Interpretation of the LHCD efficiency scaling with the electron temperature

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The figure of merit of current drive (CD) experiments is the CD efficiency (CDE) defined as η_{EXP} (10^{20} AW^{-1} m^{-2}) = I_{LH} $<n_e>_{20}$ R_0/ P_{INJ}, where R_0 is the tokamak major radius in m, $<n_e>_{20}$ is the averaged electron density in units of 10^{20} m^{-3}, I_{LH} is the LH current driven current, in A, and P_{INJ} is the injected power in W. In several experiments, the CDE by Lower Hybrid waves (LH) has been shown to increase as a function of the volume averaged electron temperature [1]. It was suggested in ref. [1], that such a dependence is due to a temperature dependence of both LH power absorption, and LH $n_{||}$ power spectrum into the plasma. In this paper such a hypothesis is confirmed by a numerical calculation based on a standard ray-tracing Fokker Planck code package, FRTC [2,3], extensively benchmarked on FTU LHCD driven discharges [4]. Here FRTC is used to model LHCD in one FTU shot, at several temperature levels. This calculation shows that, according to the experimental findings, there is an increase of the LHCD efficiency as a function of the volume average electron temperature, $<T_E>_{VOL}$. From the numerical calculations it results that at low temperature, when multiple ray-passes occur, resonant absorption in the electron tail is lower, due to the non-resonant, collisional absorption in the plasma periphery. Furthermore the $n_{||}$ spectrum in the plasma, broadened by the toroidal geometry up to the value need for the absorption, is larger in the high value side, also affecting the LHCD efficiency. On the contrary, at higher temperature, both these effects tend to disappear and the LHCD efficiency increases toward its theoretical value.

To show that, we write the LH theoretical CDE expression, η_{THEO}, as [1]:

$$\eta_{THEO} = 31 / \ln(\Lambda) \quad 4/(5+Z_{EFF}) \; 1/n_{||INJ}^2 \qquad (1),$$

arising from the kinetics of the fast electron tail interacting with the phase velocity of the LH waves [5]. In equation (1), $\ln(\Lambda)$ is the coulomb logarithm and $n_{||INJ}$ is the parallel refractive index of the wave injected into the plasma. Equation (1) holds in the limit of a narrow spectrum and it is a sort of an ideal limit, since the effective $n_{||}$ into the plasma generally degrades towards higher $n_{||}$ value, and not all the injected power is absorbed. Therefore the relation between η_{EXP} and η_{THEO} is given by $\eta_{EXP} = \alpha/\beta^2 \; \eta_{THEO}$ where $\alpha = \alpha_{LANDAU} = P_{LANDAU}/P_{INJ}$ is the absorption coefficient (P_{LANDAU} = power effectively feeding the fast electron tail, P_{INJ}=injected LH power) and $\beta = n_{||U}/n_{||INJ}$., is the ratio between the $n_{||}$ effectively present into the plasma, $n_{||U}$, in the absorption region, and the injected value. This quantity, $n_{||U}$, is related to the minimum and maximum $n_{||}$ into the plasma by the relation: $n_{||U}^{-2} = (n_{||MIN}^{-2} - n_{||MAX}^{-2}) \, (2\ln(n_{||MAX} / n_{||MIN})^{-1}$ [1]. Accordingly, η_{EXP} can depend on $<T_E>_{VOL}$ either trough α either trough β. We calculate these quantities, α and β, by means of the FTRC code, applying it to a reference FTU discharge: B_T=5.3 T, I_P=0.360 MA, q_a=7.3, $<n_e>$= 0.73 $10^{20} m^{-3}$, Z_{EFF}=2, $<T_E>_{VOL}$=0.6keV, P_{INJ}= 1.5 MW, $n_{||INJ}$=1.8 corresponding to a phasing of 90°. All the parameters and plasma profiles are kept constant, between the different cases, but T_E that, on the contrary, is taken equal to the experimental profile multiplied by a factor γ, $T_E(r) = \gamma \; T_{EXP}(r)$, with γ in the range 0.5 to ~ 3. In this way, different $<T_E>_{VOL}$, in the range 0.3 - 1.5 Kev, are considered and the effect on modeling is selected of changing only the average temperature. In fig.1 the calculated values of the LH driven current I_{LH} is reported vs. $<T_E>_{VOL}$. A linear increase is observed up to $<T_E>_{VOL}$ = 0.6 Kev, then at $<T_E>_{VOL}$ = 1Kev sign of saturation starts to appear. The Ray-tracing Fokker Planck code therefore reproduces the experimental observed feature, according to which the driven current increases with $<T_E>_{VOL}$. Figure 2 and 3 show the calculated $n_{||}$ spectrum into the plasma, as it results from the ray tracing calculation; $n_{||}$ is shown along the radial coordinate for tow different volume temperature $<T_E>_{VOL}$=0.3keV and $<T_E>_{VOL}$=1.2 keV. As a matter of fact, the $n_{||}$ spectrum inside the plasma calculated by the code starts from $n_{||INJ}$ and extends up to the local absorption value $n_{||ELD} = 6.5/T_E\,(r)^{1/2}$, as shown in fig. 2 and 3. We observe that the lower is $<T_E>_{VOL}$, the broader is the $n_{||}$ spectrum in the plasma. According to Ref. [1] that makes the CD efficiency lower, since the resonant electron tail has less energy. The guess of ref. (1), $n_{||MIN}=n_{||INJ}$ and $n_{||MAX}=n_{||ELD}$, is therefore confirmed by the present numerical calculation. To calculate β, we need to average $n_{||ELD}(r)$ on the deposition region, which is also shown in fig. 2 and 3. As an alternative we can use, as an averaged value: $n_{||ELD}=6.5/<T_E>_{VOL}^{1/2}$, inserted in the formula for β: $\beta^2=2\ln(n_{||ELD}/n_{||INJ})[1-(n_{||INJ}/n_{||ELD})^2]^{-1}$. In fig. 4, the resulting β is shown to decrease as a function $<T_E>_{VOL}$. Fig.5 shows the absorption coefficient α (=α_{LANDAU}) calculated by the code, as a function of$<T_E>_{VOL}$, as well as the fraction of power lost by the non resonant collisional process ($\alpha_{COLLISION} \sim n_{||}^4\ Z_{EFF}\ n_e^3\ T_E^{-3/2}$) at the plasma periphery. According to the previous formula, $\alpha_{COLLISION}$ decreases when $<T_E>_{VOL}$ increases. The power percentage effectively feeding the fast electrons, α, correspondingly increases and, for the parameter of this shot, it saturates at $<T_E>_{VOL}$ = 1Kev. According to fig.5 the interplay between $\alpha_{COLLISION}$ and α is particularly evident at low electron temperature, when multiple ray passes take place. In this condition LH rays spend more time on the plasma periphery and the power is absorbed at a larger percentage by the non-resonant collisional process.

Finally in fig.6 η_{THEO}, the constant value, η_{EXP}, the value of CDE calculated by the code, and $\eta_{CORRC}=\alpha / \beta^2\ \eta_{THEO}$ are shown all together. We see that η_{EXP} differs from η_{THEO} by the factor α / β^2, which totally accounts for the η_{EXP} temperature dependence.

References

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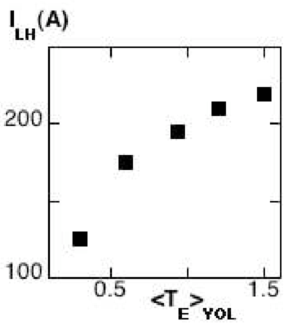

Fig.1: *The numerically calculated LH driven current, I_{LH}, increases as a function of $<T_E>_{VOL}$, as in experiments.*

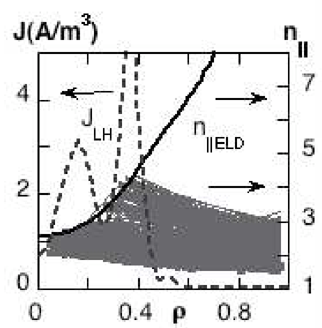

Fig.2: *$n_{//}$ along the ray (vs. ρ, gray area) at $<T_E>_{VOL}$ =1.2keV, showing $n_{||MIN}$, and $n_{||MAX}$ in the plasma, up to $n_{||ELDX}$. The calculated J_{LH} profile is also reported.*

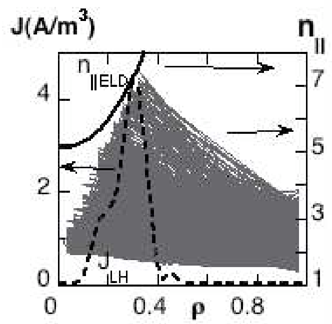

Fig.3: *The same as fig.2 but at $<T_E>_{VOL}$ =0.3keV. At low $<T_E>_{VOL}$ the $n_{||MAX}$ is correspondingly higher.*

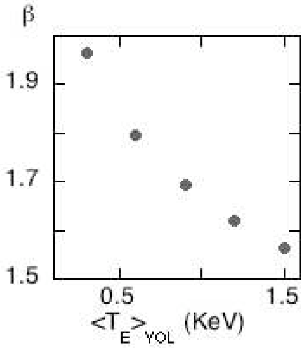

Fig.4: *Upshift factor β, vs. $<T_E>_{VOL}$.*

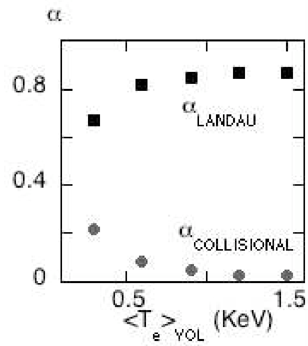

Fig.5: *Absorption coefficient, α, by fast electrons (α_{LANDAU}) and by the peripheral collisional process ($\alpha_{COLLISIONAL}$) vs. $<T_E>_{VOL}$.*

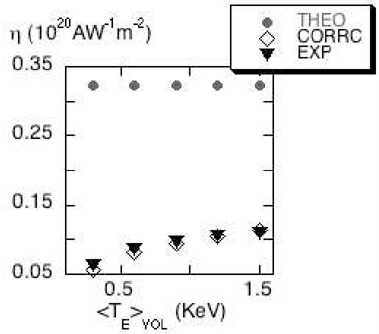

Fig.6: *η_{THEO} (dots), η_{EXP}, calculated by the code (triangles), and $\eta_{CORRC}=\alpha/\beta^2\eta_{THEO}$ (diamonds), vs. $<T_E>_{VOL}$.*