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Enhanced CD with up-shift and down-shift damping of EC waves on fast electrons in FTU

G.Granucci[1], A.Bruschi[1], S.Cirant[1], B.Esposito[2], D.Farina[1], F.Gandini[1], G.Giruzzi[3], M.Marinucci[2], S.Nowak[1], L.Panaccione[2], V.Pericoli-Ridolfini[2], S.Podda[2], A.Simonetto[1], C.Sozzi[1] and the FTU[2] and ECRH[1] Team

[1]*IFP CNR Milano, Italy, EURATOM Association*
[2] *ENEA Frascati, Italy, EURATOM Association*
[3] *CEA Cadarache, France, EURATOM Association*

In future large tokamaks, Lower Hybrid (LH) and Electron Cyclotron (EC) waves will play different roles, providing to effective off-axis CD for MHD stabilization and CD in advanced scenarios. The simultaneous interaction of the two waves can be investigated in the FTU tokamak (4 - 8 T; 0.3 – 1.6 MA; $\bar{n}_e$ = 0.3 – 4x10^{20} m^{-3}), on which a LH (8 GHz, 2.4 MW) and an EC system (140 GHz, 1.2 MW) are installed. In this work we report about current generation experiments, in conditions where EC power is absorbed by the electron tail generated by LH waves. These experiments were carried out in several conditions of magnetic field and density, some of them expected to be the same of ITER.

The different interaction regimes of the two waves can be identified analyzing the EC resonance condition $\Omega_{ce}/\gamma = \omega_0 - k_\parallel^{EC} v_\parallel$, where Ω_{ce} is the electron cyclotron frequency, ω_o and $k_\parallel^{EC}$ are the EC frequency and parallel wavevector, γ and $v_{//}$ the relativistic gamma and the parallel velocity of the electrons, respectively. For electrons resonating with the LH wave the following relation holds: $n_{//}^{LH} = c/v_{//}$, being $n_{//}^{LH}$ the LH parallel refractive index. Neglecting the contribution due to the perpendicular momentum, i.e., $\gamma = n_{//}^{LH} / [n_{//}^{LH\,2} - 1]^{1/2}$, the EC resonance condition reads

$$\frac{\Omega_{ce}}{\omega_0} = \frac{n_\parallel^{LH}}{\sqrt{n_\parallel^{LH\,2} - 1}}\left(1 - \frac{N_\parallel^{EC}}{n_\parallel^{LH}}\right).$$

Varying the launched LH spectrum, the EC toroidal injection angle θ ($N_\parallel^{EC} = \sin\theta$) and the toroidal magnetic field B_T (from 4T to 8T), it is possible to study two different schemes of the suprathermal interaction: the down-shifted ($B_{res}<B$) and the up-shifted ($B<B_{res}$). In the down-shifted regime, the "cold" EC resonance is not met anywhere in the plasma and the EC wave resonates only with the fast electron generated by the LH waves. In this case the interaction takes place mostly for counter or perpendicular injection of the EC with respect the drift velocity of the fast e^-. In the up-shifted regime, the interaction between the wave and the

electrons occurs when the local magnetic field is lower than the resonant one. The suprathermal absorption takes place when the EC wave is injected with a toroidal angle in the direction of the fast e^- tail generated by the LHCD. After interacting with the fast electrons, the wave is definitely absorbed by the bulk electrons at the "cold" resonance. It is very important to tune the LH and the EC deposition profiles (i.e., B_T and $N_{||}^{EC}$) in order to have an effective suprathermal interaction. In both schemes, the "hot" e^- tail gains energy and momentum from the wave, giving rise to an I_{ECCD} term.

<u>Down-shifted experiments</u>

A theoretical computation of the power absorption and of the driven current has been performed using a simple linear model of the interaction, described in detail in [1]. In Fig.1, the computed EC absorbed power by the fast electrons and the relevant normalized current are shown for the two polarization (O-mode and X-mode), and the following parameters, B_T=7.2 T, n_{e0}= 1 $10^{20}m^{-3}$, P_{LH}= 1.6 MW, $n_{||}^{LH}$ =1.8, Ip=500 kA (full LHCD). Both the polarizations are absorbed but with different level: X mode exhibits an absorption up to 85% while the O-mode reaches only 35% for the same launching conditions. In the experiments, the EC waves have been mainly injected as O-mode into a plasma with B_T=7.2 T (high enough to push B_{res} = 5 T outside the vessel), Ip=350-500 kA, $\bar{n}_e$ = 4 – 8 $10^{19}m^{-3}$, P_{EC}=0.8 MW, P_{LH}= 0.6 – 1.8 MW, $n_{||}^{LH}$ = 1.52 – 1.82.

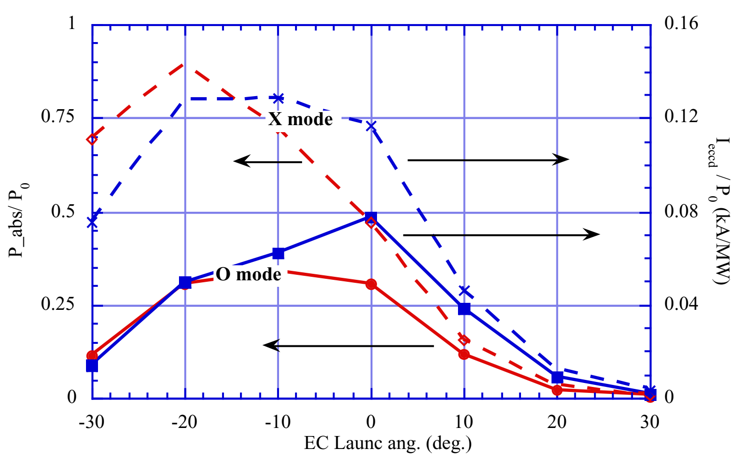

Fig.1: Absorbed power fraction and normalized driven current as a function of EC launching angle for ordinary (solid) and extraordinary (dashed) modes.

The power absorption was measured by two different RF probes [2], which detect the residual EC radiation in the vacuum vessel. Normalizing the residual power to the value measured when no resonance (i.e., no LH wave) is in the chamber, we obtain an evaluation of the overall EC absorption. In the experimental conditions we observed power absorption ranging from 20% to 40 % of the EC injected power. The absorbed power appears to be related to the rate $P_{LH}/\bar{n}_e$, as shown in Fig.2. The measurements seem to be insensitive to first pass absorption since no significant deviation from the linear dependence is observed when different injection schemes (co-cd, counter-cd, O-mode, X-mode) are considered. This fact can be explained assuming that EC first-pass power absorption is low, so that mechanisms like reflection and scrambling at the walls play an important role in the global EC absorption process.

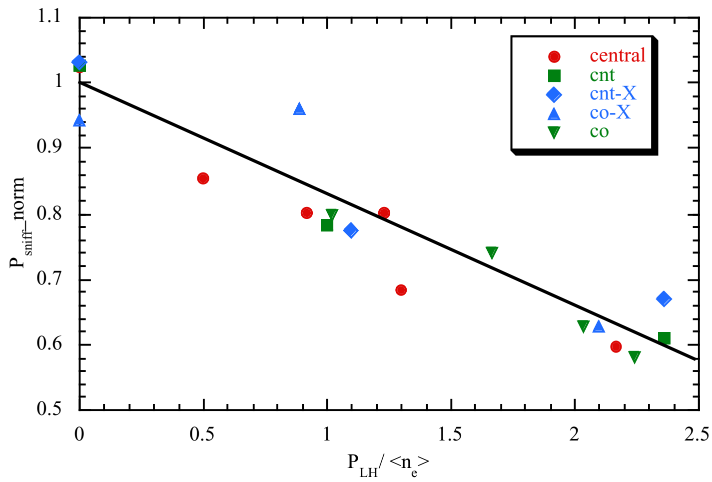

Fig.2: Residual power at a toroidal location 60° from the launching position, normalized to the one measured with no LH, vs. the ratio of the injected LH power (MW) to the line-averaged electron density ($10^{20}m^{-3}$).

Although it is difficult to obtain a direct measurement of the first pass absorbed power, we observed clear effects on the plasma parameters during the down-shifted interaction: a central temperature increase up to 1.2 keV, a V_{loop} reduction, and a strong increase of the ECE emission due to suprathermal features. From the drop in V_{loop} during the EC pulse, an extra current due to EC injection can be computed, which is estimated up to 90 kA (at I_p=350 kA). We found no direct evidence of enhanced absorption of the X-mode with respect to the O-mode, together with low effects on the ECE spectrum and on macroscopic plasma parameters. We thus conclude that a reduced coupling of the X-mode is likely to occur. The possible presence of an evanescent region outside the plasma, located in the launching port at B_T=5T, and causing partial reflection, will be investigated in the future.

<u>Up-shifted experiments</u>

In the experiment, we injected 0.7 MW of EC power, O-mode, into a plasma sustained by 1.5 MW of LHCD. The EC and LH spectra were characterized by $N_{\|}^{EC}$ =0.5, and $n_{\|}^{LH}$ =1.8, respectively, the density was varied from 4 to 8 10^{19} m^{-3} and the plasma current from 400 to 500 kA, with and without full CD. During the injection of the EC wave, we observed a full stabilization of the MHD activity and a reduction of the V_{loop} (in the case of partial LHCD, see Fig.3). With a FEB camera [4] (on loan from CEA), we observed also a broadening of the emission profile and a strong reduction of the emission from the center of the plasma (see Fig.4). This latter fact indicates a first pass total absorption of the LH power when the EC is injected. We can estimate the extra CD from the reduction of the V_{loop} by means of a volumetric formula described in [5] or by a simulation with the JETTO code. In both cases an extra CD of 70 – 100 kA is obtained, larger than the about 28 kA estimated from the linear theory [1]. This increase in the current drive efficiency is interpreted as due to the synergy of the two waves. Further experiments in full CD conditions gave less clear results, because the FEB camera was unavailable, and, moreover, no valid method to measure the EC current could be used in the case of V_{loop} = 0.

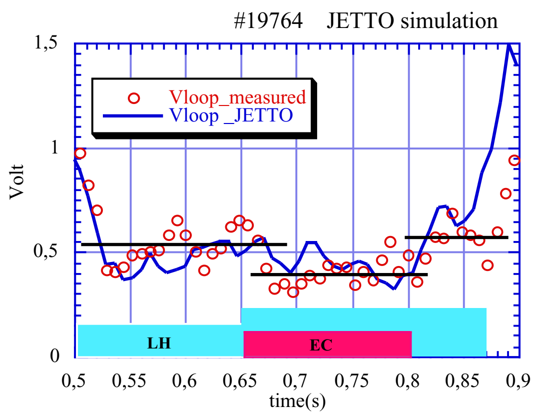

Fig. 3 Evidence of Vloop reduction with up-shifted Ec absorption. Comparison between experiment and simulation for a shot with B_T=5.2T, Ip=0.5MA, $N_{//EC}$=0.5 ,$<n_e>=5x10^{19}m^{-3}$, P_{LH}=1.5MW, P_{EC}=0.7MW

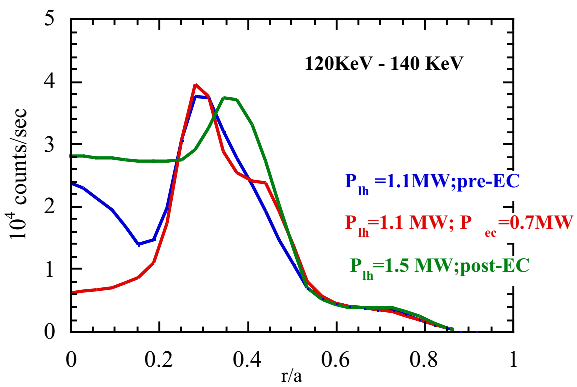

Fig.4: #19764 - FEB camera emission profiles at different times, with/without EC injection

1. FARINA D., POZZOLI R., Phys. Fluids B **1**, 1042-1048 (1989).
2. GANDINI F. et al., Fusion Eng. and Design **56-57**, 975-979 (2001).
3. PERICOLI RIDOLFINI V. et al., 15th Top. Conf. on RF Power in Plasmas, Oxnard
4. PEYSSON Y., IMBEAUX F., Rev. Sci. Instrum. **70**, 3987-4007 (1999).
5. PERICOLI RIDOLFINI V. et al., Physical Review Letters **82**, 93-96 (1999)