**Title**
The Development of Compact Magnetic Quadrupoles for ILSE

**Permalink**
https://escholarship.org/uc/item/6xp642pv

**Authors**
Faltens, A.
Mukherjee, S.K.
Brady, V.

**Publication Date**
1990-08-01

LBL-30340
UC-426

**Lawrence Berkeley Laboratory**
UNIVERSITY OF CALIFORNIA

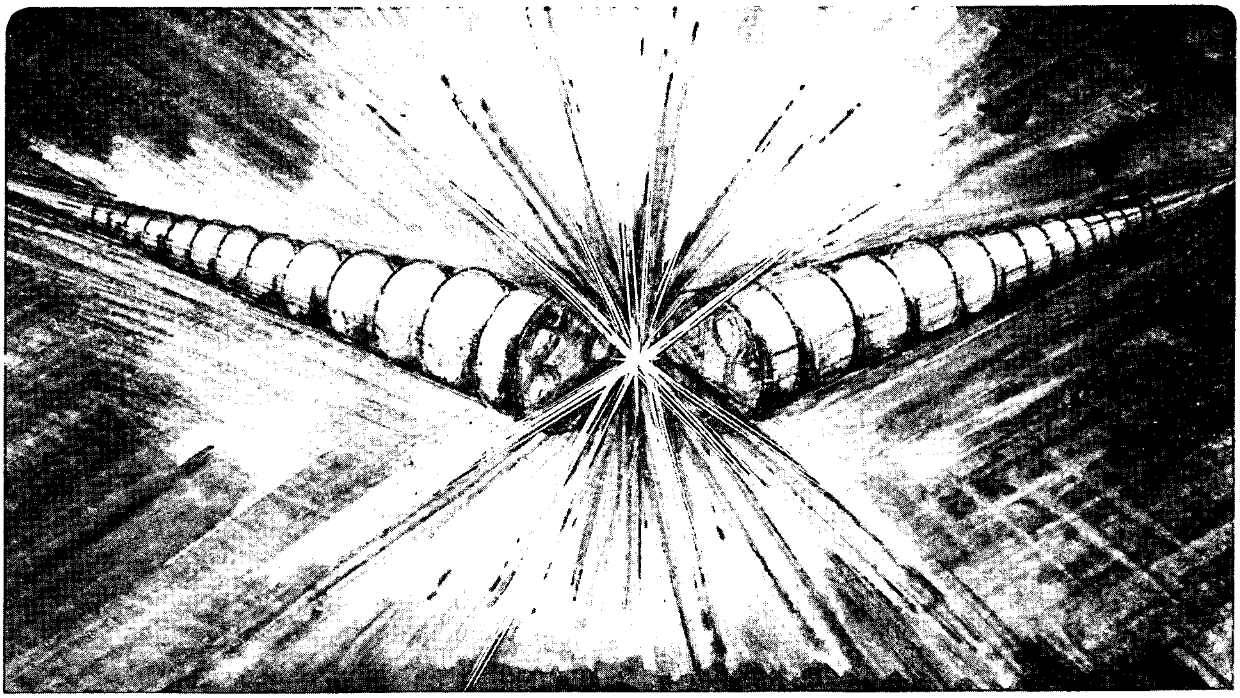
## Accelerator & Fusion Research Division

Presented at the International Symposium on Heavy Ion Inertial Fusion, Monterey, CA, December 3–6, 1990, and to be published in the Proceedings

# The Development of Compact Magnetic Quadrupoles for ILSE

A. Faltens, S. Mukherjee, and V. Brady

August 1990



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

## DISCLAIMER

# The Development of Compact Magnetic Quadrupoles for ILSE*

A. Faltens, S. Mukherjee, V. Brady, Lawrence Berkeley Laboratory,
1 Cyclotron Road, Berkeley, CA 94720 USA

## Abstract

Magnetic focussing is selected for the 4 MeV to 10 MeV section of the Induction Linac Systems Experiments (ILSE) to study the transport of magnetically focussed space-charge-dominated beams and to explore the engineering problems in accurate positioning of the magnetic fields in an array of quadrupoles.[1] A prototype development program for such magnets is currently under way. A compact design was selected to decrease the overall accelerator diameter and its cost. The design evolved from a cosine 2θ current distribution, corrected for end effects. Current-dominated magnets are used in a pulsed mode to allow higher current densities compared to standard dc water-cooled conductors. The POISSON and MAFCO codes were used in the design of the magnets.[2,3] The construction of the quadrupoles is aimed at achieving location accuracy of the magnetic center to within 1 mil ($2.54 \times 10^{-5}$ m) of the mechanical center.

## Introduction

The ILSE design includes the transport of 4 parallel beams in a transport system using arrays of four magnetic quadrupoles, as shown in Fig. 1. To maximize the transportable current, which is proportional to $(a/L)^2$, it is desirable to use the largest beam aperture, a, and the shortest half-period, L. As this is done, the magnets tend to have a large bore-to- length ratio and tend to be packed closely together in the axial direction. A consequence of such a design is that the end fields become a large fraction of the total field,

---

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

and it becomes increasingly difficult to maintain linear focussing fields in the integral sense. The initial goal was to try to achieve a 50% square-field-equivalent geometry with a bore radius of 5.5 cm and a half-period of 40 cm. This is still a reasonable goal for a future upgrade, ILSE', and the initial design proved useful for the bend section of ILSE. As the design of ILSE progressed, for various reasons the scope of the machine decreased somewhat, and as a consequence the bore could be decreased to 4.3 cm and the half period increased to 50 cm in the initial part and 60 cm in the downstream parts of the magnetically focussed portion of the machine. The design parameters are shown in Table I. Nevertheless, there is continuing interest in both the physical construction of more compact arrays of larger bore-to-length ratio magnetic quadrupoles and in the resulting beam-dynamics.

## Design and Construction of the Quadrupoles

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

A major consideration is the effect of the field leaking out of the ends of the magnet. Because of the asymmetry between the inside and outside boundaries in a 4-quad array, this leakage field is not centered on the axis of the quadrupole from which it emanates. The solution chosen for this problem was to extend the iron yoke axially past the windings for a sufficient distance for the field to decay to a low value. To decrease transverse asymmetries due to interactions between the magnets the iron yoke was limited to operating at the relatively low flux density of 18 kilogauss, where it still has a high permeability, and in this way the computed 2-D magnetic center of each quad could be kept within a mil of its mechanical tolerance.

The magnet windings were designed with the goal of making the first four higher allowed integrated multipoles vanish. This was accomplished by deviating from a cosinusoidal current distribution within the interior of the magnet by just enough to cancel the effects of the unequal lengths of the different turns, which are evident at the ends of the windings. The 3-D MAFCO code was utilized to compute the fields, without including the surrounding iron yoke. The main effect of a closely fitting yoke in this geometry is to increase the field strengths by a factor of about 1.7 and to shield the quadrupoles from each other. The quadrupole has 24 turns per pole, arranged in two layers with identical azimuthal distributions. These distributions represent a minor deviation from a $\cos 2\theta$ average current density distribution in which the density is controlled by the wire spacing. The lower allowed harmonics are countervailed, as discussed previously, and no effort is made to control the very high multipoles whose fields have a rapid decay towards the center. The conductor locations are machined on a lucite cylinder with an azimuthal accuracy of ± 7 minutes. A special assembly fixture accurately located the yoke and coil cylinders with respect to each other. The two cylinders are nested inside each other, with an 8 mil clearance which is filled with epoxy during the assembly of the coil package into the yoke. The orientation of the two coil forms is maintained during assembly by an indexing pin which is removed after final assembly. The interconnections of the coils are done such that the leads are twisted to decrease field errors. Measurements of the integrated fields would verify whether this design approach and the construction techniques were successful.

The pulsing circuit is a simple capacitive discharge through the coil inductance. An ignitron switch was chosen for the tests and the conceptual design, but SCR switching is another option. The current pulse is a half-sine of 1 ms base duration. This mode of operation reduces the temperature rise within the quad coils by getting the current into the windings and out of them in equal times, while leaving a flat top portion during which beam passes through the quad. The pulse duration is chosen with consideration of magnet heating, peak voltages, adequate flat-top for the beam, and adequate time for field diffusion through a stainless steel vacuum chamber threading the magnet bore. Because of the pulsed high-voltage operation, the windings are vacuum impregnated with epoxy. The nominal peak current is 1 kA, and the nominal peak voltage is 14 kV for driving the four quads in a cluster in series. The conductors are of sufficient size to make the resistive voltage small compared to the inductive voltage and to avoid large resistive losses; the resulting magnet inductance and resistance are 615 µHy and 0.275Ω.

The size of each lamina in the return yoke is approximately 14 cm, with a bore diameter of 12 cm. In order to decrease eddy currents, 14 mil thick M36 Silicon Steel Sheet with C5 insulation was selected. The laminations were punched from fully processed electrical steel with minimum burr at the edges. A stacking fixture was designed to index each individual lamina by its center bore for accurate mechanical centering and outside edge for proper squaring. After a light application of epoxy on the laminations, they were assembled on the stacking fixture and cured in an oven at 80 degrees centigrade.

## Measurements

The measurements of the field should show considerable deviation from a pure quadrupole field at any axial location, but a good approximation to it in an integrated measurement. The measurements for the local field distributions were made with a Hall probe using a low amplitude dc current excitation of the magnet. Cooling considerations limit the dc current to about 1% of the pulsed current value. The pulsed fields were measured with a narrow coil extending through the magnet well past the ends, and thus provide the integrated field data. The results of these field measurements are shown in Figs.#2 and 3. These results are preliminary in the sense that the measurement techniques are still being refined. The pulsed field measurements at the present time are not compatible with the usual technique of integrating the voltage from a rotating coil.

The pulsed current waveform is measured with a current transformer and is shown in Fig.4. There is a slight distortion of the current and the internal field early on in the pulse caused by eddy currents in the vacuum chamber. These die out exponentially with a time constant of about 30 μsec and have a negligible effect near the top of the current pulse when the short beam pulse would pass through. There is also expected to be a small amount of distortion from the eddy currents in the core laminations near the ends of the coils, from the axial components of the field and the anisotropic conductivity of the yoke. This problem, if serious, may be circumvented by using a wound wire yoke for the ends of the magnet, or lessened by spacing the end laminations loosely. Detailed measurements of the end field time dependence will establish whether this effect needs correction.

As this is a prototype developmental program, minor mechanical variations are incorporated in each magnet design which have little effect on the fields. The first of the three magnets built had shrinkage cracks in the epoxy casting and failed electrically at the conclusion of these tests during HV testing. The other two magnets passed the HV testing and field quality will be measured soon. All will be cut apart afterwards to measure the attained accuracy of locating the conductors. The major goals listed in Table I have been met and significantly lower-cost construction methods than used in the initial ILSE design have been developed.

## ACKNOWLEDGEMENTS

The contributions of L. Jackson Laslett, Craig Fong, Dave Vanecek, Jerry Stoker, Rudin Johnson, John Pruyn, and Eric Agol to the design, construction, and measurements of the quadrupoles are gratefully acknowledged.

## REFERENCES

1. Induction Linac Systems Experiments, Conceptual Engineering Design Study, March 1989, LBL PUB-5219.
2. M.T. Menzel and H.K. Stokes, User's Guide to the Poisson/Superfish Group of Codes LA-UR-87-115, 1987.
3. W.A. Perkins and T.C. Brown, MAFCO - A Magnetic Field Code for Handling General Current Elements in Three Dimensions, UCRL-7744 Rev. 2, 1966.

Table I. Design Parameters for the Magnetic Quadrupole

| | |
|---|---|
| Magnet bore diameter | 9.3 cm (3.661 inches) |
| Field at the edge of the bore | 8 kG |
| Gradient transfer function | 1.67 G/cm-A |
| Overall length | 25.78 cm (10.15 inches) |
| Effective length | 16.7 cm (6.614 inches) |
| Number of turns per quadrant | 24 |
| Type of coil winding | Cosine $2\theta$ |
| Current | 1 kA (Approx.) |
| Peak voltage for four quads in series | 14 kV (Approx.) |
| Conductor size | .2 Gm (nominal dia.) |
| Overall weight | 22 kg |
| Outside dimensions | 14 cm x 14 cm |

FIGURE CAPTIONS:

Fig. 1 The ILSE four quadrupole array.

Fig. 2a. $B_y$ as a function of x at the axial center of the quadrupole for a 10 Ampere de excitation. The poles are oriented at 45° from the axes of reference.

Fig. 2b. $B_y$ as a function of Z, the axial coordinate, at 92% of the magnet aperture radius. showing the relatively large fraction of "end fields."

Fig. 3a. $\int B_y dz$ as a function of x, and a reference line.

Fig. 3b. $\int \dot{B}_y dz$ from a long pickup coil extending through the magnet, and its (digital) time integral, $\int B dz$, showing the small time delay due to field diffusion through the vacuum chamber.

Fig. 4. Pulsed current waveform at full 1 kA excitation.