**Results of Magnetic Field Measurements of 40 mm Aperture
17-m Long SSC Model Collider Dipole Magnets***

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Abstract. Magnetic field measurements have been made on twelve 17 m-long, 40 mm-aperture R&D superconducting dipoles. Data on dipole field strength, multipole coefficients, and alignment have been obtained. The data indicate that the magnets as built are generally within the expectations for this design.

I. INTRODUCTION

R&D on the dipoles needed for the Collider rings of the Superconducting Super Collider (SSC) has been underway for several years. At present, work on the initial 40 mm-aperture magnets is being completed and the change to 50 mm-aperture is well underway. This paper reports magnetic field measurements made on the last 12 of the full-length (17 m) models. Other reports to this conference cover quench performance^[1] and details of the cold masses at Fermilab^[2].

II. MAGNET CONSTRUCTION

The magnet has a two-layer coil with outer diameter of 80 mm (Fig. 1). Stainless steel collars secure the coil. The yoke surrounding the collared coil has an inner diameter of 111 mm and outer diameter of 267 mm. The magnet is designed to operate at 6.6 T central field in 4.35 K helium with a current of 6.5 kA. Details of the magnet design not given here are described elsewhere^[3,4]. For all the magnets reported here, axial motion is restrained by end preload applied to the collared coil via a thick end plate and radial motion is restrained by the yoke, which is in contact with the collars.

Figure 1. Cold mass cross section.

Two of the cold masses were made at Fermilab, the remainder at Brookhaven.

The magnet R&D program has focussed on improved quench performance and manufacturing studies. For these reasons, the magnets reported here are not part of a "field

quality" series; that is, they have not been made as identically as possible. Also, the number of magnets is too small to permit accurate comparison with all the SSC tolerances. Nonetheless, the present data do permit many useful conclusions to be drawn.

III. FIELD STRENGTH AND ALIGNMENT

The transfer function has been measured in 2.54 cm steps at 1.8 T with an NMR probe. For a five-magnet subset made with the same yoke and collar design, the average transfer function is 1.0471 T/kA, in agreement with calculation. The rms variation is 0.0006 T/kA, much less than the rms tolerance on the fractional variation in integral field, 3×10^{-3} . The transfer function at 6.6 T, measured with a rotating coil normalized at 1.8 T, is about 2.5% lower due to saturation. This is also in agreement with calculation. The fractional variation of the transfer function along the magnet axis is small, of order 10^{-4} .

Room temperature measurements of one magnet before and after cold test showed no change in the average dipole angle, with an uncertainty of 0.3 mrad. No magnet has exhibited a change in twist as a result of testing. For a single magnet, the SSC tolerance on the variation of the dipole angle with axial position is that the integral over any portion of the length be less than 10 mrad-m. The two Fermilab magnets have alignment bars keyed to the yoke outer diameter at the midplane^[2]. For these magnets, the maximum values of the integral were -3.7 and -5.1 mrad-m. BNL magnets are aligned using tooling set into the yoke at five positions along the magnet length. The integral of the dipole angle for a recent magnet of this type had a maximum value of -11.3 mrad-m.

IV. HIGHER ORDER TERMS

A. Terms Due to Conductor Placement

The notation for the multipole representation of the magnetic field is defined by the following equation:

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

where B_0 is the dipole field and x and y are the horizontal and vertical coordinates measured from the magnet center. It is convenient to define a multipole "unit" as 10^{-4} of the dipole field, with the multipoles evaluated at a radius of 1 cm. In this notation the normal sextupole, for example, is b_2 .

Systems utilizing a room temperature rotating coil either 60 cm or 1 m long have been used to measure the field harmonics^[5]. Integral harmonics are determined by stepping the coil through the magnet. Effects due to off-centering of

the measuring coil in the magnet are removed by assuming that the 20-pole terms are due to feeddown from the 22-pole term. Measurements at room temperature are made in a central field of 0.01 T, and results averaged over the two polarities to remove the effects of remnant fields in the iron. At cryogenic temperatures, measurements are made from 0.05 T to over 7 T. Integral measurements are made at a field of 2 T, where the effects of both magnetization and saturation are small. Before measurements are made, there is a waiting period of sufficient length to make time-dependent effects negligible. The integral data given here exclude the fields in the end regions.

The accelerator tolerances for these 40 mm-aperture magnets have been determined by appropriately scaling the tolerances for the 50 mm magnets. The summary of the "geometric" multipoles (Fig. 2) has been obtained by dividing the measurements by the tolerances. The uncertainty in the mean has been estimated assuming a Gaussian distribution.

Figure 2. Mean values (top) and rms variations (bottom) of the geometric multipoles, normalized to SSC tolerances. The dashed lines indicate the SSC tolerances.

The mean values of those multipoles allowed by dipole symmetry (b_n , with n even, in Fig. 2) are larger than the tolerances for the decapole and 14-pole terms. It is

anticipated that one or two small iterations of the coil cross section will bring these terms within tolerance. The mean values of the unallowed multipoles are within tolerance or uncertain (a_1 , a_2). The rms variations of all the multipoles are within tolerance, except for b_2 . In a "field quality" magnet series, it is expected that the unallowed multipoles, and the rms variations, would be lower.

The allowed terms vary with current due to magnetization and saturation. The variation is as calculated and acceptable. Also, the skew quadrupole decreases $0.3 \cdot 10^{-4}$ units at high field due to the off-center position of the cold mass in the vacuum vessel. This is within the range of the correction system.

In the magnet straight-section, the axial variation of the multipoles is small. The end fields are within tolerance and could be made smaller if desired.

B. Variation with Event

Data from the magnets has also been reviewed to check for possible variations with event, such as cooldown, warmup, excitation, and quenching at 4.35 K and lower temperatures. It is expected that, if the multipoles change with event, the lowest order terms would change the most. Histories of the low-order terms through the decapole, at room temperature and 4.35 K, were generated for each magnet. An example is shown in Fig. 3. No systematic change common to them has been found, at a level comparable to the SSC tolerances. An occasional magnet does show progressive change in an occasional multipole.

Figure 3. Values of skew quadrupole measured at different times during the test of a recent magnet.

C. Variation with Time and Axial Position

The time variation of the allowed terms, first observed in the Fermilab Tevatron^[6], has also been observed in these magnets. Also, a sinusoidal axial variation with a period of the pitch of

the cable (about 10 cm in these magnets), initially observed in measurements of the DESY dipoles^[7], has been measured. Studies aimed at understanding and reducing the time drift are underway.

D. Warm-Cold Correlations

The plan for production measurements is that each magnet will be measured at room temperature. At cryogenic temperatures, the plan calls for measuring all of the first several hundred magnets and then decreasing the frequency as the production rate increases. At maximum production rate, one in ten will be measured cold. This plan requires good correlation between warm and cold measurements. The correlation plot for the skew quadrupole is shown in Fig. 4. The rms variation of the difference between the warm and cold measurements is $0.2 \cdot 10^{-4}$ units, substantially less than the tolerance, $1.7 \cdot 10^{-4}$ units. The same is true for all the multipoles - the rms variation of the warm-cold difference is much less than the rms tolerance (Fig. 5). By this scale, the correlation between warm and cold measurements for these magnets is very good.

V. CONCLUSIONS

Most of the quantities important for magnet field quality have been measured in a group of twelve 40 mm-aperture full-length R&D dipoles. These quantities include the multipole coefficients, the dipole field strength, and (at room temperature) the dipole angle. The results of these measurements are within expectations for this magnet design.

Figure 4. Correlation of room temperature and cryogenic measurements of the skew quadrupole.

Figure 5. Comparison of rms variation of the warm-cold difference (solid lines) with the rms tolerances (dashed lines).

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