

Analysis of density fluctuation frequency spectra in Tore Supra as a tool for studying plasma motion and transport properties

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Introduction

In recent years significant improvements in plasma confinement in tokamaks have been observed, generally accompanied by turbulence reduction (H-mode [1], ITB). Indeed, parameters such as velocity shear of the plasma rotation are found to affect and/or control both turbulence and transport properties. The CO₂ laser scattering experiment ALTAIR installed on Tore Supra [2] is dedicated to study density fluctuations and their relation to the transport. For this purpose, levels of observed turbulence at specific scales, are usually extensively studied in the different regimes, mainly from the modulus of the scattered signal. Frequency spectra are also essential to discriminate between possible turbulent modes; they permit also, as well as phase properties of the complex signal, an access through Doppler effect to the dynamical behaviour of the plasma flow. This is of great interest when modifications of the flow characteristics occur. Furthermore, convective or diffusive character of turbulent plasma motion presents different signature in the temporal signal behaviour; turbulent transport coefficients that can be evaluated are in good agreement with the one inferred from power balance analysis.

The ALTAIR diagnostic

The scattering signal is proportional to the spatial Fourier transform of density fluctuations at the scale corresponding to the scattering wavevector, in the wavenumber range $k \approx 3 - 25$ cm⁻¹, with an excellent wavelength resolution. Two scattering channels are available at two independent wavevectors. Heterodyne detection is used to keep modulus and phase of the signal, and thus permits the determination of the propagation direction of fluctuations.

Although the scattering angles are very small, some partial vertical localisation is possible since density fluctuations are known to be mainly perpendicular to magnetic lines [3]: signal is coming from where scattering wavevector is perpendicular to magnetic field lines. Typically, the length of the vertical scattering volume could be reduced to a fourth of the plasma diameter.

Plasma velocity shear at the edge

When the scattering volume is set to measure near the edge, the spectrum shows two peaks, in positive, respectively negative, frequency range. The radial electric field is known to reverse at the edge ($r/a \approx 0.92$) inducing $\vec{E} \times \vec{B}$ Doppler shifts in opposite directions [1, 4, 5]. The fluctuation propagation of the inner part of plasma is in the electron diamagnetic drift direction.

Separating the two contributions coming from both sides of the shear layer provides then an additional resolution. Furthermore, these inner and outer components show different behaviours of mean velocities, peak widths and shapes. This separation can be accomplished by fitting the measured spectra by a sum of two analytical functions, each with three parameters (amplitude, average frequency, and width), [4, 5, 6]. This method has also the benefit to give information about turbulent transport properties (cf. last paragraph).

Phase analysis

An alternative is to make use of phase properties of the signal. Indeed, the phase derivative of the complex signal is representative of the fluctuation velocity [7].

A first approach is to discriminate inner and outer components of the signal by their velocity direction with respect to \vec{k} , that is by their phase derivative sign [8]. This relies on intermittent character of the signal: if the difference between the level of the two components is large, the phase derivative reflects the instantaneous velocity of the largest one. This leads to a temporal separation of the signal. On figure 1a, the histogram of the phase derivative (i.e. velocity) shows a global agreement with the measured spectrum. The discrepancy visible on positive side may be due to the fact that most of the time, there is a composition of opposite velocities with different modulus, resulting in an intricate phase derivative behaviour not representative of each velocity distributions, especially of the lowest level one. Frequency shifts and widths of the spectra of the signal separated with this method are comparable with those of the raw spectrum (fig. 1b): the phase composition and the temporal separation procedure can induce fast oscillations of the phase, which appear on high frequencies.

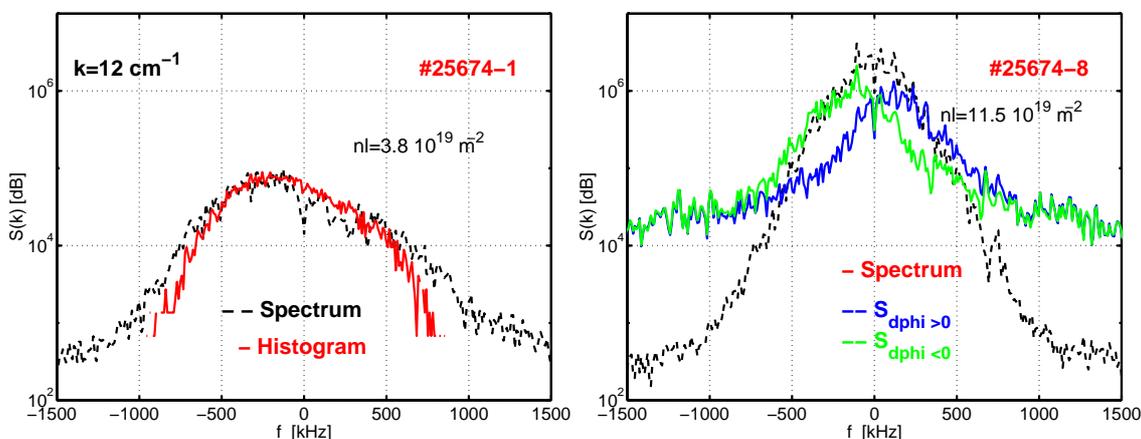


fig. 1: Frequency spectrum of the whole signal, superposed (a) with the histogram of its phase derivative, and (b) with spectra of the two processed signals. Ohmic plasma at low density (a, $nl= 3.8 \cdot 10^{19} \text{ m}^{-2}$) and high density (b, $nl= 11.5 \cdot 10^{19} \text{ m}^{-2}$).

A second approach is the complex filtering of the scattering signal, allowing arbitrary frequency range selection. Choosing to filter the signal around each peak frequency range, the signal corresponding to the inner or the outer part is separated from the other one. Since the spectrum peaks are partially overlapping, the choice of the in between frequency is tricky.

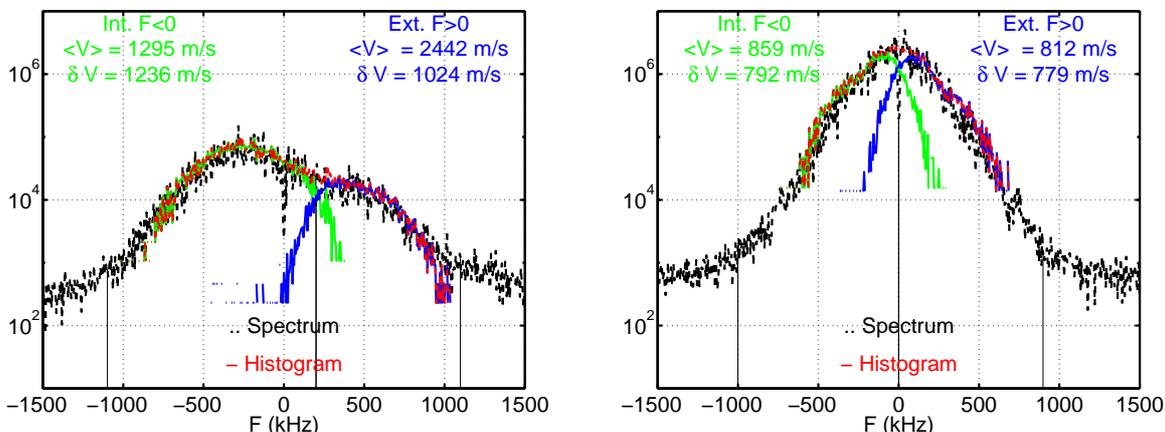


fig. 2: Density fluctuation spectra superposed with phase derivative histograms of the two signals obtained by complex filtering (green for inner, blue for outer, red curve for the sum). Same conditions as fig. 1.

Each of these signals can then be studied with the phase derivative analysis. The phase derivative histogram is compared to the signal spectrum corresponding peak form. Figure 2 shows the good agreement between them. Vertical bars show the filters frequency limits.

Statistical properties of each phase derivative give information on each plasma part dynamics behavior. Fig. 3(a) shows the evolution of inner and outer mean velocities versus lineic density in ohmic plasmas (cf. Zou et al., this Conf.), and their standard deviations in (b).

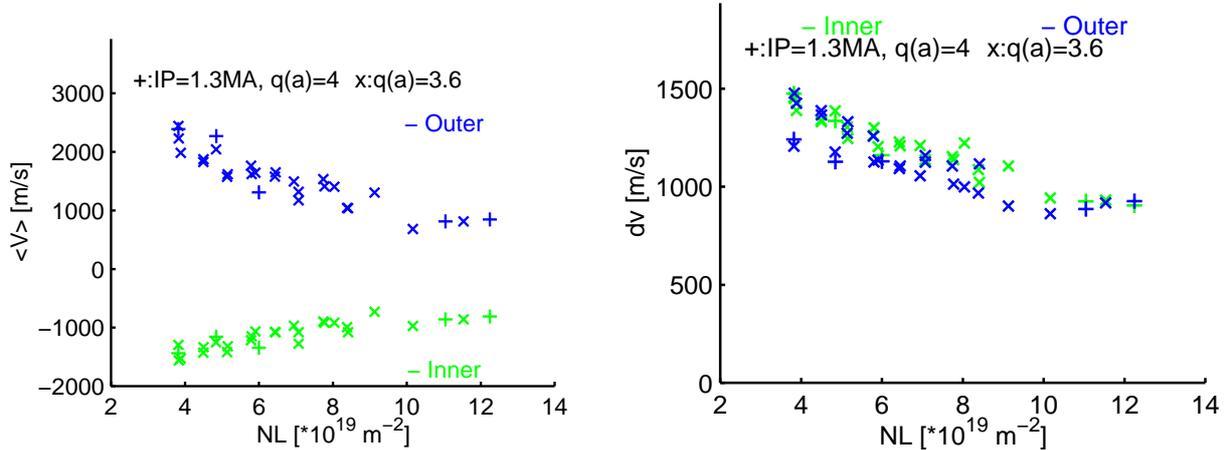


fig 3: (a) Evolution of mean velocity, (b) and of the half-width of the velocity histogram, in the inner and outer part of the plasma versus lineic density, from filtered signal phase analysis.

The poloidal velocity shear at the edge decreases with density, the change in velocity being greater for the outer part. The location of the electric shear layer seems not to be displaced in these experiments. The estimated electron diamagnetic drift velocity T/eBL_n is $\approx 300 \pm 100$ m/s, indicating that other drift terms, including $E \times B$ drift, dominate. Measurements of radial electric field or toroidal velocity are not yet available on Tore Supra, so velocity shear measurements like the above one permit to deduce the electric field change at the edge [9].

Turbulent movement statistics and transport

The temporal behaviour of the signal (through analysis of phase derivative moments or frequency spectrum width) can give information on turbulent transport properties [6] as being linked with the statistics of the turbulent movement.

Atomic or molecular diffusion coefficients are derived in a classical approach from the statistical analysis of the Lagrangian dynamics of a particle, with a velocity v . The mean square value of the displacement $\langle \Delta^2 \rangle$ is classically evaluated for times long or short with respect to Lagrangian velocity correlation time $\tau_L = \int_0^\infty C_v(\tau) d\tau$ (where $C_v(\tau) = \langle v(0)v(\tau) \rangle / u^2$, $u^2 = \langle v^2 \rangle$) and presents either diffusive ($\langle \Delta^2 \rangle = 2u^2\tau_L\tau = 2D\tau$) or convective transport properties ($\langle \Delta^2 \rangle = u^2\tau^2$).

This statistical approach applies also for turbulent macroscopic motions [10]. Transition between diffusive or convective behaviour can be studied from a typical decreasing function for the velocity correlation (Taylor): $C_v = e^{-\tau/\tau_L}$, which leads to $\langle \Delta^2 \rangle = 2u^2\tau_L^2(\frac{\tau}{\tau_L} - 1 + e^{-\tau/\tau_L})$.

The correlation function of the scattered electric field $c(\tau) = \langle \sum_{i,j} e^{i\vec{k} \cdot (\vec{r}_i(t) - \vec{r}_j(t+\tau))} \rangle_t$, can be written as the product of the static form factor $S(\vec{k})$ by the characteristic function of the probability of displacement $\langle e^{i\vec{k} \cdot \vec{\Delta}\tau} \rangle$ [6]. Hence, assuming a normal probability distribution function for this turbulent displacement, the signal correlation function is proportional to

$$F(\vec{k}, \tau) = \langle e^{i\vec{k} \cdot \vec{\Delta}\tau} \rangle = e^{-k^2 \langle \Delta^2 \rangle / 2} = e^{-k^2 u^2 \tau_L^2 (\frac{\tau}{\tau_L} - 1 + e^{-\tau/\tau_L})} \quad (1)$$

the corresponding frequency spectrum is calculated numerically, later referred as T.

When $ku\tau_L \gg 1$ only small τ contribute in $F(\vec{k}, \tau)$ to the evaluation of the spectrum, so the gaussian (convective) behaviour of the spectrum is retrieved.

Conversely, diffusive limit is reached for $ku\tau_L \lesssim 1$. Between these two limits, the width of the calculated T-spectrum evolves from a k^2 dependence to k^1 .

This transition is observed for the outer component of the spectrum, in a set of ohmic shots (D, $B = 2.5\text{T}$) where k has been changed in the range 8 to 25 cm^{-1} [11]. The frequency spectrum shown in fig. 4a for $k = 8\text{ cm}^{-1}$, is near the transition scale $ku\tau_L \approx 1$: the best fit is obtained with the T-spectrum calculated from eq. (1). The obtained diffusion coefficient ($D = u^2\tau_L \sim 2\text{ m}^2/\text{s}$), is in agreement with the evaluated heat diffusion coefficient. The same estimated parameters are used to calculate the half width Δf of the T-spectrum for the whole k range. On fig. 4b, this predicted evolution of Δf versus k (red dashed curve) is then compared to experimental data (outer peak half width vs. k , blue points). For low k values, the width behaves as $k^{1.5}$, while for large k , $\Delta f \sim k$.

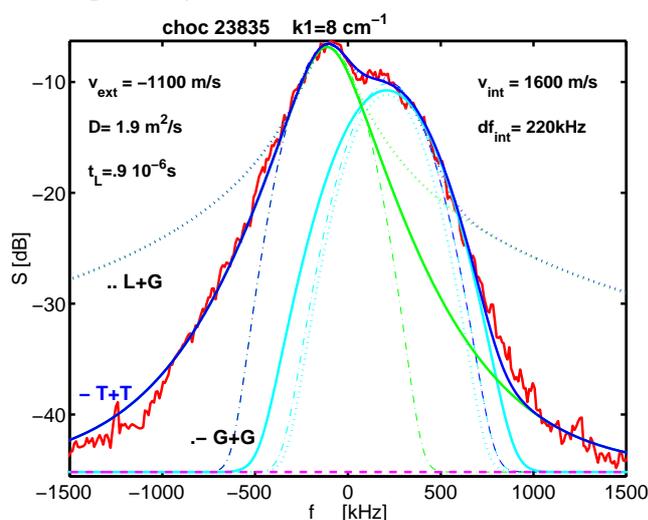
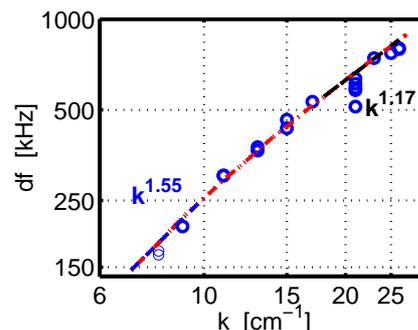


fig 4 (a): Comparison of best fit of a frequency spectrum by the sum of two calculated T-spectra, of two Gaussian functions, or of a Gaussian plus a Lorentzian.

fig 4(b): Comparison of calculated and experimental widths.



Conclusion

The different methods presented here permit to study fluctuation velocity properties with the ALTAIR diagnostic, especially at the edge where there is an important shear, and to relate them to turbulence characteristics and transport. As plasma rotation has been shown to be an important ingredient of the improved confinement regimes, the measure of plasma velocity and particularly the velocity shear is a precious information, together with turbulence level change.

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