Fermi National Accelerator Laboratory

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Field Calculation of D0 Toroids and Comparison with Measurement

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1. INTRODUCTION

The magnetic structure of the D0 detector is described in an earlier report [1]. The two-dimensional code POISSON was used for the initial design of the magnetic structures and the magnetic properties of the D0 toroids [2,3]. During the construction, the two-dimensional code ANSYS was used to perform more detailed calculations. Full three-dimensional analysis was also performed using the code TOSCA [4]. These new results are reported here and compared with measurements. In this study the magnetic flux in all toroids, CF, EF, and SAMUS is set in the same direction.

2. B-H CURVES

The vertical yokes of the CF toroid were made with SUREL iron recycled from an old synchrocyclotron. The horizontal yokes of CF and the entire EF toroids were made of distressed iron (low carbon 1006-1008 con-cast slabs) purchased from McLouth steel products Co.

To compute the field in CF and EF, we assumed the McLouth steel BH curve for both, since the SUREL iron is of better quality. The B-H curve, which is represented in Table I, was obtained from measurements made using small samples of McLouth steel, excited up to approximately 18 kG and was extrapolated beyond that level using manufacturer's data for 1010 steel. For three-dimensional calculations, the B-H curve was modified to incorporate the effect of very small air gaps, which were not included in the geometry. The modified B-H curve is presented in Table II.

The SAMUS toroids were fabricated using of a mixture of Russian steel plates equivalent to American steel 1008 and 1010. The B-H curve used for calculations was obtained from measurements up to 19 kG and extrapolated beyond that value using manufacturer's data for 1010 steel. The B-H curve used for the SAMUS toroids is presented in Table III.

All B-H curves are shown in Fig. 1 and 2 for the units of A/m and Oersted respectively.

3. 2-DIMENSIONAL FIELD CALCULATION

For this series of two-dimensional field computations the finite element analysis code ANSYS was used. The solutions were obtained using a two-dimensional vector potential formulation and the STIF13 elements. The cpu time for the simplest case of SAMUS was 3000 cpu sec with 4000 nodes in the model, and the most complicated case with the EF and SAMUS system took 15000 cpu sec (about 4 hours) with 19000 nodes, on the VAX 8800.

The calculated field distribution is shown with directional arrows whose length is proportional to its magnitude at the center of the element, and color coded on a color print-out. The range of the field magnitude is shown on the right side of the graph.

3.1 CF (Run CF041092)

The cross section of the CF toroid is shown in Figure 3, where PDT chambers and twenty unit coils inside CF are shown. The CF toroid is made of a stationary central beam and two side moving parts. There are 1/8 inch (3.2 mm) gaps on both sides of the central beam and one 3/16 inch (4.8 mm) gap at the center of the top yoke. These gaps are partially filled with stainless steel plates. The toroid is excited with twenty 10-turn unit coils at 2500 A per turn.

3.1.1. Calculation

Two-dimensional calculations for CF were performed using the B-H curve presented in Table I. As shown in Figure 4 symmetry is exploited and only half of the cross section is modeled. The magnetic flux distribution inside the CF yoke is shown in Figure 4, superimposed on the finite element mesh. The flux distribution is fairly uniform across the width of the yoke. Typical flux values, averaged across the width, are shown in Figure 3. The values at the top gap, the top yoke, side yoke, bottom yoke, and the central beam are 19.34, 19.54, 19.13, 19.69 and 18.68 kG respectively. The small differences are mostly due to the different yoke thicknesses and partly due to differences in the fringing field patterns. The ratios of the inverse of the yoke width are 100.0, 100.0, 96.8, 100.4, and 98.0 respectively. This agrees relatively well with the corresponding field ratios: 99.0, 100.0, 97.9, 100.8, and 95.6. Local variations of the flux (of the order a few percent) at proximity of the coils can also be observed.

The fringing field distribution inside CF is shown in Figure 5. There is a strong fringing field (up to 300 Gauss) on both sides of the central beam which can be attributed mainly to the uneven distribution of the unit coils, and partly to the small air gaps.

3.1.2. Measurement and Comparison

In the top gap of CF, there are five equally spaced vertical slots where a probe can be inserted to measure the field distribution across the yoke width. This was done using a Group3 Digital Teslameter. The results are shown in Figure 6. The mating surfaces in the top gap were not machined uniformly and the presence of many rough spots is obvious in this curve. The average value of the measured magnetic field in the top gap is 19.2 kG. The calculated values are 19.37 kG at the center and 19.18 kG at both edges. The calculated average field is 19.34 kG, a value which compares rather well to the measured average.

A fixed Group3 probe is now installed permanently in the gap 2 and the field value can be read in the control room [5]. The excitation curve at that point was also measured and is shown in Figure 7. The agreement with the B-H curve is good. Above 15 kG, there is no noticeable hysteresis effect.

In 1989, the flux density at the top of the vertical yoke (y = 3.15 m) was measured to be 18.4 kG using flux loops [6]. This agrees well with the calculated value of 18.67 kG (at y = 3.1445 m).

The fringing field inside CF was measured along the central vertical lines at x=0. The results at z= -300, 0 and 140 cm are shown in Figure 8. The measurement and calculation are qualitatively in agreement. However, the calculated field value on the beam axis (at x=y=0) by 2-D ANSYS is 46 G (in the horizontal direction), much higher than the measured value of 8 G. The discrepancy is probably due to a three-dimensional effect. The calculated value by 3-D TOSCA is also shown in Figure 8, which has more reasonable data near the center at y= 0. The fringing field at z= 140 cm is also shown in Figure 3, where the level zero trigger counter photomultipliers are mounted.

3.2 EF alone (Run EF051492)

The geometry of the EF toroid is shown in Figure 9, where the SAMUS toroid is also shown. The EF toroid has coils only on both side yokes, while the SAMUS toroid has coils only on the top and bottom yokes. Calculations for EF alone were performed first to understand the interaction between EF and SAMUS. The EF and SAMUS system will be examined later.

The full cross section of the EF toroid was modeled, including the 12" dia. main ring hole, and 1" thick 10" o.d. iron shield pipe placed at the nominal position (x= -0.3297 m, y=2.0691 m).

3.2.1 Calculation

Flux calculations for EF alone were performed using the B-H curve presented in Table 1. The flux distribution in EF alone at the nominal current of 2500 A is shown in Figure 10, where the actual values inside EF are shown. The average field values in the top, bottom, and the side yokes are 18.8, 18.4, and 18.5 kG. The disturbance created by the presence of the main ring hole is clearly seen. The iron immediately above and below the hole is more saturated than elsewhere.

3.2.2 Measurement

The measured B value inside the side yoke was determined to be 19.43 kG [6], which is about 5 % higher than the calculated value.

3.3 SAMUS alone (Run SA050792)

The geometry of the SAMUS toroid is shown in Figure 9. It has two unit coils of 25 turns each, which are wound on the top and bottom yokes. These coils are covered with 1 cm thick steel plates.

3.3.1. Calculation

Calculations for the SAMUS toroid alone were performed using the B-H curve in Table III. To take advantage of the symmetry, only the first quadrant of the cross-section was modeled. The flux distribution corresponding to a 1000 A excitation current is shown in Figure 11, where the flux densities just inside the steel are shown. The flux density in the side yoke is 18.97 kG and very uniform. In the top yoke, it varies from 19.84 to 19.78 kG. The 1-cm thick steel coil cover plates are saturated at 20 kG in the opposite direction. The widths of the side and top yokes are 55.9 and 57.2 cm.

The fringing field inside the hole (in the first quadrant) is shown in Figure 12. The calculated field values along the inside surface are shown together with the measured values in brackets [3]. The agreement is fairly good, considering that the calculations are two-dimensional.

3.3.2 Measurement

The measured flux densities in the top and side yokes are 18.8 and 17.7 kG [7]. these values are roughly 1 kG (~5%) lower than the calculated values.

3.4 EF and SAMUS (EFSA041092)

The EF-SAMUS system geometry is shown in Figure 9. In this calculation the main ring beam hole in EF is included, and located off the center line as designed. In order to include the effect of the off-center main ring hole in EF, it was necessary to model the complete cross section.

3.4.1. Calculation

The B-H curve from Table I was used for EF and that from Table III for SAMUS. The nominal operation current are respectively 2500 A for EF and 1000 A for SAMUS, with both currents set to produce the same flux flow direction.

The calculated flux distribution inside the EF yoke is shown in Figure 13. where the flux density just inside the steel is shown. Due to the interaction with SAMUS toroid, the side yokes of EF have higher flux values of about 19.1 kG. The top and bottom yokes of EF have lower values of about 18.2 and 17.7 kG respectively. The flux distribution inside EF is quite redistributed compared to the case of EF alone. The fringing field value just under the EF toroid is 127 G in this 2-D calculation.

The flux distribution inside the SAMUS yoke is significantly perturbed by the EF toroid, as is shown in Figure 14. The top and the bottom yokes are highly saturated, while the side yokes are not saturated. The flux density inside the top yoke is 21.1 kG and the bottom yoke is showing 21.0 kG. The left-side vertical yoke, which is closer to the main ring hole has about 14.8 kG and the right-side vertical yoke has about 14.6 kG. This asymmetry is due to the main ring hole. The flux distribution inside the cover plates for the SAMUS coils are in the opposite direction and not highly saturated.

The fringing field distribution inside the SAMUS hole is shown in Fig. 15. The field value at the center of the hole is 27 G, pointing to the left. This is due to the bottom coil cover being more saturated than the top one. At the median surfaces of the side yokes, the fringing field values are about 40G.

The flux distribution around the 12" main ring hole with 1" thick 10" o.d. iron magnetic shield, is shown in Fig. 16. The magnetic flux around the main ring hole in EF is quite distorted. The calculated field value at the center of the hole is 54 G without any more magnetic shielding for the vacuum pipe, and the flux value inside the iron shield ring is 19.8 kG at the top and bottom of the ring.

3.4.2. Measurement

The flux measurement on the EF and SAMUS system with the same flux flow direction was done and reported [8]. The flux densities in the top and side yokes of EF are estimated 18.4 and 19.6 kG respectively. The values in the top and side yokes of the SAMUS are estimated 19.9 and 15.6 kG respectively.

Inside the SAMUS hole we measured the vertical components of the fringing field at $x=+24$, and -24 cm, $y=0$. They were about +50, and -50 G respectively, while the calculated value is about 40 G. The measured fringing field at the bottom center of EF was 70 G, while the 2-D calculated value neglecting the effect of the platform is 127 G, which is a little higher probably due to the 2-dimensional calculation.

The residual field inside the main ring vacuum pipe with additional magnetic shield, placed inside the main ring hole with 1" thick shield in EF, was measured to be about 0.1 G [9].

4. 3-DIMENSIONAL FIELD CALCULATION

All three-dimensional calculations were performed using TOSCA version 6.1, a well-known finite element magnetostatics code [4]. Two cases were analyzed. In the first case, the CF and EF toroids and the supporting structure were modeled [10]. In the second case, the SAMUS toroid was added. The air gaps in CF were not included in the geometry because of their very small relative dimensions; however, the B-H curve was modified in the second case to take into account effect of the gaps on the reluctance of the CF toroid. The B-H curve for CF is shown in Table II. The B-H curves for EF and SAMUS are the same ones as for 2-D case. The main ring hole in EF was not included because of its small relative size and because its presence would have broken the left-right symmetry of the model. The preliminary data of the second case with preliminary B-H curves was reported elsewhere [11].

To minimize the size of the problem, all symmetries were exploited and a problem region representing one fourth of the total detector volume was used. The problems were solved using approximately 90,000 nodes and quadratic interpolation on a Solbourne Series 5/801 workstation (roughly equivalent to a Sun SparcStation II).

The TOSCA algorithm is based on a scalar potential formulation and requires the contribution of the coils to the total field to be calculated separately by numerical integration. The D0 detector has a total of 36 coils, 5 yoke structure and a steel platform. A typical run took about three days, most of the time being used to calculate the coil contribution.

Due to the coarseness of the discretization, the field in the corner regions of the EF and CF toroids exhibits small fluctuations and an unexpected dip in magnitude exactly on the corner bisector.

In the final calculation, the flux density in CF is 19.4 kG in the top gap, which is in agreement with the measured value of 19.2 kG. The results show 18.5 kG at the top of its vertical yoke, reflecting 3.2 % wider yoke width. The B-value in the central beam is 17.5 kG, reflecting 10 % wider yoke width and some leakage into the fringing field and into the platform.

The calculated B values in EF are 18.39 and 17.62 kG in the top and bottom yoke, and 20.12 kG in both side yokes. There is no main ring beam pipe hole in EF, and no left and right asymmetry. The fringing field under the bottom center is 114 G, while the measured value is 70 G.

The calculated B values in the inserted SAMUS are 21.02 and 20.86 kG in the top and bottom yoke, and 15.46 kG in both side yokes. These values are reflecting the interaction of the EF and SAMUS coils to the yoke of the other member.

5. OVERALL COMPARISON BETWEEN CALCULATED AND MEASURED VALUES

The typical field values, measured and calculated, with the CF, EF and SAMUS toroids are summarized and shown in Table IV. For both EF and CF, the calculated and measured flux values are within 2 % in both calculation methods. For SAMUS, the calculations and measurements agree within 5 %.

A summary of the calculation results for EF alone and SAMUS alone is presented in Table V.

6. FIELD MAPPING DATA

The field map used for Monte Carlo calculation was obtained from two-dimensional calculations using ANSYS. For CF and EF, the field was mapped on a 10-cm square grid, using cell values at 5, 15, 25 cm etc. A finer 5-cm square grid is used for the SAMUS toroid region.

To make the 10 cm or 5 cm grid for CF, EF and SAMUS, the result of an irregular mesh ANSYS calculation was used as the starting point, and the grid was calculated using the technique of submodelling with one cycle of iteration.

The resulting field maps reproduce the actual field distribution fairly well, except the areas around the SAMUS coils and the main ring hole in EF.

Acknowledgments

We would like to thank Mr. R. Wands for stimulating discussions and help with the ANSYS program.

Appendix

With the forward current setting of both power supplies, the magnetic flux in CF, both EF's and both SAMUS's circulates in the counter-clockwise direction, looking at the detector from the north (same as the direction of proton beams). For historical reasons, the reading of all Hall probes is set in negative under these conditions.

References

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Table I
B vs H for CF & EF

B (T)	H (A/m)	H (Oe)
1.20	557	6
1.40	1106	13
1.50	1799	22
1.55	2403	30
1.60	3390	42
1.65	4831	60
1.70	6263	78
1.75	8050	101
1.80	10250	128
1.85	12900	162
1.90	16220	203
1.95	20290	254
2.00	24670	310
2.05	31040	390
2.10	40590	510
2.20	91520	1150
2.30	171100	2150
2.40	238700	2999
2.60	397900	5000
2.80	557100	7000

Table II
B vs H Modified
for CF of Tosca

B (T)	H (A/m)	H (Oe)
0.73	557	6
1.02	1106	13
1.20	1799	22
1.30	2403	30
1.40	3390	42
1.50	4831	60
1.57	6263	78
1.64	8050	101
1.71	10250	128
1.77	12900	162
1.84	16220	203
1.90	20290	254
1.95	24670	310
2.01	31040	390
2.07	40590	510
2.18	91520	1150
2.29	171100	2150
2.39	238700	2999
2.59	397900	5000
2.80	557100	7000

Table III
B vs H for SAMUS

B (T)	H (A/m)	H (Oe)
1.00	650	8
1.20	1100	13
1.40	1800	22
1.50	2480	31
1.60	3620	45
1.65	4600	57
1.70	5850	73
1.75	7400	92
1.80	9350	117
1.85	11800	148
1.90	14970	188
1.95	19000	238
2.00	24170	303
2.05	30860	387
2.10	39790	500
2.20	91520	1150
2.30	167100	2099
2.40	238700	2999
2.50	318300	3999
2.85	676400	8499

Table IV Flux Distribution in D0 Toroids

The CF and EF's are excited with 2500 A, and the SAMUS's are excited with 1000 A. All toroids are in the same flux orientation.

Toroid	Position	Measured B (kG)	ANSYS B (kG)	TOSCA B (kG)	Measured Data Ref.
CF	Top gap	19.2	19.34	19.41	
	Top of vert. yoke	18.4	18.67	18.54	Ref.6
	Side yoke		19.11	18.55	
	Bottom yoke		19.51	18.62	
	Central beam		18.68	17.48	
				(No M.R. hole)	
EF	Top yoke	18.4	18.2	18.39	Ref.8
	Bottom yoke		17.7	17.62	
	Side yoke	19.6	19.1	20.12	Ref.8
SAMUS	Top yoke	19.9	21.1	21.02	Ref.8
	Bottom yoke		21.0	20.86	
	Side yoke	15.6	14.8	15.46	Ref.8

Table V Data Summary for EF alone and SAMUS alone

EF alone				
	Top yoke		18.8	
	Bottom yoke		18.4	
	Side yoke	19.43	18.5	Ref. 6
SAMUS alone				
	Top yoke	18.8	19.8	Ref. 7
	Side yoke	17.7	19.0	

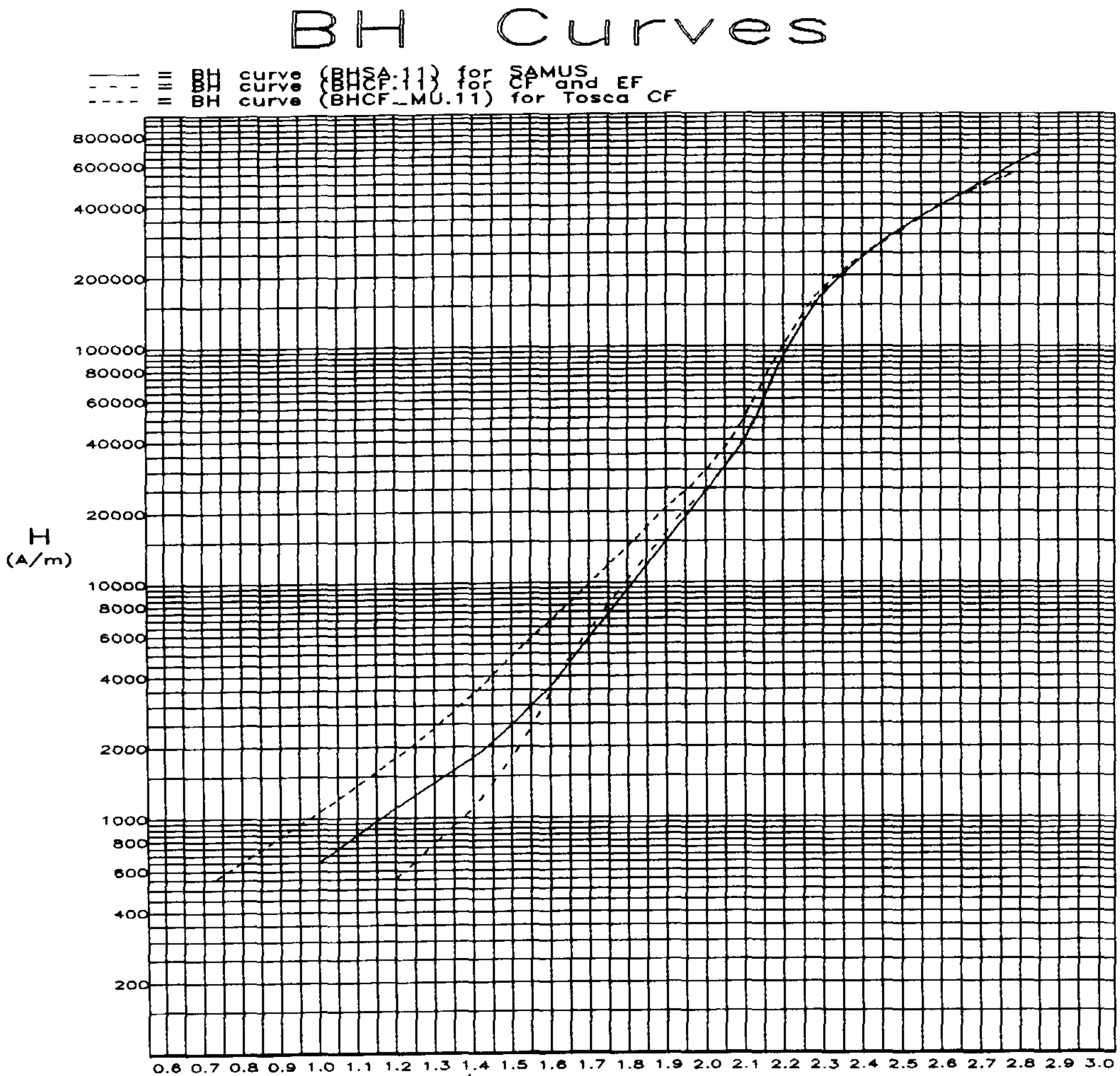


Fig. 1 BH Curves in Units of A/m

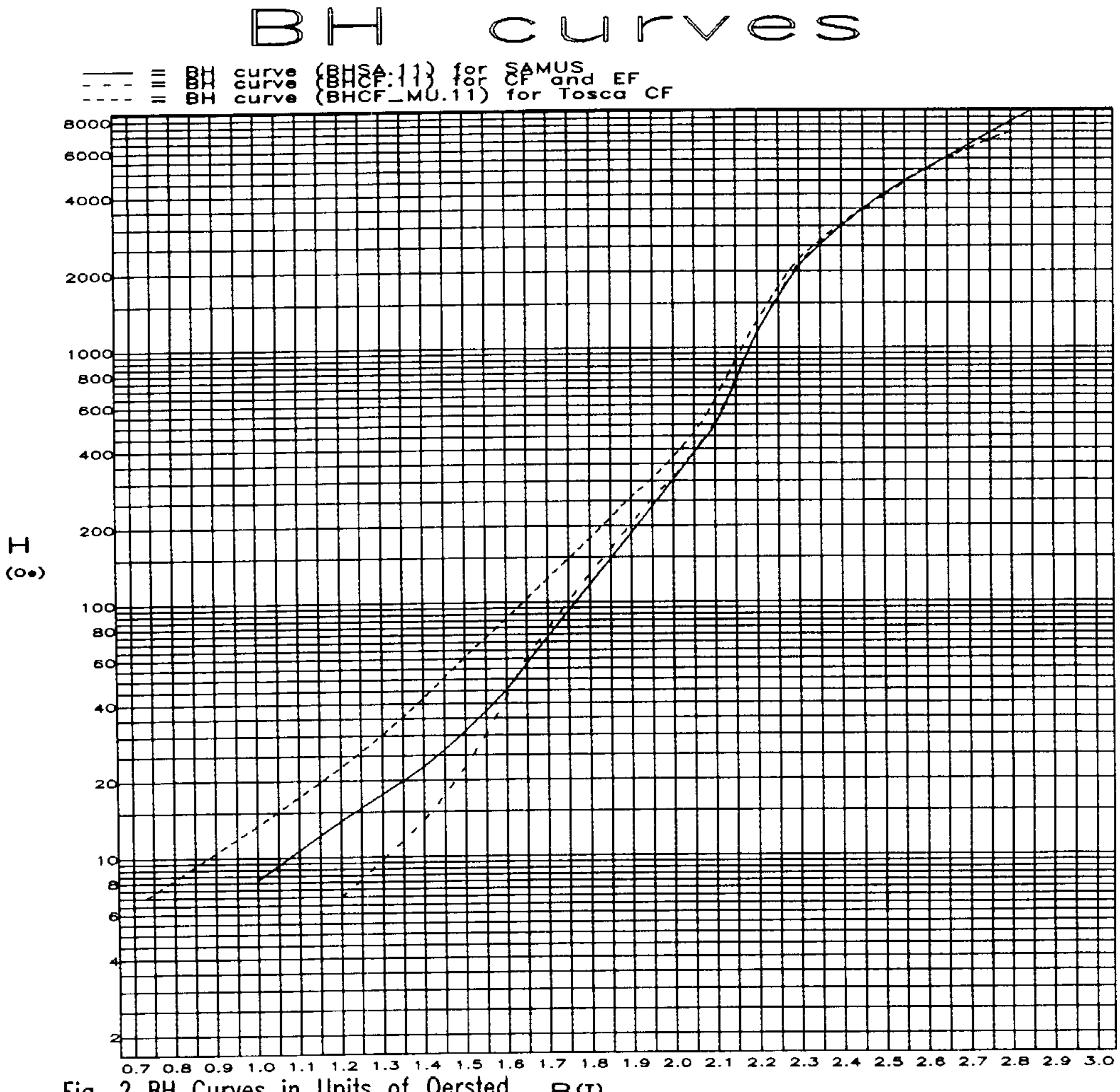
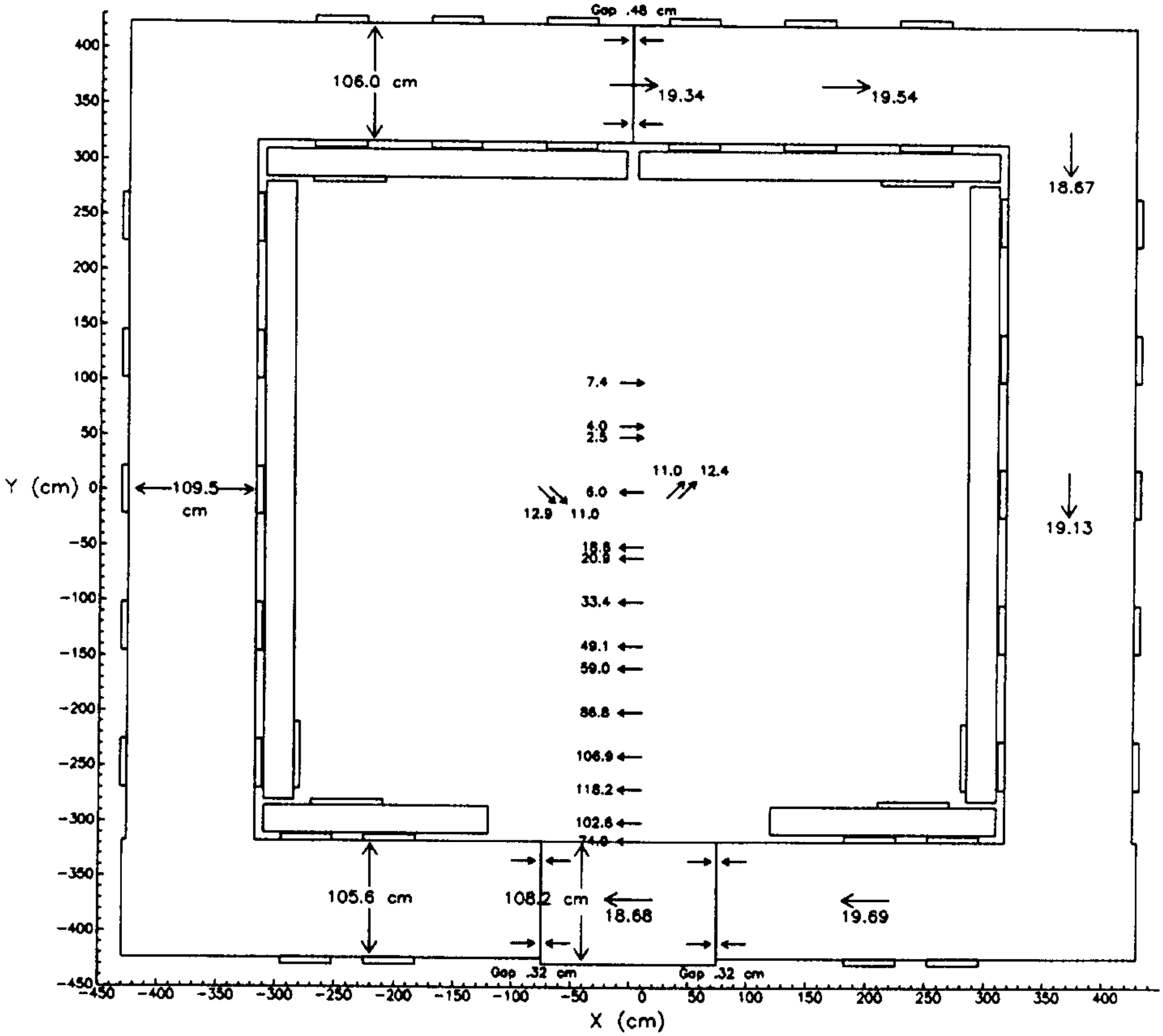


Fig. 2 BH Curves in Units of Oersted

Fig. 3 Geometry of CF Toroid

Calculated Flux Values(in kG) in CF Yoke Avereged Across Its Width(in cm)

& Measured Fringing Field inside CF at Z=140 cm (in Gauss)



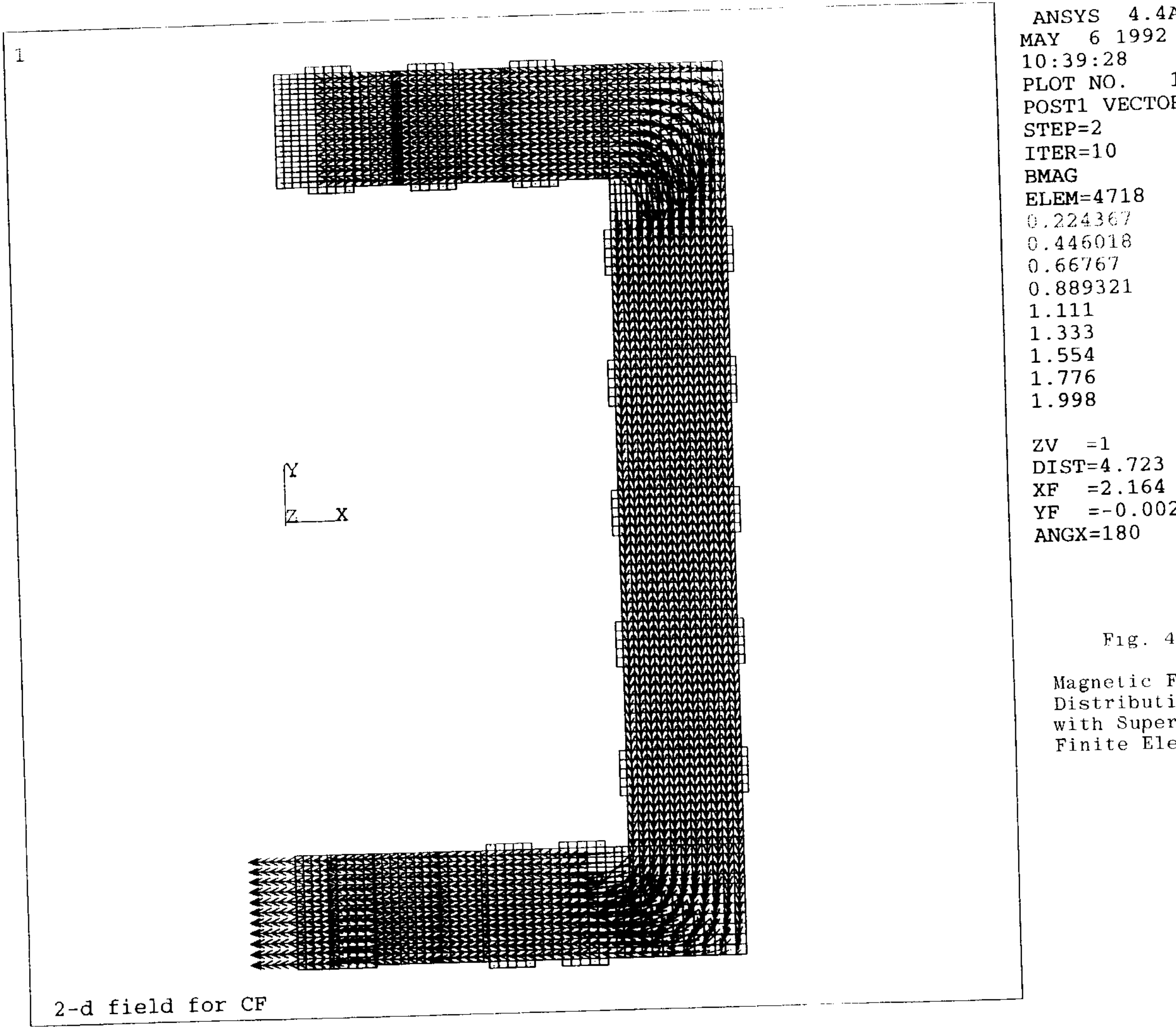


Fig. 4

Magnetic Flux Distribution in CF with Superimposed Finite Element Mesh.

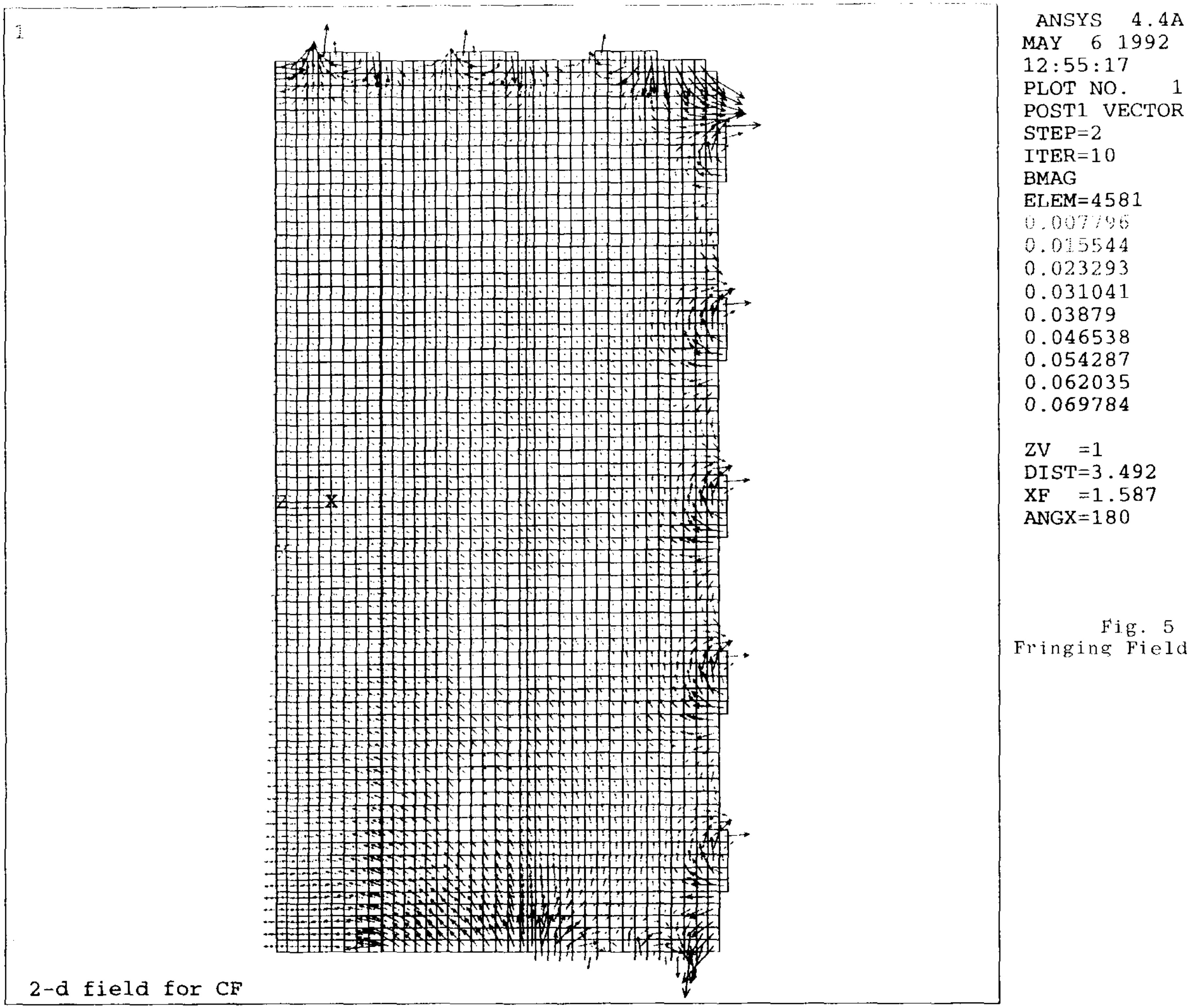
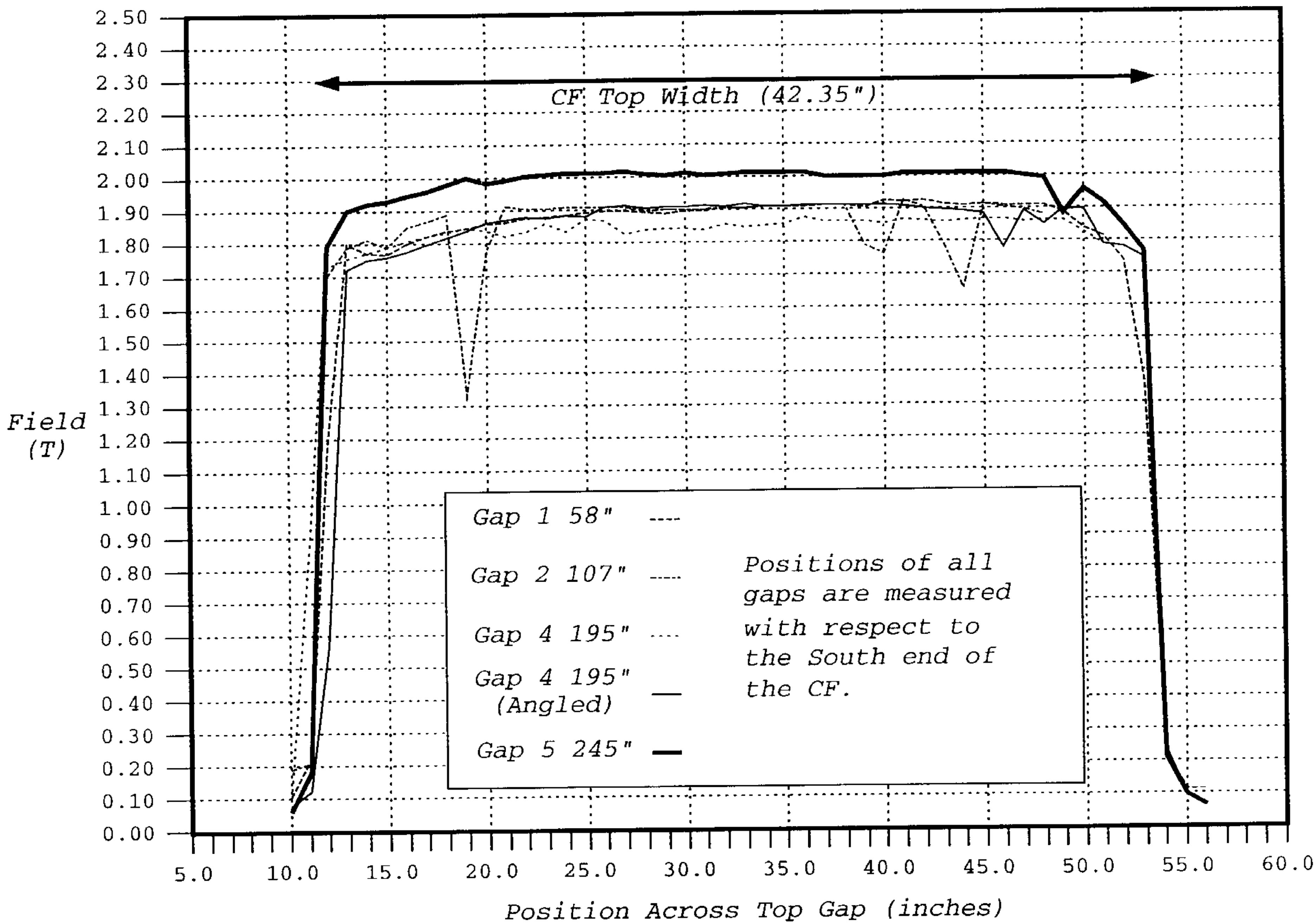


Fig. 5
Fringing Field inside CF

Fig. 6 Magnetic Field in CF Gaps at 2500 Amp.



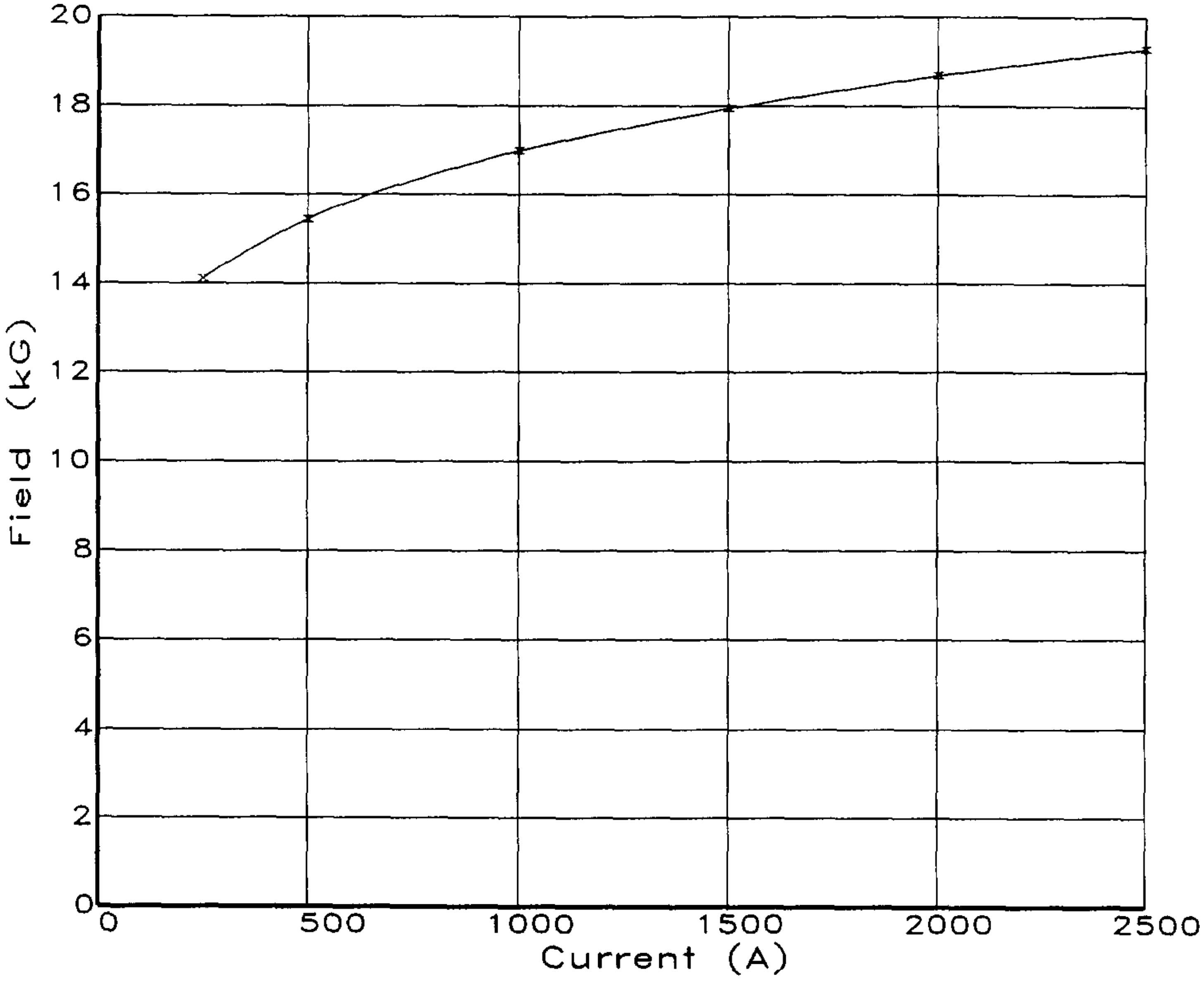
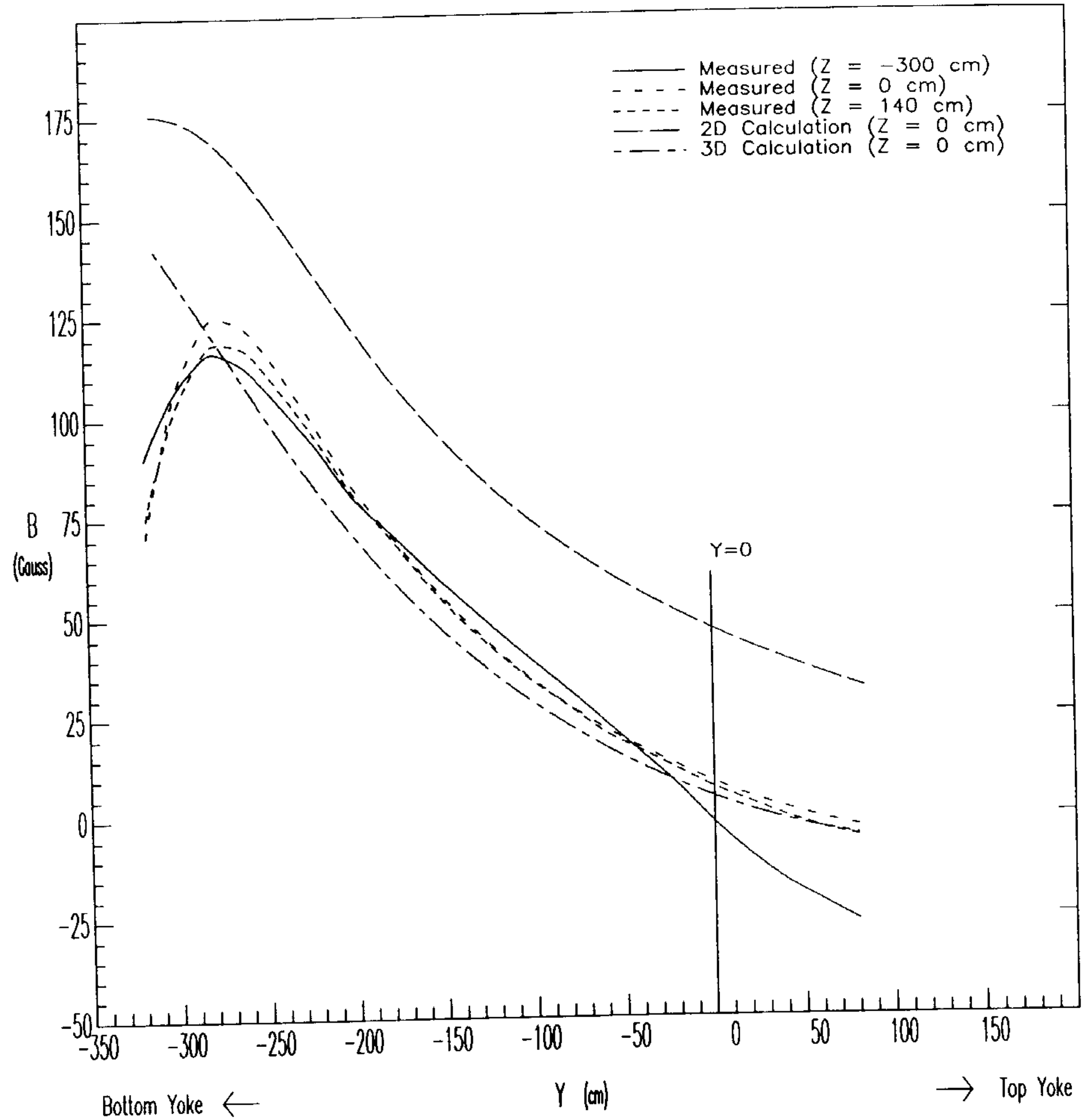
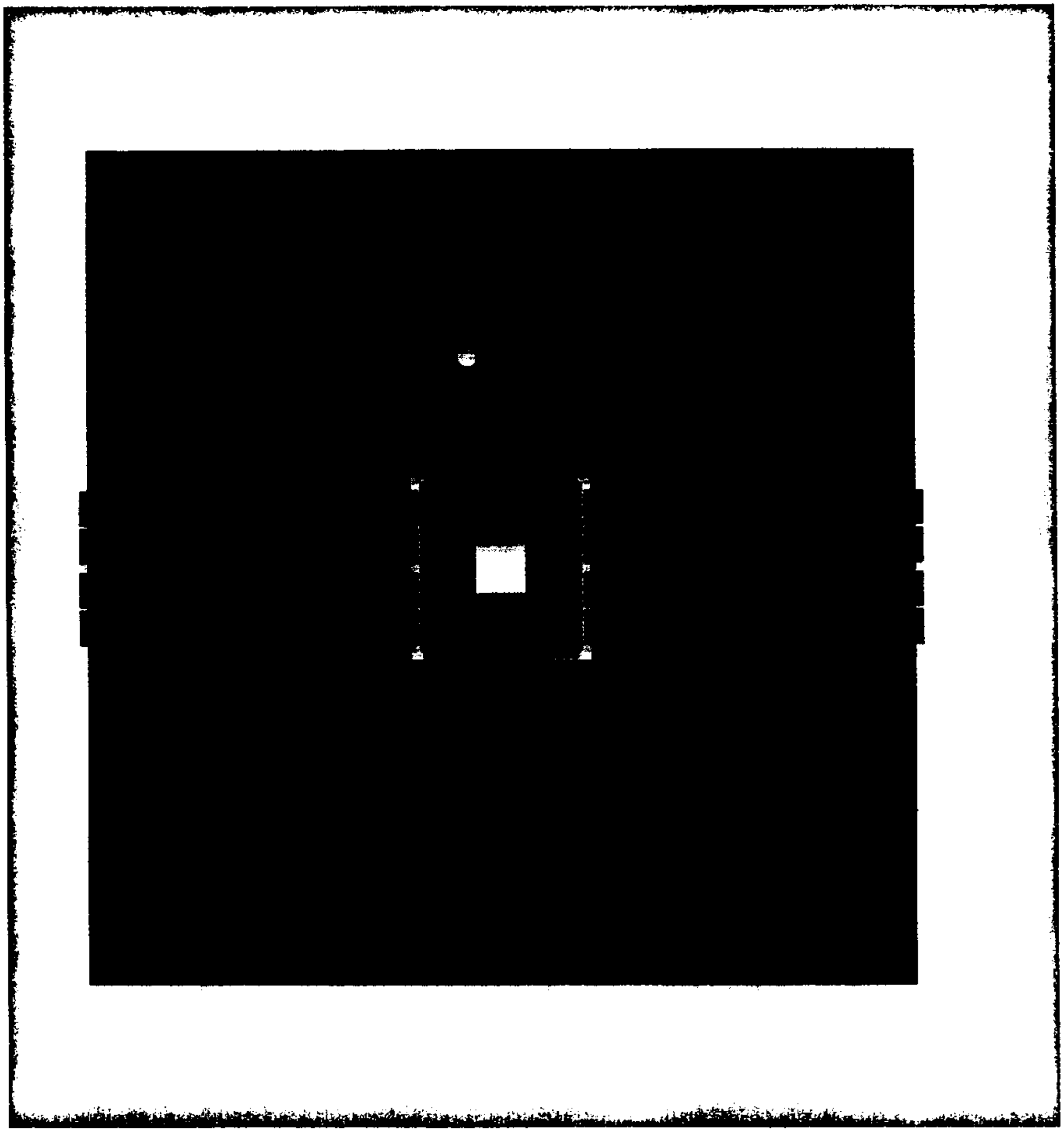


Fig. 7 Excitation Curve of CF measured in Top Gap

Fig. 8 Fringing Field in CF on Central Vertical Lines at X=0





ANSYS 4.4A
MAR 24 1992
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PLOT NO. 2
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TYPE NUM

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Fig. 9

Geometry of EF and SAMUS

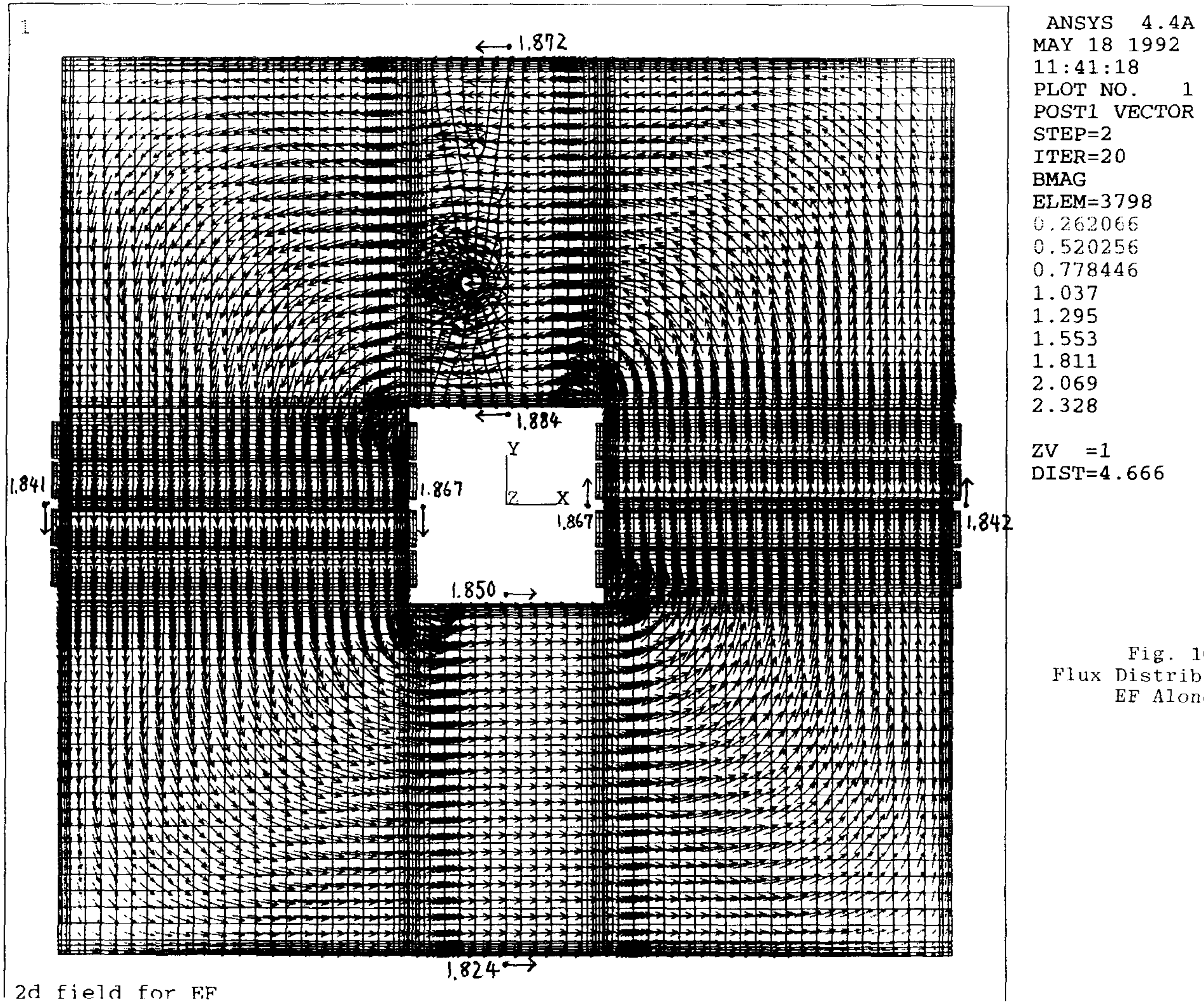


Fig. 10
Flux Distribution in
EF Alone.

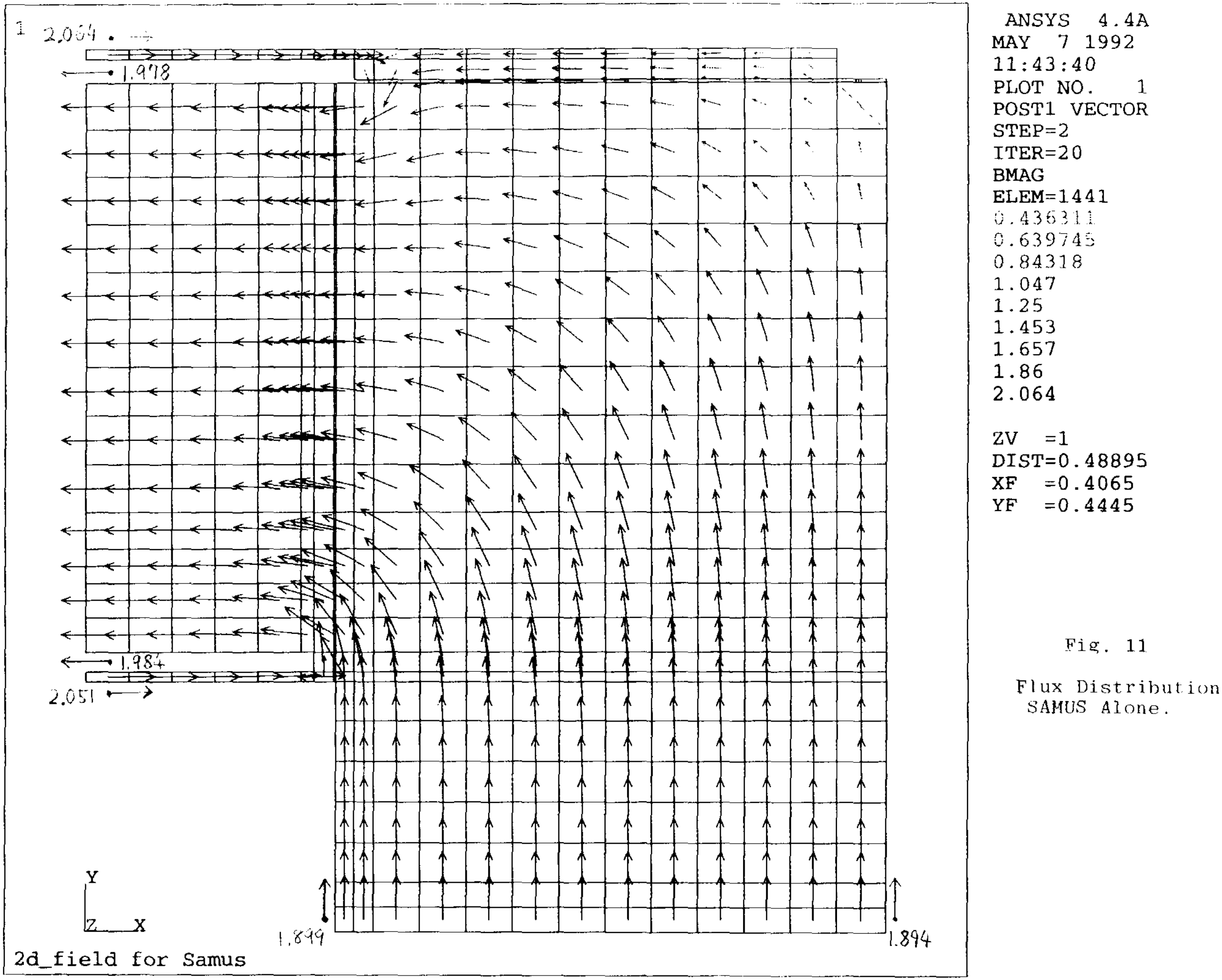
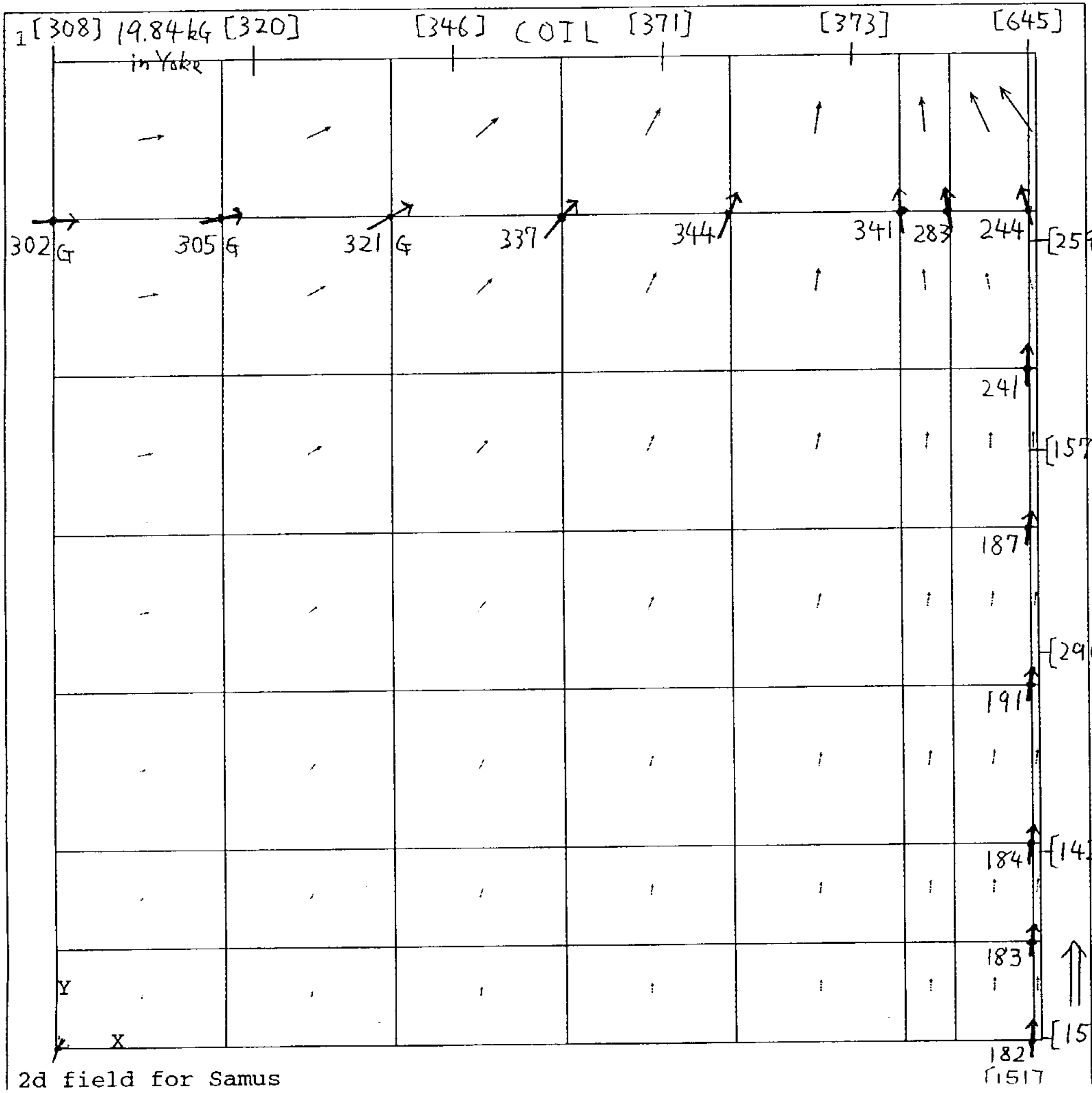


Fig. 11

Flux Distribution
SAMUS Alone.



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0.02593
0.033695
0.041461
0.049226
0.056992
0.064757
0.072523

ZV =1
DIST=0.1397
XF =0.127
YF =0.127

Fig. 12

Fringing Field inside SAMUS Hole for SAMUS Alone

Calculated Values in Gauss are shown together with measured values in square brackets.

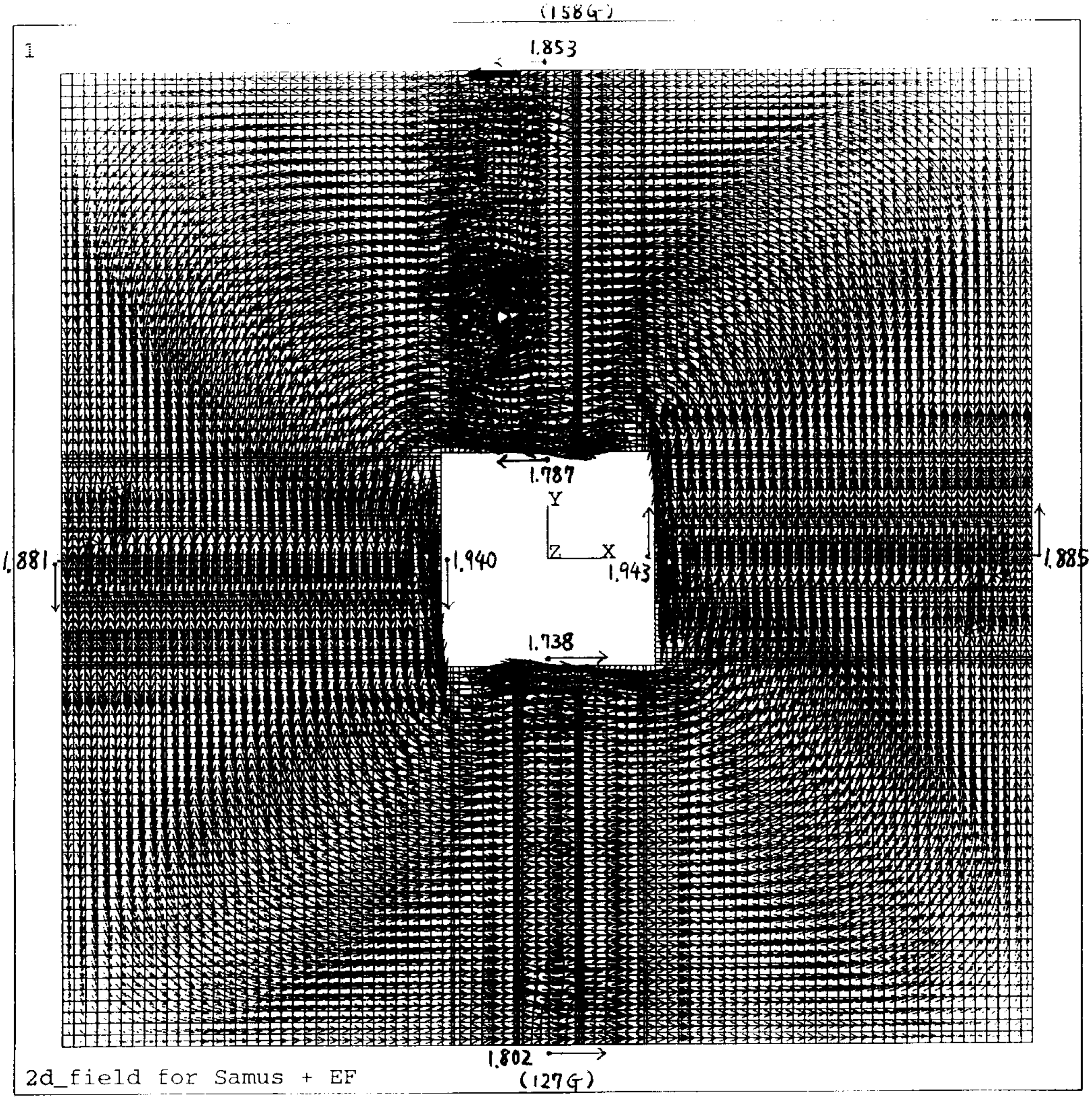


Fig. 13

Flux Distribution inside EF Yoke for EF and SAMUS Run.

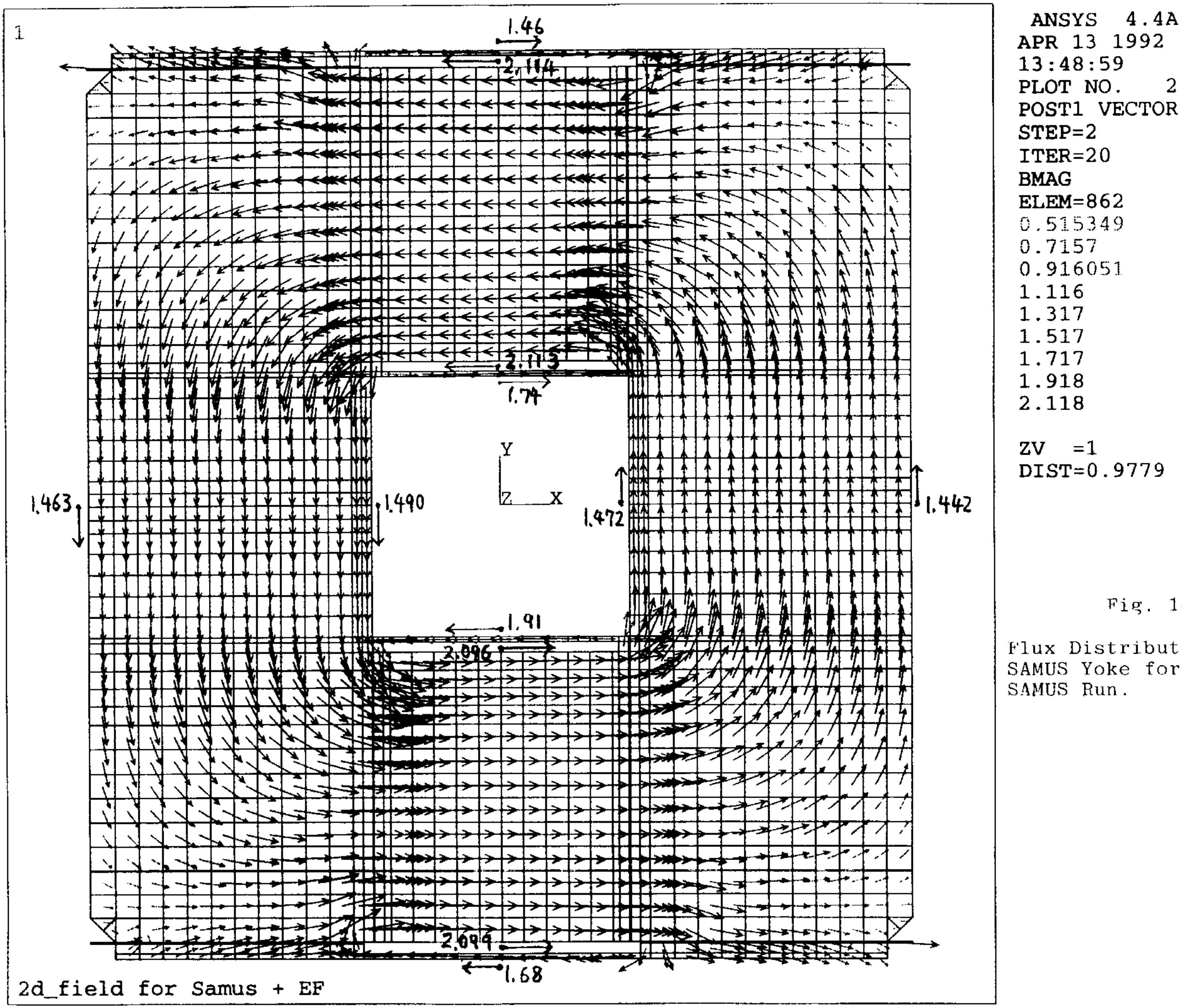
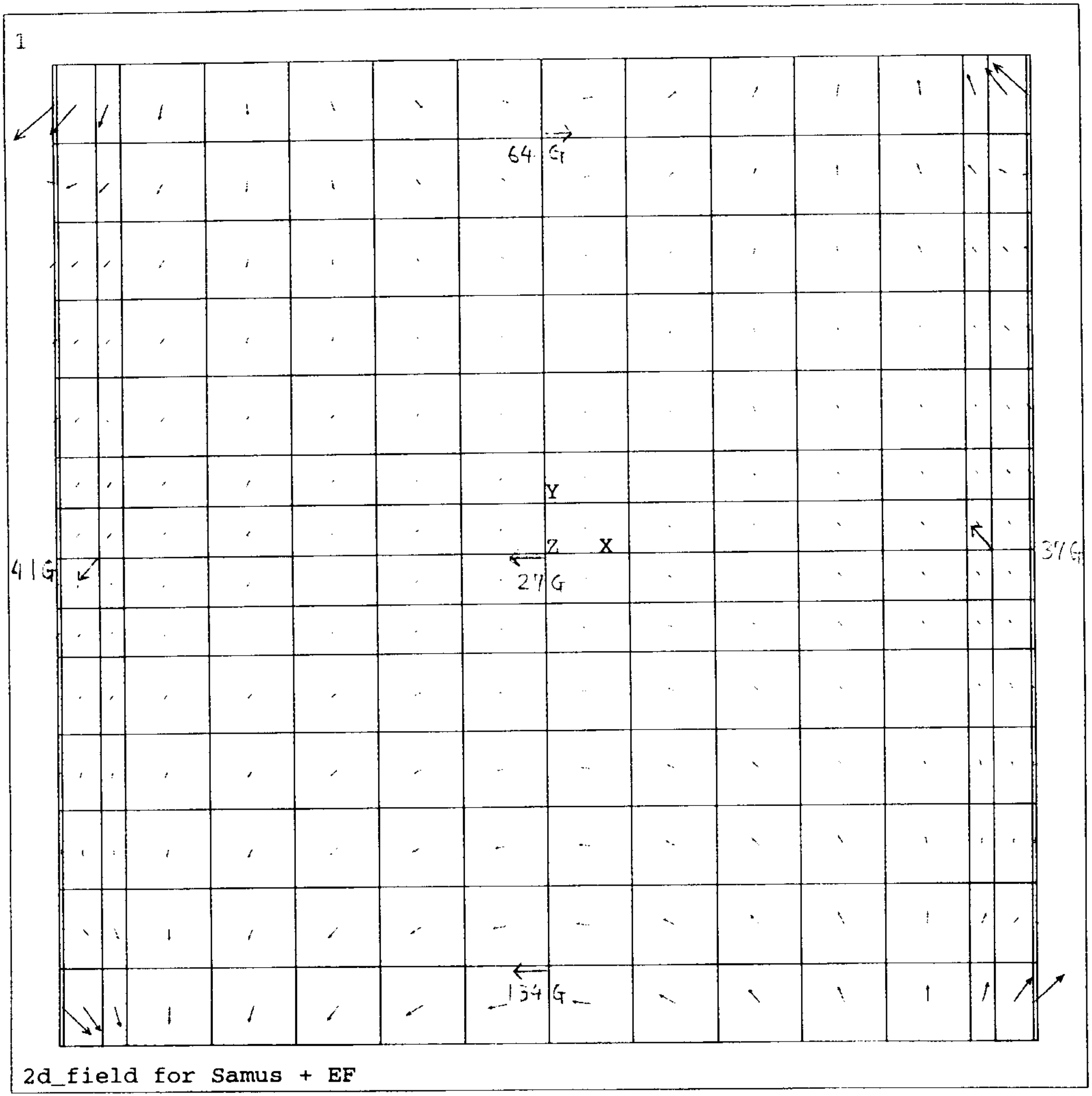


Fig. 14

Flux Distribution inside SAMUS Yoke for EF and SAMUS Run.



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0.019971
0.024808
0.029645
0.034482
0.039319
0.044155

ZV =1
DIST=0.2794

Fig. 15

Fringing Field inside SAMUS Hole for EF and SAMUS Run.

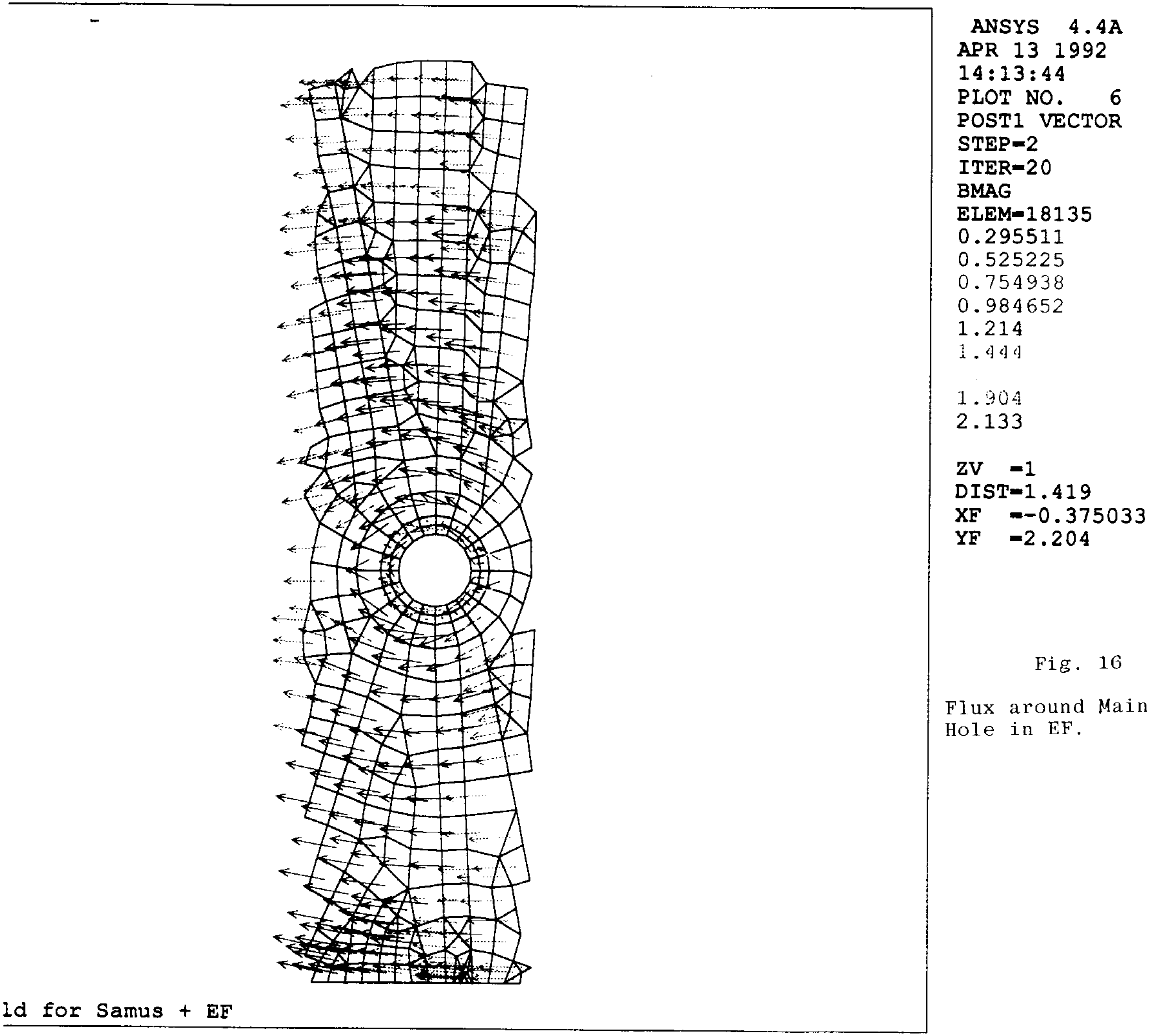

Fig. 16

Flux around Main Ring Hole in EF.