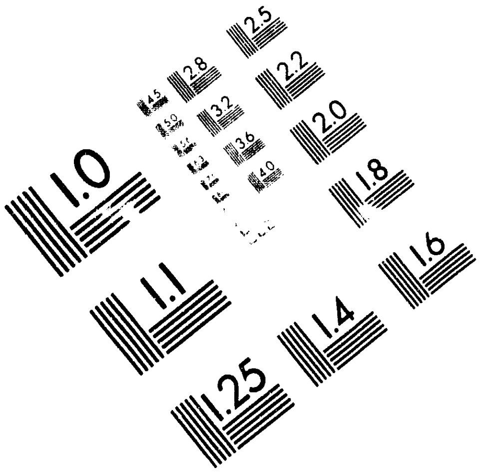

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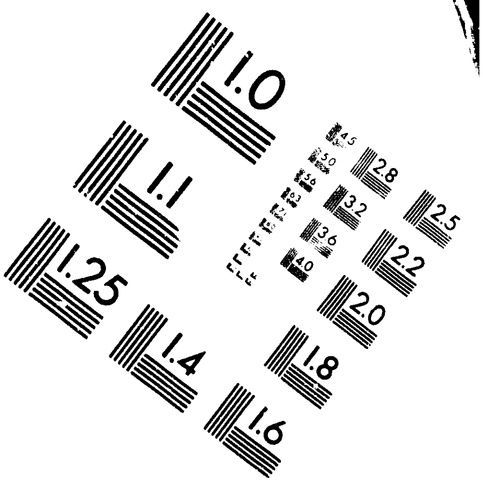

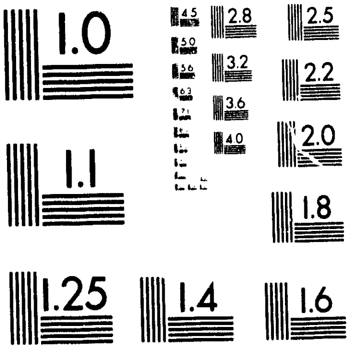

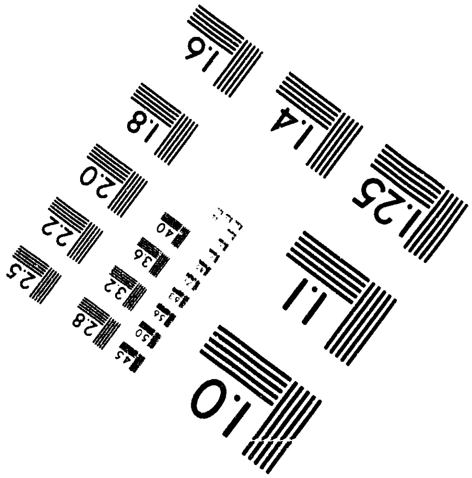

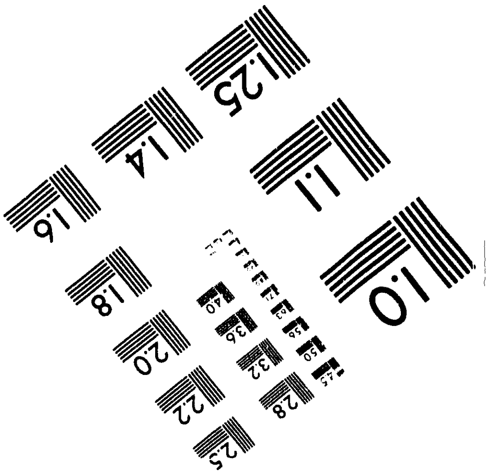

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Summary of Dipole Field Angle Measurements on 50mm-Aperture SSC Collider Dipole Magnet Prototypes*

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SUMMARY OF DIPOLE FIELD ANGLE MEASUREMENTS ON 50MM-APERTURE SSC COLLIDER DIPOLE MAGNET PROTOYPES

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INTRODUCTION

At several stages in the production of the SSC collider dipole magnets and their final installation (as well as for beam orbit calculations) the magnetic field angle needs to be known. A simple device using a permanent magnet which aligns itself with the magnetic field (the Vertical Field Angle Probe, FAP) had been developed at FNAL to survey the direction of the magnetic dipole field with respect to the vertical (as determined by gravity) along the magnet axis[1]. The determination of the dipole field angle was part of the field quality characterization of a series of thirteen full-length 50mm-aperture SSC Collider Dipole Magnet Prototypes (DCA311-DCA323) which were built for R&D purposes at FNAL (for design specification[5,6]).

Measurements with the first developed FAP system (FAP1) were performed on a regular basis through several stages of the magnet production process with the intention of fabrication quality control[2]. Part of these included measurements performed before and after cryogenic testing: these data are summarized here. The performance of a second system (FAP2) with an improved probe and data aquisition system was tested on part of the DCA series as well. This paper includes a presentation of time stability, noise and angular resolution data of this second probe. Another alternative instrument to determine the dipole field angle is the "mole" rotating coil system developed at BNL used mainly to measure the multipole components of the magnetic field[4]. In the case of magnet DCA320, a comparison is made between the field angle as determined by the mole and those determined by both of the FAPs.

SETUP AND MEASUREMENTS

The vertical field angle measurement systems consist of a small permanent magnet which is housed in a jewelled gimbal system to which an electrolytic bubble level sensor is connected. The bubble level sensor determines the angle of the permanent magnet with respect to the vertical. The probe is positioned inside the beam tube along the magnet axis by a set of interconnecting rods. Spacers attached to the rods keep the probe in the center of the beam tube. A detailed description of the FAP system can be found in reference[1,2].

For the FAP2 system, the probe and data aquisiton were redesigned. The main modifications of the probe were placing the amplifier close to the actual measuring device (inside the G10 cover). This should result in lower electronics noise (better angular resolution) and better signal stability. The heat dissipation from the amplifier should also maintain a more constant temperature on the electrolytic bubble level sensor. In addition, improve-ments on the balance of the gimbal system should give faster stabilization of the signals.

The dipole field angle is measured at various locations (z positions) along the magnet axis (every 0.0762 m – resulting in 180 measurements for the 15-m prototypes tested) once with the probe head pointing to the lead end of the magnet and then again with the head pointing towards the

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non-lead end (both measurments are taken so the zero level can later be removed). The magnet current was 8 A which results in a magnetic dipole field of the order of 0.008 Tesla.

The "FA1 mole" with an air motor and a 1m coil was used to measure the field angle for comparison with the FAPs. Mole measurements were made every meter (since the mole integrates the field over its 1m coil length), but only in one direction axially; hence the zero level of the mole is a matter of calibration. The mole data in this paper were taken at 10 A with the same polarity of magnet current as for the FAPs.

DATA PROCESSING AND RESULTS

We let $\vartheta^{+}(z)$ represent the measured dipole angle as a function of the z position in the case where the probe head points towards the lead end of the magnet, and $\vartheta^{-}(z)$ the case where the probe head points to the non-lead end. Since both of these axial scans contain mechanical and electrical contributions to the zero level, $\vartheta^{+}(z)$ and $\vartheta^{-}(z)$ must be combined according to

$$\vartheta(z) = 0.5 \bullet (\vartheta^{+}(z) - \vartheta^{-}(z)) \tag{1}$$

to obtain the true dipole field angle $\vartheta(z)$.This method cancels constant effects on the zero level, but still contains contributions from iron yoke magnetization[3] because the FAP system operates only with one polarity of magnet current. The offset o(z) defined by

$$o(z) = 0.5 \bullet (\vartheta^{+}(z) + \vartheta^{-}(z)) \tag{2}$$

contains information about the zero level. The variation of o(z) (noise) is a measure for the angular resolution of the measurement system. Because o(z) shows, in some cases, a systematic behavior as a function of z, we evaluate this portion of the error by finding a 3rd order polynomial fit, $o^{f}(z)$, to the offset o(z). The systematic portion is thus defined as

$$\sigma_{sys} = 0.5 \bullet |o^{f}(z)_{max} - o^{f}(z)_{min}| \quad , \tag{3}$$

where $o^{f}(z)_{max}$ and $o^{f}(z)_{min}$ are the maximal and minimal value of $o^{f}(z)$. The random portion is determined by the deviations of $c^{f}(z)$ from o(z)

$$\sigma_{noise} = \sqrt{\frac{1}{n-1}\sum_{z}[o^{f}(z) - o(z)]^{2}} \quad , \tag{4}$$

where n is the number of z positions.

Table 1. Summary of dipole field angle measurements using FAP1 before and after cryogenic testing.

Magnet	Δ [mrad]	<o(z)> [mrad]	σ_{noise} [mrad]	σ_{sys} [mrad]
DCA311	6.46±0.71	1.15	0.43	0.63
DCA312	8.33±0.46	1.00	0.38	0.30
DCA312	5.54±0.56	1.96	0.56	0.30
DCA313	8.26±0.34	0.02	0.34	0.19
DCA313	7.79±0.40	0.14	0.33	0.45
DCA314	8.35±0.46	-0.18	0.45	0.11
DCA314	7.48±0.78	-0.48	0.37	1.17
DCA315	6.11±0.39	0.33	0.39	0.52
DCA315	5.08±0.65	0.56	0.34	1.00
DCA316	7.65±0.86	-1.26	0.33	1.24
DCA316	8.73±0.62	-0.87	0.61	1.34
DCA317	7.36±0.43	0.50	0.43	0.25
DCA317	6.73±0.36	-1.07	0.32	0.40
DCA318	5.21±0.43	-1.06	0.38	0.52
DCA318	5.14±0.35	-0.65	0.34	0.55
DCA318	5.37±0.50	-2.14	0.40	0.59
DCA319	6.40±0.35	-0.61	0.35	0.35
DCA319	5.91±0.49	-1.33	0.43	1.46
DCA320	6.65±0.29	-3.05	0.29	0.09
DCA320	9.40±0.49	2.00	0.48	0.31
DCA321	7.75±0.31	-2.21	0.28	0.40
DCA321	8.39±0.63	0.31	0.41	0.70
DCA322	7.14±0.42	2.18	0.32	0.41
DCA322	8.22±0.34	2.99	0.32	0.24
DCA323	7.99±0.32	2.08	0.30	0.23
DCA323	8.98±0.36	1.14	0.34	0.41

SUMMARY OF FAP1 DATA

Table 1 summarizes field angle probe data of the 50 mm aperture magnet prototype series taken with the FAP1 system. In principle both the average dipole field angle and the difference in its maximum and minimum values,

$$\Delta = \vartheta(z)_{max} - \vartheta(z)_{min} \quad , \tag{5}$$

are of interest. But because the average depends on the mounting of the magnet on the test stand we present only Δ in the summary table. The error on Δ consists of two contributions, a random part represented by σ_{noise} (col. #4 Table 1) and a systematic part defined as being

$$\delta = 0.5 \bullet (o^f(z_{max}) - o^f(z_{min})) \quad , \tag{6}$$

where z_{max} and z_{min} are the z positions of the maximum and minimum field angle. Finally the error quoted in column 1 of Table 1. is obtained by adding σ_{noise} and δ in quadrature.

Changes in Δ as high as 2.79 mrad are obsereved in the measurements before and after cryogenic testing. These are not real changes but rather reflect differences in the magnetization of the iron yoke (discussed further by M. Kuchnir et al.[3]). The average Δ for the thirteen magnets is about 7 ± 1 mrad. This has to be compared with the collider dipole specification for allowed variation in $\vartheta(z)$ which is ±2.5 mrad from the average.

Comparison of FAP1 and FAP2 Performance

For three magnets the dipole field angle has been measured using both systems FAP1 and FAP2. A summary directly comparing the $\vartheta(z)$ measured by these two devices is shown in Table 2. The average values of the dipole field angle agree very well. The point by point signatures are also in good agreement, though these are not presented in this paper. The errors quoted on the average are calculated by

$$\delta <\vartheta(z)> = \sqrt{\frac{\sigma^2_{noise}}{n} + \sigma^2_{sys}} \quad , \tag{7}$$

where the factor $\frac{1}{\sqrt{n}}$ on σ_{noise} is gained from the statistics on the average. The point by point angular resolution of the new FAP2 system is 0.16 mrad and about a factor 2 smaller than in the case of FAP1. The systematic contribution for FAP2 measurements are a factor 2 smaller than the random variation except for magnet DCA320 where they are measured to be of the same order of magnitude as the random variation.

Table 2. Comparison of the measured dipole field angle for FAP1 and FAP2.

Magnet	FAP1		FAP2	
	$<\vartheta(z)>$ [mrad]	σ_{noise} [mrad]	$<\vartheta(z)>$ [mrad]	σ_{noise} [mrad]
DCA320	2.04±0.31	0.48	2.16±0.15	0.16
DCA322	-0.24±0.25	0.32	-0.01±0.09	0.16
DCA323	-0.96±0.23	0.30	-0.72±0.05	0.17

Stability and Reproducibility of the FAP2

In order to evaluate stability and reproducibility of the FAP2 system, seven measurements (21 z positions each) were made on magnet DCA320 in the region of z = -6.89 m to z = -5.89 m over a period of six days. For data recording the aquisition system of FAP1 was used, except for measurement #8 which was done using the complete FAP2 system. As shown in Table 3. the average dipole angle is measured to be stable within ± 0.1 mrad. The noise varies between 0.39 mrad and 0.1 mrad; a systematic contribution was not observed. The offset varies between ±0.15 mrad, except for measurement #5 where the probe was cooled down to a temperature of about 5 °C (beginning of the measurement) in order to evaluate temperature dependence. While the average field angle is not influenced by the temperature change it seems that the offset increased. Neither in $<\vartheta(z)>$ nor in the point by point signature $\vartheta(z)$ is a systematic drift in time observed. Standard deviations among the seven measurements at each of the 21 z positions were calculated. These point by point standard deviations are bounded by 0.16 mrad and 0.65 mrad with an average of 0.35 ± 0.02 mrad.

Table 3. Stability check of the FAP2 system for magnet DCA320.

Measurement	$\langle\vartheta(z)\rangle$ [mrad]	$\langle o(z)\rangle$ [mrad]	σ_{noise} [mrad]
1	-2.95±0.07	-0.10	0.30
2	-2.79±0.08	-0.15	0.36
3	-2.86±0.09	-0.04	0.39
4	-2.82±0.03	0.15	0.14
5	-2.77±0.05	0.40	0.22
6	-2.96±0.04	0.01	0.19
7	-2.85±0.02	-0.09	0.10
8	-2.92±0.02	-0.14	0.08

Comparison of FAP and Mole Measurements

The mole system determines the magnitudes and phases of multipole field components (including the phase of the dipole). Since gravity sensors are also mounted inside the mole, the phase of the dipole with respect to gravity can be measured. To accommodate the coil length (1 m) of the mole and the different positioning of the two devices during measurements, the FAP dipole field angle data $\vartheta(z)$ have been averaged along z accordingly. The field angle measurements presented in Figure 1 show a comparison among the three probes for magnet DCA320 after cryogenic testing. The mole data contains a zero level of 3.5 mrad (removed in Figure 1) probably reflecting a miscalibration between the gravity sensors and the angular encoder of the mole (this calibration was not repeated on site). The errors presented for the FAPs have been calculated according to equation (7); the dipole field angle patterns measured with the three devices agree well within these errors.

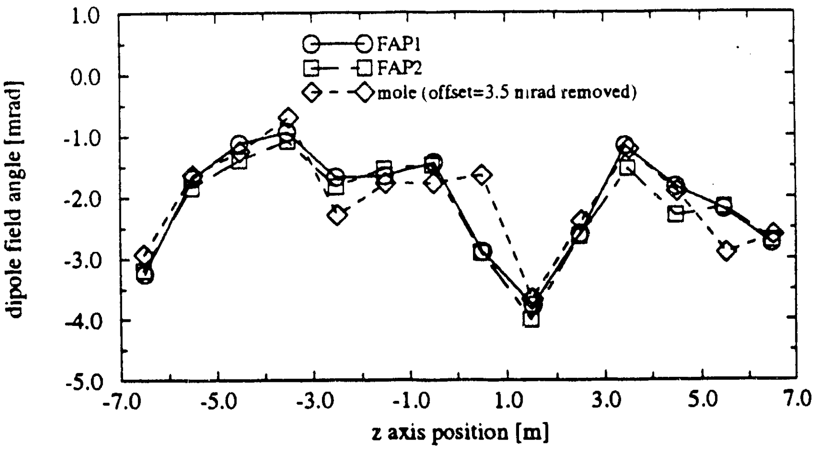

Figure 1. Comparison of dipole field angle pattern for the mole and the FAP systems (after cryogenic testing).

SUMMARY

Measurements of the dipole field angle of thirteen FNAL-built, full-length, 50-mm aperture SSC Collider Dipole Magnet Prototypes using a Vertical Field Angle Probe were presented. The average of the differences between the maxima and minima of the axial dipole angle profiles for the thirteen magnets is about 7 ± 1 mrad. Using a redesigned system the point-by-point angular resolution improved by about a factor 2 and was measured to be 0.16 mrad. A stability study shows no systematic drift of the measured field angle and the average value over 1m length is stable within ±0.1 mrad. The axial dipole angle variations as measured by the mole and the FAP systems are in good agreement.

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