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Gyrokinetic simulation for dynamic response of turbulent transport to heat source modulation

熱源変調に伴う乱流輸送の動的応答に関する
ジャイロ運動論シミュレーション

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By means of a newly developed 5D toroidal global gyrokinetic code GKNET, we investigated the prominent non-local characteristics of flux-driven ITG turbulence and their dynamic responses in toroidal system. We found that a self-organized resilient profile keeping the exponential function form is established even in the presence of zonal/mean flow, which results from explosive global transport triggered by the instantaneous formation of radially extended potential vortices ranging from meso ($\sim\sqrt{\rho_i L_T}$) to even macro-scale ($\sim L_T$). Such a resilience is also confirmed from step-up/down switching test for heat input power, which justifies a self-organized critical type transport is dominant in flux-driven ITG turbulence.

1. Introduction

Non-local turbulent transport and profile stiffness/resilience are long standing problems, which may limit the overall performance of H-mode plasmas once the pedestal temperature is given. In 1990s, full-kinetic simulation [1] demonstrated that toroidal ITG modes have a radially extended structure over many rational surfaces, which imposes a strong constraint on the functional form of the profile to keep L_T globally constant. Under this state, any significant deviation away from the self-organized temperature profile causes fast-time scale relaxation, while self-similar profile relaxation takes place, in which L_T varies in slow-time scale. However, note that this mechanism was explained in a profile-driven simulation without heat source, and the contribution from zonal flow is underestimated. We can simply estimate the radially extended structure can be disintegrated by $E\times B$ shear.

On the other hand, recent flux-driven full-f gyrokinetic simulations [2, 3] revealed that a stiff ion temperature profile is sustained with a critical gradient, and a significant part of the heat flux is carried by avalanches with $1/f$ type spectra. This suggests that self-similar profile relaxation can take place even in the presence of mean/zonal flows. Ref. [3] mentioned that avalanches are found to correlate with streamer-like structures, however, the underlying mechanism of such structure formation is not clarified yet.

To understand why such a self-organized critical type transport is observed even in the flux-driven turbulence with mean/zonal flows, here we report the non-local characteristics of flux-driven ITG turbulence and their dynamic response by means of a newly developed 5D toroidal global gyrokinetic code GKNET.

2. 5D toroidal global gyrokinetic code GKNET

Recently, we have developed a 5D toroidal global gyrokinetic code named GKNET with heat source/sink and collision. Governing gyrokinetic Vlasov-Poisson equation system is same as that shown in Ref. [3] except source, sink and collision operator. Sink operator provides constant power input near magnetic axis without particle and momentum input, whereas sink operator is Krook-type, which modifies the distribution function towards their initial values at the boundary region. Collision operator is linear Fokker–Planck one [4], which includes field particle part [5] to conserve density, momentum and energy at each grid point. Such a conservation property is basic requirements used in neoclassical theory.

3. Flux-driven non-local turbulent transport

We performed a flux-driven toroidal ITG simulation in a circular concentric tokamak configuration with $R_0/a=2.79$, $a/\rho_{ti}=150$ and $q(r)=0.85+2.18(r/a)^2$. Initial plasma parameters at $r/a=0.5$ are $R_0/L_n=2.22$, $R_0/L_{T_i}=10$ and $\nu^*=0.5$, respectively.

Figure 1 (a) shows the spatio-temporal evolution of normalized ion heat flux in the case of 16MW power input. Time evolutions of radially averaged heat flux in the case of 4MW, 16MW are also shown in Fig. 1 (b). From Fig. 1 (a), we can see that the turbulent transport is dominated by two processes. One is the fast-scale avalanches, which propagation velocity is roughly estimated as $2v_D$ (v_D : magnetic drift velocity). The other is an explosive global transport event, which spatial scale is from meso ($\sim\sqrt{\rho_i L_T}$) to even macro-scale ($\sim L_T$) and the time scale is almost simultaneous. The former can be explained by sand-pile dynamics, but the latter do not show such a tendency. From Fig. 1 (c) and (d), we can see that such explosive global events originate from the instantaneous formation of radially extended ballooning structure, which is poloidally symmetric and the amplitude becomes high. Ascribed to these events with long correlation lengths, a self-organized resilient profile keeping the exponential function form is established even in the presence of zonal/mean flow.

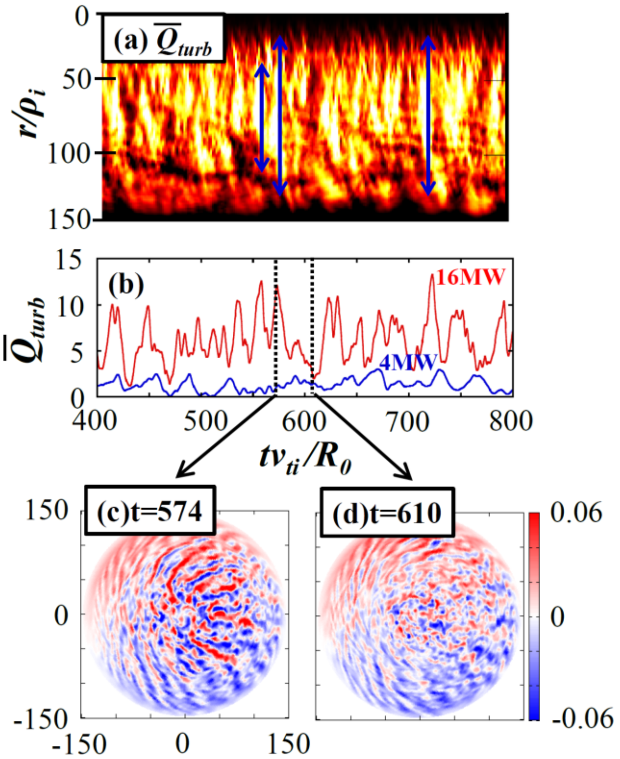

Fig. 1: (a) Spatio-temporal evolution of normalized turbulent ion heat flux in the case of 16MW. (b) Time evolutions of spatially-averaged heat flux in the case of 16MW(red), 4MW(blue) and 2D snapshots of the electrostatic potential at (c) explosive phase and (d) quiescent phase in the case of 16MW.

4. Step-up/down switching test for heat input

We also investigated the dynamic response of such transport processes by step-up/down switching test for heat input. Figure 2 (a) shows the time evolution of radial ion temperature profile after the step-down of heat input at t=400. After the step-down, the profile changes quickly in inner region, then the typical scale length of the profile in outer region slowly changes while keeping the functional form. This indicates that self-organized critical transport is dominant even in the transient phase.

Figure 2 (b) shows flux-gradient relation in step-up/down switching test. After the step-down, temperature profile relaxes quickly, while turbulent ion heat flux keeps a finite level (see Fig. 2 (a) and X phase in Fig. 2 (b)). The reduction of heat flux is accelerated after the settlement of temperature gradient (see Y phase in Fig. 2 (b)), leading to a hysteresis nature with the counter-clockwise. This indicates that temperature profile crosses a critical gradient, which is estimated as $R_0/L_{T_i}\sim 6$ in collision-less and source-less ITG simulation, then turbulence is damped.

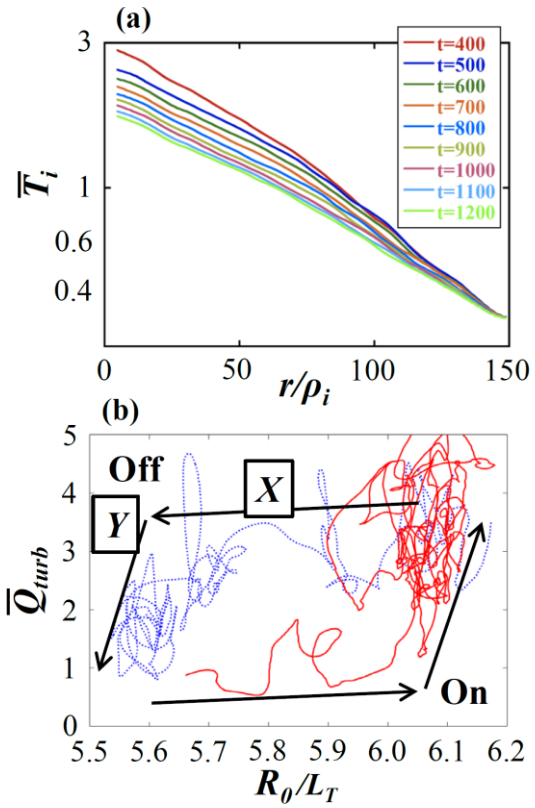

Fig. 2: (a) Radial ion temperature profile after stepped down at t=400. (b) Flux-gradient relation in the step-up/down switching test.

Acknowledgments

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