MAGNETIC MEASUREMENTS OF SUPERCONDUCTING SYNCHROTRON MAGNETS*

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Abstract

The harmonic content of a number of superconducting iron-shielded dipoles has been measured. Low field measurements have been made at 60 Hz and at temperatures of 300 K, 77 K, and 4.2 K. High field measurements have been made at 4.2 K for both dc and pulsed operation. Two harmonic coils have been used, a long coil which includes the effects of the magnet ends, and a short coil which measures the two-dimensional field distribution. The data include the field dependence of sextupole, decapole, fourteen pole and eighteen pole components to a maximum field of 40 kG. In addition, data will be presented on the residual field (trapped field) distribution and the external or leakage field just outside the iron shield.

I. Introduction

Recent advances in superconducting material fabrication and magnet construction techniques have made it possible to achieve short sample performance in pulsed superconducting magnets. The question that remains to be answered is, can magnets of suitable field quality be built for use in high energy synchrotrons and storage rings?

While it is always possible to devise a conductor configuration which will produce the desired field, variations from the "ideal" calculated field distribution can arise from four principal sources.

1. Errors in Construction

Any magnet design is subject to field errors due to imperfect positioning of the conductors. Such errors can be present in the magnet at room temperature or they may be introduced by differential contraction during cooldown. At high fields errors may be caused by coil distortion due to the severe magnetic forces. Obviously a magnet design which is relatively insensitive to errors in conductor placement is desirable.

2. Magnetization Effects

The persistent currents induced in the superconducting filaments by the changing field lead to "residual" or "trapped" fields which affect the harmonic content of the magnet. These "magnetization" effects are most pronounced at low fields where the critical current is high, since the magnetization is proportional to the excess critical current as well as the filament size. In addition, under certain conditions, dynamic effects due to intrafilament or intrawire currents may be present during pulsing.

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3. Iron Saturation

At high fields the nonuniform saturation of the iron shield will result in changes in the harmonic content of the magnet. Again a magnet design which minimizes this effect is advantageous.

4. End Effects

In addition to the above considerations the field quality of the magnet as a whole is affected by the configuration of the coil ends. Because of inherent limitations in three-dimensional calculations the design of satisfactory ends requires extensive measurement.

In this paper we describe magnetic measurements performed on some model dipole magnets built at Brookhaven as part of the superconducting synchrotron magnet program. An attempt has been made to investigate all of the aspects mentioned above.

II. Details of Magnets

The dipole magnets used in this study are of the cosθ type, wound with a wide braid made from many small wires each containing very fine filaments of superconductor. The dipoles have a cylindrical laminated iron shield and are similar in design to previously described magnets.[1,2] Two of the three dipoles measured have superconducting braid for the spacers which establish the cosine distribution while the third magnet, 2H, has inert spacers of copper braid. Table I summarizes the parameters of the magnets.

TABLE I. Parameters of dipoles used in this study.

Magnet	Filament Size	Insulation	Magnetic Constant
2F	10 μ	Polybondex 180	14.8 G/A
2G	7 μ	Fiberglass epoxy and AgSn	14.8 G/A
2H	7 μ	Fiberglass epoxy and Formvar	12.0 G/A

All the magnets have identical dimensions, 5 cm bore and 35 cm length, and are made with a braided conductor 1.6 cm wide, composed of 132 wires each 0.2 mm in diameter. Dipole 2G employs a metal-filled braid.[3] The magnetic constant of magnet 2H is smaller than the others because it has a slightly different winding configuration with a midplane wedge which gives the lowest harmonic content but at some sacrifice of magnetic constant. These magnets are members of a larger group of dipoles and the performance of the whole series will be presented in a subsequent paper.

III. Measurement Technique

The major portion of the measurements were made with a harmonic coil which reads directly the magnitude of the harmonics at a radius of 2.2 cm (83% of the magnet aperture). The details of this coil appear elsewhere in these Proceedings.[4] Two coils were used, a long coil which included the effect of the magnet ends, and a short coil which was used to investigate the two-dimensional region.

The field distribution along the median plane of a dipole magnet can be expressed by the relation

$$B = B_o(1 + b_2x^2 + b_4x^4 + b_6x^6 + \dots) \quad ,$$

where B_o is the central field, b_2, b_4, etc., are the coefficients of the sextupole, decapole and higher order components of the field, and x is the distance from the center of the aperture. Since the individual windings on the harmonic coil respond to only one harmonic it is possible to measure these coefficients directly for both dc and pulsed operation. The system employs a small calculator-computer to analyze the data and eliminate the effects of construction errors in the measuring coil. The short harmonic coil contains dipole, quadrupole, sextupole, decapole, fourteen and eighteen pole windings, while the long coil has a double set of dipole, quadrupole, sextupole and decapole windings.

In addition to these harmonic coils, magnetoresistive and Hall effect probes were used for absolute field determination and external field measurement.

IV. Experimental Results

1. Power Line Measurements

Low field measurements were made at room temperature by energizing the magnets from the power line through a transformer. Harmonic coefficients measured in this way can then be compared with calculations to determine the degree of accuracy achieved in construction. Similar measurements are made at 77 K to determine if differential contraction has appreciably altered the shape of the magnet. Since most of the thermal contraction has taken place by 77 K, this test can be used to determine the "ideal" harmonic content at 4.2 K. Actual measurements at 60 Hz and at 4.2 K (i.e., with the coil superconducting) show considerable "magnetization" effects. Table II is a comparison of the measured harmonic coefficients of magnet 2F at 300 K and 77 K and the calculated values. The 4.2 K measurements are also included in Table II. The calculations were performed with the program MAGFLD[5] which assumes that the iron has infinite permeability, a reasonable assumption for very low fields. The agreement between the measured values in the nonsuperconducting state and calculations are quite good. The superconducting measurements, however, show a marked deviation due to the large magnetization at very low fields.

TABLE II. Comparison of calculated and measured harmonic coefficients for magnet 2F at various temperatures.

Harmonic	b_n	Measured			Calculated
		300 K	77 K	4.2 K	(10^{-3} in.$^{-n}$)
Sextupole 3θ	b_2	8.6	8.7	27	8.75
Decapole 5θ	b_4	2.4	2.2	0.9	1.89
14 pole 7θ	b_6	0.7	0.8	4.1	1.24
18 pole 9θ	b_8	0.7	0.7	1.3	0.65

Measurements were also made at 500 Hz and 10 Hz at the three temperatures. In general, fully insulated braid magnets do not show any significant frequency dependence while magnets made from metal-filled braids show increased harmonics at high frequencies due to coupling of the wires.[3] The frequency dependence of the sextupole and decapole components of magnets 2F and 2G are shown in Fig. 1 for 300 K.

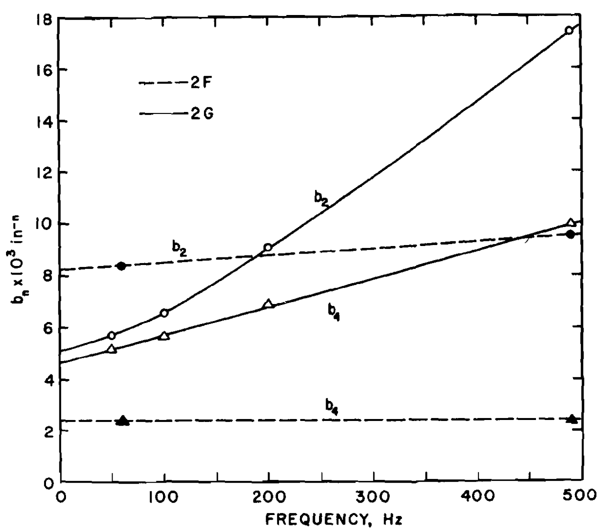

Fig. 1. The frequency dependence of the first two harmonic coefficients for magnet 2G (metal-filled braid) and 2F (fully insulated braid) measured at 300 K.

In addition to their usefulness in checking calculation at low fields, power line measurements have been used to investigate the harmonic content of the magnet ends by axial displacement of the harmonic coil.

2. High Field Measurements

By rotating the harmonic coil and Fourier analyzing the output it is possible to determine the coefficients of the various harmonics under dc

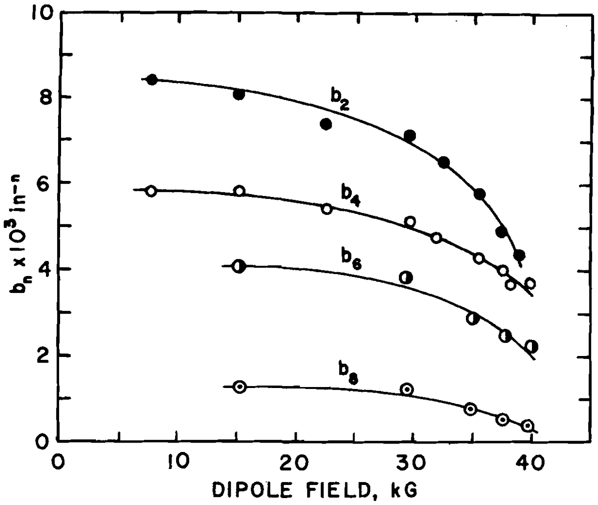

Fig. 2. The dependence of the harmonic coefficients on magnetic field for magnet 2G

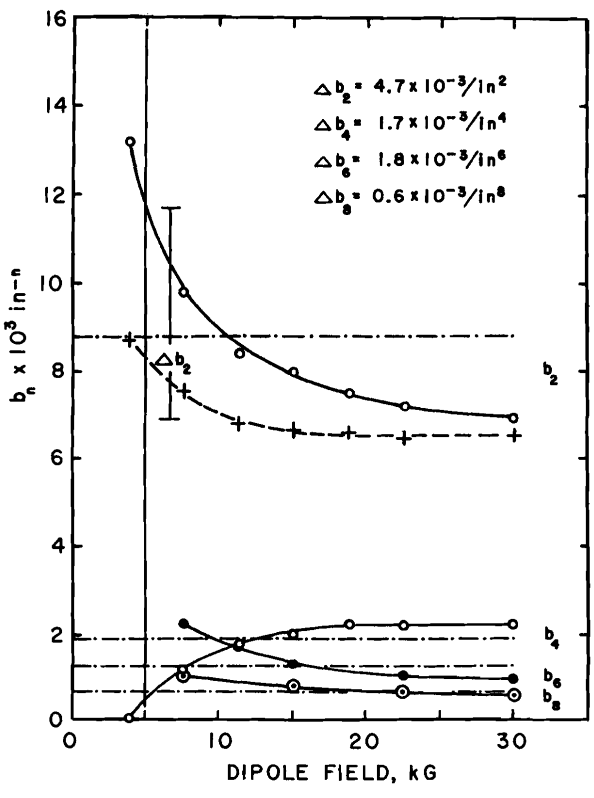

Fig. 3. The dependence of the harmonic coefficients on magnetic field for magnet 2F after a number of cycles to 30 kG. The calculated values are shown by the horizontal broken lines. The points indicated by crosses are the sextupole terms for the initial field increase.

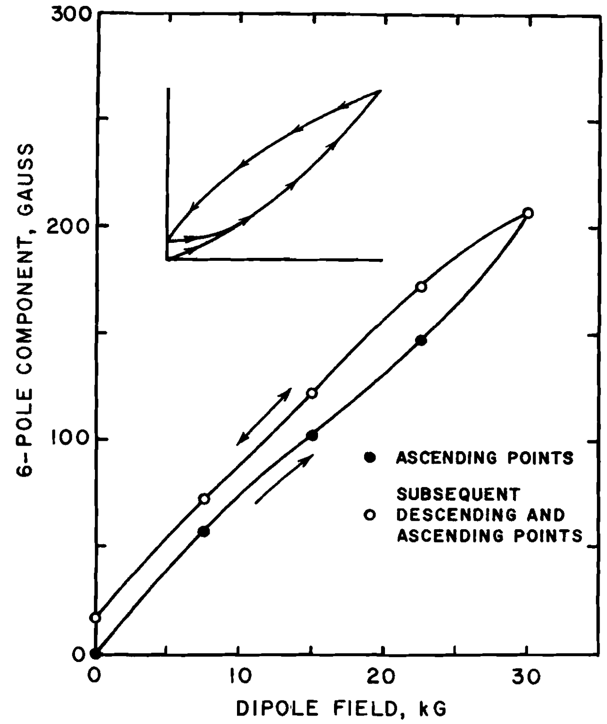

Fig. 4. The sextupole signal from magnet 2F as a function of magnetic field. The non-hysteretic nature of this harmonic is shown by the fact that after the first cycle the signal is the same for both increasing and decreasing fields. The small insert illustrates the expected behavior.

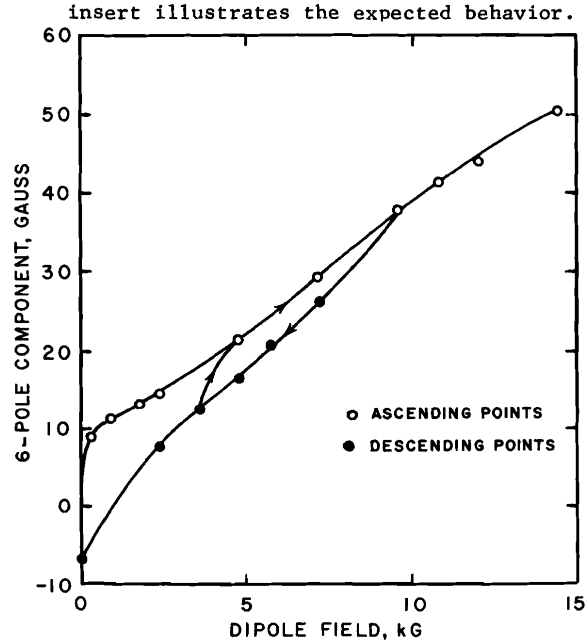

Fig. 5. The sextupole signal from magnet 2H as a function of magnetic field. The arrows show the hysteretic behavior of the signal between approximate injection field and 10 kG. This figure should be compared to Fig. 4.

conditions. Figure 2 shows the measured values of b_2, b_4, b_6 and b_8 for magnet 2G up to a central field of 40 kG. The reduction in the coefficients at high fields is attributed to iron saturation. The effects of the magnetization currents was investigated by measuring the coefficients for both increasing and decreasing field intervals. This is illustrated in Fig. 3 for magnet 2F. When this procedure was repeated for several cycles it was found that, with the exception of the first cycle, the harmonic signals were the same for both increasing and decreasing fields, as shown in Fig. 4. This behavior is unexpected since a simple theory of magnetization would suggest a curve of the type shown in the insert in Fig. 4. This unusual behavior has been attributed at least in part to the presence of the superconducting material in the spacer windings. The harmonic signals from magnet 2H, which does not have superconducting spacers, behave in a more "normal" fashion, as shown in Fig. 5.

The variation of the harmonic coefficients with field due to the magnetization currents can be characterized by a further coefficient, Δb_n, where Δb_n is defined as the change in b_n from injection field, usually about 5 kG,[6] to the peak field. A more general definition would specify two coefficients, Δb_{nm}, the change in harmonics due to magnetization (i.e., from 5 kG to approximately 35 kG), and Δb_{ns}, the change in harmonics due to iron saturation (i.e., from 35 kG to peak field). The values of Δb_n for magnet 2F are shown on Fig. 3 and are in reasonable agreement with calculations.[7] It should be pointed out here that distortion of the coil due to magnetic forces would also produce an effective Δb_n. The difference between the calculated coefficients and the measured values at 30 kG is an indication of coil distortion.

3. Pulsed Field Measurements

The same coefficients mentioned in the previous section can be measured under pulsed field conditions by simply integrating the output of the harmonic coils. For magnets made with fully insulated braids such as 2F or 2H the harmonic coefficients measured in this way are not significantly different from the dc values for rise times of 2 sec or more. For magnets made from metal-filled braids, however, the harmonic signal is strongly dependent on the rise rate of the field and the time constant of the interwire currents. This is illustrated in Fig. 6, which shows the time dependence of the harmonic signals from magnet 2G which has a conductor time constant of 200 sec.[3] Metal-filled braids with much shorter time constants (i.e., 1.5 sec) have been fabricated[3] and should be suitable for long pulsed accelerators or storage accelerators where the induced interwire current would be negligible.

4. Residual Field Measurements

As previously noted, the magnetization currents produce a "trapped" or residual field distribution when the transport current has been reduced to zero at the end of a cycle. This phenomenon has been investigated by energizing the coil to a

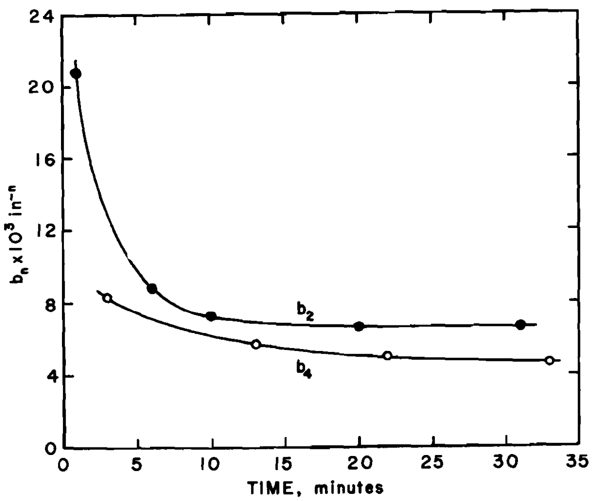

Fig. 6. The time dependence of the sextupole and decapole coefficients of magnet 2G. The metal-filled braid in this magnet is not heat-treated and has a time constant of approximately 200 sec.[3]

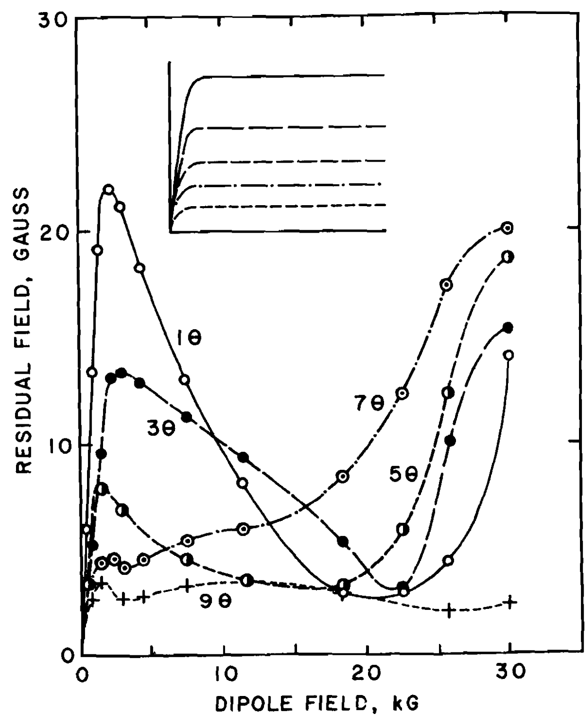

Fig. 7. The residual or "trapped" field for magnet 2F plotted as a function of energizing field. The small insert illustrates the expected behavior of the residual field.

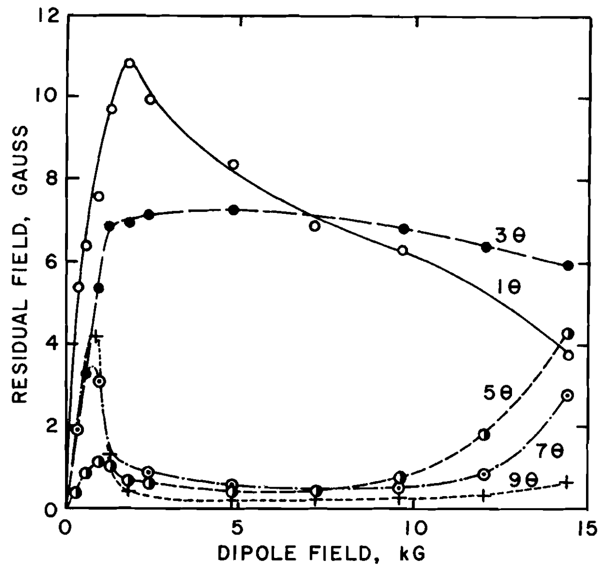

Fig. 8. The residual field for magnet 2H plotted against energizing field. This figure should be compared with Fig. 7 to show the effect of the superconducting spacer windings in magnet 2F.

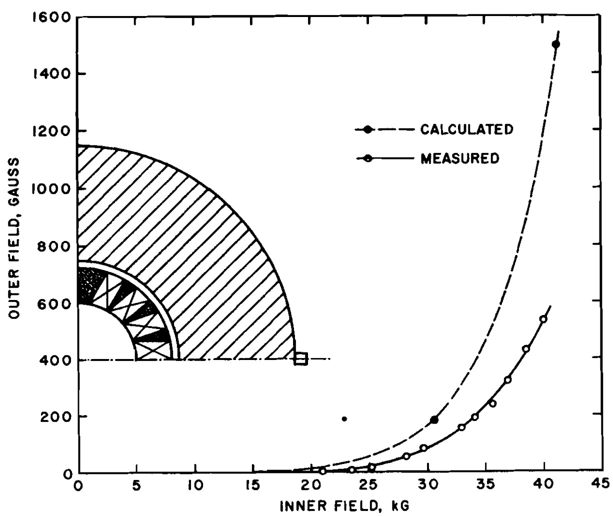

Fig. 9. The leakage field outside the iron shield plotted against the field in the magnet aperture. The diagram shows the magnet geometry and the location of the Hall plates used in the measurements.

specific field and then returning it to zero current and analyzing the field distribution. The results for magnet 2F are shown in Fig. 7 where the magnitudes of the various harmonics are plotted against the energizing field. The results are somewhat more complicated than would be expected from a simple theory (see insert in Fig. 7) and this is again assumed to be due in part to the superconducting filler turns. Similar measurements of magnet 2H shown in Fig. 8 appear to be more normal in this respect. While not of specific interest to accelerator magnet design (the field distribution at injection is the important consideration), residual field measurements are useful for checking theory and calculations.

5. External Field Measurements

The field immediately outside the iron shield on the magnet median plane was measured using two Hall effect plates, one mounted parallel and the other perpendicular to the iron surface. The results are shown in Fig. 9 and compared with calculations. The parallel field component was zero to within 0.1 G. The reason that the measured field is less than that calculated is probably due to an underestimation of the permeability of the iron at high fields. The iron shield was made from "washer" shaped laminations of M19 steel, 8.9 cm i.d., 19 cm o.d., and 0.35 mm thick.

6. End Field Measurements

The contribution of the magnet ends to the harmonic content of the magnet can be deduced by comparing the results obtained with the long measuring coil with those from the short coil. This is shown in Table III for magnet 2F.

TABLE III. Comparison of long and short harmonic coil measurements for magnet 2F.

Harmonic	Long Coil	Short Coil	End Effect
Sextupole	32.0	8.6	23.4
Decapole	2.5	2.4	0.1

The "end effect" of this magnet is quite large because of its relatively short total length to end ratio; the magnet is approximately 50% ends. A more detailed analysis of the end configuration can be made by axial transposition of the short measuring coil. Figure 10 gives the results of this procedure for magnet 2H. The peaks of these curves represents the total end contribution of the harmonic in question provided that the short coil is "long" relative to the end of the magnet. This is strictly only true if the harmonics in the "straight" or two-dimensional region are zero, but since they are small for magnet 2H it is quite a good approximation. A computer program has been developed which calculates the end harmonics and the agreement between the measurements and calculations is quite good, as shown in Table IV. This program also allows for the correction of the ends by computing the axial spacing of the current block which will eliminate the harmonics. Only one harmonic can be eliminated for each current block but the rapid decline in the magnitude of

TABLE IV. Comparison of calculated and measured harmonics due to the magnet ends.

	(10^{-3} of dipole)			
Harmonic	3θ	5θ	7θ	9θ
Measured	38.6	9.6	3.8	0.8
Calculated	33.3	9.6	2.5	0.79

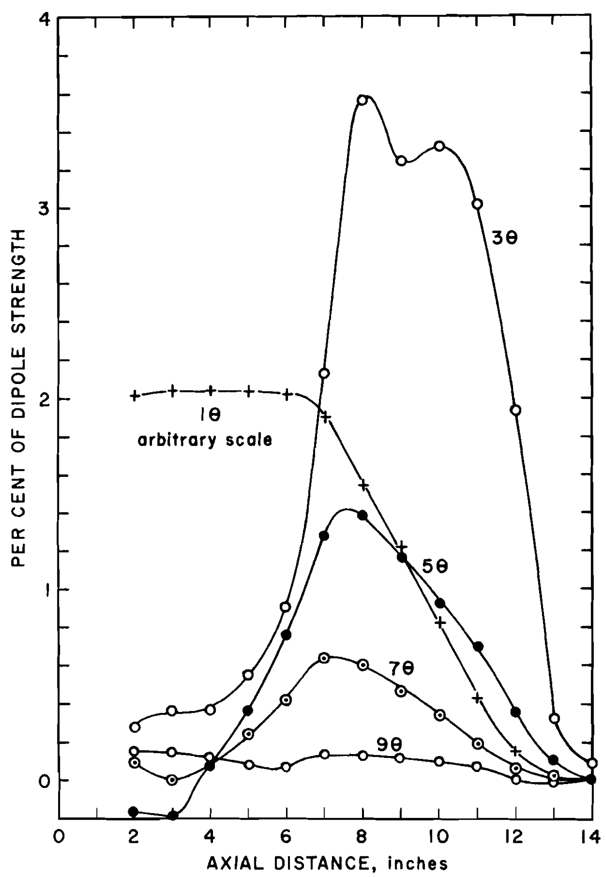

Fig. 10. The end field distribution in magnet 2H. the center of the magnet is at 3 in. on this diagram. The harmonic coil is 6 in. long, so that the two-dimensional region is about 10 in. long for a magnet of 15 in. total physical length. The peak value in this curve is the total harmonic content of the end.

the harmonics with increasing multipolarity means that very good ends are possible with four or six block coils.

V. Conclusions

Based on these measurements the following tentative conclusions can be drawn:

1) Magnets can be constructed with sufficient precision of conductor placement to give good agreement between calculation and measurement at room temperature.

2) The distortion of the magnet due to cool-down is small at least for certain types of construction.

3) Distortion due to the magnetic forces does not appear to be severe up to 40 kG.

4) At low fields the effects of magnetization currents can produce changes in the harmonic coefficients of the same magnitude as those due to iron saturation at high fields, even for conductors with filaments less than 10 μ diameter.

5) Residual fields of several gauss are present for these small filament sizes and their dependence on energizing field can be more complicated than a simple theory would indicate.

6) The field immediately outside the iron shield is only a few hundred gauss at 40 kG central field even for shield thicknesses of only 5 cm.

Newer magnets designed for much lower harmonic content such as the ISA model magnets[6] will test the validity of these conclusions.

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