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Study of entropy transport using global gyrokinetic simulation in open system
開放系プラズマにおけるエントロピー輸送に関するジャイロ運動論的解析

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We have introduced entropy balance equation in an open system with external source, sink and collisions, and investigated the entropy dynamics with global profile relaxation by performing gyrokinetic full-f Vlasov simulation. It is found that the entropy decrease due to eternal heat input/output mainly balances with the microscopic entropy decrease, which corresponds to the turbulent generation. After the formation of stiff temperature profile, we find that the main part of microscopic entropy decrease can be generated in the center region, and the entropy only propagates in the source-sink free region. This may show that the stiff temperature profile is kept by the turbulent generation in the center region.

1. Background and Motivations

Turbulent transport in magnetically confined fusion plasmas exhibits various prominent features characterized by different temporal and spatial scales. Zonal modes, such as zonal flow and pressure, which are poloidally and toroidally symmetric macro-scale structures nonlinearly generated from micro-scale turbulence, play an important role in regulating turbulent structure and then transport [1]. These zonal modes are considered to be tightly linked to non-local characteristics of turbulent transport that are not explained by the Gaussian statistics, such as intermittent transport, turbulent spreading [2], and avalanche dynamics, etc. Self-organized critical (SOC) transport [3] is also an example in which the turbulence provides a strong constraint on relaxation, leading to a self-organized stiff temperature profile.

To characterize such transport dynamics, phase space entropy, which connects micro-scale turbulent structure to macro-scale thermodynamic quantities, is introduced [4]. However, the entropy has been generally treated as a global quantity that is integrated over phase space, so that the effects of zonal flow and turbulent spreading do not appear explicitly in the entropy balance equation. As the result, the non-local nature of transport is hardly discussed.

Recently, we extended the entropy balance equation keeping the dynamics in radial direction so that it can describe the spatio-temporal dynamics not only of the entropy production related to zonal flow and local heat flux, but also of perturbed entropy convection [5].

In this work, we have developed a global gyrokinetic Vlasov code, which is based on a full-f approach and includes source, sink and collisions. Source and sink models are necessary to simulate open system, whereas collisions work as a physical dissipation mechanism of fine scale velocity space structures, which are produced by mixing due to the ballistic mode. From the viewpoint of the entropy balance relation [6], such a dissipation mechanism is essential for reaching statistically steady states in long time gyrokinetic turbulence simulations. We investigate entropy evolution in such an open system and study which components balance with the entropy decrease due to external heat input/output.

2. Entropy Balance Equation in Open System

We here employ a gyrokinetic model for electrostatic ITG/ETG turbulence in slab geometry. The entropy balance equation is derived by multiplying the gyrokinetic Vlasov equation by $-\left(1+\log f\right)$ and integrating it over whole phase space, we obtain the entropy balance equation in an open system as

$$\frac{d}{dt}\int s^{(1)}dV+\frac{d}{dt}\int s^{(2)}dV=s_{src}+s_{snk}+s_{coll}\ , \quad (1)$$

where $s^{(1)}$ and $s^{(2)}$ are defined as $s^{(1)}\equiv-\delta f\,(1+\log f_0)$ and $s^{(2)}\equiv-\delta f^{\,2}/2f_0$, which corresponds to the first and second order quantities for Taylor series of $s\equiv-f\log f$ with respect to $\delta f/f_0$. In the absence of external source and sink, macroscopic entropy $s^{(1)}$ increases due to profile relaxation, which is related to the principle of the maximum entropy. On the other hand, the microscopic entropy $s^{(2)}$ decreases, which corresponds to the self-organization of the micro-scale turbulence. s_{src} , s_{snk} and s_{coll} correspond to the entropy production due to source, sink and collision.

3. Numerical Results and Discussions

We investigate the entropy dynamics with global profile relaxation by performing gyrokinetic full-f Vlasov simulation. We here employ a shear-less slab geometry for simplicity. We use the models for a heat source S_{src} at center and a heat sink S_{snk} in boundary region:

$$S_{src}(x, v_{\|}) = A_{src}(x)\{f_M(v_{\|}, 2T_0) - f_M(v_{\|}, T_0)\}, \quad (2)$$

$$S_{snk}(x, v_{\|}) = -A_{snk}(x)\{f_M(v_{\|}, 2T_0) - f_M(v_{\|}, T_0)\}. \quad (3)$$

Here A_{src} and A_{snk} are deposition profiles, which satisfy the conservation of particle, momentum and energy, but decreases entropy in whole phase space due to the difference of temperature between center and edge. Fig. 1 shows the schematic picture of entropy dynamics in an open system.

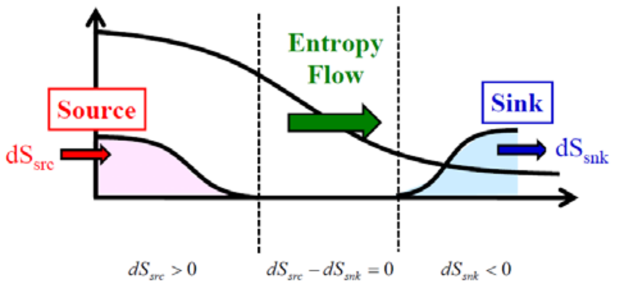

Fig. 1: Schematic picture of entropy dynamics in open system. Heat input at the core increases entropy whereas the output at the edge decreases entropy.

Fig. 2 shows the time evolution of entropy production related to macroscopic, microscopic quantities and external heat input/output. Note that the sum of them is well conserved, following Eq. (1). It is also found that the entropy decrease due to eternal heat input/output mainly balances with the microscopic entropy decrease which corresponds to the turbulent generation.

Fig. 3 shows the spatial profiles of these entropy productions after the formation of stiff temperature profile. We can see that the main part of microscopic entropy decrease can be generated in the center region, and the entropy only propagates in the source-sink region. This may show that the stiff temperature profile is kept by the turbulent generation in the center region.

We will discuss their details and the contribution from zonal flows and collisions in this presentation.

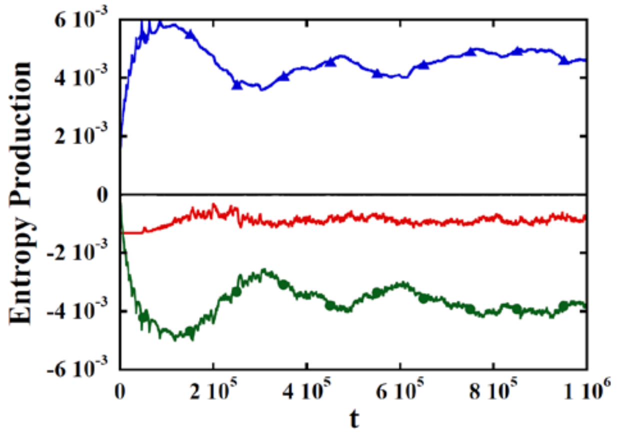

Fig. 2: Time evolution of entropy production related to macroscopic (red), microscopic (green) quantities and external heat input/output (blue). Black line shows the sum of them as a reference.

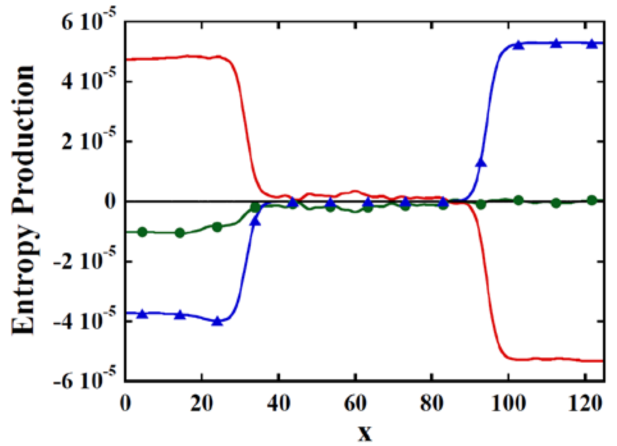

Fig. 3: Spatial profiles of entropy production. Each color line corresponds to same one in Fig. 2.

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