Global Fluid Turbulence Simulations of Pedestal Relaxation Events in the I-mode regime with GRILLIX

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Exploring operational scenarios that achieve high performance while avoiding large Type-I edge-localized modes (ELMs) and deepening our understanding of the underlying physics are crucial steps toward a future fusion power plant. One such promising scenario is the improved energy confinement mode (I-mode), characterised by enhanced energy confinement, low impurity content and the absence of Type-I ELMs [1, 2]. In some I-mode discharges, pedestal relaxation events (PREs) can be observed, particularly when the operating point is close to the I-H transition. These PREs result in periodic ejections of thermal energy, up to 1% of the plasma stored energy, which is a significantly lower fraction than for typical Type-I ELMs [3]. Unlike Type-I ELMs, which are triggered by Peeling-Ballooning Modes becoming unstable in the pedestal region [4], PREs are expected to arise from a different underlying mechanism.

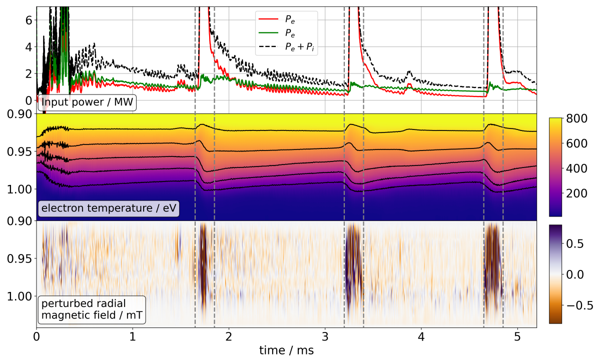

Figure 1: Timetrace of input power, electron temperature and perturbed radial magnetic field, the latter two plotted over ρ_{pol}

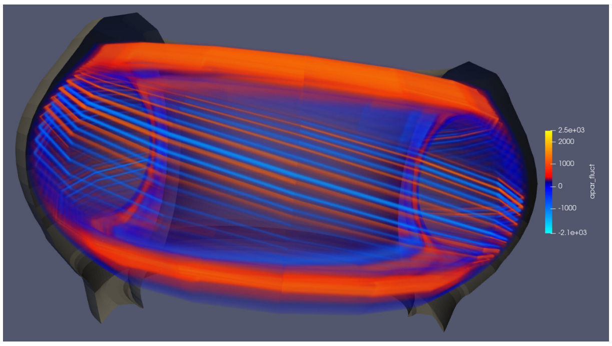

Figure 2: 3D structure of the parallel magnetic vector potential $A_{\parallel}$ during a PRE

PREs have been observed and investigated in both ASDEX Upgrade and Alcator C-Mod [5]. In these experiments, PREs primarily affect the electron pressure profile and exhibit weak magnetic precursors [3, 5]. Given their occurrence in high-performance I-mode plasmas, a detailed investigation into the underlying physics of PREs is of considerable interest. This work presents the first global edge fluid turbulence simulations for PREs with realistic geometry, conducted using the GRILLIX code [6]. Recent enhancements to GRILLIX include the implementation of electromagnetic flutter effects [7] and a Landau-fluid closure for parallel heat fluxes [8], both critical for accurately capturing the I-mode regime, where high plasma-beta and low collisionality are present in the plasma edge. The presented simulations are based on an I-mode discharge in the ASDEX Upgrade tokamak, the simulation domain includes the plasma edge starting at $\rho_{\mathrm{pol}} = 0.9$.

In these simulations, we observe periodic power ejections consistent with the experimental characteristics of PREs. Since the temperature and density are held constant near the core boundary of our simulation domain, the enhanced radial transport caused by PREs is reflected in the adaptive input power (see fig. 1). A detailed analysis of the turbulent state during PREs identifies the underlying microinstability as a micro-tearing mode (MTM). This conclusion is supported by multiple fingerprints: the dominant contribution of the radial thermal energy flux is carried by electrons, a pronounced perturbation appears in the parallel magnetic vector potential and therefore in the perturbed radial magnetic field (see fig. 1), the mode exhibits tearing parity (see fig. 2), and the calculated dispersion relation aligns closely with the analytical predictions for MTMs (see fig. 3). Additional simulations using the previously employed collisional Braginskii closure with heat flux limiters for the parallel conductive heat flux show no evidence of PREs, which emphasizes the crucial role of the newly implemented Landau-fluid closure in accurately describing operational scenarios with low collisionality in the plasma edge.

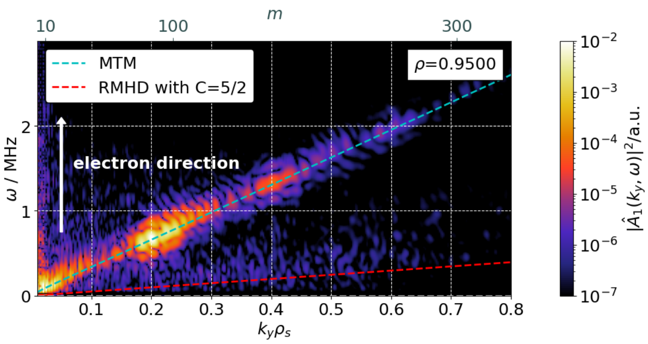

Figure 3: Dispersion relation during a PRE indicating the underlying instability to be MTM

References

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