9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Multi-scale Interaction for Edge-Localized-Mode Suppression in the Tokamak Edge

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The study of bursty, explosive relaxation events is a captivating subject that spans various areas of physics, from solar flares and magnetic substorms in space physics contexts to edge-localized modes (ELMs) in magnetically confined fusion plasmas. These phenomena turn out to share a common qualitative picture under very different physical conditions. The multi-scale interaction between pedestal turbulence and MHD modes shows a viable means for the suppression of Edge Localized Modes (ELMs). Specifically, this work examines how interactions between large-scale MHD and small-scale drift-wave turbulence modulate particle flux in the DIII-D wide pedestal quiescent H-mode (WPQH).

The recent discovery of the WPQH on the DIII-D tokamak, which achieved ELM-free high-confinement operation with net-zero input torque and other reactor-relevant parameters[1]. This unique regime exhibits a significantly broader pedestal width than predicted by conventional EPED-KBM scaling laws. A key feature of the WPQH is the presence of both broadband MHD activity and intermittent turbulence within the pedestal, which is notably observed to rotate in the ion diamagnetic drift direction and the electron diamagnetic drift direction, respectively[2]. The large-scale, k_θ <0.3cm^{-1}, low-frequency, f=10-50kHz, broadband MHD rotates in the ion-diamagnetic direction and is identified as weakly excited Peeling-Ballooning (PB) mode; the small-scale, k_θ =2-4cm^{-1}, high-frequency, f =50kHz-2MHz, turbulence rotates in the electron-diamagnetic direction and is comprised of electron drift waves[3].

Alternating cycles of PB fluctuations, electron drift waves, and background gradients are observed in WPQH mode pedestals. The amplitudes of MHD mode and turbulence exhibit a phase misalignment, indicating an out-of-phase relationship. The pedestal electron density/temperature profiles exhibit the same periodicity as the MHD/turbulence modes. Measurements from Beam Emission Spectroscopy (BES) provides direct evidence for the strong interaction between the MHD(PB) and turbulence (electron drift wave). A strong bicoherence is observed when an electron drift wave bursts. BES velocimetry analysis reveals nearly zero turbulent particle flux, and a scatter of the cross phase between density δn and radial velocity perturbation δv_r of low-frequency MHD during an electron drift wave burst. Experiments also found that the ELMs could be excited in the absence of the strong electron turbulences. Such results demonstrate that the interplay between scale-separated modes plays a crucial role in determining ELM dynamics.

Synergistic numerical modeling demonstrates that small-scale electron drift waves can scatter the cross phase of the pressure and radial velocity perturbation of PB mode, resulting in decoherence of the PB-driven flux. We investigate the interplay between PB-MHD and electron turbulence through numerical experiments in BOUT++. A significant difference emerges in the final saturation for the case with and without the existence of the electron turbulence. The numerical findings regarding the phase scattering effect of the electron turbulence align closely with experimental observations, indicating suppression of the large-scale PB-MHD.

A theoretical model to quantify the impact of electron drift wave scattering on PB modes has also been developed with reduced fluid three-field module. The electron turbulence are treated as an background scattering field and decoheres the PB-MHD driven flux. Theoretical analysis yields a shift in the linear growth rate, $\frac{\Delta\gamma}{\omega_{A0}} \sim \left(\frac{k_{PB}}{k'_{\perp}}\right)(k_{\parallel}R)(k_{PB}L_p)\langle\left(\frac{\tilde{p}_{DW}}{P_0}\right)^2\rangle^{\frac{1}{2}}$, which provides a reasonable estimation of the simulated results. This work yields a novel nonlinear prediction of the shift of the ELM onset boundary induced by the ambient electron drift waves, thereby indicating when a turbulent pedestal can be maintained in a quiescent state in this scenario. In addition, this work showcases a new type of multi-scale interaction physics, which can play a role in a wide range of physical systems.

References:
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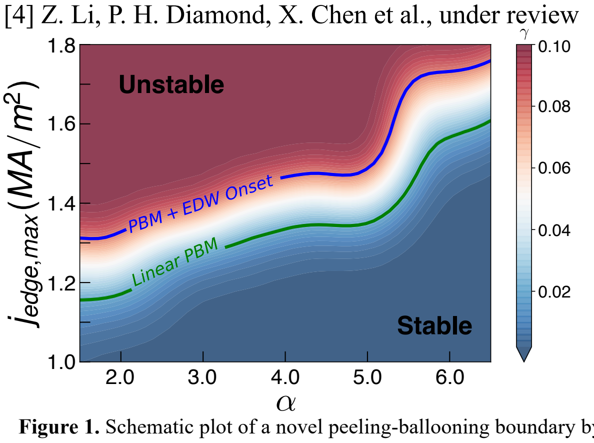

Figure 1. Schematic plot of a novel peeling-ballooning boundary by incorporating the small-scale electron drift wave scattering effect.