Poloidal Rotation Measurement in Tore Supra by Reflectometry

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1. Introduction

$E{\times}B$ velocity shear has been shown in tokamaks by both theoretical modelling and experimental observations to be the key parameter for the suppression of the turbulence and the formation of transport barrier in improved confinement regimes [1]. Experimentally, except the plasma edge and the scrape off layer where the radial electric field E_r can be measured by Langmuir probes, E_r is not directly measured, but deduced from the radial balance equation by measuring the rotation velocity and the pressure gradient of one species (electron, ion or impurity):

$$E_r = \frac{1}{q_j n_j} \nabla P_j - V_{j\theta} B_\phi + V_{j\phi} B_\theta \tag{1}$$

From this equation, one can note that a rotation shear in the poloidal direction as well as in the toroidal direction can contribute to the E_r shear. The plasma rotation in tokamaks has so far been measured by spectroscopy of impurity or neutral beam diagnostics [2]. Nevertheless both methods have drawbacks, associated with poor space and time resolution and, for the latter, to the complexity of the required neutral beam injection system.

Reflectometry is a microwave diagnostic widely and exclusively used in tokamaks to measure the density profile or to investigate the core turbulence [3]. In this paper we present a new method to measure the rotation velocity by using a non standard reflectometry, namely oblique and off-axis, where the incident wave is not perpendicular to the cut off layer. In this configuration, the turbulence frequency spectrum obtained by back-scattering is Doppler shifted, and this Doppler shift frequency allows to determine the turbulence rotation velocity. From this measurement, and then using a simple modelling for the turbulence, one can extract the plasma poloidal rotation velocity.

2. Diagnostic

The reflectometry is based on a radar technique with a reflection layer inside the plasma. The incident wave is then reflected on the cut-off layer and detected by the emission antenna (see Fig.1). The cut-off position of an ordinary mode depends only on the plasma density, and a critical density at the cut-off is defined by $n_e(r_c) = (2\pi f_0)^2 \varepsilon_0 m_e / q_e^2$. The experimental set-up of this diagnostic is described in the Fig.1. This diagnostic is constituted of three main parts: micro-wave sources, a gaussian quasi-optic system and a heterodyne detection system. The micro-wave source used here is an Extended Interactive Oscillator (**EIO**) of 60 GHz ($\lambda_0 = 5$ mm) with an output power of 8 W. The local oscillator (LO) is a Gunn diode (70 mW). Then the frequency difference between EIO and LO is stabilised by a phase lock loop. The absolute sensitivity (noise equivalent power) of this heterodyne detection system is $NEP_H = 10^{-18}$ W / Hz. The half angle of divergence of the wave beam launched by the gaussian quasi-optic antenna into the vacuum is less than 2°, the corresponding resolution in wavenumber is $\Delta k \le 0.6$ cm^{-1}.

The detected signal includes several physical processes: the direct reflection without frequency broadening; the forward scattering, where the wave-numbers of the turbulence selected by Bragg's rule $k_{fluct} = k_s - k_i \approx 0$ are small, this contributes to a small spectral broadening on the reflected signal; the backscattering, where the wav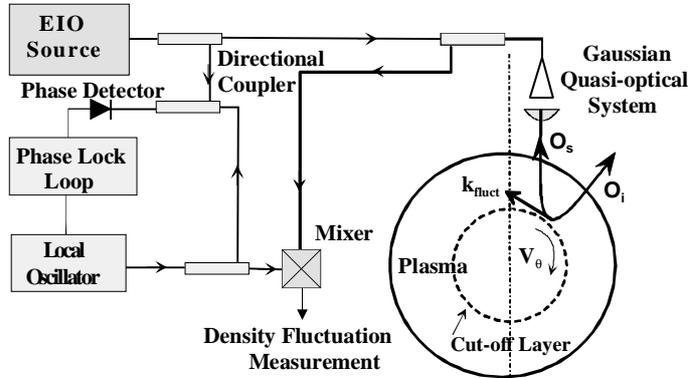enumbers of the turbulence selected by Bragg's rule $k_{fluct} = k_s - k_i = -2k_i$ are large, this contributes to a large spectral broadening of the reflected signal. In the backscattering configuration, on one hand k_{fluct} takes the minimum values in the cut-off layer, and on the other hand the turbulence energy is much more concentrated in the small k range as shown in [4], these explain why the signal backscattered by the turbulence is localised in the vicinity of the cut-off layer [5]. The spatial resolution of this diagnostic is estimated to be $\Delta r \approx 2 - 3\,\mathrm{cm}$.

Fig. 1 Schematic microwave set up of the reflectometry.

3. Doppler shift and the turbulence *k*-spectrum

In the case where the incident wave is perpendicular to the cut-off, it is difficult to distinguish the three processes descr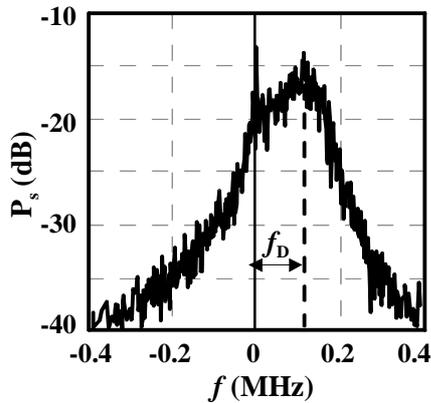ibed above. However, Fourier transform analysis allows us to separate clearly the different processes in the oblique incidence configuration. Fig.2 represents a typical frequency spectrum of the density fluctuations measured by the oblique reflectometry illustrated in Fig.1. In this figure, two spectra can be clearly observed: a narrow spectrum around $f = 0$, and another spectrum, very broad and Doppler shifted at f_D. The narrow spectrum represents the direct reflection in which the incident ray is perpendicular to the cut-off, and its wavenumber selected by this configuration is thus entirely radial i.e. $k_\theta = 0$, $k_r \neq 0$, hence the Doppler shift frequency $f_D = (1/2\pi)k_\theta V_\theta = 0$. The broad spectrum corresponds to the backscattering configuration which is shown in figure 1, in this case the wavenumber of fluctuations selected by Bragg's rule at the cut-off is given by $k_{fluct}(\rho_c) = -2k_i(\rho_c)$. The wavenumber selected by this configuration is nearly poloidal, and the Doppler shift is given by this equation : $f_D = -(1/\pi)k_i(\rho_c)V_\theta(\rho_c)$. By measuring f_D, and by calculating k_i with a ray-tracing code, one deduces the poloidal rotation of the turbulence. In Fig.3, the shift frequency f_D is plotted as a function of $k_{fluct}(\rho_c)$ in the Bragg backscattering. In this experiment, the plasma has been horizontally moved in order to change the incident angle, thus $k_i(\rho_c)$. A quasi co-linearity between f_D and $k_{fluct}(\rho_c)$ is observed, and f_D changes sign as k_i changes. This linear dependence confirms that the frequency shift is actually due to Doppler effect. The poloidal rotation velocity of the turbulence defined by the slope is estimated to be $V_\theta \approx 0.98\,\mathrm{km/s}$.
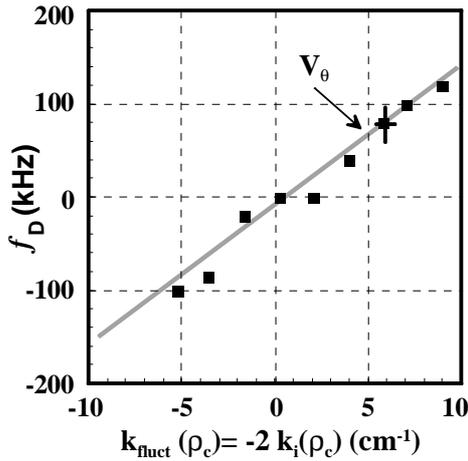

Fig.2 Typical frequency spectrum of the density fluctuations measured by the oblique reflectometry.

Fig. 3 Doppler shift frequency f_D v.s. the turbulence wavenumber selected at the cut-off.
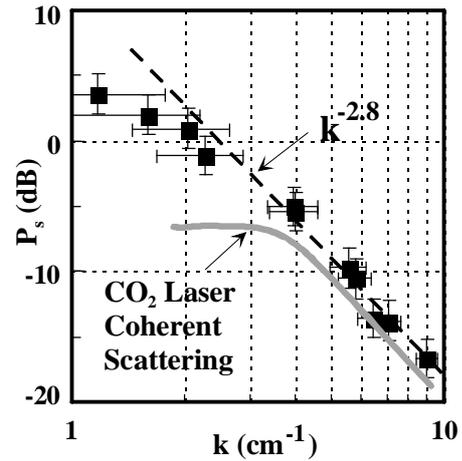

Fig. 4 k-spectrum of the density fluctuations measured by reflectometry.

Fig.4 represents the k-spectrum of the back-scattered power P_s measured by this oblique reflectometry. This backscattered signal level is proportional to the square of the density fluctuations at the cut-off. Compared to the k-spectrum previously obtained by CO_2 laser coherent scattering [4], two observations can be made: the Kolmogorov scaling relative to the 2-D turbulence ($\propto k^{-2.8}$) has been confirmed in the high k range; no saturation has been observed below $k = 4$ cm^{-1} contrary to that observed by CO_2 laser coherent scattering. The discrepancy in the low k range between the two methods likely shows the limitation of the laser scattering diagnostic in the small k values. Density fluctuation energy is hence concentrated in the large spatial scale (small k), and this emphasizes the spatial localisation effect in the cut-off layer for the perturbed phase measured by the reflectometry.

4. Rotation shear measurement

In order to measure the rotation shear *i.e.* radial profile of the rotation, one solution consists of sweeping the cut-off position from the plasma centre to the edge by density scan during a discharge. Fig.5 represents the turbulence poloidal rotation as a function of the density. Large variation of V_θ has been found for a small density change, this means that the variation in rotation is not a simple parametric dependence in density, it is likely resulting from the cut-off change *i.e.* radial profile effect. Assuming that the radial structure of the rotation is not strongly affected by the density change, a radial profile of the poloidal rotation velocities of the turbulence have hence been obtained in Tore Supra by plotting V_θ as a function of ρ_c (*cf.* Fig.6). Two regions of large rotation shear have been observed: one located at the edge $\rho \approx 0.9$; the second one located at $\rho \approx 0.6$ in the gradient region. The rotation inversion at the edge is simply a consequence of the inversion of the radial electric field. Indeed the radial electric field has to be positive in the scrape off layer due to the fact that the limiter tends to attract the electrons and push back the ions; the electric field has to be negative inside the plasma where the ion transport is larger than the electron transport according to the neoclassical transport theory. On the other hand, the presence of the rotation shear in the gradient region is more surprising. Several potential candidates exist to explain this feature: one is based on the neoclassical expression of the poloidal velocity $V_\theta = -\gamma(1 / q_e B)\partial T_e / \partial r$ where γ can change sign when the collisionality regime is changed, but this model has difficulty to explain the drastic change in the rotation; another one is due to the fast particle losses in the ripple channel. In the turbulence suppression theory by the $E \times B$ velocity shear, the key parameter is the plasma rotation. Note that the turbulence rotation

velocity can be decomposed into two terms $V_\theta = V_{e\theta} + V_{turb}$ where $V_{e\theta}$ and V_{turb} are respectively plasma rotation velocity and turbulence own phase velocity. Using the model of drift wave turbulence, V_{turb} is simply given by the diamagnetic velocity $V_e* = q_e T / (L_n B)$, where L_n is the density gradient length. It is important to note that V_e* is almost constant along the radius as shown in Fig.6. This means that the main contribution in the plasma rotation shear comes from the turbulence rotation shear. However if the turbulence suppression term is the turbulence rotation shear as in the fluid turbulence case, then the reflectometry allows us to have direct access to this quantity, and in this case the reflectometry presents a considerable advantage compared to the spectroscopy. Experiments have shown an evident effect of different additional heating(LH, FWEH and ICRH) on the rotation.
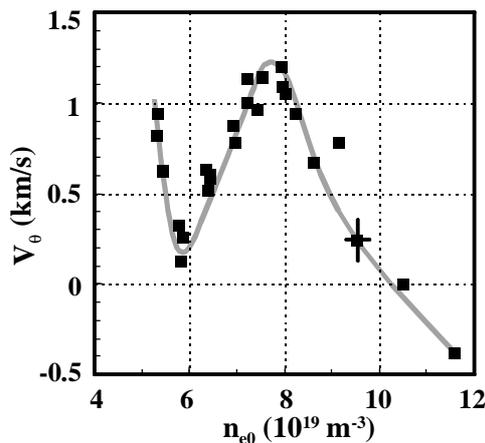

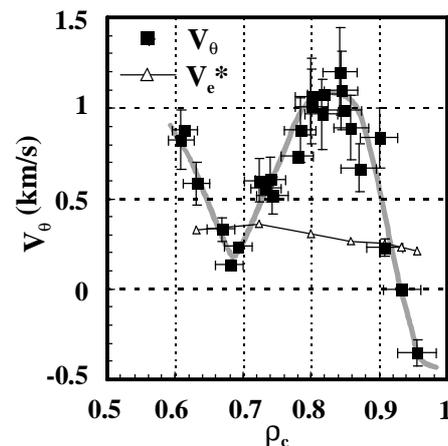*Fig. 5 Poloidal rotation v.s. density.*

Fig. 6 Poloidal rotation v.s. cut-off position.

5. Conclusions

In this paper we have shown how the turbulence rotation is directly measured by the oblique reflectometry, then this measurement allows us to deduce the plasma rotation. Compared to the spectroscopy, in addition to its simplicity, the reflectometry is a diagnostic of rotation with high spatiotemporal resolution. Moreover the turbulence level is simultaneously given by this reflectometry. Assuming that the radial structure of the rotation is not strongly affected by density variation, a radial profile of the poloidal rotation of the turbulence and plasma has been obtained in Tore Supra by sweeping the cut-off layer from the plasma center to the edge. Two rotation shear regions have been clearly observed: one located at the edge $\rho \approx 0.9$ whereas the other one located at the gradient region $\rho \approx 0.6$. Furthermore an evident heating effect has been observed on the rotation with different additional heating systems (LH, FWEH, ICRH). A new k-spectrum of density fluctuations has also been obtained by the reflectometry. It confirms the Kolmogorov scaling in the high k range, but it shows discrepancy in the low k range with that measured by laser **CO₂** coherent scattering. This spectrum indicates that the turbulence energy in the tokamak is mainly concentrated in large scales, *i.e.* small wavenumbers k $(k \leq 1 \, cm^{-1})$.

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