Electron Temperature Fluctuation Studies in Different Confinement Regimes by Means of Correlation ECE on Tore Supra

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1. Introduction. Measurements of electron temperature fluctuations aid in understanding the behaviour of the MHD phenomena and turbulent transport in fusion plasmas [1-3]. On Tore Supra tokamak (R/a = 2.40 m/0.72 m, $B_T \leq 4$ T, circular cross-section), first experimental observations of the electron fishbone mode in the LHCD plasmas, as well as hot ion instabilities in the combined LHCD and ICRH plasmas, have been made by means of a correlation Electron Cyclotron Emission (ECE) diagnostic [4-5]. A link between the evolution of the local safety factor and the frequency of the fast hot ion mode has been investigated.

2. Diagnostic setup and the basic correlation technique. The correlation ECE scheme, in which disjoint frequencies are coming from the same sample plasma volume to observe coherent temperature fluctuations and to decorrelate the thermal noise (or, in other words, the radial resolution of the sample volume can be described as two overlapping Gaussians), has been implemented on Tore Supra. For this purpose, a 32-channel heterodyne ECE radiometer [6] has been upgraded to include two channels for temperature fluctuation measurements. The central frequency of the YIG filter on each channel is remotely monitored by a driver, allowing to shift the observation volume in the plasma radially. In experiments reported in this paper, two frequency-tuneable channels of the correlation ECE were separated by 4-5 mm in the radial direction, meaning that signals are received from highly overlapping plasma sample volumes. The 3 dB video amplifier bandwidth B_V is about 150 kHz. The Intermediate Frequency (IF) YIG filters bandwidth is about 110-140 MHz (depending on the filter central frequency; Single Side Band mode). For a single channel, the minimum detectable temperature [3] (under the assumption of the black body radiated power) is calculated to be $\Delta T_{min} / \langle T_e \rangle = \sqrt{B_V / B_{IF}} \approx 3.7\%$ ***(1)***, in agreement with measurements. To resolve the fluctuation amplitude of 0.2% by doing the cross-correlation, integration time of about 1 s is required for a statistical error level of 0.1% [5]. The diagnostic in its present state has a poor sensitivity for low- and medium-scale turbulence due to the strong spectra attenuation for $k_\theta > 0.5$ cm^{-1} and $k_r > 1.5$ cm^{-1} (for $T_e < 5$ keV) because of the large spatial sample volume.

The root mean square (*rms*) value of the normalized temperature fluctuations can be obtained as $\sqrt{\overline{\tilde{T}_e^{\,2}(t)}} \Big/ \overline{T}_e = \sqrt{\mathbf{R}_{12}(0)}$ ***(2)***, in which $R_{12}(0)$ is the value of the cross-correlation function of two normalized signals at zero time lag. If a broadband mode with a bandwidth B_{BB} exists in the plasma, it causes a peak in the cross-correlation function that decays according the following time scale: $\tau_{decay} = \sqrt{ln2/\pi} \Big/ B_{BB}$ ***(3)***, or, roughly, $\tau_{decay} \approx 1/(2B_{BB})$ ***(3a)***. A mode with a narrow bandwidth exhibits itself in the cross-correlation function as an envelope of oscillations that decays with increased time lag. In this case, B_{BB} should be substituted by the width of the envelope.

3. Observation of the electron fishbone mode. Fast (6-14 kHz) MHD modes have been observed near the minimum of the safety factor *q(r)* in plasmas with a large fraction or even with non-inductive LHCD. These modes can be superimposed on a slower double-tearing m/n = 2/1 or 3/2 mode and/or oscillations of the central electron temperature (Fig. 1) [7-8]. Unlike the large 2/1 perturbation, these fast modes are hardly visible by Mirnov coils. As follows from the MHD analysis, they cannot be interpreted as a conventional tearing mode. This instability is likely to be the so-called "electron fishbone" mode that corresponds to the destabilization of the m/n = 2/1 double-tearing mode by barely trapped fast electrons with the energy above 40 keV [7]. Following Eq. ***(2)***, the (averaged over 3 s of sampling) relative amplitude $\tilde{T}_e/T_e$ for the electron fishbone is estimated to be 0.8% in the shot #33982. Interestingly, the mode amplitude may vary on the phase of a lower-frequency oscillation (double-tearing or T_e-oscillation), for example, having $\tilde{T}_e/T_e \approx$ 1% during the decay of oscillation, and less than 0.4 % during its rise. The bandwidth of the mode equals to 450 Hz, as determined from the envelope shown in Fig. 1(c). From the radial extension of the temperature perturbation due to the electron fishbone, as measured by the profile 32-channel radiometer, the radial structure size λ equals to 8 - 10 cm. In terms of k_r (at 7.7 kHz), one would expect $k_r = 2\pi/\lambda$ to be about 0.8 – 0.6 cm^{-1}. However, due to the small radial

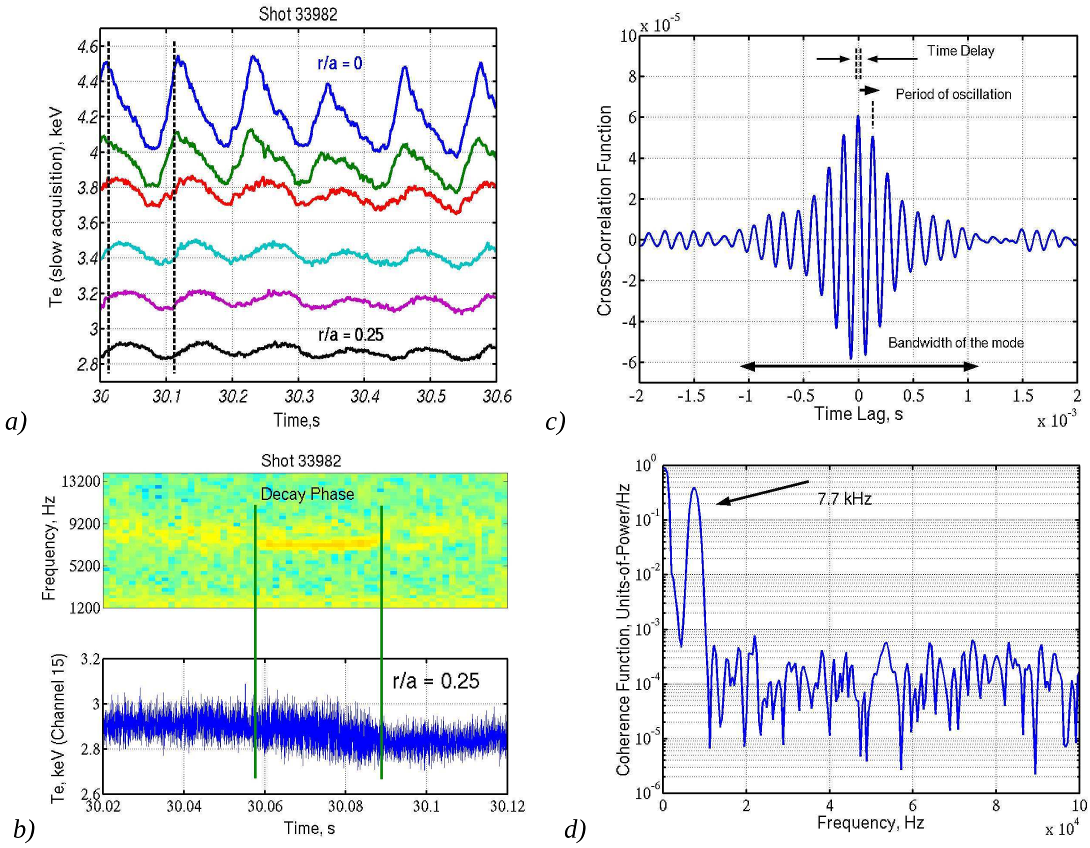

Figure 1. *Observation of the electron fishbone mode at by the profile radiometer during the phase with Te-oscillations* ***(a)***. *A spectrogram for the ECE channel at r/a = 0.25 is given in* ***(b)***. *From the correlation ECE, after 5 kHz high-pass filtering, the relative amplitude of the fast mode, as well as the bandwidth, can be determined* ***(c)***. *The cross-coherence function* ***(d)*** *gives the frequency of the mode.*

separation between channels, no useful information about the radial mode propagation from the time delay can be deduced.

4. Hot ion instabilities on Tore Supra. Two branches of high frequency (40 – 60 kHz and 90 - 150 kHz) modes have been observed for the first time in ICRF discharges with a fraction of LHCD (P_{ICRH} = 3-7 MW, P_{LH} = 1.7–3 MW, $I_p \leq 0.6$ MA, $n_e(0)$ = 3–5x10^{19} m^{-3}, majority species: D, minority: H (~10%)) by means of correlation ECE and the fluctuation reflectometer. Measurements have been made at r/a = 0.12 at the LFS (that is in the temperature gradient region). A cross-spectral density with two clearly seen frequencies at 48.8 kHz and 142.5 kHz is shown in Fig. 2(*a*). Relative amplitudes are 0.33 % and 0.3 % for 48.8 kHz and 142.5 kHz modes, respectively, as calculated from the biased cross-correlation function at the zero time lag for band-pass filtered data (depending on particular frequency of interest) and corrected for the gain of the video amplifier. Bandwidths are determined to be 2 kHz for the 48.8 kHz mode and 0.5 kHz for the 142.5 kHz mode. Interestingly, after performing the FFT analysis (a spectrogram) for a single ECE signal, the high-frequency mode with a narrow bandwidth at 142.5 kHz can still be seen, but the 48.8 kHz one with a wider bandwidth nears the noise level. It has been concluded that the minimum detectable temperature (see Eq. ***(1)***) for the narrow-band mode (NBM) should be determined as $\Delta T_{min}/<T_e>=\sqrt{B_{NBM}/B_R}$ ***(1a)***, in which B_{NBM} is the bandwidth of the mode bounded between 0 and B_V, and B_R is the bandwidth corresponding to the "effective" radial structure size and bounded between 0 and B_{IF}. For the 142.5 kHz and 48.8 kHz modes, and taking $B_R = B_{IF}$, $\Delta T_{min}/<T_e>$ are calculated to be 0.21% and 0.42% respectively, in agreement with observations.

The upper branch of high-frequency modes is thought to be related to the so-called Toroidicity-induced Alfvén Eigenmodes (TAEs) [9]. Due to the LHCD and the low loop voltage (<100 mV), most of plasmas with high-frequency modes have a slightly reversed central magnetic shear. The radial position of r/a = 0.10-0.15 corresponds to q_{min} between 1.2 and 2 (depending on the particular plasma conditions), as evidenced from the localisation of 2/1 or 3/2 double-tearing and/or electron fishbone modes, or calculated by means of the 1D-transport code CRONOS [10]. For these Tore Supra discharges, the Alfvén velocity v_A is in the range between 0.6 – 1.0 $\times 10^7$ m/s, which corresponds to the mode frequency of [9]: $f_{TAE} \approx V_A/2\pi(2qR) \approx 100-165\,kHz$ ***(4)***. For those shots, an existence of the TAE gap at $\omega=0.42\omega_A$ (for example, for a TAE with the toroidal number n = 2) has also been predicted by the code MISHKA [11]. The frequency of the fast mode depends strongly on local density and injected ICRH power, and a threshold for the fast mode to appear, with respect to P_{ICRH}, and n_e, can be identified. For the discharge mentioned above, the energy of hot ions responsible for the excitation of TAEs is estimated to be above 250 keV [12]. The frequency range for 40 – 60 kHz modes lies outside of the possible TAE range. Possibly, these modes can be identified as so-called Geodesic Acoustic Modes (GAMs) [13]: $f_{GAM} = c_s/2\pi R_0 = \sqrt{(T_e+T_i)e/M_i}/2\pi R_0 \approx 50\ kHz$ ***(5)***, in which T_e = 4 keV, T_i = 2 keV and R_0 = 2.45 m. Mass and T_e dependency of the frequency has been observed [14].

5. TAEs and the evolution of the local *q*-profile. In reversed shear plasmas with LHCD and ICRH, the TAE frequency is found to depend on the phase of the oscillation of the central temperature (at the constant density) (Fig. 2(c,d)). Because the evolution of the temperature in the Oscillation (O)-regime is linked to the evolution of the current density profile [8], this observation is a good proof that the value of the local q indeed

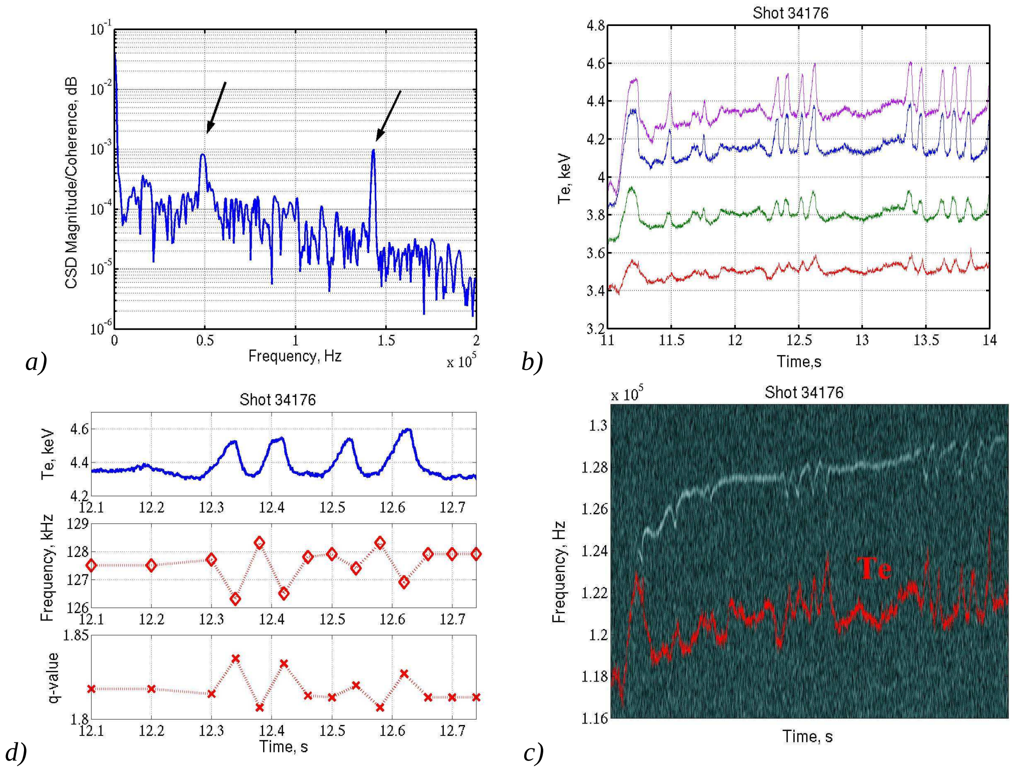

Figure 2. *Cross-spectral power density (a) show a presence of high-frequency modes in combined LHCD and ICRH discharge (shot #33894). During the O-regime in the shot #34176 (b), the frequency of the TAE (white trace in (c)) depends on the phase of the oscillation (red trace in (c)). The evolution of the q-value at r/a=0.12 (position of the measurement) for this shot is shown in (d).*

evolving periodically during the oscillation cycle. In the shot shown in Fig. 2(b,c), observation is made close to the $r = r(q_{min})$. The change in frequency of 2 kHz corresponds to the change in the local q of 1.5 – 3.0%, depending on the plasma parameters of the shot (Fig. 2(d)).

6. Future plans. In upcoming experimental campaigns, an emphasis will be given to detailed studies of high-frequency narrow-band modes at various radial positions under different plasma conditions. In the future, an improved correlation ECE diagnostic setup with a crossed line of sight, a smaller sample volume, reduced electromagnetic pickup and instrumental noise will be needed for studies of both radial and poloidal properties of the broadband turbulence and TAE-modes on Tore Supra.

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