Kinetic Ballooning Mode Turbulence Simulation based on Electromagnetic Gyrokinetics*)

Shinya MAEYAMA, Akihiro ISHIZAWA[1)], Tomohiko WATANABE[1)], Motoki NAKATA, Naoaki MIYATO and Yasuhiro IDOMURA

Japan Atomic Energy Agency, Rokkasho 039-3212, Japan
[1)]*National Institute for Fusion Science, Toki 509-5292, Japan*

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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.

Keywords: gyrokinetics, Vlasov simulation, kinetic ballooning mode

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In the next generation fusion devices, such as JT-60SA and DEMO, high-β operations are planned to make the design of a nuclear fusion reactor more realistic and attractive (where $\beta \equiv \mu_0 nT/B^2$ is the normalized plasma pressure). A finite β 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 β increases [1]. Since the finite β effect may have large impacts on turbulent transport levels, understanding of the electromagnetic turbulence is critically important for high-β operations.

In this paper, we have carried out KBM turbulence simulations by means of the flux-tube gyrokinetic code GKV [2, 3]. Plasma parameters are set to be the so-called Cyclone base case parameters without the electron temperature gradient ($R/L_n = 2.2$, $R/L_{T_\mathrm{i}} = 6.82$, $R/L_{T_\mathrm{e}} = 0$, $T_\mathrm{i}/T_\mathrm{e} = 1$, $q = 1.4$, $\hat{s} = 0.78$, $r/R = 0.18$ and $\beta = 2\%$). We have analyzed the saturation mechanism of KBM instability growth from the viewpoints of the entropy balance equation [4]. The equation describes the time evolution of the perturbed gyrocenter entropy $S_{\mathrm{s}\boldsymbol{k}}$ for ions and electrons ($\mathrm{s} = \mathrm{i}, \mathrm{e}$) and electromagnetic field energy $W_{\boldsymbol{k}}$ in the perpendicular wave number space $\boldsymbol{k}$,

$$\frac{\mathrm{d}S_{\mathrm{s}\boldsymbol{k}}}{\mathrm{d}t} = \Theta_{\mathrm{s}k} + D_{\mathrm{s}k} + I_{\mathrm{s}k} + E_{\mathrm{s}k} + R_{\mathrm{s}k}, \qquad (1)$$

$$\frac{\mathrm{d}W_{\boldsymbol{k}}}{\mathrm{d}t} = -\sum_{\mathrm{s}} R_{\mathrm{s}\boldsymbol{k}}, \qquad (2)$$

where, $\Theta_{\mathrm{s}k}$, $D_{\mathrm{s}\boldsymbol{k}}$ and $I_{\mathrm{s}\boldsymbol{k}} = \mathrm{Re}[\langle \int \mathrm{d}v^3 \sum_{\boldsymbol{k}'} \sum_{\boldsymbol{k}''} \delta_{\boldsymbol{k}'+\boldsymbol{k}''+\boldsymbol{k}=0} \boldsymbol{b} \cdot \boldsymbol{k}' \times \boldsymbol{k}'' (\chi^*_{\mathrm{s}\boldsymbol{k}'} g^*_{\mathrm{s}\boldsymbol{k}''} - \chi^*_{\mathrm{s}\boldsymbol{k}''} g^*_{\mathrm{s}\boldsymbol{k}'}) g^*_{\mathrm{s}\boldsymbol{k}} T_\mathrm{s}/(2BF_{\mathrm{sM}})\rangle]$ denote the entropy production due to the particle and heat transport, the collisional dissipation and the nonlinear transfer, respectively (where $g_{\mathrm{s}\boldsymbol{k}} = f_{\mathrm{s}\boldsymbol{k}} + e_\mathrm{s} F_{\mathrm{sM}} J_{0\mathrm{s}\boldsymbol{k}} \phi_{\boldsymbol{k}} / T_\mathrm{s}$ and $\chi_{\mathrm{s}\boldsymbol{k}} = J_{0\mathrm{s}\boldsymbol{k}}(\phi_{\boldsymbol{k}} - v_\parallel A_{\parallel\boldsymbol{k}})$ with the symbols same as Ref. [3]). The parallel streaming term $E_{\mathrm{s}\boldsymbol{k}} = -\langle \nabla_\parallel \int \mathrm{d}v^3 v_\parallel |g_{\mathrm{s}\boldsymbol{k}}|^2 T_\mathrm{s}/(2F_{\mathrm{sM}})\rangle$ represents the entropy transfer between different radial wave number components due to the periodic boundary condition for twisting mode structures in the sheared magnetic geometry [5]. As shown in Fig. 1, the electrostatic potential perturbations have large amplitudes in the bad curvature region (near at the

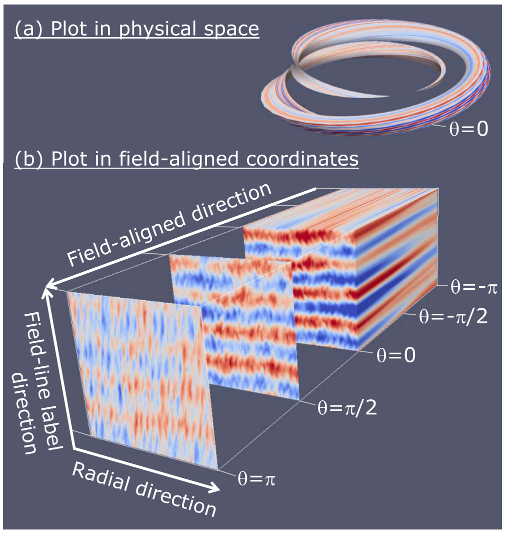

Fig. 1 Snapshot of electrostatic potentials of KBM in (a) physical space and (b) field-aligned coordinates of $-\pi \le \theta \le \pi$.

author's e-mail: maeyama.shinya@jaea.go.jp

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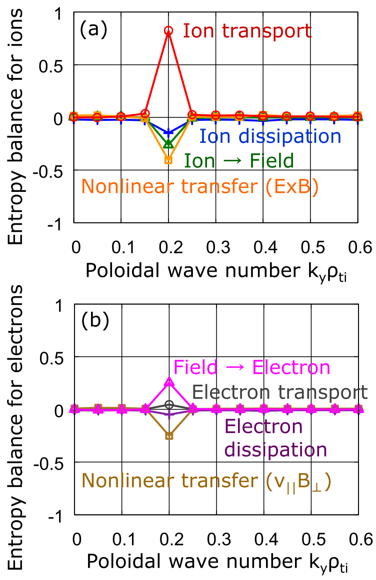

Fig. 2 Poloidal wave number spectra of the terms in the entropy balance for (a) ions and (b) electrons (summed over the radial wave number and normalized by the total ion entropy production). Circular, square, triangle, and cross dots plot the entropy production due to transport Θ_{sk}, nonlinear transfer I_{sk}, field-particle interaction R_{sk}, collisional dissipation D_{sk}, respectively. Plots are limited up to $k_y\rho_{ti} = 0.6$ for visibility, while we have employed $0 \le k_y\rho_{ti} \le 1.55$ in numerical simulations.

poloidal angle $\theta = 0$) and elongate along the magnetic field lines. In the presence of the magnetic shear, the structures twist and create radially-fine mode structures (see the $\theta = \pi$ plane). The field-particle interaction term $R_{s\boldsymbol{k}} = \mathrm{Re}[\langle\int \mathrm{d}v^3(-e_s J_{0s\boldsymbol{k}}\phi^*_{\boldsymbol{k}}\partial_t f_{s\boldsymbol{k}} - e_s v_{\parallel} f^*_{s\boldsymbol{k}} J_{0s\boldsymbol{k}}\partial_t A_{\parallel\boldsymbol{k}})\rangle]$ corresponds to the energy exchange among the ion entropy, electron entropy and field energy. We note that there is no entropy transfer between species via collisions, because we employ a self-collision model operator. In a steady state ($\mathrm{d}/\mathrm{d}t \sim 0$), the entropy production, transfer and dissipation are statistically balanced, $\Theta_{sk} + D_{sk} + I_{sk} + E_{sk} + R_{sk} = 0$, and the field-particle interactions stand for the entropy transfer among particle species, $\sum_s R_{s\boldsymbol{k}} = 0$.

The poloidal wave number (k_y) spectra of the terms in the entropy balance equation (1) are plotted in Fig. 2, where the parallel streaming term does not appear because of the conservation relation $\sum_{k_x} E_{s\boldsymbol{k}} = 0$ for the radial wave number k_x. The ion transport term ($\Theta_{ik} > 0$) drives the $k_y\rho_{ti} = 0.2$ mode, and the nonlinear transfer term $I_{i\boldsymbol{k}}$ transfers the low-k_y entropy to the other modes [where $\sum I_{i\boldsymbol{k}}(0 \le k_y\rho_{ti} < 0.2) = 0.037$, $I_{i\boldsymbol{k}}(k_y\rho_{ti} = 0.2) = -0.407$, $\sum I_{i\boldsymbol{k}}(0.2 < k_y\rho_{ti} \le 1.55) = 0.370$, and thus, the conservation relation $\sum_{\boldsymbol{k}} I_{s\boldsymbol{k}} = 0$ is satisfied]. This produces ion entropy in the wide wave-number-space range, which are dissipated by the ion collisional dissipation ($D_{i\boldsymbol{k}} < 0$). At the same time, there is a significant entropy transfer from ions to electrons through the field-particle interaction terms

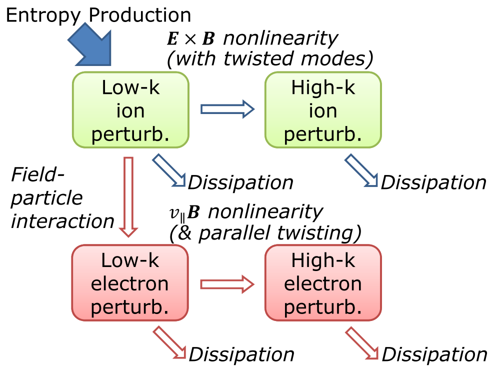

Fig. 3 Schematic picture of the entropy transfer at the saturation mechanism of KBM instability growth.

($-R_{i\boldsymbol{k}} = R_{e\boldsymbol{k}} > 0$). This is the dominant source of the electron entropy, since the entropy production due to the electron transport is small when $R/L_{T_e} = 0$. The low-k_y electron entropy is transferred to the other modes by the nonlinear transfer term $I_{e\boldsymbol{k}}$, and is dissipated by the electron collision ($D_{e\boldsymbol{k}} < 0$). As a result, the statistical balance of entropy production, transfer and dissipation is satisfied in the saturated state of the KBM instability.

A more detailed analysis of the nonlinear entropy transfer spectrum $I_{s\boldsymbol{k}}$ reveals that the mode coupling among the dominant mode and its twisted modes in the sheared geometry are the dominant nonlinear transfer process. This suggests importance of the electron dynamics, since the rapid parallel motions of electrons create elongated structures along field lines [3]. Details of the mode coupling in KBM turbulence will be reported elsewhere.

The saturation mechanism of KBM instability growth is summarized as a schematic picture in Fig. 3. The low-wave-number ($k_y\rho_{ti} = 0.2$) ion entropy is produced by the particle and heat transport. They are transferred to the same wave-number modes of electron fluctuations via the field-particle interactions. 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. Then, the nonlinear mode coupling 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.

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 [2]. 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.

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