Summary of Results for Problem 20
(3-D Static Force Problem)

N. Takahashi, T. Nakata and H. Morishige
Department of Electrical and Electronic Engineering,
Okayama University, Okayama 700, Japan

Abstract - Thirteen computer codes developed by eleven groups are applied to the benchmark problem 20 (3-D static force problem) for the TEAM workshop. The solutions are compared with each other and with experimental results.

I. INTRODUCTION

Benchmark problem 20 for the TAM Workshop [1,2] is a 3-D static force problem. The aim of this model is to compare various kinds of methods for calculating electromagnetic force.

Twenty-one solutions from eleven groups were presented. The flux distributions and electromagnetic forces analyzed by different computer codes are compared with each other and with experimental results.

II. PROBLEM DEFINITION

Fig. 1 shows the dimensions of a 3-D model for verification of the dc force calculation. The center pole and yoke are made of steel. The model is constructed so that the mechanical deformation is negligibly small. The number of turns of the coil is 381 and the ampere-turns are chosen to be 1000, 3000, 4500 and 5000 (dc) in order to investigate the saturation effect.

The quantities to be computed are as follows:

1. z-components Bz of flux densities at mid-point P_1 (0, 0, 25.75) and edge point P_2 (12.5, 5, 25.75) shown in Fig. 2,
2. z-components Bz of average flux densities along the line $\alpha - \beta$ in the center pole and the line $\gamma - \delta$ in the yoke,
3. distributions of x-components Bx of flux density along lines a-b and c-d,
4. z-components Fz of the force.

Fig. 3 shows the B-H curve of the steel. Typical values of B(T) and H(A/m) are also shown in Table 1. As the flux density at the upper edge of the center pole is very high, the B-H curve has to be known even above 2.3T. In order to measure the B-H curve in the high flux density region, a permeameter [3] is used.

III. DESCRIPTION OF COMPUTER CODES

The name and affiliation of authors, code name, formulation, force calculation method, element type, number of elements etc. of each code are summarized in Tables 2 and 3.

A. Calculation Method of Magnetic Field

Three methods are proposed for this problem: the finite element, boundary element and volume integral equation methods. In the finite element codes, either the magnetic vector potential *A* or the magnetic scalar potential Ω is taken as an unknown variable. In the boundary element code AMPERES and the volume integral equation code CORAL, the surface current *K* and the magnetic field strength *H* are used as unknown variables respectively.

Five finite element codes use the first-order edge elements. Six finite element codes use nodal elements: The second-order nodal elements are used in IGTEMAG3D and FLUX3D. The first-order nodal elements are used in other codes. In the boundary element code AMPERES, 4-sides surface element and 6-surfaced subvolume are used. In volume integral equation code CORAL, the tetrahedral edge element is used.

B. Force Calculation Method

Maxwell stress tensor method [4] is employed in nine codes. The nodal force method [3] is adopted in EDDY3D. The advanced energy method [4,5] is applied to FLUX3D, GEP/3DSTAT and FIELD(/A3DT-E and /T3DT-N). The magnetizing current method [6] is used in FIELD (/A3DT-E and /T3DT-N)[7], and the *JxB* method in AMPERES.

IV. EXPERIMENTS

Fig. 4 shows the experimental apparatus [8]. The flux densities are measured using a Hall sensor (accuracy: 2%, active area: 1X2mm) and search coils. The positions to be measured are decided using a three dimensional manipulator (resolution: 0.01mm).

The z-component of electromagnetic force is measured with a load cell which is located at the top of a supporting rod made of nonmagnetic stainless steel which is connected directly to the center pole. The positioning of yoke and center pole is improved by using a special jig which can adjust the position to be restrained within 10 μ m from the most preferable position. The displacement of the center pole is measured using an eddy current type displacement sensor (accuracy: 1%).

V. RESULTS AND DISCUSSION

Table 4 shows the z-components Bz of flux densities measured at the mid-point P1 (0,0, 25.75) and at the edge P2 (12.5, 5, 25.75) in the gap. Table 5 shows the z-components Bz of average flux densities in the center pole ($\alpha-\beta$) and yoke ($\gamma-\delta$). Table 6 shows the z-component Fz of electromagnetic force [9,10].

Figs. 5 and 6 show the z-directional component Bz of flux density at the mid-point P1 (0, 0, 25.75) and at the edge P2 (12.5, 5, 25.75) in the gap shown in Fig. 2. The discrepancies between calculations and experiment of Bz at point P2 is larger than those of Bz at point P1. This is because the errors of calculation and experiment may increase at the point where the flux density changes abruptly. Figs. 7 and 8 show the z-component Bz of average flux density in the center pole ($\alpha-\beta$) and yoke ($\gamma-\delta$). Figs. 9 and 10 show the x-component Bx at 5000AT along the lines a-b and c-d shown in Fig. 2. There are oscillations in the results of 3DFE.

Fig. 11 indicates the z-component Fz of electromagnetic force. Some results of electromagnetic force are different from measured values, although the flux densities calculated are not so much deviated from those measured.

VI. CONCLUSIONS

Twenty-one sets of results on the problem 20 were presented. Most groups used Maxwell stress tensor method for calculating electromagnetic force.

The obtained results can be summarized as follows:

1. The results of electromagnetic forces obtained using the second-order element are in better agreement with measurement compared with those obtained using the first-order element.
2. The results obtained using the advanced energy method and the nodal force method have good accuracy.
3. Most of the results by Maxwell stress tensor method are in good agreement with measurements when the number of elements is large enough, except some cases.

The measured flux densities along the lines a-b and c-d may have some errors, because the accurate measurement at the narrow gap is not easy. The comparison between flux densities calculated and newly measured will be reported in future.

REFERENCES

[1] T.Nakata, N.Takabashi, Subarutono and H.Morishige, “Proposal of a model for verification of software for 3-D static force calculation”, Verification of Software for 3-D Electromagnetic Field Analysis (Editors: Z.Cheng, K.Jiang, N.Takahashi), pp. 139-147, 1992, International Academic Publishers.

[2] T.Nakata and N.Takahashi, “Verification fo 3-D software for calculating electromagnetic force (Invited)”, Electromagnetic Field Problems and Applications (Editor: J. Baidun), pp. 7-10, 1992, International Academic Publishers.

[3] A.Kameari and S.Niikura, “Magnetic force calculation by nodal force method in FEM using edge elements”, Proceedings of Compumag Conference, PA2-13, 1993.

[4] J.L.Coulomb, “A method for the determination of global electromechanical quantities from a finite element analysis and its application to the evaluation of magnetic forces, torques and stiffness”, IEEE Transactions on Magnetics, vol. MAG-19, no. 5, pp. 2514-2519, September 1983.

[5] T.Nakata, N.Takahashi, K.Fujiwara and T.Moriwake, “Investigation of accuracy of advanced energy method for electromagnetic force calculation”, Proc. of Symposium on Simulation in Electrical and Electronic Engineering, Japan Society for Simulation Technology, I-15, pp. 107-112, March 1992.

[6] T.Kabashima, A.Kawahara and T.Goto, “Force calculation using magnetizing currents”, IEEE Transactions on Magnetics, vol. MAG-24, no. 1 pp. 451-454, January 1988.

[7] N. Takahashi, T. Nakata and H. Morishige, “Verification of software for calculating electromagnetic force and torque using IEEJ model”, Software Applications in Electrical Engineering (Editor: P.P. Silvester), pp. 221-228, 1993.

[8] T.Nakata, N.Takahashi, M,Nakano, H.Morishige and K. Matsubara, “Improvement of measurement of 3-D static force problem (Problem 20)”, Proceedings of Miami TEAM Workshop, 1993.

[9] T.Nakata, N.Takahashi, H.Morishige, J.L.Coulomb and J.C.Sabonnadiere, “Analysis of 3-D static force problem”, Proceedings of TEAM Workshop on Computation of Applied Electromagnetics in Materials, pp. 73-79, 1993.

[10] N.Takahashi, T.Nakata, Suhartono and H.Morishige, “Investigation of a model to verify software for 3-D static force calculation”, Proceedings of Compumag Conference, PB3-3, 1993.

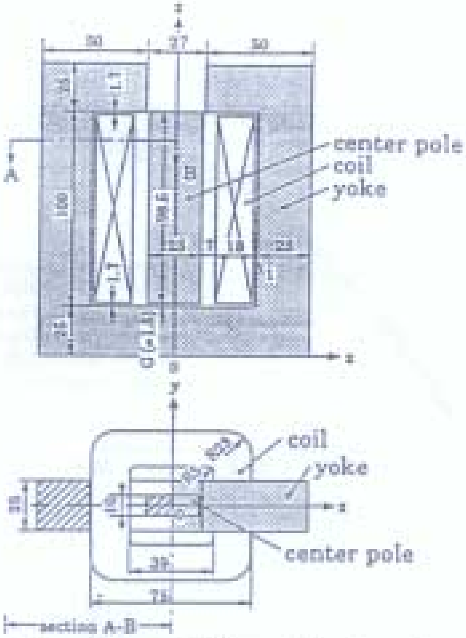

Fig.1 3-D model for verification of force calculation.

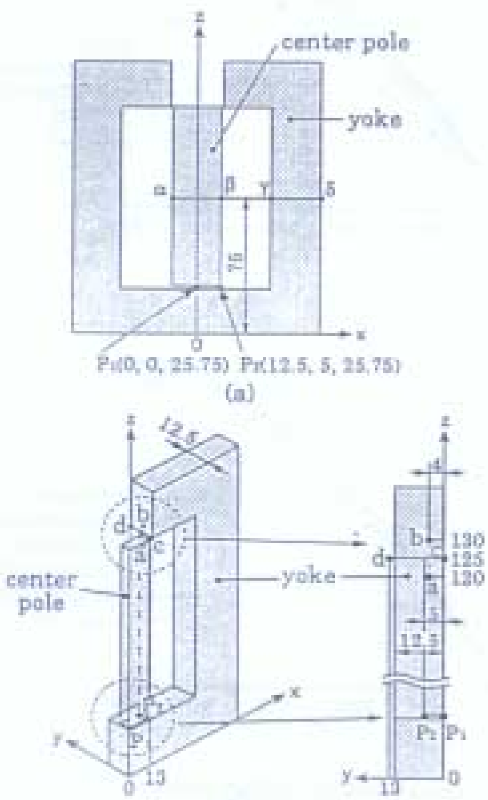

Fig.2 Positions at which flux densities are measured.

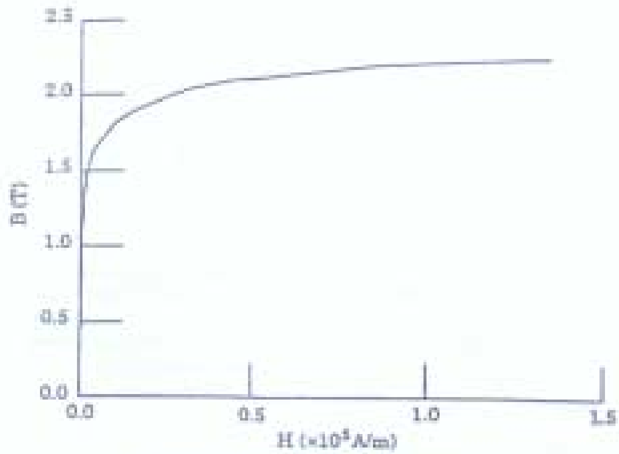

Fig.3 Measured B-H curve.

Table 1 B-H curve data

No.	B (T)	H (A/m)	No.	B (T)	H (A/m)
1	0.0	0	21	1.45	1720
2	0.01	27	22	1.50	2130
3	0.025	58	23	1.55	2670
4	0.05	100	24	1.60	3480
5	0.10	153	25	1.65	4500
6	0.15	185	26	1.70	5950
7	0.20	205	27	1.75	7650
8	0.30	233	28	1.80	10100
9	0.40	255	29	1.85	13000
10	0.50	285	30	1.90	15900
11	0.60	320	31	1.95	21100
12	0.70	355	32	2.00	26300
13	0.80	405	33	2.05	32900
14	0.90	470	34	2.10	42700
15	1.00	555	35	2.15	61700
16	1.10	673	36	2.20	84300
17	1.20	836	37	2.25	110000
18	1.30	1065	38	2.30	135000
19	1.35	1220			
20	1.40	1420			

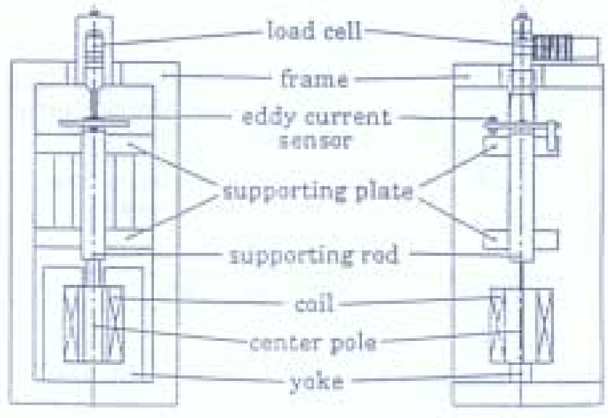

Fig.4 Measurement system of electromagnetic force.

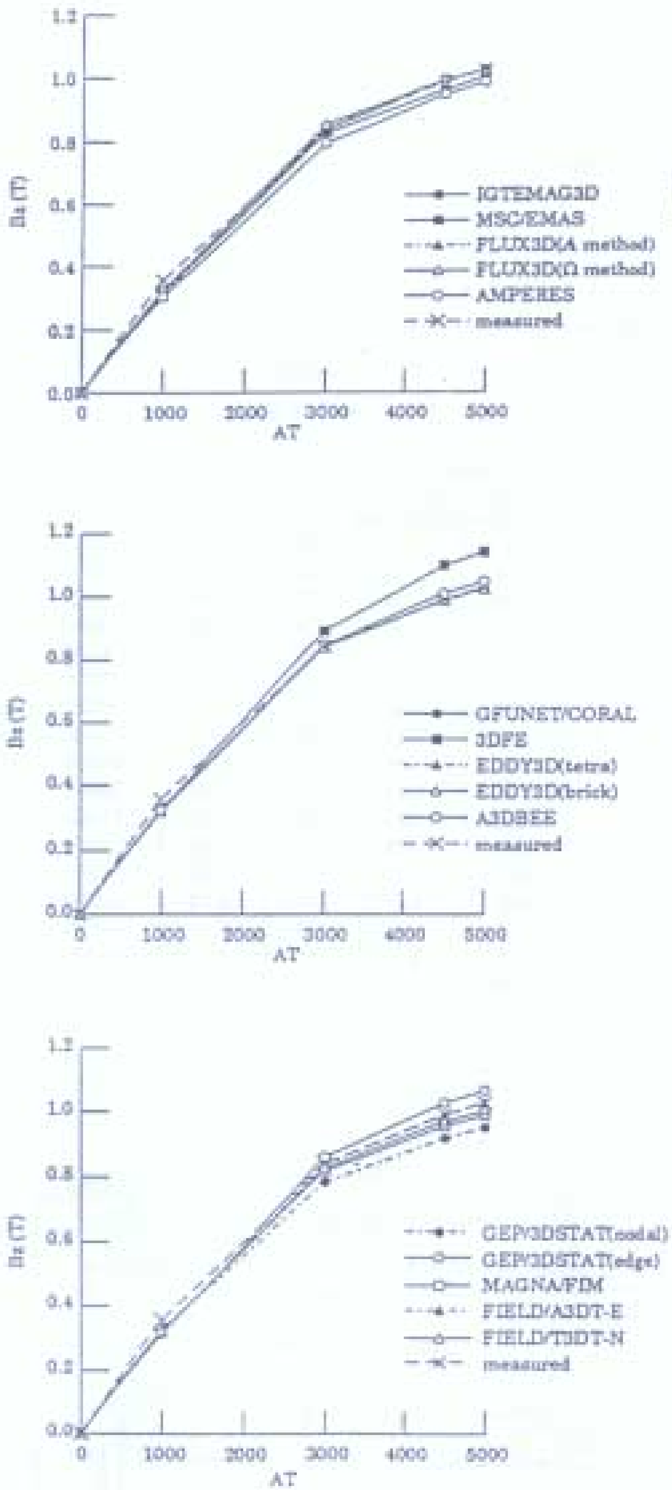

Fig.5 Z-component Bz of flux density at point P_1.

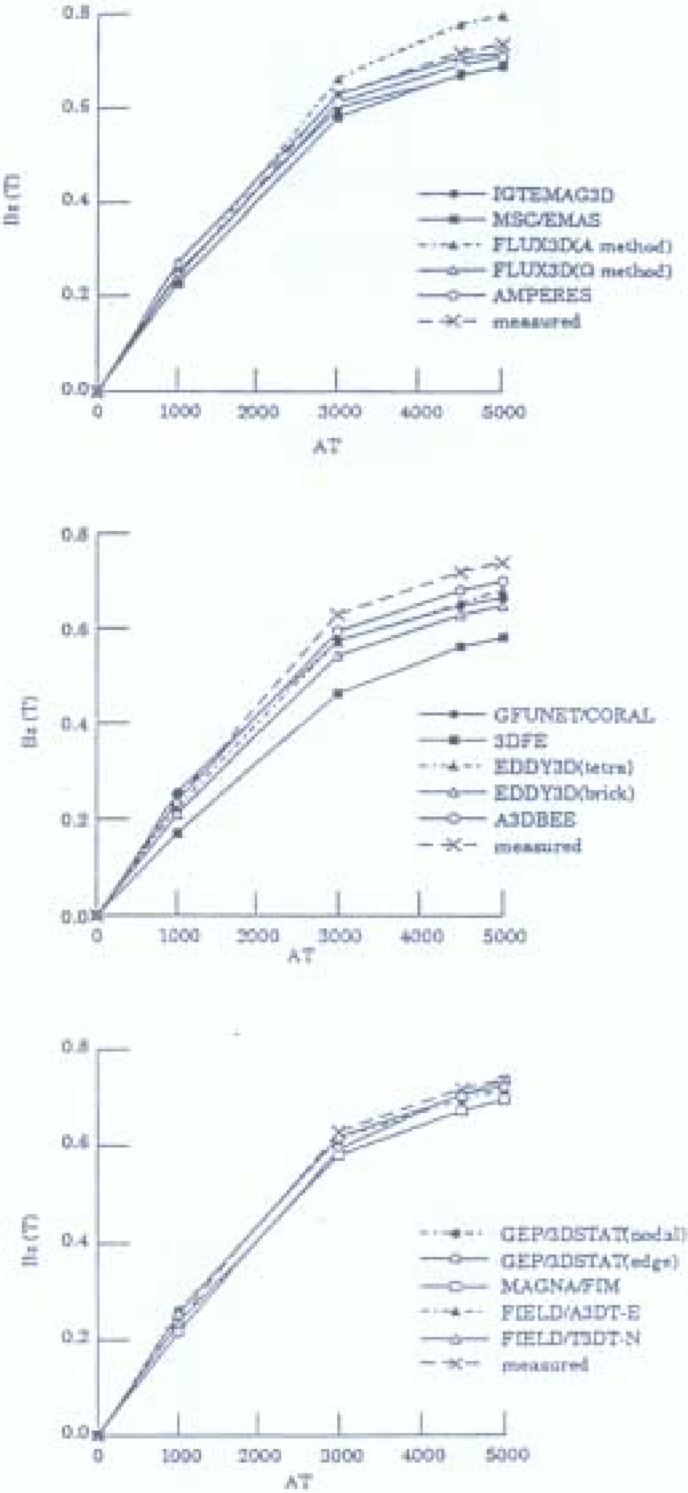

Fig.6 Z-component Bz of flux density at point P_2.

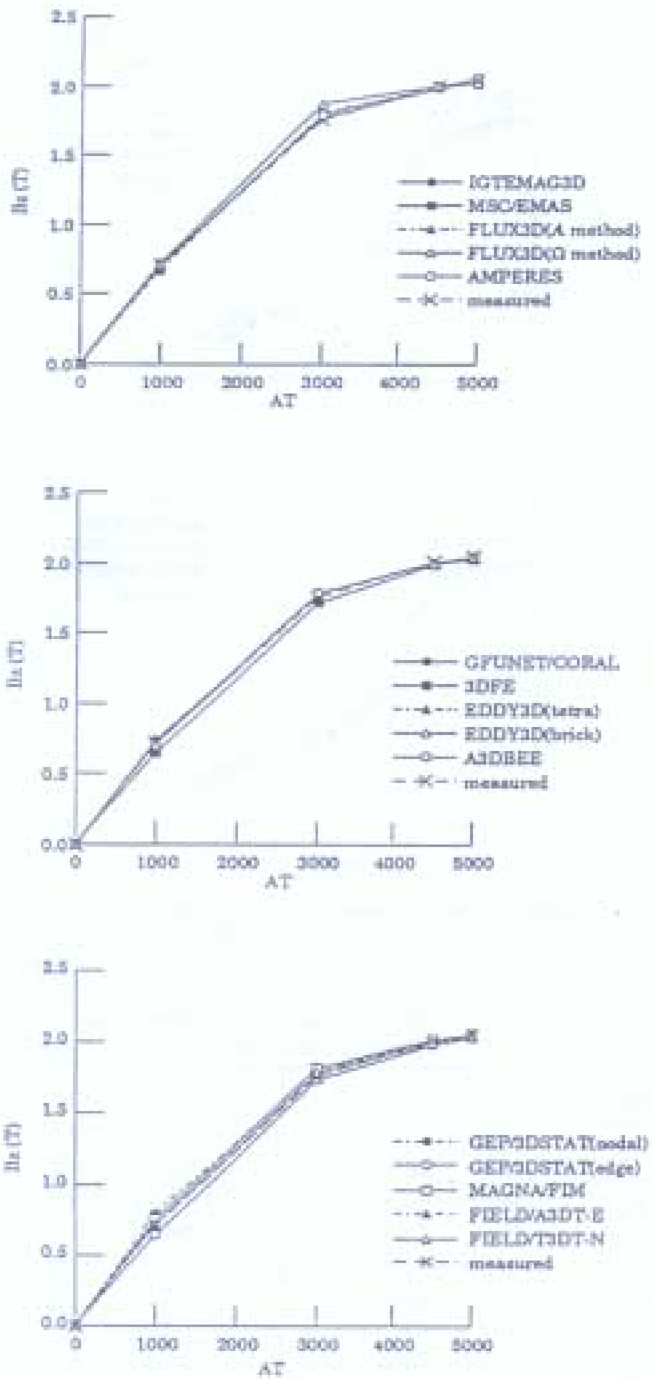

Fig.7 Z-component Bz of average flux density in center pole (α–β).

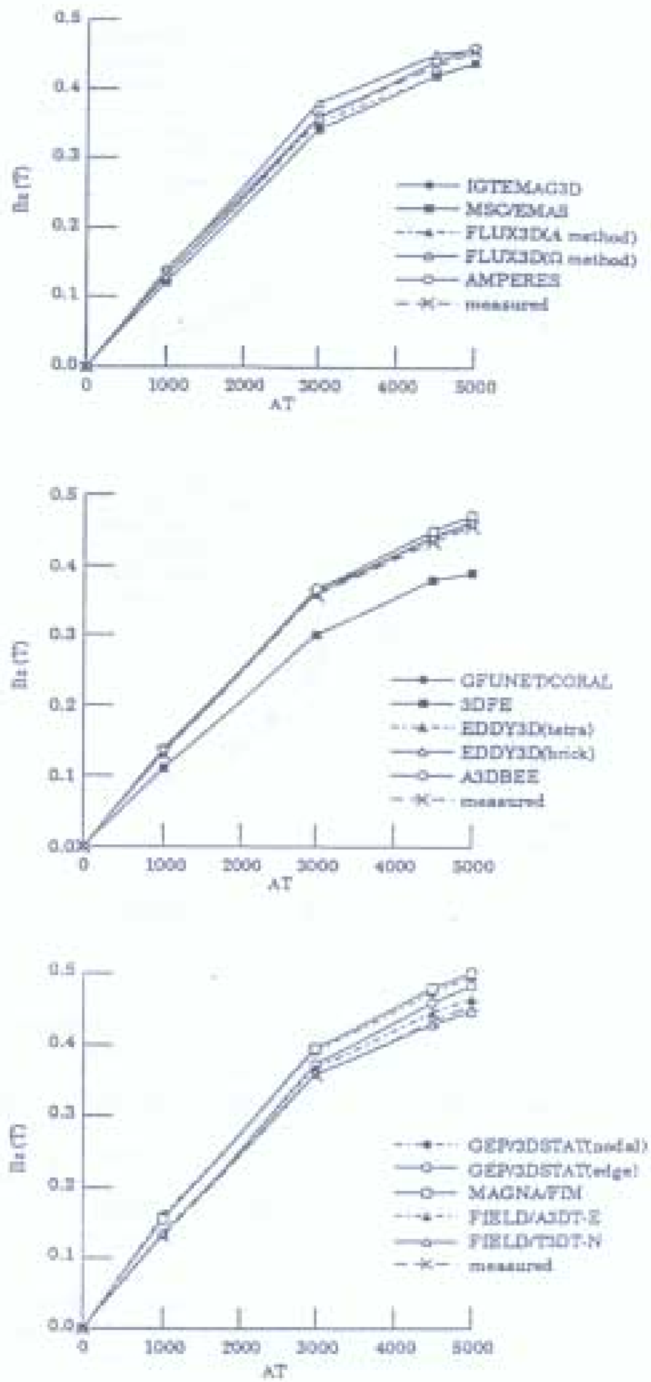

Fig.8 Z-component Bz of average flux density in yoke (γ–δ).

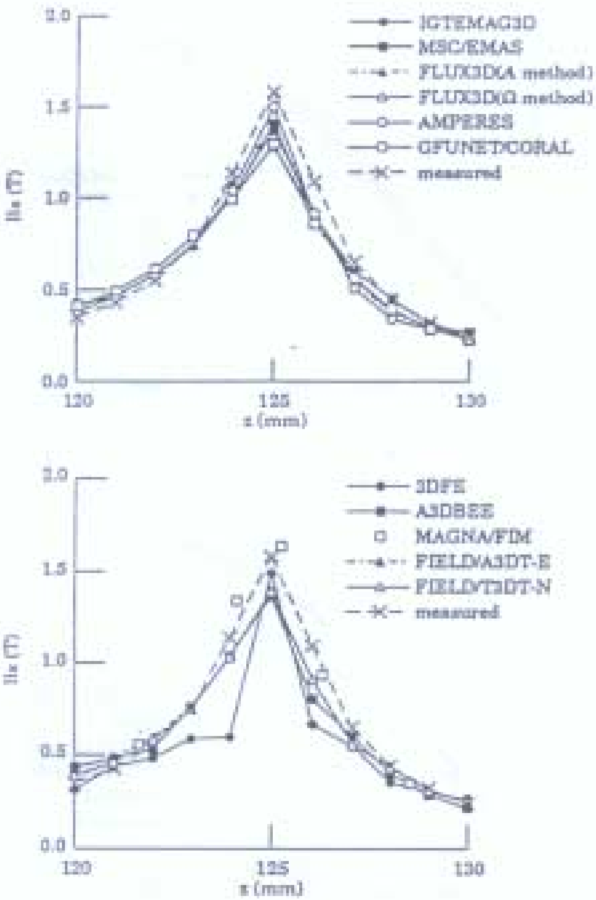

Fig.9 X-components Bx of flux densities along line a-b (5000AT).

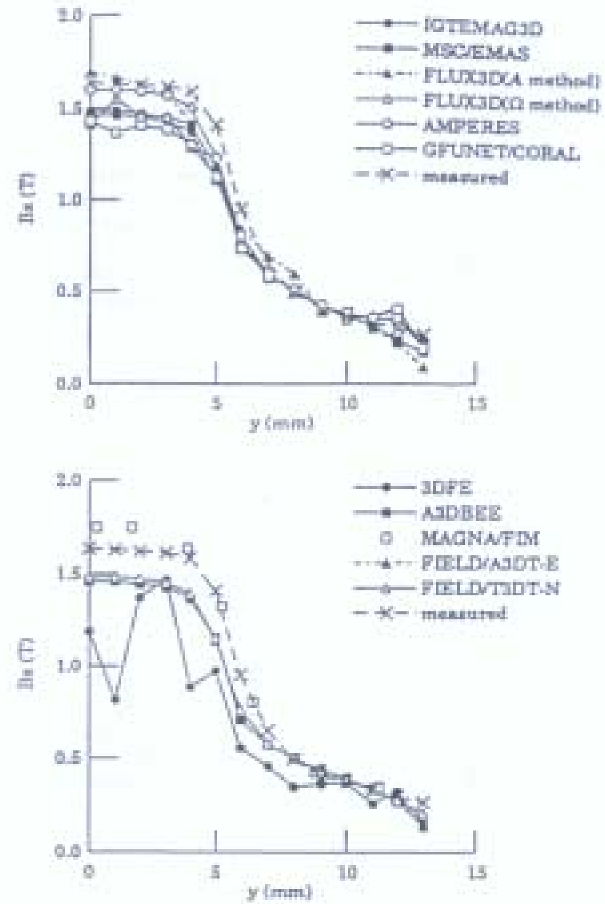

Fig.10 X-components Bx of flux densities along line c-d (5000AT).

Table 4 Z-components Bz of flux densities at points P_1 and P_2 (measured)

position	1000AT	3000AT	4500AT	5000AT
P_1	0.36	0.84	0.99	1.03
P_2	0.24	0.63	0.72	0.74

Table 5 Z-components Bz of average flux densities in center pole (α-β) and yoke (γ-δ) (measured)

position	1000AT	3000AT	4500AT	5000AT
α-β	0.72	1.75	2.01	2.05
γ-δ	0.13	0.36	0.43	0.46

Table 6 Z-component Fz of electromagnetic force (measured)

AT	Fz(N)
1000	8.1
3000	54.4
4500	75.0
5000	80.1

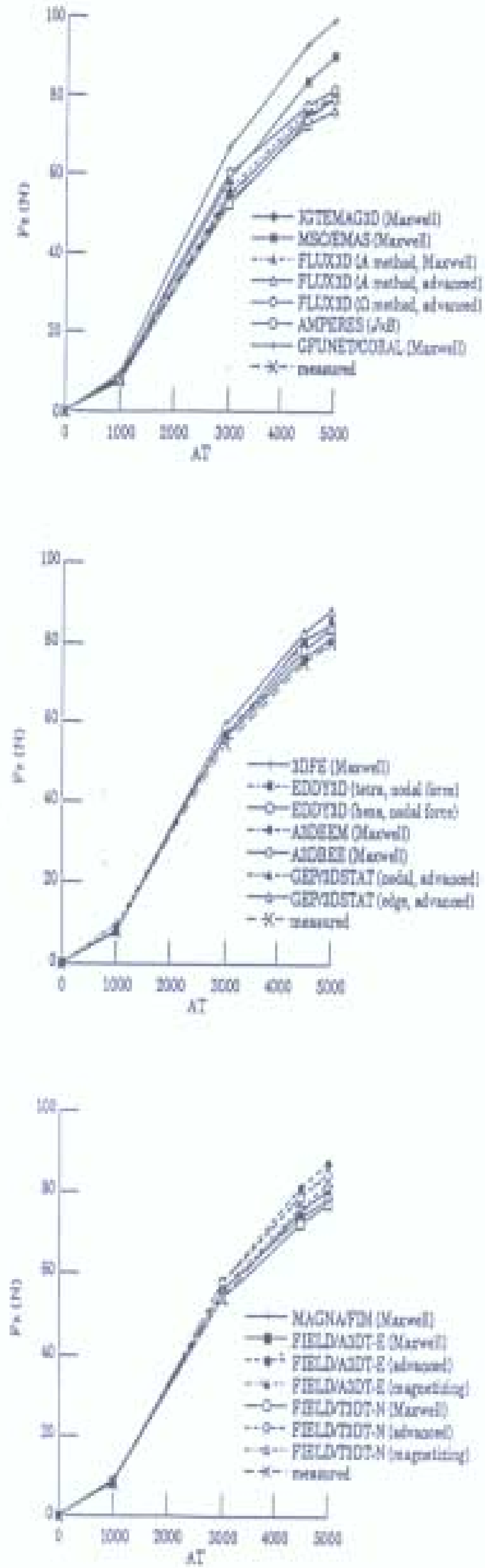

Fig.11 Z-component Fz of electromagnetic force.