Synergy of 2nd and 3rd harmonic electron cyclotron absorption mediated by suprathermal electrons in the TCV tokamak

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Introduction

The TCV tokamak is equipped with nine electron cyclotron (EC) wave sources: six $\times 0.5$ MW in the 2nd harmonic extraordinary mode (X2) and, uniquely in the fusion community, three $\times 0.5$ MW in the 3rd harmonic extraordinary mode (X3). Thus TCV is ideally suited for the study of high power density EC heating and current drive. In particular, TCV experiments have been expressly devised to study the influence of X2-generated suprathermal electrons on the X3 wave absorption. Here we discuss two of these experiments and attempt to interpret the experimental results through comparison with numerical simulations.

Experiment design and results

In a first set of experiments [1], one X2 (f2 = 82.7 GHz) and one X3 (f3 = 118 GHz) beam, of 0.47 MW power each, were adjusted such that resonant absorption of both beams took place over the same region in the plasma core. The X2 toroidal launching angle was varied from shot to shot while the X3 beam was launched within the poloidal plane, perpendicularly to the toroidal magnetic field. The X2 power is fully absorbed under these conditions. The X3 absorption was measured using a diamagnetic loop (DML) during X3 power modulation. The results are shown in Fig. 1 where the experimentally measured absorbed fraction is compared to ray-tracing calculations using TORAY-GA [2]. Enhanced absorption is observed at all X2 angles, with a peak of near 100% absorption for $\phi = 20^o$, equal to twice the linear estimate [1]. The dependence of the hard X-ray (HXR) emissivity, as measured by a vertically viewing camera [3], on the angle is qualitatively similar.

To probe the X2/X3 interplay further, a second set of experiments (Fig.2) was performed by injecting two EC beams from the LFS at a single frequency (82.7 GHz) at values of the toroidal magnetic field for which both the X2 and X3 resonant surfaces for this frequency would exist in the plasma. In a decreasing sweep of the toroidal field magnitude, there occurs a time (t$\approx$ 0.9s) at which both X2 and X3 resonances lie on the same flux surface ($\rho_V \approx 0.7$), respectively on the HFS and LFS. Because of the far off-axis location of the deposition and resulting poor X3 absorption efficiency, any enhancement in the latter is too small to measure directly. However, an indirect indication of this is provided by HXR emission, which indeed reaches a maximum at t=0.9 s (Fig. 2).

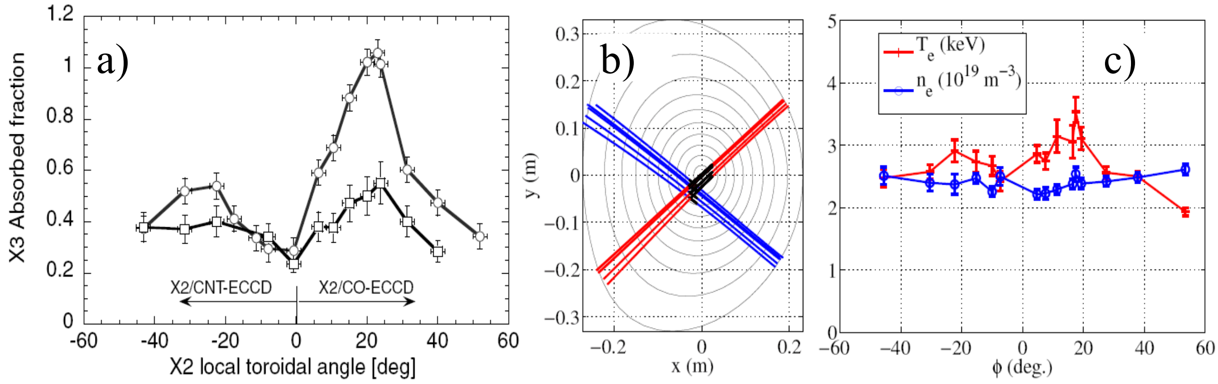

Figure 1: a) Experimental measurements (DML, circles) and ray-tracing calculations (TORAY-GA [2], squares) of X3 absorption as a function of the X2 toroidal angle [reprinted with permission from S. Alberti et al, Nucl. Fusion **42** (2002) 42]; b) poloidal projection of EC beams calculated by C3PO for TCV shot #19286; (c) central electron temperature and density obtained from Thomson scattering and used in C3PO/LUKE calculations.

Modeling tools

The experiments have been analyzed numerically with the help of the LUKE code [4]. This fully relativistic 3D bounce-averaged Fokker-Plank solver is coupled with the C3PO ray tracing code [5] and the R5-X2 bremsstrahlung calculator [6], which provides a full synthetic HXR diagnostic, implemented in particular for the specific TCV camera geometry. The code takes as input data the magnetic equilibrium of a given TCV shot reconstructed by the LIUQE code [7] as well as the launching parameters (EC injected power, mirror angles, wave polarization), and the electron and ion temperatures and effective charge provided by the Thomson scattering, charge exchange and soft X-ray diagnostics. The LUKE code includes the effect of an applied electric field, as well as the possibility of studying anomalous fast electron transport in both momentum space and in the radial direction, with velocity dependence tailored to model either electrostatic (ES) or electromagnetic (EM) turbulence.

C3PO/LUKE simulations of X2 and X3 absorption at different frequencies

Since TORAY-GA is a linear code assuming a Maxwellian distribution function, the calculated variation of X3 absorption with the X2 toroidal angle is only due to variations in the electron temperature and density. This does not account for the suprathermal electrons accelerated by X2 ECCD. It has previously been speculated, particularly in view of the HXR measurements, that these suprathermal electrons could explain the level of X3 absorption observed experimentally [1]. This hypothesis has now been tested with C3PO/LUKE. The poloidal projection of the EC beams calculated for the shot 19286 is shown in Fig. 1(b). Simulation results are shown in Fig. 3 as functions of the X2 toroidal angle. Three different calculations of the X3 absorption fraction are presented: (1) linear calculations using the C3PO code. The results are very similar to those of TORAY-GA and reflect variations in the electron density and temperature; (2) linear calculations using the LUKE code, obtained by cutting off X2 calculations and artificially reducing the X3 power to linear levels where the electron distribution function is essentially Maxwellian. The results agree very well with C3PO and provide a benchmark

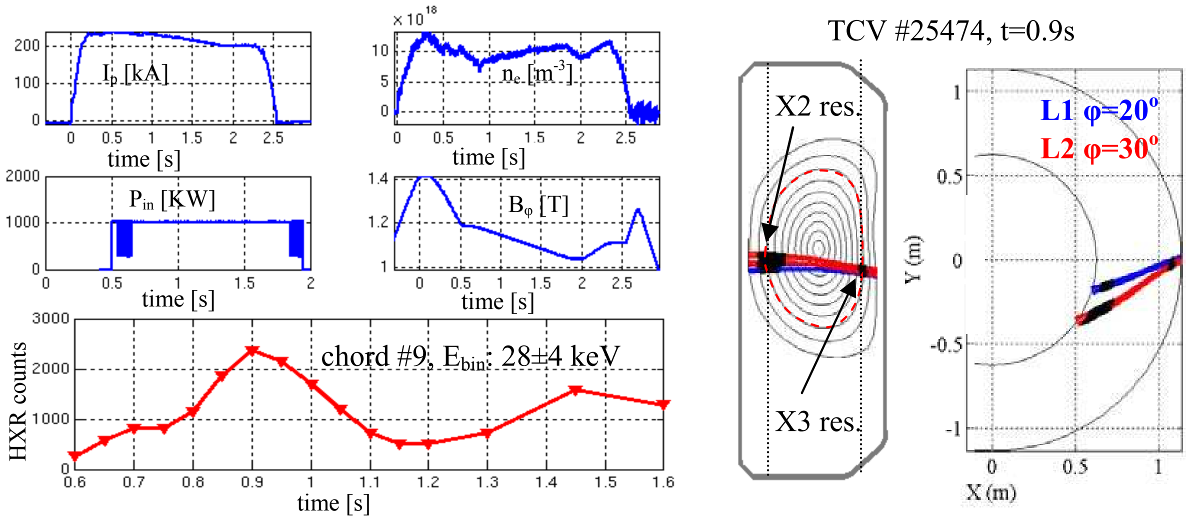

Figure 2: Experimental time traces (plasma current, injected EC power, line-averaged density, vacuum toroidal field), HXR emissivity from the resonant region; magnetic reconstruction and EC beam geometry (poloidal and top views) for TCV shot #25474.

of the calculation; (3) full X3 power calculations in the presence of X2 heating, which corresponds to the experimental situation. The absorbed fraction is generally near or slightly below the linear absorption level. A detailed analysis shows that the absorption enhancement resulting from the presence of X2-accelerated suprathermal electrons is compensated by the flattening of the distribution due to high-power X3 quasilinear interaction. It is also found that the presence of a toroidal electric field and fast electron radial transport, adjusted to match the total current calculated by LUKE to the plasma current, does not significantly affect the X3 absorption.

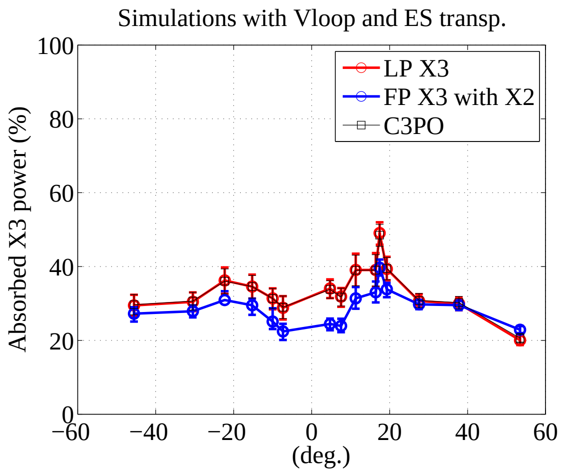

Figure 3: C3PO/LUKE calculations of X3 absorbed fraction for TCV shot #19286: ray tracing (black), linear Fokker-Planck (red), full-power Fokker-Planck (blue).

It can be concluded from these calculations that kinetic synergy with suprathermal electrons generated by X2 ECCD is indeed found by ray-tracing/Fokker-Planck calculations but cannot account for the experimentally measured X3 absorption.

C3PO/LUKE simulations of X2 and X3 absorption at the same frequency

In this section we shall focus on TCV shot #25474. Numeric simulations have been performed between $t = 0.6$s and $t = 1.6$s with the C3PO/LUKE/R5-X2 code system. Experimental results evidence a maximum of the intensity of the HXR emission for $t \simeq 0.9$s when the X2 and X3 resonance lie on the same flux surface. This experimental evidence has also been reproduced numerically (see Fig. 4). Simulations of QL wave absorp-

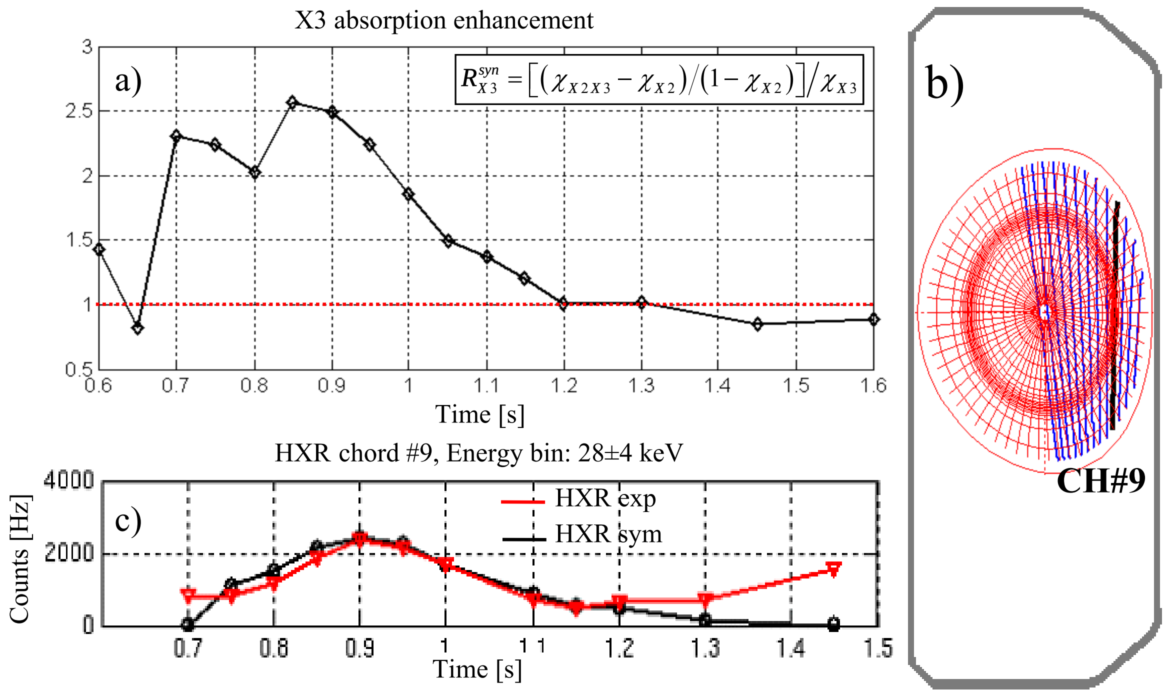

Figure 4: a) Synergy ratio R_{X3}^{syn}; b) HXR camera line of sight arrangement in the poloidal plane for TCV shot #25474; in bold black is the chord #9 which views the plasma tangentially to the X2/X3 resonant flux surface. Plot (c) shows the good agreement between simulated and measured HXR signal along chord #9.

tion have been performed for the X2 ($P_{abs}^{X2} = P_0\chi_{X2}$) and the X3 ($P_{abs}^{X3} = P_0\chi_{X3}$) absorption separately, as well as simultaneously ($P_{abs}^{X2X3} = P_0\chi_{X2X3}$). In view of the very poor X3 absorption, we assume that the X2 absorption is not appreciably modified by synergy effects; the effect of the X2/X3 synergy on the X3 absorption can then be quantified by the quantity $R_{X3}^{syn} = [(\chi_{X2X3} - \chi_{X2})/(1-\chi_{X2})]/\chi_{X3}$. The denominator in the square brackets takes into account the geometrical constraint that power absorbed at the X3 resonance is not available at X2. This ratio is unity when there is no synergy, larger otherwise. The R_{X3}^{syn} time series shown in figure 4(a) shows an increased X3 absorption over its QL level for 0.65 s $< t <$ 1.2 s; significantly, the maximum around t=0.9s coincides with the maximum in the measured HXR emission. The extra absorption of the wave at the X3 resonance on the plasma LFS can be explained by its interaction with the suprathermal electron population generated by X2 ECCD on the HFS of the resonant flux surface.

Acknowledgment

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