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

A. Faltens, V. Brady, D. Brodzik, L. Hansen, L. J. Laslett, and S. Mukherjee
Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720

D. Bubp, D. Ravenscroft, and L. Reginato
Lawrence Livermore National Laboratory, P. O. Box 800, Livermore, California 94550

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 HIFAR program has considerable experience in transporting space-charge-dominated cesium beams using electric focusing in the Single Beam Transport Experiment[2] 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 (HLP) which takes different values along the machine. Focusing arrays and acceleration gaps are arranged in cell blocks consisting of groups of eight HLP lengths, with the eighth cell used for acceleration correction core, vacuum pumping, diagnostics, and a beamline bellows. In the first two cell blocks the HLP length is 45 cm; in the third the HLP is 50 cm.

The focusing electrode assembly is shown in Fig. 1. The focusing fields occupy about half of the HLPs. 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 80kV. 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

*This work is supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Advanced Energy Projects Division, U.S. Dept. of Energy, under Contract No. DE-AC03-76SF 00098.

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-stablized 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 HLP while the balance of cell blocks have a 60-cm HLP. 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 HLP 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 2θ 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 2θ 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 μs. The 1 ms magnet drive current pulse with a half-sine waveform is long compared to this decay time. The 1 μs 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 ± 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 HIF 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 μs 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 that this consideration more than doubles the amount of core that must be provided.

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 pulsers will be designed to provide accelerating waveforms within ± 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 Coprporation 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/ρ where t is the ribbon thickness and ρ 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 acerbated 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 alignment of the finished assemblies on the beamline. The alignment system is the weakest link at this time, but is upgradeable.

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 for 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. Laseltt, 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.

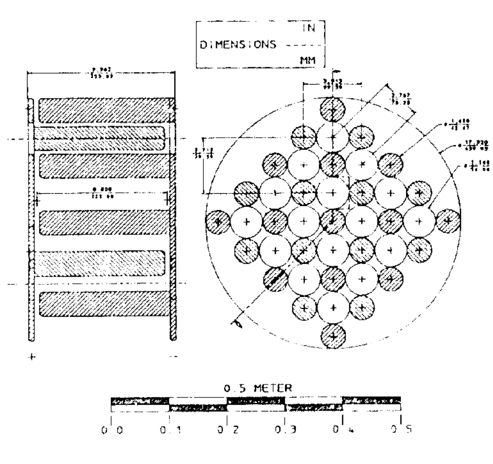

Fig. 1 Electric Quad Array

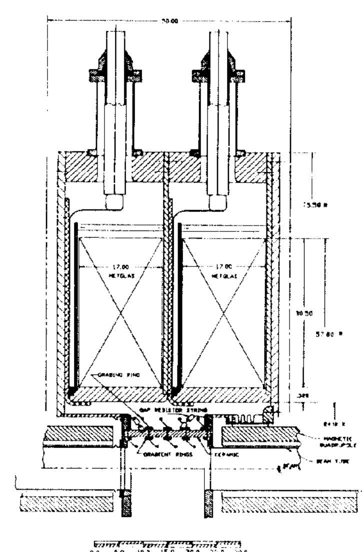

Fig. 2 Magnetic Focus Accelerator Cell