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ABSTRACT

This paper deals with the methodology of magnet technology and its application to various engineering devices. Magnet technology has experienced a rapid growth in the past few years as a result of the advances made in superconductivity, numerical methods and computational techniques. Specifically, this paper concerns itself with:

(a) Mathematical models for solving magnetic field problems;
(b) The applicability, usefulness, and limitations of computer programs that utilize these models;
(c) Examples of application in various engineering disciplines;
(d) Areas where further contributions are needed.

The author hopes that this paper will facilitate the communication of information between scientists and engineers, and the exchange of new ideas.

1. INTRODUCTION

Only 20 years ago the magnet technologist's options in calculating magnetic fields were virtually nonexistent, if one discounts resistance networks, electrolytic tanks, wire filaments and such now seemingly archaic analog devices. In less than two decades magnetic field calculations have developed to their current levels of sophistication at an explosive pace rivaling that of digital computers. If this pace continues, prospects for the future make one giddy.

Before attempting to "crystal-ball" the future, let us examine the state-of-the-art today, and ascertain the mathematical and applicational trends that exist. Let us look briefly at the mathematical models available, where they are used effectively and how one can select the most appropriate computer program for a specific application.

2. TWO BASIC MATHEMATICAL METHODS

Currently, electromagnetic field problems can be formulated by either a differential equation approach or an integral equation approach, with both methods leading to similar computational schemes that involve the solution of many simultaneous equations. Both approaches substitute a discrete problem for a problem defined on a continuum, and then efficiently solve the resultant set of equations that serve to define the approximate solution of the continuous problem. The differential equation approach discretizes these equations by means of finite differences, while the integral equation approach uses the finite-element method, which depends on formulating a functional and finding its maximum or minimum by a variational technique. Although the finite-element technique is becoming quite popular in magnetic field applications, the finite-difference method is widely used still where simplicity of programming and mesh generation are important.

Once the problem has been formulated and discretized, the resulting system of equations may be solved by iteration or elimination. Point and block overrelaxation schemes are used for linear and nonlinear equations that result from the finite-difference formulation, while elimination methods are used with the finite-element technique.

3. COMPUTER MODELS

The basic methods mentioned above have instigated a large number of computer programs, which are capable of solving Maxwell's equations with various degrees of success, efficiency, accuracy, and speed. These programs are capable of calculating

1. Magnetic field components for static or time-varying problems in two- or three-space dimension for both linear and nonlinear problems;
2. Eddy currents;
3. Forces, energy, inductance, etc.

Most of these programs use a mesh on which the magnet geometry is outlined. The mesh may be square, rectangular, triangular or, in the case of three-dimensional programs, prismatic.

Some of the programs are characterized by extensive graphic facilities, which allow the user to interact with the computer at selected levels of sophistication and convenience. Most of these programs are general enough to accept virtually any geometrical consideration; others are restricted to solving a specific class of problem. Although it is not the purpose of this paper to enumerate the computer programs available for magnet design, nor to present a judgment as to which programs are "better," the programs listed in Table I are presented as probably those most widely used throughout the world. They offer most of the desirable characteristics mentioned earlier; they are being constantly updated to improve their efficiency and speed, and they are available to any organization that desires to use them. Short descriptions follow.

Program TRIM,[1] is perhaps the most generally accepted, two-dimensional program. It is extremely flexible, accepts virtually any combination of conductors and ferromagnetic material, and has generalized boundary conditions that allow the simulation of any conceivable magnet geometry in both Cartesian and cylindrical coordinates.

The program is written in FORTRAN and machine language, and it is operational on the CDC 6600/7600 and numerous other computers. It is divided into three separately executable programs: the mesh generator, MESH; the magnetostatic program, FIELD; and the plotting package, TRIP. The purpose of MESH is to construct the irregular triangular mesh for an H-magnet, an example of which is shown in Fig. 1.

TRIM requires approximately 152(octal) memory locations for a 4000-point problem. The solution algorithm is formulated on the finite-difference approach, the resulting equations approximate the vector potential, which is used for both the air and iron regions of the problem.

GFUN[2] is an excellent program, developed by Trowbridge of the Rutherford High Energy Lab in Great Britain. It calculates magnetic fields in two and three dimensions (actually it is the only available 3-D program). It uses the integral approach mentioned earlier. The 3-D version occupies approximately 2M bytes of memory on the IBM 360/195 computer and it takes about 45 minutes to solve for a problem consisting of 220 blocks of iron. It is fully interactive with excellent graphic capabilities. GFUN is being constantly updated to improve the solution algorithms as well as the speed of convergence.

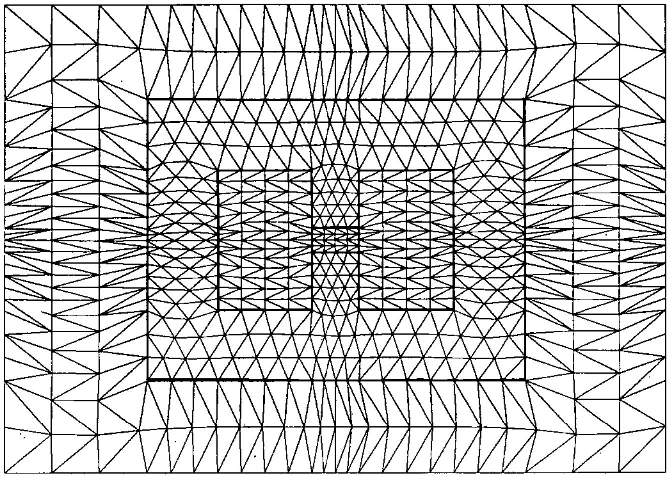

Fig. 1. Triangular mesh generated by program TRIM for a typical H magnet.

Program MAREC,[3] was developed by Perin at the CERN facility in Switzerland. It uses the finite-difference approach to approximate the two-potential problem: the modified scalar potential used in the air regions of the problem, and the vector potential in the iron regions. This program has been used at CERN almost exclusively to design magnets for their large particle accelerators.

Program MAFCO,[4] developed by Brown and Perkins from Lawrence Livermore Laboratory of the University of California, calculates magnetic fields resulting from any arbitrary two- or three-dimensional geometry of current-carrying conductors in the absence of ferromagnetic material. The solution is generated by using standard techniques and by numerically evaluating well-defined elliptic integrals. MAFCO is a very general program and is used extensively.

The accuracy with which these programs calculate magnetic fields is difficult to ascertain because many factors are involved, which are not the same for each program. For example, in program TRIM one obtains slightly different answers to a problem, depending on the type of grid used; in GFUN the accuracy is a function of the number of "iron blocks" used to simulate the ferromagnetic material; in others the errors depend on the numerical methods used to evaluate the solution function. The programs listed in Table I offer good accuracy that has been experimentally verified in most cases: For example program TRIM can produce solutions to better than one-half of one percent in the magnetic field, and approximately 1.0% in the gradient. Program GFUN produces results of similar accuracy.

TRIM takes approximately 2.0 minutes to solve a 4000-point problem on the CDC 7600. However, each problem does not behave the same, and the amount of time required to solve a problem varies from about 10 seconds (for linear problems) to 5.0 minutes for problems having many iron points.

4. APPLICATIONS

The application of magnet technology in our industrial complex has increased dramatically with the advent of superconductors, which can withstand considerable magnetic fields. Presently the range of applications spans nearly the entire spectrum of our industrial society, from fusion reactors and magnetic separators to the design of magnetic catheters in the medical field.

TABLE I

Computer Programs for Magnetic Field Computations

Name	Method of Solution	Type of Grid	Remarks
TRIM	Finite difference	Triangular, variable	General purpose. Good agreement with measurements. Two-dimensional simulation.
GFUN	Integral formulation Dipole magnetization	None	General purpose. Good agreement with measurements. Two- and three-dimensional simulation.
MARE	Finite difference Two potential: Scalar & Vector	Rectangular	Good agreement with measurements. Fast. Less satisfactory for highly saturated magnets.
MAFCO	Analytic (elliptic integrals)	None	Two- or three-dimensional. No ferromagnetic material allowed. Generalized boundaries.

In this paper I will not try to delimit the range of applications of the programs appearing in Table I, but rather, I will selectively show that indeed they can be utilized in a wide range of problems. For this purpose, I will outline some applications with which I am personally familiar.

Program TRIM is used in these applications not because it is necessarily the best program to use, but because it is one that I am more familiar with; similar results may be obtained with any of the programs listed in Table I.

4a. Particle Accelerator Design

High-energy physics has offered a reliable test-bed for superconducting magnets, by demonstrating their advantages and disadvantages under severe operating conditions. Presently, at Berkeley, a new facility is being designed called Experimental Superconducting Accelerator Ring (ESCAR), the "mini-accelerator." This accelerator will be shaped almost rectangular with rounded corners having an average radius of 15 meters, and an energy of 4.2 GeV (maximum). It will consist of 24 dipole magnets and 32 quadrupole magnets. These magnets will be designed and optimized by computer programs such as the ones mentioned earlier. A model of the superconducting dipole magnet[5] is shown in Fig. 2. In this magnet the quality of the magnetic field is predominantly dictated by the positioning of the conductors and secondarily by the shape or position of the iron jacket. Computer simulation is mandatory to effect the best possible quality of the magnetic field. Such simulation is shown in Fig. 3, which shows the TRIM-generated mesh. The computed flux distribution is shown in Fig. 4. We learned quite a few lessons by using TRIM to calculate high magnetic fields. Such lessons indicated the need to reformulate the existing boundary conditions to create more reliable ones. A model of this superconducting magnet has been built and it is undergoing measurements. The quadrupole magnets will have to be simulated by a three-dimensional program such as GFUN, since they are short and fringe fields are predominant.

4b. Calculation of Cable Tension[6]

TRIM's diversity is demonstrated by the following example which involves the calculation of tension or loading on any device, such as a crane, where cable loading is of importance. Figure 5 shows such a crane on which a "Vibra-Tension" device has been installed on the boom-tip section to measure the tension on the cable, by which is calculated the percent of loading. Briefly, the operation of this device consists of sensing the vibration of the boom cable or chain whose tension is to be measured, and transmitting the signal indicating the frequency of vibration to a control unit. There the signal is amplified and processed to control power supplies which drive an electromagnet in the

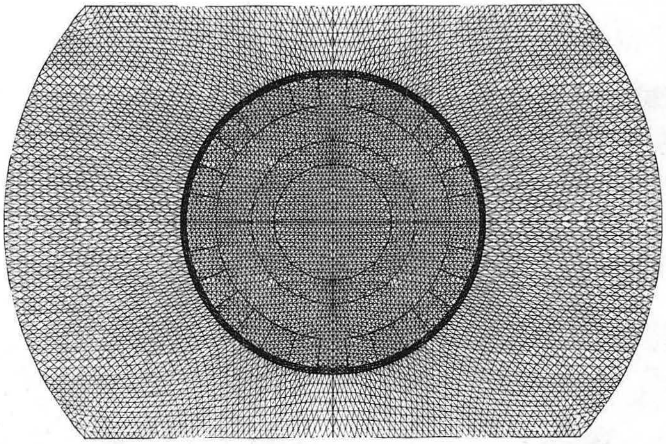

Fig. 3. TRIM mesh for the ESCAR dipole magnet.

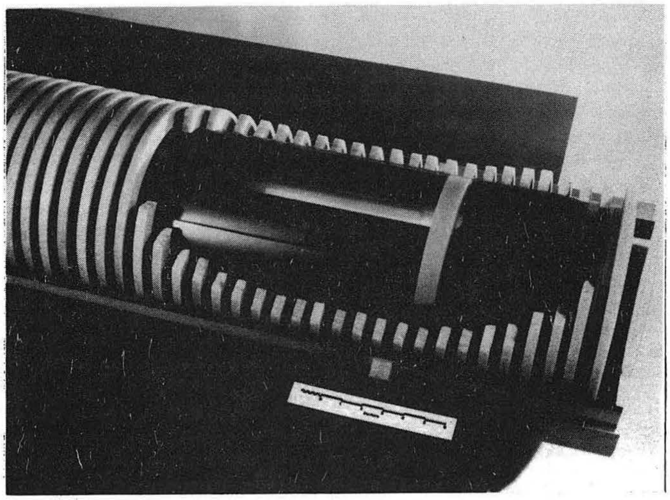

Fig. 2. ESCAR superconducting dipole model.

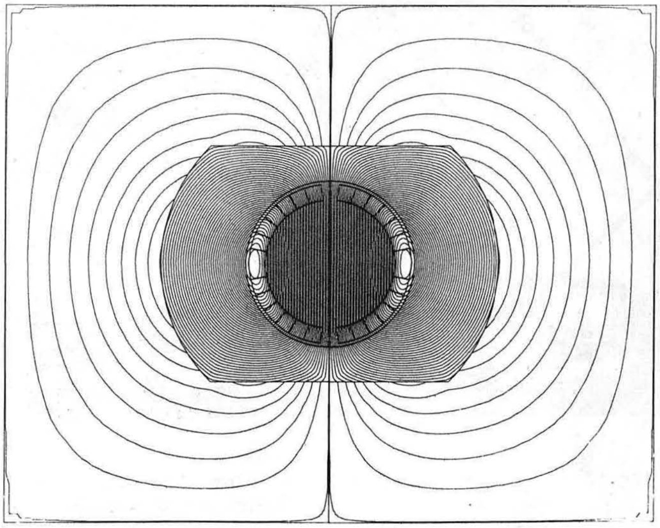

Fig. 4. TRIM-computed flux distribution for the ESCAR dipole magnet.

excitor sensor unit shown in Fig. 6. This electromagnet restores lost energy back into the cable at the measured frequency thereby keeping the cable vibrating. The dynamic tension measured is converted to load and displayed visually.

The electromagnet in the sensor unit was simulated by program TRIM to optimize the magnetic field that produces the maximum attractive force. TRIM also was used to calculate the behavior of this field as a function of the cable distance from the sensor unit. Figure 7 shows the mesh generated by program TRIM while Fig. 8 shows the computed flux distribution. This particular simulation improved the existing design considerably, without necessitating redesign of the enclosure or increase of the current excitation. The resulting increase in force was achieved by relocating the conductor positions to their optimal location.

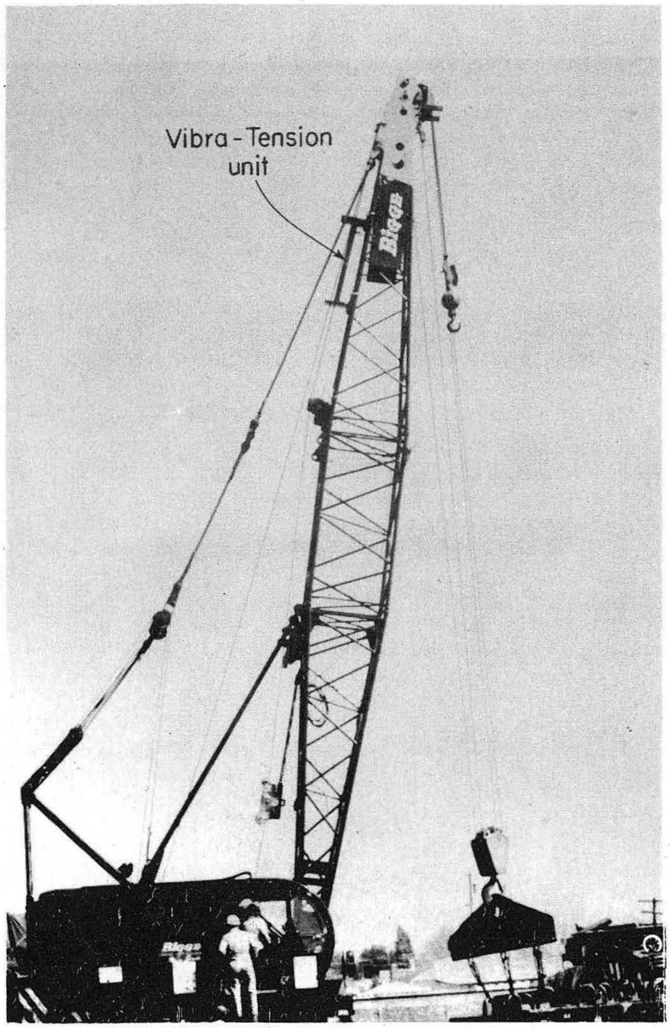

Fig. 5. Truck crane on which a "Vibra-Tension" device is attached. (Courtesy of Rucker Control Systems, Oakland, California)

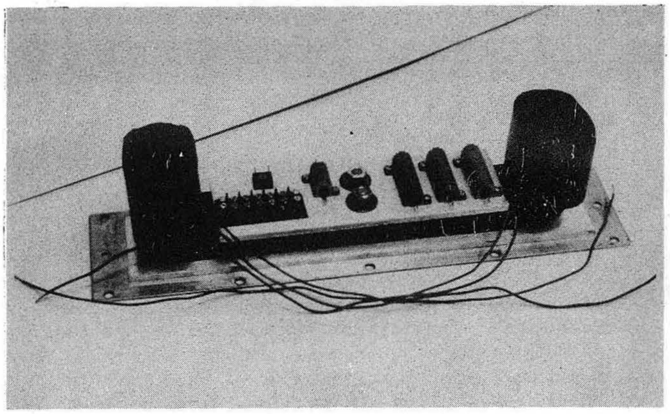

Fig. 6. "Vibra-Tension" sensor unit. (Courtesy of Rucker Control Systems, Oakland, California)

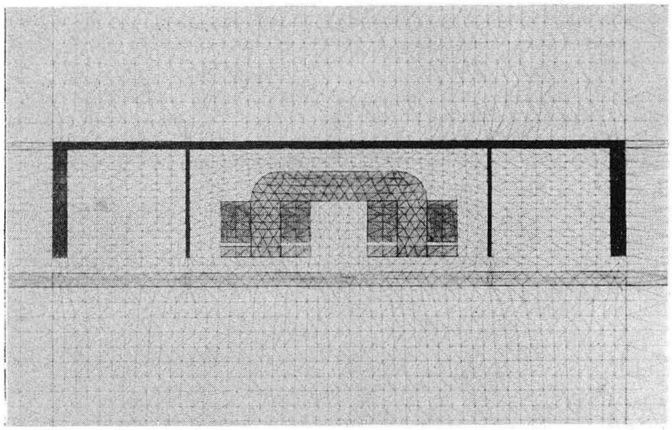

Fig. 7. TRIM-generated mesh for "Vibra-Tension" unit.

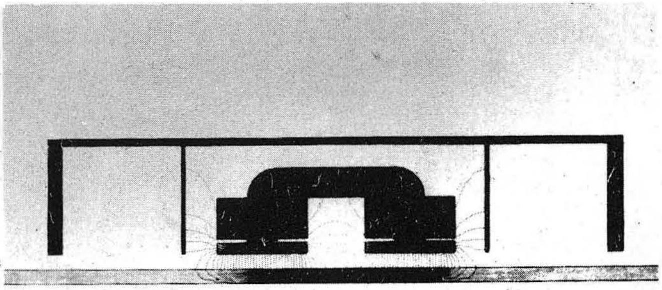

Fig. 8. Flux distribution for "Vibra-Tension" unit.

4c. Doublet-III Experiment[7]

The primary goal of this simulation, shown in Fig. 9, was to calculate the magnetic fields produced by the E-coil turns, which are positioned in such a way that the magnetic field in the plasma region is small, and hence has no significant effect on the initial plasma breakdown or the subsequent discharge configuration. Figure 10 shows the computer-generated mesh of an enlarged view of the E-coil conductor positions, while Fig. 11 shows the flux-density coil resulting from a TRIM calculation. The piece of iron shown was used as a magnetic shield. It can be seen from Fig. 11, that no appreciable flux penetrates the plasma region. Subsequent applications of TRIM are needed to relocate the position of the E-coils so that the magnetics of this field can be minimized. It is in this capacity that program TRIM can be effectively used.

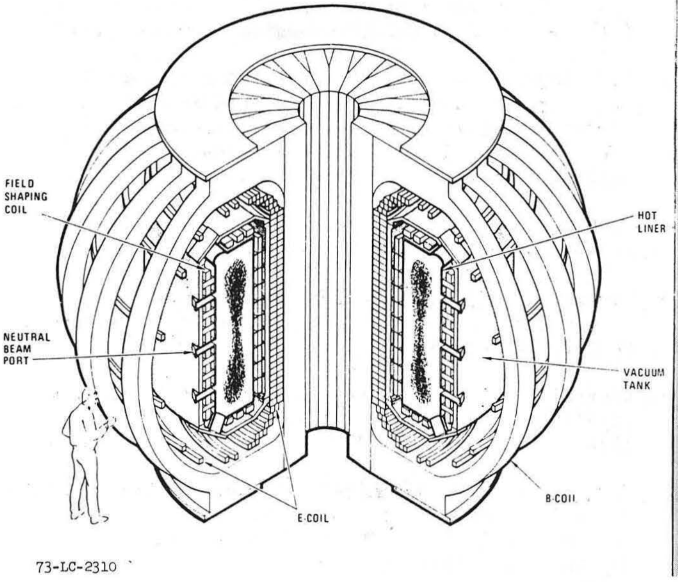

Fig. 9. Doublet-III Device. (Courtesy of General Atomic, San Diego, California)

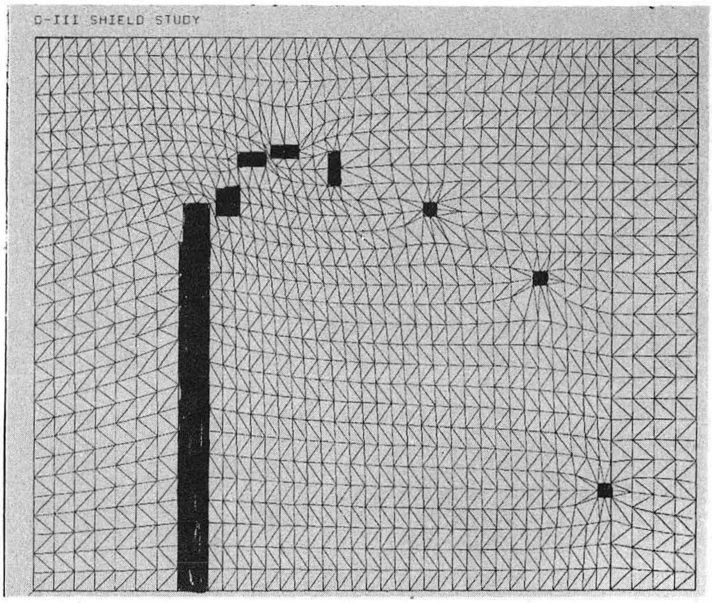

Fig. 10. Generated mesh for Doublet-III device.

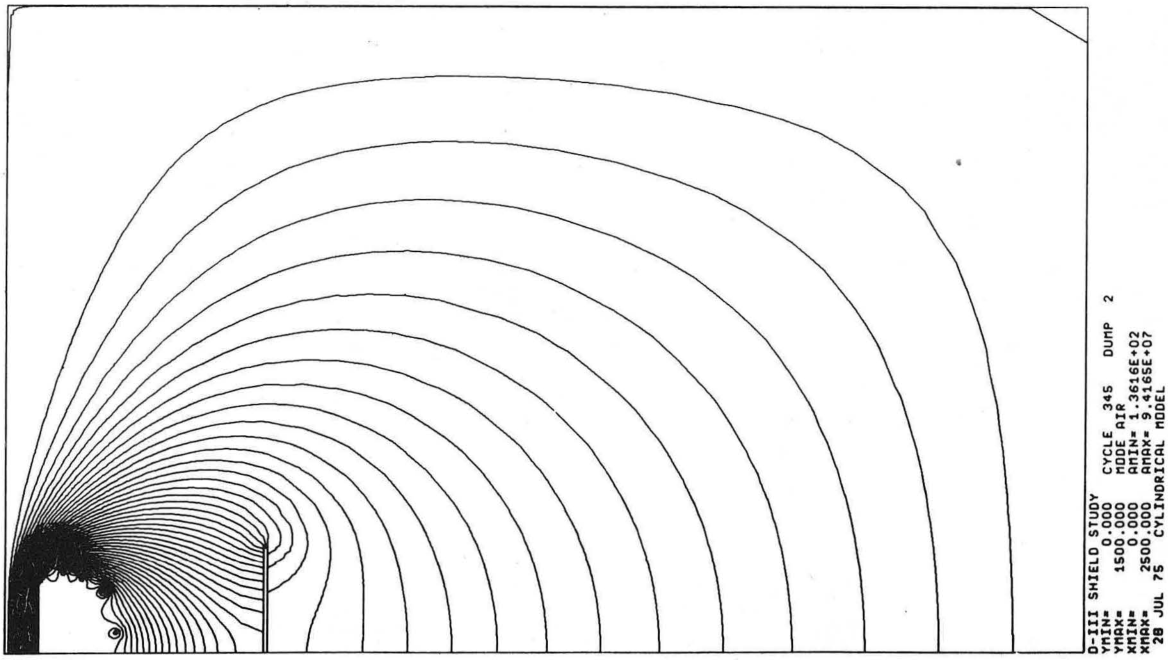

Fig. 11. Flux distribution computed by TRIM for the Doublet-III.

5. CONCLUSIONS

It is evident by now that computer programs such as the ones mentioned above are applicable to a wide range of problems. We have reached a threshold of industrial applications even further removed from the nuclear research laboratories where this technology originated. What we now need is to convince a reluctant and conservative industrial management to utilize such methods and invest in their future. There are areas that I have not covered, not because nothing has been done about them but rather, the methodology is still young and it has not produced reliable computer programs applicable to a wide range of problems. Various methods have been forwarded to calculate eddy currents and time varying fields necessary to make accurate predictions of flux and eddy-current losses in large turbogenerators. Such problems are substantially more complex in three dimensions, and various techniques for their solution have been forwarded by various experimenters.[8]

Simulation of permanent magnets[9] is also an area that deserves consideration, due to their application in electrical machine design, various meter movements, magnetic thrust bearings etc. Considerable work is required before the finite-element or finite-difference techniques can be applied successfully to permanent magnet structures.

Finally, I hope that I have created enough questions and perhaps enough interest in this area, to persuade you to look deeper in your own field and ask yourself whether such technology could help you improve the product you are designing.

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