MAGNETIC FIELD MEASUREMENTS OF THE INITIAL FERMILAB MAIN INJECTOR PRODUCTION QUADRUPOLES[*]

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Abstract

A large sample of the 2.54-meter quadrupoles for lattice matching in the Fermilab Main Injector have been fabricated and measured. The resulting properties are reported and compared to the accelerator requirements.

I. Magnet requirements

The Fermilab Main Injector is a new proton and antiproton accelerator currently under construction at Fermi National Accelerator Laboratory. 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 (2.54 m and 2.96 m, compared to 2.13 m for the Main Ring quads) to run on the same busses. The performance requirements of the quadrupoles have been studied extensively [1] [2] [3]. 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.

A. 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 fraction differences in "units" of parts in 10^4.

Based on experience, we expected to be able to hold the variation in strength to 10 units (10×10^{-4}). The majority of our tracking studies have used the more generous assumption of a root mean square deviation of 24 units and have found that with that distribution we only need to select which magnet is placed on which bus (focussing or defocussing).

B. 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

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

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. While these values are larger than the measurement errors and not yet understood, they have no significant impact on the beam dynamics. We concentrate here on the allowed components.

Given the known octupole component in the existing Main Ring quadrupoles, we could choose 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. The beam should fall out of the machine given a little push in the right direction. Based on simulations, an average of 4 to 8 units appears to satisfy both requirements. Magnet-to-magnet variations are not significant dynamically.

The twelve-pole component is clearly measurable, but not large enough to pose a problem for the dynamic aperture of the accelerator. Reasonable variations in the twelve-pole are not significant.

II. Measurement systems

The equipment and software used in measuring the magnets is described with more detail in other papers at this conference and elsewhere [4]. The request from the Main Injector project is that every magnet be measured and that in production the strength and shape be determined by at least two independent methods.

To date only a rotating coil system, using a Morgan coil that extends through the length of the magnet, has been implemented. 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.

A single wire stretched wire system is currently being commissioned. This will provide the redundant strength and shape information requested, as well as magnet center data.

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III. Measurement Data

A. Strength

We have averaged the strength at each current. Figure 1 shows the deviation of the average strength from a linear excitation calculated assuming infinite steel permeability.

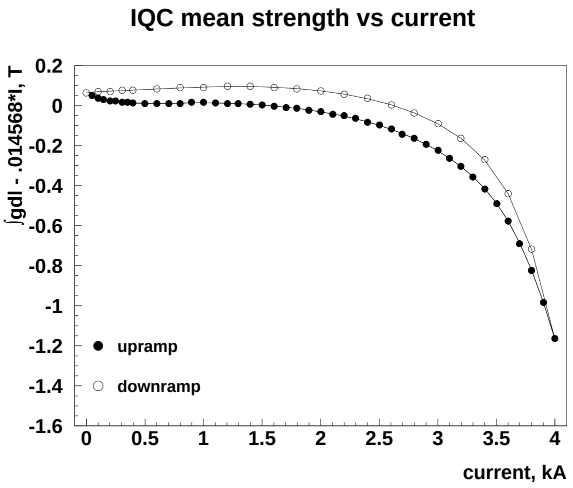

Figure. 1. Deviation of average quadrupole strength from linear vs current

To present the magnet-to-magnet variation, we calculate the fractional deviation of individual magnets from the average. Figure 2 shows the strength at 500 A for all magnets in the sample, relative to the average of all magnets except the first seven. Those seven magnets are significantly different from the later magnets due to experimental modifications of the lamination. In the low current regime the strength is dominated by the geometry, with only a small contribution from the permeabilty of the steel. Note that the strengths are tightly clustered, indicating good control of the geometry. All magnets fall within the expected range. Similarly, even as the steel begins to saturate, the spread in strength is small, as shown in Figure 3.

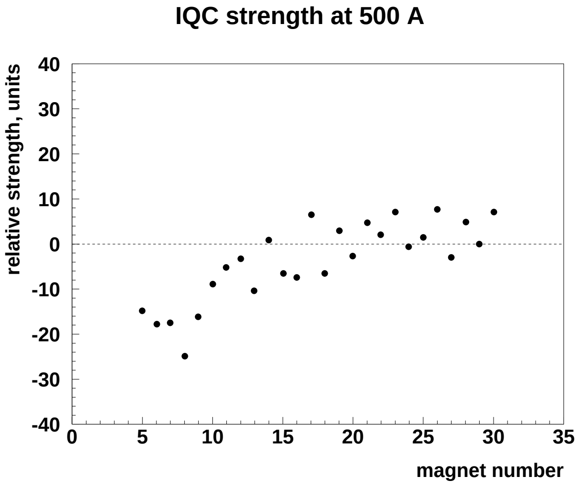

Figure. 2. Relative strength of quadrupoles at 500 A

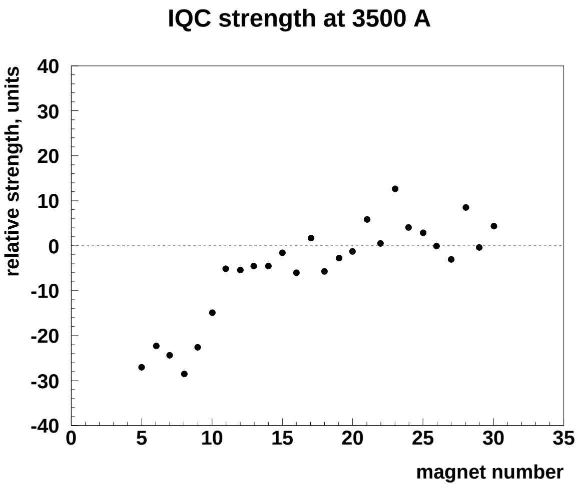

Figure. 3. Relative strength of quadrupoles at 3500 A

B. Shape

Figure 4 shows the average octupole b_4 as a function of current. This meets both the need for stability and for slow extraction. The octupole strengths are histogrammed in Figure 5. All magnets fall near the target values, and the average is certainly acceptable. The distribution of the twelve-pole component at 1500 A is shown in Figure 6. It is also within the established limits.

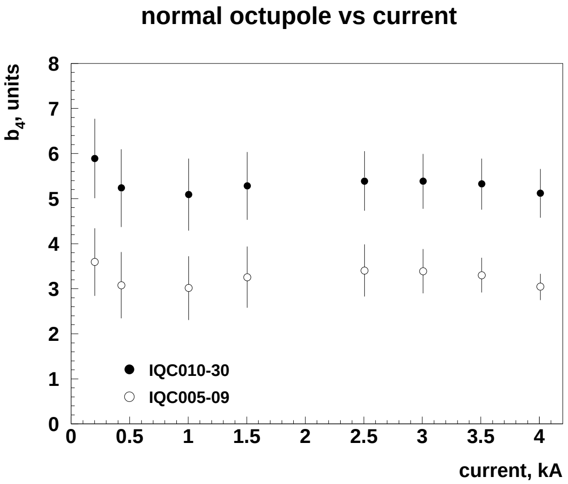

Figure. 4. Average octupole component vs current

IV. Conclusions

The Fermilab Main Injector project is well into production of the new quadrupoles for the ring. By the end of March 1995 30 2.54 m quadrupoles, out of 32 required for the ring, had been completed and measured. Magnet performance is within the acceptable range established through tracking studies. Production had just begun on the 48 2.96 m quadrupoles that are required.

References

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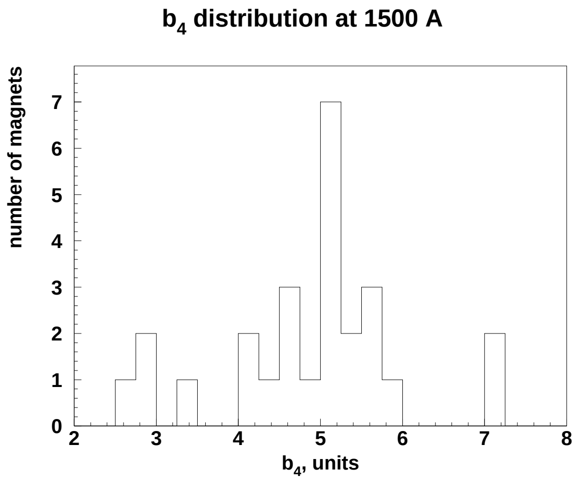

Figure. 5. Distribution of octupole strengths at 1500 A

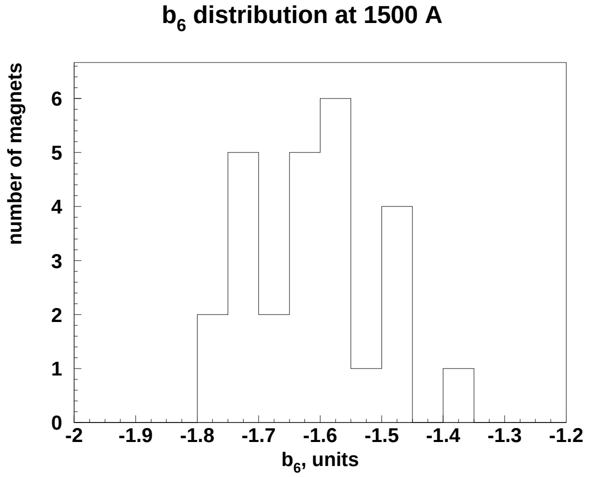

Figure. 6. Distribution of 12-pole strengths at 1500 A

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