HEAVY ION FUSION ACCELERATOR RESEARCH (HIFAR)

HALF-YEAR REPORT*

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Accelerator and Fusion Research

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MASTER

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, the induction linac, has been studied at the Lawrence Berkeley Laboratory and has reached the point at which its viability for ICF applications can be assessed over the next few years.

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 -- both new features in a linac -- without significant dilution of the optical quality of the beams; 4) Final bunching, transport, and accurate focussing on a small target.

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* Presented at IEEE PAC, Chicago, March 1989.

HIGHLIGHTS

D. Keefe

1. Since the IEEE Particle Accelerator Conference, Chicago, March 20-23, 1989, virtually coincided with the end of this reporting period, we include the six HIFAR papers given there as part of this half-year report.
2. In addition to the six papers mentioned, S. Eylon gave an oral report on MBE-4 but because this was concerned very much with work in progress we decided against submitting a text to the IEEE-PAC; we prefer to wait until a more definitive publication is appropriate.

In trying to understand emittance growth in MBE-4 and how much is due to intrinsic physics and how much to adjustment errors a basic program of calibration was initiated. A re-survey indicated that significant misalignments had arisen because of floor motion-presumably due to the massive redistribution of overburden in the neighboring construction project (AML). A new procedure is now in effect whereby we will periodically shut down (every two to three months) to resurvey for any further ground motions.

The phase-advance per cell, σ_0 , of the MBE-4 transport system was measured with very high precision by use of an off-axis pencil beam. The results can be characterized by an effective quadrupole length which can then be inserted into the computer calculations. The result was a 10% change in the value of the effective length.

Emittance growth studies continued. Intrinsic growth (~25%) has now been calculated to occur rapidly in the matching section because of non-linearities. Growth thereafter arising (a) from the change in electrostatic field energy, and (b) from mis-match oscillations is predicted by PIC calculations (SHIFTXYA) but is less than the experimental observations. A more careful envelope matching procedure has been instituted.

3. The 2-MV injector tests still employ just 10 of the 18 Marx trays. After a sequence of generator tests at 1 MV, the voltage was rung up successfully to 2 MV by mismatching the load and creating a fast-rising pulse. Two back-up engineering designs, one with a larger diameter pressure vessel, the other with an oil-gas two-compartment system, have been completed; the intent is to have a fall-back position ready if the present design is found to be unreliable. The recent 2-MV tests increase our confidence that such an option will not be needed.
4. Considerable advances have been made in making the 500-mA carbon source more reliable and reproducible. The scaling with mesh size and transparency are now understood empirically. Further enlightenment is emerging from the code calculations by Hewitt at LLNL.
5. Completion of the ILSE Engineering Design Report coincided with the IEEE-PAC and resulted in four papers being presented on various aspects of the physics and engineering design of ILSE. One was devoted to the overall design features, and the others addressed specific topics — the accelerator units which make up a large part of the cost and are the most uncertain in performance, the four-to-one transverse beam-combining system, and the bend, drift, and final focus sections.

As part of the continuing driver-component R&D program, the design of current-dominated magnetic quadrupoles suitable for an ILSE-like experiment is proceeding. Studies of the longitudinal beam dynamics affected by the fringe-field non-linearities have begun to suggest that our previous assumptions about the safe limits on tolerable aspect ratio for lenses were too conservative.

6. The question of stability against the longitudinal resistive wall instability has become a major topic of theoretical activity. (Efforts at NRL and LLNL will also be coordinated to address this question). This topic has been often studied in previous years and the idea of reflection stabilization in bunched beams arose from these studies (Bisognano). The situation has since, however, become aggravated by the choice of multiple beams and multiply-charged ions. The problem requires a 3-D, non-linear treatment; also, reflection at bunch ends is not amenable to study by PIC or other types of code.
7. A new code, SLIDE — an extended version of C. Kim's SLID code — is nearing completion; it is intended to guide interpretation of results of MBE-4 (and succeeding experiments). Unlike its predecessor, overtaking of particles is allowed.
8. Work on a new code, HILDA, to replace the old LIACEP cost evaluation code, has begun.
9. Finally, a summary of the world efforts on HIF is included.

SURVEY AND ALIGNMENT OF MBE-4

R. M. Johnson, S. Eylon, H. Meuth, W. Tiffany

MBE-4 (4-caesium beam induction accelerator) was due be resurveyed because of heavy construction work on a neighboring building. The previous survey taken in Sept. 87, one year ago, resulted in an overall alignment error of $\pm 0.007''$ (Ref. 1).

The MBE-4 was resurveyed using 2 jig transits. Paired line glass targets were positioned and surveyed one at a time at each of the 24 stations along the 53 foot long accelerator beam line. Since all 4 beam lines are built as one unit, only 2 beam lines were surveyed and are defined as a least square fit of all the measured displacements along the MBE-4 device. The beam lines were established with respect to the accelerator itself. No bench marks or monuments were needed (Ref. 2).

After the initial survey some stations were found to be more than $0.020''$ from the least square straight line fit of all the points surveyed (Fig. 1b). A fairly reasonable explanation of the observed horizontal displacements is that the 2 concrete Bldg. 58 floor slabs that MBE-4 sits on moved with respect to each other by about $0.030''$ and rotated by about 0.1 milliradian (Fig. 1a). The maximum vertical displacements were about $0.015''$ and in some places involved a rotation of the structure of about 5 milliradians.

A system of adding and removing shims was used to adjust height. Jack screws were used to adjust horizontal positions.

After alignment the survey showed the stations were within $\pm 0.007''$ of the least square straight line fit of the survey data (Fig. 2).

The source anode (emitter) position was measured after the main machine was aligned. A special L.E.D. target

Figure 1a. Floor plan of building 58A.
Figure 1b. Horizontal misalignment for n & m beams, survey 12/88.

was built that was capable of operating at vacuum and air. The results of the source survey showed that there is a $\sim 0.060''$ horizontal and a $\sim 0.040''$ vertical displacements in the source position as a result of going from air to vacuum (or vis versa). We found the south source was off vertically by $\sim 0.070''$ under vacuum from the desired beam line position. By using jack screws and clamps on the source support we were able to rotate and translate the sources to within $\sim 0.015''$ of the desired position under vacuum.

The basic sighting accuracy of our transits and targets is $\pm 0.002''$ but an error analysis shows further statistical errors can add up to $\pm 0.004''$ in sighting errors.

As a result of these measurements frequent surveying of MBE-4 alignment is recommended. Some improvements are suggested: redesign of source diode assembly, remove all obstacles to the survey telescopes line of sight, and fabricate a target that will allow survey of all quadrupoles.

The first MBE-4 alignment checkup was done on Feb. 15, 1989 on the north beam line. An acceptable misalignment of less than $\pm 0.005''$ was observed (Fig. 3). The large horizontal offset at the last station ($z=600''$) was caused by the adding of the heavy Energy Analyzer box after the 12/15 1988 survey and realignment was completed.

References:

1. H. Meuth, R. Hipple, W. Tiffany, and D. Vanecek. "Alignment of MBE-4". HIFAR Year-End Report: LBL-24519, p.4, Apr.-Sep. 1987.
2. R.M. Johnson, S. Eylon, H. Meuth, W. Tiffany. "Survey and Alignment of MBE-4". HIFAR-Note 237. Dec. 1988-Jan. 1989.

Figure 2. Horizontal displacements along the machine axis, realignment survey 12/15 1988.

Figure 3. Vertical and horizontal displacements along the machine axis. Alignment checkup 2/15 89.

ZERO-CURRENT PHASE ADVANCE MEASUREMENTS IN MBE-4

H. Meuth, S. Eylon, E. Henestroza, and K. Hahn

I. Summary:

The zero-current phase advance was determined in MBE-4 by measuring the betatron displacements of a pencil beam along the transport section [1]. While the beam energy was kept fixed, a wide variety of quadrupole voltages was used. A fitting procedure was used to extract the phase advance from the measurement. It could be concluded that (a) the phase advance for operation parameters usually used on MBE-4 never comes close to the critical value of 90° ; and that (b) the quadrupoles perform, by and large, as hitherto assumed, although with a reduced effective strength, about 10% smaller.

II. Zero-current phase advance in a syncopated lattice:

The betatron phase advance, σ_0 , is set by the beam energy, V_b , the quadrupole voltage, V_q , and the quadrupole configuration. A simple formula suitable for the syncopated quadrupole structure of MBE-4 can be derived from basic particle optics: Two quadrupoles, each of length λ , are separated by a short drift space to form a doublet. The quadrupole-quadrupole distance in such a doublet is Δ ($=17.15\text{cm}$), thus making the short drift length to be $\Delta - \lambda$. The doublets are separated by the lattice period $2L$ ($L=22.86\text{cm}$). The larger drift space length in between doublets, $2L - \Delta - \lambda$, is necessary to accommodate the acceleration gaps. In terms of V_q , V_b , the particle charge state q , and the radius of the inner clearance of the quadrupoles r_0 , we have approximately for the zero-current phase advance (per period) $\sigma_0 \cong qV_q/V_b \lambda/r_0^2 \sqrt{2\sqrt{(L-\Delta)\Delta-L\lambda/3}}$. The quadrupole supply voltage is given by $2.06 \times V_q$, taking into account the nonlinear quadrupole fields close to the electrodes. With this formula we can determine the effective quadrupole length λ_{eff} from the measured phase advance σ_0 .

III. Phase-advance measurement:

To determine the phase advance we traced the betatron oscillations in all diagnostic stations 5 through 30, along MBE-4 for various quadrupole voltages in the vicinity of 16kV. The betatron oscillations were initiated at box M04 using a stopped-down 50- μA beam. The oscillations were determined from the beam centroid's position in the subsequent diagnostic stations, whereby the beam energy was left constant as determined by time of flight (188.4keV). The approach allows for a simple, and accurate fitting procedure of the purely sinusoidal dependency on the axial coordinate. To further improve accuracy, we have devised a technique that differentiates against oscillations stemming from random quadrupole misalignments [2]: the beam was initially displaced, via a pinhole, equal positive and negative amounts ($\pm 5\text{mm}$) with respect to the channel axis. The difference between these adequately removes the cumulative misalignment errors. The fitting parameters of a fitting routine, FITCOSINE, were constrained to lead to phase advances between about 60° and 90° , as one would estimate it from our analytical formula. The beam displacement can be measured only every fifth gap at the diagnostic stations. The fitting procedure, therefore, yields only results modulo $2\pi/5$, or 72° : $\sigma_{\text{actual}} = n2\pi/5 \pm \sigma_{\text{fitted}}$. For a phase advance of 72° per period, each diagnostic station will have a phase advance of 360° , yielding identical beam displacements for $18.3 \pm 0.1\text{kV}$ (Fig. 1).

IV. Discussion of the results: zero-current phase advance and effective quadrupole length:

We have depicted the results of our measurements in Fig. 2. They can be used to determine the effective length, λ_{eff} , of the quadrupoles. The value for λ_{eff} ($=10.05\text{cm}$) corresponds, to very good approximation, to the length of overlap of the interdigital electrodes. It is about 10% shorter than assumed thus far in an envelope code [3], whose quadrupole configuration was based on field computations for an interdigital geometry. The reduced strength of the quadrupoles was used for the recent careful matching and computational modeling of MBE-4.

References:

- [1] H. Meuth, S. Eylon, E. Henestroza, and K. Hahn, HIFAR Note-232
- [2] L. Smith and K. Hahn, LBL-25099
- [3] A. Warwick, HIFAR Note-174

Fig. 1 Transverse displacement of pencil beam, vs. quadrupole supply voltage.

Fig. 2 Zero-current phase advance, vs. quadrupole supply voltage.

A DETAILED STUDY OF TRANSVERSE EMITTANCE IN MBE-4

H. Meuth, K.D. Hahn, S. Eylon, and L. Smith

1. Introduction and summary:

In the summer of 1988, we reported on preliminary measurements[1], that indicated a growth of the (normalized) transverse rms-emittance of the accelerated beams in MBE-4. On the other hand, no such growth was observed with the drifting beams. At that time, however, both the theoretical understanding for the possible growth mechanisms and the confidence in our experimental procedures were limited. Consequently, we set out to carefully re-examine in detail the transverse beam properties in MBE-4, and the operational parameters that determine them.

The experimental aspects of this re-examination included specifically: (i) The mechanical alignment of the transport channels along the device. (This matter is described separately in this half-year report by Johnson, *et al.*) (ii) The calibration of the quadrupole performance, where the zero-current phase advance was measured. (See the separate account by Meuth, *et al.* in this half-year report.) (iii) The beam characterization of the Cs⁺ ion source diode. (iv) Careful beam-envelope matching, both for the drifting and accelerated beams. While the latter is still ongoing, it appears that, again, we observe an emittance increase, when the beam is accelerated.

The theoretical and computer-modeling work encompassed (v) beam-matching calculations; and (vi) PIC-code calculations. Both utilized, with time, more and more realistic conditions, as they became available from our measurements on MBE-4, and served simultaneously as feedback, as to what direction the experiments should take. In parallel, general analytical work[2] illuminated novel mechanisms for emittance increase and decrease.

2. Beam-dynamic characteristics of the ion source

The beams' phase-space and current distribution were determined experimentally at the relevant axial position, when it enters the first quadrupole in the matching section. (In a very early stage of MBE-4, at a time when it consisted only of the source box and when diagnostic access was still simple, these parameters had been already measured; however, later the configuration was altered by the addition of a beam-steering array. Therefore, these older results are not applicable as a suitably realistic condition for beam injection.[3]) Up to the point of injection, the beam should be still cylindrically symmetric. Figure 1 shows the phase-space distribution of the beam at this point, measured with a pinhole/slit-cup combination. We observe the outermost rays having turned inward due to the overfocussing effect of the diode aberration. This leads to the current accumulation at the beam edge, seen in Figure 2. As a result the beam is hollow. The beam dynamic computations discussed below incorporate both this hollow profile and also a flat profile to examine its effects on the emittance.

3. Beam-envelope matching

Early computational results[4] suggested that mismatch oscillations have to be carefully avoided in order for the outer part of the beams not to approach the quadrupoles too closely for this could lead to emittance degradation. With the aid of a detailed quadrupole calibration, that also entailed the

determination of the beam energy to within a percent, the voltages in the matching section were reset to a somewhat increased zero-current phase advance of 71°, up from about 64°, using a matching code. Minor discrepancies between code and experiment, that may be still the result of experimental inaccuracies, were removed by iteration. (We intend to reduce these inaccuracies further to narrow down the discrepancies for even better predictability of the code.) The quality of the envelope matching is finally established by the absence of mismatch beam-envelope oscillations, which is our primary goal. Figure 3 shows good agreement between the matching code and beam-envelope measurements in the various diagnostic stations of MBE-4: in the matching section, the cylindrically symmetric ion beam is gradually focussed in diameter and adapted to the periodic alternate-gradient configuration of the main transport section. Very recently, we have resumed the measurements under acceleration, specifically using the gentle schedule. Here the matching has to be altered, because then both line-charge density and energy vary along the machine. So far, no fine-tuning has been attempted, although a complete matching of the transverse envelope is in general not possible with discrete acceleration. Moreover the MBE-4 transport channel is constructed with doublets with insufficient control over the beam envelop. As a result, we observe some mismatch by the time the beam has passed half-way through MBE-4 (Fig. 4).

4. Transverse emittance measurements

Simultaneously with the matching procedure, the transverse rms-emittance was also measured. First we consider this rms-emittance (for both principal axes *a*, or *x*, and *b*, or *y*) for the drifting beam of 10 mA, as it varies along MBE-4. Figure 5a shows at first a substantial increase of the rms-emittance that then slowly settles back to about the value at the source. The latter we inferred roughly from measurements *after* the first quadrupole, which was not powered, since the source is otherwise inaccessible to diagnostics. The increase and the decrease in the later phase, that is also borne out, at least qualitatively, by PIC beam modelling, is probably due to two different contributions: (a) Due to the relatively long drift space between diode output and first quadrupole [5], the beam has expanded transversely under its own space charge; its outer edge explores the non-linear regions of the quadrupole in the matching section, and a slight S-shape occurs. (b) The double jack-knife distribution originating from the overfocussed rays of the source rearranges itself when passing through the device resulting in a sharp increase at the matching section, thereafter slowly quieting down after about one third of the device. At the present time, measurements for the accelerated beam are only available until half-way through the device (Fig.5b). While by then the energy has about doubled to 350 keV, no corresponding decrease of the unnormalized emittance can be seen, when compared with the unaccelerated beam. Rather, the unnormalized emittance appears to be the same in both cases, similar to our results with the vigorous acceleration schedule.[1] Again, this increase compares well with the general features of the PIC computational results, while disagreeing quantitatively.

5. Theory development

Various factors which could cause emittance change have been investigated using analytic and numerical (PIC) methods. We

considered: first, non-linear fields, both from external sources such as imperfect quadrupoles, and the ones induced from the intense space charge and interactions with the boundary. Second, residual mismatch oscillations which occur because of the rather large but discrete acceleration. Third, axial compression which, indirectly, alters the radial equilibrium and the conversion of the field energy to a temperature, and vice versa, occurs. Analytic work on compression and acceleration shows the emittance is more susceptible to the profile change when the line number density is larger.[2]

The earlier studies on the effects of the non-linear field has been upgraded by using more realistic conditions in the PIC code simulation, e.g. the thick lenses and synchrotron lattice. Acceleration and compression has been added to SHIFTXY [4], thus renamed as SHIFTXYA. The reference runs are made with the parameters which were determined by the experiment whenever available, such as the initial phase space distribution, and the recently re-calibrated quadrupole strengths and beam energy. However, some quantities are taken from the numerical calculations, like external non-linear field strengths etc. Figure 6 shows the time trace of the x-emittance at both matching section and the transport channel with a uniform initial density distribution. The emittance jumps substantially at the first two quadrupoles followed by a smaller decrease at the matching section without accompanying particle loss. At the transport channel, the normalized emittances of the accelerated and drifting beam show different time characteristics; the accelerated one shows more fluctuations and higher final values which is consistent with our analytic predictions. However, this difference in the emittance is rather too small in comparison with the experimental data. The discrepancy is probably due to too simplistic assumptions made in the simulations, such as disregarding misalignment errors of the quadrupoles and accelerator modules, the time independent boundary condition, and an ideal control of the beam envelope. Superimposed in Fig. 6 is the emittance of the drifting beam based on the measured initial distribution from section 2; the more pronounced jumps in emittance at the matching section are followed by a small decrease. It approaches asymptotically the value of the uniform initial distribution.

The effect of the coherent betatron oscillations was not considered here. However, earlier studies [4] on this aspect show an approximate 1-2 mm tolerance without too much emittance degradation for the MBE-4 geometry.

6. Discussion

In recent, very detailed, experimental, theoretical and computational work we have attempted to pinpoint, and possibly eliminate the potential causes for transverse emittance growth, that appears to persist also for the gentle acceleration schedule. Source effects, although significant, probably cannot be made responsible. Matching under acceleration still has to be improved to fully exclude mismatch as a cause. And while in our experiments coherent betatron oscillations become more pronounced during acceleration, their amplitude seems not to exceed about 2 mm, although the inaccessible values in between diagnostic stations could be larger. Computations and analytical work support these findings, but quantitative agreement is still lacking. In the future, we intend to further improve both the experimental and theoretical determination of the possible cause for the emittance growth.

References

- [1] H. Meuth, T. Fessenden, D. Keefe, and A. Warwick, LBL-25098.
- [2] K.D. Hahn and L. Smith, LBL-26167.
- [3] A.I. Warwick, in LBL-18840.
- [4] K.D. Hahn, HIFAR-223.
- [5] H. Meuth, in LBL-24519.

Fig. 1 Beam distribution in (x, x') space at point of injection into first quadrupole of matching section. Comparison between experiment (-) and result from EGUN code (o).

Fig. 2 Current density $j(x=0,y)$ at point of injection into first quadrupole of matching section.

Fig. 3 Envelope matching of 10-mA beam.

Fig. 4 Envelope data for radius and angle, for accelerated beam.

Fig. 5a rms-emittance (x and y) vs. axial position for 10-mA drifting beam, for 90% and 50% current retained.

Fig. 5b Unnormalized rms-emittance (x and y) vs. axial position for accelerated beam, for 90% and 50% current retained.

Fig. 6 Normalized x-emittance vs. axial position; the emittance is normalized to the initial value. The dotted line at period 0 signifies the interface between matching section and transport channel.

THE BERKELEY 2 MV HEAVY ION FUSION INJECTOR*

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Abstract

This paper is an update on the development of the 500 mA per beam sixteen beam injector being built at LBL. An inductively graded Marx bank provides the acceleration potential on the electrostatic column. A carbon arc source provides the pulsed current for the injector. We report recent results on extracted beam parameters, column performance, the generator performance, and system design changes. The carbon ion beam is diagnosed with Faraday cups and with a double slit emittance measurement systems. Controls for the final machine are also discussed.

Introduction

The machine described in this paper is intended for use with a scaled Induction Linac Systems Experiment which is discussed in several other papers at this conference.^(1,2,3,4) The performance requirements dictated by this application are as follows:

Ion- C⁺
Ion Energy- 2 MeV
Current per Beam- 340 mA
Normalized Emittance per Beam- 5×10^{-7} π meter- radians
Number of Beams- 16
Pulse Length- 1 μ sec
Pulse Flatness- 0.1%

The actual design target for each beam is 500 mA though the matching section of the linac will not be capable of handling such a large current. The overall configuration of the injector is shown in Fig. 1. The pressure vessel is to be filled with a 30% SF₆- 70% N₂ insulating gas mixture at 65 psig. The 2MV generator is an inductively graded Marx generator. The accelerating column is made with 28 inch diameter alumina niobium-brazed modules. Two 18 inch long modules are required for the full 2 MV system.

were made to work for 2500 shots with 5 breakdowns at full charge voltage. The output pulse was approximately critically damped with a rise time (0 to peak) of 30 μ sec and a peak output voltage of 512 kV. The voltage was measured by monitoring the current through two 8 k Ω , 500 kV calibrated resistors in series which provide a dummy load for the generator. The reason for using such a slow pulse when only a 1 μ sec current pulse is needed, is the need to allow voltage equilibration to occur on the column electrodes before beam insertion, and to prevent voltage overshoot caused by stray capacitances between the column and the pressure vessel wall.

Subsequent to these tests, a new set of rings was constructed using stainless steel toroids as coil shields. In the same system, these rings worked without any breakdowns for about 2500 shots in the design gas mix and at full charge voltage.

Most recently, a ten tray subsection of the full generator was constructed to test operation at the 1 MV level. The tray and inductive ring designs were left unchanged. The vessel was filled with 90 psig dry air and the system was operated up to 1.2 MV terminal voltage without breakdown. Soon the system will be fired into an open circuit in order to ring the voltage up to the 2MV region. This will provide some early testing of the high voltage hold off capability in the existing pressure vessel.

Source Development

The source being developed for the injector is a three cathode carbon arc. The operation of the source has been described elsewhere.⁽⁵⁾ The plasma from the arc is restrained from filling the extraction gap by means of a planar electrostatic plasma switch which consists of two grids, the downstream grid being biased negatively with respect to the upstream grid. The negative grid defines a planar extraction surface for the ion gun, which prevents transient plasma meniscus effects from distorting the ion optics. The use of three

Fig. 1 2 MV Injector System

High Voltage Generator

The high voltage generator uses Marx technology with inductances distributed along the Marx to create a slow rise critically damped pulse. The inductances are 38 inch diameter coils which are shielded for breakdown protection. One inductive ring is located at each tray, as shown in Fig. 1, and provides a self inductance of 17 mH. A four tray (eight stage) subsection of the full eighteen tray system was constructed. Only the first four stages are triggered. A first design of the inductive rings which used aluminum spinnings to shield the 100 turn coils was tried and breakdown problems were encountered above 80% of the design charge voltage of 100 kV per capacitor. The breakdowns were mainly between the shields extending toward the center from opposite ends of a given coil. After considerable effort to refine the assembly of the system, these rings

cathodes is intended to produce a smoothly varying plasma by adding the plasmas from three randomly varying arcs. Streak photographs were taken of the luminosity of the three cathodes to determine whether the cathodes were igniting simultaneously. The cathodes are driven by a common pulse forming network and therefore must be ballasted. Two ballasting circuits were used for these measurements. One was a 4 Ω resistor in series with three 3 Ω resistors each of which went to a cathode. The second circuit was three 16.5 Ω resistors in parallel each going to a cathode. Both ballast schemes produced the 5 Ω load required by the PFN. The streak photographs showed that the 3- 16.5 Ω circuit produced more reliable triggering of the three cathodes and more temporally uniform firing. The maximum delay from the firing of the first arc to the firing of the last arc was 10 μ sec. This time is short compared to the normal 40 μ sec

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delay used between arc ignition and the firing of the beam extraction voltage pulse. The other circuit was checked because it had been used in another test setup with the source when good emittance data was obtained.⁽⁵⁾ The 3-16.5Ω circuit is used for the data which follows.

Fig. 2 Current Density From Three Arc Carbon Source at 350 A Arc Current.

The extracted current density from the source as measured with a gridless long Faraday cup is shown in Fig.2. The plasma switch mesh used for these measurements was a 200x200 stainless steel woven grid made of 1.6 mil wires. The geometric transmission of the grid is 46.2%. The theoretical emission curve is for a Child-Langmuir diode 1.29" in width with an 81% transmitting grid in the exit aperture to prevent beam defocusing. The data points are taken at 6 μsec after the start of the 11 μsec extracted pulse. The cup has a .25" diameter aperture and is located at the beam center. The emission surface of the planar extraction gap is 2.0" in diameter while the exit hole containing the 81% transmitting grid is 1" in diameter. The delay between the firing of the arc source and the firing of the extraction voltage pulse is 40 μsec and the plasma switch voltage is -80V. The data points lie quite close to the ideal curve. The current density shows no sign of saturation up to the voltage limits of our test system. The maximum current density obtained was almost 30 mA/cm², which after accounting for the exit grid absorption is equivalent to 37 mA/cm², compared to our design current density of 25 mA/cm². The total arc current used in these measurements was 350 A which is the maximum achievable with our pulse generator. It is desirable to keep the arc current, and consequently the arc energy, as low as possible to maximize the life of the source as well as to minimize the size of the arc pulsers needed for the complete injector. Subsequent to the experiments discussed above, we installed an electro-deposited copper mesh into the plasma switch to replace the stainless steel mesh mentioned above. This mesh is 250x250 with 0.6 mil conductor and is not woven. Its transmission is therefore 72.2% or almost 1.6 times as large as the stainless steel used above. It was not possible to get good plasma shutoff with the arc discharge current at 350 A because switch breakdowns started to occur before the plasma was fully shut off, so the discharge current was reduced to 200 A. The extracted current waveforms looked clean and the current density followed the Child-Langmuir slope without evidence of saturation up to 34 mA/cm² into the cup. When the arc discharge current was reduced to 250 A, the extracted current pulses became erratic with spikes appearing along the normal waveform trace.

The emittance of the source is measured in the same gun system used above with a double slit technique. The emittance plot for conditions corresponding to those of Fig.2 is shown in Fig. 3. The normalized emittance for this scan is 6.6×10^{-7} π m-radians which is comparable to previously obtained values for a 1" beam.⁽⁵⁾

Fig. 3 Emittance Scan for Three Arc Carbon Source at 350 A Arc Current.

This emittance is obtained by drawing an ellipse around the distribution and it corresponds closely to four times the RMS emittance. The extraction voltage was 68kV which puts the extracted current density at 22.5 mA/cm² on Fig. 2. There are two odd points in the scan. The first is a zero in the fourth vertical scan which is a true misfire of the extraction voltage pulse. The second is an "out of range" signal in the seventh vertical scan which is attributed to a plasma switch breakdown. Signals from the rest of the shots in the scan were normally shaped, reflecting the voltage pulse shape. A good scan was obtained using the copper plasma switch mesh mentioned above. The normalized emittance for this scan was 5.5×10^{-7} m-radians and was taken at 300 A arc current and -80 V plasma switch voltage.

At present the extraction system and the diagnostics have been modified to test 2" beams such as will be required in the injector. Langmuir probes have been constructed to measure the electron temperature and ion density as a function of position and time at the location of the plasma switch grid. This will provide guidance for the optimal design of the source. Another source with three widely separated and independently triggered cathodes has been constructed and will be tested soon.

Fig. 4 Acceleration Column Structure.

Acceleration Column

The column for accelerating the beam is shown in Fig.4. The electrodes for the first half of the column are presently being fabricated. Once completed, this half column will be used with the 1 MV generator and with a single, three arc source for 1 MV beam experiments. The electrodes are mounted inside 85% purity alumina brazed insulator modules which have been built and vacuum tested. Voltage grading of the column is accomplished with a double helix liquid (Na₂SO₄ in water) resistor which will provide the proper matching resistance for the inductive Marx so that a critically damped pulse will result. The source will be mounted on the left side of the

column and the associated electronics for firing the source will be located inside the high voltage dome partially shown on the left side of Fig. 4. The column focusses the beam by use of a set of aperture lenses formed by the double hole structures shown in the thick plate electrodes. These lenses also inhibit propagation of backstreaming electrons. The first electrode on the left has a grid in the aperture. This grid is the exit of a 9.8mm planar extraction diode. Once the acceleration voltage pulse has reached its peak, the source will be pulsed negatively with respect to this first electrode and the 1μsec current pulse will be injected into the column. The voltage between electrodes is 175kV with the exception of the first gap which is 69.4kV. The overall column length is 58 cm and the beam holes are 56 mm in diameter. At the end of the column is a 3" long cylindrical electron trap which produces a 900V barrier for electrons on axis. The beam exit divergences are -3 mrad for 340 mA and +6.9 mrad for 500mA.

Control System

Control philosophy will follow a highly distributed microprocessor-based architecture. Control implementation will track and make use of the work done by the Advanced Light Source Control group (see ref. 6). Initial elements of control will be largely external to the dome high voltage e.g. monitoring the water load regulating system and dome alternator data (frequency, output voltage). Eventually, status information for the vacuum and interlock systems would be monitored. The operator control will be a 386 based PC. The PC will access a remote microprocessor based controller card (ILC, Intelligent Local Controller) via a RS485 multidrop line. Later, ILC's will be added (at the high voltage level) to monitor and control the dome electronics. One would then for example, control anode pulser voltage level, arc current levels and bias voltages via light links bringing each ILC's data base into the IBM AT. Microsoft windows will be the basic operating environment. Graphics will be generated via Micrografix's Designer package. Control and monitoring will be exercised via ALS control software making use of commercial packages such as Excel. Communications between applications are via Microsoft's DDE (Dynamic Data Exchange) protocol. This control system can be extended later to follow the ALS control system architecture of which this is a subset. See this paper presented by the ALS group to the 1989 PAC conference (ref. 7).

References

1. C.G Fong, et al, Engineering Study of a 10 MeV Heavy Ion Linear Accelerator, Paper M11, this conference.
2. A. Faltens, et al, Acceleration Units for the Induction Linac Systems Experiment(ILSE), Paper M12, this conference.
3. D.L. Judd, et al, Concepts, Features, and Design of a 16 to 4 Beam Combiner for ILSE, Paper M13, this conference.
4. E.P. Lee, et al, Conceptual Design of Bend Compression and Final Focus Components of ILSE, Paper M14, this conference.
5. H.L. Rutkowski, et al, Progress on a 2-MV Injector for a Scaled HIF Accelerator Experiment, to be published in Nuc. Inst. & Meth., Proceedings of the International Symposium on Heavy Ion Inertial Fusion, GSI, Darmstadt, June 28-30, 1988.
6. The Conceptual Design Report July 1986 for the 1-2 GeV Synchrotron Radiation Source Pub-5172 Rev. and the Uranium Beams Project [Lancaster et al., 1979; Magyary et al., 1981a; Magyary et al., 1981b].
7. Advanced Light Source Control System; S. Magyary, M. Chin, C. Cork, M. Fahmie, H. Lancaster, P. Molinari, A. Ritchie, A. Robb, C. Timossi).

ENGINEERING STUDY OF A 10 MEV HEAVY ION LINEAR ACCELERATOR*

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Abstract

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

Introduction

Commercial inertial fusion (IF) offers an attractive long-term solution to the problem of future energy supplies. Of the several approaches to a commercial fusion target driver, a multigap heavy-ion driver has unique advantages in simultaneously offering repetition rate, electrical efficiency, reliability, and long stand-off focusing. Since 1983, the U.S. Heavy Ion Fusion Accelerator Research Program (HIFAR) has been assessing the multiple-beam induction linac as an inertial fusion driver. The approach includes a series of increasingly sophisticated experiments to explore, in a scaled way, the accelerator physics of the induction linac approach to a driver, to encourage and develop relevant accelerator technology, and to estimate the capital costs and potential economics of induction linac driven fusion power plants. Earlier experiments¹ have yielded significant results on the transport limits of intense ion beams. At present, the multiple ion-beam accelerator experiment² MBE-4 is examining the longitudinal dynamics of the electric-focused portion of an induction linac driver. In order to complete the HIFAR data base we have designed a sequence of experiments that collectively are called the Induction Linac Systems Experiments or ILSE. The selection of experiments is derived from the requirements for a driver as developed in the recent HIFSA study³ of induction linac driven IF for commercial energy production. While ILSE will initially use C^{++} ions (Al^{++} may be used later), most of the results will be scalable to ions with different charge-to-mass ratio such as the mass 200 charge state $+3$ ions in the HIFSA driver. A report of the conceptual engineering study of the ILSE experiments is contained in reference 4.

ILSE Description and Design Development

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

Fig. 1. ILSE block diagram

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

Table 1 Some ILSE Parameters

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

This design was developed with the aid of the INDEX induction linac code.⁵ From the initial beam parameters, this code applies the current amplifying acceleration theory⁶ to calculate the accelerating voltages that will preserve a self-similar current waveform through the acceleration and transport sections of the experiment. In developing the design, the matched beam radius was limited to approximately one-half the quadrupole aperture to allow for envelope oscillations that may occur.

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

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

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Fig. 2. ILSE plan view.

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

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

which is generated by an inductively graded Marx bank, is applied to the column electrodes with a $34 \mu\text{s}$ rise time. An electron trap at the end of the column prevents electrons created by ionization of background gas from being accelerated toward the source. The acceleration column itself consists of a series of aperture lenses that focus the beam and help prevent backstreaming electrons from achieving high energy. The status of the development is the subject of the paper⁷ by Rutkowski et al.

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

The electric focused accelerator section of ILSE is arranged into three major cell blocks, each consisting of eight electric quadrupoles and seven accelerating cells spaced at half-lattice-periods from 45 to 50 cm as shown in Fig. 3. Each cell contains two induction cores stacked radially and driven by carefully shaped 150 kV pulses. The eighth half-lattice-period contains smaller cores for correction pulsers that compensate for unavoidable waveform synthesis errors and provide longitudinal bunch control. The magnetic focus accelerator section of ILSE consists of five accelerator cell blocks, each block contains eight quadrupole arrays and seven accelerator cells distributed over half-lattice-periods. The lattice half period ranges from 50 to 60 cm and space is available to allow two accelerator cores to be arranged axially. The eighth position of each cell block is used for vacuum pumping, current diagnostics and focus/correction core as in the electric focus accelerator. A typical 50 cm cell block is shown in Fig. 4. A full lattice period at the end of this section is used for diagnostic access. More complete details on the designs for the accelerator units is contained in the paper⁸ of Faltens et al.

A key experiment in the ILSE sequence is the transverse beam combining or merging of 16 beams to 4. This is a step in complexity towards the 64-to-16 beam combiner in the IIFSA driver concept. Most important, however, it will be the first experiment of its kind ever undertaken with space-charge-dominated beams where collective phenomena play a decisive role. The paper⁹ of Judd et al. details our physics and engineering designs of this experiment.

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

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

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

Details of the conceptual design of the ILSE bend, drift-compression and final focus sections are presented in the paper¹⁰ of Lee et al.

System Wide Considerations

To eliminate the need for downstream steering in ILSE requires that each electric quadrupole be aligned to ± 0.1 mm. Since the beams are larger in the magnetic focus accelerator and downstream of the combiner, the positional tolerance of the magnetic quadrupoles could be set at ± 0.25 mm. These tolerances were driven by the accurate beam positioning needed for a successful combiner experiment and by the beam positioning and emittance limits needed for a successful final focusing experiment. Our approaches to these accelerator alignment issues are detailed in the companion paper⁶ of Faltens et al.

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

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

Conclusions and Further Developments

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

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

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

References

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

ACCELERATION UNITS FOR THE INDUCTION LINAC SYSTEMS EXPERIMENTS (ILSE)*

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Abstract

The design of a high current heavy ion induction linac driver for inertial confinement fusion is optimized by adjusting the acceleration units along the length of the accelerator to match the beam current, energy, and pulse duration at any location. At the low energy end of the machine the optimum is a large number of electrostatically focused parallel beamlets whereas at higher energies the optimum is a smaller number of magnetically focused beams. ILSE parallels this strategy by using 16 electrostatically focused beamlets at the low end followed by 4 magnetically focused beams after beam combining.¹

Electric Focusing Section

At low beam speeds electric focusing systems are less costly and can transport more current than those with magnetic focusing. Our studies show that the first 100 MeV or 400 m of acceleration in an induction linac driver will most likely use electric focusing. The total current per beam will be determined by the strength of the focusing voltages that can be used without breakdown and by the accuracy by which the focusing elements can be positioned. The maximum beam velocity tilt occurs in the electric focused portion. The IIFAR program has considerable experience in transporting space-charge-dominated cesium beams using electric focusing in the Single Beam Transport Experiment² and the MBE-4 experiment.³

For ILSE, the electric focusing initiated in the matching section is continued as the beams are accelerated from 2 MeV to 4 MeV through 21 accelerating cells. The basic unit of length is the half-lattice period (IILP) which takes different values along the machine. Focusing arrays and acceleration gaps are arranged in cell blocks consisting of groups of eight IILP lengths, with the eighth cell used for acceleration correction core, vacuum pumping, diagnostics, and a beamline bellows. In the first two cell blocks the IILP length is 45 cm; in the third the IILP is 50 cm.

The focusing electrode assembly is shown in Fig. 1. The focusing fields occupy about half of the IILPs. Electrode dc voltages range from ± 19 kV at the beginning of the electrostatic-focus accelerator to ± 34 kV at the end, based on quad apertures which are chosen to be twice the matched beam radius. The feed-throughs are similar to those used on MBE-4 at up to 80 kV. MBE-4 is built in such a way that all its focusing electrodes are mounted and located with respect to the vacuum vessels, which are in turn machined accurately and then assembled with the acceleration insulator and aligned to the accuracy required for the electrode assemblies. This method of construction has several drawbacks: 1) it is not kinematic - vacuum loads and temperature variations can affect the electrode array positions, 2) it has more, and larger, components that require precision machining, 3) its tolerance stack-up leads to larger positional errors, and 4) there is no provision for realignment of the individual electrode arrays after installation.

The approach taken in the present ILSE design is to provide separate support for the electrode arrays, vacuum vessels, and induction cores, since they each have very different positional tolerance requirements. The focusing electrode arrays, installed in grounded quad-cans inside the vacuum vessels, are supported by an articulation system that uses constant-force tension members with manual positioning devices to adjust the arrays' position and alignment. The quad-cans are tangentially supported by tension members through bellows feed-throughs in the vacuum vessel wall to the precision positioning actuators on the support structure. The system of support tension members and actuators provides control of x and y or transverse position, along with pitch, roll and yaw

rotations, of the quad-cans. Position along the accelerator axis is controlled by having the tension members angled slightly along the z-axis. Measurement of the electrode array position is done by using offset rods of a stable, low coefficient-of-thermal-expansion material such as Invar to accurately transfer the electrode position to the alignment system. This allows the determination of transverse position and all three rotations of each electrode array. The accelerator gap is located between each quadrupole set. Accelerator core is segmented and arranged radially to accommodate both the quadrupole support, its ancillary hardware, and the accelerating gap.

The vacuum vessel is a stainless steel weldment with nozzles for quad-can supporting tension members, alignment transfer rods, and high voltage feed-throughs. All vacuum flanges are sealed with Viton O-rings. Each cell's vacuum vessel is supported from the structural frame independently from the focus electrode array and can be positioned during assembly. Vacuum loads on the vessel will not impact quadrupole alignment. Between each focus electrode the accelerating gap vacuum boundary is formed by a ceramic insulator spool incorporating welded bellows at each end. After eight half periods, or cells, are assembled into a cell block, tie bars running the length of the cell block will tie the support frames of the individual cells into a monolithic structure with high bending stiffness. The assembled cell block is shown in the companion paper by Fong et al.

The performance requirements for these quadrupoles demand high field quality. The position of the center of electrostatic field is dependent on the dimensional accuracy of the various components of the quadrupole assembly. Field quality depends on a number of factors such as uniformity of electrode diameters, beam to beam and electrode to electrode spacing, as well as parallelism of electrodes. Small manufacturing errors may result in large cumulative beam oscillation.

ILSE's quadrupole arrangement for 16 beams calls for a total of 25 electrodes with 13 electrodes supported from one quad-plate and 12 electrodes supported from an opposite quad-plate. The 16 beam holes are in a 4 x 4 arrangement with center to center distance between two adjacent holes of 70.28 mm. The length of the electrode is such that the product of voltage and length in inches is ≤ 330 kV inches.

The quadrupole assembly is divided into three subassemblies: the positive quad-plate assembly, the negative quad-plate assembly, and the inner quad-can. Each quadrupole plate (approximately 1-cm thick) contains electrode fingers and 16 beam holes. The quad-plates are separated by a fixed distance of 25.4 cm with 1-cm clearance all around the plate and electrodes. The plates are individually anchored through four ceramic insulators with the inner quad-can body. The inside dimension of the grounding quad can is accurately machined and the mounting brackets are precisely located so that the fixed distance between the quad-plates are automatically maintained when assembled. To obtain a high degree of accuracy, the quadrupole assembly will be a bench operation assisted by a coordinate measuring machine. The quad-can will have openings for high-voltage feed-throughs to the respective plates. The alignment hardware is attached to the outer surface of the quad-can.

To approach the overall electrostatic quadrupole alignment criterion of ± 0.1 mm (± 0.004 in.), manufacturing tolerances of piece parts must be very tight. Thus a total fabrication tolerance or error budget for the 16-beam quadrupole assembly must not exceed ± 0.05 mm (± 0.002 in.). Tolerances for quadrupole piece parts such as electrodes, base plates, electrode insulators, and quadrupole mounts to the inner can must be specified not to exceed ± 0.003 mm (± 0.0001 in.) each. Achieving such tolerances presents a significant manufacturing challenge. One approach is conventional CNC

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machining of piece parts, which would be assembled with jigs and fixtures as previously discussed. Fabrication tolerances approaching ± 0.003 mm are attainable. Verification of critical dimensions for piece parts and assemblies will be performed by a coordinate measurement machine. Another manufacturing approach employs state of the art super-plastic forming. Though development and tooling intensive, this approach is feasible for a production run of over 30 quadrupole assemblies. In either manufacturing approach excellent surface finishes are anticipated.

Each quadrupole array will be connected to a single adjustable ± 50 kV dc bipolar power supply. Commercially available single ended voltage-stabilized power supplies will be used in a bipolar configuration. For these supplies typical stability is 0.05% over an 8-hour period, with a tracking error between the positive and negative outputs of less than 1%. The output voltage can be monitored either locally or remotely using the low level dc voltage from the supply. The ion beam passing through the apertures of the quadrupole will induce a current flow that will tend to affect the required focusing voltage. This will be minimized by a low impedance bypass circuit with a capacitor.

Magnetic Focus Accelerator

As the beams pick up speed and energy, the current that can be transported by an AG focusing system increases. However, the focusing voltage for an electrostatic quadrupole transport system tends to increase with energy until at some point it becomes impractical to transport the beams with electric focusing. Near this point the transport system switches to magnetic quadrupoles and the beams are combined four-to-one. Therefore, the magnetic focus system must be able to transport four times the current at the same energy as the electric focus system at the point of change, 4-MeV for a carbon ion (similar to 100 MeV for a uranium ion in a driver). The four beams emerging from the combiner are rematched and inserted into the remainder of the accelerator in individual magnetically focused channels all threading common accelerating cores. This section is configured into five cell blocks of eight magnetic quadrupoles and seven accelerator modules with one diagnostics module. Current-dominated pulsed quadrupoles are used. The accelerating cells each contain two cores and one graded ceramic acceleration gap insulator. Two half-periods without acceleration at the beginning of this section of ILSE provide diagnostic access.

The magnetic focus section of ILSE accelerates the four 4-MeV beams from the combiner to 10 MeV. Two of the five cell blocks have a 50-cm IILP while the balance of cell blocks have a 60-cm IILP. In all sections, the magnetic quadrupoles occupy 28 cm. Since the alignment criterion is not as demanding as that for the electrostatic sections, the four current-dominated quadrupoles located at each IILP are supported and articulated from a common support. This approach allows maximization of core volume and allows the magnetic quadrupoles to be in air. The four beam tubes and tube end sheets that constitute the vacuum chamber are placed inside of each focusing element array. Each beam tube is fitted with a bellows for compliance because alignment of the beam tubes is not critical. Beam tubes are assembled sequentially along with the acceleration gaps.

Cosine 2 θ current-dominated magnetic quadrupoles are used to focus ILSE's ion beams from the combiner through the bend section. In the bend section, quadrupole and dipole fields are combined in dual purpose magnets due to constraints in axial space and the need for independent control of focusing and bending fields. Current-dominated magnets are used in a pulsed mode to allow high current densities. This decreases the dimensions of the required conductor bundle. The use of smaller conductors also facilitates bending the conductor at a sharp angle at the ends of the coil to minimize end-field problems. Further field tuning is based on deviating from the cosinusoidal distribution by just enough to cancel the effects of the unequal length turns in the integrated fields through the magnet. The coils are in two layers and are connected in series. Four quadrupole magnets can typically be driven by one pulsed power supply in a series configuration.

A closely fitting laminated silicon steel yoke is used to return flux around the outside of the coils without saturation. This nearly

halves the drive current requirements, isolates the magnetic fields, shields multiple beams from each other, and attenuates the end fields in a desirable manner. In a cosine 2 θ design, essentially all of the flux in the return yoke is from the fields in the aperture, due to the minimal thickness required for the conductors and insulation between windings. Consequently, only a thin return yoke is needed. The orientation of adjacent magnets here is such that the poles face each other. Consequently for a symmetric design the maximum flux occurs 45° away from the poles. This makes it possible to trim off some of the steel in the region of the poles for either of the possible field polarities, allowing closer packing of the four magnet array.

Two-dimensional field computations of this geometry including the magnetic properties of the silicon steel have been performed using the program POISSON. The symmetries of the fields allow the computations to be performed on a single octant. The asymmetry caused by each magnet having two poles near neighboring magnets and two poles facing free space, produces a shift of the magnetic center by only about 0.025 mm. In these magnetostatic two-dimensional computations, the amplitudes of the vector potential for the higher multipole components have been generally less than 1% of the amplitude of the quadrupole potential. The real three-dimensional problem has been approached by first calculating the three-dimensional fields with the program MAFCO in the absence of the steel yoke, with the conductor positions adjusted azimuthally to compensate for the varying conductor lengths at the ends of the turns. If, for such a solution, the yoke were positioned immediately next to the conductors, then the image currents in the steel would produce an identical field, provided the steel extends far enough axially to be considered to be infinitely long. In the ILSE design a steel overhang of 3/4 of the aperture radius is adequate for these end effects.

Pulsed magnet operation will generate eddy currents in the thin-walled stainless steel beam tube, but they will not noticeably affect the ion beams. The eddy currents for a quadrupolar external excitation have a decay time constant of about 30 μ s. The 1 ms magnet drive current pulse with a half-sine waveform is long compared to this decay time. The 1 μ s ion beam pulse occurs near the peak of this current, when the field change from the changing current is insignificant, and the eddy currents in the beam tube have decayed to very low values. The repetition rate is 1 pulse every 12 seconds. Individual quadrupole windings and the sets of four adjacent quadrupole magnets in the magnetic focus section are arranged in series and will be driven by a single capacitive-discharge power supply. This power supply will deliver up to 13.7 kV with a stability of $\pm 0.05\%$ over 8 hours. Individual quadrupole voltages will be set either locally or integrated with the control system. A current transformer will provide magnet current data. The pulse width is determined by the circuit tuning relationship of total load inductance and the selected value of energy storage capacitance. At the end of the current pulse, a voltage reversal of about 60% of the charge voltage will occur across the energy storage capacitor. Energy recovery is then attained by triggering the second switch with a recovery choke. Silicon-controlled rectifiers or ignitrons are used for switching.

Induction Cores and Pulsers

In ILSE, 56 accelerating cells will accelerate beams from 2 to 10 MeV. In a full-scale induction linac driver, over 1000 accelerating cells will be needed to produce beams at 10 GeV. Compared to ILSE's requirement of up to 120 metric tons of core material, a IILF driver would require over 10,000 tons, which would represent a significant fraction of the overall cost. The need for inexpensive and efficient core material used in an optimum geometry and low cost accelerator pulsers becomes apparent.

The "ideal" waveforms at each gap for the ILSE point design were specified by the INDEX accelerator code. These are initially triangular and rise to 150 kV at 1 microsecond. After the tails of the beams have entered the accelerator, the waveforms become more rectangular. As the current amplifies and the pulse duration shortens, the accelerating voltages rise to 180 kV and the pulse shortens to approximately 0.3 μ s in the downstream portions of the accelerator. To engineer these waveforms, additional induction core must be provided for the rise and fall of the pulses. Our estimates indicate

alignment of the finished assemblies on the beamline. The alignment system is the weakest link at this time, but is upgradeable.

The current amplification, longitudinal dynamics, and longitudinal control of the beams as they pass through the accelerator must be provided by these accelerating waveforms. As a consequence, they must be rather accurately synthesized. The beams in traveling through the accelerator integrate the acceleration waveforms and any associated errors. However, these errors can not be allowed to accumulate over distances much longer than the length of the beam bunch. Experience with MBE-4 suggests that the total acceleration error, during the beam pulse, should not exceed approximately 1% over the length of the accelerator. Errors are particularly significant at the beginning of the accelerator. To satisfy these criteria at reasonable cost, the individual pulsed will be designed to provide accelerating waveforms within $\pm 5\%$ of the "ideal" during the time the beams are present. A fast correction pulser with induction core between cell blocks will be used to compensate for the errors accumulated by the previous seven accelerating waveforms so that the integrated error remains less than 1%.

Induction Cores

Allied Signal Corporation Metglas® material appears to have the best characteristics when considering core and pulser cost. Metglas is cast directly into a thin ribbon without subsequent rolling operations, has a relatively high resistivity, and is capable of magnetic flux swings up to 2.5 T. Because eddy current losses in an induction core are proportional to t^2/p where t is the ribbon thickness and p is the resistivity, Metglas losses are greatly reduced over silicon-iron, nickel-iron or carbon steel. Therefore, Metglas cores substantially reduce drive power requirements and costs for the associated pulsing system. Because overall costs and efficiency are pivotal considerations for drivers, comparisons between Metglas and less expensive ferromagnetic materials definitely favor Metglas. Fig. 2 shows a core arrangement in the magnetically focused part of ILSE.

The ILSE Alignment Systems

The requirements of hitting a small focal spot in a driver, and the desire to accurately position the beams in the ILSE combiner place stringent requirements on the beam transport system. The situation is exacerbated by the difficulty in providing time-dependent steering within the beam pulse duration. The desired accuracy of locating the quad field centers is due in part to the manufacturing and assembly accuracies as already discussed, and in part to the

The alignment system hardware for ILSE has been selected based on the best currently available demonstrated technology with consideration of cost constraints. This system will use quadrupole fiducial references with a conventional computerized theodolite surveying system to x and z coordinates, and a water level system for y coordinates. Both systems are referenced to building monuments. Expertise in current theodolite technology is being developed in LBL's Advanced Light Source project. Theodolites will provide ± 0.004 to 0.006 inches of resolution based on a manufacturer's specifications of ± 1 arc second. This system may be upgraded with the addition of interferometric distance measurements which would complement the angular data provided by the theodolite system. ILSE's water level system will build on the experience of the SLAC PEP storage ring, whose water level system was designed at LBL. In this case, various upgrades are possible, both in terms of accuracy and convenience in use. Finally, space and fiducials will be provided for a straight-line optical reference beam of some type. In its simplest form, this could be a fixed theodolite scope with drop-out targets in an enclosure tube. This would be upgradeable to a laser in vacuum beamline using photosensor quads, half-wave plate cross-hairs, zone plates, or Poisson spot techniques.

References

1. See the companion papers in these proceedings:
C. G. Fong, T. J. Fessenden, R. L. Fulton, and D. Keefe, "Engineering Study of a 10 MeV Heavy Ion Linear Accelerator."
D. L. Judd, C. Celata, E. Close, A. Faltens, K. Hahn, K. La Mon, E. P. Lee, L. Smith, and W. Thur, "Concepts, Features, and Design of a 16-to-4 Beam Combiner for ILSE."
E. P. Lee, C. Fong, S. Mukherjee, and W. Thur, "Conceptual Design of Bend, Compression, and Final Focus Components of ILSE."
2. W. W. Chupp, A. Faltens, E. C. Hartwig, D. Keefe, C. H. Kim, L. J. Laselti, R. Nemetz, C. Pike, S. S. Rosenblum, J. Shiloh, L. Smith, M. Tiefenback, and D. Vanecek, "A Quadrupole Beam Transport Experiment for Heavy Ions under Extreme Space Charge Conditions," IEEE NS-30, No. 4, Aug. 1983, p. 2549.
3. R. T. Avery, C. S. Chavis, T. J. Fessenden, D. E. Gough, T. F. Henderson, D. Keefe, J. R. Meneghetti, C. D. Pike, D. L. Vanecek, and A. I. Warwick, "MBE-4, A Heavy Ion Multiple-Beam-Experiment," 1985 PAC, IEEE NS-32, 1986, p. 3187.

Fig. 1 Electric Quad Array

Fig. 2 Magnetic Focus Accelerator Cell

CONCEPTS, FEATURES, AND DESIGN OF A SIXTEEN-TO-FOUR BEAM COMBINER FOR ILSE*

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Abstract

Sixteen intense parallel ion beams are to be transversely combined into four by dispersionless double bends. Emittance growth due to electrostatic energy redistribution and to the geometry is evaluated. Most bending elements are electric, and alternate with AG electrostatic quadrupoles similar to those upstream. The final elements are magnetic, combining focusing and "unbending". Electrode shapes and pulsed-current arrays (having very small clearances), and mechanical and electric features of the combiner, and described.

Introduction

Studies of induction linacs as ignition drivers for inertial-confinement fusion power plants show that many parallel ion beams are desirable at lower energies but that after some acceleration fewer beams are less costly. Therefore, we want to study and demonstrate transverse combining of ion beams. This process will inevitably increase total transverse emittance, which must not grow too much to meet target spot focusing requirements. Beam loss, which is inefficient and could cause much trouble, must also be minimized. The beams are intense; transverse space charge force cancels most of the strong external quadrupole (AG) focusing which would produce a single-particle phase advance of 60° to 85° per period. There is no experience in the efficient combining of such beams.

Design of the ILSE (Induction Linac Systems Experiment) facility (see adjacent papers M11, M12, M14) has been strongly influenced by the requirement for a beam-combining experiment. An injector, previously specified (paper M10), will provide a four-by-four square array of sixteen C^+ beams at 2 MeV with a lattice spacing of 7.03 cm. They are accelerated to about 3.2 MeV (bunch head) and 4.8 MeV (bunch tail), with linearly varying velocity "tilt" of about 20% from head to tail, while being contained transversely by AG electrostatic quadrupole fields. Groups of four adjacent beams are then combined into four final beams, emerging at the corners of a 14-cm square into four channels for magnetic quadrupole focusing and further acceleration.

Combiner Requirements

Each group of four beams to be combined must have their axes displaced by double bends to new positions parallel to the original ones but closer together, providing a closely packed pattern of four beams which become one on leaving the combiner. These double-bend systems must be dispersionless to accommodate the velocity tilt. The dipole bending-field regions must alternate with quadrupole regions to continue the upstream focusing so as to avoid beam expansion from diminished containment. To minimize emittance growth (transverse phase space density dilution) these beams must be brought as close together as possible, which requires very thin septa between them at the final stage. Further, because of the characteristic "shape throbbing" of AG-focused beams, as these beams converge at small angles they tend to get in each other's way. To deal with this, combined-function elements are needed at the end which superpose the final focusing quadrupole fields and the final "unbending" dipole fields rather than arranging them in tandem. The design, described below, to meet these requirements is based on K-V beam distributions plus a minimal allowance for more realistic beam "shoulders", with the expectation that aberrant ions in more distant (and hopefully very faint) halos can be scraped off in a judicious manner.

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Emittance Growth¹

When four close-packed original beams emerge from the combiner into a common focusing channel, the spaces between them fill with particles, forming a single elliptical beam. In accelerators with beams of negligible space charge (e.g., high energy physics accelerators), single particle orbit motion due to the external focusing forces would fill these spaces, causing the cross section of the beam to increase and thereby raising the emittance. In heavy ion fusion accelerators, however, the large repulsive space charge forces between particles cause them to move into the gaps between beams on a much shorter time scale. The decrease in electrostatic field energy stored in the beam due to this decrease in charge density becomes transverse kinetic energy. Thus there is a second increase in the emittance, due to the increase in transverse temperature, that is not seen in accelerators with less intense beams.

The growth in transverse emittance due to combining is important to consider when designing a heavy ion fusion power plant driver, since the transverse emittance at the end of the accelerator limits the minimum radius of the spot to which the beam can be focused. Present calculations and source characteristics imply that the emittance can be allowed to grow between the source and the target by a factor of 10 to 100 in a driver, before the ability to focus the entire beam on the target is compromised. Our calculations indicate that the overall emittance growth expected is sufficiently small that at least one combining operation can be considered for a heavy ion fusion driver.

Computer simulations and analytical estimates have been used to calculate the emittance growth expected from the ILSE combiner and from a combiner in a driver. These show that the ILSE combiner models a driver well in that the magnitude of the emittance growth expected and the influence of space charge forces on the emittance growth are similar to the case of the driver. Fig. 1 shows analytical results for four-to-one beam combining at ILSE and at driver parameters. Though the computer simulations include the major effects to be found in a combiner, including a self-consistent calculation of the space charge forces, they cannot model exactly the influence of either image forces due to nearby conductors or aberrations of the external focusing and bending fields on the beams. Moreover, the spacing of the actual beams as they emerge from the combiner can only be estimated until the combiner hardware is built and tested and a beam propagated through it. This spacing is crucial in determining emittance growth.

Fig.1 Emittance ($4 \times$ rms) grows for 3 mm beam-edge spacing, from methods of Ref. (1).

Fig. 3 Successive beam spacings and cross-section shapes in one quadrant.

Description of the Design

In the ILSE combiner each beam's axis is displaced by a double-bend system comprising, in sequence: full bend, full unbend, drift, drift, half bend, drift, and half unbend (see Fig. 2). These regions alternate with the quadrupoles of a focus-drift-defocus-drift (FODO) lattice with 50 cm half-period and single-particle phase advance of 60° per period. The combiner length is three full periods, or 3 m. All dipole and quadrupole fields are electrostatic except the final combined-function units mentioned above, which have pulsed magnetic fields. The succession of beam spacings and cross-section shapes for one quadrant of the sixteen-beam pattern is shown in Fig. 3.

Fig. 2 Displacement and dispersion curves.

The velocity tilt imparted to the ion bunch by the upstream accelerating section causes the ion bunch head and tail to be deflected by differing amounts in the dipole fields. This dispersion must be accommodated within the combiner by sizing the beam apertures to avoid beam scraping of the head and tail of the bunch. The most notable feature of this design, however, is that the bend/unbend sequence is arranged in conjunction with the quadrupoles to minimize final beam dispersion. It has been possible to produce a collimated final beam pattern with no significant positional or angular dispersion. Bunch head, tail, and center all exit with the same displacement (in linear approximation) from the original beam axis, as shown by the dispersion curve in Fig. 2.

The final element must unbend the converging beams at the last moment to produce a set of parallel exiting beams. Furthermore, in order to produce an optimal close-packed exiting beam pattern (last section, Fig. 3), the beam cross sections must attain maximum eccentricity at the same time that they are being unbent from their converging trajectories. Since maximum eccentricity occurs at the midpoint of an ordinary focusing quadrupole, the final element must be a special half-length quadrupole, combined with the superimposed dipole field.

Combiner Hardware

The actual ion beam bend angles in the combiner are small (about 45 milliradians, or 2.6 degrees). Constant cross sections are used and a beam-clearance allowance is maintained. Two-dimensional field calculations have been used to examine quantitatively the field nonuniformities resulting from postulated electrode geometries and voltages. In this process, a harmonic expansion is fitted to the values of the field potential at a reference beam radius. The desired pure quadrupole and dipole fields correspond to the lowest order terms of the expression, and the coefficients for the unwanted higher order terms give a quantitative measure of field quality.

Working within the spatial constraints of the converging beams, it has been possible to devise electrode geometries that limit the unwanted higher order field components to a few percent of the fundamental quadrupole or dipole component. This task becomes increasingly difficult as one progresses through the combiner, and one or two auxiliary electrodes at intermediate voltages are used to shape the fields in the last six elements. Fig. 4 illustrates such a quadrupole design for the central region of the combiner and shows the corresponding field analysis, and Fig. 5 illustrates the rounded-rectangle electrodes needed to produce the bending fields.

Fig. 4 Quadrupole electrodes and equipotentials.

Fig. 5 Dipole electrodes and equipotentials.

Individual electrodes will be shaped from solid stainless steel using computer-controlled machining and hand-lapping. Electrodes are mounted to base plates and thence to vacuum-vessel segments. A coordinate measuring machine will be required for proper bench alignment of these components relative to fixed reference surfaces on the outside of the vessel segments.

The final combined function elements must superimpose the required quadrupole and dipole fields. The combiner design dictates that these elements be short, with an effective length of 8.3 cm. Beam-to-beam spacing at this point is that of the smallest feasible close-packed pattern, and is nominally 3 mm. While it is possible to create the required electrostatic fields for this element with a number of very small electrodes at varying voltages, this is not favored because of the anticipated difficulty of maintaining the required voltages in the presence of minor beam scraping. Instead, a magnetic quadrupole/dipole design is used that positions only electrical winding conductors and minimal iron core material in the thin septum areas between the beams (see Fig. 6). Although scraping of beam

Fig. 6 Combined-function pulsed magnetic module.

halos will take place at the septa between beams, 5 mm of additional beam clearance is provided on the outboard sides of each aperture. This clearance will accommodate the beam entry angle, the rounder entry cross section, beam dispersion, field nonuniformities near the wall, beam halo, and the $\pm 0.1\text{-mm}$ ($\pm 0.004\text{-in.}$) alignment tolerance. It will also allow experiments with small converging exit angles.

Pulsed magnets and laminated iron cores within ILSE's vacuum chamber create two problems: First, the laminated structure has a very large confined surface area, and represents a high vacuum pumping load. This is minimized by spacing the individual iron laminations to provide pump-out space between them. A one-third iron density ratio is adequate for the calculated magnetic fluxes, except in the thin septum areas, where additional laminations are used. Second, the pulsed operation of the magnet windings will generate a heat load within the vacuum chamber. Although the low duty cycle (1 millisecond every 12 seconds) produces an average power dissipation of only 8 watts, the magnet is in a vacuum environment, which will cause its temperature to rise significantly with extended use. If radiation were the only heat transfer mechanism, a calculated temperature rise of 27°C would result. With a heat sink design for conductive heat transfer to the vessel wall, an approximate 5°C temperature rise is calculated. However, to minimize thermal distortions and their detrimental effects on the alignment of the element, a simple water cooling system is planned.

Beam diagnostic instrumentation will be located before, after, and within the combiner section, allowing emittance measurements with a movable slit and a beam profiling harp diagnostic. Each drift region has a diagnostic access port with grounded beam-aperture plates and accurately located diagnostic track mounts. The diagnostic ports also allow for auxiliary beam-steering dipoles, if necessary.

The 11 electrostatic quadrupole and dipole assemblies in the combiner section will each use an adjustable bipolar 50-kV dc power supply with voltage sustaining capacitors. In six of the 11 assemblies, auxiliary electrodes running at intermediate voltages are used for field shaping. An external resistive voltage-divider circuit with sustaining capacitors will be used to provide the required auxiliary voltages without need for additional power supplies. The final four magnet assemblies will require 16 separate pulsed power supplies of about 200 V and 100 A for individual control of the dipole fields.

Distributed vacuum pumping access is provided by 8-inch diameter pumping ports at each of the seven diagnostic-port box sections, with two additional 10-inch pumping ports located in the circular sections of the vessel structure.

Reference

1. C. M. Celata, A. Faltens, David L. Judd, L. Smith, and M. G. Tiefenback, *Proceedings of 1987 IEEE Particle Accelerator Conference*, p. 1167 (1987).

Fig. 7 Combiner side view showing diagnostic access boxes in drifts.

CONCEPTUAL DESIGN OF BEND, COMPRESSION AND FINAL FOCUS COMPONENTS OF ILSE*

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Abstract

The Induction Linac System Experiment (ILSE)⁽¹⁻³⁾ includes a 180° bend system, drift compression line and a final focus, which test the analogous features of a heavy ion driver for inertial fusion. These components are novel in their transport of a space-charge-dominated ion beam with large head-to-tail velocity tilt. Their conceptual design is presented, including calculations of the beam envelope, momentum dispersion, and engineering design of magnets, vacuum system, diagnostics, alignment, and support.

Bending High Current Beams

Present concepts for a heavy ion fusion driver require the ability to bend high current, high energy heavy ion beams in order to orient them to a reactor configuration. This requirement is complicated by a variation of ion velocities within a single beam on the order of 5%. ILSE's 180° bend section, located immediately following the magnetic focus acceleration section, is designed to deflect a single 10-MeV, 3.8-A carbon-ion beam with a 7.7% velocity tilt through a bend with mean radius of 4.0 meters. This bend section also functions as the initial portion of ILSE's drift-compression section. The objective of the bend section experiment is the study of high current ion beam bending with the goal of minimum beam loss and emittance growth.

The bend section consists of 23 beam-focusing quadrupole magnets in the 60-cm half-period lattice established in the upstream magnetic-focus acceleration section. An additional set of 23 magnetic dipole fields are used to deflect the beam through a total angle of 180° as shown in Fig. 1. Unlike the combiner section,⁽³⁾ it is not possible to use separate quadrupole and dipole fields because axial space is limited. Instead, combined-function current-dominated magnets are used, with separately controlled quadrupole and dipole windings sharing a common iron yoke. As in the combiner section, the beam bending sequence is designed to accommodate beam dispersion within the bend section while producing a final beam output with no significant dispersion.

Ion beam dispersion can be thought of as a systematic shift of the beam away from the design trajectory as an ion bunch passes a given location within the bend section. It is caused by the velocity tilt imparted to the ion bunch in the initial stages of acceleration; that is, in passing a given location, the tail of the bunch is moving considerably faster than the head of the bunch. This velocity tilt results in an axial bunch compression, which is an essential feature for ion current amplification in ILSE. In the bend section, however, it also causes the head and tail of an ion bunch to be deflected by differing amounts in each dipole field. The head and tail of the ion bunch thus follow off-axis trajectories that would continue to diverge through the bend system if it were not for the net restoring force of the periodic focus/defocus quadrupole fields. With careful design, the off-axis positions of the head and tail of the ion bunch can be made to oscillate about equilibrium displacements off the design axis as they pass through the bend system.

The bend section's matched dispersion is plotted in Fig. 2. A notable feature of the physics design of the bend section is that bending is initiated and terminated gradually, thereby avoiding overshooting the equilibrium displacements from the central axis and minimizing the maximum dispersion that must be accommodated in the beam tube. This is accomplished by a strategic variation of the strengths of the first four and the last four dipole fields of the bend section. The head, tail, and intermediate portions of the ion bunch will exit from the bend section almost on-axis. The small remaining angular deviations from the design axis are accommodated by the beam aperture size in the following drift-compression section. If necessary, the small residual dispersion could be further reduced

with time-dependent steering dipoles inserted in one of the diagnostics ports immediately following the bend section.

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Fig. 1 Bend section plan view.

BEAM DIAMETER: 4.0 cm.

APERTURE: 11.0 cm.

XBL 893-919

Fig. 2 Beam Dispersion in 180° Bend

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ILSE's tight bend radius of 4.0 m drives several design parameters near their limits. With a 60-cm lattice half period and a large 2/3 field occupancy, the required dipole field is 0.62 T, upon which is superimposed a 0.10 T/cm quadrupole field. With a magnet iron aperture of 15 cm, total field strengths of up to 1.4 T occur, which approaches the saturation limit of the iron. After adding minimal iron laminations to the magnet ends to control fringe fields, each magnet is 52 cm long, leaving a gap of only 8 cm between magnets to allow access for vacuum pumping, diagnostic instruments, and beam tube joints.

Although radial space is not a serious constraint in the bend section, conventional iron-dominated magnets cannot be used due to the requirement for independently adjustable, superimposed quadrupole and dipole fields. A current-dominated design with independent cosine 2θ quadrupole and cosine θ dipole windings is planned. Each bend section magnet weighs about 700 lb and is mounted in a structural steel frame with articulation links and alignment reference fittings. Windings consist of 2-mm square conductors in two layers. One-ms, 15-kV, 640-A pulses provide the required 19 full-strength dipole fields with thermal losses of about 200 watts per magnet at 5 pulses per minute. Each quadrupole field requires a 7.5-kV, 700-A pulse, with thermal losses of about 90 watts.

The layout shown in Fig. 1 shows two 3-inch vacuum ports that divide the bend into three segments. Cryopumps will be used on these ports, with turbo-molecular pumps drawing from the major diagnostics ports at both ends of the bend section. Diagnostics ports are included at the ends of the straight sections of ILSE that interface with the bend section. These ports provide room for full instrumentation to measure before and after beam current, beam profile, and emittance. Access for beam diagnostics within the bend section is limited by the narrow gaps between magnets (only 8 cm or 3.1 in.). Narrow diagnostics ports of 2-inch aperture have been placed at three locations around the bend. These ports are part of the beam tube fabrication, and are slanted at 45° from the horizontal, so that both principal axes of the beam can be traversed with a single instrument.

Drift-Compression Current Amplification

At the end of acceleration a velocity tilt remains on the beam pulse. This tilt is an essential feature of an ICF driver system because it permits further compression as the beam approaches the final focus, thereby increasing the instantaneous power at the pellet. Without tilt the pulse would, in fact, decompress under the action of its longitudinal space charge effect. For a driver, drift compression is expected to amplify power by a factor of 10 or more over a distance of about 400 m. In this case velocity tilt must be removed to a residual of well under 1% in order to achieve the required small focal spot at the fuel pellet. ILSE is designed to permit pulse compression experiments with a single beam, in which net compression after acceleration is a factor of 2 to 3. The space charge force will stop compression (i.e., remove nearly all of the initial velocity tilt), such that pulse length is a minimum in the final focus. The essential experiment is the observation of transverse and longitudinal emittance growth (if any) during compression, and the removal of tilt so that final focus is effective.

An estimate of the drift compression parameters can be made with the model equation:

$$\frac{d^2L}{dz^2} = \frac{eE_x}{T} = -\frac{e}{T} \frac{g}{4\pi\epsilon_0} \frac{\partial \lambda}{\partial z} \quad (1)$$

Here L is pulse length, T is kinetic energy, and λ is line charge density. The slope of λ is evaluated at the pulse head. The factor

$$g = \frac{1}{2} + \log \frac{b^2}{a^2} \approx 2.5 \quad (2)$$

gives the dependence of electric field on pipe (b) and beam radii (a). Integration of this equation of motion yields, for ILSE baseline parameters

$$\text{tilt removal distance} = z_{\text{drift}} \approx \frac{0.84L_0}{\Delta\beta/\beta} = 48 \text{ m}, \quad (3)$$

$$\text{compression ratio} = \frac{L_0}{L_f} = 1 + \frac{(\Delta\beta/\beta)^2}{S} = 2.1. \quad (4)$$

The factor S is the dimensionless measure of space charge

$$S = \frac{8e}{T} \frac{g\lambda_0}{4\pi\epsilon_0} = 5.4 \times 10^{-3}. \quad (5)$$

The predicted compression by x 2.1 results in current amplification by the same factor. Tilt is completely removed just before final focus in this example.

Drift compression actually begins at the two half-periods before the bend. This process continues through the bend, the two half-periods after the bend, the straight drift-compression section, and half of the final focus section. Total effective drift length from beginning to end is 51.6 m for the removal of the 7.76% velocity tilt. With drift occurring through 23 half-periods of the bend, 4 half-periods of diagnostics quadrupoles, and a portion of the final focus, an additional 56 half-periods of straight drift are required. This total drift effectively compresses the pulse length from 4.39 to 2.09 m and increases beam current from 3.78 to 7.88 A in the final focus section. A depiction of beam envelope compared to half-periods is shown in Fig. 3. Note that the beam envelope adiabatically expands during compression, remaining nearly matched to the focusing lattice.

XBL 893-920

Fig. 3 Horizontal and Transverse beam envelopes from the end of the accelerator to the focal spot as calculated by the MATCH envelope code. Over this length the beam current grows from 3.8 to 7.9 amps.

The iron dominated quadrupoles will provide a 18.2-T/m field gradient with an effective occupancy of 50%. The drift-compression section presents no serious constraints on z-axis space, so packaging is substantially simplified. To attain a uniform field, magnet iron has been sized for a 41-cm OD, 12-cm ID by 30-cm long package. The magnetic centers of each quadrupole will be indexed to a series of fiducials machined on the magnet iron. This system will provide x-y alignment resolution to better than ±0.25 mm (±0.010 in.).

Final Focus Experiment

An ICF driver must provide high-energy, high-current beams focused to a radius of a few millimeters at the fuel pellet. This must be done with a standoff distance of approximately 10 m from the last final focus magnet. To accomplish this the beam would be expanded to a radius of 10 to 20 cm and then focused with a series of special large aperture quadrupoles. Expansion is required in order to produce a convergence cone (half) angle θ sufficient to overcome the beam emittance, ε. A rough measure of spot size as a function of θ and ε is:

$$r_{\text{spot}} = E/\theta. \quad (6)$$

For the expected (unnormalized) emittance at the end of ILSE of approximately 1×10^{-4} milliradians, θ at 0.04 radians gives an r_{spot} of ~ 2.5 mm. Larger convergence angles are undesirable due to interaction with chromatic and geometric aberrations. An ILSE final focus experiment therefore appears feasible, in which the final spot radius would be about an order of magnitude smaller than the radius of the transport beam.

In order to focus the compressed ILSE beam to this small radius, several factors in addition to emittance must be controlled. These are the beam's space charge, which must be neutralized to $\sim 1\%$, and the velocity tilt which must be reduced to less than $\pm 1\%$. Also, final focus quadrupoles must be designed for low aberration content to match the large convergence angle. The achievement of a small focal spot in ILSE would be a benchmark demonstration of the beam dynamics required for an ICF driver.

The specific ILSE final focus configuration consists of four magnetic quadrupoles arranged in a focus/defocus/focus/defocus string. Figure 4 shows a MATCH code solution for the beam envelope. The beam expands due to space charge between the final lens of the drift transport and the first final focus lens. Neutralization by gas or injected electrons follows the last of the four quadrupoles. The maximum beam radius in this arrangement is approximately 130 mm and the maximum field at aperture is about 1.0 T.

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Fig. 4 Envelope calculations of the beam from the last quadrupole in the Drift-Compression section through the large final focus quadrupoles to the point of beam neutralization in the Final Focus Chamber.

For a half-angle of convergence of 40 milliradians, that yields a final spot diameter of 5 mm, a beam aperture of 300 mm is required for a maximum beam diameter of 260 mm. An approach based on demonstrated technology relies on the use of conventional iron-dominated quadrupoles. Figure 5 shows a side view of four quadrupoles mounted on a common structural steel support. The first focus quadrupole center is located 1.487 m from the last drift compression section quadrupole. A constant spacing of 0.967 m is maintained for ensuing quadrupoles, with convergence on the final

spot located 1.0 m from the last defocus quadrupole. The magnetic aperture is sized such that the beam tube is supported by the pole tips. The beam tube enclosure at the final focus is a modular experimental/diagnostic tank. To minimize end effects, magnet iron would be hyperbolically tapered at the end of each coil set. Each coil set would be removable. Total iron required for each magnet is in excess of 14,000 lb. Each quadrupole will require a pulsed power supply rated for 20 kV and 2500 A, similar in design to those for the drift-compression section. Because the magnets are in air, heat rejection will occur through natural convection.

Fig. 5 Final Focus Side View

An initial beam tube expansion section interfacing with the drift-compression section will expand the aperture from 100 to 300 mm to accommodate the expansion of the beam for focusing by the first quadrupole. The ILSE beam will terminate at the final focus spot inside the diagnostics/experimental chamber section. Several chamber configurations may be deployed. Ports for line-of-sight diagnostics, vacuum pumping, and electron or gas injection will be fitted as required.

References

- [1] C.G. Fong, T.J. Fessenden, R.L. Fulton, and D. Keefe, "Engineering Study of a 10 MeV Heavy Ion Linear Accelerator, Lawrence Berkeley Laboratory, published in these proceedings.
- [2] A. Faltens, V. Brady, L. Hansen, L.J. Laslett, S. Mukherjee, Lawrence Berkeley Laboratory, and D. Bupp, D. Ravenscroft, L. Reginato, Lawrence Livermore National Laboratory, "Acceleration Units for the Induction Linac Systems Experiment (ILSE)," published in these proceedings.
- [3] D.L. Judd, C. Celata, E. Close, A. Faltens, K. Hahn, K. La Mon, E.P. Lee, L. Smith and W. Thur, "Concepts, Features, and Design of a 16-to-4 Beam Combiner for ILSE," Lawrence Berkeley Laboratory, published in these proceedings.

LONGITUDINAL STABILITY

L. Smith

It has been recognized since the beginning of the HIF program that the accelerating modules in a driver will present a resistive impedance to the beam. This resistive impedance can lead to longitudinal instability, resulting in an intolerable increase in longitudinal emittance. The mechanism is similar to that of the well-known resistive wall instability in circular accelerators and to the principle of a slow-wave resistive wall amplifier. Unfortunately, the effect is important in a driver only in the regime of high beam currents and high efficiency and so cannot be investigated experimentally within the scope of the HIFAR program.¹ The experiments conducted on the proton accelerator at Rutherford Laboratory² are certainly relevant and instructive but cannot provide absolute assurance.

We must rely heavily on theoretical work and numerical simulation experiments to understand the phenomenon and examine possible cures. In the early years of the HIF program the subject was studied intensively, leading to the conclusion that if a disturbance moving backward and growing in the beam frame of reference experienced only a few e-foldings before reaching the end of the bunch it would be reflected forward and decreases in amplitude, thus leading to a long-term stable motion.³ The estimated magnitude of module resistance satisfied this criterion. However, that work applied to a single accelerated beam and we subsequently have been led to the use of multiple beams for economic reasons. This change presents a new situation; since the beamlets must be shielded from each other to prevent disruptive interaction in the transverse degrees of freedom, the velocity of a perturbation along the beam,

important for the earlier criterion, is proportional to the square root of the beamlet current while the driving force is still proportional to the total current. Indeed, a linear analysis suggests that for 16 beams that velocity is negligible, though the resistive impedance itself introduces a velocity as well as a growth rate.

Therefore this subject is again of primary theoretical importance, particularly since no absolutely convincing experimental information will be available in the foreseeable future. The above-mentioned linear analysis of a continuous set of beamlets has been done (bunch ends cannot be treated by this technique) and the SHIFTZ PIC code used in the earlier work is being renovated at LBL and NRL. It is close to being operational for the new parameter range and will first be applied to continuous beamlets to carry the investigation beyond the valid range of the linear approximation.

References

- ¹ However, a study is underway to determine the feasibility of experiments using a low energy, high intensity, electron beam.
- ² Results reported by R. Martin at the last HIF conference at Darmstadt (1988).
- ³ IEEE Trans. Nucl. Sci. NS-30, No. 4, Aug. 1983, J. Bisognano, I. Haber and L. Smith, p. 2501; I. Hofmann, I. Bozsik and A. Jahnke, p. 2546.

STUDY OF THE LONGITUDINAL ION DYNAMICS- EXTENDED VERSION SLIDE

E. Henestroza

A new performance evaluation code called SLIDE, based on SLID¹, has been written to analyze the effects of real (imperfect) accelerating waveforms in the longitudinal dynamics of space charge dominated beams. SLIDE is a Particle-in-Cell (PIC) code that has been optimized for short machines and low currents.

Currently SLID is being used to derive ideal acceleration schedules for the MBE-4 and ILSE experiments. The accelerating voltage waveforms are obtained by applying the so-called "current self-replicating" scheme² under the influence of longitudinal space-charge forces.

SLID can also be used to study the sensitivity of the longitudinal beam dynamics due to imperfections of the synthesized voltage waveforms. Because of the way the space-charge forces are calculated, the code does not allow the particles to overtake one another. This feature limits the ability of SLID to analyze the effects of most real voltage waveforms because imperfect voltage waveforms cause particles to overtake.

As with SLID, SLIDE follows the evolution of the longitudinal particle distribution for a set of accelerating and bunching voltage waveforms under the influence of longitudinal space-charge forces. The accelerating modules are assumed to be infinitely narrow, the beam pipe is assumed to

be an infinitely long conducting cylinder, and the beam radius is assumed to be uniform along the beam. SLIDE allows particles to overtake one another, and is therefore suitable to analyze imperfect synthesized voltage waveforms.

In order to be able to run SLIDE interactively on a microcomputer, the code has been streamlined and optimized for short machines and low currents. Therefore it can be used to analyze the longitudinal dynamics of the MBE-4 and ILSE experiments.

SLIDE handles numerical instabilities by filtering away the high frequency components of the electric field. The longitudinal space-charge force law is not assumed a priori but can be chosen from a menu. Initial temperature and module impedances are not included in this code.

Work with experimentalists is in progress to find the right graphics interface for the code.

References

1. A review of SLID can be found in: Kim, C.H. and L. Smith, "A design procedure for acceleration and bunching in an ion induction accelerator," LBL-19137, Feb. 1985.
2. Idem.

Current-Dominated Quadrupoles for ILSE

Victor Brady, Andris Faltens, and L. Jackson Laslett

The following diagram is a cross-sectional view at the midplane of an array of current-dominated quadrupole magnets for ILSE with two layers of current elements. The design is one proposed by Andy Faltens and L. Jackson Laslett suitable for use in a transport channel of 40 cm half-period.

For calculation purposes the permeability of the iron was taken from the plot labeled "Dynamo Grade (3.25% DI)" on the graph of DC Magnetization Curves published by the General Electric Laboratory. There are 12 wires per layer in each octant with the return paths in the preceding or succeeding octants. The azimuthal positions of the wires were determined so as to suppress the first four harmonics, beyond the fundamental, in the Fourier representation of the vector potential in the midplane. This results in a small value for the integrated magnetic field along a particle orbit through the end of the magnet. The effect is described in the semi-annual report of Celata, Brady, Faltens, and Laslett. The wire diameter is taken to be .2 cm. The quadrupole end windings are turned as sharply as possible to minimize the length of the region over which azimuthal currents flow, and the overall length of the coils is 17.8 cm. The following table shows the azimuthal position Φ of the wires in the first octant and the distance L from the quadrupole midplane to the end of each wire in the first octant. Their return path lies in the second octant.

Wire	Φ (degrees)	L (cm)
1	1.307	8.9
2	3.945	8.7
3	6.641	8.5
4	9.381	8.3
5	12.114	8.1
6	14.811	7.9
7	17.513	7.7
8	20.338	7.5
9	23.466	7.3
10	27.076	7.1
11	31.225	6.9
12	36.259	6.7

Harmonics a_n and b_n of the 2-D vector potential A were calculated on a circle of radius 4 cm about the quadrupole center. These give an indication of the corrections required for the end turns of this design, and they are useful for ascertaining the non-saturation of the iron yoke. The presence of harmonics other than those expected for an ideal quadrupole is due to the effect of the nearby quadrupoles. The 2-D Fourier representation of A is

$$A(r, \phi) \approx a_0 + \sum_{n=1}^N (r/R)^n [a_n \cos n\phi + b_n \sin n\phi]$$

where R is a normalization radius. The following table lists vector potential harmonics located on a circle of radius 4 cm about the center of an individual quadrupole for a current of 1575 amps per filament.

R=4 cm 1575 amps		
n	a_n (gauss-cm)	b_n (gauss-cm)
1	2.5099×10^1	0
2	1.6816×10^4	0
3	-5.2647	0
4	1.1210	0
5	2.5071	0
6	-6.7129×10^1	0
7	-1.0766	0
8	3.2292×10^{-1}	0
9	4.7815×10^{-1}	0
10	-8.2699×10^{-1}	0

INVESTIGATION OF BEAM DYNAMICS IN A MAGNETIC QUADRUPOLE OF LARGE ASPECT RATIO

C. M. Celata, V. Brady, A. Falten, and L.J. Laslett

As is well known, in a linac used to transport high current beams, at low energy the magnetic quadrupole elements tend toward large aspect ratio (magnet aperture radius divided by the magnet length). As the aspect ratio increases, the field quality of the magnet deteriorates, in the sense that fringe fields become non-negligible. It is then of interest to try to minimize the damage to beam quality which might be caused by these nonlinear fields by designing the quadrupole such that the integral of the impulse given by the nonlinear magnet field over a particle trajectory through one half of the magnet is much smaller than the impulse given by the linear focusing field. This occurs as follows. Since $v_z \gg v_x, v_y$, and $\Delta v_z/v_z \ll 1$,

$$\int \vec{F} dz \approx \int q (\vec{v}_z \hat{z} \times \vec{B}) dz \approx q v_z \hat{z} \times \int \vec{B} dz. \quad (1)$$

The magnetic field can be expressed as a power series in r and trigonometric series in θ , with z dependent coefficients. Since for the intense beams of interest for heavy ion fusion $\sigma \approx 0$, the flow is nearly laminar, and the values of r and θ are nearly constant over the trajectory of a single particle through a magnet end. Thus if one can arrange the magnet end windings so as to minimize the integrated coefficients of the low harmonics of the field, where the most significant nonlinear contributions occur, the integrated field over each particle's orbit will be small. Of course this can not be done for the 2θ components, since this would eliminate the linear focusing field. Therefore there will always remain, after the adjustment of end windings just described, some higher order nonlinear fields ($\propto r^m$, $m \geq 3$) which are proportional to $\cos 2\theta$ or $\sin 2\theta$.

A magnet following this prescription was designed for the first iteration of the ILSE design, and is described in the half year report of Brady and Laslett. Single particles were tracked in one transverse degree of freedom in the field of this magnet and an unmodulated linear space charge force. Results showed stability of particle orbits through the entire radial extent of the magnet.

We will discuss in this report the results of particle-in-cell simulation in two transverse degrees of freedom of beam dynamics in this magnet. The code SHIFTX, written by Irving Haber, was modified for this purpose to use the focusing field of Brady and Laslett. SHIFTX is a two-dimensional particle-in-cell code. Therefore changes in v_z were neglected. The proportional changes in v_z were shown to be small by integrating over the z component of the magnetic force for each particle. For all the cases that were run, the integration showed a change of less than 0.17 % in the z momentum due to the fringe fields.

In all of the cases studied, the beam was assumed to consist of C^+ ions at a longitudinal kinetic energy of 4 MeV, and the lattice half period was 40 cm. In order to model the ILSE experiment, according to the design at the time of these calculations, a perfectly conducting round pipe of radius 5.4 cm formed the boundary for the calculations. The magnet

current for all cases was set to give a zero space charge phase advance per lattice period, σ_0 , of 60° . However, it was found that image forces for the perfectly conducting round pipe boundary reduced the coherent betatron frequency, for instance, to about 55° for the case of $\lambda=0.4 \mu\text{C/m}$, where the ratio of beam major radius to pipe radius, a/R , is 55%. For $\lambda=0.768 \mu\text{C/m}$, or $a/R=75\%$, it was approximately 49° . The space-charge depressed phase advances investigated were 12° and 6° .

The results for $\sigma=12^\circ$ showed no emittance growth. Runs were done for centered beams, as well as beams offset by 1.77 and 4 mm in a direction at 45° to the x axis. (The quadrupole forces are in the x and y directions, with the first lens a y -focusing lens.) Since the beam was matched without allowing for the fringe or image fields and assuming a magnet occupancy, η , of 0.5, there was a mismatch of 4.5% in x and 2.5% in y . The values of the moments $\langle x^4 \rangle$ and $\langle y^4 \rangle$ showed a 10% increase from the uniform beam, implying the formation of a slight halo, but scatter plots indicated only some frizzling of the beam edge, and no important deterioration of the beam. Numerical parameters-- number of particles and mesh resolution-- were shown to have negligible effect on the results. Since this magnet has a larger aspect ratio than the magnet now planned for the ILSE, and since the ILSE will have a tune depression which is less than this (magnetic focusing occurs after the emittance growth of the combining experiment), these results give confidence that the ILSE magnets will not degrade beam quality. In more generality, these results imply that for space-charge dominated beams the tactic used for emittance-dominated beams, of designing the magnet to have the fringe fields of a single end self-cancelling when integrated along the particle trajectory, is an effective and safe one for these tune depressions.

For $\sigma=6^\circ$ less definitive conclusions can be drawn. All cases run showed a slow growth of emittance, about 3% in 40 periods for $\lambda=0.4 \mu\text{C/m}$, and 4% for $\lambda=0.768 \mu\text{C/m}$ for a centered beam. $\lambda=0.768 \mu\text{C/m}$ was also studied with the beam offset by 4 mm at a 45° angle to the x axis. This beam showed emittance growth of about 8% in 40 periods, and 11% in 75 periods. In order to ascertain how much of this emittance growth might be due to causes other than the fringe fields, several runs were done for this off-center beam ($\lambda=0.768 \mu\text{C/m}$) with various changes in boundary conditions and numerical parameters. Runs with and without fringe fields showed that about half of the emittance growth was due to image forces. The number of macroparticles in the simulation was doubled, with no effect on the result. However, increasing the spatial resolution of the solution of the Poisson equation had the effect of increasing the emittance growth, from 9% (x emittance) and 4% (y) over 75 periods for the 128×128 spatial grid, to 13% (x) and 11% (y) for a 256×256 grid. Since the answers are more accurate the greater the resolution of the grid, this indicates that it is likely that some emittance growth occurs for this severe tune depression, but the exact numerical value has not been ascertained.

HEAVY ION LINAC DRIVER ANALYSIS

E. Lee, E. Close, and W. Thur

A new induction linac driver cost code (called HILDA) is being written. It will replace and update the existing cost optimization code LIACEP (written in 1978), while retaining some of its model features. The new code will add the following:

- up-to data cost data
- improved beam dynamics model
- internal and external documentation
- transportability to small and medium computers
- internal modular structure
- user access to files for cost data and model parameters
- model of all major driver components
- cost optimization of accelerator modules allowing independent calculations or linked to other modules.

Specific system components to be included in the code are:

- multiple beam ion source
- injector
- matching section
- electrostatic focussed accelerator
- combiner
- magnetic focussed accelerator
- beam splitters
- bends
- transport/compression lines
- final focus system
- gas interface device at the reactor.

With these components will be models and costs for:

- Power conditioning from the plug
- vacuum

- cryogenic system
- shielding
- tunnel
- controls
- diagnostics.

It is important to note that HILDA considers only the heavy ion driver, so that many components of an entire power plant are not included. Examples of the latter are the reactor, pellet factory, heat exchange system, turbines, general balance of plant, land cost and preparation, etc. A further aspect is that costs are based on overnight construction. A direct capital cost is estimated, without contingency, escalation, loan costs, licenses, etc.

It is recognized that cost data is highly dependent on time frame, size of order (economy of scale), and experience in construction of similar systems. Therefore the code structure will allow a multiplicity of cost data files, so that the user may design a near term experiment, a tenth-of-a kind power driver, or some other linac such as an LMF driver. These files will be readily accessed and contain their own documentation (explanation). Similarly the assumed physical limits, such as surface flashover fields, will be readily available in files with documentation.

To date the effort on HILDA has concentrated on general code structure, beam dynamics and elementary cost models. We have also studied and improved LIACEP during this phase. It is expected that a preliminary version of the new code will be operating by the end of FY89 and a final documented code will be completed in FY90.

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Abstract

The Symposium hosted by GSI attracted about 130 participants from 12 countries. Progress in developments for high-current low-emittance heavy ion beams in both rf linacs and induction linacs has been reported. Significant current amplification in a proof-of-principle multiple-beam induction linac was described. Experimental results from France and Germany show enhanced energy deposition by low-energy heavy ions in hot dense plasmas. The GSI heavy ion synchrotron (SIS) and the experimental storage ring (ESR) are under construction; when completed, the beams will be used for experiments to study hot dense plasma phenomena.

Introduction

Since the beginning of interest in using high energy accelerators for heavy ions to produce high intensity beams for inertial confinement fusion, it has been the practice for interested scientists to get together roughly at two-year intervals to exchange ideas and review progress. Early on, these interchanges took the form of workshops; later as ideas became explored in detail the workshop mode was abandoned in favor of Symposia of three or four days duration with invited and contributed papers. The most recent of these was held at Gesellschaft für Schwerionenforschung (GSI), Darmstadt on June 28 - 30, 1988.

The main attraction of the accelerator approach to Heavy Ion Fusion (HIF) is that the technology, which has a large development base, can offer a combination of features (repetition rate, efficiency, lifetime, reliability, and focussing at a large stand-off distance from the fusion pellet) that makes it seem very attractive for an electricity-producing plant based on inertial fusion (IF). Thus the issues lie in (a) cost, and (b) feasibility, especially in being able to generate the very high current (tens of kiloamperes) and small focal spot size (3-5 mm radius) needed at the fusion target. HIF has suffered an historical disadvantage, however, in being a late-comer to the inertial fusion field, where much larger programs using lasers or light-ion beams had been in place for some years. Laser and light-ion systems, at least in their present forms, may have serious disadvantages for electricity-generating systems, but could be adequate for the military applications which are their primary emphasis.

In discussing the U.S. inertial fusion program directed at the energy application, Polansky (DoE) described the only such undertaking, Heavy Ion Fusion Accelerator Research (HIFAR), which concentrates on exploring the application of heavy ion induction linacs to the problem.¹ A major fraction of this 6-M\$-a-year effort is conducted at Lawrence Berkeley Laboratory (LBL) with other activities at Lawrence Livermore National Laboratory (LLNL), the Naval Research Laboratory (NRL), Stanford Linear Accelerating Center (SLAC), and Argonne National Laboratory (ANL). By contrast, the research on ICF managed by the Defense Programs part of DoE, is much larger (M\$150/year); Kahalas (DoE) summarized these activities which include glass (e.g. NOVA), and gas lasers, the Particle Beam Fusion Accelerator-2 (PBFA-2), and a classified segment of research designated Halite-Centurion. (Two months after the Darmstadt Symposium, the U.S. DoE revealed that Halite-Centurion was a program on ICF experiments conducted underground in Nevada using nuclear explosives; results remain classified).

In his talk, Kahalas gave details of the DoE Defense Programs plan to construct a Laboratory Microfusion Facility, or LMF, which would satisfy the military application needs.² A specific driver technology would be chosen in 1991 or 1992. The LMF would have a very low repetition rate (< 1 shot per day) and a short lifetime (< 10⁶ shots); efficiency is not of importance. Hence,

one could choose a driver technology, e.g. glass lasers, which did not conform to the properties desired in a power plant driver. Since LMF is intended to produce a high yield per shot (higher than in a electricity-generator) with high confidence of success the beam energy is set at 5 to 10 MJ - higher by a factor of two or so than what is believed needed for power generation, and higher by a factor of 200 than the largest operating glass laser facility (NOVA).

2. Driver Research

2.1 Induction Linac: The February issue of *Fusion Technology* was devoted to the results of a Heavy Ion Fusion Systems Assessment study, a collaborative venture by industry and DoE laboratories to evaluate a broad spectrum of power plant options that used an induction linac as a driver.³ Beam parameters that were varied included ion mass, ion charge, ion kinetic energy, total beam energy, and beam emittance. Four choices of reactor chamber and five choices of target design were also examined. Results indicated favorable electricity costs for a 1 GeV plant (5 - 5.5 cents/kWh). A 500 MWe plant, which would be more attractive for a utility company because of the lower buy-in price, gave an electricity cost of 9 cents/kWh; the price per kWh would drop at a future date if the utility were to add a second reaction chamber in an upgrade to 1 GWe. These electricity costs were quite stable over a wide range of variation in the accelerator parameters.

The apparatus for an experiment called MBE-4 had been completed some months before at LBL.^{3,4,5} See Figure 1. MBE-4 is a proof-of-principle accelerator with 4 separately focussed cesium ion beams. Twenty-four accelerating gaps raise the energy of the ions from 200 keV at injection to almost 1 MeV at the end. The induction core pulsers can provide shaped voltage waveforms, first, to speed up the end of the 1-m long beam bunch relative to its head thus initiating current amplification and second, to supply small correction acceleration/deceleration at the tail/head of the bunch to counteract the longitudinal spreading of the bunch ends due to space charge effects.

CBB 879-7734

Fig. 1 The recently completed MBE-4 apparatus; the induction cores are housed in the square boxes.

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Current amplification proceeds from two effects. First, if the voltage waveforms on the accelerating gaps just after the injector are chosen correctly the length of the beam bunch can be held constant. Thereafter, flat-topped waveforms will maintain the length constant and the beam current will rise directly as the beam velocity (the pulse duration shortening inversely as velocity). In a driver this would amount to a factor (final energy/initial energy)^{1/2} = (10,000 MeV/3 MeV)^{1/2} = 58, but in MBE-4 only by a factor (1,000 keV/200 keV)^{1/2} = 2.2. Additional current amplification is planned to take place in a driver by a second manipulation of the voltage waveforms causing the bunch length gradually to shorten by a factor of 4 leading to an overall amplification of 4x58 = 232. In MBE-4 an early experiment (so-called "aggressive accelerating schedule") accomplished an amplification of 9 (from 10 mA per beam to 90 mA per beam). See Figure 2. Thus, the bunch length was compressed by a factor of 9/2.2 = 4, about the same as needed in a full-scale driver.

Current Amplification in MBE-4

XBB 866-0237

Fig.2 Oscillograms for one of the beams in MBE-4 show the injected current trace (lowest amplitude, longest duration) at gap 0, and the amplified current traces after 4,8,12,16,20, and 24 accelerating gaps.

Preliminary measurements for a less extreme example of amplification — by a factor of 3 — which is more amenable to accurate diagnosis, were reported by Meuth.⁵ First results suggested a normalized emittance growth by almost a factor of two; significantly more than calculated. Since many instrumental effects

can cause unnecessary emittance growth, e.g., incorrect tuning, imperfect matching, or a gradual drift in the operating point, a much more careful round of experiments is needed to establish how much of the growth is due to fundamental physics effects and how much to unsatisfactory tuning procedures.

LBL are also developing a pulsed 16-beam injector in preparation for future experiments. See Figure 3. The 2-MV high voltage is produced by an inductively graded Marx generator with gas insulation. The original design and partial fabrication was done at Los Alamos National Laboratory (LANL) and the apparatus moved to LBL in September 1987. A gated metal vapor vacuum arc source, developed originally by Humphries and Burkhardt⁶ and designed to give 500 mA of C⁺ ions, is being optimized before the 16 sources for the injector are fabricated.

CBB 893-1763

Fig. 3 View of the partially completed inductively-graded Marx generator which is designed for gas insulation.

When complete, the 16-beam injector will be the first stage in a series of experiments to model many of the manipulations needed in a driver — beam combining in sets of four-to-one, magnetic transport, bending of space-charge-dominated beams, drift compression to remove energy tilt, and final focus experiments. Fessenden reported on the physics and engineering designs of the apparatus (called ILSE for Induction Linac Systems Experiment) to accomplish this program of experiments. Ho (LLNL) described results of 2 1/2 D particle-in-cell simulations of the beam behavior in the drift-compression section of a driver system, in which collective acceleration at the bunch head and deceleration at the tail remove the residual velocity tilt, $\Delta v/v$, as the beam leaving the accelerator drifts and bunches on its way to the target.⁷

Experiments on the behavior of space-charge-dominated beams are being conducted by Reiser's group using a low emittance electron beam transported through a sequence of solenoid lenses.⁸ One experiment, in which the high-brightness beam is split into several beamlets which then mix and merge in the transport system, tests the theory that redistribution of electrostatic field energy feeds directly into a change in beam emittance. Several of the experimental observations are in good agreement with simulation work by Rudd et al.⁹

2.2 rf linacs/storage rings

While the US research is devoted to the induction linac approach, the study of rf linac/storage ring systems is being pursued in West Germany, the Soviet Union and Japan. A strong, broad program at GSI is moving forward on two fronts — the physics of high energy density by heavy ion beams and the accelerator physics issues in linac/storage ring systems. While initial experiments on the

first topic have taken place with existing facilities — the new RFQ, for instance — the present construction program for the heavy ion synchrotron, SIS-18 and experimental storage ring, ESR, will lead to exciting opportunities in the next few years.^{10,11} See Figure 4.

coefficient for a heavy ion lost to the walls may be rather large. This is directly related to the "black cloud" concern identified some years ago, namely that vapor emission due to a small amount of beam loss on an injection septum could thwart attempts to stack multiple turns

XBL 893-870

Fig.4 The SIS/ESR heavy ion facility with UNILAC as the injector. SIS and ESR are to be commissioned in 1989 but the high-brightness injector will not be operational before 1991.

Several other institutions in West Germany are collaborating in the theoretical and proposed experimental program - MPQ-Garching, Frankfurt, Aachen, TH-Darmstadt, Giessen, among others. Much of the present activity is related to the planning and design of experiments on heavy-ion induced plasmas, and to some fusion target calculations. One accelerator experiment, however, on electron cooling of partially stripped heavy ions produced by the UNILAC is soon to take place.¹² This is in the nature of a preliminary evaluation of the method in anticipation of the use of electron-cooling in the ESR when it is completed late in 1989. In ESR it is hoped that the emittance can be reduced by a factor of 10 below the SIS emittance.

At the time of the Symposium, SIS-18 was nearing completion and ESR was about half complete. The invited paper by Boehne at the present Conference reports that commissioning the accelerator is already under way.¹³ I. Hofmann described the main areas of study in preparation for the use of SIS/ESR to evaluate the problems of a fusion driver system.¹⁴ Among these were (a) the three-dimensional space charge effects during multi-turn injection which can cause emittance dilution both transversely and longitudinally; (b) an interesting experiment on the longitudinal microwave instability in which SIS will be filled with Ne^{+2} ions and, after acceleration and stripping, Ne^{+10} ions will be injected into ESR to exceed the Keil-Schnell limit by a factor of 25; and (c) fast bunching to amplify the current while using electron cooling to keep $\Delta p/p$ adequately small.

Schempp et al. at Frankfurt are developing a high-current spiral RFQ in the right parameter range for HIBALL.¹⁵ Calculations show that, operating at 27 MHz, it should accelerate 25 mA of U^{+2} ions from 2.5 to 25 keV/amu. High-power models have already been built for sparking tests.

A rf/ring driver system under study at ITEF (Moscow) would use Bi^{+2} ions at 20 GeV and a beam energy of 6 MJ.¹⁶ A bismuth ion source is operating at 25 mA. Funnelling is envisioned at the front end to achieve high current in the main linac. They have already constructed an impressive 6 MHz RFQ which has undergone beam tests. Now they are examining the possibility of modifying the 9 GeV proton synchrotron to accelerate heavy ions. A beam energy of 1 kJ is achievable which if bunched to 10 nsec could provide an interesting experiment. Koshkarev was concerned that the well-known ion-gas instability (named after him and Zenkevich) could be a problem for heavy ions in a storage ring since the desorption

in a storage ring. An experiment is planned at ITEF to study the desorption coefficient by means of a H_2^+ probe beam. See Figure 5.

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Fig. 5 Schematic of ITEF experiment to measure gaseous desorption coefficient for normal impact of bismuth ions. Gas density is inferred by measuring dissociation of H_2^+ beam.

Katayama (INS) discussed a proposed experiment on heavy ion cooling that is planned for the TARN-2 ring.¹⁷ This 400 MeV/amu synchrotron has been completed and is in the process of being commissioned about now.¹⁸ One of the straight sections includes a 10 ampere electron cooling system which will be operated on the flat top of the magnet pulse. Accelerating structures suitable for low-energy heavy ions are under study in Tokyo. S. Arai and colleagues have tested a proton model of a split coaxial RFQ which offers some simplification of fabrication.¹⁹ Satoh et al., have tested two types of interdigital II-mode (IH) structures suitable for low- β acceleration and report that operation is extremely sensitive to a number of parameters especially drift-tube capacitance.²⁰

Finally, Martin reported preliminary measurements at the ISIS accelerator that addressed the question of the threshold for the longitudinal microwave instability in a bunched beam — a critical piece of design information for an IF driver.²¹ ISIS is a high-intensity synchrotron with a proton injection velocity closely matching that of the heavy ions near the end of a driver. Martin and collaborators did indeed observe the growth of a longitudinal instability in a coasting beam at the injection energy. This was observed as a 202.5-MHz signal (showing that the debunched beam still had some memory of the linac frequency) which saturated quickly and then decayed in a few hundred microseconds. Whether this stabilization is accompanied by a gross increase in momentum spread or generation of relatively weak momentum tails as suggested by Hoffmann,²² could not be determined. If more ISIS time can be scheduled, this clearly is a unique facility for further fruitful investigation of coasting and bunched beam instabilities.

2.3 Other Driver Ideas

In characteristic style, Rubbia pointed out that there were many tools developed for high-energy physics machines that could be deployed in imaginative ways to solve the driver problem.²³ He gave some examples. A possible driver configuration could consist of two rings that are tangential at a long straight section. The first is a synchrotron containing a high-brightness Bi⁺ beam (derived by charge-exchange injection of a Bi³⁺ beam). A high-power FEL shining 17-eV photons along the shared straight section is used to convert the Bi⁺ ions to Bi²⁺ which are stored in the second ring. Such an injection scheme avoids the large emittance-dilution factor arising from multiturn injection with a septum; in fact it greatly increases the density in phase-space. Also, it eliminates the "black-cloud" problem inherent in septum-injection and, further, allows a strategy of stacking several rings with minimum beam residence time per ring which helps circumvent longitudinal instability problems. Tuning to other approaches and observing that the beamstrahlung phenomenon at the interaction region of an e⁺e⁻ linear collider leads to a very high-power burst of hard photons, Rubbia encouraged examination of a driver based on a high-energy electron accelerator. The technology is well-understood and such an accelerator in the multi-GeV range could be designed for high electrical efficiency. If the beam can be focussed to a spot size of the order of a micron and sent through a gas a pinch field in the megagauss range could be realized and photon emission would occur because of the betatron motion. Alternatively, Rubbia suggested that a collective undulator might be made by creating a wiggled line of ions.

3.0 Beam-Target Interactions

Langdon and coworkers using simulation codes examined several effects that can occur in the reactor environment.²⁴ Charging-up of the target by the deposition of the positive ions appears not to be a problem — positive ion emission from the target plasma or electron-capture following photo-ionization of the residual gas in the chamber make the effect negligible. Electrons accelerated to the target in this process do not contribute any significant pre-heat to the fuel. Also, they examined the possibility that electron anisotropy caused by streaming instabilities might convect energy rapidly away from the deposition zone. Transverse instability growth, driven by such anisotropy, is too small to be damaging. Likewise, the ion-electron two-stream mode seems to pose no problem. One effect examined for the first time, however, turned out to be of considerable significance; the x-rays emitted from the hot target, Doppler-shifted by the ion motion, can cause significant photo-ionization of the incoming ion beam. In high-vacuum, at least, the shift upward in average charge-state of the ions will cause transverse beam expansion and result in some half of the particles lying outside the desired focal spot. This is an important effect to study in more detail since the real situation must include the other species present — hot ions and electrons from the target, cold ions and electrons from the residual gas, and possibly, co-injected electrons — which will have to be included in the calculation.

Direct rather than indirect drive is inherently a more efficient implosion method and, if practicable, could result in significantly reduced driver requirements. Rather than the bipolar illumination geometry usually assumed, direct drive requires a high degree of

symmetry for the impinging beams. In continuing to study the possibility of direct drive, Mark, using 2-D codes, has shown how the effect of asymmetries can be reduced while maintaining a manageable number of beams.²⁵

A number of reports addressed the opportunities that will be presented when SIS-18 and ESR are operating to study the physics of hot dense matter. Topics to be examined include the beam-plasma interaction, hydrodynamics, and plasma radiation. A set of experiments discussed by Hoffman and Meyer-ter-Vehn would use the SIS high energy beam, 100 MeV/amu, bombarding a solid target either planar or some millimeters in length.²⁶ See Figure 6. For high energy ions at relatively high charge state (e.g., Xe⁺⁴⁴) a focal spot radius of 0.1 mm can be achieved so that a columnar plasma can be formed along the axis of the target. Over time, as the beam intensity and other conditions are improved, the plasma temperature and pressure could be increased from 1 eV, 1 Mbar, to some 100 eV, 100 Mbar. Low-temperature (1 eV) solid density plasmas have already been produced in a target by the 15 kW beam from the new high-current RFQ for SIS.²⁷ The range shortening that occurs for ions when stopped in a plasma rather than cold matter continues to be the object of experiments by Deutsch at both Orsay and GSI.^{27,28} The effect is quite large — a 50-percent reduction in range — for low energy ions in the region of 1 MeV/amu, but is expected to be under 10% for the more energetic ions (50 MeV/amu) appropriate to a driver.

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Fig. 6 Conceptual design for a GSI experiment on a hot, high-density plasma produced by a neon beam.

References

At the time of writing, the Proceedings of the Heavy Ion Fusion Symposium (Darmstadt, 1988) is not yet published. It will appear as a special issue of *Nuclear Instruments and Methods*, edited by R. Bock, I. Hoffmann and J. Meyer-ter-Vehn (1989). Most of the references below will be found in that issue.

1. W.M. Polansky, *op. cit.*
2. S.L. Kahalas, *op. cit.*
3. D. Keefe, *op. cit.*
4. T.J. Fessenden, *op. cit.*
5. H. Meuth, *op. cit.*
6. S. Humphries and C. Burkhart, *Particle Accelerators*, 20, 211 (1987)
7. D. D.-M. Ho and S.T. Brandon, Symposium Proceedings.
8. M. Reiser, *op. cit.*
9. H. Rudd, C.R. Chang, D. Kehne, K. Low, M. Reiser, T. Shea and I. Haber, *op. cit.*
10. R. Bock, *op. cit.*
11. D. Boehne, *op. cit.*
12. R. Becker, E. Jennewein, M. Kleinod, U. Proebstel, K. Valdkhani, A. Mueller, W. Spies, S. Schennach, N. Angert, F. Bosch, I. Hoffmann, J. Klabunde, P. Mokler, H. Schulte, P. Spaedke and B. Wolf, *op. cit.*

13. D. Boehne, Paper B3 at this Conference.
14. I. Hofmann, Symposium Proceedings.
15. A. Schempp, H. Deitinghoff and A. Kipper, op. cit.
16. D. G. Koshkarov, op. cit.
17. T. Katayama, op. cit.
18. T. Katayama, Paper B6 at this Conference.
19. S. Arai, T. Fukushima, T. Hattori, T. Morimoto, E. Tojyo, N. Tokuda, and M. Yoshizawa, Symposium Proceedings.
20. K. Satoh, S. Kamohara, and E. Arai, op. cit.
21. R.L. Martin, I.S.K. Gardner, C.W. Planner, and G.H. Rees, op. cit.
22. I. Hofmann, Laser and Particle Beams, 3, 1, (1984).
23. C. Rubbia, Symposium Proceedings.
24. A.B. Langdon, R.O. Bangerter and D.A. Liberman, op. cit.
25. J.W-K. Mark, op. cit.
26. D.H.H. Hoffmann, J. Meyer-ter-Vehn, R.W. Mueller, I. Hofmann, R. Bock, and R. Arnold, op. cit.
27. D.H.H. Hoffmann, op. cit.
28. K. Weyrich, H. Wahl, D.H.H. Hoffmann, J. Jacoby, R. Bimbot, D. Gardez, M.F. Rivet, M. Dumail, C. Fleuriot, A. Sanbe, C. Deutsch, and G. Maynard, op. cit.

PUBLICATIONS AND INTERNAL NOTES

HIFAN-388
LBL-25047
Lee

E. P. Lee and J. Hovingh
"Heavy Ion Induction Linac Drivers for Inertial Confinement Fusion," Fusion Technology 15, No. 2, part 2A, 369 (1989).

HIFAN-400
LBL-25540(17)
Meuth

H. Meuth, S.A. Veitzer, and A.I. Warwick
"Acceleration Experiments with the Multiple-Beam Device MBE-4," Thirtieth Annual Meeting Division of Plasma Physics, October 31 - November 4, 1988, Bull. APS, 33, 1989 (1988).

HIFAN-401
LBL-25540(18)
Fessenden

T.J. Fessenden
"Design of the Induction Linac Systems Experiment," Thirtieth Annual Meeting Division of Plasma Physics, October 31 - November 4, 1988, Bull. APS, 33, 1989 (1988) (abstract).

HIFAN-402
LBL-25540(19)
Hahn

K. Hahn, C. Celata, E. Lee and L. Smith
"Simulation of Beam Dynamics for the Induction Linac System Experiment (ILSE)," Thirtieth Annual Meeting Division of Plasma Physics, October 31 - November 4, 1988, Bull. APS, 33, 1989 (1988) (abstract).

HIFAN-404
LBL-25902
Warwick

A.I. Warwick, D.E. Gough, D. Keefe, and H. Meuth
"Acceleration, Current Amplification and Emittance in MBE-4, an Experimental Beam Induction Linear Accelerator for Heavy Ions," Proc. 1988 Linear Accelerator Conf. (Williamsburg, Oct. 1988) (to be published).

HIFAN-406
LBL-25993
Meuth

H. Meuth, S. Eylon, D.E. Gough, D. Keefe, and A. I. Warwick
"An experimental Small-Scale Ion Induction Linac for Heavy-Ion Fusion," 1989 Particle Accelerator Conference, March 20-23, 1989, Hyatt Regency Hotel, Chicago, IL, Bull. APS, 34, 253, (1989) (abstract).

HIFAN-407
LBL-25985
Rutkowski

H. Rutkowski, A. Faltens, D. Vanecek, C. Pike,
D. Brodzik, R.N. Johnson, and S. Humphries Jr.
"The Berkeley 2 MV Heavy Ion Fusion Injector," Proceeding of the
1989 Particle Accelerator Conference, March 20-23, 1989, Hyatt
Regency Hotel, Chicago, IL. (in press).

HIFAN-408
LBL-25998
Fong

C.G. Fong, T.J. Fessenden, R.L. Fulton, and D. Keefe
"Engineering Study of a 10 MeV Heavy Ion Linear Accelerator,"
Proceedings of the 1989 Particle Accelerator Conference, March 20-
23, 1989, Hyatt Regency Hotel, Chicago, IL. (in press).

HIFAN-409
LBL-25995
Faltens

A. Faltens, L. Hansen, S. Mukharjee, D. Bubb, D. Ravenscraft,
and L. Reginato.
"Acceleration Units for the Induction Linac Systems Experiment
(ILSE)," Proceeding of the 1989 Particle Accelerator Conference,
March 20-23, 1989, Hyatt Regency Hotel, Chicago, IL. (in press).

HIFAN-410
LBL-25984
Judd

D.L. Judd, C. Celata, E. Close, A. Faltens, K. Hahn, K. La Mon,
E.P. Lee, L. Smith, and W. Thur
"Concepts, Features, and Design of a 16-to-4 Beam Combiner for
ILSE," Proceeding of the 1989 Particle Accelerator Conference,
March 20-23, 1989, Hyatt Regency Hotel, Chicago, IL. (in press).

HIFAN-411
LBL-25996
Lee

E.P. Lee, C. Fong, S. Murkerjee, and W. Thur
"Conceptual Design of Bend, Compression and Final Focus
Components of ILSE," Proceeding of the 1989 Particle Accelerator
Conference, March 20-23, 1989, Hyatt Regency Hotel, Chicago,
IL. (in press).

HIFAN-412
LBL-25989
Keefe

D. Keefe,
"Report from Symposium on Heavy Ion Inertial Fusion at
Darmstadt, June 1988," Proceeding of the 1989 Particle Accelerator
Conference, March 20-23, 1989, Hyatt Regency Hotel, Chicago,
IL. (in press).

HIFAN-414
LBL-25920
Fessenden

T.J. Fessenden,
"Heavy Ion-Beam Driven ICF," invited paper given at the 1989
AAAS Annual Meeting in San Francisco, Jan. 14 - 19, 1989
(abstract).

HIFAN-415
LBL-26167
Hahn

K. Hahn and L. Smith
"2-D Emittance Equation with Acceleration and Compression,"
Limited distribution only

HIFAN-416

Heavy Ion Fusion Accelerator Research (HIFAR)
A Program Briefing for Dr. Robert Hunter Director Office of
Energy. K. Berkner/LBL/R. Bangerter/LLNL/D. Keefe/LBL
11/30/88

HIFAN-417
LBL-26390a
Fessenden

T. Fessenden,
"Research on Multiple-Beam Induction Linacs for Heavy Ion Inertial
Fusion,"
Invited paper at the 1989 IEEE International Conference on Plasma
Science, 22-24 May 1989 (abstract).

HIFAN-418
LBL-26031
SLAC-PUB-4718
W. Herrmannsfeldt

W. Herrmannsfeldt and D. Keefe
"Induction Linac Drivers for Heavy Ion Fusion,"
Invited talk presented at the European Conference on Laser
Interaction with Matter, Madrid, Spain October 3-7, 1988
Laser & Particle Beams, (in press).

HIFAN-419
LBL-26482
HIF Staff

HIF Staff
Heavy Ion Fusion Accelerator Research (HIFAR) Year-End Report:
April 1, 1988 - September 30, 1988, December 1988.

HIFAN-421
LBL-26620a
K. Hahn

K. Hahn and L. Smith
"Transverse Emittance Equation with Acceleration and Compression,"
abstract Submitted for the 1989 IEEE International Conference on
Plasma Science, 22-24 May 1989 (1/20/89).

HIFAN-422
LBL-26660a
S. Eylon

S. Eylon, H. Meuth, R. Johnson and K. Hahn
"Beam Studies in the L.B.L. MBE-4 Device,"
abstract Submitted for the 1989 IEEE International Conference on
Plasma Science, 22-24 May 1989 (1/27/89).

HIFAN-423
LBL-26691a
H. Rutkowski

H.L. Rutkowski, A. Faltens, D. Vanecek, C. Pike, and D. Brodzik,
"An Injector for Heavy Ion Fusion Accelerator Research,"
abstract Submitted for the 1989 IEEE International Conference on
Plasma Science, 22-24 May 1989 (2/2/89).

HIFAN-424
LBL-26309
Hyder

A. Hyder and D. Keefe,
"Advanced Accelerator Concepts," Proceeding of the USSR All-
Union Conference on Accelerators, Dubna, USSR, November 1988
(in press).

HIFAN--427
J. Laslett

"Aperture Ratio and Related Transport Limitations," (Introduction to
two attached hand-written notes from 1982).

HIFAN-429
PUB-5219
HIF Staff

Induction Linac Systems Experiments, Conceptual Engineering
Design Study, March 1989. (ILSE Report)

HIFAR NOTES (Internal and Informal)

HIFAR NOTE-218

J. Stoker

Injector Marx High Voltage Capacitor Life Tests. October 3, 1988.

HIFAR NOTE-219

E. Meyer

Comments on Marx Column Configuration, October 20, 1988

HIFAR NOTE-220

S. Veitzer

**Pulsed Steering Corrections of Coherent Betatron Oscillations on MBE-4
November 1988**

HIFAR NOTE-221

**Brodzik, Warwick, Ghiorso
Meuth**

HIFAR Diagnostic Upgrade- March 88, November 1988

HIFAR NOTE-222

**A.I. Warwick, D.E. Gough,
H. Meuth**

**Preliminary Report on MBE-4, An Experimental Multiple-Beam Induction
Linear Accelerator For Heavy Ions. 11/8/88**

HIFAR NOTE-223

K.D. Hahn

Search for emittance change: part II, Dec. 1988

HIFAR NOTE-224

V. Brady

Optimal 12 Wire Dipole, Nov. 30, 1988.

HIFAR NOTE-225

D. Brodzik

**2 Megavolt Marx Water Load Resistor (doped with sodium sulfate), Dec. 6,
1988.**

HIFAR NOTE-226

E. Lee

Beam Combining In An ICF Driver/Joint HIF Meeting at LLNL
12/6/88

HIFAR NOTE-227

E. Henestroza

Space-Charge Forces, Velocity Tilt and Maximum Transport Current in
a HILIA. (12/22/88)

HIFAR NOTE-228

W. Thur

Alignment Expectations for ILSE. January 6, 1989

HIFAR NOTE-229

V. Brady & A. Faltens

Perturbed Electrostatic Quadrupoles/January 25, 1989

HIFAR NOTE-230

C. Fong

Vibrational and Thermal Characterization Study of Building 58A, January
27, 1989.

HIFAR Note-231

A. Faltens

Increasing Marx Breakdown Voltage
February 15, 1989.

HIFAR-Note-232

H. Meuth, H. Henestroza, K. Hahn

Zero-Current Phase Advance Measurement in MBE-4

HIFAR Note-233

E.Lee

New Induction Linac Cost Code (Un named)
LBL/LLNL HIFAR Mtg. 2/23/89.

HIFAR Note-234

L. Jackson and Victor Brady

Current Distribution for a Current-Dominated Quadrupole in a Periodic
Array

Abstract: Calculation of current distribution needed to maintain ideal
quadrupole field in a single quadrupole of a periodic array of
quadrupoles./March 6, 1989.

HIFAR Note-235

E. Meyer

Analysis of High Voltage Testing of the Marx Column,
March 24, 1989.

HIFAR Note-236

V. Brady

Stability Boundaries for Single Particle Motion in a Periodic
Electrostatic Quadrupole Lattice. 3/31/89

HIFAR Note-237

Johnson

R. Johnson, S. Eylon, and H. Meuth,
Survey & Alignment of MBE-4, Dec. '88 - Jan. '89

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