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MAGNETORESISTANCE ELEMENTS FOR THE MEASUREMENT AND CONTROL* OF HARMONICS IN SUPERCONDUCTING ACCELERATOR MAGNETS

W.B. Sampson, K.E. Robins and M.G. Thomas
Brookhaven National Laboratory
Upton, New York 11973

Summary

A system for continuously monitoring the harmonic coefficients of a superconducting accelerator is described. The method employs a series of magnetoresistance elements placed at specific locations around the circumference of the usable aperture. Difference signals from these probes are used to determine the harmonic coefficients. This method does not require integration of the field measuring signals or rotation of the probes so that the elements can be built into the magnet during construction. Experimental results are given for the simplest configuration and these results are compared to the sextupole signal measured in a more conventional way.

Introduction

The harmonic content of a superconducting accelerator magnet is affected at low field levels by the magnetization of the superconductor and at high fields by saturation if an iron return path is used. Other more subtle effects such as coil distortion at high fields due to the large magnetic forces may also cause the harmonic coefficients to vary with field in a way that is difficult to calculate. A system for continuously monitoring and controlling the harmonics has been developed. Long magnetoresistance elements located around the periphery of the aperture are used to determine the harmonic coefficients directly. End effects can be easily included by extending the measuring probes beyond the magnet ends. Information obtained from the measuring array can be used to control the currents in correction windings forcing the harmonics to follow any prescribed dependence on the main magnetic field.

Theory

The components of the magnetic field at any point inside a 2-dimensional array of conductors can be written as:

$$B_y(r,\theta) = B(0,0)\,[b_o\cos\theta + b_1 r\cos 2\theta + b_2 r^2\cos 3\theta + \ldots b_n r^n\cos(n+1)\theta + \ldots]$$

$$B_x(r,\theta) = B(0,0)\,[a_o\sin\theta + a_1 r\sin 2\theta + a_2 r^2\sin 3\theta + \ldots a_n r^n\sin(n+1)\theta + \ldots]$$

where the coefficients $a_n r^n$ and $b_n r^n$ express the harmonic distribution in the magnet. If the coefficients, other than the fundamental, are small compared to unity a condition which is met for most magnets except at positions very close to the windings, then the expressions can be combined and simplified to give,

$$B = B(0,0)[c_o + c_1 r\cos(\theta+\delta_1) + c_2 r^2\cos(\theta+\delta_2) + \ldots c_n r^n\cos(n\theta+\delta_n) + \ldots] \;.$$

For the case of perfect dipole symmetry the odd n components and the phase angles drop out leaving only the systematic coefficients so that,

$$B = B(0,0)[1 + c_2 r^2\cos 2\theta + c_4 r^4\cos 4\theta + \ldots c_{2n} r^{2n}\cos 2n\theta + \ldots] \;.$$

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Since the systematic coefficients decrease rapidly with harmonic number, the field can usually be adequately represented by the sextupole and decapole terms:

$$B = B(0,0)\,[1 + c_2 r^2\cos 2\theta + c_4 r^4\cos 4\theta] \;.$$

The angular variation of the field magnitude at a fixed radius is shown in Fig. 1 for a dipole containing either a sextupole or a decapole term. It is obvious from this diagram that the difference in field measured by two sensors at 0° and 90° will be proportional to the sextupole term and independent of the decapole field. In general, such a probe pair will respond to every other allowed harmonic (i.e. 3θ, 7θ, 11θ, etc.). An array of sensors placed around the aperture can be used to give the complete field distribution. Since field differences are measured, the number of harmonics that can be deduced from a given set of magnetoresistance elements will be one less than the number of sensors in the array.

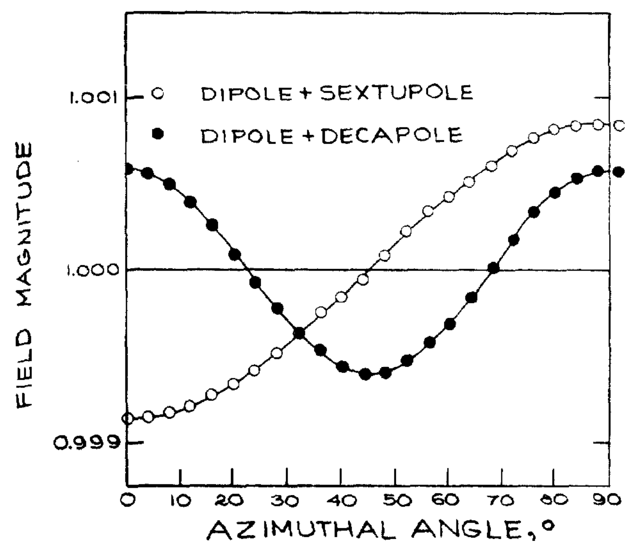

Fig. 1. Angular variation of the field magnitude in a dipole with either a sextupole or a decapole harmonic term.

As an example, consider a set of elements situated at the angles 0°, 30°, 45°, 60° and 90° measured from the median plane. If the difference field measured between any two probes is indicated by $B_{\theta_1-\theta_2}$ then it can be shown by some simple algebra that:

$$B_o c_2 r^2 = 1/3[B_{0-90} + B_{30-60}]$$

$$B_o c_4 r^4 = 1/4[2B_{0-45} - B_{0-90}]$$

$$B_o c_6 r^6 = 1/6[B_{0-90} - 2B_{30-60}]$$

$$B_o c_8 r^8 = 1/12[8B_{0-60} - 4B_{30-60} - 6B_{0-45} - 1B_{0-90}]$$

so that the harmonic coefficients can be easily calculated from the measured dc voltage.

Magnetoresistance Elements

The magnetoresistance elements are noninductively wound bundles of pure zinc wire. Each bundle consists of 30 m of 0.2 mm wire formed into a cylinder of 2.5-mm diameter, 0.5-m long. These probes are mounted in slots in the magnet beam tube as shown in Fig. 2. Zinc was chosen because it is easy to obtain in fine wire form; it is very ductile and it has a high magnetoresistance coefficient. The principal disadvantage of this material is its nonlinear dependence on field which is shown in Fig. 3. Despite this nonlinear behavior the magnetic

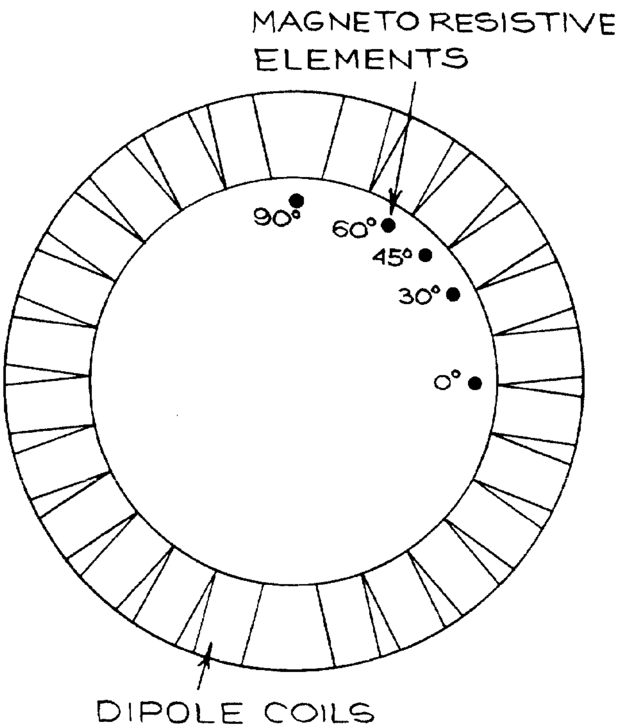

Fig. 2. The azimuthal positions of the magnetoresistance elements required to measure the first four allowed harmonics in a dipole magnet.

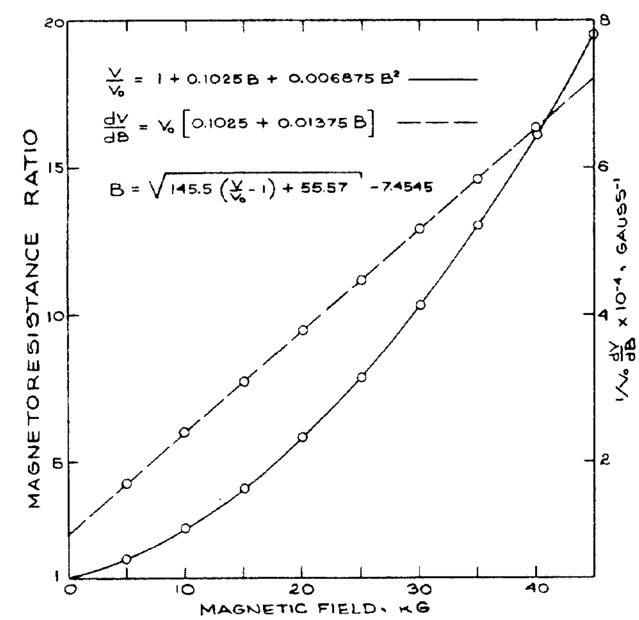

Fig. 3. The magnetoresistance coefficient and sensitivity of zinc as a function of field.

field can be calculated to a remarkably high degree of accuracy from the empirical expressions shown in Fig. 3. This is in contrast to more nearly linear materials such as copper for which no simple expression gives a good fit over a wide field range. The standard zero field voltage of these elements is v_o = 22.31 mV at a current of 100 mA. This gives a sensitivity of 4 μV/gauss for the difference signal at 5 kG which increases to 14 μV/gauss at 40 kG. The corresponding sensitivity for the sextupole coefficient, b_2, is $2 \times 10^{-5}/cm^2$ per gauss. The sensitivity can be increased by using finer wire. Longer magnets would require longer probes which would give larger signals. Since difference signals are used, the currents through the probes must be adjusted to give zero difference at zero field. The constant current circuit used is shown in Fig. 4. A separate current source is used for each element. The field is deduced from the voltage across any element using the expression in Fig. 3 and the difference field is then calculated from the difference signal and the sensitivity for that field level.

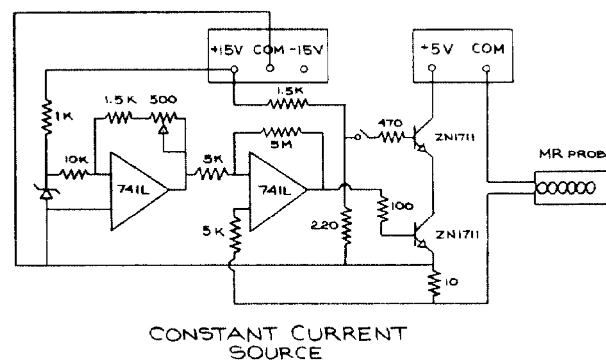

Fig. 4. Circuit diagram of constant current source for magnetoresistance element.

Experimental Details

Four magnetoresistance elements were built into the bore tube of the superconducting magnet ISA-IV.[1,2] Two probes were mounted at the midplane positions (0° and 180°) and designated M_1 and M_2 and two other probes mounted at the pole positions (90° and 270°) and designated P_1 and P_2. Two probes were used at each position so that a comparison could be made between elements at the same field level. The magnetoresistance coefficient as a function of field level is given in Table I. The results for probes M_1 and M_2 and P_1 and P_2 show very good agreement. The agreement is actually better than indicated in Table I since the fields at the different positions are not identical due to the small quadrupole component (4×10^{-4}/cm) in this magnet.

TABLE I

Field kG	v/v_o M_1	v/v_o M_2	v/v_o P_1	v/v_o P_2
4.65	1.587	1.585	1.594	1.592
11.41	3.032	3.029	3.069	3.069
17.00	4.724	4.712	4.794	4.790
28.20	9.407	9.387	9.558	9.564
33.61	12.300	12.264	12.423	12.435
38.90	15.476	15.421	15.476	15.480
43.21	18.156	18.094	18.015	18.027

The field magnitudes in Table I were measured using a rotating coil.[3] The agreement with the independent calibration of Fig. 3 is excellent differing by less than the accuracy of the calibration (one part in 10^3).

The sextupole field can be obtained from the difference voltage between any M probe and either P probe. In Fig. 5 the sextupole field and the corresponding harmonic coefficient are shown as a function of central field as measured by both the magnetoresistance technique and the rotating coils. The agreement between the two methods is quite good considering the present state of development of the magnetoresistance method. The data from the magnetoresistance elements has been corrected for the 14-pole component which is not negligible in this magnet at the large measuring radius used (97% of the dipole winding inner diameter).

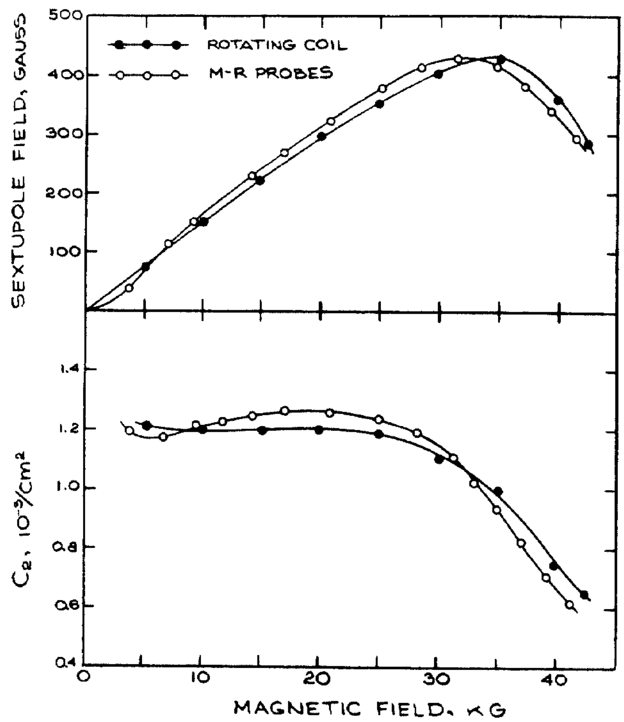

Fig. 5. Comparison of sextupole field and sextupole coefficient as measured by magnetoresistance and rotating coil techniques.

A more elaborate probe array is planned for future experiments and the difference signals will be used to control the current in correction windings so that the sextupole field can be made to follow the dipole field in a predetermined way.

Conclusions

The magnetoresistance technique shows considerable promise as a direct field measuring method. The sensitivity can undoubtedly be improved considerably by using longer elements and finer probe material. The method has the advantage of eliminating the need for rotating coils and integrators and permits the building in of sensing elements during magnet construction so that magnets can be remeasured while in service if necessary.

References

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3. G.H. Morgan, Proc.4th Intern. Conf. Magnet Technolody, BNL 1972, USAEC CONF-720908, p. 787.