FIELD QUALITY ASPECTS OF CBA SUPERCONDUCTING MAGNETS*

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Abstract

A series of superconducting dipole magnets for the BNL Colliding Beam Accelerator which were manufactured to have the proper field-quality characteristics has been tested. This report presents the analysis of the field harmonics of these magnets.

Introduction

In this paper we report on the magnetic field analysis of a series of dipole magnets constructed in the research and development program for the BNL Colliding Beam Accelerator (CBA). This series of magnets includes as a subset ten magnets specifically built to demonstrate the ability to achieve the field quality requirements of a storage ring accelerator. The magnets in this report were constructed with coils made to a uniform size with a standard design.¹ No variation in coil placement is expected and these magnets should produce similar field properties. All such magnets that have been tested at this time are included in this report. There are differences in the construction of the magnets.² One magnet (LM10) used an early yoke which is of the current design and another (LM26) reuses the yoke of an earlier magnet. These two magnets, which are included in this study, are not in the field quality series.

The field analysis is based on the harmonic decomposition of the magnetic field at any point (r, θ) :

$$B_y = B_0 \left[1 + \sum_{n=1}^{\infty} \left(\frac{r}{r_0} \right)^n (b_n \cos n\theta - a_n \sin n\theta) \right]$$

$$B_x = B_0 \sum_{n=1}^{\infty} \left(\frac{r}{r_0} \right)^n (a_n \cos n\theta + b_n \sin n\theta)$$

The definition of the b_n , a_n that is used corresponds to $r_0 = 4.4$ cm, the effective aperture of the accelerator. The b_n (a_n) specify the normal (skew) multipole component. The symmetry properties of the dipole magnets suppress the odd b_n and all the a_n harmonics. These non-allowed harmonics are to be compared to zero. The even b_n (the allowed harmonics) are not zero by design. They are to be compared to the sample average. There are two requirements currently imposed on the magnets to satisfy the accelerator field quality: (1) The standard deviation of a specific harmonic for the ensemble of magnets must be less than or equal to one random tolerance³ for that harmonic. (2) If any harmonic is more than three random tolerances from the mean of the ensemble of magnets that magnet is rejected for field quality purposes. The above criteria are applied to the integrated field $\int B \cdot dl$ and to the integrated harmonics of the order $n=4$ and below. Although these criteria are more stringent than those which will eventually be applied to the machine, we shall see that they can be met.

The Allowed Harmonics

The allowed harmonics for a dipole magnet are the dipole (B_0), the sextupole (b_2), the decapole (b_4) and the "14-pole" (b_6). Higher terms can exist but are

believed to be unimportant to the CBA machine. In Figures 1 and 2 b_2 and b_4 are shown as a function of the magnet current. In the low current region below 1000 amps superconducting magnetization is a significant contribution to these harmonics. Above 1500 amps the effects of saturation of the iron take over. In these figures the dashed (solid) lines represent a variation of ± 1 (± 3) random tolerances from the mean. One magnet, LM26, (which is not in the field quality series) has a sextupole moment which is just outside the three tolerance limit. Another magnet, LM11, is outside the three tolerance line in the low current region for the decapole. Omitting these magnets reduces the sextupole and decapole ensemble standard deviations to approximately one random tolerance.

Figure 3 gives the distribution of the deviations from the mean of the allowed harmonics normalized in units of rms random tolerances. These harmonics are integrated over the length of the magnet and include the effects of the ends. The shaded region represents the field quality series.⁴ The mean and standard deviations of the distributions are given in Table I. Figure 4 shows the distribution of all the allowed harmonics at three currents. The low current ($I=264$ amps) corresponds to the injection field and the high current ($I=3500$ amps) is near the high energy operating region. The spread in the harmonics varies only slightly with the current.

The Non-Allowed Harmonics

The non-allowed harmonics should be zero by design. These include all of the skew harmonics (a_n) and the odd normal harmonics ($b_1, b_3, b_5, \dots$). The appearance of non-zero values for these harmonics indicates imperfections in the manufacture of the magnets. The odd b_n harmonics indicate a breaking of left-right (perpendicular to the magnetic field direction) symmetry whereas the odd a_n harmonics break the up-down symmetry (along the magnetic field). The existence of an even a_n harmonic requires the breaking of both simultaneously. Figure 5 shows the deviation from zero of each non-allowed harmonic in units of tolerances for that harmonic. The shaded histograms indicate the eight field quality⁴ magnets. All of these distributions have standard deviations that are narrower than one random tolerance. It is interesting to note that although they remain within the established tolerance the odd skew harmonic (a_1 and a_3) have larger variances than the others suggesting a small up-down asymmetry. One would expect a larger up-down asymmetry, which compares different coils, than a left-right asymmetry, which compares the left and right halves of the same coils. This indicates that the upper and lower sets of coils are sufficiently similar in size to meet the requirements.

In figure 6 we have plotted all of the non-allowed harmonics normalized to their tolerances at three different currents. The shading as before indicates the field quality series. The random variations appear to be largest in the low current region which corresponds to the beam injection energy.

Precompression and Field Harmonics

This series of magnets was constructed to be identical dimensionally. The coils were wound to be

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a certain size and the variation in this size has a standard deviation of 2-1/2 mils. The coils have different epoxies and there are some variations in modulus. One sees a range in the precompression necessary to close the magnet yoke during the assembly process. The total coil stress (sum of inner and outer coil stress) varies by a factor of approximately 2 for the magnets. In Figure 7 the sextupole and the decapole are plotted against the total coil stress. There appears to be a correlation between these harmonics and the coil stress. The statistics are too small to make a strong conclusion, however one would like to keep the coil stress in a relatively narrow window.

Conclusion

As indicated in Table I the standard deviation of the harmonics is less than 1-1/2 tolerance for all eleven magnets. For the restricted field quality series all harmonics are within approximately one tolerance. The results of this analysis imply that the magnet to magnet variations of the field meet the requirements of the CBA intersecting storage ring accelerator.

Table I
Integrated Field Harmonics at 1200 Amps

Harmonic	All Magnets (10^{-4})	Field Quality Magnets (10^{-4})	RMS Random Tolerance (10^{-4})
b_2	-28.1 ± 2.4	-29.0 ± 1.76	1.6
b_4	2.96 ± 1.05	3.39 ± 0.73	0.75
b_6	0.36 ± 0.21	0.38 ± 0.24	0.35
b_1	-0.01 ± 1.00	0.23 ± 0.84	2.9
b_3	-0.16 ± 0.24	-0.18 ± 0.24	1.0
a_1	0.07 ± 2.78	-0.15 ± 2.44	2.9
a_2	0.57 ± 0.44	0.46 ± 0.45	1.6
a_3	0.37 ± 1.33	0.30 ± 0.72	1.0
a_4	-0.03 ± 0.21	-0.02 ± 0.19	0.75
a_6	-0.04 ± 0.10	-0.02 ± 0.10	0.35
$\int B \cdot dl$	8.2368 ± 0.005 Tesla-m	8.2362 ± 0.005 Tesla-m	0.004 Tesla-m

References

1. H. Hahn & R.C. Fernow, ISA TN 337 (1981) unpublished.
2. The early magnets (LM10,11,12) use a different epoxy from subsequent magnets.
3. CBA Parameter List (unpublished). The harmonic tolerances are given in Table I.
4. The field quality series includes the eight magnets LM12,13,14,17,18,19,20,21. LM10 and LM26 were not in this series for reasons indicated in the text. LM11 which should have been in this series failed the field quality requirements.

Figure 1. Sextupole moment as a function of current.

Figure 2. Decapole moment as a function of current.

Figure 3

Figure 4

NON ALLOWED HARMONICS IN UNITS OF TOLERANCES
AT $I = 1200 \text{ AMPs}$

Figure 5

Figure 6

Figure 7. Correlation of b_2 and b_4 with coil stress.

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