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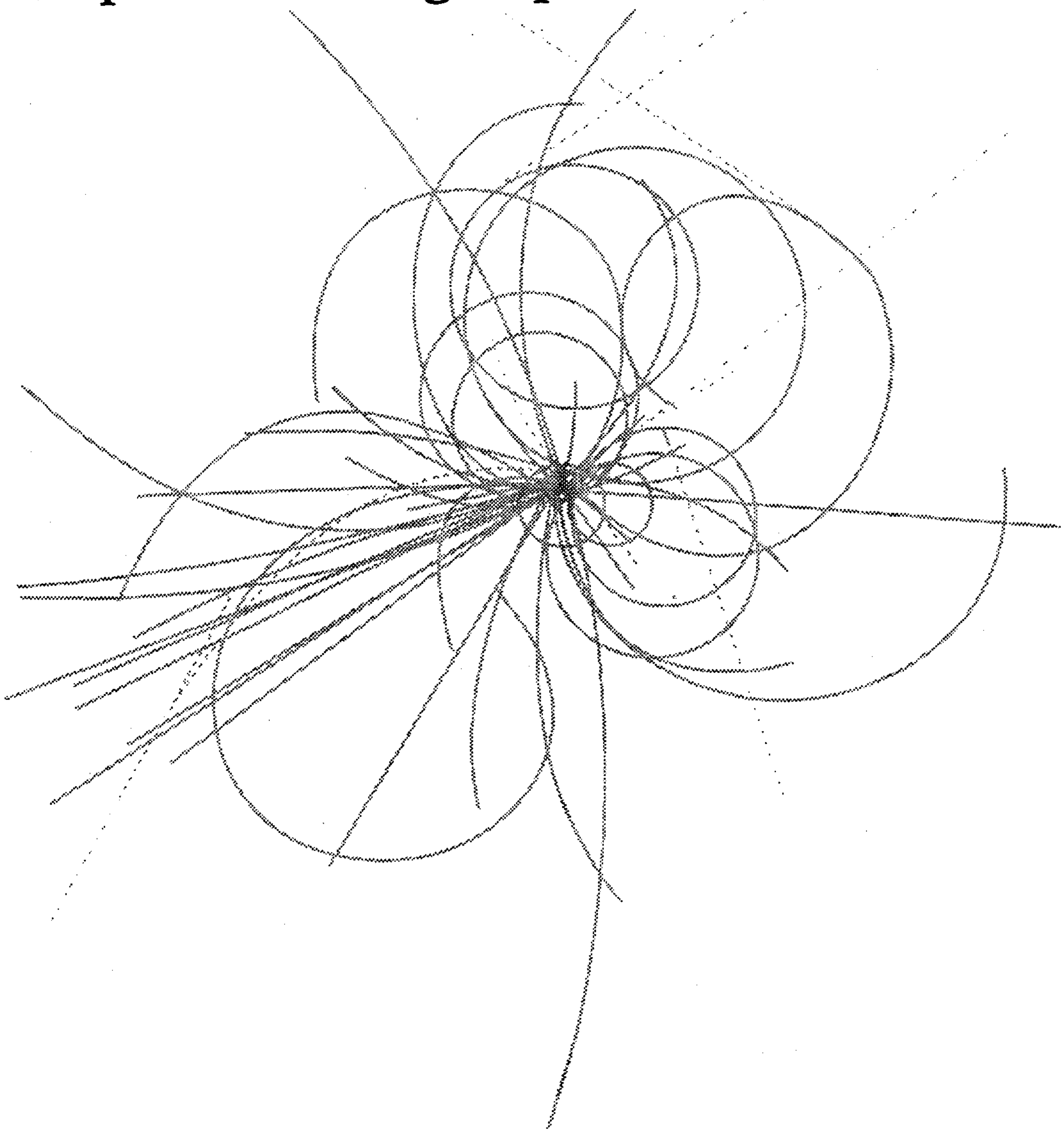

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A SUMMARY OF SSC DIPOLE MAGNET FIELD QUALITY MEASUREMENTS*

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ABSTRACT

This paper reports results of field quality measurements of the initial 15 m-long, 50 mm-aperture SSC Collider dipoles tested at Brookhaven National Laboratory and Fermi National Laboratory. These data include multipole coefficients and the dipole angle at room temperature and 4.35 K, 4.35 K integral field measurements, and time-dependent effects. Systematic uncertainties are also discussed.

INTRODUCTION

The initial series of full-sized SSC collider dipoles includes magnets made at Fermilab and BNL. At this time, field quality data are available from three magnets made by BNL and Westinghouse personnel and from five magnets made by Fermilab and General Dynamics personnel. Partly because not all magnets have been tested and partly because of uncertainties in the analysis of the multipole coefficient data, this report will serve primarily as a snapshot of work in progress. Only a minimal amount of magnet construction information is included here. More complete reports have been made in other papers to this conference[1,2,3]. The field quality measurements in the Fermilab-General Dynamics magnets have also been summarized in a separate conference paper[4].

A. Multipole Coefficients.

A useful expression for the magnetic field is:

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} (b_n + ia_n)(x+iy)^n$$

where x and y are the horizontal and vertical coordinates and B_0 is the dipole field strength. A pure dipole field has $b_0 = 1$ and all other multipole coefficients zero. The skew terms are denoted by the a_n, the normal terms by b_n. The quadrupole coefficients have n = 1, the sextupole have n = 2, and so forth. The coefficients are evaluated at a reference radius of 10 mm. Typical tolerances are at the level of 10^{-4} of the dipole field, and this scale is informally referred to as a "unit" or a "10^{-4} unit" of a multipole coefficient. The multipole data summarized in this note are for the magnet straight-section measured with a 1.0 m coil.

Multipole Coefficients at 2T.

The axial variation of the normal sextupole, b_2, in a typical magnet at 2 kA and 6.5 kA is shown in Fig. 1. (To a good approximation, 1 kA produces 1 T of field.) The value of b_2, about 4 units, is nearly the same at both fields. The axial variation is the same at the two fields, as expected. The size of b_2 is due to the use of pole shims which were not of the design thickness in this magnet. (This is discussed in more detail below.) The axial variation of the normal decapole, b_4, is shown in Fig. 2. It can be seen that b_4 at high field is systematically lower than at low field. The interesting question of whether the axial variation is the same for magnets made on the same fixturing will be addressed in a future report.

Summaries of the multipole coefficient data for the first three BNL-Westinghouse magnets and the first five Fermilab-General Dynamics magnets are presented in Figs. 3 and 4, respectively. For each multipole coefficient, the mean and r.m.s. variation have been calculated and then divided by the SSC systematic tolerance. In the plots, multipoles meeting the tolerances will have ratios plotted between the dashed lines at +1 and -1. (In estimating the uncertainty in the mean, an allowance must be made for the small number

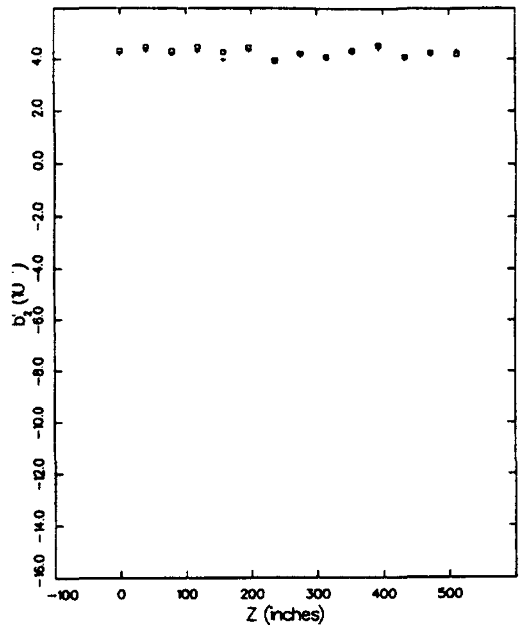

Figure 1. Axial variation of b_2 at 2 kA (+) and 6.5 kA (□).

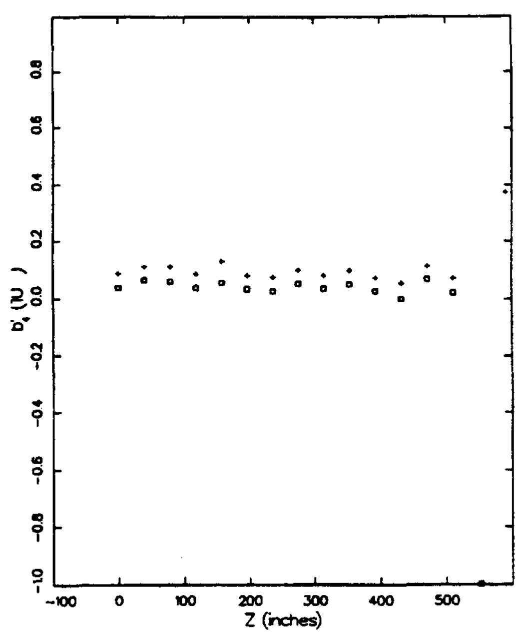

Figure 2. Axial variation of b_4 at 2 kA (+) and 6.5 kA (□).

of magnets in the sample.)

For both sets of magnets, most of the multipole coefficients lie between the dashed lines. The skew quadrupole, a_1, lies beyond the dashed lines but is particularly subject to

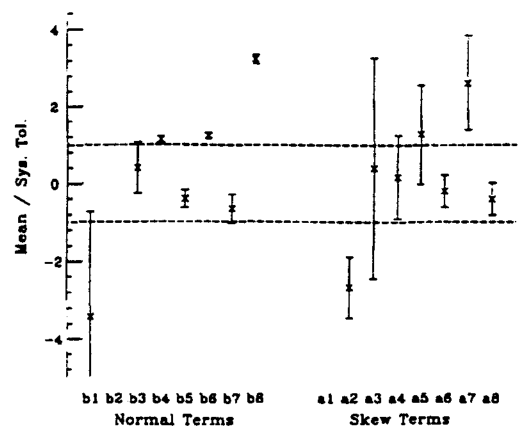

Figure 3. Mean and RMS variation of multipole coefficients measured at 2 kA for three BNL-Westinghouse magnets, scaled by the SSC systematic tolerance. (The ratios for a_1 and b_2 exceed 5.)

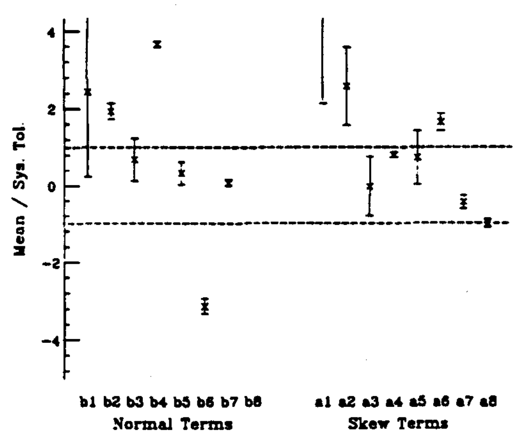

Figure 4. Mean and RMS variation of multipole coefficients measured at 2 kA for five Fermilab-General Dynamics magnets, scaled by the SSC systematic tolerance. (The ratio for b_8 exceeds 5.)

additional uncertainties in the centering correction, discussed below. The allowed multipoles (b_n's with n even) are in some cases well beyond the dashed lines, but, since they are generally in good agreement with calculations based on the actual sizes of the magnet components[5], significant reduction can be achieved by a modest redesign of the coil cross section. Only the decapole has a significant (0.4 unit) difference between the design and measured values; this offset can be taken into account in the new cross section design.

The correlation between room temperature and 4.35 K (2 T) multipole measurements is shown in scatter plots of the skew quadrupole a_1 (Fig. 5) and the normal sextupole b_2 (Fig. 6). Multipoles with the same value warm and cold would lie on the diagonal line. With some scatter, the a_1 data follow this line. However, the b_2 data lie in two groups, one for BNL-Westinghouse magnets and one for Fermilab-General Dynamics magnets. This grouping is due to differences in magnet construction, the most obvious of which are the inner coil pole angles and the orientation of the split in the yoke laminations. The data also indicate that the two designs respond differently to cooldown, although each response is acceptable for the accelerator.

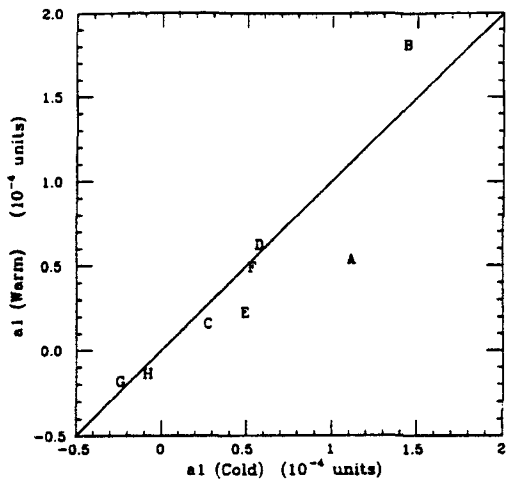

Figure 5. Scatter plot of warm and cold (2 kA) measurements of the skew quadrupole a_1 for three BNL-Westinghouse magnets (A-C) and five Fermilab-General Dynamics magnets (D-H).

A summary of the warm-cold correlation data is shown for the three BNL-Westinghouse magnets and for the five Fermilab-General Dynamics magnets in Figs. 7 and 8. For each multipole, the r.m.s. variation of the difference between the warm and cold measurements is calculated and then divided by the tolerance on the r.m.s. variation of the multipole coefficient. For all but one term, this ratio is small in comparison to 1. Hence, the use of warm measurements to predict the cold multipoles will not significantly increase the r.m.s. width of the cold multipole distribution, and the strategy of measuring all the magnets warm but only a fraction cold is acceptable. (The ratio for a_7 in Fig. 7 is thought to be an artifact.)

Magnetization, Saturation, Eddy Currents.

The next set of plots illustrates the sextupole and decapole variation with current. Typical sextupole data for BNL-Westinghouse and Fermilab-General Dynamics magnets are shown in Figs. 9 and 10 respectively. (In figures 9-13, a constant has been added to the measured values so that a detailed comparison to the calculation can be made.) The magnetization sextupole, the most important effect at low field, increases monotonically

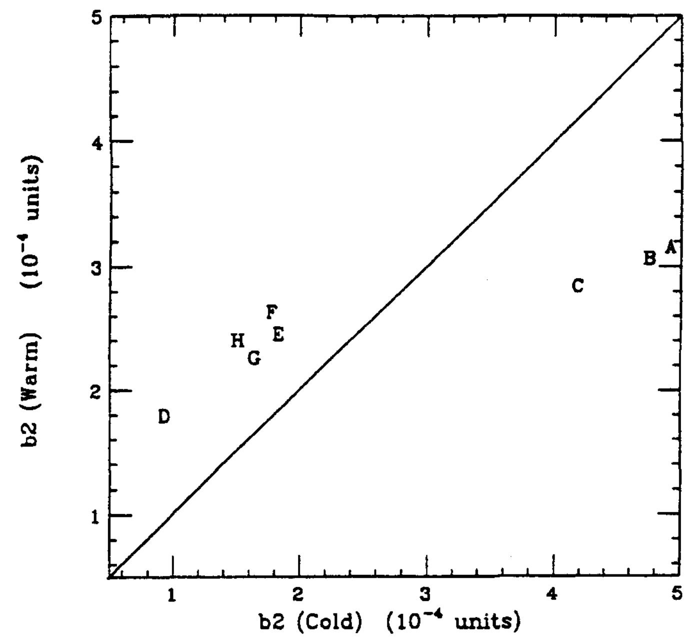

Figure 6. Scatter plot of normal sextupole b_2 data. Same notation as figure 5.

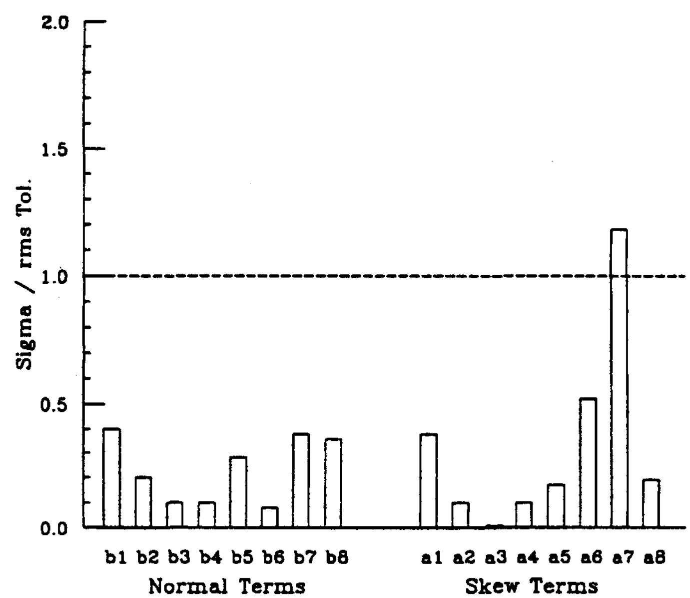

Figure 7. RMS width of the distribution of cold-warm differences in the multipole coefficients, divided by the SSC RMS tolerance, for three BNL-Westinghouse magnets.

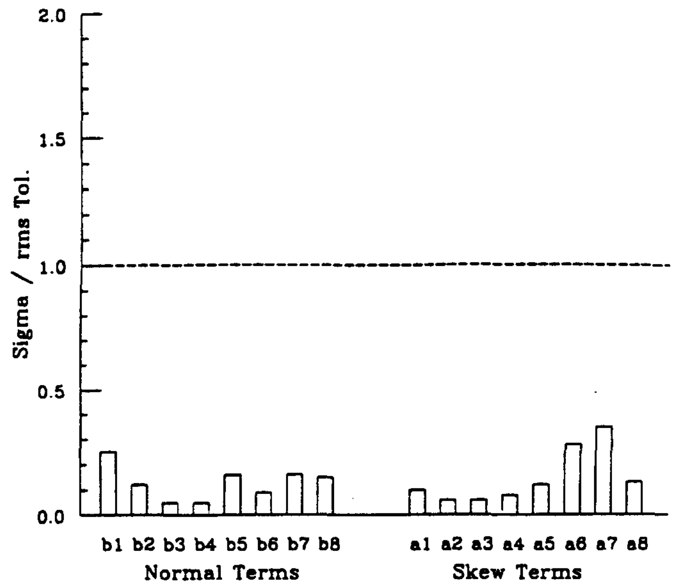

Figure 8. Same information as in figure 7, for five Fermilab-General Dynamics magnets.

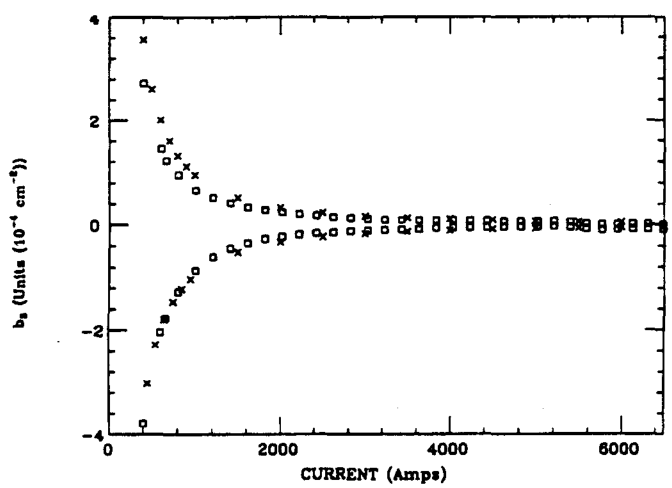

Figure 9. Normal sextupole b_2 vs. current for a typical BNL-Westinghouse magnet. In this and subsequent figures, X denotes calculations, ☐ measurements. The calculations include only magnetization effects.

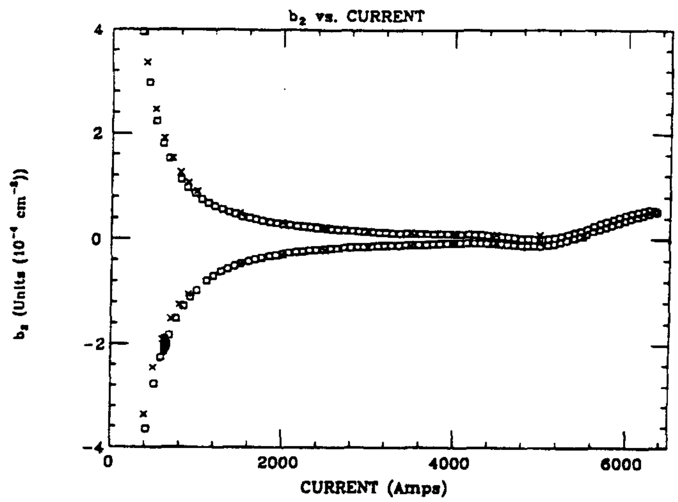

Figure 10. Normal sextupole b_2 versus current for a typical Fermilab-General Dynamics magnet. Same symbols as figure 9.

as the current is ramped up and then down again. At these fields the hysteresis curve of the sextupole in the two magnets is quite similar and in good agreement with the magnetization calculation. (The calculation is adapted from the HERA program.) For currents above 4 kA, the difference between the two magnets is qualitatively attributed to a combination of two factors: (1) the small motion of the collared coils in the BNL-Westinghouse magnets, which move outward until they contact the horizontally-split yoke[6,7]; (2) the small notches in the yoke inner edge to align the collars, located at the top and bottom in the Brookhaven-Westinghouse magnets and on the horizontal midplane of the Fermilab-General Dynamics magnets. Although not discussed in detail here, the variation of b_2 and b_4 due to yoke saturation is generally in agreement with calculations.

The variation of the decapole with current is shown in Figs. 11 and 12. At high fields, the effects of saturation can be seen in both plots. The magnetization effect in the BNL-Westinghouse magnet below 4 kA, a monotonic decrease of the decapole as the current is ramped up and then down, Fig. 11, is typical, and in fair agreement with the calculation. However, for two of the five Fermilab-General Dynamics magnets, the decapole increases monotonically as shown in Fig. 12. It is possible that eddy currents cause this behavior. Ramp rate effects are already known to have larger effects on the quench currents of these 15 m magnets[1,8] than on the quench currents of their smaller-aperture, 17 m predecessors. Eddy currents may also account for the difference in the width of the decapole hysteresis seen in Fermilab-General Dynamics magnets, Figs. 12 and 13. (The width of the sextupole hysteresis in these two magnets is nearly the same.) Measurements at different ramp rates will be made in future magnets.

At high field, a saturation skew quadrupole is produced because of flux leakage from the saturated yoke, which is located above the center of the iron vacuum vessel. Uncertainties in the centering correction (discussed below) limit the accuracy of this measurement at the moment. A preliminary result is that a_1 decreases about 0.15 to 0.2 units at high field. This is in general agreement with calculations, which predict a decrease of 0.1 to 0.2 units.

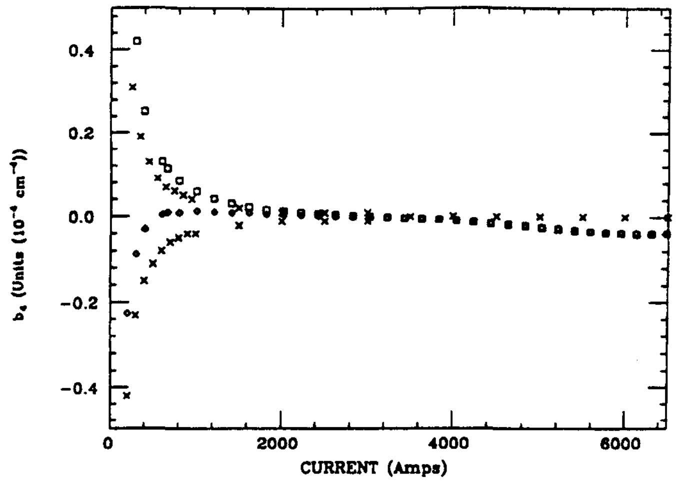

Figure 11. Normal decapole b_4 versus current for a typical BNL-Westinghouse magnet. Up-ramp data are indicated by □, down-ramp by ◇, calculation by X.

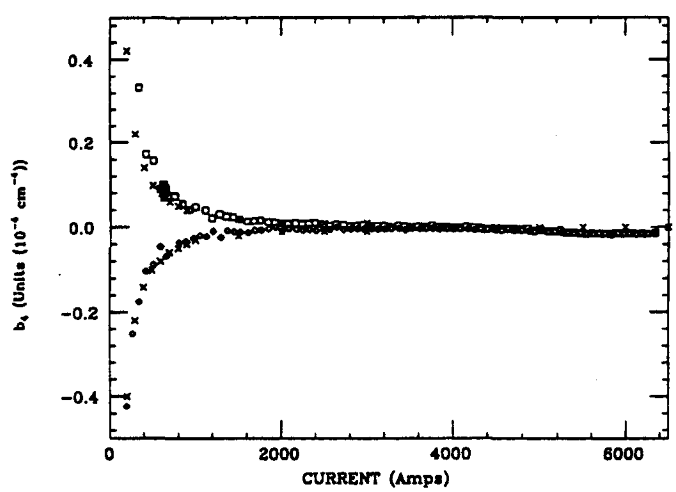

Figure 12. Normal decapole b_4 versus current for two of the five Fermilab-General Dynamics magnets. Same symbols as figure 11.

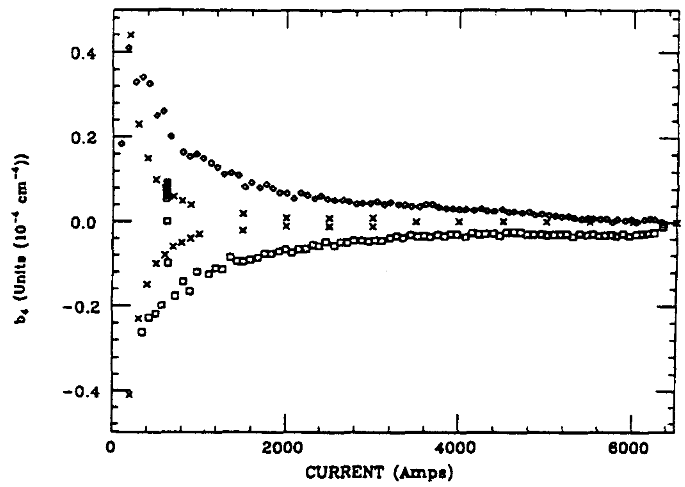

Figure 13. Normal decapole b_4 versus current for a magnet with measured hysteresis much larger than the calculated values. Same symbols as figure 11.

Sextupole Time-Dependence at Injection.

On each magnet, multipole measurements are made while the current is varied as it will be during injection and acceleration. A portion of one of these measurements is shown in Fig. 14. After an initial quench and a cycle to high field, the magnet is brought to injection (660A) and measurements start. The current is held constant for about an hour. During this time, the sextupole becomes about 0.2 units more positive. When the ramp-up is started, the sextupole "snaps back" to the value it had at the start of the constant-current period. As the current is increased, the hysteresis curve is the same as if there had been no constant-current period.

The magnets in this group have conductor from Oxford, IGC, and Supercon in various combinations. The sextupole time variation of magnets selected to have cable from all three vendors is the same to better than 0.02 units. This is interesting, because the cable for the HERA dipoles displayed two significantly different, vendor-dependent time constants[3].

Centering Corrections.

Because the center of rotation of the coil used to measure the multipole coefficients is not coincident with the magnet axis, the measured values of the coefficients will be affected by feeddown from higher order terms. For these measurements, the coil lies about 1-2 mm below the magnet axis. This offset is large enough that feeddown from terms more than one order above the term of interest may be significant. An initial understanding of this has been obtained by studying the effects of using different high-order terms, b_8 and b_{10}, to make the centering correction. In these magnets, b_8 is twice as large as b_{10}, so it is advantageous to use b_8 in making the centering correction if a way can be found to remove the effects of feedown from b_{10}. This has been achieved by taking an initial value for the displacement from b_{10}, and then iterating this initial value using b_8. An interesting experiment, raising the measuring coil a known amount, has been carried out at Fermilab. The experiment confirmed the overall method of making centering

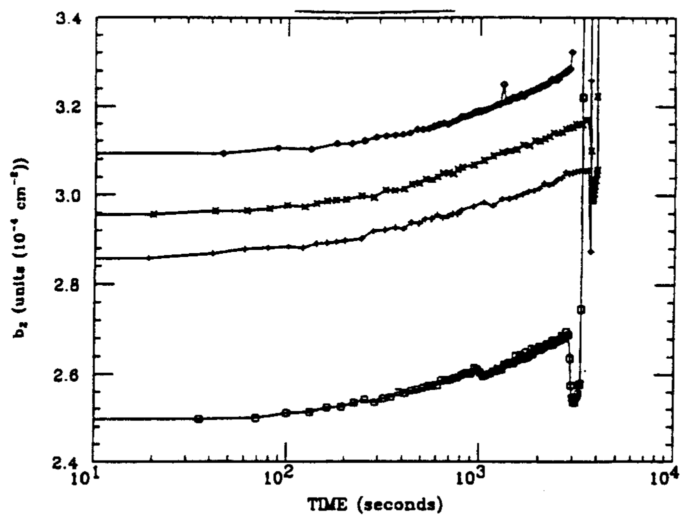

Figure 14. Time variation of the normal sextupole b_2 at 660A (up to 2.8-3.0 ksec.) and on the ramp up (after 2.8 ksec.) for four magnets which contain inner coil cable from three different vendors.

corrections. Further studies of systematic errors, using other centering methods such as that for the HERA magnets, are underway. It is hoped that these will contribute to understanding the current-dependence of the low-field skew quadrupole in certain magnets. For this paper, the offset has been determined from the 20- and 22-pole terms (b_{10}).

B. Dipole Angle.

Thus far, the angle of the dipole field with respect to vertical has been measured with a calibrated gravity sensor at 4.35 K in only one magnet. The important quantity in this measurement is the difference between the warm and cold measurments, since the test stand itself has not been constructed to replicate SSC installation. For this magnet, the difference was less than 0.1 mrad, much less than the r.m.s. tolerance of 1 mrad. These measurements will be made on additional magnets.

Room temperature measurements of the dipole angle before and after cold testing have been made on all Fermilab-General Dynamics magnets. The average dipole angle showed an increase ranging from 0.5 to 1.5 mrad. Also, there are indications of a change in the magnet twist due to cold testing.

C. Integral Field.

Precise measurements of the transfer function in the magnet straight-section, B/I, have been made with an NMR probe in three magnets at 1.8 T. All three have B/I = 1.0453 T/kA. Integral field measurements have also been made with a combination of NMR and Hall probes. Here, the accuracy has been limited by the absence of a precise measurement of the axial position of the probes. Results from three magnets are about the same as the fractional r.m.s. tolerance.[4]

D. Short-term Reproducibility of Multipole Measurements.

Results from the first F-series "mole" rotating coil system are shown in Fig. 15. These are of interest because this system will be initially supplied to the magnet vendors. The plot shows the results of 50 measurements at 2 T and fixed axial position. For each multipole, the r.m.s. width of the measurements has been divided by the SSC systematic tolerance. All the ratios are significantly less than 1, indicating that, when the signal level is adequate, the short-term variation in the measurement system is not a source of measurement uncertainty.

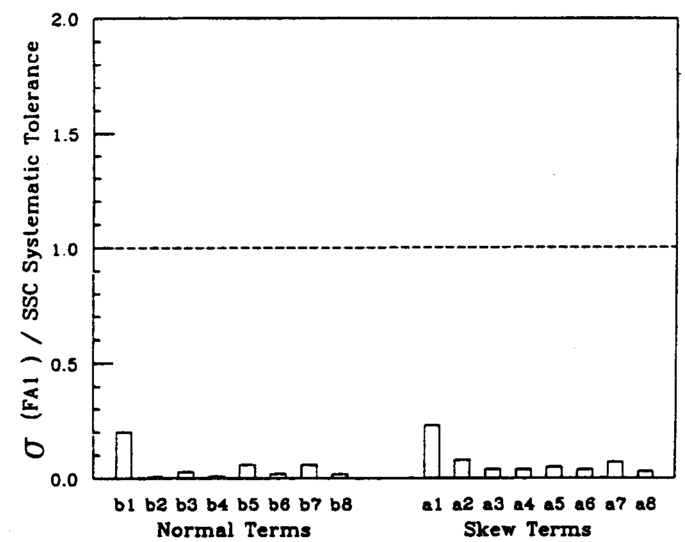

Figure 15. The RMS width divided by the SSC systematic tolerance for each multipole measured with the first F series field quality measuring system (MOLE). The plots are based on 50 measurements made at 2 kA and a fixed axial position.

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