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

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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.

Keywords: reduced activation ferritic/martensitic steel, Eurofer, P92, DEMO wall.

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.

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 Figure 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.

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All the steel tiles, together with their contiguous graphite tiles, have been redesign with a labyrinth feature (e.g. in Figure 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. 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 Figure 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 Figure 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 Figure 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 Figure 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 Figure 4).

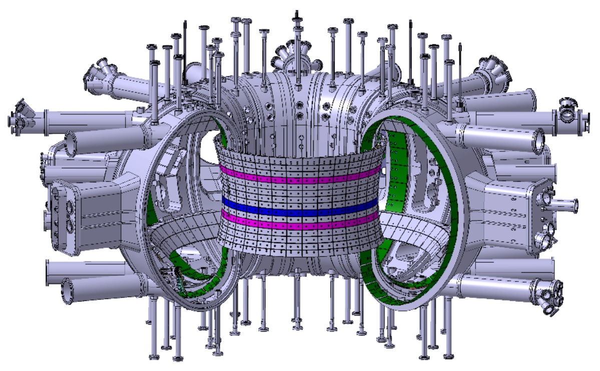

Figure 1 AUG overview of the inner vessel setup: the ferromagnetic tiles installed first are highlighted in pink. In blue is the middle steel row placed in 2015.

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 Figure 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.

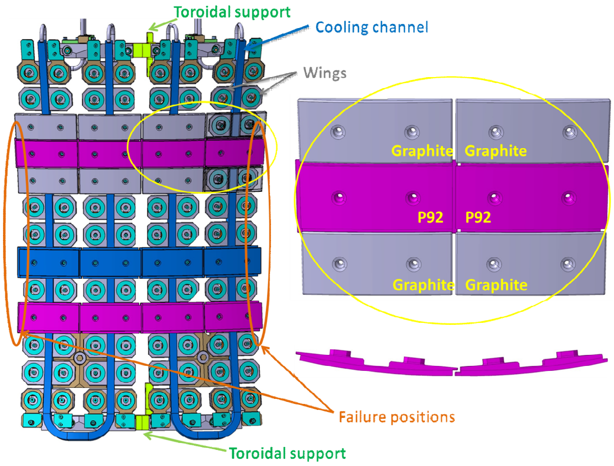

Figure 2 View of the 2 adjacent HS supporting structures belonging to a VV octant: ferromagnetic tiles installed first are in pink, the row installed in 2015 is in blue. The gray tiles are made of graphite. On the right hand side a detailed view of the tiles set up is shown: a labyrinth feature has been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

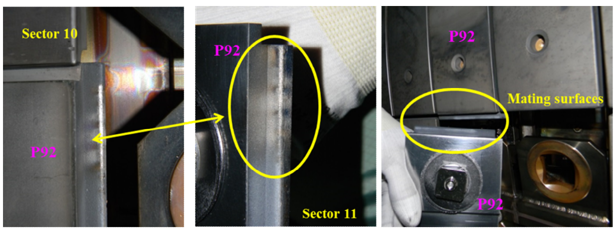

Figure 3 Damages on the P92 tiles in AUG: on the left hand side are shown the arc damages and on the right hand side the mating contact surface between tiles.

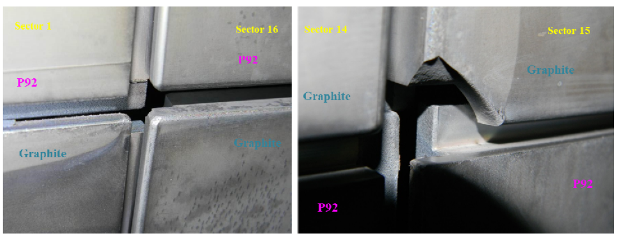

Figure 4 Damages on the graphite tiles adjacent to the P92 tiles in AUG: on the left hand side is shown an example of the notches and on the right hand side a representation of the broken edge of one graphite tile.

To quantify the induced current electromagnetic analyses were carried out. Assuming a uniform variation of the radial field of 50 T/s, the corresponding magnetic vector potential was applied to the structures. The current path in term of density current is illustrated in Figure 5.

Indeed the current passes through the extreme poloidal legs of 2 contiguous HS cooling channel and it crosses the toroidal stiffeners and supports in the upper and lower positions. The calculated induced current is of the order of 7 kA, which for a toroidal magnetic field of 3 T at the plasma center, gives rise to radial forces of the order of 35 kN. These forces are acting on opposite directions into the extreme poloidal legs of the 2 contiguous cooling channels. The 2 forces end up producing a poloidal moment acting on the whole structure which is responsible for its rotation. This moment gives rise to a maximum relative free displacement between the extreme tiles of about 10 mm, as indicated on the right hand side of Figure 5.

Since the labyrinth feature creates an overlap between the adjacent tiles reducing the radial gap to 3 mm, this gap is easily closed during a disruption where a theoretical relative displacement of 10 mm is calculated. The energy introduced in the structure leads to severe and sudden impacts between graphite and steel tiles which caused the damage of the weakest material.

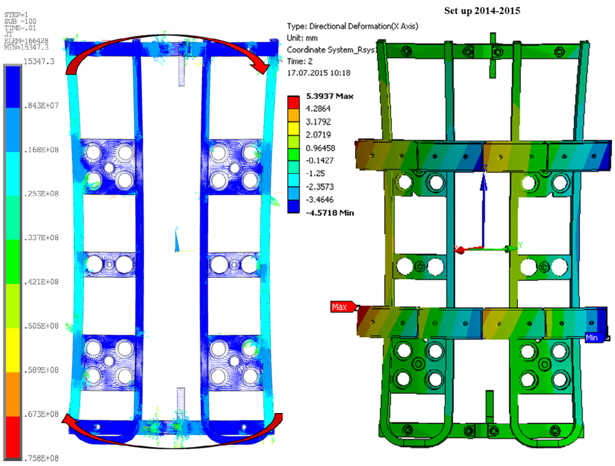

Figure 5 On the left: current density path through the HS structure for a uniform variation of radial field. On the right: corresponding displacement [mm] caused by 35 kN radial forces.

4. Diagnostics set up and results

During the 2015 VV opening, with the utmost caution, just one additional steel row is installed (see blue row in Figure 1). The third row is equipped with alternately P92 and Eurofer. Prior to installation, their magnetic properties were measured to make sure that the two are almost identical from the magnetic point of view (see Figure 6). As expected, during the operation of AUG, no difference between the two materials is remarkable.
To measure the induced current flowing between adjacent HS, a Rogowski coil is installed in the lower toroidal support of one HS structure.

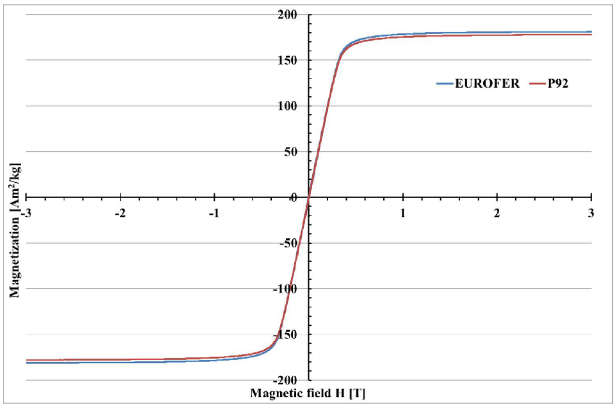

Figure 6 Magnetization curve for Eurofer and P92 in blue and red respectively.

This new diagnostic aimed to confirm the hypothesis of the current loop in the HS support structure. In Figure 7, the measured current for the shot #31899 is reported. In this case the plasma current was quite low and a value of about 4 kA is recorded. A maximum value of 7.5 kA has been measured, perfectly in agreement with the calculations.

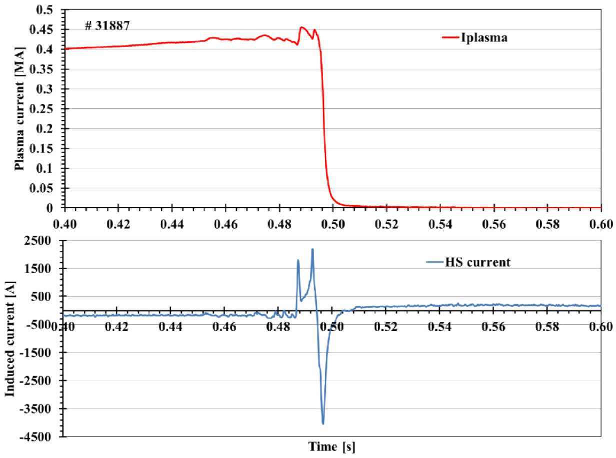

Figure 7 Induced current in the HS measured by the Rogowski coil for the shot # 31887: in correspondence of the plasma current disruption the current in the frame support increases.

Being aware of the problem caused by the HS movement, a fast infrared camera [4] from time to time was pointing to the inner column. In Figure 8, two freeze frames of a video are reported. Comparing the position of the HS in still condition on the top, and during a disruption, on the bottom, a displacement can be observed in the region between the green lines.
A better understanding of the sudden movement of the HS is given unambiguously by the video footage. The sudden movement of the HS provokes the collision between adjacent tiles leading to the rupture of the graphite.

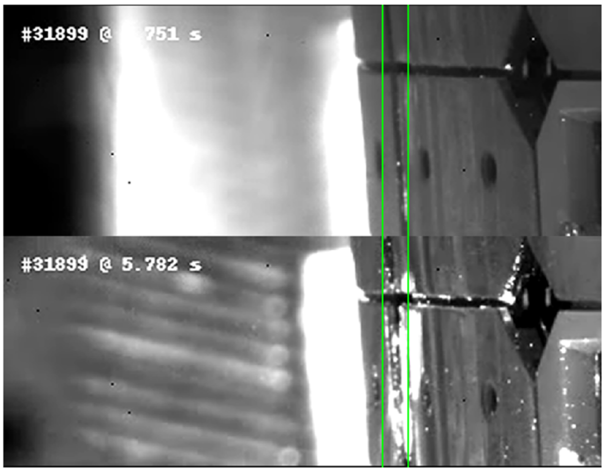

Figure 8 Infrared camera view of the HS for the shot # 31899: comparison between still condition on the top and in movement on the bottom. The green lines are limiting the displaced regions of the tiles.

5. Further developments

Having clarified the problem, the HS ferritic steel project can move on to extending the use of steel as plasma facing component. In particular, the rows between the preexisting steel tiles will be all made of P92, for a total of 7 rows. Some modifications of the design are required, as indicated in Figure 9.

To reduce the induced current in the HS frame an electrical insulation will provide the separation of current path between the 2 adjacent supporting frames. In Figure 9 the insulated bolt connections are indicated in pink. The insulation is made with silicon nitride already used in other components inside AUG. With this precaution, the induced current will flow just on a single frame and the current should be reduced to a calculated value of 2.5 kA. Reducing the current means a reduction of the forces and therefore a decrease of the relative displacement of the tiles.

Nevertheless a stiffening of the supporting structure is required in order to cope with the additional electromagnetic forces arising in the ferromagnetic tiles: green wings in Figure 9 are welded together.

With the new set up, a relative tile movement less than 1 mm is expected, which would avoid the collision between tiles. A qualification of the welding process has been carried out to verify that the deformation given by the process would remain within acceptable limits. The reinforcement of the HS with welding is still ongoing, but most of the structures are already available for installation.

6. Conclusion and summary

The upgrade of the inner column with ferritic steel tiles was conceived as a learning project. We learnt how to deal with ferromagnetic material in terms of forces, how the plasma responds to this material and how to correct the magnetic probe measurements. In addition, we learnt that FEM analysis is a powerful means to predict quantitatively and qualitatively the currents flowing through structures.

The HS has been moving since it was installed, but the consequences of such sudden displacements were recognized only after the introduction of the labyrinth feature in the HS tiles. This came in conjunction with the introduction of the ferritic steel tiles and so made it difficult to identify the problem.

The ferritic steel tiles project started in 2014. After one campaign, broken graphite tiles edges slowed the replacement of further graphite tiles with steel. Now that the underlying reason has been understood, the upgrade of the inner column can continue for the next campaign. In 2017 all the remaining graphite rows between rows 4 and 10 will be replaced with P92.

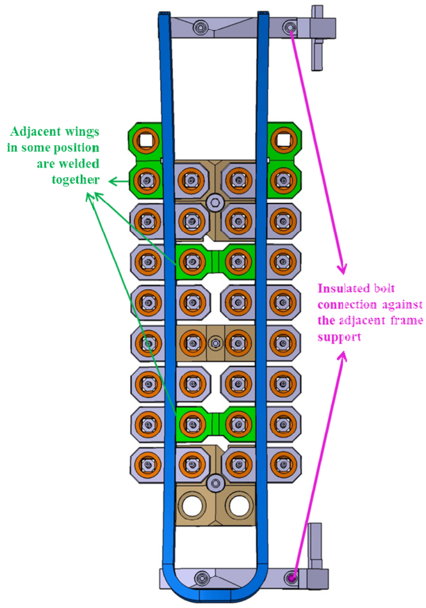

Figure 9 Modifications to the HS supporting structure are highlighted: in green welding between adjacent wings and in pink the electrical insulation between adjacent HS.

Further developments for improving this concept are planned. The investigation of surface modifications and the introduction of a tungsten coating on steel in order to increase the surface melting temperature will be the two main points.

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