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Intrinsic Multi-Scale Microturbulence in a Stochastic Magnetic Field

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Edge-localized modes (ELMs), a consequence of H-mode, may result in devastating damage to the first wall through instantaneous bursts of heat and particles. In experiments, resonant magnetic perturbation (RMP) serves as a viable way to control ELMs. It is a well-accepted consensus that the suppression of turbulence results in L-H transition when heating power exceeds a threshold value. However, recent studies indicate that RMPs tend to raise the L-H transition power threshold P_{LH}.[1] To determine how stochastic magnetic fields generated by RMPs affect L-H transition, it is essential to study their influence on instability mechanisms, since such instabilities are the origins and drives of plasma turbulence. The tractability of resistive interchange mode makes it a good focus for initial study. This work aims to investigate how a high-k stochastic magnetic field background modifies the dynamics of a low-k resistive interchange mode. This multi-scale problem is relevant to the question of L-H transition with RMPs and, more generally, also paradigmatic.

Unlike previous work, which used a test particle picture,[2] the quasi-neutrality of plasma (i.e., $\nabla \cdot \boldsymbol{J} = 0$) is enforced on all scales in this work. Due to the stochastic magnetic field $\tilde{\boldsymbol{b}}$, the parallel derivative $\nabla_\parallel$ should be interpreted as $\nabla_\parallel = \nabla_\parallel^{(0)} + \tilde{\boldsymbol{b}} \cdot \nabla_\perp$, a derivative along the main field plus a derivative along the perturbed field. Starting with the vorticity equation and electrostatic Ohm's law, we find that to maintain quasi-neutrality, a high-k electrostatic potential fluctuation $\tilde{\phi}$ is generated by the stochastic field and the low k perturbations. This outcome resembles that from the study by Kadomtsev and Pogutse, in which a temperature fluctuation $\tilde{T}$ is introduced as $\nabla \cdot \boldsymbol{q} = 0$ is maintained on all scales.[3] Physically, the appearance of $\tilde{\phi}$ means the presence of small-scale convective cells, which is consistent with previous simulation results.[4] These convective cells can drive a turbulent viscosity ν and a turbulent diffusivity χ, which may be a cause of RMP-induced pump-out. Method of averaging is used to separate the vorticity equation which is intrinsically a stochastic differential equation with $\tilde{\boldsymbol{b}}$ as a stochastic variable into coupled equations for macro and micro scales, for which slow-interchange and fast-interchange approximations apply, respectively. Applying mean field theory to the equations at the micro scale, the response of $\tilde{\phi}$ to $\tilde{\boldsymbol{b}}$ is obtained. In the end, the stochastic differential equation is transformed into a macroscopic integro-differential equation, in which a third-order magnetic torque appears along with other contributions. This result is reminiscent of that from Rutherford's nonlinear island calculation.[5] The width of small-scale island is given when this third-order magnetic torque is comparable to the first-order magnetic torque. The key physics is the same, modulo multi-scale effects which are generic for stochastic magnetic fields.

We conclude that one effect of $\tilde{\boldsymbol{b}}$ is to drive an increased effective inertia of the plasma and thus stabilize the system. Other effects are more complex, and we expect there is a competition. No electron viscosity effect appears in this model. By regarding the interactions as small perturbations, the corrected growth rate γ of the envelope of electrostatic potential $\bar{\phi}$ and the turbulent viscosity ν are calculated, approximately. The implications for the physics of turbulent transport in a stochastic field will be discussed.

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