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ESTIMATING AND ADJUSTING FIELD QUALITY IN SUPERCONDUCTING ACCELERATOR MAGNETS*

R. GUPTA

Relativistic Heavy Ion Collider, Brookhaven National Laboratory,
Upton, New York 11973, USA

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The experience with estimating and adjusting field quality in RHIC (Relativistic Heavy Ion Collider) and SSC (Superconducting Super Collider) magnets is discussed. An alternate approach which makes a better estimate for systematic and random values of harmonics is presented.

1 INTRODUCTION

An important task of magnet builders in the early phases of an accelerator project is to make a critical and a close estimate of expected field errors in a series (industrial) magnet production. The methods used in the past tend to overestimate these errors. This paper will examine the reasons behind those differences and present an alternate approach.

The following relation and convention is used in defining field harmonics :

$$B_y + iB_x = 10^{-4} B_{R0} \sum_{n=0}^{\infty} [b_n + ia_n][cos(n\theta) + i\ sin(n\theta)](\frac{r}{R_0})^n,$$

where R_0 is the reference radius, B_{R0} is the field strength at the reference radius due to the fundamental harmonic, and B_x and B_y are the components of field at (r,θ). a_n are the skew harmonics and b_n are the normal.

It is useful to develop and incorporate design strategies which can promptly adjust the field harmonics during the course of production. A rapid feedback between the accelerator physicists and magnet builders during the course of RHIC magnet production is discussed elsewhere [1,2]. These strategies should be incorporated during the R&D phase of the magnet program not only to test the methods but also to make a realistic evaluation of possible field quality in series magnets with the design and construction under use. Demonstrated good field quality and proven tunability would help *(a)* make better (less conservative) estimates of the expected harmonics and *(b)* build confidence that the estimated field quality can be maintained during the course of series production.

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2 ESTIMATING FIELD ERRORS BEFORE SERIES PRODUCTION

2.1 Sources of Errors

A non-zero value of a harmonic can be the result of the persistent currents in the superconducting cables, the non-linear magnetization properties of iron or the geometric error in the placement of various turns in the coil. The major uncertainty in estimating the harmonic errors comes from the last source (geometric multipoles). The typical tolerances in parts and manufacturing process which define the coil cross section are specified such that the error from an individual component remains within 25 μm. The exception is the thickness of cable and insulation on it. The tolerances on them are generally an order of magnitude better. Uniform coil curing tooling also plays an important role in determining the location of the coil midplane in the magnet and hence in determining the values of non-allowed harmonics.

An asymmetric error in a part (component) need not give non-allowed harmonics. To explain this, let us consider that the inner radius of the collar between 130° to 140° is systematically larger by 25μm. Since the collar inner surface defines the geometry of the coil in the magnet, this would translate into a radial shift in turns at that location. However, a typical design of a pair of collars is such that the right side can interchange with the left side on flipping. Moreover, the upper and lower side also use the same cross section. This means that given the large numbers of collar pieces used in the magnet the non-symmetrical error would average out to create a near symmetrical error condition and the non-allowed harmonics will be small. The allowed systematic harmonics could be removed in a cross section iteration. However, if the geometric error in such a component is a purely random variation, then the average effect may cancel out even in allowed harmonics. The above arguments should apply to any part as long as the quantity used in the magnet is large and the mechanical design does not prevent a four-fold symmetric placement. If the quantity of a particular component used in the magnet is not large (for example wedges), then it is possible that the random variations in the component size may create non-allowed harmonics even if the component used in the magnet follows a four-fold symmetry. This will generate a large local variation in harmonics but integral (average) value may be small if several of them are used in the magnet. The possible impacts of various errors in parts and tooling in dipole magnets are described below:

Cable and Insulation size have a major impact on coil size and hence pre-stress on the coil in the magnet. They don't influence odd b_n's and even a_n's and the influence on odd a_n's can be made negligible if the azimuthal coil size between the upper and lower halves is matched to 25μm. Unless the variation in cable or insulation thickness is so large that the change in pre-stress on the coil is unacceptable, the influence on even b_n's is also negligible.

Other Components primarily influence only the allowed harmonics as long as a large quantity of them is used in the magnet. Non-allowed harmonics may be generated if the quantity is small or the mechanical design prevents randomizing in a 4-fold dipole symmetry.

Coil Curing Tooling generates only skew harmonics because of the way coils are installed in a dipole magnet. A difference between left and right side of the coil size or curing conditions generates even a_n's and an average variation generates odd a_n's. The influence of the coil curing press on harmonics may be significant (both on RMS and systematic) if it is not stable or uniform.

Coil Collaring Tooling creates primarily odd b_n's in a horizontally split design and odd a_n's in a vertically split design. A significant variation in the collaring process may also create even b_n's. In a reasonably well constructed collaring press, it should have only a small impact on harmonics.

2.2 A Brief Review of the Approaches Used in the Past

Two types of approaches (or a combination of them) have been used in the past to estimate the expected harmonic errors in magnets. The first approach relies on field computations where the blocks of conductors are moved radially and/or azimuthally in independent or coupled modes[3,4] by corresponding 25-50 μm errors which are allowed in the parts. The errors from these modes are added to obtain sigma or "Root Mean Square deviations" (RMS) in harmonics using Monte Carlo simulation or simple RMS addition of harmonics. Many such calculations do not reflect that the measured sigma of the non-allowed harmonics is much smaller than of the allowed harmonics. Herrera[3] noted this pattern and has parameterized the harmonic errors in terms of symmetry parameters. The cause of a reduction in the non-allowed harmonics has been given earlier in the previous sub-section.

The second approach relies on extrapolating the measured harmonics in magnets built elsewhere or in-house. This method (or a scaling based on this) may perform poorly if there are significant differences in the magnet design, components and the details of manufacturing process.

2.3 Methods Used for Specifying Expected Errors in RHIC Magnets

Based on the experience that the past methods tend to overestimate the expected errors, a working group was formed to estimate the expected harmonics in all RHIC magnets. Other members of this working group are listed in the acknowledgements. The expected value of each harmonic was characterized by the expected mean, the uncertainty in mean and the sigma (RMS) of the distribution.

In the case of quadrupoles, eight magnets were built with an identical design cross section. The expected values for sigma were made equal to the measured harmonics for harmonics b_2 through b_5 and a_2 through a_5 and 0.1 for all higher order harmonics. The expected values for uncertainty in mean were made equal to the magnitude of the difference between design and measured values of the mean. The expected mean was the value calculated for the new cross section. In the case of dipoles, though a number of R&D magnets were built, they did not have the same cross section and therefore could not be used directly. For most non-allowed harmonics, the measurements of the R&D magnets still formed the basis for obtaining the expected sigma and uncertainty in the mean. However, the measured harmonics in the R&D magnets were supplemented by the harmonics of Tevatron and HERA dipoles which have nearly the same aperture.

The uncertainties in the means of the allowed harmonics were derived based on (a) the mechanical error due to the specified tolerances in the most critical component (the component which gives the largest error in that particular harmonic) and (b) the uncertainty in making the allowed harmonics zero during a change in cross section and/or during a change in tooling between the magnets built at Brookhaven National Laboratory (BNL) and at Northrop-Grumman Corporation (NGC). This error is applicable only for initial series magnets (referred to as phase 1 magnets) and should be removed once the cross section is fixed and the magnet tooling and manufacturing have stabilized.

For the insertion region magnets, data from only two 130 mm aperture R&D quadrupoles were available at the time the harmonics estimates were made. Therefore, the above methods were supplemented by scaling and other computations. The tables are revised as necessary until production data replaces the estimates.

3 COMPARISON BETWEEN ESTIMATES AND MEASUREMENTS

Estimated and measured harmonics are compared here for *(a)* the complete series of arc dipole and quadrupole magnets to be used in RHIC and *(b)* a small number of SSC prototype magnets. Although the SSC prototype magnets were built with a relatively good field quality tooling design, a better performance might have been expected in series magnets with an optimized magnet design and better coil size matching.

3.1 Statistics of Measured Harmonics in RHIC and SSC Magnets

The estimated and measured harmonics in 80 mm aperture 9.45 m long dipole magnets for RHIC are given in Table 1 at a reference radius of 25 mm. In the RHIC program only a fraction of the magnets are tested cold[7] and therefore to present the complete distribution of all (296) magnets the integrated harmonics are given for warm measurements. The allowed harmonics are further divided into three series (construction phases) of magnets as the cross section went through small changes. $<b>$ and $<a>$ are the mean values of n^{th} harmonic and $\sigma(b)$ and $\sigma(a)$ are the sigmas. The estimated values are indicated with subscript e and the measured values with subscript m. δb and δa are the estimated errors in the mean. A good warm to cold correlation has been established to determine harmonics at any field in the operating range. To obtain harmonics at 660 A (near injection) one should add -4.2, -0.3 and -0.2 respectively to b_2, b_4 and b_6. To obtain harmonics at 5000 A (near top energy) add -3.3, 0.2 and 1.1. Table 2 gives the expected and measured warm harmonics for 80 mm aperture, 1.1 meter long RHIC quadrupole magnets (380 total). To obtain values at 3000 A one should add 1.0, 0.2 to b_3 and b_5, respectively and add 1.0 and 4.4 to obtain values at 5000 A.

TABLE 1: Expected (e) and measured (m) WARM harmonics in 80 mm aperture 9.45 meter long RHIC dipoles. b denotes b_n and a denotes a_n at 25 mm radius. The first part of the table gives harmonics in all magnets and second gives the measured allowed harmonics in three series with the number of magnets in each series in parenthesis.

n	$< b >_e \pm\delta b$	$\sigma(b)_e$	$< b >_m$	$\sigma(b)_m$	$< a >_e \pm\delta a$	$\sigma(a)_e$	$< a >_m$	$\sigma(a)_m$
1	0.0±0.4	0.8	0.25	0.37	0.0±1	1.3	-0.2	1.64
2	4±4.0/2.0	2.3	3.54	1.74	-1.1±0.1	0.5	-1.11	0.23
3	0.0±0.2	0.3	-0.03	0.1	0.0±0.3	1.0	-0.01	0.50
4	0.5±1/.5	0.6	0.22	0.44	0.2±0.06	0.2	0.18	0.08
5	0.0±0.03	0.1	0.01	0.03	0.0±0.1	.26	-0.01	0.17
6	0.3±.2/.1	0.1	0.12	0.11	-0.1±0.03	0.1	-0.11	0.03
7	0.0±0.03	0.1	0.0	0.01	0.0±0.03	0.1	0.0	0.05
8	0.3±0.1	0.1	0.09	0.11	0.0±0.03	0.1	0.02	0.01
9	0.0±0.03	0.1	0.0	0.01	0.0±0.03	0.1	0.0	0.01

Series (No.)	$< b_2 >$	$\sigma(b_2)$	$< b_4 >$	$\sigma(b_4)$	$< b_6 >$	$\sigma(b_6)$	$< b_8 >$	$\sigma(b_8)$
Phase 1 (19)	4.29	1.61	-0.62	0.39	-0.05	0.09	0.20	0.06
Phase 1A (86)	5.11	1.21	-0.02	0.30	0.23	0.08	0.24	0.03
Phase 2 (191)	2.76	1.42	0.41	0.34	0.09	0.09	0.01	0.03

TABLE 2: Expected (e) and measured (m) WARM harmonics in 80 mm aperture 1.1 meter long RHIC quadrupole magnets. b denotes b_n and a denotes a_n at 25 mm radius.

n	$< b >_e \pm\delta b$	$\sigma(b)_e$	$< b >_m$	$\sigma(b)_m$	$< a >_e \pm\delta a$	$\sigma(a)_e$	$< a >_m$	$\sigma(a)_m$
2	0.0±1.4	1.4	-0.61	1.61	-1.8±0.5	2.2	-1.93	1.66
3	-1±1/.5	0.6	-1.5[a]	0.95	0.0±0.1	0.7	0.48	0.95
4	0.0±0.7	0.6	0.14	0.49	0.0±0.7	0.5	0.06	0.48
5	1±2/1	0.5	1.4[a]	0.42	-3.7±0.5	0.15	-3.76	0.29
6	0.0±0.1	0.1	0.01	0.13	0.0±0.2	0.1	0.04	0.13
7	-.6±.1/.05	0.1	-0.52	0.09	0.0±0.1	0.1	0.01	0.11
8	0.0±0.1	0.1	0.01	0.05	0.0±0.1	0.1	0.00	0.05
9	-1.3±.2/.1	0.1	-1.29	0.06	0.3±0.1	0.1	0.35	0.02

[a] b_3 and b_5 in the initial series (7 magnets) were -2.8 and 1.0, respectively.

Two sets of numbers (separated by /) in Table 1 and Table 2 in δb are for the initial (Phase 1) magnets series (19 dipoles and 7 quadrupoles) followed by the overall series. The systematic values of the non-allowed harmonics in the body of the RHIC dipoles are essentially zero[1] but the non-zero systematic integral values are the result of the particular lead end design. A similar end configuration gives the large a_2, a_5 and a_9 in the quadrupoles.

In Table 3, the harmonic tolerances (which closely followed the expected errors) and the measured harmonics at 10 mm reference radius in the 50 mm aperture 15 meter long Superconducting Super Collider (SSC) dipoles[8] are given at a current of 2000 A. The table includes the measured data from seven prototype magnets built at BNL and thirteen prototypes built at Fermilab. These two series are based on the same coil cross section design but were built with a small magnetic and significantly different mechanical designs. Despite these differences, the two series had comparable RMS errors in field harmonics. The two series of magnets are

TABLE 3: Tolerances(t) and measured(m) body harmonics at 10 mm reference radius in BNL and FNAL built (except where noted) SSC 50 mm aperture dipoles at 2000 A.

n	$<b>_t$	$\sigma(b)_t$	$<b>_m$	$\sigma(b)_m$	$<a>_t$	$\sigma(a)_t$	$<a>_m$	$\sigma(a)_m$
1	0.04	0.50	0.02	0.19	0.04	1.25	0.03^a	0.4^a
2	0.80	1.15	1.43^a	0.38	0.03	0.35	-0.026	0.14
3	0.026	0.160	-0.002	0.028	0.026	0.320	0.009	0.069
4	0.080	0.220	0.303^a	0.028	0.010	0.050	-0.001	0.020
5	0.005	0.017	-0.001	0.002	0.005	0.050	0.003	0.008
6	0.013	0.018	-0.044^a	0.005	0.005	0.008	-0.004	0.005
7	0.005	0.010	0.000	0.001	0.005	0.010	0.000	0.001
8	0.01	.0075	$.0512^a$	.0012	0.005	.0075	0.004	.0035

[a] Harmonics in the first nine magnets built at Fermilab with the same cross section.

combined here to obtain better statistics for the non-allowed harmonics; the mean and sigma in the allowed harmonics (as indicated by superscript a) are obtained from the first nine Fermilab magnets built with an identical design.

3.2 Analysis of Field Errors in RHIC and SSC Magnets

In RHIC arc quadrupoles the expected and measured harmonics are quite close to each other. As mentioned earlier, the expected harmonics were based on a series production of eight magnets at the laboratory. A comparison between expected/tolerance harmonics in RHIC and SSC dipoles suggests that in both cases the errors were overestimated. In RHIC dipoles the overestimate is small primarily because the expected errors were already revised to a lower value. The field quality in RHIC dipoles is in fact significantly better than in similar aperture magnets built previously for the Tevatron and HERA. An overestimate of these field errors therefore indicates the techniques used in estimating the expected harmonics in SSC and RHIC dipoles did not completely account for the improvements in magnet construction and design techniques over a period of time. A smaller RMS (sigma) variation reflects a better control in parts, tooling and manufacturing and a smaller value of systematic (average) means a better tooling and magnet design.

The mean of the allowed harmonics in SSC magnets is large, as expected from the deviations in the magnet cross section from the optimized design. Moreover, because of practical considerations a mismatch in the top and bottom azimuthal coil size was allowed which gave larger a_1. An iterated design would give a smaller mean of allowed harmonics and a better coil-size matching would give a smaller a_1. a_1 in Table 3 is only for the first nine Fermilab built magnets (mean value of a_1 for the complete series was 0.3 and sigma was 0.85, respectively).

The consistency in manufacturing and parts may be directly evaluated when the harmonics are normalized to the coil radius. This would directly reflect the geometrical errors in the conductor placement in the coil. One unit (10^{-4}) of harmonic would be proportional to 0.01% of circumference and the cumulative geometric error in each quadrant would be $\frac{\pi}{2}10^{-4} \times R_c$ where R_c is the corresponding radius. In this simple global model the harmonics based on same symmetric (or asymmetric) geometric errors should have comparable RMS values except perhaps for some azimuthal dependence of a particular geometric error on a particular harmonic.

The result of the above exercise for the RMS values of harmonics indicates that the cumulative geometric errors per quadrant (a) in the SSC dipoles was ~5 μm for the non-allowed harmonics and ~20 μm for the allowed harmonics, (b) in the RHIC arc dipoles was ~5 μm for even a_n's and odd b_n's, ~25 μm for odd a_n's and ~40 μm for even b_n's and (c) in the RHIC arc quadrupoles was ~40 μm for the non-allowed harmonics and ~60 μm for the allowed harmonics. The details of these calculations are not given here due to space limitations but consolidating the harmonic errors the way done here may be subjected to some debate. A smaller cumulative dimensional error in SSC magnets may be correlated with the use of stainless steel collars instead of RX630 spacers in RHIC magnets. Laminated stainless steel collars provide better dimensional and collaring control in locating coils as compared to that provided by the injection molded RX630 spacers. A smaller mean value of harmonics in RHIC magnets may be a reflection of a better magnetic and mechanical design of both tooling and of the magnet itself.

4 FIELD QUALITY ADJUSTMENT DURING MAGNET PRODUCTION

A number of methods have been used in controlling the field quality in RHIC magnets. Many of them have been discussed in detail earlier [5,6]. If the harmonic errors are determined within the statistics to have a significant systematic component then they can be removed by a proper adjustment in the design. However, to adjust the harmonics during the course of a series production, the design should be flexible enough so that the changes can be absorbed in a timely fashion with a minimum waste of expensive inventory. In RHIC insertion quadrupoles an adjustment in the coil midplane gap and coil pole shims provided an adjustment in b_3, b_5 and b_9 harmonics while using the previously built coils[5]. In RHIC arc dipoles an adjustment in the midplane cap[6] provided a correction in the critical b_4 harmonic. The benefit of such a design approach is that it allows for a rapid feedback between accelerator physicists and magnet builders to best influence the magnet production with a short turn-around time[1]. In a dipole with multi-layer coils, an adjustment in the midplane cap and pole shim would provide an adjustment in several harmonics. However an adjustment in only the two harmonics b_2 and b_4 may be adequate as higher order harmonics do not deviate sufficiently from the design values to affect the machine performance. A systematic current dependence in field harmonics due to iron saturation can be made negligible by a proper yoke design[5].

5 CONCLUSIONS & PROPOSED APPROACH FOR ESTIMATING ERRORS

It is proposed that the expected RMS errors in harmonics be based on how the errors in components and tooling get translated into the error in the average coil position in the magnet rather than on the error in the parts themselves. This may significantly reduce the expected RMS errors in non-allowed harmonics. Moreover, the dynamics and the feedback of such an approach could directly translate the improvements (or lack of it) in tooling and manufacturing process into improvements in field quality and in estimates of it. The systematic values of harmonics (mean) in large scale series production of magnets should be related to systematic errors in the parts, tooling or design. A reduction or adjustment in them should be a part of the design. In the case of RHIC magnets, such adjustments have resulted in significant improvements in the critical harmonics. These were not part of the original design and error estimate process and hence these errors were overestimated in RHIC magnets.

In conclusion, the measured field errors are smaller than previously estimated because of (a) the influence of the mechanical errors in parts on field harmonics is significantly reduced when a large number of them are used in the magnets and (b) the improvements in tooling (in particular coil curing tooling) and manufacturing techniques over a period of time. The results of estimating systematic and RMS field errors in SSC (or similar dipoles) will be presented elsewhere[9], where the design principles which reduce/adjust harmonics will be used in the estimates.

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