Electromagnetic analysis of forces and torques on the ITER shield modules due to plasma disruption

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Abstract—An electromagnetic analysis is performed on the ITER shield modules under different plasma disruption scenarios using the OPERA-3d software. The modeling procedure is explained, electromagnetic torques are presented, and results of the modeling are discussed.

Keywords-component; ITER, eddy-current analysis, electromagnetic force computation.

I. INTRODUCTION

The electromagnetic forces that occur due to plasma disruption are an important consideration in the design of the ITER device. Many different analyses with varying assumptions have been completed by a number of domestic agencies. To help standardize the different analyses the International Organization (IO) has defined geometry, plasma disruption scenarios, and a protocol for presenting the different results [1].

The purpose of this paper is to present and discuss results of the electromagnetic benchmarking analysis completed by the United States team as prescribed by the IO. This geometry consists of a forty degree sector of the device and includes the inner vacuum vessel, divertor assembly, port plugs, and simplified shield modules. The electromagnetic environment of the plasma disruption events are prescribed by DINA calculations. A number of plasma disruption events will be considered.

II. ANALYSIS

A. Geometry

The geometry of the simulated ITER device is shown in Fig. 1. Some key features of this model will now be stated. First the shield modules are simplified which implies they have eddy current slits but no cooling holes. The placement and depth of the slits have not been optimized. In addition they are electrically isolated from each other and the vacuum vessel. Finally symmetry is used so that even though a forty degree sector is modeled it is electromagnetically equivalent to the actual device. From Fig. 1 the single lower port on the vacuum vessel reveals why a forty degree sector was modeled, its symmetry is repeated every forty degrees.

B. Plasma Disruption Currents

The currents in the device are modeled from the DINA simulations for the particular plasma disruption event [2]. They include 6 central solenoid coils, 6 poloidal field coils, and an axial current (to simulate the toroidal field coil) [3]. The plasma currents are modeled by 100 loops with currents that vary with time but are stationary in space – equivalent to the plasma current in the DINA simulations.

Figure 1. Forty degree sector of the ITER Device

Figure 2. Total plasma currents for vertical up/ down disruption event
Three different disruption scenarios include the major disruption linear current decay, vertical displacement event (VDE), upward, linear current decay, and vertical displacement event (VDE), downward, linear current decay. All of the plasma disruption currents analyzed have the same features—a constant current phase, thermal quench of the current followed by an increase in current, and then a linear decay. The total plasma current for two disruption events are shown in Fig. 2. The disruption event not shown in Fig. 2 is the major disruption event which has the same character described except that thermal quench occurs at 8 ms and the plasma current goes to zero at 50 ms.

C. Solution Method

The simulations are performed with the Opera-3d software [4]. This software has a number of features needed for the electromagnetic analysis. First symmetry can be used, second the currents do not depend on the mesh, and finally the results can be exported for use in software designed for mechanical stress calculations.

A number of different mesh densities were used for the shield modules to allow the examination of numerical convergence of the solution for one disruption case. The modules were meshed with tetrahedral elements with an average edge length of 40 mm, 30 mm, and 20 mm for the coarse to the fine mesh density, respectively. Once the solution for a particular disruption was obtained the net forces and torques for each module were calculated. The torques were calculated using the pivot points and the coordinate system defined by the IO. Once the torques are calculated the forces on the shield mounts can be calculated. The results of the force computation are computed at the centroid of the elements that comprise a module and can then be exported to files ready for mechanical analysis. It should be noted that for the model in Fig. 1 there are 56 separate shield modules.

III. Results

Before the results are presented and discussed some nomenclature needs to be defined. The modules are labeled starting from the inboard to the outboard as shown in Fig. 3.

This numbering is in the poloidal direction of the machine, additional numbers are added to identify the modules in the toroidal direction. For example shield module 1 there would be SM_01_01 and SM_01_02, shield module 1 in the first and second toroidal position respectively. This is shown in Fig. 4 for shield module 18.

The torque reference points have been prescribed by the IO. These are located between the projections of the flexible reference points to the vertical mid-plane of the module. The local coordinate system is defined at this point for each module. The x-axis is the radial direction, the y-axis is in the vertical direction, and the z-axis points in the clockwise direction when viewed from the top of the machine.

The forty degree sector was considered for the baseline model because of the presence of the single lower port that breaks the twenty degree symmetry assumption. For comparison the VDE down disruption event is used since the plasma moves toward the lower shield modules on the outboard side of the machine (shield modules 17 and 18). A comparison of the x, y, and z directed torque for shield module 18_02, 18_03, and 18_04 is shown in Figs. 5, 6, 7, respectively.

Figure 5. Torque in x-direction for shield modules 18 for the VDE Down disruption case.
Figure 6. Torque in y-direction for shield modules 18 for the VDE Down disruption case.

Note that the time scale for the Figures begins at .65 sec – the onset of plasma disruption (see Fig. 2).

Figure 7. Torque in z-direction for shield modules 18 for the VDE Down disruption case.

As can be seen by the preceding Figures the effect of the asymmetry because of the port has little effect on the torque calculations on the shield module in proximity of the port. This allows one to reduce the angular sector, simplifying the model, reducing the mesh density, and decreasing solution time.

The next step is to investigate the variation in mesh density within the shield modules, which reveals the numerical convergence property of the modeling procedure. Attention is focused on shield module 1 and three different mesh densities. They correspond to 40, 30, and 20 mm which are the average edge length of a tetrahedron. This will be examined for the major disruption case with linear decay. Some of the largest electromagnetic forces are experienced by shield module 5 for this disruption case. The largest torque is in the y-direction and those results are shown in Figure 8.

Figure 8. Torque in y-direction for shield module 5 for the MD UP disruption case for different module mesh densities.

Again to the scale of the graph the results for the three different mesh densities show good agreement. This shows that numerical convergence is acceptable with the coarser mesh density thus verifying the original assumptions. To be more precise a percent difference is defined

$$ PD = \frac{T^r_y - T^{20}_y}{T^{20}_y} \cdot (1) $$

The superscript $r$ refers to the mesh resolution (30 or 40) and $T^r_y$ is the y-directed torque at the mesh resolution. The results for this error metric are shown in Figure 9.

Figure 9. Percent difference for shield module 5, y-directed torque, for the MD UP disruption case for different module mesh densities.

Fig. 9 shows that the maximum error is about 11% but occurs before the onset of the plasma disruption. The torque should be zero but some numerical noise is present giving non-zero but relatively small torque values (about 1900 N-m).

The final results combine all of the modules and different disruption cases considered in this paper. For each disruption case the maximum torque at a particular instant of time was
identified for each module then converted to axial loads. These results together with the maximum permissible loads are shown in Fig. 10. These vary with position due to their interface with the vacuum vessel.

For this reason a smaller angular model can be used without compromising the accuracy of the simulation as long as the electromagnetic modeling of the shield modules is not changed.

Additionally the numerical convergence of the modeling was also addressed by considering different mesh densities used for the shield modules. Again very promising results were obtained. The higher density meshed models did not change the calculated results significantly. The lower density meshed model provides not only accurate results but results that could now be obtained in a more timely fashion due to the reduced model size. The element count for the 20, 30, and 40 mm tetrahedron size was 32, 15.5, and 10.8 million elements, respectively. The solution times for the 20, 30, and 40 mm tetrahedron size were 13, 23, and 50 days, respectively.

Finally the results also reveal large axial loads are present on a number of shield modules. This has to be taken in the proper context since the EM benchmark geometry was an initial design not the final design. Further analyses have been completed on a select number of modules to identify optimal eddy current reducing slits, the inclusion of cooling holes, and the first wall assembly. These have been reported to the IO and will be published at a later time.

IV. CONCLUSIONS

The electromagnetic forces and torques produced in the ITER shield modules have been considered for three different plasma disruption scenarios. A number of observations useful in future modeling the device have been identified. The first is concerned with the angular sector that was modeled. A forty degree sector was chosen due to symmetry considerations with regards to the vacuum vessel. The results presented in this paper clearly show that the additional port in the vacuum vessel does not affect the results for the shield modules near the port.

V. REFERENCES