Fermi National Accelerator Laboratory

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Abstract

The Main Ring Quadrupoles have been used in the Fermilab Main Ring and will be utilized in the proposed Fermilab Main Injector. Utilizing a rotating coil harmonic measurement system, a sample of more than 35 Fermilab Main Ring Quadrupoles have been measured. The asymmetric design of these magnets provides many easily measured harmonic coefficients. Results for harmonic coefficients at various excitation levels are presented.

1 Introduction

The new 150 Gev Main Injector[1] to be built at Fermilab will reuse many of the main quadrupoles currently in use by the Main Ring. The original production of about 250 these magnets occurred in 1970-71[2]; the magnets have a beam pipe aperture of 4.9"× 3.1" (HxV) and lengths of 52" and 84". They were designed to operate at a maximum gradient of 30 T/m at 6.0 kA; routine 400 Gev operation in the Main Ring required a peak gradient of 24.1 T/m while 150 GeV operation required 1575 A to produce 9.05 T/m. At the latter excitation the gradient error is less than 0.5% in an aperture 3.5" × 2". The Main Injector design[3] calls for 19.6 T/m at 150 Gev. Given the plan to use this quadrupole design in the new Main Injector, it is of some interest to summarize the measured field shape of these magnets.

2 Measurements systems

Originally, production magnetic measurements were made on each magnet[2] using a full-length stretched wire gradient coil that was moved across the horizontal midplane in one-inch steps. These measurements were able to establish the uniformity in integral strength and and gradient error at high field but were incapable of giving the distribution of higher multipoles. In 1986 the creation of the Main Ring overpass at the CDF interaction region afforded an opportunity to measure at MTF[4] the multipole composition of 35 of these magnets at excitations in the range from 0.5-9.0 T/m.

The magnetic field measurements have been taken with a probe which integrates through the full length of the magnet. The measurements will be analyzed in terms of a two-dimensional harmonic representation for which

$$\begin{aligned} B_y + iB_x = & \sum_{J=1}^{\infty}(C_N\, a^{N-1})\left(\tfrac{r}{a}\right)^{(J-1)} c_J\, e^{i((J-1)\theta+\chi_J)} \\ c_J\, e^{i(\chi_J)} = & \qquad\qquad (b_J + ia_J) \end{aligned}$$

in which B_y, B_x are components of the magnetic field, C_N is the harmonic field of the dominant field component (N=2 for Quadrupoles), c_J, χ_J are the normalized harmonic coefficient and its phase (b_J, a_J are the corresponding normal and skew normalized harmonic coefficients), while r, θ are the cylindrical position coordinates, and a is the reference radius at which the harmonic coefficients are normalized. In this notation we normalize the measurements to the quadrupole field at the reference radius a which we will take as 25.4 mm. The quadrupole field is the angular reference and we assume no skew quadrupole ($\chi_2 = 0$). We will express b_J, a_J in 'units' by multiplying the above values by 10^4.

The measurements were taken using a Morgan Coil[5] with the following coils available for measurements: 2P, 2P-skew, 4P, 4P-skew, 6P, 8P, 10P, 12P, 20P. These were arranged on a glass-epoxy (G10) cylinder with the wires at a radius of 34.5 mm and a length of 2.34 m. The flux induced when rotating this coil was measured using an operational amplifier integrator followed by an amplifier and a 12 bit ADC. Data were recorded at 512 points around the circle (some data used 256 and some used 1024 points) using a VAX11/730 computer. The resulting data were corrected for integrator drift and adjusted for integrator and amplifier gains. An FFT converted the resulting fluxes to harmonic flux coefficients. Harmonic fields (C_2) and/or normalized harmonic coefficients (c_J) were then obtained using known probe geometry. The probe was placed near the center of the quadrupole beam pipe. Although the dipole field was measured and could be used to establish the magnetic center, these results are reported with the coordinate center on the probe rotation axis.

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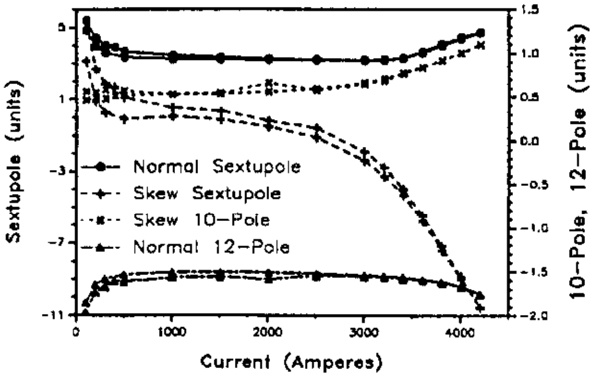

Figure 1: The current dependence of 6-pole, 10-pole, and 12-pole harmonics for an 84" quadrupole (BQB234).

3 Current Dependence of Normalized Harmonic Components

Following special studies of the current dependence of the field shape below 2 T/m for a limited number of magnets, routine measurements at 6 or 10 currents from 0 - 1575 A were selected for production measurements. If we define hysteretic effects as those for which the harmonic fields are different for increasing currents than decreasing currents, we find small hysteretic effects in the several moments including 6-pole, 8-pole, and 12-pole normal moments. Nonhysteretic current dependence of the normalized harmonics are seen at low currents in most multipoles but only as we approach saturation do any harmonics change by more than a few units (above strengths of 0.5 T/m).

One magnet (BQB234) has been studied at fields up to the fields of interest for the Main Injector. In Figure 1 we show current dependence of those harmonics for which the saturation-induced changes are most pronounced. The current dependence of the skew sextupole indicates a large symmetry-violating saturation effect which we do not understand.

4 Harmonic Distributions

Production measurements of these magnets employed a pre-ramp to 1575 A (Main Ring 150 GeV excitation) to establish the hysteresis. The quadrupole strength and harmonics were then measured at an established set of currents on the up ramp and down ramp. All harmonic coefficients for which our probes are sensitive were stored in a database. A few of the 84" quadrupoles are still of the unmodified style described by Hinterberger[2]. Included in our sample of magnets were 4 Unmodified 84" quads, 18 Modified (Standard) 84" quads, and 15 Standard 52" quads.

Table 1: Measured Harmonic Coefficient Distributions at 1575 A

Harm Coef	Std. 84" Average	Quads Sigma	Unm.84" Average	Quads Sigma	Std 52" Average	Quads Sigma
b3	0.176	2.803	5.470	5.595	0.084	2.206
a3	0.117	1.849	0.528	0.935	0.621	1.235
b4	5.037	1.059	-2.662	0.266	5.149	1.373
a4	-1.164	2.380	0.299	1.184	-0.681	2.226
b5	-0.009	1.176	-2.134	2.035	-0.142	0.891
a5	0.422	0.470	-0.054	0.502	0.340	0.558
b6	-1.680	0.562	-2.255	1.655	-2.521	0.218
a6	0.402	0.701	0.020	0.413	0.214	0.660
b7	0.272	0.566	0.584	0.328	0.123	0.465
a7	-0.545	0.443	0.387	1.182	-0.154	0.530
b9	-0.013	0.289	-0.131	0.152	0.034	0.193
a9	0.142	0.164	-0.011	0.268	0.020	0.264
b10	-0.806	0.080	-0.761	0.070	-0.807	0.078
a10	0.024	0.068	0.023	0.070	0.028	0.051
b12	0.354	0.041	0.348	0.032	0.358	0.033
a12	-0.004	0.033	-0.019	0.026	-0.012	0.031

Harm Coef	Std. 84" Calculated	Unm. 84" Calculated
b4	9.23	1.83
b6	-1.30	-1.79
b8	1.40	1.46
b10	-0.84	-0.81
b12	0.35	0.32
b14	-0.073	-0.091

At Main Ring Injection current of 90 A (.54 T/m), magnetization effects can be important. Measurements on 16 84" Standard quads are available which compare the fields on up ramps and down ramps. We find that the hysteretic width of the normal 8-pole has a mean of 1.38 units with a sigma of 0.24 units. This compares with a mean of 8.37 (9.76) with a sigma of 1.23 (1.20) on the up (down) ramp. The hysteretic 12-pole changes are typically much smaller in this set of quadrupoles than for ones of a symmetric design.

The mean and standard deviation at 9 T/m for available harmonics through 24-pole are shown in Table 1. Of the many details available in Table 1, let us note especially that b_4 is linearly related to the back-leg change described[2]. The operation of machining the core to reduce the gap changed the average as described. The accuracy limitations of that are apparent in the difference in sigma between the two cases. We show also in Table 1 a calculation of allowed harmonics. The column labeled "Unm. 84" "

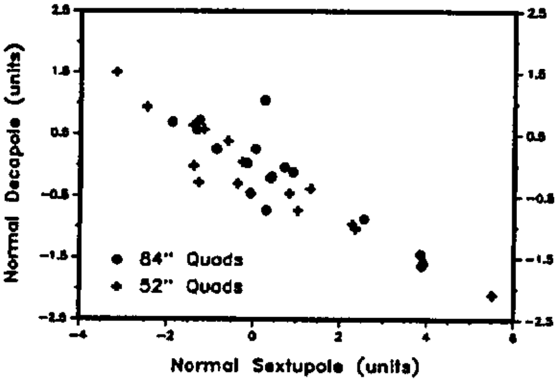

Figure 2: Correlations between Normal 6-pole and Normal 10-pole Harmonic Coefficients at 1575 A.

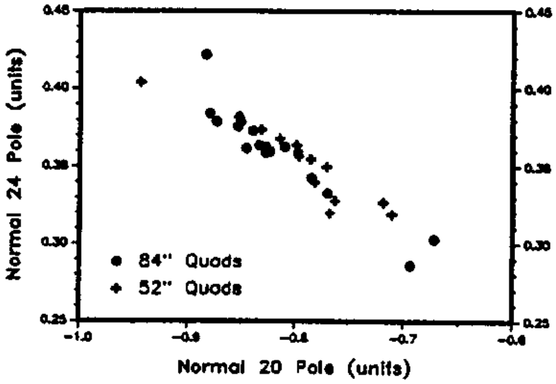

Figure 3: Correlations between Normal 20-pole and Normal 24-pole Harmonic Coefficients at 1575 A.

represents a magnet constructed from the designed lamination. The column labeled "Standard 84" " uses that lamination with 0.010" of material removed from the back leg. The change in 8-Pole (b4) between these cases is 7.7 units (7.4 units) for measured (calculated) harmonics. This and the measured octapole for the two cases supports the claim[2] that the laminations as produced have too large a backleg gap and that the average amount of steel removed was nearly 0.010".

5 Harmonic Correlations

Other interesting manufacturing errors are apparent in these harmonics. Figures 2 and 3 reveal correlations due to manufacturing errors. We note that the 20-Pole and 24-Pole errors are small when measured at a reference radius of 25.4 mm but if measured at the pole tip (a size characteristic of the quadrupole fabrication) they are comparable to the low-order harmonic errors.

6 Summary

The availability of a harmonic measurement system has allowed us to study the quadrupoles from the Fermilab Main Ring. Since these magnets were designed with an elliptical aperture, the only symmetries which are preserved by design are the top/bottom and left/right symmetries. This permits a much richer spectrum of harmonic components than a symmetric quadrupole allows. Additional effects due to magnetization and saturation provide further changes in the field shapes. Overall this harmonic measurement system allows us to characterize the gradient errors for Main Ring quadrupoles throughout the range of interest for current operations or Main Injector use. Probe rotation times are such that rotating coil harmonics cannot be measured with this apparatus at high currents (due to overheating) so we cannot compare directly with the previously published results.

7 Acknowledgements

We would like to acknowledge the efforts of the MTF measurement staff, especially David Hartness and Shree Agrawal, for carrying out these measurements, Lee Theriot and Julian Plymale for assistance in implementing the database systems from which these results were obtained, and Steve Helis who fabricated the harmonic probe.

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The following paper was presented at the IEEE 1991 Particle Accelerator Conference, San Francisco, California, 6-9 May 1991. Dr. Bruce C. Brown is the main author and we want to request 10 copies of this paper to be sent to Dr. Brown at MS 316. Thank-you.

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