The X-Point Radiator regime in the WEST tokamak for divertor operation in next step fusion devices

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The divertor of next step fusion devices such as in ITER and DEMO must survive years of quasi-continuous operation, and thus requires the divertor plasma to be cooled and controlled below 5 eV on the target plates, to prevent excessive tungsten erosion and plasma contamination. To anticipate this challenge, an ITER-grade divertor has been deployed in the WEST tokamak [1], and impurity-seeded plasmas were executed to reach such divertor plasma conditions. WEST brings a new angle for those experiments in the tokamak landscape from its full-tungsten and actively cooled environment, which allowed running those pulses over long durations (several tens of seconds), and in different magnetic configurations (Lower Single Null "LSN", Upper Single Null "USN", and Double Null "DN"). Such an operation with real-time control of cold divertor plasma conditions was successfully achieved, in L-mode scenarios. Upon sufficient seeding, the WEST divertor plasma eventually transitions within microseconds into a stable, dense and cold ($n_e \sim$ 8-10 $\times 10^{19}$ m^{-3}, $T_e <$ 3 eV at target) divertor regime featuring an X-Point Radiator (XPR) [2] with mitigated heat loads by factors of ~10, but finite ion flux to the divertor targets. XPR scenarios in WEST have been found to be highly repeatable, real-time controllable, stable over multiple tens of seconds and over a range of density and input power ($\langle n_e \rangle \sim 3 - 4.5$ m^{-2}, $P_{IN} \sim 0.5 - 5$ MW). The possibility of using a simple interferometry signal (line-integrated density, cf. Fig. 1) as a reliable control scheme for such XPR regimes was demonstrated in WEST for the first time, opening new sensor and control perspectives for next step fusion plant where sensor possibilities are limited [3].

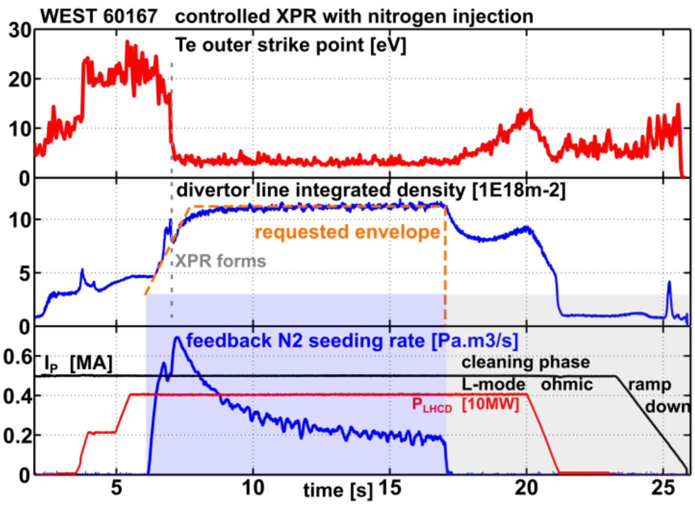

Figure 1 Time traces for WEST pulse #60167 of T_e at the outer strike point from Langmuir probe (top plot), line-integrated density at the X-point from interferometry (middle plot), and plasma current, heating power, and nitrogen seeding rate (bottom plot)

The constructed database of ~100 WEST nitrogen XPR pulses from the operational space exploration allows statistical analyses. In Lower Single Null (LSN) magnetic configuration with $B \times \nabla B$ drift towards the lower divertor ("favourable" configuration), nitrogen seeding induces the following sequence of events: first, the High Field Side (HFS) target plasma turns cold and dense, and a high density radiating region appears there, reminiscent of the so-called "High Field Side High Density (HFSHD) front" as seen in ASDEX-Upgrade [4]. With further seeding, the outer target also becomes cold and this radiating front jumps above the X-point, forming the X-Point Radiator. This re-symmetrisation of targets profiles is also associated with a strong reduction of the poloidal $E \times B$ flows in the SOL as seen from the Doppler Backscattering System (DBS) measurements. Furthermore, attempts to trigger such regimes in USN ("unfavourable" configuration) led first to the appearance of a similar HFSHD front, but instead of transitioning into a stable upper radiative ring, it either leads to a dynamic MARFE moving towards the bottom of the machine (i.e., on the opposite side of the active X-Point), or to a disruption. This highlights the importance of the direction of drift flows in the transition dynamics for such scenarios. Investigations of the main physics mechanisms associated with the onset and stability of the XPR transition are conducted with SOLEDGE3X-EIRENE transport boundary plasma modelling, including the effects of drifts and currents on SOL flows and divertor impurity content estimates from the comparison of synthetic spectroscopy signals with experimental measurements from lines-of-sight going through the divertor (see ex. Fig. 2).

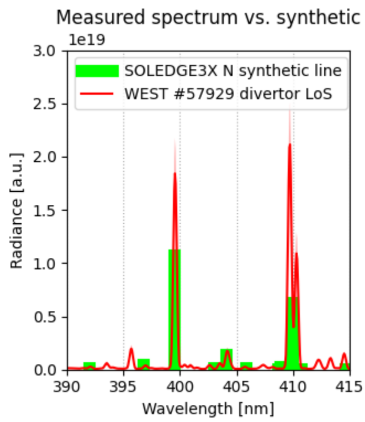

Figure 2: SOLEDGE3X-EIRENE simulation synthetic visible spectroscopy and experimental measurement for nitrogen lines, used for estimations of divertor plasma nitrogen content.

Main chamber midplane SOL profiles, measured from reciprocating Langmuir Probes plunges, are only weakly impacted by the onset of XPR's. As a consequence, Radio-Frequency (RF) heating coupling is preserved, and at the same time, potential plasma-wall interactions at the first wall and antennas and associated tungsten sources are still the same (in contrast to divertor sources which are reduced). Nevertheless, in WEST, core plasma performance improves upon nitrogen injection with significant increases of core confinement (τ_E +25%, from ion dilution effects [5]), central T_e (+20%), and T_i (+35%), and those benefits remain through the transition to the XPR state. Such improvements are concomitant effects of reduced W contamination from tamed divertor sources.

Seeding control on divertor line integrated density passing through the X-Point is a simple yet robust strategy to enter through the abrupt transition (cf. Fig. 1), and stabilize the XPR regime below disruptive limits over long pulses. After the seeding is stopped, the XPR remains in the plasma over a time scale related to the equilibration of the particle balance in WEST (injection/outgassing and pumping: ~5 s), enabling plasma landing with low disruptivity and the control of nitrogen legacy without resorting to post-pulse cleaning schemes. This is the future scenario for high-fluence campaigns at WEST, reproducing ITER divertor particle fluence and investigate residual tungsten erosion and migration in impurity-seeded low-temperature divertor plasmas.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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