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ELECTROMAGNETIC LOADS ON ITER IN-VESSEL COMPONENTS*

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Abstract

Design of the vacuum vessel and internal blanket/shield modules for the International Thermonuclear Experimental Reactor (ITER) is strongly influenced by the magnitude of electromagnetic loads due to plasma disruption. Calculations with the finite element code, EddyCuFF, have been performed to quantify these loads and incorporate them into the design process. A multifilament model of plasma motion and current decay has been developed using data generated by the Tokamak Simulation Code (TSC). Comparison with calculations employing single filament plasma models illustrates the need to use self-consistent, distributed plasma scenarios when analyzing toroidally segmented components. Application is made to design and analysis of the high aspect ratio design (HARD) option vessel and blanket/shield modules. Variations in geometry, response characteristics, and electromagnetic loads are compared to the reference design values.

Introduction

Electromagnetic forces due to plasma disruption impose strong requirements on the electrical and structural components of ITER. During the Conceptual Design Activities (CDA) phase of the project, benchmark analyses were performed to determine the effect of not only disruption parameters, such as motion and plasma decay rate, but also differences in geometry and field drivers used by the analysis codes [1]. Results indicate that modeling to accommodate three-dimensional effects and the use of self-consistent plasma disruption scenarios can have a significant effect on the accuracy of force distributions for structural analysis.

Calculations with the finite element code, EddyCuFF [2], have been performed to quantify these effects and incorporate them into current design activities. EddyCuFF determines the nodal current and force distribution on a shell element representation of the three-dimensional conducting structure. Eddy current heating and electromagnetic loads are applied to a structural analysis model to determine transient stress and deflection. A distributed plasma model, based on reference design geometry, has been developed to evaluate its effect on the in-vessel components and a thin-wall vacuum vessel concept. Results are compared with single filament models and the ITER benchmark reference values.

Application of the analysis method has been made to design

and analysis of the high aspect ratio design (HARD) option vessel and blanket/shield modules. Variations in geometry, response characteristics, and electromagnetic loads are compared to the reference design values.

Distributed Plasma Model

Studies by R. Albenese et al. [3] have shown that the shape and distribution of plasma current in a disruption simulation can have a significant effect on the calculated loads for segmented structures, such as the blanket/shield modules. To evaluate this effect, a multi-filament model of plasma current decay was developed using data generated by the Tokamak Simulation Code (TSC) [4,5]. This physics code employs a numerical model of an axisymmetric plasma and surrounding structure to determine self-consistent plasma behavior during disruption. Fig. 1 shows a TSC computational grid with vacuum vessel, inboard and outboard blanket/shield modules, and other conducting structure represented by axisymmetric filaments. Toroidal segmentation of the blanket modules is modeled by use of a common resistive gap. The resulting current history for the 2500 cell grid is reduced to approximately 550 filaments for EddyCuFF, including poloidal field coils, active control coils, and internal structure not included in the EddyCuFF model.

Fig. 1. TSC code axisymmetric plasma model

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EddyCuFF calculations were performed for the inboard blanket/shield modules, an assembly of 96 steel boxes connected to thick back plates to form 32 modules in the torus (Fig 2). The toroidally segmented blankets are subject to large vertical loads, from the interaction of circulating current with toroidal field, and large radial forces caused by saddle currents in the first wall.

A 22 MA plasma simulation, with an initial vertical displacement of 1 m and decaying at a rate of 1 MA/ms, was used to develop the distributed current driver [5]. As can be seen in Table 1, the distributed plasma has a large and beneficial effect on both radial and vertical loads. This is due primarily to an elongation of poloidal field lines in the distributed plasma that reduces the angle of incidence with the first wall and generation of saddle currents in the structure. The effect of a distributed plasma model on vacuum vessel forces is small.

Application to HARD

The high aspect ratio design option for ITER affects many important load parameters, such as the size and position of components, response characteristics, and the magnitude of driving fields. Using both single filament and distributed plasma models, calculations have been performed to quantify these effects and compare them to the reference design.

Fig. 3 illustrates the main geometric differences between HARD and the reference design, including 1) a smaller vacuum vessel cross-section with larger major radius, 2) inboard blanket closer to the plasma center, and 3) larger outboard blanket cross-section. Other parameters, such as segmentation of the blanket modules, gap dimensions, and material thicknesses are assumed to be identical to the reference design. Magnetic field differences are due to a

Table 1 - Distributed Plasma Model Results

Disruption Model	Net Circulating Current (MA)	F-Rad on 1/4 Geom (MN)	F-Vert on 1/2 Geom (MN)
TSC 0705 [5] Single Fil.	TBD	TBD	TBD
TSC 0705 Multi-Fil.	0.7	0.9	2.4
ITER Ref. [1] Single Fil.	1.3	1.0	3.0

lower plasma current and higher toroidal field for the HARD option. Table 2 summarizes the main electromagnetic parameters for the two designs.

Vacuum Vessel

Calculations were performed for an axisymmetric, uniform thickness vessel with 100 ms time constant similar to previous ITER analysis models. As distributed plasma effects are small for the vessel, a single filament plasma centered at $R=6.33$ m, $Z=-1.0$ m with an exponential current decay of various lengths was assumed.

The analysis showed that induced current in the toroidally continuous vessel varies from 5.9 MA for a 0.2 MA/ms disruption to 13.1 MA for a 3.0 MA/ms decay. When tabulated as percent of initial plasma current (Table 3), this variation follows closely the values for the reference design and suggests that small calculational differences in geometry, plasma current distribution, and PF coil currents have only a small effect on induced current compared to the effect of L/R time for the structure.

The variation of net radial and vertical forces with decay time is shown in Fig. 4-5. For a 1 MA/ms current decay, radial

Fig. 2. EddyCuFF Benchmark Geometry Model

Fig. 3. Elevation view of HARD and CDA configurations

Table 2 - Comparison of Electromagnetic Parameters

Parameter	ITER	HARD
Major Radius (m)	6.00	6.33
Plasma Current (MA)	22.0	14.9
Decay Rate (MA/ms)	1-3	1-3
Vessel L/R Time (ms)	100	100
Vessel Resistance ($\mu\Omega$)	20	>20
Toroidal Field @Ro (T)	4.85	7.11

Table 3 - Percent of Plasma Current Induced in Vessel

Decay Rate (MA/ms)	ITER ¹	HARD ²
4.0	89%	85%
1.0	79%	71%
0.2	50%	40%

1- CARIDDI 3D Analysis [1]
2- EddyCuFF Model

forces are reduced by approximately the ratio of plasma currents squared, from -45 MN/radian (20 MN per 1/16 sector) to -22 MN/radian (12 MN). Maximum vertical force is reduced from 9 MN/radian to 4.6 MN/radian.

In-Vessel Components

The magnitude of current induced in the inboard blanket/shield modules is affected by changes in size, position, and magnetic field. As shown in Fig. 6, a decrease in poloidal field at the center of the inboard module is offset by an increase in radial position and flux area per electrical segment. The result is no change in driving voltage, but a 20% decrease in circulating current since the loop resistance is higher (Fig. 7). Inboard passive stability plates, which may be required for plasma control in the HARD configuration, would increase the induced current to 3.5 MA. Toroidal field at the center of each module is increased from 8.5 T to 10.5 T, but the interaction with reduced circulating and saddle currents produces only a small increase in forces acting on a quarter of the geometry (Fig. 8). Net radial and vertical loads on a module are unchanged.

The larger outboard blanket/shield module for HARD has a 50% higher driving voltage to induce circulating currents, but a higher loop resistance, so that induced currents are only slightly higher than in the reference design. Toroidal field at the center of a module is increased from 3.5 T to 5 T, however, which leads to a 40% increase in radial and vertical loads on a quarter module. Vertical loads are also increased by the interaction of toroidal field with longer radial current paths around the box. A summary of force results is given in Table 4.

Fig. 4. Variation of Net Radial Force with Decay Time

Fig. 5. Variation of Net Vertical Force with Decay Time

Fig. 6. Magnetic Field at Center of Blanket Modules

Conclusion

A method has been developed to incorporate self consistent, distributed plasma drivers into three dimensional eddy current calculations. Comparison with single filament models accentuates the need to do so when analyzing toroidally segmented components. Application of EddyCuFF to the high aspect ratio design option has shown that reduced plasma current has a beneficial effect on disruption loads for the vacuum vessel. Reduced current in the inboard blanket/shield module is offset by higher toroidal field, but the end result is no change in local or global forces. Outboard blanket forces are increased locally over the reference design.

Reference

- [1] Y. Shimomura et al., ITER Poloidal Field System, ITER Documentation Series, No. 27, Vienna, 1991
- [2] A. Kameari, Transient Eddy Current Analysis on Thin Conductors with Arbitrary Connections and Shapes, Journal of Computational Physics, 42, 124-140 (1981)
- [3] R. Albenese et al., Electromagnetic Effects Induced by Plasma Disruptions in the NET Vacuum Vessel, Fusion Engineering and Design, 1991
- [4] S. Jardin et al., Dynamic Modeling of Transport and Positional Control of Tokamaks, Journal of Computational Physics, 66, 481-507 (1986)
- [5] R. Sayer, ITER Disruption Modeling with TSC, ITER-IL-PF-4-0, July 1990

Fig. 7. Induced Current in Inboard Module

Fig. 8. Radial and Vertical Loads on Segment of Module

Table 4 - Comparison of Blanket/Shield Module Forces

Parameter	ITER [1]	HARD
Inboard Blanket		
F-Rad on 1/4 Box (MN)	0.7	0.8
With Stability Loops (MN)		3
F-Vert on 1/2 Box (MN)	2.5	2.6
With Stability Loops (MN)		9
Outboard Blanket		
F-Rad on 1/4 Box (MN)	10	TBD
F-Vert on 1/2 Box (MN)	28	TBD
Vacuum Vessel		
Max F-Rad (MN/radian)	-45	-22
Max F Vert (MN/radian)	9	5

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