Magnetic Field Measurements of Full Length 50 mm Aperture SSC Dipole Magnets at Fermilab


Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

A. Devred, J. DiMarco, J. Kuzminski, T. Ogitsu, M. Puglisi, J.C. Tompkins, Y. Yu, Y. Zhao, and H. Zheng

SSCLaboratory
2550 Beckleymeade Ave., Dallas, Texas 75237

September 1992

Presented at the XVth International Conference on High Energy Accelerators, Hamburg, Germany, July 20-24, 1992
Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
MAGNETIC FIELD MEASUREMENTS OF FULL LENGTH 50 mm APERTURE SSC DIPOLE MAGNETS AT FERMILAB*

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510 USA

A. Devred, J. DiMarco, J. Kuzminska, M. Puglisi, J.C. Tompkins, Y. Yu, Y. Zhao, and H. Zheng
SSC Laboratory, 2550 Beckleymeade Ave., Dallas, TX 75237 USA

T. Ogitsu
SSC Laboratory, 2550 Beckleymeade Ave., Dallas, TX 75237 USA and KEK, National Laboratory for High Energy Physics, 1-1 Oho, Tsukuba-shi, Ibaraki-ken 305, Japan

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 sextuple, 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 by General Dynamics technicians with support from Fermilab personnel. The Fermilab design 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 and the mechanical behavior is well understood. In this paper we evaluate their magnetic field quality and compare it with the requirement 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.

2 Harmonics Data

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

$$B_y + iB_x = B_0 e^{(b_n + i a_n)/10^4}[(x + iy)/1cm]^{n}$$

where $B_y(x)$ 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 means 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 $b_n$ and $a_n$ 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>
<thead>
<tr>
<th>Harmonics at 2 T</th>
<th>Mean</th>
<th>Spec.</th>
<th>RMS</th>
<th>Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_2$</td>
<td>0.15</td>
<td>0.8</td>
<td>0.39</td>
<td>1.15</td>
</tr>
<tr>
<td>$b_4$</td>
<td>0.03</td>
<td>0.08</td>
<td>0.03</td>
<td>0.22</td>
</tr>
<tr>
<td>$b_6$</td>
<td>-0.043</td>
<td>0.013</td>
<td>0.004</td>
<td>0.018</td>
</tr>
<tr>
<td>$b_8$</td>
<td>0.051</td>
<td>0.010</td>
<td>0.0012</td>
<td>0.0075</td>
</tr>
<tr>
<td>$b_{10}$</td>
<td>0.03</td>
<td>0.04</td>
<td>0.18</td>
<td>0.50</td>
</tr>
<tr>
<td>$b_{12}$</td>
<td>0.001</td>
<td>0.026</td>
<td>0.03</td>
<td>0.16</td>
</tr>
<tr>
<td>$b_{14}$</td>
<td>0.001</td>
<td>0.005</td>
<td>0.003</td>
<td>0.017</td>
</tr>
<tr>
<td>$a_2$</td>
<td>0.03</td>
<td>0.04</td>
<td>0.39</td>
<td>1.25</td>
</tr>
<tr>
<td>$a_4$</td>
<td>0.114</td>
<td>0.032</td>
<td>0.16</td>
<td>0.35</td>
</tr>
<tr>
<td>$a_6$</td>
<td>-0.002</td>
<td>0.026</td>
<td>0.06</td>
<td>0.32</td>
</tr>
<tr>
<td>$a_8$</td>
<td>0.006</td>
<td>0.010</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>$a_{10}$</td>
<td>0.002</td>
<td>0.005</td>
<td>0.01</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*Work supported by the US Department of Energy.
**Current address: SSC Laboratory, USA;
Permanent address: KEK, Japan.
Permanent address: Institute of Electrical Engineering, Beijing 100089, China.
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 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. 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, 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 coil 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.

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 $b_1$ due to the magnetic effect of the yoke and its mechanical interaction with the collars. 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 the first magnet of this series buckled inducing an additional change in the coil shape and making the iron interior non-circular. This magnet, whose $b_1$ 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.
Before Cold Test

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[5]. 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[5]. 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 \( b_5 \) return to their original values. The \( b_2 \) 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 \( b_2 \).

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

<table>
<thead>
<tr>
<th>Harmonics</th>
<th>Cold - Collared Before</th>
<th>Mean RMS</th>
<th>Cold - Before</th>
<th>Mean RMS</th>
<th>After - Before</th>
<th>Mean RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_2 )</td>
<td>0.015 0.029</td>
<td>-0.005 0.004</td>
<td>0.002 0.005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( b_4 )</td>
<td>0.011 0.002</td>
<td>-0.001 0.002</td>
<td>0.000 0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( b_6 )</td>
<td>0.003 0.004</td>
<td>0.000 0.005</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( b_8 )</td>
<td>0.012 0.014</td>
<td>0.000 0.005</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Acknowledgements

We thank the Fermilab, BNL, LBL, and SSCL design team, the Fermilab and General Dynamics production staffs, and the Fermilab and SSCL testing team for their superb quality work throughout this project.

References