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Electromagnetic and structural global model of the TF magnet system in ASDEX Upgrade

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HIGHLIGHTS

- An electromagnetic and structural FE 3D model is set up for ASDEX Upgrade.
- The model is benchmarked against the old design results, present displacement measurements.
- The benchmarked model is applied to the present plasma configurations, which have a different poloidal field distribution with respect to the design case.
- The different poloidal field influences the out-of-plane force distribution, thus requiring an update of the TF safety system.

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ABSTRACT

The enhancements carried out in the tokamak ASDEX Upgrade (AUG) are oriented toward the preparation of the future physics-related activities of ITER and DEMO. To address the main ITER issues, plasma configurations with a wider operational limit (e.g. higher triangularity) are planned for the future experimental campaigns in AUG. To evaluate the mechanical impact on the toroidal field (TF) magnet system a combined electromagnetic and structural finite element model was set up.

At first extensive benchmarks of the models are carried out against the AUG reference design configurations with respect to stress [1–3], lateral displacement measurements and poloidal flux pattern. The numerical model was then applied to a set of actual high triangularity (HT) configurations generated by a more favorable poloidal field (PF) current distribution made possible by an extension of the power supply system. The resulting change of the poloidal flux pattern and the lateral force distribution has consequences for the coil shear stress and vault stability. Both aspects are monitored by a safety system measuring the PF flux placed on top and bottom of the outer surface of two TF coils (TFCs) between vault and the TFC supporting structure, so called Turn Over Structure (TOS). The range of the new HT configurations has induced a modification of the flux pattern, so that an adaptation of safety system is required to protect the TFCs system. Following the same criteria of the old safety system [4,5], a new set up of virtual coils will be integrated in the control system of AUG. The motivation of this new set up will be discussed in this paper.

1. Introduction

This paper illustrates the numerical analyses carried out to verify the load carrying capability of the toroidal field (TF) magnet system in ASDEX Upgrade (AUG).

The main purpose of these analyses is to demonstrate that the TF coil (TFC) mechanical components are able to withstand the loads induced by the high triangularity configurations which are planned for the near future of the exploitation of AUG.

The analysis has been carried out using the commercial finite element (FE) code ANSYS. A preliminary static electromagnetic (EM) calculation is performed to compute precisely the in-plane and out-of plane forces acting on the TFC during the AUG operational scenario. The outcome from this EM analysis is the distribution of EM forces per unit of length exerted on the TFC. These information are then used to load the magnet in the framework of the structural analyses.

A benchmark of the FE structural model against the design parameters has been carried out: an extensive comparison in terms of design forces, stresses and deformations [1–3] has been made and critically analyzed. In a second step, thanks to the diverse diagnostics which are monitoring the TFC behavior, a benchmark against the coil displacements has been done to demonstrate the reliability of the FE model.

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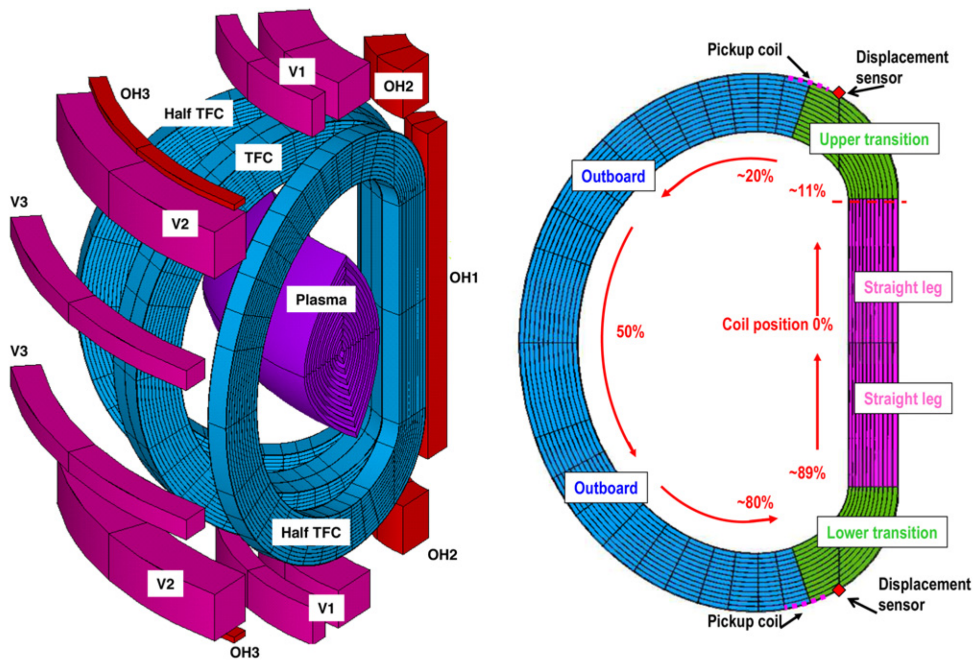

Fig. 1. On the left hand side overview of the AUG EM model: all the coils of 2 AUG sectors are illustrated. On the right hand detailed view of the TFC magnet: to include the ensuing force distributions, the route along the TFC profile is indicated. On the same TFC profile the positions of the displacement sensors and of the pickup coils are pointed out.

Finally, in the benchmarked model, an improvement of the safety system has been proposed according to the change of the poloidal field pattern.

2. Basic design information

During normal operating conditions, the TF magnet system has to withstand the EM loads arising from the interaction of its current conductors with both the toroidal and poloidal fields. The interaction with the toroidal field gives rise to the force distribution acting in the plane of the each coil. Due to the "constant tension" coil shape the turns are mainly loaded by circumferential stresses. This means that in any coil cross section there is no bending stress component due to energization of the TFC. The straight legs of all 16 coils form a vault to balance the centering force resulting from the pressure component. The centering force per coil has a maximum value of about 16 MN (B_o = 3.9 T). The poloidal field, required for balancing and shaping the plasma, gives rise to an out of plane load component due to the interaction with the TF magnet current. This load does not produce a net moment around the vertical axis of the machine center but tries to twist each TFC and to turn it around the radial-axis. A stiff stainless steel structure, the so called Turn Over Structure – TOS, counteracts mainly the out-of-plane forces. The latter consists of 8 big casings flanged in the mid plane and 8 small casings flanged laterally with the adjacent big casings. More details on the TF magnet system and its supporting structure are available in [1–3].

3. Modeling

The symmetry of the TFCs supporting structure calls for a FE model is made of two AUG sectors. The EM model consists of the poloidal field coils (PFCs), the plasma, a complete TFC and two half TFCs (see Fig. 1). The TFC consists of 2 pancakes (2 × 12 turns), which are individually modeled as conductors electrically insulated. The plasma is represented with a concentric series of ring coils with an appropriate shape and current. The scalar potential formulation is used for the static EM analyses. The coils are fed in current as function of the simulated scenario. Cyclic symmetry conditions are applied on the boundaries of the model. The resulting force distributions are then applied to the corresponding TFCs structural model. The transfer of EM forces is accomplished in a node-to-node fashion, without any numerical rework of the obtained magnetic force vector components. This ensures good accuracy of the force field used in the structural calculation.

In Fig. 2 the structural model is depicted. Besides the TFCs structure, the model consists of one big and one small casing of the TOS. The TFC interfaces have been meshed using the ANSYS technology contact elements. Such interfaces are at: (1) the vault epoxy bladders between adjacent TFCs; (2) the lateral epoxy bladders placed in the outboard between TFC and TOS and (3) the frictional weight support pad on the bottom of the coils, sliding on the TOS during ramp-up.

These interfaces are modeled by a surface-to-surface contact pair, taking into account the respective friction coefficients. Thermal effects are not considered in these analyses.

4. Comparison with the reference case

The reference case is the scenario originally used for designing the TFCs. Each plasma configuration has one reference case. In this work only the single null (SN) configuration will be considered as reference case. The current coils describing this reference configuration are reported in [2].

It is worth mentioning that, with respect to the configurations used at the time of the TFC design, nowadays additional PF coils, the OH2 coils, are used to improve the plasma shaping.

4.1. In-plane forces

From of the EM model, a total centering force of 16 MN per each TFC is obtained. In the design phase, the estimation for this force was equal to 15.7 MN. In Fig. 3 the average in plane forces per unit length (MN/m) along the TFC profile are shown. For ease of