Modeling of third harmonic ECRH experiments in TCV

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Electron cyclotron (EC) waves are widely used in tokamaks for resonance heating (RH) and current drive (CD) as they are flexible, controllable, and easily coupled to the plasma. A 4.5 MW ECRH system (3MW at 82.7 GHz, 1.5 MW at 118 GHz) is installed in the Tokamak à Configuration Variable (TCV). Given the size of TCV ($R = 0.88$ m), the ECRH system can deposit large power densities on electrons and significantly distort their distribution function. The combination of this system with a hard X-ray (HXR) bremsstrahlung diagnostic (intermittently on loan from Tore Supra) allows detailed studies of fast electron physics in tokamaks.

The propagation of ECW to the plasma core is subject to a density limit, which increases with the wave frequency. Third-harmonic ECRH can be used instead of second-harmonic ECRH to increase the density limit by more than a factor 2. However, the optical depth of 3rd harmonic (X3) ECRH is smaller than 2nd harmonic (X2) by a factor $kT/mc^2 \ll 1$. Consequently, the 118 GHz X3 ECRH system in TCV is designed to be launched from the top, nearly tangent to the resonant surface to maximize single-pass absorption. However, before the final installation, the power of one 0.5 MW 118 GHz gyrotron was temporarily coupled to the plasma from the low field side to study the absorption of X3 ECW in the presence of X2 ECRH or ECCD [1]. In this experiment, the fraction of power absorbed at 3rd harmonic (measured by the diamagnetic loop using power modulation) systematically exceeded the predictions from linear theory, an effect possibly attributable to X2- generated suprathermal electrons.

This experiment is simulated in the present paper in order to determine the role of these X2- generated suprathermal electrons. The wave propagation is calculated from the mirror angles using the ray-tracing code C3PO [2]. The wave absorption is determined using the 3-D Fokker-Planck (FP) code LUKE [3], which calculates the electron distribution function accounting for Coulomb collisions, quasilinear diffusion due to RF waves interacting resonantly with electrons at any harmonic number, the inductive electric field, and fast electron radial transport. Thus, the generation of suprathermal electrons by X2 ECRH or ECCD and the resulting effects on X3 power absorption are included in this model. From the electron distribution function, the bremsstrahlung emission can be calculated by the code R5X2 [4] and compared to the measurements from the HXR diagnostic. All three codes used in this model use the plasma equilibria and profiles reconstructed from TCV diagnostics and account for plasma shaping.

X3 absorption in an ohmic-heated plasma

In a first experiment (TCV shot 18783), the X3 absorption was measured in an ohmic-heated plasma, in the absence of X2 ECRH. In this case, the distribution function is assumed to be close to a Maxwellian and the X3 optical depth measurements $\tau_{\mathrm{exp}}^{\mathrm{X_3}} = 0.162 \pm 0.017$ can be compared to the prediction from linear theory [5]

$$\tau_{\mathrm{M}}^{\mathrm{X_3}} = \frac{243}{8}\pi\frac{\omega_p^2}{\omega^2}\left(\frac{kT}{mc^2}\right)^2\frac{R\omega}{c}\frac{|e_-|^2}{\bar{S}\cos\alpha}n_\perp^4 \tag{1}$$

which yields a simple approximate expression for TCV plasmas with $\omega_p \ll \omega$,

$$\tau_{\mathrm{M}}^{\mathrm{X_3}} = 0.030 \times n_{[19]}T_{[\mathrm{keV}]}^2\left(1 - 0.087 \times n_{[19]}\right) \tag{2}$$

The linear estimate (2) in the present case gives $\tau_{\mathrm{M}}^{\mathrm{X_3}} = 0.072 \pm 0.008$. It is validated by the very good agreement with linear C3PO calculations $\tau_{\mathrm{C3PO}}^{\mathrm{X_3}} = 0.070$. More remarkably, LUKE calculations give nearly the same result: $\tau_{\mathrm{LUKE}}^{\mathrm{X_3}} = 0.072$. In order to evaluate quasilinear effects on the X3 absorption, a X3 launching power scan is performed with LUKE and shown in Fig. 1. In this particular case, quasilinear effects play a significant role only for an incident power $P_{\mathrm{L}}^{\mathrm{X_3}} \gtrsim 1$ MW. The very good agreement between C3PO and LUKE (in the low-power limit) is also a validation of our modeling tools.

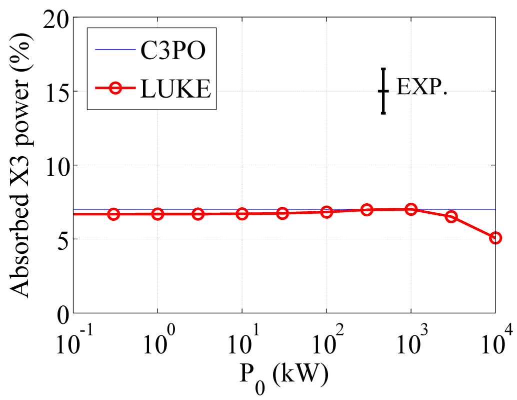

Figure 1: Power scan in LUKE calculations of X3 absorption $f = 1 - e^{-\tau_{\mathrm{LUKE}}^{\mathrm{X_3}}}$ for TCV shot 18783, $t = 0.6$ s.

The difference between the experimental measurements and the simulations of the optical depth is under further investigation. Beyond the quasilinear effects analyzed above, more detailed LUKE calculations (not presented here) show that the ohmic electric field and radial transport do not play any significant role on X3 power absorption in the present case.

X3 absorption in a X2-preheated plasma

Experiments with X3 absorption measurements were conducted with varying X2 power and toroidal angles [1]. It was found that the fraction of X3 power absorbed was much larger in the presence of X2 ECCD than X2 ECRH. An asymmetry was also found between X2 co- and counter-ECCD. In some CO-ECCD cases, full X3 absorption was measured with only 0.5 MW of X2 pre-heating power. Such X2 power and toroidal angle scans have been reproduced by C3PO/LUKE simulations, but the predicted absorption is systematically far below experimental levels [6].

In this paper, a particular shot (TCV #19285, $t = 0.9$ s) with 0.5 MW of X2 power in co-ECCD mode (toroidal X2 angle $\phi = 20^o$) is analysed. Experimentally, 100% X3 absorption was measured for this shot. The X2 and X3 wave propagation calculated by C3PO is shown in Fig 2-a). In Fig 2-b), the linear (C3PO) and quasilinear (LUKE) power deposition profiles are compared.

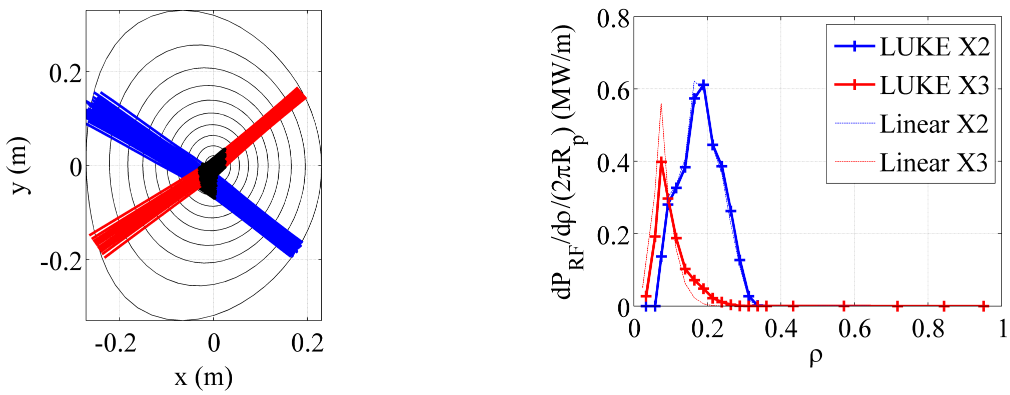

Figure 2: a) Ray trajectories for the X2 (blue) and X3 (red) beams; b) LUKE and C3PO X2 and X3 power deposition profiles.

The quasilinear absorption can be approximately expressed as

$$P_{\text{abs}} \simeq -\left\langle v_{\perp} D_{\text{QL}} \delta\left(\gamma - \frac{n\omega_c}{\omega}\right) \frac{\partial f}{\partial p_{\perp}} \right\rangle \tag{3}$$

where D_{QL} is the quasilinear diffusion coefficient (proportional to the incident power), the delta function describes the wave-particle resonance, f is the electron distribution function and $p_{\perp}$ the perpendicular momentum. If the distribution is Maxwellian ($f = f_M$), linear absorption is obtained. The quasilinear effects on the absorption result from two competing effects :

- the generation of suprathermal electrons (by X2 or X3) increases f in the resonant region, thus improving the X3 absorption (as observed on Fig. 2-b) near $\rho \sim 0.2$)
- the flattening of the distribution function in regions of large X3 diffusion coefficient

decreases $\partial f/\partial p_\perp$, thus reducing the X3 absorption (as observed on Fig. 2-b) near $\rho \sim 0.1$)

In the present case the two effects compensate nearly exactly such that the absorption calculated by LUKE (37 %) is nearly identical to the linear C3PO absorption (39 %). Both calculations remain far below the 100% absorption measured experimentally.

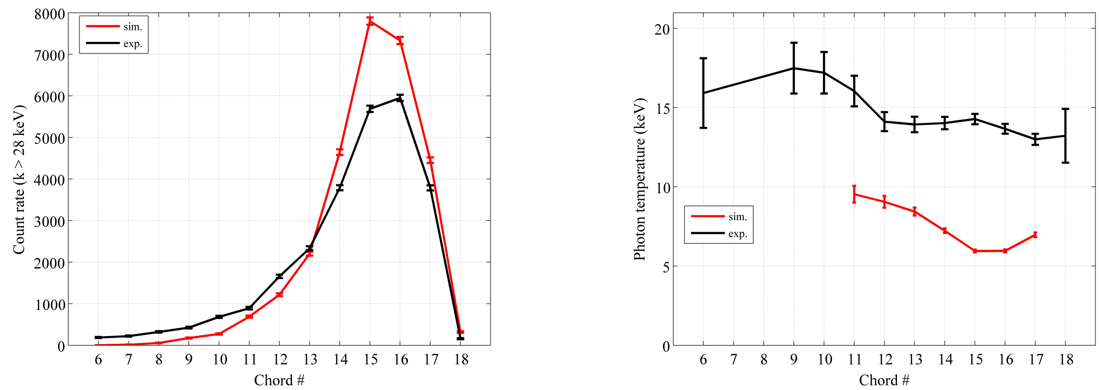

Figure 3: Line-integrated HXR emission (a), and Photon temperature (b), along chords from the edge (#6) to the core (#16) and beyond: measurements and simulation.

To compare experiments and simulations beyond the fraction of X3 power absorbed, the HXR emission profile (count rate) and spectrum (photon temperature) are compared in Fig 3-a) and 3-b), respectively. In LUKE calculations, a uniform radial transport coefficient of $D_r = 2.6$ m$^2/s$ was applied to fast electrons in order to approximately fit the total driven current and the HXR emission profiles. In this case, however, the simulated photon temperature is nearly half the experimental measurements, which is qualitatively consistent with the difference observed in the X3 power absorption.

So far, the X3 power absorption measured experimentally cannot be explained by the effect of X2-generated suprathermal electrons, and further investigation involving other mechanisms is necessary.

References

[1] S. Alberti, *et al.* *Nucl. Fusion*, **42**, 42-45, 2002.

[3] Y. Peysson and J. Decker. C3PO, a ray-tracing code for arbitrary axisymmetric magnetic equilibrium. Report EUR-CEA-FC-1739, Euratom-CEA, 2008.

[2] J. Decker and Y. Peysson. DKE: A fast numerical solver for the 3-D drift kinetic equation. Report EUR-CEA-FC-1736, Euratom-CEA, 2004.

[4] Y. Peysson and J. Decker. *Phys. Plasmas*, **15** 092509, 2008.

[5] J. Decker and A. K. Ram. *Phys. Plasmas*, **13** 112503, 2006.

[6] S. Gnesin, *et al.* Synergy of 2nd and 3rd harmonic electron cyclotron absorption mediated by suprathermal electrons in the TCV tokamak. In 36th EPS Conference on Plasma Phys. and Contr. Fusion, 2009.