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EFFECT OF MANUFACTURING ERRORS ON FIELD QUALITY
OF DIPOLE MAGNETS FOR THE SSC

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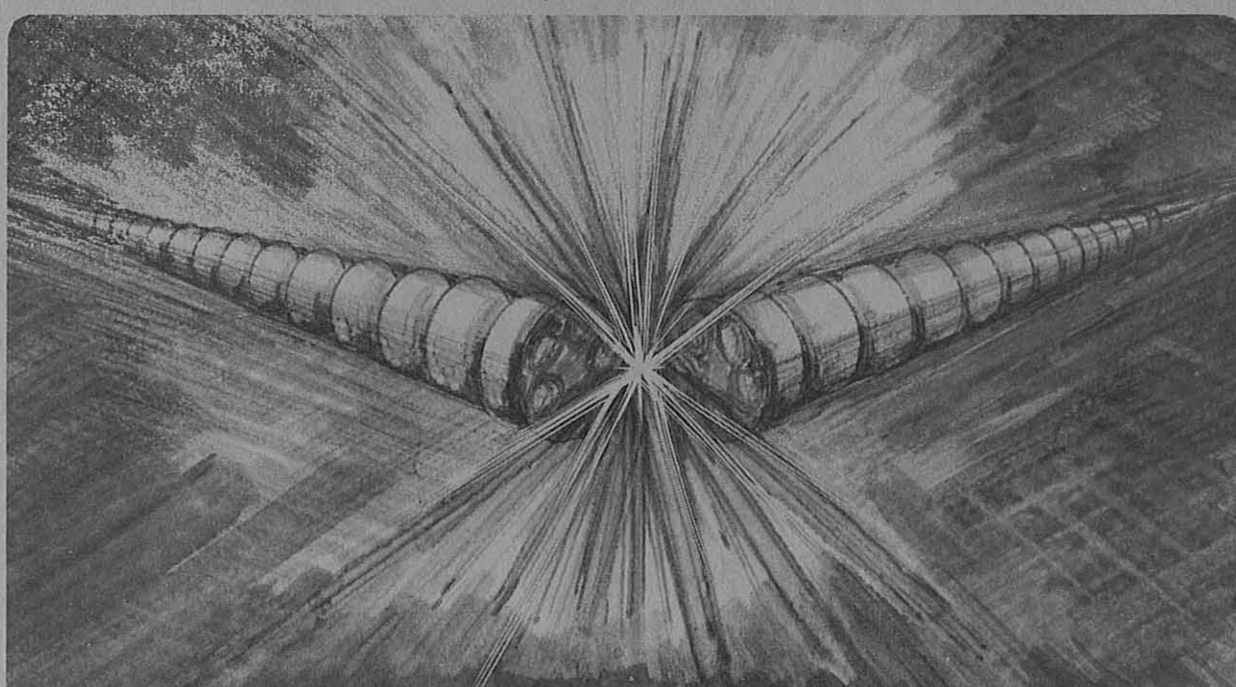

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# EFFECT OF MANUFACTURING ERRORS ON FIELD QUALITY OF DIPOLE MAGNETS FOR THE SSC*

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## Abstract

For superconducting dipole magnets of the sort proposed for the Superconducting Super Collider, the effects of various random manufacturing errors upon random magnet-to-magnet magnetic-field aberrations are analyzed. The errors considered are ones that are directly related to manufacturing tolerances and measurable dimensions of parts and materials. These errors affect the position of the boundaries of each layer of conductors in each quadrant and the positions of conductors within those boundaries.

Manufacturing errors were estimated for the Fermilab Tevatron magnets and the BNL CBA magnets. The estimates were then adjusted so that the calculated field aberrations matched the measured values. Those errors were then applied to the SSC magnet reference designs currently under study in order to obtain estimated field aberrations.

## The Problem

A vital factor in the design of the Superconducting Super Collider (SSC) is the estimation of random magnet-to-magnet field aberrations resulting from random manufacturing dimensional errors. These aberrations will affect the paths of the circulating particles, which in turn will determine whether the proposed magnet designs will function adequately. The estimation of these field aberrations was the primary purpose of this study.

## The Approach to a Solution

The approach used in this study was to: identify a set of mechanical error modes that are directly associated with manufacturing tolerances and measurable dimensions of components; calculate the field aberrations resulting from unit manfacturing error for each mode; estimate the magnitude of the error for each error mode; and finally, fold the latter two together into an estimate of expected field aberrations.

Two large groups of magnets have been constructed: those for the Colliding Beam Accelerator (CBA) and the Tevatron. While few dimensional error data are readily available, extensive field aberration data are at hand, and so this approach was made using the data from those magnets. It was assumed that the errors for the SSC designs would be similar but scaled according to the size of the magnet cross sections.

## The Magnets

The cross section of a typical magnet is shown in Fig. 1. The primary dimensions of the magnets under consideration are listed in Table 1 together with ratios of some of the dimensions. The ratios illustrate that the magnets are by no means geometrically similar, and so the various manufacturing errors affect the field aberrations for each magnet design differently.

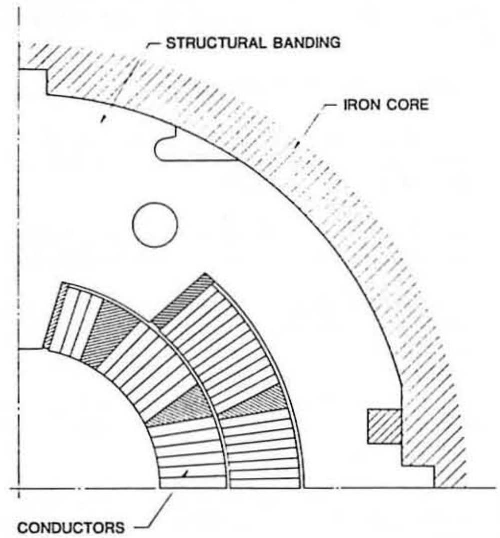


Fig. 1. Typical magnet cross section; SSC Design D. First quadrant shown.

Table 1. Magnet Dimensions

Dimensions are in centimeters.

| | Radii | | | Ratios | |
|---|---|---|---|---|---|
| | Coil inside $a_1$ | Coil outside $a_2$ | Iron inside $b$ | $a_2/a_1$ | $b/\bar{a}$ |
| CBA | 6.547 | 8.200 | 8.655 | 1.252 | 1.258 |
| Tevatron | 3.810 | 5.459 | 9.563 | 1.433 | 2.310 |
| SSC Design A/D | 1.999 | 3.993 | 5.570 | 1.997 | 2.323 |
| SSC Design B | 2.604 | 4.446 | inf. | 1.707 | inf. |
| SSC Design D-5cm | 2.499 | 4.493 | 6.070 | 1.798 | 2.095 |

$\bar{a} \doteq a_1 + 0.2(a_2-a_1)$

## Mathematical Representation of The Coils

Most of the error modes can be expressed in terms of movements of one or more of the boundaries of the conductors in the two coil layers in the various quadrants. For the purpose of this study, the cross section of each of the two layers of the magnet coil was represented by a region bounded by circular arcs and radial lines in which the current density varies inversely with radius. This representation admits to a simple mathematical description of the magnetic field and its partial derivatives with respect to boundary positions. An additional mode, the turn-to-turn variation in conductor azimuthal width, was considered.

## Manufacturing Error Modes

It was assumed that the field aberrations are dominated by errors in magnet cross section, and that the effects of variations of the shapes of the ends are small.

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Many possible error modes were considered, and of those 31 were retained. Some of these -- those for which the errors could reasonably be expected to be the same -- were combined, yielding 22 groups of modes with one or two modes in each group. For example, the thicknesss variations of the inner and outer coils could be expected to be the same, and so their effects were combined. Finally, 10 mode groups, considered to be the most significant, and sufficient for this study, and for later establishing magnet manufacturing tolerances, were retained. These error mode groups are described in Table 2 and illustrated schematically in Fig. 2.

Table 2. Manufacturing Error Mode Groups

1. Position of any one edge of either pole piece varies, inner coil and outer coil independently but with same rms error. Four occurrences.
2. Position of centerline of either pole piece varies, both inner and outer coils collectively. Two occurrences.
3. Widths of both pole pieces vary collectively, inner coil and outer coil independently but with same rms error. One occurrence.
4. Coil azimuthal width varies top to bottom, both sides collectively, inner coil and outer coil independently but with same rms error. One occurrence.
5. Coil azimuthal width varies side to side, either top or bottom half, inner coil and outer coil independently but with same rms error. Two occurrences.
6. Thicknesses of inner and outer coils vary top to bottom, independently but with same rms error. Two occurrences.
7. Thicknesses of inner and outer coils vary side to side, independently but with same rms error. Two occurrences.
8. Thickness of inter-layer insulation varies, any one quadrant. Four occurrences.
9. Thickness of coil-to-iron insulation varies, any one quadrant. Four occurrences.
10. Azimuthal thickness of conductor varies from turn to turn.

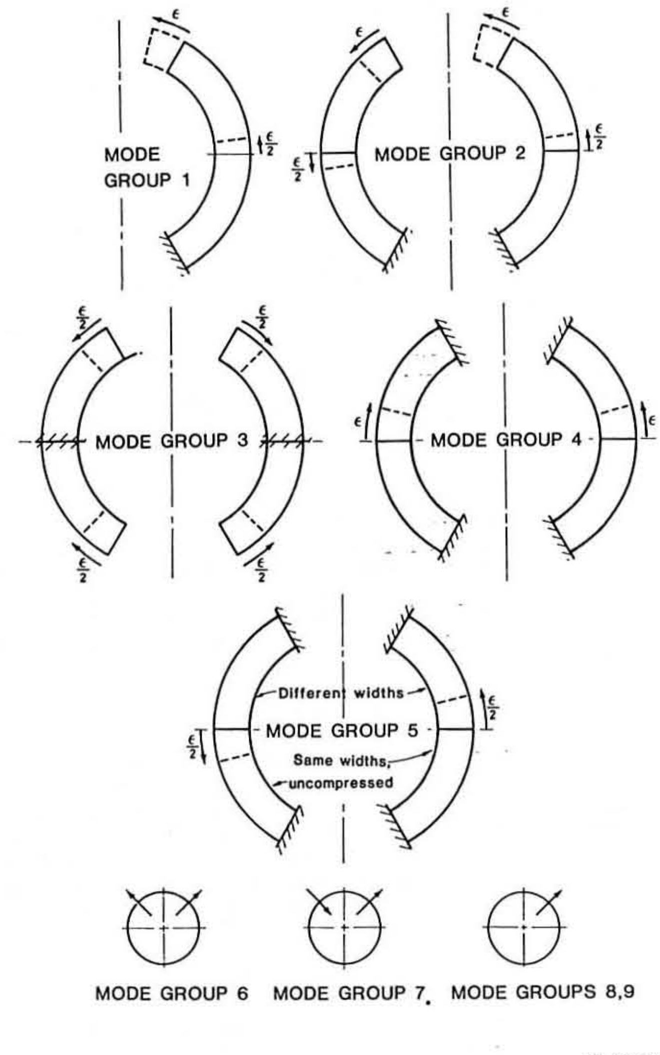


Figure 2. Error Mode Schematics

The number of "occurrences" in Table 2 deserves explanation. If an error affects each quadrant independently, for example, then we say there are four occurrences. The multipoles (see next paragraph) produced by an error in any quadrant is the same except for sign, and so the rms multipoles for all four quadrants are simply twice those for the first quadrant.

## Magnetic Field Representation

The magnetic field aberrations are expressed in terms of the usual dimensionless "multipole coefficients", or simply "multipoles", which are the a's ("skew" components) and b's ("normal" components) in the following expression:

$$B^* \quad B_x - iB_y = B_0 \sum_{n=0}^{\infty} (a_n + ib_n) \left[(x+iy)/\rho\right]^n$$

$$B_x = B_0 \sum_{n=0}^{\infty} (r/\rho)^n (a_n \cos n\theta - b_n \sin n\theta)$$

$$B_y = B_0 \sum_{n=0}^{\infty} (r/\rho)^n (-a_n \sin n\theta - b_n \cos n\theta)$$

where $\rho$ is an arbitrary reference radius, usually the limiting radius of the useful good-field region, and $B_0$ is the normal (vertical) dipole component. The multipole b is 1, and $a_0$, representing tilt of the magnet is zero, by definition, since magnets will be installed according to the measured direction of the magnetic field.

The sensitivies of the multipoles to unit error for each error mode group have been expressed in the form of tables and both linear and semi-log graphs. They require far more space than this report will allow, but will be presented in a more complete report.

## Manufacturing Errors

Some manufacturing errors for the CBA magnets were measured and others estimated by Peter Wanderer (BNL). The estimated errors were adjusted by a trial-and-error procedure to minimize the rms difference between the measured and calculated multipoles. The normal dipole field variation was ignored in this procedure as it was felt that a major part of it resulted from variation in coil length. A reference radius of about 0.9 of the coil inside radius was used, instead of the usual 2/3, in order to emphasize the higher-order multipoles.

A similar procedure was applied to the Tevatron magnets, except that the measured errors were permitted to vary also. The resulting manufacturing errors are presented in Table 3, and the corresponding field aberrations in Table 4.

Table 3. Fitted Manufacturing Errors

(Units: milli-inches.)

| Error mode group | Initial estimates for CBA (1) | Fitted errors CBA | Fitted errors Tevatron |
|---|---|---|---|
| 1 | 2.0 | 0.95 | 1.77 |
| 2 | 2.5 | 0.45 | 0.07 |
| 3 | 2.0 | 6.55 | 4.54 |
| 4 | 2.7(2) | 2.70(3) | 0.16 |
| 5 | 1.4(2) | 1.40(3) | 0.04 |
| 6 | 1.0 | 0.10 | 0.61 |
| 7 | 2.0 | 0.20 | 0.06 |
| 8 | 2.5 | 0.28 | 0.07 |
| 9 | 3.0 | 0.17 | 0.09 |
| 10 | 0.1 | 0.014 | 0.30 |

(1) Estimates by Peter Wanderer, BNL.
(2) From coil measurements.
(3) Held fixed during fitting procedure.
Unit errors correspond to $\epsilon$ in Table 2.

Table 4. Measured and Calculated Field Aberrations for CBA and Tevatron Dipole Magnets

(Units: 1/10000 of the dipole field at a reference radius of 2/3 of the coil inside radius.)

CBA Dipole Magnets

| n | Skew component, a Meas. | Calc. | Diff. | Normal component, b Meas. | Calc. | Diff. |
|---|---|---|---|---|---|---|
| 0 | | 2.156 | | | 3.676 | |
| 1 | 2.64 | 2.914 | .274 | .92 | .874 | -.046 |
| 2 | .46 | .609 | .149 | 1.89 | 2.044 | .154 |
| 3 | .72 | .576 | -.144 | .23 | .206 | -.024 |
| 4 | .18 | .099 | -.082 | 1.16 | .786 | -.374 |
| 5 | .121 | | | | .034 | |
| 6 | .11 | .049 | -.061 | .22 | .296 | .076 |

Rms of differences, .17

Tevatron Dipole Magnets

| n | Skew component, a Meas | Calc. | Diff. | Normal component, b Meas. | Calc. | Diff. |
|---|---|---|---|---|---|---|
| 0 | | 4.31 | | 4.63 | | |
| 1 | 2.9 | 2.89 | -.01 | 1.9 | 2.24 | .34 |
| 2 | 1.2 | 1.18 | -.02 | 2.5 | 2.44 | -.07 |
| 3 | 1.5 | .89 | -.61 | .8 | .64 | -.16 |
| 4 | .5 | .29 | -.21 | 1.3 | 1.18 | -.12 |
| 5 | .6 | .33 | -.28 | .3 | .18 | -.12 |

Rms of differences, .26
See text for nomenclature.

Using this procedure, one can obtain rather different sets of manufacturing errors that give calculated field aberrations that agree about equally well with the measured ones. When these errors are applied to the CBA designs, however, the resulting field aberrations are about the same. It must be emphasized that the listed errors are not necessarily the ones that exist, but are merely ones that could exist. They certainly are not to be interpreted as tolerances; that's a whole 'nuther ball game.

## Application of Errors to SSC Magnets

Feeling that the manufacturing errors for the SSC magnets can and should be smaller because the magnets are smaller, we scaled the errors according to coil radius to the 0.3 power -- giving about a 20% reduction in errors for a coil half the size -- and used a radius to a point 1/5 of the coil thickness out from the inner radius.

The scaling factors, easily reproduced using the data in Table 1, range from a low of 0.729 for scaling from the CBA to Design A/D, to a high or 0.905 for scaling from the Tevatron to Design B.

The resulting field errors for each of the three SSC designs were then calculated using the errors for the CBA and Tevatron. Some of the calculated multipoles resulting from the matching procedure were smaller than the measured ones; for the SSC magnets, a factor representing the ratio of measured to calculated values was applied to those multipoles.

For each of the three SSC magnet designs we then had two rather different sets of estimated multipoles, one from the CBA and the other from the Tevatron magnets. Rather than average the results in some fashion, we conservatively adopted the larger value of each multipole. The results are shown in Table 5.

Table 5. Estimated Random Field Aberrations for the SSC Reference Design Magnets

(Units: 1/10000 of the dipole field at a reference radius of 10 mm)

| n | Des. A/D $a_n$ | Des. A/D $b_n$ | Des. B $a_n$ | Des. B $b_n$ | Des. B-5cm $a_n$ | Des. B-5cm $b_n$ |
|---|---|---|---|---|---|---|
| 0 | 5.2 | 5.7 | 5.1 | 6.1 | 4.8 | 5.2 |
| 1 | 3.2 | 1.7 | 2.9 | 1.7 | 2.4 | 1.3 |
| 2 | .48 | 1.6 | .44 | 1.15 | .30 | 1.00 |
| 3 | .54 | .21 | .34 | .16 | .27 | .11 |
| 4 | .11 | .48 | .059 | .25 | .048 | .19 |
| 5 | .083 | .052 | .022 | .020 | .028 | .017 |
| 6 | .026 | .040 | .0078 | .016 | .0051 | .0106 |
| 7 | .012 | .0093 | .0030 | .0021 | .0025 | .0020 |
| 8 | .0043 | .0033 | .0008 | .0009 | .0007 | .0006 |
| 9 | .0012 | .0018 | .0002 | .0003 | .0002 | .0003 |
| 10 | .0006 | .0018 | .0001 | .0001 | .0001 | .0002 |
| 11 | .0005 | .0002 | .0001 | .0000 | .0000 | .0000 |

See text for nomenclature.

The estimated quadrupole (n = 1) components are probably intolerably large. In principle they can be reduced by shimming the position of the coil with respect to the iron following room-temperature measurements of the magnetic field, but at some expense.

## Conclusions

The field aberrations presented in Table 5 are the current best estimates. Refinements might be made in the near future as time permits.