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Selection rule for turbulent structural formation: Study of magnetized cylindrical plasmas

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Abstract. The three-field reduced fluid model was extended to describe the resistive drift wave turbulence in magnetized cylindrical plasmas. There include multiple energy exchange paths, and two kinds of nonlinear steady states were obtained in simulations with a fixed particle source: one with a zonal flow generated by modulational coupling of various unstable modes, which suppress transport, and the other with a streamer, which is a azimuthally-localized vortex structure and induces convective transport, formed by parametric coupling. These structures are formed selectively, depending on the ion-neutral collision frequency, which is a damping force of a zonal flow and has a stabilizing effect of linear instability in this model. This is a minimal model for analyzing the turbulent structural formation mechanism by mode coupling in cylindrical plasmas, and competitive nature of structural formation was revealed.

1. Introduction

Turbulent plasmas form a variety of meso-scale structures such as a zonal flow and a streamer [1,2]. The turbulent structures regulate micro-scale fluctuations and affect the level of anomalous transport in fusion plasmas. Therefore, the formation and self-regulated mechanism of the turbulent structures should be taken into consideration to understand the transport processes in H-mode transport barriers. The preferential formation of zonal flows and streamers has been studied, considering the spectral anisotropy of turbulent fluctuations [3,4]. Drift wave instability is one of the candidates that induce anomalous transport in magnetically-confined inhomogeneous plasmas, and its characteristics have been studied to understand the global transport phenomena [5].

Plasma experiments in a simple linear configuration have been revisited recently for quantitative understandings of the structural formation mechanism by turbulence [6-14]. Drift wave turbulence is driven by the density gradient, which is universal in confined plasmas, and has been observed in linear configurations [7,8,15]. Two-dimensional measurements have revealed the feature of turbulent structures [16,17] and their formation mechanisms by mode coupling [15,18]. Nonlinear simulations of drift wave turbulence in linear devices have been carried out to understand the fundamental mechanism of structural formation by comparison with experiments [19-22]. Measurements of the drift wave turbulence are also carried out in a toroidal configuration and the wave pattern has been identified [23].

We use a minimal model for analyzing the turbulent structural formation mechanism by mode coupling. The three-field reduced fluid model has been extended to describe the resistive drift wave turbulence in cylindrical plasmas. A zonal flow and streamer are formed in nonlinear states in numerical simulations, and their formation mechanisms have been studied. One of the structures is
selected to be formed in the turbulence, and their selection rule is obtained using a parameter, which controls a damping force of the zonal flow.

The paper is organized as follows. In section 2, the plasma configuration and the set of model equations for the analyses are described. The nonlinear calculation gives formation of the zonal flow and streamer, and their formation mechanism is discussed in section 3. The bifurcation of the turbulent structures using the ion-neutral collision frequency as a control parameter is presented in section 4, and the effect of structural formation on particle transport is discussed in section 5. Finally, we summarize our results in section 6.

2. Model

We have been developing a three-dimensional numerical simulation code called ‘Numerical Linear Device’ (NLD), which describes the resistive drift wave turbulence in a linear device [19]. The plasma configuration and the model equations for simulating the linear device, such as the Large Mirror Device (LMD) in Kyushu University [6], are described in this section.

2.1. Geometry

The plasma has a simple cylindrical shape with device length $\lambda$, and the magnetic field has only the component in the axial direction with uniform intensity $B$ (figure 1). In each end of the experimental device, functions of plasma production or plasma control by voltage biasing are installed, which are not taken into account in the present version of NLD. According to experiments, high density ($n_e > 1 \times 10^{19} \text{m}^{-3}$) and low temperature ($T_e < 5 \text{ eV}$) plasmas in an argon discharge are analyzed. The density of neutral particles is high even in the plasma core region [24], so the effect of neutral particles is taken into consideration.

![Figure 1. Plasma configuration in NLD, which has a cylindrical shape. A peaked plasma density profile is assumed.](image)

2.2. Equations

The three-field (density, potential and parallel velocity of electrons) reduced fluid model is adopted. The continuity equation, the vorticity equation and Ohm’s law can be used to obtain the fluctuating density, potential and parallel velocity of electrons [25]:

$$\frac{dN}{dt} = -\nabla \cdot V - V \nabla \cdot N + \mu_N \nabla^2 N + S, \quad (1)$$

$$\frac{d\nabla \cdot \phi}{dt} = \nabla \cdot \left( -\nabla \cdot \phi \frac{d\nabla \cdot \phi}{dt} - V \nabla \cdot N + \mu_w \nabla^4 \phi \right), \quad (2)$$

$$\frac{dV}{dt} = \frac{M}{m_e} \left( \nabla \cdot \phi - V \nabla \cdot N \right) - \nu_e V + \mu_e \nabla^2 V, \quad (3)$$

where $N = \ln (n / n_0)$, $V = v_{ix} / c_s$, $\phi = e \varphi / T_e$, $n$ is the density, $n_0$ is the density at $r = 0$, $v_{ix}$ is the electron velocity parallel to the magnetic field, $c_s$ is the ion sound velocity, $\varphi$ is the electrostatic potential, $T_e$ is the electron temperature, $d \, dt = \partial / \partial t + \left[ \phi \right]$ is the convective derivative, $S$ is a particle source term, $M / m_e$ is mass ratio of ion and electron, $\nu_{in}$ is ion-neutral collision frequency, $\nu_e = \nu_{ei} +$
steady states have been obtained with a fixed particle source. Two kinds of turbulent structures are performed to examine the saturation mechanism of the resistive drift wave turbulence. Nonlinear simulations have been using the set of model equations described in the previous section.

3. Structural Formation

Using the set of model equations described in the previous section, nonlinear simulations have been performed to examine the saturation mechanism of the resistive drift wave turbulence. Nonlinear steady states have been obtained with a fixed particle source. Two kinds of turbulent structures are formed, depending on the value of $V_n$, and their formation mechanisms are explained in this section.

3.1. Simulation parameters

For simulations of the drift wave turbulence in a linear device, the following parameters are used: $B = 0.1$ [T], $T_e = 2$ [eV], $a = 10$ [cm], $\lambda = 1.7$ [m], $\mu_i = 1 \times 10^{-2}$, $\mu_e = \mu_n = 1 \times 10^{-4}$. Larger $\mu_n$ is used to accelerate formation of the background density. Values of $\mu_i$, $\mu_e$ are little not to effect on the drift wave instability [19]. Using these parameters, $V_e$ is estimated to be $V_e = 310$ [19]. There is ambiguity of the absolute value of collision frequency $V_n$, which depends on the neutral density. Therefore, $V_n$ is used as a parameter for controlling the instability in our simulations. Simulations are performed with modes $(m, n) = (0, 0)$ and $m = \pm 1 - \pm 16$, $n = \pm 1 - \pm 16$, i.e., 1025 modes in total. In simulations discussed in this paper, modes with $(m, n) = (3 - 5, 1)$ have the largest amplitudes, so this number of modes must be taken in calculations at least. The calculation with a fixed particle source has been carried out, where the time independent source profile is given by

$$S(r) = \frac{4S_0\mu_n}{L_N^2} \left[ 1 - \left( \frac{r}{L_N} \right)^3 \right] \exp \left[ - \left( \frac{r}{L_N} \right)^2 \right],$$

with $S_0 = 5.0$, $L_N = 5$ [cm]. A density profile peaked at $r = 0$ is formed by this particle source, anddestabilizes the resistive drift wave.

A resistive drift wave can be excited with a small ion-neutral collision frequency [19]. Linear analysis gives linear growth rates and eigenfrequencies. Modes with low $m$ and only $n = 1$ are unstable with these parameters. The destabilized modes increase their amplitudes, and their nonlinear coupling generates turbulence. The density flattening occurs in the core region ($0.1 < r/a < 0.7$), which comes from an enhanced transport owing to the fluctuations [19]. The dispersion relation of the linear eigenmodes with $n = 1$ shows weak dispersion in low $m$ ($m < 4$), and $\partial \omega / \partial k_0 \sim 0$ with $m = 4 - 6$. These ranges of modes couples to each other to form zonal flows and streamers, so mechanisms of nonlinear excitation of turbulent structures can be studied by analyzing this turbulence, as explained in the following subsections.
3.2. Zonal flow formation

The case with small ion-neutral collision frequency $\nu_{in}$ is described in this subsection. Nonlinear coupling of modes with weak dispersion (modulational coupling) generates the (0, 0) mode, which affects the stability of modes. If $\nu_{in}$ is small, in nonlinear steady states, modulational coupling of unstable modes with lower mode numbers plays an important role. Figure 2 shows the time evolution of the fluctuation energy of the potential, decomposed into Fourier components, with $\nu_{in} = 0.02$. Modes with $(m, n) = (0, 0), (2 - 4, 1)$ are shown, which have the same level of amplitude. The mode amplitudes are fluctuating, and the mode with a maximum amplitude exchanges from time to time.

Figure 2 shows a bursty oscillation of the fluctuation energies. The energy of the (0, 0) mode repeat increasing and decreasing, and those of the other modes also varies, accordingly. The mechanism of the oscillation is understood by observing the relationship between $E_\phi(0, 0)$ and $E_\phi$ of the dominant mode. The trajectory is plotted in $E_\phi(0, 0) - E_\phi(2, 1)$ phase space, when the (2, 1) mode is dominant (from 2500 to 3000), in figure 3. Firstly, unstable modes, such as that with $(m, n) = (2, 1)$, increase (growing phase (i)). Then, nonlinear coupling causes the growth of the (0, 0) mode (potential generation (ii)). The generated mean potential stabilizes the unstable modes, which turn to decrease (stabilizing phase (iii)). Without the nonlinear source, the (0, 0) mode can not be sustained (mean damping phase (iv)), and once the mean potential becomes small enough, the $m \neq 0$ modes begin to grow again (phase (i)). In this way, the limit cycle oscillation is generated (as was reviewed in [1]), and the steady state is sustained. Figure 4 shows the time evolution of the contour of the fluctuating potential. The dominant mode is replaced from (4, 1) to (2, 1) at $t \sim 2520$, and the vortex structures are tilted and broken by the (0, 0) shear flow at $t \sim 2720$.

**Figure 2.** Time evolutions of Fourier modes of the fluctuation energy in the nonlinear steady state. The fluctuation energies of the electrostatic potential of Modes $(m, n) = (0, 0), (2 - 4, 1)$ are shown when $\nu_{in} = 0.02$.

**Figure 3.** Relationship between $E_\phi(0,0)$ and $E_\phi(2,1)$, which forms a limit cycle. This is the plot from $t = 2550$ to 3300.

**Figure 4.** Contour plots of the potential at the times indicated by the dashed lines in figure 2. These contours are draw with excluding $\phi_{00}$ component.
3.3. Streamer formation

The case with large ion-neutral collision frequency $\nu_{\text{in}}$ is described next. If the collision frequency is large, the zonal flow remains stable, owing to a strong collisional damping. Three-wave coupling including modes, which has the wave number and frequency close to each other (parametric coupling), can resonantly takes place in this case. Figure 5 shows the time evolutions of the fluctuation energy of the potential, decomposed into Fourier components, with $\nu_{\text{in}} = 0.1$. Modes with $(m, n) = (4, 1)$ and $(5, 1)$ are dominant, and their parametric coupling plays an important role in this case. The mode with a maximum amplitude exchanges from time to time, and evolutions of the mode amplitudes are rather periodic compared with those in the small $\nu_{\text{in}}$ case in the previous subsection.

Figure 6 shows the time evolution of the contour of the fluctuating potential. There formed a streamer, which is a strong vortex localized in the $\theta$ direction. The vortex structure is sustained for a much longer duration than the drift wave oscillation period. Figure 7 shows a time evolution of the $\theta$ profile of the radial $E \times B$ convective velocity. The localized structure, streamer, induces localized convective transport in the radial direction as shown in figure 7. There are two kinds of time scales involved: one is the characteristic time scale for the micro-scale structural (drift wave) propagation, and the other is that for the meso-scale structural (streamer) propagation. There are points where the maximum mode exchanges from one to the other. These points appear as irregular nodes such as at $t \sim 6500$ and $\theta \sim 3 / 2 \pi$ in figure 7. A continuous flow pattern of the micro-scale structure is bent or broken at these points.

Three-dimensional mode coupling is essential for preservation of a streamer structure. Figure 8 (a) shows the dependency of the linear growth rate of $n = 1$ mode on the azimuthal mode number. These growth rates are calculated with the density profile at $t = 8000$ and $\phi_0 = 0$. Modes with $m = 3 – 8$ are unstable. Figure 8 (b) shows the potential energy spectrum on $m$ with $n = 1 – 3$ at $t = 8000$. The linearly unstable modes with $m = 3 – 8$ have largest amplitudes, and couplings of these largest modes

![Figure 5](image_url)

**Figure 5.** Time evolution of Fourier modes of the fluctuation energy in the nonlinear steady state. The fluctuation energies of the electrostatic potential of modes $(m, n) = (0, 0), (2 – 7, 1), (1, 2)$ are shown when $\nu_{\text{in}} = 0.1$.

![Figure 6](image_url)

**Figure 6.** Contour plots of the potential at the times indicated by the dashed lines in figure 5.
Figure 7. Time evolution of the \( \theta \) profile of the convective velocity at \( r = 0.5a \) and \( z = 0.375\lambda \). The case with \( \nu_{in} = 0.1 \) is shown.

Figure 8. (a) Dependency of the instantaneous linear growth rate of mode \( n = 1 \) on the azimuthal mode number \( m \) with \( \nu_{in} = 0.1 \). These growth rates are calculated with the density profile at \( t = 8000 \) and \( \phi_0 = 0 \). (b) Potential energy spectrum on \( m \) with the axial mode numbers \( n = 1 – 3 \) at \( t = 8000 \).

Figure 9. Time evolutions of the effective radial wave number \( \langle k \rangle \) of \( N, \phi, V \). The time evolution of \( E_\phi(4, 1) \) is also plotted.
induce the other peak at \((m, n) = (1, 2)\) and \((10, 2)\) in the spectrum. The formation of the streamer structure is related with this coupling of dominant modes. Modes with \((m, n) = (4, 1)\) and \((5, 1)\) are coupled with each other by mediator mode \((1, 2)\) to form the streamer. This is the coupling in \(k_r\) and \(k_z\) space, which gives matching of \((4, 1)\) and \((5, 1)\) to rotate with the same velocity, though the phase velocities of the linear eigenmodes are different from each other. The other coupling such as between modes with \((4, 1)\) and \((6, 1)\), affects to give an additional perturbation to the dominant modes, and the oscillation of the amplitudes, shown in figure 5, is induced. Modes with \(n = 0\), which are not taken into the calculations, also can act as mediator modes. The case with other paths of energy exchange will be discussed in future works. In \(k_r\) space, the effective radial wave number, defined to be

\[
\langle k_r \rangle = \sqrt{\int \frac{\partial f^2}{\partial r} r dr / \int |f|^2 r dr},
\]

gives the index of the radial profile, where \(f\) implies \(\{N, \phi, V\}\). Figure 9 shows the time evolutions of \(\langle k_r \rangle\) of the \((4, 1)\) mode. When the amplitude of the \((4, 1)\) mode increases, \(\langle k_r \rangle\) increases, accordingly. The increase of \(\langle k_r \rangle\) corresponds to the induction of higher \(k_r\) components, which comes from nonlinear couplings with other modes. The evolution of \(\langle k_r \rangle\) follows the evolution of the mode amplitude (figure 9). The larger \(k_r\) tends to stabilize the mode, so the relationship between \(\langle k_r \rangle\) and the mode amplitude suggests that the profile modification affects the mode saturation. In this way, the streamer structure is sustained with three-dimensional mode coupling.

The streamers are characterized to be i) their typical scale \(k_0\): finite, \(k_r \sim k_z \sim 0, \omega << \omega\)(micro turbulence), ii) formed by nonlinear processes, and iii) localized in the direction of wave propagation (\(\theta\) direction) [1]. An azimuthally-localized structure needs several Fourier modes to be constructed. The streamer in our simulation consists of rather small number of dominant contributors, \((4, 1)\) and \((5, 1)\), which are coupled with each other by means of the mediator mode \((1, 2)\), and form quasi-mode like structure. The axial mode number of the turbulent structure discussed here is \(n = 1\), which is small enough to satisfy the definition of the streamer. On the other hand, the typical scale length of the drift wave \(\rho\) is not so small compared with the plasma radius \(a (\rho / a \sim 0.09)\). Therefore, the turbulent structure has a radial scale length close to the plasma radius, not the meso scale. However, the rotation frequency is \(f_\delta = 3 \times 10^{-5}\), which is much smaller than that of the drift wave \(f_\delta = 0.02 (f_\delta / f_\delta \sim 70)\). In this way, the characteristics of streamers are satisfied without the typical space length, and we call the structure ‘streamer’.

4. Selective formation
Two kinds of turbulent structures are formed in the nonlinear steady states, as shown in the previous section. The dispersion relation depends on the plasma parameters, and our choice of parameters, described in section 3.1, allows both kinds of structural formation to be taken place by modes with rather small \(m\). Therefore, selective formation of the turbulent structures can be discussed, using the ion-neutral collision frequency as a control parameter. A collision frequency scan is carried out from \(\nu_n = 0.01\) to 0.12. Collision frequency \(\nu_n\) brings two effects. That is, decreasing \(\nu_n\) not only strengthens the driving force of the drift wave instability [19], but also weakens a damping force of the zonal flow represented by the third term in the right hand side of equation (2). These two effects together dictate the formation of the turbulent structure and the level of fluctuations in nonlinear steady states.

Figure 10 shows the dependencies of fluctuation energies of the potential on \(\nu_n\) in nonlinear steady states. The energy components of \((0, 0)\) mode, which is the zonal flow, and the sum of \((4, 1)\) and \((5, 1)\) modes, which form the streamer, are shown. The amplitudes are oscillating with period \(T_d = O(10)\) and, the density profile, affected by the fluctuations, evolves with the time constant \(T_q = O(1000)\). Therefore, the values shown in figure 10 are averaged over the duration longer than \(T_d\) and shorter than \(T_q\). The zonal flow amplitude is small and the streamer modes are excited when \(\nu_n\) is large. As \(\nu_n\) is decreased, the zonal flow begins to be excited. The inflection point is given to be \(\nu_{in} \sim 0.052\)
in this case. Figure 10 shows that the streamer can be formed without the zonal flow formation. When the zonal flow is formed, the $E \times B$ shearing of the zonal flow breaks the phase locking of the modes, so the streamer is not formed, even though amplitudes of these modes are larger than that of the zonal flow. When $\nu_{in}$ is much smaller ($\nu_{in} < 0.01$), the distribution of the fluctuation energy to each mode is different. This is because of the modification of the density profile to change the structures in the micro, meso and macro scales, simultaneously. This global bifurcation will be studied in future works.

There are two dominant energy exchange paths for structural formation by mode coupling of $m \neq 0$ mode. One is that to (0, 0) mode to form the zonal flow, and the other is that to the mediator mode ((1, 2) in this case) to form the streamer. These two kinds of structural formation mechanisms are involved, but only one of the structures can appear in steady states from their competitive nature. A simple analytical model of the energy balance [27] can give the bifurcation. We use a model including one unstable mode (drive) and two paths of mode coupling to a stable mode (sink). The energy balance in three modes, source of instability, mediator to form a streamer and zonal flow, is solved. The critical value of the zonal flow damping rate $\Gamma_c$ is obtained, which depends on the damping rate of the mediator mode and coupling constants of the energy exchange from the drive to the mediator and zonal flow. When the zonal flow damping rate is larger than $\Gamma_c$, only the streamer mode is excited. When the zonal flow damping rate is smaller than $\Gamma_c$, only the zonal flow mode is excited, and the energy increases linearly, as the zonal flow damping rate becomes small. The value of $\nu_{in}$ represents the strength of the zonal flow damping rate, on which the selection of the turbulent structures depends. The detailed of the analytical model will be reported in the separated article. In this way, the bifurcation of the structures in turbulent plasmas has been represented using the dictating parameter ($\nu_{in}$ in this case).

![Figure 10](image)

**Figure 10.** Dependencies of the fluctuation energies of the electrostatic potential on $\nu_{in}$ in nonlinear steady states.

5. Effects on particle transport

The turbulent structure affects the level of particle transport. It is well known that zonal flows suppress turbulent transport, and streamers induce convective transport. The effect of the structural formation in our cases is discussed in this section.

Figures 11 (a) and (b) show the dependency of the instantaneous linear growth rate and fluctuation energy of the potential on $\nu_{in}$, respectively. This linear growth rate is evaluated with the density profile in the nonlinear steady state, and constant potential profile in space, i.e., only the destabilized effect of the density profile and no stabilizing effect of the potential profile is involved. The fluctuation energy is temporal average of the sum of the each potential energy of the Fourier modes except (0, 0) in the nonlinear steady state. The effects of nonlinear couplings and the
stabilization by formation of the potential profile are involved to give this magnitude of the energy. The error bars in figure 11 correspond to the intermittent variation, and are larger in the zonal flow case. When $E_\phi$ increases, the turbulent flux increases, correspondingly, and vice versa. In the streamer case, the linear growth rate, and therefore, the fluctuation energy are small and constant. On the other hand, the linear growth rate and the fluctuation energy increase as $v_{in}$ decreases in the zonal flow case. These tendencies imply that the profile change in the zonal flow case greatly destabilize the system and could induce a large turbulent particle flux. However, the particle source is the same through the $v_{in}$ scan, so the turbulent fluxes have the same level, not depending on $v_{in}$, as shown in figure 11 (c), which describes the dependency of the turbulent particle flux $\langle \bar{N} \rangle$ on $v_{in}$. The level of particle transport does not change, in spite of the strong instability, because of turbulent suppression by the zonal flow.

When $v_{in}$ is large, fluctuation amplitudes are rather small, so the turbulent conductive transport is small, but convective transport is generated by the streamer. We also carried out a simulation, in which the mediate mode $(1, 2)$ is artificially removed after the saturation with $v_{in} = 0.1$, when the streamer is formed with the $(1, 2)$ mode. The streamer is not sustained and only a single mode becomes dominant without the $(1, 2)$ mode. In this no streamer case, the fluctuation energy is 20 % larger than those in the streamer case, though the turbulent flux and density profiles are almost the same (the maximum of the difference of the density gradient is 5 %). That means the particle flux per the same fluctuation energy is larger in the streamer case. The discrepancy shows the drive of larger convective transport by the streamer. Energy condensation in the azimuthal direction by streamer formation enhances the radial transport in this case. In this way, the particle transport is affected by the selective formation of the turbulent structures, the zonal flow and the streamer, in the case when the magnitude of the particle flux is fixed (flux driven system).

Figure 11. Dependency of (a) the instantaneous linear growth rate of $(4, 1)$ mode, evaluated with the density profile in the nonlinear steady state, (b) fluctuation energy and energy of $(0, 0)$ mode of the potential, and (c) turbulent flux at $r/a = 0.5$ on $v_{in}$.
6. Summary
We have carried out the nonlinear simulation of the resistive drift wave in cylindrical plasmas, using a three-dimensional turbulence simulation code NLD. Turbulence with a zonal flow or streamer was obtained in the nonlinear steady states. In the case with smaller $\nu_{in}$, the zonal flow is formed by nonlinear mode coupling. In the steady state, dynamical energy exchange between (0, 0) and the other unstable modes plays an important role for mode saturation. In the case with larger $\nu_{in}$, the streamer is formed by coupling between a pair of unstable modes. A self-bunching of the perturbations takes place and the azimuthally-localized structure is sustained. Simulations showed the selective formation of the zonal flow and streamer using $\nu_{in}$ as a control parameter. The value of $\nu_{in}$ represents the strength of the damping force of the turbulent structures, and the bifurcation of the formed structures in turbulent plasmas has been obtained.

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