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Role of Multi-Scale MHD and Turbulence in Pedestal Stability and Transport in Wide-Pedestal Quiescent H-Mode

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Understanding the physics of the stability limits and pedestal transport dynamics is a crucial problem that dramatically impacts the confinement and safety operation of fusion reactors. In recent years, the stationary, quiescent H-mode with pedestal width larger than EPED-KBM prediction (wide-pedestal QH-mode) discovered on DIII-D is an attractive scenario for future fusion reactors as it features low edge rotation and improved confinement compared with standard QH phase and operates ELM-free [1, 2]. This scenario is found to have reactor-relevant parameters of normalized plasma beta β_N =1.5–2.3, confinement factor H_{98y2} =1.2–1.6, and normalized pedestal electron collisionality ν_{e*}=0.2–0.5, operates in a range of NBI torque and plasma rotation spanning from co- to counter-plasma current direction which fits the operation regime of future tokamaks. Multi-scale MHD/turbulences instead of edge harmonics oscillations (EHO) govern the edge of wide-pedestal QH-mode plasmas. However, the pedestal stability limit, the role of broadband turbulence regulating pedestal profiles, and pedestal transport dynamics are not well understood yet. In this work, experimental data analysis and massively parallel BOUT++ simulations are carried out to investigate the nature of pedestal stability and turbulence dynamics in the wide pedestal QH phase.

Reduced MHD modeling results are consistent with experimentally observed local pedestal profile flattening and measured turbulent fluctuations in the wide pedestal QH-mode [3]. The edge MHD and turbulence identified in BOUT++ linear and nonlinear simulation are: a) low frequency, low-k peeling-ballooning mode (PBM) rotates in the ion diamagnetic drift (IDD) direction; b) higher frequency, intermediate-high k drift-Alfvén wave (DAW) propagates in the electron diamagnetic drift (EDD) direction, as shown in Fig. 1. Experimentally observed local profile flattening in the upper pedestal is reproduced in BOUT++ nonlinear simulation. The rotation direction, mode location, as well as wavenumber of these two modes from simulations agree reasonably well with the experimental BES measurements.

The interplay between these two scale-separated fluctuations regulates the pedestal profiles, which may be responsible for the onset of rarely occurring ELMs. Experimentally, the IDD mode amplitude decreases when the EDD amplitude increases, and they regulate the pedestal density and temperature profiles, respectively. A feedback loop ("ecological niche") could be formed between PBM, DAW, and profile gradients in the pedestal of wide-pedestal QH-mode plasmas. In addition, irregular ELMs can occur in wide-pedestal QH-mode with an increase in the amplitude of the IDD mode and a decrease of the EDD mode. This indicates that the intermediate-high k electron drift waves could impact the low-k PBM, thus the ELM dynamics. A novel nonlinear criterion for the onset of ELMs by considering the small-scale electron drift wave scattering effect is produced in BOUT++ nonlinear simulation, as shown in Fig. 2.

Furthermore, the role of scale-separated modes in setting the heat flux width has been studied numerically recently. The divertor heat flux width increases with the increase of PBM amplitude, which increases turbulence intensity flux across the separatrix. In summary, this work presents an improved physics understanding of the multi-scale MHD and turbulence of wide-pedestal QH-mode.

References

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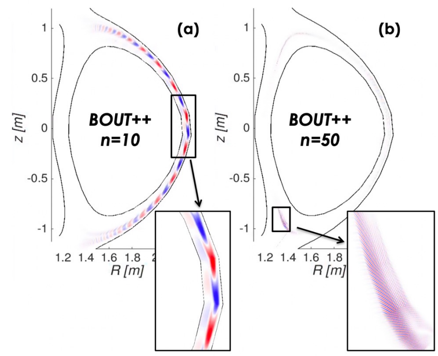

Figure 1. Mode structure of electron density perturbation ($\tilde{n}_e$) for (a) most unstable low-intermediate n peeling ballooning mode (PBM), n=10; (b) most unstable high n drift Alfvén wave (DAW), n=50.

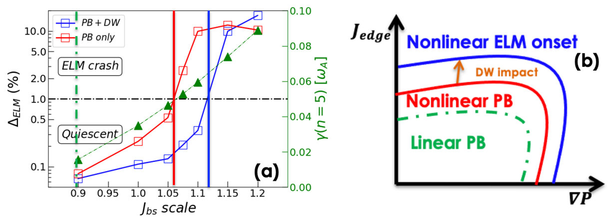

Figure 2. (a) BOUT++ nonlinear simulation of the linear growth rate of n=5 mode (green), ELM energy loss of PBM only simulation (red), and ELM energy loss with PBM and DAW (blue) with different edge bootstrap current. (b) Schematic plot of linear PBM boundary; Nonlinear ELM onset boundary with PBM; Nonlinear ELM onset boundary with drift wave impact included.