Title

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

Authors

Lee, E.P.
Fong, C.
Mukherjee, S.

Publication Date

1989-03-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

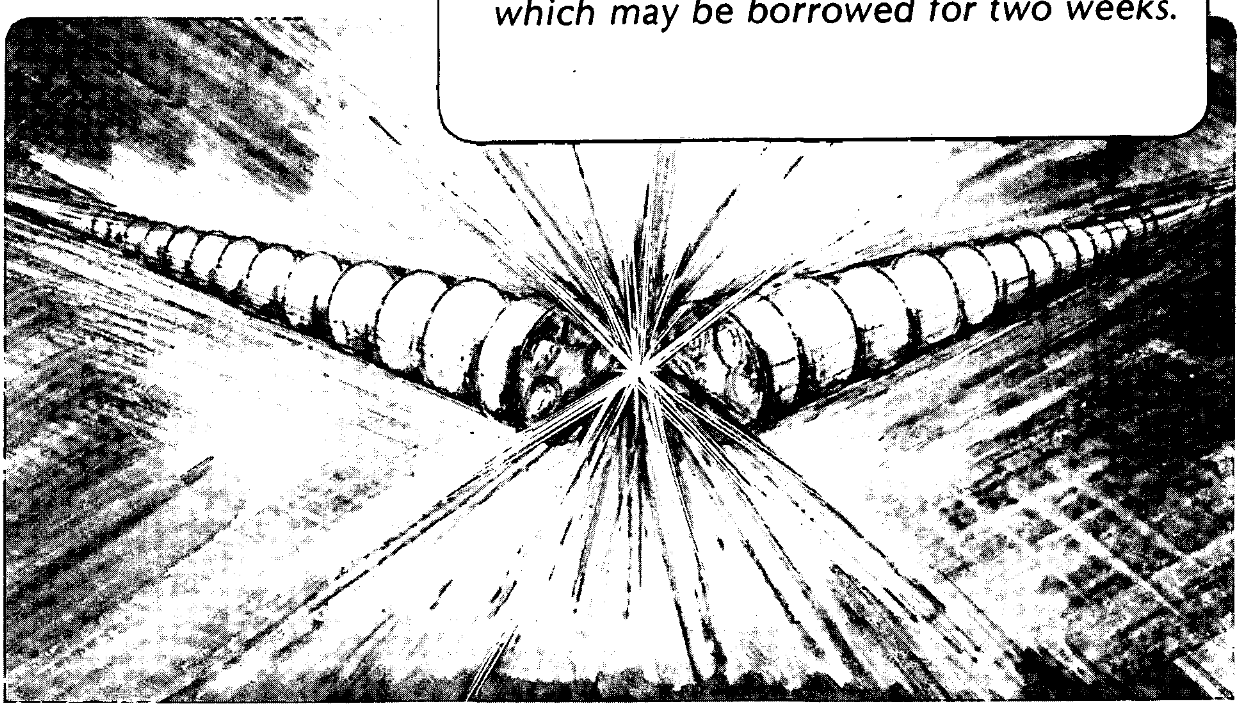
Accelerator & Fusion Research Division

Presented at the 1989 Particle Accelerator Conference, Chicago, IL, March 20–23, 1989

Conceptual Design of Bend, Compression, and Final Focus Components of ILSE

E.P. Lee, C. Fong, S. Mukherjee, and W. Thur

March 1989



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

DISCLAIMER

LBL-25996

Conceptual Design of Bend, Compression, and Final Focus Components of ILSE

E.P. Lee, C. Fong, S. Mukherjee, and W. Thur

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

March 1989

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

E.P. Lee, C. Fong, S. Mukherjee, and W. Thur
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

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.

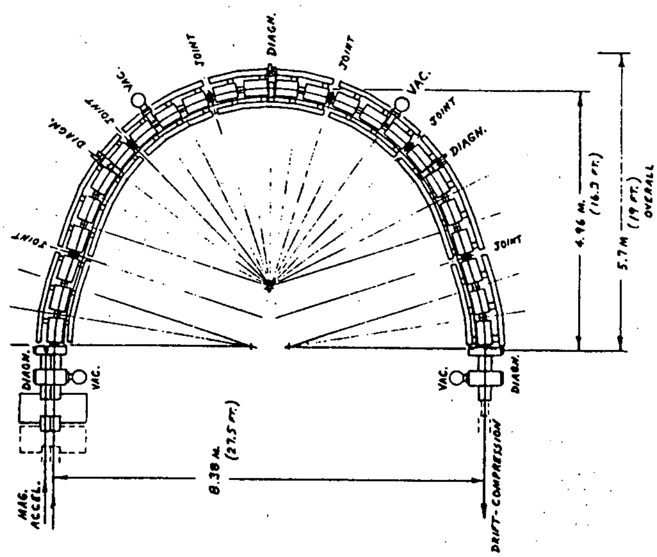


Fig. 1 Bend section plan view.

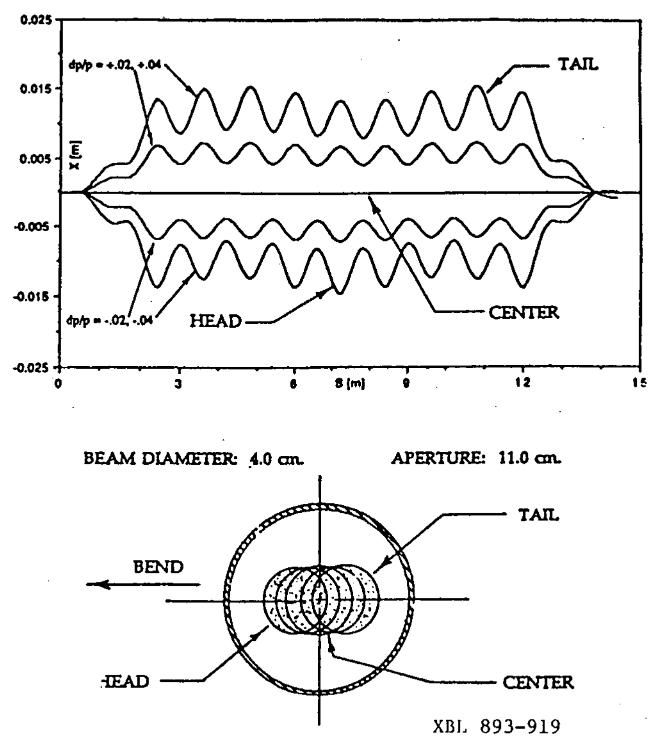


Fig. 2 Beam Dispersion in 180° Bend

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

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 filed. 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:

$$\frac{d^2L}{dz^2} = \frac{eE_z}{T} = -\frac{e}{T}\frac{g}{4\pi\varepsilon_0}\frac{\partial\lambda}{\partial z}. \qquad (1)$$

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

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

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

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

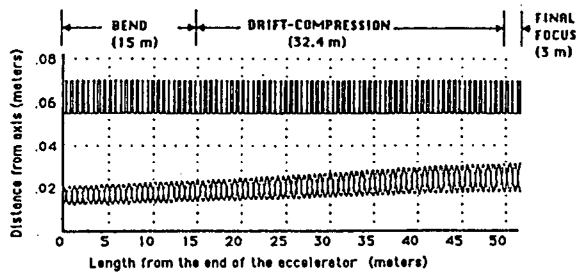
$$\text{compression ratio} = \frac{L_0}{L_f} = 1 + \frac{(\Delta\beta/\beta)^2}{S} \approx 2.1. \qquad (4)$$

The factor S is the dimensionless measure of space charge

$$S = \frac{8e}{T}\frac{g\lambda_0}{4\pi\varepsilon_0} \approx 5.4 \times 10^{-3}. \qquad (5)$$

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

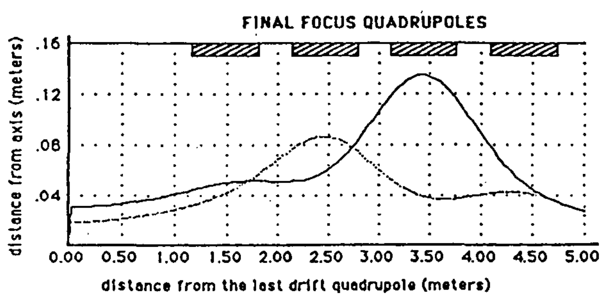
An ICF driver must provide high-energy, high-current beams focused to a radius of a few millimeters at the fuel pellet. This must be done with a standoff distance of approximately 10 m from the last final focus magnet. To accomplish this the beam would be expanded to a radius of 10 to 20 cm and then 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:

$$r_{spot} = \varepsilon/\theta. \tag{6}$$

For the expected (unnormalized) emittance at the end of ILSE of approximately 1 x 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 ~ 10%, and the velocity tilt which must be reduced to less than ±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.

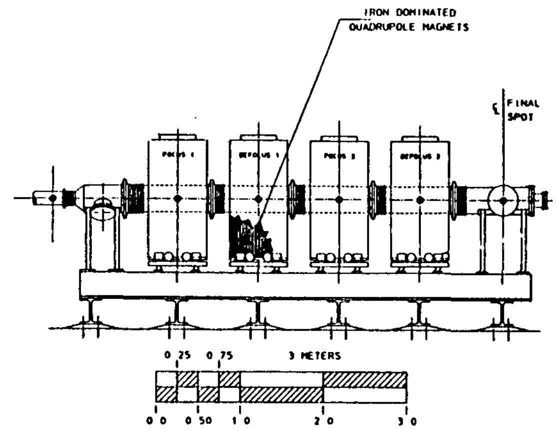
The specific ILSE final focus configuration consists of four magnetic quadrupoles arranged in a focus/defocus/focus/defocus string. Figure 4 shows a MATCH code solution for the beam envelope. The beam expands due to space charge between the final lens of the drift transport and the first final focus 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.



XBL 893-921

Fig. 4 Envelope calculations of the beam from the last quadrupole in the Drift-Compression section through the large final focus quandrupoles 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 ensueing 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.



XBL 892-568 A

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. Bubp, 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.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720