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LHCD efficiency and scattering by density fluctuations at the plasma edge

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Introduction - Lower Hybrid (LH) waves are the soundest tool to drive non-inductively the plasma current in a steady tokamak reactor. However, recent experiments have shown evidence of a drop in current drive (CD) efficiency, η_{CD}, at ITER relevant values of plasma density, $\bar{n}_e \approx 1\times10^{20}m^{-3}$ with broad profile, possibly connected with dissipation of launched LH power in the outer plasma region. Favourable evidence of good LH CD performance at high density was reported by FTU with L-mode plasmas [1, 2]. Some indication connecting LH frequency, plasma periphery and LH performances can be inferred from the old experiments on Asdex at 2.45 GHz [3] and Tore Supra results at 3.7 GHz [4]. Possible mechanisms responsible of LH performance deterioration, all occurring in the edge plasma, could be: scattering by density fluctuations [5], non-linear excitations of parametric decay instabilities (PDI) [6], diffraction and collisional dissipation. FTU has recently investigated the role of the first two, recovering LH performance at high density by successfully controlling edge plasma conditions [7].

The basic experimental findings - Signature of LH interaction is provided by the radiation emitted, in the X-ray and in the microwave range (μw), by the LH-generated fast electrons (e^-), the first due to free-free bremsstrahlung, the second to e^- cyclotron emission (ECE) at relativistic downshifted frequencies. We focus on X-ray emission detected by the multi-chord FEB (fast electron bremsstrahlung) camera, since it is better localized than ECE. However, the FEB signals from a E_φ>40 keV, integrated along the central chord and for a 5 ms time window, generally agree with ECE signal behaviour. A set of Langmuir probes located at LH grill mouth, instead, provides information on the SOL plasma, its turbulence, its averaged density (n_e) and temperature values (T_e). The important n_e T_e values at the last closed magnetic surface (LCMS) are inferred from the CO_2 laser scanning μw interferometer and from the Thomson scattering. We used the row FEB counts, N_{FEB}, as a measure of the LH driven current. This method is validated on a sound empirical basis, as discussed later in the paper. The magnitude of the loop voltage drop ΔV_{loop}, which would be more representative, cannot be used for the present set of data since it is comparable with error bar, due to the combination of the low available power and high density.

The most relevant outcome of the data is shown in **Fig. 1** where N_{FEB} is plotted versus $\bar{n}_e$ for different combinations of plasma current I_p and central toroidal magnetic field B_{T0}. The figure highlights how I_p is an important ordering parameter for the FEB signal, in addition to density dependence, consistently with the consolidated dependence of I_{LHCD} on I_p [1]. However, even within the same group of I_p=0.5 MA there is a discharge, #32336, whose FEB counts, N_{FEB}=85, are markedly above the average value for the same density, i.e. $N_{FEB}\approx28$, while the nearest discharge in terms of $\bar{n}_e$, namely #32324 has N_{FEB}=35.

The quantitative analysis of these data calls for a sound relation between the FEB counts and the LH driven current. Since no modelling of FEB has been able so far to reproduce the signal

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level, we searched for an empirical link. This link has been firstly successfully checked on the discharges where I_{LHCD} could be experimentally determined. To be noted that these data are part of those used for the scaling law [1] and agree very satisfactorily with the scaled values. A 2^{nd} degree polynomial best fit has been used to extend to the lower range of I_{LHCD} needed for the present investigation and compared with the scaled values of I_{LHCD}. The final result is shown in **Fig. 2**. Since a linear fit passing through the axes origin is not acceptable, the direct proportionality of N_{FEB} to I_{LHCD} does not hold and $\Delta I_{LHCD}/I_{LHCD}<\Delta N_{FEB}/N_{FEB}$. The 'anomalous' discharge at 0.5 MA, #32336, remains higher than the scaling. The differences due to I_p in **Fig. 1** disappear for the 0.36 MA cases, but remain, though lower, for the 0.6 MA cases. The current actually driven in these cases can be evaluated by translating horizontally the experimental N_{FEB} on the fitting curve and taking the corresponding abscissa. All the "high N_{FEB}" discharges share the fact of being limited by the outer poloidal limiter rather than the usual inner toroidal limiter. This clearly affects the edge plasma as the associated narrower LH pump frequency spectra document. Modifying the edge plasma, therefore, can favour LH penetration thus increasing I_{LHCD} and the associated suprathermal e^- tail formation.

<u>The model validation and the collection of the relevant data</u> We analyse quantitatively the LH-edge plasma interaction on the basis of a scattering by density fluctuations model [3,5]. The model results in the following 2-D diffusion equation that has been solved numerically: $\cos\vartheta \frac{\partial F}{\partial z} = \frac{\partial^2 F}{\partial \vartheta^2} + \frac{\partial^2 F}{\partial \vartheta^2}$; ϑ is the diffusion angle, $z=x/\ell_s$, x is the scattering intensity, Ω is a normalized frequency. The full definition of these two latter quantities and their link with the turbulent status of the layer can be found in [5]. Here we only stress that reliable calculations were possible after measuring the typical perpendicular wave-vector, ξ_t, of the fluctuations allowing a correct estimate of ℓ_s. Details are given elsewhere [8]. It proved also crucial having carried out these fluctuation measurements inside the flux tube connected to the LH excited grill, since outside all the main features may significantly differ. Several approximations are present both in the model and in the data. The most important are: i) a homogeneous diffusive layer in T_e, n_e, and fluctuations features. T_e, n_e are taken at LCMS, the turbulence at the measuring points and the depth of the diffusing layer D is defined by total optical depth τ, as the integral across the SOL: $\tau = \int_{SOL} dr/\ell_s(r) = D/\ell_{s,LCMS}$, ii) the fluctuations are measured on Langmuir probes for the ion saturation current, $I_{sat,i} \propto n_e\sqrt{T_e}$ rather than for n_e alone.

The validity of the model and of the approximations has been checked against the measured LH pump frequency spectral width over the whole database, i.e. for quite different values of $\overline{n}_e$, I_p, B_{T0} and the results are presented in **Fig. 3**. The resulting good agreement gives us full confidence that the mentioned approximations above are acceptable.

<u>The effect of the scattering on the CD efficiency</u>. Firstly we have checked whether our measurements of the SOL properties (+ the model calculations) could account for the large ΔI_{LHCD} in cases where the expected value is almost the same, i.e. comparing the pairs #32336 vs. #32324 and #32371 vs. #32322. We remind that the values of I_{LHCD} for each discharge are

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deduced from the relevant value of N_{FEB} translated horizontally onto the fitting curve. The difference (+ or -) of this abscissa with the starting point is ΔI_{LH}; ΔP_{LH}, is instead the relative increment of the transmission coefficient of the first member respect to the second one of each couple, therefore $\Delta P_{LH}/P_{LH}$ must be compared with the algebraic difference of the two values of $\Delta I_{LH}/I_{LH}$. The results are summarized in Table 1.

Table 1

Shot	$\Delta f_{p,exp}$ (MHz)	$\Delta f_{p,mod}$ (MHz)	$\Delta I_{LH}/I_{LH}$ -exper.	$\Delta P_{LH}/P_{LH}$ -model
32336	1.35	1.40	0.39	0.45
32324	1.73	1.72	0.0	0
32371	1.70	1.73	0.55	0.59
32322	1.86	1.89	-0.03	0

The good agreement between experiment and modelling in these striking cases encouraged us to extend the analysis to all discharges that have enough data on the SOL turbulence to run the calculations. The result is presented in **Fig. 4** as the plot of the effectively absorbed LH power fraction $P_{LH,eff}/P_{LH,coupled}$, versus τ together with the calculated transmission coefficient T_c. $P_{LH,eff}$ is derived from the definition of η_{CD} plus the assumption that the CD efficiency is well approximated by a constant times the square root of the volume-averaged T_e [1, 2], i.e.: $\eta_{CD} = cost\sqrt{\langle T_e \rangle} = \frac{I_{LH}\,\bar{n}_e R}{P_{LH,eff}} \frac{Z_{eff}+5}{6}$. The constant is fixed by a best fit to the model points, which follow approximately the law: $T_c=1/(1+0.5\tau)$ [5]. The agreement model-experiment is very good for the whole database, with the exception of #32555 that displays a very peaked density profile following a pellet injection. In this case, however, using $\bar{n}_e$ in the formula for η_{CD} leads unavoidably to an overestimate. Indeed, the $\bar{n}_e$ term derives from the collisional slowing-down of fast e^- on background ions. More correctly, this value should be replaced by averaging only in the region where LH is actually absorbed, occurring in a region where density is much less affected by the pellet than the centre.

Discussion and conclusions. The general validity of the diffusive model lies soundly on its ability to explain both the frequency spectral shape of the LH pump and the variation of the effects on the main plasma over a wide range of Δf_p (a factor $\approx$2.5), rms($\delta n_e/n_e$) (a factor 4) and FEB signal (a factor $\approx$10, equivalent to a factor 3 in I_{LHCD}). Despite its limitations and the approximations of the input data, the model can account even for the anomalously high I_{LHCD} values, above mentioned. Very important would be to learn how to control the SOL plasma to minimize its optical depth and then to maximize η_{CD}. However, across the whole database ($0.5 \leq \tau \leq 3$), no clear dependence has been found for τ on any of the main SOL parameters, n_e and T_e or their combinations, except its physical depth Δ_{SOL}. It is also clear that in the cases of anomalously high I_{LHCD} values, obtained by leaning the plasma on the outside poloidal limiter rather than on the inner toroidal limiter, not only Δ_{SOL} is reduced but also the fluctuation level drops, as a consequence of the increased magnetic connection length [8].

The change caused in $N_{||}$ by the change in the perpendicular direction plus the magnetic shear results quite negligible as compared with the natural $N_{||}$ width, due to the layer thinness, and hence to the very slight change in the angle of B. We therefore neglected this problem and all the related question of the absorption in the core plasma that could derive from it.

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We stress that the effects here described can reduce η_{CD} by more than 40%, consistently with JET [9] and ASDEX [3] results at much lower frequency and density, respectively f_{LH}=3.7, 2.45 GHz, and $\bar{n}_e$=3.5, 2.5×10^{19} m^{-3}. In addition we provide a possible physical explanation of the observations. As final comment we want to point out that higher LH frequency will enhance the overall LHCD efficiency, independently of the particular device, as discussed in more detail elsewhere [8].

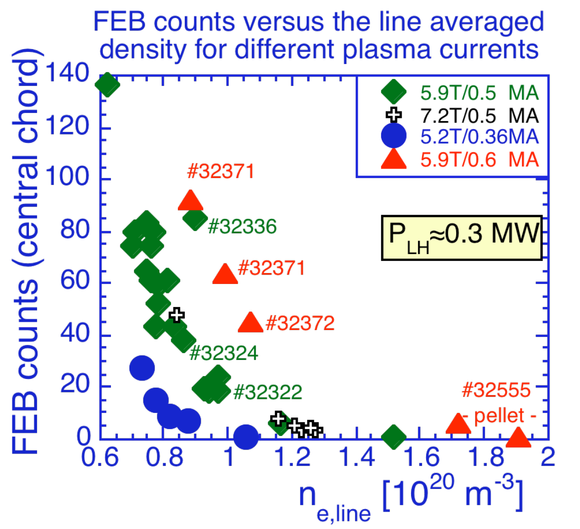

Fig. 1 - Plot of the FEB signal level versus the line averaged density for different combinations of plasma current and magnetic field

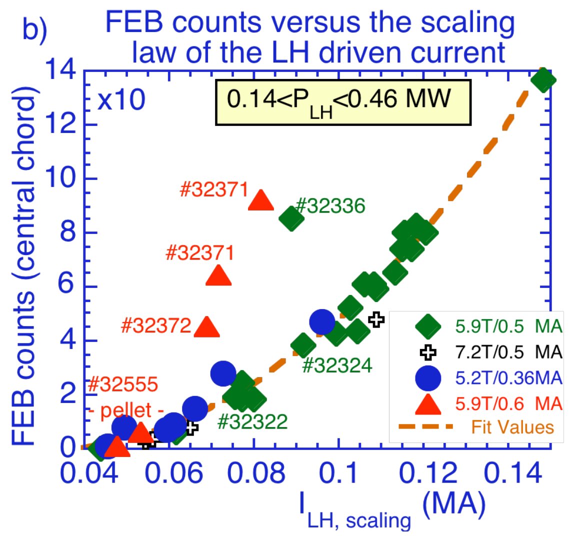

Fig. 2 - FEB counts versus the I_{LHCD} scaling law. The vertical dashed line separates the region of proved and extended validity of the scaling law

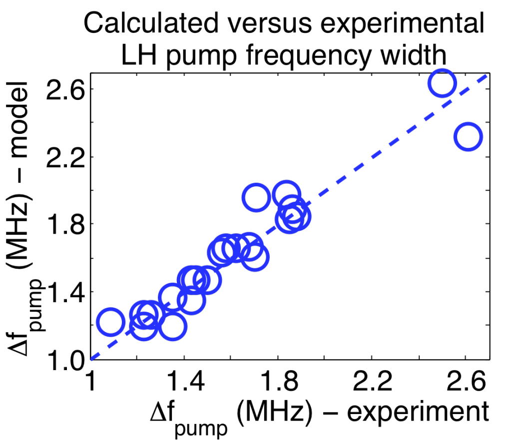

Fig. 3 – Plot of the calculated versus experimental LH pump frequency width at -10 db down the peak. Dashed: equality between the two estimates

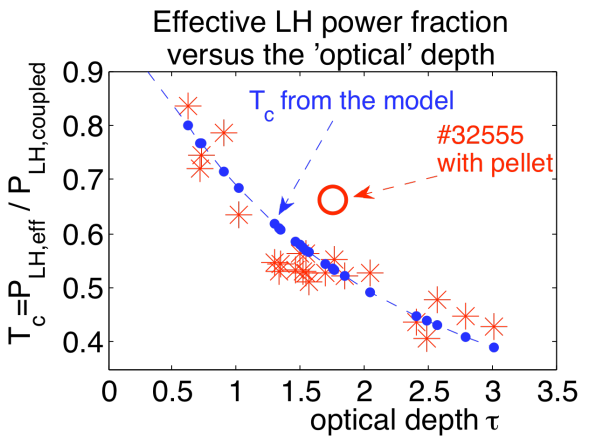

Fig. 4 - Plot of the fraction of the 'effective LH power' (see text) versus the optical depth τ. Discharge #32555 is higher because of its peaked density profile (see text)

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