Fermilab

SSC Detector Solenoid Design Note #6

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ANSYS Field Calculations for Simple Solenoid Geometries

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Introduction

The purpose of this work is to verify that ANSYS can correctly predict the magnetostatic behaviour of a simple solenoid. Some of the ANSYS solutions presented here can be compared with closed form calculations to assess their accuracy. This work also allows familiarity to be gained with the model generation and post-processing of 3-d magnetostatic problems.

Problem Description

Two problems were solved.

1. Thin solenoid 16m long, 10.526 m dia, NI=$28e^6$ amp-turns, no iron. (Fig. 1a)

2. Thin solenoid, dimensions and current density as above, with 3 meters of iron radially outside of the coil, and three meters at each end. The iron was given a relative permeability of 10000. This was an effort to simulate an "infinite mu" solution. (Fig. 1b)

Closed Form Solution

The closed form solutions for the central field and the end field for the air-only case is given in Appendix A. The central field predicted for the ironless coil is 1.84 T. The field at the ends is predicted to be 1.04

T. The central field for the "infinite mu" iron case was not calculated, but it is known that the iron should increase the field by approximately 10% and increase it's uniformity in both axial and radial directions.

Finite Element Models

A finite element model representative of those used in this analysis is shown in Fig. 2. It consists of a wedge of three dimensional ANSYS multi-field solid elements, STIF5. This element can have up to 6 degrees of freedom, namely, three structural translations, temperature, voltage and magnetic scalar potential. Only the magnetic scalar potential was used in this work. Although the problem could have been solved using the 2-d vector potential element STIF13, it was felt that since the final analysis will be three dimensional it was advisable to learn how the 3-d analysis works.

The coil itself was not represented by finite elements. It was represented by NL-source input, which is the ANSYS terminology for a current source input through the non-linear property tables. This input locates the center of the coil, its axial and radial dimensions, it's angular orientation relative to the global coordinate system, it's current, and the number of integration points used in the Biot-Savart integration for the source contribution to the H-field.

When ferromagnetic materials are not present, the only contribution to the B-field is the current source contribution. It is possible then to construct a mesh with elements only along the region of interest. When the magnetic potential degree of freedom (which is only relevant to ferromagnetic materials) is set to zero on all nodes, the result is a numerical integration of the source contribution for each element in the mesh and a virtual suppresion of the finite element calculation. This gives a very economical mesh if the region of interest is small. This technique was used to refine the air-only solenoid model to improve the agreement with the closed-form solution.

All models exploited the axisymmetry of the structure by including only a wedge of elements across an arbitrary 10 degree angle. The initial models of the air-only case did not exploit the midplane symmetry, however, because the application of symmetric boundary conditions was not well understood.

Results

1. Air-Only Solenoid

Two meshes were run for the air-only case. The first mesh used elements which were 1 m on a side, and included air both inside the solenoid and for a distance of 2 m outside both radially and axially. The current source was given 10 integration points axially and 2 integration points radially. The axial component of the central field for this case is plotted in Fig. 3. Table I is a printed listing of this component. Both the plot and the listing are easily generate with the ANSYS POST1 post-processor. The central field is seen to be a maximum of 1.70 at the center of the solenoid. This agrees to within 8% with the closed-form result of 1.84 T. The tabulated values show a slight oscillation in the field at the center. Discussions with experts at Swanson Analysis indicate that this is probably because this model used too few integration points along the axis of the solenoid. It is recommended that the number of integration points along a given direction be twice as great as the number of elements along that direction. In the air only case, the ratio of integration points to elements along the axis was only 5/8. In later models this was change to the recommended 2/1 ratio.

The field at the end was 0.65 T, which does not compare well with the 1.08 T predictated by the hand calculation.

In an effort to refine the solution a second air-only mesh was generated which consisted only of air elements .25 m on a side down the centerline of the solenoid. The number of axial integration points in the source was increased from 10 to 32, and the magnetic potential degree of freedom was set to zero at every node. The results for this case were a central field of 1.837 T and an end field of 1.07 T. This is very good agreement with the closed form solution. Fig. 4 shows a plot of the axial component of the central field along the axis , and Table II gives a printout of the this component.

2. "Infinite Mu" Iron

This model exploited both the axial and midplane symmetry. The number of integration points was increased as discussed above for the refined air-only solution. The central field is shown in Fig. 5. The field is a nearly uniform 2.21T along the entire axial length of the magnet. This is an increase from the air-only solenoid of 30%, which is somewhat more than expected.

Fig. 6 is a plot of the total B-field magnitude and direction. The large B-field values in the iron next to the source are said by Swanson to be the result of insufficient mesh refinement near the source. Fig. 7 shows the total H-field magnitude and direction, and as expected shows the H-field in the solenoid to be very uniform.

Conclusion

There are several issues which must be investigated in order to generate accurate results everywhere in a 3-d magnetostatic model. One of the most important appears to be the relationship between mesh refinement and integration points for highly permeable iron regions near the current source. Another is the extent of universe required to assure that the boundary conditions do not impose unrealistic constraints on the problem.

There are other analysis and post-processsing features to be examined. For example, there is force information available for the STIF5 elements which needs to be examined. Also, the inclusion of "real" iron means B-H table input and a fully non-linear iterative solution which can be cpu intensive. We are in the process of "creeping up" on the real multi-coil, non-axisymmetric real iron case with a series of simplified problems which will give us useful design information and an understanding of the finite element process.

PRINT VALUE ALONG PATH FROM NODE 1 TO NODE 48 OF BZZ DSYS= 0

Table I

Axial B-field Component for Air-Only Solenoid Coarse Mesh

DISTANCE	BZZ	
0.00000E+00	0.15671	
0.41667	0.22266	
0.83333	0.28862	
1.2500	0.39372	
1.6667	0.52492	
2.0833	0.65508	end
2.5000	0.78112	
2.9167	0.90715	
3.3333	1.0223	
3.7500	1.1347	
4.1667	1.2383	
4.5833	1.3287	
5.0000	1.4192	
5.4167	1.4828	
DISTANCE	**BZZ**	
5.8333	1.5463	
6.2500	1.5937	
6.6667	1.6302	
7.0833	1.6625	
7.5000	1.6775	
7.9167	1.6925	
8.3333	1.6977	
8.7500	1.7005	
9.1667	1.7020	
9.5833	1.7017	
10.000	1.7013	Center
10.417	1.7017	
10.833	1.7020	
11.250	1.7005	
DISTANCE	**BZZ**	
11.667	1.6977	
12.083	1.6925	
12.500	1.6775	
12.917	1.6625	
13.333	1.6302	
13.750	1.5937	
14.167	1.5463	
14.583	1.4828	
15.000	1.4192	
15.417	1.3287	
15.833	1.2383	
16.250	1.1347	
16.667	1.0223	
17.083	0.90715	
DISTANCE	**BZZ**	
17.500	0.78112	
17.917	0.65508	
18.333	0.52492	
18.750	0.39372	
19.167	0.28862	
19.583	0.22266	
20.000	0.15671	

PRINT VALUE ALONG PATH FROM NODE 1 TO NODE 5 OF BCZ DSYS= 0

Table II

Axial B-Field Component for Air-only Solenoid Refined Mesh

DISTANCE	BCZ
0.00000E+00	1.0698 — end
0.16667	1.0866
0.33333	1.1117
0.50000	1.1451
0.66667	1.1781
0.83333	1.2106
1.0000	1.2428
1.1667	1.2740
1.3333	1.3048
1.5000	1.3349
1.6667	1.3639
1.8333	1.3922
2.0000	1.4198
2.1667	1.4460

DISTANCE	BCZ
2.3333	1.4715
2.5000	1.4962
2.6667	1.5195
2.8333	1.5420
3.0000	1.5637
3.1667	1.5840
3.3333	1.6035
3.5000	1.6223
3.6667	1.6396
3.8333	1.6563
4.0000	1.6723
4.1667	1.6869
4.3333	1.7010
4.5000	1.7144

DISTANCE	BCZ
4.6667	1.7265
4.8333	1.7381
5.0000	1.7492
5.1667	1.7591
5.3333	1.7685
5.5000	1.7774
5.6667	1.7853
5.8333	1.7927
6.0000	1.7996
6.1667	1.8056
6.3333	1.8112
6.5000	1.8163
6.6667	1.8206
6.8333	1.8245

DISTANCE	BCZ
7.0000	1.8280
7.1667	1.8307
7.3333	1.8330
7.5000	1.8349
7.6667	1.8360
7.8333	1.8368
8.0000	1.8372 — Center

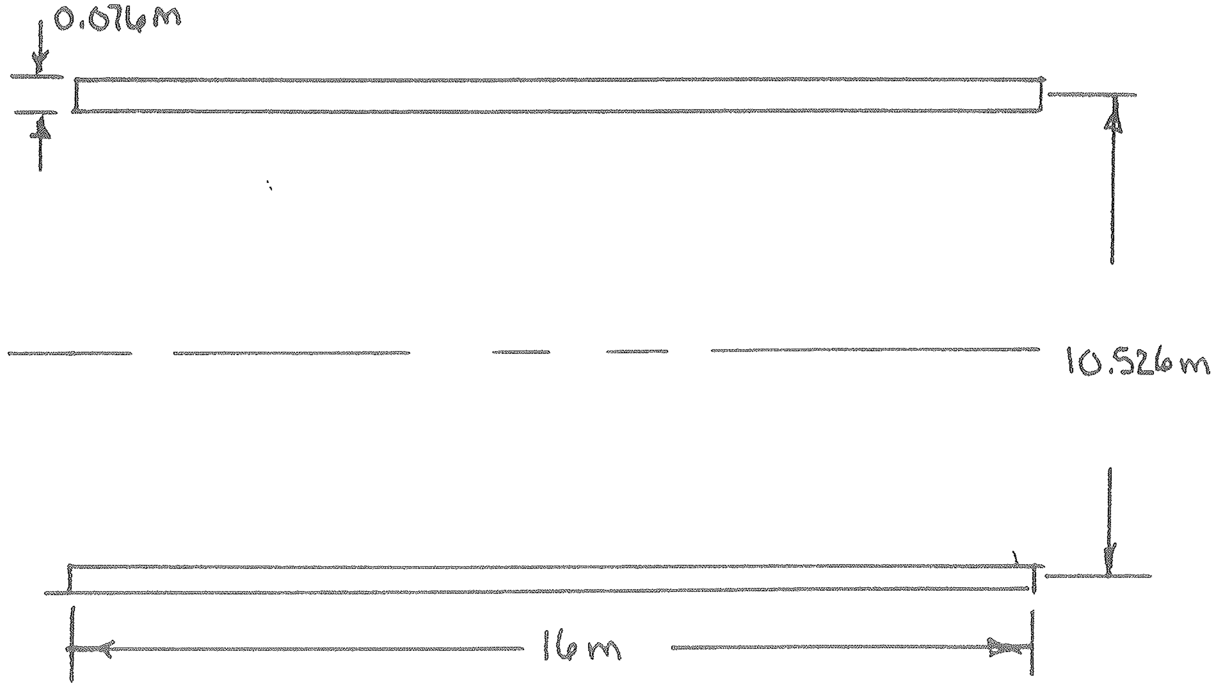


Fig 1a. Air-only Solenoid

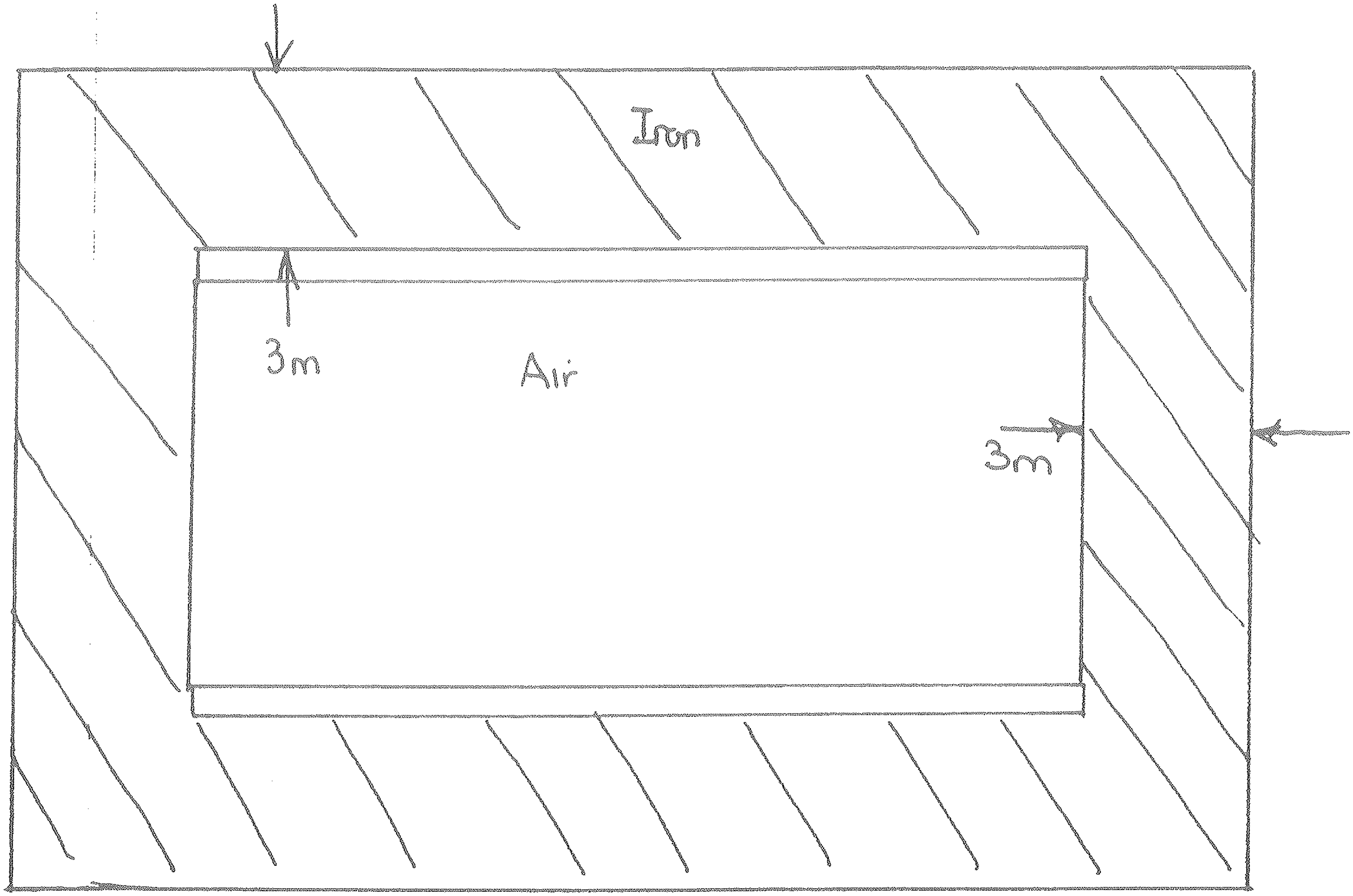
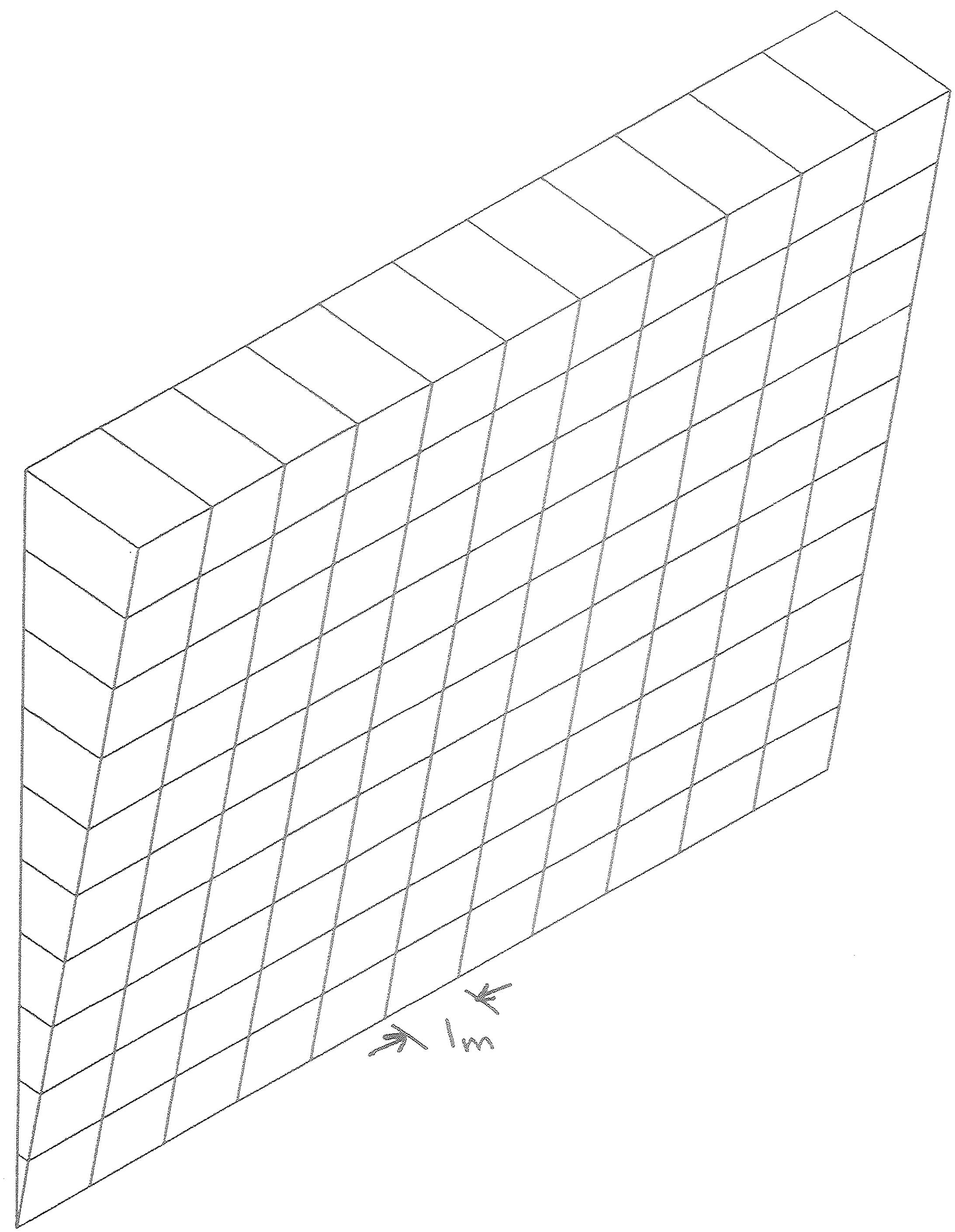


Fig 1b. Air-Iron Solenoid



1 MU=10000

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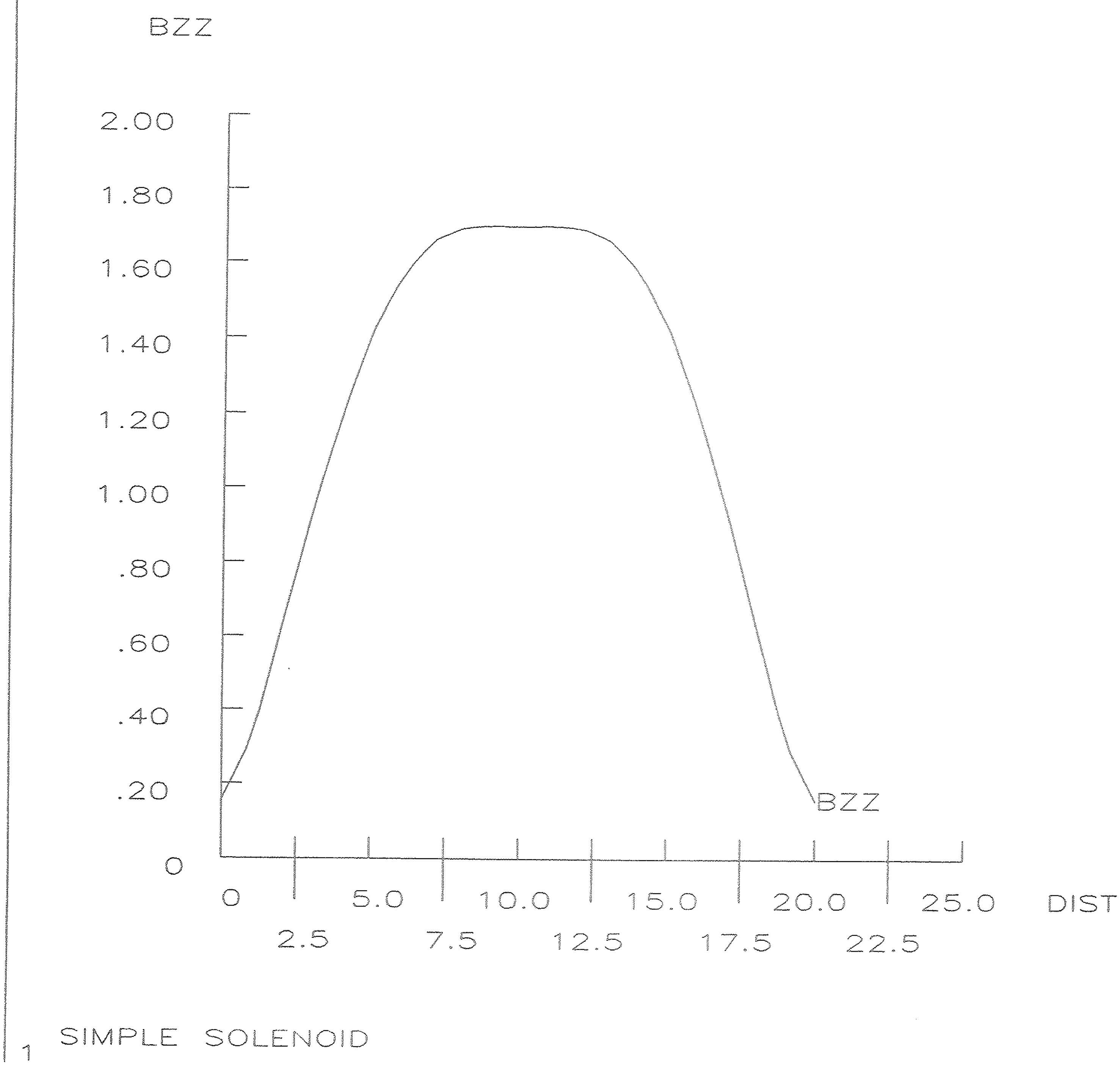
JAN 18 1988
14:17:29
PLOT NO. 1
POST1 ELEMENTS

ORIG
XV=1
YV=1
ZV=1
DIST=6.51
XF=.629
YF=4.74
ZF=5.35
HIDDEN

Fig 2. Typical "Wedge" Mesh of STIF5 multi-field Solids, 1m on a side



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POST1
STEP=1
ITER=10
PATH PLOT
NOD1=1
NOD2=48
BZZ

ORIG
ZV=1
DIST=1.41

Fig 3. Central field for Air-Only Coarse Mesh

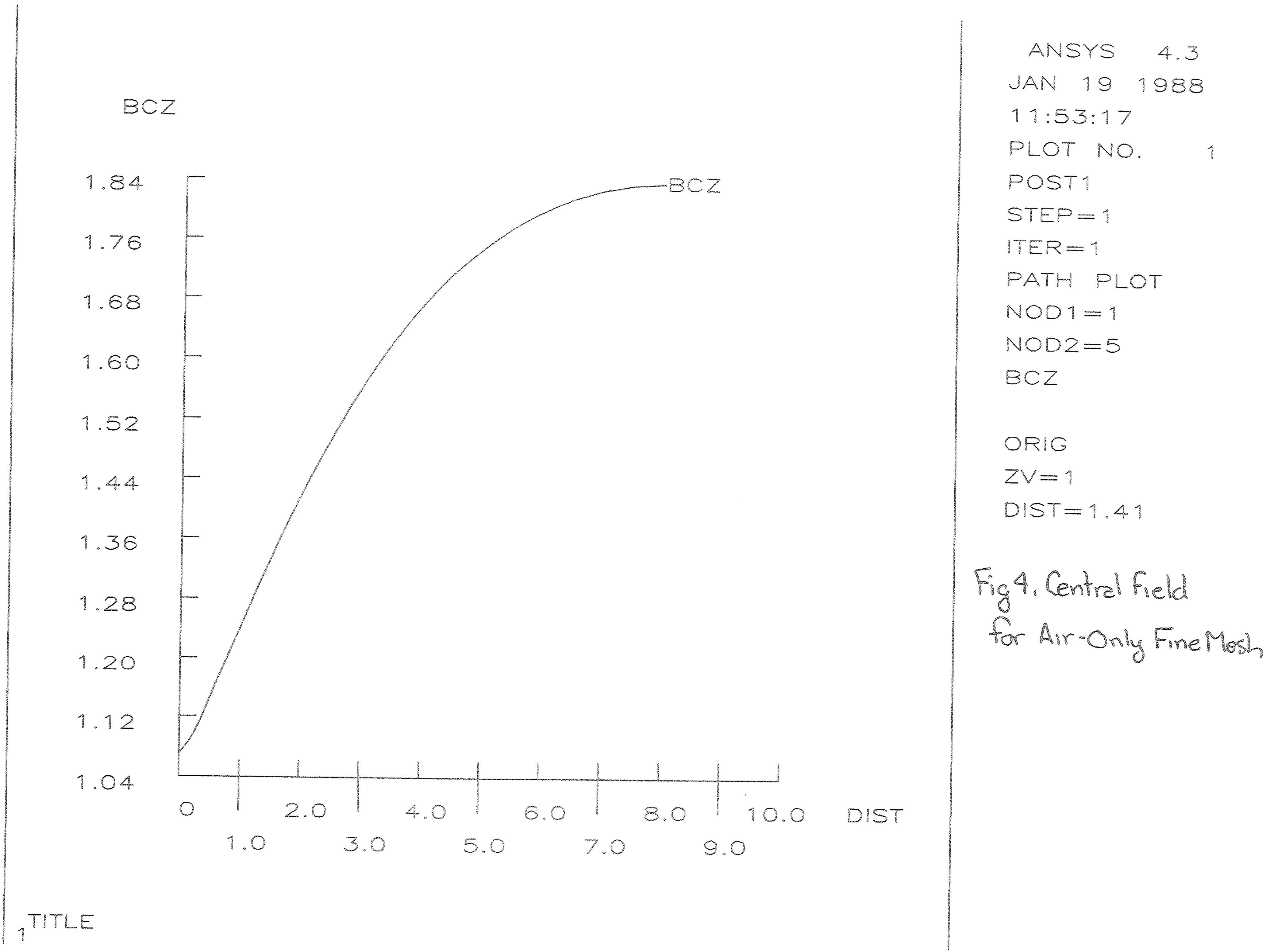
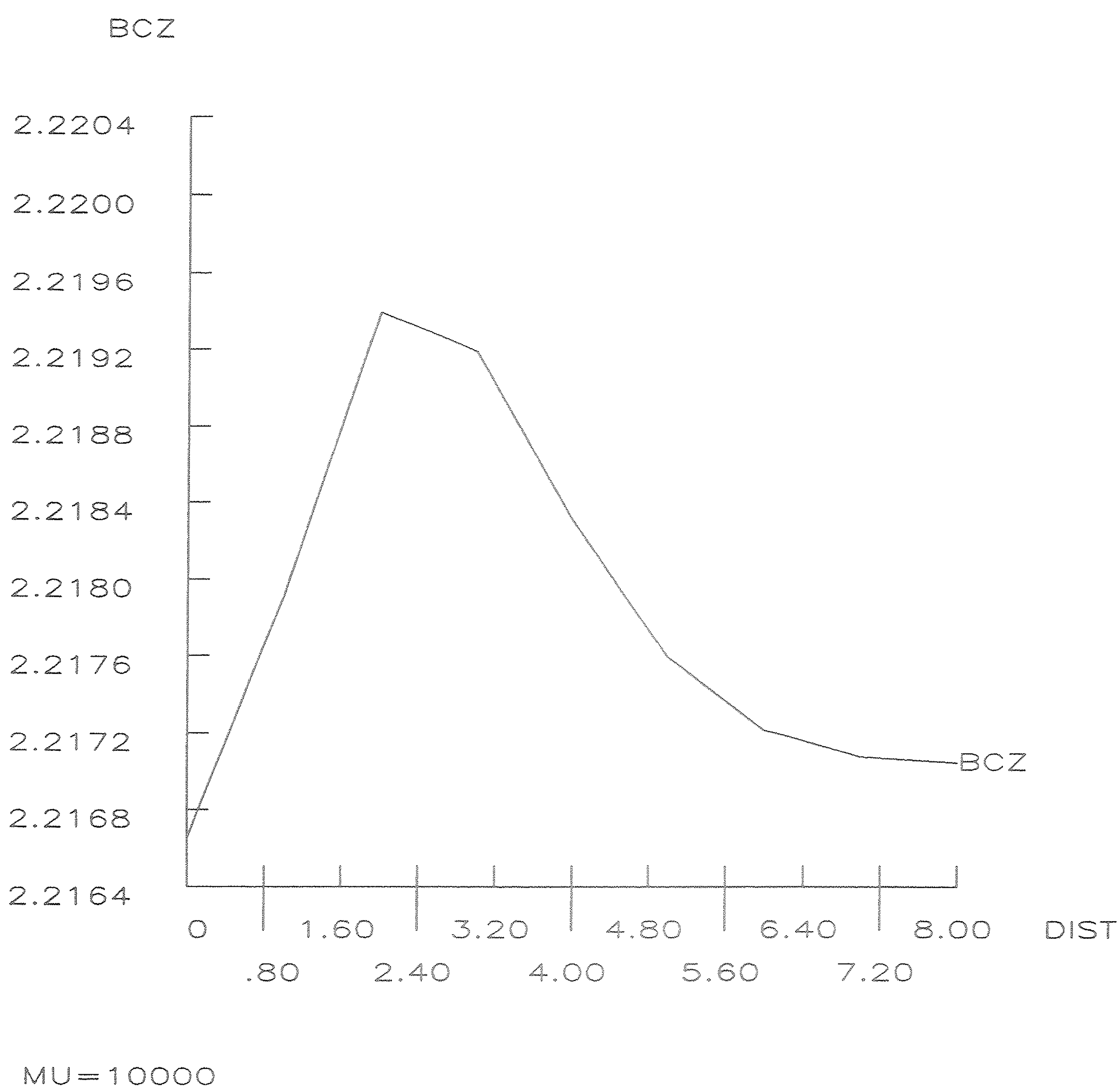


Fig 4. Central field for Air-Only Fine Mesh



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ITER=1
PATH PLOT
NOD1=18
NOD2=15
BCZ

ORIG
ZV=1
DIST=1.41

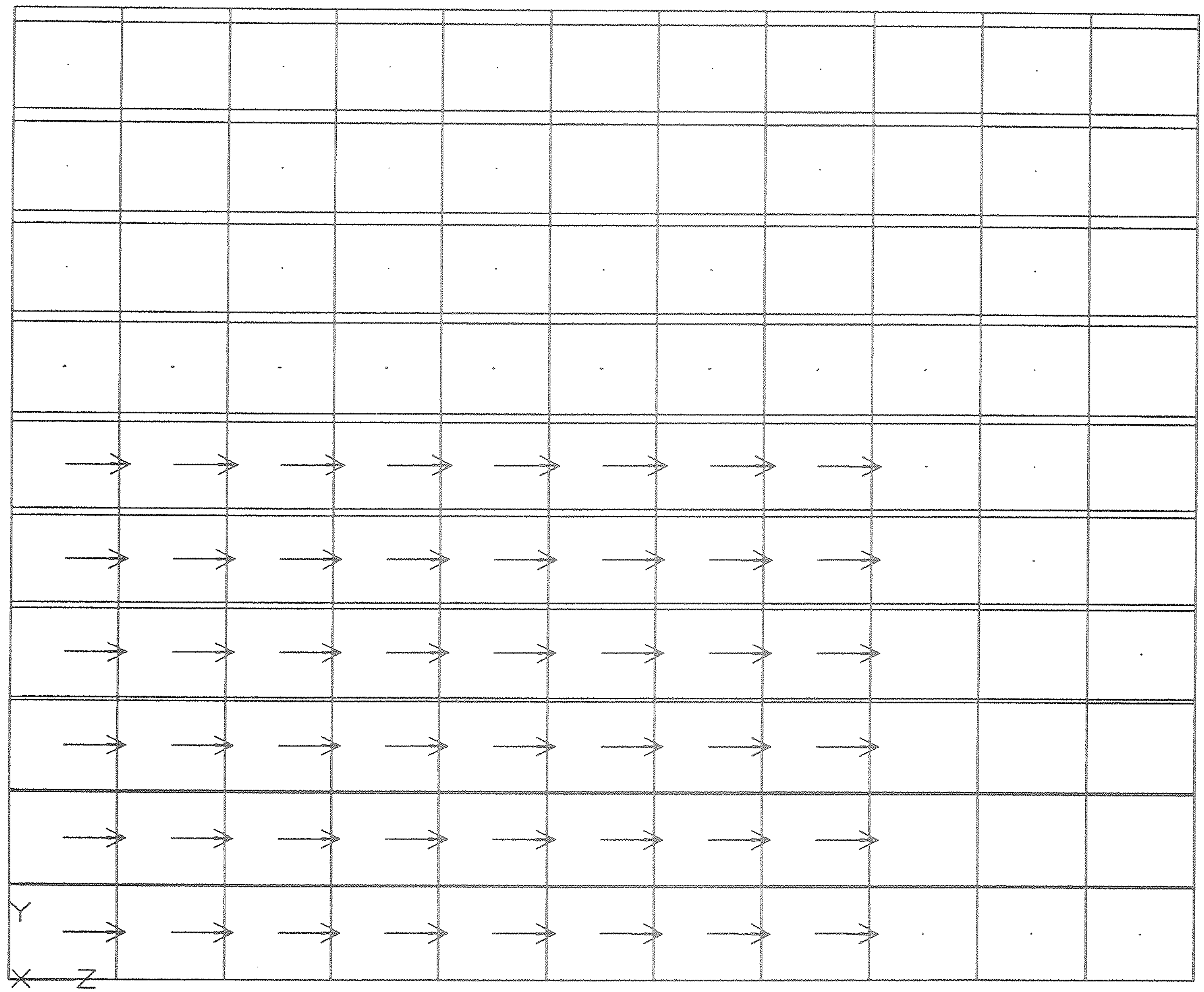
Fig 5. Central Field for Air-Iron Solenoid

MU=10000

ANSYS 4.3
JAN 18 1988
8:27:21
PLOT NO. 2
POST1 VECTOR
STEP=1
ITER=1
BMAG
MAX=849
ELEM=77

ORIG
XV=-1
DIST=6.05
XF=.781
YF=4.5
ZF=5.5

Fig 6. B-Field in Air-Iron Solenoid



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JAN 18 1988
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ITER=1
HMAG
MAX=1836889
ELEM=66

ORIG
XV=-1
DIST=6.05
XF=.781
YF=4.5
ZF=5.5

Fig 7. H-Field in
Air-Iron Solenoid

1/18/88 B. Wends

Appendix A Central and End Fields for Air-Only Solenoid

Central Field

$$H = \frac{In'\ell}{(\ell^2 + 4b^2)^{1/2}}$$

where $In'\ell$ = amp-turns = $28(10^6)$

ℓ = length of solenoid = 16 M

b = radius of solenoid = 5.263 m

Then $H = \frac{28(10^6)}{(16^2 + 4(5.263)^2)^{1/2}} = 1461993$

The B-field in Tesla is

$$B = \mu_0 H = 4\pi(10^{-7})(1461993)$$

$$\boxed{B = 1.84\ T}$$

Field at End

$$H = \frac{\frac{1}{2} In'\ell}{(\ell^2 + b^2)^{1/2}} = 831187.5$$

$$\boxed{B = 4\pi(10^{-7})(831187.5) = 1.04\ T}$$