Reflectometry synthetic diagnostic coupled with gyrokinetic simulations for study of quasi-coherent modes in the Tore Supra machine

S. Hacquin¹, J. Citrin¹ ², H. Arnichand¹, R. Sabot¹, C. Bourdelle¹, X. Garbet¹ and the Tore Supra Team

¹ CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.
² FOM Institute DIFFER – Dutch Institute for Fundamental Energy Research, Trilateral Euregio Cluster, PO Box 1207, 3430 BE Nieuwegein, The Netherlands

Abstract

The presence of Quasi-Coherent fluctuations linked to Trapped Electron Modes (QC-TEM) has been observed experimentally in the core region of various fusion devices and predicted by gyrokinetic computations. This paper reports on the simulation of reflectometry measurement in Tore Supra Ohmic discharges, for which gyrokinetic non-linear simulations predict an additional separate peak corresponding to QC mode in the fluctuation spectrum of Linear Ohmic Confinement (LOC) regimes. Synthetic reflectometry simulations obtained with such gyrokinetic data allow to retrieve the experimental observations, in particular the bump in the reflectometry spectra that is identified as a QC-TEM signature. This highlights the importance of such a synthetic tool to cross-validate experimental measurements and gyrokinetic computations.

1. Introduction

The development of synthetic diagnostics is of prime interest in fusion researches as they help interpret the experimental data and improve the diagnostic design [1]. In the case of reflectometry for which the data analysis is often tricky synthetic diagnostics are particularly relevant. In this work we use a synthetic reflectometry diagnostic, which relies on 1D and 2D full-wave computations with GENE [2] gyrokinetic data, to study the mechanisms underlying quasi-coherent (QC) modes associated with Trapped-Electron-Mode (TEM) turbulence. Simulation of reflectometry measurement of QC modes in a Tore Supra Ohmic discharge is presented, showing that the synthetic diagnostic can reproduce the experimental observations. In Section 2 a brief summary of experimental observation and gyrokinetic prediction of QC modes is given. The results from the synthetic reflectometry diagnostic are then presented in Section 3. A few concluding remarks are discussed in Section 4.
2. Evidence of Quasi-Coherent (QC) modes in fusion plasmas

2.1 Experimental observation of QC modes

Quasi-coherent modes have been observed in a number of existing fusion devices: T-10 [3], TEXTOR [4], Tore Supra [5-7], JET [6], ASDEX-Upgrade [7], etc. While they are usually detected in frequency spectra of reflectometry signals they display the following features:

- a carrier frequency on the order of magnitude of 50 - 150 kHz with a bandwidth of about 10 – 50 kHz
- an amplitude ballooning in the mid-plane Low-magnetic-Field-Side (LFS)
- a poloidal correlation length larger than those of other turbulence components
- a poloidal rotation velocity in the electron diamagnetic direction compared to those of turbulence components at lower frequencies

Whereas their spatial structure ($k_i \rho_i < 1$-10) has long been proved to be characteristic of drift-wave turbulence their link with Trapped Electron Modes (TEM) was established only recently [6]. A first proof of the TEM nature of the QC modes was obtained through the study of two distinct ohmic confinement regimes: the Linear Ohmic Confinement (LOC) and the Saturated Ohmic Confinement (SOC), in which the turbulence is expected to be dominated by TEM and Ion Temperature Gradient (ITG), respectively [5-8]. As shown in Figure 1, QC modes are clearly observed in LOC regimes while they disappear in SOC regimes, the transition from a regime to the other being achieved from a scan of either the electron density or the plasma current.

*Figure 1*: Fluctuation spectra of reflectometry signal measured during LOC-SOC transition in Tore Supra Ohmic discharges (from [5]), demonstrating that QC modes are detected in LOC regimes only.
2.2 Gyrokinetic prediction of QC modes

To help interpret the measurement of QC modes in Ohmic discharges non-linear gyrokinetic computations were carried out with the GENE code [2]. Using the main parameters of Tore Supra Ohmic discharge #48102 the turbulence spectra were estimated for both the LOC and the SOC regimes [9]. As depicted in Figure 2 significant dissimilarities can be noticed. Firstly, the spectrum peak lies in the electron diamagnetic direction ($\omega < 0$) for the LOC regime and in the ion diamagnetic direction ($\omega > 0$) for the SOC regime. Secondly, while the spectrum displays a typical broadband structure in the case of the SOC regime, a double-peak structure appears in the LOC regime (a narrow peak around the zero-frequency, which might be due to zonal flows and another peak centred around 70 kHz, which is reminiscent of a QC mode). The resulting density fluctuations in the poloidal plane at initial time are displayed in the lower part of Figure 2. In order to simulate the experimental reflectometry measurements the density fluctuations given by GENE were used as input in full-wave reflectometry code computations, which are presented in the next section.

**Figure 2**: GENE simulation of LOC (left hand-side) and SOC (right hand-side) regimes of Tore Supra discharge #48102 (from [9]):

- Turbulence spectra
- Density fluctuations
3. Synthetic reflectometry simulations of turbulence measurements in a Tore Supra Ohmic discharge

3.1 Synthetic reflectometry diagnostic tools

Reflectometry simulations reported here were completed with full-wave computations of the Maxwell's curl equations in the presence of a cold plasma tensor. The plasma was described by the radial profiles of electron density and temperature displayed in Figure 3 (left hand-side), in agreement with those used in the GENE simulations presented in section 2.2. The electron temperature was taken into account for correction of the electron mass due to the relativistic effects [10]. An usual radial profile, inversely proportional to the major radius, was considered for the magnetic field, which is required for simulation of X-mode reflectometry. The corresponding radial profiles for the O-mode and the upper X-mode cut-off frequencies are depicted in Figure 3 (right hand-side). The vertical dashed lines delimit the zone of density fluctuations given by GENE. The horizontal dashed red lines indicate the probing frequencies that are needed to probe the centre of the density fluctuation zone, namely ~ 40 GHz for the O-mode and ~ 100 GHz for the X-mode.

![Figure 3: Radial profiles of electron density, electron temperature and magnetic field (left hand-side) and resulting radial profiles of O-mode and upper X-mode cut-off frequencies (right hand-side) used as input in the reflectometry simulations.](image)

In order to reproduce the reflectometry signal, the full-wave computations have to be performed for each map of density fluctuations given at successive time steps. One should stress that the time evolution of the density fluctuations was computed by GENE in the plasma frame. In order to properly reconstruct the reflectometry signal then a correction factor for the time axis was introduced to add the E x B rotation velocity contribution up.
The technical details of the Tore Supra reflectometer diagnostic used in the experimental results summarised in section 2.1 are given in [11]. It is a heterodyne X-mode system equipped with two GOLA antennas for emission and reception of the probing signal. Since the emitting and receiving antennas lie far away (i.e. about 1m) in front of the plasma, one might expect 1D approximation to be quite relevant to simulate the reflectometry measurements.

### 3.2 1D full-wave simulations

1D simulations were carried out with a fast and accurate full-wave code solving the Helmholtz equation for either the O-mode or the X-mode polarization [12-13]. The outcomes of the code for the inputs defined in sections 2.2 and 3.1 are presented in Figure 4, for the LOC and the SOC regimes respectively.

**Figure 4:** Simulation results from 1D Helmholtz code in the LOC (upper) and SOC (lower) regimes: phase fluctuations of the reflectometry signals normalised to the same amplitude (left hand-side) and subsequent spectra of the phase fluctuations (right hand-side)
A first comment regarding these results is that although the amplitude of the phase fluctuations is larger for the X-mode than for the O-mode, their pattern is identical whatever the polarisation mode (see left hand-side of Figure 4). As a consequence, under these circumstances the fluctuation spectrum from X-mode measurements can be well reproduced by O-mode simulations (see right hand-side of Figure 4). In agreement with experimental observation one can also note that a QC mode appears in the spectrum at around 90 kHz in the LOC regime only.

### 3.3 2D full-wave simulations

With the purpose to validate the 1D results presented in the previous section 2D simulations were carried out with a 2D O-mode FD-TD code [14]. As illustrated in Figure 5 the code computes iteratively the probing electric field for a number of time steps large enough to ensure that the probing wave returns back to the receiving antenna. These computations are repeated for all successive maps of density fluctuations, then allowing for the synthetic reflectometry signal to be reconstituted.

![Figure 5](image)

**Figure 5**: Example of the probing electric field computed by 2D FDTD O-mode code in the LOC (left hand-side) and SOC (right hand-side) regimes

Figure 6 (left hand-side) depicts the phase fluctuations of the reflected signal computed for both the LOC and SOC regimes. Similarly to 1D simulation the amplitude of the phase fluctuations is larger in the SOC regime than in the LOC regimes (consistently with the fact the level of turbulence is higher in the SOC regime). Though it was noted that the phase fluctuations have smaller amplitude in 2D simulations than in 1D simulations, whatever the confinement regime. A likely explanation is that the 2D computations see the global
movement of the density fluctuations and subsequently the apparent change of refractive index is less substantial than in the 1D case. In Figure 6 (right hand-side) it can be noticed that the spectra of phase fluctuations are qualitatively the same either from 1D or 2D computations. In particular the QC mode is well reproduced in the case of the LOC regime.

Figure 6: Simulation results from 2D FD-TD code in the LOC (upper) and SOC (lower) regimes: phase fluctuations of the reflectometry signals (left hand-side) and subsequent spectra of the phase fluctuations (right hand-side)

4. Final remarks

In this paper the simulation of reflectometry measurements in a Tore Supra Ohmic discharge was presented. First of all it was found from 1D full-wave computations that both O-mode and X-mode yield the same fluctuation spectra, even though the amplitude of phase fluctuations is larger for the X-mode. This is most likely due to the fact that in Ohmic discharges the level of turbulence is small enough so that the reflectometer response remains linear. 1D and 2D results were also compared in the O-mode case, then showing
quite a good qualitative agreement. While the amplitude of phase fluctuations is smaller in the 2D case the shape of fluctuation spectra is still pretty similar from both 1D and 2D calculations. The simulated fluctuation spectra reproduce qualitatively well the experimental ones. Outstandingly a QC mode is recovered in the LOC regime only, at a frequency consistent with experiments. However a small discrepancy for the QC mode frequency was noticed between the 1D results (~ 90 kHz) and the 2D results (~ 80 kHz). A possible explanation is that in 2D simulations the probing beam is sensitive to different poloidal wavenumbers of turbulence than in 1D simulations. As the various poloidal components of the turbulence might fluctuate at slightly different frequencies this could explain such a small divergence. 2D full-wave simulations for the X-mode are foreseen to consolidate these findings.

Acknowledgments
The authors are grateful to their colleagues Andreas Krämer-Flecken and Vladimir Vershkov for fruitful discussions. 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.

References