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Implementation of ferritic steel as in vessel wall: Lessons learnt and follow up

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ABSTRACT

ASDEX Upgrade (AUG) is the only tokamak in Europe to have low activation ferritic steel as the inner vessel wall facing component. Together with the massive tungsten tiles in the lower divertor, AUG is the tokamak with the closest DEMO wall. The project is a first step towards the extensive use of ferritic steel in future fusion reactors. For example, the test blanket module of ITER is planned to have a ferritic steel wall and thick tungsten tiles as a plasma facing component.

The 'ad hoc' ferritic steel built with low activation capability is known as Eurofer. As the low activation property is not a requirement for AUG, the material selected for the project is the martensitic steel P92 which is the most similar material to Eurofer from a magnetic point of view. The purpose of the project is to improve understanding of the magnetic perturbation of the ferritic steel both on the plasma and magnetic probes, evaluating and controlling these effects. Additionally, the effect of the additional forces on the supporting structure has been addressed.

Bearing this in mind, in 2013 a step wise program has been started and part of the W coated graphite tiles in the region of the inner column were replaced by steel tiles [1]. The first campaign did not suffer any particular issue related to the new material. According to the calculations, the plasma was almost unperturbed, thanks also to the toroidal symmetry of the tiles inside the vessel, and the magnetic probe measurements were properly corrected [2].

Inspection of the machine pointed out some hardware problems. The graphite tiles adjacent to the steel tiles were damaged. The graphite tiles had broken edges in 5 from 64 positions and notches in many others. The coating of the graphite and steel tiles, made of tungsten and TiO respectively, was damaged. At first glance it was clear that the steel tiles were moving but it was definitely unexpected. In understanding the process, the location of the damage was the crucial hint. In fact all failures were located at the boundary between 2 vacuum vessel octants. To justify this failure mode inside the vessel, a hypothesis (about current flowing in the heat shield supporting structure) was made and FEM analyses were carried out in this direction. With extreme caution, in 2015 just one additional row of steel tiles was added together with diagnostics that confirmed the hypothesis. Now that a clear understanding of the problem has been reached, the project to add further rows of steel tiles can be continued. For the next campaign it is planned to replace all the tiles in the middle region of the heat shield together with stiffening and modification of the supporting structure.

In this paper the learning process from the damage of the tiles and its causes, from the FEM analysis results to the data diagnostics will be reported. The future plans for steel tiles in AUG will be discussed.

1. Introduction

Since 2013, ASDEX Upgrade (AUG) has been equipped with ferromagnetic steel as a plasma facing component [1]. The ferromagnetic material closest to Eurofer is P92 steel. Tiles of this material have replaced the graphite tiles mounted on the inner column of the vacuum vessel, so called heat shield (HS). A stepwise approach was followed in order to reduce the risk of unexpected behaviour. The first step of this upgrade was the replacement of 2 graphite tile rows with P92 and this is already described in [1]. In the same paper calculations of the additional load and the characterization of the material are given.

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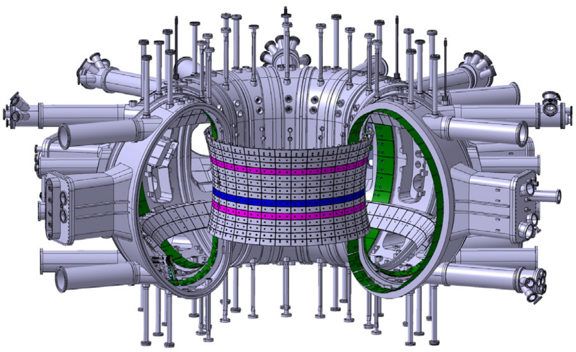

Fig. 1. AUG overview of the inner vessel setup: the ferromagnetic tiles installed first are highlighted in pink. In blue is the middle steel row placed in 2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

One experimental campaign with more than 1700 shots was conducted and the whole campaign did not suffer any issues related to the steel tiles. The magnetic perturbations caused by the tiles were correctly simulated as described in [2]. The influence on the plasma was almost negligible, as predicted by the calculation. At the end of 2015 the HS was inspected and damage at the graphite tiles adjacent to the steel tiles and of the steel tiles itself were observed. After careful estimation of the damages configuration, it was clear that the steel tiles were not responsible of these damages or at least not directly. In 2015 an additional steel row was implemented alternating P92 and Eurofer tiles allowing a direct comparison between the two materials. In addition new diagnostics were installed to test the hypothesis that induced currents in the structure were responsible of the damages. In Fig. 1 the layout of the AUG HS is shown: the 2 rows in pink refer to the configuration of 2014/2015 and the blue row installed at beginning of 2016.

All the steel tiles, together with their contiguous graphite tiles, have been redesign with a labyrinth feature (e.g. in Fig. 2) in order to reduce the ECRH stray field [3].

This paper reports on the experience gained with P92 tiles. In Section 2, the findings of the inspection carried out on 2015 are given. In Section 3 the logical path that led us to the hypothesis, together with the FEM analysis is described. Section 4 reports the cautious step forward together with the measures set out to confirm the hypothesis along with experimental results. In Section 5 the further steps planned for the next campaign 2017 are reported. Finally in the last section the results and conclusions are summarized.

2. Layout and inspection outcome

A single HS consists of a structure made of a U-shaped cooling channel on which supporting plates or wings are welded on. The tiles are screwed onto the plates by means of a bolt and spring system.

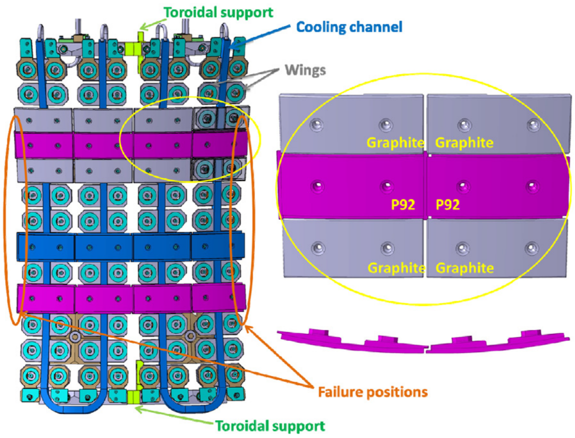

Fig. 2. View of the 2 adjacent HS supporting structures belonging to a VV octant: ferromagnetic tiles installed first are in pink, the row installed in 2015 is in blue. The gray tiles are made of graphite. On the right hand side a detailed view of the tiles set up is shown: a labyrinth feature has been implemented together with the P92 tiles.

The HS supporting structure follows the electrical scheme of the vacuum vessel (VV): this is split in 8 octants which are electrically insulated by means of 8 high resistance bellows. In Fig. 2, two adjacent HS supporting structures belonging to the same octant, therefore sharing the same electrical potential, are shown. Each HS is directly connected to the VV by means of 5 bolts (in Fig. 2 partially covered by the tiles). Adjacent supporting HS structures belonging to the same octant are connected to each other via 2 toroidal supports (in green in Fig. 2) which in turn are connected to the corresponding VV octant.

After the first campaign with the 2 steel rows, the inspection of the in vessel components disclosed some unexpected damage of the HS tiles. In particular, some steel tiles exhibited a coating failure as clear indication of a possible contact against the adjacent tiles. Some of them were burned along their poloidal edges. These damages are shown in Fig. 3. Some of these steel tiles also had melted areas in the sectors placed opposite to Neutral Beam Injectors. The striking findings were observed on the graphite tiles adjacent to the P92 tiles. In many locations, the graphite tiles showed notches and in 5 positions their edges were broken (e.g. in Fig. 4).

3. Hypothesis and precautions

At first, our thoughts were completely focused on the new material. A deep examination of the damage configuration revealed that the HS supporting structure was moving inside AUG. In fact, the above mentioned damages were all placed between 2 VV octants (orange regions in Fig. 2). Broadening our view, it was assumed that during a disruption with plasma displacement, the variation of the radial field could induce a current flowing in 2 adjacent HS supporting structures.

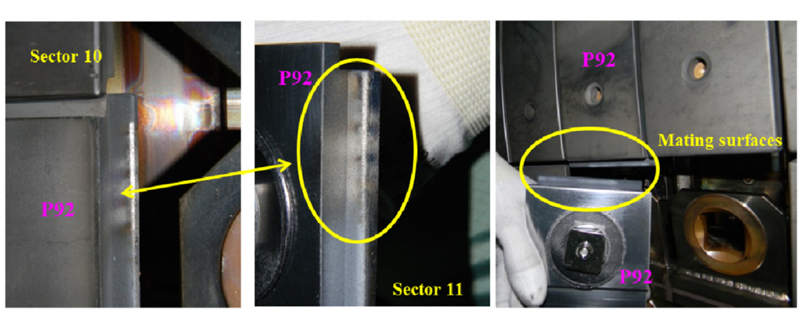

Fig. 3. Damages on the P92 tiles in AUG: on the left hand side are shown the arc damages and on the right hand side the mating contact surface between tiles.

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