Peaked Density Profile Circular Limiter H-Modes on TFTR

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Abstract

Circular limiter H-modes are obtained on TFTR during high power neutral beam heating. The transition is usually from the supershot to the H-mode rather than the usual L- to H- transition, and thus is obtained in a low recycling environment with core fueling mainly from the heating beams. As a result, the density and pressure profiles are highly peaked at the center. Global confinement time, τ_E , is enhanced over L-mode scaling by up to ≈ 2.5 times. The onset of ELMs shortly after the H-mode transition appears to limit τ_E . Limiter H-modes of up to 1.5 sec duration have been realized.

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Limiter H-mode plasmas were first reported on JFT-2M.¹⁻³ Since that initial report, limiter H-mode studies have been carried out on other tokamaks.^{4,5} The appeal of circular limiter H-mode plasmas lies in the possibility of obtaining good confinement without a divertor or shaping coils to obtain elongated plasmas. This is the first report, for large tokamaks, of H-mode plasmas with highly centrally peaked density profiles and of significantly enhanced confinement in circular limiter H-modes. Thus, TFTR offers the possibility of studying and comparing the physics of the supershot,⁶ H-mode, and L-mode⁷ regimes on the same tokamak.

The main sign of the divertor H-mode, first reported for neutral beam injection (NBI) heated discharges in ASDEX,⁸ was a sudden transition (often within 2 ms or less) from the "low confinement" or L-mode to the "high confinement" or H-mode. The improved confinement was attributed in part to the establishment of a transport barrier at the plasma edge which reduced the particle and energy transport. D_{α} light at the periphery decreased sharply due to reduced recycling, the electron temperature profile developed an edge pedestal, the electron density profile became broad and flat with a steep edge gradient, and the global energy confinement time, τ_E , could improve by a factor of 2 or more over L-mode. Edge localized MHD modes (ELMs)⁹ were often triggered. These modes cause periodic spoiling of the enhanced confinement and result in the expulsion of particles, energy, and impurities from the edge region of the plasma. Most of these characteristics were also observed in the JFT-2M limiter H-modes, however, smaller improvements in

within the range 3.5 to 6.8 ($q_{\psi} = 4.3$ to 10.4, with most > 6.0). Neutral beam injection (NBI) powers, P_b , of 11 to 28 MW have been used with the higher P_b values being required to obtain H-modes at the higher values of I_p . All TFTR H-mode shots were initially deuterium target plasmas heated with deuterium NBI except for three helium target plasmas. Circular limiter H-mode plasmas were obtained on TFTR only during NBI heating. Beam heating pulses of 0.5 to 2.0 sec were used. Bidirectional beam heating apparently is a requirement, with slightly counter-dominated injection being favorable. A unique feature of TFTR H-mode plasmas is that most are results of transitions from the supershot to the H- regime rather than the usual L-mode to H-mode transition. In order to obtain supershots, the graphite limiter on TFTR must be highly conditioned, i.e., degassed.¹⁰ Thus, except when specifically labeled as high recycling, the limiter H-mode data presented are for low recycling conditions. The combination of high power NBI in the low recycling environment of the supershot results in central beam fueling, and consequently in transitions to limiter H-mode plasmas which are highly peaked at the center. The range in $\bar{n}_e$ was 2.2×10^{19} to $4.5 \times 10^{19} / \text{m}^3$ for H-mode plasmas obtained under low recycling conditions.

The longest duration of an H-mode plasma realized in TFTR is 1.5 sec, apparently limited only by the 2 sec beam pulse used. Time evolutions of various parameters for this plasma are shown in Fig. 1, and most of the usual phenomena associated with the H-mode are

confinement could occur. τ_E enhancement ranging from 20% for circular plasmas to 40% for elongated plasmas were reported in Ref. 2 and somewhat greater improvement was reported for elongated plasmas in Ref. 3. This paper describes circular limiter H-modes on TFTR which are qualitatively more like the JFT-2M limiter H-modes than the ASDEX divertor H-modes.

The main results for TFTR H-modes reported here are: (a) the density profiles are unique for H-modes in that they can be highly peaked at the center, (b) the characteristic changes in D_α light and in n_e and T_e profiles are usually observed, (c) the global energy confinement time, τ_E , can be > 2.5 times the L-mode value, (d) the ELM instability is observed for nearly all TFTR H-modes, and (e) the parameter range in which H-modes are obtained on TFTR is relatively broad. For considerations relative to future reactors such as the Compact Ignition Tokamak (CIT) and the International Thermonuclear Experimental Reactor (ITER), these plasmas are attractive alternatives to the flat density profiles reported previously for H-modes on other tokamaks. As the density and temperature profiles become more peaked, the confinement enhancement required for ignition decreases.

H-modes have been obtained on TFTR for plasma current, $I_p = 0.8$ to 1.7 MA, toroidal field, $B_T = 3.0$ to 5.2 T, and major and minor radii, $R_p = 2.45$ to 2.60 m and $a_p = 0.79$ to 0.95 m, respectively. Transitions have occurred on TFTR for values of the cylindrical safety factor, q_c ,

evident. The transition on TFTR is often, but not always, signalled by a decrease in the D_{α} signal. Time delays (after the beams turn on) before the transition to the H-mode can be 150 to > 600 ms. For the discharge of Fig. 1, beam turn on is at 4.0 sec and the transition takes place after the initial 390 ms of heating. Transitions to the H-mode with little or no drop in main-chamber D_{α} have also been reported for other tokamaks.¹¹ Drops in D_{α} and CII intensity, both located in the edge plasma, are seen in Figs. 1(a) and (b). The slow rates of fall of the signals of Figs. 1(a) and (b), occur frequently on TFTR for transitions accompanied by decreases in D_{α} and CII light. These rates are slower than usually observed for divertor H-modes. Increases in edge n_e , T_e , and T_i are clear in Figs. 1(c), (d), and (e). The edge T_i as measured by charge exchange recombination spectroscopy (CHERS) increases from ≈ 1 to ≈ 2 keV at the transition, while the edge toroidal velocity (also from CHERS), $v_{\phi}(\text{edge})$, of the plasma decreases by a factor of 2.

The increase in electron stored energy, E_e , obtained for this shot [Fig. 1(h)], is typical for the limiter H-modes observed in TFTR. However, the total stored energy, E_{Tot} , either remains constant or decreases slightly. In this case E_{Tot} remained relatively constant during the transition, and then decreased at the onset of ELMs. This is reflected in the decrease, beginning at about 4.5 sec, in the global confinement [see Fig. 1(i)] from its value during the initial supershot phase. However, for the remainder of the discharge or a duration of

≈ 13 energy confinement times, τ_E remains near 110 ms or > 2.3 times the L-mode value. This is evident from Fig. 1(i) which is a plot of the ratio τ_E to $\tau_{E,L\text{-mode}}$, where the latter is given by⁷

$$\tau_{E,L\text{-mode}} = 0.037 * I_p(\text{MA}) * P_b(\text{MW})^{-0.5} * R_p^{1.75} * a_p^{-0.37}.$$

Electron temperature and density and ion temperature profiles, $T_e(R)$, $n_e(R)$, and $T_i(R)$, respectively, are plotted in Figs. 2(a)-(c) for several times of the discharge of Fig. 1. Profiles at times during the supershot phase (4.3 and 4.4 sec), during the transition (4.45 sec), and 50 ms after the initial ELM burst (at 4.55 sec) are included. The profile shape at 4.55 sec is typical for the remainder of the beam pulse. The $n_e(R)$ profiles of Fig. 2(a) are clearly highly centrally peaked and significantly different from the flat density profiles obtained for the H-mode on other tokamaks. During the transition, the largest fractional increase in $n_e(R)$ is for the edge plasma at $R \leq 180$ cm (inner edge), and at 320 cm (outer edge). This may be seen by comparing the $n_e(R)$ profile at 4.4 sec to that at 4.5 sec. In contrast, during the time evolution of the supershot phase (up to 4.4 sec), the core density increases rapidly while there is little or no change in the edge density (compare the profiles for 4.3 and 4.4 sec). For supershots which do not result in transitions to the H-mode, $n_e(\text{center})$ continues to increase and the peaking factor, $F_{ne} = n_{e0}/\langle n_e \rangle$, can be > 3.0 . For the discharge of Figs. 1 and 2, F_{ne} has a maximum value of 2.5 in the supershot phase and is

only slightly lower, ≈ 2.3 , for the duration of the H-mode phase. The corresponding pressure profile peaking factor for the H-phase is $p_{e0}/\langle p_e \rangle = 5.0$. Also, the ion temperature profile [Fig. 2(c)] is highly peaked with $T_i(\text{center}) > 20 \text{ keV}$ or about $3 \times T_e(\text{center})$.

Plasma fluctuations at times near the transition and during the H-phase of TFTR limiter H-modes have been studied.¹² During the H-mode transition, the magnetic fluctuations in the range 15-25 kHz increase, while the high frequency magnetic fluctuations in the range 150-200 kHz decrease. The improving confinement of the edge plasma, as manifested by increasing T_i , T_e , and n_e near the edge with time, appears to be arrested by ELM activity, which for the discharge of Fig. 1, begins just after $t = 4.5 \text{ sec}$. The ELM instability is detected as intense bursts of D_α and CII light using arrays of detectors which view along chords perpendicular to the plasma column. In contrast to "q-mode"¹³ discharges, the D_α signals for all chords are in phase with each other. This is another feature of the H-mode which is often observed on a number of tokamaks. This is demonstrated in Fig. 3 (for a different discharge from that of Figs. 1 and 2) where signals are plotted for D_α detectors viewing the edge plasma located at poloidal angles of 7° and 25° above the midplane. In TFTR, the D_α bursts appear to be preceded by high frequency magnetic oscillations [see $\tilde{B}_\theta$ signal plotted in Fig 3 (d)]. Additional studies are being done to determine if these magnetic oscillations are similar to the high frequency magnetic activity identified as precursors to ELMs on PBX-M.¹⁴ Measurements of electron

cyclotron emission (ECE) during ELMs, using a grating polychromator, show 20 to 30 μ sec duration intense emission spikes which occur simultaneously with the magnetic oscillations. These spikes are consistent with dumping of electrons, from a volume 15 to 20 cm within the plasma edge, which move radially outward at a velocity $\approx 2 - 3 \times 10^5$ cm/s.¹⁵ This interpretation is supported by the soft x-ray array data plotted in Figs 3(e) and (f). The signal for the viewing chord with tangency radius of $r = 70$ cm (near the edge) begins to drop simultaneously with the beginning of the magnetic oscillations and the ECE spikes. However, the x-ray signal for the chord at $r = 45$ cm drops ≈ 0.6 ms after that for the chord at $r = 70$ cm. This behavior of the soft x-rays also indicates that the ELM disturbance is initiated with a dump of energy from the plasma edge, and that the resulting edge cooling and subsequent reheat propagate radially inward.

Recently there has been interest in poloidal rotation and radial electric fields associated with the H-mode.^{16,17} On DIII-D,¹⁶ a poloidal "spin-up" in the $-E_r \times B_T$ direction has been observed during the L- to H-mode transition. Evidence of similar behavior on TFTR is provided by microwave scattering measurements of density fluctuations. The measurements show an edge feature during the H-mode for $f > 0.8$ MHz (at $k_{\perp} \approx 5 \text{ cm}^{-1}$) in the scattered spectrum, which is consistent with a wave at the plasma edge propagating in the electron diamagnetic drift direction. On TFTR, this would also be in the direction of a poloidal velocity ($v_{\theta} \approx 10^4$ m/s) arising from an inwardly directed E_r .

The discharge of Fig. 1 is one of a number of limiter H-modes

obtained using an I_p of 0.8 MA and balanced beam power, $P_b = 11$ MW. These are the lowest current and lowest beam power at which limiter H-modes have been obtained on TFTR. In general there appears to be a current dependence on the threshold power for the transition. This behavior is apparent in Fig. 4, which includes plots of P_b and τ_E vs plasma current for the full range of TFTR H-mode plasmas. For I_p in the range 0.8 and 1.0 MA, the minimum P_b required for a transition to the H-mode to occur is ≈ 11 MW, while at 1.4 MA, 18 MW are required and at 1.6 MA a slightly higher value of ≈ 21 MW of NBI is needed. On a given day the boundary in P_b - I_p space can be relatively sharp. In fact (with $P_b \approx 14$ MW) a shot-to-shot change in I_p setting as small as 50 kA, from 1.0 MA to 1.05 MA, was found to be sufficient to block the transition to the H-mode. On the other hand, the threshold power for a given I_p deduced from Fig. 4(a) is not precise since the data was collected over many weeks of operation. Uncertainties are introduced due to day-to-day variation in limiter conditioning, co-/ctr- beam mixture, and sawtooth activity.¹⁸

The values of τ_E plotted in Fig. 4(b) are only for low recycling conditions. Limiter H-modes with enhanced confinement have only been realized on TFTR under low recycling conditions where the transition is from the supershot to the H- regime. Under high recycling conditions only L-mode confinement has resulted. Also, at high recycling and often with deuterium gas puffing (with high or low recycling limiters),

H-modes with especially "grassy" ELM activity are realized. The ratio of τ_E of the H-mode to $\tau_{E,L\text{-mode}}$, also plotted in Fig. 4(b), can be >2.5 . The decrease in this ratio with increasing current is due to the I_p dependence of $\tau_{E,L\text{-mode}}$. Thus, the improvement in energy confinement over L-mode can be of the order observed for divertor H-mode discharges. However, although there is a significant increase in n_e at the edge, the improvement in particle confinement appears to be less than observed on divertor tokamaks. This conclusion is also supported by X-ray PHA measurements which show the metal concentration to remain fairly constant (no accumulation) during the H-mode phase.

In summary, a peaked density H-mode discharge with $\tau_E > 2.5$ times L-mode scaling has been obtained in a circular TFTR limiter configuration. The density peaking factor can be > 2.3 , and the transition is usually from a supershot to the H-mode. Most of the standard features associated with the H-mode are observed. For many of the H-modes studied so far, the ELMs were found to originate 15 to 20 cm within the limiter radius. These peaked density profile H-modes may offer an alternative scenario for future tokamaks such as the CIT and ITER.

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Figure Captions

Figure 1. - Characteristics of a TFTR limiter H-mode of 1.5 sec duration. The time variation of D_α , CII, edge n_e and T_e , T_i , V_ϕ , density peaking factor ($n_e(0)/\langle n_e \rangle$), E_θ , and $\tau_E/\tau_{E,L-mode}$ are plotted. $R = 2.45$ m, $a = 0.8$ m, $B_T = 4$ T, $I_p = 0.8$ MA, $P_b = 11$ MW (balanced), and $\bar{n}_e = 2.5 \times 10^{13}/\text{cm}^3$. Shot # 42935.

Figure 2. - Profiles of $n_e(R)$, $T_e(R)$, and $T_i(R)$ for the discharge of Fig. 1 are shown. Data for four times are included, during the supershot phase (4.3 and 4.4 sec), at the end of the transition (4.5 sec), and 50 ms after (at 4.55 sec) the first ELM. $F_{n_e} \approx 2.2$ at 4.55 sec.

Figure 3. - Shows time correlation of D_α signals for the plasma edge at poloidal angles of 70° and 25° above the midplane of an 80 cm minor radius discharge. Mirnov loop ($\vec{B}_\theta$), soft x-ray, and CII signals are also plotted. $R = 2.45$ m, $B_T = 4$ T, $I_p = 0.9$ MA, $P_b = 13$ MW. Shot # 44008.

Figure 4. - (a) Plot of P_b vs I_p for the TFTR limiter H-mode. Data for supershots are also included (but only a small fraction of the TFTR supershot database). An apparent threshold power dependence on I_p is indicated. (b) τ_E or $\tau_{E,H-mode}$ (from magnetics), $\tau_{E,L-mode}$, and their ratio as a function of I_p . $B_T = 3.0$ to 5.2 T.

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Fig. 1

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Fig. 2

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