# Sextupole Magnets for the Fermilab Main Injector

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*Abstract*

A sextupole magnet has been designed to satisfy the dynamical, geometrical, and electrical requirements of the Fermilab Main Injector. The steel length is 0.457 m. The top and bottom pole tips are 26.4 mm from the center line; the side pole tips are 48.0 mm from the center line. The design integrated strength is 55 T-m/m$^2$ at 294 A.

## I. Introduction

The natural chromaticities of the Fermilab Main Injector [1, 2] (FMI) are -33.65 horizontally and -32.87 vertically. The lattice has been designed to have low $\beta$ and $\eta$ (58 m and 1.9 m are the maximum values). Thus, very strong sextupoles are needed to cancel natural chromaticity. The configuration chosen places an F(D) sextupole at each F(D) main quadrupole in the arcs, where $\eta$ is significant. The sextupoles must also compensate for large sextupole components in the dipole magnets induced by saturation of the steel as the energy approaches 150 GeV and by eddy currents in the beam pipe. These effects produce inherent chromaticities of -77 horizontally (at 150 GeV) and -55 vertically (near 20 GeV).

The chromaticity sextupole magnets for the FMI are a new, nonsymmetrical design, tailored to the geometrical, optical, and electrical requirements of the ring.

## II. Requirements

We take as a requirement that the sextupoles be capable of producing a corrected chromaticity of 10 in each plane through the entire ramp, -10 below transition and +10 above transition. The sextupole requirements have been calculated using the natural chromaticity and the measured sextupole contributions from the dipoles[3]. The sextupoles need to have a peak integrated field strength of 55 T-m/m$^2$. We were restricted by space to to a steel length of 0.457 m (18 in). This leads to a field strength of 120 T/m$^2$. The beam pipe size limits the dimensions of the pole faces.

The cost and complexity of fabrication, installation, and operation of the magnets, the power supplies, and the buses must also be taken into account. The dipole end packs have been designed to provide a sextupole component small enough that the sextupoles may be run on a unipolar power supply. To allow use of 300 MCM cable for the bus work, we want to keep the root mean square current under 200 A during all of the operating modes except the short duration Collider injection cycles. The reduction of the current by the usual technique of increasing the number of turns increases the inductance. The rapid change in the current needed in switching the sign of the chromaticity at transition limits the allowable inductance.

To allow convenient testing of the magnets at peak field, the cooling water circuits must be capable of cooling the coil during DC operation at the peak current.

## III. Conceptual Design

The conceptual design of the FMI sextupole was done using the spreadsheet program 20/20. A model of the sextupole cross section was built in a worksheet. Input parameters include the required integrated field strength, the magnet length, the number of turns in the coils, and the pole tip radius (distance of closest approach of the pole tip to the central axis). From this we obtain the required current.

Adding the conductor cross section dimensions, including the central hole for cooling water, allows calculation of resistance, power dissipation, water flow, and thus temperature rise. Adding a few additional dimensions and angles allows calculation of corner coordinates of the lamination and conductor. The spreadsheet plots the corners and points along the pole face and presents a fairly good picture of the magnet. It also calculates some critical clearances where the coils will need to slip past the poles during assembly. Material quantities are calculated to provide a cost estimate.

The model was used to try a large number of combinations of magnet parameters. The chosen design satisfies the requirements while striking a balance among the other

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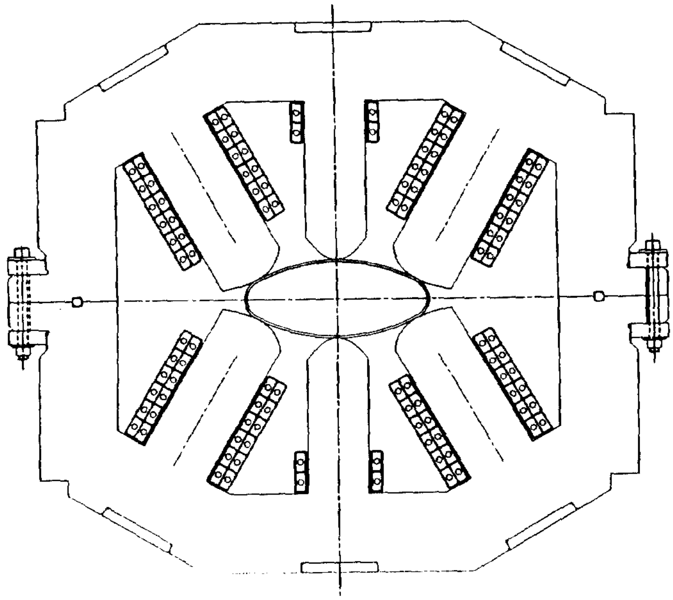

Figure 1: Cross section of the Fermilab Main Injector Sextupole showing the lamination, conductors, and beampipe

competing design factors. To reduce the resistance and inductance of the magnet the design is not six-fold symmetric, but rather matches the beam pipe with top and bottom poles that are closer to the axis than are the side poles. The number of turns on the top and bottom poles is correspondingly smaller. The cross section of the magnet is shown in Figure 1. The basic magnetic, electrical, and mechanical properties are summarized in Table 1. The six coils are connected in series electrically. In operation the water paths will be connected in series as well. During testing the top and bottom halves will be cooled in parallel to allow running DC at the peak current.

A portion of the worksheet was arranged to generate an input file for the detailed magnetic modeling program PE2D. This allowed maintenance of the full two-dimensional magnetic model in synchrony with the other properties. It allowed testing changes to the magnet model by varying a single worksheet parameter and propogating the changes through to the magnetic model, avoiding typographic errors or inconsistancies.

We have also studied the sensitivity of the field purity to the position of the pole tip. Experience has shown that during production the largest variations in the lamination geometry come in the distance between poles, not in the shape of an individual pole. We moved a single pole tip by varying amounts, ran the model, and analyzed the resulting field for its harmonic components. Figure 2 shows the effect on all normal harmonics up to the decapole of moving one pole horizontally by varying amounts. The quantity plotted is the field one inch from the magnet center due to the relevant component normalized to the field due to the sextupole component at one inch. Note the non vanishing decapole field resulting from the assymetric crossection. Figure 3 shows the effect on the skew components of horizontal motion. As expected from the symmetry, all components vanish in the unperturbed case. The effects of vertical motion are comparable.

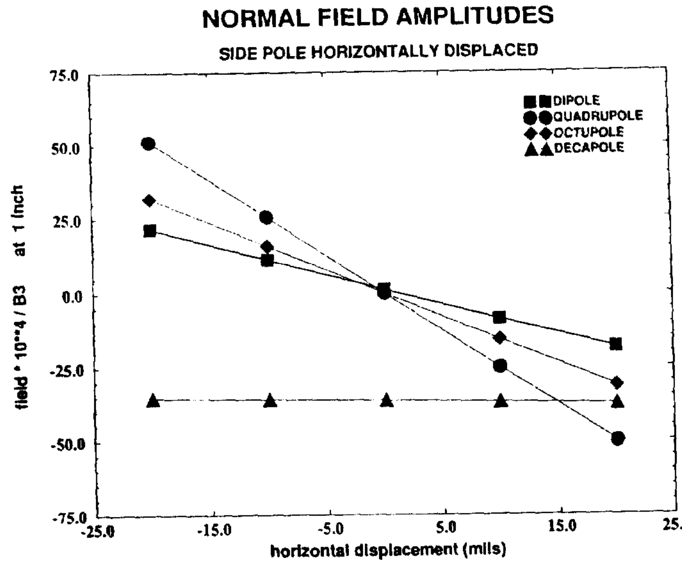


Figure 2: Normal Field Component Amplitudes as a Function of Horizontal Displacement of One Side Pole

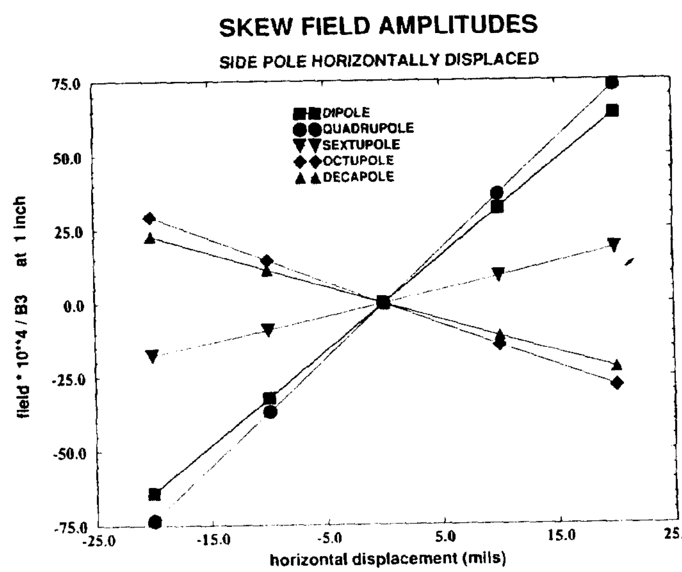


Figure 3: Skew Field Component Amplitudes as a Function of Horizontal Displacement of One Side Pole

## IV. Mechanical Design

The half-cores of the FMI sextupole will be fabricated from stamped steel laminations. The laminations will be

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|---|---|
| Integrated field (peak) | 55 T-m/m$^2$ |
| Length | 0.457 m (18.0 in) |
| Field (peak) | 120 T/m$^2$ |
| Color | Yellow |
| Pole tip radius<br>top/bottom<br>sides | <br>26.4 mm<br>48.0 mm |
| Number of turns<br>top/bottom<br>sides | <br>2<br>12 |
| Current (peak) | 294 A |
| Conductor | 6.35 mm x 12.7 mm<br>(0.250 in x 0.500 in) |
| Resistance | 4.2 m$\Omega$ |
| Inductance | 0.7 mH |
| Water flow | 0.019 l/s @ 0.070 kg/mm$^2$<br>0.30 gpm @ 100 psi |

Table 1: Main Injector Sextupole Magnet Parameters

stacked on a dedicated fixture and compressed with a screw mechanism. The outside edges will be held together by bars inserted in notches in the laminations and welded down the length of the core. The pole tips will be held in compression by steel rods threaded at one end to accept a nut and washer.

The copper conductor will be insulated as it is wound onto a bobbin. The coil will then be ground wrapped, impregnated with epoxy in a mold, and cured. The coils will be installed into the half cores and brazed together in series.

The two half core assemblies will be bolted together to form a complete magnet. After testing, the complete magnet will be stored until it is needed in the tunnel. Installation will require separating the magnet into its halves and reassembling it around the beam pipe in the tunnel.

## ACKNOWLEDGMENTS

We would like to thank Alex Bogacz for his calculations regarding the beam requirements for the sextupoles and Phil Martin for several useful suggestions on the design. Dick Wegforth has done most of the design drawings.

## REFERENCES

[1] Fermilab Main Injector. Title I Design Report, August 1992.

[2] V.D. Bogert, W.B. Fowler, S.D. Holmes, P. Martin, and T. Pawlak. Status of the Main Injector Project. In *Procedings this conference.*

[3] S.A. Bogacz. Chromaticity Compensation Scheme for the Main Injector. In *Procedings this conference.*