# USE OF AN ELLIPTICAL APERTURE TO CONTROL SATURATION IN CLOSELY-COUPLED, COLD IRON, SUPERCONDUCTING DIPOLE MAGNETS

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## Abstract

The high fields permitted by superconducting windings result in saturation of closely-coupled iron in dipole and quadrupole beam transport magnets. Coupland[1] suggested using a triangular cutout at the poles to reduce the change in the sextupole ($b_2$) term due to saturation. The use of an elliptical aperture in a close-coupled dipole for the Relativistic Heavy Ion Collider (RHIC) has been studied using the BNL computer program MDP (a version of GFUN). The ellipse aspect ratio was varied while holding the horizontal (minor) radius constant. The proper aspect ratio gives no shift in $b_2$ due to saturation, and a reduction in the $b_4$ shift. A modification of the ellipse also reduces $b_4$. The elliptical aperture introduces a large $b_2$ term at low field which must be compensated for by the coil design. A practical coil design which does this for the RHIC magnet is presented.

## Introduction

An ideal cosine theta coil produces a perfect dipole field with or without a concentric circular iron shield having infinite permeability, and this is almost true of cosine theta approximations with a high but finite permeability iron shield of sufficient thickness. When the field at the inner face of the iron exceeds about 2T, localized saturation occurs which, if the iron is close to the coils, distorts the central dipole field and generates undesired harmonics. Usually saturation occurs first at the poles and spreads toward the midplane. If the iron thickness on the midplane is limited, saturation may occur there at any time, but usually the thickness is such that saturation on the midplane begins only at the maximum design field. The effect of pole saturation is to generate positive even harmonics, sextupole ($b_2$), decapole ($b_4$) etc. in dipoles. When the midplane approaches saturation, the reverse occurs, and by judicious choice of iron thickness, the $b_2$ term can be set equal to zero at the peak operating field. There remains a maximum in $b_2$ below the peak field which must be compensated for by correction windings or by separate sextupole magnets in particle beam transport systems. However, schemes which rely on limited iron thickness to control saturation are tricky to implement because the permeability near saturation varies strongly with impurity content and with packing factor. Also frequently there are cutouts in the iron interior or periphery, the effects of which are sensitive to permeability and packing factor.

To avoid pole saturation, Blewett[2] suggested leaving an annulus between the coil and the iron of sufficient thickness to limit the field at the iron surface to 2T. Unfortunately, this also reduces the gain in central field due to the iron, which approaches 2T with closely coupled iron. In the present SSC magnet design "D",[3] there is a fairly large gap between coil and iron (almost equal to the 20 mm coil thickness), and only 1.3T of the 6.0T operating field is due to the iron. Even with this gap, the sextupole shift is over $3 \times 10^{-4}$ $cm^{-2}$, which must be compensated for.

Coupland[1] studied both exterior and interior iron shaping using program TRIM and preferred a triangular cutout on the inner surface near the poles. Using this cutout and modeling a large, 4.5T magnet he achieved complete control of the sextupole term between zero and 4.5T, but at the expense of a considerable increase in the shift of the decapole term.

## Elliptical Aperture

It has been found that achieving a pole cutout by use of an elliptical aperture also gives complete control of the sextupole harmonic and in addition gives only a modest negative change in the decapole with increasing field. Several (paper) magnet designs have been made with an elliptical aperture. The first was a "two-in-one", single-layer design for an early version of the Relativistic Heavy Ion Collider (RHIC).[4]

The present RHIC design[5] uses the same superconducting cable that is presently intended for the SSC high-field design outer layer.[3] In the larger RHIC aperture, the cable is fully keystoned. Also for commonality with the SSC program, the RHIC iron outer diameter has been set to 10.5 inch. The SSC cable has high performance and design of a single-layer coil and close-coupled iron to make full use of this performance presents an interesting challenge.

The current RHIC design[5] has been estimated to be capable of operation at about 4.1T central field at 4.5K with an adequate margin with the SSC cable, so this was taken for the goal of the present work. At the same time, 100 x 100 GeV/AMU requires 3.26T with the present machine lattice and dipole length, so attention was also given to this field.

For electrical insulation reasons, the gap between the coils and the iron cannot be less than 3 mm, and the coil i.d. must be 40.11 mm. The coil thickness is .973 mm (bare), so the iron inner radius a, on the midplane is fixed at 52.84 mm. This is about 2 mm less than the current design.[5] The only remaining free variables are the vertical semi-major axis b, and the shape of the iron surface.

On the assumption that this shape should be elliptical, a series of computer models with b-a variable was calculated, with b-a from 0 to 8 mm in 2 mm steps. The coil structure used in these calculation is the current design.[5] The results are given in Table 1. Since saturation effects are a function of field the current for the two higher fields was adjusted iteratively to give approximately the same central field in each case. The units used for harmonic content are the ratio of the harmonic to the dipole at about 2/3 the coil inner radius, (25 mm) times $10^4$. The harmonic is the Taylor expansion of the field on the midplane.

The data show that at low field, $b_2$ and $b_4$ increase monotonically with b-a, but $b_6$ is almost constant. At 3.29T, $b_6$ is still almost constant with b-a, but at 4.13T, $b_6$ has a monotonic increase from -0.96 to -0.46. The behaviour of $b_2$ and $b_4$ at the higher fields is shown in Fig. 1, which displays $\Delta b_2 = b_2(B_0) - b_2(0.38T)$ and $\Delta b_4 = b_4(B_0) - b_4$

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Table 1

Harmonics as a Function of Ellipse Eccentricity

| b-a,(mm) | I,(A) | Bo,(T) | $b_2$ | $b_4$ | $b_6$ |
|---|---|---|---|---|---|
| 0 | 460 | 0.378 | -.1 | - .16 | - .05 |
| 0 | 4040 | 3.291 | 16.0 | -2.81 | 0.04 |
| 0 | 5260 | 4.119 | 53.7 | -4.87 | - .96 |
| 2 | 470 | 0.377 | 48.9 | 0.14 | - .06 |
| 2 | 4120 | 3.290 | 53.6 | - .70 | - .10 |
| 2 | 5345 | 4.122 | 78.2 | -3.35 | - .83 |
| 4 | 480 | 0.378 | 91.2 | 0.61 | - .08 |
| 4 | 4196 | 3.287 | 91.4 | 0.53 | - .09 |
| 4 | 5419 | 4.121 | 101.2 | -1.96 | - .69 |
| 6 | 480 | 0.371 | 128.6 | 2.05 | - .03 |
| 6 | 4272 | 3.289 | 126.3 | 1.96 | - .06 |
| 6 | 5496 | 4.133 | 121.2 | - .41 | - .51 |
| 8 | 500 | 0.380 | 161.3 | 3.38 | 0.01 |
| 8 | 4346 | 3.291 | 157.3 | 3.26 | - .01 |
| 8 | 5571 | 4.130 | 141.4 | 0.96 | - .46 |

(0.38T) as a function of b-a. In the case of $\Delta b_2$, the curves for the two fields do not intersect the axis at the same gap; furthermore the curves for $\Delta b_4$ do not intersect the axis. In other words, the $b_2$ saturation shift cannot be exactly nulled at all field levels, and the $b_4$ saturation shift cannot be exactly nulled at any field level.

The next step is to design a coil which has low harmonics in the elliptical aperture selected for minimum harmonic shift. It was noticed in the earlier work[4] that such a coil, which has more turns near the poles, increases the $b_2$ saturation shift. In the present case, therefore, the ellipse with b-a = 6 mm was initially selected for design of a matching coil, since it overcompensates for $\Delta b_2$. At present, the coil design program (which makes use of the MINUIT optimization routine) can be used only with circular iron apertures. Hence the new coil configuration, termed "E" with $b_2$ = -127.9, $b_4$ = -1.51 and $b_6$ = 0.43 with a circular aperture, is the closest, integer-turn configuration found to offset the harmonics for low field at b-a = 6 mm given in Table 1. The configuration has four blocks of 15, 10, 7 and 4 turns with 3 wedges separating the blocks. The harmonic content of the "E" coil in the b-a = 6 mm elliptical aperture is given in the first three lines of Table 2, with A = 0 mm(q.v.). These data show that although the $b_2$ shift with saturation is small, the $b_4$ shift is large enough to require a correction winding, about -2.5 units, about the same as was obtained with the standard coil.

To control the $b_4$ shift, a modification of the elliptical aperture was attempted. The approach was to remove iron at the first $b_4$ pole away from 90 degrees. The mathematical form used for the purpose should have zero slope at both 0 and 90 degrees in order to avoid cusps there that would interfere with construction, and should have a maximum at 54 degrees. The form used is

$$\Delta N = kA\theta^n \sin^2 2\theta \qquad (1)$$

where n is 1.225 for a maximum at 54 degree. $\Delta N$ is the magnitude of the perturbation whose direction is normal to the unperturbed ellipse. The constant k is the reciprocal of $\theta^{1.225} \sin^2 (108)$, or 1.189, so that A is the maximum amplitude of $\Delta N$. Two

Table 2

| A, mm | $B_0$ | $b_2$ | $b_4$ | $b_6$ |
|---|---|---|---|---|
| 0 | 0.379 | 2.27 | - .75 | 0.29 |
| 0 | 3.291 | 1.07 | - .88 | 0.25 |
| 0 | 4.123 | 1.74 | -3.28 | - .16 |
| +1 | 0.376 | - 7.29 | 6.77 | 0.06 |
| +1 | 3.290 | - 7.83 | 6.17 | 0.07 |
| +1 | 4.123 | - 4.54 | 1.90 | - .11 |
| -1 | 0.381 | 12.25 | -9.17 | 0.61 |
| -1 | 3.292 | 10.43 | -8.79 | 0.50 |
| -1 | 4.133 | 8.32 | -8.68 | - .21 |

values of A, +1 and -1 mm, superimposed on the y-x = 6 mm ellipse gave the harmonics in the last 6 lines of Table 2, using the "E" coil. The data of Table 2 show that the $b_4$ shift can be nulled at 4.1T with a value for A of -0.8 mm which also, however, introduces a $b_2$ shift of -3.2 units.

## The Final Configuration

The configuration used has b-a = 5.6 mm and A = -0.9 mm. The "E" coil was run in this new iron configuration, termed "6N" and the harmonics at low field obtained with 6N/E were used to readjust the spacers in the "E" coil, while retaining the 15, 10, 7, 4 turns per block. The resulting coil configuration is termed "G" and has the structure given in Table 3: Figure 2 shows one quadrant of the resulting coil and iron. Note the increasing gap between coil and iron as the pole is approached.

Table 3

| Block | No. of turns | Included Angles (degree) |
|---|---|---|
| 1 | 15 | 0.14 - 25.31 |
| 2 | 10 | 26.90 - 43.67 |
| 3 | 7 | 48.19 - 59.93 |
| 4 | 4 | 68.48 - 75.19 |

The harmonics of the 6N/G combination are given in Table 4. These data show that between 3.3 and 4.1T, $b_2$ has a slight minimum, with a shift from the value at low field of -2.66 units. At 4.1T, the $b_2$ shift is +0.64 unit; $b_4$ is almost constant with field and $b_6$ decreases -.87 unit from low field to 4.1T. Not shown in the table are higher harmonics; the largest is $b_{10}$ = 0.28, and none above $b_6$ show any field dependence. One higher field value, 4.46T shows that midplane saturation is affecting the harmonics. At a central field of $B_0$ = 4.1T, the mean flux density in the iron on the midplane is 2.20T, and at $B_0$ = 4.46T, the mean iron flux density is 2.31T. The saturation flux density of this iron is about 2.13T. This means that optimization of the elliptical aperture for a field greater than 4.1T cannot be done without increasing the iron diameter.

At 5225 A, the peak field in the superconductor is 4.612T, and at 5800 A it is 5.030T. Using these values and a standard correlation for the superconductor planned for the SSC (which has cu/sc = 1.8), the quench current at 4.5K would be 6078 A with $B_0$ = 4.63T.

The large variation of $b_2$ and $b_4$ with b-a and A offers a degree of freedom in design not possible with circular apertures. A perennial problem with coils of this sort is that the constraint of an in-

Table 4

| I,(A) | $B_0$,(T) | $b_2$ | $b_4$ | $b_6$ |
|---|---|---|---|---|
| 465 | 0.377 | - .80 | - .64 | - .59 |
| 2300 | 1.865 | - .84 | - .65 | - .59 |
| 2900 | 2.352 | - .99 | - .65 | - .60 |
| 3500 | 2.836 | - 1.29 | - .60 | - .63 |
| 4070 | 3.290 | - 2.14 | - .37 | - .70 |
| 4700 | 3.764 | - 3.46 | - .60 | - .97 |
| 5225 | 4.112 | - .16 | - .66 | -1.46 |
| 5800 | 4.460 | -14.33 | -1.41 | -1.86 |

teger number of turns may result in small amounts of undesired harmonics. In the present case, low field values of $b_2$ and $b_4$ of about +1 and 0, respectively, would be desireable, i.e. changes of 1.8 and 0.64 in the present low field values. Letting e = b-a, from the tables above one obtains the Jacobian $\Delta b_n/\Delta e$ and $\Delta b_n/\Delta A$ of Table 5 (the variation in A was with e fixed at 6 mm). Solving for the required e and A shifts, one obtains $\Delta e$ = 0.133 mm and $\Delta A$ = -.067 mm. With changes this small, the shifts due to saturation would be very small.

Table 5

| | n = 2 | 4 |
|---|---|---|
| e | 18.62 | 0.58 |
| A | 9.98 | -8.42 |

## Summary

Reduction of harmonics due to iron saturation can be achieved by a circular aperture with a sufficient gap between coil and iron, but at the expense of increased amp-turn requirements for a given field. It has been shown that shifts in both $b_2$ and $b_4$ due to iron saturation can be greatly reduced by appropriately shaping the closely-coupled iron aperture in a moderate field dipole. The shape consists of a basic ellipse on which is superimposed a perturbation peaked at 54 degrees. In the magnet analyzed, the $b_2$ shift at 4.1T is reduced from 53.8 to 0.6, with a negative shift of -2.7 at 3.8T. The $b_4$ shift at 4.1T is reduced from -4.71 to -0.02. The $b_6$ shift of -0.91 is almost unchanged at -0.87. Application to higher field magnets should be straightforward, although the technique may be limited by the lack of a practical coil with sufficient negative $b_2$ to compensate for the positive $b_2$ due to the elliptical aperture. Shaping of the iron aperture permits one to compensate for small amounts of harmonics introduced by the integer turn constraint.

## References


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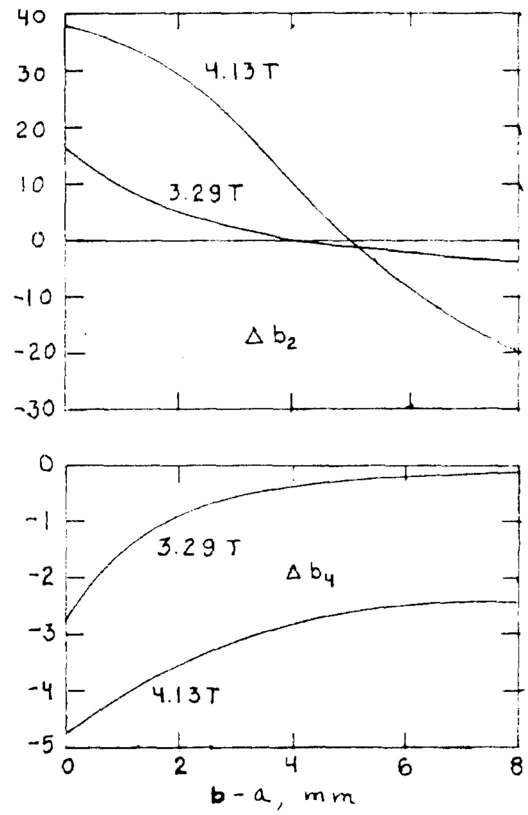


Figure 1. Shifts in sextupole and decapole at two high fields as a function of elliptic eccentricity.

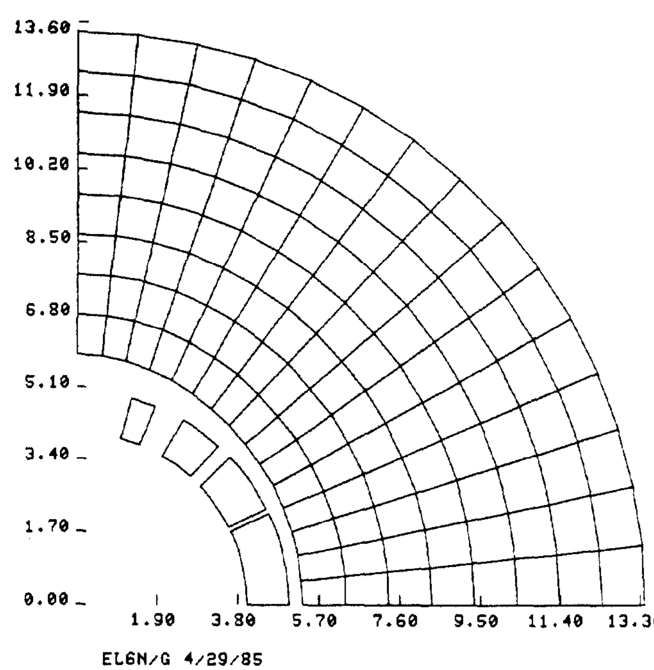


Figure 2. Iron with shaped elliptical aperture for correction of $b_2$ and $b_4$ saturation shifts with matching coil.