Emergence of plasma turbulent structures in the presence of ITG instability

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Abstract. A possible mechanism of turbulent structure formation is considered. Specifically, a transition from unstable ion temperature gradient (ITG) drift wave to a turbulent state of plasma. A theoretical model is developed. Increase and decay of the drift wave are taken into account. A condition of wave decay is proposed. Direct relationship between dimension of turbulent structures, fluctuations, plasma and drift wave parameters are established for the cases of existence and absence of velocity shear. Approximation of plasma density fluctuations is obtained. The approximation satisfactorily corresponds with the experimental data and theoretical estimates of other authors. Experimental results of beam emission spectroscopy (BES) diagnostic are discussed. It is proposed that velocity shear prevents but does not break down large turbulent structures at the H-mode regime.

1. Introduction

It is commonly assumed that one of the main causes of high intensity of magnetized plasma transport is connected with turbulent processes. Turbulence development can be due to different disturbances including those that are induced by unstable waves.

It is of interest to study mechanisms of developing turbulent processes that are induced by drift instabilities, such as the ion temperature gradient (ITG) mode, which is unstable at wide range of plasma parameters in high-temperature plasma of fusion devices. There is a partial turbulence suppression at the H-mode, which is characterized as a decrease of density fluctuation scale in the frequency range of the ITG mode due to the influence of shear flow. This work is focused on this subject.

The first objective of the present study is to define the mechanism of emergence of initial turbulent structures that are induced by the ITG drift wave. The second objective is to establish a direct relationship between density fluctuation, plasma parameters and parameters of instability.

We investigated how the influence of shear leads to the decrease of density fluctuation scale in plasma assuming that the mechanism of turbulent emergence is the same for the cases with and without velocity shear.

2. Discussion of experiments

An experiment was performed on the TAU-1 linear machine [1]. Under certain conditions, appearance of drift oscillation signal followed by its increase and disruption was observed. Then, this process repeated itself. In other words, transition from regular oscillations to chaotic turbulent fluctuations was observed.
Several experiments were performed during an examination of the classic turbulent theory of fluid [2]. These experiments studied a fluid that flowed near a plate. The clear sinusoidal disturbances were observed. They arise in the downstream, which leads to their decay. In the first experiment, when induced by random (“natural”) disturbances, the pulsation of longitudinal velocity was tracked in the boundary layer as fluid flowed along the flat plate. In the second experiment, the images of constant temperature lines (waves) were obtained using the method of interference stripes as fluid flowed along the vertical plate (a natural convective flow).

Similar to the abovementioned experiments, one can assume that drift waves emerge, increase and decay in plasma. As a result, turbulent structures are formed by decay of drift waves. Presumably, this mechanism has been observed in previous experiments [3].

3. Theoretical model

A consideration of unstable ITG drift wave of finite amplitude was recently presented [4], and plasma density fluctuations were studied under the conditions without shear flow. To evaluate a shear flow effect on drift wave, we consider the following results from [4].

An ensemble of wave elements is taken in a slab geometry. The start form of small amplitude drift wave is taken at the initial time (Figure 1). Hydrodynamic Lagrangian approach is used. A sample of wave profiles is shown in Figure 2.

![Figure 1. Diagram of drift wave profile displacement.](image)

![Figure 2. Wave profile at finite time (black curve $\gamma_s = 0$, gray curve $\gamma_s = \gamma$).](image)

Coordinates of wave profile displacement are calculated according to parametric equations

$$
\tilde{x}(y_0, t = 0) = x_0 \sin(k_y y_0),
\tilde{y}(y_0, t = 0) = y_0.
$$

Here, $x_0$ is the initial amplitude of cross displacement ($x_0 << \lambda$), $y_0$ is the parameter, $k_y = 2\pi/\lambda$ is the wave number of the mode. All fluid elements of the wave profile have identical density $n_0$ and temperatures $T_{io}, T_{e0}$.

External transversal (relative to the wave) gradients of density and temperature $dn_0/dx, dT_{io}/dx$ and $dT_{e0}/dx$ are constant in time and space. Magnetic field $B$ is also constant.

A local assumption [5] is used, from which the allocation of density deviation $\delta n$ is defined at $x = 0$

$$
\delta n(y_0, t) = \tilde{x}(y_0, t) \frac{dn_0}{dx}.
$$
Growth rate $\gamma$ is constant. Its value is defined from a linear assumption [6–8]. Growth rate characterizes an exponential increase of wave amplitude. It is considered as a summand of a cross velocity $v_x$

$$v_x(y_0,t) = \frac{\partial \tilde{x}(y_0,t)}{\partial t} = \gamma \tilde{x}(y_0,t).$$

The addend of velocity $v_x$ characterizes an oscillation of wave. It is obtained from linearization of the Boltzmann formula

$$v_x(y_0,t) = \frac{k_B T_e}{q n_0} \frac{d \delta n(y_0,t)}{dy}.$$

Here, $k_B$ is the Boltzmann constant, $q$ is the electron charge. Shear velocity is given as follows [9]

$$v_S(y_0,t) = \gamma_S \tilde{x}(y_0,t).$$

Here, the velocity shear parameter $\gamma_S$ is denoted as $dv_x/dr$ [9].

The presented expressions compose a set of equations that can be solved by numerical computations.

Non-uniform increasing gradient of plasma density along the axis $Oy$ arises in accordance with increasing amplitude of cross displacement. According to this statement, the condition of wave decay is established in ref. [4]. It leads to equality of the mean square value of deviation density gradient $<d(\delta n)/dy>$ and is given a value of $dn_0/dx$:

$$<d(\delta n)/dy> = dn_0/dx.$$

This relationship means that existence conditions of ITG instability are violated. A similar statement in ref. [10] was obtained independently.

4. Results and conclusions

At $\gamma_S = 0$, a mixing length result $<\delta n>/n_0 = 1/(k_x L_n)$ is obtained according to [4] ($<\delta n>$ is the root mean square value of deviation density, which is calculated via wave profile, $L_n$ is the gradient scale length). At $\gamma_S = 0$ and $\gamma = 0$, wave profile fluctuates with a frequency of $\omega^* = k_y T_e/(qBL_n)$. In a general case, an approximation of density fluctuations versus growth rate $\gamma$ and sheared flow parameter is obtained (Figure 3), which is similar to the result in ref. [9]:

$$\Theta = \frac{\left(\left<\delta n\right>/n_0\right)^2_{\gamma_S=0}}{\left(\left<\delta n\right>/n_0\right)^2_{\gamma=0}} \equiv 1 + K \frac{\gamma_S}{\gamma}, \quad K = 1..2.$$

Thus, a hypothesis stating that velocity shear prevents (does not break down) the formation of large radial turbulent eddy structures at H-mode is justified qualitatively. Under the condition of wave decay, the suggested finite amplitude is lower in the case of $\gamma_S \neq 0$ compared with $\gamma_S = 0$ (Figure 2).

The suggested method of defining the scale of density fluctuation depends on plasma parameters because the growth rate $\gamma$ is a function of $T_e, T_i, L_n$ and other parameters.

Images of turbulent density fluctuations from four similar discharges at four radial locations were obtained using a BES diagnostic and are presented in ref. [3] (color-coding: green-neutral, red-positive and blue-negative). Displacement of turbulent structures on a plane $xOy$ is schematically shown in Figure 4 in compliance with images in ref. [3]. Dimensions of observed turbulent structures are congruent with quantities of ITG drift wave lengths and derived quantities of displacement amplitude.
\[ \bar{x}_{\text{max}} \leq \frac{\sqrt{2}}{2\pi} \lambda. \]

It is assumed that turbulent structures observed in the images [3] result from drift wave decay. Organized alternation of minima and maxima and their joint movement in the poloidal direction are signs of drift wave propagation.

\textbf{Figure 3.} Relative density fluctuations versus shear parameter $\gamma_s$.

\textbf{Figure 4.} Displacement of turbulent structures on a plane $xOy$ in compliance with images in the experiments [3].

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