First LHCD experiments in WEST

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Introduction. The WEST tokamak has achieved L-mode X-point plasmas in lower single null configuration with plasma current up to $I_P = 0.8$ MA, magnetic field $B_T = 3.7$ T and $q_{95} \sim 3$, during the experimental campaign in October 2017 - February 2018 [1]. WEST is the first and only full tungsten (W) device relying on only radiofrequency systems for heating and current drive. This paper presents the first results with additional power from the lower hybrid current drive (LHCD) system, using two launchers designed for coupling 6-7 MW LHCD power in view of WEST long pulse operation [2].

WEST LHCD system. The high power CW LHCD system (9 MW at generator, f = 3.7 GHz) has been extensively used in Tore Supra mainly for long pulse operation [3], but has since undergone modifications [4] and maintenance [5] for WEST. The toroidal profile of the Full Active Multijunction launcher (FAM, LH1) has been reshaped in order to optimise LH wave coupling on the smaller WEST plasmas. The Passive-Active-Multijunction (PAM, LH2) has not yet been modified, since this launcher design gives lower reflection coefficient at low edge density. The CFC side protections used in Tore Supra are reused for WEST, with an added W-coating on a layer of molybdenum (80 μm Mo + 80 μm W). The launchers with side protections are moveable radially between shots.

Figure 1 shows an overview of WEST pulse 52702 ($I_P = 0.7$ MA, $B_T = 3.7$ T, line average $n_e = 2.1\times10^{19} m^{-3}$), with 2.4 MW LHCD power coupled in L-mode. The different launcher designs result in different levels of power reflection coefficient (RC), i.e. ~ 15% for the FAM (LH1) and ~ 2% for the PAM (LH2).

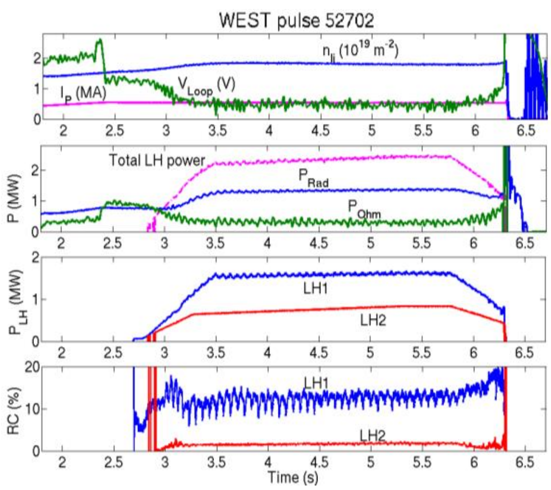

Figure 1: Time evolution of plasma parameters in WEST pulse 52702, with $P_{LHCD} = 2.4$ MW.

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LH coupling. Several plasma equilibria were tested aiming at minimising the reflection coefficient (RC) of the LHCD power. As expected, it was found that RC was sensitive to the radial outer gap (ROG), which could be different for the waveguide rows above and below the mid-plane. Two Langmuir probes are installed in a poloidal limiter located approximately 180° toroidally from the LH launchers, 26 cm above and 26 cm below the mid-plane, respectively. These probes therefore yield values of the electron density at the poloidal locations of the upper and lower waveguide modules of the LH launchers, but which were overestimated by roughly a factor of ~ 2 and ~ 4 for LH1 and LH2 respectively, since the launchers were located 3 mm and 16 mm behind the poloidal limiter. We consider a density decay length in the Scrape-Off Layer of ~ 20 mm. Figure 2 shows the reflection coefficients on all waveguide modules except the two lateral ones (modules 1 & 8), as a function of the corrected electron density, as described above. The RC on the upper and lower waveguide modules overlay perfectly when plotting RC versus the corrected density on the corresponding probe. The theoretical curves from the linear coupling code ALOHA, using a density decay length of 20 mm are also plotted in Figure 2. Low reflection coefficients on LH1 (< 10%) could only be obtained when the actual electron density on the probes exceeded ~ 0.8×10^{18} m^{-3} (corrected density ~ 0.4×10^{18} m^{-3}). This corresponds to shots where the Last Closed Flux Surface was set a few mm from the poloidal limiter. Especially on LH1 (Figure 2a), the results indicate that ponderomotive effects may take place already at relatively low power (400 kW), since RC increases with increasing electric field (as calculated by a simplified model of the multijunction).

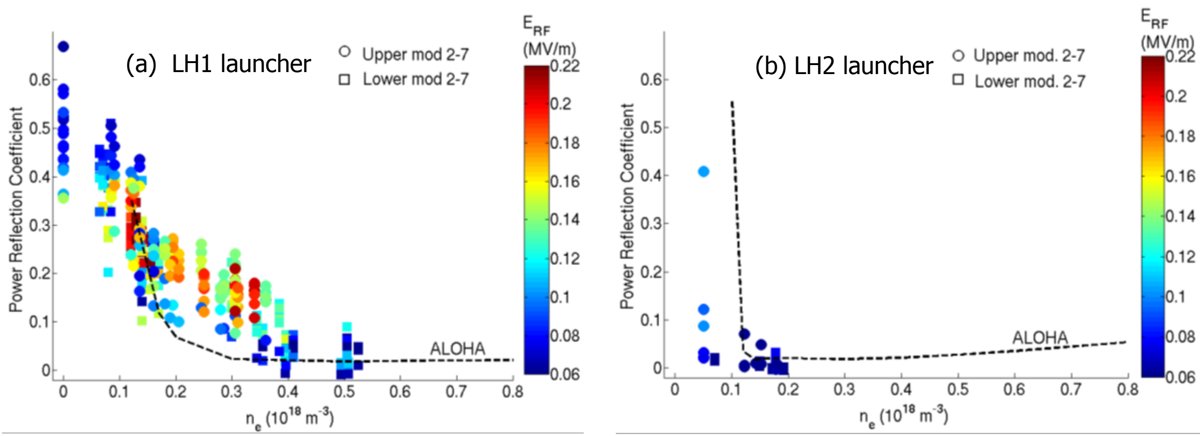

Figure 2: Power reflection coefficients (RC) on the modules on the LH1 (a) and LH2 (b) launchers. The RC-values are shown for the central modules (modules 2 - 7), but not the edge modules (1 & 8). The circles correspond to the waveguide modules above the mid-plane, while the squares are for the modules below the mid-plane. The dashed line is the average RC obtained from the ALOHA code.

Plasma behaviour. Once adequate plasma equilibrium had been found, the LHCD power could rapidly be increased, within four sessions only, resulting in 2.4 MW LHCD power coupled to the plasma for 0.5 s (and 2.3 MW for 2 s), see Figure 1. The presence of a fast electron population was clearly visible on the Hard X-Ray (HXR) signals collecting photons in the energy range 40 - 200 keV. The HXR emission for two energy ranges on a central plasma chord is shown in Figure 3a. The HXR emission for the energy range 60 - 80 keV increases continuously with the normalised LHCD power, P_{LHCD}/n_eI_pR, which is related to the LHCD efficiency via $\eta_{LHCD} = n_eI_{LHCD}R/P_{LHCD}$), where I_{LHCD} is the non-inductive current driven by LHCD and R is the tokamak major radius. The HXR emission > 160 keV on the other hand follows two branches. The emission at low normalised LHCD power is due to the radiation from runaway electrons that were often present during the plasma current ramp-up phase, especially in the first part of the experimental campaign [1]. The emission at higher normalised LHCD power corresponds to the fast electron tail generated by LHCD. The photon temperature deduced from the HXR diagnostic is approximately 45 keV. This is higher than in Tore Supra discharges, which was in the 20 - 30 keV range for similar density and plasma current. Evidence of fast electrons in the plasma centre can also be inferred from the change in sawtooth period, from 13 ms to 71 ms in pulse 52702, as the LHCD power was applied.

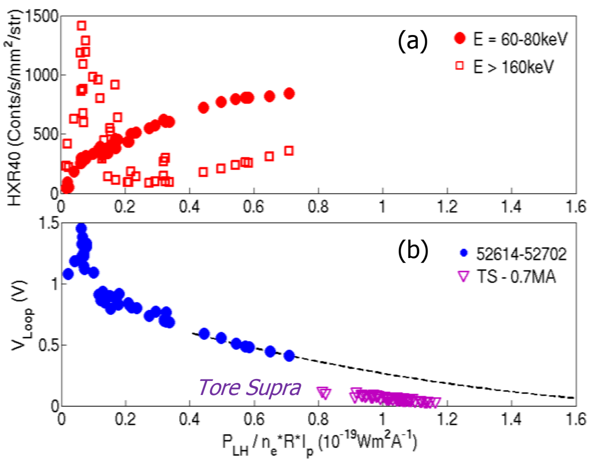

Figure 3: Central Hard X-Ray emission (a) and loop voltage (b) versus normalised LHCD power.

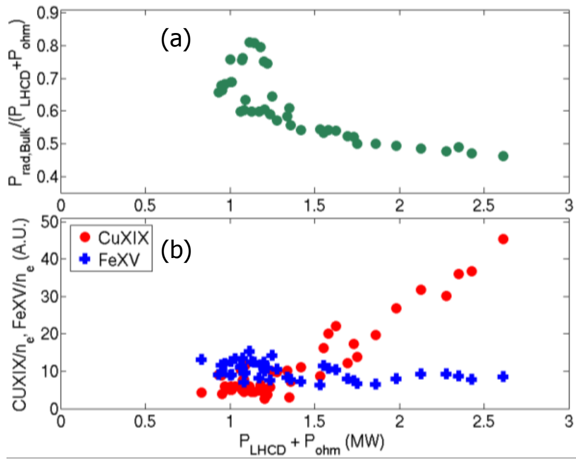

Figure 4: Radiated power fraction in the plasma bulk (a); CuXIX- and FeXV-emission (b).

The loop voltage drop for the WEST discharges has been compared to that of Tore Supra at same plasma current (I_P = 0.7 MA), see Figure 3b. The figure indicates that the LHCD efficiency in Tore Supra was higher than in WEST. An efficiency of $\sim 0.7\times10^{19}$ $m^{-2}A/W$ was obtained in Tore Supra discharges close to zero loop voltage [3]. The dashed line in Figure 3b is a possible extrapolation of the experimental points for WEST assuming a LHCD efficiency of

0.5×10^{19} $m^{-2}A/W$. The lower efficiency in WEST could possibly be attributed to the following effects. Firstly, the coupling of the LH waves, and thus the directivity of the LH wave spectrum, is quite poor due to too low density at the launcher mouths. Optimum coupling condition is important for maximising the current drive effect on multijunction launchers [6]. Secondly, Z_{eff} is most likely higher in WEST than in Tore Supra. VUV spectroscopy analysis [7] indicates that the WEST plasmas contained higher levels of oxygen than Tore Supra, which may lead to higher Z_{eff}. Thirdly, sawtooth activity could lead to loss of fast electrons during reconnection, leading to a large effective radial transport and a reduction of the current drive efficiency.

It is worth noting that the radiated power fraction in the plasma bulk decreased as the LHCD power increased, from $P_{rad,Bulk}/(P_{LHCD+}P_{ohm})$ ~ 80% down to 45%, see Figure 4a. This suggests that LHCD is not directly acting on W-sources, like the W-coated launcher side protections. However, the plasma radiation still remained high at the end of the campaign in February 2018, which could partly be due to the high level of oxygen [7]. It is also found that the copper (CuXIX) emission increased with injected power, as seen in Figure 4b, indicating that a fraction of the plasma bulk radiation comes from copper. One hypothesis could be that the copper was generated during glow discharges (400 hours of D_2 glow discharge cleaning were carried out during the campaign). However, this hypothesis does not seem consistent with the fact that the iron (FeXV) emission is not increasing in a similar way (Figure 4b).

Summary. The last experimental campaign in WEST has allowed obtaining the first results of LHCD in a full tungsten (W) environment. 2.4 MW LHCD power has been coupled in X-point plasmas at low density. Once the magnetic equilibrium had been optimised, the coupled LHCD power could rapidly be increased (in four sessions only). The current drive efficiency is found to be lower than in Tore Supra, which could probably be due to high Z_{eff} and non-optimised coupling conditions, the latter of which could be improved by operating at higher plasma density, using local gas injection and new improved plasma outer gap control.

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