Mechanical Design Aspects of the Fastening/Guiding Support System for the Tokamak First Wall Components Subjected to Plasma Disruption Events

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ABSTRACT

The effects of plasma disruption events on the structural integrity of the Tokamak inboard and outboard first wall (FW) foreseen for NET (Next European Torus) are investigated. The transient nature of the electromagnetic-type phenomena and the complex multi-layered structure of the internal components, including different conducting materials, require fully three-dimensional (3D) dynamic analyses, based at least on a finite element thin shell formulation, for both the electrical and mechanical computations. The choice and position of the fastening and guiding support systems combined with the strengthening of the rear part can have a major impact on their integrity. The proper solution through the comparative study of various options is described.

1. INTRODUCTION

Most of the present day experiments as well as next generation fusion devices are based on the Tokamak approach characterized by the magnetic confinement of a thermonuclear plasma. Due to the resulting complexity of the strong magnetic field distribution, the large current plasma configuration and the time-varying electromagnetic phenomena occurring in the conducting components of the reactor, several eddy current models and computer codes have been developed recently (Albanese et al., 1989). They are also of interest for related design studies when they are fully integrated in a computer-aided engineering environment with mechanical computer tools and computer graphic techniques (Chaussecourte and Crutzen, 1988).

In a Tokamak reactor, the presence of plasma current instabilities generates electromagnetic-type transient phenomena which lead to strong induced loads that must be correctly accommodated in the general engineering design of the machine. In particular, the plasma disruption events have a significant impact on the mechanical design of all the internal reactor components such as the first wall structures including their supports. The effects of plasma disruptions on the structural integrity of the FW inboard and outboard removable segments assembled inside the vacuum vessel and foreseen for NET (Next European Torus (Toschi et al., 1988)) are investigated. Previous papers (Crutzen et al, 1987; Crutzen and Rubinacci, 1989) have already illustrated how the high segmentation of the internal structural components reduces the amplitude of the induced loads during electromagnetic transients. But, the subdivision in a relatively high number of pieces makes the design of the guiding and fastening systems for the removable internal segments placed side-by-side around the plasma ring difficult. These systems must satisfy not only the maintenance requirements, but also the electromagnetic and mechanical boundary conditions. Attention must be paid on the way to absorb the huge induced electromagnetic forces transmitted by the internal segments to the vacuum vessel. The paper gives the first indications of possibilities to support the internal removable modules inside the vacuum vessel, during such accidental events.

2. ENGINEERING DESIGN CONCEPT

This study refers to the NET I design of the double-null plasma configurations which are foreseen during the initial physics phase of the machine operation for the inboard first wall and during the final technological phase when a breeding blanket will be installed in the outboard region. According to the NET design concept, the removal of the FW internal segments is carried out, in each of the 16 reactor sectors, from the top of the vacuum vessel, through the upper access ports. Each Torus sector includes, as shown in Figures 1 and 2:

- 3 inboard segments (1 central and 2 lateral pieces);
- 3 outboard segments (1 central and 2 lateral pieces);
- 1 key-plug on top of the access port, between inboard and outboard regions.

Both inboard and outboard regions are, consequently, split into 48 internal removable segments. The preliminary design of the divertor plates is still in progress and, therefore, nothing is mentioned here on that specific subject.

Each inboard module corresponds to elongated thin shielding panels, water cooled, while each outboard module consists of a closed and tight box-like thin structure enclosing the breeding blanket units (not considered in the calculations at this moment). According to the NET FW concept (Toschi et al., 1988), the main plasma-facing walls are relative thin structures in austenitic stainless steel including poloidal cooling tubes. Each internal segment is provided with one upper extension, which is fastened by bolting at the top of the access port and which should allow to transmit the gravity and electromagnetic reaction forces to the vacuum vessel. The upper extension closes the access port tightly, acts as shielding plug in this zone, and is used for the supply lines penetrations and for handling the segments from the top during withdrawal. The guiding system at the bottom inside the vacuum vessel should be able to support the electromagnetic torques induced during plasma disruptions and to provide, at the bottom, for thermal expansions, vertical removal and angular adjustment.

3. ELECTROMAGNETIC-MECHANICAL ANALYSIS

The finite element technique is applied for the numerical simulation of the electromagnetic-mechanical interaction induced in the inboard and outboard NET FW segments during a major plasma disruption event (20 ms plasma current quench). It causes a rapid variation of the poloidal magnetic field and induces time-varying eddy currents in the passive metallic components surrounding the plasma column. Electrical insulation from the supporting structure and between each segment is assumed. The additional vertical extensions have been included but only from a mechanical standpoint. Fully three-dimensional (3D) dynamic analyses, from both the electrical and mechanical viewpoints are required.

As far as the 3D electromagnetic computations are concerned, the induced eddy current distribution in space and time in the conducting component are computed first. Then the electromagnetic body force distribution, acting upon the structure and generated by the coupling between eddy currents and magnetic fields, is determined. Specific reports are dedicated to these computations (Crutzen et al., 1987; Crutzen and Rubinacci, 1989; Crutzen and Rigo, 1989). The electromagnetic body loads generate large resulting forces and tilting moments creating an overturning situation which must be balanced by appropriate mechanical boundary conditions as discussed below.

As far as the 3D mechanical simulations are concerned, static and fast dynamic analyses have been performed considering a multi-layered shell approach in order to reproduce correctly the anisotropic behaviour of the poloidal cooling tubes between the outer and inner plates. Stress and deformation results have been illustrated by Crutzen and Rubinacci (1989) and Crutzen and Farfaletti-Casali (1988). The deformed shapes of the central and lateral FW segments are shown in Figure 4a. Specific studies into the vulnerable overturning deformation behaviour (local buckling of the thin box outboard module and snake-type deformation shape of the inboard panel segment) are still in progress.

The function and position in space of the supporting and guiding systems has been reproduced exactly by fixing the needed degrees of freedom at certain nodal points (see Figures 4a and 5a):

- a guiding system made of two pins on a pad has been modelled at the bottom by two nodes, still allowing thermal expansion in the vertical direction;
- a fastening system simulating the bolted connection has been modelled by four nodes placed at the upper extension corners.

Transient plots provide concise summary information about the history of the reaction forces at the nodal supports of central and lateral outboard FW segments, as shown in Figure 4b.

4. MECHANICAL DESIGN ASPECTS

The 3D numerical simulations provide a general guide to the conceptual design of the Tokamak first wall structures and their support systems. A first analysis of the impact of the huge transient electromagnetic loads induced during a major plasma disruption on the fastening and guiding systems of the internal removable segments of NET, considering the three segments of the outboard region of one reactor sector, have been already reported (Crutzen and Farfaletti-Casali, 1988). Detailed investigations related to the effects of the support system position combined with the rear part strengthening on the global structural integrity for both the outboard and inboard modules have been performed recently during the process of structural design optimization.

As far as the outboard FW segments are concerned, a comparative study of various options for support position/function/choice in connection with a plasma disruption (10.8 MA/20 ms) is summarized as follows. Figure 3 illustrates for an empty outboard module the wide range of variation of the maximum local reaction forces transmitted to the vacuum vessel, combined with the maximum Von Mises stresses generated inside the plasma-facing wall (from 110 to 190 MPa) and with the peak strain energy indicating the global structural stability level (from 101 to 332 KJ). In general, the strengthening of the back region and of the vertical extensions improves the structural integrity of each FW module, preventing local/global collapse-modes, and therefore is always included in the further considerations. In Figure 3, the first case, proposed already by Bond and Thomson (1987), and considering only two central supports, shows critical values for stress and strain energy (max displacements/deformations). The upper fastening system in the region of the vertical extension has been investigated more in detail considering two different solutions. In the case of the FW fixation on top to the access port (second case in Figure 3), the reaction force distribution shows a pronounced lack of balance due to the flexibility of the vertical extension and particularly in the case of the lateral FW segments for the radial and vertical reaction components. On the contrary, the solution of the FW fastening in an intermediate level of the extensions and very near to the box-shape breeding blanket containment for the horizontal reactions components (radial and toroidal) and on top of the access port for the vertical reaction components, offers more satisfactory results in terms of stress/strain energy (third case in Figure 3). Concerning the guiding system at the bottom of the central and lateral FW segments, two lateral support were finally defined in order to equilibrate the tilting moments (last two cases in Figure 3). This guiding system is equivalent to two pins, placed on a pad, vertically guided inside the same vessel sector, which has also the advantage to compensate, at least partially, the reaction forces transmitted by the adjacent segments (see also Figure 4a). Two radial reactions of opposite sign (max values of about 1.0 MN: 100 tons) are dynamically acting on the pins (curves (a),(b) in Figure 4b) while the toroidal reaction components exhibit a quite small amplitude (curves (c),(d)). In the case of coupling between the central and lateral segments, the reaction compensation could be satisfactory (from 70% to 90% observing respective curves (a),(b) in Figure 4b) even if the lateral FW segment shows unbalanced reactions because the upper vertical extension looks like an asymmetric and more flexible structure. The optimized configuration of the fastening/guiding support systems for each outboard component (last case in Figure 3 and Figure 4a) minimizes the reference parameters of stress/strain energy, reducing the latter by a factor of three. In addition, this solution allows the coupling and compensation of the reaction forces between the central and lateral FW segments in order to relieve the vacuum vessel partially.

As far as the inboard FW modules are concerned, the same considerations are proposed to find the best way for mitigating the effects of impulsive loads transmitted to the corresponding vessel sector and access port in the presence of a plasma disruption (15 MA/20 ms). A first case (Figure 5a), considering only upper and lower local fixations, was checked but high values of stresses (more than 200 MPa), strain energy (about 400 KJ) and large lateral displacements (about 2 cm) arising from a snake-type deformation-shape, were obtained (Crutzen and Rigo, 1989). Even with a fastening system located at the oblique flange of the access port, continuous lateral fixations have been proposed afterwards (see Figure 5b) in order to redistribute the huge radial reaction forces and torques better. Therefore, in addition to a better connection on top and two pins vertically guided on the bottom, a locking system in the radial direction has been localized at the back of the lateral wings in the upper and lower regions, as shown in Figure 5c. Having radial reaction forces of opposite sign between the central and the two lateral inboard slender FW modules, a coupling and compensation can be obtained and the effects of the impulsive-type loading condition on the vacuum vessel can be alleviated.

At this conceptual stage, the specific integrity of the fastening and guiding support systems, has not yet been investigated completely, because clearances and gaps have to be preserved during the removal of the in-vessel components in agreement with maintenance requirements. Anyway, additional dissipative systems, such as shock absorbers, will be included locally into the locking system in order to contrast the impact-type electromagnetic reaction forces efficiently.

5. CONCLUSIONS

The reaction forces, transmitted to the vacuum vessel at the levels of both the lower guiding and the upper/intermediate/lateral fastening/locking systems of the inboard and outboard FW segments, result very high and indicate the criticality of the problem. Nevertheless, such reaction forces and torques appear to be manageable, after a detailed study of the supports during the process of structural design optimization of the FW reactor components.

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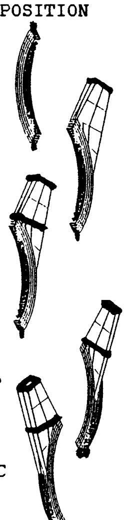

CASE N.	TYPE/SUPPORT POSITION	MAX. REACTION FORCE LEV(*)	DIR.	VALUE (t)	MAX. VON MISES STRESS (MPA)	TOTAL STRAIN ENERGY (J)
1	C	MED MED PIN	Z T T	19 40 40	190	332000
2	C	SUP SUP PIN	Z R T	74 66 41	130	261000
3	C	SUP MED PIN	Z R T	30 51 42	125	211000
4	L	SUP MED PAT	Z R T	21 85 107	120	151000
5	C	SUP MED PAT	Z R R	15 44 82	110	101000

(*): LEVEL OF FASTENING AND GUIDING SYSTEMS

C : CENTRAL SEGMENT L : LATERAL SEGMENT
SUP : UPPER FASTENING SYSTEM
MED : INTERMEDIATE FASTENING SYSTEM
PAD : INTERMEDIATE RADIAL TWIN PIN GUIDING SYSTEM
PAT : BOTTOM TOROIDAL TWIN PIN GUIDING SYSTEM
PIN : BOTTOM CENTRAL ONE PIN GUIDING SYSTEM

MAJOR PLASMA DISRUPTION CURRENT QUENCH (10,8 MA/20MS)

FIGURE 3: SUPPORT POSITION EFFECTS ON OUTBOARD FW STRUCTURAL INTEGRITY

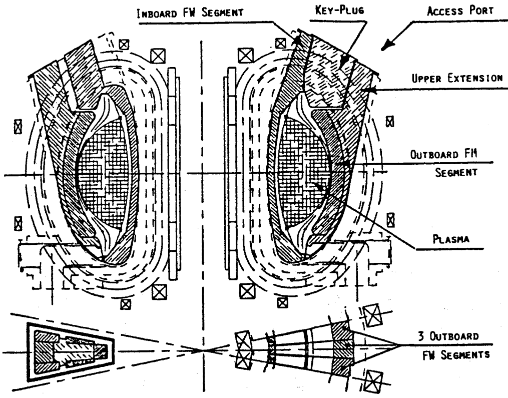

FIGURE 1: NET I REACTOR CROSS-SECTION - INTERNAL COMPONENTS

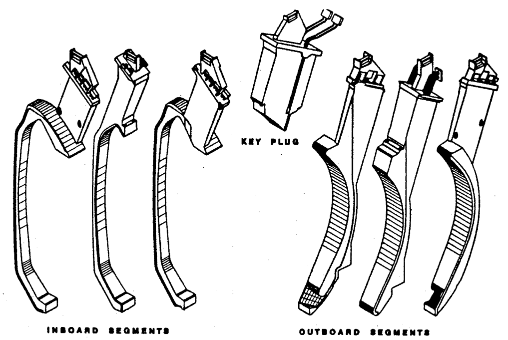

FIGURE 2: IN-VESSEL SEGMENTATION

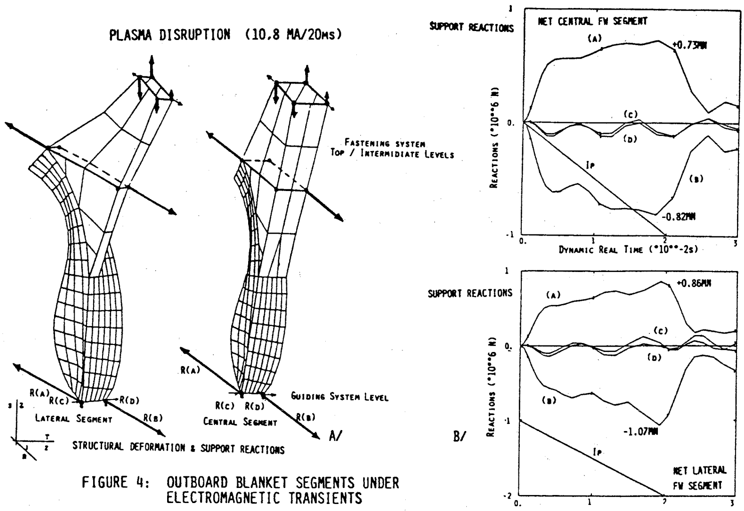

FIGURE 4: OUTBOARD BLANKET SEGMENTS UNDER ELECTROMAGNETIC TRANSIENTS

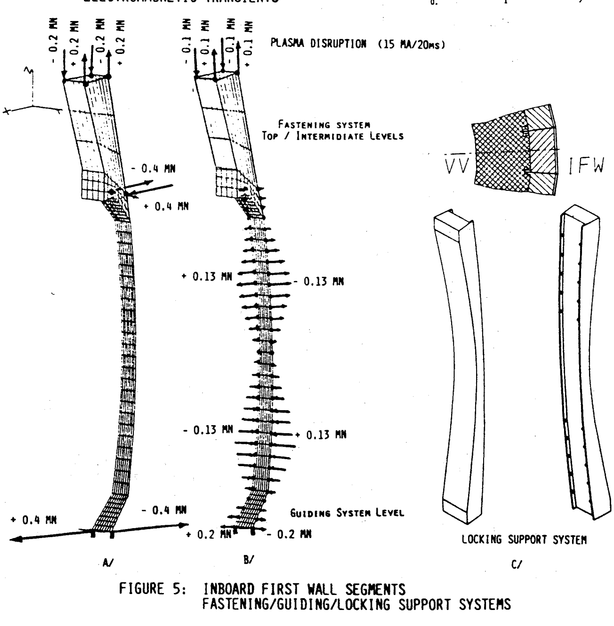

FIGURE 5: INBOARD FIRST WALL SEGMENTS FASTENING/GUIDING/LOCKING SUPPORT SYSTEMS