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Observation of tungsten plasma-facing components after the first phase of operation of the WEST tokamak

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Turning Tore Supra into the WEST configuration has been achieved through the development of new plasma-facing components (PFCs) with tungsten surfaces in order to provide a full tungsten environment, as foreseen for future fusion devices. In this framework, tungsten-coated PFCs were developed and qualified according to well-defined specifications, including fatigue tests under high heat flux density up to 10 MW/m². In 2016, both divertors, baffle and limiters PFCs with W coatings were manufactured and installed in WEST [1]. Additionally, a set of actively cooled ITER-like plasma-facing units (PFU) made of bulk tungsten (W) was installed in one of the 12 sectors of the lower divertor to test the ITER tungsten monoblock technology in a real tokamak environment [2].

In total, four experimental campaigns (C1 to C4) were conducted between 2017 and the end of 2019 in the WEST tokamak. This paper aims at giving an overview of the PFCs ageing during this first two years of operation. The main results of the in-situ inspections carried out after each campaign of WEST, as well as intermediate inspections using the robotic articulated inspection arm (AIA) are presented here.

The C1/C2 campaign was devoted to developing plasma scenario and plasma control in the new full tungsten configuration of WEST. In particular, the first discharges performed were prone to runaway electrons, requiring a specific control scheme to be worked out, which was successfully established by the end of the campaign. Although the plasma exposure time was modest (~25 min), off normal events and/or disruptions have provoked localized damages on the upper divertor and the outer limiter. In particular, a number of W-coated carbon tiles of the outer limiter needed to be replaced after the C2 campaign.

Less damages due to off-normal events were observed after the C3 campaign (2018), although the heat loads on the components and the plasma operation time were significantly higher (~ 2 hours of plasma exposure, ~1000 transients, L mode operation with peak heat flux on the lower divertor up to 2.5 MW/m2). In total, 12 ITER like PFUs were installed in WEST during C3, provided by a number of potential ITER divertor suppliers. Some of them had chamfered poloidal edges while others had unchamfered (sharp) edges.
Microscopic observations carried out after the campaign revealed they suffered damages on poloidal edges, such as local melting and cracks formation. The damages were more severe for PFUs installed on the sector with a significant relative misalignment, for which poloidal leading edges were irradiated at near perpendicular incidence by the heat flux (measured misalignment up to 0.8 mm, to be compared with ITER specifications of 0.3 mm).
In addition, infrared images obtained during a disruption clearly showed local heat flux deposition on isolated points of the leading edges of PFUs, as the result of penetration of charged particles into the toroidal gaps. The formation of these so-called optical hot spots were found on both chamfered and non-chamfered PFUs, as well as for PFUs misaligned and aligned within the specifications. They were evidenced experimentally for the first time in a tokamak environment, confirming the modelling predictions developed for ITER [3].
During the C3 campaign, boronization was used for the first time and first significant operation was performed on the upper divertor. The plasma footprint was clearly observed both on the upper and lower divertor.

During the C4 campaign, both deuterium (D) and helium (He) operation were performed, with a significantly higher power coupled to the plasma (~2.5 hours of plasma exposure, including 45 mn in He, ~1000 transients, L mode operation with peak heat flux on the lower divertor up to 5 MW/m2). Boronizations were run on a weekly basis.
Two additional PFUs were installed on the lower divertor test sector, leading to a total number of 14 ITER-like PFUs during C4. With the help of optical metrology, the PFUs were realigned in order to respect ITER relative alignment specifications and to decrease the direct exposure of their poloidal edges.
First results of the PFUs observation show the formation of microscopic cracks on the poloidal edges of the two new PFUs in the outer strike point region. In addition, newly-formed optical hot spots could be seen on the PFUs, which confirms that adequate assembly procedures cannot eliminate the risk of OHS formation, even though they were not detrimental to the WEST operation.
The W coated tiles of the outer limiter were replaced by bulk W tiles, in order to better cope with runaway electrons and prepare for long pulse operation. No surface modification or melting was observed on the new bulk W tiles after C4.

To conclude, in-situ inspections and preliminary post mortem analysis revealed no major structural damages over the whole phase I operation of WEST, despite the fact that the PFCs were exposed to the plasma for about 6h in total. A more detailed analysis will now be performed to assess changes in the tungsten material properties and its microstructure, in particular to understand the impact of helium operation and boronization. WEST phase II will start at the end of 2020 with an actively-cooled, full tungsten divertor while inner limiter W coated CFC tiles will be replaced by bulk tungsten tiles.

[1] M. Firdaouss et al., Fusion Engineering and Design 124 (2017) 207-210
[2] J. Bucalossi et al., Fusion Eng. Des. 89 (2014) 907-912
[3] J.P. Gunn et al., Nucl. Fusion 57 (2017) 046025

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