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Developing high performance RF heating scenarios on the WEST tokamak

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WEST is an actively cooled full W tokamak aiming at power exhaust studies in long / steady-state pulses. WEST can operate in lower single null (USN), upper single null (USN) and double null configuration with an aspect ratio of 5-6. The lower divertor was partially made of ITER-like target in phase 1 (2016-2019), it will be fully made of ITER-like PFC in phase 2 starting autumn 2020 [1, 2]. For this purpose two lower hybrid current drive (LHCD) launchers and three ion cyclotron resonance heating (ICRH) antennas, all actively cooled, have been installed and commissioned.
In the 2019 campaign, the LHCD and ICRH coupled powers have both reached ~5MW/1s separately and 8.8MW/0.5s when combining the two RF systems. Long pulse operation was also carried out with LHCD (PLH=3.0MW) extending the pulse length to 55 seconds (Figure 1). The experiments were performed at high magnetic field (Bt=3.6-3.7T) in a large range of plasma configurations: X-point plasmas (R~2.5m, a~0.45m, kappa~1.3) in LSN and USN configuration, plasma current in the 0.3-0.7MA range (q95~3-6), electron density in the 2.5-8.5×10¹⁹ m⁻³ range (n_e/n_{GW}=0.3-0.8).
The fraction of radiated power P_{rad}/P_{tot} is generally 50-55% but boronization of the vessel walls reduces this fraction to 30-40%. The effective charge Z_{eff} is also significantly reduced to ~2 at high power. Tungsten is, in most cases, the major radiating species but no sign of tungsten accumulation in the core is observed in MHD-free discharges. Nitrogen injection during the early phase of the discharge is found to be beneficial for increasing the edge radiation and peaking the electron temperature. It results a weaker MHD activity and higher performance of the RF-heated plasma.
In L-mode, the stored energy, W_{MHD}, increases according to the H96 L-mode scaling law up to 350kJ, L-H transition was observed, after fresh boronization, when combining 4MW of LHCD with 1MW of ICRH (Figure 2). It results a significant increase of the particle confinement time (30% increase of plasma density with gas injection turned off) but the plasma radiation increases leading to an oscillatory regime.
LHCD allows to reduce the loop voltage to ~0.1V up to ne=4x10¹⁹ m-3 indicating a current drive efficiency of 0.5-0.6×10¹⁹ A.W⁻¹m⁻² for 0.5MA discharges (Figure 1). Higher efficiency (~0.7-0.8×10¹⁹ A.W⁻¹.
m⁻²) can be achieved after a fresh boronization or at lower plasma current (0.4MA) when the LH power deposition profile, deduced from the hard X-ray diagnostic, is more peaked.
Although the stored energy of ICRH-heated discharges increases accordingly with the confinement scaling law, moderate central electron heating is found in particular when ICRH is combined with LHCD. Tungsten sources from an ICRH antenna were investigated from visible spectroscopy [4, 5]. When the antenna is powered with 1MW, the tungsten flux (resp. sputtering yield) increased by a factor 10 (resp. 5) near the antenna mid-plane. However, the increment of fraction of radiated power is generally small when ICRH power is added on a LHCD discharge for well-tuned antennas [4].
In addition to the experimental results, simulations with the 1.5D METIS code [6] and the 3D C3PO/LUKE code [7] to verify the coherency between electron temperature, loop voltage, radiation , plasma composition are presented.

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