EXPERIENCE WITH COMPUTER MODELS OF TWO-DIMENSIONAL MAGNETS*

Joseph H. Dorst

Lawrence Radiation Laboratory
University of California
Berkeley, California

Abstract

Computer programs have been used extensively in the design studies for a 200-BeV synchrotron. Two magnet codes, SIBYL (originated by Richard S. Christian, then of MURA) and TRIM (originated by Alan M. Winslow of LRL), are currently in use at the Lawrence Radiation Laboratory, Berkeley, for static evaluation of two-dimensional magnets, including finite nonuniform permeability of the iron.

In this paper are discussed some of the magnet problems for which the computer codes have been used, and the validity or accuracy of the results. Applications include shaping of the pole for good medium-field profiles and shaping of the pole base to reduce saturation effects.

The comparison of calculated and measured fields of the CERN proton synchrotron magnet indicates the attainable quality of computer results. At 14.4 kG, within the limits of the vacuum chamber, the gradient computed by SIBYL was within 1% of the reported gradient.

Introduction

By late 1963, no magnets had been designed for our 200-BeV accelerator, and yet there was general agreement that we wanted to explore a wide range of possible magnets. The development of computer programs for calculating magnetic fields has made such exploration possible. In this paper we discuss our experience with the mathematical models of two-dimensional magnets.

The Magnetostatic Computer Programs

Our most valuable computer program is SIBYL. It was written in 1963 by Richard Christian, then of MURA, for the static evaluation of symmetrical two-dimensional magnets, including finite nonuniform permeability. The general method of solution is by relaxation of a set of finite-difference equations approximating Poisson's equation. The primary characteristic of SIBYL is that the total cross section is divided into two regions (air and iron) and the regions are solved separately. Alternate solutions are for a modified scalar potential in the air-and-conductor region, and for the magnetic vector potential in the iron, with revisions to the boundary conditions as necessary. SIBYL is a lengthy program with some restrictions on the shapes that may be studied. It is written in FORTRAN II for the IBM 7094 or 7090. The uniform rectangular mesh may have 12 000 points, and the 40 possible rectangular conductors and many points of the iron-air interface do not have to be on mesh lines or mesh points. The program is very well suited for calculations of the effects of perturbations, such as slight changes in the pole surface and in the location of the water-cooling holes in the conductors. The systematic errors associated with mesh size and boundary conditions are detectably present at all times, but even those small errors approximately cancel when differences between similar magnets are considered.

SIBYL has demonstrated validity in calculations of the CERN proton synchrotron (CPS) ring magnets. (See Fig. 1.) The CPS data are from Table 2 of CERN-PS/Int. MM 59-5. The value of k_s (= B'/B_0) is 4.115 meters^{-1} and the full gap at the centerline is 10 cm. The SIBYL mesh was 1 cm by 1 cm; the stacking factor of the laminations was assumed to be 0.95; and the B(H) data of the mathematical model were substantially that for pure iron, with a saturation induction of 21.4 kG. The calculated gradients at the very highest excitation are sensitive to the choice of material parameters; at an orbit field of 14.42 kG a change of 1% in either the saturation induction or the stacking factor changes the calculation of the centerline gradient by about 0.4% and changes the gradient at 6 cm toward the narrow gap by about 1.5%. There are also some changes in the magnet gap from magnetic forces. For the open-C magnet, the effects of the average gap closure and the rotation of the pole almost cancel, and the net changes in gradient are small. In a closed-C magnet, the average deflection is greater and both the average gap closure and the pole rotation increase the gradient. For the CPS closed-C magnet, a gap closure of 0.01 cm increases the gradient at the centerline by about 0.2%.

In addition to providing a tabulation of midplane gradient, SIBYL provides other useful information about the magnets, such as the magnetic efficiency, the distribution of magnetomotive force or potential along the pole, the flux density in the iron, and the total flux linkage of the coils. We have challenged the computations many times and often discovered mistakes of coding or input. Without mistakes, a SIBYL evaluation has always been reasonable and self consistent, even when the computed results were surprisingly good or bad.

One example of surprising information is the ratio of the subsurface flux density along the central surface of the pole to the midplane flux density. For the CPS magnets, the ratio is about 1.4 at all excitations. The normal

*Sponsored by the U. S. Atomic Energy Commission.

component of flux is less than 3% greater than the vertical component in air, and the lamination stacking accounts for a factor of only 1.05. The remainder of the ratio is due to the component of subsurface flux in the tangential direction.

The second computer code, TRIM, was written by Alan Winslow of LRL. Its primary feature is the use of a nonuniform triangular mesh. TRIM solves the whole problem without cycling, by relaxing the magnetic vector potential throughout. There are no geometrical restrictions, but the conductor sides and the iron-air interface must be on mesh lines. The present number of possible points is only about 1600, which is too low for the evaluation of fine structure. The coding is almost entirely in machine language for the IBM-7094 and the program cannot yet be run under a monitor system. The program has confirmed SIBYL results for gradient-magnet excitation curves and for changes of field shape due to saturation. It has also calculated the effect of nonsymmetrical currents and has been used to evaluate some multipole magnets.

Figure 2 shows the gradients at several field levels that we expect to have from the present design of our gradient magnet. The cross section of a gradient magnet is approximately that of Fig. 3. The profile has four parts: the central section, the low-field side, the high-field side, and the nose and the pole base. The coordinates of the central section follow the analytic equipotential. The dimensions of the low-side and high-side sections were determined by trial and error that began with some assumed location of the edges. With the assumption that the iron of the magnet was infinitely permeable (that the pole surface remained an equipotential), the side shapes were adjusted to produce the required fields within the aperture. These edge shapes were then slightly modified after consideration of the field shapes at full excitation.

Medium-Field Profiles

The trial-and-error process of shaping the profiles for good "equipotential" fields included the use of SIBYL to calculate the effects of many small perturbations of a profile. These elemental effects were then added and subtracted, by hand and by computer, to select new profiles for further evaluation and next adjustment. The number of times that this process is repeated varies with the skill and patience of the user. We found that the field gradient within the aperture is surprisingly sensitive to small changes in the pole profile. At the most sensitive location, r = -7 cm, the addition or removal of a shallow section, approximately triangular with a 1-cm base and a height of 0.01 cm, changes the gradient at r = -6 cm by ± 1.2%. Profile changes or errors near the center of the pole produce both positive and negative changes, but the maximum amplitudes of the gradient change fall off rapidly with larger gaps. In fact, a constant size perturbation produces maximum effects that are inversely proportional to the fourth power of the gap.

$$\frac{(\delta B'_1)_{max}}{(\delta B'_2)_{max}} = \left(\frac{g_2}{g_1}\right)^4$$

Pole-Base Shaping

One feature of our design is the continuation of the slant side of the pole for the full distance to the iron return path. One surprising result of such a pole-base angle is that the potential differences between all points on the pole-tip surface are reduced, especially those mmf drops between the center of the pole profile and the high-field side. Figures 3 and 4 are CRT plots of contours of the magnetic vector potential and the scalar potential in iron. The interval between scalar potential lines is 0.5 percent of the gap potential. The pole shape, the location of the conductors, the overall size of the magnet, and the flux density (15.0 kG) at the orbit centerline were held constant for these comparisons. Only the angle of the pole base and the total excitation are different for the two magnets. The more vertical side of case 9716 is 6° from the vertical; the more slanted side of case 9720 is 36° from the vertical. The slanted side increases the total flux that the return path must carry, but the current required for 9720 is 1.1% less than for 9716.

The difference in field quality is shown in Fig. 5 and is due entirely to the difference in pole-base angle. Both curves of midplane gradient as a function of position are for a B_0 of 15.0 kG and a centerline gap of 6.2 cm. For these profiles, the radius of curvature of the nose (the coil side of the minimum gap region) was 3.7 cm and the minimum gap of 4.56 cm was 11.7 cm from the centerline.

The maximum subsurface flux density, 22.0 kG in the iron, was in the nose about 13 cm from the centerline. In the square-sided pole, the flux density remains high along the entire side, and the effect on the scalar equipotentials can be seen in Fig. 4. The angle that the flux lines make with the normal to the pole surface is large all along the profile. In the slant-sided magnet, the region of high flux density is more local although the maximum flux density is about 1/2 % higher. The component of flux that is tangent to the pole surface has been reduced, the potential drops are less, and the gradient curve does not suffer as much from saturation effects.

The worth of good field quality should not be overestimated. Some corrective lenses must be used with any gradient magnets, and we have attempted to optimize our design on the basis of cost. The cases shown are the extremes of a set of four. Analysis of the differential costs led to the selection of a pole-base angle of about 33° for the main gradient magnets of the proposed 200-BeV synchrotron.

We will continue to use the computer programs for the final designs. Physical magnet models are still very necessary to provide what might be called calibration checks of our mathematical models. Precise profiles will be specified and full-scale models will be built and carefully measured, physically and magnetically. The calculation of the last small changes necessary to achieve better fields will be the final phase of cross-section development. The final changes will include any desired corrections for such things as end effects, final desired sextupole components, and so forth.

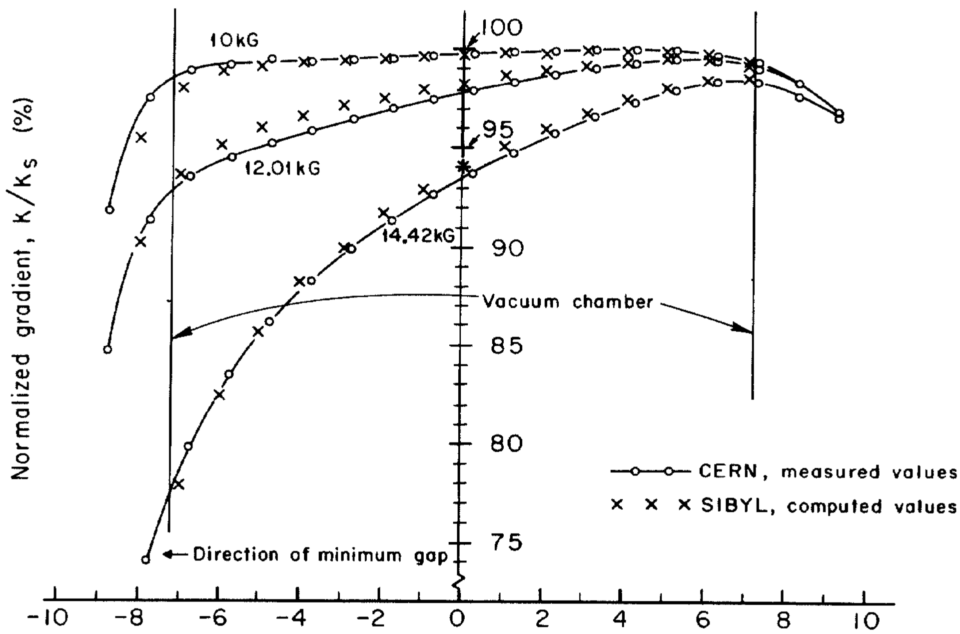

Fig. 1. Computed and measured gradients, CERN PS open-C magnet.

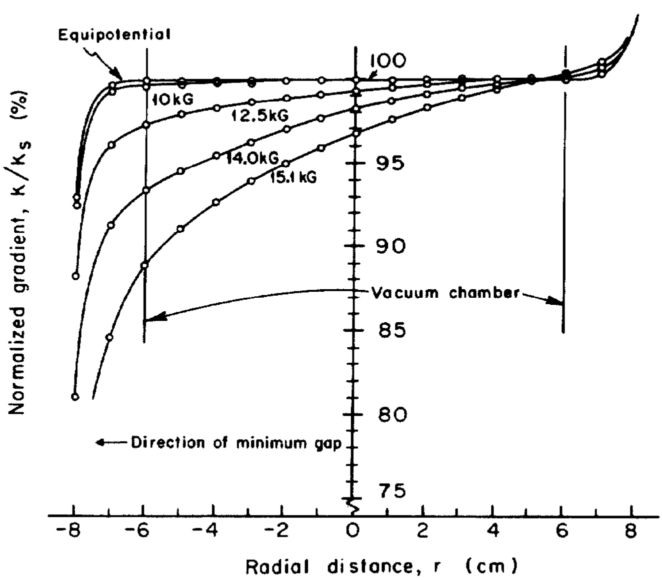

Fig. 2. Computed gradients, 200-BeV gradient magnet.

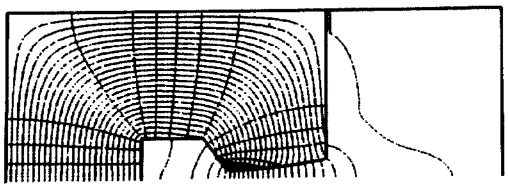

Fig. 3. Outline and potential contours, Case 9720.

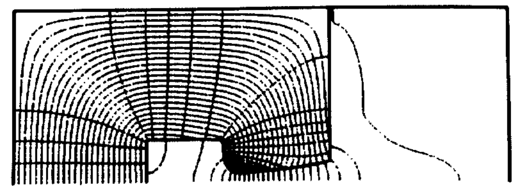

Fig. 4. Outline and potential contours, Case 9716.

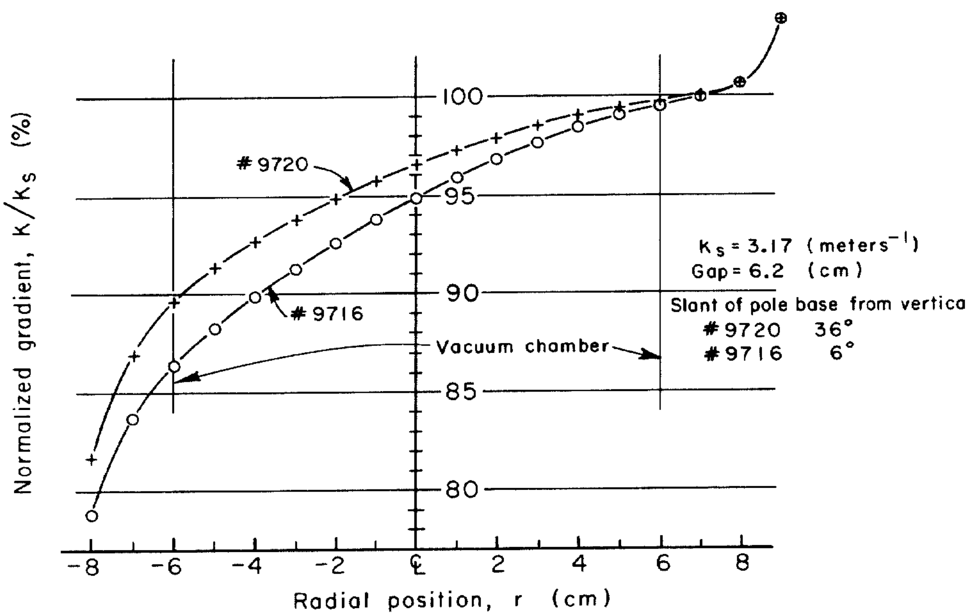

Fig. 5. Computed gradients as function of pole-base angle.