A COMPARISON OF CALCULATIONS AND MEASUREMENTS OF THE MAGNETIC CHARACTERISTICS OF THE SSC DESIGN D DIPOLE

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Introduction

The SSC design D dipole[1] has two, circular, superconducting, 10 mm thick coil layers with an inner diameter of 40 mm. Surrounding these coils and compressing them is a 15 mm thick, stainless-steel collar. The collar has tabs at the poles and on the midplane which fit into notches in the iron yoke, the latter having an outside diameter of 267 mm. The coils are composed of partially-keystoned cable, molded into radial blocks separated by copper wedges and positioned in azimuth by a protrusion inward of the Nitronic 40 collar at the poles. Between the protrusion and the coils are G-10 shims of variable thickness. The nominal maximum working field is 6.6 tesla. Eight, 4.5 m long magnets of this design (the first was no. 8) were built and tested at BNL, and more recently, two, 16.6 m long magnets were built at BNL and tested at FNAL. The present report compares measurements which do not include the ends, on two of the 4.5 m magnets, no.s 8 and 9, with computer calculations. These two magnets were tested at higher fields (up to about 7.5 T) than the others by subcooling, so data from them is best suited for comparison with calculations showing the effects of saturated iron. Similar magnets have been made and measured at LBL[2].

Computational Considerations

Three computer programs were used in the design and analysis for the present report. The first is a program which optimises the coil positions to acheive high field quality subject to the various constraints. This program, the current version of which is called "PAR2DOPT", evaluates analytical expressions for the harmonics due to a polygonal conductor inside a circular, infinitely-permeable iron aperture. The other two programs are general-purpose, two dimensional, saturable-iron programs. The first is a version of GFUN[3] called MDP. It is a finite element program which solves integral equations for the field of both the conductors and the iron. No meshing of the conductor or air regions is required, which greatly facilitates use of the program, and also results in almost exact modeling of the conductors. The third program is POISSON, the present version of which incorporates a means of effectively extending the outer boundary to infinity[4], and has improvements in the mesh generator[5] permitting more accurate modeling of the conductor.

The accuracy of modeling of the coil structure can be examined by comparing Fourier harmonics of the field computed by the three programs. The two saturable-iron programs are used with low coil current to get high permeability and with a circular iron aperture. The results are shown in Table I. We observe that all harmonics ($b_i = 10^4 B_i/B_0$ at a radius of 10 mm) are in agreement to 0.2 units.

Table I

PROGRAM	$B_0/I, T/kA$	b_2	b_4	b_6	b_8	b_{10}
PAR2DOPT	1.0361	-.16	0.00	0.12	0.87	-.03
POISSON	1.0350	-.19	0.24	0.19	0.89	-.03
MDP	1.0344	-.24	0.00	0.12	0.87	-.03

Although the cable is thicker on one edge than the other, the current per unit width of cable is no greater at the thick edge than on the thin; the wires there are simply compressed less. Since the programs assume constant current density, to obtain a realistic current density distribution, two approaches are used. In PAR2DOPT and in MDP, each cable is modified from the physical trapezoidal shape to a rectangle having the same base and radial width. It is this shape that is shown in Figure 1(a). In POISSON, because of meshing limitations, the cables are not modeled individually; each group of cables between the wedges is modeled as a block and the block outlines closely follow the cable outlines. Each block is divided into four radial sub-blocks having the same radial width and carrying the same current. Figure 1(b) shows this model.

Comparison of Calculations and Measurements

The effects of iron saturation on harmonic content in these round iron dipoles has been discussed elsewhere[6]. The notches at the poles in the present design, shown in Fig.2, modify the effects of iron saturation in a distinctive way. Field lines which would normally be almost perfectly vertical and uniformly spaced at the poles are diverted towards the near corner of the notch, leading to premature iron saturation at this corner at relatively low fields with an associated increase in sextupole, b_2. The path length in air is also increased, resulting in both a small decrease in transfer function (TF) and an increase in b_2 at low field. Saturation of the iron on the midplane causes a decrease in b_2 and an increased reluctance of the yoke, resulting in a rapid decrease in transfer function at high excitation. A notch in the aperture at the midplane aggravates these effects.

Both MDP and POISSON predict a decrease of 0.17% in the low field transfer function due to all notches from the case of a smooth circular iron aperture. With the notches the values are 1.0318 T/kA by MDP and 1.0332 T/kA by POISSON. The relative decrease with excitation is given in Table II. The measurements are the average of the two magnets, except at 7.4 kA which is Magnet 8 alone.

Table II

I, kA	3.0	5.0	6.0	7.0	7.2	7.4
MDP	1.000	.995	.987	.973	.970	.966
POISSON	1.000	.995	.985	.968	.964	.960
Measured	1.000	.996	.982	.969	.967	.962

The low field transfer function was measured accurately using an NMR device[7]; the value reported is the average of 6 magnets. Since the coil positioning shims differ from magnet to magnet and the transfer function is affected by the shimming, a correction to the shims used in Magnet 8 (the first of the 6) was made to the transfer function of the other 5 magnets. The value calculated by MDP and POISSON must be corrected to the same shim sizes; the factor is 1.0018. The measurements are made at a temperature of 4.5 K, and the calculations are based on room temperature dimensions, so a correction to the calculated values for the decrease in coil and iron sizes must

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also be made. This correction is estimated to be 1.0027. The Nitronic 40 collar, with a permeability of 1.0025, increases the transfer function by a factor of 1.00078 and b_2 is decreased by 0.68. The 3 corrections multiplied are 1.0053. With this correction, the transfer function calculated by MDP is 1.0373 at 2.0 kA, by POISSON is 1.0388 at 2.36 kA, and the measured value is 1.0358 $\pm$ .0007 T/kA at 1.8 kA.

There may be an additional correction, the magnitude of which is known for only one magnet; this arises from the distortion of the coil during curing and collaring. Magnet no. 11 was sectioned, photographed and the conductor locations determined by an x,y, measuring device[8]. It was found to have an oblateness (increase of the radius at the midplane and decrease of the vertical radius) of about 10 mil. An ellipse is an approximation to the observed distortion. Calculations using this amount of ellipticity indicate it would increase the transfer function by a factor of 1.00045. There was considerable variation in curing and assembly pressures in the remaining magnets and it is not known if this amount of distortion is typical. There is some indication from b_2 measurements that the distortions in Magnets 8 and 9 are smaller.

By both MDP and POISSON calculations, the pole and midplane notches introduce a low field value of b_2 of about 1.1 units compared to smooth circular iron. Figure 3 shows the variation of b_2 with current, both calculated and measured; no corrections for shims have been made to the calculations. Harmonics are measured with a rotating tangential coil[9,10]. The two programs agree on a low field value of $b_2 = +1.1$, and Magnets 8 and 9 have 0.0 and -1.0 at 2 T, resp. The shims in Magnets 8 and 9 increase b_2 over the value calculated by 3.1. With this correction, and the one for the Nitronic 40 collar, the calculated value is 3.5, for differences from measurement of -3.5 and -4.5, resp. If these differences are attributed entirely to elliptical coil distortion, at $\Delta b_2 = 0.64$ per mil of distortion[11], this would indicate Magnet 8 had 5.5 mil and Magnet 9 had 7.0 mil of oblateness. Magnet 11, with an oblateness of 10 mil and a b_2 increase of 2.0 in the calculated value due to shims, has a $b_2 = -3.8$ by measurement, for a difference of -6.2, compared with -6.4 that one would calculate from the measured oblateness.

The measurements of both magnets show a shift in b_2 from the 2 T value to the peak value of 2.05 units. The shift computed by both POISSON and MDP is 2.0. The same iron permeability table was used in both programs, based on measurements and an assumed packing factor of 97.5%; the actual packing factor was 97.34%.

The measurements in Figure 3 show a slight droop in b_2 at low field. The measurements are the average of data for up and down current ramps in order to eliminate the effects of superconductor magnetization. The droop is thought to be due to an asymmetry in the magnetization at these low fields.

The notches in the iron aperture change b_4 very little from the value for a smooth circular aperture; MDP predicts a low field b_4 offset of -.07 and POISSON an offset of -.03. At 2 kA, the values of b_4 by MDP and POISSON are -0.07 and +0.18, respectively. Recall that the POISSON model has an error in the coil of $b_4 = +0.24$, so the 2 kA value should be -.06, about the same as MDP. The correction for shims is -.47, for a total of about -.53. Coil ellipticity, if present in the amount previously calculated from the b_2 measurements, would increase this to about -.47. The measurements in Magnets 8 and 9 are -.2 and -.45, resp. The lack of agreement in Magnet 8 and a similar discrepancy in Magnet 11 suggest that coil distortions other than elliptical are responsible for b_4 errors. The change in decapole with excitation is less than 0.1 by both calculation and measurement. Both MDP and POISSON show $\Delta b_4 = -.03$ from 2 to 6 kA, and the measurements of the two magnets are -0.05 and -0.10. Both calculation and measurement indicate a rise back to or above the low field value above 7 kA.

Discussion and Summary

Measurements and calculations of the low field transfer function are in agreement to +0.14% by MDP and 0.29% by POISSON, neglecting coil distortion, which may increase these errors by .05%. POISSON tracks the change in transfer function with excitation to within 0.1% up to 7 kA, and 0.3% at 7.2 kA. MDP tracks to within 0.5% up to 7 kA, but is only 0.3% high at 7.2 kA.

The measured sextupole at 2 kA differs from that calculated by $\Delta b_2 = -3.5$ and -4.5 unit in the two magnets, after corrections. The difference is probably due to elliptical coil distortion during fabrication. At higher fields, the calculations track the changes in b_2 due to iron saturation to within about 0.3 unit.

The measured decapole at low field differs from that calculated by about 0.2 unit. An elliptical model of the coil distortion does not predict the b_4 errors very well. Changes in b_4 due to saturation are accurately tracked by both programs.

The shift in b_2 of 2 units because of iron saturation was found during the present study to be largely due to the notches at the poles, whereas the notches at the midplane reduce it. A redesigned, smaller pole notch will be used in new magnets. With other minor changes in the iron, the new design is predicted to have a b_2 shift of about 0.4 units at the peak.

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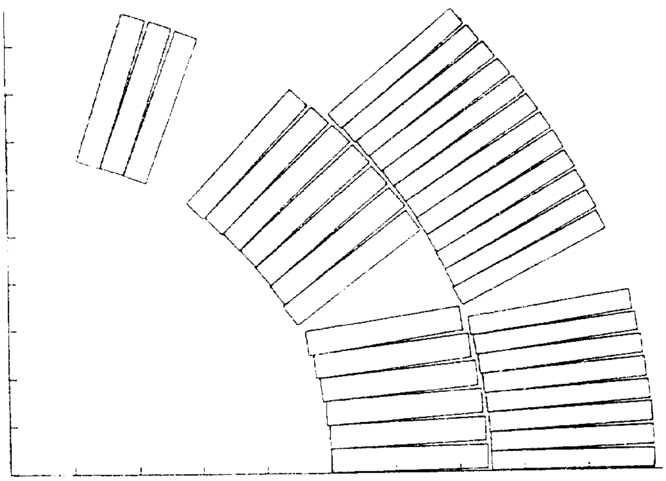

Figure 1(a) C5 coil modeled in program MDP to give the proper current density variation with radius.

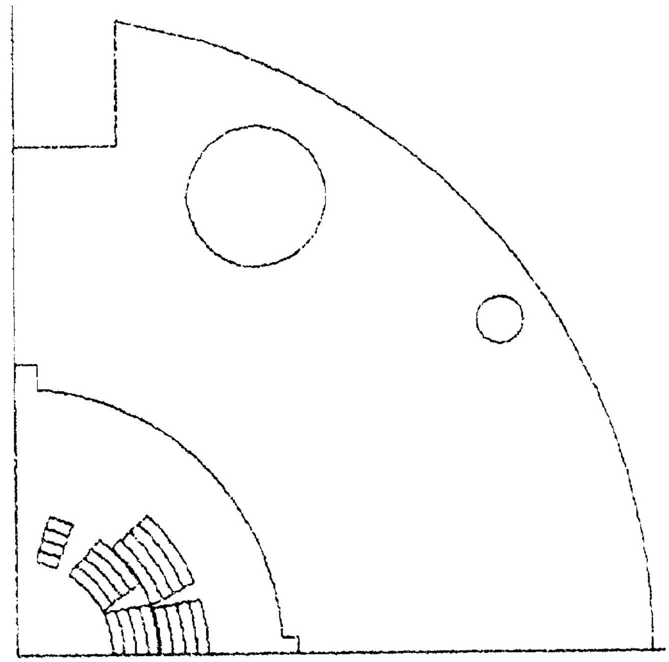

Figure 2 Outline of one quadrant of an iron lamination showing halves of the inner radius notches, the helium flow and pin holes, and half of a bus notch.

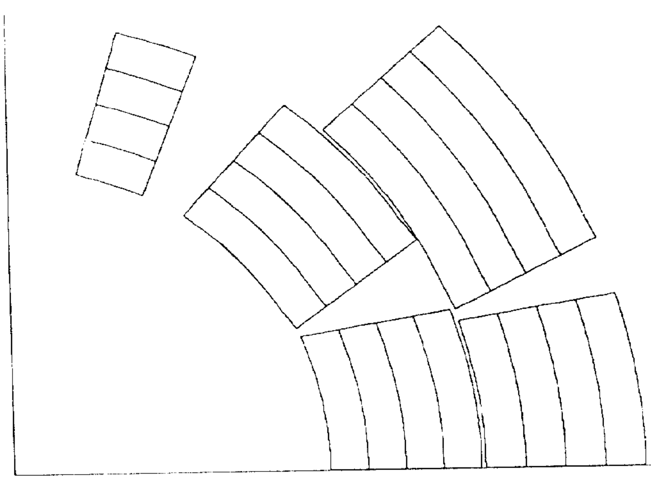

Figure 1(b) C5 coil as modeled in program POISSON to give the proper current density with radius.

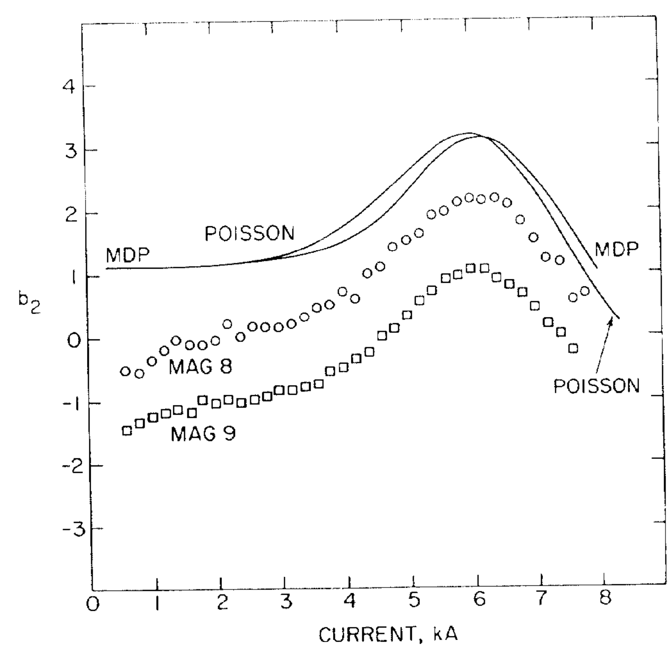

Figure 3 Variation of b_2 with current; the solid lines are as computed with no corrections for shims, and the open points are measured data.