Impact of collisionality on fluctuation characteristics of micro-turbulence

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The influence of changing collisionality on density fluctuation characteristics is studyied during dedicated $\nu*$ scaling experiments, using Doppler backscattering system. First, the repartition of fluctuation energy over different spatial scales, as represented by the wavenumber spectrum is investigated and an effect on the shape of the perpendicular wavenumber spectrum in the low wavenumber part of the spectrum is observed when changing collisionality . In addition, a new procedure to evaluate the dispersion relation of micro-turbulence is presented. From the behaviour of the perpendicular mean velocity of density fluctuations with the perdendicular wavenumber, different dispersion relations are obtained between low and high collisionality cases.

I. INTRODUCTION

Particle and heat transport induced by micro-turbulence largely determine the performances of the modern day tokamaks. The understanding and the prediction for next step devices such as ITER, of turbulent transport requires precise comparisons between experimental observations and theoretical predictions, in particular via studies of parametric dependencies of turbulence characteristics. The description of plasma dynamics using dimensionless paramaters is another powerful and commonly used tool to extrapolate from present day devices to next step experiments. The dependence of turbulent transport on dimensionless parameters such as $\rho*$, β and $\nu*$ can be studied by performing dedicated scan experiments in which one of these paramaters is varied while the others are kept constant (also keeping the geometry of the plasma unchanged). This kind of experiments constitute an excellent framework to perform comparisons between the observed characteristics of micro-turbulence and the results from simple theoretical models and gyrokinetic simulations.

In the present paper, we investigate the effect of the collisionality on the shape of the perpendicular wavenumber spectrum using Doppler backscattering system[1]. In addition to providing access to the spatial scales of density fluctuations, this technique also allows us to probe the dispersion relation of micro-turbulence through the representation of the perpendicular velocity with the wavenumber. In the following, a short description of the Doppler backscattering system is given in the section 2. In the section 3, the shape of the wavenumber spectrum communly observed on Tore Supra is first presented then the effect of collisionality on the shape of the spectrum highlighted during the ν^* scans is exposed. The section 4 is dedicated to the impact of changing the collisionality in the behaviour of the dispersion relation of micro-turbulence is presented. Finally, a discussion is proposed in the last section.

II. DOPPLER BACKSCATTERING SYSTEM ON TORE SUPRA

The Doppler backscattering system combines advantages of both reflectometry and scattering techniques. It is based on the detection of the field backscattered on density fluctuations in the vicinity of the cut-off layer. In practice, the probing wave is chosen in the microwave range and is launched in oblique incidence with respect to the normal vector to the surfaces of isoindex-of-refraction (α being the angle of incidence with the normal vector to the iso-index-of-refraction surface), thereby only the back-scattered signal (little or no reflected signal is received) is detected by the emitter antenna which also serves as a receptor. The fluctuations whose wave-number matches the Bragg rule $\overrightarrow{k}_f = -2\overrightarrow{k}_i$ are selected exclusively, where $\overrightarrow{k}_i$ and $\overrightarrow{k}_f$ are respectively the local probing wave-vector and the density fluctuations wave-vector. This technique thus provides the instantaneous spatial Fourier analysis of density fluctuations, $\tilde{n}(\vec{k},t) = \int_V n(\vec{r},t)e^{i\vec{k}.\vec{r}}d\vec{r}$, acting as a band pass filter in k-space around $k = k_0 sin\alpha$ at the cut-off layer. The power spectral density that is detected, is Doppler shifted by $\triangle\omega = \overrightarrow{k}_f.\overrightarrow{v}_f$ due to the movement of density fluctuations perpendicular to the field lines. This property allows us to determine the fluctuation velocity at the cut-off layer. In addition to the flow profile, the Doppler reflectometers can be used to obtain the perpendicular wave-number spectra, locally, since the integration of the power spectral density, gives the power of density fluctuations contained at a radial position and at a specific spatial scale. Results presented in this paper are obtained using the channel operating in the V-band frequency range in ordinary polarisation. This channel allow us to probe the plasma from $r/a = 0.5$ to $r/a = 0.9$ (where a is the minor radius) for wavenumber $k = 3 - 20cm^{-1}$. The radial position and the wavenumber of the probing wave at the cut-off layer are determined using a 3-D beam tracing code [2] simulating the propagation of a Gaussian beam in a stationary plasma represented by a radial density profile (measured using fast-sweep reflectometers [3]).

III. COLLISIONALITY DEPENDENCE OF DENSITY FLUCTUATIONS CHARACTERISTICS

A. Shape of the wavenumber spectrum

Thanks to the steady-state operation of the Tore Supra tokamak and to the flexibility of the Doppler backscattering system installed on it, we can scan a large number of probing frequency and incident angle (F,α) pairs and obtain the wavenumber spectrum with a high level of resolution in terms of wavenumber discretization. Figure III.1 presents an example of wavenumber spectrum of density fluctuations measured around $r/a = 0.8 \pm 0.08$.

This spectrum corresponds to a typical discharge of Tore Supra at B=3.8T, in which the plasma is heated using Ion Cyclotron Resonance Heating system. At small wavenumber ($k\rho_s$ $\leq$0.6) the spectrum seems to saturate while, for the range of wavenumbers $k\rho_s = [0.6 - 0.9]$, it follows a power law as $s(k) \propto k^{-3}$ and starts to decrease faster for higher wavenumbers, consistent with previous observations[4]. For $k\rho_s = [0.7 - 1.2]$, this form is correctly described using the shell model derived in[5]. Note that the shell model expression does not have any fitting paramaters (apart from the fluctuation level). Therefore, the correct agreement between experiment

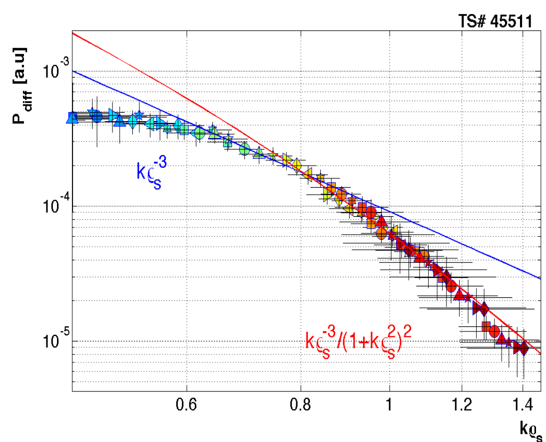

Figure III.1: k-spectrum of density fluctuations measured using Doppler backscattering system.

and this model is remarkable and suggests that interaction between disparate scales including zonal flows is an important ingredient to determine the wavenumber spectrum shape. As already noticed in [4], the wavenumber spectrum may also be fitted using exponential functions.For the smaller wavenumber ($k\rho_s < 0.7$), the measurements are well fitted using an exponential as $e^{-1.7k\rho_s}$. This wavenumber range corresponds to the anisotropic part of the spectrum and is labelled as the "linear part" . Although non-linear processes inevitably affect this region as well, it appears mainly as the region of energy injection from the plasma micro-instabilty, driven unstable by gradients in background profiles. In the range of larger wavenumbers, where the nonlinear interactions and the energy transfer dominate, the spectrum has the form: $e^{-5.2k\rho_s}$. This region is akin to the inertial range in fluid turbulence, even though the dominant mechanism for energy transfer may be different and some residual instabilities may exist in this region, due to the final form of the spectrum, the energy these instabilities can inject (i.e. $\propto \gamma_k P$) is quite small.

B. Impact of ν^* on the shape of the wavenumber spectrum

In this section, we focus on the effect of collisionality on the shape of the perpendicular wavenumber spectrum during dedicated ν^* scan experiments in which the entire radial profile of the collisionality has been varied by more than a factor 4 between two different discharges while other dimensionless parameters such as $\rho*$ and β were kept constant. In order to quantify the effect of the collisionality on the wavenumber spectrum shape we use fitting processes. The best agreements occur when treating the two wavenumber ranges $k\rho_s < 0.7$ and $k\rho_s > 0.7$ of the spectrum separately using exponential $A_1 e^{-\gamma k}$ functions (or a Gaussian $A_2 e^{-\xi k^2}$ for the linear region), and a generalized expression of the spectral model for drift waves derived in [6] :

$$A_3 \frac{k^{-3}}{(1+\alpha k^2)^2 + \beta k^2} \tag{III.1}$$

This generalized form is more flexible and permits fitting processes while the standart form has no fitting parameters.

The results from the fitting processes for both low and high collisionality cases are presented in figure III.2. For the smaller wavenumber range ($k\rho_s < 0.7$), the spectrum is well described, for both cases, by Gaussian and exponential functions. Note that for small value of k, both

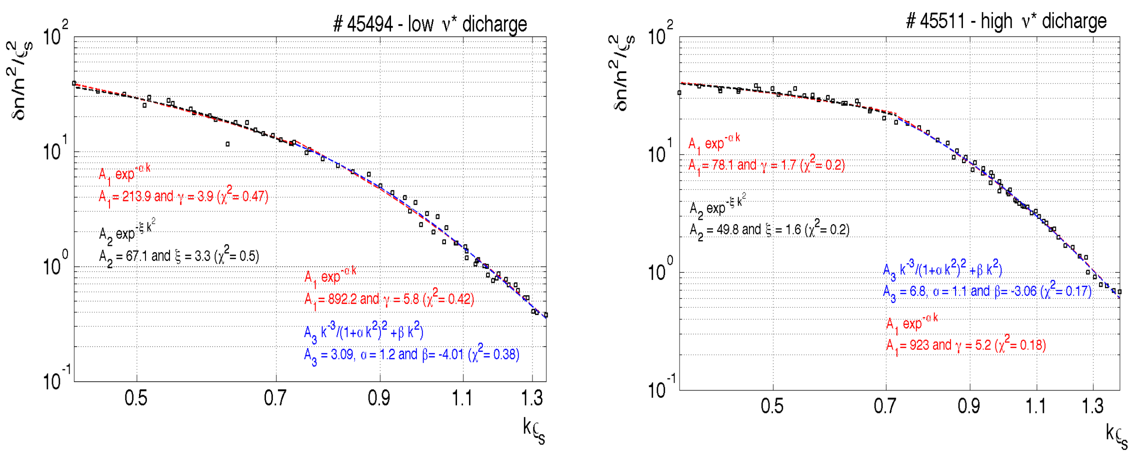

Figure III.2: Fitting of the wavenumber spectra considering separately the wavenumber range $k\rho_s < 0.7$ and $k\rho_s > 0.7$ for both discharges 45494 (left) and 45511 (right)

functions are similar and can not be distinghuished. However, the justification of the Gaussian function comes from the shape of the linear growth rate of the main instabilities. The quasi-linear approach, which involves balancing the linear growth with a quasi-linear transfer rate, gives a spectrum in the linearly driven region and explains roughly the shape of the spectrum near the region of the drive ($k_\perp \rho_s \lesssim 0.5$). The change of the value of $\nu*$ affects this region such as decreasing $\nu*$ the spectrum decreases faster. This effect can be quantified by comparing the fitting paramaters of the Gaussian function ξ : for the low $\nu*$ discharge $\xi = 3.3$ while for the low $\nu*$ discharge $\xi = 1.6$. In the higher wavenumber range, the spectrum is well fitted using the generalized form of the spectral shell model (eq. III.1) as well as by the exponential function and is almost not affected by the variation of $\nu*$. Comparing the exponential paramaters $\gamma = 5.8$ for the high $\nu*$ case while $\gamma = 5.2$ for the low $\nu*$ case and comparing the parameters from shell model expression, $\alpha = 1.1$ and $\beta = -3.6$ for the high $\nu*$ case while $\alpha = 1.2$ and $\beta = -4$ for the low $\nu*$ case.

C. Evolution of the dispersion relation

In addition to the spatial scales of micro-turbulence, Doppler backscattering system also permits to access the dynamic of the density fluctuations. The Doppler shift of the spectral density power $S_{k,r}(f)$ gives the perpendicular velocity of density fluctuations in the laboratory frame : $V_\perp = v_{E\times B\perp} + v_{fluc}$, where $v_{E\times B\perp} = -E_r/B$ (E_r being the radial electric field) and v_{fluc} is the mean phase velocity of the density fluctuations. For all the discharges presented in this paper, the Doppler shift is in the electron diamagnetic direction (negative frequency) as it is almost always the case in Tore Supra plasmas. For reasons of simplicity, we will consider in the following the absolute value of $V_{\perp}$, which correspond to convention that $V > 0$ means in the electron direction and $V < 0$ means in the ion direction. The mean phase velocity of the density fluctuations v_{fluc} is known to be small as compared to $v_{E\times B\perp}$[7] therefore its evaluation remains untrustable. Nevertheless, analysing the perpendicular wavenumber dependence of this measured perpendicular velocity $V_{\perp}$, gives an indication on the dependence of v_{fluc} with $k_{\perp}$ since $v_{E\times B\perp}$, which is a mean quantity, does not depend on the wavenumber. This then allows us to get informations on the dispersion relation $\omega_{fluc}(k_{\perp})$ from $v_{fluc} = \omega_{fluc}/k_{\perp}$. The perpendicular wavenumber $k_{\perp}$ dependence of the measured Doppler velocity $V_{\perp}$, for the discharges that are presented above at the same radial location ($r/a = 0.8 \pm 0.025$) are shown in figure III.3. A clear difference in $V_{\perp}(k_{\perp})$ is observed between both discharges : for the high $\nu*$ discharge, $V_{\perp}$ decreases with increasing $k_{\perp}$ while $V_{\perp}(k_{\perp})$ remains rather flat during the low $\nu*$ discharge. In the high collisionality discharge, the behaviour of the perpendicular velocity with the wavenumber can be interpreted/translated as following. If we consider that the density fluctuations are dominated by ion turbulence $v_{fluc} < 0$ and the decrease of $V_{\perp}$ with $k_{\perp}$ means that v_{fluc} increases with increasing $k_{\perp}$.This led to a dispersion relation such as $\omega_{fluc}(k_{\perp}) = k_{\perp}v_{fluc} \propto k_{\perp}^{\alpha}$ with $\alpha > 1$. On the opposite, if we consider that $v_{fluc} > 0$ (electron turbulence), v_{fluc} decreases with increasing $k_{\perp}$ leading to $\omega_{fluc}(k_{\perp}) = k_{\perp}v_{fluc} \propto k_{\perp}^{\alpha}$ with $\alpha < 1$. Now, if we consider the low $\nu*$ discharge, the $k_{\perp}$ dependence of $V_{\perp}$ indicates that regardless of the type of turbulence (pure ion mode or pure electron mode), $\omega_{fluc}(k_{\perp}) = k_{\perp}v_{fluc} \propto k_{\perp}$. One can also imagine a case of mixed ion and

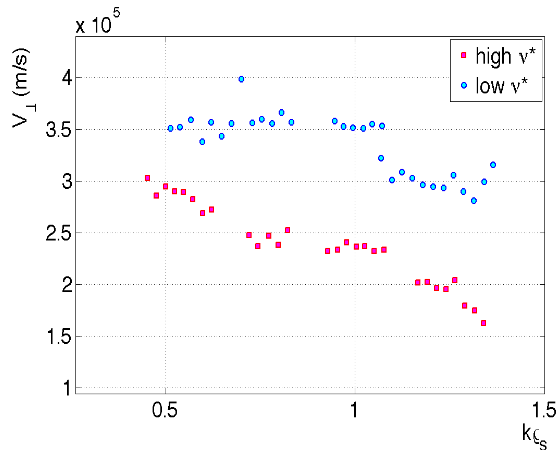

Figure III.3: Evolution of the mean perpendicular velocity of density fluctuations (in electron diamagnetic direction) versus the normalized perpendicular wavenumber at $r/a = 0.8 \pm 0.025$

electron turbulence that generates density fluctuations in both ion and electron diamagnetic directions at the same spatial scales leading to a Doppler shift associated to the mean of both components (ion and electron componements respectively shifted in the negative and positive directions with respect to the $v_{E\times B\perp}$component).

IV. DISCUSSION

In the present paper, we used Doppler backscattering system to study certain micro-turbulence characteristics such as perpendicular wavenumber spectrum and perpendicular velocity of density fluctuations, and their collisionality dependence. At a basic level, its form seems to be a robust feature of all wavenumber spectra measured in various plasma conditions. We observed that the wavenumber spectrum is composed of two regions : at the smaller wavenumbers ($k\rho_s < 0.7$), a region of energy injection from the main instability/instabilities in which the spectrum is rather flat and/or decreases slowly; at larger wavenumbers ($k\rho_s > 0.7$), a region of energy transfer in which the spectrum decreases in a regular fashion. In the range of small k (referenced as the linear part of the spectrum), the shape of the spectrum is well represented by Gaussian functions. At larger k, the form is correctly described by the simple form $k^{-3}/\left(1+k^2\right)^2$(from the shell model [6]) suggesting that the interactions between large scale flow structures and fluctuations may play an important role in determining the wave number spectrum shape in this energy transfer region. This part of the spectrum is also well fitted using a generalized form of the shell model (eq.III.1) or using an exponential function $A_1 e^{-\gamma k}$ (with typicaly $\gamma \simeq 5-6$).

During dedicated $\nu*$ scan experiments it is found that the shape of the perpendicular wavenumber is affected by changing the collisionality : in the linear part, the spectrum decreases faster with decreasing $\nu*$. At larger wavenumbers no impact is observable. Those observations are in contrast with explanations condidering from strandart effet on collisionliaty on TEM or/and on ZF. Considering the impact of zonal flows, it is expected that a decrease of $\nu*$ would reduce the damping on zonal flows , which would lead to a decrease of energy content on small wavenumbers due to the shearing by large scale stuctures. This would give a flatter wavenumber spectrum when decreasing $\nu*$. On the other hand, considering the role of TEM, the increase of $\nu*$ is supposed to stabilize TEM and then is expected to peak the spectrum (since only the ITG "peak" remains). Possible explanations might come from the fact that the TEM may cause a reduction of the zonal flow activity [8, 9] or on the role of GAMs as a second predator species feeding on the main instability [10].

In addition to the effect of collisionality on the wavenumber spectrum, an impact is also observed in the behaviour of the perpendicular velocity of density fluctuations. Doppler backscattering system permits to acces to the wavenumber dependence of the perpendicular velocity which can then be used to obtain information about the dispersion relation of the microturbulence, measured inside the plasma. While the measurements are indicative of a change of the behaviour of $V_{\perp}(k_{\perp})$ between the two $\nu*$ discharges, the results are not conclusive. We present it as an illustration of this powerful procedure to evaluate the form of the dispersion relation, which can then be compare with theoretical predictions from simple models as well as from complete gyrokinetic simulations.

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