Demonstration and Investigation of a Reactor-Relevant, Low-Collisionality, High-Performance, Intrinsic Grassy ELM Regime in DIII-D

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Recent DIII-D tokamak experiments have demonstrated the integration of a low-collisionality grassy edge-localized mode (ELM) regime with a high-performance hybrid core scenario, offering a core-edge compatible solution for ITER and future fusion reactors. This regime features grassy/small ELMs (ELM size Δ_{ELM}<2%) at ITER-relevant pedestal top collisionality (ν_e^*~0.1) and shape, while maintaining high core performance (H_{98y2}~1.6) in non-inductive hybrid scenarios, aligning closely with projected operational conditions for future reactors. Access and sustainment of this regime appear to be favored by high plasma beta (β_N=3.5, β_p=2.0), elevated separatrix density ($n_{e,sep}/n_{e,ped}$>0.4) and low pedestal top collisionality ($\upsilon_{e,ped}^*$=0.1-0.4). In this scenario, multi-scale turbulence generates a turbulent pedestal that limits pedestal growth, rendering the pedestal weakly unstable to, and facilitating strong interactions among peeling-ballooning (PB) modes. Linear and nonlinear edge modeling using ELITE and BOUT++ indicate that this grassy ELM regime is along the peeling boundary, with nonlinear BOUT++ modeling quantitatively reproducing the observed ELM sizes. This scenario also features a broader heat decay width and significantly reduced ELM-induced heat fluxes. These findings demonstrate a promising ELM-mitigated, divertor-favorable, high-performance scenario for future fusion reactors, offering both operational advantages and enhanced physics understanding.

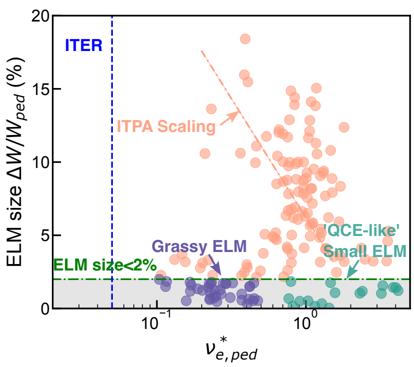

Fig. 1. Recent DIII-D experiments reveal low collisionality grassy ELM in ELM database

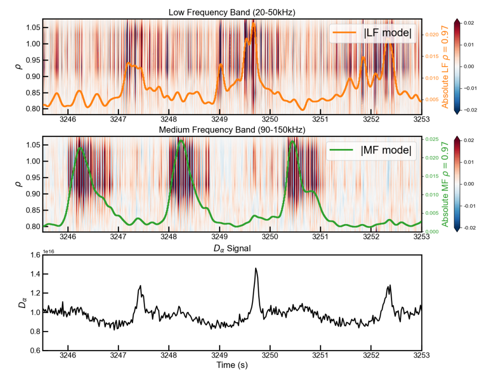

Fig. 2. Inter-ELM medium frequency and Intra-ELM low frequency electromagnetic modes dominate different phases of the ELM cycle

This regime is identified as a branch of low-collisionality small ELM, featuring high ELM frequency (~400Hz) and ELM size (<2%), closely aligned with ITER relevant scenarios. The regime is achieved with weak gas puffing, ITER-similar shape, and exhibits a wider pedestal compared with EPED-KBM scaling[1]. Analysis of the DIII-D ELM database reveals this grassy ELM branch, which shows increasing ELM size at higher collisionality, in contrast with the ITPA type-I ELM scaling (Fig. 1). The database also indicates that both the low-collisionality grassy ELM and the high-density small ELM scenarios share favorable conditions, including: 1) high plasma poloidal beta (β_p >1.5) and 2) weak pedestal density gradient ($n_{e,sep}/n_{e,ped}$ >0.4). These conditions are further supported by experimental diagnostics and numerical simulations.

Strong multi-scale inter-ELM turbulence has been observed by a comprehensive set of diagnostics, revealing its role in limiting pedestal growth and enhancing ELM stability.

Intermediate-k ($k_y\rho_s$~1) turbulence with high frequency (HF, 0.5-2.0 MHz) and electron-directed characteristics was observed; Ion scale ($k_y\rho_s$<0.1) turbulence includes medium frequency (MF, 100-150 kHz) quasi-coherent mode and low frequency (LF, <70kHz) broadband mode, both displaying ion-directed and electro-magnetic signature (Fig. 2). Ensemble analysis across multiple ELM cycles indicates that intermediate-k turbulence peaks around 50% of the ELM cycle, aligning with the saturation of the pedestal electron temperature profile. The MF mode appears in between grassy ELMs, while the LF mode intensifies right before and dominates during grassy ELM bursts (Fig. 2). Bicoherence analysis reveals strong interactions in the low-frequency range. These modes exhibit characteristics consistent with PB turbulence, which suggests that PB turbulence interactions play a role in limiting ELM size. CGYRO linear stability modeling identifies unstable η_e-driven toroidal ETG mode for the intermediate-k turbulence, aligning with the role of electron-driven turbulence driven in sustaining wider pedestals below the KBM limit[2, 3]. This broader pedestal remains weakly unstable to PB modes, leading to the excitation of mild PB turbulence and the subsequent grassy ELM behavior.

Both eigenvalue (ELITE) and initial value (BOUT++) modeling indicate that the grassy ELM regime lies along the peeling boundary in the pedestal stability diagram, aligning with ITER-relevant conditions (Fig. 3a). ELITE and BOUT++ three-field module simulations identify the grassy ELM as most unstable n=10-15 PB mode. Compared to the giant ELM cases, grassy ELMs exhibit a weaker linear growth and broader spectrum (Fig. 3b). BOUT++ nonlinear simulations replicate the observed ELM sizes. The lower linear growth rate and strong nonlinear mode coupling between n=10 and n=15 modes limit grassy ELM sizes to <0.5% (Fig. 3c and 3d), emphasizing the significance of experimental measured PB turbulence interactions in small ELM excitation, which is consistent with ELM phase coherence theory[4]. The Grad-Shafranov stabilization effect on edge MHD modes, combined with inter-ELM turbulence that renders the pedestal weakly unstable to PB modes, and the strong nonlinear interaction between PB modes that trigger ELMs, provides a comprehensive explanation and key physics insights into the origin of grassy ELMs. These are consistent with the database findings that indicate critical roles for high β_p and a low density gradient in the pedestal.

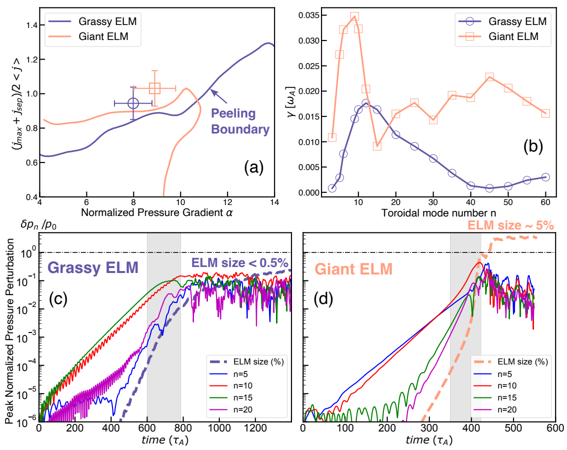

Fig. 3. The low collisionality grassy ELM locates along the peeling boundary; BOUT++ nonlinear simulation reveals the crucial role of mode-coupling in reducing ELM size

The new grassy ELM scenario offers significant advantages for power handling. Compared to giant ELMs, both inter- and intra-ELM heat decay widths are ~50% broader, correlating with turbulence spreading that contributes to the widening of the SOL width[5]. The grassy ELM reduce the transient peak heat load on divertor by a factor of 5. Partial and full divertor detachment are achieved while maintaining high core performance (β_N~3.0, H_{98y2} ~1.2) through the use of N_2 gas puff. However, the grassy ELM condition is lost during detachment as upstream collisionality increases, when both shallow and deep X-point radiators (XPR) can be observed[6]. By leveraging high heating power, divertor compression with minimal impact on the upstream pedestal, and an opaque pedestal structure that primarily influences the separatrix density, it is expected to be a sustainable and promising scenario for ITER, FPP and other future fusion reactors.

[1] P. B. Snyder, 2011, *Nucl. Fusion* **51** 103016; [2] H. Q. Wang, 2024 *Nucl. Fusion* **64** 126061; [3] Z. Li, 2025 2025 *Nucl. Fusion* **65** 016030; [4] P. W. Xi, 2014 *PRL* **112** 085001; [5] Z. Li, 2024 *Commun. Phys* **7**, 96; [6] X. X. Ma, 2025 IAEA-FEC;