6th Asia-Pacific Conference on Plasma Physics, 9-14 Oct, 2022, Remote e-conference

Theory of Pedestal Micro-turbulence with RMP-induced Stochasticity

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In this work, we present a detailed analytic theory of an electrostatic resistive interchange mode in an extrinsic, static, and ambient stochastic magnetic field [1]. Nowadays, resonant magnetic perturbation (RMP) is widely adopted to mitigate and suppress edge-localized mode (ELM). However, RMP also raises the L-H transition power threshold. Therefore, it is essential to study plasma dynamics, especially plasma instabilities and turbulence in a stochastic magnetic field. Unlike previous works pursing and developing the hyper-resistivity idea [2], this work addresses issues such as effect of stochasticity on the structure of a single mode and maintains the quasi-neutrality ($\nabla \cdot \boldsymbol{J} = 0$) of the system at all orders.

As shown in figure 1, it is found that the externally prescribed stochastic magnetic field results in a small-scale current density fluctuation $\tilde{\boldsymbol{J}}_{\parallel}$, which is not divergence free. As suggested in Kadomtsev and Pogutse's paper on heat transport in a stochastic field [3], a temperature fluctuation is generated by the interaction between the mean temperature profile and the imposed magnetic perturbations under the constraint of $\nabla \cdot \boldsymbol{Q_e} = 0$, where $\boldsymbol{Q_e}$ is the electron heat flux. So in our model, a potential fluctuation $\tilde{\varphi}$ is driven by the beat of small-scale magnetic perturbations and large-scale cell, to produce $\tilde{\boldsymbol{J}}_{\perp}$, a perpendicular current density fluctuation so as to maintain $\widetilde{\nabla_{\parallel} J_{\parallel}} + \widetilde{\nabla \cdot \boldsymbol{J}_{\perp}} = 0$. The generation of $\tilde{\varphi}$ indicates the presence of a spectrum of small-scale convective cells, i.e., micro-turbulence. Therefore, as illustrated in figure 2, this theory is intrinsically multi-scale and actually contains three "players": a large-scale cell, a background stochastic field, and small-scale convective cells. The micro-turbulence can react on the large-scale cell via an effective turbulent viscosity and turbulent diffusivity, as well as electrostatic scattering, thus forming a feedback loop.

This model provides several testable predictions:

- The appearance of micro-turbulence is consistent with the increase in small-scale structure and spatial roughness of the turbulence field, as in the simulation of Ref. [4].
- The net effect of stochastic magnetic fields is to reduce the resistive interchange growth. The corrected growth rate is calculated by using a perturbation method.
- The velocity fluctuations '*lock on*' to the stochastic field. The correlation between electrostatic turbulence and ambient magnetic perturbations is explicitly calculated. This correlation can explain the decrease in Jensen-Shannon complexity and predictability observed in the RMP ELM suppression phase on KSTAR [5].
- The scaling of the turbulent viscosity result from micro-turbulence is calculated via nonlinear closure theory.
- Stochastic magnetic perturbations produce a magnetic braking effect, which is similar in structure to the nonlinear force identified by Rutherford [6]. But this effect differs from Rutherford's result by a factor of $k_{\theta}^2/k_{2\theta}^2$, on account of the multi-scale nature of this model.

References

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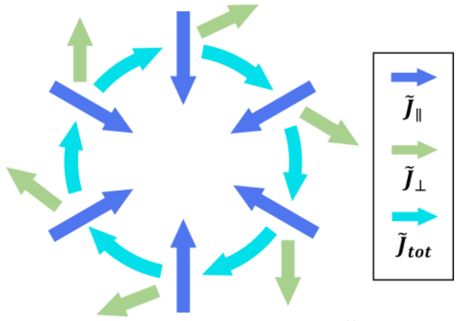

Figure 1. A current density fluctuation $\tilde{\boldsymbol{J}}_{\perp}$ is driven to balance $\tilde{\boldsymbol{J}}_{\parallel}$, so that the total current density fluctuation $\tilde{\boldsymbol{J}}_{tot}$ is divergence free.

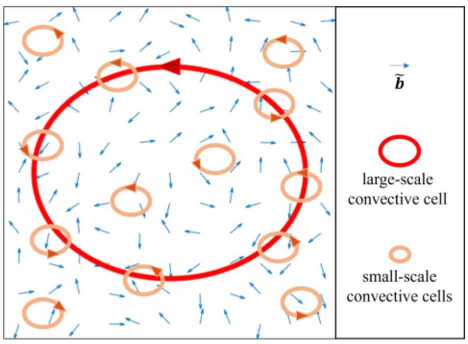

Figure 2. Illustration of three main players in this model: large-scale single cell, prescribed background static stochastic magnetic field, and micro-turbulence.