§6. Mean Flow Generation Mechanism Detected in Turbulence Diagnostic Simulator

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Turbulence in toroidal plasmas forms meso-scale structures, and it is important to clarify the role of the turbulence structures on anomalous transport [1]. High resolution measurements of fluctuations have been carried out in experimental devices to make quantitative estimation of turbulent transport [2]. Numerical simulations can give three-dimensional (3-D) turbulent fields, which represent fundamental phenomena in plasmas, so the simulation data are suitable as a test field to carry out detailed analyses for comparison with experimental results [3]. We have been developing a turbulence diagnostic simulator (TDS), which is the combination of fluid turbulence codes and numerical diagnostic modules to simulate experimental measurements of plasma turbulence [4].

To provide turbulence data in a helical plasma, the simulation code has been extended to calculate the drift-interchange turbulence in helical plasmas with a circular cross-section. The averaging method with the stellarator expansion [5] is applied to give a set of model equations for stream function u, ζ component of the vector potential A and total pressure P, as described in Ref. 6. The nonlinear simulation is performed, using the following parameters: magnetic field $B = 2.0$ [T], electron temperature $T_e = 1$ [keV], minor radius $a = 0.6$ [m], major radius $R_0 = 3.75$ [m], viscosities $\mu = \eta = \eta_\perp = 1 \times 10^{-4}$, pole number $l = 2$, pitch number $M = 10$. Rotational transform ι is given by a monotonically increasing function with the radius from $\iota(0) = 0.31$ to $\iota(a) = 0.88$, so rational surfaces with $m / n = 2 / 1$ and $3 / 2$ are included, but $1 / 1$ is not in the plasma, where m and n are the poloidal and toroidal mode number, respectively. 1024 grids in the radial direction and Fourier modes $-32 \le m \le 32$, $-8 \le n \le 8$ are taken. Spatio-temporal data of turbulent fields are generated by this global simulation.

The calculation with a fixed pressure source, which forms a pressure profile peaked at $r = 0$, is carried out. Low m, n modes whose rational surfaces exist in the plasma are excited in the linear growing phase, and saturation is obtained with energy exchange between various modes by nonlinear couplings. In the saturated state, mode structures of low m, n modes, such as $(m, n) = (1, 1)$ and $(2, 1)$, spread broadly in the radial direction, and those of medium m, n modes, such as (3, 2) and (8, 4), are localized near their rational surfaces. Here, we assume that variables u and P represent the normalized electrostatic potential and density, respectively. Numerical diagnostics are carried out on the simulation data. Several modules are available for simulation of experimental diagnostics in the TDS. The examples to show the characteristic features of fluctuations are introduced here.

In our model, the mean flow is generated by the toroidal coupling with the mean pressure profile. In addition, turbulence perturbs the mean with nonlinear couplings. Here, we analyze the relationship between the turbulence and turbulence induced components. In experiments, a finite number of local observations give the radial profile. 1-D signals at $\theta = 0$ and $\zeta = 0$ are taken from 3-D fields to show the radial profile. Figure 1 (a) shows the time evolutions of the pressure fluctuations including all modes without the (0,0) mode in the simulation ($\tilde{P}_{m\neq0}$) and the (0,0) mode only ($\tilde{P}_{00}$). There exist localized modes in $r / a > 0.8$ as in the evolution of $\tilde{P}_{m\neq0}$, and the (3,2) mode has the largest amplitude, whose resonant surface is placed at $r / a \sim 0.83$. On the other hand, the perturbation of the (0,0) mode mainly exists in $r / a = 0.4 - 0.7$, and its temporal variation is rather slower, whose typical oscillation period is 400, compared with the oscillation period of the (3,2) mode ~ 60. Correlation between the turbulence ($\tilde{P}_{m\neq0}$) and the (0,0) mode ($\tilde{P}_{00}$) is calculated to estimate their relation. The 2-D profile of the correlation with the (0,0) mode at $r / a = 0.5$ is shown in Fig. 1 (b). The turbulence in $r / a = 0.4 - 0.6$ and $\theta = -\pi / 6 - \pi / 4$ (low field side) is strongly correlated with the (0,0) mode, though the perturbations in the region where the localized modes exist have no correlation. In this way, it is found that there is a region where the turbulence and the (0,0) mode are coupled with each other. In addition, the (0,0) mode is broad in the radial direction, and a two-time, two-point correlation analysis shows that the change in the region where the (0,0) mode exists propagates faster than those in the other regions. This is one of the candidates to cause the non-local transport observed in the magnetized plasmas.

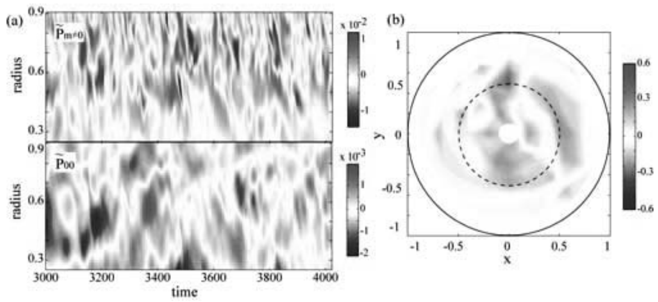

Fig.1: (a) Time evolutions of the radial profiles of the electrostatic potential at $\theta = 0$ and $\zeta = 0$. The sum of the fluctuations without that of the (0,0) mode $\tilde{P}_{m\neq0}$ and the fluctuations of the (0,0) mode $\tilde{P}_{00}$ are shown. (b) 2-D profile of the correlation of $\tilde{P}_{m\neq0}$ at $\zeta = 0$ with $\tilde{P}_{00}$ at $r / a = 0.5$ (indicated with a dashed line).

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