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Nonlocal structure and intermittency of turbulence based on the first order ballooning theory
1次ballooning理論に基づく乱流の非局所構造と間欠性

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We found from flux driven gyro-kinetic toroidal simulation that the profile is suffered from a constraint even in the presence of neo-classical flows and zonal flows, which leads to stiffness /resilience in the profile, and also to self-similarity in relaxation. The radially extended global modes which are spontaneously and intermittently excited via phase alignment is found to the origin of the constraint. The cancellation of the diamagnetic shear by the neo-classically driven $\mathbf{E}\times\mathbf{B}$ shear rotation is found to play an important role. The dynamics are analyzed on the basis of the 1st order ballooning theory.

1. Introduction

Profile formation and relaxation regulated by the turbulence with various time and spatial scales are the central concern in magnetically confined toroidal plasmas such as tokamak and stellarator. Among them, the stiffness/resilience of the profile, where the profile is suffered from the constrain over a finite radial length, are of special interest since such characteristics restrict the established profile and then the fusion performance [1]. Such constraints were observed in toroidal particle simulation of ion temperature gradient (ITG) turbulence, refereed as "*self- similar relaxation*"[2]. This was found to ascribe to the radially extended meso-scale mode structure scaled by $\sqrt{\rho_i L_T}$, where ρ_i the ion Larmor radius and L_T the scale length of temperature gradient. However, it has been believed such a structure is hardly survived in plasmas dominated by zonal flows.

Recently, full-f flux driven toroidal simulations have been extensively done. Non-diffusive transport dominated by heat avalanches has been studied, which causes non-Gaussian PDF tails of the heat flux, while the radially extended structure is disintegrated apparently due to the zonal flows [3,4]. However, even in the presence of such zonal flows and also neo-classically driven plasma flows, the self-similar relaxation with a constrained profile is found to be observed. As the origin of such a constraint, a radially extended global mode which ranges from meso to even macro/devise scale ($\sim L_T$) is found to be spontaneously established, which cause a global burst which simultaneously takes place over the whole radius [3].

Here, we study the underlying physical mechanism for the formation of such global mode structure based on the 1st order balloon theory [4],

2. Formation of radially extended global mode and intermittent bursts in GKNET simulation

We performed full-*f* flux-driven toroidal ITG turbulent simulations using GKNET (Gyro-Kinetic based Numerical Experimental Tokamak) with the normalized minor radius of $a/\langle\rho_i\rangle = 150$, where neo-classical effects are taken into account [4].

Figure 1 illustrates the time history of heat diffusivity (logarithmic plot) and the electrostatic potential contour at the bottom (*t*=566) and peak (*t*=574) of the burst [4,5]. Here, the time is normalized by R_0/υ_i , where R_0 and υ_i are the major radius and ion thermal speed, respectively. The burst displays an exponential growth estimated by $\gamma \sim 0.15$, while it is smaller than that of the ITG linear growth rate given by $\gamma_L \sim 0.45$. Furthermore, a radially extended global structure, which size is comparable to the system size L_T , is found to emerge as seen in Fig.1(*t*=574) growing from smaller vortices near the bottom of the diffusivity (*t*=566). Such a structure is disintegrated quickly and damped as seen in Fig.1. The structure is similar to that of the ballooning mode, while the radial correlation length is longer as $\Delta r \sim L_T$ and

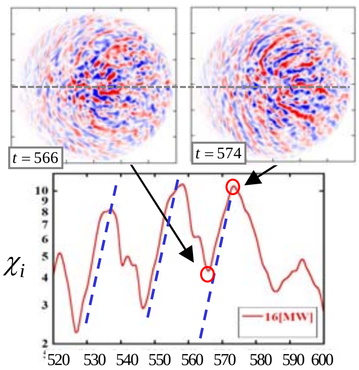

Fig. 1. Time history (logarithmic plot) of the spatially-averaged heat diffusivity and electrostatic potential at the bottom (t=566) and peak (t=574) in the case of 16MW (heat input).

the ballooning (titling) angle θ_0 is smaller as $\theta_0 \sim 0$ than those for the linear ITG eigen-mode, which are given by $\Delta r \sim \sqrt{\rho_i L_T / \hat{s}}$ and $\left|1/\hat{s}\, k_\theta L_T\right|^{1/3}$, respectively.

Here, we found that the profile tends to the exponential function form, $\sim \exp\left[-r/L_T(t)\right]$, and only the scale length changes in time during the relaxation [4], which is the typical characteristic of the self-similar relaxation [2]. The radially extended global mode and associated intermittent bursts are considered to be the origin producing the constraint on the profile formation and relaxation.

3. The 1st order ballooning theory and neo-classical cancellation of diamagnetic shear

According to the 1st order ballooning theory which takes into account the effect of radial variation of the profile represented by the diamagnetic shear, $\partial\omega_d/\partial r$ and the poloidal and $\mathbf{E}\times\mathbf{B}$ shear, $\partial\omega_f/\partial r$, $(\Delta r, \theta_0)$ are given by

$$\Delta r \sim \left|\frac{2\gamma_0 \sin\theta_0}{\mathrm{k}_\theta \hat{s}\left(\partial\omega_r/\partial r + \partial\omega_f/\partial r\right)}\right|^{1/2}, \qquad (1)$$

$$\theta_0 \sim \mp\left|\frac{\left(\partial\omega_r/\partial r + \partial\omega_f/\partial r\right)}{2\mathrm{k}_\theta \gamma_0 \hat{s}}\right|^{1/3}, \qquad (2)$$

where (ω_r, γ_0) is the eigen-mode frequency determined by the 0th order ballooning theory, and $\hat{s}$ is the magnetic shear. If we simply assume $\omega_r \sim \gamma_0 \sim \omega_d$ (magnetic drift frequency) and $\omega_f = 0$, Eqs. (1) and (2) yields to $\Delta r \sim \sqrt{\rho_i L_T/\hat{s}}$ and $\theta_0 \sim \mp\left|1/\hat{s}\, k_\theta L_T\right|^{1/3}$. The mode is then tilted form the mid-plane due to the diamagnetic shear, causing a symmetry breaking. Note that the growth rate is reduced as $\gamma(\theta_0) \simeq \gamma_0 \cos\theta_0$.

From Eqs. (1) and (2), a radially extended global mode with zero tilting angle which recovers symmetry, is found to be established when the effect of the diamagnetic shear rotation is canceled by that of the $\mathbf{E}\times\mathbf{B}$ shear as $\partial\omega_d/\partial r + \partial\omega_f/\partial r \sim 0$. This corresponds to the case that the poloidal rotation of the potential vortices estimated by

$$\begin{aligned} \left\langle\dot{\theta}\right\rangle &= \iint \frac{d\theta}{dt} f_0 dv_{\parallel} d\mu = \omega_d + \omega_f \\ &= \frac{1}{B}\left[-\frac{2}{R}\cos\theta + \left(\frac{1}{L_n} + \frac{1-k}{L_T}\right)\right] nT \end{aligned} \qquad (3)$$

becomes spatially constant so that $\partial\left\langle\dot{\theta}\right\rangle/\partial r \sim 0$. Here, k is the constant determined by the collisionality and the temperature profile is assumed to be self- organized to $\sim \exp\left[-r/L_T(t)\right]$.

Figure 2 illustrates the radial dependence of $\left\langle\dot{\theta}\right\rangle$ using the profile in Fig.1 for the case with only the diamagnetic shear, and with including the $\mathbf{E}\times\mathbf{B}$ shear using different k values, i.e. $k=0$ (only equilibrium E_r determined by the pressure gradient), and $k=0.9$ and $k=1.19$. The simulation

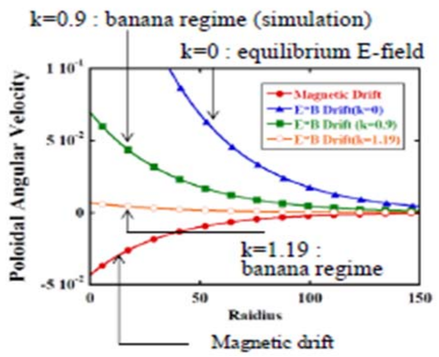

Fig.2. Radial dependence of poloidal angular velocity for the case of (1) magnetic drift only, (2) with ExB (k=0), (3) with ExB (k=0.9) and (4) with ExB (k=1.19). The simulation in Fig.1 corresponds to the case between (3).

in Fig.1 corresponds to the case around $k=0.9$. It is found that the $\mathbf{E}\times\mathbf{B}$ shear rotation has a role in cancelling the diamagnetic shear, which is consistent with the idea discussed in the above.

4. Spontaneous phase alignment

In toroidal system, the toroidal coupling force inevitably exists even in nonlinear phase, so that the phases of small scale potential vortices excited in different radial locations can be aligned spontaneously, leading to the radially extended structure as schematically illustrated in Fig.3. Since their angular velocities are different with the radius, the structure is subsequently disintegrated. However, the process is recurrence as seen in Fig.1. The recurrence time can be estimated as

$$\tau_{rec} \sim \frac{\pi}{1-\alpha}\sqrt{\frac{L_T}{\rho_i}}\frac{\hat{s}^{1/2}}{\omega_d}$$

where α represents the effect of diamagnetic cancellation. Namely, $\alpha \sim 1$ corresponds to the exact cancellation as in the case of $k=1.19$ in Fig.2, In this case, though the recurrence time tends to $\tau_{rec} \to \infty$, the zonal flow instead regulate it.

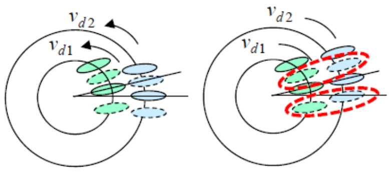

Fig.3. Schematic view of spontaneous phase alignment leading to radially extended global mode

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