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プラズマ乱流が作り出す平行流れ場構造と密度分布構造
Structure of parallel flows and density profiles produced by plasma turbulence

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Understanding the behavior of turbulent plasmas is an important issue. Conventionally, turbulent plasmas are thought to arise from the primary free energy source, e.g. the pressure gradient. Recent studies have revealed the importance of the secondary structure, such as zonal flows, which are generated from the primary turbulence driven by the scalar gradient. Once excited, these flows become another source for driving fluctuation, and the resultant fluctuation can impact the evolution of the primary structure. As such, turbulent plasmas are characterized by the multiple free energy source, including the pressure gradient, velocity shear, etc, and its dynamics shows strong interference among transport channels for density, momentum (both in the perpendicular and the parallel direction to the magnetic field). This leads us to the notion of *cross-ferroic turbulence*[1], where multiple free energy source drive various turbulent fluctuations, and its interference causes the chained reaction for the evolution of structures.

In this work, we describe a typical example of such coupled dynamics. As a specific example, we discuss the coupled dynamics of parallel flows and density gradients. Eigenmodes in the presence of both the density gradient and parallel velocity gradient are characterized by calculating the dispersion relation based on a simplified fluid model[2,3]. The result is

$$\omega = \frac{\omega_{*e} + \sqrt{\omega_{*e}^2 + 4(1+k_\perp^2\rho_s^2)(k_z^2c_s^2 - k_y\rho_s k_z c_s\langle v_z\rangle')}}{2(1+k_\perp^2\rho_s^2)}. \tag{1}$$

Here ω_{*e} is the frequency of electron drift waves. The term with $\langle v_z\rangle'$ denotes the effect of parallel flow shear. The behavior is summarized in Fig.1. Here, the blue curve denotes the instability threshold in the absence of drift waves. In this case, the mode is purely driven by parallel velocity shear. In the presence of drift waves, the parallel flow shear driven mode is stabilized, and its threshold is denoted by the red curve. Above the red curve, the mode is driven by parallel flow shear, while below the curve, the mode is stable against the parallel flow shear, and fluctuations are mainly supported by the density gradient driven drift waves.

The coupled dynamics is further studies by calculating the quasilinear transport fluxes:

$$\frac{\Gamma_n}{n_0c_s} = \sum_{\mathbf{k}} k_y\rho_s\frac{-\omega+\omega_{*e}}{k_z^2D_z}\left|\frac{e\tilde{\phi}_{\mathbf{k}}}{T_e}\right|^2 + \sum_{\mathbf{k}} k_y\rho_s\frac{c_s^2k_z^2 - c_sk_z\rho_sk_y\langle v_z\rangle'}{k_z^2D_z\omega}\left|\frac{e\tilde{\phi}_{\mathbf{k}}}{T_e}\right|^2, \tag{2}$$

$$\frac{\Pi_{xz}}{c_s^2} = \sum_{\mathbf{k}} k_y\rho_s\frac{(-\omega+\omega_{*e})c_sk_z}{k_z^2D_z\omega}\left|\frac{e\tilde{\phi}_{\mathbf{k}}}{T_e}\right|^2 + \sum_{\mathbf{k}} ik_y\rho_s\frac{c_sk_z - \rho_sk_y\langle v_z\rangle'}{\omega}\left(1 - i\frac{k_z^2c_s^2}{k_z^2D_z\omega}\right)\left|\frac{e\tilde{\phi}_{\mathbf{k}}}{T_e}\right|^2. \tag{3}$$

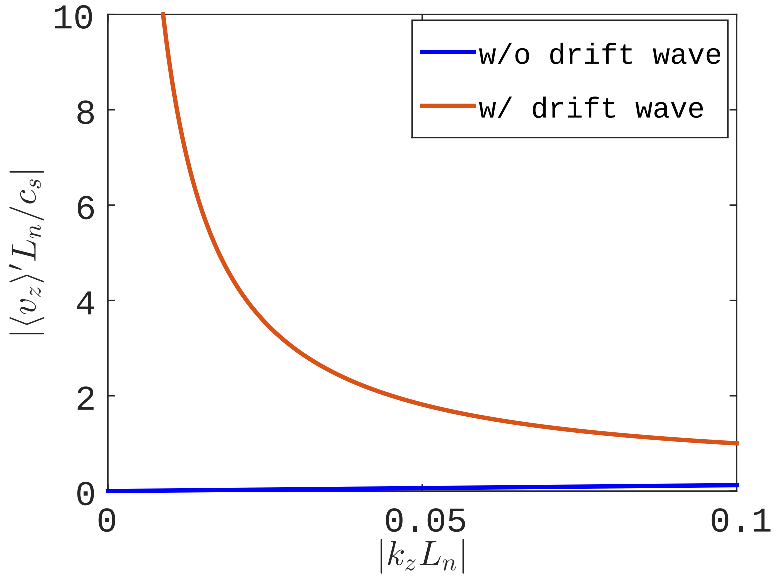

図 1: The instability diagram for PSFI with (red) and without (blue) drift waves for $k_x \rho_s = k_y \rho_s = 0.8$ ($k_\perp \rho_s \cong 1.13$).

Γ_n is the turbulent particle flux and Π_{xz} is the turbulent flux of the parallel momentum. D_z is the parallel electron diffusivity, which causes phase shift for the electron response. The physical picture becomes clearer by investigating limiting cases. When drift waves dominate, the particle flux is mainly driven by the diagonal term $\Gamma_n \propto \nabla n$, while the momentum flux can arise from the off-diagonal term (the first term, $\Pi_{xz} \propto \nabla n$). This off-diagonal term can generate the secondary parallel flows. On the other hand, when parallel flow shear dominates, the momentum flux is mainly driven by the velocity shear, while the off-diagonal term in the particle flux can drive inward contribution and competes against the outward, diffusive flux. This may result in the peaked density profile, which can be viewed as a secondary structure generated in turbulence driven by the primary parallel velocity shear. The coupled dynamics is also formulated by calculating the turbulence production rate, which is related to thermodynamic function. Ongoing work on calculating the production self-consistently with the dispersion relation and nonlinear dynamics with spreading effect will be reported as well.

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