# A Quadrupole Magnet for the Fermilab Linac Upgrade

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*Abstract*

New quadrupole focusing magnets have been designed and are being tested and produced for use with the side-coupled accelerating structure of the Linac Upgrade at Fermilab. Beam dynamics calculations require 1.84 T-m/m for a 2 cm radius aperture. The choice of a $3\beta\lambda/2$ bridge coupler limited the longitudinal dimension of the magnet core to 7 cm. The magnet is pulsed at the linac's 15 Hz repetition rate which forced the development of new field quality measurement techniques. The studies that were made during the design of the magnet and the evaluation of a prototype will be presented in this paper.

## I. Introduction

A quadrupole magnet for an accelerator is conceptually a very simple device; the realities of a particular application force compromises in its design and eliminate some of this simplicity. The ideal quad would be much longer than its aperture so that end effects would be negligible. It would have wide hyperbolic pole pieces and a small pole-tip aperture. The coil would have a large number of turns to minimize the current required and be made of conductor with a large cross section to minimize the resistance and therefore the power requirements and heat generation. It would run DC to eliminate the concern for inductance and transient effects.

In terms of its effect on the beam, a quadrupole magnet must satisfy only two parameters, strength and quality. The quadrupole for the Upgrade is required to produce 1.84 T-m/m and must have a harmonic content of less than .1% of the quadrupole field at 1 cm. However, physical constraints imposed by the layout of the Upgrade project require compromises in the ideal features of a quadrupole mentioned above.

The accelerating structure for the Linac Upgrade at Fermilab is a series of side-coupled cavities. The gaps between sections of cavities were chosen to be $3\beta\lambda/2$, which at the low energy end of the structure turned out to be 26 cm. Into this space must be squeezed 2 bellows, the quad, and combinations of wire scanners, beam position monitors, current pickups, steering elements, and vacuum valves. This allowed 8.6 cm for the quadrupole. The cavity aperture, and therefore the pole-tip aperture, was chosen to have a radius of 2 cm.

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## II. Design

### A. Physical Design

The 8.6 cm must include as much iron length as possible to lower current requirements and keep end effects small. It must also include as much conductor as possible to keep the current low and to lower heat production. A single layer stack was chosen to optimize these demands which allowed 7 cm for the core length. The harmonic quality requirement dictates how wide the hyperbolic pole face needs to be. It was decided to minimize the heat production by using a pulsed power supply. This gave a duty factor of 3% but added the complication of inductance and eddy currents. With the gradient and aperture defined, the number of turns in the stack is about the only free parameter. Figure 1 shows how the number of turns affects the current, inductance, resistance, reactive voltage, and power requirements. For the Linac Upgrade quad, a single layer of 25 turns was chosen.

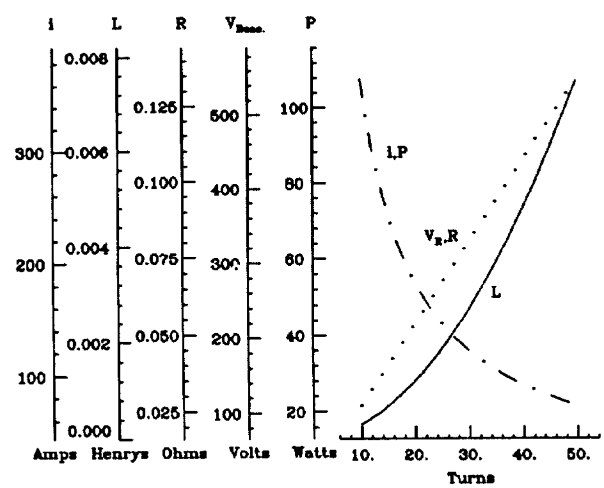


Figure 1. The dependence of various quadrupole parameters on the number of conductor turns in a magnet of otherwise fixed geometry.

Part of the compromise between iron length and space taken by the conductor was to not cool the coils directly so that the space normally taken up by the water path could be used for conductor. Cooling tubes were placed in the iron of the core. Since some of the cooling is through radiation and air convection, the cooling tubes are to make sure that temperatures do not get so high that the magnet poses a safety hazard. Figure 2 shows an outline of the final configuration.

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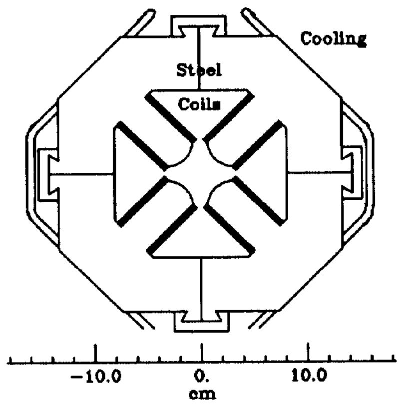


Figure 2. Outline of the quadrupole for Fermilab's Linac Upgrade.

*B. Poisson Analysis*

Once the potential geometry was determined, the magnet was simulated with Poisson. This enabled verifying the current, inductance, and harmonic content, and made sure that the iron would not be saturated. Of the allowed harmonics ( n = 6, 10, etc.) in an unperturbed magnet, Poisson showed that none would be larger than $3 \times 10^{-4}$ of the quadrupole field at r = 1 cm.

Another result of the small space in which the quadrupole resides was that it had to be removable to allow maintenance to it and other components near it. This along with the geometry of the coils and poles dictated that the magnet be made of four pieces. Therefore, the effects of assembly errors needed to be investigated. Poisson was used to simulate a 1 mill gap in the backleg and a 1 mill displacement in the pole position. The results were $2 - 3 \times 10^{-4}$ of the quadrupole field. However, due to the finite mesh of Poisson it is hard to determine the accuracy of this value.

*C. Analytical*

To try to get a better feel for the distortion induced by a back leg gap, an analysis was conducted based on work by Halbach [1]. The results of this indicated that a two mill gap would induce errors only on the order of $1 \times 10^{-4}$ of the reference quadrupole field.

Many quadrupoles are assembled from halves. In laminated versions of these, the laminations are alternately flipped to average out any errors in pole position. However, this risks degrading the quality of the pole face if there are deviations in the contour of the face. Since the Upgrade magnet was made from four pieces, the laminations were not flipped in order to preserve as much of the pole shape as possible. This is consistent with the analysis of Halbach. Halbach's analysis also suggested that the four core pieces should maintain a rotational symmetry so that as much of the quadrupole symmetry as possible be retained despite any perturbations in the pole.

## III. Testing

Once the constraints of the application had been incorporated into the design, a prototype was built for evaluation to make sure it met the various performance criterion. After the prototype was built, it was taken to Fermilab's Magnet Test Facility to evaluate its harmonic content. Figure 3 illustrates the testing process.

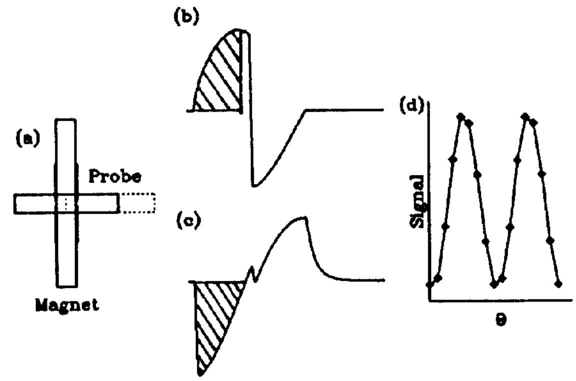


Figure 3. a) Orientation of probe w.r.t. the magnet. b) Current waveform supplied to magnet. c) Induced quadrupole signal. d) Variation of induced signal w.r.t. probe rotation angle.

A Morgan coil probe with windings for n = 1-7 was passed through the magnet, extending beyond the field on either side. In DC magnets, the probe rotates about the beam axis through 360° through the static field. As the angle of the coils vary, signals are induced in the coils as the flux passing through them varies. In the Upgrade's pulsed magnet the changing excitation induced the signal in the static coil. The current waveform supplied to the magnet is shown in Figure 3b. (Just beyond the peak, the power supply is rectified, and the energy in the magnet is recovered.) The signal induced in the coil for the quadrupole field is shown in Figure 3c. The area of the shaded portion is calculated by digitizing the waveform and summing numerically. The variation of this area with probe angle, Figure 3d, gives the same information as for the DC magnet. The information was passed through a Fast Fourier Transform (FFT) which broke the signal down into its n-tupole components. Most of this was automated under the control of a personal computer (PC). With the magnet power supply pulsing, the PC rotated the coil and armed the digitizer. The magnet pulse trigger was fanned to the digitizer. Once the digitizer had been armed, it recorded the signals from each of the coils after the next trigger. The waveform of the current was also digitized. The PC then integrated each waveform and normalized them to a constant current value to remove any fluctuations in the current over the course of a measurement. Then the coil was rotated and the sequence was repeated. After a complete revolution, the signal areas as a function of angle were stored on disk.

Next, the FFT analysis was performed giving the results shown in Table 1. Each column is the result from one of the seven coils on the probe. Each row is the FFT breakdown for each harmonic for those coils. The results are expressed in Units, where a unit is 1 part in $10^4$ of the reference field (in this case the quadrupole field). The results in Table 1 were measured at a radius of 1.6 cm, whereas the limits on field quality were stated at 1 cm. Renormalizing to 1 cm gave the results shown in Table 2. The results on the diagonal from upper-left to lower-right are the most significant. The 160 units of dipole field indicate that the probe was off center with respect to the magnetic field by .016 cm (6 mills). The sextupole contribution is 40 units. The goal set for the Upgrade was 10. There are also 9 units of dodecapole.

Table 1
Measured Harmonic Components at 1.6 cm

| FFT Harm | /Pole | 2-P Coil | 4-P Coil | 6-P Coil | 8-P Coil | 10-P Coil | 12-P Coil | 14-P Coil |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 101 | 14 | 0 | 0 | 0 | 0 | 0 |
| 2 | 4 | 129 | $10^4$ | 11 | 6 | 6 | 1 | 6 |
| 3 | 6 | 74 | 24 | 63 | 1 | 0 | 0 | 0 |
| 4 | 8 | 21 | 23 | 1 | 8 | 1 | 1 | 0 |
| 5 | 10 | 20 | 16 | 1 | 1 | 7 | 0 | 0 |
| 6 | 12 | 6 | 55 | 1 | 2 | 4 | 56 | 2 |
| 7 | 14 | 26 | 16 | 3 | 2 | 1 | 1 | 6 |

Table 2
Harmonic Components Renormalized to 1. cm

| FFT Harm | /Pole | 2-P Coil | 4-P Coil | 6-P Coil | 8-P Coil | 10-P Coil | 12-P Coil | 14-P Coil |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 160 | 22 | 0 | 1 | 0 | 0 | 0 |
| 2 | 4 | 129 | $10^4$ | 11 | 6 | 6 | 1 | 6 |
| 3 | 6 | 47 | 15 | 40 | 0 | 0 | 0 | 0 |
| 4 | 8 | 8 | 9 | 0 | 3 | 0 | 0 | 0 |
| 5 | 10 | 5 | 4 | 0 | 0 | 2 | 0 | 0 |
| 6 | 12 | 1 | 9 | 0 | 0 | 1 | 9 | 0 |
| 7 | 14 | 3 | 2 | 0 | 0 | 0 | 0 | 1 |

The $z$-dependence of the field was measured by withdrawing the probe along $z$ in steps (the dotted position in Figure 3a) and running the analysis at each step. This made it possible to get a good measurement of the effective length of the magnetic field. The points in Figure 4 show the strength of the integrated field as a function of $z$. Within 2 cm of the center, the integrated field varies linearly. Dividing the total integrated field by the slope at the center gave an effective length of 8.53 cm. Using this value and a cubic spline fit, the solid line in Figure 4 was produced. Its first derivative (dashed) gives an indication of the shape of the field.

The prototype magnet had 24 turns. Taking the integrated field and the probe radius and correcting to 25 turns, one finds that the magnet will produce the required 1.84 T-m/m at 170 amps which is within the design limit.

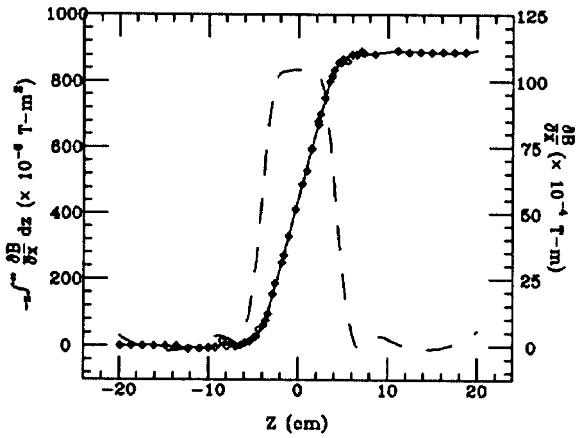


Figure 4. Integrated field, $\int_{-z}^{\infty} \frac{\partial B}{\partial x} dz$ with cubic spline fit (solid) and first derivative $\frac{\partial B}{\partial x}$ (dashed) as measured by withdrawing probe from aperture.

In performing the $z$ measurements, it was observed that the sextupole field was discontinuous in $z$. The discontinuity, about 20% of the total sextupole field, seemed to correlate with changes in the thickness of a backleg gap found in one of the four joints. However, while the discontinuity may be due to the gap, it is unclear whether all of the sextupole is due to it.

The prototype magnet was not assembled according the the prescription of Halbach, with the quadrants oriented in rotational symmetry; one of the quadrants was flipped. In analyzing the sextupole, both the Halbach and Poisson studies show that the sextupole induced by a two mill gap should be at most 6 units. A study was done where shims of various sizes were placed in one joint. A plot of shim thickness versus sextupole was a straight line with a slope that agreed with the predictions of the Halbach and Poisson studies but with a 36 - 40 unit offset at zero shim thickness. This indicated that there was a second source of the sextupole and suggested that the core orientation may be the more important factor.

## IV. Summary

A quadrupole magnet for the Fermilab Linac Upgrade has been designed. Tests indicate that it has the required strength. Magnetic measurement techniques presently in use at Fermilab have been successfully adapted to pulsed magnets and the measurements of the harmonic quality are close to the required values. Further investigations in the source of the sextupole field, such as core orientation, are planned.

## V. References


1. K. Halbach, "First Order Perturbation Effects in Iron-Dominated Two-Dimensional Symmetrical Multipoles," Nuclear Instruments and Methods, vol. 74, pp. 147-164.