Refined Electromagnetic Analysis of W7-X Thermal Insulation during Fast Plasma Current Decay Event

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During the second operation phase of the most advanced stellarator Wendelstein 7-X (W7-X) in 2018, a fast plasma current decay event was observed with the time constant of ~1 ms. The event is much more rapid than the design phase assumptions: 100 kA and 2.7 MA plasma current decay with the time constants of 140 and 50 ms for toroidal and diamagnetic currents respectively. As a result, significantly higher eddy currents are expected to be induced in some of the W7-X components. The comprehensive campaign of electromagnetic (EM) analyses has been launched in order to identify the necessity of proper reinforcement of critical in-vessel diagnostics or lowering the plasma currents for future operation. One of the critical W7-X system found is the complex thermal insulation (TI).

The TI is located in the cryostat to separate cryogenically cooled magnet system and warm vessels. The system consists of actively cooled thermal radiation panels and port tubes, multi-layer insulations, supports and clamps. The TI panels and tubes form the main frame of TI covering the plasma vessel (PV) and ports respectively. Preliminary EM analysis with few panels and tubes indicates that the EM forces are increased by about 7 times due to the newly postulated faster plasma current decay event in comparison with original design loads. To obtain more accurate results, an elaborated EM model has been created, which includes the excitation coils for toroidal and diamagnetic plasma currents, superconducting coils, TI panels and tubes, the PV and ports.

The paper introduces at first the TI structure, continues with the field and eddy current accuracy studies and the lessons learned for the modelling accuracy improvement in ANSYS®. Then the EM analysis results of different plasma current decay scenarios are presented and discussed. Finally, the EM forces for static and transient mechanical analyses are chosen and extracted for further mechanical analyses.

Keywords: Wendelstein 7-X (W7-X), stellarator, thermal insulation, eddy current analysis, electromagnetic analysis.

1. Introduction

The advanced modular stellarator Wendelstein 7-X (W7-X), in Greifswald, Germany, is under operation since 2015. During the second operation phase (OP1.2) in 2017 and 2018 [1], some events of fast plasma current decay with the time constant of around 1 ms (for both toroidal and diamagnetic plasma currents) are observed. They are much faster than the assumptions considered during the design phase of W7-X components, i.e. 100 kA and 2.7 MA plasma current decay with the time constants of 140 and 50 ms for toroidal and diamagnetic plasma currents respectively [2]. As a result, significantly higher eddy currents and electromagnetic (EM) forces are inevitably induced in some of the components. In order to identify the necessity of proper reinforcements of critical in-vessel diagnostics or lowering the plasma currents for future operation, corresponding EM analyses have been performed for many W7-X components. In order to cover wider range of plasma operation scenarios, the EM analyses use the newly postulated events: 100 kA and 2.7 MA with decay time constants of 1 ms for toroidal and diamagnetic plasma currents respectively.

The complex thermal insulation (TI) of W7-X is located in the cryostat to separate the cryogenically cooled magnet system and warm vessels [3, 4]. The TI consists of many actively cooled panels and tubes, multi-layer insulations, supports and clamps. The panels are following the complex 3D shape of plasma vessel (PV) and outer vessel (OV) and forming the main frame of TI together with the TI tubes (covering all 254 ports). The design loads of the TI and its supports are defined base on the superconducting (sc) coil current decay scenario (currents corresponding to 3.0 T magnetic configurations decay with time constant of 3 s), and verified through TI static mechanical analysis with the consideration of certain safety factor [3, 4]. According to the preliminary EM analysis of part of the TI structure with the new postulated plasma current decay scenarios, the EM forces are increased by about 7 times. In order to obtain more accurate and reliable results, a detailed EM model was created, which comprises the excitation coils for plasma currents, sc coils, TI panels and tubes, the PV and ports. The model size in terms of element number is minimized to model only 1/5 of the entire domain (called ‘sector model’) with special cyclic boundary conditions (BC), which could represent the quasi five-fold symmetric W7-X [5].

This paper introduces at first the TI structure followed by the field and eddy current accuracy studies and the lessons learned for the modelling accuracy improvement with SOLID 236 / 237 elements in ANSYS®. Then the TI EM model is described and the analysis results of different plasma current decay scenarios are presented and discussed. Finally, the

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EM forces for static and transient mechanical analyses are chosen and extracted, and some additional issues found during EM analysis are discussed.

2. Thermal Insulation Structure

The sc coils of W7-X magnet system are located in the cryostat interspace formed by the inner PV and the OV. In order to access the plasma volume from outside, there are 254 ports passing through the cryostat volume by connecting their ends to the PV and OV. To assure the sc coils are reliably operated at low temperature (~4 K), all the warm surfaces, i.e. PV outer surfaces, OV inner surfaces and ports outer surfaces, are covered with the TI of different types to minimize radiative heat loads [3, 4].

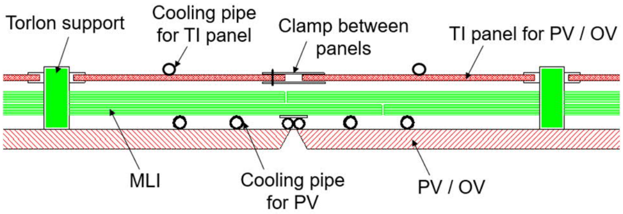

Fig. 1. Layout of TI for PV and OV.

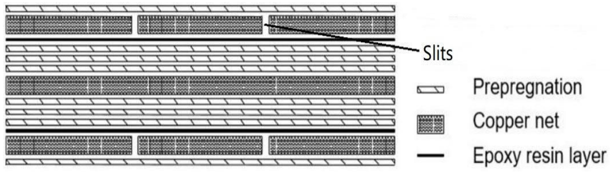

Fig. 2. Details of TI panel structure: slit for middle copper net (not shown) is perpendicular to slits for top and bottom copper net (see also Fig. 5).

The TI is made of 20 double sided aluminized thin Kapton layers with silk like glass spacers as radiation shields (MLI, multi-layer insulation) and actively cooled thermal shields (panels and tubes). Fig. 1 is the schematic view of the thermal shield structure for the PV and the OV. There are many different shapes of panels to follow the 3D shape of the PV and the OV. The panels are made of pre-impregnated laminates of glass fiber compound (GFC), in which three annealed copper nets were embedded with some slits to improve the thermal conduction and mitigate the induced eddy current. Fig. 2 shows the details of the TI panel structure. The TI panels are fixed on the warm cryostat surfaces with hollow cylindrical supports made of Torlon (polyamide), which offers a low thermal conductivity combined with good mechanical properties. The out-of-plane displacements at the edge of adjoining panels are coupled through clamps (see Fig. 1), in order to enhance the mechanical strength of the entire TI and to allow free shrink of each panel during cool down.

The TI tubes cover the warm ports and are thermally connected to the panels. Each of the TI tube includes two parts, i.e. the inner tube and the outer tube, to allow their lateral and axial movements relative to each other. The inner tube is made of brass sheets and fixed axially on the PV. The outer tube is welded to the OV shield and is made of copper sheets.

Since the TI for the OV and outer TI tube are relatively far from the plasma, the induced eddy currents are to be small, therefore the detail EM analysis is focused on the TI for the PV and for the inner TI tubes as more critical parts. Meanwhile, due to the TI structures in different modules are to some extend similar, only the module 3 is modelled. The model comprises the TI as described above, the sc coils and the plasma current coils as shown in Fig. 4.

3. Studies of Field and Eddy Current Accuracy

In order to allow wider range of operation scenarios with relatively high plasma currents, the safety margins considered during the design phase of TI structure could be utilized to some extent, but the accuracies in EM forces calculation and mechanical assessment need to be improved in order to meet the goal and to avoid a TI system failure. As already studied in [6, 7], the ANSYS® element type SOLID 236/237 (edge-based formulation) produces much more accurate results of both B-field and eddy currents than the legacy element type SOLID 97 (vector potential formulation). However, the accuracy of SOLID 236/237 depends also on the mesh density, its shape and quality. Therefore, in order to establish an accurate EM model for the complex TI structure the following steps have been done:

1) development of the required meshing approach on a simple EM model with the excitations and the PV with one port. The model allowed to study several mesh-related issues in addition to the studies in [6]. Table 1 list the details and results of the studies.

2) extension of the model with the remaining ports, TI panels and tubes step by step (~11 steps in total) and to check the corresponding accuracies.

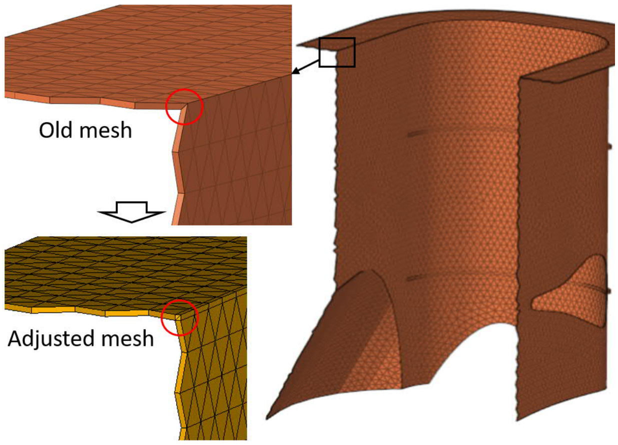

Fig. 3. Example of adjusted local mesh during the optimization process.

The optimized model is achieved by adjusting the local meshes where necessary (see example in Fig. 3). The accuracy study focus is mainly on the following three aspects (as indicated in Table 1):

1) Comparison of the fields from the sector model and the Biot-Savart method using SOLID5/SOLID98 elements in ANSYS® [6];

2). Comparison of the B-fields and eddy currents from sector model and 360° model (expanded from the sector model, no cyclic BC);

3). Comparison of the B-fields and eddy currents in different modules of 360° model.

According to the study results presented in Table 1, the following conclusions are drawn:

- With tetrahedral mesh, refined and improved mesh quality for conducting components, the field accuracy is improved by ~60 % for the PV body and by ~70 % for the ports (see Cases 1, 2, 5 and 7);
- Refinement of air mesh between coil and conducting components does not improve the B-field accuracy significantly (see Case 3);
- Refinement of the coil mesh does not improve the B-field accuracy significantly (see Case 4);
- With SOLID 97 elements, even if the mesh is considerably refined, the B-field accuracy is not as good as with SOLID 236/237 with reasonable refinements (See Case 8 and 9).

Table 1. Summary of the field and eddy current accuracy studies

Cases	Model description	Elements number of the model (Million)	Comparisons (Max. deviations in %)			
				1)	**2)**	**3)**
Case 1	prism mesh for PV and port	4.27	PV body Port	8.56 19.34	/ /	/ /
Case 2	From Case 1, with tetrahedral mesh and improved mesh quality for PV and port	5.00	PV body Port	3.94 13.08	/ /	/ /
Case 3	Case 2 plus refined mesh of air field between sc coils and PV	6.69	PV body Port	3.80 15.19	/ /	/ /
Case 4	Same as Case 2 but two sc coils are with tetrahedral mesh	6.37	PV body Port	3.75 13.68	/ /	/ /
Case 5	Case 2 plus port mesh improved further	4.82	PV body Port	3.76 5.71	/ /	/ /
Case 6	Case 5 plus air field between PV and sc is further refined	6.50	PV body Port	3.80 6.01	/ /	/ /
Case 7	Case 5 plus PV mesh refined further	5.03	PV body Port	3.43 5.70	0.0017 / 0.008[a] 0.00035 / 0.19[a]	0.0017 / 0.0077[a] 0.00031 / 0.204[a]
Case 8	From Case 5, with SOLID 97, air between sc and PV is refined	6.51	PV body Port	5.55 19.66	/ /	/ /
Case 9	From Case 8, with SOLID 97, PV mesh is further refined	10.21	PV body Port	3.84 19.61	/ /	/ /

[a] For field and eddy current respectively.

As listed in Table 1, the maximum B-field deviation in ports is higher than in the PV, which is due to the fact that B-field contributions of the neighboring coils compensate practically each other and the sum B-field in some of the ports is much smaller than background field. The sector model of Case 7 is considered as the most optimum one, since the field deviations are much smaller than in other cases and the model size in terms of element number is also moderate. Therefore, the comparisons of 2) and 3) in Table 1 are only necessarily to be performed for Case 7. As listed in Table 1, for both the comparisons of 2) and 3), the maximum field deviation is only 0.0017 %; the maximum eddy current deviation is 0.204 % from the comparison 3), which is also small and result from the very small eddy current at the beginning of the plasma current decay. As a result, the model of Case 7 is selected as the start point for the modelling of complex TI EM model (see Section 4.1).

In addition, the study of B-field and eddy current symmetry issue using the 360° model discovers the following important ANSYS® issue: the tree gauging for version 2021 R2 and lower is not robust for huge EM models (with total element number higher than ~20 million) and lead to inaccuracies in both the B-field and the eddy current. The resulted inaccuracies are related to the improper gauging on excitation coils. This issue could be mitigated by renumbering to have the excitation coils element numbers at the beginning followed by the conducting components and the air field element numbers at the end. The good symmetry of Case 7 is presented after this renumbering. This issue is still relevant until one develop their own gauging procedure to make the results more robust and accurate, or the gauging procedure from ANSYS® is improved in future version.

4. EM analysis of Thermal Insulation

4.1 The optimized EM model

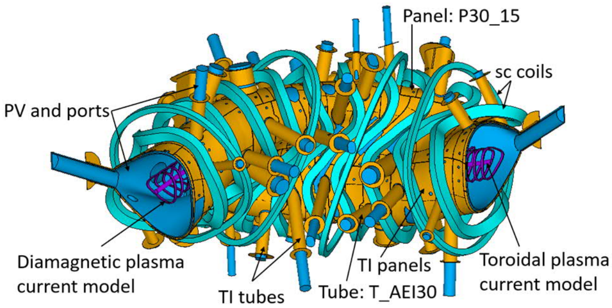

Fig. 4. EM model without air field model.

The final optimized EM model shown in Fig. 4 is achieved by adding the conducting components gradually and adjusting the local mesh to ensure good accuracies. The size of the model is 36.6 Million elements and 62.3 Million nodes. The applied BC is the same as presented in [6]. The air field with coarser meshes fills the space between excitation coils and conducting components. The TI panels are modelled with 5 layers of mesh, three of them represent the Cu net layers (see Fig. 2 and Fig. 5) with smeared resistivity of 1.745×10^{-8} Ω·m. The slits in Cu nets are also simulated by changing the material of corresponding mesh to non-conducting one.

The maximum B-field deviation compare to Biot-Savart is about 3.6 % for the PV, and about ~2.5 % for TI panels, which are more or less the same as for the PV in Case 7. However, for the ports and TI tubes, some elements have higher field deviations in percentage (>20 %) due to much smaller field in-between neighboring coils or at the outboard region. Therefore the mesh quality check includes both the relative differences and absolute B-field difference, which turn out that only ~60 elements are with the relative difference over 3 % and absolute differences over 50 mT. Such accuracies are considered for the results of EM analyses as satisfactory and this optimized model is used for the EM loads calculation. Fig. 6 shows the magnetic flux intensity in TI panels and tubes for one of the magnetic configuration as an example.

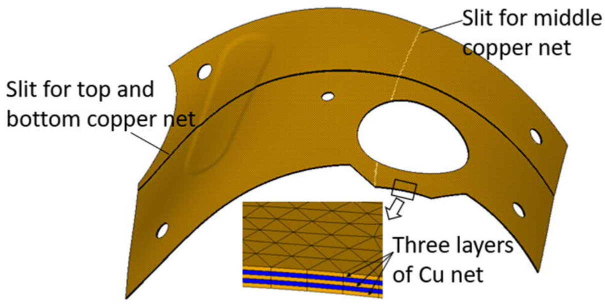

Fig. 5. Example of TI panel FE model with slit.

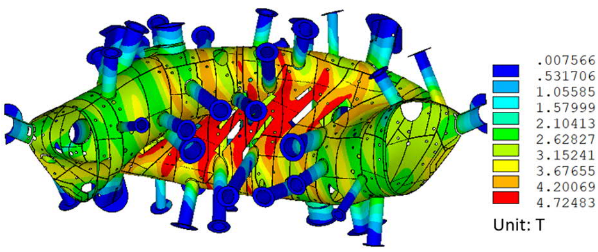

Fig. 6. Magnetic flux intensity in TI panels and tubes.

4.2 EM analyses and results

To cover all possible plasma currents discharge events during W7-X operations, three postulated plasma currents decay scenarios are analyzed with the developed EM model (see Table 2):

Table 2. Plasma currents decay scenarios

Plasma currents and decay time constant	1	2	3
Toroidal, 100 kA @ 1ms	×		×
Diamagnetic, 2.7 MA @ 1 ms		×	×

Due to the strong electromagnetic coupling between the PV and TI panels and the relatively high time constant of the PV (~52 and ~17 ms for toroidal and poloidal eddy currents respectively), the solution for each scenario is performed up to time point of 80 ms with varying time intervals to catch the peak eddy current and to consider steep current changes.

As an example, Fig. 7 and Fig. 8 show the eddy current density and force density distribution in TI panels and tubes at time 5.5 ms of scenario 3. The eddy current and forces in TI tubes are much smaller than the ones in TI panels due to relatively large distance from the plasma. The eddy current tends to be concentrated at the edges / near slits of panels due to skin effect (especially at the beginning of the plasma current decay) and relatively higher magnetic flux derivative for the current loop at the edge. The force density in the TI panels located at the inboard region of the W7-X is much higher than others due to higher eddy currents and B-fields.

Fig. 9 shows the evolution of the summed forces of one representative TI panel and TI tube in local coordinate system. It indicates also that:

1) the forces in the TI tube are much smaller than in the TI panel;
2) the force magnitude in the TI panels is significant;
3) the peak forces in different conducting components could be reached at different time points, which is related to different time constant and complex coupling between components (especially the coupling between the TI panel and the PV).

Additional run has been performed with the optimized EM model for the scenario of the sc current decay to see the design loads on TI supports (as mentioned in Section 1). The comparison of the forces confirms again the load increase factor of ~7 for the plasma current decay scenarios. Therefore, the assessment of the TI structural stability with detailed static and transient mechanical analysis is absolutely necessary.

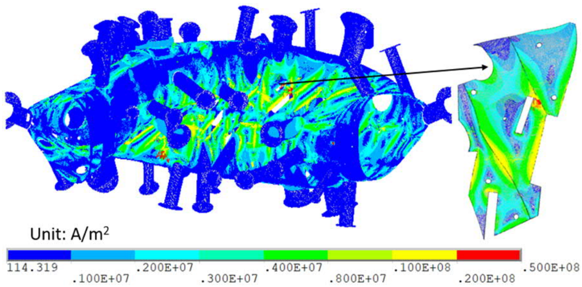

Fig. 7. Eddy current density distribution in TI, from scenario 3 at time 5.5 ms.

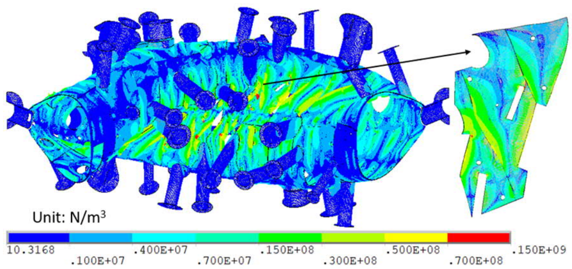

Fig. 8. Force density distribution in TI, from scenario 3 at time 5.5 ms.

4.3 EM forces preparation for mechanical analysis

As mentioned above, the time constant of TI components is varying from location to location, therefore the peak eddy currents / EM forces of different TI panels and tubes are reached at different time points. For the conservative static mechanical analysis, seventeen typical sets of EM forces (at different time points) are selected and extracted for each plasma current decay scenario. The selection is performed on the basis of the maximum summed forces and moments in TI panels and tubes. As a result, static mechanical analyses of ~51 cases are expected to be performed before transient runs. Due to the mesh inconsistency between the EM and mechanical models, the EM forces are to be mapped on the mechanical model through interpolation procedure.

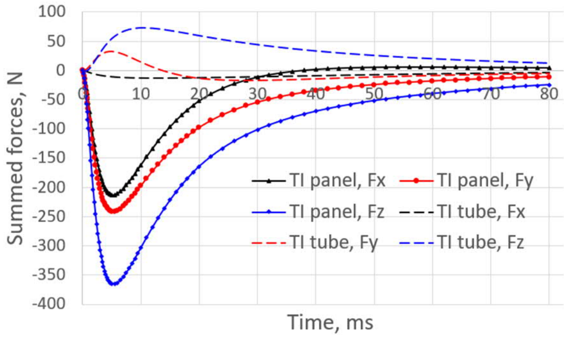

Fig. 9. Summed forces of one TI panel (middle Cu net of panel P30_15, see Fig. 4) and one TI tube (T_AEI30, see Fig. 4) in local coordinate system (with z-axis perpendicular to the panel surface or along the port axis) as an example.

The background field from sc coil currents is considered as constant during plasma currents decay events and it is larger in magnitude than the field generated by plasma currents. For this reason, the EM force in TI tubes and panels under the same plasma currents decay can be analytically evaluated for different magnetic configurations concerned (with different sc coil currents). The corresponding EM forces could be easily calculated by using $\boldsymbol{I}\times\boldsymbol{B}$, where $\boldsymbol{I}$ is the eddy current from the performed plasma currents decay scenarios and $\boldsymbol{B}$ is the B-field obtained by Biot-Savart analysis from sc coil currents. It allows to perform mechanical analysis for different magnetic configurations without another time-consuming transient EM analysis.

4.4 Discussions on further issues

During the EM analysis of the TI, two important issues related to the huge ANSYS EM model (element number over ~20 million) with SOLID 236/237 elements are found and to be mentioned:

1). With asymmetric matrix (keyopt (2) = 0) and direct solver, the required memory is increased drastically as the model size (in terms of number of elements) increases. Typically, the optimal TI EM model requires RAM of about 1664 GB. However, with symmetric matrix (keyopt (2) = 2), the requirement is moderate (only 270 GB RAM is required) and the results are unchanged for the presented analysis case without ferromagnetic materials. The known drawback is that the VOLT DOF is formulated as a time integrated one. However, it is not relevant for the purpose of the analysis.

2). The tree gauging procedure for SOLID 236/237 elements becomes imperfect for huge EM models and introduces some inaccuracies. Although the inaccuracies could be partially mitigated by elements renumbering as mentioned in Section 3, few TI panels has some irrational distribution of eddy currents such as small concentration of eddy current in some region. Such imperfections of eddy currents appear only at the beginning of the plasma current decay and the overall eddy current evolution is not affected. Nevertheless, it is an indication that the tree gauging procedure in ANSYS® is not fully reliable and robust for huge models.

5. Conclusion

The complex EM model comprising superconducting coils, plasma currents, PV, ports, TI panels and tubes has been developed to calculate the eddy currents in TI components during fast plasma current decay events. The model has been refined and optimized to deliver results with required accuracy. The optimization process required a deep study of the B-field and eddy current accuracy in ANSYS®, and the gradual adjusting of the local mesh quality and density to reach the goal. The corresponding EM forces are extracted for further static and transient mechanical analyses. Several issues in respect to the use of ANSYS® SOLID 236/237 elements are found and successfully tackled.

Acknowledgment

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