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Fast Electron Bremsstrahlung Energy Spectrum of Lower Hybrid Current Driven Plasmas

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The bremsstrahlung emission in the hard x-ray (HXR) energy range is now a well established technique for diagnosing the fast electron population resonantly accelarated by the Lower Hybrid (LH) quasi-electrostatic wave in tokamaks [1,2]. A key point is to determine not only the radial localization of the power, but also the characteristics of the propagating wave, from the kinetic response of the plasma. It is a well known difficult problem to recover the shape of the tail part of the electron distribution function *f(p,r,t)* from the plasma bremsstrahlung emission, owing to the ill-conditionned nature of the problem. Therefore, the natural approach consists in estimating *f* from a realistic model with few adjustable parameters, whose values can be supplied by a best-fit of the experimental HXR data. Instead of using a convenient class of functions that can reproduce qualitatively the ansitropic shape of the tail [3,4], a method which has proven its efficiency for characaterizing the distribution but also its limitation due to the lack of consistency with the underlying mechanisms that take place in the build-up of *f*, an alternative approach is considered, based on the solution of the 2-D relativistic Fokker-Planck equation [5]. A realistic, though simplified modelization of the fluxes in momentum space is considered, under the influence of the quasilinear diffusion, the residual Ohmic electric field, and the collisional relaxation. In such a way, the shape of the distribution function *f* is fully determined on physical grounds, and in particular, it is possible to calculate unambiguously the perpendicular HXR emission, as measured by the tomographic system installed in TORE SUPRA [6]. Since the photon energy spectrum falls off with energy like an exponential function, it is characterized by an experimental photon temperature T_{ph}^* defined by $k\frac{(\Delta N_k/\overline{\eta}_k)}{\Delta k\Delta t} \propto A_0^* \exp\left(-\frac{k}{T_{ph}^*}\right)$, where ΔN_k is the line-averaged number of photons detected in

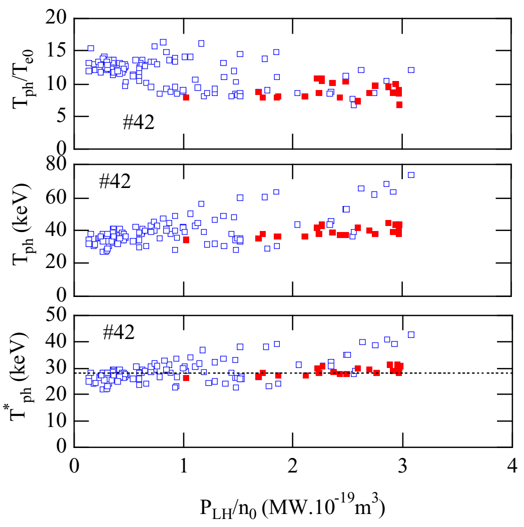

Fig. 1.Quiecent (blue) and MHD regimes (red)

the energy channel centered on the photon energy k of width $\Delta k = 20$ keV, during the time interval Δt, $\bar{\eta}_k$ being the mean stopping efficiency of the corresponding energy channel. The measured photon temperature T_{ph}^* depends critically from the energy interval which is set between 50 and 110 keV, in view to avoid the Maxwellian contribution, and also the noise level due to neutrons at high energy [6]. Due to the specific HXR detector response, a significant distortion is expected between the actual plasma photon temperature T_{ph} and T_{ph}^*, the linear rangebeing limited to $T_{ph}^* \leq 25\ keV$ approximately [6]. The behaviour of T_{ph}^* and T_{ph} have been first studied for the large LH database of the 1999 experimental campaign, from partial to full replacment of the Ohmic current in stationnary condition with respect to the resistive time scale [1,2]. Despite the large variation of the central line-averaged density $\bar{n}_0$, ranging from 1.3 to $4.5\times10^{+19}$m^{-3}, and the the plasma current I_p from 0.4 to 1.2 MA, the photon temperature is very weakly varying, from $P_{lh}/\bar{n}_0$ up to $3\times10^{+19}$m^{-3} MW.m^3, as shown in Fig. 1. When $P_{lh}/\bar{n}_0$ exceeds 1.5 approximately, the T_{ph} profile becomes progressively broad and slightly peaked, while at lower values, it remains flat troughout the plasma, as already seen on several other machines [4]. In most cases, as displayed in Fig. 2, the lower accessible wave refractive index value $n_{//acc}$ is found to be of the order *1.4* [2], so that the runaway velocity is usually larger than the upper bound of the expected quasilinear domain $v_{//\max} = 1/n_{//acc}\beta_{th}$ where β_{th} is the ratio of the thermal velocity v_{th} to the speed of light c. This result is consistent with the lack of runwavay electrons, which validates the HXR emission in the studied energy range as a fully relevant diagnostic of the LH physics. At low plasma current, I_p = *0.4 MA*, T_{ph} is found independent of $P_{lh}/\bar{n}_0$, while a linear scaling is observed at I_p = *1.0-1.2 MA* (Fig.3). Conversely, at high I_p, the waveguide phasing has only a small effect on T_{ph}, while it becomes significant as the plasma current is lowered. Finally, a large MHD activity strongly modifies the fast electron dynamics in LH discharges, and the T_{ph} level never exceeds the values corresponding to the lowest $P_{lh}/\bar{n}_0$ levels, despite 5 MW is coupled to the plasma. The reduction takes place on a MHD time scale, indicating a loss of confinement of the fastest electrons, as expected from magnetic perturbation [1,2]. The T_{ph} profile remains however globally weakly peaked, the core region, inside the formed *m/n* = *2/1* island

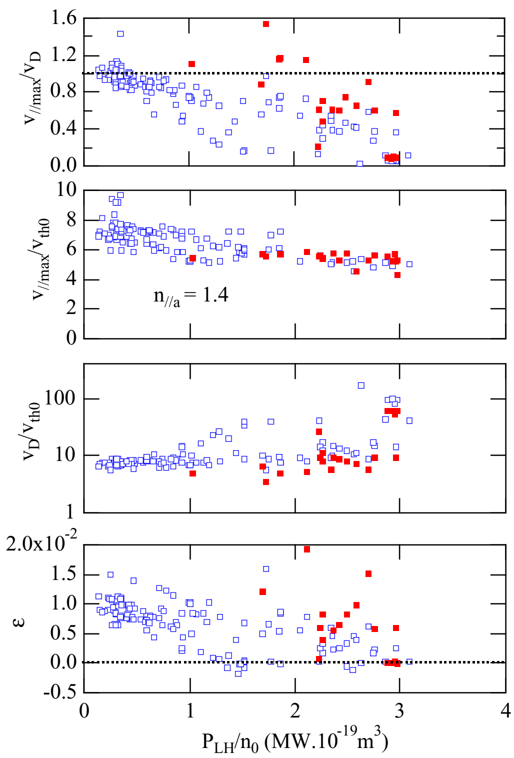

Fig. 2. Normalized plasma parameters

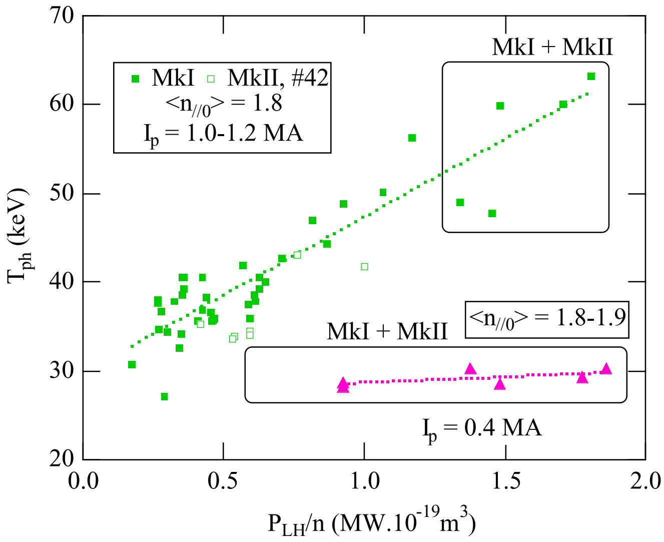

Fig. 3. Power effect at different plasma current

being only affected. In such regimes, except in the vicinity of the island, the radial transport of the fast electrons is found very weak, as already observed in similar experiments [7], thus allowing a local analysis of T_{ph} by Fokker-Planck calculations. Since T_{ph} characterizes a relative falls-of of the photon energy spectrum, simulations may be performed in normalized units, vth for the lower bound of the quasilinear domain, and $\nu_e p_{th}^2$ for the quasilinear diffusion coefficient D, which is assumed to scales like $D = D_0 \frac{v_{th}}{v_{//}}$. In the calculations, D_0 = {0, 0.1,0.2, 0.5, 1, 2}, $v_{//min}$ = {3,3.5,4}, $v_{//max}$ = {5.5,6,7}. The effective charge Z_{eff} has no influence on T_{ph} and is usually set to *1*. The Ohmic electric field ε, normalized to the Dreicer field $\nu_e p_{th}/e$ is varied from 0 to 0.02, by step of 0.005. Here ν_e is the thermal collision frequency [4], while *e* the the absolute value of the electron charge. As shown in Fig. 4, T_{ph} is weakly sensitive to ε , the increase being less than 10% provided ε never exceeds 0.007. This result which is fully consistent with experimental observations confirms the dominant role played by the LH wave, and therefore that the variations of T_{ph} are only relevant from the changes of the chacracteristics of the wave in the plasma during the propagation. In Fig. 5, the quasilinear saturation at large D_0 is well observed numerically. In that case, T_{ph} becomes independent of D_0, the only pertinent parameter being the upper velocity bound $v_{//max}$ characterizing the width of quasilinear domain of interaction. When $D_0 \leq 1$, T_{ph} scales like D_0 which is roughly given by the ratio $P_{lh}/\bar{n}_0$, the slope depending upon the value of $v_{//max}$. When D_0 is very small, i.e. of the order of 0.1, T_{ph} is nearly independent of $v_{//max}$. A comparison between simulations and experimental observations give important trends. The linear scaling of T_{ph} with $P_{lh}/\bar{n}_0$ at high I_p suggests that the quasilinear saturation is

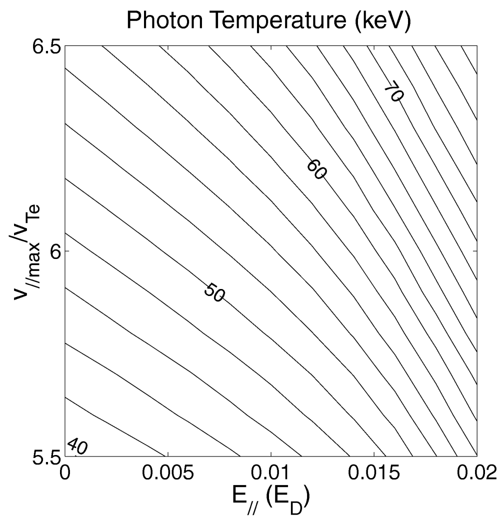

Fig.4. E-field effect ($v_{//min}$ = 3.5, D_0 = 1, T_e = 6 keV)

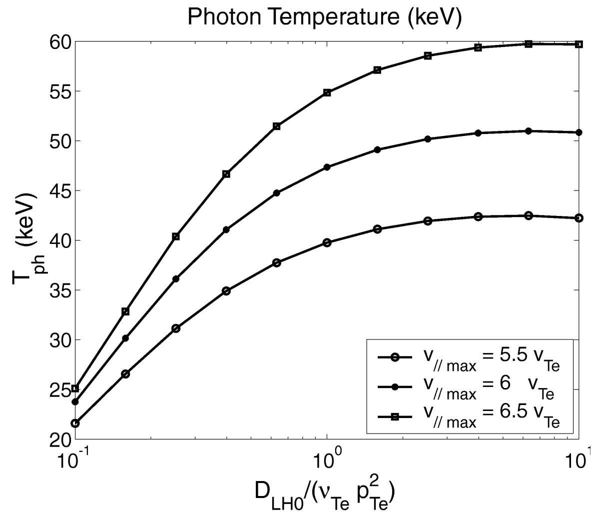

Fig.5. D_0 scaling ($v_{//min} = 3.5$, $\varepsilon = 0$, $T_e = 6$ keV)

not achieved in this regime, while it takes place at lower I_p level. Such a result is consistent with the fact that $v_{//max}$ increases with I_p. The weak dependence of T_{ph} with the waveguide phasing at large I_p, which becomes much more significant at lower I_p values is also consistent with this picture. Moreover, the fact that T_{ph} reaches its mean level even at very low $P_{lh}/\bar{n}_0$ whatever the waveguide phasing is consistent with the level found by calculations and indicated in Fig. 5. The reduction by the MHD from *55 keV* down to *45 keV*, is in agreement with a reduction of $v_{//max}$ from approximately *7.5* in quiescent regime down to *6* in MHD phase. A detailed analysis has shown that is this case, the relative decrease of the HXR intensity predicted by the calculations is of the order of *50%*, while the current drive efficiency is lowered by only *15%*, all the relative variations being well consistent with experimental observations [8]. These results point out the important role played by the plasma equilibrium (namely the plasma current at fixed toroidal magnetic field, and for circular shaped plasmas like in TORE SUPRA [1,2]), on the upper velocity limit of the quasilinear domain. This picture is in agreement with the one that has emerged from the joined LH current drive efficiency and HXR analysis [1,2], which suggests that the upper part of the driven fast electron tail plays the prominent role, as expected from the theory [9], leading to strong consequences on the origin of the observed volume-averaged temperature scaling of the current drive efficiency and extrapolation of the results to the reactor [1,2].

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