FIELD QUALITY IN SUPERCONDUCTING MAGNETS FOR LARGE PARTICLE ACCELERATORS *

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Abstract

The expected field quality in superconducting magnets for large particle accelerators has improved over a period of time due to the development and application of a number of techniques. These design techniques will be described and as an example the expected harmonics in an improved design of the 50 mm aperture dipole magnets for the Superconducting Super Collider (SSC) will be presented. This field quality is based on experience with the Relativistic Heavy Ion Collider (RHIC) and SSC magnet programs. The initial results of a design approach will also be presented where the first design itself is adopted to produce good field quality in RHIC D0 insertion magnet.

1 INTRODUCTION

The purpose of this paper is *(a)* to give a brief outline of the concepts which either have been used or can be used in designing and then assuring good field quality in accelerator magnets, *(b)* to present a design concept which avoids the need of a normal magnetic design iteration which is both time consuming and expensive, *(c)* to present methods which can be used to control and match the field quality in the magnets built by several vendors, *(d)* to present techniques which overcome the influence of normal errors in parts and assembly and *(e)* to apply these concepts in a quantitative way to estimate field quality in a magnet which can be used as a reference for the next generation machines.

The field quality in accelerator magnets is characterized in terms of the normal and skew harmonics, b_n and a_n. They are defined in the following expression

$$B_y + iB_x = 10^{-4} \times B_{R0} \sum_{n=0}^{\infty} (b_n + ia_n)[(x+iy)/R]^n ,$$

where B_x and B_y are the components of field at (x,y) and B_{R0} is the magnitude of the field due to fundamental harmonic at a “reference radius” R.

2 METHODS FOR CONTROLLING FIELD QUALITY

The methods for controlling field quality are only discussed briefly here (see references [1] to [9] for details).

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2.1 Allowed Harmonics and Pre-stress on Coils

Two allowed harmonics can be adjusted by adjusting *(a)* the coil-to-midplane gaps (or midplane shims) and *(b)* the coil pole shims. This is an efficient technique for small adjustments in lower order harmonics (e.g., b_2 and b_4 in dipoles). It may be used either for normal cross-section iteration or to compensate for the differences in field quality of the magnets built by different vendors based on the same magnetic design.

The pre-stress on the collared coil, however, will change if there is a net change in the combined thickness of the pole and midplane shims. A small variation in pre-stress may be tolerated but if it is larger than a few kpsi, then to avoid it one should adjust the coil curing pressures to change the cured coil size. The first magnet of a series usually requires larger adjustment in field harmonics. This is further complicated by the experience that the desired pre-stress on the coils may also not be obtained by the nominal size pole shims. A change in pole shims in order to get the desired pre-stress also changes the field quality.

To deal with the above difficulties, an approach has been developed for the RHIC 100 mm aperture insertion dipole D0 [5] with the goal that the first design itself can be adopted for production by applying small adjustments which are part of the initial design. A third parameter to provide the desired pre-stress on the coils is obtained by increasing the effective thickness of one (or more) selected wedge(s) by changing the number of layers of insulation on it. This resulted in low field harmonics in the body of the magnet as good as those expected after a number of cross-section iterations. Also the magnet had the desired pre-stress on the coils. The first D0 magnet is being used in the RHIC machine. Based on measurements in the first magnet, small adjustments were made in the thickness of the midplane insulation caps and pole shims to compensate the end harmonics and 0.4 mm radius magnetic rods were inserted in the saturation control holes to reduce small values of saturation induced b_2 and b_4 harmonics.

A regular cross-section iteration generally requires a large mechanical change in several wedges and is associated with *(a)* a change in tooling and *(b)* a change in the end design. Both of these are time consuming and expensive and are avoided in the above approach. Moreover, this approach requires only small mechanical changes and therefore has a better chance of succeeding.

2.2 Integral Transfer Function

A difference in the integral transfer function (or effective length, $\delta L/L$) between the magnets built by different vendors has been observed in HERA magnets [10]. A similar situation was observed in RHIC when different length magnets were built for the insertion regions. Even though the magnets were built by the same vendor (Northrop Grumman Corporation) and on the same design, the integral transfer function was off by a small amount from the expected values.

In most magnets the coil ends are enclosed by non-magnetic stainless steel laminations instead of magnetic low carbon steel in order to reduce the field on the conductor. It is proposed here that the axial location where the transition between the low carbon steel laminations to stainless steel laminations takes place be used as a parameter to adjust the integral transfer function. This adjustment may be applied after the first few magnets are built and measured. A rough estimate suggests that a 50 mm adjustment on each end should be adequate in most cases.

An adjustment in the change in transfer function between low field and high field due to iron saturation can be obtained by changing the iron packing factor (i.e. the number of yoke laminations for the same yoke length). This technique has been used in adjusting the integral transfer function in the different length RHIC magnets.

2.3 Skew Quadrupole in Dipole Magnets

The presence of a skew quadrupole harmonic in dipole magnets reflects a top-bottom asymmetry. A difference in the yoke length between the top and bottom halves can similarly be used to compensate for this asymmetry [8]. The current dependence in the variation of this harmonic can be adjusted by adjusting the yoke packing factor between the two halves [7].

2.4 Twist in Field Angle of the Magnets

A change in field angle (or twist) along the axis of RHIC magnets has been reduced by applying slanted welds on the outer diameter of stainless steel shell. The weld moves the magnet in the direction it is applied. Slanted weld in opposite directions on the two sides of the shell effectively generate a torque which takes out the twist of the magnet.

2.5 Harmonic Correction after Initial Assembly

In a perfect design, the field quality is limited only by the errors (tolerances) in parts and assembly. To overcome these limitations, a "tuning shim method" is being used in 130 mm aperture RHIC insertion quadrupoles [6]. Eight tuning shims of variable iron thickness are inserted to cancel out the measured values of eight harmonics. The test results of the first five magnets show that the harmonics can be corrected within their repeatability and measurement errors.

2.6 Current Dependence in Field Harmonics

At high field the harmonics change as a function of current due to iron saturation and also due to Lorentz forces on the coil. A larger variation is expected in RHIC type magnets where the iron contribution to the total field is large. However, the saturation induced harmonics can be minimized by forcing the yoke iron to saturate uniformly with the help of holes, cutouts, etc. in the yoke geometry. A good parameter to examine [9] the iron saturation is $(\mu-1)/(\mu+1)$. The value of this parameter is ~1.0 at low field (no saturation or $\mu>1000$) and zero at very high field (complete saturation or $\mu=1$). The variation in this parameter as a function of azimuthal angle should be small, particularly near the yoke inner radius. In RHIC magnets, despite a large contribution from the yoke, the saturation induced harmonics are small (see references [2] to [5]).

3 EXPECTED FIELD QUALITY IN SSC-TYPE DIPOLE MAGNETS

The expected field quality presented in this section for a 50 mm aperture SSC-type dipole is significantly better than previously assumed in SSC beam tracking studies [11]. The improvement comes from *(a)* the use of the above methods for controlling field quality *(b)* a feedback from the measurements in the SSC prototype magnets and *(c)* the use of revised methods of estimating field errors. The methods that are commonly used for estimating the field harmonics tend to over-estimate the expected field errors. This has been discussed in detail in reference [4] where the possible sources for this over-estimate are discussed and the experience with RHIC and SSC magnets is presented. The expected field harmonics are described by *(i)* the expected mean *(ii)* the uncertainty in mean and *(iii)* the expected RMS width or sigma (σ).

The expected integral values of field harmonics in a 50 mm aperture, 15 meter long, 2-layer SSC-type dipole magnet built along the lines discussed here are given in Table 1 at 10 mm reference radius for an operating range of 2000 A (2 tesla) to 6600 A (6.6 tesla). At injection (660 A), the allowed harmonics are dominated by the effects of the persistent currents. Since the issue of persistent current is not discussed here, the harmonics are given only at or above 2000 A, where their influence is negligible. The last row gives the expected systematic difference in the integral transfer function or effective length ($\delta L/L$) between the magnets built by two or more vendors; the σ is for the whole accelerator. For reference, SSC specifications at high field are also given.

The use of the RHIC insertion quadrupole type tuning shims [6] is not assumed here. The tuning shims may reduce those harmonics selected for correction by about a factor of five, as long as they are reproducible.

Table 1. The expected normal (b_n) and skew harmonics (a_n) in 50 mm aperture SSC type dipole magnets at a reference radius of 10 mm in an operating range of 2000 A to 6600 A. $<b_n>$ and $<a_n>$ are the expected mean, d(b_n) and d(a_n) are the uncertainty in the mean and σ(b_n) and σ(a_n) are the expected sigma. The last two columns show the SSC tolerances/specifications for the mean (ssc < >) and sigma (ssc σ) at high field. Since $<b_n>$ and $<a_n>$ are zero d(b_n) and d(a_n) should be compared to the ssc < >. The last row gives the expected systematic difference in the effective length (δL/L) between the magnets built by two or more vendors and σ for the whole accelerator.

	SSC Expected Harmonics			SSC Tolerances	
n	**$< b_n >$**	**d(b_n)**	**σ(b_n)**	**ssc < >**	**ssc σ**
1	0.0	0.04	0.2	0.04	0.5
2	0.0	0.2	0.4	0.8	1.15
3	0.0	0.002	0.03	0.026	0.16
4	0.0	0.02	0.05	0.08	0.22
5	0.0	0.001	0.002	0.016	0.02
6	0.0	0.002	0.005	0.013	0.02
7	0.0	0.0004	0.001	0.01	0.01
8	0.0	0.0005	0.001	0.02	0.0075
n	**$< a_n >$**	**d(a_n)**	**σ(a_n)**	**ssc < >**	**ssc σ**
1	0.0	0.04	0.5	0.04	1.25
2	0.0	0.02	0.15	0.032	0.35
3	0.0	0.01	0.07	0.026	0.32
4	0.0	0.002	0.02	0.02	0.05
5	0.0	0.002	0.008	0.016	0.05
6	0.0	0.001	0.005	0.013	0.01
7	0.0	0.0004	0.001	0.01	0.01
8	0.0	0.0004	0.001	0.008	0.0075
δL/L	--	0.0003	0.0004	--	0.0006

4 CONCLUSIONS

The expected field quality shown in Table 1 is generally a factor of 2 to 5 better than that previously assumed in SSC beam tracking studies [11]. Such improvements should have some influence on the expected performance of the machine. Most concepts presented/reviewed in this paper have already been successfully tested in RHIC or SSC magnets. The spirit behind the techniques presented here is that simple mechanical adjustments can make significant improvements in the performance of a series of magnets, if they are planned ahead and made part of the initial design.

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