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Berkeley, California

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Summary

The computer program SIBYL has been used extensively in the design studies of magnets for a 200-BeV synchrotron at the Lawrence Radiation Laboratory, Berkeley. The code was written by Richard S. Christian, then of MURA and now at Purdue University, for static evaluation of two-dimensional magnets including the effects of finite non-uniform permeability of the iron. The general operation of the code and some of the special features are described. The code is especially useful for studying small differences between similar magnets. Applications include evaluation of the effects of iron saturation as a function of current, shaping of the pole base of AGS-type gradient magnets, shaping of magnet poles for good medium-field profiles, and partial evaluation of quadrupole magnets. The validity or accuracy of the computed results is discussed. The comparisons of calculated and measured fields of the CERN Proton Synchrotron Magnet indicate the attainable quality of computed results. At 14.4 kG, within the limits of the vacuum chamber, the gradient computed by SIBYL was within 1% of the measured gradient.

Introduction

The computer program called SIBYL is a powerful tool for the design of high-precision magnets. Although it was written for the two-dimensional evaluation of gradient magnets like those of the CERN Proton Synchrotron and the Brookhaven AGS, the program has already been applied to other magnets and to other magnet problems. Some of these applications have been reported in two papers at the Particle Accelerator Conference in March of this year,[1,2] and other uses will be discussed in this paper.

The first section is a description of how the program operates and a discussion of some of the reasons why SIBYL is so useful to us at the Lawrence Radiation Laboratory. Some of this material is taken from an earlier unpublished paper[3] and the rest comes from our additional experience with the code and from talks with Dr. Christian.

The second section is a discussion of the two general kinds of applications, those with calculations in iron and those without. These may be classified as "finite permeability" and "equipotential" applications, respectively. An example of the finite permeability studies is the complete evaluation of the CPS open-C gradient magnets. An example of equipotential applications is the partial evaluation of a quadrupole.

General Description of the Program

SIBYL was written in 1963 by Dr. Christian for the static evaluation of symmetrical two-dimension magnets, including the effects of finite non-uniform permeability of the magnet iron. It 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. SIBYL uses a fixed rectangular mesh throughout with 12 000 possible points.

Two outlines of magnets that can be studied are shown in Figs. 1 and 2. For an H magnet, the air region is completely bounded by the air-iron interface and the median plane. In a C magnet, the air region is also bounded artificially at the top and right. The usual boundary assumption is equivalent to requiring that no flux cross the external borders.

The most obvious characteristic of SIBYL is that the total problem area is divided into two regions, air and iron, and the regions are solved separately. Alternate solutions are found for a modified scalar potential field in the air-and-conductor region, and for the magnetic vector potential field in the iron.

The block diagram is shown in Fig. 3. The smaller blocks connect the two main relaxations in a rough circle. The connective operations are all necessary to the process, but the problem-solving occurs in the two large blocks labeled AIR and IRON, and in the overall cycling. In the large blocks, SIBYL solves the AIR region and the IRON region as two distinct problems. We present only one problem to the computer: What will be the fluxes and flux densities from a particular configuration of currents and iron? For a complete evaluation of a magnet, there must be a repeated alternation or cycling, a sort of macroscopic iteration, to get a pair of solutions that are consistent with each other.

The process begins with a selection of initial boundary conditions for the scalar potential. These boundaries and the currents uniquely determine the solution to the scalar potential field in air. The flux distribution in air determines the vector potential boundary conditions for the iron. These boundary values and the properties of the iron determine the final solution to the vector potential field in iron. The flux distribution in iron and the permeabilities determine the scalar potential field in the iron and we are back to the starting point, the scalar potential boundaries. The MMF drops in the iron are a direct result of a particular set of initial boundary values. At this point in the major circle or loop, we use a weighting factor to select a new scalar boundary between the old input and its consequent output.

The number of cycles required to evaluate a magnet depends on many factors such as the geometry, the excitation level, the precision wanted in the final results, and the particular set of operating numbers and weighting factors used by the code. Three cycles are usually enough for normal magnets, and difficult magnets can be evaluated to high precision in no more than six cycles.

This "SIBYL method" of using two unlike potential functions was selected to handle the necessary continuity conditions at an irregular air-iron interface. At an interface the normal component of B and the tangential component of H must be continuous. With a single kind of potential and an irregular interface, the numerical methods become exceedingly complicated. The method of cycling is also fast because each sub-problem has fixed values on the boundaries.

Calculations in Air

The general method of solution is by relaxation of a set of finite-difference equations approximating Poisson's equation. The potential is a "modified scalar" potential and currents in finite areas are handled by the use of "current cuts" or "capping with Amperian hats."[4] Current effects are computed for each mesh point and the "shadow" of these currents modifies the boundary values of the potential. The final values of the potential are the basic solution as far as the computer is concerned, and all information about flux density and flux is directly calculable from two sets of numbers, the potential and the current effects. These two arrays occupy a total of 24 000 words in the computer memory, and the boundary values use several hundred more. The number of iterations in air is determined by a "tight" convergence criterion, but the time required for the solution of the air scalar is usually a small fraction, perhaps 10 or 15%, of the time required for a complete solution of a magnet. The arithmetic solution is very exact—the flux densities are solved to better than 1 part in 10^5—for all air calculations.

Calculations in Iron

The basic difference equation for the magnetic vector potential field simply says that the sum of Hdl around each point should be zero. Gamma, the reciprocal permeability or reluctivity, relates H and B: $H = \gamma B$. The set of difference equations relate the value of the vector potential at a point with the values at neighboring points, the values of the gradients in the normal directions—which are flux densities—and the properties of the iron at those flux densities. There are many points near the irregular boundary where the distances to the neighboring points must be included in special equations. At each mesh point in the iron we have some expression that relates the vector potential at that point to the vector potential values at four other points and to the values of gamma at five points. (The use of reluctivities at points is another characteristic of SIBYL.) The values of the potential are improved with equations that weight the values of the potentials according to the values of gamma. The normal gradients of the vector potential determine the flux densities; the flux densities determine the values of gamma; and the values of gamma determine the weights of the basic potential difference equation. The coefficients in the set of difference equations are constantly changing.

In closing the loop between potential and reluctivity, a damping factor is used for calculating new coefficients. The new values of gamma for the next iteration are selected at some value between the former value and the value calculated directly from the existing gradient of the potential. In SIBYL this factor has been 0.15 for most of the last year. When used with a relaxation factor of 1.2, we have had no problems with convergence of the two arrays of numbers, the potentials and the reluctivities. In the iron relaxation we do not use a convergence criterion but rely on experience with similar problems and select the number of iterations to be performed. In general, the time for one iteration of the vector potential plus one recalculation of gammas is 10 times longer than the time for a single iteration in air.

Output Information

The simplest form of output is the tabulation of midplane flux densities and gradients, including some normalized ratios and the dimensions of the pole gap. Much useful information is calculated "en route" to the final table, and study of the full print-outs also gives valuable insight about magnets in general. This supplemental information can help the magnet designer to change a magnet for improved performance. Complete runs provide information such as the total excitation required for a specified value of flux density at any particular point on the midplane, the distribution of magnetomotive force in the iron and along the pole, and the flux densities in the iron. The total flux linked by the coils and the flux distribution at the air-iron interface are output quantities in all runs, whether complete runs through iron or equipotential runs through air only. A family of complete runs provides magnetization data and coil flux linkage data that can be used in the design of power supply systems for pulsed operation.

Similar Magnets

The most useful feature of SIBYL is that the pole portion of the air-iron interface does not have to be on mesh lines. Special equations are used for points of the mesh near the irregular boundary. These equations are theoretically less accurate than the difference equations for points that are symmetrically located with respect to the neighboring points. In other words, the equations for points with one or more short "legs" neglect terms of low order that are included in the standard equation. We have looked for a step change in the systematic error by moving one point of the contour in regular increments between mesh lines and across mesh lines, and then studying the computed fields and the differences between successive runs. We observed that the computed effects are continuous. Similarly, the sides of the 40 possible rectangular conductors do not have to be on mesh lines. Families of runs with repeated small changes in conductor location also show a smooth family of effects in the computed fields.

The continuity of SIBYL results makes the program very well suited for calculations of the effects of perturbations to the iron surface and changes in the location of the conductors. The discretization errors due to finite mesh size are always present, but even those small errors approximately cancel when differences between similar magnets are computed.

Finite Permeability Applications

Two years ago, we knew relatively little of the details of flux distribution in magnet iron, and we needed SIBYL for finite permeability problems. It has been used to study the effects of saturation by computing midplane gradients and the changes in gradient with excitation on many magnets. Our study of pole-base shaping was a step in the evolution of the gradient magnets for the proposed 200-BeV synchrotron.[2] The primary validation of SIBYL was done by calculating the ring magnets of the CERN proton synchrotron (CPS) and comparing the computed and measured gradients.

Figure 4 shows contours of equal vector potential on an outline of the CPS open-C magnet; Fig. 5 shows the computed and measured gradients at three field levels. These magnets, especially at the highest excitation, are the most "difficult" magnets that we have computed. The CPS data are from Table 2 of CERN-PS Int. MM 59-5. The value of $k_s (= B'/B_o)$ is 4.115 m^{-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 0.95; and the B-H data of the mathematical model were for a pure iron, with a saturation induction of 21.4 kG.

The computed 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 computed 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 and both the average gap closure and the pole rotation increase the gradient. For the CPS closed-C magnet, a deflection that decreases the centerline gap by 0.01 cm increases the gradient at the centerline by about 0.2%.

It is difficult to measure the gradients of magnetic fields to a sufficiently high precision to accurately determine the net quality of the program. The absolute value of flux density at a point can be measured with precision, but the B-H data that are entered into the code may be responsible for any difference between computed and measured values. Small differences between computation and measurement of the gradient profile can be due to very slight uncertainties in the dimensions of the actual physical profile, especially under dynamic conditions. In other words, we believe that the accuracy of the computed effects of finite permeability is primarily determined by the accuracy of the input data.

Equipotential Applications

In most magnets the effects of finite permeability are small. The distribution of flux is primarily determined by the location of the pole surface near the region of interest. For many studies saturation effects may be neglected altogether or may be considered as additive effects. The exact location of remote surfaces and currents may also be unimportant. Consequently, the mathematical model may often be simplified to study the pole surface with a finer mesh. The contour of the 200-BeV gradient magnets was optimized to the present design by mixing results of complete runs, using a 1-cm-mesh interval, and equipotential runs using a 0.5-cm mesh. The computed fields differ significantly only near the edges of the pole.

SIBYL has been used for so many other equipotential studies that only a few can be mentioned here. The flux density through the conductors of the booster synchrotron magnets has been calculated for studies of coil forces and eddy-current effects. SIBYL is now helping to shape the ends of the booster magnets to equalize the flux in each lamination. (The reduction of eddy-current heating is important in fast-cycling magnets.)

The general problem for a designer of high precision magnets is: "What surface is needed to produce a particular field?" rather than "What field is produced by a particular surface?" SIBYL can accurately evaluate the steps in a trial-and-error process of shaping a surface. It has also computed the separate effects of many very small perturbations, and these elemental effects have been used as matrix elements by a computer program that "recommends" improved surfaces. After measuring magnet models, we will use these additional programs for final design of the poles.

The use of SIBYL for our quadrupole

magnet design is interesting because the program cannot represent the whole magnet with a single mathematical model. Figure 6 shows the total cross section of a quadrant of the quadrupole. The return path must be artificially simplified for SIBYL to be used at all. Information about the flux at the air-iron interface was obtained from two simplified models, called "long axis" and "short axis," and the data were combined to specify the whole return path. (The computer program called TRIM has evaluated the effects of finite permeability.) At the present stage of quadrupole design, our questions included: "Are the pole edges far enough from the center and are the gaps at the edges small enough to produce useful fields within the elliptical aperture?" The minimum gap on the short axis must be large enough to install the coils. The dashed circle of Fig. 6 is the region of interest on the short axis of the quadrupole.

Figure 7 shows the physical surface of the pole and the gradient curves for three different edges. The central part of the contour was a hyperbola. The pole edge of case No. 1 has no bumps. There is a 0.4-cm flat at the minimum gap of 2.0 cm. The normalized gradient is 3.0% low at the aperture limit of 3 cm. The pole edge of case No. 2 has a relatively large local bump. There is a 0.4-cm flat at the minimum gap of 1.8 cm. The gradient is 3% high at $x = 4$ cm. The pole edge in case No. 3 has a relatively small bump, beginning smoothly at $x = 4.4$ cm. The flat is 0.8 cm wide and the minimum gap is slightly greater than 2.0 cm. The error in gradient is less 0.3% out to $x = 3$ cm. Note that the computed gradient of case No. 3 is high (0.12%) at the origin.

These calculations have a great deal of convincing power to us. We know that we can shape this edge to satisfy the design limits. We also know that the maximum flux density inside the short-axis edge will be less than 16 kG at the design peak gradient of 1500 gauss per cm. The mesh interval for these studies was 0.2 cm, and we believe that the computations of gradients within the aperture are accurate to better than 0.05%.

Addendum

Operating instructions for SIBYL, as of last year, have been written for our own use within the laboratory.[5] It is not a simple program, and although we believe that all mistakes in coding have been found and corrected, there are many pitfalls or booby traps that still give us "garbage" when we forget that SIBYL has some peculiar restrictions. Dr. Christian has just begun to write a general two-dimensional program, using the methods of SIBYL, as part of a three-dimensional program for infinite iron. We hope to extend the new two-dimensional program to include the finite permeability of iron. The combination of three dimensions with finite iron is an eventual goal.

The success of numerical methods means that we will probably always use computer programs for the final designs of high-precision magnets. Physical magnet models are still very necessary to provide what might be called calibration checks of our mathematical models. For the gradient, quadrupole, and sextupole magnets of the proposed 200-BeV synchrotron, 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.

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2. Joseph H. Dorst, Experience with Computer Models of Two-Dimensional Magnets, IEEE Transactions on Nuclear Science NS-12, No. 3, p. 412, June 1965.

3. Joseph H. Dorst, A Computer Program for Magnet Design, Lawrence Radiation Laboratory UCRL-10022, June 30, 1964 (unpublished).

4. L. Jackson Laslett, Use of a Scalar Potential in Two-Dimensional Magnetostatic Computations with Distributed Currents, MURA Internal Report 211, Dec. 4, 1956 (unpublished).

5. John S. Colonias, Operating Instructions for "SIBYL" Magnetostatic Program, Lawrence Radiation Laboratory Internal Report AS/Theoretical/03, July 15, 1964 (to be revised; unpublished).

Figure Captions

Fig. 1. Outline of an H magnet.

Fig. 2. Outline and potential contours.

Fig. 3. Block diagram, SIBYL magnetostatic program.

Fig. 4. CPS open-C magnet with flux lines.

Fig. 5. Computed and measured gradients, CPS open-C magnet.

Fig. 6. Quadrant of a Collins quadrupole magnet.

Fig. 7. Collins quadrupole, short axis edge profiles and computed gradients.

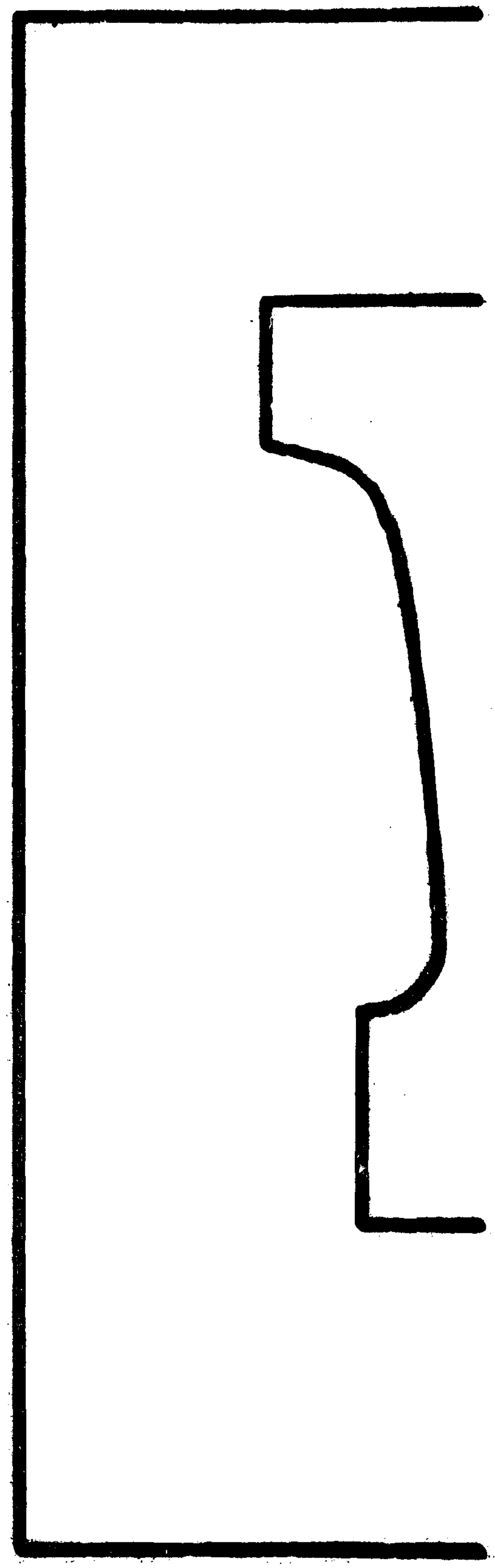
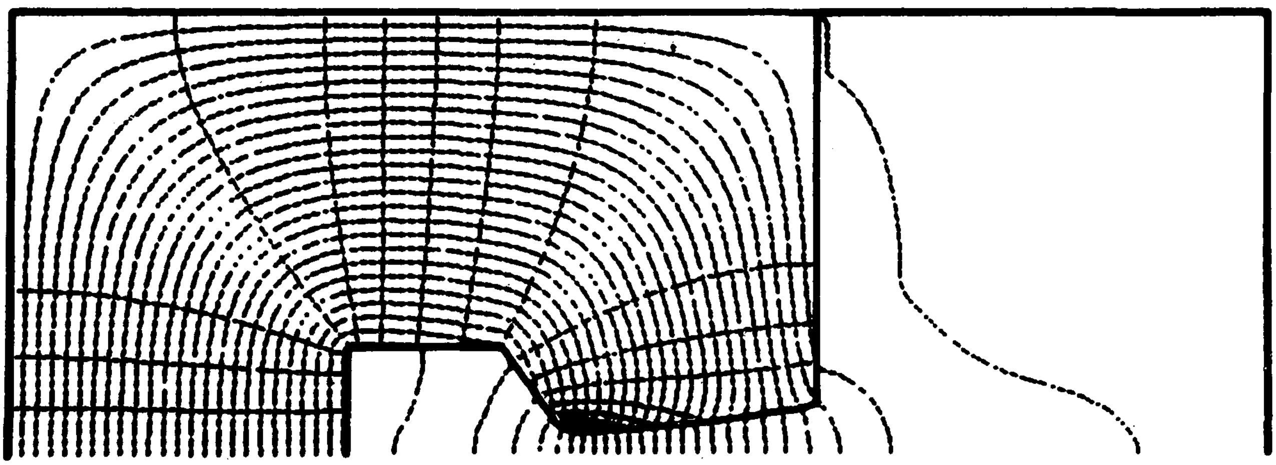


Fig. 1

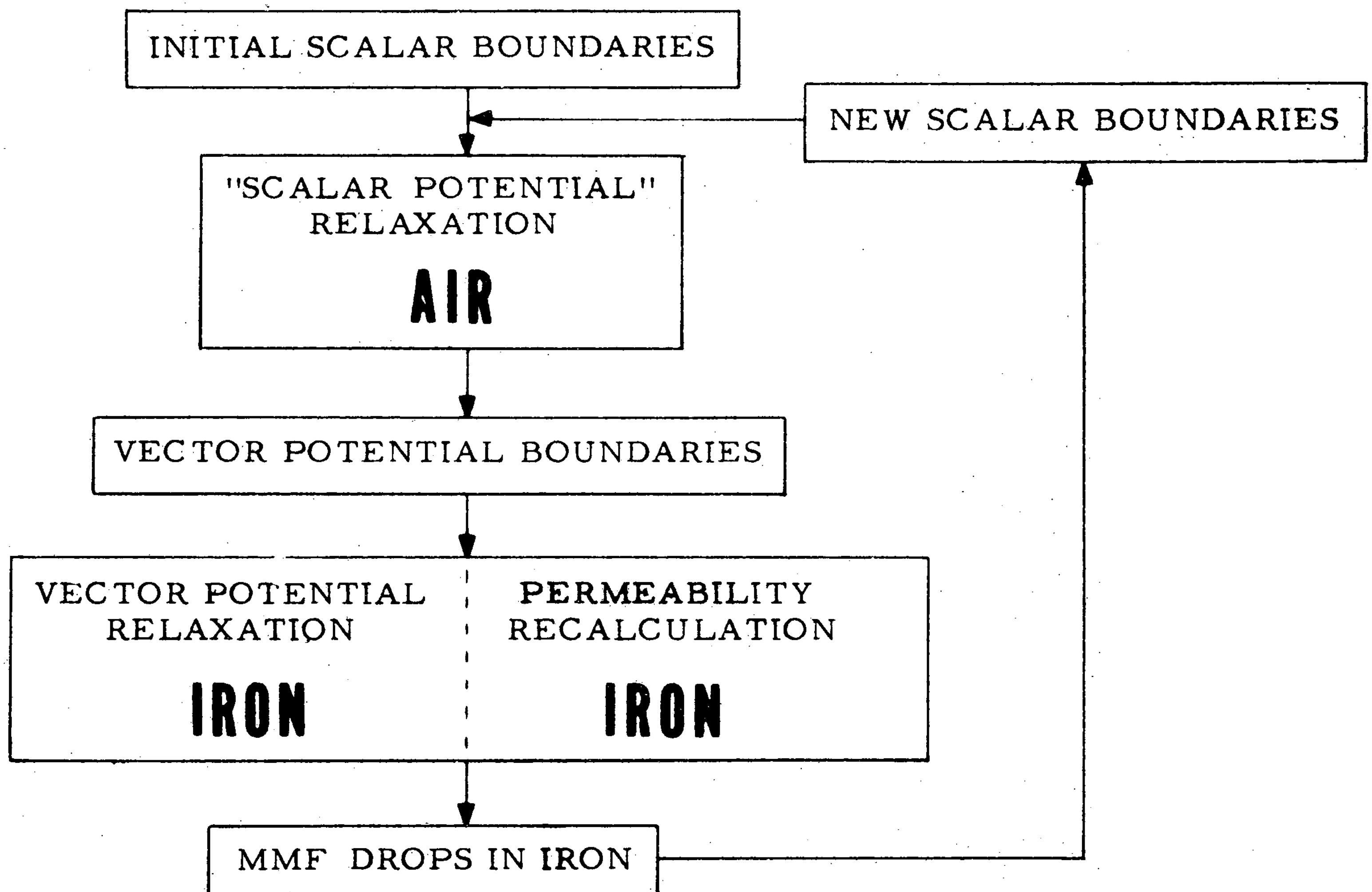
MUB-7840



MUB-5449

Fig. 2

BLOCK DIAGRAM
SIBYL MAGNETOSTATIC PROGRAM



MUB-7841

Fig. 3

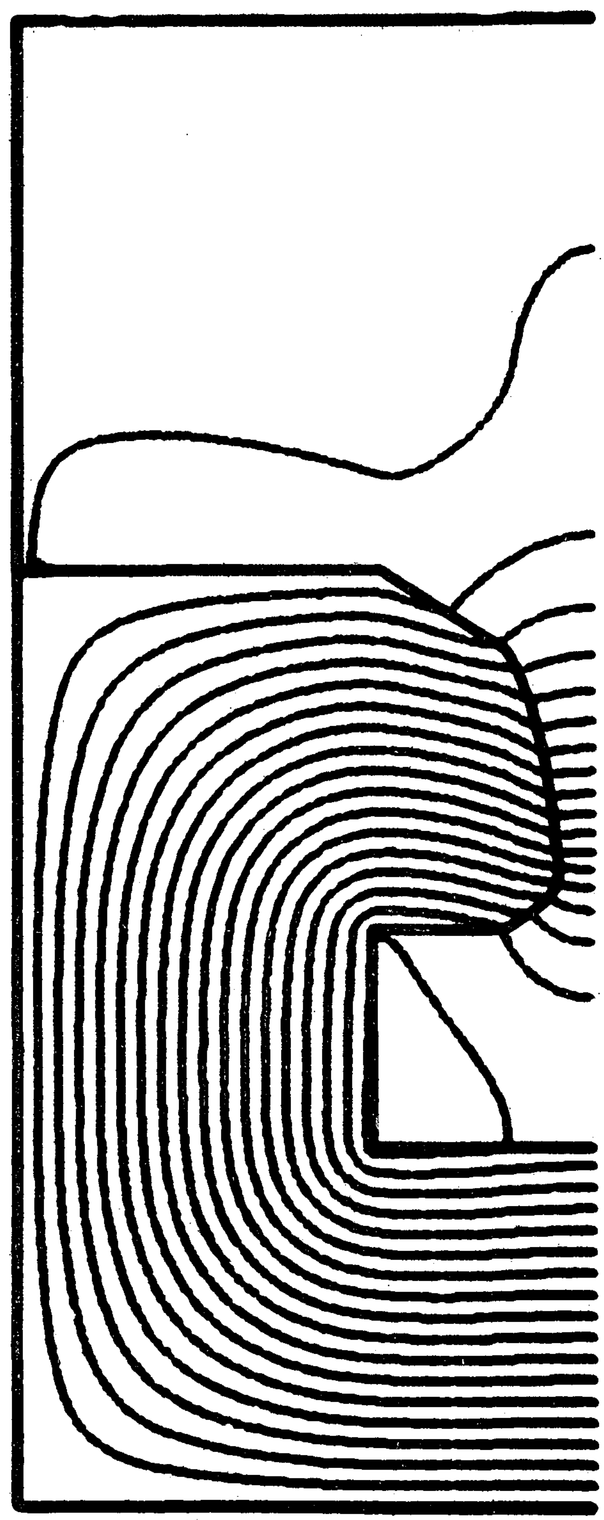
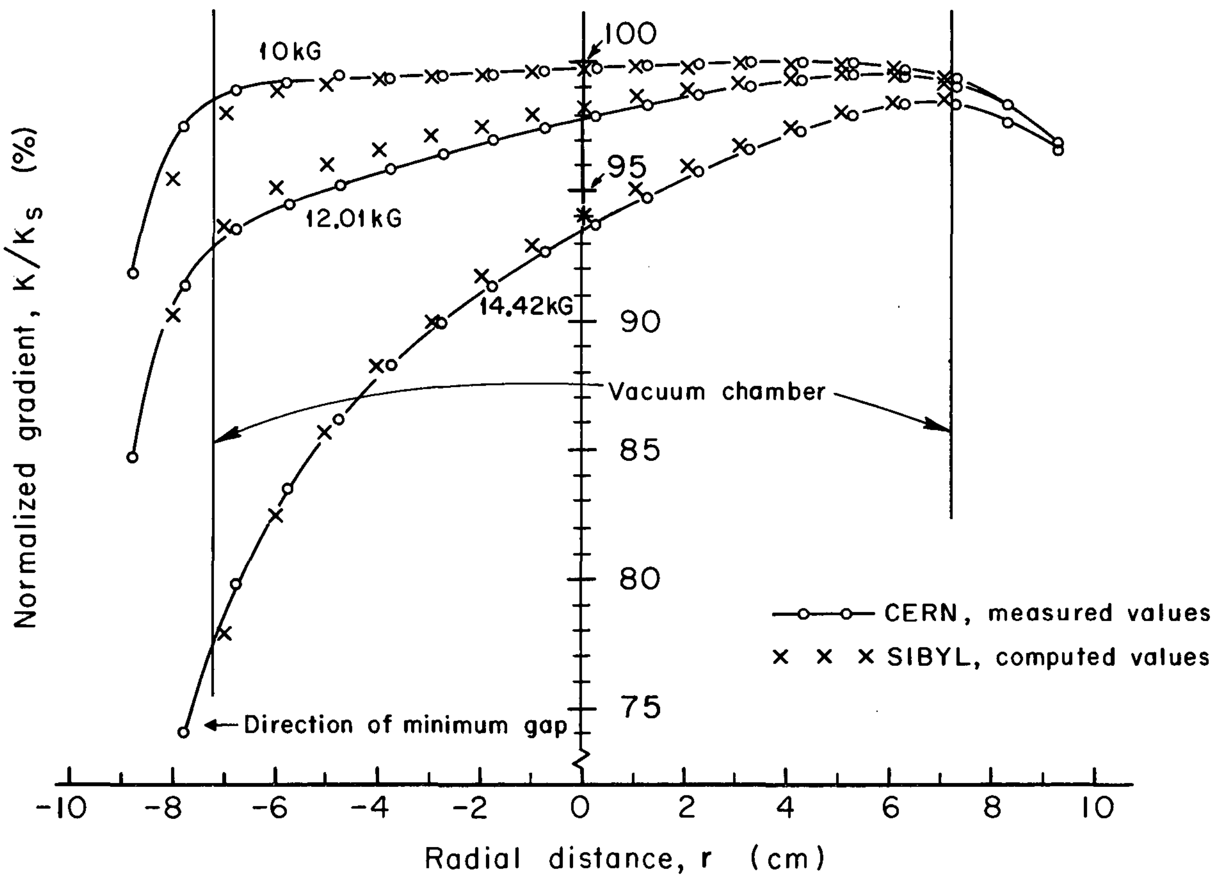


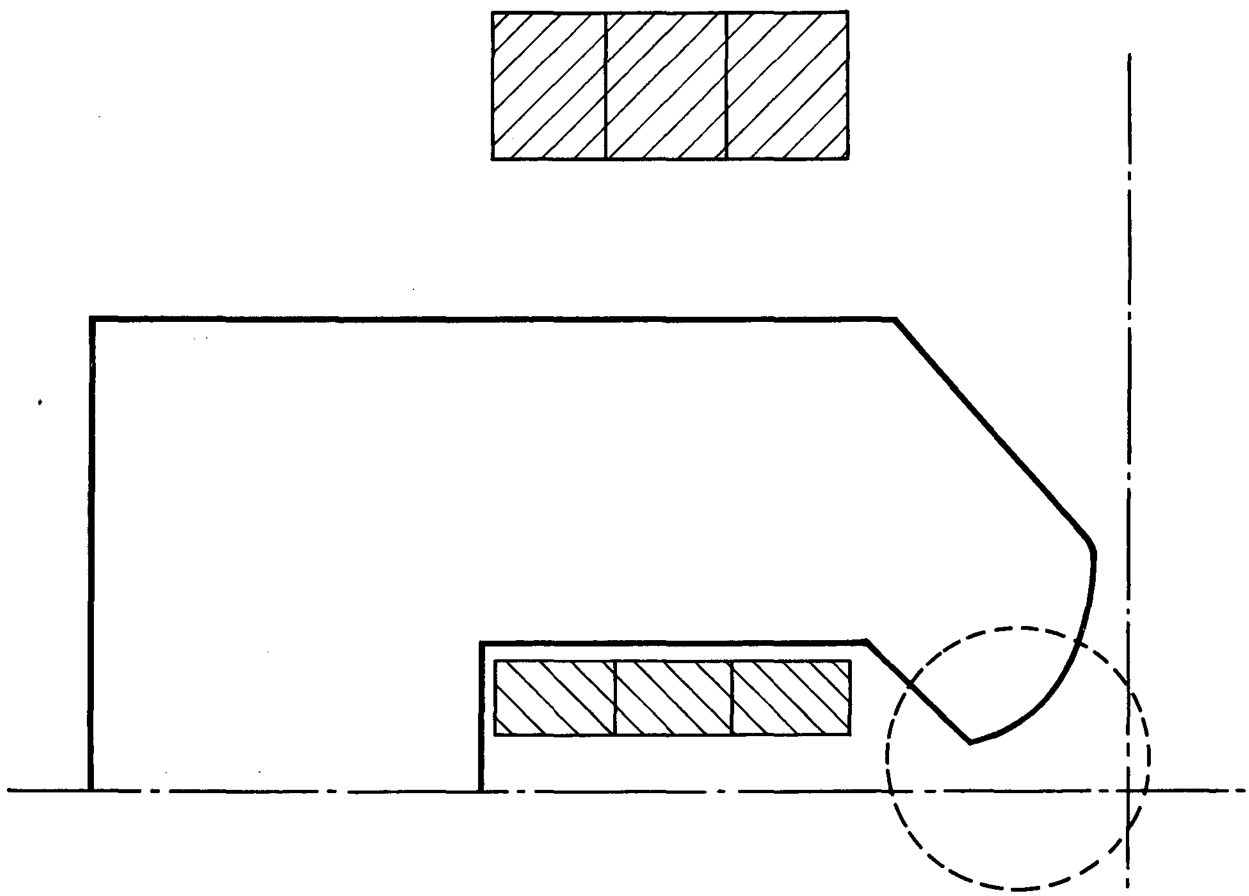
Fig. 4.

MUB-7819



MUB-5441

Fig. 5



MUB-7751

Fig. 6

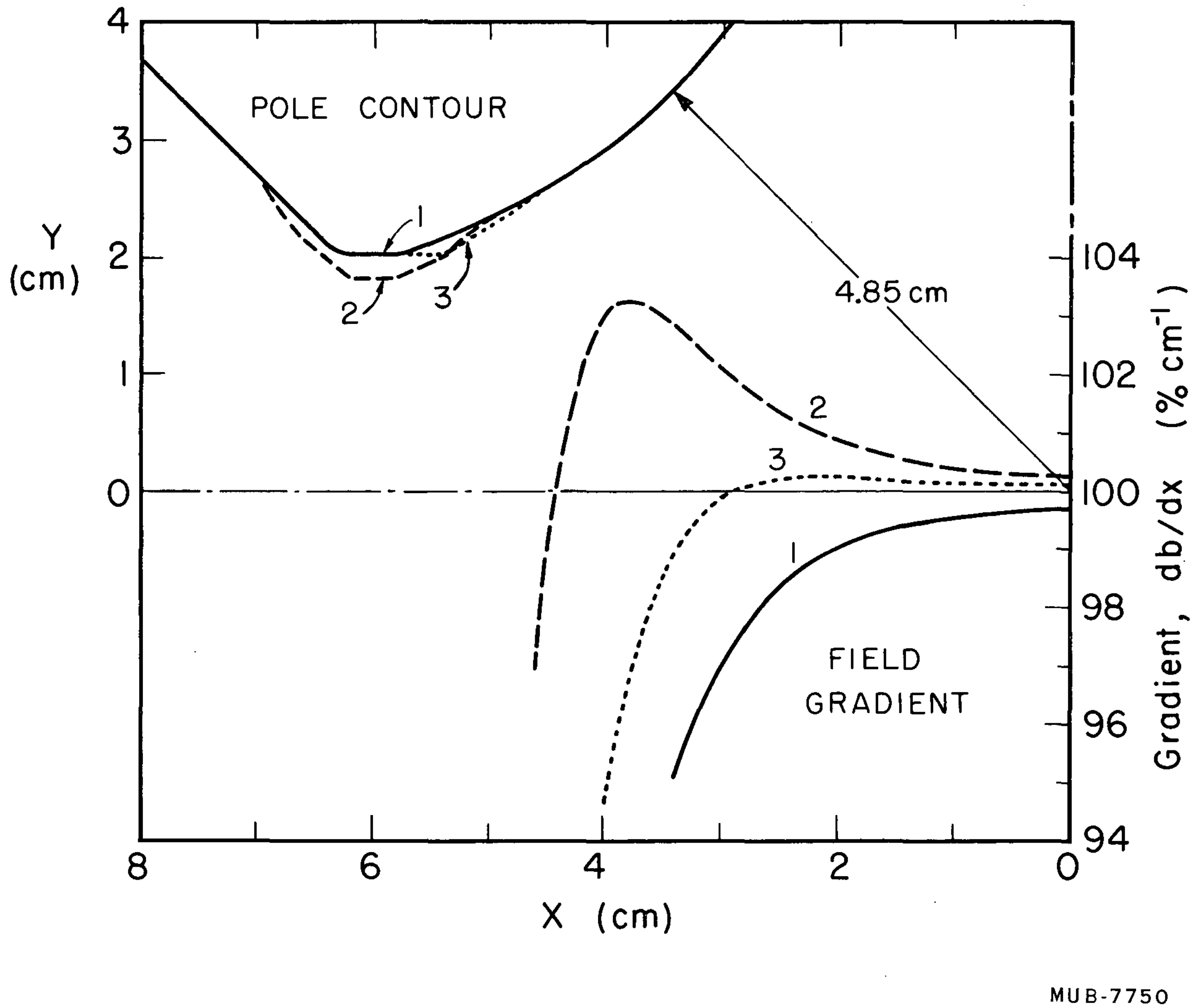

POLE CONTOUR
Y (cm)
4.85 cm
FIELD GRADIENT
X (cm)
Gradient, db/dx (% cm^{-1})
MUB-7750

Fig. 7

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