Structure, Stability and ELM Dynamics of the H-Mode Pedestal in DIII-D*

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This paper describes experiments that have increased our understanding of the transport and stability physics that set the H-mode edge pedestal width and height, determine the onset of Type-I ELMs, and produce the nonlinear dynamics of the ELM perturbation observed in the pedestal and midplane SOL. These are critical issues for future reactors such as ITER because, for stiff profiles, the height of the pedestal determines the overall confinement, and the size of the ELMs determines material surface lifetimes. Results show that predictive theories exist for the density pedestal profile and the pressure height at the onset of Type-I ELMs, and significant progress has been made toward generating predictive models of the temperature pedestal profile (transport barrier) and nonlinear ELM evolution.

The pedestal transport and stability mechanisms were investigated both with new diagnostics in DIII-D and in similarity experiments with matched plasma shape and dimensionless pedestal parameters between DIII-D and JET. The similarity experiments focussed on the transport mechanisms that set the pedestal widths (Fig. 1). Pedestal stability physics studies on DIII-D combined detailed pedestal profile measurements with new, unique pedestal current density measurements (Fig. 2) to predict the onset of ELMs using a linear peeling-ballooning theory with all relevant parameters measured. Pedestal dynamics during ELMs were measured on DIII-D with multiple fast diagnostics near the outer midplane.

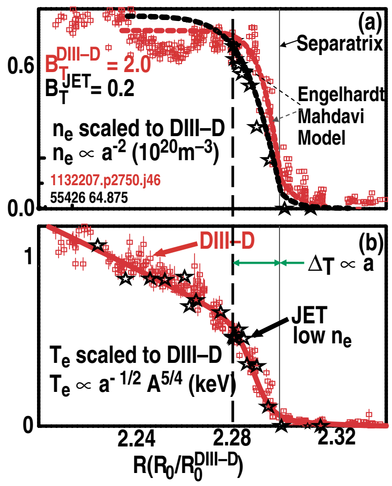

Fig. 1. (a) Pedestal density profiles well predicted by neutral penetration model in both DIII-D and JET; (b) temperature profile width scales with minor radius.

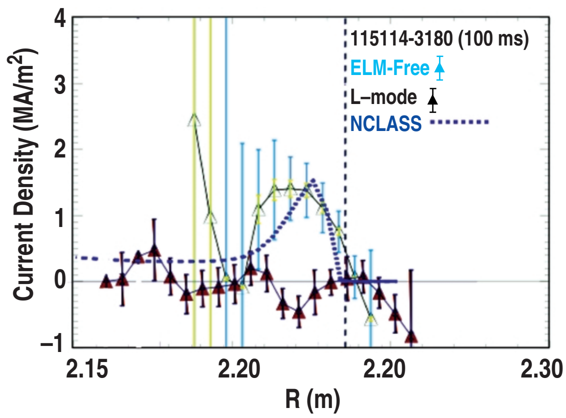

Fig. 2. First measurements of edge current density profile j^{edge}, using Li-beam polarimetry. Profile before the first ELM in H-mode (open triangles) shows large $j^{edge} \sim 1.5$ MA/m^2 compared with L-mode profile (closed triangles) in agreement with NCLASS bootstrap prediction (dashed).

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Data from similarity experiments between DIII-D and JET (Fig 1) suggested that neutral penetration physics dominates in setting the relationship between the width, Δ_n, and height, n_e^{ped}, of the density pedestal. In contrast, plasma physics that scales with dimensionless parameters appears to dominate in setting the temperature pedestal width (transport barrier), Δ_T. The density pedestal profile was simulated by a neutral penetration model [1,2] in DIII-D and JET plasmas with matched dimensionless parameters (β, ρ^*, ν^*, q) at the top of the pedestal. The simulation reproduced the observation that the steep gradient region of the density profile in DIII-D was significantly outboard of the steep gradient region of the temperature profile while the n_e and T_e profiles were nearly aligned in JET for these similarity conditions. Some theories suggest that neutral penetration also sets the temperature pedestal width [3]. However, in the pedestal similarity experiments between DIII-D and JET, Δ_T normalized to the minor radius, a, was constant suggesting that plasma physics, not neutral penetration controls the transport barrier width. Also consistent with this interpretation was that Δ_T/a ~ constant was independent of density (collisionality). Finally, no obvious variation of Δ_T/a with $\rho*$ was seen at fixed (β, ν^*, q) in a scan of B_T between DIII-D and JET.

Measured ELM onset conditions compared favorably with ELITE intermediate-n peeling-ballooning stability constraints calculated using the measured pedestal plasma profiles and the measured j^{edge} in self-consistent equilibria. First direct measurements of the pressure driven current density peak in the pedestal (Fig. 2), made with a new Li-beam polarimetry diagnostic [4], were consistent with calculations of edge bootstrap current using the measured pedestal plasma profiles in the NCLASS bootstrap model [5]. Free boundary equilibria that included the measured j^{edge} were generated by the CORSICA [6] equilibrium solver for the ELITE [7,8] stability calculations. This confirms the effect of j^{edge} on the peeling-ballooning stability constraints that limit the height of the pressure pedestal as calculated by ELITE.

Midplane ELM dynamics measurements show the expected peeling-ballooning structure at ELM onset, large, rapid variations of the SOL parameters suggesting a filamentary structure of the perturbation and fast radial propagation in later phases. This is in agreement with poloidal narrowing of the density perturbation into filaments seen in non-linear ELM simulations with the BOUT code [9]. Thomson data show a reduction of n_e^{ped} at all densities during an ELM and of T_e^{ped} at low n_e^{ped} but no change to T_e^{ped} during ELMs at high density. Scanning reflectometer data show that the particles lost from the pedestal during an ELM appear far out in the SOL at the midplane. This result is independent of the pre-ELM density. In the far outer SOL where n_e^{SOL} increases substantially, no increase in T_e^{SOL} is observed. Scanning probe data near the separatrix show large, rapid variations of both n_e^{SOL} and T_e^{SOL} during ELMs suggesting a filamentary structure of the perturbation. Radial velocity of the density perturbation, inferred from both the probe and reflectometer data, is ~1000 m/s near the separatrix. The velocity decreases with radius in the SOL. The calculated strong localization to the outer midplane is consistent with the data. Finally, in the similarity experiments the measured narrowing of the ELM mode width was consistent with reduced ELM energy loss as ρ^* decreased, but changes in neutral penetration were also playing a role.

The quantitative understanding gained here has increased our ability to predict two critical aspects of future high-power tokamak operation, namely the width of the density pedestal and the energy loss during Type-I ELMs. Progress has also been made toward understanding the complex coupling of transport and stability mechanisms that set the temperature pedestal height and width. These results suggest that it may be possible to control Δ_n, by controlling neutral sources. The lack of ρ^* dependence of Δ_T/a implies favorable confinement in future devices with small ρ^*. Finally, scaling of ELM size with ρ^* suggests that tolerable sized ELMs may be possible in future devices.

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