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MAGNETIC FIELD CALCULATION OF THE SUPERCONDUCTING VERSION OF THE CHICAGO CYCLOTRON MAGNET USING GFUN 3D

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INTRODUCTION

GFUN 3D, a three-dimensional magnetostatic program was used to generate the magnetic data for the superconducting version of the Chicago Cyclotron Magnet (CCM). The results of the calculation presented in this report serve both as structural design data for the construction of the superconducting CCM and as data in a comparison of GFUN 3D with the currently widely used two-dimensional magnetostatic programs LINDA and TRIM. The quantities to be compared include forces and maximum magnetic field B_{max}, in the coils; the central field B_0, and the mid-plane field profiles.

MAGNETOSTATIC PROGRAMS

A substantial number of 2D and 3D magnetostatic programs had been developed in the past 15 years as a result of the advancement of the computer technology and the demand for sophisticated programs by magnet designers in the accelerator industry.[1] Programs that compute three-dimensional geometries have only been successfully tested very recently. The best and the most general one is GFUN 3D, an interactive magnet design program developed by the Rutherford Laboratory.[2-4] In GFUN, the magnetization of the iron is found by the solution of the integral equations it obeys. The magnetic field anywhere can then be found from the current sources and previously determined magnetization. This is termed the "Direct Method", as distinguished from the classical approach in which partial differential equations describing the field are solved and which in general involves a large number of mesh points like in LINDA and TRIM. LINDA and TRIM[1] are two very popular 2-D magnetostatic programs. In fact, TRIM had been the most reliable magnet design program for a number of years. Both of the above programs are available at Fermilab through the IBM 360 computer facility at ANL. TRIM has two versions: 1) TSO (with graphics) and 2) batch; while LINDA can be done only through batch processing. A comparison of LINDA, TRIM and GFUN as a computer code is presented in Table 1.

Because of its versatility and high accuracy (< 0.5%), GFUN 3-D is becoming more and more important as a magnet design tool.[5] The version used in the present calculation was implemented by L. Turner and R. Lari at ANL. One can use up to 200 tetrahedral elements to define the iron-geometry. Graphics facilitating the input of data and special output plotting features are also available. According to L. Turner, a newer version that can handle up to 400 iron elements will be ready in the beginning part of 1978. One purpose of this report is to make magnet designers at Fermilab aware of the existence of this new, sophisticated tool.

Because of the large number of simultaneous equations that have to be solved to obtain the magnetization of the iron, the computer CPU time and core size required are substantial. For a given number of specified iterations, the cost to run the GETM portion (the subprogram in GFUN that calculates the magnetization) increases roughly as the number of tetrahedral iron elements to the power of e = 2.71828. On the IBM 360 at ANL, the turnaround is about 1 run per week for the computer would only handle such a big job during the weekend. (Very often > 40 min. CPU time is required.)

THE GEOMETRY FOR CALCULATION

The superconducting CCM will have a current density about 40 times greater than that in the conventional case. Accurate prediction of the electromagnetic forces acting on the coil is hence required for structural calculation. As shown in Fig. 1. CCM has an eight-folded symmetry. It's almost square as viewed from the top and yet a non-axisymmetric problem because of the presence of the iron return legs in the YZ plane(s). Two-dimensional programs like LINDA and TRIM can best handle long magnets with relatively small lateral dimensions and are, therefore, not exactly appropriate here. The necessity of a program like GFUN 3-D is indicated.

SETTING UP THE PROBLEM USING LINDA, TRIM & GFUN

Two GFUN 3-D runs were set up for the geometry in Fig. 1; one using 92 tetrahedrons in the iron and the other using 152. These runs hopefully can give us an idea of the dependence of accuracy and cost per run on the number of iron elements used. Figures 2, 3 and 4 show the set-up geometry in 3 different planes. Only one-eighth of the magnet has to be specified because of symmetry. The iron geometry can be rotated in space using Euler angles to further make sure that the correct geometry has been specified.

In the TRIM runs, the axisymmetric mode has to be used for the coil is a split solenoid type. The actual iron geometry was replaced by an axisymmetric geometry such that the magnet flux at any point in the iron would see the same cross section of its return path as in the actual case. The YZ plane result is obtained from the set-up shown in Fig. 5, while Fig. 6 represents a simulation of the XZ plane situation, noting that an infinite permeability return leg is required for this case to run.

Since LINDA can't handle axisymmetric geometries at all, the approach is to only have a Y-Z plane cut simulating the solenoid coil with 2 infinitely long straight sections. This approach would probably introduce quite an error but it does represent a limitation of the first generation magnetostatic 2-D programs.

RESULTS

The results obtained from the various runs is summarized in Table 2 and Figs. 7 and 8. By going from 92 elements to 152 elements, the vertical forces in both planes were observed to go down while the radial forces go up. The change is always less than ± 6%. There is less than 0.5% change in both the central field B_0 and the maximum fields B_{max} inside the coil. However, the cost for running the GETM portion (subprogram for generating the magnetization of the iron) almost doubles. The indication is that even for a huge iron geometry like we have in CCM, around 100 tetrahedral elements would likely be sufficient to generate fairly accurate results.

TRIM compares favorably with the GFUN 3-D 152 elements run in the XZ plane (3.8% higher for the vertical force and 13.8% for the radial force.) In the YZ plane (plane with iron return leg), the radial force is always exactly the same (+ 0.3%) but the vertical force is off by 48%. Both the forces and the magnetic fields calculated are higher than those calculated with GFUN. The mid-plane field profiles as obtained from TRIM (Figs. 7 & 8) have small bumps (at y = 15" in the YZ plane and x = 20" in the XZ plane) which cannot be adequately explained. The irregularity observed at y = 130" → 140" in the YZ plane probably arises from the iron boundary at y = 140". This is a typical error observed in programs adopting a partial differential boundary value problem approach and where one cannot put enough meshes to deal with the local situation. The GFUN runs give very smooth mid-plane magnetic field profiles.

The version of LINDA we are working with requires an input of the central field B_0 rather than the total ampere-turn in each coil. LINDA gives a central field of 15.2 kG with 1.42×10^6 A-turns while GFUN with 1×10^6 A-turns. The radial force obtained in the YZ plane is almost an order of magnitude higher. This great discrepancy was actually expected for we are actually simulating a solenoid field with 2 straight runs of current.

Any attempt to study the CCM problem with LINDA invariably would lead to erroneous results.

DISCUSSION & CONCLUSION

GFUN 3-D is working rather well. From now on, we have a powerful tool for handling magnets with an almost square cross section as viewed from the top, i.e., a short magnet with a large bore, regardless of whether the coil assumes the shape of the solenoid, racetrack or even bedstead; the latter of the three can hardly be sufficiently handled by 2-D program in the case of a short magnet. The total cost per run for GFUN using around 100 elements is about $200.

TRIM can compute axisymmetric coils with an eight-folded symmetric iron geometry as in the CCM case pretty well. Because of the large expense and long turnover time of GFUN 3D, it is recommended that for magnet of this type, one can use TRIM in doing the initial design and then finalize the design and obtain accurate force data using a single GFUN 3-D run.

LINDA offers a quick and easy method in solving straight 2-D problems, especially no iron problem, because of the extreme ease in setting up and inputting the run. It cannot solve axisymmetric problems and would introduce error if one uses it to solve short, large gap magnets.

If one is to rank the versatility and general usefulness of the three programs on a 1 to 4 scale (the higher, the better), one would tend to give GFUN 3D a 4, TRIM a 3 and LINDA a 1. Undoubtedly, GFUN 3-D will become more and more important as a magnet design tool for there are unique cases for which the 2-D programs are inadequate. CCM is a special case where a good 2-D program like TRIM can still compete with a 3-D program.

GFUN 3-D is still a program under development. An improvement that can be made to GFUN 3-D is an automatic force calculating feature analogous to the subprogram FORGY in TRIM.

We feel secure enough that the force data obtained for the structural calculation of the CCM is the best we can obtain. Comparison of the measured magnetic field profile (or field map inside the aperature) of the superconducting CCM upon completion of construction to the result presented in this report will prove most interesting: A comparison of the best in numerical magnetostatic field calculation to the actual world.

ACKNOWLEDGMENT

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2. C.W. Trowbridge, Proc. 4th Int. Conf. on Magnet Technology, Brookhaven (1972) p. 555.
3. M.J. Newman, J. Simkin, et al., "GFUN User's Guide -- A User Guide to an Interactive Graphics Program for the Computer Aided Design of Magnets", RHEL/R 244.
4. L.R. Turner, "Direct Calculation of Magnetic Fields in the

Presence of Iron, As Applied to the Computer Program GFUN", RL-73-102.

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Table 1

A COMPARISON OF LINDA, TRIM & GFUN

	LINDA	TRIM (1964)	GFUN (1971)
Calculation Method	Partial Differential Equation (PDE) Approach Fixed size rectangular mesh Max. (10,000)	PDE, Vector Potential Bdd value problem Variable (size) triangular mesh Max. (2500) - TSO (5000) - Batch	Direct Method: Solving integral equations in iron Tetrahedral or prismatic elements for defining iron geometry
Mode & Dimension	Batch 2D	Batch or Interactive (graphics) 2D	Interactive (graphics) or batch 2D & 3D
Versatility	Can solve both air & iron problems. The latter limited to only about 10 configurations.	Can solve both air & iron problems. No particular iron symmetry required. Quite versatile. Can handle axi-symmetric problems.	Can solve both air & iron problems. Large number of symmetry cases defined, specially geared towards detailed magnet design. Has optimization feature in certain geometries in 2D.
Force & Energy Calculation	Need to hand calculate forces from field maps. No energy calculations available.	Calculates forces on iron & in coil automatically. Gives energy stored in magnet.	Force calculations only exists for a limited number of cases. Need to hand calculate forces from fields in most cases. Energy calculation not available.
Ease of Use	Easy	Difficult	Fair
Cost of Running	Inexpensive	Inexpensive	Expensive

Table 2

SUMMARY OF RESULTS AS OBTAINED FROM RUNS OF LINDA, TRIM & GFUN

Programs	Force per unit length*		B_0 (kG)	B_{max} in Coil (kG)	Remarks
	Fr/ℓ (lb/in)	Fz/ℓ (lb/in)			
LINDA	13273.5	2025.6	15.15	27.5	Input set B_0 = 15.15 kG, Required NI = 1.42×10^6
TRIM	a) 1555.3	1598.7	15.9	27.9	XZ plane with no iron
	b) 1447.1	1819.7	15.7	28.5	YZ plane with iron return yoke
GFUN 3D	a) 1448.0	1488.0	15.15	25.3	XZ plane with no iron, 92 iron elements
	b) 1526.0	1160.0	15.15	24.9	YZ plane with iron return yoke, 92 iron elements
	c) 1366.0	1541.0	15.2	25.4	XZ plane with no iron 152 iron elements
	d) 1442.0	1230.0	15.2	25.5	YZ plane with iron return yoke, 152 iron elements.

*Fz/ℓ = vertical forces per unit length; in the +Z direction for the upper coil and -Z direction for the lower one.

Fr/ℓ = radial forces per unit length; always in a radially outwards direction.

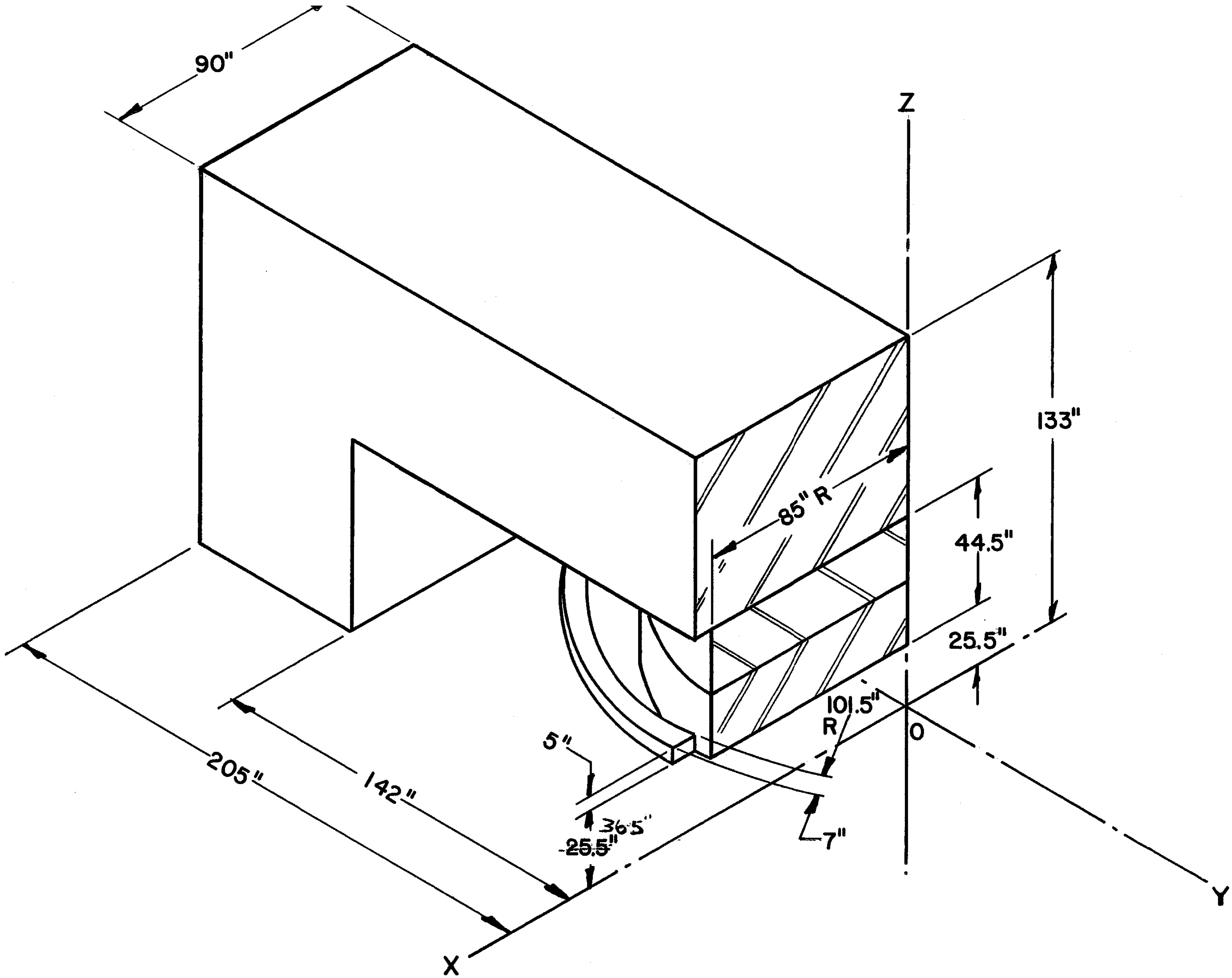

FIG. I SHOWING ONE-EIGHT OF A MAGNET

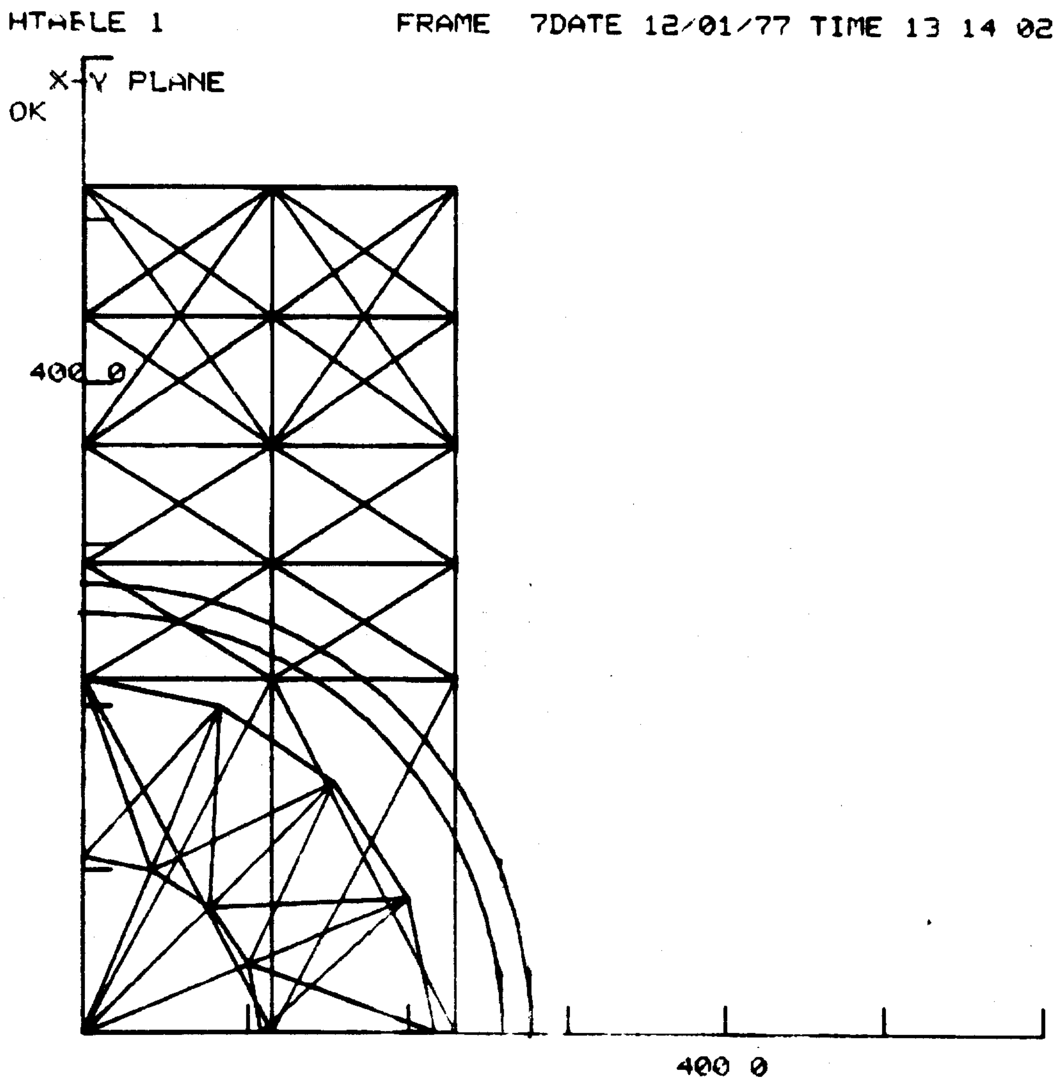

FIG.2 152 ELEMENT GFUN 3D XY PLANE SET-UP

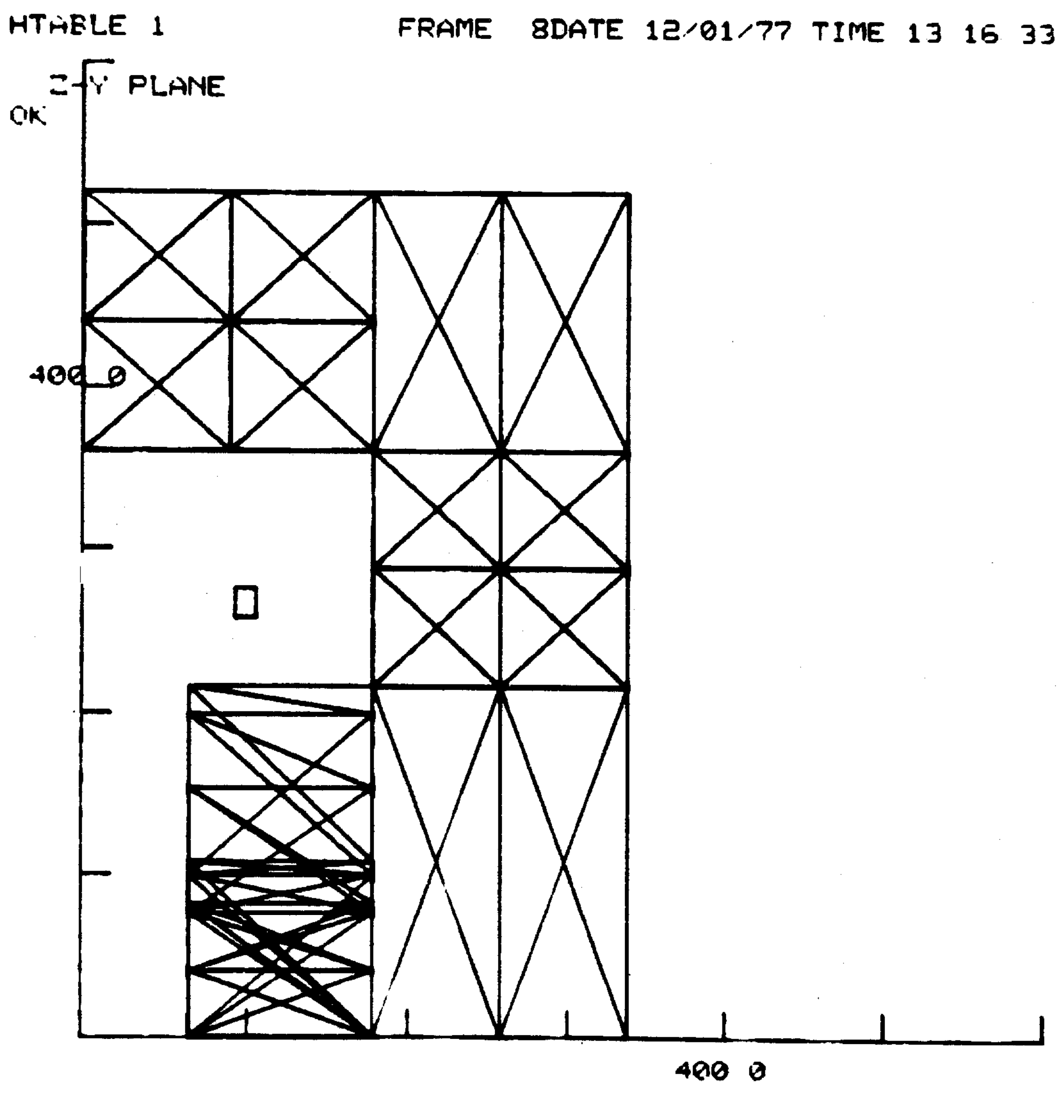

FIG. 3 GFUN3D 152 ELEMENT SET-UP AS VIEWED IN Z-Y PLANE

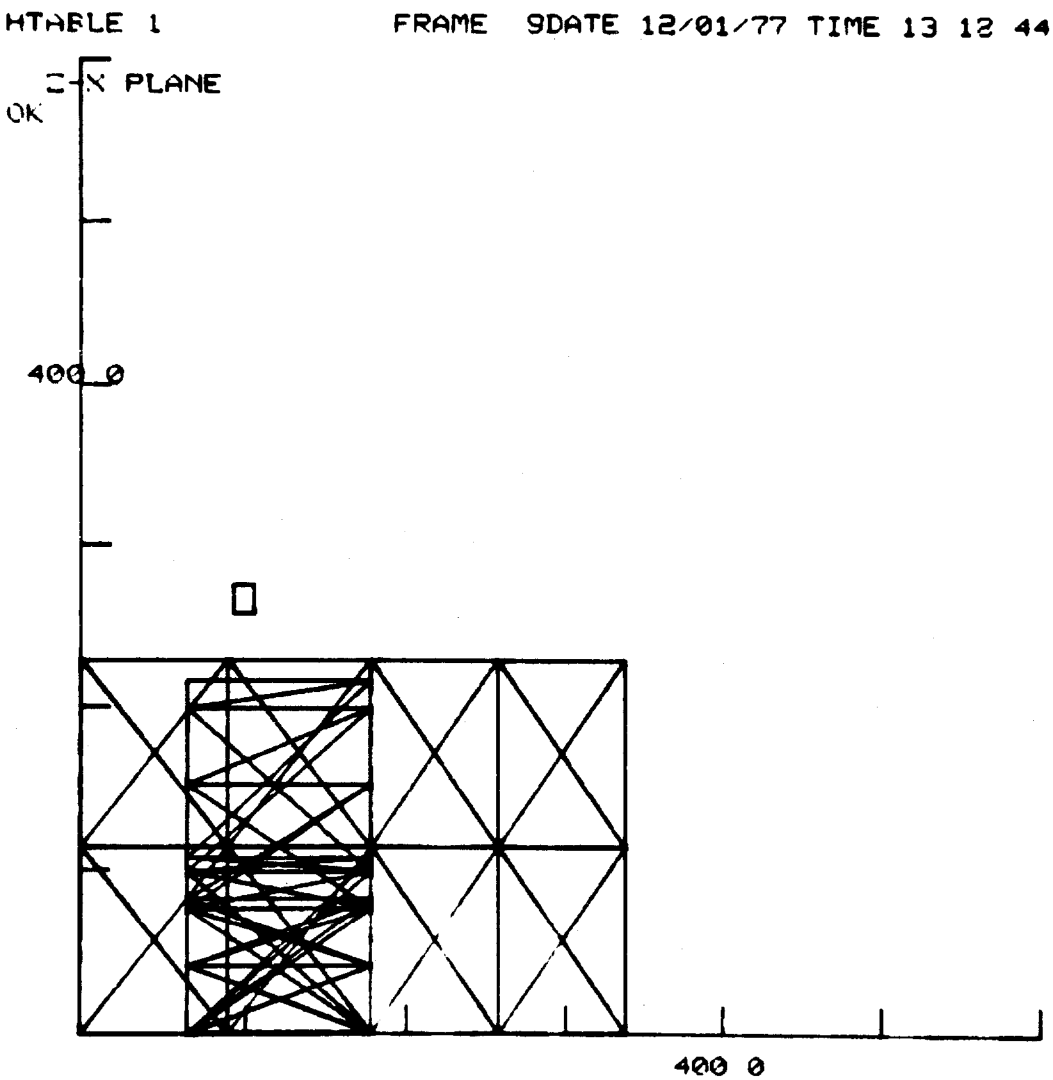

FIG.4 GFUN 3D 152 ELEMENT SET-UP AS VIEWED IN Z-X PLANE

CM04

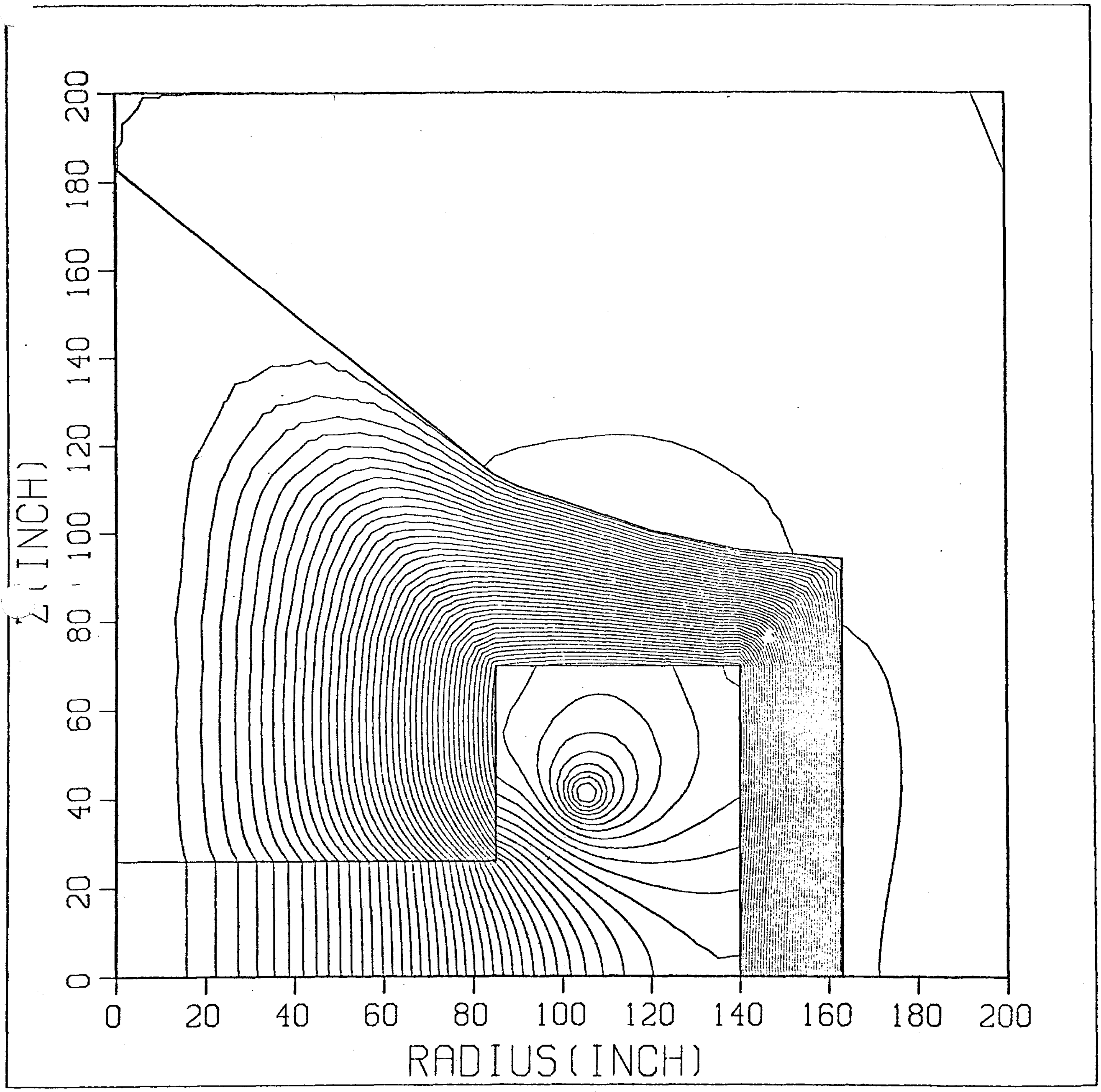

FIG.5 TRIM SET-UP ZY PLANE SIMULATION

NOTE: IN FIG 5 & 6, THE COIL LOCATION IS A LITTLE BIT DIFFERENT FROM THE ONE SPECIFIED IN FIG.1 HENCE THE FLUX PATTERN IN THE ACTUAL CASE MAY BE SLIGHTLY DIFFERENT.

CM09

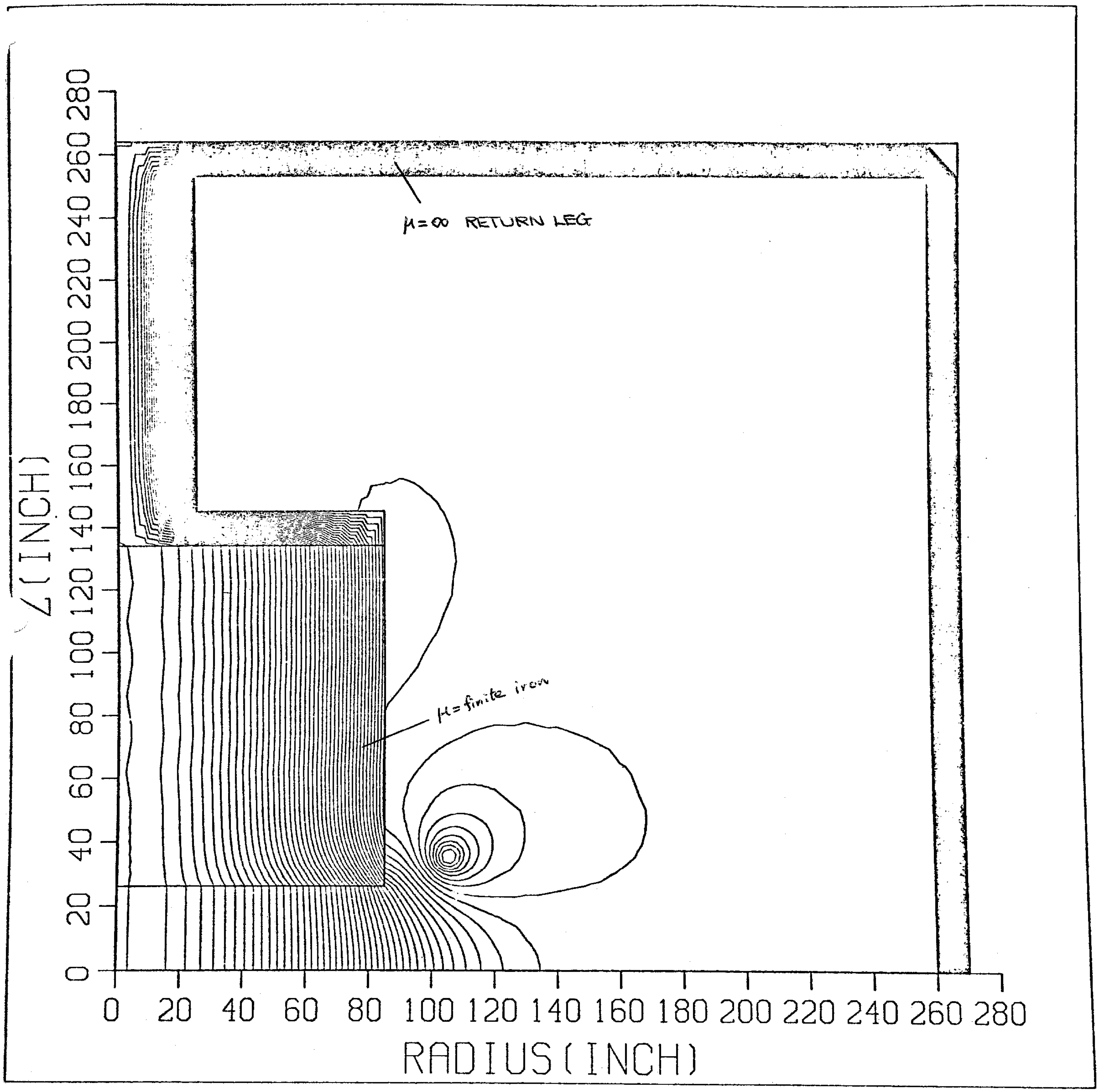

FIG.6 TRIM SET-UP, ZX PLANE SIMULATION

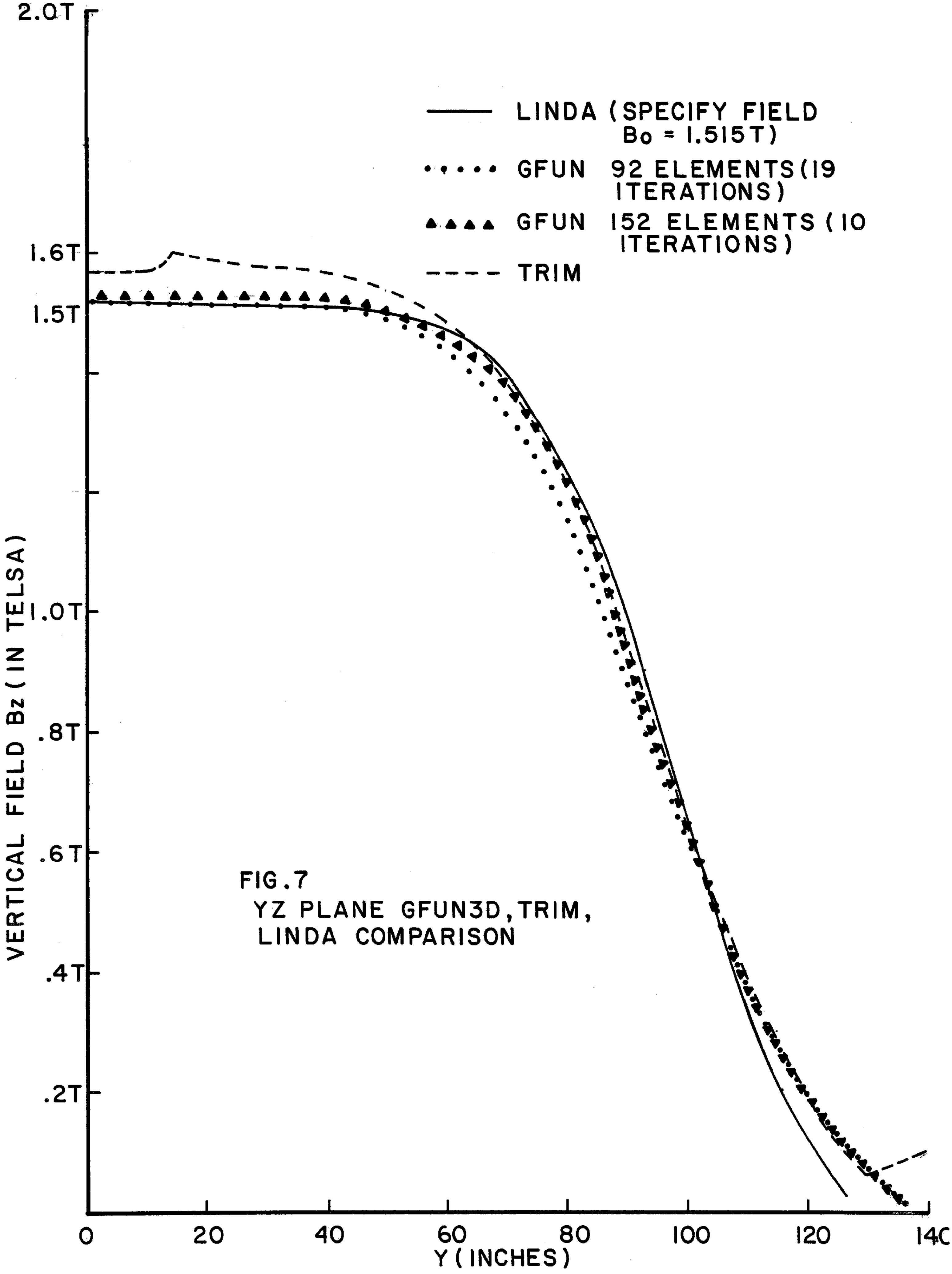

FIG. 7
YZ PLANE GFUN3D, TRIM, LINDA COMPARISON

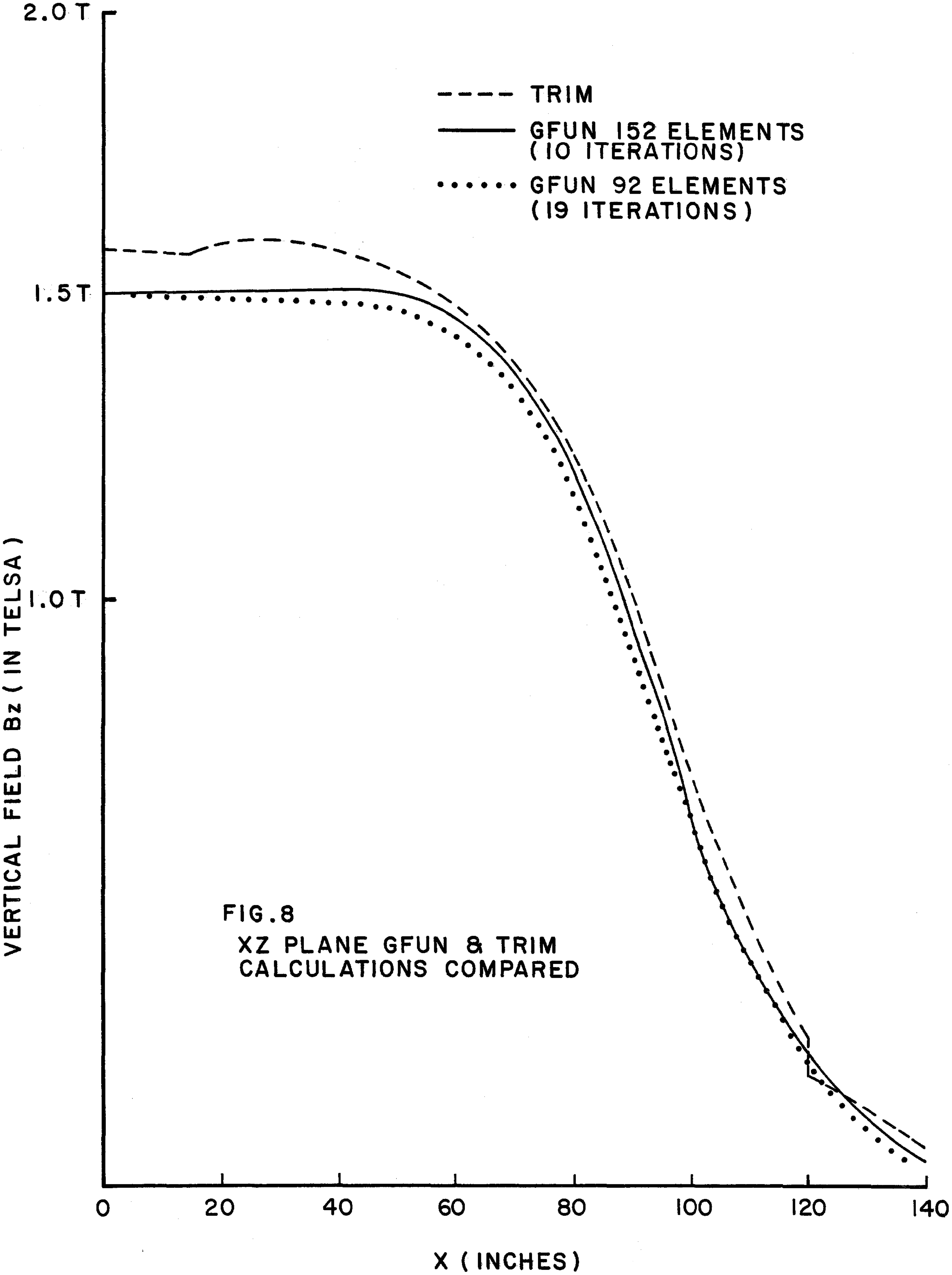

FIG. 8
XZ PLANE GFUN & TRIM CALCULATIONS COMPARED