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MAGNETIC FIELD MEASUREMENTS OF FERMILAB/GENERAL DYNAMICS BUILT FULL SCALE SSC COLLIDER DIPOLE MAGNETS*

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INTRODUCTION

This paper presents preliminary results of magnetic field measurements made on a series of 50 mm aperture 15 m long SSC collider dipole magnets designed and manufactured at Fermi National Accelerator Laboratory (Fermilab) for use in the Superconducting Super Collider Laboratory (SSCL) Accelerator System String Test. The magnets were assembled by Fermilab and General Dynamics personnel, and were tested at the Magnet Test Facility (MTF) at Fermilab. Measurements of the dipole field angle, dipole field strength, and field shape parameters at various stages in magnet construction and testing are described.

DIPOLE FIELD ANGLE

SSC collider dipole magnets are required to have their average field angles aligned to within ±1 mrad of the vertical. A system to measure the dipole field angle was designed and built at Fermilab (Kuchnir and Schmidt, 1988). The field angle probe contains a small permanent bar magnet mounted on jeweled gimbals attached to a plastic frame. The bar magnet is free to rotate within the frame, and the frame is free to rotate about the longitudinal axis of the magnet whose field angle is being measured. The axis of the bar magnet oscillates about the local dipole field direction, and the azimuthal oscillations of the frame are converted to an electronic signal using the varying resistance of an electrolytic bubble level mounted to the frame.

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The magnet current used for all field angle measurements is ~7 - 9 A, corresponding to a central dipole field of ~70 - 90 Gauss. Readings are taken at 76.2 mm (3") intervals along the length of each magnet. Two complete longitudinal sweeps of the magnet are made for each measurement, with the probe facing towards the lead end in one sweep and towards the non-lead end in the other. Taking half of the difference of corresponding readings from the two sweeps gives the relative dipole field angle signature of the magnet as a function of position. Before and after each measurement, the field angle probe is calibrated in the range ±9.696 mrad.

	Location of Measurement (see text)	Mean Value of Angle (about the Vertical) (mrad)	Standard Deviation of Angle (mrad)	Range of Angle about Mean Value (mrad)
DCA311	ICB-2	0.87	2.82	13.06 ± .57
	MTF-1	1.07	2.58	13.49
	MTF-2	0.75	1.89	9.89
DCA312	ICB-1	-0.28	2.61	9.46
	ICB-2	0.00	2.25	9.75
	MTF-1	0.42	1.88	9.51
	MTF-2	1.37	1.12	5.42
DCA313	ICB-1	0.50	1.42	7.11
	ICB-2	-0.20	1.68	8.75
	MTF-1	0.76	1.68	8.38
	MTF-2	1.30	1.70	7.93
DCA314	ICB-1	0.15	3.17	11.89
	ICB-2	-0.11	2.04	8.38
	MTF-1	0.54	2.10	8.35
	MTF-2	2.00	1.62	7.52
DCA315	ICB-1	-4.02	2.31	11.06
	ICB-2	1.04	1.57	9.91
	MFT-1	1.11	1.30	8.04
	MTF-2	1.58	1.09	6.01
DCA316	ICB-1	1.44	1.92	8.04
	ICB-2	1.24	1.60	7.50
	MTF-1	2.14	1.68	7.77

Table 1. Preliminary Results for Field Angle Probe Measurements on 50 mm Aperture SSC Collider Dipole Magnets

The mean and standard deviation of the dipole field angle with respect to the vertical, and the peak-to-peak range of field angles about the mean, are shown in Table 1. Positive values of average field angle correspond to counter-clockwise rotation viewed from the lead end. Measurements labeled ICB-1 are done in a set of roller cradles at the Fermilab Industrial Center Building (ICB). ICB-2 indicates a measurement made at ICB after the cold mass has been installed in the cryostat. MTF-1 and MTF-2 indicate measurements on the MTF test stands before and after testing at 4.3 K.

The uncertainties in the measurement of field angle at a single position and in the mean angle about the vertical were estimated to be ±0.4 mrad and ±0.03 mrad respectively for measurements made on 40 mm aperture SSC collider dipoles built at Brookhaven National Laboratory and Fermilab (DiMarco, J., Kuchnir, M., and Yu, Y., 1991). The values in Table 1 for the standard deviation of field angle about the mean are upper limits, since contributions from random measurement errors, which can in principle be evaluated from existing data, have not been removed. A more complete report on these measurements is planned for a conference in the near future (Kuchnir, 1992).

Detailed examination of the data reveals evidence of changes in the field angle profile between data taken before and after cryostating at ICB, and before and after cold testing at MTF. The latter changes are implied by the changes in the standard deviation of the field angle between MTF-1 and MTF-2 measurements shown in Table 1. There is no evidence of such changes between cryostated data at ICB and data taken at MTF before cold-testing[1].

ABSOLUTE FIELD STRENGTH

Measurements of the transfer function (ratio of the central field strength to the magnet current) are made on each magnet at MTF. A system combining a Hall Probe and and NMR magnetic spectrometer system (Borer and Fremont, 1977; DiMarco and Radusewicz, 1991) is used for these measurements. The Hall probe is used in the end sections of the magnet, where the NMR system does not give a stable signal due to the large spatial field gradient. Both NMR and Hall probe readings are taken in 304.8 mm (1 foot) overlap sections just inside the end sections, to normalize the Hall probe readings. The NMR system is used over the entire central section of the magnet. Readings are taken every 6.35 mm (1/4") in the ends and overlap sections, and every 25.4 mm (1") in the central section of the magnet. For each NMR reading, the current and field are measured simultaneously.

Before a longitudinal sweep of the Hall Probe/NMR system, the magnet is cleared of all persistent currents by ramping the current until a quench occurs above 5000 A. The current is then ramped at 4 A/sec from 0 A to 6.5 kA, where it is held for 5 minutes, reduced to 115 A at 4 A/sec, where it is held for 2 minutes, and finally ramped at 4 A/sec to 1900 A, where the sweep is performed.

The straight section transfer function average value TF_{ave} is determined by taking the average over the data in the center (NMR-only) section, leaving out ±76.2 mm (±3") about the strain gauge pack centers, to avoid including perturbations in the transfer function caused by the permeability of the strain gauge block materials. Values for TF_{ave} for magnets DCA311 through DCA316 and DCA319 are shown in Table 2.

Magnet	Transfer Function (TF_{ave}) (Tesla / kA)	Magnetic Length (L_m) (meters)
DCA311	1.0450	14.863
DCA312	1.0454	14.867
DCA313	1.0453	14.860
DCA314	1.0453	14.862
DCA315	1.0453	14.867
DCA316	1.0452	14.866
DCA319	1.0449	14.868

Table 2. Transfer Function and Magnetic Length for 50 mm Aperture SSC Collider Dipoles

Another parameter of interest, the "magnetic length" L_m, is obtained from the formula (DiMarco and Radusewicz, 1991)

$$L_m = \frac{(\int TF\, dl)_{\text{lead end}} + TF_{ave}*L_{ss} + (\int TF\, dl)_{\text{non-lead end}}}{TF_{ave}}$$

where the integrals are obtained from the Hall Probe data taken at the lead and non-lead end sections and L_{ss} is the length of the straight section. Values for L_m are given in Table 2. The estimated uncertainty in L_m at this time is ± 2 mm.

[1]The mean angle about the vertical may change between ICB and MTF due to changes in mounting of the cryostat.

MAGNETIC FIELD HARMONICS

The magnetic field may be expressed as an expansion in multi-pole fields, each having some strength relative to the fundamental dipole field strength B_0. The harmonic coefficients b_n and a_n may be defined by

$$B_y = B_0 * [1 + \Sigma_n [b_n \cos(n\theta) - a_n \sin(n\theta)] (r / r_0)^n] \quad n = 1,...,\infty$$

In this expression for the vertical component of the magnetic field in the magnet aperture, the b_n and a_n are "normal" and "skew" harmonic coefficients respectively. Note that in the convention represented by this expression, b_n and a_n are the normal and skew *(2n+2)-pole* coefficients. For example, b_1 and a_1 are the normal and skew quadrupole coefficients, b_2 is the normal sextupole coefficient, and so on. This differs from the convention used more frequently in Europe. The radius r_0 is called the reference radius, and has the value 10 mm for SSC collider dipoles.

To date, the device used to measure the harmonics of the 50 mm aperture SSC magnets at Fermilab has been the B2 mole (Ganetis et al., 1987), designed and built at Brookhaven National Laboratory. The active part of the probe is 609.6 mm (2 feet) in length and consists of a rotating shaft with two dipole coils and a third "tangential" coil sensitive to the dipole and higher order harmonics. The dipole coils are used to remove the dipole field component from the tangential coil signal, so that only contributions from the higher order harmonics remain.

The harmonics of each magnet are measured after collar-keying, and again at room temperature after the fully assembled magnet has been mounted on a test stand at MTF. The harmonics are next measured at 4.3 K, then at room temperature after warm-up, again at 4.3 K during a second thermal cycle, and finally at room temperature following the final warm-up of the magnet. Each measurement consists of a longitudinal sweep of the magnet aperture with the mole center positioned at 609.6 mm (2 foot) intervals.

Collared Coil Harmonics

Table 3a shows the collared coil harmonics averaged over the straight section of the coils for magnets DCA311 through DCA319. (The odd normal harmonics and skew harmonics for magnet DCA316 are not available at this time due to an error during data taking on this magnet.) The mean, standard deviation about the mean, and r.m.s. about zero for the harmonics are given in Table 3b. The estimated uncertainty in the mean due to measurement error is also shown. All harmonics in this paper are given in prime units at r_0[2].

Harmonic mixing will occur if the mole device is off-center in the magnet aperture. An attempt has been made to remove such mixing effects from the harmonics given in this paper by calculating the horizontal and vertical centering errors δx and δy of the mole using an expression for a_7 and b_7, both expected to be zero, in terms of a_{8-10}, b_{8-10}, and δx and δy. The expression is used iteratively until stable values of δx and δy are obtained. If the iteration does not converge, a simpler correction based on either a_8 and b_8 (for collared coil data) or a_{10} and b_{10} (for MTF data) is used to zero a_7 and b_7 and determine δx and δy.

The observed mean value of the normal sextupole b_2 is -3.11, which is close to the expected value -3.8. The average value of b_4 0.42 differs significantly from the expected .07 and is still not well understood. The b_8 and b_{10} harmonics were built into the coil cross section to allow the removal of harmonic mixing due to imperfect centering of the mole within the aperture. Of the remaining harmonics only b_6, a_2, and a_4 have average values not consistent with zero (Mean $\geq \sim 3\sigma/\sqrt{N}$, with N = 9 in this case.). Like b_4, the non-zero b_6 is allowed for coils with perfect dipole symmetry. The small average a_2 and a_4 must be due to some asymmetry in the coils, which were all wound and cured on the same tooling.

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[2]One prime unit is one part in 10,000 of the fundamental field, in this case the dipole. So for example, one prime unit at r_0 of normal sextupole means that the sextupole field amplitude is .0001 times the dipole amplitude 10 mm from the center of the aperture. (Multi-pole fields have constant amplitude on circles of constant radius.)

	311	312	313	314	315	316	317	318	319
b2	-2.76	-3.15	-2.19	-3.01	-2.98	-2.52	-3.94	-3.52	-3.33
b4	0.46	0.40	0.35	0.38	0.37	0.40	0.50	0.46	0.42
b6	-0.06	-0.05	-0.05	-0.06	-0.07	-0.06	-0.07	-0.06	-0.07
b8	0.06	0.06	0.07	0.07	0.06	0.06	0.06	0.06	0.06
b10	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02
b1	0.05	<.01	-0.39	-0.55	0.09		0.46	-0.03	-0.32
b3	<.01	-0.04	-0.04	-0.07	0.04		0.04	0.06	0.05
b5	<.01	-0.01	<.01	-0.01	<.01		<.01	<01	<.01
b7	<.01	<.01	<.01	<.01	<.01		<.01	<.01	<.01
b9	<.01	<.01	<.01	<.01	<.01		<.01	<.01	<.01
a1	0.60 (0.79)	0.56 (0.67)	0.69 (-0.42)	-0.10 (-0.62)	-0.31 (-0.10)		-0.15 (-0.28)	-0.51 (-0.30)	-0.32 (-0.35)
a2	-0.25 (-0.12)	-0.12 (-0.12)	-0.21 (-0.07)	-0.08 (-0.07)	-0.14 (-0.11)		0.04 (-0.21)	-0.16 (-0.13)	-0.42 (-0.09)
a3	-0.07 (0.03)	0.10 (0.03)	0.06 (-0.02)	-0.06 (-0.03)	0.06 (0.00)		-0.13 (-0.01)	0.17 (-0.01)	-0.03 (-0.02)
a4	-0.04	-0.05	-0.05	-0.06	-0.06		-0.02	-0.06	-0.08
a5	-0.01	-0.01	<.01	0.02	0.01		0.01	0.02	-0.01
a6	<.01	<.01	-0.01	<.01	<.01		<.01	<.01	<.01
a7	<.01	<.01	<.01	<.01	<.01		<.01	<.01	<.01
a8	<.01	-0.01	-0.01	-0.01	-0.01		-0.01	-0.01	-0.01
a9	<.01	<.01	<.01	<.01	<.01		<.01	<.01	<.01
a10	<.01	<.01	<.10	<.01	<.01		<.01	<.01	<.01

Table 3a. Collared Coil Harmonics for DCA311 - DCA319
(Expected values for a_1, a_2, and a_3 shown in parentheses)

	Mean	σ (about mean)	r.m.s. (about zero)	δMean (estimated measurement uncertainty)
b2	-3.11	0.41	3.09	0.02
b4	0.42	0.04	0.41	0.01
b6	-0.06	0.01	0.06	<.01
b8	0.06	<.01	0.06	<.01
b10	0.02	<.01	0.02	<.01
b1	-0.09	0.30	0.31	0.07
b3	0.01	0.04	0.04	0.01
b5	<.01	——	——	——
b7	<.01	——	——	——
b9	<.01	——	——	——
a1	0.06	0.45	0.40	0.07
a2	-0.17	0.13	0.20	0.02
a3	0.01	0.10	0.07	0.02
a4	-0.05	0.02	0.05	0.01
a5	<.01	——	——	——
a6	<.01	——	——	——
a7	<.01	——	——	——
a8	-0.01	<.01	0.01	<.01
a9	<.01	——	——	——
a10	<.01	——	——	——

Table 3b. Collared Coil Harmonics for
50 mm SSC Collider Dipoles

An attempt has been made (Mokhtarani, 1991) to calculate the expected values of a_1, a_2, and a_3 based on known asymmetries in coil manufacture and pole shimming. The predicted values for these harmonics are shown in Table 3a in parentheses below the measured values. The correlation between predicted and measured values of a_1 is fairly good, with the exceptions of DCA313 and DCA314. For a_2, with the exception of DCA317 the measured harmonic has the expected sign, but the magnitude is generally greater than predicted. For a_3 there is no noticeable correlation, and the measured magnitude is always larger than that predicted by the model. Calculations of a_4 gave values much smaller than the measured values.

Harmonics of Fully Assembled Magnets

Room Temperature Measurements. Table 4 shows the harmonics measured at MTF before testing at 4.3 K. The mean, standard deviation, and r.m.s. about zero are shown for each harmonic. As before, the harmonics have been averaged over the straight section of the magnet. Only the allowed harmonics (even b's), a_2, and a_4 show evidence of a non-zero central value.

	311	312	313	314	315	Mean	σ	RMS
b2	1.80	2.47	2.54	2.27	2.41	2.30	0.26	1.83
b4	0.35	0.32	0.30	0.30	0.30	0.31	0.02	0.25
b6	-0.04	-0.03	-0.03	-0.04	-0.04	-0.03	0.01	0.03
b8	0.05	0.05	0.06	0.05	0.05	0.05	<.01	0.04
b10	0.02	0.01	0.01	0.02	0.02	0.02	<.01	0.01
b1	-0.20	-0.06	-0.36	-0.33	0.18	-0.15	0.20	0.20
b3	0.02	-0.03	-0.03	-0.03	0.03	-0.01	0.03	0.02
b5	<.01	0.01	0.01	-0.01	<.01	<.01	——	——
b7	<.01	<.01	<.01	<.01	<.01	<.01	——	——
b9	<.01	<.01	<.01	<.01	<.01	<.01	——	——
a1	0.63	0.29	1.77	-0.18	-0.16	0.47	0.72	0.68
a2	-0.20	-0.03	-0.05	-0.04	-0.05	-0.07	0.06	0.08
a3	-0.06	0.07	0.13	-0.04	0.03	0.03	0.07	0.06
a4	-0.01	<.01	<.01	-0.02	-0.01	-0.01	<.01	0.01
a5	-0.02	-0.01	<.01	0.01	0.01	<.01	——	——
a6	<.01	<.01	-0.01	-0.01	<.01	-0.01	<.01	0.01
a7	<.01	<.01	0.01	<.01	<.01	<.01	——	——
a8	<.01	0.01	0.01	0.01	<.01	<.01	——	——
a9	<.01	<.01	<.01	<.01	<.01	<.01	——	——
a10	<.01	<.01	<.01	<.01	<.01	<.01	——	——

Table 4. Room Temperature Harmonics for DCA311 - DCA315
(prime units at 10 mm)

Measurements at 4.3 K. For longitudinal sweeps of the mole at 4.3 K, the magnet is prepared in the same manner as for Hall Probe/NMR sweeps, except that the final current is 2000 A instead of 1900 A. Table 5 shows the values for harmonics measured at 4.3 K. The mean, standard deviation, and R.M.S. about zero are given for each harmonic, and where available, the SSC "systematic" and "σ" values are given in the final two columns[3].

Magnetization effects cause the harmonics measured at 2000 A to differ by some amount from their geometric values[4]. A correction is obtained for each harmonic from the hysteresis loop of the harmonic during a sawtooth ramp between 115 A and 6500 A. Up and down ramp values of the harmonic are averaged at current values between 2000 and 3000 A,

[3]The average value of a harmonic over the entire ensemble of magnets in the SSC is required to be less than the SSC systematic value, and any given magnet must have harmonics within 3σ of the mean.
[4]The "geometric" value of a harmonic coefficient is the value it would have if only the geometry of the coils and yoke iron and the distribution of transport current in the coils were determining the field shape.

to calculate the geometric value of the harmonic. The difference between the measured harmonic on the up ramp at 2000 A and the geometric harmonic value is then the correction for the harmonic in question. The correction is only large (greater than .05 units) for the normal sextupole b_2, for which about 0.3 units should be added to the uncorrected value.[5]

The measured hysteresis values for b_2 are consistent with calculations based on the critical current properties of the cable. For magnets DCA311, DCA313, and DCA316, the predicted b_4 agrees well with the observed value. For DCA312 and DCA314, the sign of the b_4 hysteresis is the opposite of that expected and the amplitude is much larger than expected. For DCA315, the up and down ramp branches of b_4 cross, which is not expected.Two of the magnets, DCA314 and DCA315, have shown much larger hysteresis than expected in the skew quadrupole a_1.

	311	312	313	314	315	Mean	σ	RMS	SSC sys.	SSC σ
b2	1.00	1.90	1.83	1.69	1.52	1.59	0.32	1.62	0.80	1.15
b4	0.31	0.30	0.27	0.28	0.29	0.29	0.01	0.29	0.08	0.22
b6	-0.05	-0.04	-0.04	-0.04	-0.05	-0.04	0.01	0.04	0.013	0.018
b8	0.05	0.05	0.05	0.05	0.05	0.05	<.01	0.05	0.01	0.008
b10	0.02	0.02	0.02	0.02	0.02	0.02	<.01	0.02	na	na
b1	0.06	-0.01	-0.24	-0.36	0.06	-0.10	0.17	0.20	0.04	0.50
b3	<.01	-0.04	-0.03	-0.05	0.04	-0.02	0.03	0.03	0.026	0.16
b5	<.01	<.01	<.01	-0.01	<.01	<.01	——	——	0.005	0.017
b7	<.01	<.01	<.01	<.01	<.01	<.01	——	——	0.005	0.01
b9	<.01	<.01	<.01	<.01	<.01	<.01	——	——	na	na
a1	0.58	0.55	0.57	-0.22	-0.06	0.28	0.35	0.45	0.04	1.25
a2	-0.17	-0.05	-0.08	-0.01	-0.06	-0.07	0.05	0.09	0.32	0.35
a3	-0.07	0.04	0.05	-0.01	0.02	0.01	0.05	0.05	0.26	0.32
a4	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	<.01	0.01	0.01	0.05
a5	-0.01	<.01	<.01	0.02	0.01	<.01	——	——	0.005	0.05
a6	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	<.01	0.01	0.005	0.008
a7	<.01	<.01	<.01	<.01	<.01	<.01	——	——	0.005	0.01
a8	<.01	0.01	0.01	0.01	0.01	0.01	——	——	0.005	0.008
a9	<.01	<.01	<.01	<.01	<.01	<.01	——	——	na	na
a10	<.01	<.01	<.01	<.01	<.01	<.01	——	——	na	na

Table 5. 4.3 K Harmonics for DCA311 - DCA315
(Uncorrected for Hysteresis Effects)

The allowed harmonics show systematic values inconsistent with zero. If the mean value of b_2 for subsequent magnets could be brought within the tolerance band of 0.80, then all magnets tested so far would pass the 3σ criterion. The same statement applies to b_4 and b_6. Finally, b_8 and b_{10} are expected to be .043 and .015 for the chosen coil cross section, and these harmonics will be tuned out in future cross section designs. Of the un-allowed harmonics, only a_2 and a_4 show mean values inconsistent with zero, and both of these are within the SSC specifications.

Warm-Cold Harmonics Correlations. Table 6 shows the mean and standard deviation of the change in the harmonics between room temperature and 4.3 K. Also given are the slopes and intercepts for linear fits to and correlation parameters for cold vs. warm distributions of the harmonics. The correlations for b_1 and a_1 are not good, so that it would be difficult to correct cold values of these harmonics with changes made at room temperature. However, as mentioned before, there is no evidence that the mean values for these harmonics lie outside the SSC tolerances for magnets manufactured so far.

[5]The persistent currents affecting b_2 decay slowly, so that b2 changes by ~.06 units during a typical longitudinal scan.

	<w - c>	σ (w - c)	slope	intercept	correlation parameter
b2	-0.70	0.12	1.14	-1.02	0.95
b4	-0.03	0.01	0.59	0.10	0.94
b6	-0.01	0.00	0.72	-0.02	0.83
b8	-0.00	0.00	0.42	0.03	0.86
b1	0.05	0.15	0.64	-0.01	0.76
a1	-0.20	0.58	0.36	0.11	0.73

Table 6. Differences and Correlation Coefficients between Room Temperature and 4.3 K Harmonics

CONCLUSIONS

Measurements of dipole field angle, dipole field strength, and field quality have been made on a set of full scale 50 mm aperture SSC collider dipole magnets built at Fermilab. There is evidence of change in the field angle profile of magnets during assembly and cold testing. The transfer functions and magnetic lengths of magnets measured so far appear to be quite stable. Harmonics measurements show no evidence of systematic harmonics outside of the SSC specifications, with the exception of several of the allowed multi-poles which may be removed by iteration of the coil cross section design.

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