i$ and $\omega_0^2 = \frac{1}{L_i C_i}$.

Each $Z_i(\omega)$ is solved by a simple RLC circuit analysis which can be further simplified by using the approximation $\frac{d^2}{dx} - \frac{\omega_0^2}{R}$. Thus the longitudinal field equation can be written for each equivalent RLC circuit as;

$$C(\omega) \frac{d^2}{dx^2} e - \frac{1}{R} (\frac{\partial}{\partial x}) e + \frac{1}{L} e = (\omega_0^2) I_b$$

which is integrated numerically. Notice that the time dependence becomes only implicit in this approximation.

The longitudinal space charge term is also included by;

$$(1 - \alpha \frac{d^2}{dx^2}) e = - g \frac{\partial}{\partial x} A$$

where $\Lambda$ is the line charge density and $\alpha$ is a dispersion term which is of the order of the square of the radial dimension.

The equivalent circuit has been implemented in PIC code SHIFTZ and the impedance parameter space of relevance to HIF has been tested. Typical runs are made with the velocity spread of $\frac{\delta v}{v} = 0.001$, $\beta = 0.23$, $I_b = 3.5$ kA, $m_e = 200$ amu, charge state = +1, geometry factor $\frac{A}{N_b} = 2$, and a beam traversal distance of longer than 5 km is tried to test the effect of the external impedance on the beam dynamics. Here $N_b$ is the number of beamlets in a common channel. The ever present random fluctuation of the velocity distribution due to finite size of the particles in the PIC code, whose magnitude is given by $\frac{\delta v}{v}$, behaves like white noise and is utilized as an input perturbation. Here $L$ is the longitudinal bunch length and $N$ is the total number of macro particles in the simulation. Since the stability criterion depends on the velocity spread $v_{th}$, care is needed when comparing data with two different temperatures.

Figure 1 shows the phase space plot after traversing $z = 1.1$ km when the external impedance is a real $R = 100$ $\Omega$/m. Since the velocity spread is smaller than 2% required for the full stability, the long wave length mode structure has developed. In the low frequency regime, below a few 10 MHz, the module impedance resembles the R and C parallel circuit. The effect of the added C is to lower the real part of the impedance at high frequency above the inverse of the RC time. When $R = 100$ $\Omega$/m and $\tau_{c} = 5 \times 10^{-8}$ sec. are used, better beam dynamics are shown in Figure 2 at $z = 5.6$ km compared with Figure 1 of real impedance R. The lower limit of the required C to have a tolerable growth rate based on the initial random noise level and a velocity spread of 0.1% is $\approx 5 \times 10^{-10}$ F/m.

In summary, the longitudinal instability in the HIF driver parameter range has been tested with 1-D PIC code with the required causal condition and the frequency response as represented by an external impedance. The circuit model fails at high frequency where radial pulse transit time is comparable to the resonance period and a full electromagnetic treatment would be desirable.

![Fig. 1](https://example.com/fig1.png)

Phase space plot at $z = 1.1$ km. $R = 100$ $\Omega$/m. Velocity spread of $\approx 0.1\%$ is used.

![Fig. 2](https://example.com/fig2.png)

Phase space plot at $z = 5.6$ km. $R = 100$ $\Omega$/m and $C = 5 \times 10^{-10}$ F/m.
Module Impedance Model

Edward P. Lee

The predicted longitudinal instability of a high current ion beam in an induction linac has growth rate dependent on the longitudinal coupling impedance \( Z \). For a perturbation of beam current \( \delta I = e^{-i\omega t} \), the induced voltage of an acceleration module acting on the beam is \( \delta V = -Z(\omega)\delta I \). An analytical model of \( Z(\omega) \) is required for evaluation of the instability and in guiding module design. The on-going work in this area is described here.

At very low frequencies \( (\nu = \omega/2\pi \text{ less than an inverse pulse length}) \) the coupling impedance is approximately given by the resistive impedance \( R \) of the external drive circuitry. However, at low-to-moderate frequencies \( (\nu = 1-10 \text{ inverse pulse lengths}) \), \( Z \) is expected to be approximately given by the parallel combination of \( R \) and the module gap capacity \( C \):

\[
Z(\omega) = \frac{R + i\omega R^2 C}{1 + (\omega RC)^2}.
\]

Here it is assumed that the core inductance is large enough to simply block currents to ground in this frequency range and makes no significant contribution to impedance other than its capacity (which is included in \( C \)).

Values of \( R \) and \( C \) can be estimated in a straightforward way from module and pulser design and are to some extent specifiable in order to limit unstable growth while maintaining acceptable efficiency of acceleration (see contribution of L. Smith and E. Lee in this report for a discussion of instability with an RC impedance model). In general the maximum possible growth rate with distance for given real frequency scales as

\[
\text{growth rate} \propto \left(\frac{\omega |Z| Z_{\omega}}{Z_{\omega} - Z}\right)^{1/2}.
\]

For \( \omega RC \gg 1 \) the growth rate drops with increasing \( \omega \) as \( [\sqrt{2\omega RC}]^{-1} \) rather than increasing as \( \sqrt{\omega R} \) as it would in the absence of \( C \). This simple model therefore suggests that the main problem of instability occurs at relatively low frequencies. If this is true then predicted growth rates may be low enough to make feed-forward control a reasonable option.

The existence of module resonances at high frequencies can, in principle, drastically change this picture. Simple estimates based on module cavity dimensions show that the lowest resonant modes have frequencies on the order of 100 MHz and greater, and are therefore well separated from the lower-frequency (RC) zone. If resonances are narrow (large Q) then they may have large, real valued \( Z \) at their peaks and could be a serious cause of unstable growth. This holds even when taking into account the stabilizing effects of the beam momentum spread, gap transit time, and direct space-charge force. Off resonance, the imaginary part of \( Z \) is generally negative (inductive) on the low frequency side; this is also a destabilizing feature. At high frequencies the ferromagnetically-loaded core side of an induction module, which is coupled in parallel with the drive source and the acceleration gap cavity, is expected to act as a lossy transmission line. As such it can lower the Q of the cavity resonances considerably and possibly render them harmless.

Although these features of the coupling impedance are understood in a qualitative way, a detailed model is desired in order to test sensitivity of \( Z \) to variations in parameters (such as dielectric constant, core permeability, etc.). In addition, planned tests on available modules should be compared with predictions from a simple model (see contributions by A. Fallens in this report). To this end we have devised several analytical models of impedance.

An approximate solution of Maxwell's equations is obtained as follows. A beam cavity region is specified by a length \( l \) and radius \( a \). The multiple beam current is assumed to fill this volume uniformly, but is modulated with real \( \omega \). This current is the source for fields in the combined beam cavity and gap cavity. At the outer edge of the gap cavity the wall current is forced to flow into a lumped circuit impedance, which is the parallel combination of the resistor representing the external drive and a complex core impedance. The latter quantity is obtained by an approximate solution of Maxwell's equations for a cylindrical cavity loaded with an insulated magnetic tape (Metglas, SiFe or other type). At high frequencies this region is expected to act like a low impedance transmission line and should considerably reduce the coupling impedance seen by the beam. Numerous material and dimensional parameters appear in this model and can be adjusted to fit experimental and design data. In addition, the impedance can be approximately reproduced by an equivalent circuit used to represent the module in 1-d PIC code simulations of beam dynamics.
A large induction acceleration module designed to address several driver issues is presently being constructed. The module is representative of current LBL conceptual driver designs, which have a multiple beam array of 1-1.5 m diameter and a core buildup of 0.5-1.0 m typically, depending on the location along the driver and the number of beams in the array. The module is being built to full physical scale, but its core is only partially filled with metglas tape because of the relatively high cost of the material. By filling the core to an effective 10% density while keeping the geometric size of a solid core, and at the same time reducing the drive voltage to a tenth of the solid-core value, the individual laminations experience the same magnetization cycle they would have in a full scale solidly filled module.

The magnetic metal tapes have nonlinear and anisotropic properties which manifest themselves in several ways. When a voltage pulse is first applied to a core with square-loop hysteresis characteristics, the voltage drop tends to concentrate around the central regions, and progressively moves outward as the inner turns saturate. The capacitive charging currents associated with the time dependent voltage distribution are non-negligible, and are partially responsible for the attainable rise times. In addition to the overall risetime problem is the question of the excitation and damping of the various modes of oscillation of the module structure by the applied voltage pulse. The unknown for these oscillations is how much the core region affects them. A similar transient occurs when the beam pulse, and a possible voltage compensating pulse, enter the module. Because these transients are systematic errors, their cumulative effects have to be kept extremely small, of the order of 0.01%.

The recently reactivated subject of longitudinal beam stability needs information on both the effective gap capacity and the resonant behavior of the modules. The major difference between the information required for the transients of the previous paragraph and the beam driven instabilities is that the drive amplitudes due to the instability are unknown. Whether or not a small signal equivalent circuit and coupling impedance are useful concepts would depend to a large extent on the r.f. properties of the core material.

To effect the various measurements the test core, made of Allied’s 2605CO material, is divided into 6 radial segments. Capacitive voltage dividers and r.f. loops are distributed over the module to measure the voltage and current distributions of the applied voltage pulse, the beam loading response, and the resonant modes.
3-D multipole decomposition of the MBE-4 focusing lattice potential

Martin Berz, William M. Fawley, Kyoung Hahn

The syncopated strong focusing lattice used in MBE-4 has many additional multipole components besides the wanted quadrupole components. Although weak, the presence of these components, in conjunction with non-negligible transverse beam displacements, will lead to emittance growth during beam transport. We have computed the z-dependent strength of the multipole moments through sixth order (i.e., dodecapole terms) using the Differential Algebra (DA) methodology to decompose the three-dimensional focusing potential. The latter is first determined by solving the capacity matrix of the actual MBE-4 electrode and aperture plate geometry. Our results are in good agreement with previous determinations of the effective quadrupole lengths and dodecapole strengths and we believe that this method may prove useful wherever multipole decomposition of complicated static fields is needed.

I. Potential Problem Solution by the Capacity Matrix Method

Both the presence of boundary surfaces with different potential values and the possible presence of a non-neutral ion beam will lead to image charges on the conducting boundaries. Using the capacity matrix technique, as can be seen later, this induced charge at the boundary surface is calculated directly rather than specifying the field boundary condition. Once the boundary charge distribution is known, the field at the location of a particle can be calculated straightforwardly. Since the number of required mesh nodes is confined to where the actual charges are, i.e. at the boundary, substantial reduction in total mesh points is obtained. In essence, this capacity matrix method is equivalent to replacing a Dirichlet boundary value problem by the equivalent free space potential problem.

The capacity matrix \( C_{ij} \) relates the charge induced at location \( x_i \) on the boundary to the potential specified at location \( x_j \), i.e. \( \sum C_{ij} \phi_j = Q_i \). In order to determine \( C_{ij} \), one actually solves the inverse problem \( \phi_j = \sum C_{ij}^{-1} Q_i \) with the \( x_i \) chosen to fall at strategic locations (hereafter called "nodes") on the different quadrupole electrodes, plates, and outer boundary. The \( C_{ij}^{-1} \) are sometimes called the coefficients of potential.

For the case of the three dimensional MBE-4 lattice structure, one may use the simple interaction potential of \( C_{ij} = \frac{\sigma}{r_{ij}} \) for \( i \neq j \). When computing the self-potential (i,j), the fast charge profile must be carefully considered. In this calculation, a triangular charge distribution was used which gives \( C_{ij} = \frac{\sigma}{2} \). The distribution width \( \sigma \) is typically set to the internode spacing. This choice smooths the potential by greatly reducing the contribution of high spatial frequencies and also prevents the self-potential from unphysically dominating the problem. Although we are representing the physically thin surface image charge by non-zero thickness spherical charges, the electric field on and near the beam transport axis should be little affected so long as the internode spacing and charge distribution width \( \sigma \) are small compared with the clear aperture between electrodes and the electrode-aperture plate separations in \( z \).

II. Multipole Expansion and Differential Algebra

Once the boundary surface charge has been determined, the electric potential at arbitrary point in space can be computed by the summation over the charges. At interior positions where the potential varies smoothly, an approximate functional expansion can prove extremely useful in terms of computational economics. Thus a systematic multipole decomposition of the field around an aperture axis is used.

The multipole coefficients \( M_{k,i}(z) \) of the potential \( \phi \) are defined in cylindrical coordinates system by

\[
\phi(r, \theta, z) = \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} M_{k,l}(z) r^k \cos(l \theta)
\]

where a Fourier series expansion in \( \theta \) and power series in \( r \) are used. Notice that the up-down symmetry, i.e. symmetric under \( (y \rightarrow -y) \) transformation, of the MBE-4 geometry is implicitly assumed. No \( z \)-axis expansion is performed and \( M_{k,i}(z) \) is calculated at numerous locations in \( z \).

The source-free vacuum potential \( \phi \) satisfies the Laplace equation and thus the \( M_{k,i} \) obey the following recursion relation:

\[
M_{k,l} = M_{k-2,l} (l^2 - k^2),
\]

where double prime denotes the second derivative with respect to \( z \). Since \( \phi \) is analytic inside, the relation \( k \geq l \geq 0 \) and \( k-l \) = even must be true for non-zero coefficients. The entire ensemble of multipole coefficients can then be determined from \( M_{k,k} \) and its z-derivatives. Hence

\[
M^{(2i)}_{k,k} = \sum_{n=even}^{k} \frac{(-1)^{(n/2)}}{2^{k-1} n! (k-n)!} \left( \frac{\partial}{\partial x} \right)^n \left( \frac{\partial}{\partial y} \right)^n \left( \frac{\partial}{\partial z} \right)^{2i} \phi(0,0,z)
\]

for \( k \geq 1 \) where the up-and-down symmetry has again been used.

Away from the nodes \( \phi \) is infinitely differentiable, and it is in principle possible (although very tedious for high orders) to compute the required derivatives \( M^{(2i)}_{k,k} \) by differentiating \( \phi(0,0,z) \). To circumvent this difficulty, we use DA techniques for the computation of the higher order derivatives to machine precision without numerical errors. These techniques have been discussed in detail elsewhere [1,2], and the interested reader is referred to these papers.
III. Computational Results

A FORTRAN code was written to evaluate the coefficients of potential, and then invert them to obtain the capacity matrix \( C_{ij} \) and the node charges \( Q_j \). The nodes were distributed uniformly over the surface of the electrode rods and with an \( \approx 1/r \) dependence on the endplates. Beam holes in the endplates are represented by the absence of nodes in the interior and by a clustering around the boundary circles. The charge distribution width \( \sigma \) was set to a constant (= 2.5 mm for total node number \( N=5000 \)), somewhat smaller than the typical internode distance in order to minimize the size effect.

Since our main interest was calculation of three-dimensional multipole components of the MBE-4 focussing lattice, the potential at the electrostatic quadrupole electrodes was set to \( \pm V_q \) rather than grounding one of the electrode pairs. From there, the \( M_{k,l} \) were computed from 0th to 6th order.

The coefficients were made dimensionless by scaling the potential by a factor of \( V_q \) and using a normalization length of the aperture radius \( a \), i.e.:

\[
\varphi = V_q \sum_{k=0}^{6} \sum_{l=0}^{6} M_{k,l}(z) \left( \frac{r}{a} \right)^{k} \cos(l \theta)
\]

Figures 1a and 1b show the results for the case of \( N=5000 \). The relative computational error is about 2% or better at the middle of the quadrupole assembly \( (z=0) \) when compared with previous 2-dimensional calculations. For example, Brady [3], using the POISSON program to calculate multipole moments for a 2-D MBE-4 geometry (i.e. \( z \)-independent), found \( M_{2,2}=0.9658 \) and \( M_{6,6}=0.03461 \) in comparison with our midplane values of 0.9855 and 0.03460 respectively. Meuth et al. [4] determined an effective quadrupole length of 10.11± 0.14 cm, 5% shorter than our predicted effective length \( \left( \int M_{2,2}(z)dz / M_{2,2}(z=0) \right) \) of 10.60 cm. Our measurement, however, is quite close to the actual electrode length of 10.74 cm.

Since only the quadrupole \( (M_{2,2}) \) and dodecapole \( (M_{6,6}) \) components are non-zero at the midplane due to symmetry, the 3-dimensional contribution to the \( M_{2,2} \) midplane discrepancy is small. Instead, we believe the quadrupole error is due to an insufficient number of nodes per rod in the azimuthal direction. However, near the endplates, the field contains large multipole field components because of the inter-digital structure of the quadrupole rods, their closeness to the endplates, and the beam aperture holes. Our numerical errors may be larger in this region because \( \sigma \) exceed the optimal value around the aperture holes and the spherical charge shape is a poor approximation to the true image charge distribution on the flat endplates. Thus, perhaps additional nodes and a variable charge distribution width and shape would be required in order to maintain \( -1\% \) accuracy everywhere.

References

HIF Beam Propagation in a "High" Pressure Reactor Environment

William M. Fawley

A reinvestigation of HIF beam propagation in high pressure (P > 1 Torr) reactor environment has been initiated. Much work was done on this topic in the late 1970's and early 1980's, concentrating both on the equilibrium properties of the ion beams (e.g. pinched radius) and the possible virulence of various plasma-induced instabilities such as filamentation. One question that some felt was not satisfactorily answered was the basic strength of the self-pinch force for kA-magnitude currents: the rapid generation of conductivity tends to limit the net current while, on the other hand, stripping phenomena tend to increase the beam current and possibly the net current also. In collaboration with colleagues at LLNL, we are using a number of different simulation codes to examine the pinch formation.

I. Scaling of self-pinched propagation

High current beams propagating in gas reach equilibrium when the radially attractive force due to the azimuthal magnetic field is locally balanced by the radially expansive forces of beam temperature (i.e. transverse emittance) and unneutralized space charge. Denoting $B = v/c$, and $\epsilon$ as the unnormalized emittance, equilibrium results when the radius ($r$) is constant, i.e.

$$\frac{d^2r}{dz^2} = \frac{\varepsilon^2 r^3}{r} \left( \frac{2\pi^2 r^2 I_{\text{beam}}}{\gamma \beta \epsilon} \right) \left( \frac{\gamma \beta e c^3}{Q_{\text{eff}}} \right)$$

The term in the integral is generally referred to as the beam's "effective current". In the absence of any electric neutralization (such as in vacuum propagation), $I_{\text{eff}}$ always is in opposite sign to the beam current, the emittance term cannot be balanced by a pinch force and no self-pinched equilibrium is possible. In order to estimate the size of the needed effective current, let us set $r_{\text{equiv}} = 3$ mm, $I_{\text{beam}} = 4$ kA, $Q_{\text{eff}} = 40$, $\gamma \beta e = 20$ mrad-mm, and $\beta = 0.3$ and presume full neutralization of the beam's radial electric field. We then find,

$$I_{\text{eff}} \approx 23 \text{ kA}.$$ 

While this value is small compared with the unneutralized, stripped beam current of 160 kA, a high degree of current neutralization due to rapid conductivity generation might limit $I_{\text{eff}}$ to well below this value.

A related question is the topology of the pinch field near a target symmetrically illuminated by $N > 2$ beams. Even though the individual beams may propagate without problems far from the target, in immediate vicinity of the target, the loss of pinch force due to the presence of other beams might be quite serious.

II. Ulysses simulation code

We have adapted a 2-D ($r$-$z$) full E&M beam simulation code named Ulysses to study the physics of pinch formation and target charging. With the assumption of full azimuthal symmetry, only $E_r$, $E_z$, and $B_\theta$ need be followed. The beam is modeled as a series of axial slices, each of which expands or contracts self-similarly obeying an envelope equation. Plasma currents are determined either with Ohm's law or through integrating the equations of motion with a resistive term. Optionally, both the background gas and plasma electron temperature (including their effects upon conductivity) can be followed. The plasma ionization, beam energy loss, and beam stripping rates are modeled using the results of Gillespie and Janda (Gillespie, G. H. and Janda, R.S., Phys. Rev A, 23, 2220 (1981)).

III. Preliminary results

Early Ulysses results suggest that the effective pinch current is too small by a large factor (<400 A) to achieve a 3-4mm equilibrium beam radius for $\epsilon \sim 45$ mm-mrad. Although $I_{\text{eff}}$ (see Fig. 1) does increase in $z$ with the increase in effective charge state due to stripping, it never approaches the needed 20$^+$ kA magnitude. The expansion of the beam head does not induce enough conductivity to cause significant return currents to flow outside the main body of the beam which would help increase $I_{\text{eff}}$. Over propagation distances of a few meters, the effective nose erosion is so small (< 1 ns) as to be inconsequential.

![Figure 1. Plot of effective and net current for a heavy ion beam propagating in 1-torr gas. The beam head is at $z = 120$ cm.](image-url)
Magnetic focusing is selected for the 4-MeV to 10-Mev section of Induction Linac System Experiments (ILSE). Compact, current-dominated magnetic quadrupoles are being developed to study transport of magnetically focused space-charge-dominated beams and to explore the engineering problems involved in accurate positioning of the magnetic fields in an array of quadrupoles. A prototype development program for such magnetic quadrupoles was undertaken during FY 90. In this design the traditional iron yoke is minimized so that the multiple beam-to-beam spacing is minimized. The overall accelerator diameter and its consequent cost are then lowered. The design evolved from a cosine 28 current distribution corrected for end effects. 2D field computations of this geometry including the magnetic properties of the silicon steel have been performed using the POISSON code. The field at the edge of the coils is 1 tesla and the magnet aperture is 43 mm. Each quadrupole, in an array of four, will be subjected to 1000 amp current with \( \leq 12 \) kV voltage for 1 millisecond (half sine curve). Current-dominated magnets are used in a pulsed mode to allow higher current densities compared to standard dc water cooled conductors. The mechanical construction of this quadrupole is aimed at achieving location accuracy of the magnetic field center within \( \pm 0.001 \) inches of the mechanical center of the quadrupole.

The ILSE design includes the transport of four parallel beams in a transport system using arrays of four magnetic quadrupoles. To maximize the transportable current, which is proportional to \((aL)^{2}\), it is desirable to use the largest beam aperture, \(a\), and the shortest half-period, \(L\). As this is done, the magnets tend to have a large bore-to-length ratio and tend to be packed closely together in the axial direction. A consequence of such design is that the end fields become a large fraction of the total field, and it becomes increasingly difficult to maintain linear focusing fields along the length of the magnet. The initial goal was to try to achieve a 50% square-field-equivalent geometry with a bore radius of 5.5 cm and a half-period of 40 cm. This is still a reasonable goal for a future upgraded ILSE, and the initial design proved useful for the downstream portion of ILSE. As the design of ILSE progressed, for various reasons certain performance parameters changed, and as a consequence the bore was decreased to 4.3 cm and half-period increased to sections of 50 cm and 60 cm in the downstream part of the machines. The design parameters are shown in Table I. Nevertheless, there is continuing interest in both the physical construction of more compact arrays of larger bore-to-length ratio magnetic quadrupoles and in the dynamical consequences of the resulting fields.

**Design of the quadrupole**

To reduce costs of an induction linac it is desirable to make the diameter of the beam cluster as small as possible so that the surrounding insulators and induction cores have a small diameter. In the design of the magnet, this translates to a choice of small clearance between the beam and the vacuum chamber, a thin coil package driven with a pulsed current, and a minimal iron return yoke. A standard iron-dominated design was considered and rejected because of the radial space taken up by the poles. A part of the design depends on the proximity and orientation of the neighboring quadrupoles. In the configuration selected, the separation is not the minimum possible, but a compromise, as shown in Fig. 1, which positions the poles of adjacent quadrupoles to face each other with the same polarity. For a small number of beams the radial space wasted is tolerable, but for a large array a different configuration would be chosen in which the facing poles have opposite polarity.

Another major consideration is the effect of the field leaking out of the ends of the magnet. Because of the asymmetry between the inside and outside boundaries in a 4-quad array, this leakage field is not centered on the axis of the quadrupole from which it emanates. The solution chosen for this problem was to extend the iron yoke past the windings for a sufficient distance for the field to decay to a low value. For similar reasons the iron yoke was limited to operating at the relatively low flux density of 18 kilogauss, where it still has a high permeability, which results in the computed 2-D magnetic center of each quad being within \(10^{-3}\) inch of its mechanical center.

The magnet windings were designed with the goal of making the higher allowed multipoles vanish in the integral sense. This is accomplished by deviating from a cosine-sinusoidal current distribution within the interior of the magnet by enough to cancel the effects of the unequal lengths of the different turns, which are evident at the ends of the windings. A 3-D MAFCO computation was utilized to check the fields, without including the surrounding iron yoke. The main effect of a closely fitted yoke is to increase the field strength by a factor of 1.7 and to shield the quadrupoles from each other. Measurements of the integrated fields will verify whether this design approach and the construction techniques are successful.

In phase I of this prototype development, efforts were concentrated to hold the mechanical dimensions as close to design as possible through cost effective fabrication methods. The details of the design and fabrication are described in the following paragraphs.

**Iron Yoke**

The size of each lamina is approximately 5.5 inches square with a bore diameter of 4.661 inches. In order to avoid eddy current induced core heating and minimize the effect of material coercive force on the residual field, 0.014 inch thick M36 Silicon Steel Sheet with C5 insulation is selected for the core laminations. In this geometry of the lamina, with respect to the poles of the quadrupole, the region of maximum flux concentration was determined. From the B-H curve of the material 15 kga per cm was found to be the safe limit of saturation. The region of maximum flux concentration is approximately 30 degrees off from pole centers where the iron width was just adequate to avoid saturation.

The laminations were punched from fully processed electrical steel with \( \pm 0.001 \) inch accuracy and minimum burr at the edges. A stacking fixture was designed to index...
individual lamina by its center bore for accurate mechanical center and outside edge for proper squaring. The central indexing mandrel has a ground surface with tolerance of ±0.0005 inches. After the application of suitable epoxy on the laminations, they were assembled on the stacking fixture and cured in the oven with maximum temperature of 80 degree centigrade. After 24 hours of controlled curing of the stack, the fixture was disassembled with removal of the central indexing mandrel which is collapsible in design for easy separation from the yoke bore.

Coil Form

The quadrupole has 24 turns per pole, arranged in two layers with identical azimuthal distributions. These distributions are a minor deviation from cosine 2φ average current density distribution in which the density is controlled by the wire spacing. The lower allowed harmonics are nullled out, as discussed previously, and no effort is made to control the very high multipoles, which have a rapid decay towards the center. The conductor locations on the coil form are machined on a lucite cylinder with azimuthal accuracy of ±7 minutes. Two such cylinders are nested inside each other, with 8 mil clearance which is filled with epoxy during the final assembly of the quad. The magnet wire required for the lower layer was saved inside the inner coil form and after the outer coil form is slipped in position, the magnet wire is pulled out and wound over the outer coil form. The azimuthal orientation of the two coil forms is maintained by an indexing pin which is removed after final assembly. The interconnections of the four coils are done such that the connecting leads are twisted to decrease field errors.

Assembly of the quadrupole

The final assembly method involves vacuum potting the coil cylinder and the iron yoke with proper high voltage insulations on surfaces inside and outside of the coil form. A special assembly fixture was designed to locate the yoke and the coil cylinder accurately both in azimuthal and concentric manner. The outside and inside surfaces of the coil cylinder were wrapped with two turns of 5 mil thick glass impregnated mylar film which ran the total length of the yoke.

The fixture plate has entry ports for epoxy filling from the bottom end and the controlled flow is in the upward direction to eliminate air bubbles. The top is open and acts as reservoir for compensating shrinkage during curing at room temperature. The epoxy chosen has very low viscosity and uses low isotherm hardening additive that can provide 8 to 10 hours of pot life during vacuum potting process. The total process of epoxy filling is done in vacuum which eliminate any possibility of air bubbles in the epoxy layers that enclose the high voltage insulations.

Testing of the quadrupole

The design is based on eliminating the first four allowed higher multipoles in the integral sense. The measurements of the field should show considerable deviation from a pure quadrupole field at any axial location, but a very good approximation to it in an integrated measurement.

The measurements for the local field distributions will be made with a Hall probe using a low amplitude dc current excitation of the magnet. Cooling considerations are expected to limit the dc current to about 1% of the pulsed current value. The pulsed fields will be measured with a narrow coil extending through the magnet well past the ends, and thus provide the integrated field data.

### TABLE- I

<table>
<thead>
<tr>
<th>Magnet Bore Diameter</th>
<th>9.3 cm (3.661 in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field At the edge of the bore</td>
<td>0.807 T</td>
</tr>
<tr>
<td>Gradient</td>
<td>17.3 T/m</td>
</tr>
<tr>
<td>Overall Length</td>
<td>25.78 cm (10.15 in)</td>
</tr>
<tr>
<td>Effective Length</td>
<td>16.7 cm (6.614 in)</td>
</tr>
<tr>
<td>Cross Section</td>
<td>13.97 cm² (5.5 m²)</td>
</tr>
<tr>
<td>Number of turns per Quadrant</td>
<td>24</td>
</tr>
<tr>
<td>Type of coil winding</td>
<td>Cosine 2φ</td>
</tr>
<tr>
<td>Current</td>
<td>1 kAmp (Approx.)</td>
</tr>
<tr>
<td>Charging voltage required for four such Quads. in series</td>
<td>11.1 kV</td>
</tr>
<tr>
<td>Conductor Size</td>
<td>2 mm (nominal dia.)</td>
</tr>
<tr>
<td>Overall Weight</td>
<td>45 pounds</td>
</tr>
</tbody>
</table>

**MAGNETIC QUADRUPOLE ARRAY DEVELOPMENT**

![Fig 1. Isometric view of ILSE 4 quad array showing the orientation of the poles and the coils.](image-url)
<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIFAN-462</td>
<td>Heavy Ion Fusion Accelerator Research (HIFAR).</td>
</tr>
<tr>
<td>LBL-29094</td>
<td>Year-End Report, October 1, 1989 - March 31, 1990</td>
</tr>
<tr>
<td>HIF Staff</td>
<td>March 1990</td>
</tr>
<tr>
<td>HIFAN-463</td>
<td>Driver Issues, DOE HIFAR Review, March 29, 1990</td>
</tr>
<tr>
<td>HIFAN-464</td>
<td>Program, DOE HIFAR Review, March 28, 1990</td>
</tr>
<tr>
<td>R. Bangerter</td>
<td>T. Fessenden, S. Eylon, K. Hahn, H. Rutkowski, D. Hewett, C. Fong</td>
</tr>
<tr>
<td>K. Berkner</td>
<td>E. Storm</td>
</tr>
<tr>
<td>HIFAN-466</td>
<td>LBL Response and Update, Presented to the National Academy of Sciences ICF Review Committee, June 5, 1990</td>
</tr>
<tr>
<td>HIF Staff</td>
<td></td>
</tr>
<tr>
<td>HIFAN-467</td>
<td>Heavy-Ion Fusion Accelerator Research 1989 - 1990</td>
</tr>
<tr>
<td>Joe Chew</td>
<td>May 1990</td>
</tr>
<tr>
<td>HIFAN-468</td>
<td>Thomas J. Fessenden, &quot;Foreign Trip Report: 3rd Workshop on Inertial Confinement Fusion Driven by Heavy Ion Beams, Varenna, Italy, April 27 - May 2, 1990&quot;</td>
</tr>
<tr>
<td>Fessenden</td>
<td></td>
</tr>
<tr>
<td>HIFAN-469</td>
<td>E. P. Lee and L. Smith, &quot;Asymptotic Analysis of the Longitudinal Instability of a Heavy Ion Induction Linac&quot;</td>
</tr>
<tr>
<td>Lee</td>
<td></td>
</tr>
<tr>
<td>HIFAN-470</td>
<td>R. O. Bangerter, &quot;Heavy Ion Induction Linacs for Fusion&quot;</td>
</tr>
<tr>
<td>Bangerter</td>
<td></td>
</tr>
<tr>
<td>HIFAN-471</td>
<td>E. P. Lee and L. Smith, &quot;Asymptotic Analysis of the Longitudinal Instability of a Heavy Ion Induction Linac&quot;</td>
</tr>
<tr>
<td>Lee</td>
<td></td>
</tr>
</tbody>
</table>
K. Hahn and L. Smith,
"Effect of Multiple Beamlets on Longitudinal Stability"

E. R. Colby, S. Eylon, T. J. Fessenden, and T. Garvey,
"Measurements of Emittance Growth due to a Wire Grid"

R. O. Bangerter,
"Heavy Ion Inertial Fusion"

Henry Rutkowski
Foreign Trip Report, Akademgorodok, USSR and Moscow, USSR, June 29-July 12, 1990.

W. Fawley, K. Hahn
3-D Multipole Decomposition of the MBE-4 Focussing Lattice Potential (8/2/90), W. Fawley, K. Hahn

Edward P. Lee, Lloyd Smith
<table>
<thead>
<tr>
<th>HIFAR Note-271</th>
<th>Impedance Plots Pertaining to Longitudinal Instability May 31, 1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIFAR Note-272</td>
<td>Theoretical Status of HIFAR September 1986. (6/6/90)</td>
</tr>
<tr>
<td>HIFAR Note-273</td>
<td>The Circular Linear Induction Accelerator - An Oxymoron? (June 1990)</td>
</tr>
<tr>
<td>HIFAR Note-274</td>
<td>Questions for HIFAR/June 14, 1990</td>
</tr>
<tr>
<td>HIFAR Note-275</td>
<td>Heavy Ion Fusion Meeting at LLNL, Thursday, July 19, 1990, Bldg. 319, Room 205</td>
</tr>
<tr>
<td>HIFAR Note - 276</td>
<td>Required Stand-Off Distance for HYLIFE II</td>
</tr>
<tr>
<td>HIFAR Note - 277</td>
<td>Letter to Dr. Marshall N. Rosenbluth, University of California, San Diego, from Ed Lee.</td>
</tr>
<tr>
<td>HIFAR Note-278</td>
<td>LLNL Recirculator Meetings - I August 1990</td>
</tr>
<tr>
<td>HIFAR Note-279</td>
<td>&quot;On the effect of a symmetric mismatch on emittance in a continuous focussing system.&quot;</td>
</tr>
<tr>
<td>HIFAR Note-280</td>
<td>Instruction for Diagnostic System Programs, September 1990.</td>
</tr>
<tr>
<td>HIFAR Note-281</td>
<td>Diagnostic System Program Listings, September 1990.</td>
</tr>
<tr>
<td>HIFAR Note-282</td>
<td>Investigation of Coherent Transverse Emittance Oscillations with Increased Emittance, September 1990.</td>
</tr>
<tr>
<td>HIFAR Note-283</td>
<td>Maximum Compression and Tilt Limits September 6, 1990</td>
</tr>
<tr>
<td>HIFAR Note 284</td>
<td>LLNL Recirculator Meetings - II September 1990</td>
</tr>
</tbody>
</table>
H.I.F. STAFF ROSTER

Roger Bangerter

Donald A. Brodzik
Warren Chupp
E.R. Colby
Robert D. Edwards
Andris Faltens
Thomas J. Fessenden
Craig Fong
Terence Garvey
William B. Ghiorslo
Wayne Greenway
Michael Gross
Ralph Hipple
Cai Houston
Rudin Johnson
Brian Lipps
Carl Lionberger
Sam Mukherjee
Harry Meyer
Joseph Perez
Chester D. Pike
John Pruyn
Thomas Purtell
James Rice, Jr.
Henry L. Rutkowski
Gerald L. Stoker
Bill Tiffany
David Vanecek
Gerald West

Clerical Staff

Joy Kono
Diana Morris
Alline Tidwell
Olivia Wong

Visiting Participants

RAFAEL

Shmuel Eylon

SLAC

William B. Herrmannsfeldt

MIT

Bob Bieri

Lloyd Smith

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