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Characterization of Pedestal Turbulence and Its Role in ELM Dynamics in KSTAR Plasmas

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The pedestal, located at the plasma edge, plays a critical role in regulating particle and energy transport into the scrape-off layer (SOL), resulting in steep temperature and density gradients. These gradients can trigger edge instabilities, most notably edge-localized modes (ELMs), which cause abrupt pedestal collapses, degrade plasma performance, and damage plasma-facing components due to intense heat and particle fluxes. While ELMs pose a significant threat to future fusion reactors, the high pedestal pressure achieved just before an ELM crash is essential for optimal fusion performance. Therefore, understanding the underlying transport mechanisms and micro-instabilities is key to establishing a predictive pedestal model.

Despite extensive theoretical and simulation-based investigations, experimental validation of the dominant transport mechanisms in H-mode pedestals remains challenging due to low fluctuation amplitudes and rapid timescales. In this study, we employed a broadband electron cyclotron emission (ECE) diagnostic system based on the ECE imaging (ECEI) optical layout to directly measure turbulent fluctuations in the KSTAR H-mode pedestal [1]. The system incorporates a high-speed broadband digitizer with an analog bandwidth of 6.5 GHz (4 channels) and a sampling rate of 16 GSa/s, enabling enhanced radial resolution and broad frequency coverage. Frequency-resolved electron temperature fluctuations were digitally extracted from DC-converted signals using custom-designed bandpass filters, allowing flexible tuning of spatial and temporal resolutions to focus on relevant physical phenomena while minimizing external noise.

Using this diagnostic system, we observed high-frequency turbulence during the type-I ELM cycle in KSTAR. Electron temperature fluctuations appeared as precursors to the ELM crash, predominantly within the $\leq$ 50 kHz range and with a characteristic spatial scale on the order of 0.1. These turbulent eddies generally propagated in the electron diamagnetic drift direction in low-shear regions, while a reversal to the ion diamagnetic drift direction was observed near mode-splitting locations where flow shear significantly increased—consistent with flow shear influencing turbulent mode dynamics.

To further characterize the turbulence, we applied a 2D velocimetry technique to estimate radial velocity fluctuations. Although the cross-coherence between radial velocity and electron temperature fluctuations was relatively low, it remained above the measurement error within the 0–50 kHz range. During pedestal evolution, the cross-phase between these quantities approached $\pi/2$, suggestive of drift-wave or tearing-mode-like behavior. This contrasts with ELM suppression by resonant magnetic perturbations (RMPs), where the cross-phase is near zero highlighting distinct turbulence characteristics in the two scenarios [2, 3].

Turbulence growth rates were estimated using a first-order Volterra system model, where the linear coefficient reflects both the growth rate and dispersion relation. The inferred growth rates exhibited weak linear dependence on a/L_{Te}, indicating a link between turbulence and the electron temperature gradient. A similar trend was observed with β_{ped}, supporting the possibility that micro-tearing modes (MTMs) contribute significantly to pedestal transport and ELM triggering under high β_{ped} conditions [4]. MTM characteristics estimated via Thomson scattering profiles and theoretical wavenumbers yielded a lab-frame frequency of ~30 kHz, consistent with observed broadband ECE spectra.

The direction of propagation (e.g., KBM, ITG), characteristic size (e.g., KPBM, IPM, ETG), and parity analysis (e.g., IBM, KBM, RBM, TEM) of electron temperature fluctuations allowed for exclusion of many candidate modes, reinforcing MTMs as the most plausible turbulence type in the pedestal.

To investigate the role of MTMs in ELM triggering, we computed a quadratic transfer function (QTF) to trace nonlinear energy exchanges between fluctuations. The results confirmed that MTM-scale eddies satisfy three-wave coupling conditions, receiving energy from ambient turbulence and growing steadily. However, these fluctuations did not persist indefinitely; instead, the system transitioned to a magnetohydrodynamic (MHD) mode just prior to the ELM crash. This suggests that MTM-driven turbulence shapes pedestal structure and acts as a precursor to MHD instabilities, ultimately leading to pedestal collapse. Notably, a sharp increase in radial correlation and correlation length of MTM turbulence immediately before the crash implies a strong connection between turbulence and magnetic reconnection at the onset of the ELM.

References

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