Impact of collisionality on fluctuations characteristics of micro-turbulence

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Abstract

The influence of changing collisionality on density fluctuations characteristics is studied during dedicated $\nu^*$ scaling experiments using Doppler backscattering system.

First, we investigate the repartition of fluctuation energy over different spatial scales, as represented by the wavenumber spectrum and we found that changing collisionality affects the shape of the perpendicular wavenumber spectrum in the low wavenumber part of the spectrum.

In addition, we present a new procedure to evaluate the dispersion relation of micro-turbulence. From the behaviour of the perpendicular mean velocity of density fluctuations with the perpendicular wavenumber, different dispersion relations are obtained between low and high collisionality cases.
Outline

1. Dimensionless description of transport and turbulence & dedicated experiments on Tore Supra

2. Doppler backscattering system installed on Tore Supra & density fluctuations measurements

3. Wave-number spectrum of density fluctuations

4. Impact of $\nu^*$ parameter on micro-turbulence characteristics
Dimensionless description

Similarity principle:

The dynamic of the plasma is described using limited set of dimensionless parameter (B.B.Kadomtsev, J. Connor)

=> Normalized confinement time $\tau$ as a function of dimensionless parameters $\rho^*, \nu^*, \beta$ ...

\[
B_0 \tau_E = F(\rho^*, \beta, \nu^*, q, \epsilon, \frac{m_e}{m_i}, \frac{T_e}{T_i}, Z_{eff}, \ldots, \kappa, \delta, M_{rot})
\]

- gyroradius: $\rho^* = \frac{\rho_i}{a}$
- beta: $\beta = \frac{p}{B^2/2\mu_0}$
- collisionnality: $\nu^* = \frac{v_{ie}}{e\omega_{be}}$
Dedicated dimensionless scaling experiments

Scan en ν*

\[ T \propto B^2 \]

\[ n \text{ constant} \]

\[ \nu^* \propto B^{-4} \]

- Motivations of this new scan (previous scan [C. Bourdelle et al, NF 2010])
  - reach the lowest collisionnality regime

- Significative variation in ν* achievable
  (limitation from the heating power)

- The density remains constant during the scan
  - reflectometry accessibility also
Dimensionless parameters well matched

\[ \nu^* \propto \frac{n}{T^2} \]

\[ \rho^* \propto \sqrt{\frac{T}{B}} \]

\[ \beta \propto \frac{nT}{B^2} \]

![Graphs showing dimensionless parameters vs. r/a](image)
Doppler backscattering system on Tore Supra

Measurement of the backscattered electric field \( E_d(t) \):
\[
E_d(t) \propto \int_V \tilde{n}(\vec{r},t)e^{-i\vec{k} \cdot \vec{r}} d^3r \equiv \tilde{n}(\vec{k},t)
\]

- Tiltable motorized antenna
  - Gaussian optics
  (beam waist 40mm)
  - Low diverging beam
  (2.2° HPBW)
  - Poloidal angle 0 to 20°
  (typically 3° to 9°)
  \( \Rightarrow k : 3 \text{ to } 25 \text{ cm}^{-1} \)
  \( \Rightarrow k\rho_i \sim 0.5 \text{ to } 5 \)

- O mode / V-band
  \( r/a = 0.3 \text{ to } 0.9 \)

- New channel:
  - X mode / W-band
  \( r/a = 0.5 \text{ to } 1.2 \)

Cut-off layer : \( N=0 \)

\[ E_0 e^{i(k_i \cdot r - \omega t)} \]

Incident wave

Selection in wavenumber:
Bragg rule
\[
k_d = k_i + k
\]
backscattered \( k_d=-k_i \Rightarrow k=-2k_i \)
Density fluctuations measurements

Tore Supra => long pulse discharges : stationary phases long enough to scan the poloidal angle => kθ-spectrum

Steps of the probing frequency (~20ms)
Scattering position and wavenumber

Beam Tracing using density profiles from fast sweep reflectometry

\[ (F, \theta) \leftrightarrow (r, k) \text{ from ray tracing} \]

\[ S(k) \pm 0.05 \]

\[ [C. \ Honoré \ et \ al, \ NF \ 2006] \]
Frequency spectra

Best fitting function: Taylor function

\[ T(\tau) \propto e^{-k^2u^2\tau L^2 \left[ \frac{\tau}{\tau L} - 1 + e^{-\frac{\tau}{\tau L}} \right]} \]

from the fit \( \Rightarrow \)

\[ S(k, \omega) \propto \langle |\tilde{n}(k, \omega)|^2 \rangle \]

Doppler shift \( \Rightarrow \Delta \omega \sim k \cdot v_\perp \)
Transition in the $k$-spectrum at high $k$

Usual power law: $S(k) \sim k^{-3 \pm 0.5}$ for $k\rho_s < 1$

Faster decrease at higher $k$

Laser scattering [Hennequin et al. PPCF 2004]

Doppler [Hennequin et al, NF 2006]

=> Observed with various diagnostics & conditions on Tore Supra + others machines [Gusakov EPS06, Basse PPCF05]
Comparison against gyrokinetic simulations

Low-k part of the spectrum (for $k\rho_s < 1$)

$=>$ Compared against gyrokinetic simulations: good agreement
Fluid turbulence / magnetized plasma turbulence

- **3D Fluid Turbulence:**
  - Kolmogorov direct energy cascade
    
    Kinetic Energy $E(k) = \langle v_k^2 \rangle \sim k^{-5/3}$

- **Magnetized plasma turbulence:**
  - strong anisotropy induced by large $B \Rightarrow 2D$
  - 1 field isotropic 2D simplified picture
  - inertial range

- **2D Fluid turbulence:**
  - Inverse energy cascade leads to the formation of large scale structures.
Transition in the $k$-spectrum at high $k$

Faster decrease at higher $k$

$\Rightarrow$ Recently: Interaction with disparate scales (drift waves – ZF)

[O. Gürcan et al, PRL09]

$$\left| \tilde{n}_k \right|^2 \approx \left| \tilde{\phi}_k \right|^2$$

$$\left| \tilde{n}_k \right|^2 \approx \frac{k^{-3}}{(1 + k^2)^2}$$

Generalized form:

$$\tilde{n}_k \approx (1 + i\delta)\tilde{\phi}_k$$

$$\left| \tilde{n}_k \right|^2 \approx \frac{k^{-3}}{(1 + \alpha k^2)^2 + \beta k^2}$$
Shape of k-spectrum on Tore Supra

Example of a ICRH discharge (#45511) @ r/a = 0.8 ± 0.08:

- Similar shape than observed previously without a clear transition
- Fair agreement (except for low k) for all cases with the model taking into account interactions between disparate scales (drift-waves-zonal flows)

[L. Vermare et al, CRAS 2010]
\( \nu^* \) dependence of spectrum shape
Universality of k-spectrum shape? Effect of $\nu^*$

**High $\nu^*$**

$A_1 \exp^{-\xi k}$

$\xi = 78.1$ and $\gamma = 1.7$ ($\chi^2 = 0.2$)

$A_2 \exp^{-\xi k^2}$

$\xi = 49.8$ and $\gamma = 1.6$ ($\chi^2 = 0.2$)

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

$A_3 = 6.8$, $\alpha = 1.1$ and $\beta = -3.0$ ($\chi^2 = 0.17$)

$A_4 \exp^{-\xi k}$

$\xi = 923$ and $\gamma = 5.2$ ($\chi^2 = 0.18$)

**Low $\nu^*$**

$A_1 \exp^{-\xi k}$

$\xi = 213.9$ and $\gamma = 3.9$ ($\chi^2 = 0.47$)

$A_2 \exp^{-\xi k^2}$

$\xi = 67.1$ and $\gamma = 3.3$ ($\chi^2 = 0.5$)

$A_3 \exp^{-\xi k}$

$\xi = 892.2$ and $\gamma = 5.8$ ($\chi^2 = 0.42$)

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

$A_3 = 3.09$, $\alpha = 1.2$ and $\beta = -4.0$ ($\chi^2 = 0.38$)

*Generalized form:*  

$$\left| \tilde{\phi}_k \right|^2 \approx \left| \tilde{n}_k \right|^2 \approx \frac{k^{-3}}{(1 + \alpha k^2)^2 + \beta k^2}$$
Perpendicular velocity profile

Perpendicular velocity in the laboratory frame:

\[ V_\perp = V_{E \times B, \perp} + \langle \omega / k \rangle_{fluc} \]

with usually \( \langle \omega / k \rangle_{fluc} \ll V_{E \times B, \perp} \)

\( \Rightarrow \) direct access to the radial electric field

\[ [E. \ Trier \ et \ al, \ NF \ 2008] \]

- In Tore Supra, \( V_\perp \) profiles measured using Doppler are always **counter-current direction (\( V_\perp < 0 \)), inside the separatrix**

- **Hollow profiles** \( \Rightarrow V_\perp \) decreases from the edge to the core
Perpendicular velocity evolution with $k$

$$v_\perp (k) = I \mathbf{V}_{E\times B} + \mathbf{V}_\phi (k) I$$

$$V_\phi \equiv \omega_{\text{dia}} / k$$

- **high $\nu^*$:**
  - $\omega_{\text{dia}} (k) \propto k^\alpha$
  - $V_\phi > 0$: ion
    - with $\alpha > 1$
  - $V_\phi < 0$: e-
    - with $\alpha < 1$

- **low $\nu^*$:**
  - $\omega_{\text{dia}} (k) \propto k$

- mixed turbulence?
Summary

- Robust features observed in $k\theta$-spectrum: departure from a classical $k$-spectrum power law with fast decrease for $k_{\rho_i} > 1$

- Fair agreement with model taking into account interactions between disparate scales (*drift-waves/zonal flows*)

- Effect of collisionality observed on the shape of the wavenumber spectrum in the low-$k$ part of the spectrum

- New procedure to access the dispersion relation: modification observed when changing the collisionality