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MAGNETIC FIELD PROPERTIES OF FERMILAB ENERGY SAVER DIPOLES

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SUMMARY

At Fermilab we have operated a production line for the fabrication of 901 21 foot long superconducting dipoles for use in the Energy Saver/Doubler. At any one time 772 of these dipoles are installed in the accelerator and 62 in beamlines; the remainder are spares. Magnetic field data are now available for most of these dipoles; in this paper we present some of these data which show that we have been able to maintain the necessary consistency in field quality throughout the production process. Specifically we report harmonic field coefficients, showing that the mechanical design permits substantial reduction of the magnitudes of the normal and skew quadrupole harmonic coefficients; field shape profiles; integral field data; and field angle data. Details of the measurement apparatus and procedures are described elsewhere.[1]

HARMONIC COEFFICIENTS

We describe the magnetic field B in a harmonic expansion about the coil center:

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

where y is positive up, x is positive outward (the center of the ring curvature is at negative x), and the protons circulate in the positive z direction. The angle ϕ is measured from the x-axis. The a_n's are known as skew harmonic coefficients and the b_n's as normal coefficients; $b_o = 1$ and $a_o = 0$. The pole number is 2n+2. The length units employed are inches, and our harmonic search coil samples the field out to a radius r of one inch. In these units the significant coefficients are of magnitude 10^{-4}inch^{-n}; we suppress this factor and report coefficients in the resulting "standard" units.

In Figure 1 we show a schematic cross-section of a dipole at one of the nine suspension stations. Note that the coil assembly is made up of an upper coil and a lower coil (each of which is composed of an inner and an outer coil) held together by stainless steel collars. The magnetic field in the bore of a perfectly constructed coil of this design will have all the a_n's equal to zero; and all the b_n's, n odd, will also be zero. The sharp coil corners give rise to significant b_6, b_8, and b_{10} coefficients whose magnitudes are fairly independent of minor construction errors. Left-right asymmetries due to construction errors produce b_n's, and up-down asymmetries produce a_n's.

The collared coil assembly is supported in the cryostat by G11 spacers at the suspension stations; these transmit the collared coil's weight and any magnetic forces downward to the ends of the suspension preload screws threaded into the yokes below. Spring loaded cartridges bear down on the suspensions above the coil to provide a mechanical preload and to oppose any magnetic forces. This design permits changing the position of the collared coil assembly relative to the center-line of the yoke by adjusting the thickness of the shim packs on the preload screw ends. The iron yoke contributes about 18% of the total dipole field within the magnet bore. When the collared coil is off center with respect to the yoke, the iron can also modify the field harmonics. However since the iron is far away relative to 1 inch, it is only the quadrupole coefficients a_1 and b_1 that can be materially affected

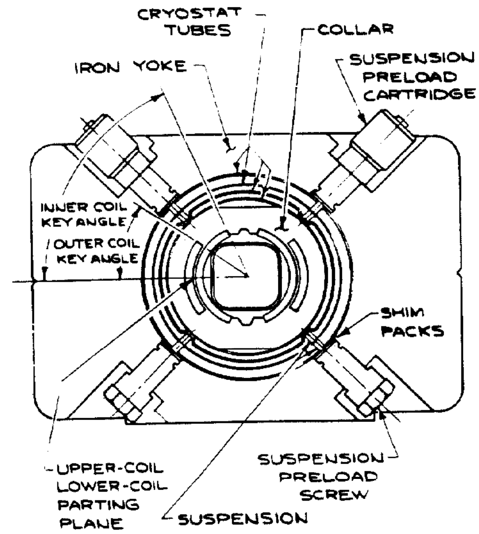

Fig. 1. Schematic cross section of dipole

in the region of interest for circulating beam. Moving the coil 0.0037 inches in the + x direction increases b_1 by 1 unit, while moving it 0.0037 inches in the + y direction decreases a_1 by 1 unit.

It is very desirable to have the a_1 and b_1 coefficients as small as possible, for this simplifies the field correction problem. In the original Energy Saver/Doubler design report,[2] acceptance criteria for both quadrupole coefficients were set as 0± 2.5 units; however we can now easily reduce these coefficients to even smaller magnitudes. Prior to fabricating the collared coil assemblies, the physical dimensions of the upper and lower coils were carefully measured and then the coils were matched in order to minimize the up-down asymmetries which result in a_n harmonics, especially a_1. Later we measured the harmonics of the completed magnet when it was in a superconducting state on a test stand. We then removed the suspension preload screws and altered the thicknesses of the shim packs in order to bring $|a_1|$ and $|b_1| < 1.0$ units and then remeasured the harmonics to verify the success of the operation. In Figure 2 we show the resulting values of a_1 and b_1 for 870 dipoles at 4000 A excitation. Note that for a small fraction of these dipoles the final value of a_1 exceeds 1.0 unit. Further reduction in the value of a_1 for these few magnets would require decentering the coil package upward by a distance so large that the magnetic decentering force during excitation could no longer be adequately opposed by the spring cartridges.

Since there is an unavoidable large negative sextupole at each end, these dipoles are designed to have a large positive b_2 in the body field to compensate. The magnitude of the body field sextupole is controlled by the key angles, which are nominally

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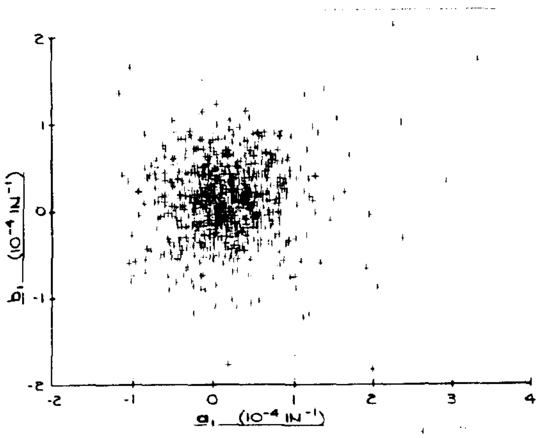

Fig. 2. a_1 and b_1 coefficients

72° for the inner coil and 36° for the outer coil. The magnitude of b_4 is also sensitive to these key angles. During collared coil fabrication we occasionally adjusted the key shims between the collars and the coils in order to maintain values of b_2 within the acceptance range of 0± 6 units at 4000 A excitation. In Figure 3 we show b_2 at 4000 A as a function of magnet number, which closely approximates the date of collared coil construction. Note that a trend toward unacceptably large values of b_2 developed

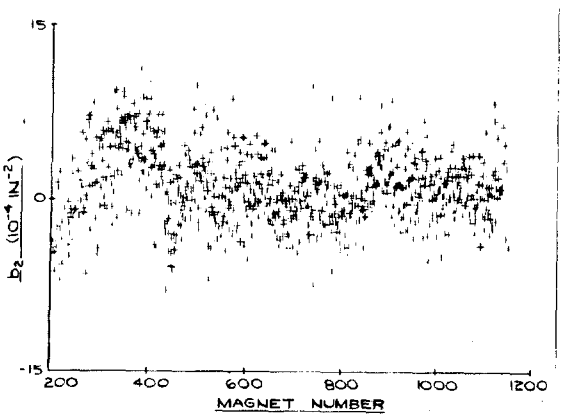

Fig. 3. b_2 coefficient at 4000 A as a function of magnet number (construction date)

during startup of the production line; the underlying construction problems were identified and brought under control after magnet number 410; and as the figure shows, thereafter we were able to maintain the average value of b_2 near zero.

Pole Index n	b_n Design	b_n Mean	b_n RMS	a_n Mean	a_n RMS
1		0.09	0.48	0.17	0.50
2	.04	0.95	3.12	0.10	1.16
3		-0.23	0.77	-0.07	1.46
4	1.04	-0.57	1.32	-0.10	0.46
5		-0.07	0.32	-0.07	0.55
6	4.44	5.48	0.54	-0.07	0.29
7		0.04	0.17	0.22	0.26
8	-12.09	-12.52	0.33	-0.07	0.41
9		0.02	0.23	0.28	0.38
10	3.63	3.70	0.26	0.08	0.25
11		-0.01	0.20	-0.24	0.25
12	-0.82	-0.80	0.19	-0.05	0.22

Table 1 Harmonic coefficients of the magnetic field at 4000 A in standard units for 870 dipoles

In Table 1 we show a table of values of harmonic coefficients at 4000 A excitation up to the 26-pole together with the original design estimates for b_n, n even, made for 4500 A. The n=7 data are artifacts of the data handling procedure.[3] The rms values shown for higher order a_n and b_n, n odd, probably indicate the measurement precision. The widths of the distributions of b_2, a_2, and a_3, which represent real magnet to magnet variation, are relatively large; as a consequence dipoles are assigned locations in the accelerator to reduce undesirable orbit effects that may arise from these field components.[4]

FIELD SHAPE

Another way to characterize the magnetic field is to show B_y/B_o along the x and y axes out to ± 1 inch. Figures 4 and 5 show these distributions. The mean value of B_y/B_o for the sample of 870 dipoles at each x or y is traced by the solid lines, and the dotted lines give a band containing 90% of the magnets.

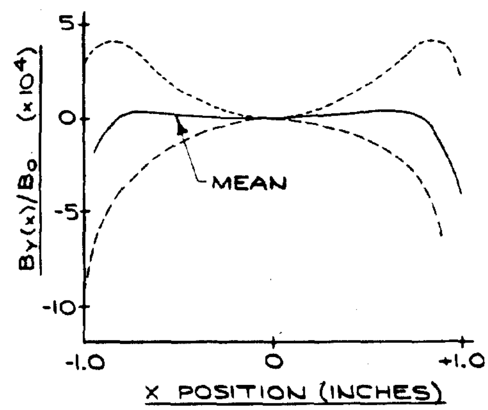

Fig. 4. B_y/B_o as a function of x at y=o

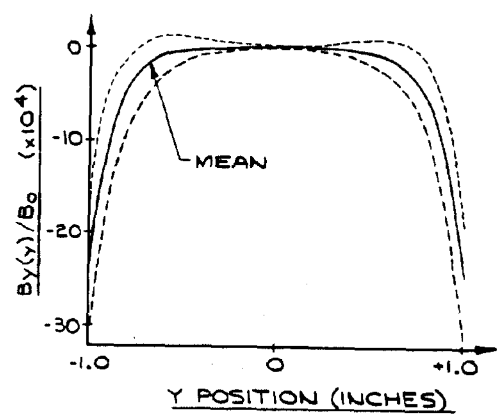

Fig. 5. B_y/B_o as a function of y at x=o

INTEGRAL FIELD

Integral field measurements were made using stretched wire loops at many magnet excitation currents. Figure 6 shows the distribution of normalized field integral at 2000 A magnet excitation as a function of magnet number.

It can be seen that the construction problems that affected b_2 also affected the integral field. These same data are shown as a histrogram in Figure 7;

the shaded portion is the contribution of magnets numbered above 410. The acceptance criterion for the integral field is ± .1% about the mean; 89% of the total sample fall within this band. Excluding the magnets numbered between 200 and 410 raises this to 95%.

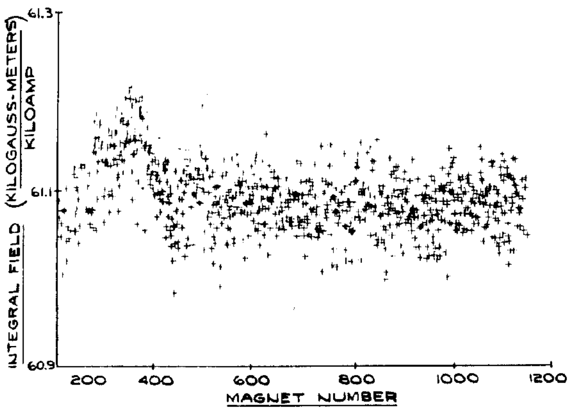

Fig. 6. Normalized integral field at 2000 A as a function of magnet number (construction date)

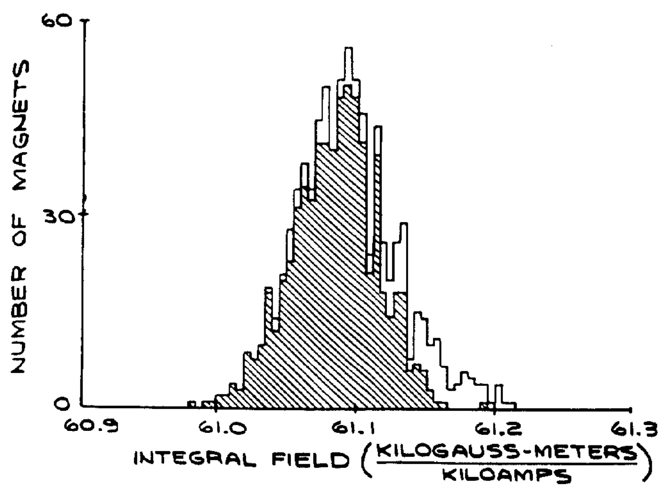

Fig. 7. Normalized integral field; shaded area excludes early magnets

In these dipoles the normalized integral field rises slightly from the injection current of 660 A to a maximum between 2000 A and 2500 A and then falls slightly due to onset of yoke saturation and coil deformation. In Figure 8 we show this variation in the way we presented the field shape: The solid line marks the mean integral field and the dotted lines enclose 90% of the dipoles. We routinely measured the integral field to a maximum current to 4000 A but some magnets have been measured to 4500 A. At 4500 A the integral field is .12% below its maximum value. These features of the integral field are well within our acceptance window, and the placement of dipoles within the accelerator is not influenced by the integral field results.

FIELD ANGLE

We measured the average field angle using a stretched wire array technique. The angles obtained, as referenced to the yoke, were usually within 5 milliradians of vertical. We encoded the measured field angle onto the yokes with survey markers so that the dipole could be "rolled" at installation time to bring this angle vertical. In Figure 9 we show that aspect of the field angle that can not be adjusted at installation: the variation with excitation current. The maximum variation between the injection current of 660 A and 4000 A is always less than 0.2 milliradian and should present no problem in the accelerator.

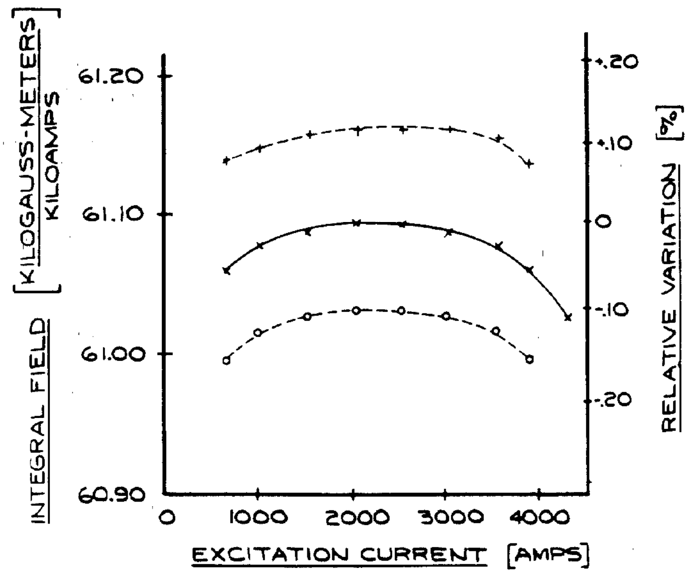

Fig. 8. Normalized integral field as a function of excitation current

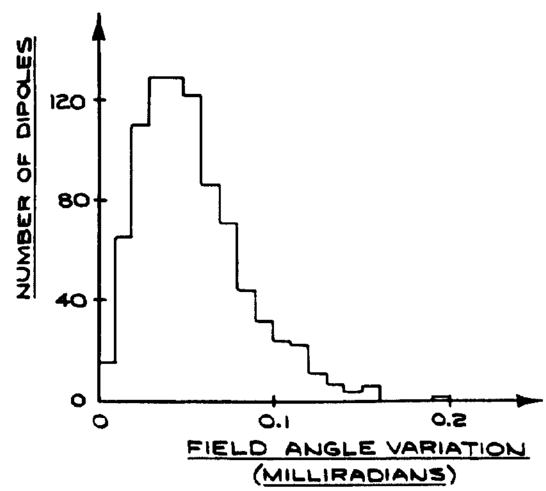

Fig. 9. Maximum field angle variation between 660 A and 4000 A excitation current

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