Title
CALCULATION OF TWO-DIMENSIONAL MAGNETIC FIELDS BY DIGITAL DISPLAY TECHNIQUES

Permalink
https://escholarship.org/uc/item/1jv6v42n

Author
Colonias, John S.

Publication Date
1967-04-28

UCRL-17340

University of California

Ernest O. Lawrence Radiation Laboratory

CALCULATION OF TWO-DIMENSIONAL MAGNETIC FIELDS BY DIGITAL DISPLAY TECHNIQUES

Berkeley, California

For Proceedings of the
Second International Conference
on Magnet Technology, Oxford, England,
July 1-14, 1967

UCRL-17340
Preprint

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

CALCULATION OF TWO-DIMENSIONAL MAGNETIC FIELDS BY DIGITAL DISPLAY TECHNIQUES

John S. Colonias

April 28, 1967

CALCULATION OF TWO-DIMENSIONAL MAGNETIC FIELDS BY DIGITAL DISPLAY TECHNIQUES*

John S. Colonias

Lawrence Radiation Laboratory
University of California
Berkeley, California

April 28, 1967

ABSTRACT

The purpose of this paper is twofold. It describes first a method by which two-dimensional (including axially symmetric) magnetic fields may be calculated by utilizing digital display techniques, and second the manner in which this method is used in designing magnets "on line" with a computer system.

The digital display technique used allows the experimenter to draw the magnet geometry on a cathode-ray-tube screen, it permits the use of a light pen to introduce perturbations or alter various magnet dimensions as necessary, and it displays the resulting field distribution, along with various pertinent curves at the option of the user.

The computer programs utilized in this method involve existing magnetostatic programs properly modified to include axially symmetric conditions, and their speed has been increased for fast interactions with the light pen.

The utilization of this method is demonstrated by the design of an axially symmetric correlation spectrometer magnet, and it is shown that the computed results have an excellent agreement with those measured.

---

*Work supported by the U. S. Atomic Energy Commission.

INTRODUCTION

Recent use of magnetostatic computer programs and advances in computing machinery have speeded up the calculation of magnetic fields. Faster computers and introduction of on-line graphic display systems open new horizons in the man-machine relationships. Conventional input-output devices gradually give way to remote inquiry stations, and light pens or similar styluses allow the experimenter to "talk" with the computer and participate in a dynamic sense.

This paper describes use of graphic display systems in calculating magnetic fields.

MAN-MACHINE INTERACTING SYSTEMS

At present, man-machine interacting systems, in general, involve the user in a passive way: he is responsible for the formulation of the mathematical model and for the transformation of the model into a program--i.e., a set of symbolic expressions describing the model in the language of the particular computer. Upon submitting this program to the computer he receives a set of results which somehow describe the performance of the model specified. If this performance is not satisfactory, repeated attempts are made until an acceptable solution is found. Thus the experimenter is only passively involved, and the dynamic response of his system is buried under a few pages of FORTRAN statements. If, however, the user can somehow interact with the computer and direct the progress of the solution on the basis of information displayed on some graphic device, then the response of his system is dynamic.

Such an interacting process requires (a) availability of display devices suitable for on-line graphical use, and (b) some standards of quality.

1. The device must produce accurate pictures with legible characters, well focused, and with good resolution. 2. The flicker rate must be high enough so that one does not have to wait 2 or 3 minutes for a display to be refreshed. 3. The modification time must be short (this is probably most important to the user). Though we have become accustomed to waiting for 3 to 6 hours for results from a conventional input-output device, we become impatient upon waiting 2 to 3 minutes at an on-line console. The system must have a fast response. 4. A light pen or some similar stylus must be available, with appropriate pen-tracking hardware and software, and with the capacity of pointing. That is, the input device must allow the user to point to some feature and tell the computer "I want to add a line <u>here</u> or I want to modify <u>this</u> curve."

A system with these characteristics (represented in Fig. 1), is now in use with our CDC 6600 Computer system.

CALCULATION OF MAGNETIC FIELDS

The mathematical model involved in the application under consideration has been set forth in previous papers;[1, 2] however, for the sake of continuity a brief description follows:

A wide and significant class of phenomena in many areas of science and engineering may be described by Poisson's equation,

$$\vec{\nabla} \cdot (\lambda \vec{\nabla} \cdot \vec{\phi}) + S = 0, \qquad (1)$$

where λ is a function of ϕ or its derivatives, S is a function of position, and ϕ is specified on the boundary. That Poisson's equation describes magnetostatic problems may be shown by making use of the magnetic vector potential $\vec{A}$. The magnetic field, $\vec{B}$, may be determined from the magnetic vector potential $\vec{A}$, by

$$\vec{B} = \mu\vec{H} = \vec{\nabla} \times \vec{A}, \tag{2}$$

and the curl of the magnetizing force $\vec{H}$ is equal to

$$\vec{\nabla} \times \vec{H} = 4\pi\vec{J}, \tag{3}$$

where $\vec{J}$ is the current density.

Substituting $\vec{H}$ from Eq. 2 into Eq. 3 gives

$$\vec{\nabla} \times (\frac{1}{\mu}\, \vec{\nabla} \times \vec{A}) = 4\pi\vec{J}. \tag{4}$$

Now, since $\vec{A}$ and $\vec{J}$ each have only one component (for two-dimensional problems) Eq. 4 reduces to

$$\nabla \cdot (\gamma\, \vec{\nabla} \cdot \vec{A}) = 4\pi\vec{J}, \tag{5}$$

where $\gamma = \frac{1}{\mu}$.

Equation 5 is of the form of Eq. 1, and it is approximated by finite-difference equations, which are solved by a relaxation process.

Recent additions to the existing programs include the calculation of cylindrically symmetric magnetic fields and the calculation of magnetostatic energy in both air and iron regions.

The computation model of this program is described (in the references) as consisting of an irregular triangular mesh of about 4000 points, on which the magnet geometry is outlined. No geometrical restrictions are imposed on the magnet; symmetrical planes may or may not be included, depending upon the requirements of the problem; any current distribution may be considered; also several different kinds of iron may be used in the same magnet.

The calculation of magnetic fields involves basically five distinct stages: preparation of input data; generation of the resulting triangular mesh; examination of CRT plots to insure proper triangle distribution (repeated attempts may be necessary before good "zoning" is produced); calculation of the resulting field distribution; generation of field distribution plots.

Under the present graphic display method these five stages have been combined in the manner described below.

GRAPHIC DISPLAY METHOD

a. Preparation of Input Data

Under the graphic display method, the geometry of the magnet is drawn on a CRT screen with a light pen, while the coordinates of the specified boundary points may be entered either by a teletype attached to the CRT console or with a light pen. Let us consider an example.

Figure 2 shows an electron directional correlation spectrometer used to investigate the correlation between successively emitted nuclear radiations.[3] The magnetic lens of this spectrometer was chosen to show both the generality of the program and its ability to calculate fields possessing axial symmetry.

The experimenter proceeds with the light pen to describe, in a clock-wise direction, the intersection of the coordinates of each point desired, and the computer interpolates for nonspecified boundary points. He then enters the (x, y) coordinates of each specified point, beginning from some arbitrary reference point. In case of curved boundaries, a generalized pole-face routine has been prepared which allows the user to describe on the CRT console ellipses and hyperbolas as well as straight-line segments.

Figure 3 shows the completed geometry of the magnet as simulated on the irregular triangular mesh. (Details of the triangular coordinate system appear in Refs. 1 and 2.) Once the magnet geometry has been completed the computer, under the direction of the user, proceeds with the next phase.

b. Generation of Triangular Mesh

Here the computer produces a triangular mesh to conform with the requirements imposed by the magnet geometry, and displays it on the CRT screen so that the user may make sure that the distribution of the interior points made by the computer is smooth and that the generated mesh has relatively few triangles with obtuse angles or elongated sides (which would hamper the convergence of the problem). If he finds irregularities, he may rectify them by using the light pen and the functional keyboard attached to the CRT console. He may also check that input data are correctly displayed and the magnet geometry properly represented.

In the case of input error (as shown in Fig. 4) or if the user wants to change any portion of the displayed geometry he proceeds as follows:

a. He points the light pen at the point where the error appears or at the point he wants to change.
b. He presses the "interrupt" button.
c. Next, he moves the light pen to the new location desired.
d. He presses the "interrupt" button.

Immediately, the screen is refreshed with the corresponding change displayed or the error corrected. This process may continue until the experimenter is satisfied that both the geometry and the distribution of triangles are correct. Figure 6 shows various portions of the generated mesh.

c. Execution of Main Program

The main program is initiated by the experimenter from the console, once he is satisfied that the generated mesh properly represents the magnet geometry under consideration. He may view the progress of the solution to check convergence, or wait for the final solution. The final flux distribution in both air and iron is displayed, as well as pertinent curves relating to the character of the solution on the median plane and elsewhere in the magnet.

The experimenter either accepts this solution as satisfactory and records the results on microfilm for permanent record, or takes action to change some input parameters, according to the needs of the experimenter. Thus the calculation loop is closed with the experimenter dictating the action to be taken.

PROGRAM CHARACTERISTICS AND TIME RESPONSE OF THE PROGRAM

The adaptation of this program for graphic display purposes is outlined in Fig. 7, which shows the overall flow chart of the program FIELD. The time response is almost instantaneous except in blocks 11 and 12. Here the response is perceptibly slow, depending on the number of points used to simulate a magnet. That is, an 800-point problem requires about a minute; a 2500-point problem, about 5 minutes; and a 4000-point problem, 15 minutes.

Since the accuracy of the solution is a function of the number of mesh points used, the maximum number of points should be utilized to obtain the maximum attainable precision. This, however, drastically reduces not only the time response of the system, but also the feasibility of the program, since it requires about 214000_8 memory locations for a 4000-point program, and such a large amount of memory cannot be easily allocated to an experimenter even with a multiprocessing computer system such as the CDC 6600. For this reason a "strategy" was devised which would reduce the time to about 1/6 and the storage required to about 1/5. This strategy consists of the following scheme: (a) Simulate a magnet by a coarse mesh, say 30×30. (b) Obtain a solution. (c) Determine the region at which the highest accuracy is required. (d) Enlarge this region. (e) Insert the vector potentials obtained from the coarse solution in the enlarged region. (f) Interpolate for the in-between vector potentials. (g) Freeze the boundary, and finally solve this enlarged or "zoomed" region.

This scheme was used in the magnet shown in Fig. 5 with excellent results. We first ran this magnet with a 50×50 mesh and saved the results for comparison; then we ran the same magnet with 25×25 mesh. We zoomed the region within the poles shown in Fig. 7 to a 17×17 mesh, and solved the 17×17 mesh with fixed boundary obtained by interpolating from the vector potentials of the 25×25 solution. The results were almost identical to the 50×50 solution, indicating that a coarse mesh may be used as an initial solution and the region where high accuracy is desired may be "zoomed"; significantly less time and core memory are used without sacrificing accuracy.

Figure 8 shows the flux distribution for the magnet in Fig. 5, and Fig. 9 shows the flux of the zoomed region.

This method has not been programmed yet, as further experimentation with interpolating routines is needed to obtain a better understanding and experience in this type of boundary problem.

ACCURACY OF COMPUTED RESULTS

The accuracy of the computed results was obtained by comparing the measured values of the previously discussed electron spectrometer. The computed and measured B_z component of the field as a function of radial distance is shown in Fig. 11. As can be seen, the computed values of B_z are within 1% of the measured values.

A flux distribution for this magnet is shown in Fig. 10. Here we should be careful in interpreting the lines shown. In the rectangular version such as shown in Fig. 8, the lines are lines of constant $\vec{A}$ (vector potential), and in the axially symmetric version the lines shown are lines of constant $r\vec{A}$ (where r is the radius of rotation), and the gradient of rA, gives the intensity at the field, $\partial(rA)/\partial S = -rB$, where B = flux density.

CONCLUSIONS

Perhaps the most obvious conclusion is that great progress is being made in this field. Only a few years ago magnetic fields were calculated by either graphic or analog (electolytic tank) methods (not to mention conformal mapping and Schwartz-Christoffel transformations). Now, utilization of digital display techniques and light-pen interactions will show the way for new approaches in calculating magnetic fields; for three-dimensional fields which might be calculated by somehow rotating on CRT screen its two-dimensional counterpart; and for a host of other interesting problems associated with the design of magnets for higher energy particle accelerators.

Even though this application of graphic display techniques is still experimental, it definitely shows that graphic communication is important in computer technology, and an effort should be made by both manufacturers and users to improve both hardware and software.

ACKNOWLEDGMENTS

The author expresses his appreciation to Dr. Kleinheinz for his permission to use the correlation spectrometer measurements, to Dr. David Newton for his assistance in evaluating the spectrometer magnet, and to James Spoerl, Robert Healey, Bobby Powell, Bruce Burkhart, and Richard Ahlstrand for their programming assistance.

REFERENCES

1. A. M. Winslow, Magnetic Field Calculations in an Irregular Triangle Mesh, UCRL-7784-T Rev-1, Aug. 23, 1965.

2. J. S. Colonias and J. H. Dorst, Magnet Design Application of the Magnetostatic Program called TRIM, UCRL-16382, Sept. 1, 1965.

3. P. Kleinheinz, L. Samuelsson, R. Vukanović, and K. Siegbahn, A Four-Detector Electron Directional Correlation Spectrometer, Nucl. Instr. Methods <u>32</u>, 1 (1964).

FIGURE CAPTIONS

Fig. 1. Organization of the CDC 6600 computer system.

Fig. 2. Electron directional correlation spectrometer.

Fig. 3. CRT display of the simulated spectrometer magnet.

Fig. 4. CRT display of input error creating negative triangles.

Fig. 5. CRT display of the window-frame magnet used to experiment with "zooming."

Fig. 6. Generated mesh for various portions of the spectrometer magnet.

Fig. 7. Overall flow chart of program FIELD.

Fig. 8. Flux distribution of the window-frame magnet shown in Fig. 5.

Fig. 9. Flux distribution of the "zoomed" region.

Fig. 10. Computer plot showing flux distribution (constant $r\vec{A}$) for spectrometer magnet.

Fig. 11. Calculated and measured B_z component of field on the axis normalized to units of maximum.

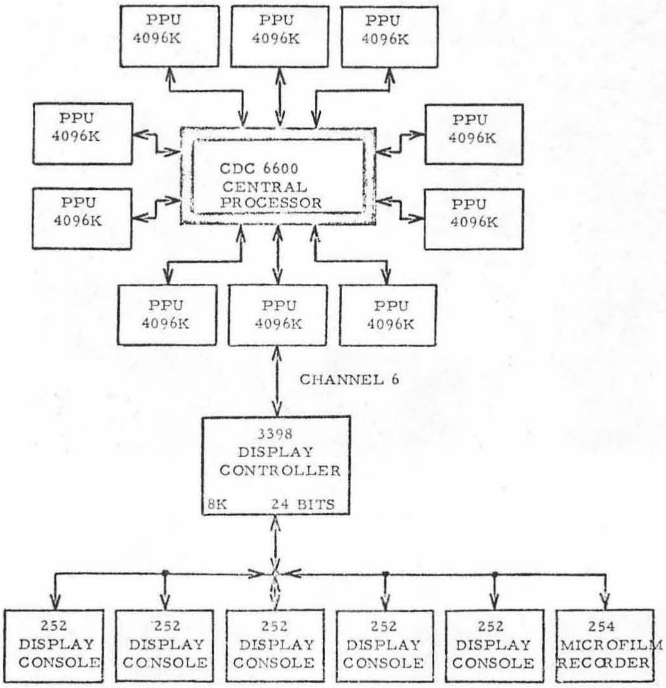

PPU 4096K
PPU 4096K
PPU 4096K
PPU 4096K
CDC 6600 CENTRAL PROCESSOR
PPU 4096K
PPU 4096K
PPU 4096K
PPU 4096K
PPU 4096K
PPU 4096K
CHANNEL 6
3398 DISPLAY CONTROLLER
8K 24 BITS
252 DISPLAY CONSOLE
252 DISPLAY CONSOLE
252 DISPLAY CONSOLE
252 DISPLAY CONSOLE
252 DISPLAY CONSOLE
254 MICROFILM RECORDER

Fig. 1

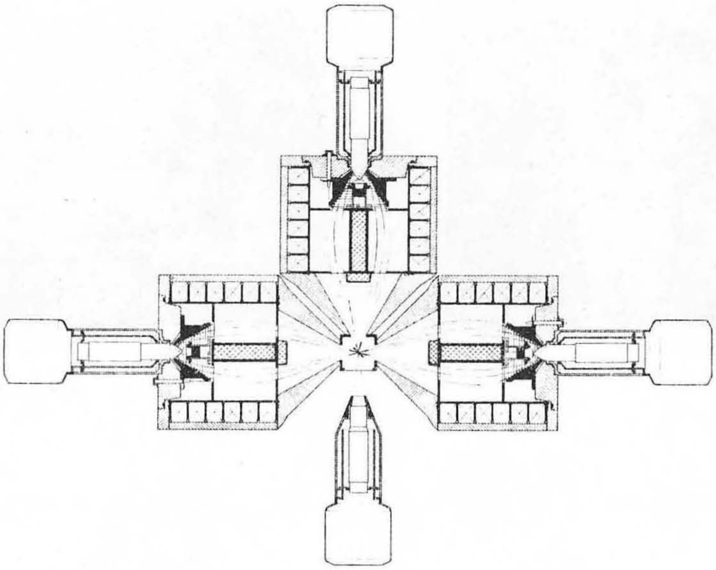


Fig. 2

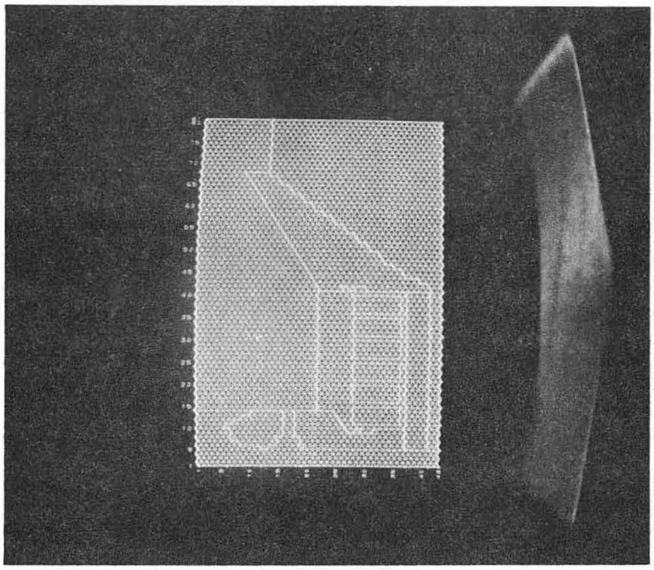


Fig. 3

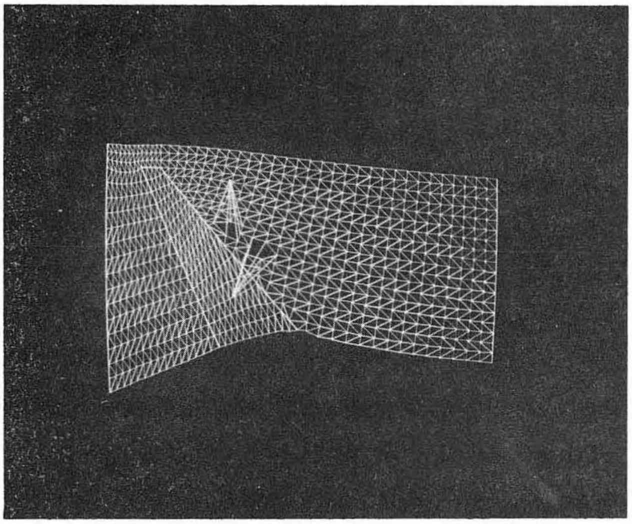


Fig. 4

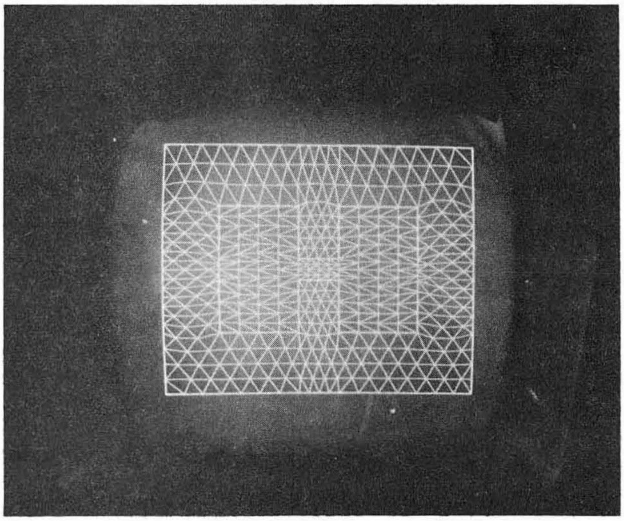
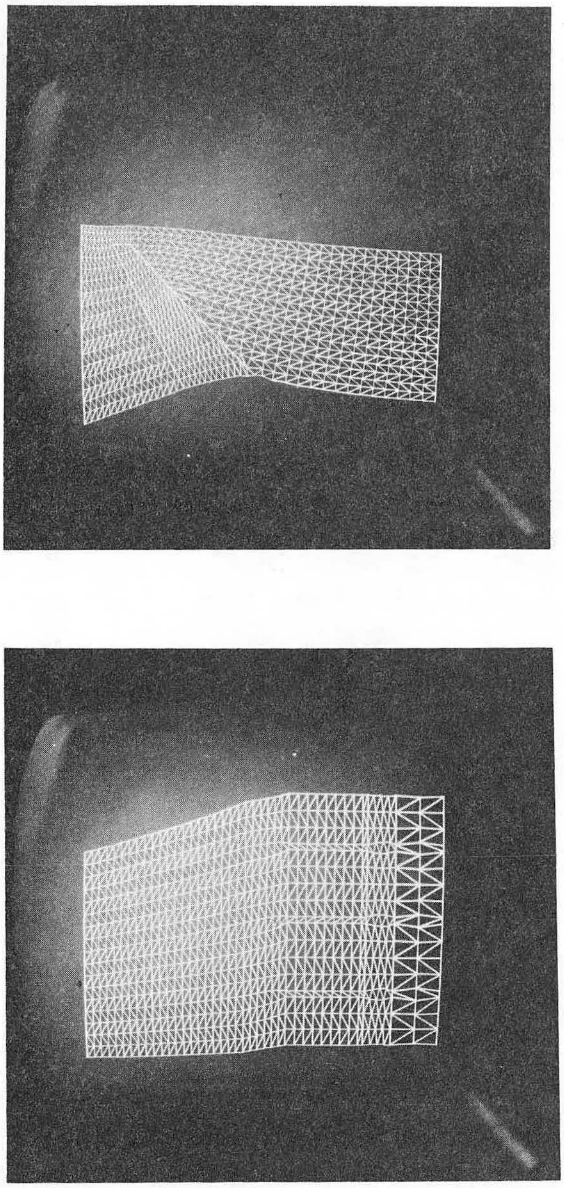


Fig. 5

XBB 675-2488



XBB 674-2426

Fig. 6

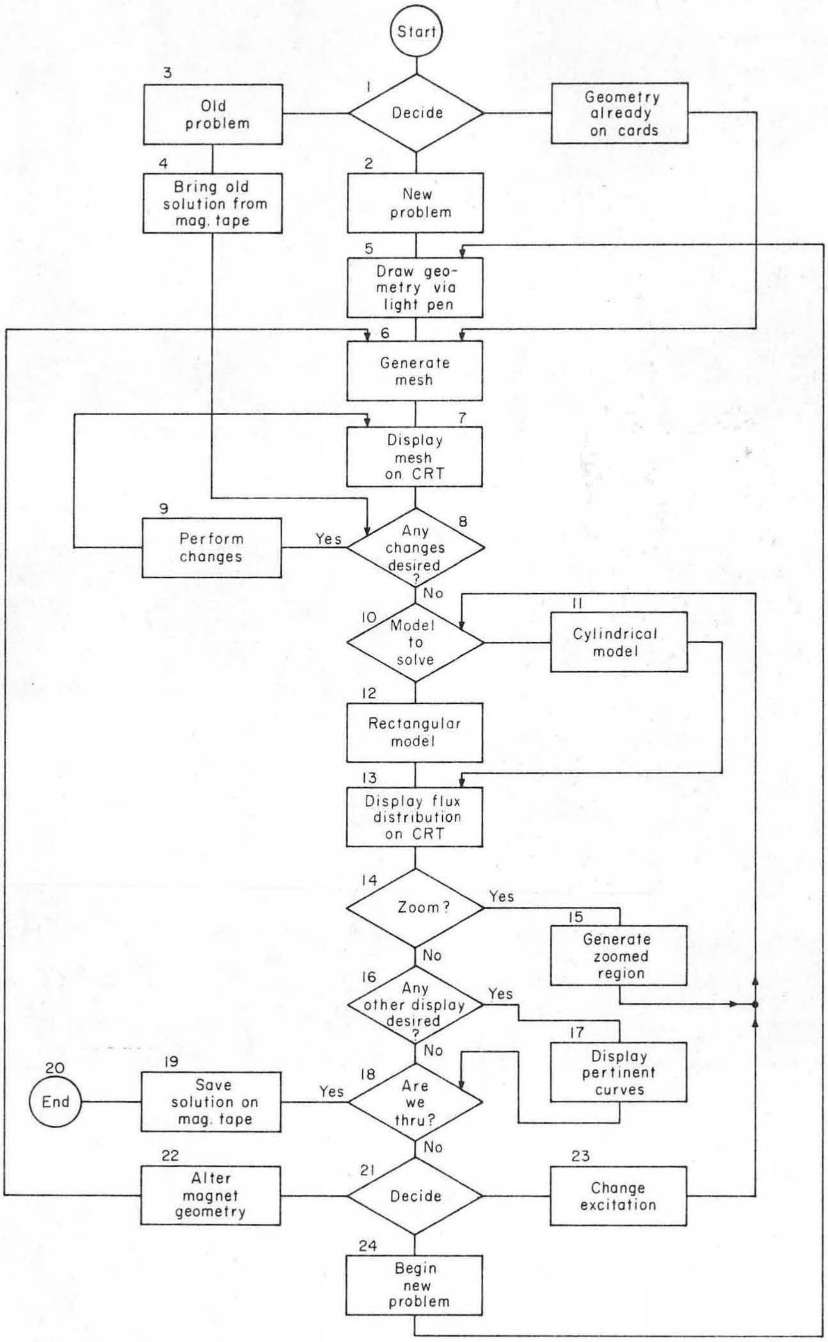


Fig. 7

XBL674-2211

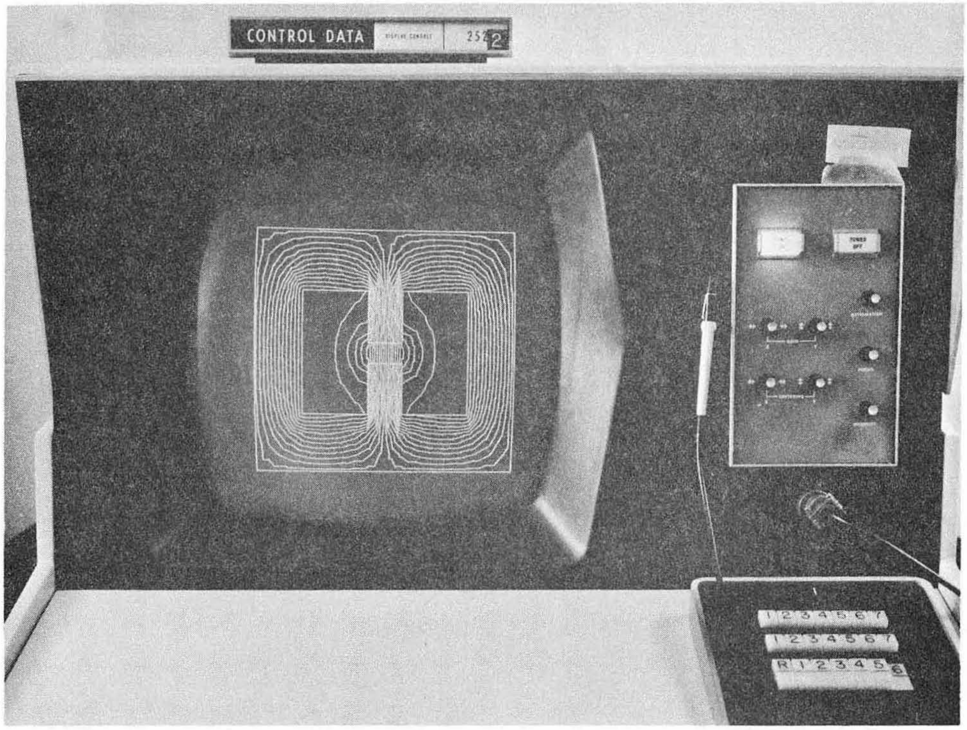


Fig. 8

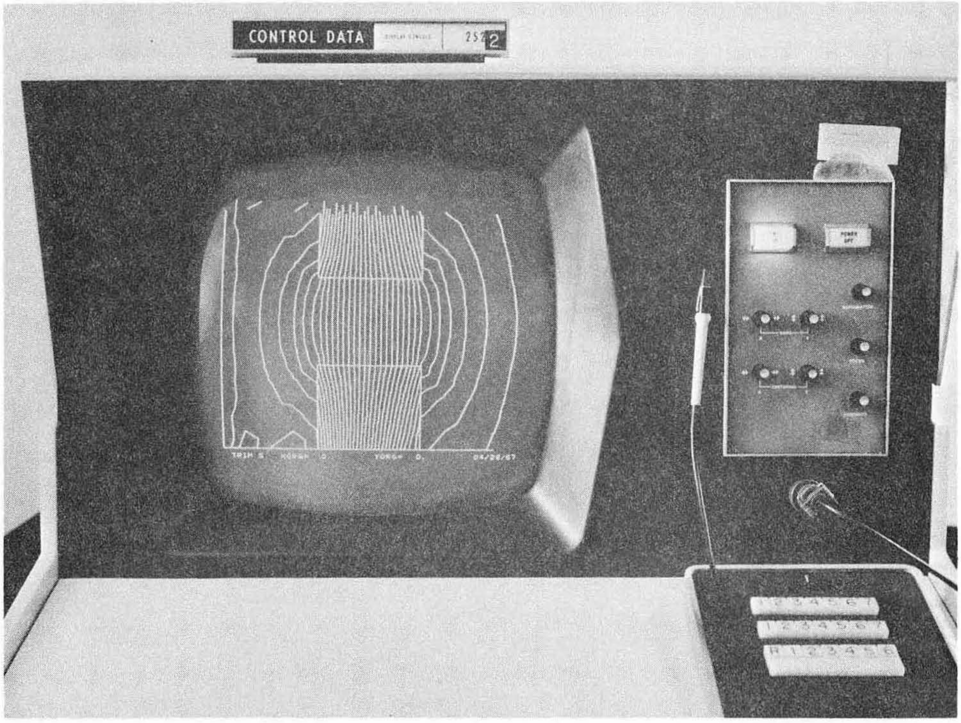


Fig. 9

XBB 675-2489

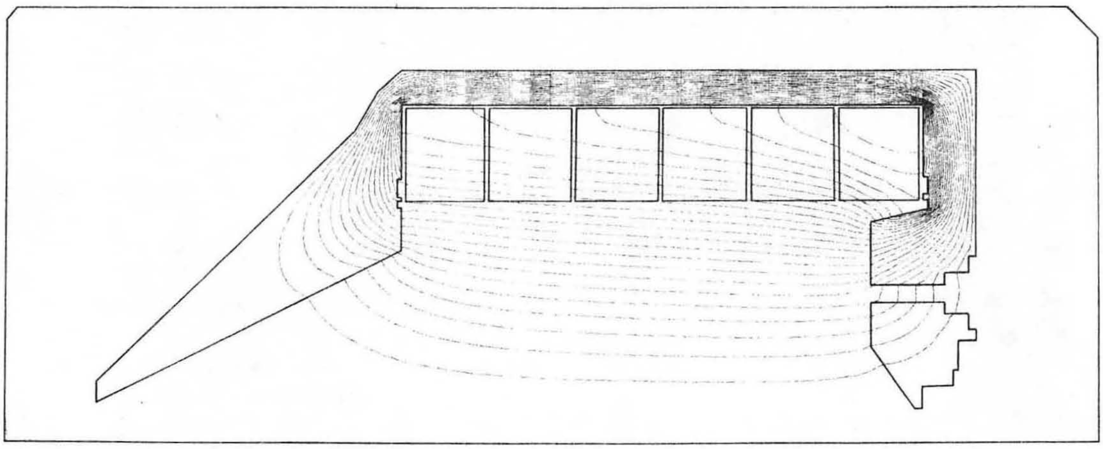
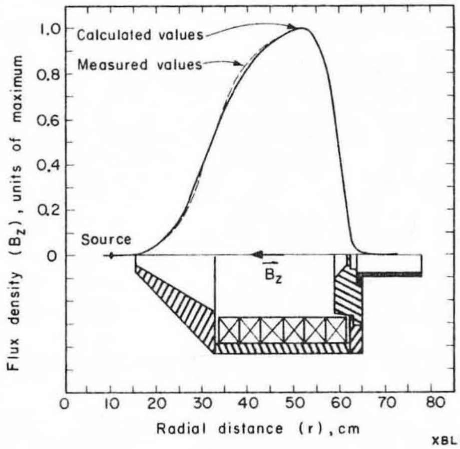


Fig. 10



XBL 675-3034

Fig. 11