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APPROCHER LES DEUX INFINIS PAR LES ONDES ELECTROMAGNETIQUES

Étude de turbulence dans les plasmas de fusion à l'aide du radar FMCW ultra-rapide
Study of turbulence in fusion plasmas with the ultra-fast FMCW radar

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Abstract
The description of the relationship between plasma turbulence, flows and confinement is one of the milestones in the global understanding of fusion plasma physics. In order to study the turbulence dynamics with the best possible spatial and temporal resolution, we developed a FMCW (frequency-modulated continuous-wave) microwave radar diagnostic. The density fluctuation is recorded by the reflected signal. The time resolution of 1 µs and the spatial resolution of a few millimetres allow to study the turbulence spectra and the fast density dynamics due to confinement transitions. The ongoing work is dedicated to the development of a synthetic diagnostic which couples the turbulence maps resulted from gyrokinetic simulations with the 2D wave propagation code to be compared with the experimental reflectometry data.

Résumé
La description de la relation entre la turbulence, les écoulements et le confinement dans le plasma est l’une des étapes importantes de la compréhension globale de la physique des plasmas de fusion. Afin d’étudier la dynamique de la turbulence avec la meilleure résolution spatiale et temporelle possible, nous avons développé un diagnostic radar micro-ondes FMCW (à onde continue à modulation de fréquence). La fluctuation de densité est enregistrée par le signal réfléchi. La résolution temporelle de 1 µs et la résolution spatiale de quelques millimètres permettent d’étudier les spectres de turbulence et la dynamique rapide de densité due aux transitions de confinement. Les travaux en cours sont consacrés à la mise au point d’un diagnostic synthétique couplant les cartes de turbulence issues des simulations gyrocinétiques au code de propagation d’ondes 2D pour être comparés aux données expérimentales de réflectométrie.

1 Introduction

The new generation of fusion installations has been built to implement the industrial reactor project. The future tokamak reactor will achieve the necessary parameters to allow the production of energy through the fusion of the hydrogen nuclei present in the plasma. However, the confinement time of the tokamak plasma is currently limited by the particles and energy transport. Turbulence plays the most important role in this transport, but the complete understanding of its properties and mechanisms has not been reached. One of the major objectives is to explain the rapid transition between a mode of operation with a short plasma confinement time (L-mode from "low confinement") and a plasma mode with fewer losses of energy (H-mode) where the turbulence is reduced. In order to study the radial and temporal dynamics of this transition with the best possible resolution microwave radar diagnostics are used on most tokamaks.

Plasma microwave reflectometry is based on the dependence of the plasma refractive index on the electron density. Reflectometry was first used for the radiowaves reflected from the ionosphere [1] and now is widely applied for laboratory plasmas as a non-perturbative density diagnostic [2]. A microwave propagates in an inhomogeneous plasma until it reaches the so-called cutoff layer where it gets reflected. As the position of the cutoff depends on the wave frequency, the plasma density can be measured at different magnetic surfaces. By using several frequencies of the probing wave, the electron density profile can be reconstructed. The first frequency modulated continuous-wave (FMCW) reflectometry measurements were performed at CEA on the tokamaks TFR [3] and Petula-B [4]. This type of diagnostic was installed shortly after at many other fusion devices (ASDEX [5], TFTR [6], JET [7], JT60 [8], URAGAN-3M [9]).

In this contribution we discuss a FMCW radar system used to measure density and its fluctuation with the unprecedented time resolution of 1 μs. The capabilities of this ultra-fast reflectometer are presented through an overview of the recent results on the turbulence dynamics. The ongoing work on a synthetic diagnostic which couples the turbulence maps resulted from gyrokinetic simulations with the 2D wave propagation code is covered to complete the paper.

2 Ultra-fast swept reflectometer

The technique of a swept reflectometer is based on the modulation of the probing wave frequency. The wave propagation introduces a time dependent phase shift $\Delta\Phi$ containing the beat frequency F_{beat}:

$$\Delta\Phi = 2\pi F_{\mathrm{beat}} t. \qquad (1)$$

The beat frequency is proportional to the time of flight τ_{flight} of the probing wave of frequency F:

$$F_{\mathrm{beat}} = \tau_{\mathrm{flight}} \frac{dF}{dt} \qquad (2)$$

and therefore defines the position of the cutoff layer. The principle of the heterodyne detection compared to the homodyne scheme is to mix the signal carrying the beat frequency with a low frequency modulation. The Fig. 1 depicts a typical design of a heterodyne reflectometer used for the swept reflectometers developed at CEA. The probing wave with swept frequency (12–20 GHz) is generated by a voltage controlled oscillator (VCO). The signal is separated in two parts: one launched into the plasma (RF) and the other serving as a reference signal (LO). The single side band modulator adds a modulation frequency f_m to the main frequency F. Before launching the probing wave to the plasma through the emitting antenna at the midplane of the tokamak, its frequency is multiplied by n, in the case of V- and W-band equal to 4 and 6 respectively. After the reflection from the cutoff layer, in the case of bistatic system the wave is received by the second antenna. The reference signal (also multiplied by n) compensates the propagation of the probing wave into the wave guides and mixes to the reflected probing signal. At the mixer output the signal (IF) contains only $F_{\mathrm{beat}} + nf_m$ frequency.

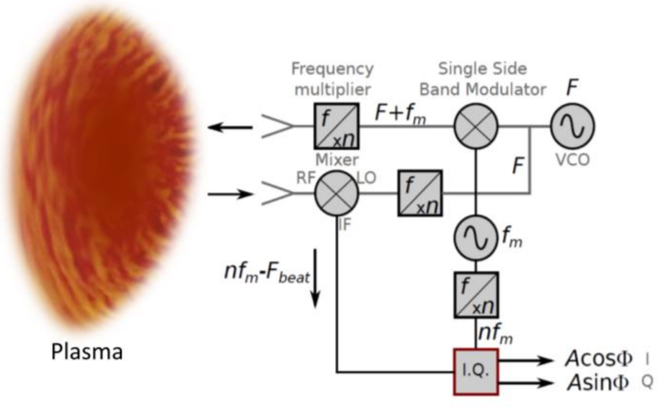

Figure 1 : Ultra-fast swept reflectometer design

The shift of the signal by the carrying frequency ensures the good signal quality [10]. At the end the modulation frequency is removed and an I/Q detector is used to separate the two parts of the signal shifted by π/2. This separation allows to measure independently $A\cos\Phi$ and $A\sin\Phi$, where A is the signal amplitude. The turbulence measurements extracted from the phase fluctuation became possible after improving the signal-to-noise ratio to about 30 dB.

The V- (50–75 GHz) and W-band (75–110 GHz) ultra-fast swept reflectometers (UFSR) are a result of the upgrade of the acquisition system and of the increased modulation frequency [11]. The sweep time decreased to 1 μs ensures to have a frozen density profile including the density fluctuations over the probing time. The X-mode polarisation provides a large radial access from the very edge to the centre of plasma for central densities up to $5{\cdot}10^{19}$ m^{-3} with a spatial resolution of a few millimeters. As for the X-mode the position of the cutoff depend both on the magnetic field and density, the Bottollier-Curtet algorithm [4] is used to determine the positions of cutoff layers step by step, starting from the edge of the plasma.

The phase fluctuation, being induced by density fluctuations, give information about the turbulence level, frequency and wavenumber turbulence spectra. The UFSR time resolution allows to reconstruct the frequency spectra up to 400 kHz and to study fast plasma turbulent events of the order of few microseconds. In the case of low-amplitude turbulence and O-mode polarization, the phase fluctuation wavenumber spectrum is directly proportional to the density fluctuation spectrum [12]. We have extended the concept to the X-mode and introduced a k_r-dependent transfer function which links the phase fluctuation and the density fluctuation. The transfer function needs to be found for each radial position and time using a 1D full-wave propagation simulation [13]. However, it was shown that 2D effects should be introduced [14]. The ongoing work aims to investigate these findings and integrate turbulence maps provided by gyrokinetic calculations to be coupled to 2D full wave code for the analysis of the reflectometer data. This coupling with simulations would provide a better interpretation of the reflectometer data and a tool of validation of the gyrokinetic codes.

3 Turbulence study with reflectometry

Above a threshold of additional heating power, tokamak plasmas have been shown to spontaneously organise into regimes of high confinement (H-mode), with respect to “usual” low confinement modes (L-mode). This transition occurs when turbulence is suppressed due to sheared E × B flows as the radial electric field forms a deep well in the plasma edge region. Dynamic interplay between local gradients, radial shear of the electric field, flow velocity and turbulence has been evidenced during the intermediate phase between L and H-mode, called I-phase [15]. The ultra-fast swept reflectometers have been installed on Tore Supra, ASDEX Upgrade and WEST tokamaks. On ASDEX Upgrade the UFSR has provided the measurements of the fast density and density fluctuation evolution across major parts of tokamak plasma radius. In addition, several channels of Doppler reflectometer have been used for the measurements of the poloidal flow velocity and electric field. Thus, the L-H transitions in a series of plasma discharges in ASDEX Upgrade have been studied with a high temporal resolution. In H-mode the turbulence and the turbulent transport are reduced in the edge region due to the increased radial electric field shear. A phase shift between the turbulence and the radial electric field has been observed in the beginning of the I-phase, indicating that the turbulence grows first and the radial electric field increase follows. After a few limit-cycle oscillations the electric field and the turbulence continue oscillating in phase, while an edge transport barrier develops due to the turbulence reduction. The absence of the phase shift supports the description of the I-phase as type III ELM-like phenomenon [16].

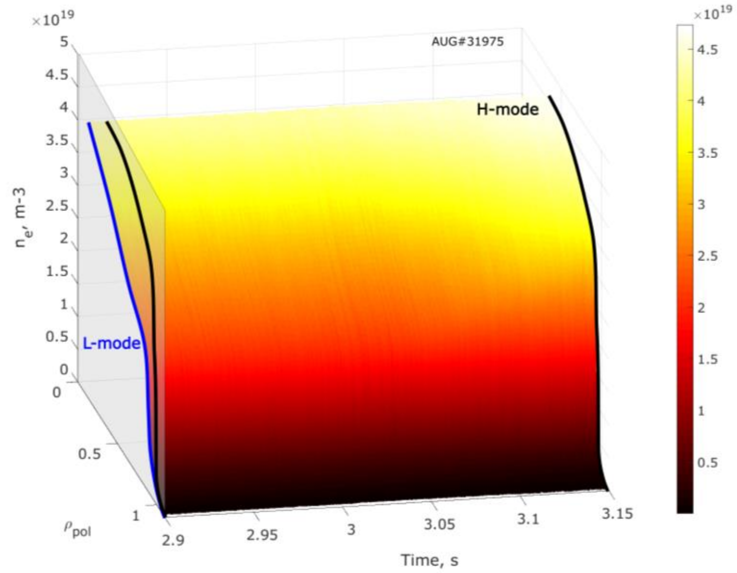

Figure 2 : Electron density evolution during L-H transition

An example of electron density profiles reconstructed from the ultra-fast swept reflectometer data is shown in Fig. 2. The profile builds up inside $\rho_{\mathrm{pol}} = 0.99$ of normalized plasma radius from shallow in the L-mode (2.9 s, blue line in Fig. 2) to steep in the H-mode (after 3.1 s, black line in Fig. 2) due to the better confinement. The precise density profile reconstruction, confirmed through the cross-comparison with other diagnostics, was used for the study of the density gradient during I-phase [16], of the boundary displacements due to ideal kink modes [17] and of the density curvature effect on the plasma intrinsic rotation [18].

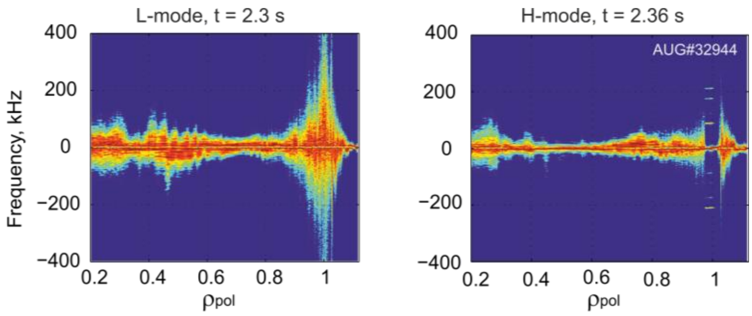

Figure 3 : Turbulence frequency spectra in L- and H-mode

If the density profile is reconstructed, the probing frequency can be expressed as a monotonic function of the radial position $F(R)$. Hence the frequency spectra of turbulence can be interpolated to the radial points of the averaged density profile. Figure 3 depicts the frequency power spectra of the density fluctuation. Two time windows of 12.5 ms each have been chosen to describe the spectra modification in L-mode (left) and H-mode (right). In the pedestal region, $0.95 < \rho_{\mathrm{pol}} < 1$, during the I-phase the fluctuation amplitude decreases and the spectra become narrower compared to the L-mode broadband turbulence due to the radial electric field shear [16]. The frequency spectra reconstruction for different radial positions equally allowed to investigate the LOC-SOC confinement transition in Ohmic plasma [19] and turbulent trapped electron modes [20].

4 Synthetic diagnostic

The ongoing research with the ultra-fast swept reflectometer is focused on the experimental study of the flows and their influence on the turbulent transport in L- and H-mode. The main objective is to interpret reflectometry data using a synthetic diagnostic. The synthetic diagnostic couples the turbulence maps resulted from the gyrokinetic simulations with the 2D full-wave code used for the simulation of the reflectometer signal. The wave propagation 2D code has been developed and commissioned. Optimisation of the numerical calculation led to a factor of hundred improvement of the simulation speed.

The code exploits the Yee discrete scheme of the Finite Domain Time Difference method (FDTD) [21]. The computational grid simulates the propagation of an electromagnetic wave in 2D in X-mode polarisation. Absorbing boundaries were implemented to avoid parasitic reflections. The probing wave emission simulates the realistic antenna radiation pattern of a Gaussian beam. At each time step, the source beam is added to the calculated field forming a so-called soft source. The phase and the amplitude of the reflectometer signal are extracted from the field value in the centre of the source. The comparison between a simulated Gaussian beam and an analytical solution in the vacuum gives a precision of 1%. The code efficiency has therefore been proved in terms of propagation, boundary absorption and cutoff reflection. Work has progressed on the coupling with gyrokinetic simulations. The turbulence maps were constructed from the results of the GYSELA simulations [22]. The interpolation of GYSELA data was implemented into the 2D full-wave code as an input through HDF5 files.

5 Conclusion

Plasma turbulence is one of the most important factors which limit the plasma confinement in a tokamak. In H-mode the improved confinement is reached after an intermediate phase, when an edge transport barrier develops due to the turbulence reduction. The temporal evolution of the density profile, its gradient and the density fluctuation level were studied using the ultra-fast swept reflectometer. The potential of the UFSR as turbulence diagnostic exceeds the results presented in this contribution. Its fast temporal resolution allows to measure density dynamics and density fluctuation characteristics, such as frequency and wavenumber spectra, correlation lengths and time during fast transitions in a plasma discharge.

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