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Circular Limiter H-mode Plasmas in the Tokamak Fusion Test Reactor (TFTR)

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ABSTRACT

Circular 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 in other tokamaks. Bi-directional beam heating is required and the threshold power needed to induce the transition increases linearly with plasma current. 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 and the global confinement, τ_E, can be > 2.5 times L-mode scaling. Microwave scattering data from the edge plasma shows broad spectra at k = 5.5 cm^{-1} which begin at the drop in D_α radiation and are strongly shifted in the electron diamagnetic drift direction This implies a poloidal rotation, which begins at the transition to the H-mode, of ~ 10^4 m/sec. During an edge localized mode instability (ELM), these apparent rotations cease and Mirnov fluctuations in the 50-500 kHz range increase in intensity. Electron cyclotron emission data shows the origin of the ELMs and probably the transition layer to be located a few centimeters inside the plasma surface. A short review of requirements for controlled thermonuclear reactions is given in the introduction.

INTRODUCTION

Large-scale research and development efforts in the science and technology of fusion energy are underway in a number of countries including the United States, USSR, United Kingdom, France, Japan, and others. In addition, there are numerous plasma physics studies, both in theory and experiment, which are being carried out at universities and research laboratories around the world in both industrialized and developing nations. Though many of these may be small-scale efforts, all are providing information relevant to eventual harnessing of the fusion reaction of isotopes of hydrogen for energy and power production. The long term goal is to use the D-D reaction, so that the fuel could be extracted from sea water, and thus would be available to all countries. However, for near term goals, the requirements for fusion of a fuel mixture of deuterium and tritium (D-T) are less stringent. The reaction and products are as follows:

$$D + T \rightarrow {}^4He + n + 17.6\ MeV.$$

A sustained reaction of this fuel mixture in a magnetic confinement device requires a temperature greater than 100 million degrees Celsius (^oC) or ~ 8 to 10 keV. This is > 6 times hotter than the interior of the sun.

The 17.6 MeV of energy is in the form of 14.1 MeV of kinetic energy of the product neutron and 3.5 MeV for the alpha particle (^{4}He nucleus). The alpha particle is charged and will be trapped by the magnetic field, and thus is expected to provide a significant amount of self-heating of the burning D-T fuel. The energy of the neutron is expected to be converted to electrical energy similar to the process in a fission reactor. That is, by use of a moderating blanket around the fusion reaction chamber, with a heat exchange loop passing through the blanket coupling to the usual turbine for the thermal to electrical conversion. However, unlike the fission reactor, the fusion reactor would be inherently free of the possibility of a meltdown accident similar to those which occurred at Three Mile Island and Chernobyl.

The requirement for obtaining a burning plasma in a fusion reactor is usually given as the lower limit on the triple product of the plasma (D-T fuel mixture) particle density n_e, temperature T, and the time, τ_E, the energy deposited for heating to fusion temperature is held before it is lost; where τ_E is usually referred to as the energy confinement time. For a D-T plasma at a temperature of 10 to 20 keV, this product, $nT\tau_E$, is $\sim 1.5\text{-}3 \times 10^{21}$ sec•keV•m^{-3}. At these high temperatures the plasma must be held or "confined" using non-material bottles. The tokamak is the most promising magnetic confinement approach. A schematic drawing of a tokamak, showing some of its main components and parameters, is shown in Fig. 1. For tokamaks, there are several confinement regimes, each with different characteristic variations in τ_E. The most prominent of these are the low or L-mode,[1] the high or H-mode,[2] and the supershot.[3] Here we report results for a new regime, the TFTR (Tokamak Fusion Test Reactor) circular limiter H-mode,[4-6] which apparently is a combination of the usual H-mode and the supershot.

During the early 1980s, results from different tokamaks around the world were found to be well defined by low mode scaling, given by the following empirical relation:[1]

$$\tau_E = 0.037\, I_p P_b^{-0.5} R_p^{1.75} a_p^{-0.37}.$$

Where I_p is in MA, P_b in MW, R_p and a_p in meters, and τ_E in seconds. In 1982, the "H-mode" or high confinement regime[2] was obtained on a tokamak in Germany called ASDEX. In this regime, the plasma energy was held two or more times [τ_E(H-mode) $\geq 2 \cdot \tau_E$(L-mode)] as long as for the L-mode. This implies that the energy transported out of the H-mode plasma is reduced due to the establishment of an edge transport barrier. A bifurcation in confinement occurs with essentially an instantaneous transition from the L- to the H-mode regime taking place. Thus, the density and temperature at the edge increase dramatically. The increased density at the edge causes the plasma to take on the flat $n_e(r)$ profile associated (historically) with the H-mode. A new regime of operation called the "supershot" found in TFTR located at the Princeton University, Plasma Physics Laboratory in Princeton, NJ was reported in 1987.[3] In contrast to the usual

H-mode, as typified by the ASDEX tokamak, the supershot has a density profile which is peaked at the center. Thus, the improved confinement in this case is at the center of the plasma rather than the edge.

Recently on TFTR, a transition from the supershot to the H-mode was obtained. This leads to an H-mode with a centrally-peaked density profile. The main change from the supershot is that particle and energy confinement at the plasma edge are enhanced while the centrally-peaked $n_e(r)$ profile of the supershot is retained. A schematic drawing showing the minor cross section of TFTR along with conceptual drawings of n_e profiles of the L-mode, normal H-mode, and the TFTR limiter H-mode for purposes of comparison are shown in Fig. 2. In TFTR, the vacuum vessel, plasma, and limiter (structure which "limits" contact of the hot plasma with material surfaces) have minor radii which are circular. The original ASDEX H-modes were obtained using a divertor magnetic configuration. TFTR has no divertor but does have a limiter, and thus the name "circular limiter H-mode." The central peaking of the n_e profile is important for fusion reactor considerations since this makes the most efficient use of available power by placing additional fuel particles at the center of the plasma where it is hottest.

CHARACTERISTICS OF TFTR LIMITER H-MODES

The operational parameter range for obtaining limiter H-modes on TFTR are plasma current I_p = 0.8 - 1.7 MA, toroidal field B_ϕ = 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) powers, P_b ~ 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. Co-NBI means that the heating beam atoms are injected into the plasma in the direction parallel to plasma current flow, and counter-NBI means injection anti-parallel to I_p. Balanced-NBI means that equal power is injected in both the co- and counter- directions. No H-modes have been obtained with all co- or all counter-NBI. (3) The threshold power for the supershot to H-mode transition is linearly dependent on I_p, and (4) the threshold power also 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.

Characteristic features of the TFTR limiter H-modes agree in general with those of other tokamaks;[7] however, there are differences. Figure 3 shows the time evolution of some of the plasma parameters typical of the TFTR limiter H-mode: the D_α, CII, $n_e\ell$(edge), T_e(edge), $n_e(0)/\langle n_e \rangle$, and $\tau_E/\tau_{E,L\text{-mode}}$. The features seen here, and usually observed in other tokamaks, are the drops in D_α and CII light (CII drop is usually larger than the D_α) at the transition, with corresponding increases in edge n_e, T_e, 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-modes. During the transition, there is an increase in n_e across the entire profile; however, the largest fractional increase is at the plasma edge (outer 20 cm). A time series of n_e profiles showing the evolution of a TFTR limiter H-mode is shown in Fig. 4. For comparison, a similar set of profiles for a supershot are also shown. The maximum peaking factors, $n_e(0)/\langle n_e \rangle$, were ~ 2.5 and 2.2 for the supershot and H-mode plasmas, respectively. The transition usually occurs within 150 msec to > 600 msec after beam turn-on. This delay appears to be inversely dependent on beam power. The D_α drop at the transition to the H-mode 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. However, 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 msec period, compared to ≤ 2 msec for H-modes in divertor tokamaks. Circular limiter H-modes of ~ 1.5 sec duration have been obtained on TFTR and the duration appears to be limited only by the beam pulse length.

The I_p dependence of the power required to obtain H-modes can be seen from Fig. 5 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. 5 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, n_e is usually $\geq 2 \times 10^{19} m^{-3}$ 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.

RESULTS FROM FLUCTUATION STUDIES

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 (probably indicative of a decrease in plasma turbulence). The drop in D_α indicates a change in particle transport at the edge and 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 system[8] show broadband activity at $k_\theta = 5.5$ cm^{-1} in the electron diamagnetic direction. A contour plot of scattered power as a function of frequency and time is shown in Fig. 6a for a limiter H-mode with nominally balanced beam injection. This spectrum has fluctuations up to 1.8 MHz located near the plasma edge (z = -0.7 m ± 0.2 m, R = 2.85 m) and is consistent with wave activity propagating poloidally at a velocity $v_\theta \sim 10^4$ m/sec. This feature begins to grow at the time of the transition reaching a steady state value during the ELM phase and persisting for the duration of the H-mode. No similar activity is observed in the central region of H-mode discharges, indicating that the poloidal rotation is mainly near the plasma edge. Fast time resolved microwave scattering data shows narrowband fluctuations to be enhanced dramatically at the time of the ELM while the shifted spectral feature, more apparent in the time averaged data of Fig. 6a, 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 indicating that the implied rotation is associated with the general H-mode phenomenon.

ELMs can lead to a significant loss of stored energy resulting in a cessation of the rise of stored energy and density after the H-mode 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, 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.[9] 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 coils were used to characterize the mode responsible for the ELM. The data were digitized at 2 MHz and showed an increase in the intensity of high frequency (50 to 500 kHz) magnetic fluctuations just before (a precursor to) an ELM (usually taken to be the burst of D_α light). The oscillations were in phase toroidally for all of the coils in the upper half of the torus and 180^0 out of phase with the coils mounted in the lower half of the torus, indicating an up/down motion of the plasma during the precursor magnetic fluctuations. The fast digitization of the data allowed identification of the dominant mode of oscillation, which was found to be an m=1, n=0 MHD mode. This is in contrast to the ASDEX results[10] where m=3 or 4 and n=1. Thus, the TFTR ELM precursor is not ballooning in structure, unlike precursors on ASDEX. High frequency precursor oscillations have also been observed on PBX.[11]

Data from the grating polychromator (GPC), with a 10 μsec time resolution, are shown in Fig. 7. Intense ECE spikes, with a 20 to 30 μsec duration, sometimes precede the rise in D_α emission and occur after or simultaneously with the high frequency magnetic oscillations monitored by the Mirnov coils. The increase in ECE (the spikes) begins and ends before there is any appreciable increase in D_α light (compare the middle signal of Fig. 7 with the signal at the bottom of the figure). The spikes are consistent with the dumping of electrons (of energy ~ 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 ~ 2×10^3 m/sec. The D_α signal begins to increase at about the time the burst of electrons reaches the wall. Chord averaged soft X-ray emissivity, with a tangency radius of 0.7 m (a_p = 0.8 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 m drops 0.6 msec later, indicating that the effect of the ELM propagates slowly inwards from a region near the plasma edge. Further studies are being done to determine if, in general, the same MHD mode (indicated by the Mirnov coil system) and spatial origin (indicated by the ECE data) are common for all occurrences of ELMs in TFTR.

COMPARISONS WITH THEORY

Some qualitative comparisons of the TFTR limiter H-mode results with various theoretical models can be made. If the shift in frequency of the microwave scattering data is interpreted as a poloidal drift in the electron diamagnetic direction, an inwardly pointing radial electric field can be inferred. This is in agreement with the predictions of Itoh & Itoh,[12] and with v_θ measurements on other tokamaks.[13,14] 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.[15] Qualitative agreement with Biglari, et al.[16] 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 apparent poloidal rotation during the ELMs is also in qualitative agreement with the model of Biglari, et al.

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 is 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 measurements show the onset of poloidal rotation at the transition, which persists 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 0.2 m of the plasma edge but 0.3 m inside of the scrapeoff. There are no strong low-m modes before ELMs, however, high frequency (50 - 500 kHz) precursor magnetic oscillations have been observed for some ELMs and were found to be $m = 1$, $n = 0$ standing waves and were not ballooning in structure.

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FIGURE CAPTIONS

Fig. 1. - Schematic drawing of a tokamak. I_p is the current flowing through the plasma and B_t (or B_ϕ) is the main toroidal magnetic field. TFTR has 20 toroidal field coils.

Fig. 2. - Illustration comparing density profiles for the L-mode, normal H-mode, and the TFTR circular limiter H-mode.

Fig. 3. - Characteristics of a TFTR limiter H-mode of 1.5 sec duration. Shown are the D_α, CII, edge chord averaged density $n_e \ell$, T_e(edge), density peaking factor, and the ratio of the energy confinement time of the H-mode to that for Goldston 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 $n_e = 2.5 \times 10^{19} m^{-3}$. Shot # 42935.

Fig. 4. - Comparison between density profiles for a limiter H-mode and a supershot, for four times during each plasma. $I_p = 0.9$ MA and $B_\phi = 4.8$ T in both cases.

Fig. 5. - 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 for the threshold (minimum) power, P_{th}, required for a transition to the H-mode is indicated.

Fig. 6. - Microwave scattering spectrum for a limiter H-mode and corresponding D_α signal. The transition is at ~ 4.57 sec (H-mode from ~ 4.57 sec to 5 sec) and ELMs begin at ~ 4.8 s. Here $k = 5.4\ cm^{-1}$, $z = -0.7$ m, $R = 2.85$ m, $I_p = 1.05$ MA, $a_p = 0.8$ m, $B_\phi = 4.8$ T, and $P_b = 14.5$ MW (from 4 s to 5 sec).

Fig. 7. - Correlation of ECE and D_α data. The ECE spikes precede the rise in D_α emission. The disturbance moves radially outward with velocity of about 2×10^3 m/sec. The ECE emission frequency was 208 GHz. Plasma, beam, and machine parameters were the same as for Fig. 5.

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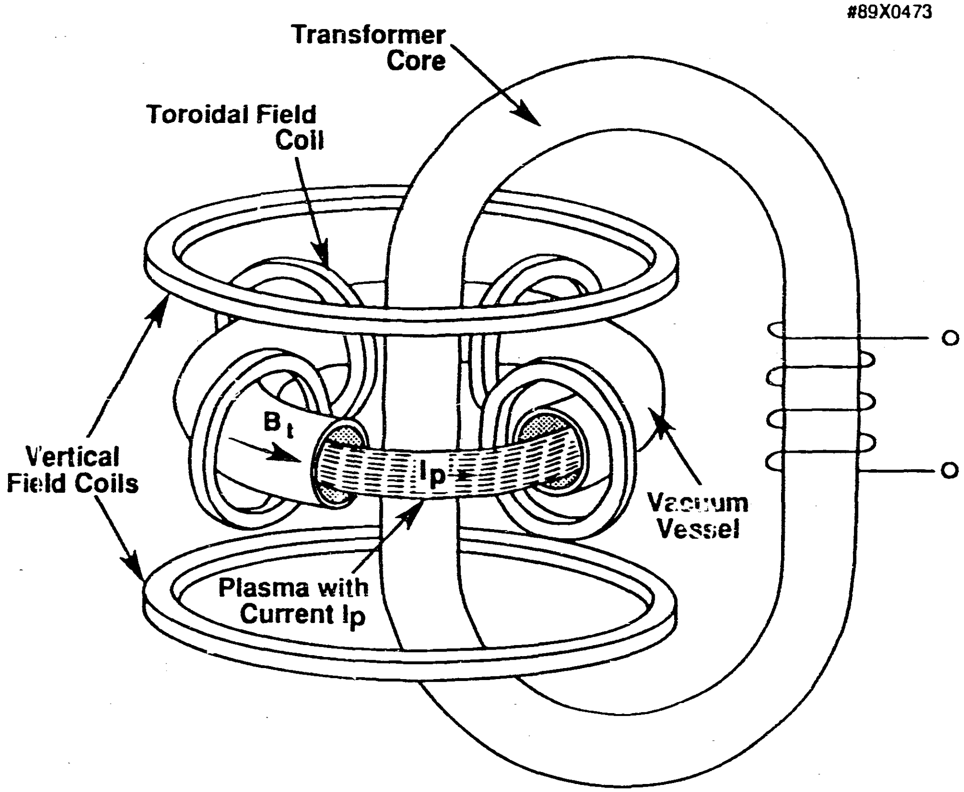
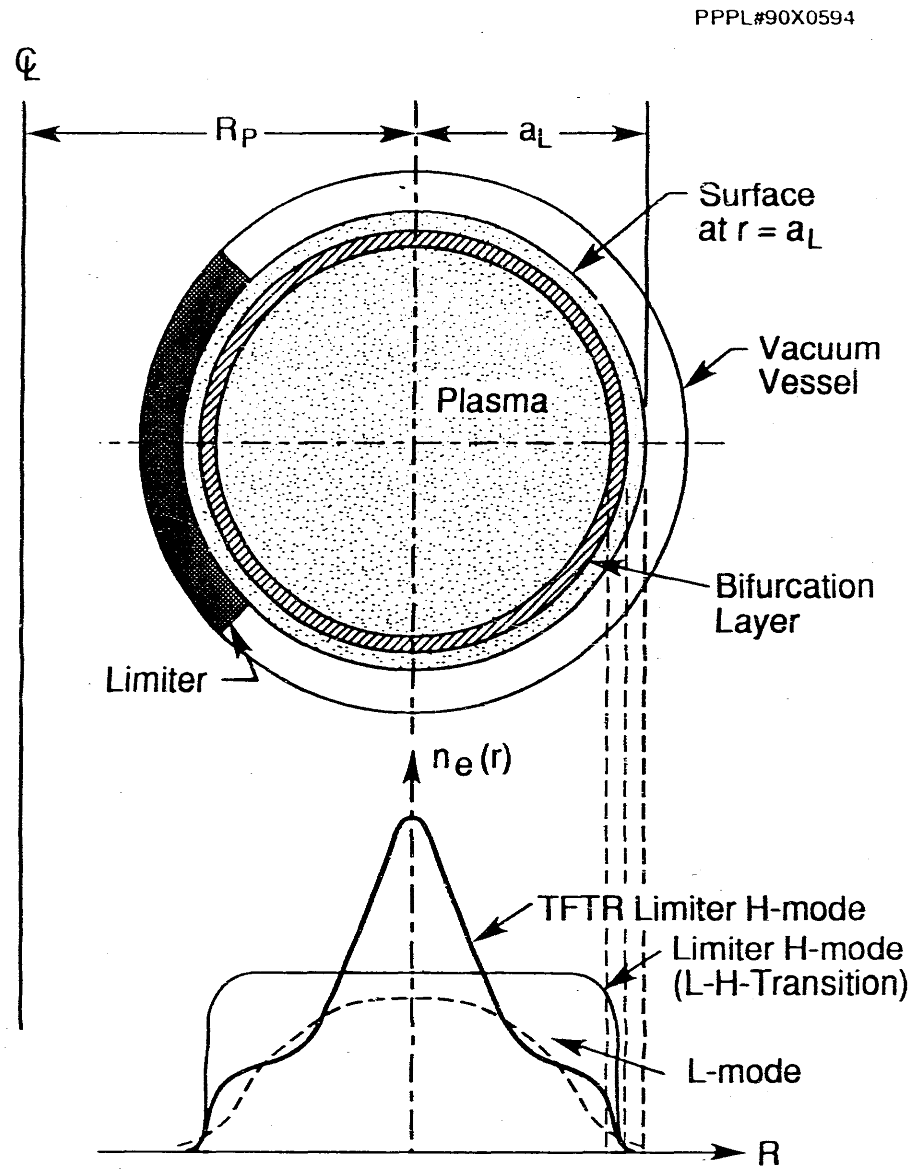

#89X0473
Transformer Core
Toroidal Field Coil
Vertical Field Coils
Vacuum Vessel
Plasma with Current Ip
Bt
Ip
FIG. 1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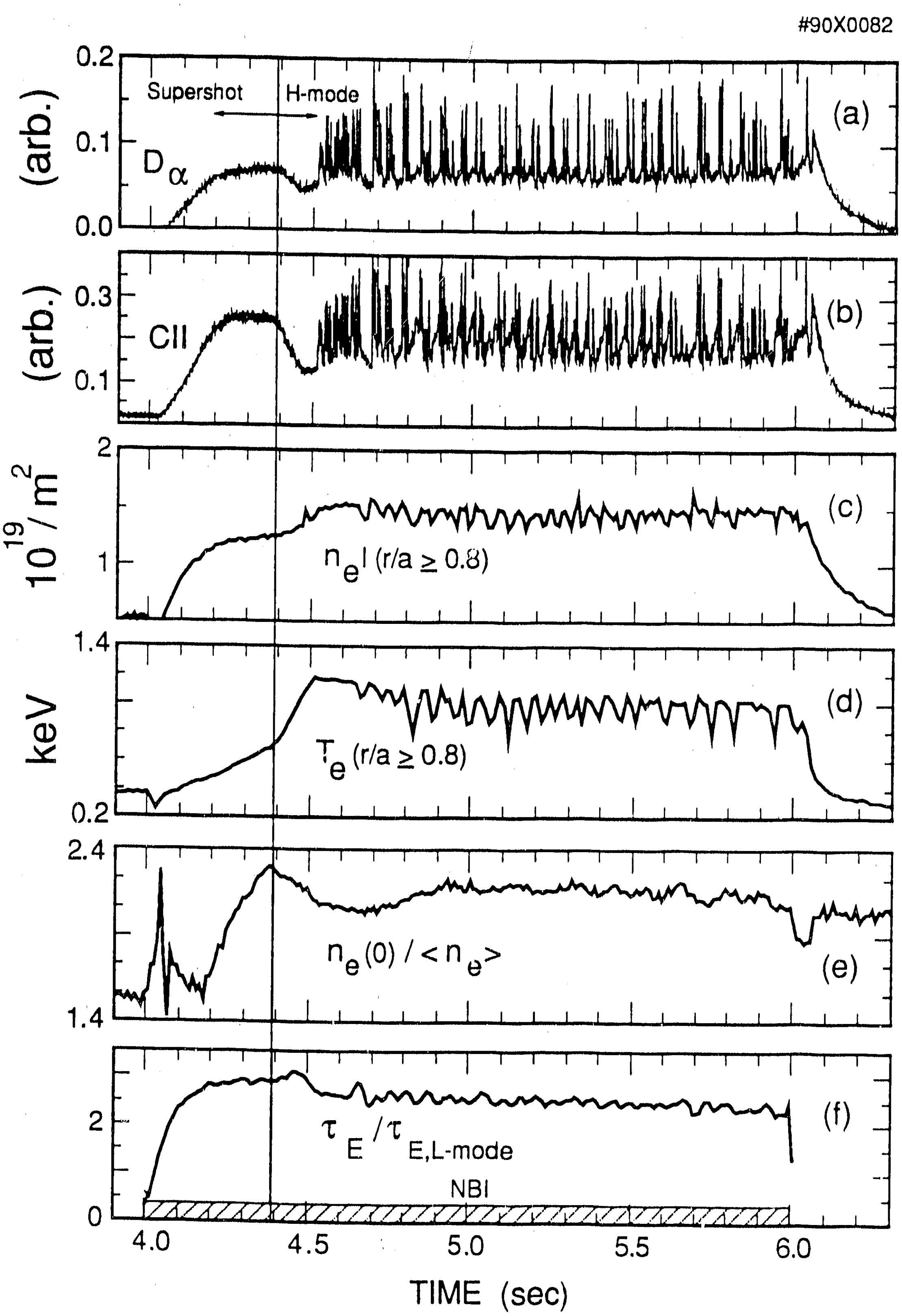
RP
aL
Surface at r = aL
Vacuum Vessel
Plasma
Bifurcation Layer
Limiter
ne(r)
TFTR Limiter H-mode
Limiter H-mode (L-H-Transition)
L-mode
R
FIG. 2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Supershot
H-mode
(arb.)
Dα
(a)
(arb.)
CII
(b)
10^19/m^2
n_e l (r/a ≥ 0.8)
(c)
keV
T_e (r/a ≥ 0.8)
(d)
n_e(0) / < n_e >
(e)
τ_E / τ_E,L-mode
(f)
NBI
TIME (sec)

Fig. 3

#90X0308

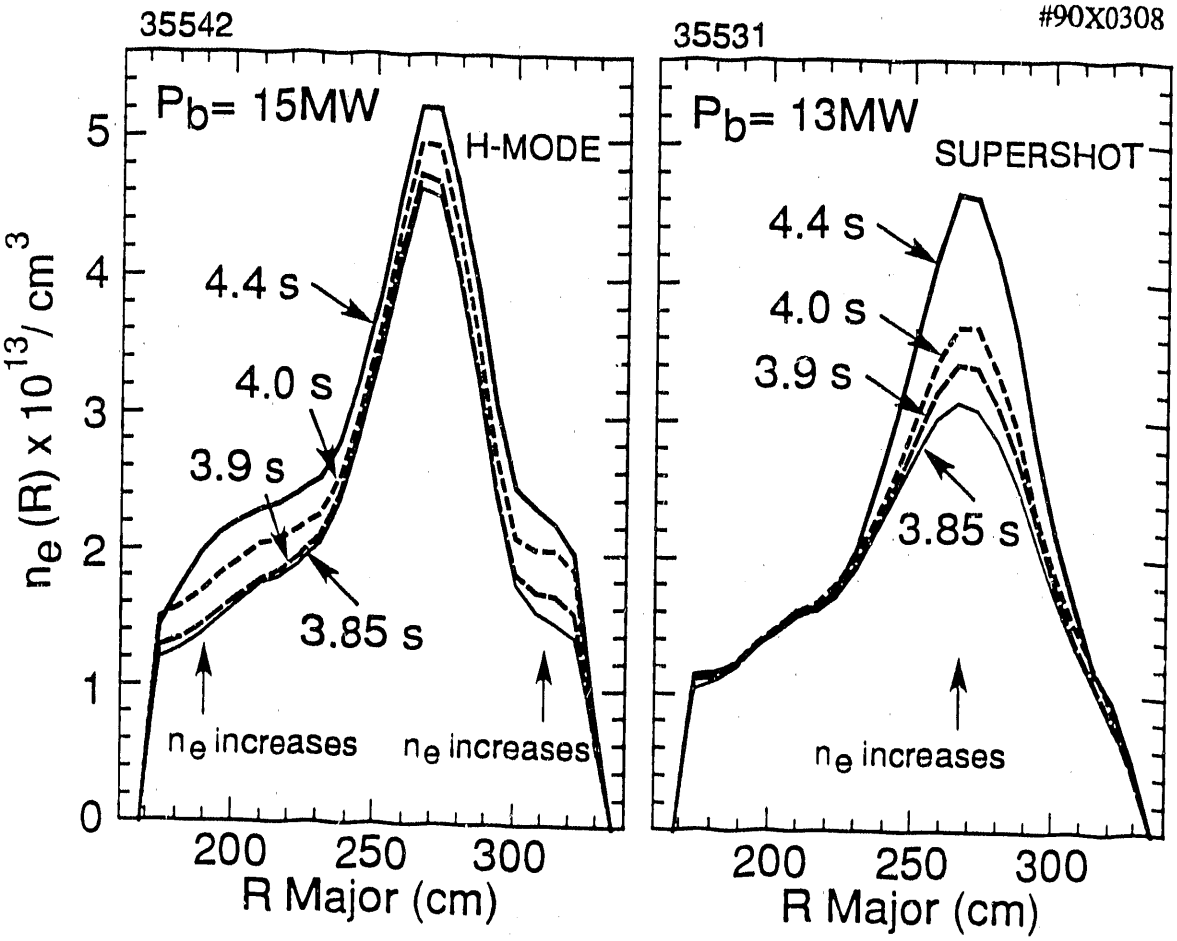

Fig.4

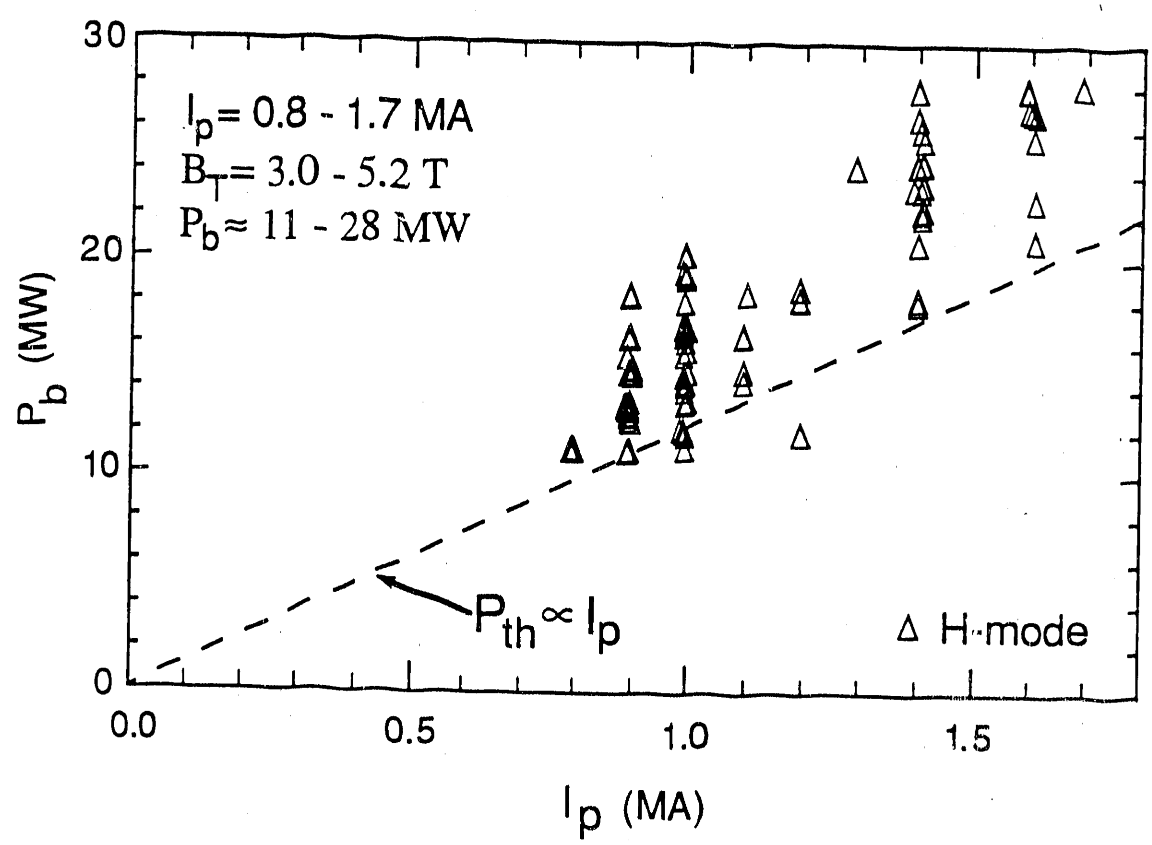

Fig.5

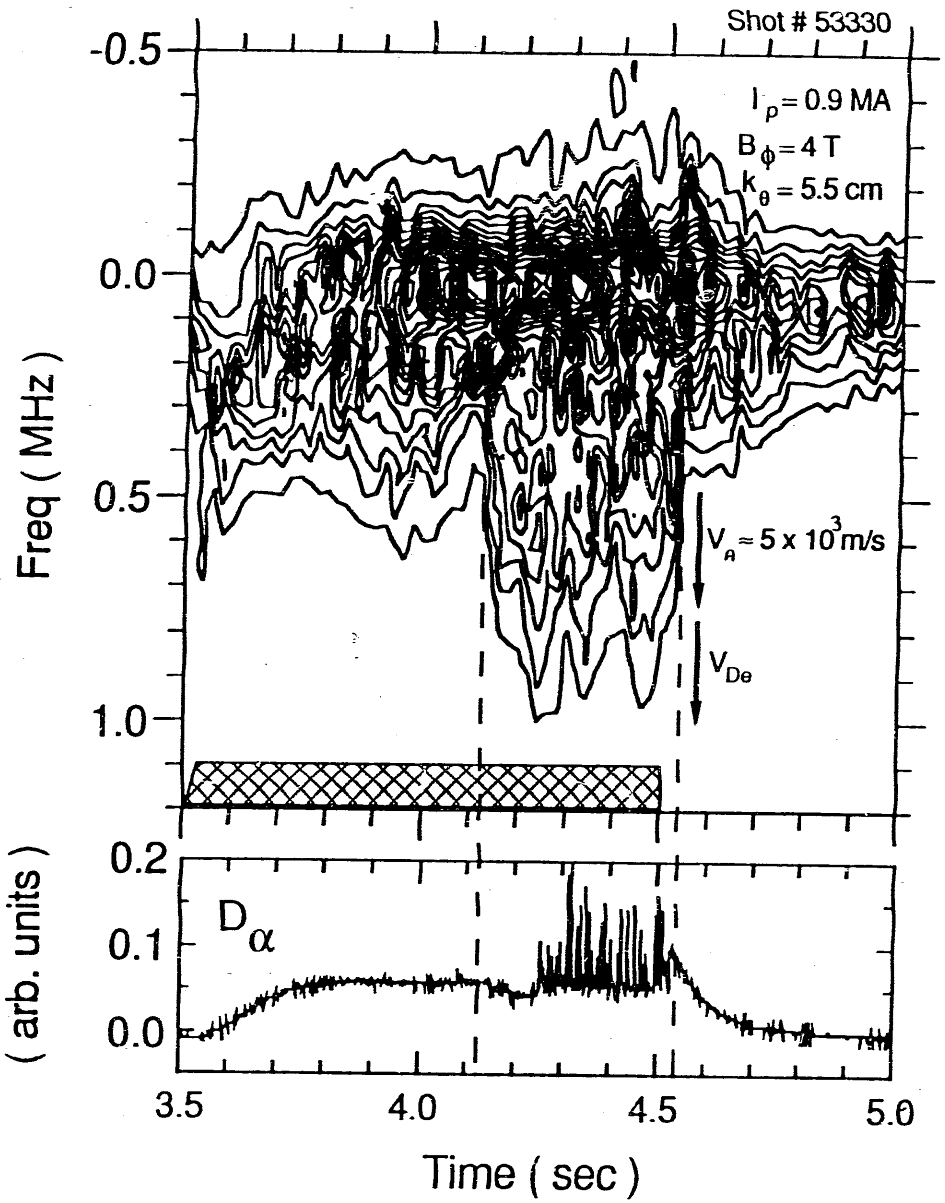
Shot # 53330
Ip = 0.9 MA
Bφ = 4 T
kθ = 5.5 cm
VA ≈ 5 x 10³ m/s
VDe
Freq (MHz)
-0.5
0.0
0.5
1.0
Dα
(arb. units)
0.2
0.1
0.0
3.5
4.0
4.5
5.0
Time (sec)

Fig.6

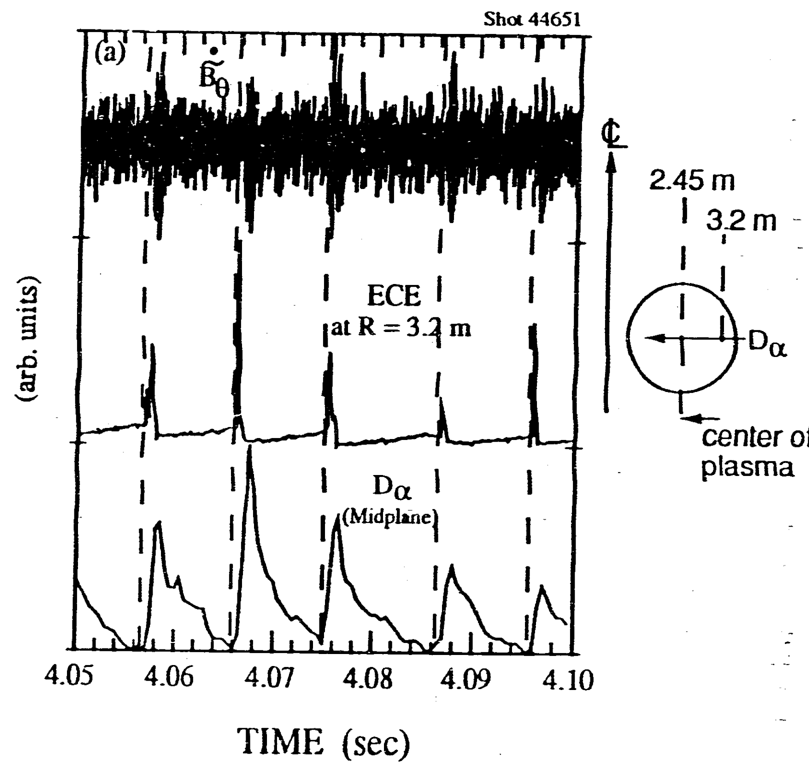
Shot 44651
(a)
Bθ
ECE
at R = 3.2 m
Dα
(Midplane)
(arb. units)
4.05
4.06
4.07
4.08
4.09
4.10
TIME (sec)
2.45 m
3.2 m
Dα
center of
plasma

Fig.7

CIRCULAR LIMITER H-MODE PLASMAS

ON THE

TOKAMAK FUSION TEST REACTOR (TFTR)

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