Core density fluctuations observed on Tore Supra by Doppler back-scattering: perpendicular velocity modification in high power ICRH experiments

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Abstract

Backscattering of a microwave beam close to the cut-off allows for measurement of density fluctuations $\tilde{n}(k_\perp)$ at a specified wave-number, selected by the scattering geometry $k_\perp = -2k_i$, where $k_i$ is the beam wave-number at the reflection layer. On the system installed on Tore Supra, both the scattering wave-number $k_\perp$ and the scattering localisation $r/a$ can be changed during the shot for probing $0.5 < r/a < 0.95$ and $2 < k < 15$ cm$^{-1}$, owing to the steppable probing frequency and the motorised antenna. The perpendicular fluctuation velocity in the laboratory frame is obtained from the Doppler shift of the frequency spectrum $\Delta \omega = k_\perp v_\perp$. It is dominated by the plasma $E_x \times B$ velocity. In the core, the latter is mainly due to the projection of the toroidal velocity, as this is shown by comparison with measurements by charge exchange recombination spectroscopy. In the set of analysed Tore Supra ohmic and ICRH plasmas, the observed rotation is consistent with a poloidal velocity in the electron diamagnetic direction and/or a toroidal velocity in the counter current direction. Strong modification of velocity profiles and turbulence level are observed together with improved confinement in experiments with ICRH heating at high power and high concentration of minority ions. Preliminary results on associated wave number spectra will also be shown.

1 Introduction

Progress in understanding turbulence and anomalous transport requires localised measurements of turbulence characteristics, i.e. amplitude and typical length scales, or better the $k$ spectrum, and their temporal dynamics. This is particularly the case for improved confinement regime where the improvement is generally not global (in space, in wavenumber, for ion or electron channel). In these regimes, the plasma velocity and its shear have been shown to play a crucial role and are important to be simultaneously measured with the fluctuation level. Furthermore, theoretical comprehension and modeling advances \cite{1} now make detailed comparison with experiments meaningful \cite{2}: knowledge of turbulent scales is especially crucial for identification of instabilities implicated that might have different drives and scales.
Taking advantage of both scattering and reflectometry technics, Doppler backscattering has emerged as a promising means giving access to fluctuations at a specific scale, and their velocity, in a volume small compared to plasma minor radius. It is based on the possibility to separately detect the field backscattered on fluctuations along the beam path from the field reflected at the cut-off layer (standard reflectometry), by launching the probing beam in oblique incidence with respect to the cut off layer. Fluctuations whose wavenumber matches the Bragg rule are selected $\vec{k}_f = -2\vec{k}_i$, where $\vec{k}_i$ is the local probing wavevector. The localised swelling of the incident field at the cut-off, amplifies the scattering process and allows localisation of the scattering process near the cut-off layer. At the cutoff, the probing beam wave-vector is determined by its angle $\theta$ to the cut-off normal: $k_i = k_o \sin \theta$ (slab geometry) where $k_o$ is the vacuum wavenumber. This techniques thus provides the instantaneous spatial Fourier analysis of density fluctuations, $\tilde{n}(\vec{k}, t) = \int_V n(\vec{r}, t) e^{i\vec{k} \cdot \vec{r}} d\vec{r}$, acting as a band pass filter in $k$-space around $\vec{k} = -2\vec{k}_i$ at the cut-off layer. The wavenumber selectivity $\Delta k$ is related to the overlapping and shape of the probing and scattered beams. The turbulence frequency spectrum is Doppler shifted $\Delta \omega = \vec{k}_f \cdot \vec{v}_f$, that allows to determine the fluctuation velocity. Also referred to as Doppler reflectometry, it shares with standard fluctuation (CW) reflectometry good spatial and temporal resolution, easy access and low cost.

2 The Doppler back-scattering system on Tore Supra

The diagnostic has been designed to be able to measure the $k$-spectrum (from medium to small scale) and the velocity profiles of the fluctuations: exploring $k$ and $r$ space yields the choice of a tiltable antenna and a probing frequency in the V band (50-75 GHz range). This corresponds to O-mode cut-off density from $3.1$ to $7 \times 10^{19}$ m$^{-3}$ suitable for enhanced performance regimes [3, 4].

The antenna pattern must be optimized to separate the reflected signal from the backscattered one and to get a good $k$ selectivity. Gaussian beams have been preferred for their low divergence: a gaussian optics lens antenna associated with a corrugated horn, yields a beam waist of 40 mm (divergence 2.2° HPBW) The whole system is at 125 cm from the plasma (potential heavy heat load on non actively cooled components leads to limit plasma view angle from diagnostic ports, keeping away the windows and limiting their size). The antenna and the attached millimetric unit (see below) is tiltable and motorized, with an angular excursion from -1° to 10° (angle of the line of sight with respect to the last closed magnetic surface in the range -3° to 20°).

In O mode, the selected wave number at the cut-off is mainly poloidal. However, since the density fluctuations are nearly aligned along the magnetic field lines ($k_\parallel \ll k_\perp$), the beam wavevector should have a small toroidal component to fulfill the Bragg selection condition near the cut-off layer. The beam is thus launched with a small toroidal tilt angle so that the wavevector makes at the cut-off an angle $\xi_k$ with the poloidal plane nearly equal to the pitch angle of the magnetic field lines (around 5° depending on the safety factor profile). This condition is not critical due to the beam slight divergence, but important to get a good sensitivity.

The actual incident angle varies with the plasma shape, cut-off layer position and refraction. Ray tracing is therefore needed to evaluate the reflection layer location $r$. 
from where the scattered signal is expected to come and \( k \) at the reflection layer. It is computed in 3D geometry with geometrical optics approximation [5], and takes into account the divergence of a gaussian beam: the beam is simulated with multiple rays diverging from the center ray, whose propagation is conditioned by its neighbors.

The microwave part of the system is based on a fluctuation reflectometer scheme with heterodyne detection with a single side band modulator (modulation frequency 80MHz, IQ detection) which allows for measuring the turbulence propagation velocity through the Doppler shift \( S(k_\perp, \omega) \rightarrow \Delta \omega \sim k_\perp v_\perp \).

Choice has been made of stable source, a synthesizer, in the 12.5 to 19 GHz frequency range, with a typical switch time between steps smaller than 5 ms with a step duration from 5 ms, that can also be linearly swept in 5 ms typically. This signal is set to the 50 to 75 GHz range by use of an active multiplier which provides an output power of the order of 10 mW. It is then sent to the plasma through the high gain antenna via a high directivity coupler, to separate emission and reception signals. Modulation and demodulation are performed with the same quartz oscillator. A 12 bits VME system controls the data acquisition at 4 MHz acquisition rate, to account for the signal bandwidth expected (Doppler shift up to 1 MHz).

### 3 Probing frequency and tilt angle combined scans

Changing the probing frequency \( F \) changes both \( r/a \) and \( k \) and the same for \( \theta \). Thus obtaining radial profile at fixed \( k \) or wave-number dependence at fixed radius requires combined scans that are realised on a stationary phase of the plasma as shown in figure 1, by programming several sets of frequency steps during a tilt angle sweep. Figure 1(b) is a zoom showing the frequency steps timing: acquisition is triggered at each pre-set probing frequency step, recording typically 32k samples per step (10 steps require less than 200 ms), the whole pattern can be repeated several times during the shot; the angle sweep is sufficiently slow (5 to 2°/s) to ensure that the angle has not changed much during the acquisition time (typically 8 ms).

![Figure 1: Combined probing frequency (in blue, b) and antenna tilt (red, a) scan scenarios during stationary plasma phase; black line is the back-scattered signal rms value](image)

For each \((F, \theta)\) and plasma conditions, ray tracing is used to determine \((r/a, k)\) which map is shown on figure 2.
Density fluctuation profile can be measured for a fixed wave number (around $k_s = 8 \text{ cm}^{-1}$) from $r/a = 0.3$ to $r/a = 0.9$, and density fluctuation $k$ spectrum can be obtained for a smaller region, for example around $r/a = 0.6$, range of $k$ values is between $k_s = 4 \text{ cm}^{-1}$ and $k_s = 15 \text{ cm}^{-1}$. The access region both in $k$ and real space highly depends on the plasma density profile, beam frequency and tilt angle combinations.

Figure 2: $k_\perp$ versus $r/a$ for the probing frequency and antenna tilt angle scan of figure 1

### 3.1 Doppler spectra vs $r$ and $k_\perp$

Figure 3 shows the frequency spectra obtained for selected values of $r/a(\pm 0.05)$ and different $k$’s, for figure 1 plasma in the ohmic phase (a) and during ICRF heating at high power (b). The sign of the Doppler shift corresponds to the electron diamagnetic direction. There is no $f = 0$ component, i.e. the backscattered signal is separated from the reflected one, except for the magenta and black line of figure 3 (b), which corresponds to large values of the tilt angle. In these cases, the probing beam is deflected towards the wall, where it intersects metallic elements (ripple protection...) and is probably reflected and come back to the antenna experiencing forward scattering (and thus, frequency broadening). However, the Doppler shift increases with $k$ as expected (see § 3.2). The spectrum width is rather small in the ohmic case, less than 100 kHz, increasing with $k$ and heating power as previously observed on other tokamaks.

![Figure 3: Frequency spectra at fixed $r/a$ and various $k$ for ohmic plasma, $n_l=7 \times 10^{19} \text{ m}^{-2}$ (a) and during ICRH, $P=8\text{MW}$, $n_l=8 \times 10^{19} \text{ m}^{-2}$ (b).](image)

### 3.2 Perpendicular fluctuation velocity radial profile

Fluctuation perpendicular velocity is derived from the Doppler shift, $v_\perp = \Delta \omega/k$ and is plotted as a function of $k$ (figure 4(b)): fluctuation velocity very weakly depends on $k$
(within the error bar) as expected for fluctuation velocity dominated by the flow velocity, i.e. fluctuations play the role of tracers. The fluctuation perpendicular velocity profile (figure 4) is the derived (for \( k = 4 \pm 0.5 \text{ cm}^{-1} \)) for the ohmic and heating phase of figure 1. Values and shape are consistent with previous measurement in ohmic [6]. \( v_\perp \) decreases towards the center, and slightly to the edge. However the edge has not yet been probed in this configuration and requires high density plasmas (the smallest probing frequency, 50 MHz, corresponds to a density of \( 3 \times 10^{19} \text{ m}^{-3} \)).

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\begin{align*}
&\text{Figure 4: Fluctuation perpendicular velocity profile (at fixed } k = 4 \pm 0.5 \text{ cm}^{-1} \text{) for ohmic and heating phase, } n_l = 7 \times 10^{19} \text{ m}^{-2} \text{ (a), and its dependence with } k \text{ at fixed radius (b).}
\end{align*}
\]

### 3.3 Fluctuation k spectrum

The power spectral density \( \propto \tilde{n}(\vec{k}_\perp) \) is then evaluated as a function of \( k \) by integrating frequency spectra. The \( k \)-spectrum, plotted for a ohmic plasma at fixed radius in logarithmic scale (5a) is similar to observations from CO\(_2\) laser scattering experiment on Tore Supra [10] with a spectral index \( \sim 3 \) at low \( k \), increasing at higher \( k \), or an exponential dependence as shown in semi-logarithmic plot (b).

\[
\begin{align*}
&\text{Figure 5: Fluctuation } k \text{ spectra in ohmic plasmas.}
\end{align*}
\]
4 fluctuation velocity compared with $V_{E \times B}$

The Doppler scattering experiment gives a measurement of the perpendicular fluctuation velocity in the laboratory frame: $v_\perp = V_{E \times B, \perp} + < \omega/k >$. The radial component of the electric field generates the perpendicular component $V_{E \times B, \perp} = -E_r/B$. It can be derived from the radial projection of the force balance equation: $E_r = v_{\phi}B_\theta - v_\theta B_\phi - \nabla P_i/nq_i$.

The toroidal rotation velocity is measured by charge exchange recombination spectroscopy. Its contribution to $V_{E \times B, \perp} = -v_{\phi}B_\theta/B$ is compared to $v_\perp$ in figure 6, showing close values in various plasma conditions, as observed with other Doppler reflectometry systems [7, 8, 9].

The plasma scenario of figure 6 and 7 corresponds to high density, high heating power shots (8MW ICRH, 2MW LH) with a high concentration of minority ions (H). A good confinement (with an improvement factor H around 1.5) is observed as well as a strong spontaneous toroidal rotation (in the counter current direction). This is also seen from the large increase of the fluctuation velocity, up to 4 to 5 km/s and strong modification of the $V_{E \times B, \perp}$ profile, with a shearing zone around $r/a=0.7$. Fluctuation levels are evaluated at different radii and show a drop for $r/a <= 0.7$.

Since the toroidal term of $V_{E \times B, \perp}$ dominates, small values of fluctuation phase velocity $< \omega/k >_{fluc}$ are expected. It should be of the order of the remaining part of the $E \times B$ velocity $< \omega/k > \sim -v_{\theta}B_\phi/B + \nabla P_i/nq_i B$ which is plotted on figure 7(b), where the poloidal term $v_{\theta}$ is calculated from neoclassical evaluation. This part is seen to be rather small and of the order of $\omega_n^*$, in the electron diamagnetic direction. This is consistent with linear stability code calculations (TEM around this frequency in this k range).
5 Conclusion and future plans

The Doppler scattering system is operating on Tore Supra since 2004 for measuring fluctuation perpendicular velocity profile, turbulence level, and $k$ spectra in various plasma conditions: it can investigate particularly the role of the velocity shear and turbulence scales improved confinement regime; the impact of $Te/Ti$ ratio or other non dimensional parameters on the level and the mean fluctuation frequency, their link to ion/electron modes; the link with the density peaking and thermo-diffusion; and electron transport related to small scale fluctuations.

On the diagnostic point of view, we are now testing X mode polarisation (105-150GHz) configuration, for a possible operation in both O/X mode. A faster acquisition (20 to 100MHz) is also under development for higher Doppler shift (in case of probing higher $k$) and also for developing instantaneous Doppler frequency evaluation from parametric analysis for dynamical and statistical analysis.

References