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Characteristics of fluctuations in ELMFIRE simulations

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Introduction

An increased understanding of turbulent fluctuations in plasmas is needed for future high-performance fusion reactors. Fluctuations observed in simulations and experiments can be characterized by statistical quantities allowing the ensemble averaging procedure. In this work we investigate three different statistical quantities of this kind, the power spectrum $S(k)$, the two-dimensional correlation function $C(\theta,\tau)$ and the probability distribution function (PDF) $p(\delta n/n)$, as measured in ELMFIRE simulations. All three quantities describe different properties of the fluctuations and add to our understanding of the simulated turbulence.

ELMFIRE [1] is a global full f gyrokinetic particle-in-cell code developed for studies on electrostatic turbulence and associated transport phenomena in tokamaks. The electrostatic potential ϕ is solved self-consistently from a gyrokinetic Poisson equation using a discretized grid. Electrons are treated drift-kinetically or adiabatically.

The simulations are carried out in the FT-2 tokamak ($a = 0.08$ m, $R = 0.55$ m) geometry. In the FT-2 [2] both an internal transport barrier (ITB) and an edge H-mode have been observed. In this work we present results from a deuterium discharge simulation with evidence of an ITB-formation (more on the observation of ITB:s in ELMFIRE simulations, see [3]). Also the PDF in a hydrogen discharge simulation is investigated. The physical parametres at $\rho = 2$ cm are $B = 2.2$ T, $I = 22$ kA, $n = 3.5\cdot 10^{19}$ m^{-3}, $T_i = 250$ eV and $T_e = 300$ eV.

Spectral investigation

In this section we investigate the power spectrum of density fluctuations $S(k) = \langle|\hat{n}_{\mathbf{k}}|^2\rangle$ at a constant radial surface, where averaging $\langle\ldots\rangle$ is done over 25 wavenumbers and over 20 sample spectra. In Fig. 1 are power spectra from simulations with drift-kinetic and adiabatic electrons.

The spectra peak near $k_\perp\rho_i = 0.1$, consistent with earlier results [4] and follow Kolmogorov-type power laws $S(k_\perp) \propto k_\perp^{-\alpha}$ above this source region. In simulations with adiabatic electrons $\alpha = 4\pm 0.3$ is obtained, while for kinetic electrons we observe a variation of α with radius, Fig. 2.

The nonlinear behaviour in the adiabatic case is described by the well-known Hasegawa-Mima equation

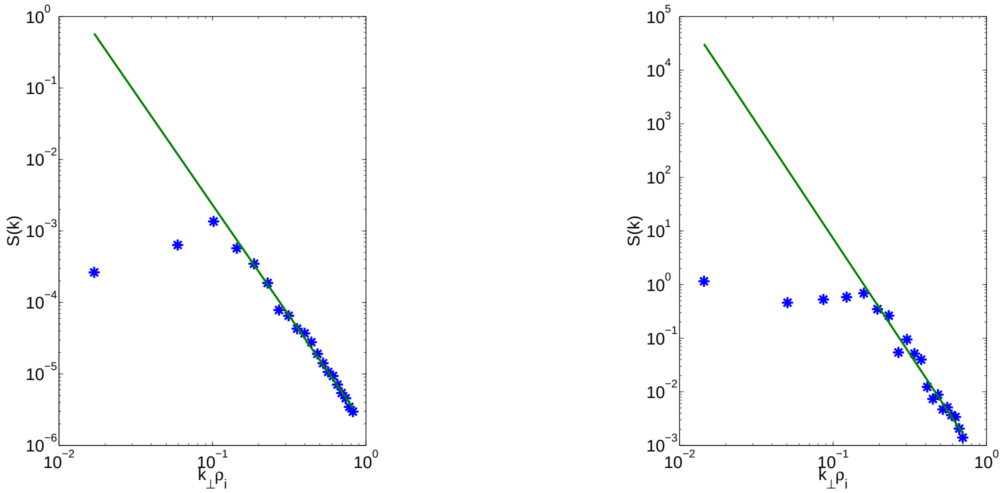

Figure 1: Spectrum of ion density fluctuations from simulations with kinetic (to the left) and adiabatic (to the right) electrons together with power law fits $\propto k_\perp^{-\alpha}$ ($\rho = 7.5$ cm).

$$\frac{\partial \phi_{\mathbf{k}}}{\partial t} = i\omega_{\mathbf{k}}\phi_{\mathbf{k}} + \sum_{\mathbf{k}_1+\mathbf{k}_2=\mathbf{k}} \Lambda^{\mathbf{k}}_{\mathbf{k}_1,\mathbf{k}_2}\phi_{\mathbf{k}_1}\phi_{\mathbf{k}_2}, \tag{1}$$

where $\omega_{\mathbf{k}}$ is the solution of the linear dispersion law, and $\Lambda^{\mathbf{k}}_{\mathbf{k}_1,\mathbf{k}_2} = \frac{1}{2}\frac{\hat{\mathbf{z}}\cdot(\mathbf{k}_1\times\mathbf{k}_2)}{1+k^2}(k_2^2 - k_1^2)$ is the mode coupling matrix element. Solving this equation numerically, with an added artificial source-sink model, has been performed in [5], giving α close to 4. The result in the kinetic simulation could possibly be explaind by constructing a similar two-field model with FLR-effects included. This is planned as future work.

Comparing the simulations with kinetic and adiabatic electrons, also interesting is the difference in the wavenumber $k_\perp \rho_i$ corresponding to the maximum value of $S(k)$.

Cross-Correlation

We define the two-dimensional cross-correlation function as

$$C(\theta,\tau) = < \tilde{n}(\rho_0,\theta_0,\zeta_0,t_0)\tilde{n}(\rho_0,\theta_0+\theta,\zeta_0,t_0+\tau) >, \tag{2}$$

where averaging is done over small time and poloidal angle intervals and where $\tilde{n} = n - < n >$. We fit the cross-correlation function to [6]

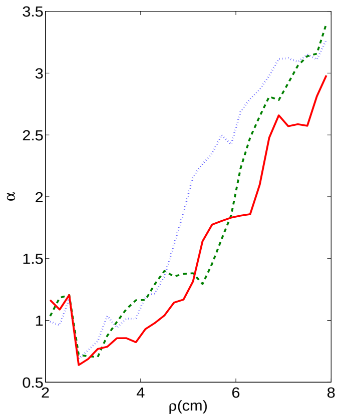

Figure 2: α before (dotted line), during (dashed line) and after (solid line) the transition.

$$C(\theta,\tau) = A\cosh\left(\frac{\tau}{\tau_L}\right)^{-1}\exp\left[-\left(\frac{\theta - v_\theta\tau}{l_\theta}\right)^2\right] + c, \tag{3}$$

where τ_L is the lifetime of the fluctuations, l_θ is the poloidal size (correlation length) of the fluctuations, v_θ is the poloidal $E\times B$ velocity of the plasma and where A and c are constants.

In Fig. 3 is shown the cross-correlation function before and after the ITB formation from a radius in the ITB-region ($\rho = 5.1$ cm). We obtain the parametres $\tau_L = 1.4\,\mu$s, $l_\theta = 0.70$ cm and $v_\theta = 3.9$ km/s before the transition and $\tau_L = 1.5\,\mu$s, $l_\theta = 0.33$ cm and $v_\theta = 12.5$ km/s after the transition. A decreased correlation length is consistent with the observed reduction in transport. Also, an increase in poloidal velocity is observed, and a comparison of adjacent radii reveals the presence of a strong shear in this velocity.

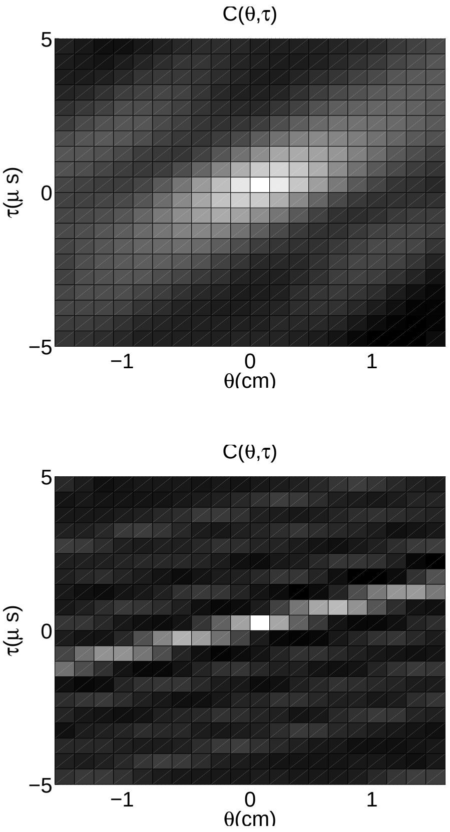

Figure 3: Cross-correlation of density fluctuations before and after the ITB formation.

In general, this analysis reveals a wave-like behaviour of the turbulence with the cross-correlation having negative side minimums and small secondary maximums outside the correlation length and time.

Probability distribution function

In this section we investigate the probability distribution of density fluctuations $p(\delta n/n)$. In Fig. 4 is shown the PDF in a hydrogen discharge simulation from different locations of the tokamak.

Inboard the PDF is much narrower than outboard. This is due to the excitation of larger fluctuations outboard in the region of unfavourable magnetic curvature. Also going to the core, where the temperature is higher, has a narrowing effect on the PDFs. The distributions have higher tails than their best Gaussian fits. A detailed comparison to general Lévy-type distributions is planned as future work.

Summary and conclusions

Three different statistical quantities were investigated in gyrokinetic simulations performed with the ELMFIRE code. Investigation of wavenumber spectra shows the presence of a source near $k_\perp\rho_i = 0.1$. In simulations with kinetic electrons Kolmogorov-type power laws with the exponent α varying with radius were found, showing a dependence of nonlinear properties on specific plasma conditions. Correlation analysis reveal wave-like structures and show the effect of a transport barrier on these structures. Probability distribution functions measured deviate from their best Gaussian fits.

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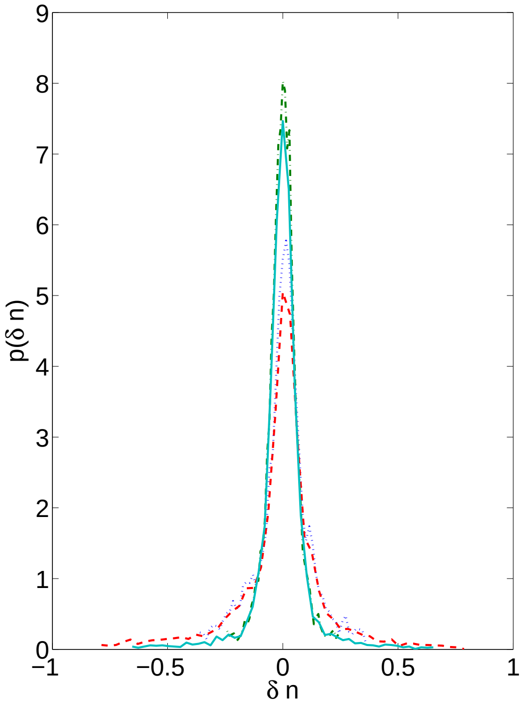

Figure 4: PDF from plasma core (ρ = 3.5cm) outboard (dotted line) and inboard (dash-dotted line) and near plasma edge (ρ = 6.9cm) outboard (dashed line) and inboard (solid line).