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LIMITER H-MODE EXPERIMENTS ON TFTR

BY

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Limiter H-mode Experiments on TFTR

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ABSTRACT

Limiter H-modes with centrally peaked density profiles have been obtained in TFTR using a highly conditioned graphite limiter. The transition to these centrally peaked H-modes takes place from the supershot to the H-mode rather than the usual L- to H-mode transition observed on other tokamaks. Bi-directional beam heating is required to induce the transition. Density peaking factors, $n_e(0)/\langle n_e \rangle$, greater than 2.3 are obtained and at the same time the H-mode characteristics are similar to those of limiter H-modes on other tokamaks, while the global confinement, τ_E , can be > 2.5 times L-mode scaling. The transport analysis of the data shows that transport in these H-modes is similar to that of supershots within the inner 0.6 m core of the plasma, but the stored electron energy (calculated using measured values of T_e and n_e) is higher for the H-mode at the plasma edge. Microwave scattering data for the edge plasma shows broad spectra at $k = 5.5 \text{ cm}^{-1}$ which begin at the drop in D_α radiation and are strongly shifted in the electron diamagnetic drift direction. At the same time, beam emission spectroscopy (BES) shows a coherent mode near the boundary which propagates in the ion direction with $m = 15-20$ at 20-30 kHz. During an ELM event these apparent rotations cease and Mirnov fluctuations in the frequency range of 50-500 kHz increase in intensity.

Introduction

The circular limiter H-mode plasmas on TFTR¹⁻³ are of interest for a number of reasons. First, under low recycling conditions the transition is from the supershot⁴ to the H-regime rather than the usual L- to H- transition.⁵ A new and important consequence is that the resulting H-mode density profile is highly peaked at the center. Peaked density profiles are of interest to advanced tokamaks such as CIT and ITER. Reactor design studies indicate that the degree of enhanced confinement required for ignition is lowered as the temperature and density profiles become more centrally peaked. Second, the good global confinement of the supershot is largely retained in these H-modes, often with a small increase in τ_E during the transition, but usually decreasing at the start of ELMs. Third, even with the peaked electron density profile the usual H-mode characteristics are observed. Thus, the experimental findings from the TFTR H-modes will be useful for other tokamaks. Fourth, on TFTR aspects of transport and confinement of limiter H-mode, L-mode, supershot, and high beta poloidal plasmas may be compared.

Obtaining TFTR Limiter H-modes: Characteristics

Limiter H-modes, both with the usual L- to H- transitions and with supershot to H- transitions have been realized on TFTR. These regimes are obtained under different limiter conditions, high recycling and low recycling, respectively. However, since the resulting confinement is significantly enhanced over L-mode and the density profile is highly peaked for the supershot to H-mode case, it has been studied in more detail and will be the subject of this paper.

The operational parameter range for obtaining limiter H-modes on TFTR is plasma current $I_p = 0.8 - 1.7$ MA, toroidal field $B_\phi = 3.0 - 5.2$ T, major radius $R_p = 2.45 - 2.60$ m, minor radius $a_p = 0.79 - 0.95$ m, and neutral beam injection (NBI) power. $P_b \sim 11 - 28$ MW. Beam heating pulses of 0.5 - 2.0 sec have been used. Information about operational and plasma parameter effects on the threshold power for the transition has been obtained. (1) H-modes have only been obtained with neutral beam injection heating. (2) Bi-directional NBI is required, with modestly counter dominated injection being favorable. No H-modes have been obtained with all co- or all counter-NBI. (3) The threshold power for the transition is linearly dependent on I_p and (4) the threshold power appears to be lowered when a) the current is ramped down, reaching a minimum just before beam turn on, or b) carbon pellets or short duration, medium to high flow, deuterium or helium gas are injected during the plateau of the heating pulse.

The need for nearly balanced-NBI can be seen qualitatively from Fig. 1. Plotted are the D_α signals for a discharge which had 2 secs of balanced-NBI, and for a discharge which was heated by 1 sec of counter-NBI followed by 1 sec of balanced-NBI. The H-mode transition (indicated by drop in D_α signals) in each case begins shortly after the start of balanced-NBI, and the ELMs begin shortly after the transition. The I_p dependence can be seen from Fig. 2 which is a plot of P_b vs. I_p . The bottom of the envelope of the data points is an indication of the threshold beam power. The data of Fig. 2 include a large part of the H-mode database and thus the range of I_p and B_ϕ values indicated earlier. No strong B_ϕ dependence of the threshold power for the transition has been observed. The line averaged density, $\bar{n}_e$ is usually $\geq 2 \times 10^{19} \text{ m}^{-3}$ for H-modes obtained under low recycling conditions. The effect of co-/counter-NBI mix (i.e. net beam momentum) is thought to be due to ion orbit loss effects which lead to the proper radial electric field, E_r , needed to trigger the transition. This will be discussed in more detail in a later section.

Characteristic features of the TFTR limiter H-modes agree in general with those of other tokamaks;⁶ however, there are also differences. Figure 3 shows the time evolution of some of the plasma parameters typical of the TFTR limiter H-mode: D_α , $n_e l(\text{edge})$, $T_e(\text{edge})$, $n_e(0)/\langle n_e \rangle$, $\bar{B}_\theta$, and $\tau_E/\tau_{E,L\text{-mode}}$. The features seen here, and usually observed in other tokamaks, are the drop in D_α light (the drop in CII light is usually larger than that for the D_α) at the transition, with corresponding increases in edge n_e , T_e , electron stored energy (W_e), and T_i . The global energy confinement is enhanced over L-mode and can be > 2.5 times the value for Goldston low-mode scaling.

Peaked density limiter H-modes were first observed on TFTR, and are in contrast to the flat n_e profiles characteristic of divertor H-mode discharges. During the transition, there is usually an increase in n_e across the entire profile; however, the largest fractional increase is at the plasma edge (outer 0.2 m). A time series of n_e profiles showing the evolution of a TFTR limiter H-mode is shown in Fig. 4. The maximum peaking factors, $n_e(0)/\langle n_e \rangle$, were ~ 2.5 and 2.2 for the supershot and H-mode phases of this plasma respectively. For comparison, a similar set of profiles for a supershot are also shown. The transition usually occurs within 150 ms to > 600 ms after the start of neutral beam injection. This delay correlates inversely with neutral beam power. The D_α drop in TFTR (see Fig. 3) is not as large (and often it is undetectable) as for divertor H-modes, but the characteristic increases in edge n_e and T_e still take place. Similar behavior has been observed for limiter H-modes on other tokamaks. Also, the D_α drop can proceed relatively slowly. In Fig. 3 the D_α signal decreases over a 50 ms period, compared to ≤ 2 ms for H-modes in divertor tokamaks. H-modes of ~ 1.5 sec duration have been obtained and the duration appears to be limited only by the beam pulse length. On the other hand, the H-mode can be degraded by MHD activity, similar to what is observed during some supershots.

The Transition, ELMs, and Fluctuations

Plasma fluctuations characteristic of the H-mode and ELM activity have been studied. At the H-transition, magnetic fluctuations (as measured by a system of Mirnov coils) in the range 15-25 kHz increase, while the high frequency magnetic fluctuations in the range 150-200 kHz decrease (see Figs. 3e and 3f). The drop in D_α indicates a change in particle transport at the plasma edge and edge probes show a corresponding drop in floating potential during the transition. Also, at the transition density fluctuations near the

plasma edge measured by the microwave scattering system⁷ show broadband activity at $k_{\theta} = 5.5 \text{ cm}^{-1}$ propagating in the electron diamagnetic direction. A contour plot of scattered power as a function of frequency and time is shown in Fig. 5a for a limiter H-mode with nominally balanced beam injection. This spectrum shows density fluctuations up to 1.8 MHz located near the plasma edge ($z = -0.7 \text{ m} \pm 0.2 \text{ m}$, $R = 2.85 \text{ m}$) and this is consistent with wave activity propagating poloidally at a velocity $v_{\theta} \sim 10^4 \text{ m/s}$. This feature begins to grow at the time of the transition, reaching a maximum frequency just before the ELM phase and persists for the duration of the H-mode. No similar activity is observed in the central region of the H-mode discharges. Fig. 5c shows a similar contour plot over a narrow time range (4.2 - 4.25 sec) for the discharge of Fig. 5a,b. Narrowband fluctuations are enhanced dramatically at the time of the ELM while the shifted spectral feature, more apparent in the time averaged data, is associated with the period between the ELMs. This data is consistent with a slowing down of the poloidal rotation immediately after an ELM burst and a speeding up in rotation in the time window between the ELMs. The strongly shifted spectra are also characteristic of the occasional discharge with no ELMs. The BES system shows density fluctuations which are more coherent and which propagate in the ion diamagnetic direction. These disturbances start about 3 cm inside the scrapeoff with a frequency of 20-30 kHz and have a highly coherent poloidal structure with $m = 15$ to 20. At present, they are known to extend radially over at least 4 cm near the plasma edge. This coherent activity is associated with the period between the ELMs. The relation between the BES coherent activity and the scattered spectra is not understood at present.

ELMs can lead to a significant loss of stored energy resulting in a cessation of the rise of stored energy and density after the transition as is clear from Fig. 3. The studies on TFTR are important since in understanding the nature and physical causes of ELMs, it may be possible to suppress or control them. ELMs can play a useful role in impurity control and in maintaining a steady-state H-mode if the associated energy loss is not too great. In divertor tokamaks, such as DIII-D, single giant ELMs have been observed to cause deterioration in confinement to the extent that the plasma returns to the L-mode and v_{θ} decreases significantly.⁸ This extreme has not been observed on TFTR. The reason for this may be that since $n_e(r)$ and the pressure profile, $p(r)$, are peaked on axis, energy loss from the edge plasma due to ELMs is a smaller fraction of the total stored energy than for the flat density profiles of divertor discharges.

The ELMs are clearly observed on the Mirnov coils, soft x-ray signals, and the edge probe signal during the H-mode phase. The Mirnov coil system was used to characterize the mode responsible for the ELM. The data was digitized at 2 MHz and showed an increase in the intensity of high frequency (50 to 500 kHz) magnetic fluctuations during an ELM. The oscillations were in phase toroidally for all of the coils in the upper half of the torus and 180° out of phase with the coils mounted in the lower half of the torus. The mode is not ballooning in structure as there is a dominant $m/n = 1/0$ MHD mode, or an up-down motion of the plasma, with amplitude of 0.1 to 1 gauss. The spectrum of a magnetic loop signal digitized at 2 MHz during an ELM is shown in Fig. 6a, and is compared to that for an ELM free period. The identification of the mode number as $m/n = 1/0$ (shown in Fig. 6b), is in contrast to the ASDEX results⁹ where $m = 3$ or 4 and $n = 1$. The TFTR ELM precursor is not outward ballooning in structure, unlike precursors on ASDEX. High frequency precursor oscillations have also been observed on PBX;¹⁰ these oscillations also were not outward ballooning in character, but did not reflect the up-down motion observed during ELMs in TFTR H-modes. Further studies are being done to determine if, in general, the same MHD mode and spatial origin are common for all occurrences of ELMs in TFTR.

Data from the grating polychromator (GPC), with a $10 \mu\text{s}$ time resolution, are shown in Fig. 7. Intense ECE spikes, with a 20 to $30 \mu\text{s}$ duration, sometimes precede the rise in D_α emission and occur simultaneously with or slightly after the start of the high frequency magnetic oscillations monitored by the Mirnov coils. The spikes are consistent with the dumping of electrons (with energy 10 to 20 keV), from a radius 0.15 to 0.2 m inside the plasma edge. The disturbance associated with the ELM moves radially outward at a velocity of $\sim 2 \times 10^3 \text{ m/s}$ as is indicated by the data shown in Fig. 7b. The D_α signal begins to increase at about the time the electron burst reaches the wall.

Chord averaged soft x-ray emission observed at a tangency radius of 0.7 m ($a_p = 0.8 \text{ m}$) starts to drop approximately at the beginning of the increase in magnetic oscillations and the ECE spikes. Interestingly, the x-ray signal for a chord at $r = 0.45 \text{ m}$ drops 0.6 ms later, indicating that a precursor induced disturbance propagates slowly inwards from a region near the plasma edge.

Transport Calculations and Comparisons with Theory

Some qualitative comparisons of the TFTR limiter H-mode results with various theoretical models can be made. If the feature in the microwave scattering spectra at high frequency is interpreted as a poloidal drift in the electron diamagnetic direction, then, an inwardly pointing radial electric field can be inferred. This is in agreement with the predictions of Itoh & Itoh,¹¹ and with v_{θ} measurements on other tokamaks.^{12,13} The fact that there is no x-point within the TFTR plasma, along with the observation that slight counter dominance in NBI is favorable, is in qualitative agreement with the neoclassical model (e.g. preferable loss of counter injected ions) for the transition.¹⁴ Qualitative agreement with Biglari, et al.¹⁵ is provided by the observation that the magnetic fluctuations at ~ 200 kHz decrease during the transition, possibly indicating stabilization of turbulence. Increase of fluctuations and modulation of the inferred poloidal rotation during the ELMs is also in qualitative agreement with the model of Biglari, et al.

As indicated earlier, there is evidence for a change in transport in the plasma edge at the transition as provided by several results in addition to the increase in T_e and n_e , including changes in magnetic fluctuations and the apparent onset of edge poloidal rotation. However, the onset of ELMs results in a modest degradation of confinement and increase in transport at the plasma edge. Transport calculations (using the TRANSP code) have been carried out for the discharge of Fig. 3. Characteristics of the transport for the three different phases of the discharge can be compared. These are the supershot, which includes the time up to the transition at ~ 4.39 sec, the time from 4.4 to 4.52 sec, which includes the transition and a short ELM free period, and finally the ELM phase which lasts for the remainder of the H-mode and the beam pulse. Microwave scattering measurements show that except for the outer 0.2 m, density fluctuations, $\delta n/n$, are very similar during the H-mode (including the ELM phase) to those for supershots across most of the plasma cross section. TRANSP calculations show little difference in χ_i and χ_e for the supershot and H-mode phases of the discharge of Fig. 3, and results of the calculation are plotted in Fig. 8a and 8b along with values for an L-mode plasma with comparable values of I_p , B_0 , and n_e . The values for the supershot and H-mode are significantly lower than those for the L-mode plasma. During the transition and short ELM free period the thermal energy confinement time rises slightly, whereas confinement of thermal deuterons is not affected significantly during and after the transition. Stored energies, W_e and W_i in the outer quarter of the plasma minor cross section increase up to the onset of ELMs. Z_{eff} begins to rise from a

value of ~ 3.4 at the transition, and plateaus at a value of ~ 3.9 (15 % increase) at 4.65 sec or about 150 ms into the ELM phase.

Conclusions

The circular limiter H-modes on TFTR have density profiles with peaking factors up to ~ 2.3 . Bi-directional NBI power is required in order to obtain the transition from the supershot to the H-mode. Global energy confinement can be enhanced over Goldston L-mode scaling by a factor of ≥ 2.5 . The threshold power for the transition is directly dependent on I_p . Features in the spectra from microwave scattering and BES measurements show the onset of poloidal rotations at the transition, which persist for the duration of the H-mode. During the transition from supershot to H-mode, low frequency magnetic fluctuations increase and high frequency fluctuations decrease. The bifurcation layer and the ELMs are found to originate within the layer of plasma between 0.03 to 0.2 m from the plasma surface. There are no strong low-m modes before the ELMs, however, high frequency (50 - 500 kHz) precursor magnetic oscillations have been observed for some ELMs and these were found to be $m = 1$, $n = 0$ standing waves which were not outward ballooning in structure. This is very similar to the quasi-coherent mode observed on PDX using infrared scattering.¹⁶ TRANSP code calculations show the transport to be similar for supershots and limiter H-modes, but different for L-mode plasmas. The main difference between limiter H-modes and supershots on TFTR is the reduced electron transport at the plasma edge.

Acknowledgments

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Figure Captions

Figure 1. - This data illustrates the need for bi-directional NBI heating in order to obtain the transition from the supershot to the limiter H-mode on TFTR.

Figure 2. - Plot of P_b vs I_p for the TFTR limiter H-mode. Data for a few supershots are also included. An apparent dependence on I_p of the threshold power, P_{th} , required for a transition to the H-mode is indicated.

Figure 3. - Characteristics of a TFTR limiter H-mode of 1.5 sec duration. Shown are the D_α , CII, edge chord averaged density n_e , $T_e(\text{edge})$, density peaking factor, and the ratio of the energy confinement time of the H-mode to that for Goldston's L-mode scaling. The parameters were $R = 2.45$ m, $a = 0.8$ m, $B_\phi = 4$ T, $I_p = 0.8$ MA, $P_b = 11$ MW (balanced), and $\bar{n}_e = 2.5 \times 10^{19} \text{ m}^{-3}$. Shot # 42935.

Figure 4. - Comparison between density profiles for a limiter H-mode and a supershot. $I_p = 0.9$ MA and $B_\phi = 4.8$ T in both cases.

Figure 5. - (a) Microwave scattering spectrum for a limiter H-mode. The transition is at ~ 4.04 sec (H-mode from ~ 4.04 sec to 4.42 sec) and ELMs begin at ~ 4.18 sec. Here $k = 5.5 \text{ cm}^{-1}$, $z = -0.7$ m, $R = 2.85$ m, $I_p = 0.8$ MA, $a_p = 0.8$ m, $B_\phi = 4$ T, and $P_b = 12.7$ MW (from 3.5 sec to 4.5 sec). (b) D_α signal (c) Spectrum digitized at fast rate. (d) Expanded D_α signal.

Figure 6. - Magnetic fluctuation measurements during an ELM; (a) The spectrum of a Mirnov loop during and before an ELM. (b) The mode number identification using a poloidal array and many toroidal coils. (Plasma parameters were $R_0 = 2.45$ m, $a = 0.8$ m, $I_p = 0.9$ MA, $B_\phi = 4.8$ T, and $P_b = 13$ MW and $n_e = 2.5 \times 10^{19} \text{ m}^{-3}$, H-mode transition at 3.9 sec.)

Figure 7. - (a) Correlation of ECE and D_α data. The ECE spikes precede the rise in D_α emission. (b) The disturbance moves radially outward with velocity of about 2×10^3 m/s. ECE emission frequency = 208 GHz. Plasma, beam, and machine parameters are the same as for Fig. 5.

Figure 8. - Comparison of transport between a supershot, an L-mode plasma, and a limiter H-mode. (a) χ_e , (b) χ_i .

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Fig. 1

Fig. 2

Fig. 3.

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Fig. 4

Fig 5 a,b

Fig. 5 c,d

a)

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b)

Fig. 6

Fig. 7