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ABSTRACT

Two clear signatures of the L-H transition in the DIII–D tokamak are that the edge poloidal rotation velocity v_θ abruptly increases, implying that the radial electric field E_r becomes more negative, and the level of density fluctuations is abruptly suppressed in a narrow region at the plasma edge. The absolute values of E_r and v_θ have maxima within 1–2 poloidal gyroradii $\rho_{i\theta}$ of the plasma edge, indicating that large negative and positive gradients of E_r and v_θ exist near the plasma edge in a region called the "shear" layer. Density fluctuations are reduced and the gradients of $\mathrm{T_i}$, $\mathrm{T_e}$, $\mathrm{n_e}$ and the carbon density increase in the shear layer at the time of transition. These data qualitatively support theoretical scenarios in which changes in E_r or of the gradients of E_r or v_θ cause a suppression of microturbulence, resulting in increases in the $\mathrm{T_i}$ and density gradients.

INTRODUCTION

Theoretical predictions that E_r should change from the L– to the H–mode [1,2] were followed by the observation in the DIII–D tokamak that E_r within 1–3 cm of the plasma edge was negative in the L–mode and became more negative in the H–mode [3-6]. The poloidal flow velocity of He ions was also observed to increase at the transition. A large body of observations based on emission spectroscopy of He II [3,5,7] show that these changes occur independently of the heating method used to produce the H–mode: ECH-heating only, Ohmic-heating only, co-injected NBI heating and counter-injected NBI heating. These changes also occur when the H–mode is produced in a plasma limited by a material limiter or when the toroidal field is reversed from its normal direction [4-6]. In all cases, the changes in E_r and v_θ start to occur either simultaneously with or a few milliseconds before the drop in the D_α signal at the transition. Based on these experimental results, Biglari, Diamond and Terry noted that an increase in $|dv_\theta/dr|$ could suppess microturbulence [8], and Shaing and Crume extended their theory and emphasized that a more positive value of dE_r/dr could reduce the amplitude of microturbulence [9], leading to improved confinement in the H–mode. Experimental data from DIII–D show that each of these requirements for suppression of fluctuations is fulfilled in the H–mode plasma [5]; furthermore, application of a criterion developed in Ref. 8 shows that $|dv_\theta/dr|$ is large enough to suppress modes with wavenumbers greater than 0.1 cm^{-1}, a range which covers the modes which are thought likely to be present at the plasma edge [5]. Additional evidence for the role of E_r is that the transport barrier, originally discovered on ASDEX [10], is correlated with shear in E_r and v_θ, as shown in recent data from JFT-2M [11]. Very strong evidence for the role of E_r comes from work in the CCT tokamak in which the H–mode was produced in Ohmically-heated discharges by biasing the plasma with an internal electrode [12].

Several scattering experiments have shown a general decrease in microturbulence during the H–mode [13-16]. FIR scattering data on DIII–D also shows a narrowing of the k spectrum in the H–mode [15]. Reflectometer measurements, which have much better spatial localization than scattering measurements [17], have also shown a drop in microturbulence in the H–mode [18-21]. The reflectometry system on DIII–D has shown for the first time that coincident with the D_α drop, there is a reduction of turbulence in a narrow zone which extends inwards from the separatrix for several centimeters [19-21]. Although it has been shown that the reduction of fluctuations in this "suppression" zone is correlated with the changes in E_r [6], it has not been demonstrated that confinement improves throughout the suppression zone or that the suppression and shear layers are identical. This paper presents data from recent well-diagnosed DIII–D discharges for which profiles of v_θ, E_r, $\mathrm{T_i}$ and the density of carbon were obtained with 1 ms time resolution and reflectometer data were obtained with 50-100 microsecond resolution. The results show that, within error bars, the shear layer and suppression zone overlap and are established simultaneously; furthermore, the confinement in this layer, as indicated by the gradients of $\mathrm{T_i}$, $\mathrm{T_e}$, $\mathrm{n_e}$ and carbon density, improves markedly at the onset of the H–mode. These results have been established for a small number of well-diagnosed discharges for which profiles of E_r are available by the use of active CER spectroscopy. They are also consistent with the large body of data obtained from passive spectroscopy of He II [3-7].

RESULTS

Simultaneous measurements of $\mathrm{T_i}$, v_θ and v_ϕ have been made with the techniques of passive emission spectrosopy [7], for which a single point measurement was possible, and with active CER spectroscopy, for which profiles are available [22]. In either case, E_r is calculated from the force balance equation for a single ion species [3-7]. The contribution of the pressure gradient term is estimated to be 20%–30% of the $\vec{V} \times \vec{B}$term for the single point measurement and is measured to be 10%–20% when profiles are available. Due to atomic physics effects near the plasma periphery, it is possible that the pressure gradients and therefore the poloidal rotation velocities of different species are not the same. However, the value of E_r determined from the sum of the $\vec{V} \times \vec{B}$ and pressure gradient terms applies to all of the plasma species. The instrumentation used to measure profiles [22] has overlapping views from horizontally-viewing and vertically-viewing systems, with each system having eight chords separated in minor radius by 1.5 cm. The nominal spatial resolution is 0.5 cm. Data have been taken by measuring the C VII flow velocity, as inferred from the Doppler shift of the C VI 5290 Å line produced by charge transfer between a neutral beam and C VII ions.

Density fluctuations are studied with an O–mode reflectometer system, consisting of seven discrete homodyne channels spanning 15–75 GHz, with corresponding critical densities of 2.8×10^{18} to 7×10^{19} m^{-3}. An X–mode system, using a frequency tunable BWO source is used to obtain fluctuation data from critical densities intermediate to those available from the O–mode system [21], thus increasing the spatial resolution.

The time histories of several edge parameters during an L-H transition are illustrated in Fig. 1 for a discharge with $I_p = 1.6$ MA, $B_T = 2.1$ T, $P_b = 8$ MW, and for which D° beams were injected into a D^+ plasma. Figure 1 shows that for a chord about 1 cm inside the separatrix, large changes in v_θ and E_r occurred in a time much less than 1 ms coincident with the transition. These results are consistent with the results obtained from the emission spectroscopy measurements, which showed that the changes in E_r and v_θ were coincident with the transition, with the exception of some observations showing presursors a few ms prior to the transition [5]. Although the issue of causality has not been settled, a possible explanation for the precursors is that they were caused by motions of the He II emission shell further into the shear region in the L–mode. The location of the He II shell is determined by atomic physics and could change as the edge n_e and T_e profiles evolve in the L–mode. Similar effects could explain the changes in E_r and v_θ after the transition, which occurred on the timescale for edge profile changes [5,7]. As shown in Fig. 1(e), the fluctuation level, monitored by a reflectometer channel 1–2 cm inside the separatrix, decreases coincidentally with the drop in the D_α signal. The

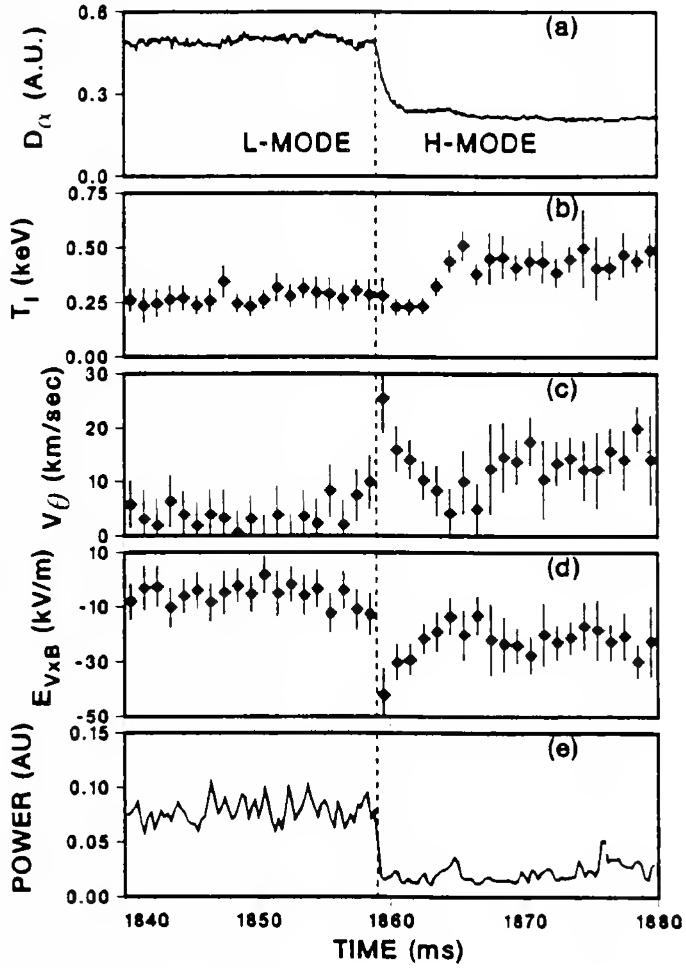

Fig. 1. D_α (a) shows that L-H transition occurred at 1859 ms, as indicated by dashed line. (b), (c), and (d) show T_i, v_θ and E_r from $\vec{V} \times \vec{B}$ term obtained with 1 ms time resolution for location approximately 1 cm inside separatrix. (e) shows integrated power in range of 0–400 kHz from reflectometer channel viewing the same location. E_r and v_θ increase and fluctuation level decreases immediately at time of transition. Increase in T_i is delayed for a few ms.

decrease in fluctuation levels near the separatrix is a consistent feature of all L-H studies in DIII–D.

Figure 2 compares profiles of several quantities obtained in the time intervals 1–2 ms prior to the transition, 1–2 ms after the transition and 10–11 ms after the transition. The changes in poloidal rotation [Fig. 2(a)] and E_r [Fig. 2(b)] occur abruptly at the time of transition and persist during the H–mode. The changes are seen most clearly on the chord at

2.27 m and may extend to one chord (1.5 cm) on either side of 2.27 m. The region of shear in E_r extends over 3–5 cm. The peaks in the profiles of E_r and v_θ occur about 0.8 cm inside the nominal separatrix and the poloidal ion gyroradius $\rho_{i\theta}$ is about 0.7 cm at the time of the transition. The uncertainty of the separatrix location, determined from magnetics, is about 1 cm. These results are supported by the data from emission spectroscopy which showed that large values of E_r and v_θ existed 1-3 cm inside the separatrix and that the E_r and v_θ profiles were sheared just inside the separatrix [5,7].

The gradients of T_i [Fig. 2(c)] and the carbon density [Fig. 2(d)], measured from the amplitude of the C VI signals, increase abruptly in the shear region at the onset of the H–mode, demonstrating very high correlation between the formation of the transport barrier and the increase in shear. As the H–mode progresses, the T_i and carbon density gradients remain approximately constant in the shear layer, but the boundary values of T_i and the carbon density increase, so that pedestals are produced on the T_i and density profiles. The T_i and carbon density gradients for locations more than 3-4 cm from the edge show little, if any, change from the L–mode to the H–mode, indicating that the transport barrier forms only in the shear layer. Data obtained from a Thomson scattering system with closely spaced channels near the separatrix show that T_e and n_e also steepen in the region of shear coincident with the transition.

As shown in Fig. 3, the suppression zone at the time of transition as determined from the reflectometery channels is approximately 4 cm wide with an uncertainty of ±1 cm. The width and location of this zone is identical to that of the shear layer within the error bars. Data obtained for a 0.8 MA discharge, for which $\rho_{i\theta}$ is twice that of the 1.6 MA discharge, show that the suppression and shear layers have about the same width as for the 1.6 MA discharge, although the error bars on the shear width are slightly larger. For both the 0.8 and 1.6 MA discharge, the suppression zone coincides with the steep n_e gradient, as is expected if a reduction of fluctuations improves the local confinement.

CONCLUSIONS

A large body of data have been obtained in the previous two years from the DIII–D tokamak regarding the role of the edge E_r and v_θ in the L-H transition. This work has demonstrated the existence of a shear layer in v_θ and E_r at the plasma edge and that v_θ abruptly increases and E_r becomes more negative at the L-H transition. Profile data show

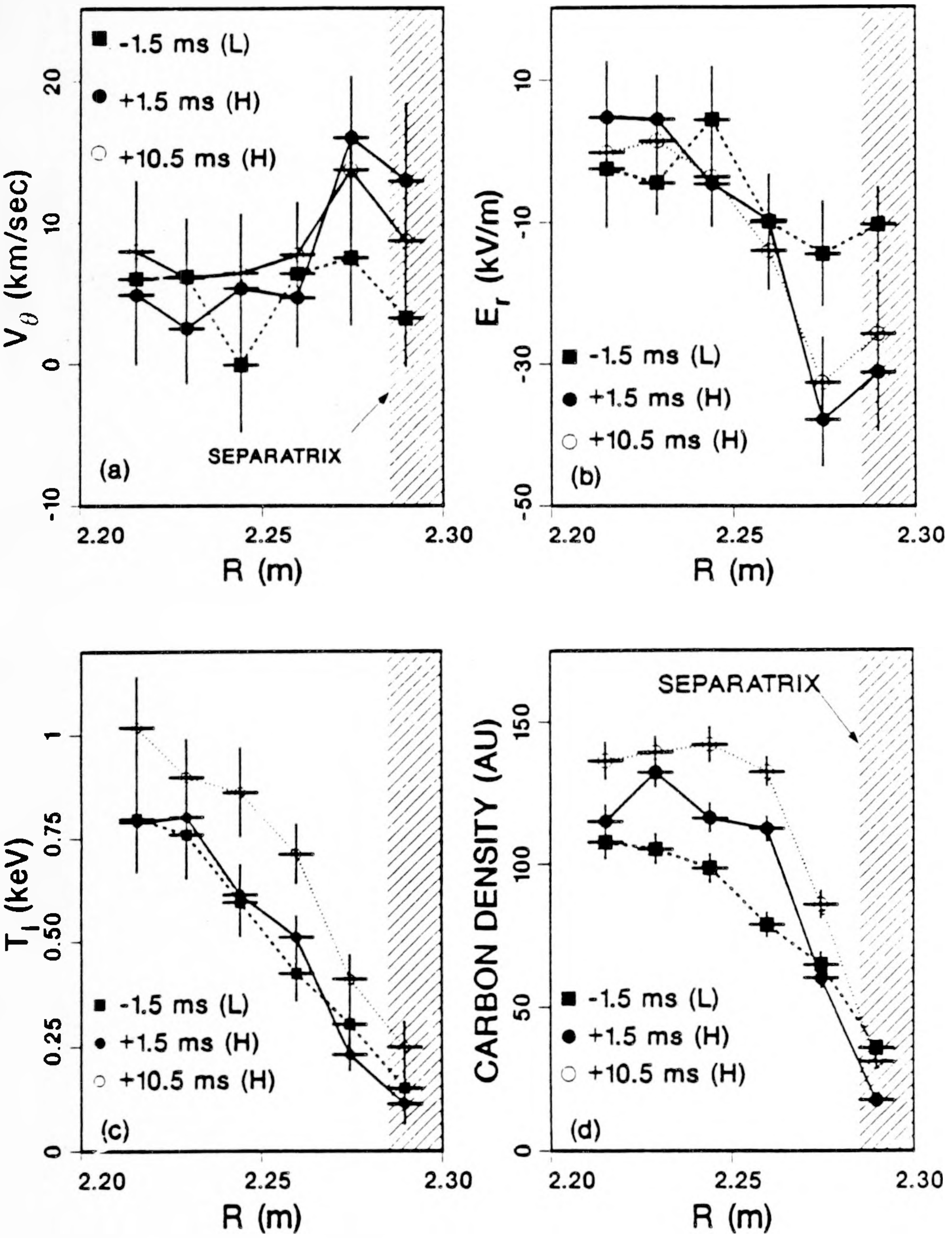

Fig. 2. Profiles of v_θ, total E_r, T_i and C VII density vs major radius 1–2 ms before, 1–2 ms after and 10–11 ms after L-H transition displayed in (a), (b), (c), and (d) respectively. T_i and density gradients increase in region of sheared E_r and v_θ immediately after transition and continue to increase during ELM-free phase of H–mode.

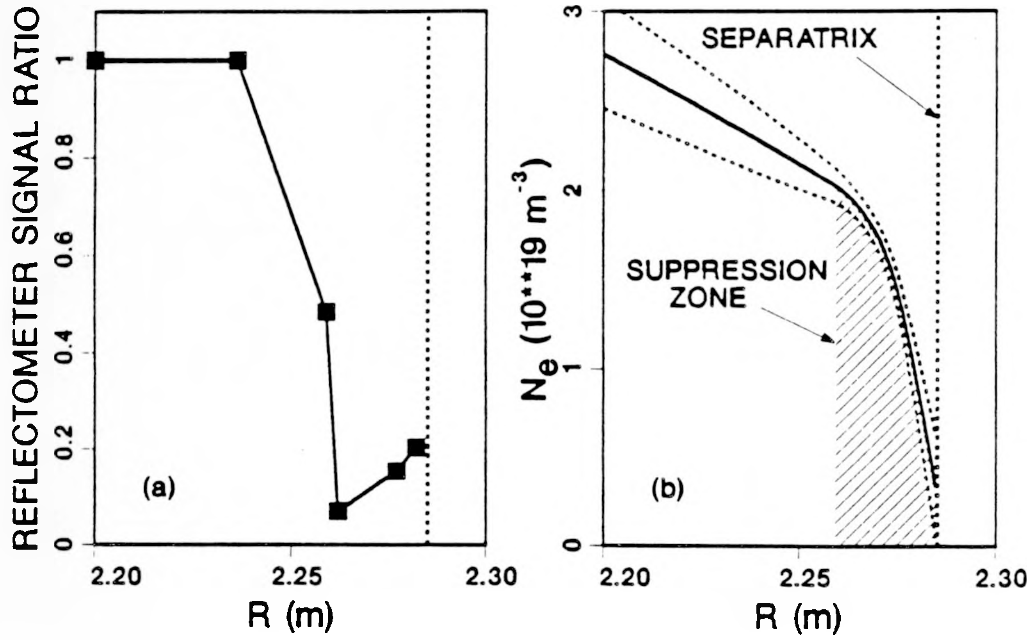

Fig. 3. (a) Ratio of power from reflectometer channels after the transition to power prior to transition. No reduction in signals occurs outside suppression zone with roughly order of magnitude reduction in suppression zone. (b) Suppression zone for microturbulence at onset of L-H transition is shown in shaded region, superimposed on n_e profile obtained 7 ms before the L-H transition. Width of zone is determined by finding largest critical density whose signal is suppressed coincident with L-H transition, under assumption that n_e profile has not changed before the instant of transition.

that changes in v_θ and E_r and suppression of density fluctuations occur simultaneously in the same layer at the edge of the plasma as soon as the D_α signal starts to drop at the L-H transition. Profiles of T_i, T_e, n_e and of the carbon density show that the region of improved confinement near the edge also overlaps the shear layer. These results are consistent with recent theoretical ideas which indicate that changes in the gradients of E_r or of v_θ or changes in the magnitude of E_r itself cause a suppression of microturbulence which leads to confinement improvement at the L-H transition [8,9].

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