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STABILIZATION OF SAWTEETH WITH ADDITIONAL HEATING IN THE JET TOKAMAK

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ABSTRACT

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 sudden transition to a new regime in which the sawtooth instability is suppressed for periods of up to 1.6 s and the level of long wavelength, coherent mhd activity is very low. Possible mechanisms for the observed stabilization of the m=1 instability and the potential gains in the near-ignition regime are discussed.

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], particularly during additional heating experiments, where the modulation of the central electron temperature $T_e(0)$ may reach a factor of two[4] and the sawtooth collapses eject energetic charged particles produced by fusion reactions[5]. Recognition that sawtooth activity limits heating and confinement in the plasma centre have recently stimulated efforts to control the instability[6]. Here we report observations, obtained during high power additional heating in JET, of a regime in which the sawtooth instability is suppressed for up to 1.6 s and the coherent low m,n number mhd activity becomes quiescent. 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.

Experiments with additional heating have been carried out in JET (R_0 = 2.96 m, a = 1.25 m, $\kappa < 1.6$, $I_p \leqq 5$ MA, $B_T \leqq 3.4$ T) under a wide range of plasma conditions, and at auxiliary power levels of up to 15 MW. The NBI system can deliver 10 MW of 80 keV deuterons into the plasma and the ICRH system has injected up to 8 MW of power[2]. In the present experiments, the neutral beams are injected in the direction of the plasma current, and the ion cyclotron resonance layer (H minority ion heating) is located within 10 cm of the plasma centre. Under such conditions, the sawtooth and mhd activity exhibit two distinct types of behaviour. The more usual behaviour is illustrated in figure 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 ~ 2 during auxiliary heating. A variety of mhd activity accompanies the sawteeth. This is predominantly m=n=1 in the plasma centre, but due to toroidal and non-circular effects, higher m (m=3,4) components appear at the plasma edge and are detected by external magnetic pick-up coils.

The second, newly discovered and dramatically different, type of behaviour is exemplified by figure 2. The rise of the 'sawtooth' beginning at 9.6 s is characterised by weak mhd activity and a small amplitude partial sawtooth, but after 300-400 ms the level of coherent mhd activity becomes very low ($\tilde{B}_\theta/B_\theta \leq 5 \times 10^{-5}$). Although both the plasma density and energy usually rise slowly until the sawtooth collapse occurs, $T_e(0)$ saturates. The temperature saturation lasts for ~ 0.7 s (and can last up to 1.4 s), during which time no low m,n number coherent mhd activity is observed by the ECE or soft X-ray diagnostics or external magnetic pick-up coils. This quiet period with T_e quasi-stationary can be seen in figure 2. The presence of stationary helical perturbations can be excluded since (a) a monitor which detects stationary perturbations of the poloidal field 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 behaviour follows that of the ideal instability model proposed recently[8]). In addition, a substantial m=3, n=2 mode ($\tilde{B}_\theta/B_\theta \sim 7 \times 10^{-4}$) is often destabilized, as shown in figure 2. This may be due to changes in the central current profile during the stable period which could steepen the current gradient at the $q = {}^3/_2$ surface at the time of the sawtooth collapse. The observed increase of the sawtooth inversion radius , from $r_i \sim 40$ cm during the normal sawtoothing period to $r_i' \sim 50-60$ cm at the collapse which ends the stable period, tends to support this. Figure 3 shows electron temperature profiles before (A) and after (B) a sawtooth collapse during the ohmic phase of the discharges in figure 2, and before (C) and after (D) the collapse which terminates the long quiescent period. The expansion of the inversion radius from r_i to r_i' can clearly be seen, and is confirmed by more precise measurements from an ECE polychromator and soft X-ray tomography.

With combined NBI and ICRF heating the (3,2) mode persists until near the end of the heating pulse, and apparently prevents a further quiescent period. However, with ICRH alone, the (3,2) mode is either quenched more quickly (<1s), or is not excited, and a second long quiescent period occurs. An example, obtained during hydrogen minority heating in a He^3 plasma, is shown in figure 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. In several cases a mode with n=1 grows and locks soon after the sawtooth collapse, and the plasma thereafter deteriorates, with a lower central electron temperature and a poorer energy confinement time.

The quiescent regime has been obtained under a wide range of conditions in JET (I_p = 2-5 MA, B_T = 2-3.4 T, q_ψ = 3.4-6, $\bar{n}_e = 1.5-4 \times 10^{19}$ m^{-3} and $T_e(0)$ = 4-7.5 keV), but it is not clear which parameters 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 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 ICRF-heated plasmas. Finally, the regime can be produced by NBI heating alone.

In general, fusion neutron production either saturates or continues to increase during the stable period. However, in a few cases with combined heating, the sawtooth behaviour of the neutron emission continued as shown in figure 5. The neutron production, mainly from beam-plasma interactions, shows good correlation with sawteeth (A) and partial sawteeth (B) observed with ECE and soft X-ray emission. 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 j(r)[10] have confirmed that sawtooth stabilization by lower hybrid current drive is due to a broadening of the current profile which raises q(0) above 1. In the present work, the evolution of j(r) was followed by analysing magnetic measurements using the JET equilibrium codes[11]. The results indicate that q(0) is in the range 0.9 - 1.0 during the quiescent period and that it may decrease by 5-10% during this time. However, the systematic uncertainty (20%) in the derived value of q(0) makes it impossible to determine unambiguously whether q(0) is above or below 1. The most significant result obtained is that the plasma inductance ℓ_i remains constant, or decreases slightly, during the stable period, suggesting that j(r) is not peaking. Furthermore, ℓ_i decreases by ~4% at the collapse which terminates the quiescent regime indicating a broadening of the current profile (which may destabilize the m=3, n=2 mode).

In view of the agreement between experimental observations of the sawtooth collapse in JET[4,7] and the predictions of the ideal instability model[8], a mechanism involving a broadening of the current profile so that q(0) > 1 seems most likely to explain the sawtooth suppression. Explanations requiring non-inductively driven currents appear to be excluded since the calculated beam-driven current profile is too peaked and since the ICRH is not predicted to drive currents. However, the neoclassical bootstrap current[12] is an alternative possibility. Calculations of the bootstrap current profile, using measured temperature and density profiles in JET, predict that the total bootstrap current should increase from ~ 50 kA in the ohmic phase to greater than 100 kA during the quiescent period. In addition, most (~90%) of this current should flow outside the normal sawtooth inversion radius, leading to a broadening of the current profile. However, resistive diffusion calculations have shown that, in the absence of some further mechanism to reduce the rate of inward current diffusion, this would be insufficient to maintain q(0) > 1 for the required period.

Alternative explanations cannot be eliminated conclusively. Energetic particles - due to neutral beam injection or acceleration by RF fields - might stabilize the sawtooth by finite Larmor radius effects[13] (ions) or their influence on the conductivity profile (electrons). While the theory of finite Larmor radius stabilization of ideal modes is unclear under these conditions, it appears that this effect will not significantly affect the growth rate of the instability, but could change the value of q required for instability by a small but significant amount. A further, possibility is that a change in the impurity profile could directly change the rate of current diffusion, but the extreme peaking of the temperature profile ($T_e(0)/T_e(r_1) \sim 2$ in many cases) would necessitate a change in the central impurity density of, perhaps, a factor 3 (far greater than has actually been observed).

The most significant aspect of this regime is that it indicates the possibility of stabilizing sawteeth without active stabilization measures. On the other hand, these results do provide encouragement for active stabilization studies since resistive diffusion calculations and analysis of ℓ_i indicate that the observed stabilization was achieved with only a small change in the current profile. The long stable period achieved (3-5 energy confinement times) allows the potential advantage of full sawtooth stabilization for near-ignition plasmas to be assessed. Although the plasma energy content usually rises slowly during the stable period, resulting in a value of τ_E which is up to 20% better than in the normal sawtoothing regime, our calculations predict that the major advantage obtained will be significant enhancement in the D-T fusion yield (which is approximately proportional to $n_i^2 T_i^2$ under conditions of interest). The precise enhancement will depend on detailed geometric factors and profile shapes.

It is a pleasure to acknowledge the cooperation and assistance of our colleagues at JET who have operated the tokamak and its diagnostics during the experiments reported here.

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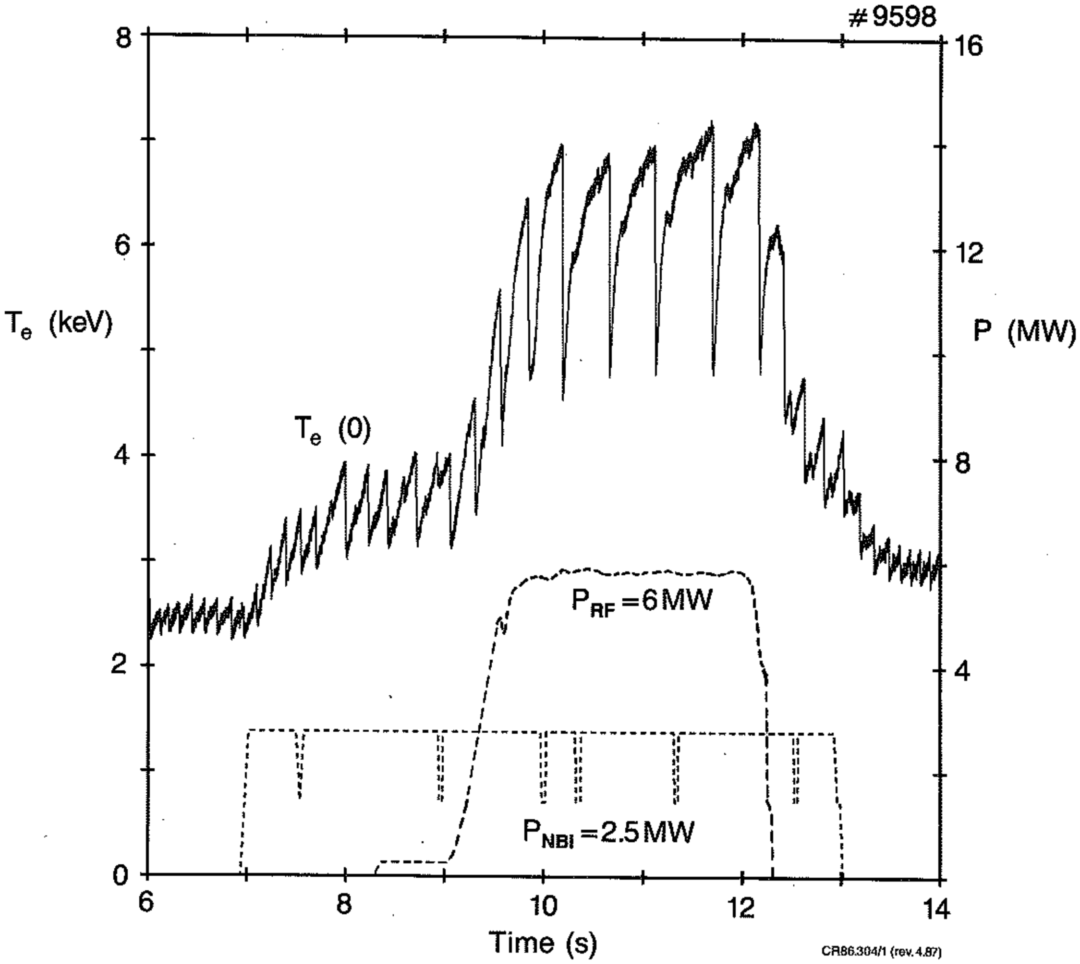

Fig. 1 Usual behaviour of sawtooth activity in JET showing the increase in amplitude and period of sawteeth during additional heating.

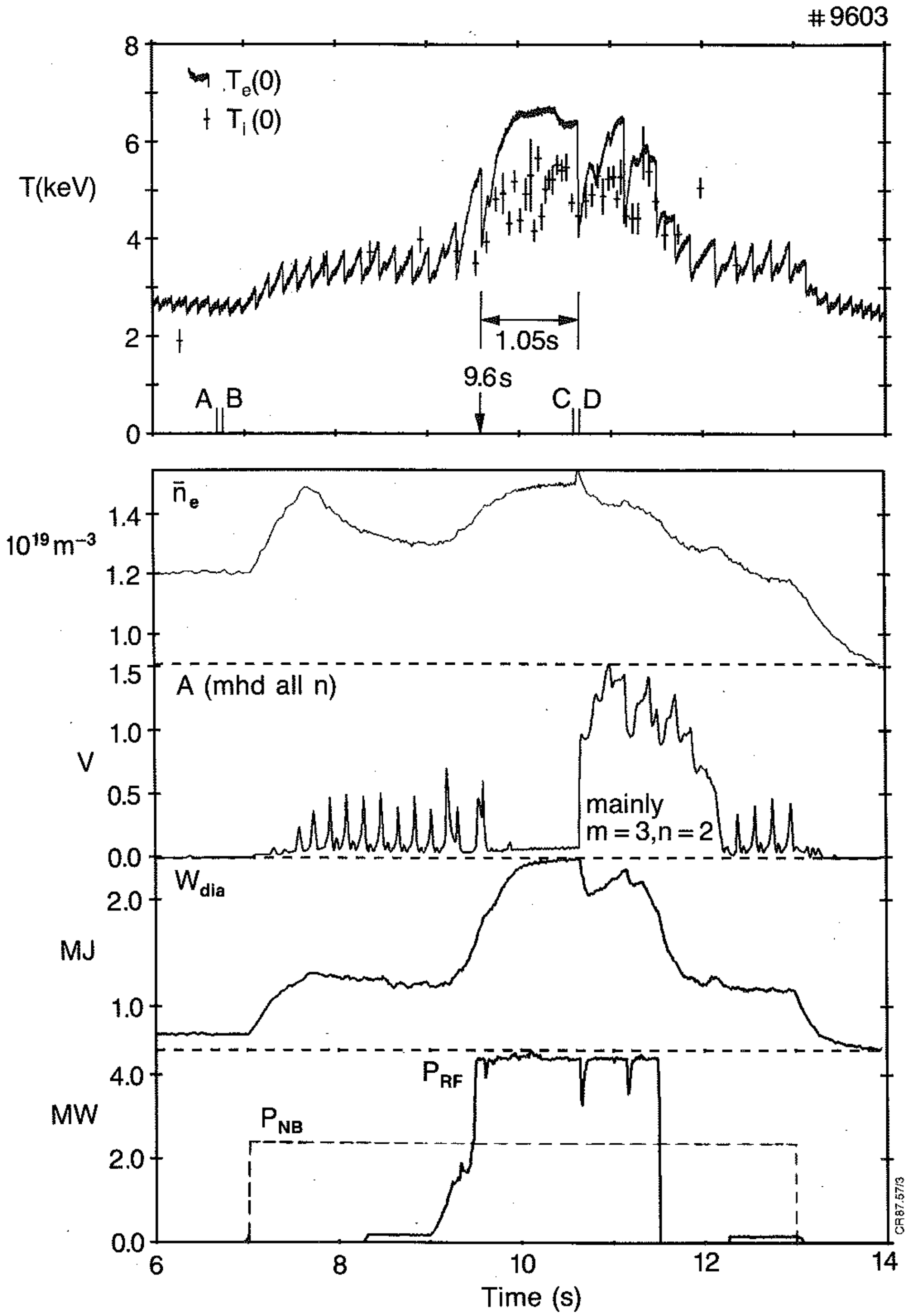

Fig. 2 Evolution of a JET discharge in which sawtooth stabilization occurred: $T_e(0)$ central electron temperature; $T_i(0)$ central ion temperature (from Doppler broadening of N_i^{26+}); $\bar{n}_e$ average density; A amplitude of mhd activity; W_{dia} plasma energy from diamagnetic measurements; P_{NB} NBI power and P_{RF} ICRH power.

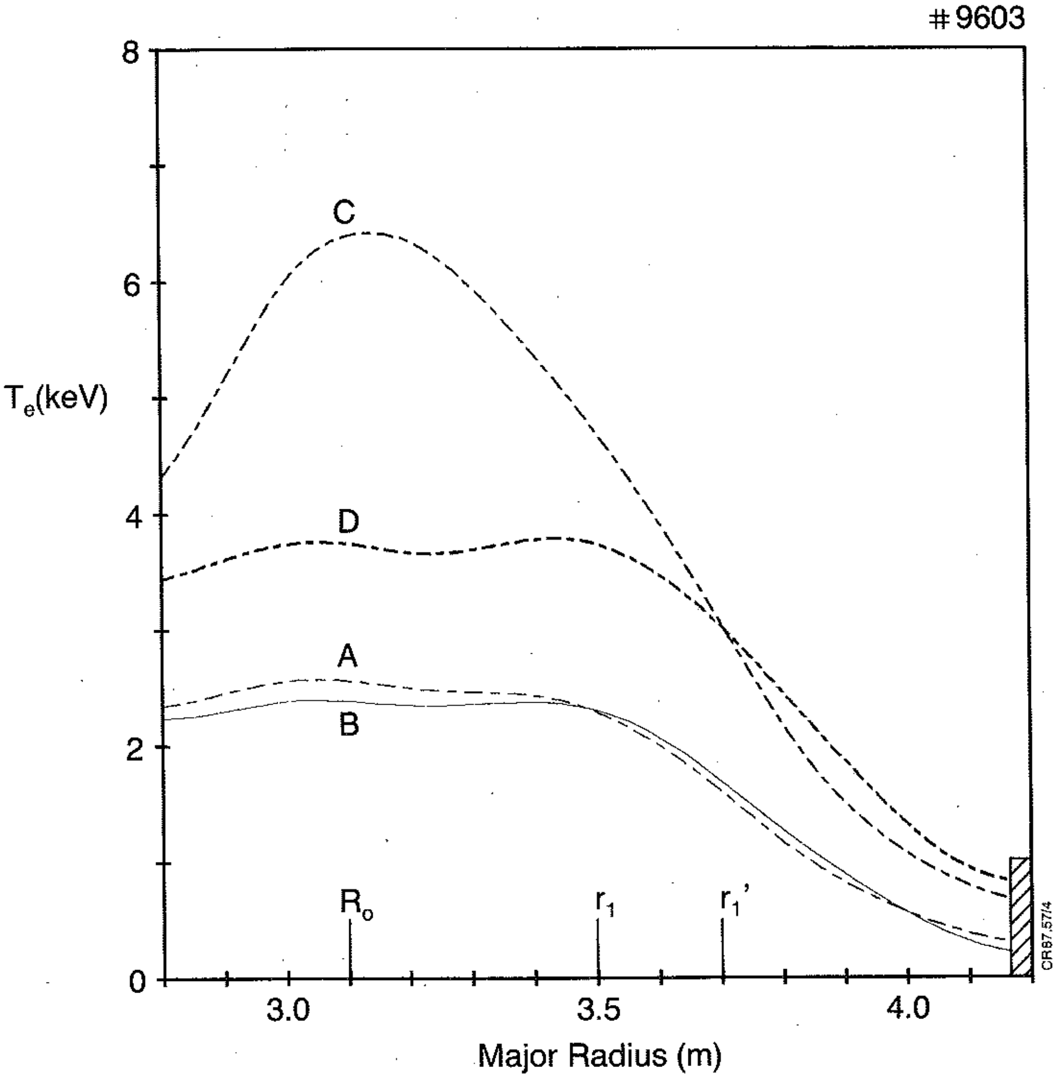

Fig. 3 Electron temperature profiles before (A) and after (B) an ohmic sawtooth collapse (see Fig. 2), and before (C) and after (D) the collapse terminating the 1.05 s sawtooth-free period of Fig. 2. The expansion of the sawtooth inversion radius from r_1 to r_1' is clear.

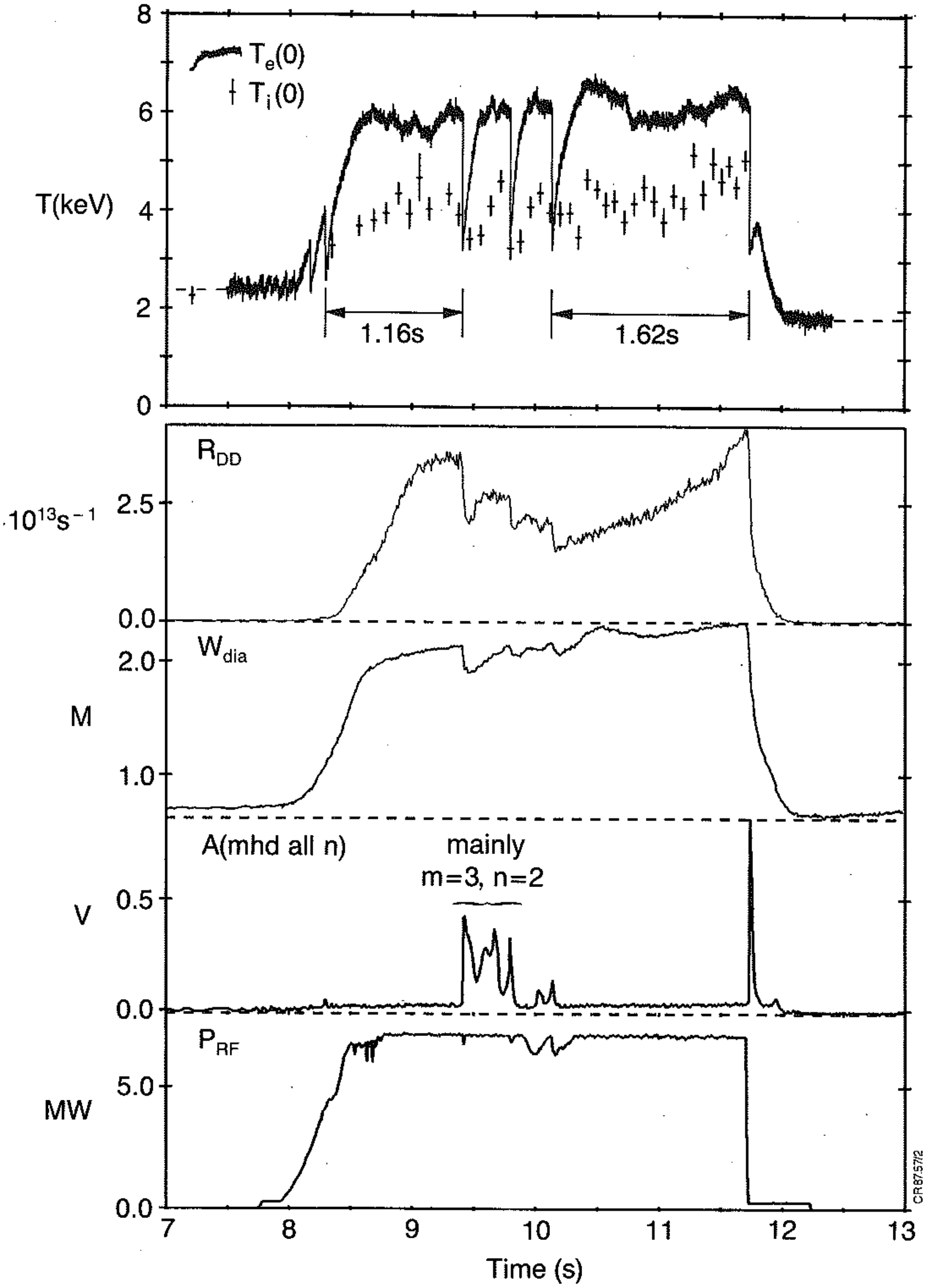

Fig. 4 A JET discharge with sawtooth stabilization during ICRH: $T_e(0)$ central electron temperature; $T_i(0)$ central ion temperature; R_{DD} neutron production rate; W_{dia} plasma energy; A amplitude of mhd activity; P_{RF} ICRH power.

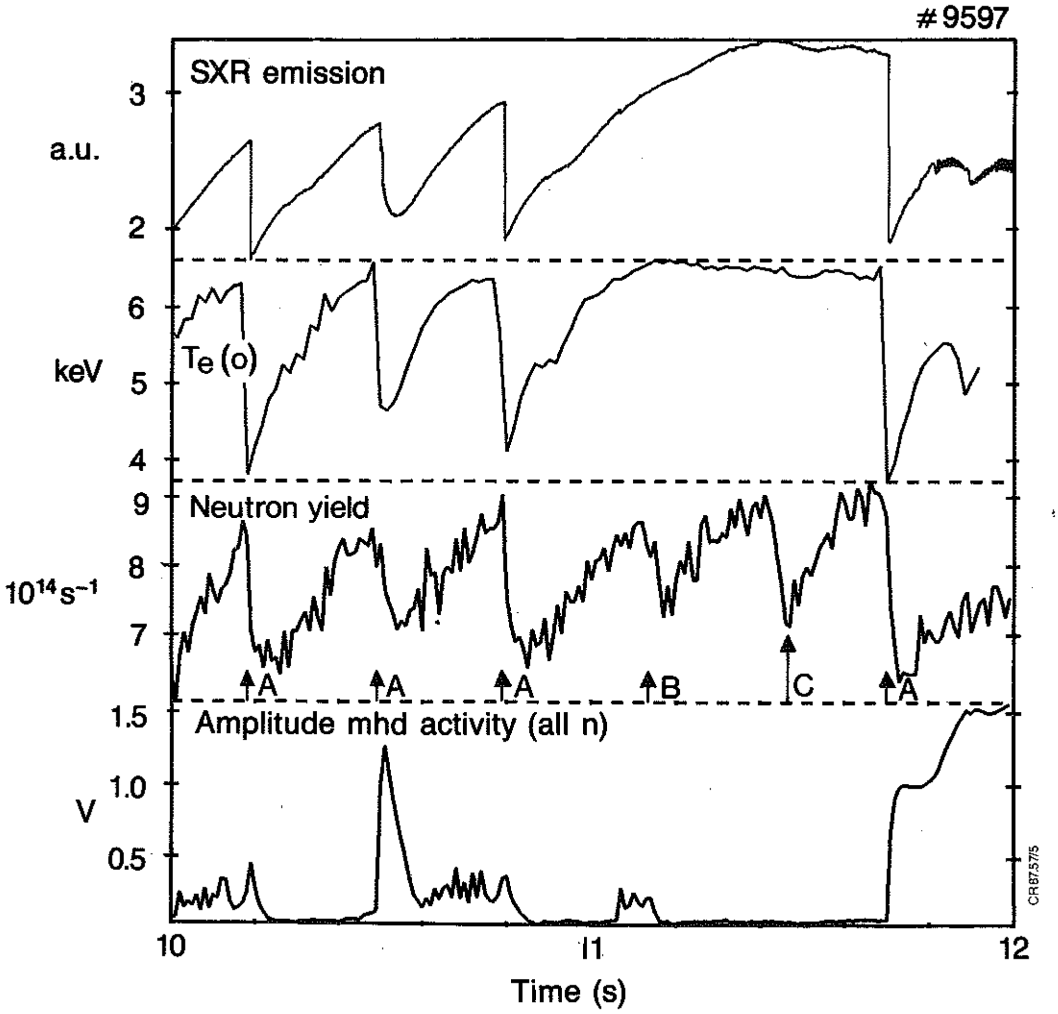

Fig. 5 Events at A in neutron yield correspond to sawteeth and event B is a partial sawtooth. At event C there is no identifiable signature in soft X-ray emission, electron temperature $T_e(0)$ from ECE, or total mhd signal.