SOL and pedestal density profile evolution during DIII-D ELMy and ELM-suppressed H-mode operation

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Abstract

A fast profile reflectometer has been used to study the detailed characteristics of scrape-off-layer (SOL) and pedestal density profile evolution in DIII-D ELMy H-mode plasmas with high temporal ($\sim 100$ $\mu$s) and spatial ($\sim 4$ mm) resolution. Results show a significant enhancement in radial particle transport to the outer vessel wall during Type-I ELMs. The radial particle transport time ($\sim 140$ $\mu$s) becomes comparable to the parallel transport time, as a result of a high radial velocity ($\sim 620$ m/s) of SOL profile expansion. The dynamics can vary from ELM-to-ELM. Scalings with pedestal density have been obtained, indicating that ELM is less affected as the pedestal density increases. Finally, during ELM-suppressed H-mode operation with a stochastic magnetic boundary, the radial extent of observed SOL profile modifications do not extend to the vessel wall, and profiles are steeper, substantially different from the SOL changes associated with Type-I ELMs.

1. Introduction

In high confinement H-mode plasmas, edge localized mode (ELM) instabilities produce transient perturbations of the edge pedestal and scrape-off-layer (SOL), modulating the heat and particle transport into the SOL and divertor [1–6]. In a leading theoretical model for ELMs, the Type-I ELM is driven both by the pedestal pressure gradient and current profile (peeling-ballooning model [3]). However, questions remain concerning the magnitude of the ELM-induced energy and particle pulses leading to the vessel wall, the propagation of the pulses from the SOL to the vessel wall, the fraction of ELM particle or energy deposited to the vessel wall, how the deposition scales with plasma parameters, etc. [4]. Consequently, detailed investigation of plasma characteristics in the SOL and pedestal regions remains important for ELM physics understanding.

A fast profile reflectometer with high temporal ($\sim 10$ $\mu$s) and spatial ($\sim 4$ mm) resolution [7,8], has been
successfully used to measure the SOL and pedestal density profile modifications associated with ELMs in DIII-D [8–10]. The reflectometer system was recently upgraded to expand the measured density range to 0–6.4 × 10^{19} \text{ m}^{-3}, with high time resolution, such that the system now has the capability to resolve the whole pedestal profile evolution associated with ELMs. Through the investigation of the time resolved electron density profile modifications, a number of the outstanding ELM physics issues mentioned above have been directly addressed. In addition, reflectometer data have also been used to investigate detailed SOL density profile characteristics during ELM-suppressed operation with a stochastic magnetic boundary, an ELM suppression technique recently developed on DIII-D [11].

2. Fast profile reflectometer system

On DIII-D, both Thomson scattering and profile reflectometer systems provide electron density profile measurements. Normally, Thomson scattering measures a density profile every 12 ms, which is insufficient for ELM evolution studies. The profile reflectometer on DIII-D uses solid-state microwave sources such that the system can be continuously frequency swept full-band in as little as 10 \mu s, every sweep providing a profile measurement. In a new dual-polarization configuration, probe beams are launched at a 45° polarization into the plasma, so as to couple to both O- and X-mode waves. Use of simultaneous O- and X-mode measurements expands the measured density range, which is now 0–6.4 × 10^{19} \text{ m}^{-3}, with no unmeasured density gaps [7].

3. SOL and pedestal density profile evolution associated with ELMs

A detailed example of the density profile evolution through a single Type-I ELM is shown in Fig. 1. The ELM timing is shown by a divertor Dα signal, Fig. 1(a), where the numbers and vertical lines represent the times for the density profile sequence shown in Fig. 1(b). The plasma parameters for this typical ELM discharge were 1.0 MA, B_T = 1.7 T and T_e0 = 2.1 keV, in a lower single null plasma configuration. The pedestal density was 3.2 × 10^{19} \text{ m}^{-3}, corresponding to a normalized pedestal density of ~0.3 times the Greenwald density. \(n_{GW}(10^{20} \text{ m}^{-3}) = \frac{I_p(\text{MA})}{[\pi a^2(\text{m})]}\). Under these conditions the reflectometer system can track the complete profile evolution to the top of the pedestal density. In Fig. 1(b), profile 1 is taken just before the ELM onset, and shows a typical steep edge pedestal which defines the H-mode edge barrier region. At the onset of the ELM, profile 2 shows an increase in SOL density, with the density at the top of the pedestal slightly reduced.

At the time of the ELM crash (1st peak of the Dα profile 3), about 100 \mu s later, the SOL profile has expanded radially outward to the vessel wall, where there is a relatively large density rise of ~2×10^{18} \text{ m}^{-3}. During the recovery phase, profile 4 shows the pedestal gradually rebuilding, and SOL density reducing. The final profile in the sequence, 5, shows a return to a well defined edge pedestal several ms after the ELM onset. Thomson scattering data obtained at the same time as reflectometer profile 5 are shown via points with error bars, showing good agreement between the two measurements. The illustrated evolution of the pedestal and SOL density profiles demonstrates that the density rise observed in the SOL is directly linked to the pedestal loss during the ELM.

The observed ELM dynamics are shown in more detail in Fig. 2, which shows the density profile evolution through a sequence of three Type-I ELMs. The profile evolution is depicted via contours of constant density as shown in Fig. 2(b), where the density of each numbered contour is marked on a scale, and the density range is 0–4.5 × 10^{19} \text{ m}^{-3}. The horizontal solid line represents the midplane separatrix radius, and the ELM timing is again shown by a Dα signal from the divertor, Fig. 2(a). During the ELMs, the SOL profile expands rapidly outwards, as indicated by the movement of contours 1 and 2 in Fig. 1(b). The lowest density contour, shows that the SOL density profile expands out to the outer wall radius (tile radius \(R = 2.377 \text{ m}\)). By contrast, the density profile inside the separatrix is flattened and the pedestal transiently eliminated, as indicated by the inward movement of contours 4, 5 and 6 and increased separation from contour 3. The minimal modification of...
Fig. 2. Time evolution of the SOL and pedestal profile through a sequence of three ELMs, showing: (a) $D_\alpha$ signal, (b) contours of fixed density as a function of radius and time, with 25 $\mu$s time resolution, where the labels indicate the different density layers and the horizontal solid line shows the separatrix position.

contour 7 indicates that the ELM profile modification is edge localized, consistent with previous results from Thomson scattering [12], while contour 3 shows the existence of a density pivot point.

An interesting feature of the data shown in Fig. 2 is the varying dynamics from ELM-to-ELM. Specifically, ELM precursors in the form of changes in the SOL density profile are observed just before ELMs 2 and 3, but not for ELM 1. This precursor in the density profile behavior is localized to the SOL and occurs up to $\sim$1 ms before ELM onset; no precursor is observed inside the separatrix. An expanded view of this varying precursor activity is shown in Fig. 3(a) and (b) (with precursor) and (c) and (d) (no precursor). In Fig. 3(a) density fluctuations, which are measured by a 15 GHz O-mode reflectometer at a $2 \times 10^{18}$ m$^{-3}$ density layer, indicate a growing coherent oscillation (also seen on magnetic probes) for $\sim$2–3 ms before the ELM onset. For this ELM, the SOL density layer at $n_e = 2 \times 10^{18}$ m$^{-3}$, Fig. 3(b), clearly starts to move radially outwards $\sim$1 ms before ELM onset, while the $n_e = 2.5 \times 10^{19}$ m$^{-3}$ density layer, located inside the separatrix shows no significant change until ELM onset. Comparable data for an ELM without this profile precursor activity are shown in (c) and (d).

The varying precursor behavior illustrates that ELM dynamics can vary, and is consistent with results reported from JET [13].

The ELM radial propagations with significant velocities have been found in several tokamaks [2,4]. The radial velocity $V_r$ of density layer movement during ELMs can be derived directly from the time resolved profile data; it was previously shown that the radial velocity derived in this manner is in good agreement with Langmuir probe measurements, and consistent with BES measurements [4,14]. At the time of the ELM crash, as indicated by the $D_\alpha$ signal in Fig. 4(a), the radial velocity close to the tile radius is observed to be $\sim$620 m/s, as shown by the dashed line in Fig. 4(b). With this velocity, the radial transport time is $\sim$140 $\mu$s, comparable to the parallel transport time, normally $\sim$100 $\mu$s in DIII-D [4].

The radial particle flux, $\Gamma = nV_r$, can also be obtained from the time resolved profile data. As shown in Fig. 4(b), the particle flux (solid line) close to the tile radius is $\sim 1.5 \times 10^{21}$ m$^{-2}$ s$^{-1}$ during an ELM crash (at $n_{ped}/n_{GW} = 0.3$ in this case). Since the radial flux at the last closed flux surface is $\sim 6.0 \times 10^{19}$ m$^{-2}$ s$^{-1}$ measured by Langmuir probes [14], a significant particle flux fraction $\sim$25% to the wall illustrates the enhanced particle radial transport due to ELMs. The density scaling of the particle flux as a function of pedestal density was investigated by obtaining a series of discharges with the same $B_T$, $I_p$, $q$ and separatrix position, but varying density. The radial particle flux at the time of the ELM crash is plotted as a function of $n_{ped}/n_{GW}$ in Fig. 4(c), the data being averaged over 10 ELMs for each discharge. As can be seen, the particle flux substantially reduces with increasing density. In previous work [9], the normalized density at the vessel wall, and normalized density fluctu-
ation level in the pedestal were also shown to similarly decrease with increasing pedestal density.

4. Edge density profile with a stochastic magnetic boundary

DIII-D has recently demonstrated an ELM suppression technique utilizing a stochastic magnetic boundary produced by an MHD control coil inside the vessel [11]. While the ELMs are suppressed, the H-mode edge can display rapid, small $D_a$ oscillations with a bursty character, modulated by a coherent 200 Hz envelope. Edge density profiles before and after ELM suppression are presented in Fig. 5. Profiles 1 and 2 in Fig. 5(b) are from before and during an ELM, respectively, in the ELMy phase of the discharge, before the stochastic magnetic boundary is formed and ELMs were suppressed. The SOL density profile expands to the tile position during the ELM, consistent with other Type-I ELMs, as discussed above. After the application of the stochastic magnetic boundary and with ELMs suppressed, however, the profiles are distinctly different. Profiles 3 and 4 in Fig. 5(b) show data from different phases of the $D_a$ oscillations observed during ELM suppression. Profile 4, at the maximum of the oscillation amplitude, is broader than profile 3 at the minimum of the oscillation. However, the profile during ELM suppression never expands to the outer midplane tile radius. Also, profiles 3 and 4 show steeper density gradients than profiles 1 and 2, respectively, indicating a change in SOL radial transport due to the stochastic magnetic boundary.

5. Discussion and conclusions

A novel, high-performance fast profile reflectometer system has been used to investigate the detailed evolution of SOL and pedestal density profiles during Type-I ELMs on DIII-D. There is a significant and rapid enhancement in radial particle transport and particle flux to the outer vessel wall during Type-I ELMs, e.g. the particle flux at the outboard midplane tile radius rises $\sim 1.5 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$, which is about 25% at LCFS. Also during the ELMs, the radial transport time $\sim 140 \mu s$, is comparable to the parallel transport, as a result of a high radial velocity (up to 620 m/s), with which the SOL profile expands. With some, but not all ELMs, an ELM precursor in the form of a radial expansion in the SOL density profile was observed on a $\sim 1 \text{ ms}$ time scale before ELM onset. That such precursors are not always observed is indicative of varying ELM dynamics.

Scalings with pedestal density have been obtained, indicating that ELM effects decrease as the pedestal density increases. Specifically, the normalized density at the vessel wall, particle flux to the wall and normalized density fluctuation level in the pedestal all decrease with increasing pedestal density. Edge stability analysis of ELMs in other, similar, DIII-D discharges using the...
ELITE code [15,16], shows that the radial extent of the unstable mode decreases as density increases, indicating ELM strength is diminished at higher density. The results are consistent with the experimental scaling results presented in this paper.

During ELM-suppressed H-mode edge pedestal operation using a stochastic magnetic boundary, the measured density profiles indicate that the radial extent of SOL profile modifications are reduced and do not expand to the midplane tile radius, substantially different from the profile modification observed with large Type-I ELMs. In addition, the SOL profiles are steeper than in the ELMy phase, indicating that the stochastic magnetic boundary affects the particle transport. Such ELM-suppressed operation may offer a promising operating mode for future tokamak reactors.

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