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Abstract

The central or two-dimensional field of a dipole magnet can be calculated with some precision. The fields at the end of the magnet, which are three-dimensional in nature, provide a more complicated problem. Starting with an end design that produced a relatively good end in terms of multipole components, a method of extending parts of the straight section was used to reduce the most important harmonics, the sextupole and decapole, to a negligible level. In addition, the effect of extending an iron yoke over the ends of a magnet was investigated and it was found to have little effect on the harmonics, though it will raise the dipole field. These results are encouraging as they imply that good ends can be developed with relative ease should the two dimensional cross-section of a dipole magnet such as the SSC have to be changed.

Introduction

The ends of dipole magnets frequently have a generous collection of multipole components, and the reduction, or possibly the elimination, of end-field aberrations has been a goal of magnet designers for some time.[1-6] These approaches generally address the problem of a thin current sheet at a fixed radius, i.e., the radial thickness of the conductor is in essence ignored. This approximation many give good results for large bore dipoles, where the conductor thickness is small compared to the bore radius, but it is not accurate for the SSC dipoles where the thickness of each of two layers is about half the bore radius.

The two ends of a dipole are not identical. The non-lead end has only those multipoles allowed by dipole symmetry while the lead end has additional components produced by the leads and block-to-block and layer-to-layer crossovers. In this report we will address only the simpler of the two, the non-lead end.

Because of the need for both a mechanically-sound and magnetically-good end, the design of a superconducting magnet end depends on several magnet parameters. These include the 2-dimensional field, the mechanical and electrical characteristics of the cable/conductor, the acceptable field rise or peak field in the ends, and the proximity of ferromagnetic material. Each 2-d magnet design will require its own special end configuration.

In the central or 2-dimensional region of a magnet the field can be expressed in the form

$$\vec{B} = \sum_{m=1}^{\infty} C_m\, r^{m-1} \left[1 + \left(\frac{r_c}{r_{Fe}} \right)^{2m} \right] \left(\cos(m\theta + \phi_n)\hat{\theta} + \sin(m\theta + \phi_m)\hat{r} \right) \quad . \qquad (1)$$

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For dipole magnets a variation in the numerology based on the harmonic number relative to the dipole has developed. The field, can be expressed in cylindrical Eq. (2a) or cartesian Eq. (2b) coordinates.

$$B = B_o \sum_{n=0}^{\infty} \left(\frac{r}{r_o}\right)^n \left\{ \left(b_n \cos(n+1)\theta - a_n \sin(n+1)\theta \right) \hat{\theta} + \left(a_n \cos(n+1)\theta + b_n \sin(n+1)\theta \right) \hat{r} \right\} \quad (2a)$$

$$B_y + iB_x = B_o \sum_{n=0}^{\infty} (b_n + ia_n)\left((x + iy)/r_o\right)^n \qquad (2b)$$

The values of the skew and normal harmonics, the a_n and b_n, are expressed in "units", or parts in 10,000 of the dipole field at some radius r_o. For the SSC and this report the reference radius is 10 mm.

The sextupole, $n = 2$, is the first harmonic with the same symmetry characteristics as the dipole -- it is the first "allowed" harmonic -- and is the most likely field error to be produced by design errors or variations in material characteristics such as conductor thickness etc. In the following section we use the sextupole as an example. However, except for the different angular and radial characteristics, the discussion applies equally to all the "allowed" harmonics.

Calculations of the Sextupole in the Ends

It can be shown[1,3] that the integrated multipole character of the fields at the ends of the magnet can be determined by an integration over the currents that produce these fields. Thus, we need consider only the harmonic character of the currents.

For a thin coil at radius r_c, usually approximated by a $\cos(m\theta)$ current sheet, $J = J_m(z) \cos m\theta\ \delta(r - r_c)$, it is possible to produce several end coil configurations that have no sextupole contribution.[2,4,5] This is accomplished by assuming that

$$\int_{z=z_0}^{\infty} dz \int_0^{2\pi} J_3(z) \cos(3\theta)\, d\theta = 0 \qquad (3)$$

where z_0 is a point well within the 2-dimensional region of the coil. A coil that is relatively thick can be considered as multiple thin coils at different radii, each of which can be made to conform to Eq. (3). A more realistic approach, however, is to adjust the various nonzero contributions from different radial conductor layers to cancel inside the innermost conductor. Effectively J_3 becomes a function of both radial and axial position, $J_3 = J_3(r,z)$, and the integral must be made over r as well as θ and z. Since the sextupole field drops off as r^2 inside the current sheets, the contribution of each layer must be adjusted by a factor, $1/r^2$. For a 2 or more layer coil where the angular variation of conductors produces a good two-dimensional field and where the conductor layers are relatively large compared to the bore radius, it is clear that the second approach must be followed. In addition to the radial correction given above, the effect of iron is included as in Eq. (1).

The value of the integral over the end in Eq. (3) can be normalized to the central field and can be expressed as "units" x length. Here we use the "unit-cm" as the dimensions. The harmonic content of the end is thus expressed in terms of the effect of one unit of a multipole over a certain length or of a multipole of the given magnitude for one centimeter. Also, to avoid confusion of the terms for the integrated end value and the central field value of a given harmonic, the integrated harmonics are referred to as β_n. Thus $\beta_n = \int b_n \, d_z$.

Measurement of the Harmonics in the Ends

Two methods exist for the measurement of the fields in the end of a magnet. One is to use a relatively short field measuring element (coil) to determine the field at many locations along the length of a magnet and then separate out the harmonics of the ends from those of the straight sections through the use of graphic or tabular data. The second is to use a long measuring element that extends effectively from the 2-dimensional region of the dipole to infinity. The harmonic content measured this way is thus adjusted by subtracting out the contribution of the two dimensional region.

Both techniques have been used in our study of SSC model dipoles and the results are in rather good agreement, particularly in the case where the central field multipoles are small, i.e., the corrections to either measuring technique are small. The values of the end harmonics of several different model dipole magnets as determined by the two methods are given in Table I. The differences between the two measurements, Δ, and the possible uncertainties in the measurements are also included in Table I. The sources of differences in the two measurements are associated with a lack of knowledge of the exact fall off of the sextupole in the end region, the fact that the sextupole varies some in the 2-dimensional region, calibration, etc. As mentioned above, the smaller the 2-dimensional sextupole the smaller this uncertainty will be. It is of significance here that when both the central field and the end field are good, the two approaches give the same result, i.e. about zero, for the model D14B-6.

Table I End-field sextupole components, β_2 in unit cm, measured by a long coil and by a scan by a short coil for several model SSC dipoles

Magnet Description	Short Coil scan	Long Coil	Δ	Possible Uncertainty
MD3	-380	-400	-120	±75
D-14B-2	-310	-350	-40	±30
D-14B-3	-480	-420	+60	±60
D-14B-4	-180	-220	-40	±50
D-14B-6	-10	-30	-20	±20

Ends for the SSC Dipoles

An end configuration for the SSC dipoles with an early cross-section (designated C-5) was designed by one of the authors, G. Morgan, and a close approximation was used in several model dipoles at LBL. The number of winding blocks and conductors per block varies in the different models and may be somewhat different in the final SSC magnets. The point here is in the procedure and approach, thus, in the future a new cross-section will require a single iteration to obtain a good end. To facilitate calculations of the fields at the ends of the magnets each turn is assumed to form a semicircle on the flattened surface of a cylinder having the radius that is the average of the inner and outer radii. In other words, the conductors form circular paths in the developed plane. The resulting idealized axial distribution of conductors in the pole region la y,z plot at $\theta = 90°$ is shown in Fig. 1.

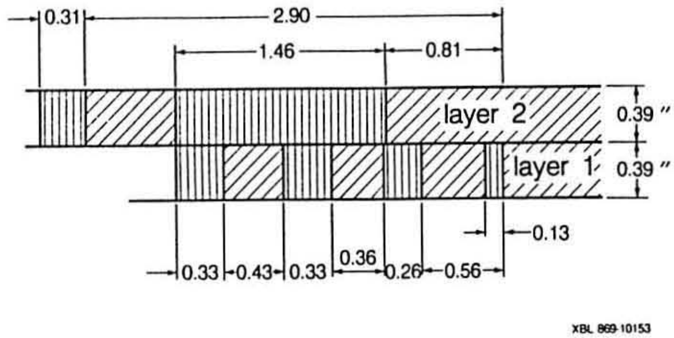

Fig. 1. A view of the conductors in the pole region of LBL model dipole MD3, all dimensions in inches.

When the end of a dipole coil was constructed as close as possible to these specifications two related problems appeared. First, the cable conductor was not too happy with the proposed configuration and, second, the ends had a relatively large negative sextupole. That the proposed end geometry should have little or no sextupole component has been verified by other calculations. Both calculations are all based on ideal conductor positions, which are close, but not perfect, representations of the as wound ends.

An end shape that has been termed "elliptical", and which is based on the conductors' mechanical characteristics, is easier to wind and has less inward radial force in the pole region. Unfortunately, it is also more difficult to approximate mathematically, so again the end fields cannot be easily predicted. However, since the field prediction was not accurate in any event, it seemed appropriate to develop a method to correct any end based on measurements of the ends and knowledge of the 2-dimensional characteristics.

Figure 2 shows the sextupole fields from the inner and outer layers of a model dipole. (Note the unit scale is relative to the dipole of each layer alone.) The inner coil gives a negative sextupole in the 2-d region and the outer

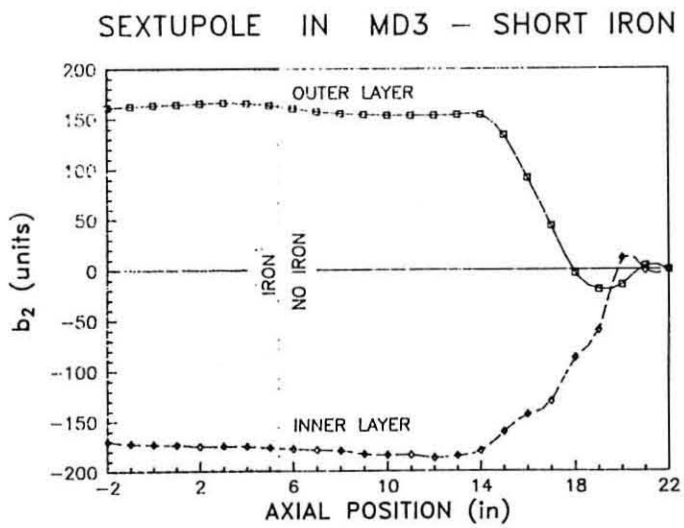

Fig. 2. Sextupole fields for inner and outer layers of MD-3, in a short iron configuration.

coil a positive value. Since the observed sextupole in the end is too negative, the outer layer could be lengthened to compensate. For a variety of reasons, including the fact that magnet length would increase without a comparable increase in effective length, this is not a good solution. A straightforward approach to correct the ends was proposed by Laslett et al.[6] It is similar to an earlier effort by Meuser.[1,2] The method proposed is to simply extend selectively the 2-d sections of some of the conductor blocks to compensate. The multipole component m of a winding block k is given by[6]

$$J_k \frac{\sin m \phi_{b,k} - \sin m \phi_{a,k}}{m\, r_k^{m-1}}, \qquad (4)$$

where $\phi_{b,k}$ and $\phi_{a,k}$, are the lower and upper angles respectively of the k^{th} block. r_k is the effective conductor radius and J_k is the current density.

This component can be normalized to the dipole field of the entire conductor package by dividing by the dipole term

$$\sum_k J_k \left(\sin \phi_{b,k} - \sin \phi_{a,k}\right) \qquad (5)$$

Equations 4 and 5 must be modified by the effect of the iron $(1 + (r_c/r_{Fe})^{2m})$, which is most important for the dipole term, Eq. (5). The contribution of each conductor block[6] to the harmonics (in unit cm/cm), are shown in Table II for b_2, and b_4. The values for b_4 are given because it is possible to correct this harmonic as well as the sextupole. In fact, it is possible to adjust the lengths of all but one of the 6 blocks to correct 5 multipoles.

Table II The harmonic contribution of two conductor blocks in unit-cm/cm

layer	block	b_2	b_4
1	1*	218	25
1	2	-20	-25

*Block 1 is closest to the midplane.

The values of β_2 and β_4 in the original coil were 380 and 18 unit cm respectively. We first tried increasing the lengths of the first two blocks of layer 1 by 6.3 and 14.5 mm respectively, the correction required if iron did not contribute to central field, and obtained the expected ~60+% reduction in sextupole -- see Table I, magnet D-14B-4. The block closest to the midplane was then extended by another 8 mm and a third model was constructed. The end fields for these three coils are given in Table III.

Table III Measured end field components for three model dipoles. The first coil is as originally designed. The second coil had blocks 1 and 2 moved 16 and 8 mm respectively. The third had an additional 8 mm of displacement for the midplane block alone.

	β_2	β_4
MD3	-380	+18
D14B-4	-180	+4
D14B-6	-20	-6

Accordingly, the method for developing a "good" end in the future should be:

1. Choose a good mechanical design based on conductor characteristics, field rise in the ends, no shorts, etc.

2. Calculate the length of each block needed to get a good magnetic end.

3. Measure the end for field quality and fine tune if necessary.

This is a powerful technique that gets around the problems of determining exact conductor placement and that can be used simultaneously for several conductors.

The effect of iron on end fields

To understand the effect of iron on the fields at the ends of the magnets it is first useful to look at its effect on the harmonics in the central field region. In Eq. 1 the factor $(1 + (r_c/r_{Fe})^{2m})$ describes the effect entirely. The fractional increase of any harmonic inside the windings depends only on the harmonic number m and the ratio of the mean conductor radius and the iron radius. For the SSC dipoles $r_c/r_{Fe} \approx 0.5$. Thus the dipole field is increased by ~25%, as shown in Fig. 3, and the sextupole by only 2% or so. This is shown graphically in Figs. 2 and 4. The large sextupole component in each of the layers, Fig. 2, is only slightly changed as the iron boundary is crossed at 5.4" in this configuration. In Fig. 4 the sextupole field for the short iron configuration and one where the iron extends beyond the ends of the coils are compared. This figure shows that the iron has little effect on the field variations in the ends. The difference in integrated sextupole in the ends for these two cases is within the error of measurements, and is certainly no more than the ~2% predicted.

The obvious conclusion is that the addition of iron over the ends of the magnet, presumably to isolate more completely the two beams of the SSC, will not affect the sextupole fields. Thus, a good end in terms of multipoles will remain a good end. It is not clear what effect variations in the iron radius will have at the ends, but, in another test configuration of the same magnet, terminating the iron near the end did not appear to affect the end field. It is likely, however, that adding iron will cause the peak field seen by the conductor to increase and may thus reduce the operating current and field.

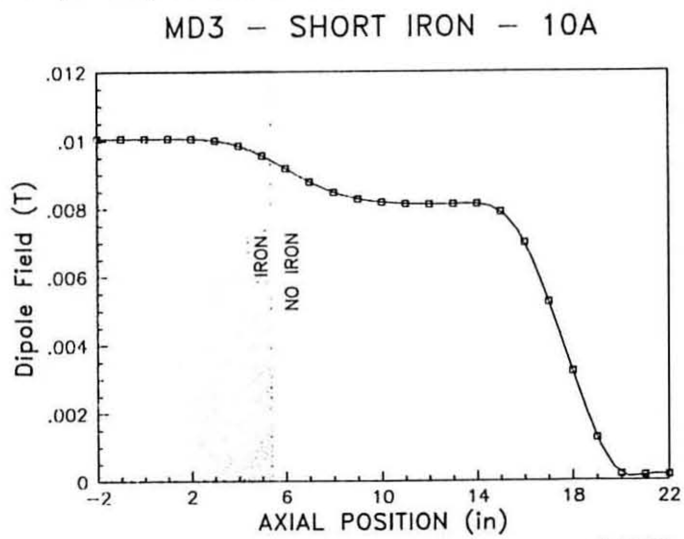

Fig. 3. Dipole field in MD-3 for the short iron configuration.

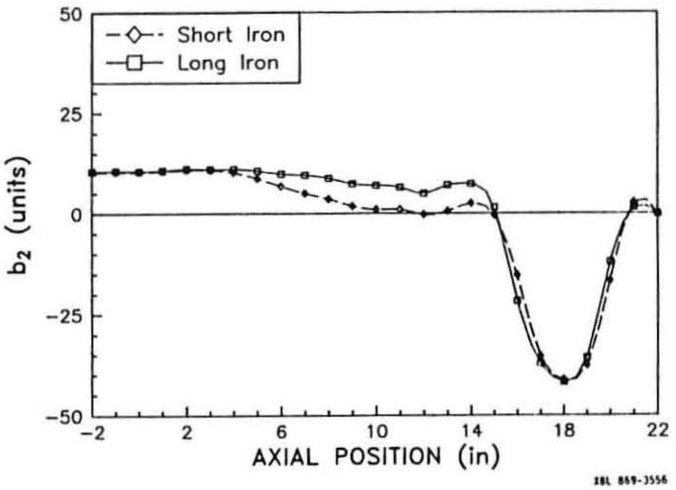

Fig. 4. Sextupole field in MD-3 for the short and long iron configuration.

Conclusions

The accuracy of calculating the multipole components in the ends of a dipole magnet is limited by the approximations used to estimate the actual conductor placement. The error is expected to be greater for small bore magnets than for larger bore magnets. Though the calculation from first principles may not give acceptable results, a technique based on end field measurements and knowledge of the two dimensional field can result in a magnetically good end after a single iteration.

The effect of iron on the dipole field in SSC magnets is on the order of 25%. The effect on the sextupole is at least a factor of 10 smaller. The result is that once a "good" magnetic end is developed, it will be acceptable with or without a surrounding iron yoke. Thus the decision to shield or not shield the ends to limit cross-talk between adjacent magnets in a storage ring case be made at a later date in the development program.

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