# Zonal Magnetic Fields Quench ELM Avalanches via Dynamic Perturbed Force Balance

Nami Li[1], X. Q. Xu[1], Ben Dudson[1], and R. Falgout[1]

[1]*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

[*]Email: li55@llnl.gov

## Abstract:

Edge-localized modes (ELMs) eject intense bursts of heat and particles that threaten plasma-facing components in future fusion reactors and remain a critical challenge for devices such as ITER. While external actuators—including resonant magnetic perturbations (RMPs) and pellet pacing—can mitigate ELMs in present experiments, a passive, self-regulating mechanism would be transformative for reactor-scale operation.

Building on nonlinear BOUT++ simulations that established ELM crash dynamics (Phys. Rev. Lett. 105, 175005, 2010), extended them to a tearing-parity $n = 1$ trigger with two-stage relaxation (Phys. Plasmas 31, 032513, 2024), and identified a plasmoid-mediated reconnection pathway at high Lundquist number $S$ (Nucl. Fusion 63, 126042, 2023), we demonstrate that turbulence-driven zonal magnetic fields (ZMFs) provide a key nonlinear feedback that suppresses avalanche-like propagation. Full-torus simulations show that turbulence-driven zonal flows (ZFs) mitigate the initial crash through shear, but alone allow avalanche-like propagation to persist, sustained by a large inward flow driven by a net perturbed radial force. In contrast, self-generated ZMFs provide a compensating Lorentz-force feedback that suppresses the axisymmetric ($n = 0$) perturbed radial force imbalance between magnetic stresses and pressure gradients ($\mathbf{J} \times \mathbf{B} \approx \nabla P$), converting avalanches into localized turbulence. Although the early crash dynamics depend on the specific linear instability drive, including resistive-ballooning and ideal peeling–ballooning cases, zonal-magnetic-fields–mediated suppression of the perturbed force imbalance emerges as a universal nonlinear regulatory mechanism in the post-crash phase. The predicted signatures—radial electric-field shear and parallel current redistribution—are accessible to existing diagnostics, enabling experimental assessment in present devices and ITER-relevant regimes.

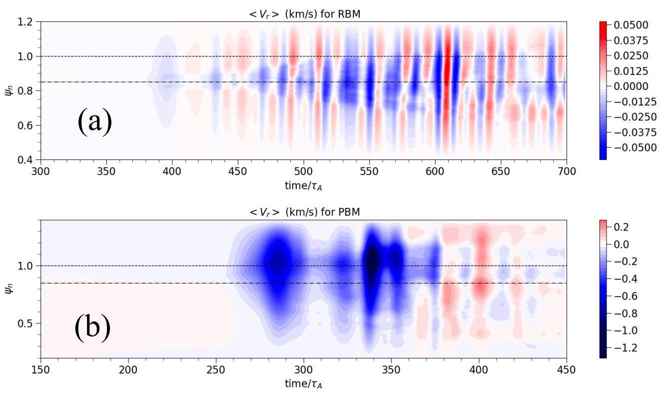


*Fig. Comparison of post-crash dynamics for ELMs. Shown is the time evolution of the flux-surface-averaged radial velocity Vr for (a) a resistive-ballooning-driven small-ELM case and (b) an ideal peeling–ballooning (PB)-driven large-ELM case.*

This research was conducted on behalf of the US DOE at Lawrence Livermore National Laboratory (LLNL) under Contract DE-AC52-07NA27344 and was supported by the SciDAC ABOUND Project, SCW1832.