WEST advanced wall protection achievements toward long pulse operation

R. Mitteau[1*], **M.H. Aumeunier**[1], **L. Dubus**[1], **J. Gerardin**[1], **V. Gorse**[1], **E. Grelier**[1], **V. Moncada**[1], **S.Vives**[1], **M. Jakubowski**[2,3], **J. Fellinger**[2], **X. Litaudon**[1,3] and the **WEST Team**[4]

[1] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[2] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
[3] EUROfusion, Germany
[4]See http://west.cea.fr/WESTteam
* Corresponding author, raphael.mitteau@cea.fr

Long pulse operation in magnetic fusion devices requires well controlled plasma power exhaust to the divertor & wall. The thermal energy leaving the plasma is distributed to the divertor and main wall. Any deviation to the carefully engineered power exhaust scheme results in wall hot spots and possible damage to the internal components, an effect being exacerbated by plasma duration.

At WEST, 8 major internal components (lower and upper divertor, baffle, inner and outer guard limiters, Lower Hybrid –LH- and ion cyclotron heating antennae, ripple dump plates) are monitored using 10 series of temperature/power indicators, largely based on the image stream from the InfraRed (IR) viewing system [1]. These indicators span from the most basic ones (temperatures, power and energy from deterministic models) to advanced processes using neural networks and machine learning techniques [2]. Some processes operate in Real Time (RT) and feedback on actuators through the Plasma Control System (PCS), providing active strategies toward remaining within the operational domain [3]. Other processes intervene post discharge as forensic tools to identify possible evolution of the wall and divertor under power loading. They are used for the preparation of the following discharge.

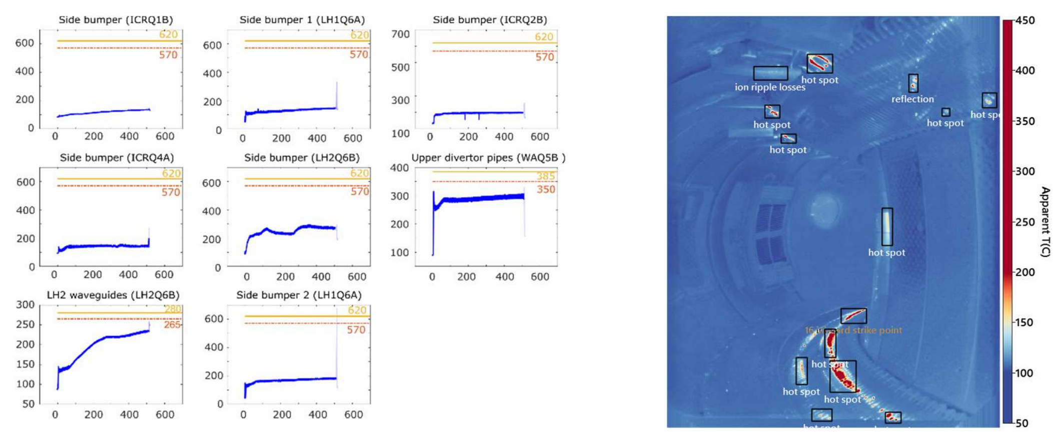

Fig. 1 Left (a): temperature plots of monitored regions of interest that define the operational domain of the LH antenna LH2 during #60738. The disruption data has been shaded. Right (b) : A tangential line of sight in WEST during discharge #60223, showing wall temperatures up to 500°C, and automatic detection of thermal events, outlined with the black boxes.

This paper focusses on the 7 advanced wall protection processes that either rely on machine learning techniques, or cross diagnostics data merging : the thermal event detector, the divertor strike-lines descriptor; the LH heating system arc detector, the Runaway Electrons detector (REs), the UFO detector (Unidentified Flying Objects), the post discharge automatic expert assessment of the wall thermal response, and the RT estimation of heat flux to the divertor from RT power balance.

During the experimental campaign C9 (Jan-Apr 2024), the availability of the wall protection is of 94.1 %. 15.6 % of the discharges entered the active control region, meaning that automatic wall protection measures were activated. Only 1 discharge out of 1389 is lost as a result of the hard wired wall protection system, while no automatic feedback control operated, showing a >99.9% reliability of the wall protection system.

Specific detectors are added to the wall protection system in 2024 : the LH arc detector, the REs and UFO detectors. All these methods are based on convolutional neural networks and are implemented on dedicated computers equipped with graphical processor units (GPUs). Parallel processing is enabled by storing the RT image stream in a shared memory, making it available to all processes. The detectors are trained on annotated image databases.

These developments of advanced wall protection processes are done in an international framework, mainly through EUFOfusion agreements. Thermal events formats (instances, categories, annotations) are developed jointly with IPP-W7X [4]. Most data workflows used in both institutes use common libraries. These formats and frameworks are also accessible to other possible users, through a policy of open source software developments [5]. Data privacy and security is enabled by proprietary front-end layers. Further compatibility with ITER and the IMAS data storage architecture is pursued with EUROfusion [6]. The ability to share data and knowledge is viewed as crucial, because cross-machine diversity is key to obtain high-performance models.

The LH arc detector is currently the most mature. It aims at detecting arcs at the waveguides of the LH1 launcher. IR images are a relevant footprint of arcs, better than the copper signal or the antenna reflection coefficient. Despite its long cycle time (20 ms), an image-based detector is viewed as the most effective to mitigate arcs as they occur. The detector is operating on the image stream, and communicates the possible presence of arcs to the PCS. 53 arcs were detected during C10 (Nov-Dec 2024), with only one false positive.

During the experimental campaign C10, all wall protection processes are active. Campaign C10 includes a long pulse program with several record discharges of 824 s (1.93 GJ), 514 s and 461 s. Fig. 1.a illustrates the temperature history of 8 key control regions (in blue) that may trim LH2 power during the 514s discharge. The active control bands are plotted in orange and red lines. The hottest actively cooled regions are maintained below 300°C over 514 s.

In the control room, an ergonomic dashboard gives fast access to the most notable wall thermal events having occurred during the previous discharge. A human expert assesses the thermal behaviour of components within minutes, before the preparation of the next discharge. The work is now assisted by an intelligent assistant able to communicate in natural language. It uses a Large Language Model (LLM), fine-tuned using previous WEST expert analyses of the wall behaviour. The human expert satisfaction regarding this LLM is currently of 62%, which is a promising performance. The LLM is being further improved by training with the aim of supplementing the post discharge human assessment of wall thermal behaviour during future campaigns.

No critical wall power event happened during C10. While it cannot be demonstrated that active wall protection enabled the new plasma records, it is bound that the active wall protection as a whole helped significantly obtaining these records by preventing wall hot spots to become critical.

References

[1] Nucl. Fusion 65 (2025) 016059
[2] Fus. Eng. Des. 192(2023) 113636
[3] Fus. Eng. Des. 165 (2021) 112223
[4] Rev.Sci. Instrum. 2018 89(10)10E116
[5] https://github.com/IRFM/thermavip
[6] Nucl. Fusion 64 (2024) 112006