Investigations of H-Mode Plasmas Triggered Directly by Pellet Injection in the DIII-D Tokamak

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The transition from low-confinement (L-mode) to high-confinement (H-mode) plasmas has been directly produced by injecting frozen deuterium pellets in the DIII-D tokamak. H-mode transitions were produced at edge electron and ion temperatures below the L-mode values. This implies that a critical edge temperature is not necessary for H-mode transitions. The experimentally determined edge plasma parameters were well below those predicted by several theories of the H-mode transition to trigger the H-mode, indicating a need for revision of these theories.

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Fusion plasmas can operate in a high performance operational regime with high plasma confinement called the H-mode regime [1]. The H-mode is attractive because it requires less input power and smaller plasma confinement devices to reach fusion temperatures. The H-mode regime is characterized by the formation of a transport barrier at the plasma edge at the transition from L-mode to H-mode plasmas. A key issue in the physics of H-mode plasmas is determining which plasma quantities at the plasma edge are critical for the formation of the edge transport barrier. One approach is to directly perturb the edge plasma and observe the subsequent changes at the transition to H-mode plasmas. In the DIII-D tokamak, injection of frozen deuterium pellets has been used to directly change the edge plasma conditions and produce H-mode transitions. Subsequently, pellet injection can provide a novel means of testing H-mode transition theories and also provide a tool for reducing the H-mode power threshold. Previously, the production of H-mode plasmas by the injection of solid lithium deuteride pellets into an Ohmic plasma has been reported in the TUMAN-3 tokamak [2]. However, the H-mode plasma there could not be extended in duration past 5 ms.

The experiments reported in this paper utilize pellet injection to provide significant results in several areas of H-mode physics. First, the hypothesis that the attainment of a critical edge electron temperature is required for the H-mode transition [3–9] is disproved in this paper. This result has been determined from high spatially resolved measurements of the edge plasma conditions across a pellet-induced H-mode (PH-mode) transition. Second, the edge plasma conditions at the PH-mode transition have been compared with predictions from models of the H-mode transition [6,10,11], and the experimentally determined edge parameters are well below the H-mode threshold values predicted by these theories. These theories, which fit well-developed H-mode conditions, fail at the pellet-induced H-mode transition and need improvement. Third, it is demonstrated that the pellets can reduce the H-mode power threshold for a fixed set of operating parameters and plasma configuration.

These experiments were performed on the DIII-D tokamak with the following ranges of operational parameters: major radius $R = 1.67-1.68$ m, minor radius $a = 0.61-0.62$ m, vertical elongation $\kappa = 1.63-1.71$, plasma current $I_p = 1.6$ MA, and toroidal magnetic field strength $B_T = 1.8-2.1$ T. The plasma configuration was an unbalanced double-null diverted discharge with the vertical drift of the ions being in the $\nabla B \times B$ direction which was away from the dominant X-point [12]. This plasma configuration resulted in a high heating power threshold (>9.2 MW) for the H-mode transition. The pellets were composed of frozen deuterium with diameters of 2.7 mm [13]. Pellets were injected horizontally through a port in the outside vessel wall [i.e., low toroidal magnetic field side (LFS)] at 4 cm above the midplane of the vessel. Pellets were also separately injected from the inside vessel wall (i.e., HFS) at about 72.1 cm above the vessel midplane and directed downwards towards the plasma center at an angle of 45°. The LFS pellets were shattered in the guide tube before entry into the DIII-D vessel in order to minimize the pellet penetration and produce a greater edge density perturbation. The HFS launched pellets produce a deeper density deposition profile into the plasma core than the LFS pellets due primarily to the outward radial drift of the pellet ablatant [14]. The pellet velocities varied from about 300 $\mathrm{m\,s^{-1}}$ for the LFS pellets to about 230 $\mathrm{m\,s^{-1}}$ for the HFS pellets.

The application of neutral beam power ($P_{\mathrm{NBI}} =$ 9.2 MW) at below the H-mode power threshold produced discharges which remained in L-mode throughout the beam heated phase (>700 ms) and reproducibly so from shot to shot, even in the presence of strong sawteeth. Clearly, the conditions required for the H-mode transition were absent in these plasmas. Figure 1 shows the time evolution of various quantities for a reference discharge without pellets which remained in L-mode at a total input power of 9.5 MW (NBI + Ohmic). The total radiated power increased from 2.2 to 3.2 MW in the time window shown. Also shown is a discharge in which an H-mode transition was directly triggered by pellet injection. Three LFS pellets were injected into this discharge at a reduced

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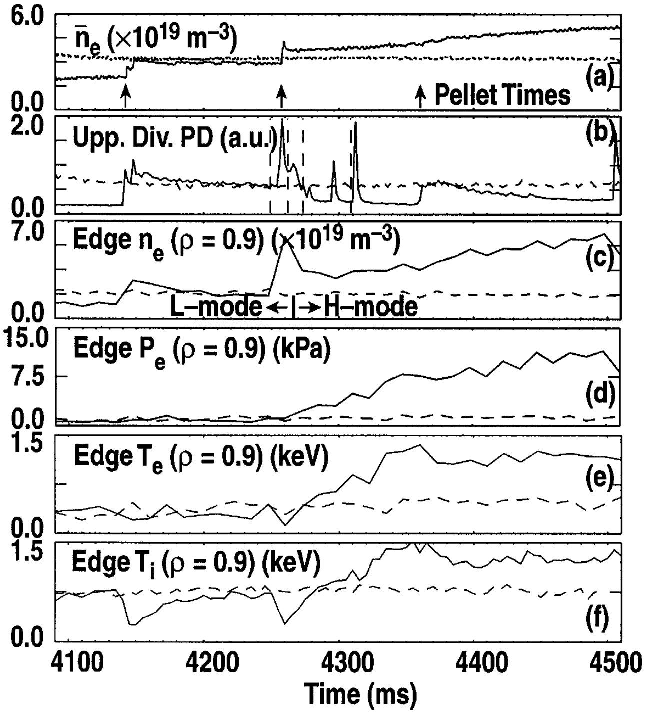

FIG. 1. Time histories of edge quantities for reference discharge with no pellet (shot 99573, dashed line) and PH-mode discharge (shot 99559, solid line) produced by a LFS launched pellet. Dashed vertical lines in (b) represent times of profiles shown in Fig. 2. n_e = electron density, T_e = electron temperature, P_e = electron pressure, T_i = ion temperature.

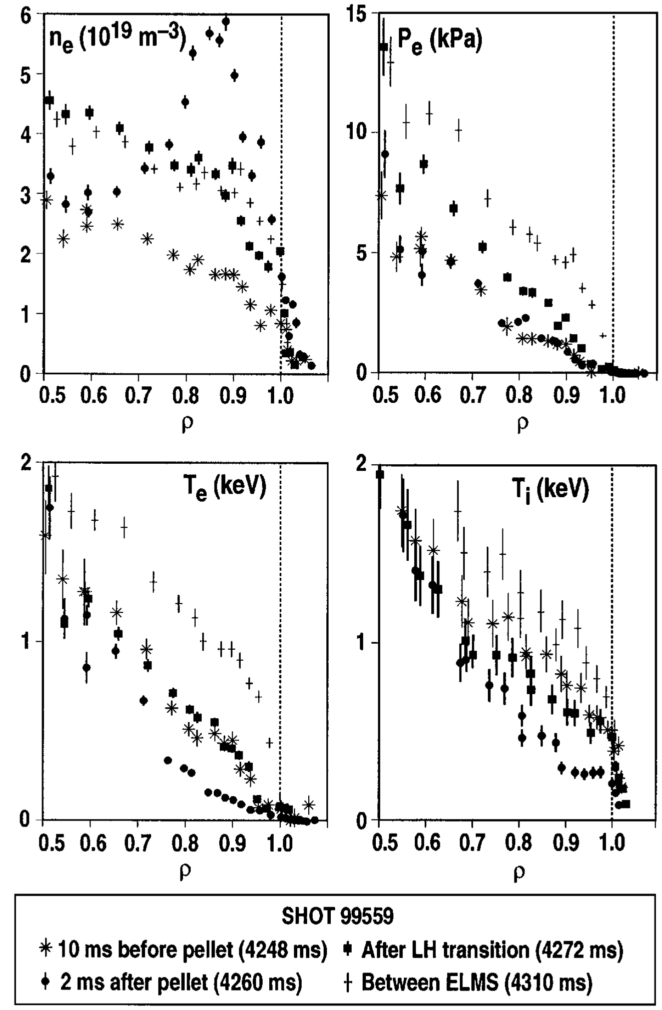

FIG. 2. n_e, P_e, T_e, and T_i radial profiles across the PH-mode transition for the H-mode shot in Fig. 1. The dashed vertical line in the profile plots represent the location of the separatrix. ELM = edge localized mode.

total power of 7.3 MW. Note that the third pellet broke up in the guide tube and was mainly deposited in the scrape-off layer and not the main plasma. The total input power was reduced by 2.2 MW. The pellet injection reduced the power threshold by more than 23%. The total radiated power before pellet injection was 1.9 MW. Typically, the power threshold for the H-mode transition is quite sharp such that, if the power is close to the threshold power, an increase of just a few 100 kW can produce the transition. Measured on a scale of a few 100 kW, the reduction in the power threshold by 2.2 MW is significant. It should also be noted that pellets reduced the H-mode power threshold even in plasmas with the $\nabla B \times B$ drift towards the X-point, which have nominally lower H-mode power thresholds. The H-mode power threshold in these plasmas was reduced from 2.1 to 1.5 MW (i.e., by about 29%).

The important dynamics of the PH-mode transition occur in the region of greatest perturbation by the pellet ($\rho \geq 0.8$). Here ρ is a normalized magnetic flux surface proportional to the square root of the toroidal flux enclosed by the surface. Figure 2 shows detailed profiles of n_e, P_e, T_e, and T_i for $\rho > 0.5$ across the PH-mode transition. The n_e and T_e profiles are determined from Thomson scattering (TS). The T_i profiles are determined from charge exchange recombination (CER) spectroscopy measurements of carbon impurities with a sampling time of 5 ms. The vertical dashed lines on the time trace of the Balmer-alpha photodiode signal in Fig. 1(b) indicate the times of the TS measurements of n_e, T_e, and P_e. The T_i profiles are shown for the closest times to the TS measurements given that the sampling time of the CER measurements is 5 ms. The pellet produces substantial increases in n_e (cf. to the L-mode profile) in the region $\rho > 0.6$. Correspondingly, there are large reductions in the T_e and T_i values everywhere over the same region ($\rho > 0.6$). The process appears to be adiabatic since the P_e profile for $\rho > 0.6$ is unchanged. However, the H-mode transition occurs within 12 ms after pellet injection since the absolute value and gradient of the edge pressure profile for $\rho \geq 0.9$ have increased significantly by time 4272 ms as a result of the formation of the edge transport barrier. However, even by this time, the T_e at $\rho = 0.9$ is still at or below the L-mode value and the T_i at $\rho = 0.9$ is well below the L-mode value. Furthermore, Fig. 1 shows that the reference discharge without pellet injection (dashed line) remained steadfastly in

L-mode throughout, despite reaching edge T_e and T_i values even greater than the T_e and T_i observed after pellet injection during the PH-mode transition.

The above observations imply that the attainment of a critical edge T_e or T_i is not necessary for the H-mode transition. The hypothesis on a critical edge T_e for the H-mode transition has been propagated by both experimental and theoretical studies [3–9]. These studies have based the need for a critical edge temperature at the H-mode transition on the following: (a) modeling and fitting to edge local parameters such as n_e and T_e (e.g., plots of n_e vs T_e) [5–7,9]; (b) studies of H-mode transitions triggered by sawtooth heat pulses [3,4]; (c) H-mode power threshold requirements [8]; (d) a critical edge temperature for the stabilization of the drift Alfvén mode [6]. Conflicting positions to this hypothesis have arisen as a result of different temperature behavior depending on the exact radial location of the measurement, such as with respect to that of the last closed flux surface or at a particular point along the edge temperature profile [15]. The ability of the pellet to strongly perturb the edge plasma and lower the edge temperature *everywhere* over a significant region at the plasma edge (for $0.6 < \rho < 1.0$ as can be seen for the T_e and T_i profiles in Fig. 2 for time 4260 ms) means that issues relating to uncertainties and ambiguities in the spatial location and absolute value of the temperature measurement become insignificant since the temperature is reduced far below a critical edge temperature over a large region of the plasma. The use of pellet injection, therefore, to directly perturb the edge plasma and significantly lower the edge temperature is the clearest proof that a critical edge temperature is not important for the H-mode transition.

The large changes in the edge n_e, T_e, and T_i produced by pellet injection provide a direct means of testing theories of the H-mode transition. The theories considered [6,10,11] postulate certain critical threshold parameters for the H-mode transition determined from the local plasma parameters and their gradients at the plasma edge. These theories have shown agreement with experimental data on nonpellet triggered, spontaneous H-mode transitions in ASDEX-Upgrade [6,9], C-Mod [5,7], and COMPASS-D [11]. However, the agreement in these studies is limited due to the large scatter in the experimental data which has led to confused results. Pellet injection provides a direct means of testing these theories, so removing the confusion. The high spatial resolution of the relevant edge diagnostics on DIII-D provided the necessary measurements to make these comparisons with the theories. Figure 3 shows the comparisons between experimental results for a LFS pellet H-mode transition and the formulated threshold parameters postulated by three theories of the H-mode transition. Figure 3(a) is a comparison with the model of Rogers and Drake [10] which is based on 3D simulations of the Braginskii equations where the H-mode threshold requirements are parametrized in terms of the edge MHD ballooning parameter α_{MHD} and a diamagnetic parameter α_{DIA}. The model is for a shifted circle magnetic geometry, but the equations have been modified for a close approximation to the shaped discharges in DIII-D. In their model, transport is suppressed when $\alpha_{\mathrm{MHD}} \gtrsim 0.5$ and $\alpha_{\mathrm{DIA}} \gtrsim 0.5$ in DIII-D. This then defines the parametric region for access to the H-mode (shaded region). The experimental points are evaluated at the location of the maximum edge density gradient and, hence, pressure gradient which gives the highest value for α_{MHD} for the various points. The injection of the pellet greatly increases the collisionality and, hence, lowers the α_{DIA} parameters. After the H-mode transition, the increased temperatures lead to increases in the edge pressure (increased α_{MHD}) and to lower edge collisionality

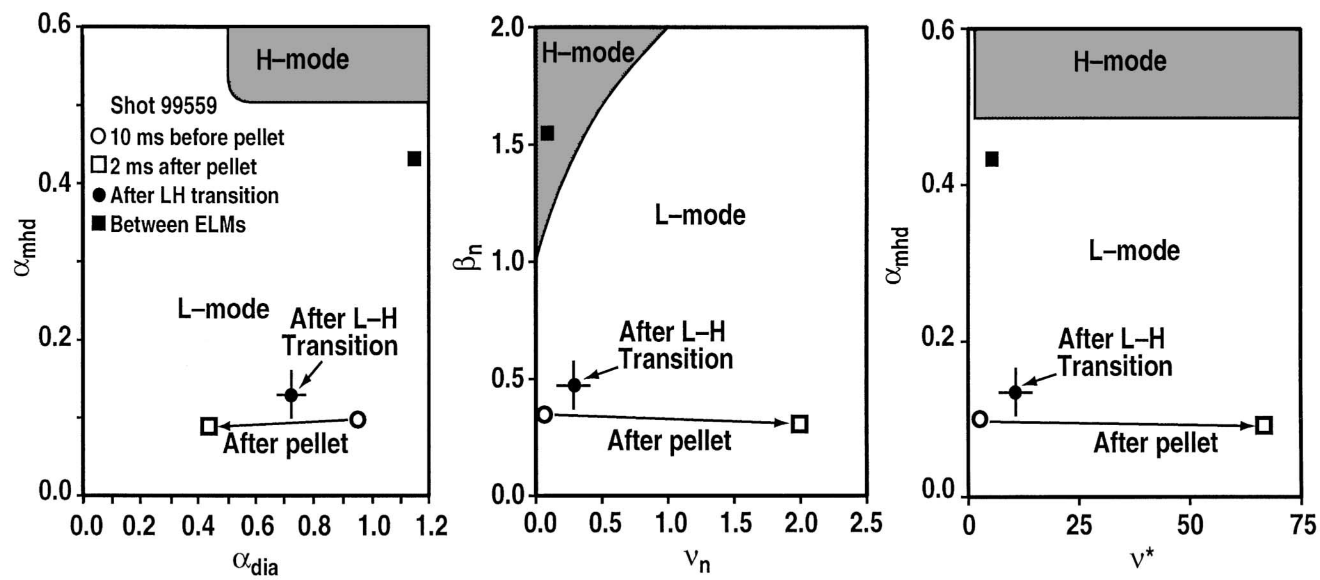

FIG. 3. Comparison of experimental edge local parameters with predictions from theories of the H-mode transitions.

(increased $\alpha_{\rm DIA}$). Also shown is the experimental point well into the H-mode and just before a giant ELM. These conditions are in closer agreement with the model requirements, but represent well established H-mode values by which time the edge pressure gradients have increased substantially.

In another model of the H-mode transition by Pogutse *et al.* [6], an increased plasma pressure leads to the Alfvén waves mixing with the electron drift waves and stabilizing the long wavelength turbulence. Their Alfvén drift model predicts that turbulent transport is suppressed when $\beta_n > 1 + \nu_n^{2/3}$, where β_n and ν_n are the edge normalized beta and normalized collision frequency, respectively. This inequality is satisfied for the shaded region in Fig. 3(b) and represents the requirements for H-mode. The experimental values for β_n and ν_n are well below the model predictions for all points up to and through the H-mode transition.

In another model of the H-mode transition, unstable peeling modes at low edge collisionality are invoked by Wilson *et al.* [11] to explain the increased difficulty in obtaining H-mode transitions at low edge collisionality in the COMPASS-D tokamak. At higher edge collisionality ($\nu^* > 1$), the peeling mode can be stabilized by increasing the edge pressure gradient, i.e., $\alpha_{\rm MHD} \gtrsim 0.5$ and $\nu^* \gtrsim 1$. This parameter space for reduced transport and improved confinement is shown in Fig. 3(c). Once again, the experimental edge pressure gradient at the H-mode transition is far below the theoretical predictions. The theories exhibit near agreement with the experimental data later into the H-mode implying that the theories appear to be more applicable to well established H-mode conditions well after the H-mode transition. However, they are clearly inadequate in describing the conditions at the H-mode transition itself.

In conclusion, pellet-induced H-mode plasmas have shown the following: (1) the H-mode power threshold can be reduced by more than 23%; (2) the attainment of an edge critical T_e or T_i is not important for the H-mode transition; and (3) the experimental edge local parameters at the H-mode transition are in disagreement with predictions of various H-mode transition theories [6,10,11].

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