MAGNETIC FIELD DATA ON FERMILAB ENERGY SAVER QUADRUPOLES

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The Fermilab Energy Saver/Doubler (Tevatron) accelerator contains 216 superconducting quadrupole magnets. Before installation in the Tevatron ring, these magnets plus an additional number of spares were extensively tested at the Fermilab Magnet Test Facility (MTF). Details on the results of the tests are presented here.

INTRODUCTION

The Tevatron lattice contains 180 "standard length" quadrupoles plus 36 quadrupoles of five "special lengths". The construction of the various length magnets is essentially similar and also similar to the construction of Tevatron dipoles (cold "collared" coils in a warm iron yoke). The magnets are put through a series of tests including extensive tests in the superconducting state. Details on magnet construction and the Magnet Test Facility can be found elsewhere[1,2] as can results on the quench performance of the quadrupoles.[3] Tests are routinely done to a current of 4000 A although a limited number of magnets have been tested to higher currents. In the Tevatron, injection at 150 GeV/c occurs at a magnet excitation current of 660 A and 1 TeV/c corresponds to 4440 A.

FIELD GRADIENT

The integrated field gradient ($\int G.dl$) is measured with a Morgan coil stretched through a warm bore in the magnet. Measurements of the $\int G.dl$ of magnets returned to MTF for a second set of cold tests agree to 0.1% or better. The 180 standard length quadrupoles have a design effective (magnetic) length of 66.10" and gradient of 19.3 kG/in. at 4440 A.[4] Assuming a 66.10" length, the measured average $\int G.dl$ at 4000 A of 1150.8 kG yields a field gradient of 19.32 kG/in. when extrapolated to 4440 A. The measured effective lengths of the special length quadrupoles can be calculated by taking the average $\int G.dl$, dividing by the average for standard length quadrupoles, and multiplying by 66.1". Table 1 shows the design and measured effective lengths for the special quadrupoles.

Table 1
Effective Lengths of Quadrupoles

Design	Measured	Number in Ring
25.50"	25.48"	4
32.07"	31.97"	8
82.72"	82.60"	8
90.19"	90.07"	4
99.40"	99.38"	12

Figure 1 shows the average value of $\int G.dl$ divided by magnet current in kA as a function of current for the 216 installed quadrupoles. The special length quadrupoles have been included in the average by weighting their gradients by their design magnetic lengths. The point at 4800 A is based on only 18 magnets. The $\int G.dl$ per kA shows no saturation of the iron yoke up to 4800 A but does show the effects of persistent currents in the superconductor below 2000 A. The quadrupole excitation curve does not track the excitation curve for Tevatron dipoles which shows saturation effects in the iron yoke.[5] The difference in the two curves will be compensated by correction coils incorporated into the so-called "spool pieces".

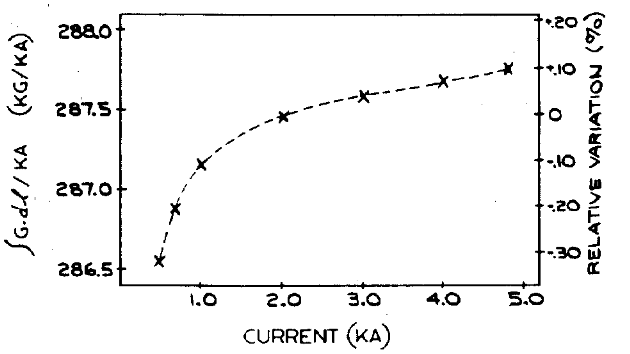

Figure 1 $\int G.dl$ normalized to the excitation current.

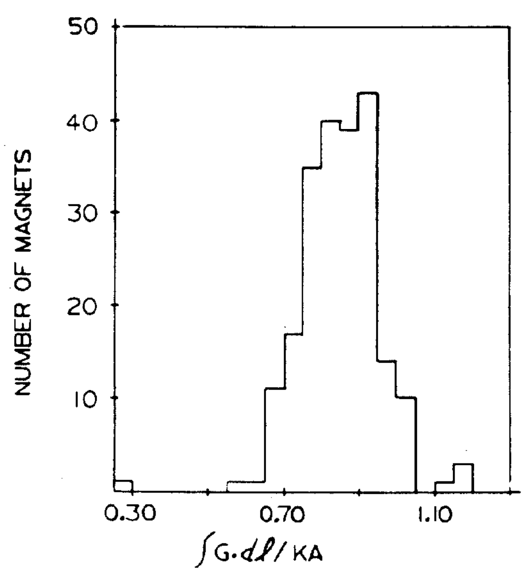

Figure 2 $\int G.dl/kA$ at 4000 A minus $\int G.dl/kA$ at 660 A

Although Figure 1 shows the average excitation curve, the individual magnets show excitation curves of essentially the same shape except that the net rise has some spread. Figure 2 shows the $\int G.dl/kA$ at 4000 A minus $\int G.dl/kA$ at 660 A. The change in $\int G.dl/kA$ from 660 A to 4000 A has a mean value of 0.85 kG/kA and an rms width of 0.11. Figure 3 shows the $\int G.dl/kA$ at 4000 A. Again, special length quadrupoles have been included in the plots by weighting their gradients by their design magnetic lengths. Figure 3 has a mean value of 287.68 kG/kA and an rms width of 0.60. Note that the width of the distribution in Figure 3 does not reflect production control of the field gradient. Regular production procedures controlled the field gradient to about ±0.2%. Figure 4 shows a plot of magnet number (roughly production time) versus $\int G.dl/kA$ at 4000 A for standard length quadrupoles. The slight rise at magnet number 102 was due to a production change to reduce the 12-pole while the dip starting at magnet 200 was due to a reworking of coil winding mandrels.

* Operated by Universities Research Inc., under contract with the U.S. Dept. of Energy.

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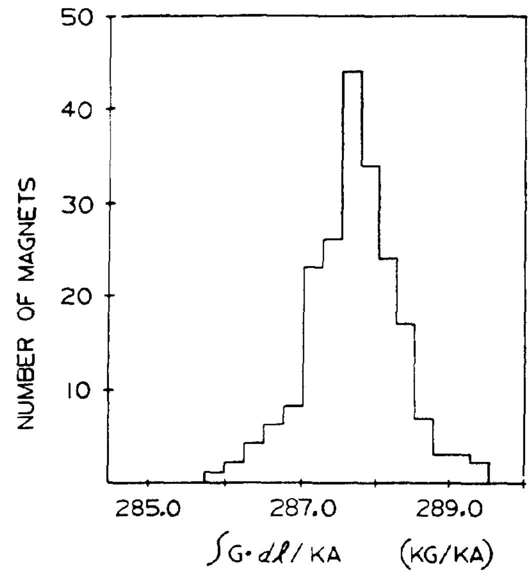

Figure 3 ∫G.dl/kA at 4000 A

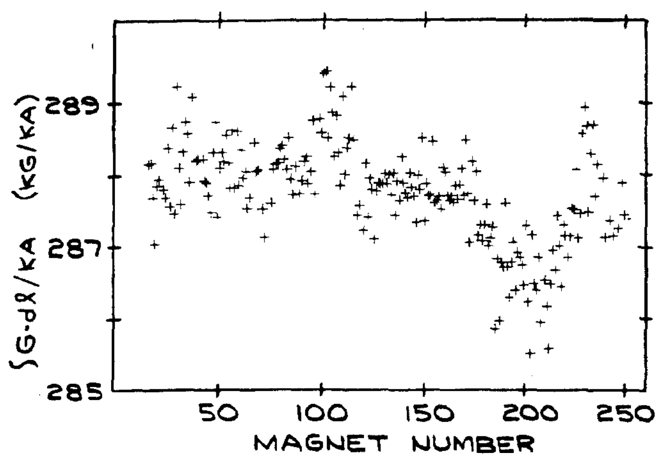

Figure 4 ∫G.dl/kA as a function of magnet number

FIELD LOCATION AND ORIENTATION

A pair of stretched wire loops is used to measure both the field orientation and the magnetic center of the quadrupole relative to the center of the yoke. This information is then encoded on a set of survey lugs used to position the magnet in the accelerator. If the measured field angle was greater than ±7.5 mr relative to the iron yoke vertical, the magnet cryostat was realigned within the yoke. During excitation from 660 to 4800 A, the field angle changes less than 0.4 mr in all the quadrupoles. The average values of the shifts (Δx and Δy) of the measured field center relative to the yoke center are -0.5 mils and -2.8 mils respectively with rms widths of 8.3 mils and 8.0 mils.

FIELD HARMONICS

The 2-dimensional magnetic field of the quadrupoles can be expressed in a multipole expansion.

$$B_y + iB_x = B_0 \sum_{n=o} (b_n + ia_n)\, r^n\, e^{in\phi}$$

The convention for the Tevatron ring has z in the beam direction, y "up" in the tunnel, and x positive away from the center of the ring. In the above expression, ϕ is measured with respect to the x-axis. The b_n are referred to as the "normal" coefficients and the a_n as the "skew" coefficients. The quadrupole is the n=1 term, the sextupole is the n=2 term, and in general the k-pole is the k=2n+2 term. If we choose B_0 such that the normal quadrupole, b_1, is 1.0, and we express radius in inches, then the value of most multipoles are less than a few times 10^{-4}. In other words, a convenient "unit" is the ratio of the multipole to 10^{-4} times the quadrupole at a radius of 1 inch.

Harmonics are measured twice during the production of a quadrupole. The bare collared coil is measured at low-power and room temperature using a 84" long Morgan coil of radius 1.1".[6] During cold tests, the completed magnet is measured with a 94" long probe of radius 0.92". Cold measurements are made in 7 current steps from 200 A to 4000 A and then back again to 200 A. For the quadrupole magnets, a transformation is done from the probe coordinate system to a system in which the dipole coefficient b_0 is zero.

The quadrupole coil package geometry is two circular shaped shells wound around a 3.5" diameter mandrel. Each of the 4 separate inner shell coils is wound in 2 sections (one with 6 conductors, the other with 8) separated by a spacer. Perfectly symmetric coils would produce a field with only 4, 12, 20, and 28 poles. In fact azimuthal asymmetries of 2 to 3 mils in the cable placement lead to non-zero values for some of the other harmonic coefficients, particularly the 6, 8, and 10 poles. Table 3 lists the warm and cold (at 4000 A) coefficients for all multipoles with a mean value of 0.1 unit or larger. The spread in the values of the 12 and lower poles represents real variation from magnet to magnet.

Table 3
Quadrupole Harmonic Coefficients

	Normal				Skew			
Pole	Cold		Warm		Cold		Warm	
	Mean	rms	Mean	rms	Mean	rms	Mean	rms
6	1.98	3.69	1.19	3.75	2.83	3.41	0.83	3.56
8	1.25	0.93	1.22	0.90	-0.45	1.97	-0.67	1.96
10	-0.26	0.74	-0.25	0.65	-0.72	0.80	-0.65	0.87
12	-1.91	1.70	-1.01	1.81	0.21	0.44	0.17	0.28
14	0.05	0.28			0.18	0.29		
18	-0.03	0.26			-0.10	0.22		
20	-1.66	0.32	-1.71	0.27	0.19	0.29	0.01	0.14
22	0.01	0.22			0.12	0.22		
28	0.75	0.33			-0.19	0.26		

In principle the non-zero sextupole could be reduced by changing the center of the coil package within the iron yoke (a change in x by +10 mils increases the normal sextupole by 1.32 units while a change in y by +10 mils decreases the skew sextupole by the same amount). In practice the necessary off centering would be prohibitively large in some cases. In addition, since the integrated sextupole field from the quadrupoles is small relative to that accumulated from the dipoles (considering both the total quadrupole to dipole length ratio and beta-functions at the quadrupoles and dipoles), no correction was deemed necessary.

The harmonics measured with the magnet superconducting correlate well with the room temperature measurement[1] although there is a systematic shift in the sextupole and 12-pole. Correcting the sextupole for the measured Δx and Δy does not entirely eliminate the shift. This implies a systematic offset in the measurement of the yoke (or field) center. The change in the 12-pole from warm to cold may be due to mechanical changes in the coil package upon cooldown.

The thickness of the spacer between the two inner coil sections controls the 12-pole and also slightly affects the 20-pole. Decreasing the spacer thickness by 10 mils increases the 12-pole by about 3.2 units and decreases the 20-pole by 0.7 units. Since the ends of the magnet give rise to a natural negative 12-pole, the body field is adjusted to give a net 12-pole close to zero. This design also leads to a natural hysteresis in the 12-pole due to persistent currents in the superconductor.

Figure 5 shows the magnitude of the normal 12-pole, b_5, as a function of magnet number (production time) for standard length quadrupoles.

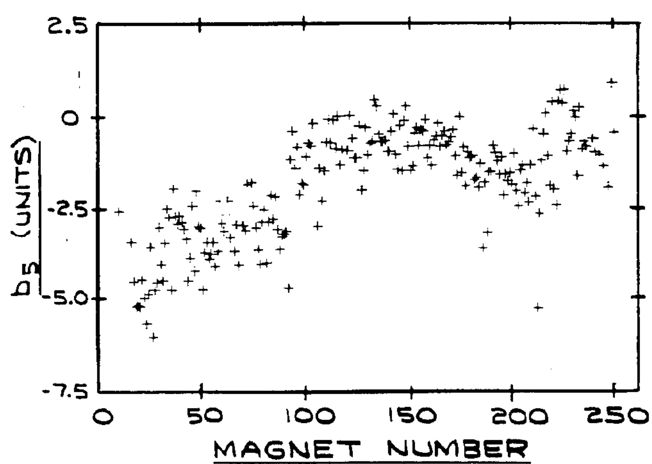

Figure 5 Normal 12-pole as a function of magnet number

At magnet 102, the inner coil spacer was adjusted to bring the 12-pole closer to zero. Table 2 shows the average normal 12-pole and 20-pole for several classes of magnets.

Table 2
Normal 12-pole and 20-pole

TYPE	12-POLE	20-POLE (units)	
66"	-3.5	-1.3	(magnet numbers < 102)
66"	-1.1	-1.9	(magnet numbers > 102)
25"	-9.6	-2.0	
32"	-6.2	-1.9	
82"	-0.5	-1.8	
90"	-0.0	-1.8	
99"	-0.1	-1.8	

The short quadrupoles are "mostly ends", and the adjustment of the net 12-pole was not done for these magnets.

The anticipated current hysteresis for the normal 12-pole is seen in the cold measurements. Figure 6 shows the distribution of b_5 at 660 A on the up ramp minus b_5 at 660 A on the down ramp. The mean value is 3.96 units with a width of 0.34 units.

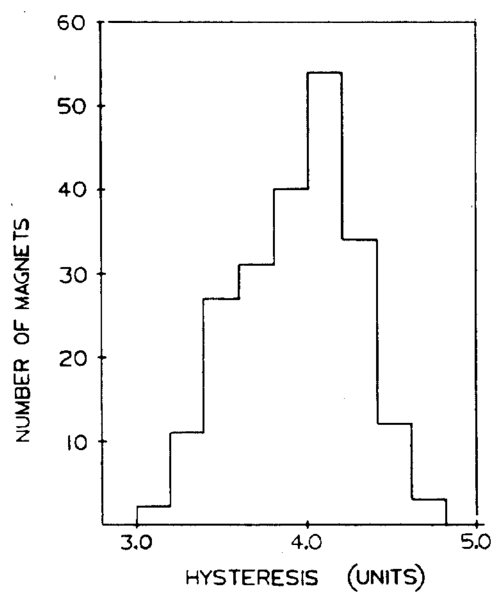

Figure 6 Normal 12-pole (b_5) hysteresis

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