

Effect of the scattering from edge density fluctuations on the lower hybrid waves in FTU

G. Calabrò, V. Pericoli Ridolfini, L. Panaccione and FTU Team

Associazione EURATOM-ENEA, CR ENEA Frascati, C.P. 65, 00044 Frascati, Rome, Italy

Introduction.

A lower hybrid (LH) wave can change significantly its spectral characteristics in crossing the outer layer of a tokamak plasma. Here, the relatively cold and dense plasma can favor either the non linear interaction of the fluctuations with the pump wave or simply modify the poloidal distribution of the incoming wave through linear scattering. Both these phenomena, that can simultaneously occur in an edge tokamak plasma, can alter the parallel index of refraction (N_{\parallel}) spectrum, changing the propagation and absorption properties of the originally launched waves. The first mechanism, which produces secondary LH waves via parametric decay instabilities, has been recently analyzed in ref [1], the second one is quantitatively analyzed here for the FTU case, where a 8GHz system is operating. The envelop of the scattering processes occurring on single points sampled at fixed $\Delta\theta$, along the poloidal shape of the LH antenna, is considered and the trajectories and N_{\parallel} evolution of the corresponding ray bundle is followed using the fast ray tracing code FRTC [2], coupled to the transport code ASTRA [3] in order to infer the radial absorption profile on a target plasma. Comparison with the radial profile of the hard X-rays emitted perpendicularly to the magnetic field by the LH generated fast electron, which is assumed representative of the LH power deposition profile, is presented for two LH pulses of FTU with quite different LH deposition profiles. Comparison of measured pump frequency spectral broadening on FTU and theoretical prediction is also presented.

Analytical description of the scattering of LH waves from edge density fluctuations.

The modification suffered by the LH waves are calculated on the basis of an analytical description of the scattering occurring in a turbulent layer given in ref [4]. The fluctuations are supposed to have no structure parallel to the magnetic field lines, perpendicularly, instead, they show a wave vector ζ_{θ} that, even considerably lower than that of the wave, can deflect this latter non negligibly in the poloidal plane, through multiple events. This angular spread, in turn, causes a broadening of the original N_{\parallel} spectrum via toroidal propagation

effects. Evidence of such linear processes has been produced in the past for the ASDEX tokamak [5]. The quantity that characterizes the intensity of the scattering phenomena is $\tau = l/l_s$, the optical thickness of the plasma layer crossed by the LH waves of depth l , with the scattering length l_s given by:

$$\frac{1}{l_s} = \frac{\sqrt{\pi}}{8} \left\langle \left(\frac{\delta n_e}{n_e} \right)^2 \right\rangle_{\xi_0} \left[1 + \frac{3}{2} \left(M \frac{\xi_0}{k_0} \right)^2 \right] \quad 1)$$

where δn_e is the fluctuating part of the electron density n_e and $M = \langle \omega_{pe}^2 \rangle / \omega_0 \omega_{ce}$, with ω_{ce} the local electron cyclotron frequency, ω_{pe} and ω_0 denote the local electron plasma frequency and the wave angular frequency, ξ_0 is a measure of poloidal wave vector of the drift wave fluctuations, k_0 is the wave vector of the LH pump. For an incoming spectrum with a narrow Gaussian distribution in the poloidal plane, the angular distribution of LH power emerging from the scattering layer steadily changes from a broadened Gaussian to a $\cos\theta$ distribution with the increase of τ . Generally, as in our cases, it will be a combination of the two distributions with different weights. The parallel index of refraction near the outer periphery of the plasma of the tokamak, in turn, depends on the cylindrical safety factor q_{cyl} value through the relation:

$$N_{||} = \left(1 + \sin\theta \left(\frac{\omega_{pe}}{\omega_0} \right) q_{cyl} \left(\frac{a}{R_0} \right) \right) N_{||0} \quad 2)$$

where θ denotes the angle at which the ray emerges from the scattering layer, a is the plasma minor radius, R_0 is the plasma major radius, $N_{||0}$ are the $N_{||}$ sample values of incoming spectrum. The envelop of the scattering processes occurring on single points sampled at fixed $\Delta\theta$ is considered and the trajectories and $N_{||}$ evolution of the corresponding ray bundle is followed using the fast ray tracing code FRTC, coupled to the transport code ASTRA in order to infer the radial absorption profile on a given target plasma. In our investigation we made the simplifying assumption that all the rays emerging from the scattering layer with equal poloidal wave number follow the same trajectory. This allows, for example, to treat a ray scattered at a given θ on the equatorial plane as the ray launched at the same θ from the antenna, and as the ray launched at $-\theta$ but scattered at an angle of 2θ respect to the launching direction.

Comparison of pump frequency spectral broadening and theoretical prediction.

Satisfactory results of comparison of pump frequency spectral broadening and theoretical predictions for ASDEX has already been presented in ref [5]. Here, we will report the

preliminary results for FTU in support of the correctness of the scattering model assumed. As experimental data we will use the frequency spectra of radiation collected by RF probes external to the plasma, and the density fluctuation measurements in the scrape-off layer (SOL) of FTU plasma. Following the same assumptions described in ref [5], the spectral shape of the LH pump is given by:

$$I(f - f_0) \propto \frac{1}{1 + \cosh \pi \Omega / \sqrt{2\tau}} \quad \tau > 1 \quad 3)$$

where Ω is a normalized frequency $\Omega = \sqrt{3}[(f - f_0)/f_i] \xi_0 / k_0$ and f_i is the characteristic fluctuation frequency. We used Eq. (3) to best fit the experimental spectral shape for the FTU discharge # 11977 described in ref [6], with $f_i = 0.4$ MHz. The result is shown in Fig. 1. Measurements of the density fluctuations were carried out in the SOL of the plasma by means of Langmuir probes.

Interpretive studies and conclusions.

In this paper two Internal Transport Barriers (ITBs) discharges #26671 and #27928, discussed in ref [7], have been chosen, with quite different LH deposition profiles according to the Fast Electron Bremsstrahlung (FEB) camera measurements. The interpretative ASTRA simulations for the two shots were performed in order to compare the calculated deposition profiles with the measured ones.

The typical FTU parameters and the scattering quantities described in Eqs. (1) and (2) for these FTU shots are the followings: $a = 0.285$ m, $R_0 = 0.935$ m, $f_0 = \omega_0 / 2\pi = 8$ GHz, plasma current $I_p = 360$ kA for the discharge #26671 and 500kA for the discharge #27928, density at the Last Closed Magnetic Surface (LCMS) $n_{e,LCMS} = 0.1 \times 10^{20} \text{ m}^{-3}$, electron temperature at LCMS $T_{e,LCMS} = 20$ eV, vacuum toroidal magnetic field $B_{T0} = 5.3$ T, $\delta n_e / n_e \approx 0.3$ as experimentally founded, the product $\xi_0 \rho_i \approx 0.13$ as suggested in previous work [5], peak value of the power spectrum of the parallel index of refraction $N_{||,pk} = 1.82$ and depth of plasma layer crossed by the LH waves, i.e. the FTU SOL, $l = 1$ cm.

The assumed $N_{||}$ distribution of the incoming LH power (dotted line) and the scattered one (solid line) are shown in Fig. 2. The tail which develops at high $N_{||}$ though quite small has a big relevance in determining the actual absorption. Indeed a very good agreement is found between the measured HXR profiles and calculation performed with the scattering effect considered, differently from the case that does not take into account the effect of the density fluctuations. This is shown in Figs 3 and 4, where both the calculated and experimental profiles refer to the time slice 0.7 sec, averaged over 50ms, when the discharges exhibit a

steady phase. In particular are well reproduced for the cases here considered, the peak location and the width of the deposition for both discharges.

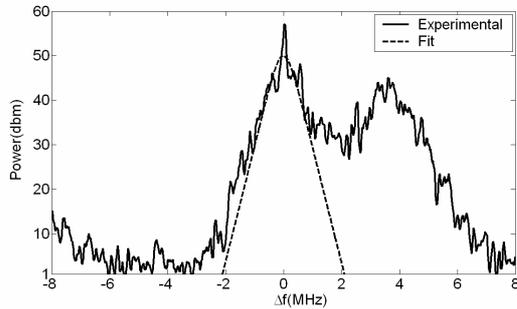


Fig. 1. Fit of the experimental spectral shape of the LH pump with a function of the kind in Eq. (3) for the shot #11977.

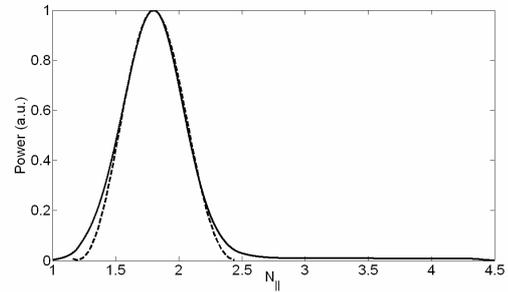


Fig. 2. The assumed $N_{||}$ distribution of the LH power (dotted line) and the scattered one (solid line) for the two shots #26671 and #27928.

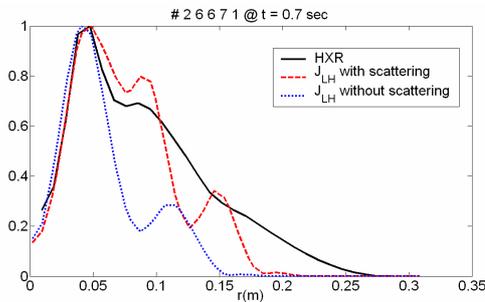


Fig. 3. HXR measurement (black solid line, A.U., normalized with respect to the maximum value), calculated J_{LH} (red dashed line, MA/m^2 , normalized with respect to the maximum value) with scattering and calculated J_{LH} (blue dotted line, MA/m^2 , normalized with respect to the maximum value) without scattering for the shot #26671.

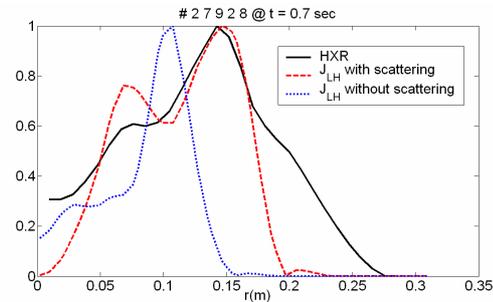


Fig. 4. HXR measurement (black solid line, A.U., normalized with respect to the maximum value), calculated J_{LH} (red dashed line, MA/m^2 , normalized with respect to the maximum value) with scattering and calculated J_{LH} (blue dotted line, MA/m^2 , normalized with respect to the maximum value) without scattering for the shot #27928.

References.

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