# A Comparison of Calculations and Measurements of the Field Harmonics as a Function of Current in the SSC Dipole Magnets*

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## Abstract

A large number of short and long superconducting dipole magnets for the Superconducting Super Collider(SSC) have been constructed and measured for their magnetic field properties at Brookhaven National Laboratory (BNL) . In this paper we compare the calculations and measurements for the variation of field harmonics as a function of current in 40 *mm* aperture and 50 *mm* aperture dipole magnets. The primary purpose of this paper is to examine the iron saturation effects on the field harmonics. The field harmonics also change due to the persistent current in the superconducting wires and due to the deformation of the coil shape because of Lorentz forces. We discuss the variation in the sextupole harmonics ($b_2$) with current and explain the differences between the calculations and measurements. We also discuss the skew quadrupole harmonic at high field in the long dipole magnets.

## Introduction

A comparison between the calculations and measurements in a large number and variety of magnets not only allows one to check the reliability of computer codes and design procedure but also allows one to estimate the contribution from sources not included in the calculations. The data on magnet to magnet variation allows one to estimate the uncertainty to be expected in the future magnets to be built. The variation in the calculated harmonics from one computer program to other allows one to estimate the uncertainty in the computer calculations. It may be noted that in the present yoke design for the SSC dipoles the maximum change in the sextupole harmonic with current can be varied by simply relocating and/or re-sizing the stainless steel key at the midplane which aligns the top and bottom yoke halves. Therefore, a systematic difference between the designed and measured change in $b_2$ with current can be empirically corrected. However, before such correction is incorporated a large number of magnets should be analysed.

## Procedure

The absolute values of multipoles, measured or computed, will not be discussed in detail in this paper. However, the source of them both in the construction and in the computer modelling and the method used to compare the relative variation of field harmonics as a function of current is discussed below briefly :

- *Persistent Current Multipoles* are primarily removed from the analysis in these magnets by averaging the measured multipoles for the up and down ramp and by starting the comparison at 2000 A.
- *Geometric Multipoles* arising due to variations in the magnet construction are removed by forcing $b_2$ to be zero at 2000 A for each magnet.
- *Model Dependent Multipoles* present in the computed multipoles due to practical limitations in accurately describing the conductor geometry, are also removed by requiring that for each magnet, the $b_2$ starts from zero.

## Analysis

The magnetic design of the cross section of 40 mm and 50 mm dipole cross section is described elsewhere[1,2,3]. The variation of field harmonics with respect to current can be attributed to two independent factors. The first and the major source is the non-linear properties of iron. If there is any variation in the magnetic properties of the iron from magnet to magnet then that would be reflected in the measured harmonics and the transfer function as well. The second source of the variation of the field harmonics with respect to current is the deformation of the coil shape due to Lorentz forces. The Lorentz force is proportional to $I^2$ (strictly speaking I × B). The force on the coil can be resolved in two components – the radial and the azimuthal. The radial component of the force is large on the turns at the midplane. It moves them outward towards the yoke and thus causes a negative change in $b_2$. The azimuthal component of the force acts as a compression on the coil. This causes a positive change in $b_2$. It should be noted that the azimuthal component of the force interacts with the pre-compression applied on the coil during assembly process. The effect of Lorentz force on $b_2$ may vary from magnet to magnet due to constructional variations as discussed below.

## Comparison

In Fig 1(a), we present the calculations (solid lines) with the computer codes POISSON, MDP(GFUN) and PE2D and the measurements (dotted lines) in the first three 50 mm aperture short magnets built at Brookhaven National Laboratory (DSA207, DSA208 and DSA209) for the sextupole harmonic, $b_2$. The calculations and measurements agreed within 1/4 prime unit for predicting the maximum change in $b_2$ and change in $b_2$ at 6.7 tesla. A somewhat larger difference in the intermediate region may be attributed to (a) that the iron used in building the magnet was different then the one presumed in the calculations; (b) that some irregularly shaped magnetic laminations with punched out cooling channels were used along the length of the magnet (c) that some $b_2$ change may be because of coil deformation due to Lorentz forces.

In Fig 1(b), we present the calculations with the computer code POISSON (solid line) and the measurements in seven 40 mm aperture SSC short dipoles (dotted lines).

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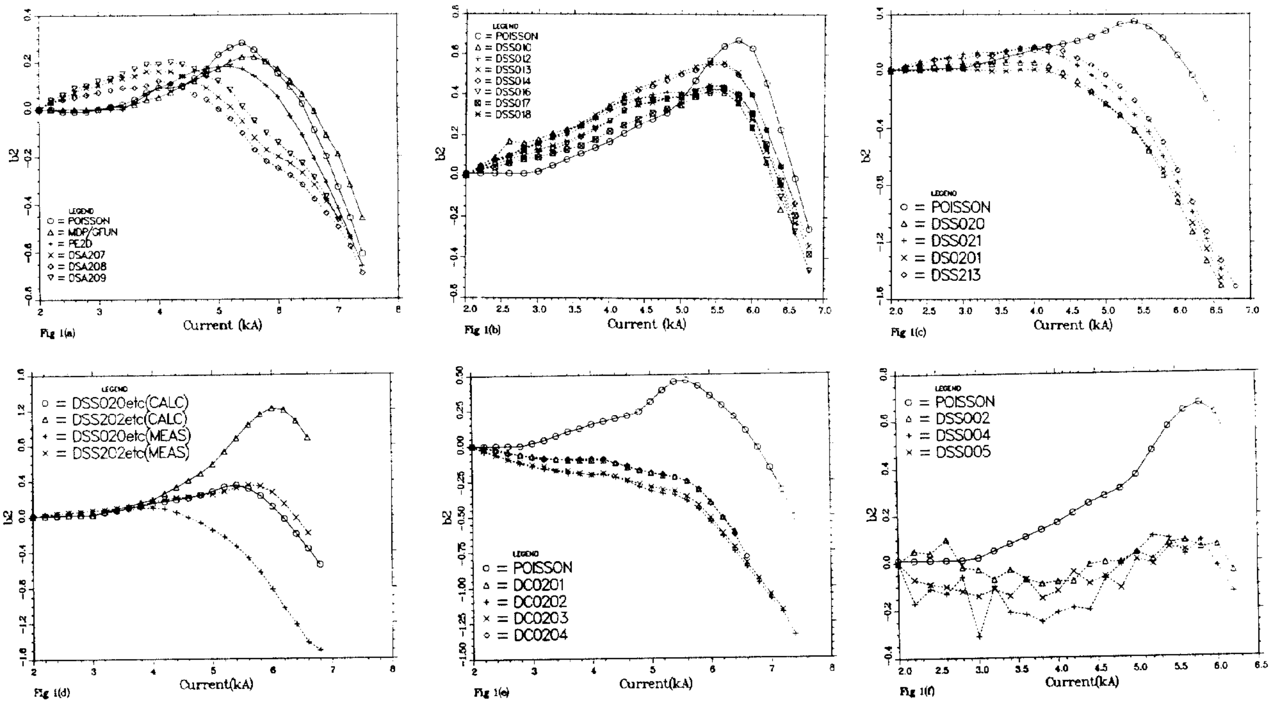

**Figure 1:** Sextupole harmonic in prime units as a function of current. Solid lines are the computed curves with the code indicated in the legends and the dotted lines are the measured curve for the magnet indicated in the legend.

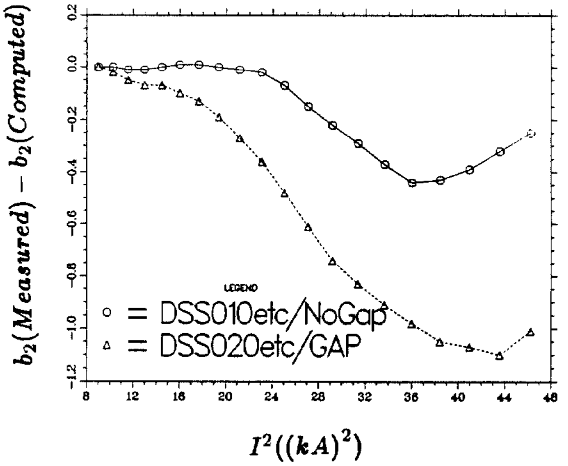

**Figure 2:** $b_2$(Computed) is subtracted from $b_2$(Measured) to remove the iron saturation effect in $b_2$ in the magnets.

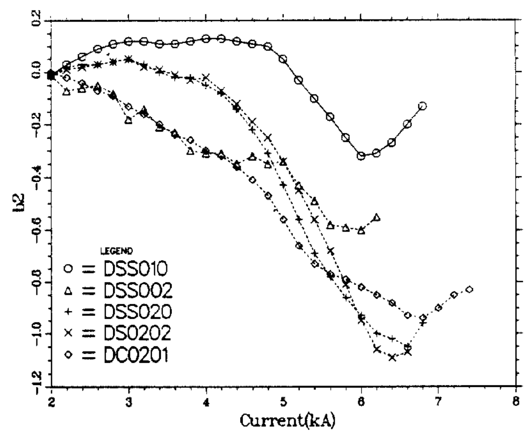

**Figure 3:** The average difference between the calculations and measurements in each group of magnets shown in Fig 1.

The following should be noted. (a) In all computations we used a single measured B-H table. (b) The irregularly shaped laminations were non-magnetic. (c) There was no gap between the collar and the yoke. Therefore, this is a good example to demonstrate what kind of variations are to be realistically expected between the magnets and between calculations and measurements. In analysing the variations in the measured relative change in $b_2$ (in these and a large number of other magnets) and also in analysing the variations in the calculated relative change in $b_2$ with several computer codes (see Fig 1(a)), we come to the conclusion that 1/4 unit of uncertainty in predicting the relative change in $b_2$, is in general a reasonable thing to expect, particularly above 5000 A.

Now we discuss those magnets where we found a large differences between the calculations and the measurements. The following major changes were made between the 40 mm aperture short magnets up to DSS018 and after DSS020. (a) The magnetics of the yoke cross section was changed with the midplane notch removed and the material of the yoke-yoke alignment key changed from magnetic to non-magnetic. (b) The yoke iron was changed with the new iron possibly having a different B-H table. (c) A radial gap of ~ 0.1 mm was introduced by a yoke die modification. In Fig 1(c), we present $b_2$ calculations with POISSON (solid line) and $b_2$ measurements (dotted lines) in four short dipoles DSS020, DSS021, DS0201 and DS0213.

A large disagreement between the calculations and measurements can be easily seen. This disagreement was of great concern for a while since it could not be explained by assuming any reasonable change in the magnetic properties of the yoke material. To eliminate the concern about the reliability of computer codes in predicting the effect of the hole at the midplane (caused by the use of the stainless steel key), new to these magnets, the material of the key was changed to magnetic iron in short magnets DS0202 and DS0203. It brought the "$b_2$ versus I" curve close to the design case (see Fig 1(d)). However, the difference between the calculations and measurements in the two cases remained essentially the same which suggests that the major source of explanation may be something other then the iron saturation considerations.

The cause of the disagreement is presently attributed to the 0.1 mm gap between the collar and the yoke which gives extra space for the coil to elongate at the midplane due to the radial component of the Lorentz force. It may be mentioned that even if there is a line to line contact at room temperature, a gap may develop at operating temperature due to a difference in thermal contraction between the yoke and collar material. To study the effect of the Lorentz force in this situation, we first compute $\delta b_2 = b_2(\mathit{Measured}) - b_2(\mathit{Computed})$, to remove much of the iron saturation effects from the measurements. For the measured values we take the average of measurement in a number of magnets which use the same magnetic design. This is done for the magnets which had the above mentioned gap (DSS020 and after) and those which did not (DSS010 to DSS018). In Fig 2, we have plotted $\delta b_2$ against $I^2$, which is proportional to the Lorentz force. However, once the contact is made between the coil and the collar, there will not be any more such change in $\delta b_2$. In Fig 2, initially there is a little change in $\delta b_2$ which may be due to a small magnitude of the Lorentz force. A linear negative change in $\delta b_2$ in the vicinity of 5000 A is attributed to the coil deformation due to Lorentz forces. We note that the change in $\delta b_2$ is 1.0 unit in the magnets with gap against the 0.4 unit in the case of magnets with no gap (except the one created during cool down). One may also note in Fig 2, that the linear negative change in $\delta b_2$ continues to higher current in the magnets with gap, which is consistent with "the extra gap and the Lorentz force" explanation. The Lorentz force argument is further confirmed by the calculations that $\sim$ 0.1 mm gap produces this order of change in $b_2$. These calculations are, however, model dependent and there could be as much as a factor of two difference depending on how the deformation is exactly included in a model.

An upward swing in $\delta b_2$ in Fig 2 at high current may be due to the the movement of the pole turn towards the midplane because of the azimuthal component of the Lorentz force. It may also be due to a higher packing factor or due to a higher saturation magnetization, $M_s$, in the iron used in building the magnets then the one presumed in the calculations.

Now we discuss the calculations and measurements in long dipoles. Though the long dipoles use the same cross section as short dipoles, the saturation properties of them are modified by the proximity of the magnetic cryostat wall which is not present in the short dipoles. The horizontal axis of the cryostat wall is vertically offset from the axis of the coil and yoke by 96.8 mm. At high field when the yoke no longer can contain the total flux in the iron, the un-allowed harmonics, such as $a_1$, become a function of current. In Table 1, we compare the measurements and calculations for the effect of the cryostat wall on $a_1$ and $b_2$ at 6500 A. For calculations we take the difference of harmonics computed with and without the cryostat wall. For $b_2$ measured the difference between the average change in long magnet and short magnet $b_2$ is taken. For $a_1$ measured in magnets DC0203 and DC0204, an average along the normal axial positions was taken since a significant variation along the axis of magnet was found. In Fig 1(e), we present the calculations and measurements for $b_2$ variation with current in long dipoles DC0201, DC0202, DC0203 and DC0204. The difference between the calculations and measurements are similar to those discussed above in DSS020 short magnet since the cross section is the same in these magnets.

**Table 1:** Computed and measured effects of the proximity of the cryostat wall on the change in $a_1$ and $b_2$ harmonics between 6500 A and 2000A.

| | Measured | PE2D | POISSON |
|---|---|---|---|
| $a_1$ | -0.3±0.1 | -0.27 | -0.38 |
| $b_2$ | 0.39 | 0.40 | – |

In Fig 1(f), we present the calculations and measurements for $b_2$ variation with current in short dipoles DSS002, DSS004, and DSS005. These were the earlier magnets which deliberately had a gap between the collar and the yoke.

In Fig 3, we plot the difference between the calculations and measurements in a large number of 40 mm aperture magnets. Instead of presenting a curve for each magnet we group all similar magnets into a single curve and take the average. We refer each curve to the name of the first magnet in that group (see Fig 1(a) to Fig 1(f)). Note that the agreement between the calculation and measurement is better in those magnets which did not have a gap between the collar and the coil.

## References

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