Operating near the L-H power threshold in WEST full tungsten environment

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On WEST, in order to test actively cooled ITER-like tungsten divertor tiles during very long pulses, large current drive capabilities are required [1]. For this purpose two lower hybrid current drive (LHCD) launchers, in addition to three ion cyclotron resonance heating (ICRH) antennas, all actively cooled, have been installed and commissioned. The antennas guard limiters are tungsten-coated like the other in-vessel components such as outboard limiters and baffle.

These RF heating and current drive systems do no provide large toroidal torque, neither central particle source. Moreover long discharges with very low loop voltage have low Ware effect. In this context, operation issues with tungsten accumulation are minimized [2, 3].

In the 2019 campaign, the operational domain was extended to higher density (up to $8\times10^{19}m^{-3}$) and additional power. The LH coupled power has reached 4.7MW/3.5s (5.2MW for 1s), the IC power 4.7MW for 1s and the total RF power 8MW for 3s (figure 1). Long pulse operation was also carried out with LHCD (P_{LH}=3MW) extending the pulse length to 55 seconds [4].

1. Plasma radiation and tungsten contamination and sources

On a large database covering a wide range of density ($3\text{-}6\times10^{19}$ m^{-3}) and power (1.5-8MW), the fraction of radiated power in the bulk plasma, Frad-Bulk, was found to be quite constant (~50%) and independent of the heating scheme, LH only or LH+IC (figure 2). After a boronisation of the torus, this fraction can decrease from 50% to less than 30% but Frad-bulk recovers the pre-boronisation value after less than 10 discharges. Following METIS simulation indicating that mid-Z impurities (mostly copper on WEST) contribute by less than 20% of the core radiation (r/a<0.3), it was assumed that the whole radiation is caused by the W atoms. The tungsten concentration was then estimated by inverting the 16 bolometry horizontal chords. This W concentration in the core of the plasma (r/a<0.2) increases linearly with RF power and reaches 4×10^{-4} with 5MW for an electron line-averaged density in the range of 4.0-5.4 $\times10^{19}$ m^{-3}. Although the plasma radiation from IC-only discharges exceeds the one of LH-only discharges by ~15%, the W source, estimated from a set of lines-of-sight of the visible spectroscopy diagnostic viewing the guard limiters of two LH and one IC antennas, was found to be much stronger for the IC antenna. This indicates that the antenna sources are not the sole W sources contributing significantly to the plasma contamination [5].

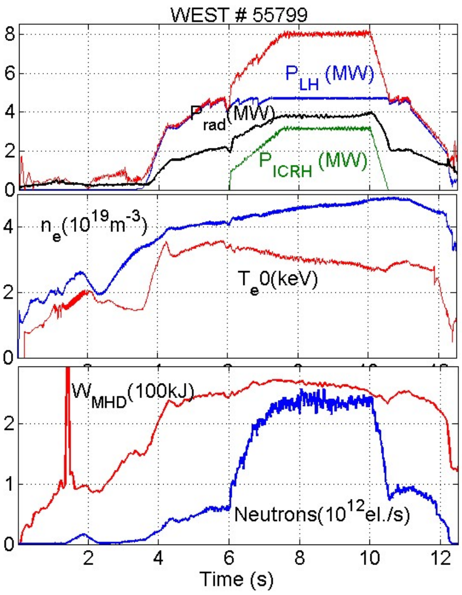

Figure 1. WEST discharge with 8MW of RF power

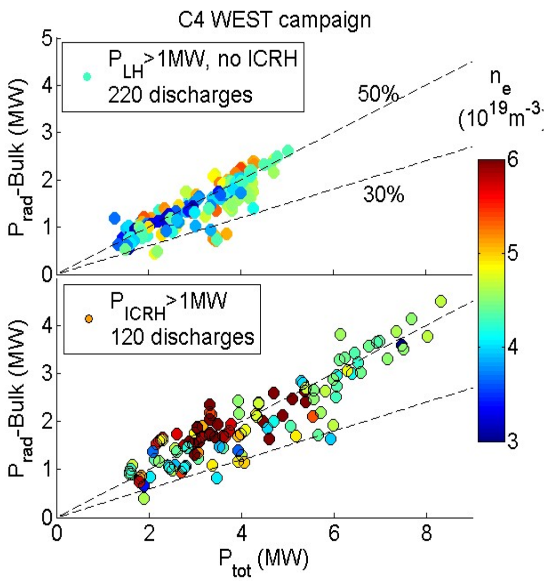

Figure 2. Radiation of the bulk plasma vs. total power for LH and LH+IC discharges .

2. Radiation collapse

For core electron temperature in the 1.5-3 keV range, the cooling factor of tungsten, decreasing with temperature, is very unfavorable with respect to the stability of the plasma. During the ramp-up of the density, radiation collapse was observed in 15% of the discharges. Typically, the core radiation (r/a< 0.25) increases by a factor 3 when the total bulk radiation increases by less than 10%. This instability occurs when the ratio of the core radiation to the heating source, here quantified by the electron thermal power ($<n_e.T_e>/\tau_E$), exceeds a threshold (Figure 3). This threshold increases with temperature and vanishes for $T_e(0)$>3keV when the cooling factor is quasi-independent of the temperature. A good control of the density and the RF power is essential, in particular in the beginning of the high power phase, for burning-through tungsten radiation.

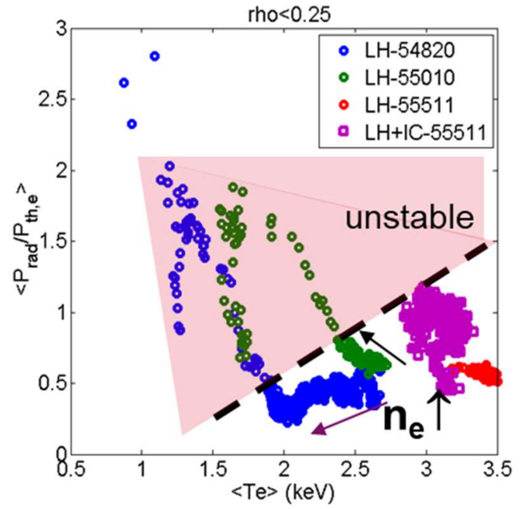

Figure 3. P_{rad}/P_{th} versus T_e in the plasma core (r/a<0.25) during a density ramp.

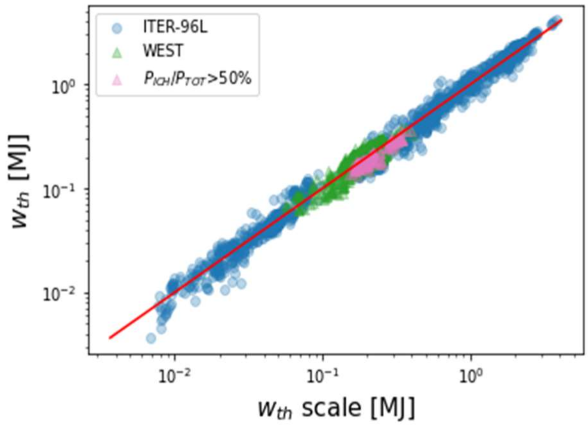

Figure4. Stored energy of WEST and ITER databases versus a scaling law combining these two sets of data

3. Confinement of high power discharges

In L-mode, the scaling of the energy confinement time of WEST discharges (I_p=0.2-0.8MA, P_{AUX}=0.5-9MW, n_e= 1-9 $10^{19}m^{-3}$, 1087 entries) is very close to the ITER96 L-mode scaling but a better scaling is obtained with a lower exponent for the density $n_e^{-0.2}$ instead of $n_e^{0.4}$ (figure 4). Whereas in the ITER database most of the discharges have an aspect ratio between 2.4 and 5, WEST discharges have a high aspect ratio (A=5.5-6) and confirm that this parameter is not a scaling factor. For high power discharges (P_{AUX}>2.6MW) at medium/high density (n_e=3.5-5×10^{19} m^{-3}), no correlation is found between the fraction of radiated power and the H96-L factor (figure 5). LH discharges (107 entries) have slightly better confinement than LH+IC discharges (34 entries).

L-H transitions are observed, when the power crossing the separatrix is close to that predicted by the Martin 2008 scaling law [6]. The line-averaged density increases by ~30%, indicating a significant increase of the particle confinement time but the global energy confinement time increases marginally. Higher bootstrap current at the edge decreases the internal inductance (figure 6). The Doppler reflectometry E×B velocity well gets deeper, reaching -6km/s and the density profile at the edge, measured by reflectometry, gets steeper [7]. Density of these plasmas is likely below that of the minimum L-H threshold [8] suggesting that these transitions are on the low density branch.

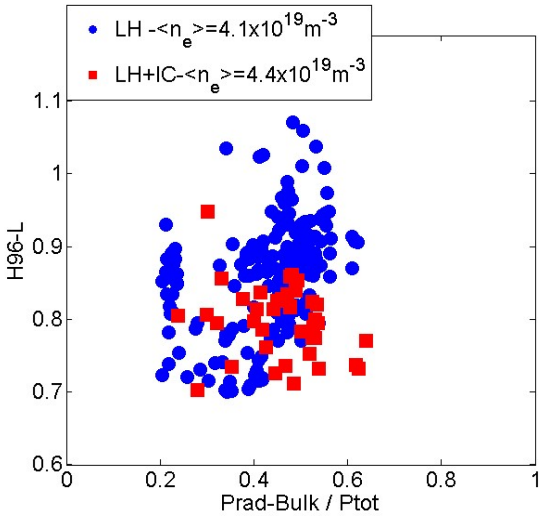

Figure 5. H96-L factor versus Frad-Bulk (Bt=3.7T, Ip=0.4-0.5MA, n_e=3.5-5×10^{19} m^{-3}).

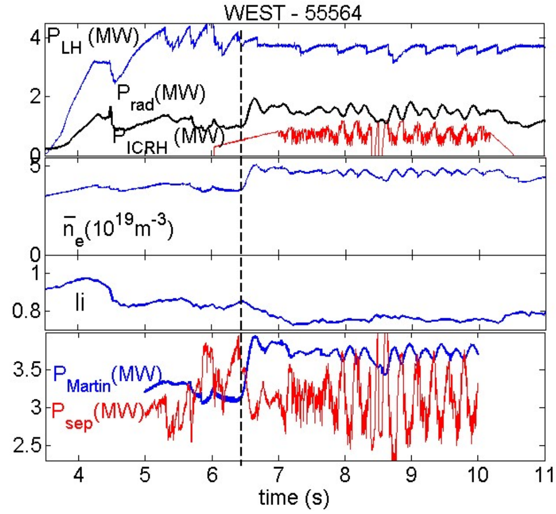

Figure 6: L-H transition at t=6.5s (Bt=3.7T, Ip=0.5MA)

4. Conclusions and outlook

Although the bulk plasma radiation is high (Frad-Bulk ~50%), high power stationary L-mode discharges with good confinement (H96-L~1) were achieved on WEST. Most of these power discharges have a flat tungsten profile in the core (r/a <0.4) thanks to the absence of toroidal torque and central particle source. Tungsten from the RF antennas guard limiters is a major contributor of the plasma contamination but other sources are at play and quantification of other sources (divertor and baffle) is in progress. H-mode access with more margin with respect of the threshold is expected by operating at higher density. It will also ease the IC coupling and maximize the power.

Acknowledgements

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