MAGNETIC FIELD STRENGTH AND SHAPE MEASUREMENTS OF THE FERMILAB MAIN INJECTOR QUADRUPOLES

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Abstract

All of the new quadrupoles for the Fermilab Main Injector ring have been built and measured. The magnets are 2.95 m and 2.54 m in length with a 41.7 mm bore. In operation, the magnets run from 1.61 T/m at 8.9 GeV/c to 15.7 T/m at 120 GeV/c and 19.6 T/m at 150 GeV/c. These points correspond to injection, Main Injector fixed target physics and antiproton production, and extraction for transfer to the Tevatron. Good field uniformity is required to ensure a stable beam over the whole acceleration cycle. A significant octupole is included to assist in resonant extraction. The performance of these quadrupoles, in both integrated strength and field uniformity, is presented. All magnets produced meet the accelerator requirements.

1 MAGNETIC REQUIREMENTS

The Fermilab Main Injector is a new proton and antiproton accelerator currently under construction at Fermi National Accelerator Laboratory [1]. It will replace the existing Main Ring in all functions. While many of the quadrupoles used in the Main Injector will be reused from the Main Ring, the lattice requires some new quadrupoles of the same design but different lengths to run on the same busses. Some key design parameters are shown in Tables 1 through 3. The performance requirements of the quadrupoles have been studied extensively [2] [3] [4]. The two significant areas of magnetic performance are the magnet-to-magnet variation in the integrated magnetic field ("strength") and the variation of the strength as a function of transverse position ("shape"). These are discussed here separately.

Parameter	Value
Pole Radius	41.68 mm
Number turns / pole	4

Table 1: Basic Main Injector magnet parameters.

Magnet Type	IQB	IQD	IQD
Steel length (m)	2.134	2.540	2.946
Effective length (m)	2.118	2.522	2.930
Number in Ring	128	32	48

Table 2: Lengths of Fermilab Main Injector quadrupoles.

	Injection from Booster	FMI Fixed Target and P-Bar Production	Extraction to Tevatron
Momentum	8.9 GeV/c	120 GeV/c	150 GeV/c
Gradient	1.20 T/m	16.15 T/m	20.19 T/m
B at pole	0.0500	0.6744 T	0.8430 T
Current (A)	207	2830	3560

Table 3: FMI quadrupole strengths..

1.1 Strength

We define the strength to be $\int_{-\infty}^{\infty} (dB_y / dx) dz$ The integral is taken at the center of the aperture. When discussing relative strengths we quote fractional differences in "units" of parts in 10^4. The majority of our tracking studies have assumed a root mean square deviation of the strength of 24 units.

A systematic difference from nominal in the ratio of IQD strength to IQC strength of 25 units produces a negligible beta wave, and up to 50 units would be tolerable.

1.2 Shape

We define the shape to be the variation in the strength as a function of position. We characterize the field by its harmonic decomposition. The normal component of a quadrupole's field can be reconstructed as

$$B_y(x) = B_1(b_1 + 1(\frac{x}{r_0})^1 + b_3(\frac{x}{r_0})^2 + b_4(\frac{x}{r_0})^3 + ...),$$

where B_1 is the quadrupole strength, b_n are the normal harmonic components. We quote the components at r_0=25.4 mm and in "units" of parts in 10^4. Properly centered, the dipole component b_1 is zero.

From the symmetry of the magnet design we expect the field to have significant quadrupole, octupole, and twelve-pole components. For our tracking studies we have assumed distributions of the forbidden components that are consistent with the measured spread in values.

Given the known octupole component in the existing Main Ring quadrupoles, we chose the octupole of the new quads to meet the beam dynamics needs. The octupole has two demands placed upon it. One need is that the dynamic aperture be large enough to meet the accelerator requirements. The beam

should not fall out of the machine on its own. The other need is that the beam be close enough to the edge of stability so that the existing trim octupoles can bring the beam to the point of slow extraction. Based on simulations, an average of 4 to 8 units appears to satisfy both requirements. Magnet-to-magnet variations are not significant dynamically.

The tracking studies assume 12-pole components based on old measurements of a sample of Main Ring quadrupoles. The simulation uses -1.49 ±0.63 units at 8.9 GeV/c and -1.86 ±0.16 at 120 GeV/c.

2 MEASUREMENT SYSTEMS

All magnets were measured with a rotating Morgan-style coil, and most were also measured with a single wire stretched wire system to provide redundancy and a better absolute calibration.

The Morgan coil extends through the length of the magnet. The probe has two orthogonal dipole coils, two orthogonal quadrupole coils, and one each sextupole, octupole, decapole, 12-pole, and 20-pole coils. One quadrupole coil is used to measure the strength of the magnet. The other coils measure the harmonic components while suppressing the signal from the quadrupole field. The rotating coil measurements are performed at multiple currents on every magnet, measuring on both the up ramp and the down ramp.

The single stretched wire system moved a single wire to multiple positions in the magnetic field. The field was measured at a limited number of currents for each magnet, providing a constant cross-check of the rotating coil data.

3 MEASUREMENT DATA

We present data on the IQC and IQD magnets. The IQB magnets, the 84 inch Main Ring Quadrupoles, are still in use in the Main Ring. All of the quadrupoles that will be used in the Main Injector will be measured after they have been removed from the tunnel and refurbished.

3.1 Strength

We have averaged the strength over all magnets of each type, excluding only the first seven IQC's. There are slightly larger strength variations among those magnets due to experimental modifications to the laminations. The mean can be compared to a strength calculated assuming infinite permeability. These differences are plotted in Figures 1 and 2. We also calculated the RMS deviation from the mean of the magnets of each type and display the results in the same figures. This spread in strengths is well within the acceptable range.
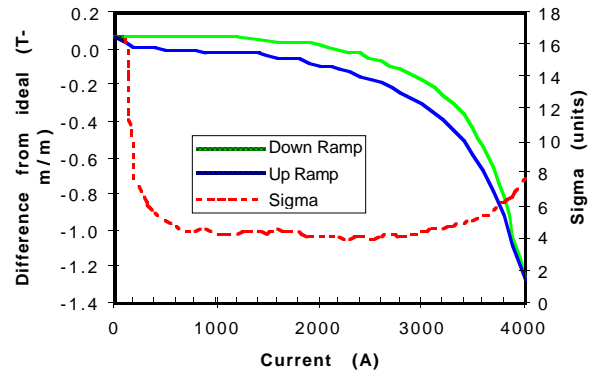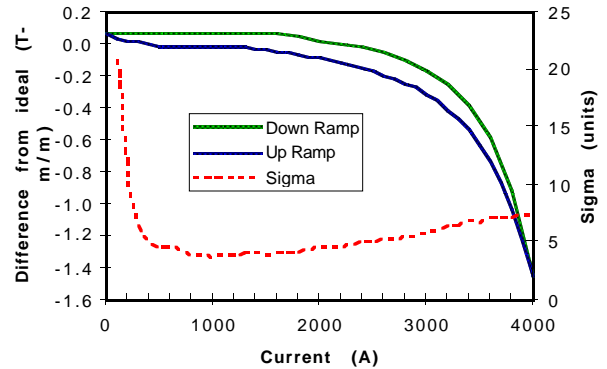

Figure 1. IQC strength.

Figure 2. IQD strength.

We write the fractional difference between the design strength ratio and the measured strength ratio:

$$\frac{\left(\dfrac{S_{IQC}}{S_{IQD}}\right)_{measured} - \left(\dfrac{S_{IQC}}{S_{IQD}}\right)_{nominal}}{\left(\dfrac{S_{IQC}}{S_{IQD}}\right)_{nominal}} x10^4$$

This quantity is plotted in Figure 3. It is everywhere well under the specified 25 unit threshhold for paying attention to it.

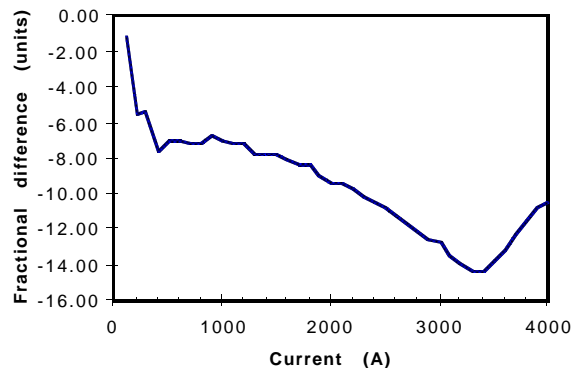Figure 3. Fractional difference between measured IQC/IQD ratio and nominal.

3.2 Shape

Figure 4 shows the mean octupole component of the newly constructed quadrupoles as a function of current. The value falls comfortably in the allowed range. The sigma of the distribution is everywhere less than the value used in the tracking studies.
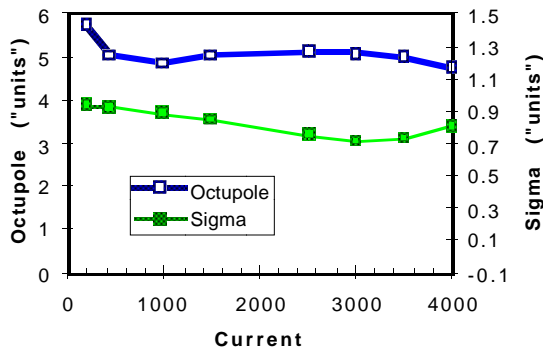

Figure 4. Octupole component of quadrupoles.

Figure 5 shows the mean 12-pole component of the newly constructed quadrupoles as a function of current. The mean value at injection is slightly higher than has been used in the tracking studies, but the spread in values is much tighter. Further studies will be required.
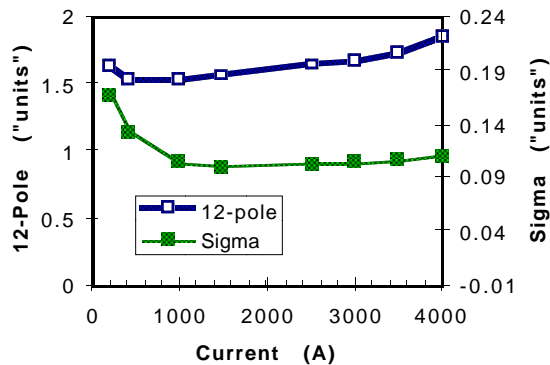

Figure 5. 12-Pole component of quadrupoles.

3.3 Hysteresis

In general we want to be able to run an arbitrary mix of accelerator cycles, intermingling ramps to 120 GeV/c and 150 GeV/c. At injection the magnets are at a low enough field (pole tip field 0.0500 T) that hysteretic effects can be noticeable, so we must pay attention to the history of the magnet. At the end of each ramp cycle we expect to lower the current below the injection level to a "reset level", then return to the injection level. The further below the injection excitation we make the reset level, the less memory the magnet has of the maximum excitation level on the previous ramp cycle when we return to the injection level.

To study this effect we have measured the strength of a quadrupole at the injection excitation after each of several ramp cycles to different maximum excitation and with different reset levels. This is not a perfect measurement, because the power supplies currently in use at the Fermilab Magnet Test Facility do not "invert", or generate a negative voltage to drive the current down as fast as the FMI ramp will run. None the less, we believe that in these magnets the effect of overshoot due to eddy currents in the laminations is small.

Figure 6 demonstrates that at injection we are insensitive to the energy of the previous ramp cycle even if we do not use a reset level below the injection field. Each data point was taken at 200 A, approximately the 8.9 GeV/c injection current, after running the magnet up to a maximum current I_{max} then down to reset current I_{min}. For each reset current five cycles to the 120 GeV/c level were followed by five cycles to the 150 GeV/c level. We are sensitive to the reset level used, and must control this carefully to maintain a stable tune at injection. The effect of running the current to 0A before each super-cycle is clearly seen in the first data point at each I_{min}.
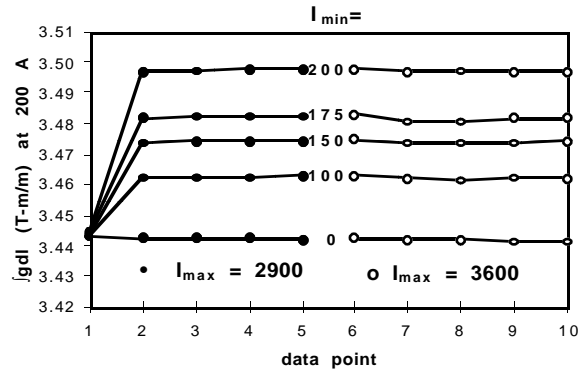

Figure 6. IQD052-0, ∫gdl at 200 A.

4 CONCLUSIONS

We have constructed and measured all of the new quadrupoles that we will build for the Fermilab Main Injector Ring. They meet our expectations and do not appear to offer any serious problems to the operation of the Main Injector.

REFERENCES

[1] S.D. Holmes, et. al. "Status of the Main Injector and Recycler," *these proceedings.*
[2] C.S. Mishra P.S. Martin D.J. Harding, H.D. Glass and B.C. Brown. Fermilab Main Injector Magnet Acceptance Criteria," *Proceedings of the Particle Accelerator Conference (1995).*
[3] C.S. Mishra. "Requirement of the Fermilab Main Injector Quadrupole Strength Matching," *Proceedings of the Particle Accelerator Conference (1995).*
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