Acceptable ELM Regimes for Burning Plasmas*

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Small edge-localized-modes (ELMs) are found in the H–mode plasmas of DIII–D for high density and/or high collisionality conditions in the edge pedestal. This is an attractive regime for future burning tokamak plasmas where ELM size must be maintained below a critical threshold in order to avoid ablation of the divertor target. In addition, this small ELM regime maintains a robust edge pedestal pressure that will also be required for achieving adequate central energy confinement in future burning plasmas. This paper reports on the scaling of reduced ELM energy with increasing pedestal density, and/or collisionality, with variations in safety factor *q* and plasma triangularity. The ELM energy is examined in terms of convected energy, as evidenced by loss of density from the pedestal, and conducted energy, indicated by a loss of pedestal temperature.

The ELM energy and perturbations to the pedestal profile are measured by the DIII–D Thomson scattering diagnostic. For steady, continuously ELMing discharges, the Thomson profiles are ordered in time with respect to the nearest ELM to determine the time behavior of the edge profiles due to an average ELM. The relative perturbation to the edge electron density and temperature profiles due to a typical ELM are shown in Fig. 1. Significant perturbations to the profiles are seen into ρ ~0.8, which is much deeper than the steep gradient region of the pedestal that drives the ELM.

The total ELM energy, derived by integrating the measured perturbed profiles, decreases with increasing density as shown in Fig. 2. The ELM energy is normalized by the pedestal energy in order to account for variations in pedestal height. The ELM energy is considered to be lost by two processes, a temperature perturbation that represents conductive losses, Fig. 2(a), and a density perturbation for convective losses, Fig. 2(b). This analysis assumes an ELM ion loss equal to the lost electron density, but no significant loss in ion temperature due to lower ion conductivity. The sum of the two loss channels is consistent with the ELM energy measured by fast magnetic equilibrium reconstruction.

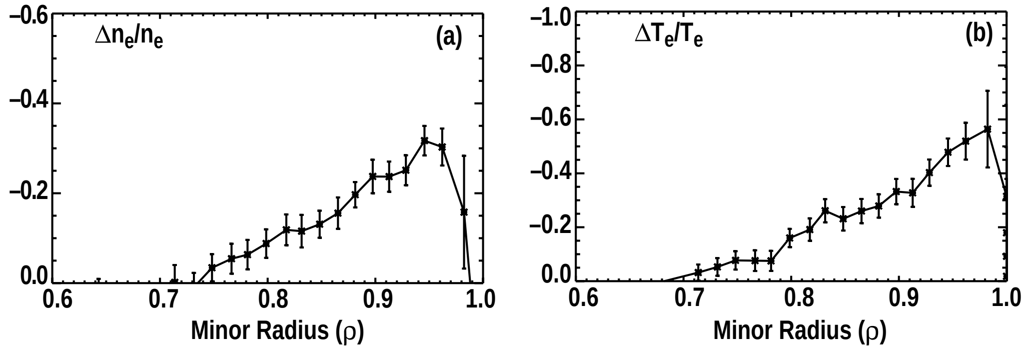

Fig. 1. The relative perturbation to the (a) electron density profile and (b) the electron temperature profile as measured by Thomson scattering. The data are ordered and fit in time with respect to the nearest ELM during steady conditions to determine the average perturbation due to an individual ELM.

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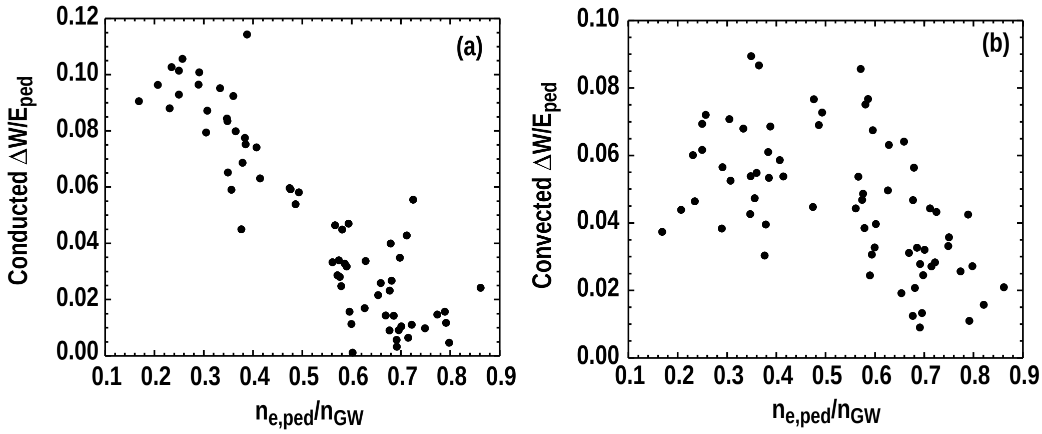

Fig. 2. The fraction of pedestal energy that is lost at an average individual ELM through (a) conduction and (b) convection. Due to the ELM energy normalization the ELMs above a pedestal density of 60% of n_{GW} are very small because of significant degradation of the pedestal pressure.

The conducted ELM energy, Fig. 2(a), decreases with increasing density until the pedestal density reaches ~65% of the Greenwald density limit. Above this density the ELMs become small and irregular with a temperature perturbation smaller than the measurement uncertainty. For the convected ELM energy, Fig. 2(b), there is much more scatter in the data, but there is no clear trend below a pedestal density of ~65% of n_{GW}. Above this density the density perturbations and convected energy also become smaller.

The ELM conducted and convected energy, as a function of pedestal n_{GW} remains constant as the safety factor, q, is varied from 2.5–3.9 through scans in toroidal field, B_T=1.5–2.1 T and plasma current, I_p=1.2–2.0 MA. The normalized ELM energy also remains constant to variations in plasma triangularity, δ=0.0–0.4. The small ELM amplitude measured at 70% of n_{GW} is estimated to be within the tolerable limit for the ITER-FEAT divertor and the predicted pedestal parameters. Reducing the conducted energy is important because the conductive energy, traveling at the electron thermal speed, will be deposited in a shorter time than the convected energy, thereby resulting in a lower ablation threshold.

The difference in scaling of the conducted and convected ELM energies may be accounted for by the different parallel transport times for the two processes in the scrape off layer (SOL). Heat transported into the SOL by the ELM instability is conducted very quickly, ≤ 20 μs, to the divertor target by parallel electron conduction. This is much shorter than the ELM duration of ~200 μs. Parallel convection, traveling at the slower ion sound speed, requires a time equal to or longer than the ELM duration. Parallel transport in the SOL then becomes the limiting process for the convected energy. The pedestal density lost during an ELM can be accounted for by distributing the particles throughout the SOL to a width of 2 cm at the midplane and at a density equal to the post-ELM pedestal density. This width is similar to the ELM heat flux profile measured at the divertor target by an IR camera.

A significant concern is whether a high collisionality pedestal is necessary to achieve small ELMs in a future burning plasma. A burning plasma requires a high pedestal temperature, and thus low collisionality, in order to achieve adequate central confinement. Small ELMs, though, may need high collisionality to reduce the edge bootstrap current that is thought to play a large role in the ELM instability. In DIII–D, the ELMs become small at the same normalized density, rather than similar collisionality, for variations in plasma shape and plasma current. This offers hope that small ELMs may be possible in a low collisionality pedestal at high normalized density in a burning plasma. Initial modeling of the ELM indicates a correlation of the radial profile of the computed instability to the profile of the measured pedestal perturbation.