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CORRECTING FIELD HARMONICS AFTER DESIGN IN SUPERCONDUCTING MAGNETS*

R.C. Gupta

Accelerator Development Department
Brookhaven National Laboratory
Upton, NY 11973 USA

ABSTRACT

For a variety of reasons the actual field harmonics, as measured, in the superconducting magnets come out to be somewhat different than what were intended at the time of design. In this paper we shall discuss the schemes which can be used to correct them in the magnets. We shall discuss them for both the allowed and non-allowed harmonics. Since the deviation in field harmonics from their design value is mainly related to the mechanical properties of the coil cross section, in order for a scheme to work as planned, the mechanical configuration of the coil should not be changed significantly while this correction is being implemented.

INTRODUCTION

The field harmonics have been measured in a large number of superconducting magnets for the Superconducting Super Collider (SSC) and for the Relativistic Heavy Ion Collider (RHIC). The following relation is used to define the field harmonics :

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} \left[b_n' + ia_n'\right] \left[cos\,(n\theta) + i\;\; sin\,(n\theta)\right] \left(\frac{r}{R_0}\right)^n ,$$

where B_0 is the field at the midplane at a radius R_0, B_x and B_y are the components of the field at (r,θ) and R_0 is the normalization radius which is 10 mm in SSC magnets. a_n' are the skew harmonics and b_n' are the normal. Only b_{2k}, with k being an integer, are the allowed harmonics in a magnet having a dipole symmetry.

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The measured values of field harmonics in the dipole and quadrupole magnets for SSC and RHIC have been observed to be different than what was intended at the time of design. This is particularly true for the lower order harmonics like allowed b_2 and b_4 in dipoles (b_5 in the quadrupoles) and non-allowed a_1 in dipoles. One practical way to obtain the intended values of allowed harmonics is to carry out an iteration in the original design of the the coil cross section. This change should be small mechanically for the process to converge in one or two iterations. Therefore, it would be useful to carry out a theoretical study to examine the flexibility of a particular coil cross section in terms of its ability to accommodate some changes in field harmonics without significantly changing its mechanical properties. In principle, one can also correct these harmonics, in particular b_2, by modifying the iron aperture. We shall briefly discuss the feasibility of that also in this paper.

The non-allowed geometrical multipole a_1 in the coil, which reflects an up-down asymmetry in the coil, can be corrected by a deliberate up-down asymmetry in the iron yoke. The multipole a_1 is also introduced by iron saturation at high field when the flux lines can not be contained in the iron yoke. This is because of the fact that the yoke is asymmetrically located inside the magnetic cryostat wall both in the SSC and in the RHIC dipoles. To correct this multipole inside the dipole, one has to introduce another up-down asymmetry in the iron yoke in the opposite direction.

First we shall discuss the schemes for correcting the non-allowed harmonic a_1 and then discuss the approaches which can be used in correcting the allowed harmonics.

CORRECTING NON-ALLOWED HARMONICS

Among the non-allowed measured harmonics, only a_1 (skew quadrupole) has a magnitude to be of any concern in SSC dipoles. Therefore, we restrict our discussion to just a_1. We shall discuss first the geometric a_1 and then the saturation induced a_1.

Geometric a_1

The major source of geometric a_1 in the dipole magnets is the up-down asymmetry in the collared coil since the iron yoke contributes very little to it. A good correlation has been observed[1] in the measured a_1 in the collared coil before and after it was placed in the iron yoke. This a_1 is related to the tolerances in the manufacturing process of the coil. This is of random nature and is the major source of the random variations in the geometric a_1.

In this paper we propose that an up-down magnetic asymmetry in the collared coil be compensated by deliberately introducing another asymmetry in the magnetic length of the yoke between the upper and and lower halves of the magnet. It may be pointed out that in the two ends of the magnet, the place where this correction would take place, there is a transition from the low carbon steel laminations to the stainless steel laminations. Therefore, the difference in the magnetic length between the top and bottom half can simply be obtained by switching the type of laminations between the upper and lower half of the yoke on the two sides of this transition plane. In order to adopt this scheme, one would first measure the a_1 in the collared coil at room temperature. This would determine the number of laminations to be switched in the top and bottom half of the magnet. Our preliminary estimates show that to correct 1 unit of a_1 one would need to switch 25 mm of the magnetic laminations with the 25 mm of stainless steel laminations from the top to bottom in the two ends of the magnet. The total amount of either the stainless steel or the low carbon steel lamination does not change in the process. But for the end effects, there would be theoretically no change in the allowed harmonics. Locally, this creates ~ 200 units of a_1 with respect to the central field there (which is 85% of B_0 in the magnet straight section). Other non-allowed harmonics introduced in the process, for example a_3, etc., are $\sim .01$ unit or less – well within the specifications for them. There is some loss[2] in the a_1 correction at high field due to iron saturation. This loss is not expected to be linear with the length of the correction and therefore one would make a table of length versus a_1 correction both at low and high field and choose a proper length accordingly. This scheme should be a relatively easy to implement, particularly in the BNL type horizontally split yoke design where the geometry of the non-magnetic stainless steel and magnetic low carbon steel lamination is identical. It may, for example, be implemented in the following manner in a large scale industrial production environment:

- The usual thickness of a pack of laminations in the BNL built SSC magnets is 3 inch. We propose that in the end region this pack be made $\frac{1}{4}$ inch thick. This is also a natural choice in those designs where $\frac{1}{4}$ inch thick laminations are used. This should be done for both the magnetic and the stainless steel laminations.
- Paint low carbon steel and stainless steel laminations differently. Note that the amount of the two types of laminations to be used in any magnet is independent of the amount of a_1 correction to be applied.
- Each $\frac{1}{4}$ inch block in one end corrects $\frac{1}{8}$ unit of a_1. Decide the number of the two painted laminations to be distributed in the top and bottom halves of the magnet based on the measured a_1 in the collared coil. Note that if a_1 is measured 0 then the paint will change at the same axial location in the top and bottom half of the magnet.

In the BNL 50 mm dipole design, the length of the coil straight section is ~ 585 inch, the length of the space occupied by the low carbon steel laminations is ~ 582 inch and the length of the space occupied by the stainless steel laminations in the two ends is ~ 6 inch in each end.

Saturation Induced a_1

Both the calculations and measurements show a significant variation in a_1 (skew quadrupole) as a function of current beyond 6 tesla central field in SSC dipoles[3,4]. This is because of the fact that the yoke is located asymmetrically 93.7 mm above the horizontal axis of the magnetic cryostat vessel. One starts seeing this a_1 when the iron yoke is well saturated and the flux lines can not be contained inside the yoke. This is a systematic effect and is in addition to the random geometric a_1, discussed above. The effect is several times the allowed specification of 0.04 unit for the systematic a_1. In SSC 50 mm Dipole the computed a_1 saturation is in the range of 0.1 to 0.2 unit. The measured values also appears to fall in the same range in those long SSC 50 mm dipole magnets for which the preliminary data are examined.

In this paper we discuss a few ways to reduce this systematic a_1 and to bring it within the allowed specifications. The final choice of a particular scheme may depend on it's overall impact on the magnet production and the degree of cancellation desired at all values of central field. A detailed finalized design would require a confirmation with the measurements and an iteration may be desired to achieve a proper compensation/cancellation.

1. Placing Conductors in a Specified Location in Buss Work

It has been found that with a proper spacing and polarity of the two conductors in the buss, the a_1 produced by the proximity of the cryostat wall can be compensated by the a_1 produced by the conductors in the buss slot. The calculations show that if the mid-point of the two conductors is placed 5 mm off the vertical axis on either side, the net a_1 in the magnet stays within the specified tolerance. The direction of the current in the buss cable should be opposite to the direction of the current in the coil below it on the same side. A tuning of a_1 cancellation can be obtained by changing the spacing between the conductors in the buss work.

2. Using a few Non-magnetic Steel Laminations in Upper Yoke-half

If the number of magnetic laminations are different between the top and bottom half of the magnet, a skew quadrupole term is created. A practical way to implement this in a magnet would be that some of the magnetic low carbon steel laminations be replaced by the non-magnetic stainless steel laminations in the upper yoke-half. If the number of non-magnetic laminations is a small fraction of magnetic laminations and if they are evenly distributed, the situation can be simulated in a computer program by using two different packing factors in the top and bottom half of the magnet. The calculations show that $\sim 0.1\%$ difference in packing factor is adequate to bring the net a_1 within the specified tolerance. Since the thickness of lamination is 16 Gauge (0.0598 inch) in BNL built magnets, it means that in a long magnet one would need to change only 9 laminations from magnetic to non-magnetic in the top half. This scheme has easy tunability – one would simply change the number of stainless steel laminations.

3. Placing Extra Magnetic Steel at the Bottom of Yoke

Since the saturation a_1 is caused by the proximity of cryostat wall at the top half of the magnet, a natural solution to this problem would be to put some extra iron on the opposite side of it. We examined several configuration and ways to put this extra iron at the bottom half of this magnet. The calculations show that 1 mm thick iron strip from 180 degree to 360 degree will be adequate to produce the required compensation. If the strip is put from 225 degree to 315 degree (width = 90 degree) the thickness required would be 1 cm. This scheme also has easy tunability – one would simply change the width or thickness (or both) of the iron strip.

General Dynamics is looking[5] into placing this extra iron inside the shell (within the outer diameter of iron yoke) and those schemes have been found to be adequate according to the calculations carried out by them.

CORRECTING ALLOWED HARMONICS

A 4-fold symmetry has to be maintained while changing (correcting) the values of the allowed harmonics b_2, b_4, b_6, etc. First we shall consider correcting the geometric multipoles. They are present at all field level. Then, we shall consider the saturation induced multipoles which is only a high field effect. However, before one undertakes the task of removing these systematic effects, sufficiently good statistics must be obtained by measuring field harmonics in a large number of magnets to separate the random and systematic variations.

Geometric Multipoles

Geometric multipoles can be corrected by either modifying the coil cross section or by modifying the iron aperture. Such modifications should be incorporated only after the mechanics of the manufacturing process and the mechanical dimensions of cable, etc. are finalized since they may influence the harmonics in the magnet.

1. Modifying Coil Cross section

One way of obtaining a small systematic values of field harmonics in the final magnets may be to let the coil design program re-optimize the original cross section to cancel out the measured systematic values in the previous magnets. In such coil optimization process the computer program can change the dimensions of all wedges to do, for example, a least square fit optimization to obtain the desired values of field harmonics. This approach may not necessarily give a solution which is the best for bringing harmonics within specifications with a minimum change in the mechanics of the cross section. Therefore, a systematic study of observing the influence of changing the size of an individual wedge or of more than one at a time in various combinations, should be useful to steer the optimization process in a controlled direction. The following study is done on DSX201/W6733C cross section[6] which has all wedges symmetric in the inner layer but not in the outer layer.

In figure 1, we study the effect of changing the size of individual wedges, one at a time, on the field harmonics. The original wedge size is changed by ±1 degree in the steps of 0.1 degree. The pole angle also changes as the size of a wedge changes. The wedges are counted from the midplane to pole starting from the midplane. In figure 2, we change the size of 2 or 3 wedges together such that the pole angle does not change. Since there is only one wedge in the outer layer, the outer layer can not participate in this scheme. However, there are three wedges in the inner layer. In the first three cases, only two of these three wedges are changed at a time and the remaining third wedge is kept at its original value. As the size of one wedge increases the size of the other would decrease by the same amount. In the last case, all three wedges of the inner layer are involved. As the size of wedge 1 increases the size of wedge 2 and wedge 3 would decrease by half the amount of the increase in the size of wedge 1 to keep the pole angle constant. Obviously one could study many more combinations on exactly how to change the size several wedges in a coupled manner. In figure 3, we change the tilt angles of one block at a time (wedge changes accordingly) by ±5 degree in the steps of 0.5 degree. The tilt angles of the blocks closest to the midplane in the inner and in the outer layer is not allowed to change. The tilt angles 1, 2 and 3 are respectively for blocks 2, 3 and 4 in the inner layer (counting from the midplane to pole) and the tilt angle 4 is for block 2 in the outer layer.

One can see from these plots that some parameters are more sensitive than others to produce a large change in one particular harmonic and small change in other harmonics. For example, in figure 1, the change in the size of wedge 4 produces a large change in b_2 and small change in all other harmonics.

We present the original and re-optimized cross section in figure 4. This cross section should produce the magnets in which the systematic values of all harmonics is close to zero provided they are built with the same cable. The change in cable size, for example due to change in cable insulation, can be incorporated as a perturbation to this cross section in a pre-determined way to still produce harmonics close to zero. In this re-optimized cross section we could make all wedges, both in the inner and in the outer layer, mechanically symmetric. This relaxes the quality control process during the magnet production.

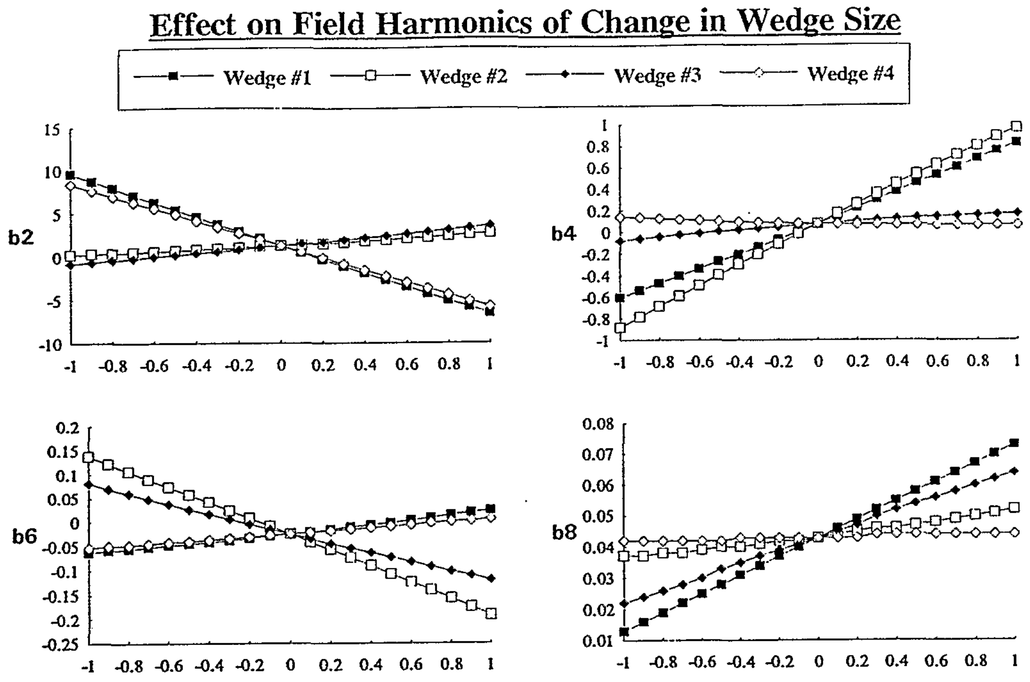
Effect on Field Harmonics of Change in Wedge Size

Figure 1: The size of all four wedges is changed one at a time by ±1 degree to study the effect of this change on the computed value of field harmonics in prime units. The pole angle will change in this case.

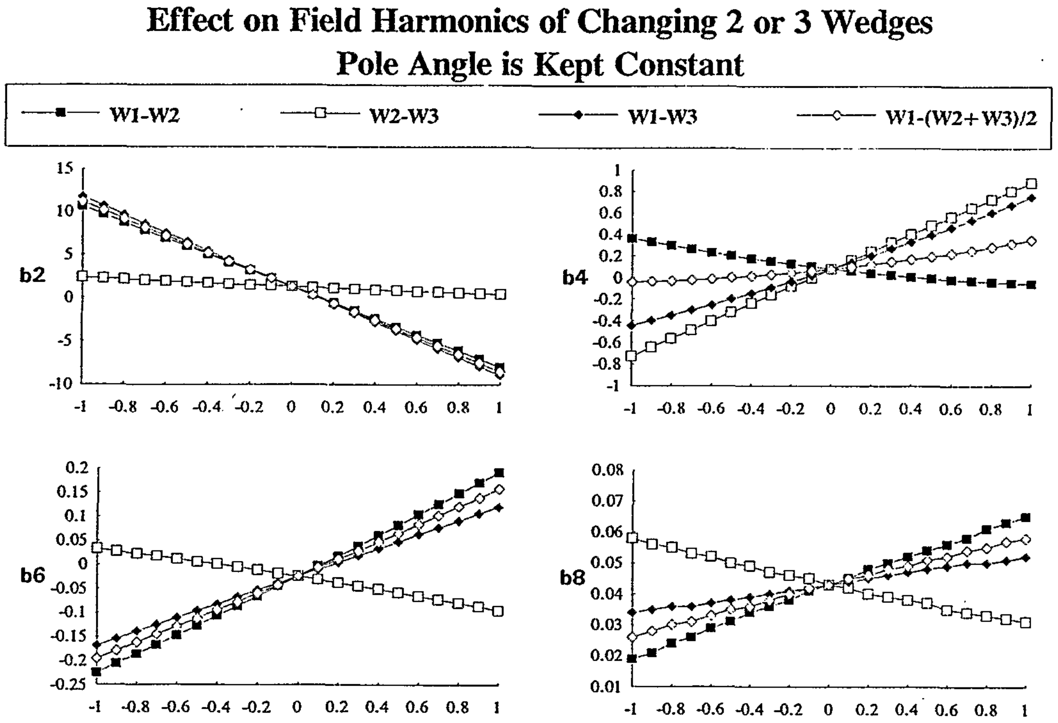
Effect on Field Harmonics of Changing 2 or 3 Wedges
Pole Angle is Kept Constant

Figure 2: The size of the three wedges in the inner layer is changed with two or more at a time such that the pole angle does not change. The symbol W1 represents the wedge 1. The maximum change in the size of any wedge is ±1 degree. The effect of this change on the computed value of field harmonics in prime units is shown here.

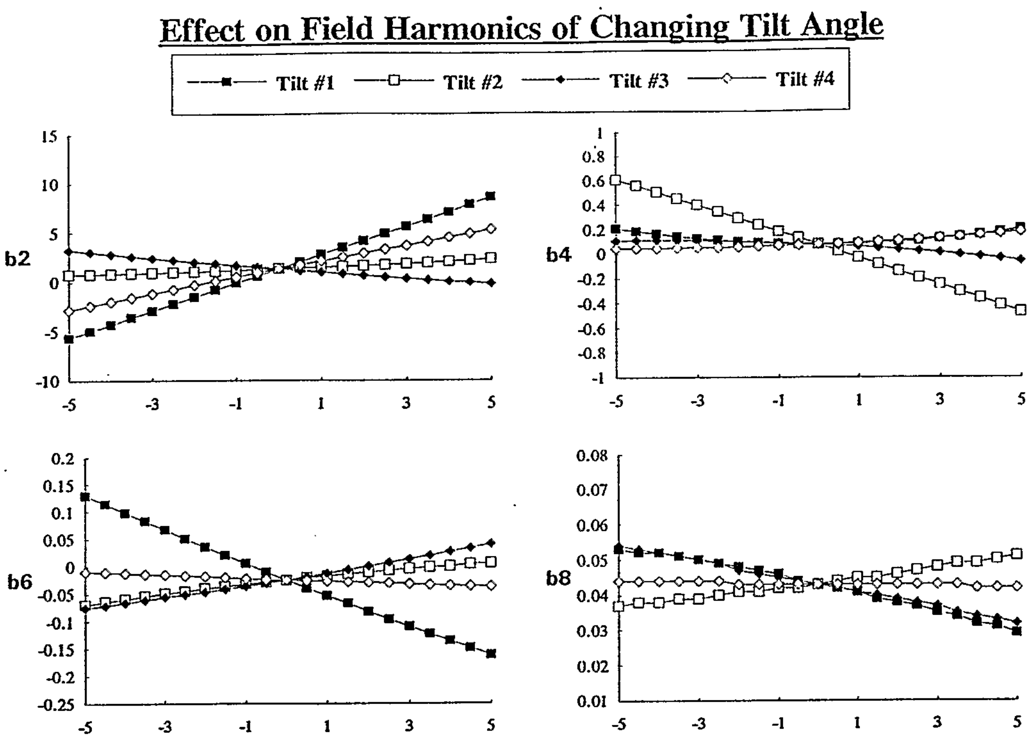

Figure 3: The tilt angle of all blocks except those at the midplane is changed one at a time by ±5 degree to study the effect of this change on the computed value of field harmonics in prime units.

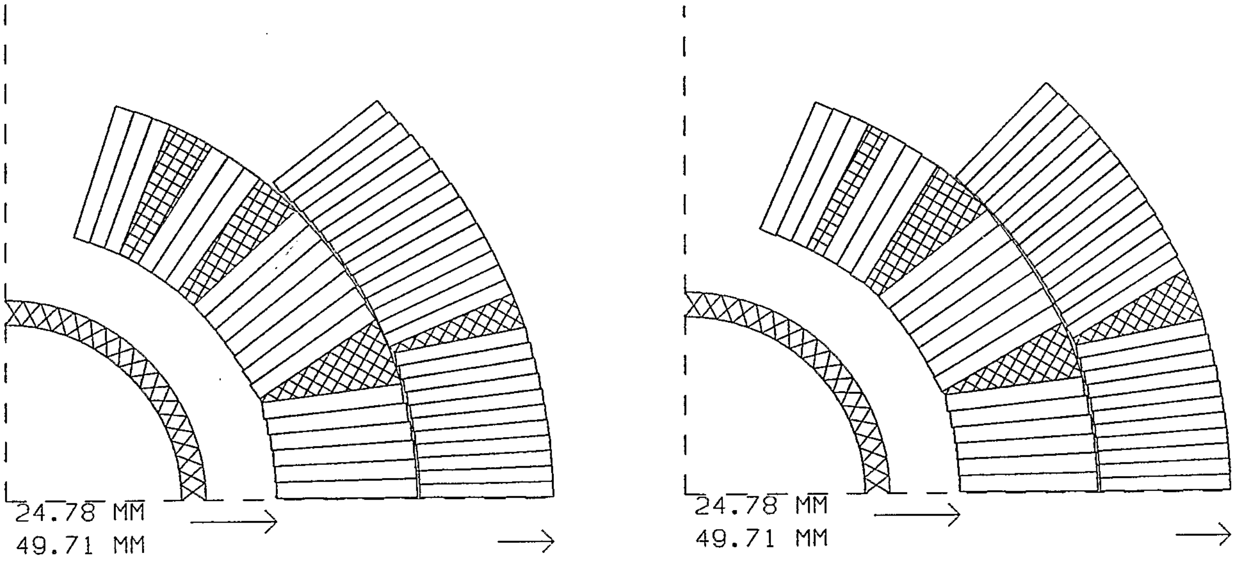

Figure 4: The original cross section DSX201/W6733C is shown in the left. Measurements show that this produces non-zero systematic harmonics. The re-optimize cross section to eliminate these harmonics is shown in the right. This cross section has all wedges symmetric.

2. Modifying Iron aperture

The field harmonics can also be changed by modifying the iron aperture. But in practice we found that for any reasonable change in iron aperture, the scheme is mostly effective for changing b_2 only and for higher harmonics it is not efficient. To introduce a change in field harmonics, one can either put some cutout or extrusion in the aperture or can modify the aperture as a whole, for example by introducing a little ellipticity in the circular aperture. Both of these changes in the aperture also bring a change in the iron saturation which must be compensated if the change in b_2 is to be kept constant at all excitations. It may be noted that the geometry of the stainless steel collar may also have to be changed together with the iron aperture. The only advantage of correcting b_2 by modifying the iron aperture would be that it does not change the coil.

Saturation Induced Multipoles

The saturation in the magnetic properties of the iron brings a change in the field harmonics at high field. In addition, the coil deformation due to Lorentz forces[4] on the coil also changes the harmonics at high field. Whereas, the calculations for the change in harmonics due to iron saturation are fairly reliable the calculations for the change in harmonics due to Lorentz forces are not as reliable. In addition the change depends on the gap between the collar and the yoke. In the magnets one would like to obtain a small values of these harmonics not only at low field but also at high field by minimizing the combined variation in the field harmonics due to iron saturation and Lorentz forces. The iron yoke for the SSC dipoles is designed[6] such that the iron saturation, and in particular the variation in b_2 saturation as a function of current, can be modified by simply changing the size and location of the midplane cutout in the yoke. One would do that, if need be, in the final design. In the BNL built magnets, there is a small variation in b_2 as a function of current and therefore no corrective action is required.

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