Combined LH and EC Waves Injection in FTU Tokamak

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1. INTRODUCTION

The simultaneous use on FTU (Frascati Tokamak Upgrade) of a Lower Hybrid (LH) (8 GHZ, P_{RF} = 2 MW) and an Elecrton Cyclotron (EC) (140 GHz, P_{RF}= 1.6 MW) wave injection systems, allows to combine the high current drive (CD) efficiency of the first one with the very localised power deposition of the second to perform different combined launch experiments.

Two scenarios have been selected. In the first we try to produce a term of I_{ECCD} to exploit the interaction of the EC waves with the fast electrons (e^-) generated by the LH waves as described in Ref. [1]. The resonant equation, considering the parallel momentum only, gives the following relation:

$$\frac{B_T(r)}{B_{res}} = \frac{n_{\|} - N_{\|}}{\sqrt{n_{\|}^2 - 1}} \qquad (1)$$

where B_{res} is the cold resonant field for the EC waves, $n_{\|}=c/v_{e,f}$ and $N_{\|}$ are the parallel refractive indexes of the LH and EC waves respectively. The interaction with the fast electrons can be controlled by varing $N_{\|EC}$ (from —0.5 to 0.5) and B_T (from 4T to 8T). The $n_{\|LH}$ spectrum in the plasma extends from the launched value $n_{\|0}$=1.52 to $n_{\|M}\approx c/3.5v_{th}$.

In the second scenario the EC wave is injected during full LHCD plasma where any magneto-hydrodynamic (MHD) activity is suppressed and a flat or slightly inverted q(r) profile is established. The EC wave was absorbed by central bulk electrons in order to test the confinement behaviour of such a plasma. The expected central heating should not strongly modify q(r), because the direct link between j(r) and the electron temperature profile $T_e(r)$ is released due to the absence of the toroidal electric field. Therefore, conditions for a stationary high performance plasma can be achieved.

2. EC Waves Absorption on LHCD Fast Electron Tails

We operate in the two possible schemes: the so called down-shifted , where the decrease of electronic resonance is due to the relativistic increase of m_e (giving interaction for $B > B_{res}$) and the up-shifted scheme in which the toroidal-injection of EC (in the direction of the fast e^-) produce the doppler shift of the wave frequency, allowing interaction for $B < B_{res}$.

In both schemes the 'hot' e^- tail gains parallel momentum from the wave, giving a term of I_{ECCD}.

<u>"Down-shifted" experiment</u>. For this scheme we chose a central value of B_{T0}=7.2 T, high enough to push B_{res} (=5 T) well outside the vacuum vessel. The time evolution of the main plasma quantities is presented in Fig.1 for a shot where the central electron temperature, T_{e0}, increases in two steps following the two levels of the injected EC power (0.35 and 0.7 MW). The loop voltage (V_{loop}) drop indicates an increase of the CD efficiency ($\eta_{CD}=\bar{n}_e I_{LH} R_0/P_{LH}$ [10^{20} m^{-2}A/W]) and the ECE signal shows a large non thermal feature. This is a clear sign of direct absorption of the EC waves on the tail [2].

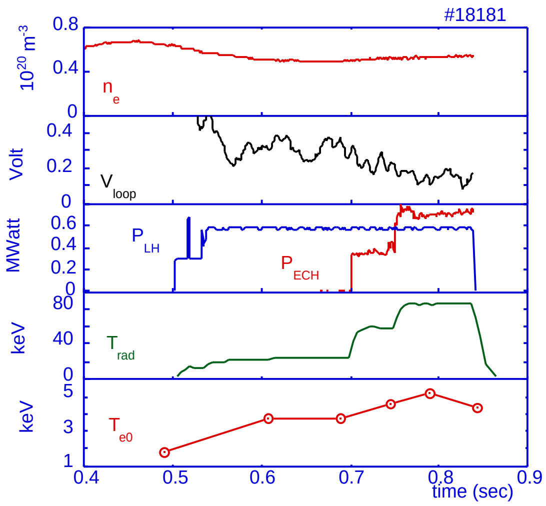

FIGURE 1. Shot 18181, B_T=7.2, time evolution of 1) line density; 2) loop voltage; 3) coupled LH and ECH power, 4) ECE emission along a central chord; 5) central electron temperature

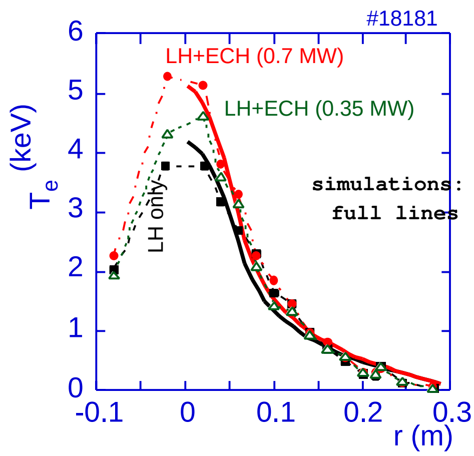

FIGURE 2 — #18181, electron temperature profiles. Experiment: symbols. a) LH only phase (squares), b) P_{ECH}=0.35 MW, triangles; c) P_{ECH}=0.7 MW, dots. Computation: full lines (cases a) and c))

Fig. 2 shows the $T_e(r)$ profiles during the pure-LHCD phase (P_{LH}=0.6 MW) and for the two steps of the ECH power. Comparison [3] is made with simulations by the ASTRA transport code. The temperature rise extends all over a region with r<10 cm (r/a=0.34) and reaches the value of 1.2 keV on the magnetic axis. No significant change occurs in the density profile $n_e(r)$.

The overall absorption fraction of the ECH power is between 40% and 80% for the explored different experimental conditions, as indicated by the RF probes detecting the escaping EC radiation [4]. Other parameters have been varied during the experimental campaign: B_T from 7.2 to 6.9 T, the EC wave polarization from O to X, but all the variations recorded are within the experimental errors and the reproducibility of the shots.

"Up-shifted" experiments. For this scheme we chose a central value of B_T = 5.3 T and a toroidal launching angle of EC wave of 30¡ ($N_{\|}$ = +0.5). The launched $n_{\|0}$ was 1.8 with P_{LH} =1.5 MW and P_{EC}=.7 MW. The first estimate of the absorption, made following ref.[1], give I_{ECCD} = 22 kA located around r/a = 0.4 . The polarization was in the equatorial plane with a residual X-mode portion of around 15% (reflected by cut-off). In this shot the cold resonance is shifted outward (by doppler effects on bulk e-) to r/a = 0.3.

During the injection of the EC wave we observe a full stabilization of the MHD activity, a broadening of the HXR camera [5] emission profile. These effects can be correlated with a broadening of the current profile. For more evident consequences of the up-shited absorption it is neccessary to increase the distance of the tail absorption from the bulk one.

3. EC Central Heating of Full LHCD Plasmas

The main plasma parameters for the experiments at B_T=5.3 T are $\bar{n}_e \leq 0.4 * 10^{20}$ m^{-3}, $P_{LH} \approx 600$ kW, I_p=350 kA. In order to maximize the heating effects on the electrons a low plasma density is preferred to reduce the collisional losses to the ions, and the LH power is chosen close to the available ECH power. The plasma current is then fixed by the need to fully stabilize the MHD and sawteeth activity already in the LH alone phase. Under these conditions, the electron temperature increases inside a wide region, r ≤ 15 cm (r/a≤ 0.5), much larger than the ECH deposition width (≈ 2-3 cm), at the border of which large gradients develop, $dT_e/dr \geq 0.7$ keV/cm, typical of an electron transport barrier [6] , as shown in Fig.3. Despite the very large $T_e(r)$ modification, no MHD activity develops during the ECH phase; according to all our diagnostics this regime is quasi stationary. Rather, the β_p behaviour indicates a further increase of T_{e0} during the short interval when P_{ECH} is doubled. The behaviour of the HXR radial profile emission indicates that no direct interaction between the EC waves and the current carrying e^- is taking place. Consistently, the q(r) profile, according to the magnetic reconstruction, is also unchanged.

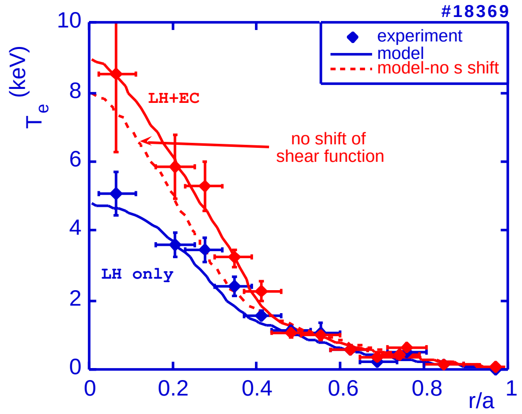

FIGURE 3. Electron temperature profiles for shot 18369. Solid symbols: experiment; lines: computation. P_{LH}=0.65 MW, P_{ECH}=0.36 MW. In the LH+ECH case the shear variable s has been shifted by 0.5, i.e s -> s-0.5.
The dashed line refers to unshifted s .

4. Conclusions

The FTU results extend the evidence of direct absorption of EC waves on the fast electron tails generated by the LH waves to more interesting and reactor relevant regimes and to quasi stationary conditions, as compared with previous experiments [7]. We operated both in the down- and up-shifted schemes. The latter needs however a deeper investigation because of the partial overlapping of the bulk and e^- tail absorption. The tail dynamics is well reproduced by calculations. Macroscopic effects, the increase of the temperature, of the total energy content and of the CD efficiency are observed.

Launching EC power in a fully MHD and sawteeth free plasma, sustained by LHCD, can produce a stable and high performance plasma. The high T_{e0} ($\geq$ 8 keV) and the large increase of the temperature profile inside half radius ($T_{e0}\approx$ 4 keV) for only 0.35 MW of ECH power can be reproduced satisfactorily by the transport codes, provided an electron transport barrier is admitted to be formed by the α stabilization effect of large scale turbulence.

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