EUROFUSION CP(15)05/116

H. Arnichand et al.

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(22nd June 2015 – 26th June 2015)
Lisbon, Portugal

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Differentiation of TEM in fluctuation spectra: evidences, limitations and first application

H. Arnichand[1], J. Citrin[1,2], S. Hacquin[1], R. Sabot[1], A. Krämer-Flecken[3], X. Garbet[1], C. Bourdelle[1], C. Bottereau[1], F. Clairet[1], J.C. Giacalone[1], Z.O. Guimarães-Filho[4], R. Guirlet[1], G. Hornung[5], A. Lebschy[6,7], P. Lotte[1], P. Maget[1], A. Medvedeva[1,6,7], D. Molina[1], V. Nikolaeva[6], D. Prisiazhniuk[6,7], the Tore Supra and the ASDEX Upgrade teams

[1] CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France

[2] FOM Institute DIFFER-Dutch Institute for Fundamental Energy Research, Nieuwegein, The Netherlands

[3] Institute for Energy Research (Plasma Physics) Forschungszentrum Jülich, D-52425 Jülich, Germany

[4] Institute of Physics, University of São Paulo, 05315-970 São Paulo, Brazil

[5] Department of Applied Physics Ghent University, Sint-Pietersnieuwstraat 41 B4, 9000 Gent, Belgium

[6] Max-Planck-Institut für Plasmaphysik, IPP, D-85748 Garching, Germany

[7] Physik-Department E28, Technische Universität München, D-85748 Garching, Germany

E-mail: `hugo.arnichand@cea.fr`

Abstract.

Ion temperature gradient (ITG) and trapped electron modes (TEM) are two important micro-instabilities in the plasma core region of fusion devices. They are usually mixed in the same range of spatial scale (around $0.1 < k_\perp \rho_i < 1$), which make their differentiation complicated. To investigate them one can perform gyrokinetic simulations, transport analysis and phase velocity estimations. We show in this paper that a surprising finding achieved in Tore Supra makes the discrimination between TEM and ITG also possible in 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 become a possible additional tool to differentiate TEM from ITG. We evidence the TEM signature of the core QC modes by comparing frequency fluctuation spectra from reflectometry measurements, gyrokinetic simulations and synthetic diagnostic results. Then the scope and the limitations of the analysis of QC-TEM are discussed and an application is shown. It relates a transition between electrostatic TEM turbulence and electromagnetic fluctuations.

Keywords: turbulence, micro-instabilities, trapped electron modes, MHD, electron cyclotron resonance heating, ohmic confinement, reflectometry

Introduction

Plasma turbulence is responsible for the anomalous transport observed in magnetic fusion devices. It is attributed to drift waves whose perpendicular wave numbers $k_\perp$ normalized to the ion gyroradius ρ_i range between 0.1 and a hundred. Among the most important micro-instabilities present in the plasma core region, one can cite the ion temperature gradient (ITG), the trapped electron modes (TEM) and the electron temperature gradient (ETG). Usually the ETG modes have a rather distinct scale ($k_\perp\rho_i \approx 10$) while the ITG/TEM branches are mixed at the same scale (around $0.1 < k_\perp\rho_i < 1$) [1, 2]. This makes the distinction of TEM and ITG-dominated regimes complicated. Even though it is not always possible, discriminating them is useful to study their effects on plasma parameters (rotation, transport, etc.).

To achieve this, gyro-kinetics simulations can be done to determine which of TEM and ITG growth rate is dominant [3] but they rely on theoretical predictions of phenomena that we do not fully understand. It is also possible to investigate them experimentally. For instance by estimating their phase velocity at a given wavenumber in the plasma frame as they are usually in opposite directions [4]. This is difficult since the rotation components must be measured with accuracy [5]. Discriminating ITG/TEM from transport is also a possibility but a precise estimation of the diffusion coefficient and the convection velocity is required [6].

We show in this paper that a surprising finding makes the discrimination of TEM and ITG also possible in frequency fluctuation spectra. TEM-dominated regimes can induce "quasi-coherent" (QC) modes named QC-TEM, instead of showing a broad-band 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 evidences of these QC-TEM are shown in section 1, where measured and simulated spectra are compared, together with the spectra of a synthetic diagnostic. The scope and the limitation of this new technique are discussed in section 2 and an example of an application is presented in section 3.

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

All the data presented in this section are related to the Tore Supra tokamak with a major and a minor radius $R_0 = 2.4$ [m] and $a = 0.72$ [m] meters respectively. To evidence the TEM signature of the core QC modes in fluctuation spectra, 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, 7–11]. This study compares frequency fluctuation spectra from (i) reflectometry measurements, (ii) non-linear gyro-kinetic simulations and (iii) simulations from a synthetic reflectometer.

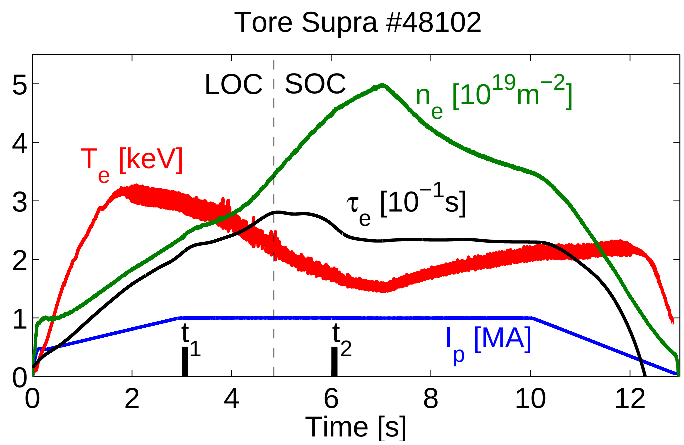

Figure 1. Main parameters of the Tore Supra discharge #48102 ($B_t = 3.82$). I_p is the plasma current, T_e is the central temperature and n_e is the central line averaged density and τ_e the energy confinement time. The dotted line indicates the LOC-SOC transition and the two vertical black dashes show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

1.1. Spectra from reflectometry measurements

Previous analysis of Tore Supra and TEXTOR spectra measured by reflectometry have shown that QC-TEM disappear at the LOC-SOC transition during n_e ramp-up or I_p ramp-down [11]. The decrease of QC-TEM during such ramps has also been reported in JET. A qualitative agreement has been found with the Tore Supra and the TEXTOR observations [12].

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: $t_1 \approx 3s$ in the LOC regime and $t_2 \approx 6s$ in the SOC regime. The LOC-SOC transition occurs at around $n_e \approx 3.45 \cdot 10^{19} m^{-2}$ which correspond to $t \approx 4.85s$ [see dotted line in figure 1].

Data used for figure 2(a,e,b,f) are obtained experimentally with two X-mode reflectometers. Figures 2(a,e) show fluctuation spectra obtained at $r/a \approx 0.18$ with a fixed-frequency reflectometer [13]. In figures 2(b,f), an ultra-fast-swept reflectometer [14] 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 do not allow to distinguish them. They translate phase increments and decrements respectively. The small spectra asymmetry observed can be due to various phenomena (nonlinear reponse of the reflectometer, Doppler shift induced by rotation and combined to vertical plasma shift, sawteeth, misalignment of the antenna, etc.) [15, 16].

As previously shown [16, 17], QC modes are observed in the LOC case around $25 < f_{QC}[kHz] < 75$ kHz in figure 2(a) and for $r/a < 0.75$ in figure 2(b). In the SOC case, only broad-band fluctuation spectra remain [see figure 2(e,f)]. The link between these differences in spectra shape (QC, broad-band) and the turbulence (TEM, ITG) is detailed in the following section.

1.2. Spectra from non-linear gyro-kinetic simulations

Figures 2(d,h) show frequency fluctuation spectra from gyro-kinetics simulations made with the GENE code [18] at t_1 and t_2 for r/a=0.37. Such plasma region has been chosen due to the good estimation of ∇T_i available. Measurements shown in the previous section are made at $r/a = 0.18$ and $0.65 < r/a < 0.75$ but one can note that QC modes can be observed at many different radius in the LOC regime [11,12].

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 these spectra show that the LOC and the SOC regimes are dominated by ITG ($f > 0$) and TEM ($f < 0$) respectively. It supports the linear runs previously carried out [11] and the *ansatz* on the link between the LOC/SOC regimes and the TEM/ITG instabilities.

The additional information of great interest provided by the non-linear runs is the difference in the spectra shape. In figure 2(h), the ITG-dominated case shows a single broad-band spectrum which mixes the turbulence and the low frequency density zonal flows (ZFs) i.e. $k_\theta = 0$. On the contrary, the non-linear frequency broadening of TEM is small enough to lead to a discernible frequency gap between them and the ZFs [see figure 2(d)]. As TEM instabilities coalesce in few wavenumbers, they induce a narrow frequency spetrum which shows a double peak (TEM+ZFs). This can explain the observations made in the previous section: the onset of QC modes occurs in the TEM dominated regimes, while the broad ITG spectra can explain the broad-band spectra measured in the SOC regime.

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}. $v_{E\times B}$ is taken into account in the spectra from a synthetic reflectometer show in the next section.

1.3. Spectra from a synthetic reflectometer diagnostic

The experimental fluctuation spectra were simulated with a synthetic reflectometer diagnostic, which relies on a 2D full-wave code solving the O-mode wave equation by means of a 2^{nd} order Finite Difference Time Domain (FDTD) scheme [19]. The maps of density fluctuations for 1024 successive time slots inferred from the non-linear gyro-kinetic simulations were used as input in the 2D full-wave computations. For each map of density fluctuation 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 simulations of the reflectometry measurements, the drift velocity $v_{E\times B} = (E_r \times B)/B^2$ which is in-

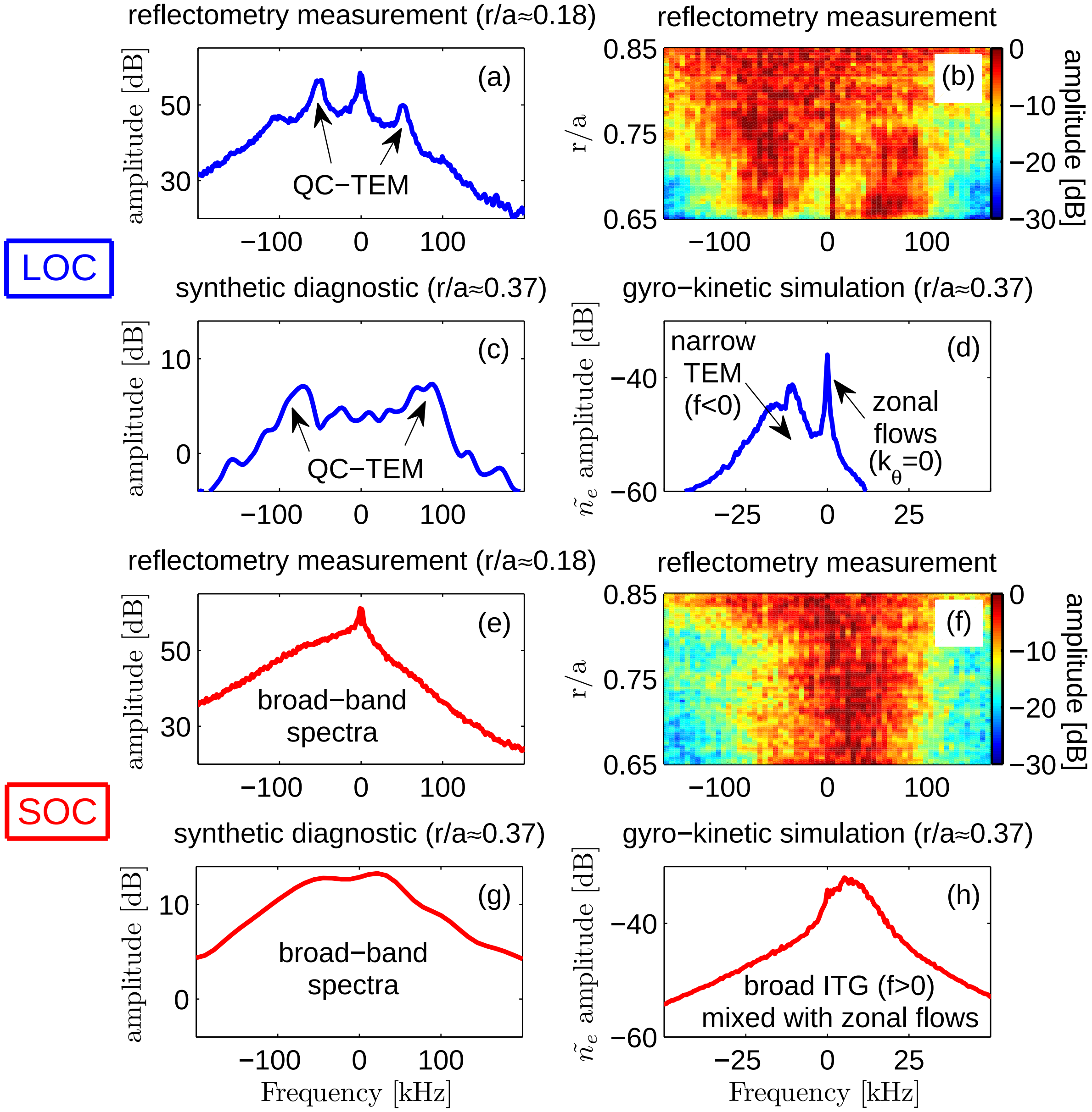

Figure 2. Fluctuation spectra from (a,e) fixed-frequency reflectometry, (d,f) ultra-fast-swept reflectometry, (d,h) non-linear gyro-kinetic simulations and (c,g) synthetic reflectometer. (a-d) correspond to the LOC regime and (e-h) to the SOC regime. They have been measured at t_1 and t_2 respectively, excepted (h) which has been measured at $t = 5.25$ s.

ferred using the radial electric field estimated with the formula $E_r = T_i(\nabla n_i/n_i + 3.37\nabla T_i/T_i)/e$ [20] is taken into account in the total fluctuation velocity ($v_{tot} = v_{E\times B} + v_{phase}$). As shown in the fluctuation spectra of figure 2(c,g), QC-TEM appear in the LOC regime at around ≈ 75 kHz while the SOC regime shows only a broad-band spectrum. 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-TEM.

Although the synthetic reflectometry diagnostic relies on O-mode computations while 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 [21].

2. Scope and limitations of the QC-TEM analysis

The comparison of frequency spectra from non-linear simulations, reflectometry measurements and a synthetic diagnostic shows 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 gyro-kinetic 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) it exists edge phenomena not attributed to TEM which can have a rather similar QC signature. In the following subsections we discuss these issues, together with the diagnostics and the devices for which this technique could be applied.

2.1. Fusion devices and diagnostics

This paper reports observations of QC-TEM in Tore Supra but they have been detected in several other tokamaks such as TEXTOR [11, 12], JET [12] and first indication have been recently obtained in ASDEX-Upgrade (AUG) [22] [see section 2.4]. The onset of QC-TEM in fluctuation spectra measured in the plasma core seems also possible in other fusion devices. Recent measurements in a MST reversed field pinch plasma have shown a similar QC signature whearas gyro-kinetic simulation predicted the turbulence to be TEM-dominated [23]. These findings on QC-TEM may also help to investigate whether TEM are stable in stellarators [24, 25] or if they can play a role [26, 27].

The diagnostics able to perform such a study require a sensitivity to low wavenumbers in the order of the ITG/TEM instabilities ($k_\theta\rho_i \leq 1$) and a capability to measure in the plasma core region. Apart from reflectometry [11, 28–30], 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 [23, 31–34].

These studies have reported modifications of fluctuation spectra in TEM dominated regimes, without interpreting a mode as being the signature of TEM. The fact that QC-TEM are in fact a direct signature of TEM suggest that the spectral modifications reported in TEM-dominated regimes by BES, CECE, PCI and FIR may translate the same QC-TEM phenomena.

2.2. Edge quasi-coherent fluctuations

Phenomena presenting QC signature have been observed at the plasma edge during H-mode [35, 36], Enhanced D_α H-modes [37, 38] and I-mode [39]. At the moment, there is no unified explanation for these modes which present rather similar QC spectral signature. Several instabilities have been suggested to interpret them, as for example the kinetic ballooning mode which limits the pedestal growth in H-mode [35]. Presently, none of these modes have been linked to TEM. Therefore, at the moment the observation of QC modes can be taken as an indication of TEM in the plasma core region only, where no other QC fluctuations phenomena have been reported.

2.3. 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 [40]. In gyrokinetic simulations, an artificial increase of R/L_{T_e} and R/L_{n_e} 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 2(d) becomes unobservable [41]. In these two cases, TEM would not remain oscillating at a rather defined frequency (i.e. with a narrow spectrum) but would become broad-band (such as ITG) as expected generally for a turbulent phenomenon.

2.4. $E \times B$ Rotation

We have seen in section 1 that the $E \times B$ drift strongly influences the mode frequency. If $v_{E\times B}$ is too low, the QC-TEM peak may be close 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 ($t \approx 1.4s$). Figure 3(a) shows neoclassical estimations of $v_{E\times B}$ performed with the NEOART code [42], and figure 3(b) displays the radial evolution of the fluctuation spectra obtained by ultra-fast-swept reflectometry [14, 43, 44]. QC modes reminiscent of QC-TEM are observed around $0.25 < \rho < 0.4$ in a region where we expect $v_{E\times B} \geq 1$ km/s. For $\rho > 0.4$, QC modes cannot be properly observed in figure 3(b) and NEOART estimations indicate $v_{E\times B} \leq 1$ km/s. One can notes 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 $\approx 3km/s$).

The error bars of the $v_{E\times B}$ provided are in the order of 0.5 to 1 km/s. A more detailed study involving estimations of $v_{E\times B}$ and v_{phase} with DBS reflectometry and charge exchange recombination spectroscopy [45] is planned. Besides, a deeper study of fluctuation spectra across the LOC-SOC transition is required to properly identify these QC modes as QC-TEM in AUG plasmas.

Figure 3 shows for $\rho \approx 0.73$ spectra of the complex signal (c) and coherence (d) estimated with a poloidal correlation reflectometer (PCR) [22, 28, 29]. As pre-

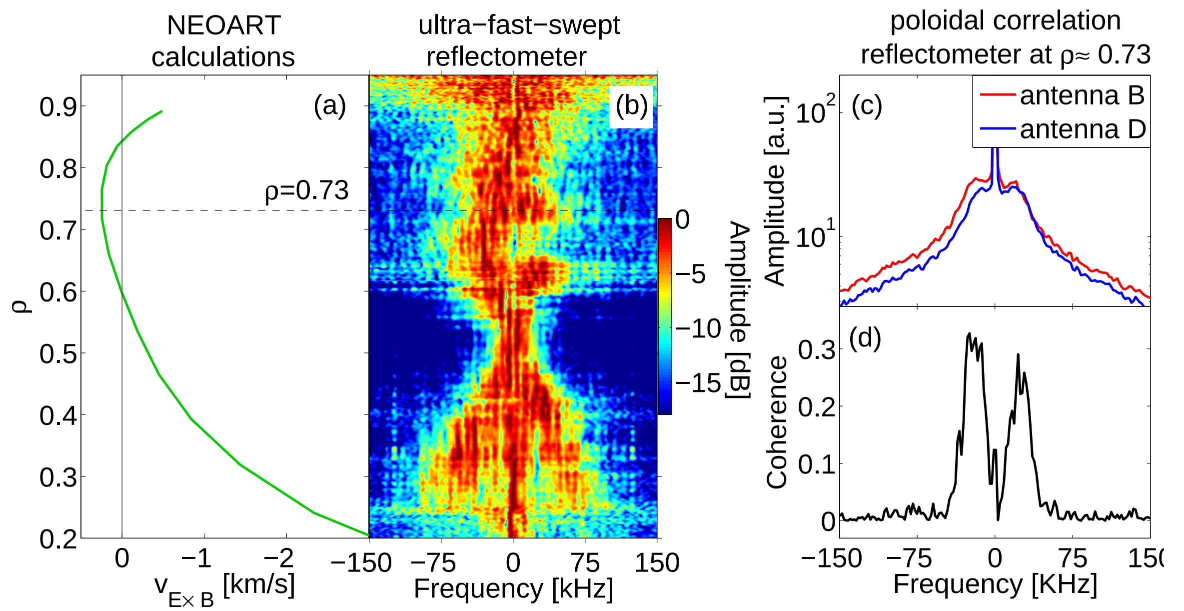

Figure 3. Data from the AUG discharge #31427 measured in the LOC regime ($t \approx 1.4$s). In (a) the neoclassically predicted $V_{E\times B}$ provided by the NEOART code [42]. The negative/positive directions correspond to the electron/ion diamagnetic direction. Fluctuation spectra from an ultra-fast swept reflectometer are shown in (b) for $0.2 < \rho < 0.95$ and from two antenna of a PCR (c) at $\rho = 0.73$. The coherence between the two antenna of the PCR is displayed in (d).

viously reported in [22], coherence shows clear QC modes wheras they are not/barely observable in the spectra of the complex signal shown in figure 3(b)/(c) respectively. Hence, a too low $v_{E\times B}$ may not allow to distinguish QC modes which are too close to the zero frequency. In that case, coherence obtained by the PCR is required to show clear QC peaks separated from the low frequencies.

3. Application: interplay between TEM and MHD instabilities

An application of the technique described so far is made in this section. It is used to investigate an interplay observed between turbulent fluctuations due to QC-TEM ($f \approx 100$ kHz and $\Delta f \approx 50$ kHz) and a coherent mode ($f \approx 15$ kHz and $\Delta f \approx 1$ kHz). Using previous observations, the turbulent phenomena involved is identified as TEM. The study of the coherent modes is out of the main scope of the present paper. However its underlying mechanism will be discussed and attributed to MHD activity, without being clearly identified. The nature of such an interplay is of specific interest because it implies electrostatic (TEM) and electromagnetic (MHD) modes.

The analysis is focused on the Tore Supra discharges #40806 where 250 kW of ECRH power is deposited with two gyrotrons at $r/a = 0.58$ and $r/a = 0.35$ on the High Field Side (HFS). The safety factor is maintained above unity to avoid sawteeth ($B_t = 3.8$ T and $I_p = 0.5$ MA). Reflectometry measurements were performed at $r/a \approx 0.17$, a region predicted to be TEM-dominated by linear gyro-kinetic simulations, Nickel transport analysis [6,

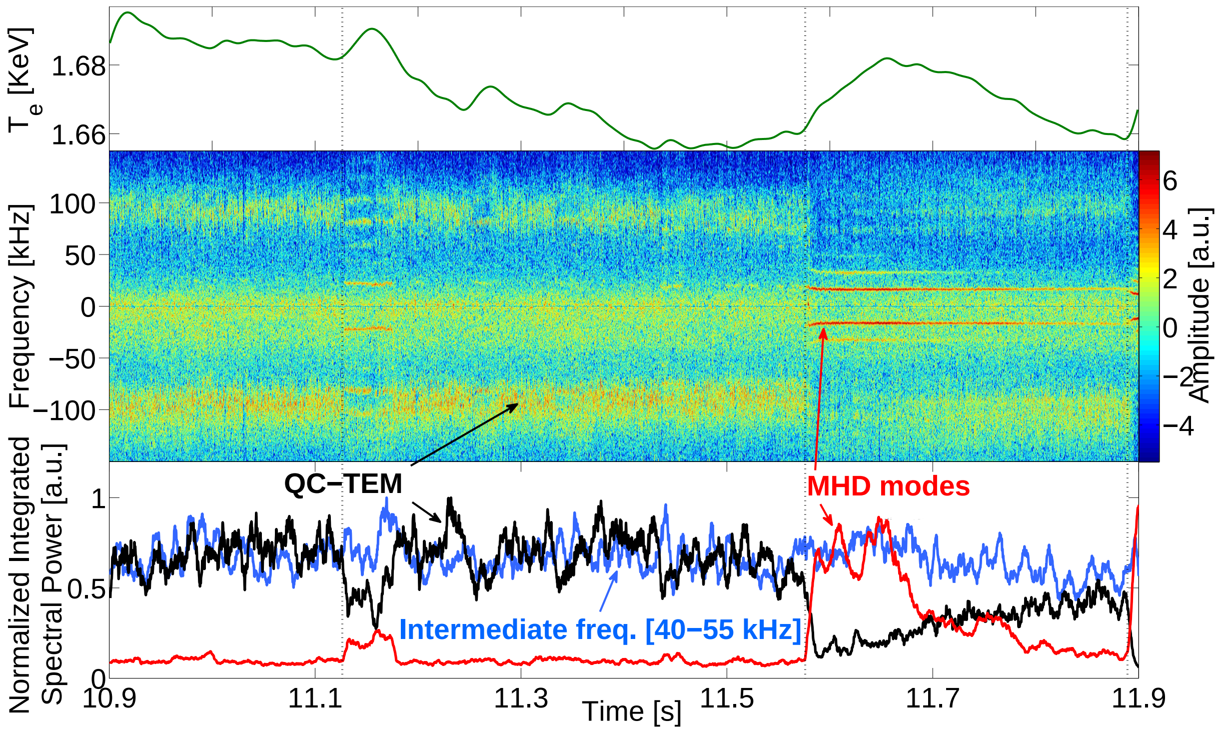

Figure 4. Data from the Tore Supra discharge #40806 measure at $r/a \approx 0.17$: Evolution of the temperature (top), spectrogram from reflectometry data (middle) and normalized integrated spectral power for the QC-TEM [70-120 kHz] the MHD mode [10-25 kHz] and and intermediate frequency [40-55 kHz] (bottom). The main transitions between QC-TEM and the MHD mode are shown by the vertical dotted lines.

46] and fluctuation spectra study [11].

The interesting observation is made when the QC-TEM are suddenly stabilized while a coherent mode appears at $t \approx 11.58$ s [see figure 4]. After this clear transition, the coherent mode is progressively damped during 300 ms while the QC-TEM amplitude recovers rather linearly. Such interplay 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 percents, suggesting that the local confinement may be improved. Such an increase may progressively drive TEM unstable again. The spectral power of the intermediate frequency range selected $40 < f[kHz] < 55$ shows no dramatic change in time. This highlights the fact that the interplay occurs between the QC-TEM and the coherent mode.

The coherent modes cannot be due to geodesic acoustic modes (GAM) because they are damped at such radial position. There is no heating system producing fast ions (ICRH, NBI) required for energetic GAM (eGAM). Other acoustic frequency range modes such as the toroidal Alfvn eigenmode (TAEs) or the beta-induced Alfvn eigenmode (BAEs) cannot explain these oscillations at $\approx$ 15 kHz because they are expected at much higher frequencies. Other MHD phenomena can be con-

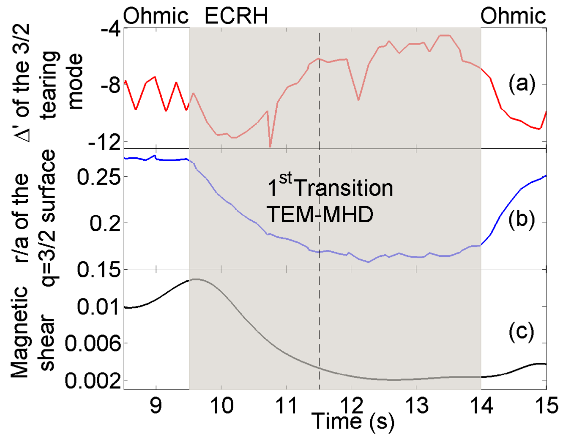

Figure 5. Data from the Tore Supra discharge #40805 (similar condition to #40806): (a) Δ' parameter for the m/n=3/2 tearing mode, (b) position of the q=3/2 surface and (c) magnetic shear at $r/a \approx 0.16$.

sidered to explain these coherent modes, two of them are discussed in the following sections: electron fishbones and tearing modes.

3.1. tearing modes

The stability of tearing modes is determined by the parameter delta prime [47], which shows the difference of the slopes for the flux function ψ inside ($r_s - \delta$) and outside ($r_s + \delta$) the radius of the mode rational surface (r_s): $\Delta' = \left[\psi'_+(r_s+\delta) - \psi'_-(r_s-\delta)\right]/\psi(r_s)$. In theory $\Delta' > 0$ implies an instability and $\Delta' < 0$ a stability. Figure 5(a) shows an estimation of Δ' for the $m/n = 3/2$ tearing mode as a function of time. We observe that even though Δ' remains negative, the ECRH has a destabilizing effect because Δ' increases progressively during the power deposition. It is also interesting to notice in figure 5(b) that when the ECRH is applied, the radius of the $m/n = 3/2$ flux surface moves toward the location of the reflectometer measurements ($r/a \leq 0.2$).

As the MHD mode appears in reflectometry spectra after $\approx 2s$ of ECRH, it can be explained by the destabilization of the 3/2 tearing mode combined with the displacement of its rational surface. A local improvement of the confinement due to the stabilization of TEM could be responsible of the increase of temperature, which would tend to destabilize TEM again.

3.2. electron fishbones

Another phenomenom that may explain the MHD mode is an electron-driven fishbone mode (e-fishbone). These MHD modes are triggered by the interaction of fast electron and internal kink mode, the frequency of the mode allowing a resonance with the toroidal precession of energetic trapped electrons [48–52]. Fast electron can be generated by ECRH, even though the deposition angle of 0.5^o is not favorable for this. The resonance is possible when the toroidal precession velocity v_{prec} of trapped electrons is oriented in the ion diamagnetic direction, in the opposite direction than the trapped electrons which resonate with drift-waves in the case of TEM instability.

The magnetic shear $s = r\,[dq/dr]\,/q$ influences v_{prec} as shown in figure 2 of [53]. v_{prec} is expected in the electron diamagnetic direction for $s > 0$. At $s = 0$ a reversal of v_{prec} can occur in the ion diamagnetic direction for the barely trapped electrons, which makes them important for the onset of e-fishbones.

Estimations of s made with polarimetry at $r/a \approx 0.16$ [54] show that it decreases progressively during the ECRH deposition [see figure 5(c)]. It might decrease even more because the data analysis tends to produce a monotonic q profile ($s < 0$ is avoided). As the MHD mode appears after $\approx 2s$ of ECRH, an excitation of e-fishbone can appear 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 deposition region on the HFS is in favor of e-fishbone destabilization [49] because it can affect the barely trapped electrons more present in this plasma region. The lack of trapped electrons with a v_{prec} in the electron diamagnetic direction may stabilize TEM and explain the onset of the MHD modes.

Conclusion

A new experimental way to study TEM is proposed. It aims to analyze fluctuation spectra and detect the onset of quasi-coherent fluctuations due to TEM named QC-TEM.

QC-TEM have been reported in reflectometry fluctuation spectra of several tokamaks: Tore Supra [11, 12], TEXTOR [11, 12] and JET [12], together with recent AUG indications [22]. Other fluctuations diagnostics able to measure in the plasma core region may allow to study them (PCI, BES, CECE, FIR).

It has been shown in frequency spectra deduced from non-linear simulations that TEM can induce a narrow frequency spectra separated from ZFs. Such a double peak structure being responsible of the QC mode observed in the measured frequency spectra during a TEM-dominated regime. Fluctuation spectra from a synthetic diagnostic confirm this interpretation.

Researches dedicated to TEM instability can then use this technique in the plasma core region besides gyro-kinetic simulations, transport analysis and phase velocity estimations. Such analysis can be done in tokamak plasmas but may also be valid for RFP [23] and stellarators. An example of a study using this knowledge on QC-TEM has been presented. It shows an interplay between electrostatic turbulence (TEM) and electromagnetic fluctuation (MHD), the latter being possibly due to e-fishbones or m/n=3/2 tearing modes.

The lack of QC-TEM may come from a fully developed TEM turbulence or a too low plasma rotation velocity and does not imply that the TEM are stable. Besides, it exists edge phenomena not attributed to TEM which can have a rather similar QC signature. Significant progresses are still required to understand these issues. The theoretical mechanism of the reduced broadening of TEM and its link with ZFs coupling is currently investigated [55].

Acknowledgments

The authors thank J. Bernardo and D. Villegas for the experiments they have carried out together with C. Angioni and J. C. Hillesheim for discussions. This work, in partnership with ATEM, is financially supported by the "Conseil regional Provence-Alpes-Côte d'Azur". It has been carried out within the framework of the Erasmus Mundus International Doctoral College in Fusion Science and Engineering (FUSION-DC) and the EUROfusion Consortium. It has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] X Garbet, P Mantica, C Angioni, E Asp, Y Baranov, C Bourdelle, R Budny, F Crisanti, G Cordey, L Garzotti, N Kirneva, D Hogeweij, T Hoang, F Imbeaux, E Joffrin, X Litaudon, A Manini, C McDonald, H Nordman, V Parail, A Peeters, F Ryter, C Sozzi, M Valovic, T Tala, A Thyagaraja, I Voitsekhovitch, J Weiland, H Weisen, and A Zabolotsky. Physics of transport in tokamaks. *Plasma Physics and Controlled Fusion*, 46:B557, 2004.

[2] F. Jenko, D. Told, T. Görler, J. Citrin, A. Banón Navarro, C. Bourdelle, S. Brunner, G. Conway, T. Dannert, H. Doerk, D.R. Hatch, J.W. Haverkort, J. Hobirk, G.M.D. Hogeweij, P. Mantica, M.J. Pueschel, O. Sauter, L. Villard, E. Wolfrum, and the ASDEX Upgrade Team. Global and local gyrokinetic simulations of high-performance discharges in view of iter. *Nuclear Fusion*, 53:073003, 2013.

[3] C. Bourdelle, X. Garbet, F. Imbeaux, A. Casati, N. Dubuit, R. Guirlet, and T. Parisot. A new gyrokinetic quasilinear transport model applied to particle transport in tokamak plasmas. *Physics of Plasmas*, 14:112501, 2007.

[4] G.D. Conway, C. Angioni, R. Dux, F. Ryter, A.G. Peeters, J. Schirmer, C. Troester, CFN Reflectometry Group, and the ASDEX Upgrade team. Observations on core turbulence transitions in asdex upgrade using doppler reflectometry. *Nuclear Fusion*, 46:S799, 2006.

[5] R.M. McDermott, C. Angioni, G.D. Conway, R. Dux, E. Fable, R. Fischer, T. Ptterich, F. Ryter, E. Viezzer, and the ASDEX Upgrade Team. Core intrinsic rotation behaviour in asdex upgrade ohmic l-mode plasmas. *Nuclear Fusion*, 54:043009, 2014.

[6] D. Villegas, R. Guirlet, C. Bourdelle, X. Garbet, G.T. Hoang, R. Sabot, F. Imbeaux, and J.L. Sgui. Experimental and theoretical study of nickel transport dependence on gradients in tore supra. *Nuclear Fusion*, 54:073011, 2014.

[7] C. Angioni, A. G. Peeters, F. Ryter, F. Jenko, G. D. Conway, T. Dannert, H. U. Fahrbach, M. Reich, W. Suttrop, and L. Fattorini. Relationship between density peaking, particle thermodiffusion, ohmic confinement, and microinstabilities in asdex upgrade l -mode plasmas. *Physics of Plasmas*, 12:040701, 2005.

[8] C. Angioni, R. M. McDermott, F. J. Casson, E. Fable, A. Bottino, R. Dux, R. Fischer, Y. Podoba, T. Pütterich, F. Ryter, and E. Viezzer. Intrinsic toroidal rotation, density peaking, and turbulence regimes in the core of tokamak plasmas. *Phys. Rev. Lett.*, 107:215003, 2011.

[9] J. E. Rice, I. Cziegler, P. H. Diamond, B. P. Duval, Y. A. Podpaly, M. L. Reinke, P. C. Ennever, M. J. Greenwald, J. W. Hughes, Y. Ma, E. S. Marmar, M. Porkolab, N. Tsujii, and S. M. Wolfe. Rotation reversal bifurcation and energy confinement saturation in tokamak ohmic l-mode plasmas. *Phys. Rev. Lett.*, 107:265001, 2011.

[10] C. Sung, A.E. White, N.T. Howard, C.Y. Oi, J.E. Rice, C. Gao, P. Ennever, M. Porkolab, F. Parra, D. Mikkelsen, D. Ernst, J. Walk, J.W. Hughes, J. Irby, C. Kasten, A.E. Hubbard, M.J. Greenwald, and the Alcator C-Mod Team. Changes in core electron temperature fluctuations across the ohmic energy confinement transition in alcator c-mod plasmas. *Nuclear Fusion*, 53:083010, 2013.

[11] H. Arnichand, R. Sabot, S. Hacquin, A. Krämer-Flecken, X. Garbet, J. Citrin, C. Bourdelle, G. Hornung, J. Bernardo,

C. Bottereau, F. Clairet, G. Falchetto, and J.C. Giacalone. Quasi-coherent modes and electron-driven turbulence. *Nuclear Fusion*, 54:123017, 2014.

[12] H. Arnichand, Sabot, S. R. Hacquin, A. Krämer-Flecken, Bourdelle, J. Citrin, X. Garbet, J.C. Giacalone, R. Guirlet, J.C. Hillesheim, Meneses L., and JET Contributors. Discriminating the trapped electron modes contribution in density fluctuation spectra. *Submitted to Nuclear Fusion*, 2015.

[13] R. Sabot, A. Sirinelli, J.-M. Chareau, and J.-C. Giaccalone. A dual source d-band reflectometer for density profile and fluctuations measurements in tore-supra. *Nuclear Fusion*, 46:S685, 2006.

[14] F. Clairet, S. Heuraux, C. Bottereau, D. Molina, L. Ducobu, F. Leroux, and A. Barbuti. Fast sweeping reflectometry upgrade on tore supra. *Review of Scientific Instruments*, 81:10D903, 2010.

[15] G D Conway. Effects of reflectometer asymmetries on fluctuation measurements. *Plasma Physics and Controlled Fusion*, 41:65, 1999.

[16] G. Hornung. *Study of plasma turbulence by ultrafast sweeping reflectometry on the Tore Supra tokamak*. PhD thesis, 2013.

[17] J Bernardo, C Fenzi, C Bourdelle, Y Camenen, H Arnichand, Joo P S Bizarro, S Cortes, X Garbet, Z O Guimares-Filho, T Aniel, J-F Artaud, F Clairet, P Cottier, J Gunn, P Lotte, and the Tore Supra Team. Density impact on toroidal rotation in tore supra: experimental observations and theoretical investigation. *Plasma Physics and Controlled Fusion*, 57:035002, 2015.

[18] F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers. Electron temperature gradient driven turbulence. *Physics of Plasmas*, 7:1904, 2000.

[19] Bruce I Cohen, Lynda L LoDestro, E Bickford Hooper, and Thomas A Casper. Simulations of broadband short-pulse reflectometry for diagnosing plasma density and magnetic-field profiles. *Plasma Physics and Controlled Fusion*, 40:75, 1998.

[20] E. Trier, L.-G. Eriksson, P. Hennequin, C. Fenzi, C. Bourdelle, G. Falchetto, X. Garbet, T. Aniel, F. Clairet, and R. Sabot. Radial electric field measurement in a tokamak with magnetic field ripple. *Nuclear Fusion*, 48:092001, 2008.

[21] S. Hacquin, J. Citrin, H. Arnichand, R. Sabot, C. Bourdelle, Garbet X., and the Tore Supra Team. Reflectometry simulations using gyrokinetic code data or study of quasi-oherent modes. 12th International Reflectometry Workshop (IRW12), FZ-Jülich, Germany, 2015.

[22] D. Prisiazhniuk, A. Krmer-Flecken, G. Conway, P. Manz, T. Happel, P. Simon, Stroth U., and the Asdex-upgrade Team. Application of poloidal correlation reflectometry to study turbulence at asdex-upgrade. 12th International Reflectometry Workshop (IRW12), FZ-Jülich, Germany, 2015.

[23] J.S. Sarff, A.F. Almagri, J.K. Anderson, M. Borchardt, W. Cappechi, D. Carmody, K. Caspary, B.E. Chapman, D.J. Den Hartog, J. Duff, S. Eilerman, A. Falkowski, C.B. Forest, M. Galante, J.A. Goetz, D.J. Holly, J. Koliner, S. Kumar, J.D. Lee, D. Liu, K.J. McCollam, M. McGarry, V.V. Mirnov, L. Morton, S. Munaretto, M.D. Nornberg, P.D. Nonn, S.P. Oliva, E. Parke, M.J. Pueschel, J.A. Reusch, J. Sauppe, A. Seltzman, C.R. Sovinec, D. Stone, D. Theucks, M. Thomas, J. Triana, P.W. Terry, J. Waksman, G.C. Whelan, D.L. Brower, W.X. Ding, L. Lin, D.R. Demers, P. Fimognari, J. Titus, F. Auriemma, S. Cappello, P. Franz, P. Innocente, R. Lorenzini, E. Martines, B. Momo, P. Piovesan, M. Puiatti, M. Spolaore, D. Terranova, P. Zanca, V.I. Davydenko, P. Deichuli, A.A. Ivanov, S. Polosatkin, N.V. Stupishin, D. Spong, D. Craig, H. Stephens, R.W. Harvey, M. Cianciosa, J.D. Hanson, B.N. Breizman, M. Li, and L.J. Zheng. Overview of results from the mst reversed field pinch experiment. *Nuclear Fusion*, 55:104006, 2015.

[24] J. H. E. Proll, P. Xanthopoulos, and P. Helander. Collisionless microinstabilities in stellarators. ii. numerical simulations. *Physics of Plasmas*, 20:122506, 2013.

[25] P. Helander, J. H. E. Proll, and G. G. Plunk. Collisionless microinstabilities in stellarators. i. analytical theory of trapped-particle modes. *Physics of Plasmas*, 20(12), 2013.

[26] N. Dominguez, B. A. Carreras, V. E. Lynch, and P. H. Diamond. Dissipative trapped electron modes in l=2 torsatrons. *Physics of Fluids B: Plasma Physics*, 4:2894, 1992.

[27] W. Guttenfelder, J. Lore, D. T. Anderson, F. S. B. Anderson, J. M. Canik, W. Dorland, K. M. Likin, and J. N. Talmadge. Effect of quasihelical symmetry on trapped-electron mode transport in the hsx stellarator. *Phys. Rev. Lett.*, 101:215002, 2008.

[28] A. Krämer-Flecken, V. Dreval, S. Soldatov, A. Rogister, V. Vershkov, and the TEXTOR-team. Turbulence studies with means of reflectometry at textor. *Nuclear Fusion*, 44:1143, 2004.

[29] V.A. Vershkov, D.A. Shelukhin, S.V. Soldatov, A.O. Urazbaev, S.A. Grashin, L.G. Eliseev, A.V. Melnikov, and the T-10 team. Summary of experimental core turbulence characteristics in ohmic and electron cyclotron resonance heated discharges in t-10 tokamak plasmas. *Nuclear Fusion*, 45:S203, 2005.

[30] A. Krämer-Flecken, S. Soldatov, Y. Xu, H. Arnichand, S. Hacquin, R. Sabot, and the TEXTOR-team. Long range correlation properties of quasi coherent modes at textor. *Submitted to New Journal of Physics*, 2015.

[31] A. E. White, L. Schmitz, W. A. Peebles, T. L. Rhodes, T. A. Carter, G. R. McKee, M. W. Shafer, G. M. Staebler, K. H. Burrell, J. C. DeBoo, and R. Prater. Simultaneous measurement of core electron temperature and density fluctuations during electron cyclotron heating on diii-d. *Physics of Plasma*, 17:020701, 2010.

[32] A. E. White, W. A. Peebles, T. L. Rhodes, C. H. Holland, G. Wang, L. Schmitz, T. A. Carter, J. C. Hillesheim, E. J. Doyle, L. Zeng, G. R. McKee, G. M. Staebler, R. E. Waltz, J. C. DeBoo, C. C. Petty, and K. H. Burrell. Measurements of the cross-phase angle between density and electron temperature fluctuations and comparison with gyrokinetic simulations. *Physics of Plasmas*, 17:056103, 2010.

[33] J. E. Rice, M. J. Greenwald, Y. A. Podpaly, M. L. Reinke, P. H. Diamond, J. W. Hughes, N. T. Howard, Y. Ma, I. Cziegler, B. P. Duval, P. C. Ennever, D. Ernst, C. L. Fiore, C. Gao, J. H. Irby, E. S. Marmar, M. Porkolab, N. Tsujii, and S. M. Wolfe. Ohmic energy confinement saturation and core toroidal rotation reversal in alcator c-mod plasmas. *Physics of Plasmas*, 19:056106, 2012.

[34] J. C. Hillesheim, J. C. DeBoo, W. A. Peebles, T. A. Carter, G. Wang, T. L. Rhodes, L. Schmitz, G. R. McKee, Z. Yan, G. M. Staebler, K. H. Burrell, E. J. Doyle, C. Holland, C. C. Petty, S. P. Smith, A. E. White, and L. Zeng. Experimental characterization of multiscale and multifield turbulence as a critical gradient threshold is surpassed in the diii-d tokamak. *Physics of Plasmas*, 20:056115, 2013.

[35] A. Diallo, W. Hughes, J. M. Greenwald, B. LaBombard, E. Davis, S-G. Baek, C. Theiler, P. Snyder, J. Canik, J. Walk, T. Golfinopoulos, J. Terry, M. Churchill, A. Hubbard, M. Porkolab, L. Delgado-Aparicio, L. Reinke, M. A. White, and Alcator C-Mod team. Observation of edge instability limiting the pedestal growth in tokamak plasmas. *Phys. Rev. Lett.*, 112:115001, 2014.

[36] Q. Wang, H. S. Xu, G. N. Wan, B. Y. Ding, S. Y. Guo, H. M. Shao, L. C. Liu, S. Q. Xu, X. E. Wang, N. Yan, V. Naulin, H. Nielsen, A. J. Juul Rasmussen, J. Candy, R. Bravenec, W. Sun, Y. H. Shi, T. F. Liang, Y. R. Chen, W. Zhang, L. Wang, L. Chen, N. Zhao, L. Li, Y. L. Liu, Y. H. Hu, G. and Z Gong, X.˙ New edge coherent mode providing continuous transport in long-pulse h-mode plasmas. *Phys. Rev. Lett.*, 112:185004, 2014.

[37] T. Golfinopoulos, B. LaBombard, R. R. Parker, W. Burke, E. Davis, R. Granetz, M. Greenwald, J. Irby, R. Leccacorvi, E. Marmar, W. Parkin, M. Porkolab, J. Terry, R. Vieira, S. Wolfe, and Alcator C-Mod team. External excitation of a short-wavelength fluctuation in the alcator c-mod edge plasma and its relationship to the quasi-coherent mode. *Physics of Plasmas*, 21:056111, 2014.

[38] J. L. Terry D. Brunner E. Davis M. Greenwald J. W. Hughes B. LaBombard, T. Golfinopoulos and Alcator C-Mod Team. New insights on boundary plasma turbu-

lence and the quasi-coherent mode in alcator c-mod using a mirror langmuir probe. *Physics of Plasmas*, 21:056108, 2014.

[39] I. Cziegler, P. H. Diamond, N. Fedorczak, P. Manz, G. R. Tynan, M. Xu, R. M. Churchill, A. E. Hubbard, B. Lipschultz, J. M. Sierchio, J. L. Terry, and C. Theiler. Fluctuating zonal flows in the i-mode regime in alcator c-mod. *Physics of Plasmas*, 20:055904, 2013.

[40] Private communication with V.A. Vershkov.

[41] Private communication with J. Citrin.

[42] A. G. Peeters. Reduced charge state equations that describe pfirsch schlter impurity transport in tokamak plasma. *Physics of Plasmas*, 7:268, 2000.

[43] G Hornung, F Clairet, G L Falchetto, R Sabot, H Arnichand, and L Vermare. Turbulence correlation properties measured with ultrafast sweeping reflectometry on tore supra. *Plasma Physics and Controlled Fusion*, 55:125013, 2013.

[44] A. Medvedeva, C. Bottereau C., F. Clairet, G.D. Conway, S. Heuraux, D. Molina, Stroth U., and the Asdex-upgrade Team. Density fluctuation measurements with an ultra-fast-swept reflectometer in asdex-upgrade. 12th International Reflectometry Workshop (IRW12), FZ-Jülich, Germany, 2015.

[45] A. Lebschy, R. M. McDermott, B. Geiger, M. Cavedon, M. G. Dunne, R. Dux, R. Fischer, E. Viezzer, and the ASDEX Upgrade Team. Indirect measurement of the poloidal rotation in the core of asdex upgrade plasmas with cxrs. 42nd EPS Conference on Plasma Physics, Lisbon, Portugal, 2015.

[46] D. Villegas, R. Guirlet, C. Bourdelle, G. T. Hoang, X. Garbet, and R. Sabot. Experimental electron temperature gradient dependence of heavy impurity transport in fusion devices. *Phys. Rev. Lett.*, 105:035002, 2010.

[47] H. P. Furth, J. Killeen, and M. N. Rosenbluth. Finite resistive instability of a sheet pinch. *Physics of Fluids*, 6:459, 1963.

[48] P. Maget, F. Imbeaux, G. Giruzzi, V.S. Udintsev, G.T.A. Huysmans, J.-L. Sgui, M. Goniche, Ph. Moreau, R. Sabot, and X. Garbet. Temperature oscillating regimes in tore supra diagnosed by mhd activity. *Nuclear Fusion*, 46:797, 2006.

[49] F. Zonca, P. Buratti, A. Cardinali, L. Chen, J.-Q. Dong, Y.-X. Long, A.V. Milovanov, F. Romanelli, P. Smeulders, L. Wang, Z.-T. Wang, C. Castaldo, R. Cesario, E. Giovannozzi, M. Marinucci, and V. Pericoli Ridolfini. Electron fishbones: theory and experimental evidence. *Nuclear Fusion*, 47:1588, 2007.

[50] Z.O. Guimarães Filho, D. Elbeze, R. Sabot, D. Molina, J.L. Segui, C. Nguyen, J. Decker, P. Maget, A. Merle, X. Garbet, N. Dubuit, and S. Benkadda. Energetic particle driven magnetohydrodynamic instabilities during relaxation cycles in tore supra. *Plasma Physics and Controlled Fusion*, 53:074012, 2011.

[51] A. Merle, J. Decker, Xavier X. Garbet, R. Sabot, Z. Guimaraes-Filho, and T. Nicolas. Stability of the electron-driven fishbone mode. *Physics of Plasma*, 19:072504, 2012.

[52] Z.O. Guimarães Filho, S. Benkadda, D. Elbeze, A. Botrugno, P. Buratti, G. Calabró, J. Decker, N. Dubuit, X Garbet, P. Maget, A. Merle, R. Pucella, G.and Sabot, A.A. Tuccillo, and F. Zonca. Electron fishbones in ftu and tore supra tokamaks. *Nuclear Fusion*, 52:094009, 2012.

[53] B. B. Kadomtsev and O. P. Pogutse. Plasma instability due to particle trapping in a toroidal geometry. *Soviet Physics JETP*, 24:1734, 1967.

[54] Y. G. Li, Ph. Lotte, W. Zwingmann, C. Gil, and F. Imbeaux. Efit equilibrium reconstruction including polarimetry measurements on tore supra. *Fusion Science and Technology*, 59:397, 2011.

[55] J. Citrin, H. Arnichand, C. Bourdelle, J. Bernardo, X. Garbet, S. Hacquin, and R. Sabot. Progress in understanding quasi-coherent modes through gyrokinetic simulation. Joined US-EU TTF workshop, Culham, United Kingdom, 2014.