Transition from Bursting ELMs to Continuous Turbulence Fluctuations in High SOL Density Regimes

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Executive Summary

BOUT++ simulations of DIII-D hybrid plasmas reveal that the separatrix-to-pedestal density ratio ($n_{e,sep}/n_{e,ped}$) is key to transitioning ELM behavior. High $n_{e,sep}/n_{e,ped}$ ratios promote localized ideal ballooning modes near the separatrix, which stabilize global peeling-ballooning instabilities and suppress type-I ELMs. As the ratio increases further, the regime transitions from small ELM bursts to continuous turbulence fluctuations, offering an effective pathway for managing edge plasma transport and mitigating large ELMs in ITER.

Nonlinear simulations confirm that high SOL density conditions induce localized pressure spikes coinciding with ELM bursting. Parameter scans reveal that precise shaping of the separatrix density profile stabilizes large ELMs while enhancing turbulence-driven transport, effectively maintaining small ELMs and preventing large ELM crashes.

These findings have significant implications for ITER and future fusion reactors, where controlled separatrix density is essential for steady plasma operation to suppress large ELMs. Identified diagnostic metrics, such as post-crash pressure fluctuation peaks (ΔP_{rms}) and normalized turbulence intensity flux (Γ_s), offer predictive tools for real-time control of edge stability, enabling the design of advanced control strategies for sustaining small ELM regimes in reactor-scale plasmas.

Simulation Methodology and Core Results

Two DIII-D high-beta hybrid discharges (#195642 and #195649) are compared, with the latter exhibiting small ELMs due to higher gas fueling and flattened pedestal density profiles (Figure 1 demonstrates the plasma profiles). BOUT++ simulations show:

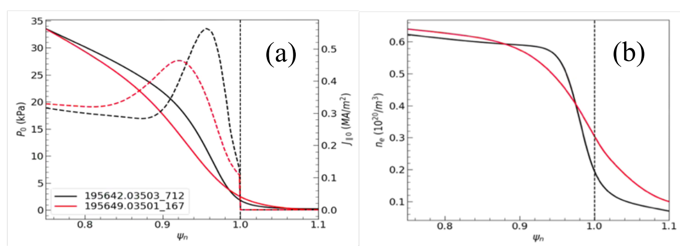

Fig. 1. Plasma profiles for shot #195642 with large ELMs (black) and shot #195649 with small ELMs (red). (a) pressure (solid) and current density (dashed) profiles and (b) electron density profiles.

1. **Linear Stability:** Figure 2 demonstrates the shift in dominant instabilities from global modes for large ELMs to localized modes for small ELMs under high SOL density conditions. Large ELMs are driven by global ideal peeling-ballooning modes (black solid curve) with low separatrix density, while small ELMs arise from localized ideal ballooning modes (red solid curve) near the separatrix due to reduced pedestal density gradients. Drift-Alfvén instabilities (DAI) yield significant contributions to pedestal top fluctuations (red dashed curve).

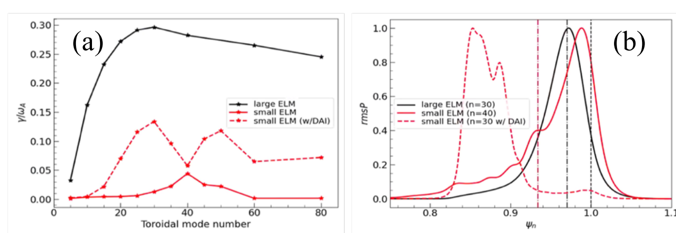

Fig. 2. (a) Linear growth rate from the linear toroidal mode number scan for shot #195642 (black solid) and #195649 (red solid) for ideal MHD, and for ideal MHD with drift-Alfvén instabilities (red dashed); (b) radial mode structure of perturbed pressure for shot #195642 with n=30 (black solid) and for shot #195649 with n=40 (red solid) for ideal MHD; and for ideal MHD with drift-Alfvén instabilities for shot #195649 with n=30 (red dashed). The dot-dashed vertical lines indicate the peak pressure gradient location for shot #195642 (black) and #195649 (red).

2. **Nonlinear Dynamics:** Nonlinear BOUT++ simulations clearly demonstrate that under high SOL density conditions, small ELMs produce distinct post-crash pressure peaks (ΔP_{rms}) driven by localized separatrix ballooning modes.

This work was supported by the US Department of Energy under Contract No. DE-AC52-07NA27344, LLNL-ABS-872068, DE-FC02-04ER54698, DE-AC02-05CH11231 and LLNL-led SciDAC ABOUND Project SCW1832.

This unmistakable signature not only marks the transition from burst-like ELMs to continuous turbulence as the separatrix-to-pedestal density ratio increases, but also serves as a powerful diagnostic for edge stability.

Parameter Scans and Sensitivity Analysis

1. **SOL Density:** Increasing $n_{e,sep}/n_{e,ped}$ reduces steepness in the pedestal density gradient, stabilizing global modes and promoting turbulence-driven transport or small ELMs.
2. **Density Gradient Location:** Shifting the peak density gradient outward toward the separatrix enhances local ballooning instabilities, enabling small ELMs.
3. **Resistivity Effects:** Elevated resistivity by increasing Zeff triggers global resistive MHD instabilities, potentially leading to disruptive ELM bursts even in high SOL density scenarios - distinct from localized ideal separatrix ballooning modes discussed above.

Diagnostic Metrics for Edge Stability

The post-crash pressure fluctuation peak, calculated as $\Delta P_{rms} = P_{rms}^{max} - P_{rms}^{min}$, serves as an essential diagnostic indicator for distinguishing between continuous turbulence fluctuations and ELM bursting. Here P_{rms}^{max} and P_{rms}^{min} represent the maximum and minimum RMS values of pressure fluctuation during the initial ELM crash process. Larger values correspond to ELM bursts, while smaller values indicate turbulence-dominated transport. Normalized turbulence intensity flux Γ_s quantifies fluctuation entrainment from the pedestal to SOL, highlighting the role of radial turbulent transport in shaping edge plasma dynamics.

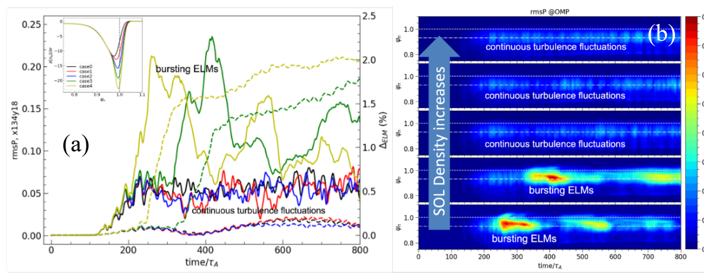

Fig. 3. (a) Time evolution of the RMS pressure fluctuations (solid curves) at OMP and at the peak pressure gradient location along with ELM sizes (dashed curves) across a range of SOL densities. The insert shows the corresponding density gradient profile of the scan. (b) 2D spatial-temporal evolution of RMS pressure fluctuations at the OMP, illustrating the shift from discrete ELM bursts to continuous turbulence.

Implications for ITER and Future Fusion Devices

Research on JET, ASDEX-U, Alcator C-Mod shows that separatrix electron density ($n_{e,sep}$) scales with both plasma current, heating power, and the divertor neutral pressure [1]. On EAST, shifting the strike point likewise regulates $n_{e,sep}$ [2]. Together, these insights offer a clear pathway to optimize $n_{e,sep}/n_{e,ped}$ for stable, small-ELM regimes in ITER and beyond.

For the ITER hybrid scenario, BOUT++ simulations demonstrate that large type-I ELMs persist, with energy loss fractions of around 2% [3]. Although the ITER hybrid scenario does not achieve small/grassy ELMs, insights from BOUT++ simulations of the DIII-D hybrid scenario indicate that optimizing separatrix density and q_{95} could help transition the hybrid scenario toward a more favorable small-ELM regime. This would reduce divertor heat loads and facilitate long-pulse operations. Key takeaways for ITER and future fusion reactors include:

Edge Profile Control: Manipulating $n_{e,sep}/n_{e,ped}$ and separatrix density gradients can suppress large ELMs and facilitate manageable small ELM regimes.

Predictive Modeling: The identified metrics (ΔP_{rms} and Γ_s) provide valuable tools for predicting and optimizing edge stability.

High-Performance Operations: Strategies focusing on separatrix density shaping and pedestal gradient flattening can enhance compatibility with ITER's operational goals, enabling sustained plasma performance.

Reference

[1] D. Silvagni, et. al., *Nuclear Materials and Energy* 42 (2025) 101867. [2] X. Lin, et al., *Phys. Plasma* 32 (2025) 012503. [3] X.Y. Wang et al., *Nucl. Fusion* 62 (2022) 026024.

This work was supported by the US Department of Energy under Contract No. DE-AC52-07NA27344, LLNL-ABS-872068, DE-FC02-04ER54698, DE-AC02-05CH11231 and LLNL-led SciDAC ABOUND Project SCW1832.