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COMPUTER SIMULATION OF THE INTERACTION OF A SUPERCONDUCTING SYNCHROTRON MAGNET GOOD FIELD REGION WITH A PARTICLE BEAM*

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SUMMARY

This paper illustrates how the results of several magnetic field calculation computer programs can be combined to form a single graphical representation of magnetic field quality within the aperture of a superconducting accelerator magnet. The graphical technique can be applied on a magnet by magnet basis over a range of current excitations. The paper illustrates the value of such graphics when the accelerator beam profile is shown within the simulated magnet bore.

INTRODUCTION

Every synchrotron accelerator designer is faced with the problem of determining the magnet aperture. This aperture is a function of the machine lattice, beam energy and momentum spread and the field quality of the magnets. The use of superconducting magnets in accelerators and storage rings presents some new dimensions to the problem.

Superconducting accelerators must have as small an aperture as possible and they should carry beams which are as near round as possible. Unlike conventional magnets, superconducting magnet aperture costs the same whether that aperture is horizontal or vertical. Furthermore, the aperture of the superconducting magnet has a greater effect on the cost of interconnected machine subsystems (power supply, refrigerator, etc.) than does the magnet aperture in a conventional accelerator.[1]

The superconducting dipoles and quadrupoles which make up the accelerators may have two major types of errors;[2] 1) Asymmetric errors (all multipoles are generated) caused by construction errors and errors in iron placement, and 2) Symmetric errors which are caused by finite conductor size, magnetic forces, certain systematic winding errors, residual fields and iron saturation. Experience at Rutherford and Karlsruhe show that random construction and iron placement errors, residual fields, and iron saturation are the dominant errors in well-built superconducting dipoles or quadrupoles.[3] The computer simulation technique described here includes the three dominant errors.

Simulation of the particle beam may be done passively or actively. The passive approach is shown here; the active interaction approach requires more computer work before it can be completed. The graphical technique illustrated here can help the beam dynamicist and the magnet designer see where the beam in an accelerator is likely to be with respect to the good field region of an accelerator magnet.

REPRESENTATION OF THE MAGNETIC FIELD

The two dimensional magnetic field can be represented by a complex power series;

$$H^*(Z) = \sum_{N=1}^{\infty} C_N \left(\frac{Z}{Ro}\right)^{N-1} \qquad (1)$$

where $H^*(Z)$ is the complex conjugate of the magnetic field H. Z is the location ($Z = x + iy$) where the field is calculated. Ro is the reference radius, and C_N a complex coefficient representing the various multipoles comprising the field. ($N = 1$ dipole, $N = 2$ quadrupole, $N = 3$ sextupole and so on.)

The infinite integrated field can in most cases be represented by a complex power series;

$$K^*(Z) = \sum_{N=1}^{\infty} f_N \left(\frac{Z}{Ro}\right)^{N-1} \qquad (2a)$$

where $K^*(Z)$ is the complex conjugate of K(Z) which is the infinite integrated field a line from $\omega = -\infty$ to $\omega = +\infty$ at a location Z in x,y coordinates (see Fig. 1)

$$K(Z) = \int_{-\infty}^{\infty} H(x,y,\omega)\,d\omega \qquad (2b)$$

The C_N and f_N are the two dimensional field and integrated field power series coefficients of the real magnet. The C_N coefficients may be divided into the four primary parts

$$C_N = C_N' + C_N'' + C_N^R + C_N^S \qquad (3)$$

where $C_N = a_N + b_N$, $C_N' = a_N' + b_N'$, $C_N'' = a_N'' + b_N''$, $C_N^R = a_N^R + b_N^R$ and $C_N^S = b_N^S$. The a_N coefficients are due to the coil and the b_N coefficients are due to the iron. A similar set of coefficients may be generated for the integrated field complex coefficient f_N.

The C_N' term represents the perfect magnet coefficient as generated by the computer. $C_N' = a_N' + b_N'$ is symmetric and generally has the following properties $C_N' = 0$ when $N \neq T(2P+1)$ $P = 0,1,2,\ldots$ where $T = 1$ for a dipole and $T = 2$ for a quadrupole. The $C_N' = C_T'$ term ($P = 0$) is the fundamental and $C_N'/C_T' \leq 10^{-3}$ when $N = T(2P+1)$ $P = 1,2,3,\ldots$. Ro, the reference radius, is generally 70 - 75% of the magnet inner coil radius. The C_N' coefficients usually have only imaginary parts. Coil configurations which generate the proper C_N' terms are designed by computer programs similar to the LBL SCMAG1[4] program.

Random errors in coil construction and coil-iron placement will generate multipole coefficients which are not present in the perfect computer generated coils; these errors are represented by the C_N'' terms. These multipole coefficients may be of any N and they have both real and imaginary parts. The magnitude of the C_N'' terms is determined by the tolerance to which the magnet is built. Program SCMAG3[4] is used to simulate random errors within a magnet and random magnet to magnet variations.

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The third primary power series coefficient C_N^R is generated by circulating currents flowing in the superconducting filaments. This term may also include iron residual field and the effects of eddy currents and coupled currents. The C_N^R term is symmetric (only the imaginary parts of C_N^R, $N = T(2P+1)$ $P = 0,1,2,\ldots$ are present.) The C_N^R term is usually larger at low current excitations than at high excitations. Generally the C_T and C_{3T} terms are about the same magnitude when R_o is 70 - 75% of the inner coil radius. The field due to circulating currents in round or nearly round filaments can be modeled using the computer program SCMAG4.[4] This program uses the complex doublet equation to describe the residual field, and has been successful at calculating residual fields which agree with measured values.[5]

The fourth primary power series coefficient is the one which describes the behavior of saturated iron. The C_N^S terms are a perturbation of the iron power series coefficient b_N'. C_N^S is symmetric (only the $N = T(2P+1)$ terms are present). Even these terms approach zero when the maximum induction in the iron is less than about 1.8T. As the magnet iron saturates the fundamental C_T^S term grows. The next term to appear is the C_{3T}^S and so on. By proper design of the iron, it is possible to control the C_{3T}^S term and sometimes even the C_{5T}^S term. Superconducting synchrotron magnets with small apertures can be designed to run with saturated iron. The power series coefficients C_N^S can be generated by computer programs like TRIM and POISSON.[6]

MAGNETIC FIELD QUALITY

The four power series coefficients are summed into a single power series in program SCMAG6. The deviation of the field from the true value may be calculated in a number of ways. Within a given magnet, it is appropriate to represent the true field as the fundamental multipole alone C_T. One can define ΔB over B as follows

$$\frac{\Delta B}{B} = \frac{\left| H^*(Z) - C_T\left(\frac{Z}{R_o}\right)^{T-1} \right|}{\left| C_T\left(\frac{Z}{R_o}\right)^{T-1} \right|} \qquad (4)$$

There is a different $\Delta B/B$ profile for each magnet in the accelerator plus there is a variation in C_T from magnet to magnet. Figure 3a through 3d illustrate how field quality may be represented graphically by $\Delta B/B$ lines; these figures show field quality variation with current excitation.

The coil and iron profile used to develop the field quality plots shown in Fig. 3a - 3d is shown in Fig. 2a and 2b. Such a magnet could be used in a PEP proton ring (Phase II). The magnet, which uses cold close in iron, illustrates the effects of the residual field, random construction errors, and iron saturation. Figure 3a clearly shows the effect of residual field. Figure 3b shows almost no residual field effect (fig. 3b corresponds to injection into PEP-II at an energy of 13 GeV). Figure 3c shows only the effects of random construction errors; and iron saturation errors are barely visible in Fig. 3d.

THE MAGNETIC FIELD AND THE BEAM

The beam may be coupled to the magnetic field in two ways. The first is a passive analysis and second is an active interaction. The former is illustrated in this paper, the latter unfortunately will not be completed for some time.

The magnetic field analysis permits one to see a simulation of the $\Delta B/B$ within a given magnet and it permits one to see visually the magnet to magnet variations of the magnetic field. Once one has determined the field quality of a series of simulated magnets, it is easy to overlay the expected beam profile over the $\Delta B/B$ plot of the magnet field. Figures 3b through 3d illustrate how the particle beam profile may be overlayed on the $\Delta B/B$ diagram. The particle beam profile may be obtained from a transfer matrix program such as SYNCH or TRANSPORT.[7] The $\Delta B/B$ plot and beam profile can be obtained on a magnet by magnet basis. The resulting overlay gives the beam dynamicist a much better feeling of what is going on in a projected lattice than does pages of computer printout.

The active interaction approach to the relationship of the magnetic field quality to the beam dynamics will potentially save the accelerator builder money. Existing accelerators work (many work very well) despite rather gross errors in their magnetic field. This fact is sometimes overlooked when the beam dynamicist makes out his "wish list". This can result in a machine that is well engineered but expensive. It is desirable to use low cost magnets in an accelerator. An analysis of the interaction of these magnets with the accelerated beam will show the accelerator designer the limit to which one can cut corners on magnetic field quality.

The active simulation particle beam dynamics in a series of magnets with simulated field errors requires a ray tracing program like GOC3D.[7] Since the program requires large blocks of computer memory and time, GOC3D should be modified so that two dimensional field and integrated field profiles can be used. Such simulations should result in a relaxation of the field quality needed for a particular machine lattice. For example, the need for built-in correction windings in superconducting storage ring magnets could be eliminated. These windings could be replaced by lumped elements around the ring. A truly interactive system would permit various magnet design philosophies to be tested in a machine lattice.

REFERENCES

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4. SCMAG1, SCMAG3 and SCMAG4 are not documented; a brief description is given in "The SCMAG Series of Programs for Calculating Superconducting Dipole and Quadrupole Magnets" (to be published), Proceedings of the CUBE Symposium (Oct. 1974).

5. M. A. Green, "Residual Fields in Superconducting Magnets", Proceedings of the 4th International Symposium on Magnet Technology (Sept. 1972). A later version of the theory is used in SCMAG4.

6. TRIM private communication with J. Colonias. POISSON private communication with K. Halbach, both are saturated iron computer programs.

7. SYNCH, and TRANSPORT are MATRIX transfer programs; GOC3D, a ray tracing program, private communication with A. C. Paul of LBL.

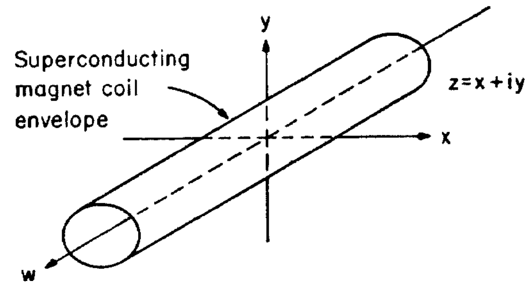
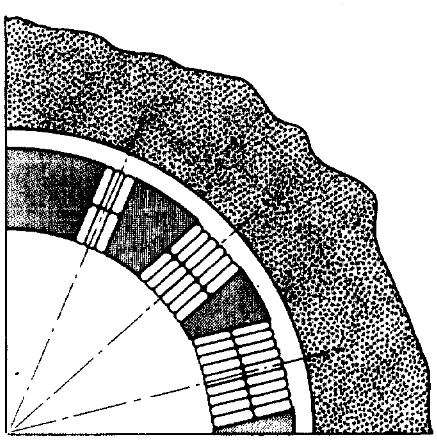
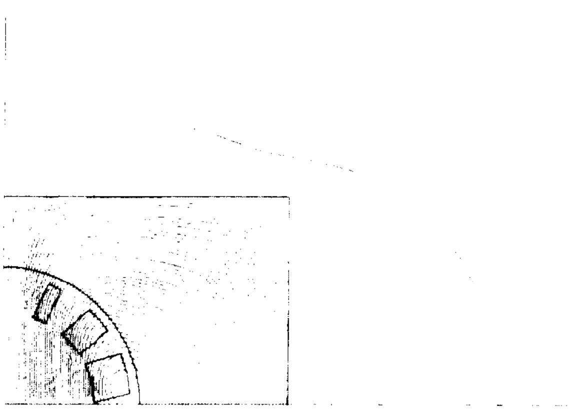


Fig. 1. Superconducting magnet coil envelope in x, y and ω space.

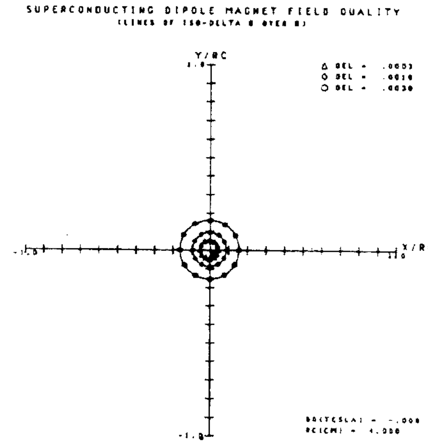


a. Superconducting coil

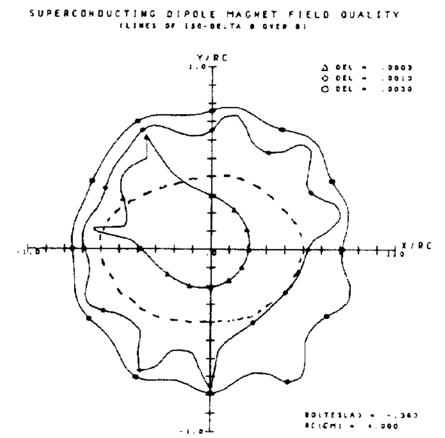


b. Iron saturation at 3.5T central field

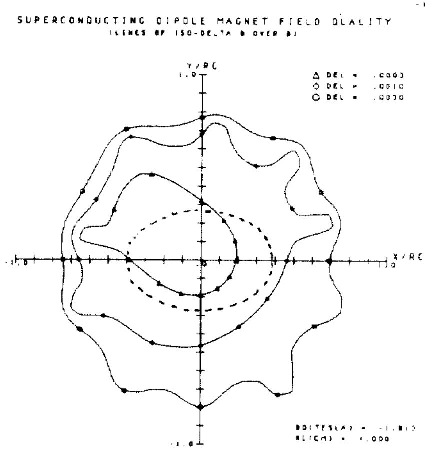
Fig. 2. A saturated iron dipole (inner coil radius = 40 mm, inner iron radius = 60 mm).



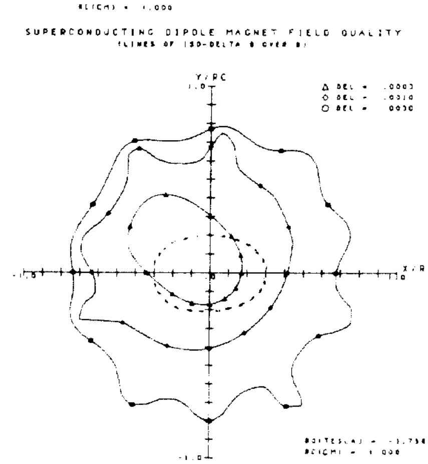
a. Very low field



b. Injection into PEP-II



c. Mid-field range



d. High field range

Fig. 3. Iso ΔB over B plots for the dipole shown in Fig. 2. (Possible PEP-II beam spot is shown.)