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A new phenomenon has been observed in TFTR discharges with neutral beam injection and slowly ramped plasma current. When $q_{\psi}(a)$ reaches certain values close to low-order rational numbers, the D_{α} emission decreases and the electron density profile broadens and increases, similar to observations during the H-mode in other tokamaks. This "*q*-mode" appears to have a neutral beam power threshold of ~ 6 MW. During co-injection, the plasma toroidal rotation decreases by $\sim 50\%$ at the transition. Very slowly toroidally rotating coherent edge modes, which slow and lock at the transition, were identified from the measured perturbations in $\tilde{B}_{\theta}$ with $m/n \sim q_{\psi}(a)$.

Calculations based on a tearing-mode model indicate that large islands, consistent with these measurements, could be present in the plasma edge and alter the plasma-limiter interaction. At the transition Z_{eff} increases typically from 3 to 3.5. This increase and the electron density increase are caused largely by an increase in the carbon density. These increases raise the drag on fast ions, rapidly thermalizing some of the energy stored by beam ions, causing a transient rise in the plasma thermal energy. In addition, the global energy confinement time increases transiently.

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The energy confinement time, τ_E , is too low for breakeven or ignition conditions in presently operating tokamaks. In L-mode discharges, τ_E scales unfavorably with increasing auxiliary heating power,¹ but in divertor H-mode discharges, it is sometimes twice the L-mode value, and it may scale more favorably with power.² A limiter H-mode was observed in JFT-2M.³⁻⁴ There, small increases in τ_E and density were observed, and the H_α transitions had brief (~ 50 ms) durations.

Several experiments were done in TFTR to attempt to achieve an H-mode using the toroidal inner limiter. In JFT-2M, the safety factor at the plasma edge, $q_\psi(a)$, was typically low ($\sim 2-4$), and the threshold power for the transition to the H-mode was seen to scale with $q_\psi(a)$, so TFTR was operated at low $q_\psi(a)$ and the plasma current, I_p , was ramped slowly during neutral beam injection.

The discharges exhibited a phenomenon which we call the " q -mode" when $q_\psi(a)$ passed into certain ranges such as $\sim 3.05-3.15$. The electron density profile $n_e(r,t)$ broadened, while the D_α emission detected at some of the views decreased abruptly. These constitute the signature of the q -mode.

Phenomenology - Figures 1-4 show plasma conditions for a q -mode discharge. Nine MW of D^0 beam power were co-injected (co-parallel to I_p) into D^+ plasma between 2 and 4 s. Traces of the chord-integral electron density, shown in Fig. 1a, increase when the neutral beam injection starts, then increase again at 3.1 s when the transition occurs. Concurrently, the D_α emission decreases and $q_\psi(a)$ decreases below 3.15. (The systematic uncertainty in the $q_\psi(a)$ measurement is $\sim \pm 0.1$). The increase in $\beta_{p, dia}$ lasts 0.3 s, and the increase in the neutron production rate, indicated in Fig. 1b, lasts 0.2 s.

Figure 2a-d shows four other views of chord-integral D_α emission (produced predominantly from D^0 recycled from the inner limiter). The intensities decrease at 3.1 s, then exhibit periodic modulation with different phases in the different views. The sum of the D_α signals drops 30%, and then oscillates. The soft X-ray emission and the fluctuations of the poloidal magnetic field, $\tilde{B}_\theta$, measured by some of the Mirnov coils have similar modulations. The time integral of a Mirnov coil signal from the inside midplane is shown in Fig. 2e. These observations indicate a helical structure rotating toroidally in the co-direction with a velocity of 1.5×10^3 m/s from 3.11 to 3.15 s, then slowing to 2.5×10^2 m/s at 3.2 s, and finally stopping or locking at 3.25 s. TV images of visible light, D_α emission, and C II (510 nm) and C III (530 nm) line emissions show localized bright spots near the limiter.

Figure 3a shows the electron temperature, $T_e(x,t)$, measured near the midplane at various distances x from the plasma edge at the inner limiter. The

temperature at $x \sim 1-8$ cm decreases and flattens when the transition occurs and has modulations similar to those in Fig. 2. Closer to the plasma center (at $x \approx 34$ cm) $T_e(x,t)$ is relatively constant until large amplitude sawteeth occur. The electron density profile, $n_e(r,t)$, shown in Fig. 3b broadens toward the inner limiter, then rises after the transition.

Figure 4a shows that the charge-exchange efflux of energetic ($\sim 10-100$ keV) beam ions drops precipitously by a factor of ~ 10 within 120 ms after the transition. Co-injection was used for most of the experiments aimed at obtaining the q -mode. For these discharges, the central toroidal rotation velocity, $v_\phi(0,t)$, shown in Fig. 4b, decreases by $\sim 50\%$. This decrease occurs simultaneously with the decrease in the rotation of the modulations shown in Fig. 2.

Several attempts with approximately balanced injection and with slightly more counter-injection than co-injection also resulted in the q -mode, but $v_\phi(0,t)$ was small and did not change significantly at the transition. Also β_{pdia} decreased or remained unchanged, unlike the co-injection cases.

The visible bremsstrahlung signal increased at the transition, often $\sim 120\%$. The radiated power profile measured by a bolometer array had a hollow profile, with the radiating ring moving radially inward and becoming slightly narrower after the transition. The total radiated power decreased slightly ($\sim 10\%$). Probes in the scrape-off region 25 cm from the last-closed-flux (LCF) surface measured a decrease in the ion saturation current.

The q -mode has been observed under a variety of plasma conditions. The toroidal field varied from 2.8 to 4.8 T, and the minor radius varied from 67 to 83 cm. All the discharges were on the inner limiter and the shortest distance between the LCF surface and the movable limiter varied from $\sim 7-16$ cm. Ranges in $q_\psi(a)$, in the neutral beam power threshold, P_{NB} , and in the line-averaged electron density, $\bar{n}_e$, are summarized in Table I. Most of the observations have $q_\psi(a) = 3.0-3.2$, and for these, I_p is $\sim 1-1.5$ MA. Transitions were seen with $q_\psi(a)$ entering this range from either higher or lower values. The power threshold is ~ 6 MW.

The range in $\bar{n}_e$ prior to the transition is limited, so neither upper nor lower $\bar{n}_e$ thresholds can be deduced from the data. Usually no gas-puffing (except for a pre-fill) was used, though several shots with gas puffs during neutral beam injection had transitions. The discharge in Figs. 1-4 had D_2 gas-puffing of 40 Tl/s between 2.5 and 2.95 s. The lowest value of $\bar{n}_e$ prior to the transition was $2.4 \times 10^{19}/m^3$. With the limiter conditioning necessary for achieving supershots,⁵⁻⁶ $\bar{n}_e$ prior to neutral beam injection is $(0.4-1.0) \times 10^{19}/m^3$.

Transitions with $q_\psi(a) = 2.5-2.6$ were always preceded by a 3.0-3.2

transition, and often led to disruptions. The signatures of these were poor (with brief D_{α} transitions and small increases in $\overline{n_e}$). The transitions with $q_{\psi}(a)$ above 4 had very small $\overline{n_e}$ increases.

Analysis - The Mimov coil signals were analyzed to find resonant modes. During some q -mode discharges, slowly rotating modes were identified with the ratio of the poloidal and toroidal periodicities, m/n being less than, but close to $q_{\psi}(a)$. A 3/1 mode was identified for the discharge in Figs. 1-4. The helicity of the mode agrees with the toroidal and poloidal time delays for the various measurements of the modulations. Figure 2e shows that the intensity of the mode, indicated by the magnitude of the modulations, grew from the start of the transition until the mode appeared to stop or lock at ~ 3.25 s. Locked modes and modes with $m > 5$ are difficult to identify accurately in TFTR, so possibly all of the transitions had locked modes near the LCF surface with $m/n < q_{\psi}(a)$. Cases where modes were identified are shown in Table I.

Detailed transport analysis with the TRANSP code⁷⁻⁹ was performed for nine q -mode discharges. Values for the electron energy transport coefficient, $\chi_e(r,t)$, were calculated from the observed profiles and the ion energy transport coefficient, $\chi_i(r,t)$, was assumed to be $f \chi_e(r,t)$ where $f=1-3$. The heat convection multiplier was assumed to be $g=5/2$ or $3/2$. The values $f=2$ and $g=3/2$ gave reasonable agreement with the measured $\beta p^{dia}(t)$ and the central ion temperature, $T_i(0,t)$; these also give reasonable agreement for other TFTR discharges where the profile $T_i(r,t)$ was measured.¹⁰

The calculated $q_{\psi}(r)$ profiles and the toroidal current density profiles $j_{\phi}(r)$ were used to calculate the radial eigenfunctions of the resistive linear tearing mode.¹¹⁻¹² The measured amplitude of the Mimov signals and the radial mode structure were used to calculate the helical flux contours. Figure 5 shows the resulting islands for the discharge in Figs. 1-4. The peak in the D_{α} emission, in B_{θ} and in T_e correspond to the X-point between the islands. The island location intersects the limiter, whose presence, however, is not included in the model.

The island width is predicted to grow in time as the square root of the amplitude of the modulations shown in Fig. 2e. The width is in rough agreement with the range in x where $T_e(x,t)$, shown in Fig. 3a, oscillates coherently. Kink modes appear less compatible with the observations, but cannot be eliminated.

The effective ion charge, $Z_{eff}(t)$, calculated from the visible bremsstrahlung emission, generally decreases with increasing $\overline{n_e}$ until the transition occurs, and then increases ~ 0.5 , as shown in Fig. 6a. Carbon and oxygen line emission increases as well. Modeling of these measurements with the MIST

code¹³⁻¹⁴ indicates that the oxygen concentration was $\sim 1/10$ the carbon concentration and that metallic impurities had negligible relative concentrations ($\sim 10^{-3}$ that of carbon). The value of Z_{eff} measured by a pulse-height-analyser (PHA) agrees well with the calculated $Z_{\text{eff}}(t)$. The PHA value for the metallic contribution to Z_{eff} was 0.22.

Assuming that the deviation of $Z_{\text{eff}}(t)$ from 1 is caused by carbon and oxygen, the density of electrons from them can be calculated. The result, plotted in Fig. 6b, shows that most of the increase in the volume-averaged electron density, n_e , is attributed to carbon. Subtleties of profile distributions of the impurities and Z_{eff} were not included in this analysis. The effects of these uncertainties could result in all of the increase in n_e being due to carbon and oxygen. This result is not dissimilar to observations during the H-mode in JET.¹⁵

If the carbon comes from the inner limiter, which is covered with graphite tiles, then the carbon electron source would be in the plasma near the inner limiter. This would explain the increase of $n_e(x,t)$ near the inner limiter, shown in Fig. 3b. The n_e profile measured by Thomson scattering along the midplane does not exhibit the bump near the inner limiter, so the bump is believed to occur near the plasma edge close to the limiter, but above and below the midplane.

The increase in density reduces the slowing down time for beam ions, thus the calculated beam power deposited in electrons and impurities, shown in Fig. 6c, increases at the transition. The beam power deposited directly on deuterium increases by a relatively small amount; however, energy is rapidly equilibrated among the ions. The kinetic energy stored in the fast co-moving ions from the neutral beams, shown in Fig. 6d, decreases, in qualitative agreement with the decrease in charge-exchange efflux shown in Fig. 4a. Figure 6d also shows the decrease in rotational energy. In the TRANSP calculations, the beam ion and rotation energy were converted to thermal energy, causing a transient increase in heating power when the transition occurred.

The calculated thermal energy confinement time, τ_E , is shown in Fig. 7. Before the transition it is 15% larger than the prediction from Goldston's L-mode scaling for $H^0 \rightarrow D^+$ discharges,¹⁶ and it increases by $\sim 15\%$ at the transition due to the increased thermal energy. Most of the other q -mode discharges analysed had τ_E closer to, or below the L-mode scaling value before the transition, and had smaller increases during the transition.

Discussion - Apparently, a necessary condition for the q -mode is the occurrence of resonant surface modes which rotate slowly or lock. Observations in other tokamaks of islands (TEXT¹⁷⁻¹⁸) and of locked modes (ATC,¹⁹ JET,²⁰ and

DIII-D²¹) indicate that both are deleterious to plasma performance. However, it has been suggested²² that coherent surface modes may reduce edge turbulence, which is believed to be a cause of edge transport.

What causes $\bar{n}_e$ to increase and the D_α emission to decrease is not obvious. An increase in the global particle confinement τ_p would cause both since the rate of carbon and deuterium leaving the plasma would decrease. However, if τ_p is proportional to τ_E , which increases at the transition, but decreases soon after, $\bar{n}_e$ should decrease as well. Generally, the $\bar{n}_e$ increase and the D_α emission decrease last much longer. Possibly a bifurcation occurs at the transition, leaving τ_p at a larger value.

An enhanced source of carbon could also explain the increased density. The limiter temperature remained below 300° C, so it was not hot enough to sublimate carbon. Another possible source is increased sputtering, which could be caused by an increase in the number or energy of the sputtering particles. If high energy ions escape through the X-points between islands, they would increase the sputtering. Their escape would increase the charge-exchange efflux, but the charge-exchange detector measured a large decrease of the 8-110 keV efflux after the transition.

A more likely mechanism of increasing the carbon source is that the LCF surface becomes distorted, modifying the region of contact of the plasma with the limiter. The calculated islands (Fig.5) imply a large distortion. Since the shape of the inner limiter is toroidal, small changes in the plasma shape cause large displacements of the plasma contact with the limiter. An amorphous layer of carbon deposits onto low flux areas of the limiter during or after each discharge.²³ The distorted plasma boundary transiently increases the plasma flux on these normally low flux areas, and could increase the sputtering or ablation of carbon from these areas. Since these areas are above and below the midplane, the increased electron source would be in regions measured by the infrared laser interferometry along vertical chords near the inner limiter, but not along the midplane measured by Thomson scattering.

The reduction of D_α emission indicates a decrease of D^0 recycled from the walls. The source of D^0 is given by $N_D R / \tau_p$, where N_D is the number of D^+ within the LCF surface and R is the recycling coefficient. As seen in Fig. 6b, N_D increases slightly, so the decrease in D_α could be caused by either an increase of τ_p or a reduction of R . The latter could be caused either indirectly by increased co-deposition of deuterium onto the new carbon layers caused by the increased efflux of carbon, or directly by the distortion of the LCF surface. During steady-state portions of discharges, the region of contact appears to become

saturated with deuterium, but if the contact changes, unsaturated regions could become available to absorb more deuterium. During growing plasmas, the plasma boundary intercepts unsaturated limiter areas, so R and D_α should decrease similarly.

Comparisons - The q -mode has many of the features of the H-mode. Besides the D_α transition and the power threshold, both exhibit increases in τ_E and Z_{eff} , broadening of $n_e(r)$, and decreases in the amplitudes of the charge-exchange efflux and the ion saturation currents in the scrape-off layer. Differences are the requirement of special $q_\psi(a)$, the drop in $T_e(r)$ near the edge, and the absence of edge relaxation modes (ERPs or ELMs). Also in the H-mode, the increase in τ_E sometimes lasts longer, and the decrease in D_α is attributed to an increase in τ_p , not a decrease in R .

Some of the differences may be superficial. Calculations²⁴ of field line traces and guiding center orbits in ASDEX indicate that islands are present at rational surfaces near the separatrix, limiting $q_\psi(r)$, so the edge structure of diverted H-mode discharges may be similar to that in q -mode discharges. The drop in $T_e(r)$ near the radial location of the island (Fig.3a) causes the $T_e(r)$ profile to become steeper at values of r less than those where the mode occurs, and steeper $T_e(r)$ gradients are usually observed in H-mode discharges.

Enhanced confinement was seen in scoop limiter discharges in PDX,²⁵ but although the D_α emission was low, D_α transitions were not observed and impurity fueling alone could not explain the rise in density in these discharges. Since the q -mode involves an increase in impurities, it resembles the Z-mode seen in ISX,²⁶ where injection of impurities such as neon caused a rise in τ_E , but no D_α transition. Injection of methane into ISX could not cause the Z-mode.

Summary - The q -mode in TFTR consists of a decrease in D_α and an increase in $\bar{n}_e$ when $q_\psi(a)$ obtains certain values such as ~ 3.1 . Slowly rotating coherent edge modes were identified. Much, if not all, of the increase in $\bar{n}_e$ is caused by an increase in carbon. We speculate that distortion of the LCF surface by islands causes the increase in carbon and a decrease in R . This decrease in R , possibly combined with a transient increase in τ_p , causes the decrease in D_α emission. A transient rise in τ_E was computed.

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Table I

Ranges of $q_\psi(a)$ and parameters where the q -mode has been observed and the m/n values when modes have been identified.

$q_\psi(a)$	2.5-2.7	3.0-3.2	~ 4	~ 5	~ 9
$P_{NB}(MW)$	8-10	6-10	6	18	6
$\bar{n}_e (10^{19}/m^3)$	2.7-3	2.4-3	3.3	2.7	2.8
m/n	5/2	3/1	4/1	5/1	-

FIGURE CAPTIONS

- Fig. 1 Overview of a discharge with major radius = 233 cm, minor radius = 67 cm, and a transition to the q -mode occurring at 3.10 s. (a): chord-integral electron density, D_α emission at 30° above the midplane (10^{10} photons/m²/s/st), and plasma current; (b): safety factor, $\beta_{p^{dia}}$, and the measured neutron production rate.
- Fig. 2 D_α emissions (10^{10} photons/m²/s/st) at one toroidal location with poloidal angles (a): 23° , (b): 14° , (c): 7.5° , and (d): 0° above the midplane, and (e): integrated Mirnov coil signal (Tesla) measured at the inner midplane, at a toroidal angle 117° past the D_α measurements in the co-direction.
- Fig. 3 (a): $T_e(x,t)$, where x = distance along the midplane from the inner limiter, measured by electron-cyclotron emission; (b): $n_e(x,t)$ measured by Abel inversion of infrared laser interferometry through vertical chords.
- Fig. 4 (a): Charge-exchange efflux of fast D^0 , (b): toroidal plasma rotation at $r=0$, measured by Doppler broadening of Ni K_α lines.
- Fig. 5 Plots of constant helical flux at 3.12 s showing $3/1$ islands at two toroidal locations separated by 120° , and the location of the inner limiter. Chords where the D_α emissions and the Mirnov signal were measured are indicated.
- Fig. 6 (a): Z_{eff} calculated from the visible bremsstrahlung emission and measured with a pulse-height-analyser and the measured intensities of the CII(904 nm) and CIV(312 nm) lines; (b): volume-averaged electron densities and contributions from D, C, O, and neutral beam ions, (c): calculated neutral beam deposition power on electrons, D, impurity ions, and thermalized ions, (d): stored energy in ions, electrons, rotation, parallel beam ions, perpendicular beam ions, thermal plasma, and their total.
- Fig. 7 Thermal energy confinement time for the plasma, ions, electrons, and the Goldston prediction for the L-mode.

#88P0010

Fig. 1

Fig. 2

Fig. 3

Fig. 4

#88P0009

Fig. 5a

88P0016

Fig. 5b

Fig. 6

Fig. 7

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