Stabilization of Sawteeth with Additional Heating in the JET Tokamak

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Experiments in the JET tokamak with additional heating power (ion cyclotron resonance heating and/or neutral beam injection) above 5 MW show that the plasma can undergo a transition to a new regime. In this regime, the sawtooth instability is suppressed for periods up to 1.6 s and the level of long-wavelength, coherent MHD activity is very low. An improvement in the global energy confinement time of up to 20% is observed. Possible mechanisms for the stabilization of the $m=1$ instability and the implications for the near-ignition regime are discussed.

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The internal disruption, or sawtooth instability,[1] is one of the fundamental instabilities of tokamak plasmas. In JET,[2] sawtooth activity dominates the evolution of the plasma core[3] and, during additional heating experiments, the modulation of the central electron temperature $T_e(0)$ may reach[4] a factor of 2 with the sawtooth collapses ejecting energetic charged particles produced by fusion reactions.[5] Recognition that sawtooth activity limits heating and confinement in the plasma center has recently stimulated efforts to control the instability.[6] Here we report the first observations of a regime in which the sawtooth instability is suppressed for up to 1.6 s and the coherent low-(m,n) number magnetohydrodynamic (MHD) activity becomes quiescent. These results may have significant implications for the theory of the sawtooth instability. In addition, the duration of this long quiescent period (3–5 energy replacement times) permits an analysis of the possible benefits of sawtooth stabilization in near-ignition plasmas.

The present experiments were carried out in JET[2] (major radius $R_0=2.96$ m, minor radius $a=1.25$ m) with both neutral-beam injection (NBI) and ion cyclotron resonance heating (ICRH) at combined power levels of up to 15 MW. Under such conditions, the sawtooth and MHD activity exhibits two distinct types of behavior. The more usual behavior is illustrated in Fig. 1. The sawtooth period increases by a factor of 2–3 relative to the Ohmic phase of the discharge, and the relative modulation $T_e(\max)/T_e(\min)$ increases from 1.1–1.2 in the Ohmic phase to up to $\simeq 2$ during auxiliary heating. A variety of MHD activity (predominantly $m=n=1$) accompanies the sawteeth.

The second, newly discovered and dramatically different, type of behavior is exemplified by Fig. 2. The rise of the "sawtooth" beginning at 9.6 s is characterized by weak MHD activity and a small-amplitude partial sawtooth, but after 300–400 ms the level of coherent MHD activity becomes very low ($\tilde{B}_\theta/B_\theta \lesssim 5\times10^{-5}$). Although both the plasma density and energy usually rise slowly until the sawtooth collapse occurs, $T_e(0)$ saturates. The temperature saturation lasts for $\simeq 0.7$ s (and can last up to 1.4 s), and during this time no low-(m,n) number coherent MHD activity is observed by the electron-cyclotron emission or soft x-ray diagnostics or external magnetic pickup coils. This can be seen on the MHD signal in Fig. 2. The presence of stationary helical perturbations can be excluded since (a) a monitor of

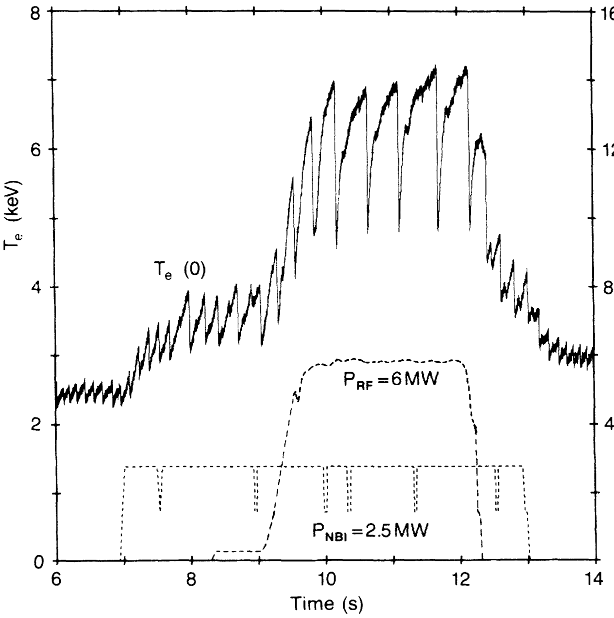

FIG. 1. Usual behavior of sawtooth activity in JET with the increase in amplitude and period of sawteeth during additional heating ($I_p=2.2$ MA, $q_\psi=5.2$).

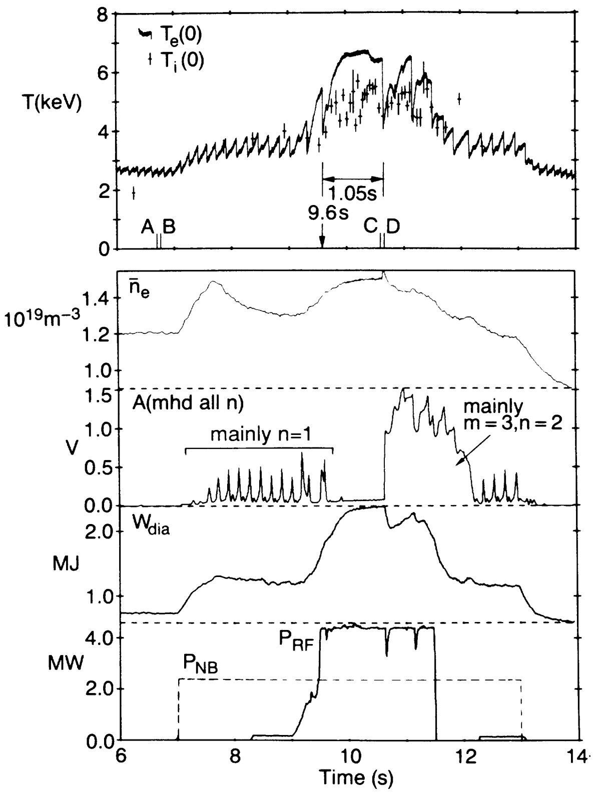

FIG. 2. Evolution of a JET discharge ($I_p=2.2$ MA, $q_\psi=5.2$) in which sawtooth stabilization occurred: $T_e(0)$, central electron temperature; $T_i(0)$, central ion temperature (from Doppler broadening of N_i^{26+}); $\bar{n}_e$, average density; A, amplitude of MHD activity; $W_{\rm dia}$, plasma energy from diamagnetic measurements; $P_{\rm NB}$, NBI power; and $P_{\rm rf}$, ICRH power.

stationary perturbations of the poloidal field (B_θ) gives no indication of such structures and (b) the plasma is known to be rotating from analysis of Doppler-shifted impurity lines by x-ray crystal spectroscopy. Throughout this period, therefore, the $m=1$ mode appears to be stabilized. One significant consequence is that the global energy confinement time, τ_E, can improve by up to 20%.

The stable period is terminated by an $m=n=1$ instability which exhibits the dynamics of the normal sawtooth collapse in JET[7] (the behavior follows that of the ideal instability model proposed recently[8]). In addition, a substantial $m=3$, $n=2$ mode ($\tilde{B}_\theta/B_\theta \simeq 7\times10^{-4}$) is often destabilized, as shown in Fig. 2. This may be due to changes in the central current profile during the stable period which could steepen the current gradient at the $q=\frac{3}{2}$ surface when the sawtooth collapses. The observed increase of the sawtooth inversion radius, from $r_1 \simeq 40$ cm during the normal sawtoothing period to $r_1' \simeq 50$-60 cm at the collapse which ends the stable period, supports this. Figure 3 shows electron temperature profiles before (A) and after (B) a sawtooth collapse during the Ohmic phase of the discharge in Fig. 2, and before (C) and after (D) the collapse of the long quiescent period. The expansion of the inversion radius can clearly be seen, and is confirmed by more precise measurements from an electron-cyclotron emission polychromator and soft x-ray tomography.

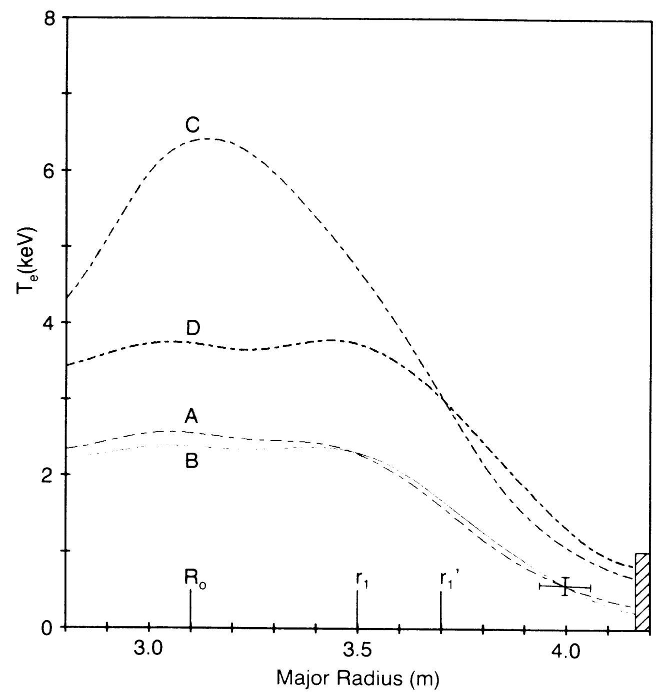

FIG. 3. Electron temperature profiles before (A) and after (B) an Ohmic sawtooth collapse (see Fig. 2), and before (C) and after (D) the collapse terminating the 1.05-s sawtooth-free period of Fig. 2. The expansion of the sawtooth inversion radius from r_1 to r_1' is clear.

With combined NBI and ion cyclotron-resonance frequency heating the (3,2) mode persists until near the end of the heating pulse, and apparently prevents a further quiescent period. In several cases with ICRH alone a mode with $m=2,n=1$ grows and locks soon after the sawtooth collapse, and the plasma thereafter deteriorates, with reduced $T_e(0)$ and a poorer energy confinement time. However, when these modes are quenched more quickly (<1 s), a second long quiescent period can occur. An example, obtained during hydrogen minority heating in a He^3 plasma, is shown in Fig. 4. In this case both the ion temperature, $T_i(0)$, and the neutron production rate, R_{DD} (due to background deuterium), increase throughout the second quiescent period.

The quiescent regime has been obtained under a wide range of JET parameters (plasma current $I_p=2$-5 MA, toroidal field $B_T=2$-3.4 T, edge safety factor $q_\psi=3.4$-6, average density $\bar{n}_e=(1.5$-$4)\times10^{19}$ m^3, and $T_e(0)=4$-7.5 keV, but it is not clear which of these are critically involved. The regime occurs in discharges limited on the torus inner wall, on the outer limiters, or by an internal separatrix. It was first observed in combined-heating (NBI plus ICRH) discharges with

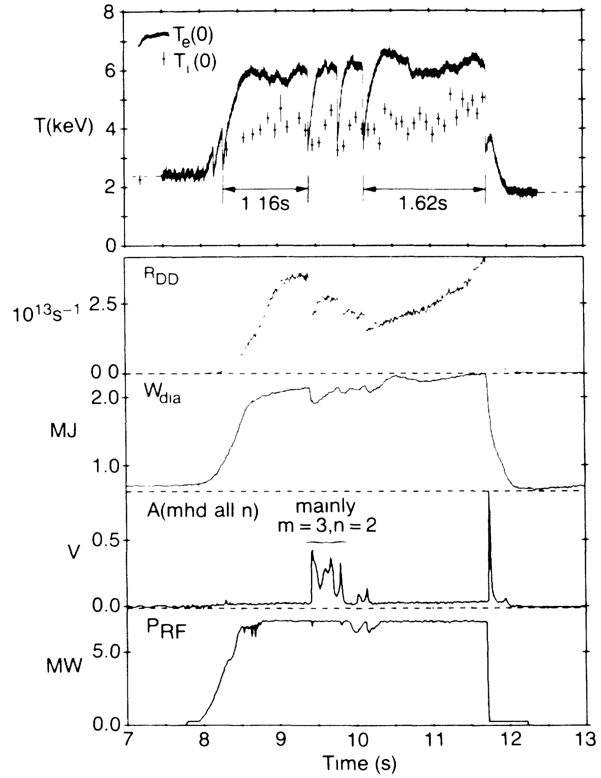

FIG. 4. A JET discharge ($I_p = 2.0$ MA, $q_\Psi = 4.6$) with sawtooth stabilization during ICRH: $T_e(0)$, central electron temperature; $T_i(0)$, central ion temperature; R_{DD}, neutron production rate; W_{dia}, plasma energy; A, amplitude of MHD activity; P_{rf}, ICRH power.

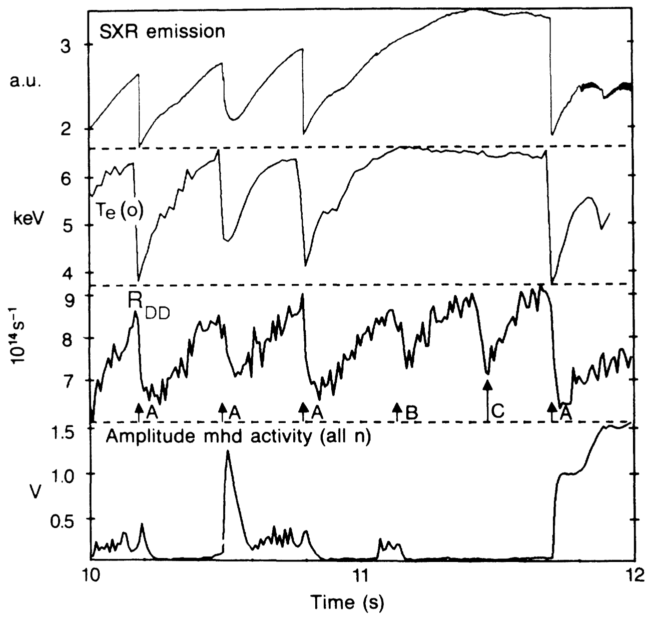

FIG. 5. Events at A in neutron yield R_{DD} correspond to sawteeth and event B is a partial sawtooth. At event C there is no identifiable signature in soft x-ray emission, electron temperature $T_e(0)$ from electron-cyclotron emission, or total MHD signal. For this pulse, $I_p = 2.2$ MA, $q_\Psi = 5.2$, $P_{\text{rf}} = 4.5$ MW, and $P_{\text{NB}} = 2.5$ MW.

auxiliary powers in the range 7.5–15 MW. Subsequently the regime has been attained with ICRH alone in $He^3(H)$, D(H), and $D(He^3)$ minority-heating schemes and with rf powers of only 5 MW. Sawtooth stabilization has also been observed following pellet injection into ICRH-heated plasmas. Finally, the regime can be produced by NBI heating alone.

In general, fusion neutron production either saturates or increases continuously during the stable period. However, in a few cases with combined heating, the sawtooth behavior of the neutron emission continues as shown in Fig. 5. The neutron production, mainly from beam-plasma interactions, shows good correlation with sawteeth (A) and partial sawteeth (B). However, no coherent MHD activity or change in signal level is observed in the MHD diagnostics at the time at which event (C) occurs. This event does not have the characteristics of the "fishbone" instability[9]; in particular there is no observable MHD signature. It may, therefore, be due to some hitherto unidentified instability.

In ASDEX detailed measurements of the current profile[10] $j(r)$ have confirmed that sawtooth stabilization by lower hybrid current drive is due to a broadening of the current profile which raises the central safety factor $q(0)$ above 1. In the present work, the evolution of $j(r)$ was followed by analysis of magnetic measurements with the JET equilibrium codes.[11] Although the systematic uncertainty in the resultant value of $q(0)$ is $\simeq 20\%$, this analysis indicates that $q(0)$ is in the range of 0.9–1.0 during the quiescent period and that it may decrease by 5%–10% during this time. Calculations of the resistive diffusion of $j(r)$ show that $q(0)$ decreases from $\simeq 1$ to $\simeq 0.9$ during the stable period, in support of the magnetic analysis.

The good agreement between experimental observations of the sawtooth collapse in JET[4,7] and the predictions of the ideal instability model[8] suggests that a broadening of the current profile resulting in $q(0) > 1$ would explain the sawtooth suppression. However, explanations requiring noninductively driven currents appear to be excluded since the calculated beam-driven current profile is too peaked, the ICRH is not predicted to drive currents, and the neoclassical bootstrap current[12] is calculated to be too small. In addition, the change in the central impurity density required to drive $q(0)$ above unity is far greater (factor $\simeq 3$) than that actually observed.

The absence of an adequate mechanism for the broadening of the current profile and the experimental evidence that $q(0) < 1$ during the stable period suggest that a mechanism exists which allows the plasma to cross the predicted boundary for the ideal instability at $q(0) \simeq 1$ and which also stabilizes resistive modes [which are expected to grow when $q(0) < 1$]. Although it is expected theoretically[8] that the ideal mode should be stable with $q(0) < 1$ until a critical value of central plasma pressure $\beta_p \simeq 0.2$–0.3 is reached, the crossing of the stability boundary at $q(0) \simeq 1$ represents a fundamental problem. However, in the discharges discussed here, neutral-beam injection and intense rf electric fields accelerate a fraction of the ions to energies above 100 keV. This fast-ion population could contribute substantially to the stabilization of the $m=1$ mode. For example, finite Larmor-radius stabilization[13] and kinetic effects due to trapped particles[14] could play a role, although the theory applicable to these conditions is incomplete.

Perhaps the most significant aspect of this regime is the possibility that the $m=1$ mode may be stable in tokamak plasmas with $q(0)$ well below unity and that, as a result, substantially improved plasma conditions can be obtained. In addition, the long stable period achieved (3–5 energy confinement times) allows the potential advantages of full sawtooth stabilization for near-ignition plasmas to be assessed. We find that the plasma energy content usually rises continuously during the stable period, resulting in a value of τ_E which is up to 20% better than in the normal sawtoothing regime. However, our calculations predict that the major advantage obtained will be a significant increase in the D-T fusion yield (which is approximately proportional to $n_i^2 T_i^2$ under conditions of interest), although the precise enhancement will depend on detailed geometric factors and profile shapes. As a final point, the existence of this regime may prove beneficial for studies of sawtooth stabilization by lower hybrid current drive.[6]

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