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Kernforschungszentrum
Karlsruhe GmbH
Institut für Neutronenphysik
und Reaktortechnik

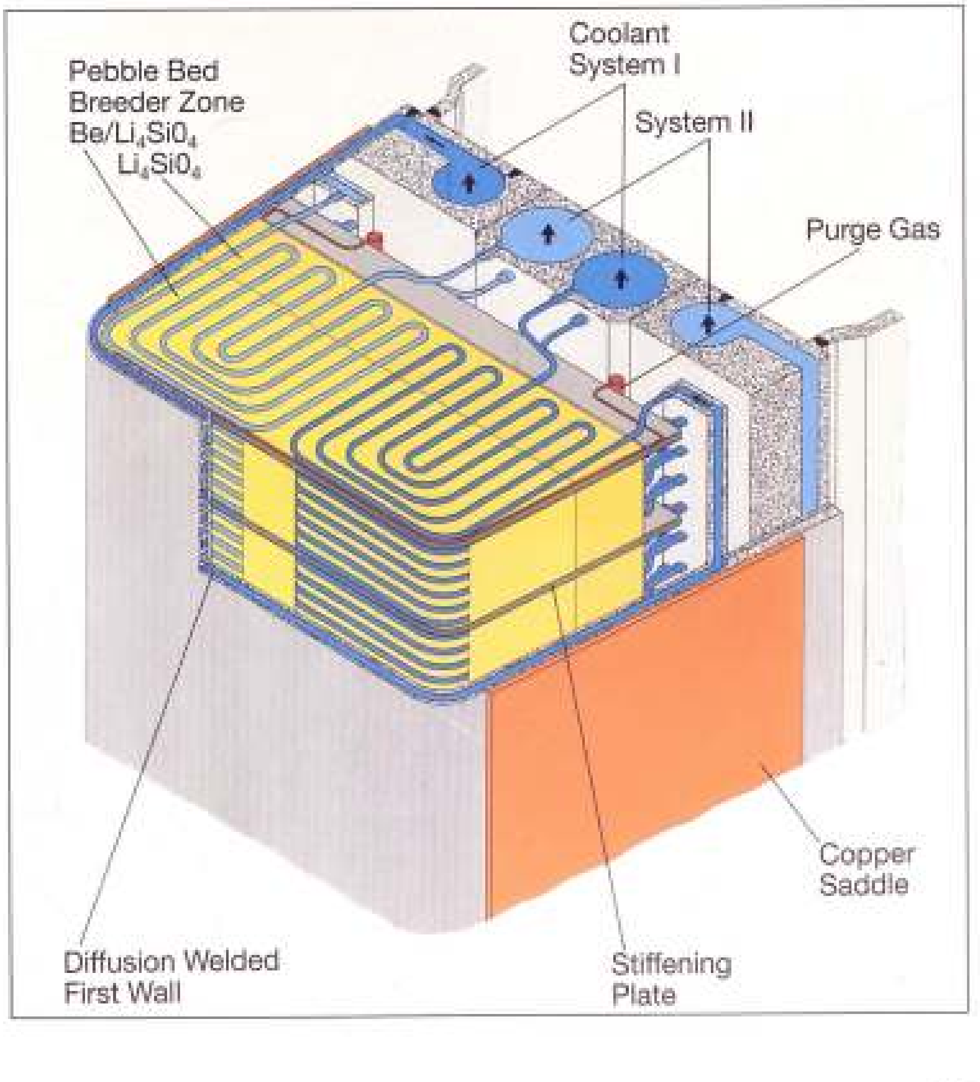
Workshop on Electromagnetic Forces and Related Effects on Blankets and Other Structures surrounding the Plasma Torus

Karlsruhe, Germany, 20-21 October 1992

Organised by
Kernforschungszentrum Karlsruhe

Proceedings

Edited by
M. Dalle Donne, L.V. Boccaccini
Y. Crutzen



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WORKSHOP ON ELECTROMAGNETIC FORCES AND RELATED EFFECTS ON BLANKETS AND OTHER STRUCTURES SURROUNDING THE PLASMA TORUS

KARLSRUHE 20 - 21 OCTOBER 1992

Summary and acknowledgement

One of the major items in fusion with magnetic confinement is the study of forces caused by variation of magnetic fields in the structures surrounding the plasma. This problem has been recognized and many organizations are working, both theoretically and experimentally, in this field. The design of the blankets and the other structures surrounding the plasma is strongly affected by the necessity of maintaining the stresses caused by rapid magnetic field variations, e.g. during disruptions, within acceptable limits.

Therefore the Karlsruhe Nuclear Center organized a two day Workshop in Karlsruhe on this matter. Short 20 minutes presentations were foreseen and considerable time was left for discussions.

The meeting was structured in four parts (see Workshop Agenda). The first four papers (see Workshop Agenda; Barabaschi et al., Gruber et al., Streibl et al., Pautasso et al.) presented the experience with disruptions in two large operating tokamaks. In particular the plasma vertical displacements, which produce the most dangereous disruptions were dealt with.

In the second part of the meeting three papers (Crutzen et al., Boccaccini, Bottura et al.) dealt with the validation, by comparison with experiments, of computer codes to calculate the effects of disruptions on structures surrounding the plasma.

The third part was dedicated to the papers dealing with calculations of the electromagnetic forces caused by plasma disruptions in the blanket placed around the tokamak. The first two papers (Boccaccini, Ferrari et al.) dealt with solid breeder blankets. The third (Ruatto) was concerned with the problem of a blanket with ferromagnetic structural material and the fourth (Jordan) performed the calculations in case of a liquid breeder blanket.

Finally, in the fourth part a paper (Takagi) dealt with the magnetic damping effect, which in certain instances could considerably decrease the electromagnetic forces caused by disruptions.

The editors wish to thank the peoples who helped to run the meeting and in particular Miss H. Hofmann for the organization and typing.

M. Dalle Donne

L.V. Boccaccini

Y. Crutzen

WORKSHOP ON ELECTROMAGNETIC FORCES AND RELATED EFFECTS ON BLANKETS AND OTHER STRUCTURES SURROUNDING THE PLASMA TORUS

KARLSRUHE, 20 - 21 OCTOBER 1992

Meeting Agenda

20. October 1992

9.00	Welcome and Introduction by M. Dalle Donne
9.30	P. Barabaschi and P. Noll (JET): *Effects of Vertical Plasma Displacements and Disruptions on Internal Structures in JET*
10.00	O. Gruber, et al., (MPI für Plasmaphysik): *Overview on Vertical Displacement Investigations on ASDEX-Upgrade*
10.30 - 11.00	Coffee Break
11.00	B. Streibl, H. Schneider, U. Seidel, H. Vernickel, (MPI für Plasmaphysik): *Vessel Forces due to Vertical Disruptions in ASDEX-Upgrade*
11.30	G. Pautasso et al.,(MPI für Plasmaphysik): *Simulation of Vertical Displacement Events with the Tokamak Simulation Code*
12.00 - 14.00	Lunch
14.00	Y. Crutzen, et al., (CEC Ispra): *Integration of Validation Studies in Transient Magneto-Mechanical Analysis*
14.30	L.V. Boccaccini, (KfK Karlsruhe): *Experimental Validation in ASDEX Upgrade of an Eddy Current Program in Frequency Domain and Applications*
15.00	L. Bottura, et al., (NET Garching): *Experimental Validation of Numerical Procedures for Tokamaks Devices*
15.30	Coffee Break, adjourn
16.00	Bus Excursion with Dinner

21. October 1992

9.00	L.V. Boccaccini, (KfK Karlsruhe): *Electromagnetic Forces and Stresses Caused by a Plasma Disruption in the Karlsruhe Solid Breeder Blanket*
9.30	M. Ferrari, L. Pellegrino, G. Simbolotti, (ENEA Frascati): *Electromagnetic Forces on ITER First Wall Box and Blanket*
10.00 - 10.30	Coffee Break
10.30	P. Ruatto, (KfK Karlsruhe): *Calculation of the Electromagnetic Forces Caused by a Plasma Disruption in a Solid Breeder Blanket with Ferromagnetic Structural Material*
11.00	T. Jordan, (KfK Karlsruhe): *A Computational Procedure for Coupled Electromagnetic-Structural Dynamic Problems and its Application to the Self-Cooled Liquid Metal Blanket*
11.30	T. Takagi, J. Tani, S. Kawamura, (Tohoku University): *Dynamic Behaviour of a Thin Conducting Plate Under Magnetic Field - Magnetic Damping Effect -*
12.00 - 12.30	General Discussion
12.30	End of Workshop

CONTENTS

Experimental Validation of Numerical Procedures for Tokamaks Devices

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This paper prepared for presentation at:
Workshop on Electromagnetic Forces and Related Effects on Blankets and other Structures Surrounding the Plasma Torus, Karlsruhe, October 20-21 1992

Abstract

Aim of the paper is to show a selection of the results obtained from a campaign of validation runs of two computational procedures of interest for tokamak design and analysis. In particular, computed values of magnetic signals are compared with experimental measurements made during some ASDEX-Upgrade discharges. The experimental database of ASDEX-Upgrade contains dry runs (i.e. in absence of plasma), normal plasma discharges and discharges terminated by a plasma disruption. We have simulated them adopting both 2-D and 3-D models for the metallic structure. The quite good agreement found between computed and experimental values allows us to conclude that these computational procedures, originally developed for NET and ITER, can be considered as experimentally validated in conditions relevant for the design and analysis of an experimental fusion reactor.

1. INTRODUCTION

Electromagnetics plays a central role in the design and operation of a tokamak device, since the magnetic coupling existing between the plasma and the surrounding circuits and metallic structure is the bulk of the tokamak principle. Among the various problems of prevailing electromagnetic nature occurring in the design and operation of tokamak devices, we mention here the following ones:

- penetration delays of electric and magnetic fields in the plasma region during startup;
- disturbances to the plasma equilibrium due to stray (eddy) fields;
- passive and active control of macroscopic plasma instabilities (vertical and radial displacements);
- mechanical and thermal loading on the metallic structures coming from eddy currents induced during rapid transient phases;
- effects of magnetic field changes on the superconductors;
- feedback control of the plasma current and shape;
- on- and off-line plasma identification;
- optimization of the PF scenario to obtain the desired plasma parameters.

The inherent complexity of the tokamak geometry imposes the use of sophisticated numerical methods and associated computer codes, quite often developed *ad hoc* for the design of a particular machine. The strong interaction existing among the above mentioned engineering problems suggests the use of a set of well integrated codes, i.e. capable of being easily interfaced to each-other. For this reason the development of effective computational procedures is a relevant activity, especially in view of the analysis tasks for the next generation of fusion experiments such as NET[1] or ITER [2]. Available codes for the above problems can be classified as follows:

- eddy current codes for pure electromagnetic analysis;
- static and evolutionary MHD equilibrium codes;
- circuital procedures based on lumped parameters and axisymmetric schematizations;
- algorithms for inverse and optimization problems (like plasma identification and PF coil design).

In addition, we will differentiate here the eddy current codes in 2-D axisymmetric and 3-D, based on different levels of geometric description. The former are useful tools especially because they can include plasma evolutionary equilibrium calculations in presence of conducting structures[3]. The possibility of equivalence between 2-D and 3-D models of the structure has already been satisfactorily explored elsewhere [4]. The latter type of codes[5] is employed whenever the objective of the study prevents from adopting a simplified axisymmetric modeling of the structure (e.g. stress analysis of the in-vessel components).

The use of these complex and advanced numerical codes is nowadays a common practice for the scientific and technical community involved in the design of the experimental tokamak devices to come. However, a satisfactory experimental validation has to be considered as a strict requirement for a reliable use of these codes. Therefore, apart from further code development and refinement, a good deal of the present and near-term activity is devoted to assess the code reliability. The best means to achieve this target is, obviously, to have a comprehensive series of reactor-relevant experimental results to which we desire compare the computer simulations. For this validation we have chosen ASDEX-Upgrade[6] because it is a device well suited for providing the experimental database, for this machine is reactor-relevant in many aspects (e.g., elongated plasma, X-point configurations, PF coils outside the TF coils, air-core OH coils) and possesses a large number of magnetic measurements [7].

2. ASDEX-Upgrade

2.1 Geometry and characteristics

A general description of the geometry of ASDEX-Upgrade can be found in [6,7]. Here we will limit us to the aspects of relevance for the analyses presented. The plasma chamber is delimited by a segmented vacuum vessel (VV) with a toroidal resistance of 280 μΩ (of which the contribution of the bellows is 240 μΩ). Inside the vessel the massive copper structure of the passive stabilizer (PS) provides reaction to the vertical instability modes. The PS is formed by two segmented copper loops, up-down connected so that no net toroidal current can flow in the structure. The Poloidal Field (PF) system, as shown in Fig. 1, consists of several coils. The main data for the coils are given in Tab. 1.

Table 1. - Main data for the coils of the PF system of ASDEX-Upgrade

Coil System	Coil module	r (m)	z (m)	Δr (m)	Δz (m)	N (-)
OH	OH1	0.38	0.00	0.25	3.02	510
	OH2	0.66	2.07	0.34	0.41	81
	OH3	3.01	2.01	0.15	0.05	5
	OH4	0.66	-2.07	0.34	0.41	81
	OH5	3.01	-2.01	0.15	0.05	5
V1	V1upp	1.384	2.358	0.218	0.346	35
	V1upp	1.598	2.358	0.199	0.346	31
	V1upp	1.957	2.358	0.172	0.346	27
	V1low	1.382	-2.358	0.218	0.346	35
	V1low	1.596	-2.358	0.198	0.346	31
	V1low	1.956	-2.358	0.172	0.346	27
V2	V2upp	3.011	1.682	0.159	0.431	39
	V2upp	3.246	1.682	0.195	0.431	47
	V2low	3.012	-1.682	0.159	0.431	39
	V2low	3.246	-1.682	0.195	0.431	47
V3	V3upp	3.600	0.694	0.248	0.184	28
	V3low	3.600	-0.694	0.248	0.184	28
CoI (Control)	CoIo	2.51	0.72	0.08	0.21	5
	CoIu	2.51	-0.72	0.08	0.21	5

2.2 Measurements

In ASDEX-Upgrade several magnetic measurements are used to infer and control the plasma position and shape. For the comparison we have considered five types of measurements, involving quantities of relevance for the validation:

- Poloidal flux differences. These are measured by means of 14 coils (Fig. 2a) placed around the poloidal perimeter of the vacuum vessel. The quantity measured is the difference of poloidal flux existing between two such coils. Note that this measurement is also proportional to the average component of the poloidal field normal to the vessel surface in the space between the two measuring coils.

- Magnetic field. The poloidal distribution of the component of the magnetic field tangential to the vessel surface is measured by means of 20 field sensors (Fig. 2b) placed and bolted on the inner surface of the vessel.

- Vacuum vessel current. This is measured indirectly as the difference of the signals of a (continuous) Rogowski coil surrounding the vessel and a (segmented) Rogowski coil placed inside the vessel (Fig. 2c). This last is also used as a measure of the plasma current.

- Passive stabilizer current. This is measured by means of a Rogowski coil wound around the PS (Fig. 2c).

- Loop voltage. The voltage is obtained by measuring the time derivative of the poloidal flux linked with the flux sensor No. 12 (R=0.99÷1.01 m , Z=0.23 m).

- Plasma data. The plasma current, beta poloidal βp, internal inductance l_i and safety factor $q(95\%)/q_{axis}$, geometric parameters (e.g. major and minor radius, elongation, X-point location, etc.) are either directly measured or reconstructed by means of a Principal Component Analysis (PCA) [8].

2.3 Experiments selected

For an extensive validation of the codes we have considered a variety of experimental runs performed in ASDEX-Upgrade, falling in three typical categories:

- Purely electromagnetic transients, without involving plasma formation. These runs, that we called *dry*, were performed in order to asses the capabilities of the models to describe eddy currents in the passive structures in the case of a linear problem. In order to explore different responses regimes of the passive structures we selected symmetric(++) and antisymmetric(+-) sinusoidal excitations of the control coils (CoI) at various frequencies between 4 and 32 Hz (see Tab. 2), and a fast discharge of the OH system (run 584). Both excitations are critical from the point of view of the response of the structure, in particular the vacuum vessel, as in the first case the CoI coils are very close to the vessel wall, thus causing non-uniform current distribution, while in the second case the OH produces a negligible field and the magnetic measurements are mostly governed by the contribution of the eddy currents. The map of the exciting fields for the different runs considered is reported in Fig. 3.

Table 2. - Data for the sinusoidal *dry* runs selected for the electromagnetic validation of the codes. The coil system excited is the CoI

Run Number	mode	frequency (Hz)	Conductor Current (kA)
870	++	4	
871	++	8	
873	++	32	
875	+-	4	5
876	+-	8	
878	+-	32	

- Plasma shots, to validate the MHD plasma modeling. One typical plasma shot involving formation and current rise in a 340 kA plasma was analyzed (run 942) The main data for the flat top of the plasma shot are reported in Tab. 3.

Table 3 - Main data characterizing flat top of shot No. 942

Plasma current (kA)	346
Major radius (m)	1.62
Minor radius (m)	0.56
Toroidal field (T) at R=1.65 m	2.00
R-coord. of null point (m)	1.54
Z-coord. of null point (m)	-0.90
Poloidal beta	0.38
Internal inductance	1.50
$q(95\%)/q_{axis}$	6.90

- Plasma disruption, to assess the code capabilities in predicting magnetic and mechanical loads in the components surrounding the plasma chamber. In this case we have studied the transient following a plasma current disruption from 270 to 0 kA in about 100 ms (run 1162). During the plasma disruption the radial and vertical plasma position remained nearly constant. The PF system, due to the long time scale involved, reacted to the plasma soft disruption. As a consequence, we had to consider also the PF coils as part of the exciting field.

3. MODELLING OF ASDEX-Upgrade

According to the selection of the experimental runs to be simulated, it clearly appears that most attention should be devoted to those components in which there is a possibility for toroidal currents to flow. Therefore we concentrated on the vacuum vessel, which is toroidally continuous, and on the passive stabilizer, with an extremely long time constant (of the order of 0.5 s). All other structures (in-vessel components, coil supports, etc.) have been neglected for this study.

For the time scales of interest the vessel behaves as a thin shell because the penetration time of the field is much smaller than the time constant of the exciting fields considered. However, the presence of highly resistive bellows introduces a toroidal segmentation which can force a part of the toroidal current to circulate in saddle loops in each segment. In addition the vessel has a large number of penetrations, ranging from large horizontal access ports to small feedthroughs for the instrumentation.

In uniform PS structure the eddy current flow mainly in toroidal direction, except in the vicinity of the bridge where the segmentation forces the current direction to reverse. Because the bridge is formed by two coaxial branches with negligible inductance, we have assumed that its effect is only an increase in the resistance of the PS structure. In the case of the PS, however, additional complication is added by the fact that the skin depth for the time scales in the transients considered is smaller than the size of the structure, i.e. we can expect non-uniform current distribution in the cross section of the PS.

As anticipated, for the modelling and simulation of the experiments we used two codes:
- a 2-D axisymmetric code capable of performing MHD free boundary equilibrium calculations [3];
- a 3-D FE eddy current code, CARIDDI, extensively used for NET and ITER studies [5];

Previous studies [9] have shown that the eddy-current code CARIDDI is well suited for the analysis of transient electromagnetic phenomena occurring in a tokamak. This code is particularly well suited for the computation of the 3-D effects introduced by the lack of axisymmetry of the device (e.g. ports, bellows, poloidal cuts, etc.). On the other hand plasma equilibria and related magnetic measurements are axisymmetric. For this reason we have developed codes 2-D codes where some 3-D features are taken into account via a parameter perturbation of an axisymmetric modeling; a transformation from a fully 3-D modeling to the equivalent 2-D axisymmetric is possible[10]. In accordance with the dimensionality of the two codes, we have developed 2-D axisymmetric and 3-D meshes. The discretizations of the structures adopted for the calculations are shown in Fig. 4. Note that, due to the non-symmetry of the PS structure, a full 3-D mesh had to be produced, thus increasing dramatically memory occupation and CPU time requirements with respect to an up-down symmetric model. In the 3-D mesh a more complex model of the vessel was included, compared to the 2-D representation based on the theorical envelope of the resistive bellow. Note that, in addition, the 2-D model was not able to describe saddle modes in the segmented vessel. In both cases the PS structure was segmented so to describe properly the shielding effects.

Finally, for all simulations we have considered the PF currents as inputs, thus avoiding the additional complication (and related uncertainties) of including controllers and power supply characteristics in the simulation.

4. DRY RUNS

The aim of this first part of the validation campaign, the dry runs, was to test the codes in situations where any possibility of mis-modeling of non purely electromagnetic phenomena was automatically eliminated. Indeed, a necessary - though not sufficient - condition for a code validation is a satisfactory simulation of purely electromagnetic experiments, as it occurs when we have a shot in the absence of plasma. As a further advantage of this approach, one can benefit of the well established experience gained within the TEAM Workshops [11] on smaller scale validation experiments. Both the 2-D and the 3-D codes were tested in the dry runs We concentrated our attention on the total vessel and PS current induced, the field components and the flux differences at selected sensors.

4.1 Sinusoidal excitations of the CoI coils

The response to the sinus excitation of the CoI coils was studied using transient and analysis. The simulations were performed for the first cycles of the excitations, until the response of the passive structures had practically reached *steady state*. In Figs. 5 and 6 we show the induced currents results of the transient simulations of four runs, two in symmetric mode (870 and 873) and two in anti-symmetric mode (875 and 878). The computed PS current agrees with the experimental measurements for both *low* and *high* frequency runs. In the case of the vessel current, the *low* frequency response (4 Hz) is in much better agreement with the measurements than in the 32 Hz case. While at 4 Hz the error is nearly zero, at 32 Hz the relative amplitude error is about 30 %, with both 2-D and 3-D computed values higher than the measurements. From the results of an harmonic analysis [12] we can see that while the response of the PS in the frequency range of the measurements is always in the inductive regime, the vessel is in resistive regime at 4 Hz and in a transition regime at 32 Hz. Part of the disagreement between measurement and simulation at 32 Hz could be explained by the behavior of the signal integrators on the measurement chain, which yield phase shift and gain reduction at medium and high frequencies.

Local comparison of calculations and measurements are shown in Figs. 7 and 8 where magnetic field components at selected sensors are presented. We have chosen for the comparison sensors at locations where the signal attains significant values, i.e. different locations are taken for the symmetric and anti-symmetric runs. Here we note that, apart from a rigid shift of the experimental curves due to the particular triggering procedure adopted in the ASDEX-Upgrade data acquisition system, the simulation is again in excellent agreement with the experiment at low frequency. At high frequency, especially in the symmetric case, minor discrepancies are found.

4.2 OH ramp

In this run the OH coil current has been first ramped down from 25 kA to about 11 kA in 100 ms and then brought to nearly zero in 500 ms. This induces the currents in the vessel and in the PS shown in Fig. 9.
Also in this case there is a good agreement between experimental and computed values, although here we have an indication that the 3-D pattern of the eddy currents has a local influence on the poloidal field. See for instance Fig. 10, showing the flux difference $\Delta\psi_{11}$ measured in the lower part of the vessel, where the difference between 2-D and 3-D results can be attributed to the influence of the saddle currents induced in the vessel segments.

4.3 Discussion

In generâl a good agreement is found on global (total induced currents) and local (magnetic field and flux) parameters, with a typical deviation between simulation results and experiment within (and often much below) 30%, so that we can say with good confidence that the models developed are adequate. In addition, the agreement between 2-D and 3-D models confirms the validity of the former. This is particularly important because, at present, plasma equilibrium simulations can only be performed using 2-D (or 2-D equivalent) models of the conducting structures. Obviously, 3-D models are necessary for detailed studies of the structure.

5. NORMAL PLASMA DISCHARGES

Aim of this part of the code validation activity was to test the available computation tools for determining the P.F. coil currents waveform corresponding to a desired plasma scenario and for reconstructing the plasma shape. For this task, we have adopted an engineering approach where the eddy currents are the only responsible for the evolutionary character of the MHD equilibrium code, whereās the time hiŝtory of the main plasma parameters (current, poloidal beta, internal inductance) is given in input. As an additional goal of this task, we have assessed a simplified plasma modeling, where the plasma is simulated by a rigid current filament.

5.1. Static and quasi-static analysis

In this first part of the study, we have assigned the poloidal field coil currents at 640 ms together with the plasma current, the poloidal beta and the plasma internal inductance. As far as the currents in the passive stabilizer (PS) and the vacuum vessel (VV) are concerned, we study separately 6 cases. In case 1 the eddy currents are taken as zero, in case 2 we set them at their experimental value and in case 3 they are given by an eddy current analysis of the first 640 ms of the discharge assuming a filamentary plasma current model. Case 1 can be regarded as a purely static analysis while cases 2 and 3 involve some eddy current computation as pre-processing and we then regard them as quasi-static (in case 2 we use the eddy current distribution of case 3, rescaled is such a way as to match the experimental values of the total PS and VV currents).
Cases 4 to 6 are equal to case 3 as far as the induced currents are concerned, but ß is decreased by 20% in case 4 and l_i is decreased by 10% in case 5. In case 6 the plasma current is given by the (reliably measured) sum of vessel plus plasma current, minus the computed vessel current. Computed and measured fluxes and fields at sensors are given in Figs. 11 and 12 respectively.

5.2. Dynamic analysis: electromagnetic model

In this part of the analysis we compute the eddy currents induced in the vacuum vessel and in the passive stabilizer by the external coils and plasma current changes. The plasma is approximated as a rigid filament positioned in the (identified) plasma current center. Plasma current and loop voltage waveforms are shown in Fig. 13. The computed and measured PS and VV currents are given in Fig. 14 while fluxes and fields at two different locations are shown in Fig. 15.
The nearly rigid shift between experimental and computed values can be explained by the presence of an initial off-set (which is taken into account in ASDEX-Upgrade, but is not reported in the diagrams).

5.3. Dynamic analysis: MHD model

The complete scenario of shot #942 is simulated assuming that the plasma is in MHD equilibrium during the whole discharge. The plasma parameters (current, poloidal beta and internal inductance) are those obtained in ASDEX-Upgrade by measurements or a PCA of the shot data.
Computed plasma equilibrium data (X-point position, minor and major radii) are given in Fig. 16 and compared with the PCA performed by ASDEX-Upgrade. The computed eddy currents and fields, compared with the measured values, are given in Figs. 17 and 18, respectively. Fig. 19 shows the MHD equilibrium at 640 ms, consistent with the computed eddy currents in the passive structures.
Note that to avoid plasma vertical instability in the simulation we have artificially brought the PS time constant to infinity by zeroing its ohmic resistance. Of course, this introduces not completely negligible approximations. Better results will certainly be achieved by properly introducing the feedback control system.

5.4 Discussion

On the basis of the analysis performed in the paper, the following conclusions can be drawn:

- the most important parameters affecting the electromagnetic field distribution outside the plasma are plasma current and position of its centroid; other parameters, like beta poloidal and internal inductance, have a smaller impact; this is shown by the good results achieved using the filamentary approximation for the plasma current;
- in general, good agreement is found between experimental and computed values, in both static and dynamic analyses;
- there is a discrepancy between experimental and computed vacuum vessel current; this can be explained by a considerable drift of the integrator and by the fact that the measured current is given by the difference of two large signals close to each other;
- as expected, the MHD dynamic simulation fails in the absence of feedback control, since the plasma is vertically lost with a time constant closely related to that of the passive stabilizer; to overcome this problem, one can either artificially expand the PS time constant beyond the discharge duration (e.g. by reducing the ohmic resistance) or properly introduce the feedback controller.

6. ELECTROMAGNETIC SIMULATIONS OF PLASMA DISRUPTION

Aim of this part of the code validation activity was to check the reliability of the computation tools for the forecast of the electromagnetic forces acting on the structure as a result of a major disruption; a well balanced treatment of the plasma behavior and of the structure geometry is needed for this purpose.

The code used for the simulation of normal discharges can also be used for the disruption simulation, since it has been shown that the filamentary model for the plasma current gives a good approximation. Therefore, a disruption can be simulated by driving the time history of the plasma current filament as well as its position in the chamber.

6.1 Disruption simulation

We have considered the ASDEX-Upgrade run 1162, where a plasma current of 270 kA vanishes in 150 ms, with a limited motion of the current centroid. Fig. 20 shows the time history of the plasma current and plasma center position. One of the simulations performed has neglected the plasma movement , while in the other the motion has been reproduced by using three filamentary conductors, whose currents reproduce in each instant the total plasma current, I_p, and the current moments (of the second order for the radial coordinate, $r^2 \cdot I_p$, and of the first order for the vertical coordinate, $z \cdot I_p$). As already said, the currents in the poloidal filed coil measured in the experiments were used as input in the analysis.

The calculated and measured total toroidal eddy currents induced in the PS are compared in Fig. 21(a): the two curves are in good agreement, but for a shift due to the fact that the simulation begins with the start of the disruption. Figures 21(b) and (c) show the same comparison for the vessel currents and for the sum of vessel and plasma current; it must be noted that the measured value of the current in the vessel is obtained as difference between two large signals. In Fig. 22 is illustrated the current distribution in the Vacuum Vessel [13].The results clearly show that the presence of bellows and ports in the vacuum vessel gives rise to sensible non axisymmetric effects. These effects are very important for the stress analysis (poloidal currents interacting with the toroidal field produce heavy loads which must be taken into account), but are less significant if the interest is focused on the average toroidal currents and in the poloidal field configuration; in this respect a 2-D axisymmetric schematization is expected to be adequate.

The comparison of the local values of the magnetic field components and flux differences shows a generally good agreement between the simulation and the experiment, apart the rigid shift already mentioned. Figures 21 and 22 show such comparison for some selected sensors. Some significant discrepancy was found only in the flux difference sensors in the inner part of the torus (sensors $\Delta\psi_{14}$ and $\Delta\psi_{15}$) where a sudden change in the poloidal flux the vessel was not obtained from the calculation.

The force distribution and resultant loads on the PS and VV were computed for the run 1162; the peak radial force was 1.8kN/octant in the VV and 0.27 kN/octant in the PS. It was not possible , because of lack of time and information, to use these results as input for a stress analysis to compare deformation and displacements of the mechanical structure with existing measurements.

6.1 Discussion

The simulation of the plasma disruption has confirmed that both the model and the assumption of a single filament plasma was adequate for the purposes of the eddy currents analysis. The results of the simulation are generally in very good agreement with the experimental values both for local values, such as magnetic field at specific locations and global parameters such as total currents; the discrepancies consist mainly in a rigid shift of the experimental curve, due to the previous history of the shot, neglected in the simulation.

From the comparison with the analyses of design case disruptions, it was found that the radial forces are consistently related to the product of plasma current and vessel current ($F_r \propto I_P \cdot I_{VV}$). However, the results of the experimental disruption does not allow a simple scaling of the forces with the plasma current and disruption duration ($F_r \propto I_P/\tau$,) which would be very useful for prediction purposes, since the magnetic field in the experiment considered is significantly affected by the behavior of the PF coils.

7. WHAT COMES NEXT ? WORK IN PROGRESS

Starting from the satisfactory results of this first phase of comparison between code predictions and experimental results, we plan to extend the validation to other experimental situations, as well as to test other features and algorithms included or being included in the codes of interest. In particular, in the next future we intend to:

- simulate shots abnormally terminated by a major disruption caused by the intrinsic electromagnetic instability of the vertically elongated plasma in ASDEX-U and extend the comparison to the resultant displacements and forces on the structures;
- test a more sophisticated plasma model in which the total current is an outcome of the simulation instead of being prescribed;
- test a new procedure [14], which takes into account the the presence of eddy currents for the design of the poloidal field scenario and for the identification of the plasma parameters.

8. CONCLUSION

We showed here how the main features of the electromagnetic phenomena of relevance for the electro-mechanical design of a tokamak can be studied both experimentally and numerically. The numerical study integrates the experiment when local information is needed. The effect is an improved understanding of the effects of transients common to all reactor designs (during plasma start-up, control and disruptions). As a general conclusion of this validation exercise, we have found that reliable simulation codes that account for the effects of the eddy currents in the passive structures are not only an essential tool for the design and interpretation of the experimental data, but also an efficient means for detecting possible failures, inaccuracies or lack of reliability of the individual sensors.

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The authors are grateful to the ASDEX-Upgrade Team for the tight and fruitful cooperation during the whole activity of code validation.

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Figure 1. Schematic view of the vertical cross section of ASDEX-Upgrade, showing the plasma chamber, the vacuum vessel, the passive stabilizer loops and the PF system.

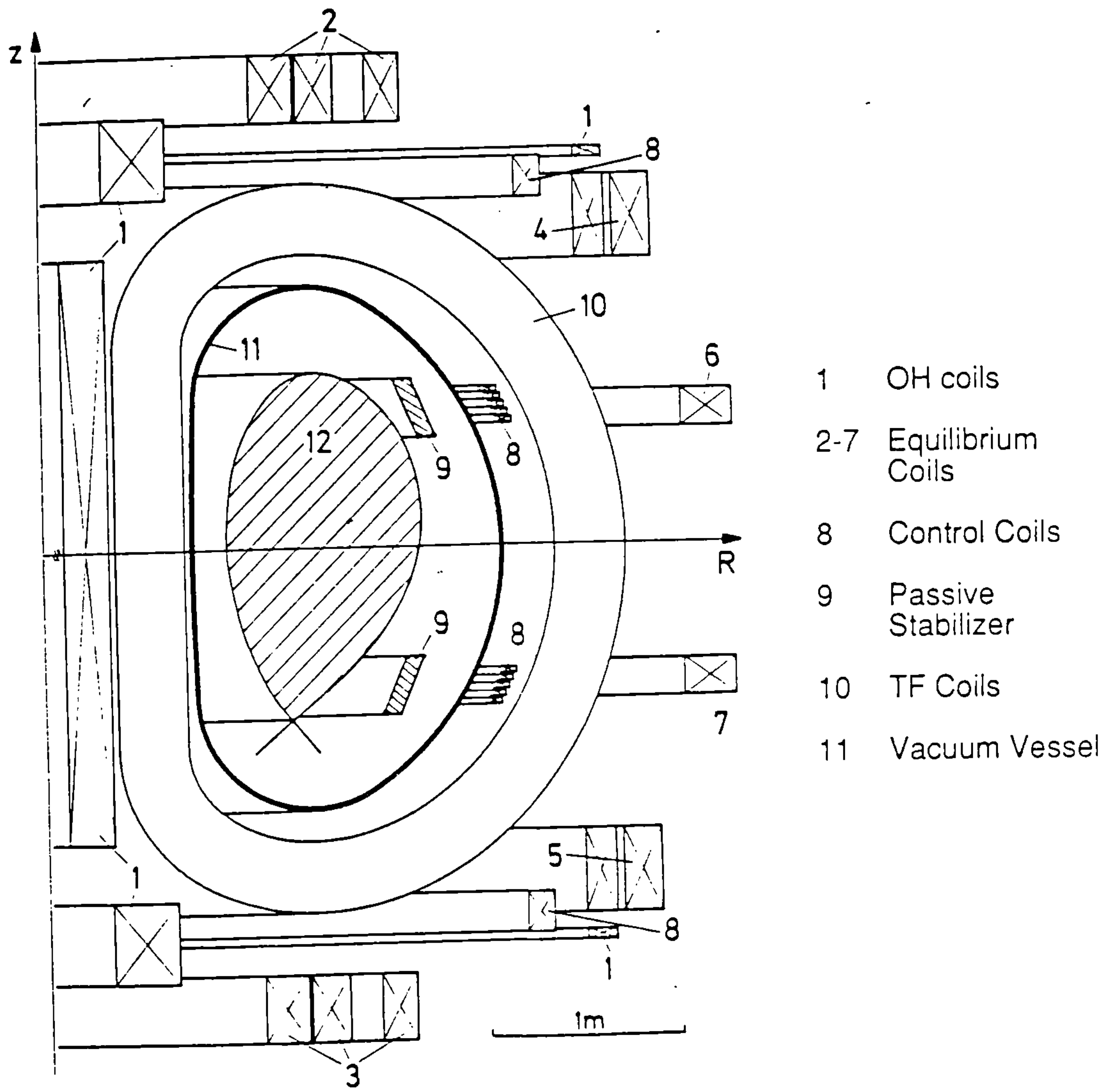


Figure 2. Location and type of the magnetic measurements in ASDEX-Upgrade used for the validation runs.

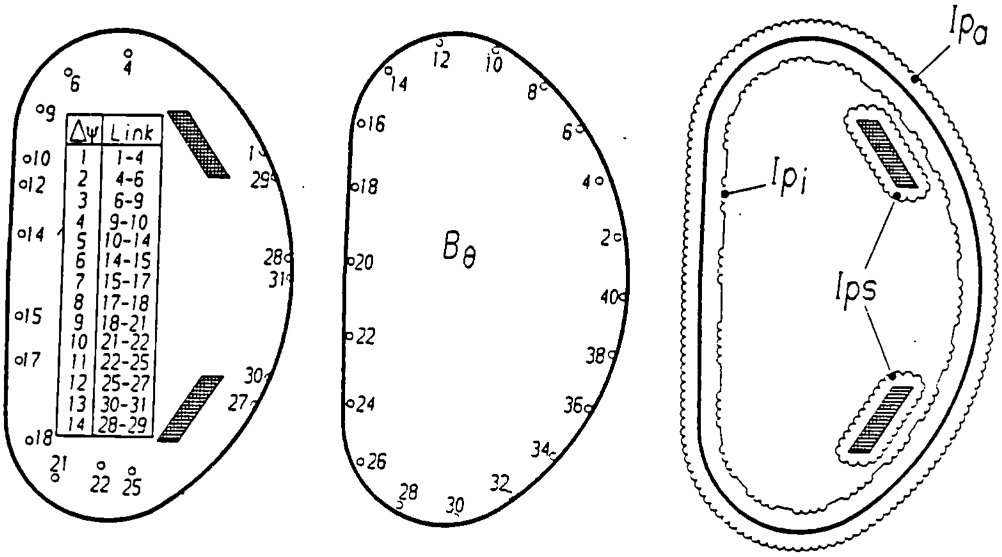


Figure 3. Map of the external field in case of symmetric (a) and anti-symmetric (b) CoI excitation, and for the OH discharge (c).

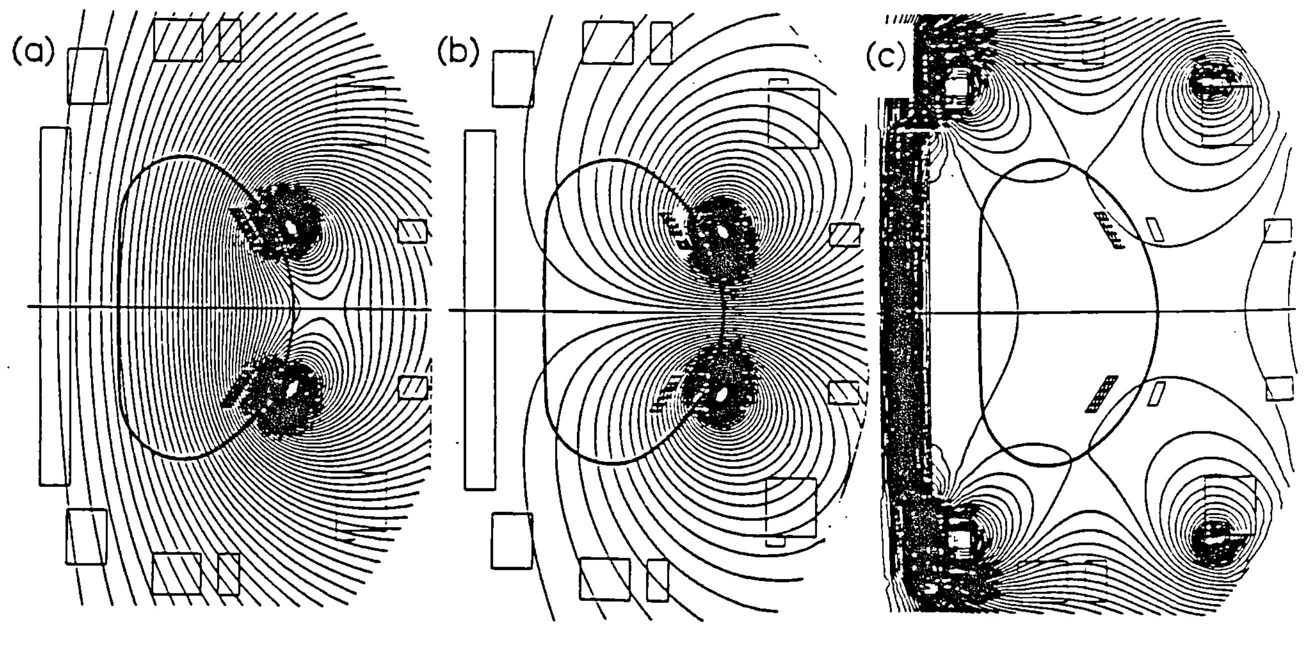


Figure 4. Meshes used for the simulations with the 3-D code CARIDDI (a,b) and the 2-D MHD code (c).

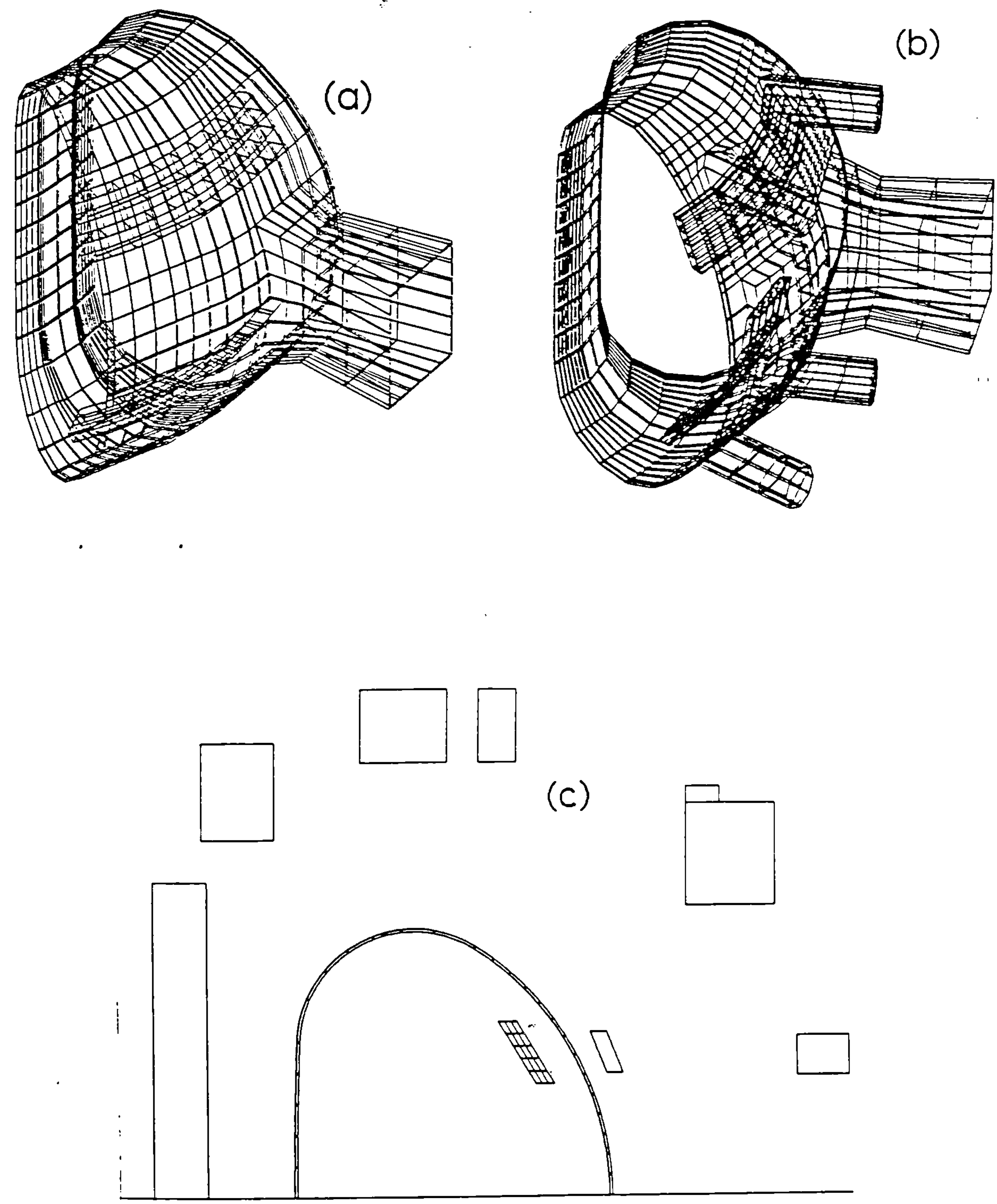


Figure 5. Vessel current I_V for runs 870(a) and 873(b) (respectively 4 and 32 Hz symmetric CoI excitation).

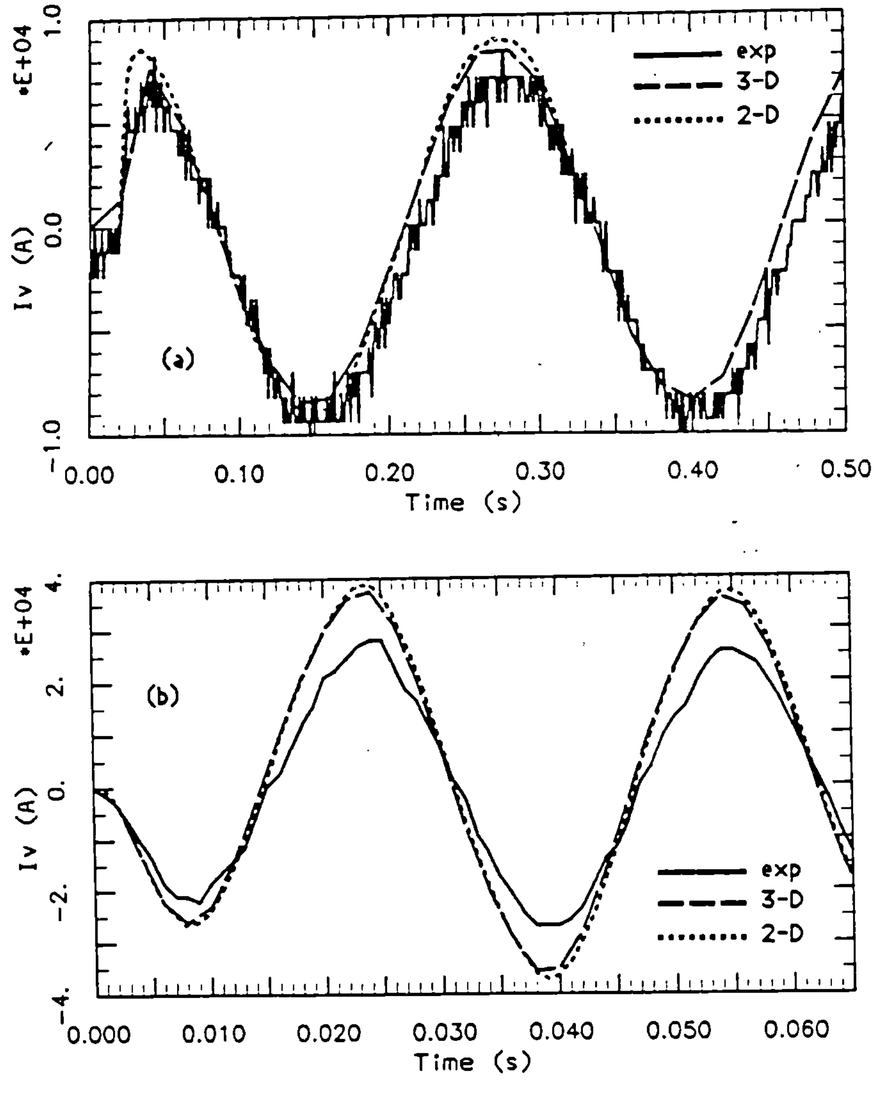


Figure 6. PS current I_{PS} for runs 875(a) and 878(b) (respectively 4 and 32 Hz anti-symmetric CoI excitation).

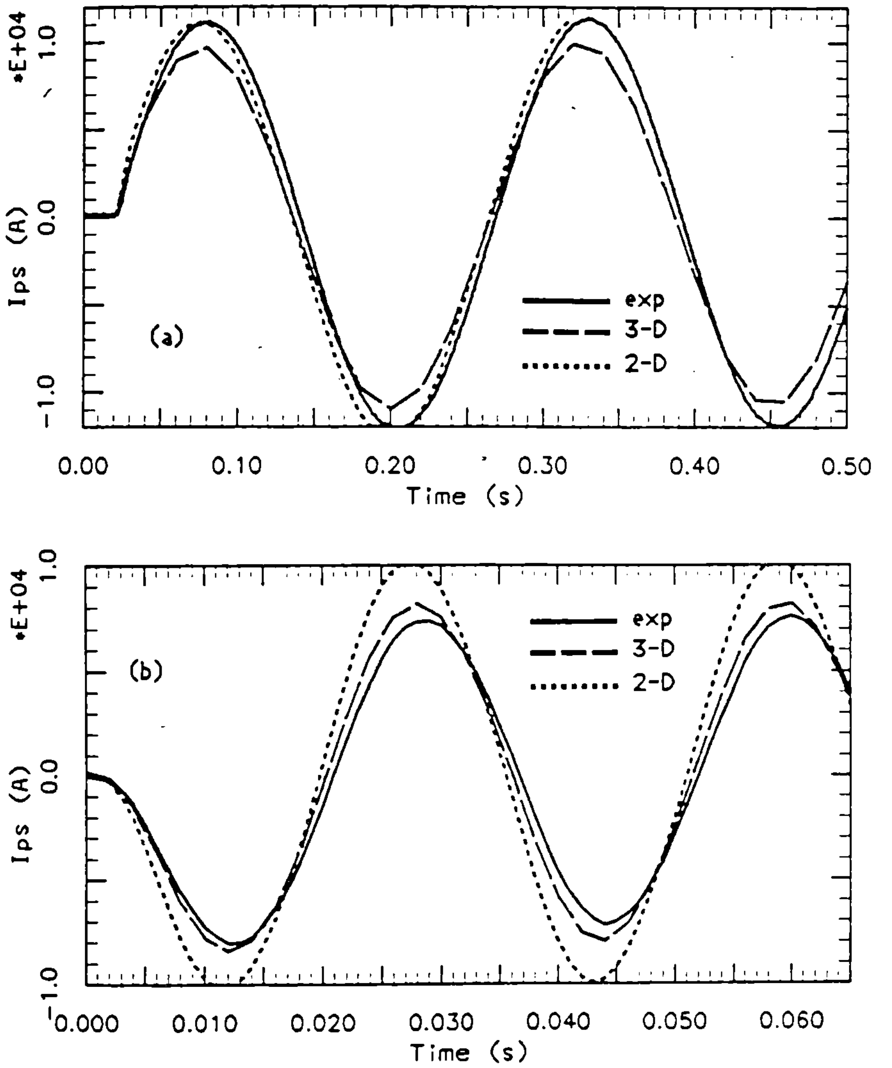
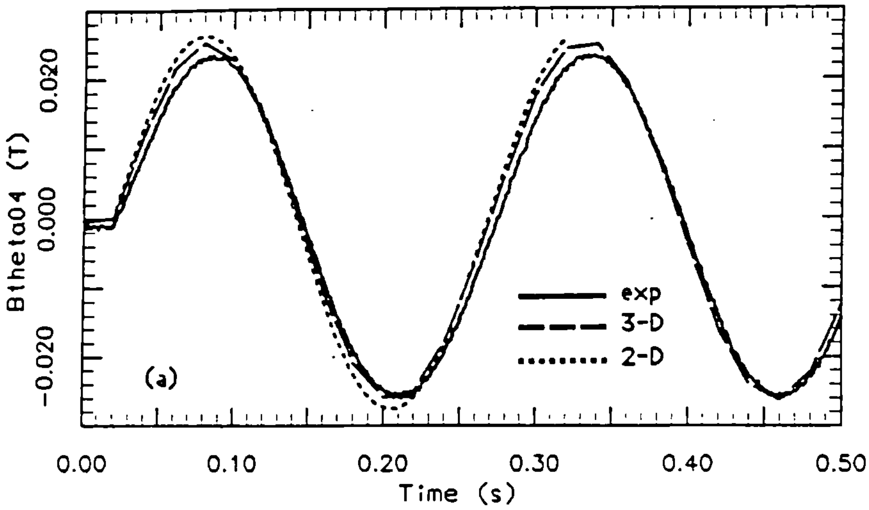


Figure 7. Comparison of simulated and measured magnetic field at sensor $B_{\theta 4}$ for runs 870 (a) and 873 (b) (respectively 4 and 32 Hz, symmetric CoI excitation).



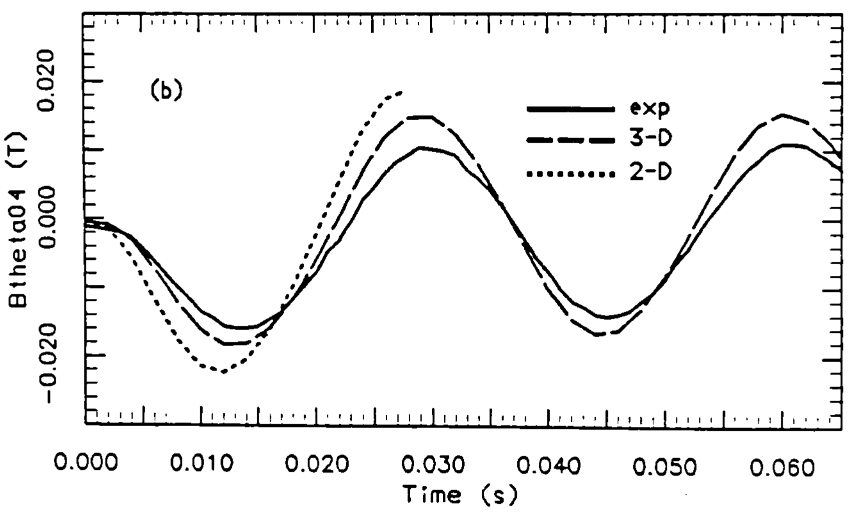


Figure 8. Comparison of simulated and measured magnetic field at sensor $B_{\theta 10}$ for runs 875 (a) and 878 (b) (respectively 4 and 32 Hz, anti-symmetric CoI excitation).

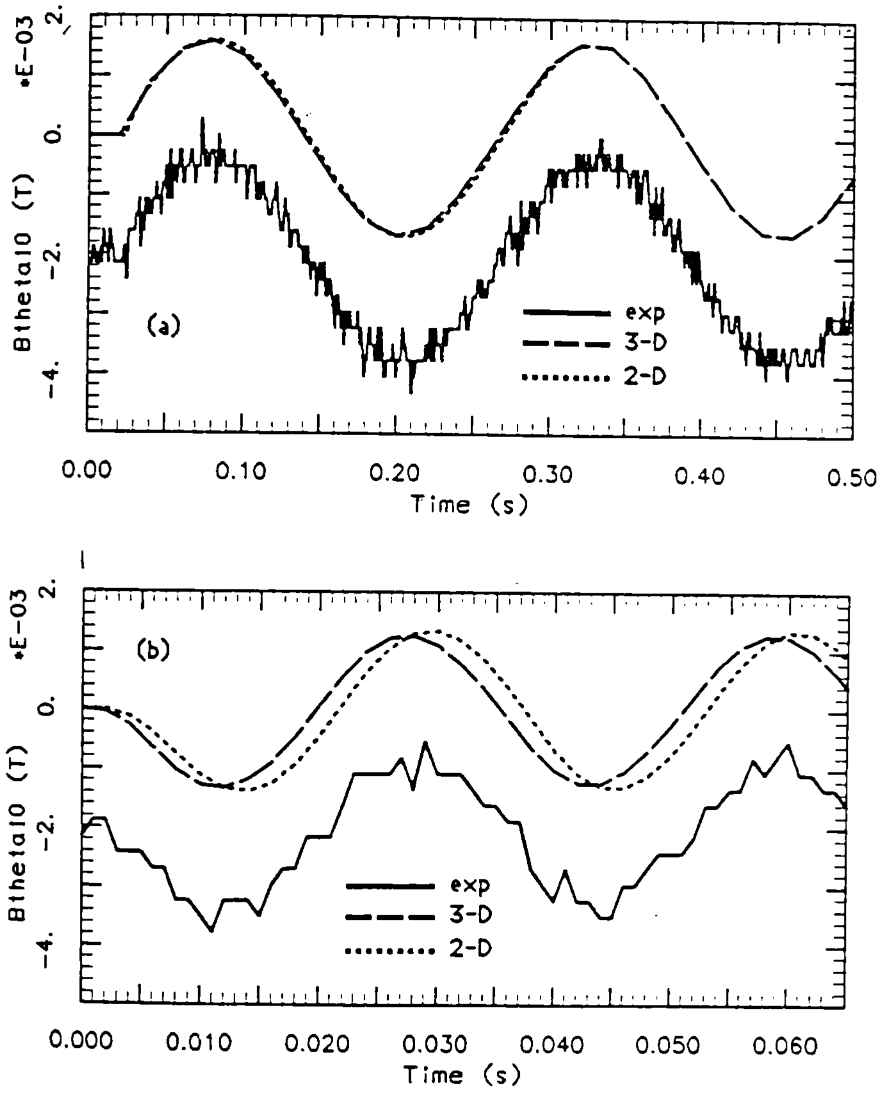


Figure 9. Vessel current I_V (a) and PS current I_{PS} (b) for run 584 (ramp-down of the OH current).

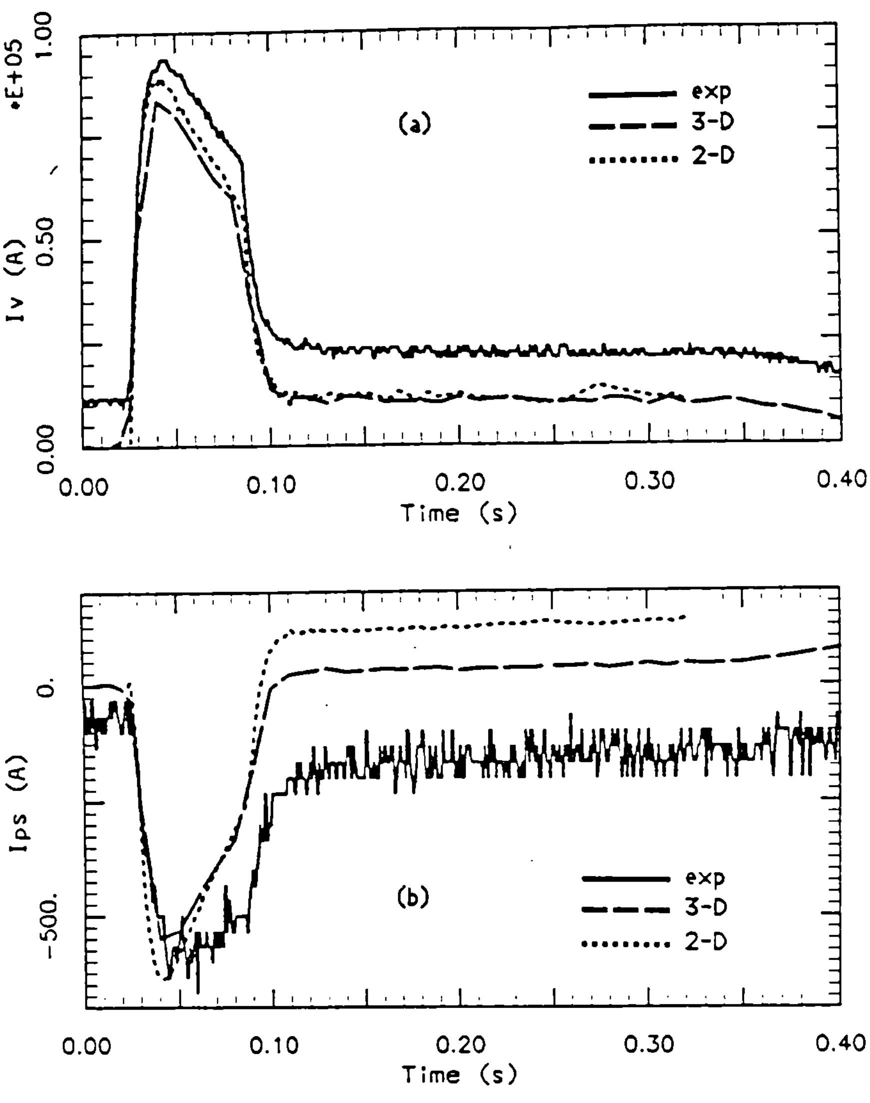


Figure 10. Comparison of simulated and measured flux difference $\Delta\psi_{11}$ for run 584.

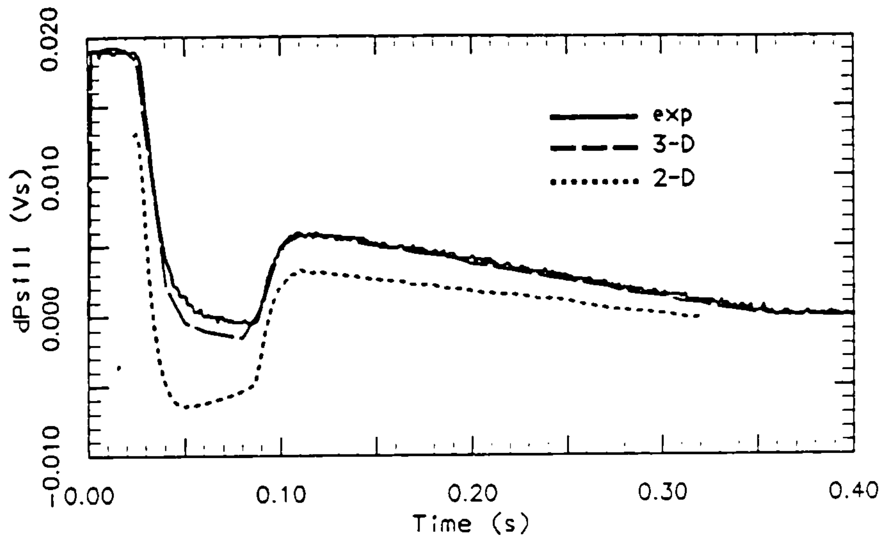
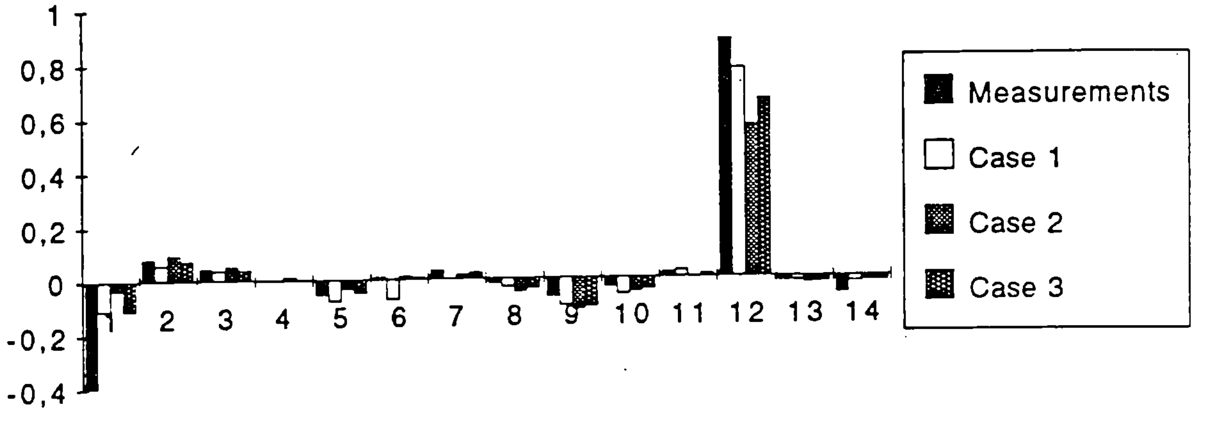


Figure 11. Measured and computed flux differences for cases 1 to 6 of the static and quasi-static analysis of run 942



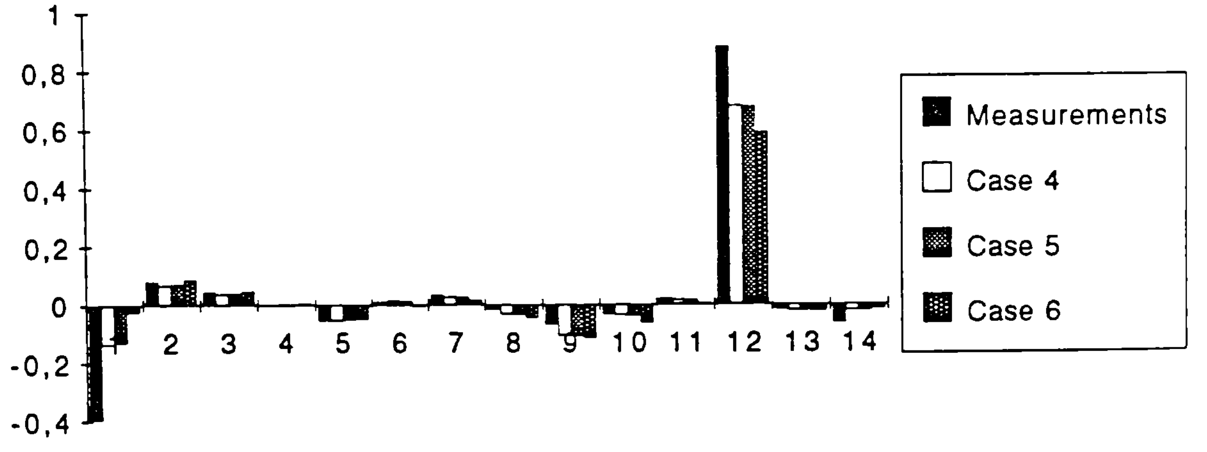
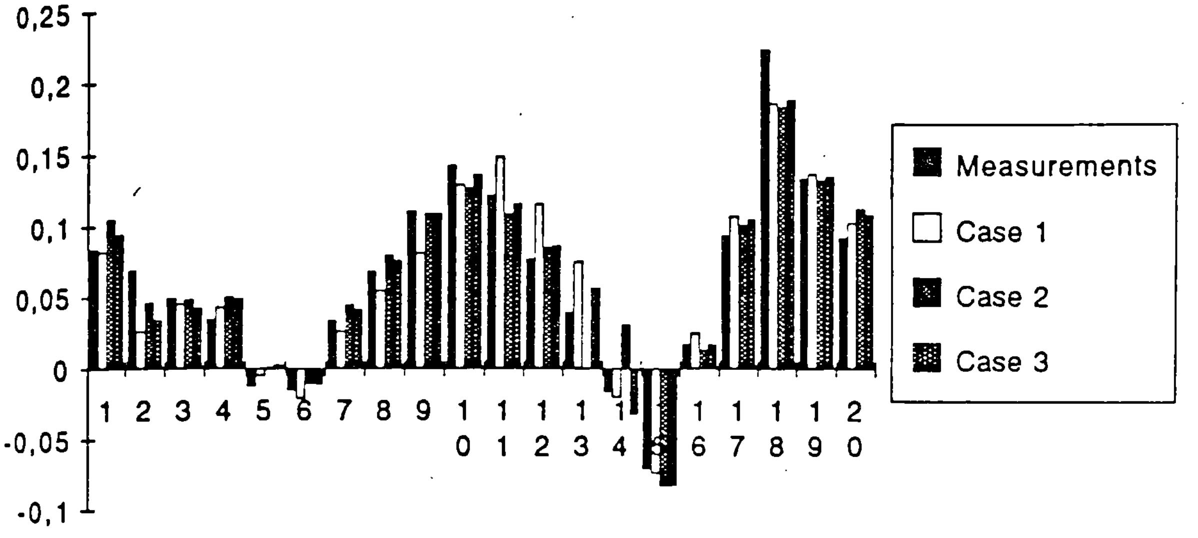


Figure 12. Measured and computed fields for cases 1 to 6 of the static and quasi-static analysis of run 942



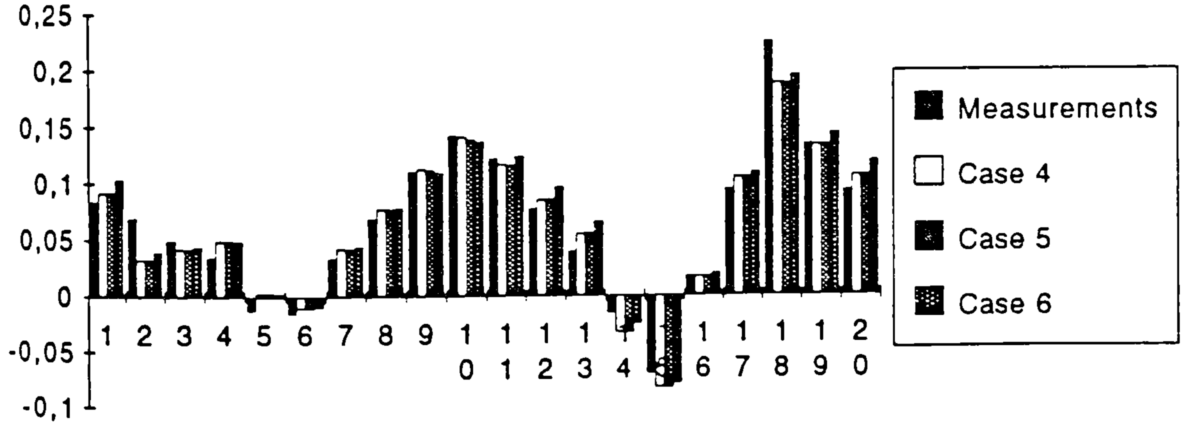
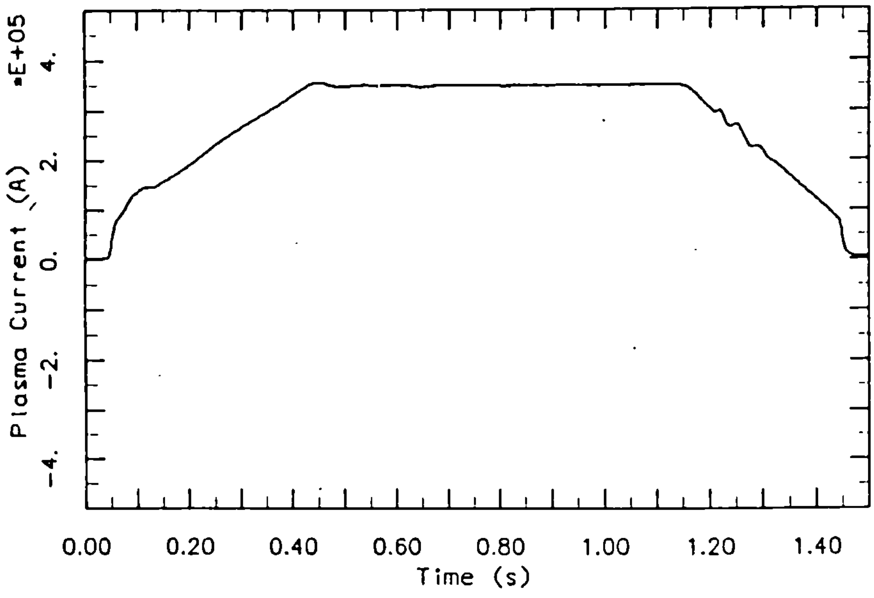


Figure 13. Plasma current waveform in run 942 (a), and loop voltage (b) at sensor 12 as measured (solid) and computed (broken) with the purely electromagnetic analysis



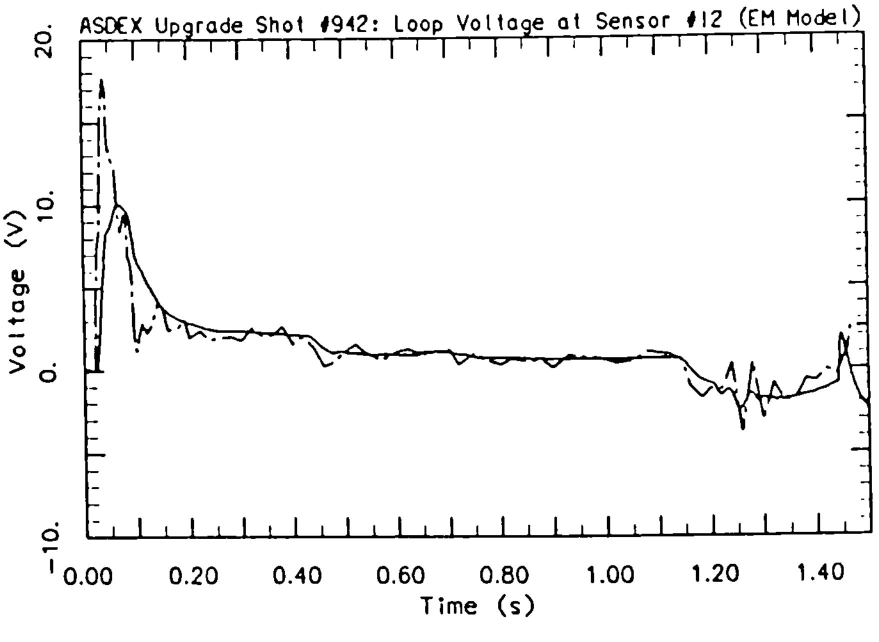
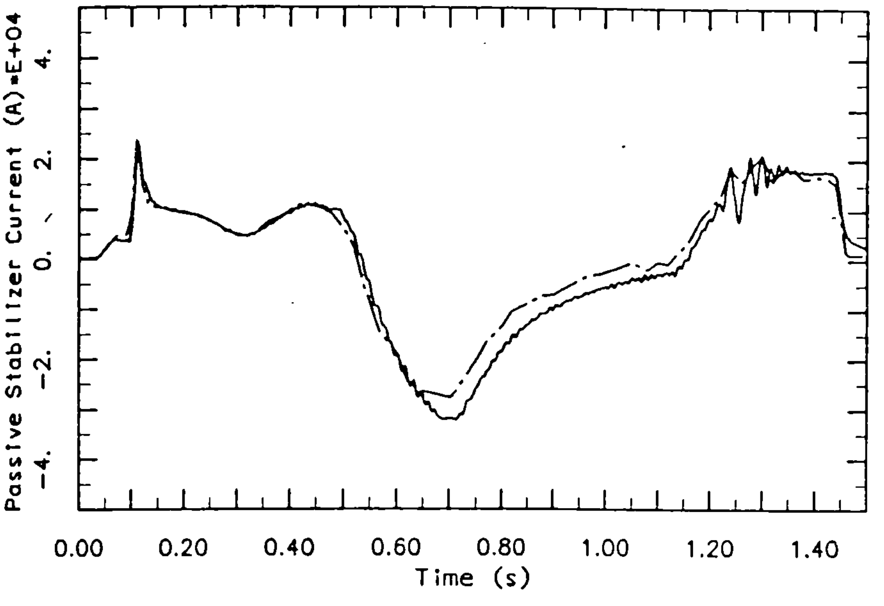


Figure 14. Measured (solid) and computed (broken) PS current (a) and vessel current (b) during run 942, purely electromagnetic analysis



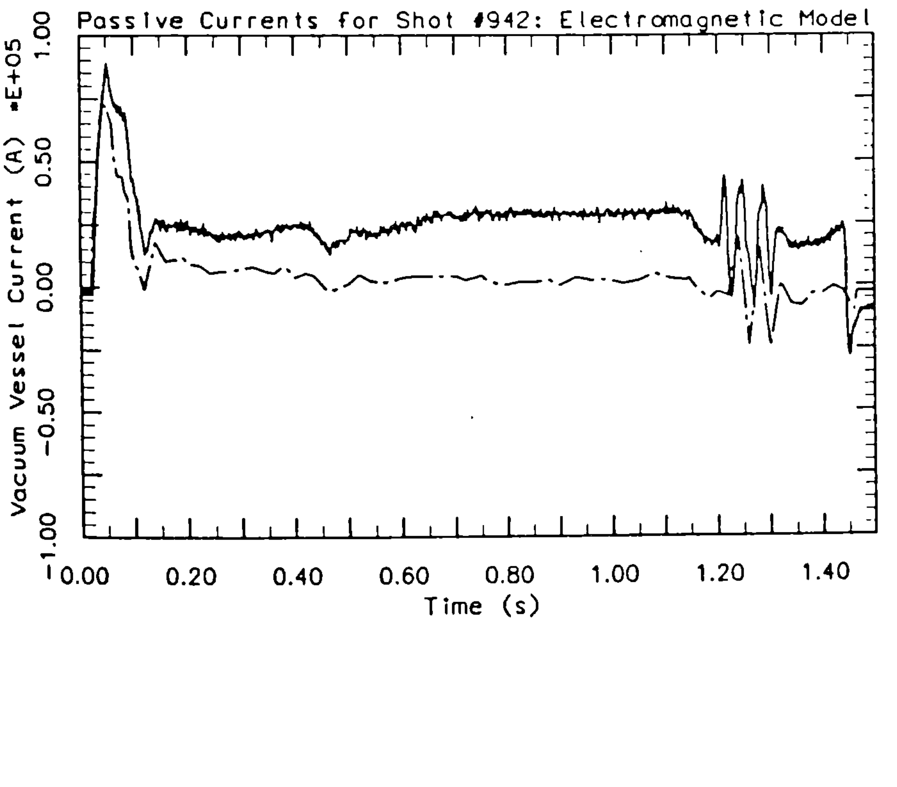
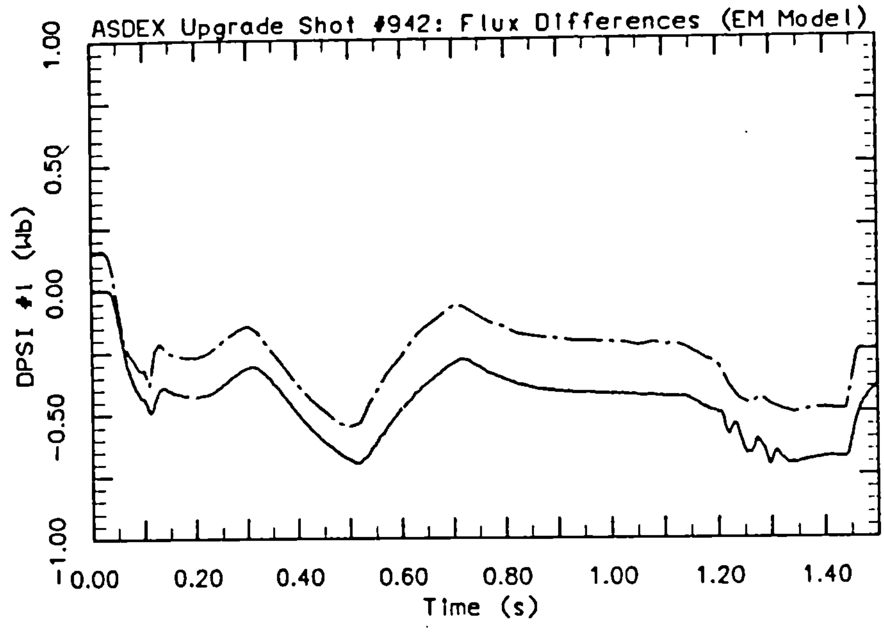


Figure 15. Measured (solid) and computed (broken) flux difference at sensor $\Delta\psi_1$ (a) and field at sensor $B_{\theta 10}$ (b) for run 942, purely electromagnetic analysis



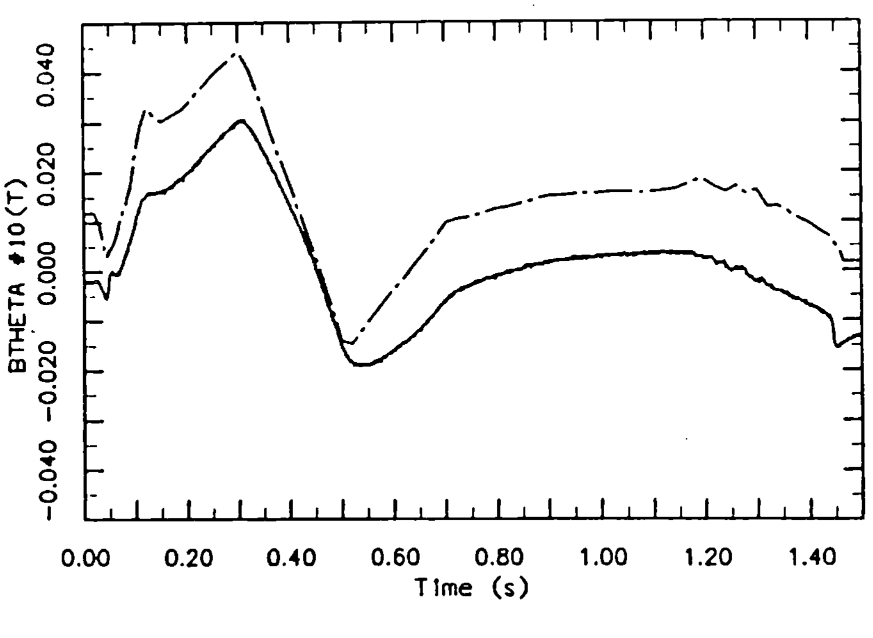


Figure 16. Reconstructed (solid) and computed (broken) geometric parameters for run 942, MHD dynamic analysis

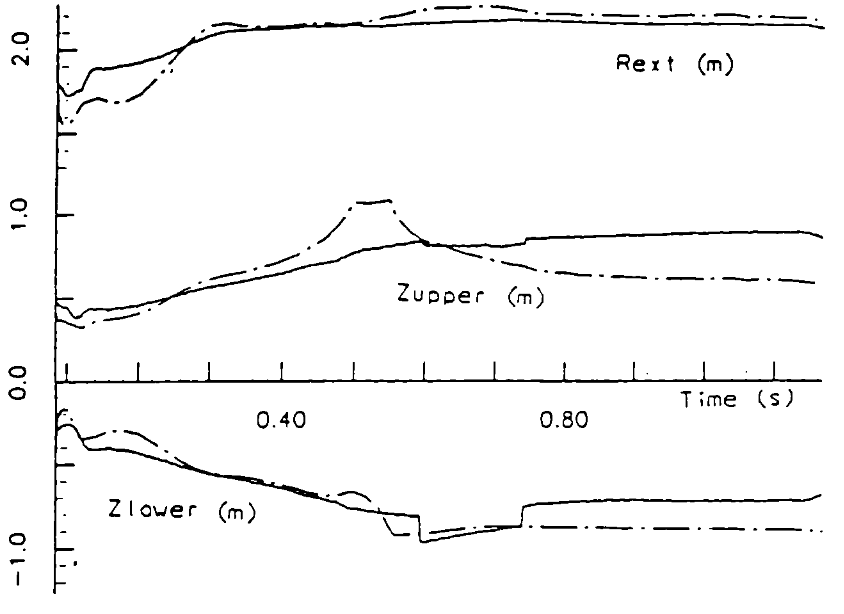


Figure 19. Map of the poloidal flux at 640 ms (flat top) for run 942, MHD dynamic analysis

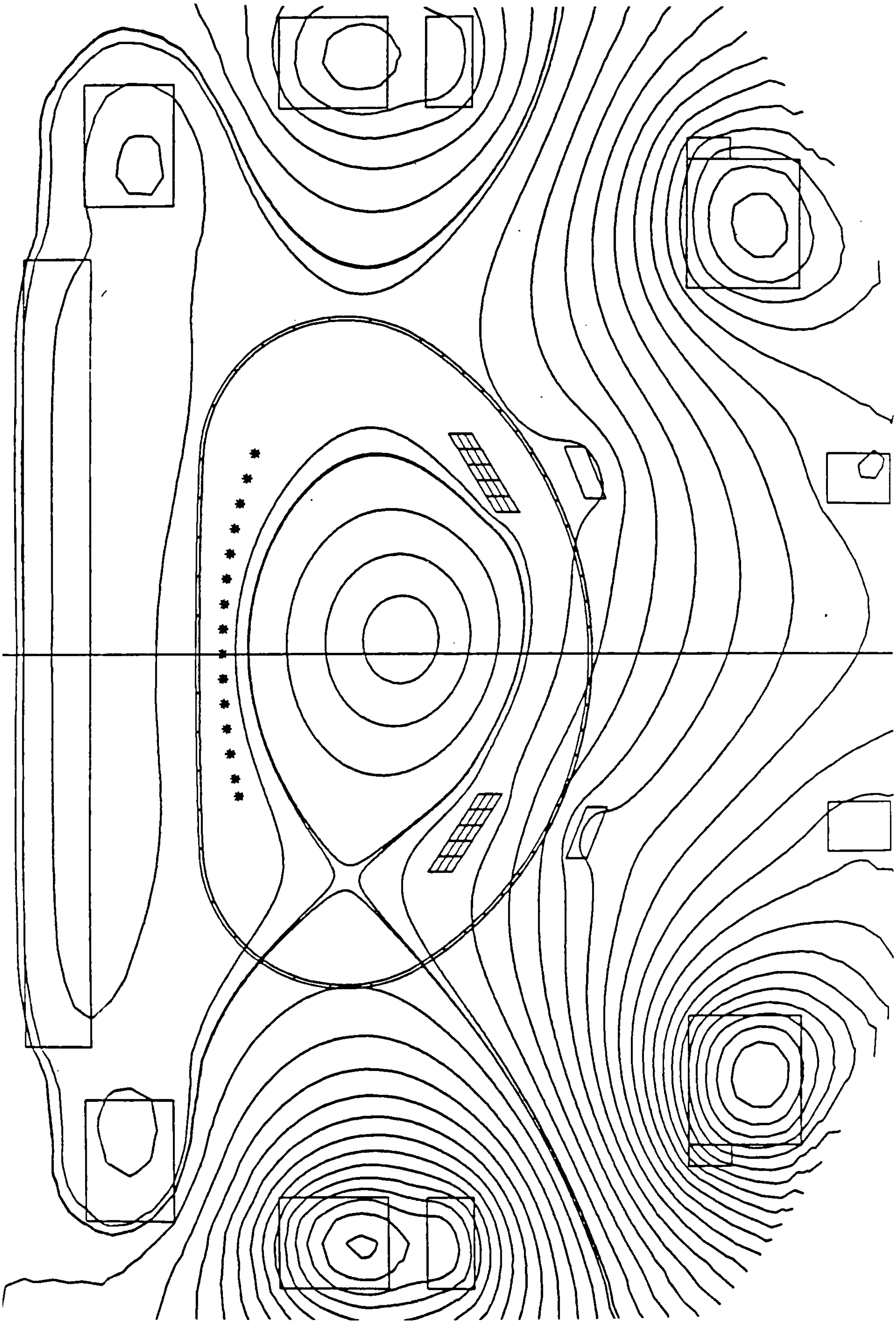


Figure 20. Plasma Current and Position during the disruption run 1162.

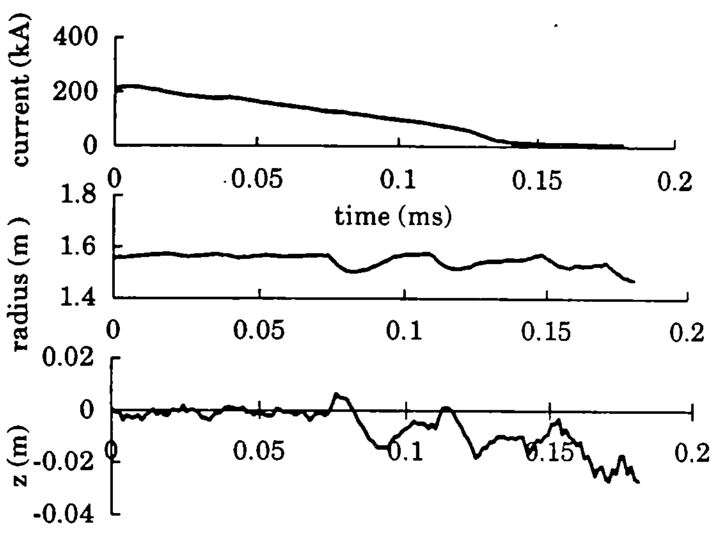


Figure 21 Measured (solid) and computed (broken) toroidal current in the PS I_{PS} (a), in the vessel I_v (b) and total toroidal current (plasma + vessel) (c)

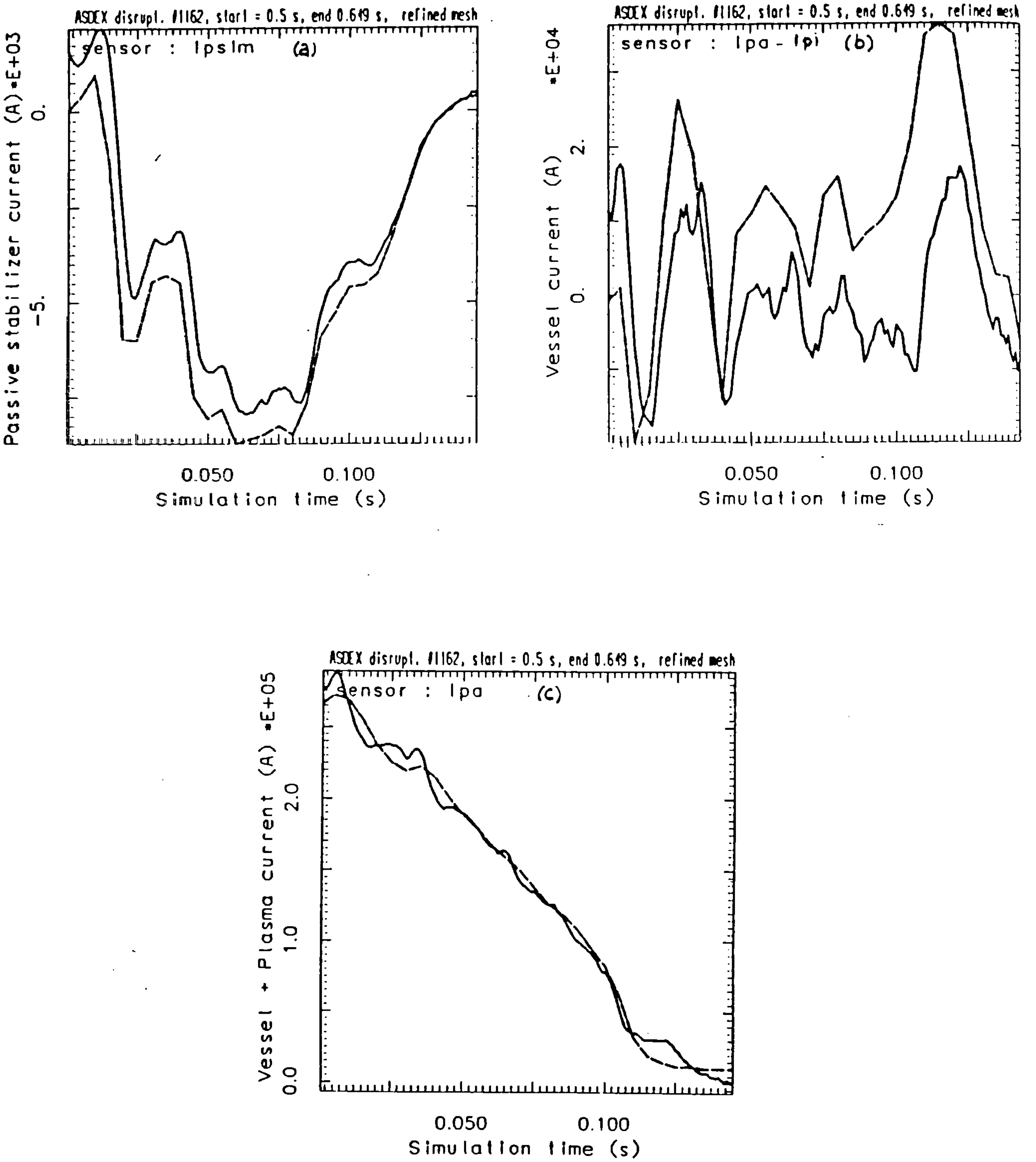
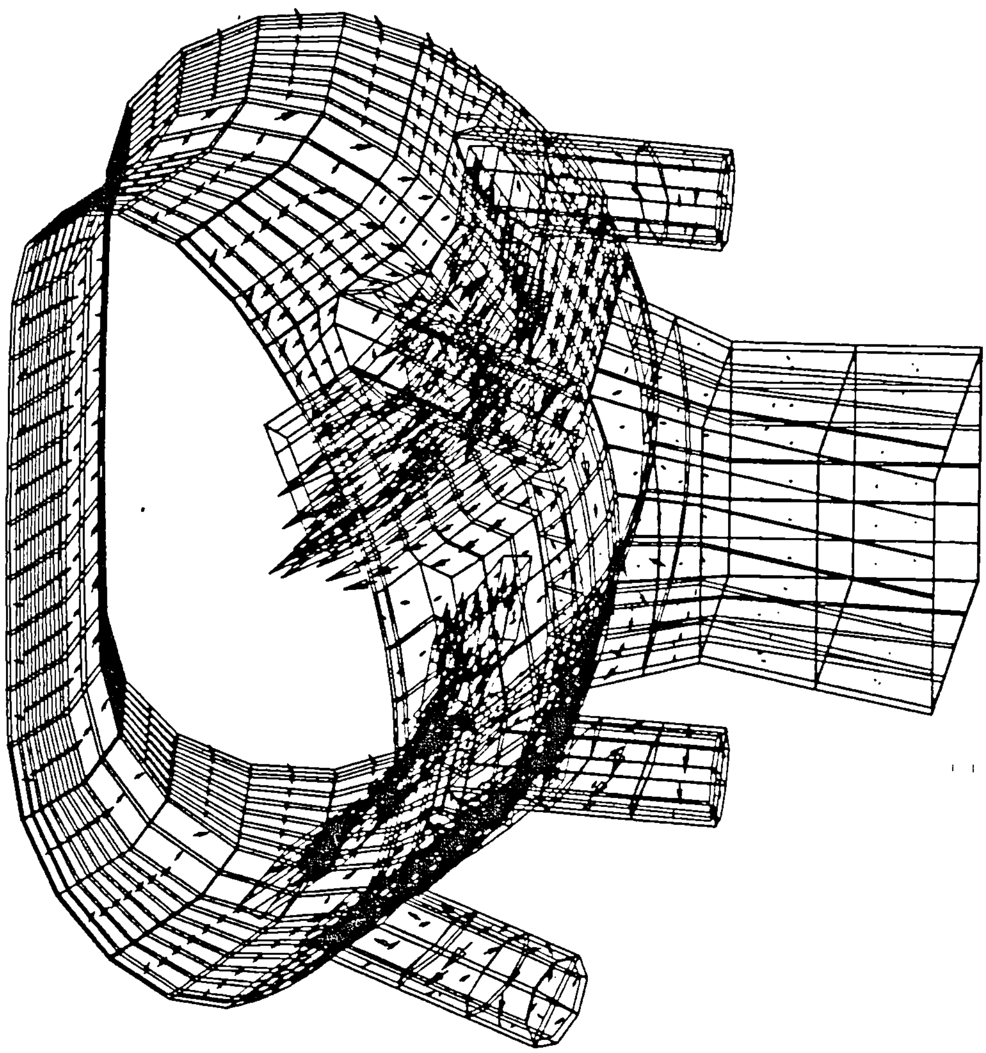
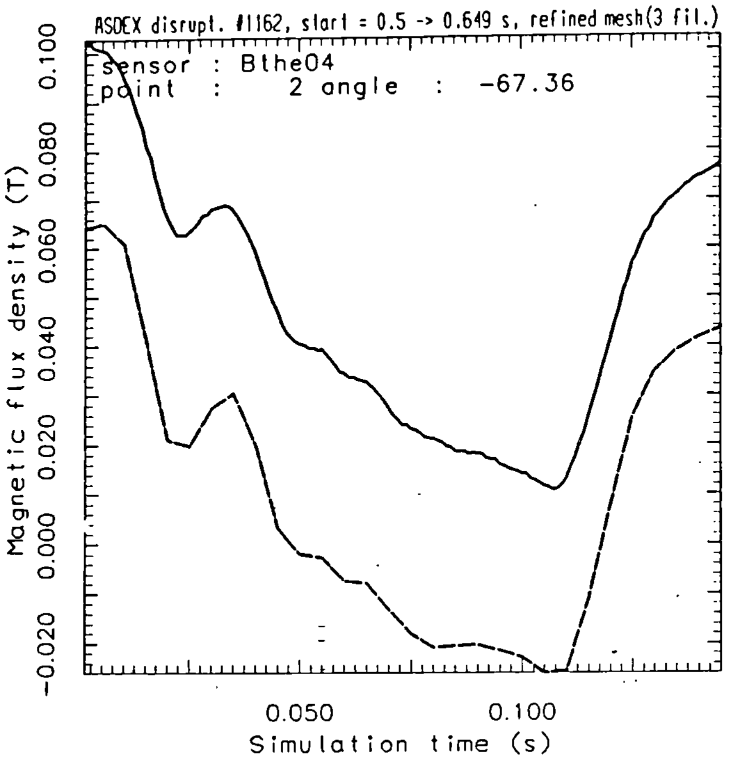


Figure 22. Eddy current distribution in the vessel computed for the disruption run 1162.



CURRENT DENSITIES - TIME = 3.50E-02

Figure 23. Measured (solid) and computed (broken) magnetic field at sensor $B_{\theta 4}$ and $B_{\theta 12}$ for the disruption run 1162



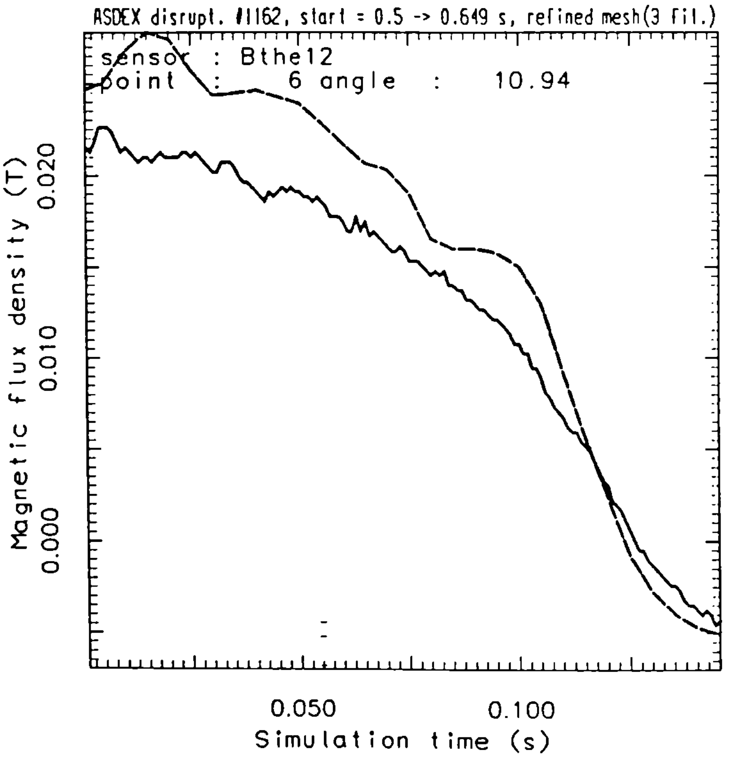


Figure 24. Measured (solid) and computed (broken) magnetic flux differences $\Delta\psi_1$ and $\Delta\psi_6$