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Quasi Coherent Modes Correlated With Electron Transport and Velocity

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This letter reports on Quasi-Coherent (QC) modes observed in fluctuation spectra from Tore Supra and TEXTOR reflectometers. In both devices QC modes share commons properties which indicate that they most probably have the same underlying mechanism. These fluctuations are poloidally ballooned and appear over a wide frequency band (tens of kHz) usually centered between 40 and 120 kHz. QC modes onset in reflectometry spectra is correlated with an enhanced electron transport. In Tore Supra, their destabilization by Electron Cyclotron Resonance Heating (ECRH) has been observed in a region where Trapped Electron Modes (TEM) are expected to play an important role. In ohmic plasmas from both tokamaks, QC modes are detected only in Linear Ohmic Confinement (LOC) regime and disappear in Saturated Ohmic Confinement (SOC) regime. Perpendicular velocity measurements of density fluctuations have been made from the top of TEXTOR by correlation reflectometry. They show that QC modes rotate $\sim$ 300 m/s faster than lower frequency fluctuations in the electron diamagnetic direction. These observations suggest a link between QC modes and TEM.

1 Introduction

In fusion devices, measurements of a large variety of plasma parameters fluctuate (density, temperature, magnetic field, etc). Their spectra may show several components reflecting various phenomena responsible of such fluctuations. In reflectometry spectra which translate density fluctuations, three categories of components can be distinguished.

Coherent modes are associated with macroscopic plasma behavior. They translate oscillations at a defined frequency spread over a narrow frequency band ($\Delta f \sim$ 1kHz). Coherent modes include for example magnetohydrodynamics modes [1] and Geodesic Acoustic Modes (GAMs) [2] intensively investigated over the last decade.

Broad-band fluctuations composed the main part of reflectometry spectra. They are maximum at low frequency but extended to much higher frequencies ($\Delta f \sim$ hundreds of kHz). Even if their origins remain unclear, they are associated with micro-scale events and considered as the signature of a turbulence, i.e. a system with a large number of degrees of freedom [3].

Quasi Coherent (QC) modes shares properties of both previous spectra components. As coherent modes they are centered around a given frequency. However their large frequency spreading ($\Delta f \sim$ tens of kHz) reminds broad-band signature, indicating that they may be coupled to turbulence background. Various mechanisms have been proposed to explain QC oscillations observed by reflectometry [4–7] but their origins remains unclear and might differ.

QC modes observed in Tore Supra, T-10 and TEXTOR share similar properties suggesting that they may have the same underlying mechanism. They are commonly observed at many different radial positions from the core to the edge, depending on the plasma scenario. Frequencies of these QC modes is usually located around 40-120kHz and previous observations made in TEXTOR [4] and T-10 [5] indicate that they have a similar perpendicular wave numbers $k_\perp$ normalized to the ion gyroradius ρ_i ($0.1 < k_\perp\rho_i < 0.5$). Strong asymmetry is observed between spectra measured at Low Field Side (LFS) where QC modes are observed, and High Field Side (HFS) where they are damped. Such poloidal ballooning of QC modes is observed both in T-10 [5] and Tore Supra (see FIG. 1b). These general characteristics suggest that micro-instabilities may play a role in these QC fluctuations.

QC modes analysis is performed in Tore Supra and TEXTOR plasmas when transitions are expected between Ion Temperature Gradent (ITG) and Trapped Electron Modes (TEM). ITG and TEM are electrostatic micro-instabilities both unstable in the limit of "long" wavelengths $k_\perp\rho_i < 1$, considered to dominate the core/edge plasma turbulence [8–10]. Identifying their impacts in fluctuation spectra is still challenging as nonlinear effects are expected to mix their various contributions when several branches are linearly unstable. Moreover, several fluctuation diagnostics integrate measurements over space or wavenumbers, thus hindering a conclusive identification of the underlying modes driving the turbulence. Consequently most experimental investigations on ITG and TEM are not directly focused on the fluctuations they induce, but rather on their different properties (e.g., dependency on gradients and collisions, impact on radial pinch and fluctuations velocities) [11–15].

This letter repports on the correlation of QC modes onsets with enhanced electron transport regimes. Such QC modes onsets being linked with predicted TEM destabilization. Transitions from ITG to TEM dominated plasmas have been previously investigated during changes from SOC to LOC regimes and during ECRH activation [13–19]. For both scenario, behavior of QC modes is investigated experimentally and linear stability analysis is carried out. Additionally from the top of TEXTOR, perpendicular velocity are carried out for different fluctuations frequency. They indicate that QC modes rotate faster in the electron direction compared to low frequency broad-band fluctuations. For these investigations, Tore Supra X-mode reflectometers are used [20, 21] together with TEXTOR O-modes reflectometers able to perform poloidal correlation [22].

Other fluctuation diagnostics showed spectra modifications ITG-TEM transitions predicted by simulations. In Alcator C-Mod, a correlation between a “wing” structure and the Low Ohmic Confinement (LOC) regime has been highlighted in Phase Contrast Imaging (PCI) spectra [18]. Correlation Electron Cyclotron Emission (CECE) spectra have also shown specific fluctuations appearing in LOC only. Nevertheless their similarity with PCI “wing” structure remains unclear as they might not be observed simultaneously [19]. In DIIID Beam Emission Spectroscopy (BES) spectra, ECRH activation enhanced a fluctuations peak at around 100kHz, even though $\tilde{n}_e/n_e$ was not affected [16]. Moreover, CECE spectra showed an increase of both $\tilde{T}_e/T_e$ and a fluctuations peak similar to the one observed with BES. A comparison of CECE and reflectometer spectra made in [17] tends to indicate that that both diagnostics may translate the same phenomena (i.e. QC modes). Each of these fluctuations onsets in spectra where correlated with TEM destabilization but no perpendicular velocity measurements were provided.

2 Quasi Coherent modes destabilization by ECRH

In Tore Supra, comparison of 0.5 MW ECRH phase with a pure Ohmic phase of a discharge shows that ECRH onset enhances QC modes amplitude (see FIG 1a) as previously reported in T-10 [23]. Additionally to these qualitative observations, local measurements of reflectometers allow to study their radial dependency. FIG 1b show that their onet occurs only at LFS. FIG 1c shows that QC modes are present only in the deep plasma core ($r/a < 0.2$). They are damped for $0.2 < r/a < 0.3$ and disappear from the spectra further out ($r/a > 0.3$).

The existence of two regions has been already reported in a previous study based on the same plasma discharges [12, 24]. The aim of this study was to investigate turbulent impurity (nickel) transport dependence on the normalized electron temperature gradient in sawtooth-free plasmas. ECRH power from two Tore Supra gyrotrons was injected at a different location to modify the temperature gradient length.

In the deep plasma core ($r/a < 0.15$), measurements and simulations with the quasilinear gyrokinetic code

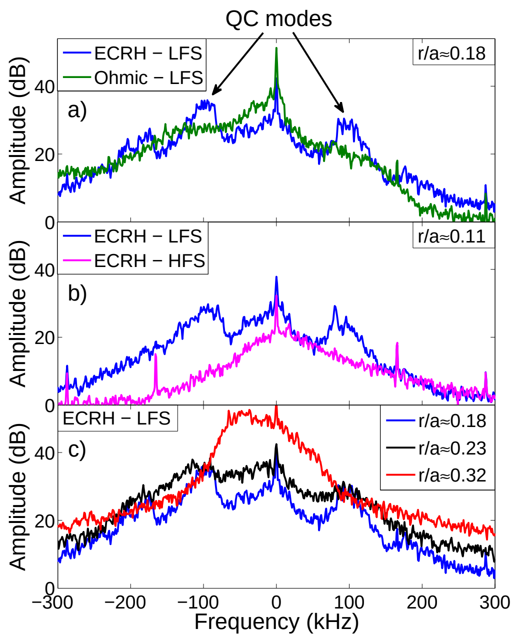

FIG. 1: Reflectometer spectra during Tore Supra #40801 compared between the ECRH and Ohmic phases a), between the LFS and HFS during ECRH phase (b) and between several radial positions measured at the LFS during the ECRH phase (c). Incertainties of r/a=0.01 is taken for radial position indications.

QuaLiKiz [25] indicate an increase of the impurity diffusivity together with the normalized logarithmic temperature gradient $R/L_{T_e} = -R\Delta T_e/T_e$. Further out ($r/a > 0.25$), no dependence of the impurity diffusion on R/L_{T_e} was observed. Linear gyrokinetic calculations performed with the KINEZERO [26] and GYRO [27] codes have shown that modes drifting in the electron diamagnetic direction dominate turbulence in the inner part of the plasma ($r/a < 0.15$). Further out ($r/a > 0.25$), ITG was predicted to be dominant as modes drifting in the ion diamagnetic direction dominate turbulence.

TEM tubulence which is generally predicted to play a significant role in ECRH plasmas [16, 17, 28] was proposed to explain these observations. Indeed TEM destabilization for $r/a < 0.15$ can explain the dependency on R/L_{T_e} observed. Furthermore, TEM are generally expected to rotated in the electron diamagnetic drift direction, as indicated by linear simulation in this region. In Tore Supra, both in term of amplitude and radial localization, QC modes behavior in reflectometry spectra suggests a link with TEM.

3 Quasi Coherent modes onset and ohmic regimes

QC modes behavior is analyzed during different transition scenarios between the two main Ohmic regimes: the LOC regime in which energy confinement time τ_e increases linearly with the density n_e, and the SOC regime where τ_e saturates with n_e. This saturation is governed by the behavior of electron confinement [29] and many investigations tend to support the long-standing hypothesis describing that TEM stabilization occurs in SOC [11, 14, 15, 19, 30–32]. The LOC-SOC transition is predicted to occur at n_s, the Shimomura density [33] which can be written as $n_s = I_p \mu_0 \sqrt{A_i \kappa}/2\pi a^2 \sqrt{2}$, where I_p is the plasma current, A_i the plasma atomic mass number, κ the plasma elongation and a is the minor radius. In this analysis A_i, κ and a are constant, therefore n_s depends only on I_p. It implies that a LOC to SOC transition is also possible by keeping n_e constant and decreasing I_p. Both n_e scan and I_p scan approaches are investigated.

3.1 Density scans approach

In FIG. 2 we analyze two density scans on a shot-to-shot basis, looking at the fluctuation spectra evolution as a function of density. The two n_e scans have been performed at two different plasma currents (I_p = 1.2 MA and I_p = 0.5 MA) to transit from LOC to SOC at a different density. Due to the reflectometer setup, measurements were carried out at r/a=0.3 and r/a=0.2 during the high and low I_p scan respectively. In both scans, QC modes were observed at around 40-80kHz in the LOC regime and were stabilized in the SOC regime. A previous investigation [5] has highlighted the QC modes

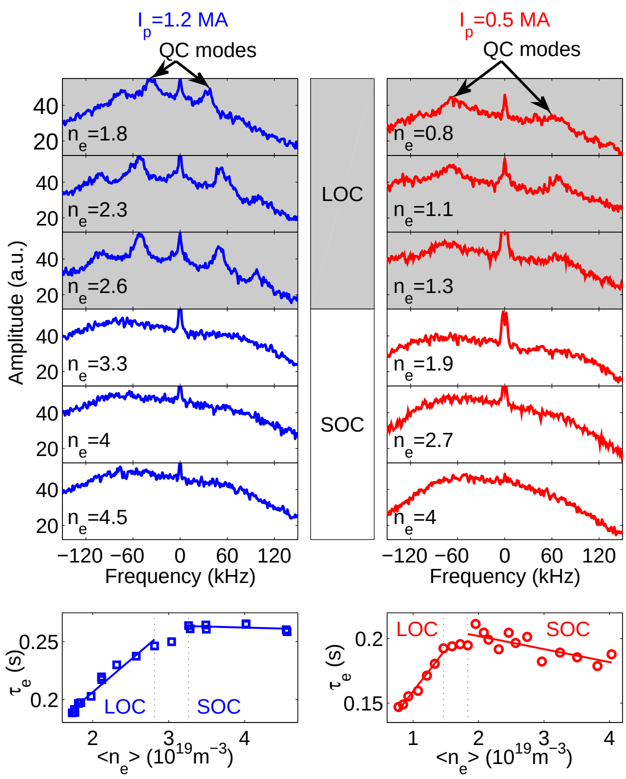

FIG. 2: n_e scans showing reflectometry spectra before and after LOC-SOC transitions at $I_p = 0.5MA$ ($TS41261-41272$) and $I_p = 1.2MA$ ($TS41003-41013$). In both cases, QC modes are observed at around 60kHz in the LOC regime only. The LOC-SOC transition is highlighted by the behavior of the energy confinement time τ_e during each n_e scan ($B_t = 3.8T$).

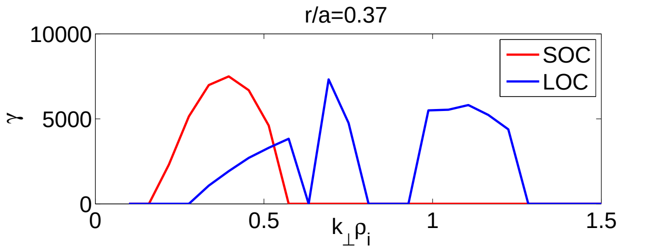

FIG. 3: QuaLiKiz linear instability growth rate calculations in Tore Supra #48102 for low n_e (LOC) and high n_e (SOC) performed at r/a=0.37.

dependency on n_e but the present Tore Supra results show that it is not n_e but rather the ohmic confinement regime which governs QC modes amplitude. Previously, TEM damping has been linked with other abrupt changes observed in electron heat diffusivity [13] and velocities [11, 15].

FIG 3 shows QuaLiKiz simulations performed in a LOC and SOC phase of a n_e scan. The predicted quasi-linear growth rate in LOC regime is non zero for a broad range of fluctuation wavenumbers ($0.2 < k_\theta \rho_i < 1.3$). In SOC regime, only the low wavenumber branch remains ($k_\theta \rho_i < 0.6$), suggesting a TEM stabilization. These simulations support a link between QC modes and TEM as already suggested by the ECRH plasma results.

3.2 Current scans approach

In FIG. 4 we analyze a Tore Supra shot in which an I_p scan is performed. The left column of FIG. 4 shows data measured at $r/a = 0.3$ with the reflectometer used for the spectra shown in FIG. 1. The LOC/SOC dependency of QC modes is similar to the one observed in the n_e scan at this radial position. They are detected in LOC regime only within a similar frequency range (40-80kHz).

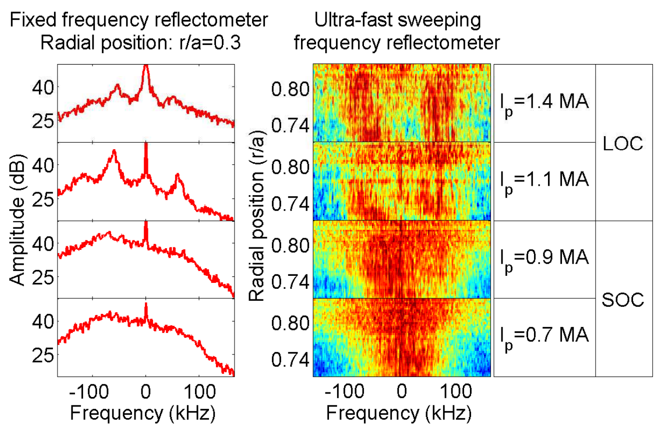

FIG. 4: Reflectometry spectra during I_p scan performed in the Tore Supra shot #47670. B_t = 3.7T and $1.9 < n_e(10^{19}m^{-3}) < 2.2$. Spectra shown in the right column have been normalized. In Both column, QC modes are visible around 50kHz, in LOC regime only.

Usually below $r/a \approx 0.15$, sawtooth phenomena do not allow for clear conclusions as they yield a complicated interpretation of the measurements and change the fluctuation physics. Above $r/a \approx 0.3$ no measurements are provided by this reflectometer, but the right column of FIG 4 presents spectra from another reflectometer able to measure in the outer part. It probes the plasma with an ultra-fast sweeping frequency system [21] which has the advantage to provide good radial resolution [34]. The drawback of such techniques is to give spectra with a degraded quality compared to the ones previously shown. For a better visualization, they are normalized for each r/a (i.e. for each probing frequency). Up to $r/a \approx 0.8$ qualitative observations are similar to the ones made at $r/a = 0.3$ as QC modes are detected in LOC regime only. Above $r/a \approx 0.8$ no radical change is observed in the spectra at the LOC/SOC transition, as QC modes are not even detected in the LOC regime. These observations made during the I_p scan confirm those made in the n_e scan. They show that fluctuations change occurs over a wide radial range during the LOC-SOC transition.

FIG. 5 presents TEXTOR reflectometer data measured from the top of the torus during a shot in which a current ramp-down is performed. For the analysis, two times have been selected at $I_p = 400$ kA (left column) and $I_p = 250$ kA (right column). Previous investigations [35] are used to determine that $I_p = 400$ kA and $I_p = 250$ kA correspond to LOC and SOC regimes respectively.

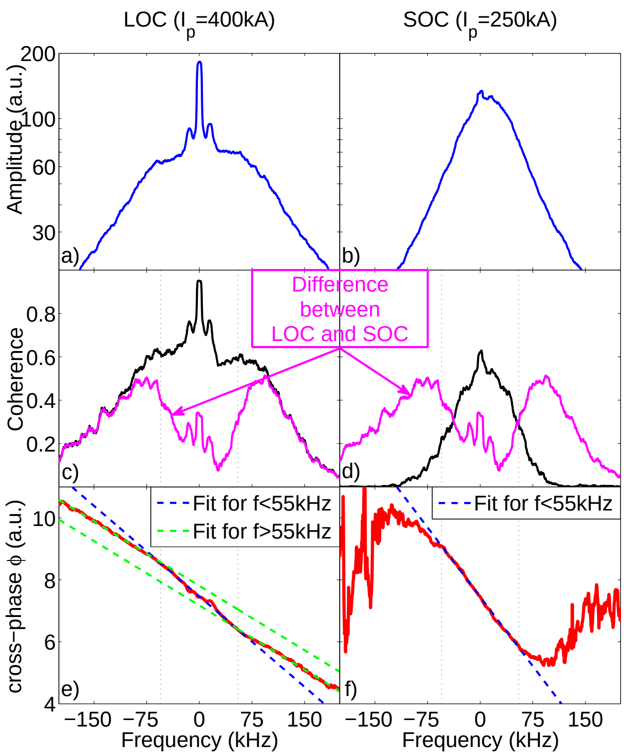

FIG. 5: TEXTOR reflectometer spectra measured at r/a=0.91 from the top of the torus during shot number #117780

Spectra of TEXTOR reflectometer signals show weak QC modes in LOC (FIG. 5a) and only a broad-band spectrum in SOC (FIG. 5b). This is in accordance with Tore Supra observations made during the I_p scan (see FIG 4). One can note that even if they are still detectable, QC modes are not as pronounced than in Tore Supra spectra. QC modes can be highlighted in TEXTOR by coherence analysis. Indeed, the correlation system made of antenna poloidally separated [22] can provide the coherence between each pair of antenna, as shown in FIG. 5 (c-d) for both I_p values. In the SOC regime, QC modes are not observed and only low frequency broad-band fluctuations appear with a coherence of ~ 0.5. In the LOC regime QC modes are observed at a coherence of ~ 0.5 together with low frequency broad-band fluctuations.

4 Quasi Coherent modes perpendicular rotation

The TEXTOR reflectometer system can also provide the local perpendicular rotation of electron density fluctuations $\Omega_\perp^{measured}$ as a function of fluctuation frequency [4]. This can be inferred from $d\phi/df$, the slope of the cross-phase obtained with two antenna separated poloidally by an angle α with $\Omega_\perp^{measured} = {}^{2\pi\alpha}/_{d\phi/df}$. In the SOC regime, only one slope is observed in the cross-phase spectra for frequencies below 55kHz (see FIG 5f). Above this value, the cross-phase degenerates because no fluctuations are measured in the coherence. FIG 5e shows spectra obtained in LOC regime. One can notice that GAMs are observable for $f \approx 15 \sim 20$ kHz in the coherence and amplitude spectra and that they deviate the cross-phase as they have no rotation in the laboratory frame [2]. Excluding GAMs two distinct slopes can be identified in the LOC regime. Within the part of the spectra corresponding to the low frequency broad-band ($f < 55kHz$) the slope is steeper than for higher frequencies dominated by QC modes ($f > 55kHz$). Correlation between velocity bifurcation and QC modes is highlighted by the difference between the coherence calculated for the LOC and SOC regimes (see FIG. 5 c-d). This difference observed in the cross-phase slope indicates a faster rotatation for QC modes than for the low frequency broad-band. As the $E \times B$ drift is in the electron diamagnetic direction, QC modes rotate faster in the electron direction compared to the low frequency broad-band.

To determine the velocity of both slopes, frequency ranges have been carefully selected for the low frequency fluctuations to avoid the impact of GAMs on the velocity ($25kHz < f_{lowfrequency} < 45kHz$) and for QC modes to exclude high frequency disturbance and overlap with low-frequency fluctuations ($75kHz < f_{QC} < 120kHz$). The perpendicular velocity estimations give 3.5 km/s for the low frequency broad-band fluctuations and 3.8 km/s for QC modes. Both velocities measured being in the electron diamagnetic direction, QC modes rotate 300m/s faster in this direction compared to low frequency broad-band fluctuations.

The $\tilde{n}_e$ velocity perpendicular to magnetic field lines can be decomposed into two components: $\Omega_\perp^{measured} =$

$\Omega_\perp^{E\times B} + \Omega_\perp^{phase}$. With $\Omega_\perp^{E\times B}$ the rotation due to the $E \times B$ drift, and $\Omega_\perp^{phase}$ the rotation due to the phase velocity of the drift waves in the plasma frame. Measurements does not allow to distinguish both components as it provides the total velocity. Nevertheless it is known that $\Omega_\perp^{E\times B}$ is the same for all the species and its order of magnitude corresponds to several km/s, far above from the difference of velocity measured. However, the sign of $\Omega_\perp^{phase}$ does depend on the species involved, and its order of magnitude corresponds to the velocity difference estimated (several hundreds of m/s [15]). It is generally expected to be directed in the electron and ion diamagnetic direction for electron and ion driven turbulence respectively. This would suggest that the observed difference of 300m/s might be explained by a phase velocity in the electron diamagnetic direction for the QC modes (as expected for TEM), and/or an ion diamagnetic direction for the low frequency broad-band (as expected for ITG modes for example).

5 Conclusion

The present reflectometry results and instability calculations support the link between QC modes and TEM. The question of the deep nature of QC modes and their connection with TEM is under investigation and still needs to be answered. A reservoir modes seeded by TEM turbulence might be a proposal for further investigations.

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