OVERVIEW OF WEST CONTRIBUTIONS TO THE NEW ITER BASELINE AND FUSION POWER PLANTS

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In the context of the new ITER baseline, the WEST programme has recently enhanced its efforts in supporting the goal of a robust start of the ITER scientific exploitation. The WEST super-conducting tokamak is a full tungsten wall long pulse device equipped with an actively cooled ITER grade divertor [1]. As such, it is best placed to address scientific and operational issues relevant to next step devices with a full tungsten (W) environment. For this purpose, WEST has developed reliable, routine and controlled long pulse regimes with durations now reaching 1337s with 2.6GJ of injected energy and exposed its actively cooled tungsten (W) divertor mono-blocks (MB) to heat flux up to $11MW/m^2$.

This paper reports on the key achievements of the past two years, namely: i) plasma start-up studies in a full tungsten environment, ii) conditioning by boronization mimicking the ITER set-up and the impact of boron on plasma performance and fuel retention, iii) the progress in X-point Radiator (XPR) controlled detached regime, iv) 3D tungsten sources analysis, and v) the comprehensive testing of W divertor elements when exposed to high power and particle flux thanks to the long pulse capabilities.

Recently WEST has achieved a record pulse length (Fig. 1) in a full tungsten wall featuring good confinement with H_{98y2} close to unity and stationary central electron temperature. Predict-first simulations have been performed using the High Fidelity Plasma Simulator (the European IMAS-coupled version of JINTRAC) for the first time and have been applied to determine the operational domain and design scenarios to access pulses exceeding 1000s duration [2]. Technically, long pulse operation was also made possible by improving the availability of the tokamak and all subsystems [3] and advanced wall protection processes relying on either machine learning techniques or cross diagnostics data merging [4]. When running repetitive long pulses an increasing number of radiative events is observed, becoming significant once the cumulated injected energy reached ~20GJ [5]. These radiative events are related to loose flakes ejected from the redeposited layers near the inner strike points on the divertor target. A new laser cleaning technique has been successfully developed to remove these deposits during a vessel vent.

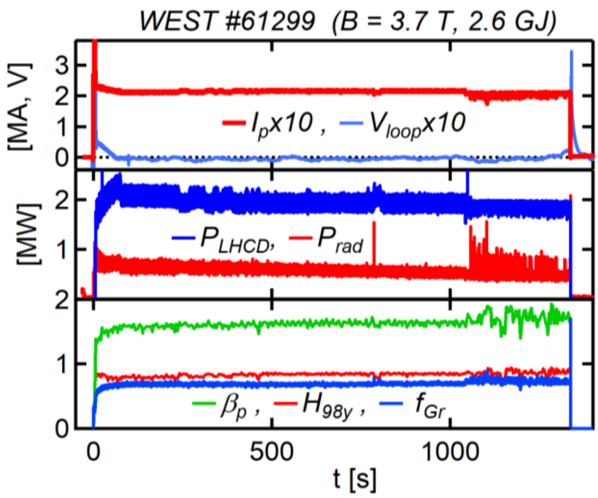

Figure 1: Long pulse of 1337s and 2.61GJ of injected energy achieved in WEST in 2025.

Plasma start-up experiments have been carried out on newly installed inner wall tungsten tiles without and then after boronization [6], confirming that boronization is essential for efficient plasma start-up. Fuel retention after boronization shows an increase lasting less than a couple of pulses compared to pre-boronization cases [7]. Toroidally non-uniform boronization is investigated and modelled since ITER will have a non-uniform toroidal distribution of the glow anodes. In addition, the effectiveness of Boron particulates on the discharge properties (confinement, impurity transport etc.) has been analyzed [8] using the injection of boron with the Impurity Powder Dropper (IPD). First Ion Cyclotron Wall Conditioning (ICWC) experiment has also taken place as an alternative conditioning method for ITER.

The study of exhaust physics with the long pulse X point radiator regime has been extended to different plasma magnetic configurations (double null and upper/lower single null) and interpreted by SOLEDGE modelling in view of assessing its potential use in future devices [9] (Fig 2). This modelling gives encouraging results as the so-called “Te cliff” and XPR like radiative patterns are obtained consistently in simulations. Integrated modelling of core conditions suggest that the experimental improvement of confinement (Te +20% and Ti +35%) during seeding and XPR is a combined result of mitigated core tungsten contamination (taming of divertor tungsten sources) and core dilution effects from nitrogen ions. Ongoing modelling and experiments aim at investigating the role of main chamber tungsten sources during seeding.

For predicting H-mode transition, edge turbulence is analysed by SOLEDGE now including electromagnetic effects [10]. Also, in view of integrated edge-wall modelling, it has been further improved to include detailed 3D magnetic complex geometries such as magnetic ripple and reduced model of tungsten erosion and sheath re-deposition has been introduced [11] and compared with ERO2.0.

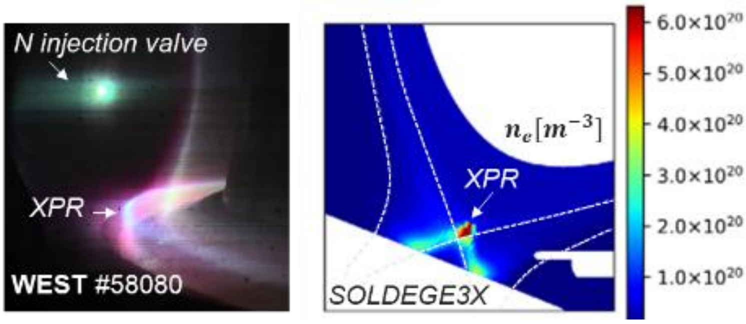

Figure 2: Camera image of XPR WEST pulse #58080 (left) and SOLEDGE modeling showing a transient rise of density at the X-point (right).

The evolution of the ITER grade divertor was monitored under steady state heat fluxes up to 11 MW/m^2 on the top surface (nominal ITER conditions) and particle fluence reaching a total in excess of 10^{27} D/m^2 at the outer strike point (corresponding to a few ITER pulses). Several shaping options, sharp or chamfered leading edge, unshaped or shaped mono-blocks (MBs) with a toroidal bevel as foreseen for ITER were investigated. On beveled MB, cracks networks were observed on the top surface in the outer strike point area after the first WEST high particle fluence campaign [12]. However, no cracks were observed on the protected leading edge (Fig 3), in contrast to non beveled MB [13]. Post-mortem and numerical analysis with the T-REX code [14] are made to determine the dominant failure mechanism. Also, most important for ITER, the impact of runaway electrons (RE) on WEST tungsten tiles has been characterized using radioactivity signature [15] and modelled using RE-induced brittle failure workflow.

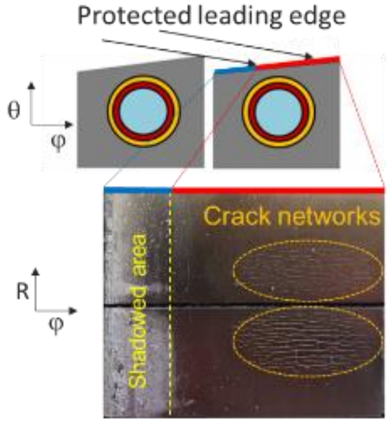

Figure 3: Crack networks observed on the WEST divertor outer strike point on mono-blocks with toroidal bevel.

Erosion of bulk W ITER-grade divertor components was compared with previously used W-coated graphite tiles [16]. For equivalent plasma duration (5h of plasma exposure), they both follow the same erosion pattern. A tungsten net erosion in a range of 5-10 µm is observed with post mortem analysis in the strike point areas in both cases, which is in good agreement with recent SOLDEGE/ERO2.0 simulations [17.

Modelling of D/H retention in the WEST divertor was performed with the MHIMS code for a D/H/D changeover experiment [18]. It shows similar exponential decay of the post discharge outgassing compared to experiment. The analysis also indicates that the changeover is an efficient tool to recover hydrogen isotopes in the plasma-exposed near surface, but not enough to reach D trapped deeper in the material.

The ongoing installation of a 3MW Electron Cyclotron Resonant Heating (ECRH) system at frequency 105GHz [19] will expand WEST plasma scenarios and will allow for sustaining H-mode. Integrated modelling confirms that this additional power source can be instrumental in opening the operational space of WEST [2]. Design of an innovative actively cooled ion cyclotron Traveling Wave Array (TWA) system for WEST is on-going [20], aiming at increasing RF coupling, enhancing directivity and lowering electric field at the antenna mouth. These power enhancements will allow long pulse operation at higher performance and heat flux.

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