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Identification of trapped electron modes in frequency fluctuation spectra

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Abstract

Ion temperature gradient (ITG) and trapped electron modes (TEM) are two important micro-instabilities in the plasma core region of fusion devices ($r/a \leqslant 0.9$). They usually coexist in the same range of spatial scale (around $0.1 < k_\perp \rho_i < 1$), which makes their discrimination difficult. To investigate them, one can perform gyrokinetic simulations, transport analysis and phase velocity estimations. In Tore Supra, the identification of trapped electron modes (TEM) is made possible due to measured frequency fluctuation spectra. Indeed, turbulent spectra generally expected to be broad-band, can become narrow in case of TEM turbulence, inducing 'quasi-coherent' (QC) modes named QC-TEM. Therefore the analysis of frequency fluctuation spectra becomes a possible tool to differentiate TEM from ITG. We have found indications that the TEM can have a QC signature by comparing frequency fluctuation spectra from reflectometry measurements, gyrokinetic simulations and synthetic diagnostic results. Then the scope of the analysis of QC-TEM are discussed and an application is shown, namely transitions between TEM turbulence and MHD fluctuations.

Keywords: turbulence, micro-instabilities, trapped electron mode, MHD, reflectometry, LOC-SOC, ohmic confinement

1. Introduction

Plasma turbulence is responsible for the anomalous transport observed in magnetic fusion devices [1]. It is driven by instabilities whose perpendicular wave numbers $k_\perp$ normalized to the ion gyroradius ρ_i range between 0.1 and a few tens. Ion temperature gradient (ITG) modes, trapped electron modes (TEM), and the electron temperature gradient (ETG) modes are the most important micro-instabilities in the plasma core region. Usually the ETG modes have a rather distinct scale around $k_\perp \rho_i \approx 10$ while the ITG/TEM branches overlap at $0.1 < k_\perp \rho_i < 1$ [2]. This makes the distinction of TEM and

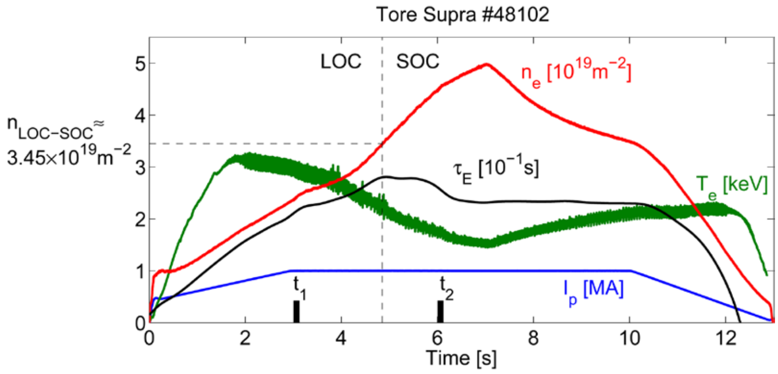

Figure 1. Main parameters of the Tore Supra discharge #48102 ($B_t = 3.82$). I_p is the plasma current, T_e is the central temperature and n_e is the central line averaged density and τ_e the energy confinement time. The dotted line indicates the LOC-SOC transition and the two vertical black dashes show the two times investigated.

ITG-dominated regimes complicated. However, discriminating them enables to study their respective effects on rotation, impurity transport, etc.

To achieve this goal, gyrokinetic simulations can be performed to determine which of TEM and ITG growth rate is dominant [3]. It is also possible to investigate them experimentally, for instance by estimating their phase velocity as TEM and ITG rotate in opposite directions in the plasma frame [4]. This is difficult since the rotation components must be measured with high accuracy [5]. Thanks to the modulations of radio-frequency heating or to the injection of a particle pulse, the estimation of the transport coefficients can also help to discriminate ITG from TEM dominated regimes. For instance, transition between the dominant instabilities can be inferred from the parametric dependency of the diffusion [6, 7] or by a reversal of the convection velocity direction [8, 9]. However, both phase velocity and transport coefficient estimations currently used to investigate ITG and TEM are complex and not always feasible as they require advanced diagnostics or specific perturbation experiments scenario.

We show in this paper that a rather simple experimental indication can be provided by frequency fluctuation spectra. Indeed, TEM-dominated regimes can induce 'quasi-coherent' (QC) modes named QC-TEM, instead of showing a broadband spectra as it is usually the case for turbulence. Therefore the analysis of frequency fluctuation spectra may become an additional tool to address the issue of TEM/ITG differentiation.

The indications of the QC signature of TEM are first shown in section 2 which compare frequency fluctuation spectra obtained from experimental data, gyrokinetic simulations and reflectometry synthetic diagnostic computations. Then, the scope and the limitation of the QC signature of TEM are discussed in section 3 and an example of an application is presented in section 4.

2. Evidences of the TEM signature of the core QC modes

All the data presented in this section come from the Tore Supra tokamak with a major and a minor radius $R_0 = 2.38$ m and $a = 0.72$ m respectively. To investigate the nature of the QC modes, we focus on a density scan performed in an Ohmic plasma. This type of discharge shows two distinct Ohmic regimes: at low density the confinement time increases linearly with the density in the linear Ohmic confinement (LOC) while it saturates at higher density in the saturated Ohmic confinement (SOC). Such plasma configuration is investigated because TEM and ITG are expected to dominate in the LOC and the SOC regimes respectively [4, 10–14]. This study compares frequency fluctuation spectra from reflectometry measurements, nonlinear gyrokinetic simulations and a synthetic reflectometer using the nonlinear runs as input.

2.1. Spectra from reflectometry measurements

Previous analysis of Tore Supra and TEXTOR spectra measured by reflectometry have shown that QC modes are measured in the LOC regime and disappear at the LOC-SOC transition during n_e ramp-up or I_p ramp-down [14]. The decrease of QC modes during such ramps has also been reported in JET. A qualitative agreement has been found with the Tore Supra and the TEXTOR observations [15].

Figure 1 shows the main plasma parameters of the Tore Supra Ohmic discharge #48102 in which a density ramp-up is performed. As indicated, two times are considered for this analysis: $t_1 \approx 3$ s in the LOC regime and $t_2 \approx 6$ s in the SOC regime. The LOC-SOC transition occurs at around $n_e \approx 3.45 \cdot 10^{19}$ m^{-2} which corresponds to $t \approx 4.85$ s.

Data used for figures 2(a)–(d) were obtained with two X-mode reflectometers. Figures 2(a) and (c) show fluctuation spectra obtained at $r/a \approx 0.18$ with a fixed-frequency reflectometer [16]. As the density increases, the selected probing frequency of the reflectometer is changed between t_1 ($f_1 = 110.9$ GHz) and t_2 ($f_2 = 122.6$ GHz) to ensure a constant measurement location. In figures 2(b) and (d), an ultra-fast-swept reflectometer [17] is used to provide a radial range of fluctuation spectra ($0.65 < r/a < 0.85$). These reflectometry spectra are obtained with a Fourier transform of the measured complex signal $A(t)e^{i\phi(t)}$, with $A(t)$ and $\phi(t)$ the amplitude and the phase respectively. Here, the positive and negative frequencies do not correspond to any diamagnetic direction of the turbulence as reflectometry does not allow to distinguish between them. The positive frequencies translate phase increments whereas the negative frequencies show the phase decrements. The

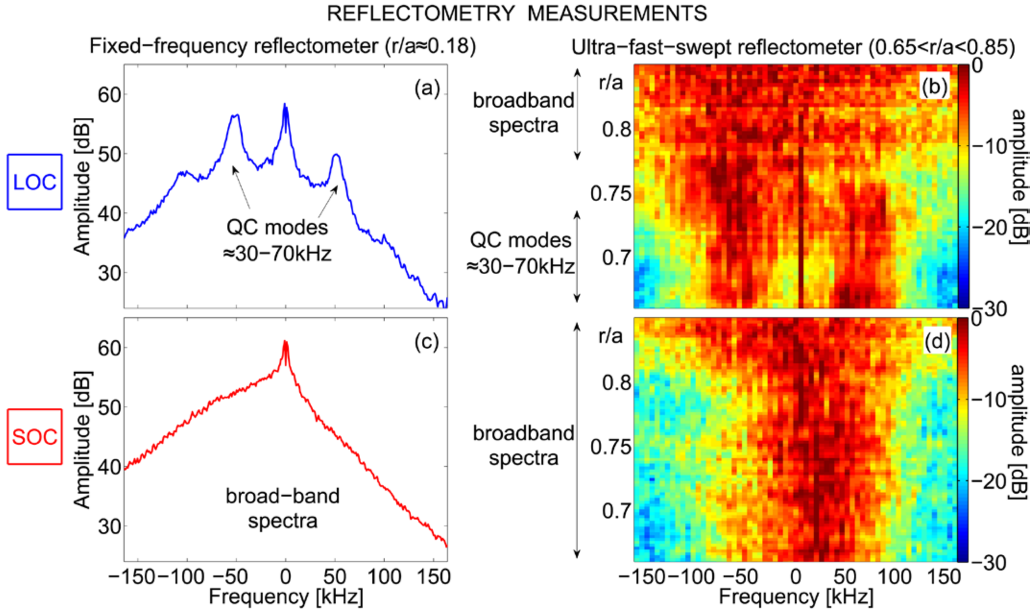

Figure 2. Fluctuation spectra from Tore Supra discharge #48102 which show ((a), (c)) fixed-frequency reflectometry measured at $r/a \approx 0.18$, ((b), (d)) ultra-fast-swept reflectometry measured for $0.65 < r/a < 0.85$. ((a)–(b)) correspond to the LOC regime and ((c)–(d)) to the SOC regime. They have been measured at t_1 and t_2 respectively, except (d) which has been measured at $t = 5.25$ s.

Table 1. Electron and ion heat fluxes from the GENE simulations and from the power balance.

	Power balance		GENE	
	q_i	q_e	q_i	q_e
LOC regime	4.5 ± 1	6.7 ± 1	3 ± 1	12 ± 3
SOC regime	14 ± 3	-1 ± 3	14 ± 2	9 ± 2

small spectral asymmetry observed can be due to various phenomena such as nonlinear response of the reflectometer or Doppler shift induced by rotation combined to vertical plasma shift, sawteeth, misalignment of the antenna [18, 19].

As previously shown [19, 20], QC modes are observed in the LOC case at $f \approx 50$ kHz in figure 2(a) and for $r/a < 0.75$ in figure 2(b). In the SOC case, only broad-band fluctuation spectra are seen (see figures 2(c)–(d)). The link between these differences in the spectral shape (QC modes, broad-band) and the dominant instabilities in the LOC and the SOC regimes (TEM, ITG) is investigated in the following section.

2.2. Spectra from nonlinear gyrokinetic simulations

Nonlinear simulations based on the Tore Supra discharge #48102 have been performed with the GENE code [21] at the times t_1 and t_2 indicated in figure 1 and corresponding to the measurements shown in section 2.1. Table 1 compares the heat flux for the electrons q_e and the ions q_i of the GENE simulations to those of the experimental values. As one can see the fluxes are low in the LOC regime where the QC modes are observed. An agreement is found between the GENE simulation and the experimental values, apart from q_e in the SOC regime.

The input parameters used are available in [14], where the output from the linear runs performed at the same location and times are discussed. This plasma region has been chosen because T_i measured by charge exchange recombination spectroscopy diagnostic has a higher resolution in this plasma region. Fluctuation measurements are not available at this radius (see previous section) but one can note that QC modes can be observed at many different radii in the LOC regime [14, 15, 22].

Figures 3(a) and (b) show for $r/a = 0.36$ the frequency fluctuation spectra from the nonlinear gyrokinetic simulations at t_1 and t_2 respectively. Simulated frequency spectra of $\tilde{n}_e$ can be compared qualitatively to the frequency spectra from reflectometry (sensitive to $\tilde{n}_e$). Contrary to reflectometry spectra, the diamagnetic direction of the phase velocity (ion/electron) can be distinguished by looking at the sign of the frequency (+/−). Thus figure 3 spectra show that the SOC and the LOC regimes are dominated by ITG ($f > 0$) and TEM ($f < 0$) instabilities respectively, the latter being a ∇T_e-driven TEM. This supports the linear runs previously carried out [14] and the hypothesis on the link between the LOC/SOC regimes and the TEM/ITG instabilities.

One should note that intermediate hybrid regimes where ITG modes can rotate in the electron diamagnetic direction exist [23]. However, in the present study the linear sensitivity analysis [14, 24] indicates that the turbulence is dominated by TEM in the LOC case and by ITG modes in the SOC case.

Additional significant information provided by the nonlinear runs is the difference in the spectral shape. In figure 3(b), the ITG-dominated case shows a single broad-band spectrum which includes the turbulence and the density zonal flows (ZFs) i.e. $k_y = 0$, $\omega = 0$. The nonlinear frequency broadening of TEM is smaller and shows a sharp peak, separated from ZFs (see figure 3(a)). As TEM instabilities coalesce in few wavenumbers, they induce a narrow frequency spetrum which can explain the QC modes measured in the TEM dominated regimes. The broad ITG spectra can explain the broad-band spectra measured in the SOC regime.

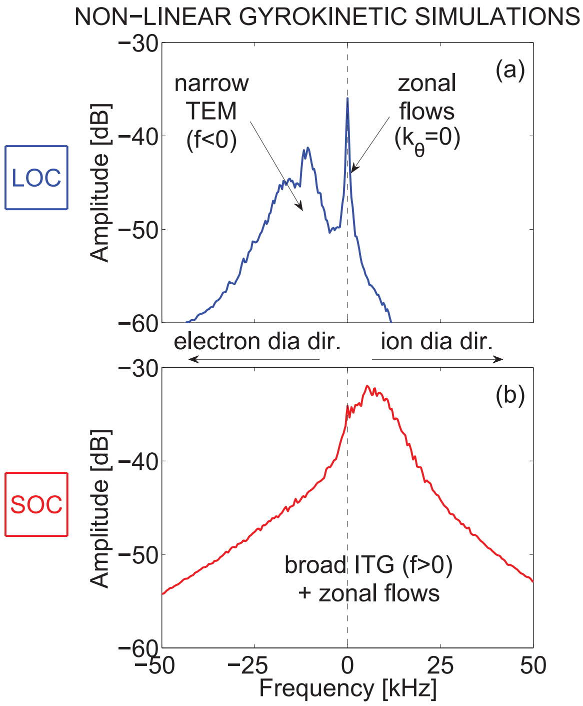

Figure 3. Fluctuation spectra from Tore Supra discharge #48102 provided by nonlinear gyrokinetic simulations computed at $r/a \approx 0.37$ in (a) the LOC regime at t_1 and (b) to the SOC regime at t_2.

The frequency of the TEM peak (≈12 kHz) is significantly lower than the frequency measured for QC modes (≈50 kHz). It comes from the fact that the GENE simulations do not take into account the rotation due to the mean $E \times B$ drift $v_{E\times B}$ but only the rotation due to the averaged phase velocity of the mode in the plasma frame v_{phase}. As the density fluctuations rotate with a total velocity $v_{\mathrm{tot}} = v_{E\times B} + v_{\mathrm{phase}}$, they are measured at higher frequency (see figures 2(a)–(d)) than the one shown in the GENE spectra (figures 3(a)–(b)). $v_{E\times B}$ is taken into account in the spectra from a synthetic reflectometer shown in the next section.

2.3. Spectra from a synthetic reflectometer diagnostic

The experimental fluctuation spectra were simulated with a synthetic reflectometry diagnostic using GENE nonlinear density fluctuations. This synthetic reflectometer relies on a 2D full-wave code solving the O-mode wave equation by means of a 2nd order Finite Difference Time Domain (FDTD) scheme [25]. Although the reflectometry measurements were obtained with the X-mode polarization, it was shown that both O-mode and X-mode simulations qualitatively produce the same signal spectra [26]. The maps of density fluctuations for 1024 successive time slots inferred from the GENE nonlinear gyrokinetic simulations were used as input in the 2D full-wave computations. For each map of density fluctuations the FDTD code was run over a number of time iterations large enough to reach the stationary regime and compute properly the reflected complex signal.

To ensure accurate comparison with the reflectometry measurements, the drift velocity $v_{E\times B} = (E_r \times B)/B^2$ is taken into account in the total fluctuation velocity. It is inferred using the radial electric field constrained by thermal ripple losses: $E_r = T_{\mathrm{i}}(\nabla n_{\mathrm{i}}/n_{\mathrm{i}} + 3.37\nabla T_{\mathrm{i}}/T_{\mathrm{i}})/e$ [27]. As shown in the fluctuation spectra of figures 4(a)–(b), QC modes appear in the LOC regime at around ≈75 kHz while the SOC regime shows only a broad-band spectrum. Even though there is a discrepancy with the QC modes observed in the measured spectra (shown in figure 4 as a reminder) at around ≈50 kHz, a qualitative agreement is found. This confirms the previous comparison between simulated and measured fluctuation spectra, indicating that the ITG modes can have a broad-band spectrum while the TEM can induce QC modes. The present results indicate that QC modes measured in the plasma core region can be due to ∇T_{e}-driven TEM instability in case of low flux. We will now refer to them as QC-TEM.

3. Scope of the QC-TEM analysis

The comparison of frequency spectra from nonlinear simulations, reflectometry measurements and a synthetic diagnostic indicates that TEM instability can have a QC signature in fluctuation spectra. This finding can then be used as a new technique to study TEM, besides gyrokinetic simulations, transport analysis and phase velocity estimations. However, it has to be used cautiously because (i) the lack of QC-TEM does not necessarily imply that the TEM are stable and (ii) there exist edge phenomena presently not attributed to TEM which can have a rather similar QC signature. This is discussed in the following sections together with the diagnostics and the devices for which this technique could be applied.

3.1. Fusion devices and diagnostics

QC-TEM have been observed in Tore Supra, TEXTOR and JET [14, 15] and first indications have been recently obtained in ASDEX-Upgrade (AUG) [28] (see section 3.4). The onset of QC-TEM in fluctuation spectra measured in the plasma core seems also possible in other fusion devices. Recent measurements made in the Madison symmetric torus (MST) reversed field pinch have shown a similar QC signature whereas gyrokinetic simulations predicted turbulence to be TEM-dominated [29]. These findings on QC-TEM may also help to investigate whether TEM can play a role in stellarators [30] and if they are stabilized in optimized stellarators [31].

The diagnostics able to perform such a study require a sensitivity to low wavenumbers in the order of the ITG/TEM instabilities scale ($k_\theta\rho_{\mathrm{i}} \leqslant 1$) and a capability to measure in the plasma core region. Apart from reflectometry [14, 32–34], structures possibly similar to QC-TEM may have been observed in TEM-dominated regimes with phase contrast imaging (PCI), far infrared interferometry (FIR), beam emission spectroscopy (BES), Doppler backscattering (DBS) reflectometry, and correlation electron cyclotron emission (CECE) systems [29, 35–38].

These studies have reported modifications of fluctuation spectra in TEM dominated regimes, without interpreting

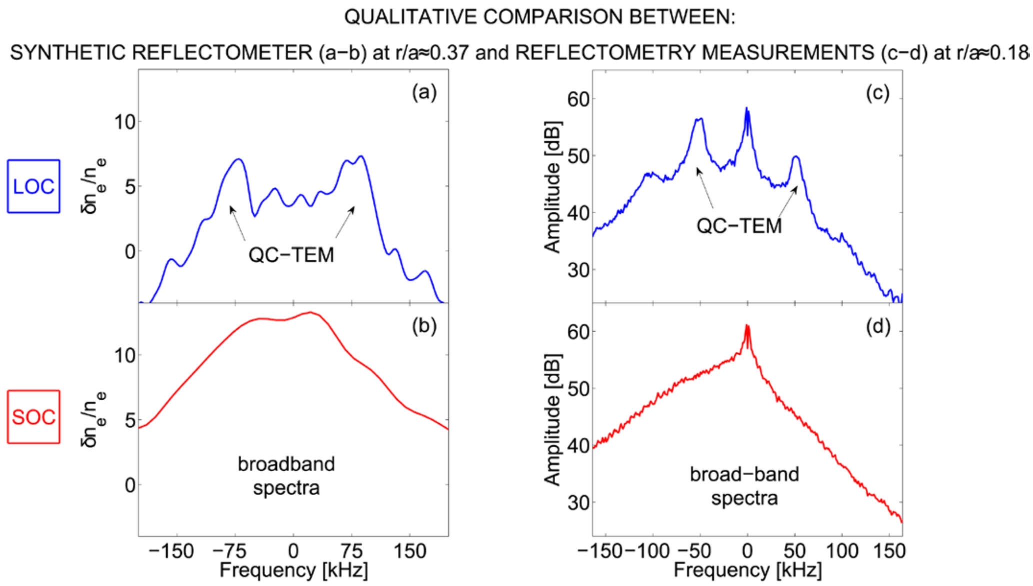

Figure 4. Fluctuation spectra from Tore Supra discharge #48102 provided by a synthetic reflectometer diagnostic using the nonlinear gyrokinetic simulations as an input. They are computed at $r/a \approx 0.37$ in (a) the LOC regime at t_1 and (b) to the SOC regime at t_2. On the right-hand side the spectra previously shown in figure 2 are plotted for a qualitative comparison.

a mode as being the signature of TEM. The present results suggest that the spectral modifications reported in TEM-dominated regimes by BES, CECE, PCI, DBS and FIR may translate the same QC-TEM phenomena.

3.2. Quasi-coherent fluctuations at the very edge of the plasma

Phenomena presenting a QC signature have been observed at the very edge of the plasma during H-mode [39, 40], enhanced D_α H-modes [41, 42] and I-mode [43]. At the moment, there is no unified explanation for these modes which present rather similar QC spectral signatures. Several instabilities have been suggested to cause them, as for example the kinetic ballooning mode which limits the pedestal growth in H-mode [39]. Presently, none of these modes have been linked to TEM. Therefore, the observation of QC modes can be taken as an indication of TEM in the plasma core region only ($0.1 < r/a < 0.95$), where no other QC fluctuations phenomena have been reported.

3.3. Fully developed TEM turbulence

The QC signature of TEM may disappear in case of fully developed TEM turbulence. Experimentally, the disappearance of QC-TEM has been observed while increasing ECRH power at high values [44]. In gyrokinetic simulations, an artificial increase of the electron temperature and density gradients R/L_{T_e} and R/L_{n_e} by a factor 1.4 while maintaining constant the gradient parameter $\eta_e = L_{n_e}/L_{T_e}$ has been done in the LOC regime. It shows that the double peak structure of TEM-dominated spectra (QC-TEM and ZFs) observed in figure 3(a) becomes unobservable [24]. In these two cases, TEM would not remain oscillating at a rather well-defined frequency (i.e. with a narrow spectrum) but would become broad-band (such as ITG) as expected generally for a turbulent phenomenon.

3.4. $E \times B$ rotation

We have seen in section 2 that the QC-TEM frequency depends on $v_{E\times B}$. If $v_{E\times B}$ is too low, the QC-TEM peak may be closer to the zero frequency. In that case QC-TEM could not be distinguishable even if TEM are driven unstable.

To highlight this effect, we analyze the Ohmic discharge #31427 from AUG ($R_0 = 1.65$ and $0.5 < a < 0.8$) in the LOC regime ($t \approx 1.4$ s). Figure 5(a) shows neoclassical estimations of $v_{E\times B}$ performed with the NEOART code [45] which use measurements of the toroidal velocity measured with charge exchange recombination spectroscopy [46]. The error bars of the $v_{E\times B}$ provided are of the order of 0.5–1 km s^{-1}. Figure 5(b) displays the radial evolution of the fluctuation spectra obtained by ultra-fast-swept reflectometry [17, 47, 48]. QC modes reminiscent of QC-TEM are observed around $0.25 < \rho < 0.4$ in a region where we expect $v_{E\times B} \geqslant 1$ km s^{-1}. For $\rho > 0.4$, QC modes cannot be properly observed in figure 5(b) and NEOART estimations indicate $v_{E\times B} \leqslant 1$ km s^{-1}. One can note that from $\rho = 0.4$ toward $\rho = 0.25$ the increase of the QC modes frequency (up to ≈75 kHz) is in qualitative agreement with the increase of $v_{E\times B}$ observed (up to ≈3 km s^{-1}).

Figure 5 shows for $\rho \approx 0.73$ spectra of the complex signal (c) and coherence (d) estimated with a poloidal correlation reflectometer (PCR) [28, 32, 33]. As previously reported in [28], coherence shows clear QC modes wheras they are not/barely observable in the spectra of the complex signal shown in figures 5(b)/(c) respectively. Therefore, in case of low $v_{E\times B}$, PCR can be used to investigate QC-TEM.

4. Application: transitions between TEM and MHD instabilities

An application of the identification of QC-TEM described so far is presented in this section. The analysis focuses on the Tore Supra discharge #40806 where 250 kW of ECRH power

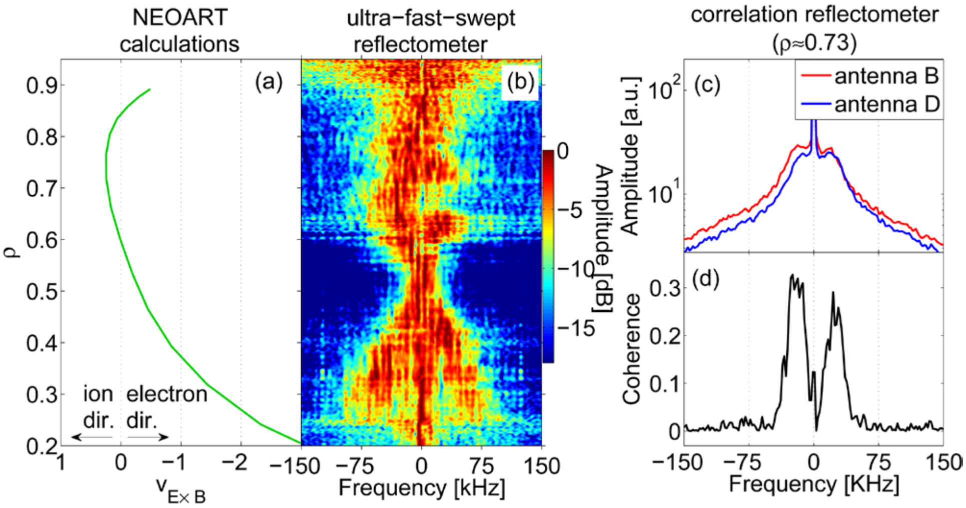

Figure 5. Data from the AUG discharge #31427 measured in the LOC regime ($t \approx 1.4$ s). In (a) the neoclassically predicted $V_{E\times B}$ provided by the NEOART code [45]. The negative/positive directions correspond to the electron/ion diamagnetic direction. Fluctuation spectra from an ultra-fast swept reflectometer are shown in (b) for $0.2 < \rho < 0.95$ and from two antennas of a PCR (c) at $\rho = 0.73$. The coherence between the two antennas of the PCR is displayed in (d).

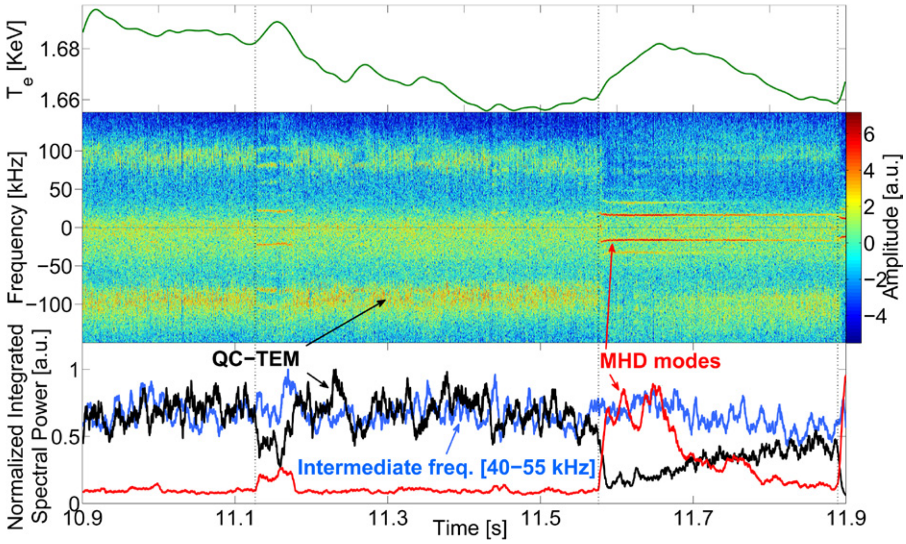

Figure 6. Data from the Tore Supra discharge #40806 measured at $r/a \approx 0.17$: evolution of the temperature (top), spectrogram from reflectometry data (middle) and normalized integrated spectral power for the QC-TEM (70–120 kHz) the MHD mode (10–25 kHz) and and intermediate frequency (40–55 kHz) (bottom). The main transitions between QC-TEM and the MHD mode are shown by the vertical dotted lines.

is deposited on the High Field Side (HFS) by two gyrotrons at $r/a = 0.58$ and $r/a = 0.35$. The safety factor is maintained above unity to avoid sawteeth ($B_t = 3.8$ T and $I_p = 0.5$ MA). As previously shown [14, 15], reflectometry measurements performed at $r/a \approx 0.17$ show QC-TEM in a region predicted to be TEM-dominated by linear gyrokinetic simulations and Nickel transport analysis [6, 7].

The ECRH power starts to be deposited at $t = 9.5$ s, and an interesting observation is made when the QC-TEM ($f \approx 70$ –120 kHz) are suddenly stabilized while a coherent MHD mode ($f \approx 15$ kHz) appears at $t \approx 11.58$ s (see figure 6). After this clear transition, the MHD mode is progressively damped during 300 ms while the QC-TEM amplitude recovers rather linearly. Such a transition appears to be a cycle which starts again at $t \approx 11.89$ s (no fluctuation measurements are available later). Before these cycles start, one can note that small precursors are first observed, the main one being at $t \approx 11.13$ s.

When QC-TEM are damped, T_e rises by a few percent, suggesting that the local confinement may be improved. The spectral power of the intermediate frequency range selected $40 < f[\text{kHz}] < 55$ shows no dramatic change in time. This highlights the fact that the transition occurs between the QC-TEM and the MHD mode. The nature of such a transition is of specific interest because it implies turbulent and MHD modes. The identification of the underlying mechanisms of the MHD modes is out of the main scope of the present paper. However, one of the possible candidate is discussed in the following paragraphs: the electron fishbones (e-fishbones).

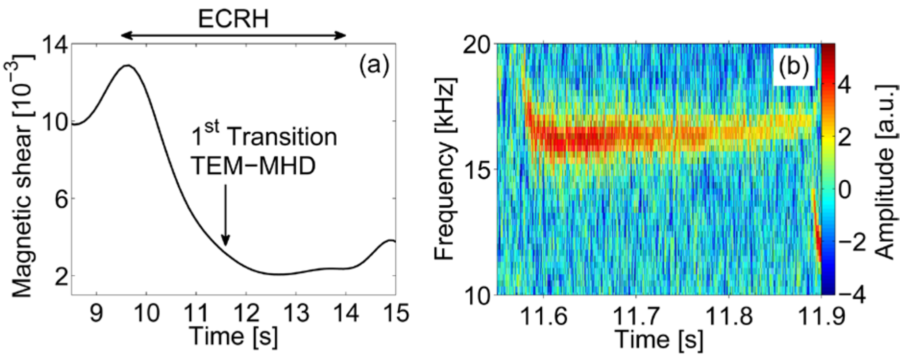

Figure 7. (a) magnetic shear estimated at $r/a \approx 0.16$ with polarimetry for the Tore Supra discharge #40805 (similar conditions to #40806), (b) shows the MHD modes observed in the reflectometry fluctuation spectra for #40806.

E-fishbones [49–53] require fast electrons which can be generated by ECRH and trapped electrons with a toroidal precession velocity v_{prec} oriented in the ion diamagnetic direction. Usually, the trapped electrons rotate in the electron diamagnetic direction (such as the ones which resonate with drift-waves in the case of TEM instability). However, at low magnetic shear $s = r\,[\mathrm{d}q/\mathrm{d}r]\,/q$, a reversal of v_{prec} can occur in the ion diamagnetic direction for the barely trapped electrons [54].

Estimations of s made with polarimetry [55] at $r/a \approx 0.16$ show that it decreases progressively during the ECRH deposition (see figure 7(a)). As the MHD mode appears after ≈2 s of ECRH, it can be explained by an excitation of e-fishbone when s is low enough due to barely trapped supra-thermal electrons with a reversed v_{prec} in the ion diamagnetic direction. One can note that the frequency chirping-down shown in figure 7(b) is characteristic of e-fishbones and that the deposition region on the HFS is in favor of e-fishbone destabilization [50]. The lack of trapped electrons with a v_{prec} in the electron diamagnetic direction may contribute to the stabilization of TEM.

5. Conclusion

The observation of QC modes in reflectometry fluctuation spectra measured in the plasma core region of AUG and Tore Supra LOC regime discharges has been reported.

Frequency spectra deduced from nonlinear simulations performed with the GENE core have been analyzed. They indicate that TEM can induce a narrow frequency spectra being responsible of the QC mode observed in the measured frequency spectra in the LOC regime. Fluctuation spectra from a synthetic diagnostic using the nonlinear simulations support this interpretation. Therefore these results suggest that core QC modes are a signature of TEM instabilities at least in case of low flux and ∇T_e-driven TEM. Conversely, TEM do not lead systematically to QC modes. Indeed QC modes and low frequency fluctuations can overlap in case of low $v_{E\times B}$. Furthermore, TEM frequency spectrum becomes broadband in gyrokinetic simulations performed at that larger R/L_{T_e} and R/L_{n_e} drives and there exist edge phenomena not attributed to TEM which can have a rather similar QC signature [39–43].

The identification with reflectometry of the QC modes signature of TEM can then be used to study turbulence besides gyrokinetic simulations, transport analysis and phase velocity estimations. Such analysis may be done with other diagnostics (PCI, BES, CECE, FIR, DBS) and may be valid in other fusion devices (RFP [29], stellarators). An example of a study using this knowledge on QC-TEM has been presented. It shows a transition between TEM turbulence and MHD modes, the latter being possibly due to e-fishbones.

The theoretical mechanism of the narrow TEM spectra frequency width (compared to the broader ITG spectra) is currently investigated [24, 56].

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