## §13. Kinetic Ballooning Mode Turbulence Simulation based on Electromagnetic Gyrokinetics

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The kinetic ballooning mode (KBM) turbulence in Tokamak plasma is investigated by electromagnetic gyrokinetic simulations. From the entropy balance analysis, it is revealed that the field-particle interactions transfer a significant fraction of the ion entropy produced by the instability to electrons. Then, the produced ion entropy balances to the sum of the ion and electron dissipations at the saturation of the KBM instability growth, in contrast to ITG turbulence where ion entropy production mostly balances to ion dissipation [1,2].

In the next generation fusion devices, such as JT-60SA and DEMO, high-$\beta$ operations are planned to make the design of a nuclear fusion reactor more realistic and attractive (where $\beta \equiv \mu_0 n T / B^2$ is the normalized plasma pressure). A finite $\beta$ effect introduces coupling of drift and Alfvén waves in magnetized plasma, and changes the nature of plasma turbulence from electrostatic to electromagnetic, where stabilization of the ion temperature gradient modes (ITG) and destabilization of the kinetic ballooning modes (KBM) are observed as $\beta$ increases. Since the finite $\beta$ effect may have large impacts on turbulent transport levels, understanding of the electromagnetic turbulence is critically important for high-$\beta$ operations.

We have carried out KBM turbulence simulations by means of the flux-tube gyrokinetic code GKV. Plasma parameters are set to be the so-called Cyclone base case parameters without the electron temperature gradient ($R/L_n = 2.2, R/L_{T_i} = 6.82, R/L_{T_e} = 0, T_i/T_e = 1, q = 1.4, \hat{s} = 0.78, r/R = 0.18$ and $\beta = 2\%$). We have analyzed the saturation mechanism of KBM instability growth from the viewpoints of the entropy balance equation. The equation describes the time evolution of the perturbed gyrocenter entropy $S_{s\boldsymbol{k}}$ for ions and electrons (s = i, e) and electromagnetic field energy $W_{\boldsymbol{k}}$ in the perpendicular wave number space $\boldsymbol{k}$,

$$\frac{dS_{s\boldsymbol{k}}}{dt} = \Theta_{s\boldsymbol{k}} + D_{s\boldsymbol{k}} + I_{s\boldsymbol{k}} + E_{s\boldsymbol{k}} + R_{s\boldsymbol{k}}, \qquad (1)$$

$$\frac{dW_{\boldsymbol{k}}}{dt} = -\sum_{s} R_{s\boldsymbol{k}}, \qquad (2)$$

where, $\Theta_{s\boldsymbol{k}}$, $D_{s\boldsymbol{k}}$ and $I_{s\boldsymbol{k}}$ denote the entropy production due to the particle and heat transport, the collisional dissipation and the nonlinear transfer, respectively. The parallel streaming term $E_{s\boldsymbol{k}}$ represents the entropy transfer between different radial wave number components due to the periodic boundary condition for
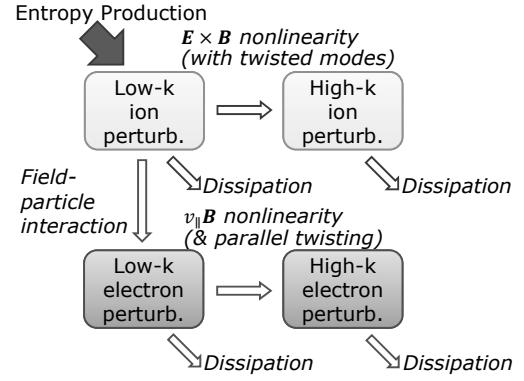


Fig. 1: Schematic picture of the entropy transfer at the saturation mechanism of KBM instability growth.

twisting mode structures in the sheared magnetic geometry. The field-particle interaction term $R_{s\boldsymbol{k}}$ corresponds to the energy exchange among the ion entropy, electron entropy and field energy. In a steady state ($d/dt \sim 0$), the entropy production, transfer and dissipation are statistically balanced, $\Theta_{s\boldsymbol{k}} + D_{s\boldsymbol{k}} + I_{s\boldsymbol{k}} + E_{s\boldsymbol{k}} + R_{s\boldsymbol{k}} = 0$, and the field-particle interactions stand for the entropy transfer among particle species, $\sum_s R_{s\boldsymbol{k}} = 0$.

The saturation mechanism of KBM instability growth is summarized as a schematic picture in Fig. 1. The low-wave-number ion entropy is produced by the particle and heat transport $\Theta_{i\boldsymbol{k}}$. They are transfered to the same wave-number modes of electron fluctuations via the field-particle interactions $R_{i\boldsymbol{k}} = -R_{e\boldsymbol{k}} < 0$. Rapid parallel advection of electrons leads to elongated mode structures along field lines, which in turn enhances the twisted modes in the sheared magnetic fields $E_{e\boldsymbol{k}}$. Then, the nonlinear mode coupling $I_{s\boldsymbol{k}}$ with the dominant unstable mode and its twisted modes transfers the low-wave-number ion and electron entropy to wide wave-number-space range. Finally, the total ion entropy production balances to the total ion and electron dissipations $D_{s\boldsymbol{k}}$.

The importance of the entropy transfer between ions and electrons via the field-particle interactions is identified. This is in contrast to ITG turbulence where the ion entropy production mostly balances to the ion dissipation. In addition, it is revealed that the KBM instability growth is saturated through the coupling of the dominant and its twisted modes, rather than the zonal flow shearing.

1) S. Maeyama, A. Ishizawa, T.-H. Watanabe, M. Nakata, N. Miyato, Y. Idomura, Plasma Fusion Res. 9, 1203020 (2014).

2) S. Maeyama, A. Ishizawa, T.-H. Watanabe, M. Nakata, N. Miyato, M. Yagi, Y. Idomura, Phys. Plasmas 21, 052301 (2014).