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MAGNETIC FIELD MEASUREMENTS OF FULL LENGTH 50 mm APERTURE SSC DIPOLE MAGNETS AT FERMILAB*

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Abstract

Thirteen 15 m long, 50 mm aperture SSC dipole magnets, designed jointly by Fermilab, Brookhaven National Laboratory, Lawrence Berkeley Laboratory and the SSC Laboratory, have been built at Fermilab. The first nine magnets have been fully tested to date. The allowed harmonics are systematically shifted from zero by amounts larger than the specification. The unallowed harmonics, with the exception of the skew sextupole, are consistent with zero. The magnet-to-magnet RMS variation of all harmonics is much smaller than the specification.

1 Introduction

Thirteen full-scale SSC dipole magnets have been built at Fermilab and nine have been fully tested to date. Of these nine, seven were built[1] by General Dynamics technicians with support from Fermilab personnel. The Fermilab design[2,3] features a vertically-split yoke which supports the collars in the horizontal direction. The collars are designed to position the conductors as specified by the magnetic design after all assembly and cooldown deflections have occurred. No pole shims are used. The conductor insulation is Kapton plus epoxy-impregnated fiberglass tape similar to the Tevatron and HERA.

The quench performance of these magnets is very good[4] and the mechanical behavior is well understood[5]. In this paper we evaluate their magnetic field quality and compare it with the requirments for the SSC main collider. The values of selected unallowed harmonics are compared with predictions based on measured coil sizes, and comparisons are made among harmonics measured at several points in the assembly and testing sequence.

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2 Harmonics Data

Field harmonics are measured with a 61 cm long rotating coil probe[6]. The harmonic coefficients are defined by

$$B_y+iB_x = B_0\Sigma[(b_n+ia_n)/10^4][(x+iy)/1\mathrm{cm}]^n$$

where $B_{x(y)}$ is the horizontal (vertical) component of the field, B_0 is the dipole field strength, and b_n and a_n are the normal and skew 2(n+1)-pole coefficients respectively. Table I shows the mean and RMS of the length averaged harmonics (excluding the ends) at 2 T over the nine magnets tested and compares them with specifications. The data are uncorrected for persistent current effects, which contribute about -0.3 and +0.02 to b_2 and b_4 respectively. The data are taken sufficiently long after the DC current has been established that time dependent effects are negligible.

The means of the allowed multipoles (b_{even}) are larger than the specification. However, only small adjustments would have to be made to the cross-section to set these harmonics to zero. For these multipoles the RMS is computed about the

Table I
Harmonics at 2 T

	Mean	Spec.	RMS	Spec.
b_2	1.5	0.8	0.39	1.15
b_4	0.30	0.08	0.03	0.22
b_6	-0.043	0.013	0.004	0.018
b_8	0.051	0.010	0.0012	0.0075
b_1	0.03	0.04	0.18	0.50
b_3	0.001	0.026	0.03	0.16
b_5	0.001	0.005	0.003	0.017
a_1	0.03	0.04	0.39	1.25
a_2	0.114	0.032	0.16	0.35
a_3	-0.002	0.026	0.06	0.32
a_4	0.006	0.010	0.02	0.05
a_5	0.002	0.005	0.01	0.05

measured mean.

The means of the unallowed harmonics, with the exception of a_2, are consistent with zero. However, the number of magnets is too small to determine if a production series with this design and assembly method[1] would have means within the specifications. For these harmonics the RMS is computed about zero.

The RMS variations of all harmonics are considerably smaller than the allowed values. Assuming that the harmonics have a normal distribution, 95% C.L. upper bounds for the RMS of a production run coming from the same distribution as these magnets is obtained by multiplying the measured RMS of this sample by 1.7. At this confidence level the RMS of all harmonics are within the specified limits.

3 Predictions from Coil Sizes

From the measured difference in upper and lower coil sizes, the expected a_1 can be computed[7]. Although no effort was made to match upper and lower coils by size, (in most cases sequential coils from the production line were used) the RMS length averaged mid-plane shift, computed from coil size measurements[1], is only 0.01 mm. The predicted and measured values of a_1 are compared in Fig. 1.

The non-zero value of the skew sextupole a_2 results from the coils being molded with one side systematically 15-20 μm larger than the other, which in turn generates a left-right asymmetric mid-plane shift. The measured a_2 is compared in Fig. 1 with that predicted from the coils sizes. Although there is a systematic asymmetry in these coils, in a larger production run using several sets of tooling this effect would tend to average to zero. Even with this systematic effect, the 95% confidence limit on the RMS about zero is within the specification.

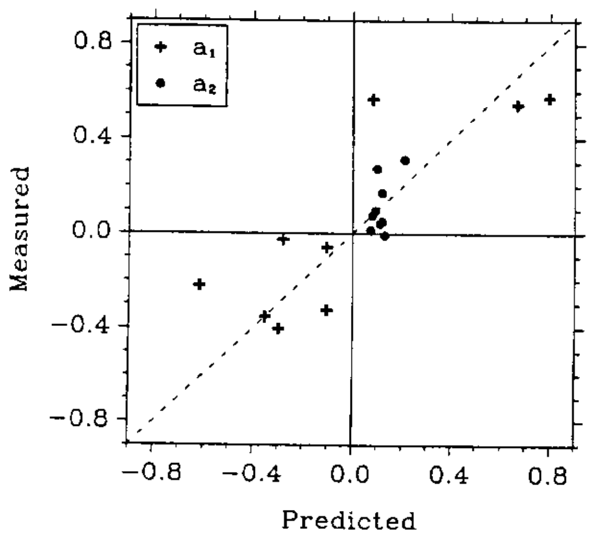

Fig. 1. Measured and predicted harmonics.

4 Warm-Cold Comparison

Only a sample of the production SSC dipoles will be tested at 4K before installation into the accelerator. Therefore warm measurements will be the major quality control method. Further, field measurements made on the collared coil before the yoke is assembled about it may allow corrections to be made at an intermediate point in the production if some harmonics are out of specification. Therefore it is important to understand the correlations of the harmonics at various stages of assembly and testing.

Table II summarizes the differences in the measured harmonics among four measurements: at 293 K on the collared coil and the complete magnet, at 4.35 K, and after cold testing. Figures 2 and 3 illustrate the correlations for several low order harmonics.

Figure 2 compares the quadrupole and sextupole measurements made on the collared coil at 293 K with those made at 4.35 K and 2 T. There is a large shift in b_2 due to the magnetic effect of the yoke[2] and its mechanical interaction with the collars[3]. With this shift accounted for the collared coil measurements predict the cold values with an RMS uncertainty of about 0.3. During the shell welding operation the two yoke halves of of the first magnet of this series buckled[1] inducing an additional change in the coil shape and making the iron interior non-circular. This magnet, whose b_2 lies at the lower right of the distribution, has been excluded from the first two columns of Table II.

The unallowed harmonics lie on a line with a slope a little less than one, since the yoke enhances the dipole field more strongly than the higher harmonic fields. The collared coil measurements in Fig. 2 predict the cold values with an RMS uncertainty of about 0.1.

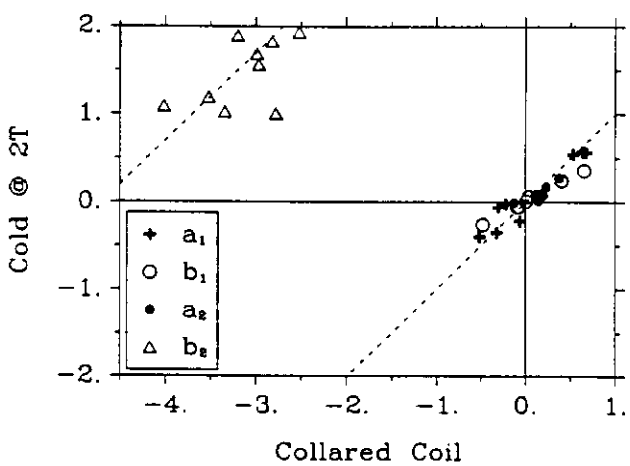

Fig. 2. Harmonics measured on the collared coil and on the complete magnet at 4.35 K. The dotted lines are of unit slope.

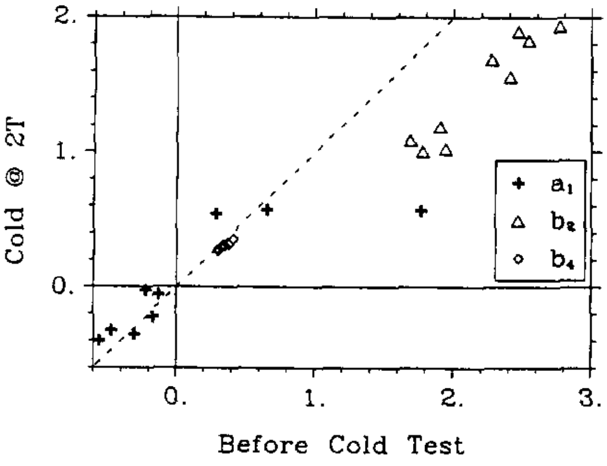

Fig. 3. Harmonics at 293 K and 4.35 K.

Figure 3 displays the values of several harmonics before and after cooldown. With cooldown the coil moves closer to its design shape because of the greater thermal contraction of the collars than the yoke[3]. This causes b_2, and to a lesser extent b_4, to move closer to zero. There is no shift in a_1. For one magnet, the measured a_1 agrees well among three of the four measurements, but is significantly different in the pre-cold test complete magnet. The cause of this apparent error is unknown. This point has been excluded from the last four columns of Table II.

The RMS variations of the unallowed harmonics among the data sets in Table II are consistent with estimated measurement errors, which are dominated by the warm measurements. Additional fluctuations may occur in the allowed multipoles due to yoke-collar interactions[3]. In all cases the RMS of the warm-cold difference is small compared with the RMS specification in Table I, indicating that warm measurements are adequate to specify the field under operating conditions.

The last two columns of Table II compare the harmonics before and after two cold testing cycles. All multipoles except the decapole b_4 return to their original values. The b_4 shifts in columns 3 and 5 are comparable suggesting that whatever occurs on cooldown does not fully reverse on warm up. The source of this shift is not understood, nor why it affects only b_4.

5 Summary

The field quality of these nine SSC dipoles is good and the magnet-to-magnet reproducibility is excellent. The values of a_1 and a_2 can be understood in terms of measured coil sizes. There is a good correlation among measurements taken at several assembly and test cycle points, and systematic differences in the allowed harmonics can be understood in terms of the magnetic and mechanical interactions of the yoke.

Table II
Comparison of harmonics measured in the collared coil, the complete magnet before cold testing, cold at 2 T, and after cold testing.

	Cold - Collared		Cold - Before		After - Before	
	Mean	RMS	Mean	RMS	Mean	RMS
b_2	4.70	0.27	-0.73	0.12	0.01	0.09
b_4	-0.115	0.029	-0.032	0.015	-0.022	0.016
b_6	0.019	0.005	-0.005	0.004	0.002	0.005
b_8	-0.011	0.002	-0.001	0.002	0.000	0.002
b_1	-0.03	0.15	-0.02	0.13	-0.02	0.11
b_3	0.003	0.020	0.005	0.008	-0.004	0.014
b_5	-0.003	0.004	0.001	0.007	0.000	0.005
a_1	0.02	0.15	0.08	0.13	-0.01	0.10
a_2	-0.07	0.08	0.00	0.03	0.00	0.03
a_3	-0.018	0.031	-0.019	0.031	-0.011	0.039
a_4	-0.047	0.011	0.000	0.006	-0.001	0.008
a_5	-0.004	0.006	0.004	0.005	0.002	0.008

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