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Ballooning Mode in a Stochastic Magnetic Field —A Quasi-mode Model

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Resonant magnetic perturbation (RMP) is widely adopted to generate a stochastic magnetic field to suppress ELM. But it is also found that RMP can lead to an increase in the power threshold for L-H transition. Therefore, good confinement must be achieved along with good boundary control and power handling. Given that peeling-ballooning mode is a quite probable mechanism of ELM, understanding how a stochastic magnetic field affects ballooning mode is crucial for fusion devices that employ RMP, such as ITER.

Recent experiments provide important observations that deserve our attention. Choi et al. applied complexity-entropy analysis to characterize the change in the statistics of pedestal turbulence with RMP switched on and off [1]. In this approach, a metric called Jensen-Shannon complexity C_{JS} is defined to quantify a system's complexity. They observed a reduction in the rescaled C_{JS} of the temperature fluctuations in the RMP ELM suppression phase, compared to the RMP ELM mitigation phase and natural ELM-free phase. This indicates that stochastic magnetic field can reduce the predictability of plasma turbulence. In addition, an increase in the bicoherence of the pedestal turbulence was also observed in the RMP ELM suppression phase. These results are very intriguing and need to be understood.

Due to the fact that models for ballooning mode are set up in a toroidal geometry while theories involving RMP typically focus on resonant surfaces within a cylindrical geometry, we need to reconcile these two different geometries in order to develop a comprehensive theory that includes both the ballooning mode and RMP. Based on the resemblance between a quasi-mode in a cylinder and a ballooning mode in a torus, our strategy is to replace ballooning mode by quasi-mode first, and then extend the results we get to ballooning mode.

In this work, a multi-scale model of quasi-mode in a static stochastic magnetic field is presented. The framework of this model can be summarized by the flowchart in figure 1. The lessons we learned for ballooning mode in a stochastic magnetic field are:

i.) To maintain $\nabla \cdot \boldsymbol{J} = 0$ at all scales, the beat of the quasi-mode and stochastic magnetic field drives a microturbulence, which could promote spectral transfer by increasing the number of triad interactions. This may account for the increase in the bicoherence of the pedestal turbulence reported by Choi et al.

ii.) The microturbulence can further generate a turbulent viscosity and a turbulent diffusivity, which damp the ballooning mode growth by boosting the mixing. N.B., as a result of the difference in mode structure, the scaling of the turbulent viscosity/diffusivity is larger than that in our study on resistive interchange mode [2].

iii.) The stochastic magnetic field can enhance the effective plasma inertia and reduce the effective drive. This result is similar to the "magnetic braking effect" in Rutherford's work on nonlinear tearing mode [3]. But the critical magnetic island in our work is reduced by a factor $\left(k_y/k_{1y}\right)^{1/2}$, which is a footprint of the multi-scale nature of our model. Combining with ii.), we can conclude that stochastic magnetic field can slow down the mode growth.

iv.) A non-trivial correlation develops between the magnetic perturbations and the velocity fluctuations. In other words, the microturbulence 'locks on' to the ambient stochastic magnetic field, thus becoming more stochastic. This theoretical prediction may explain the reduction in the C_{JS} of the pedestal turbulence.

Several experiments for future investigations are also proposed. Especially, it would be interesting to perform a similar analysis on the velocity fluctuation data collected from BES in both the RMP ELM suppression phase and the natural ELM-free phase, not only as a complement to Choi's results, but also as a verification of our theory.

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References

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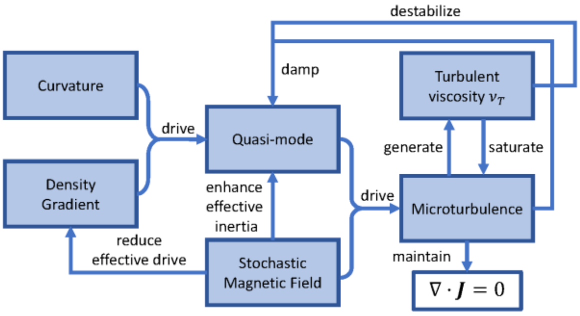

Figure 1. Multi-scale feedback loops of quasi-mode and microturbulence