SAWTOOTH INSTABILITY IN TOKAMAK PLASMAS

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Abstract. The Sawtooth instability is a familiar feature in Tokamak plasmas. It appears as a regularly recurring reorganisation of the core plasma. A brief survey of the experimental observations on many Tokamaks is presented. A qualitative description of the relevant theoretical ideas and of how they have evolved from early magnetic reconnection models in response to increasingly detailed experimental data, is also presented.

1. Introduction

The Tokamak is a toroidal plasma confinement device in which a combination of toroidal and poloidal magnetic fields is employed to confine hot plasma (Figures 1(a–d)). A strong toroidal magnetic field is created by external coils while the poloidal magnetic field is generated by currents in the plasma in the toroidal direction. This current is induced by transformer action or can be driven by launching electromagnetic waves (at ion cyclotron, lower hybrid or electron cyclotron frequencies) into the plasma. Injection of high energy beams of neutral atoms (NBI), with the primary objective of heating the plasma, also drives toroidal current. Typical plasma density and temperature in the plasma core (near the magnetic axis in Figure 1) are $n_e \approx 10^{20}$ m^{-3} and $T \approx 1 - 10$ keV, while the energetic ions created by neutral beam injection have energies up to 100 keV and those ions heated by resonance with ion cyclotron waves have energies up to, and in excess of, 1 MeV. Typically the density, $n_e(r)$, temperatures $T_e(r)$, $T_i(r)$ and toroidal current density $j_\phi(r)$, are all peaked functions of the minor radius r, falling to small values at the plasma boundary ($r = a$), where the edge plasma is in direct contact with a set of limiting structures (limiter plasmas) or is defined by a magnetic separatrix (divertor plasmas). The different types of plasma boundary will be of little concern to the topic of this review which is devoted to events in the 'plasma core', a region which we can roughly define as that volume for which $r/a \lesssim 1/2$, (Figure 1(a)).

Generally speaking Tokamak plasmas are predicted, and observed, to suffer from a variety of instabilities; i.e. they do not exist in a totally quiescent state and their transport properties are not those predicted by collisional transport theory. It appears that fine scale instabilities (known as micro-instabilities) are usually

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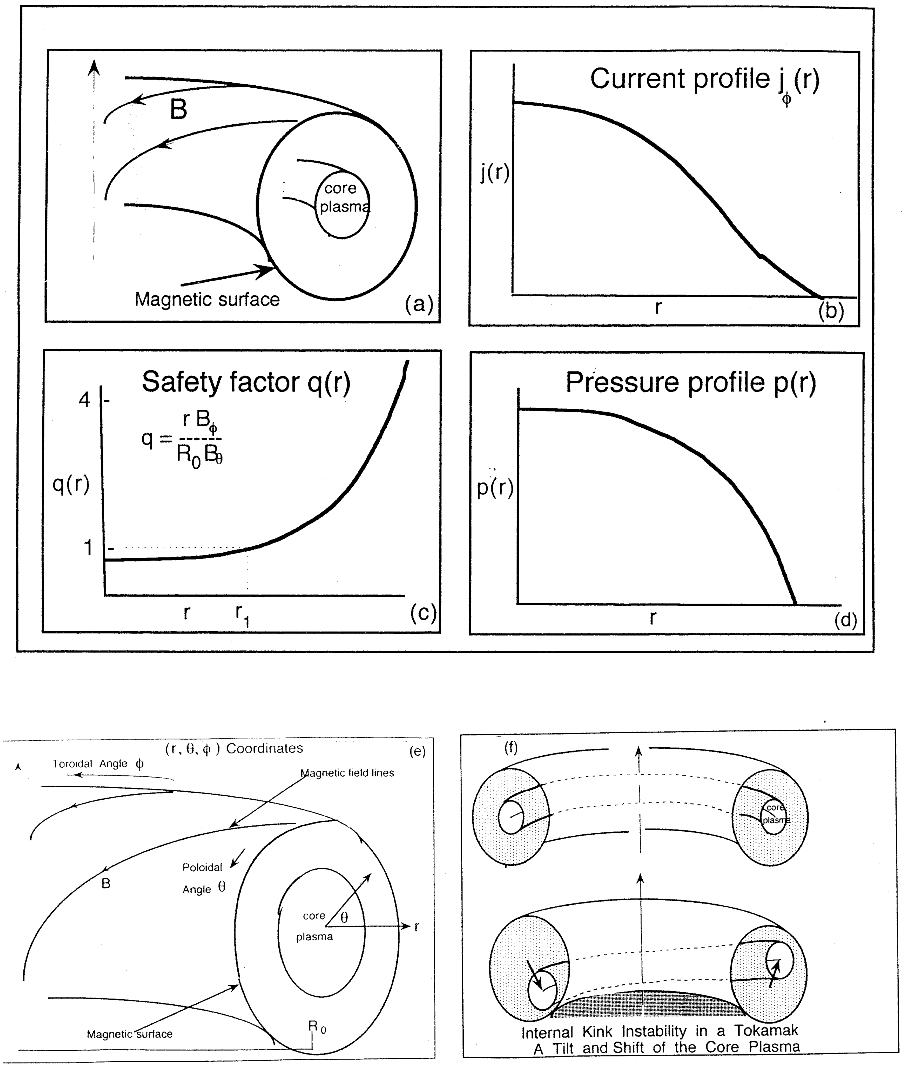

Figure 1. (a) Geometry of a Tokamak. (b), (c), (d), typical profiles for the toroidal plasma current $j_\phi(r)$, the field line winding number, or 'safety factor', $q(r)$ and the pressure $p(r)$. (e) The magnetic coordinates r, θ, ϕ. (f) Geometry of the internal kink instability in a torus.

present and determine local transport properties. It is also evident that certain large scale instabilities can occur and that, when they do, complete loss of plasma confinement often results. The stability boundaries for such gross instabilities therefore determine the normal operating regime of Tokamaks.

The Sawtooth instability is, however, an interesting exception to the above statement. It is a macroscopic instability which affects a significant volume of the plasma (the plasma core), but which is benign in the sense that termination of the discharge does not follow. The core plasma quickly recovers and the instability repeatedly occurs in a regular manner.

This review is concerned with the current understanding of the Sawtooth instability in Tokamak plasmas.

2. The Sawtooth Instability

The Sawtooth instability manifests itself as a regular periodic reorganisation of the core plasma surrounding the magnetic axis in Tokamaks. First reported by von Goeler et al. [1] in 1974, it is evident on many diagnostics in all Tokamaks, both large and small. The complete cycle of events can be subdivided into three regimes: (i) the Sawtooth ramp phase; a quiescent period during which the plasma density and temperature increase approximately linearly with time (see Figure 2) in the plasma core; (ii) the precursor oscillation phase, during which a helical magnetic perturbation grows and, due to toroidal rotation of the plasma, the soft X-ray (SXR) emission, electron cyclotron emission, ECE, (measuring $T_e(r)$) and interferometric data (measuring $n_e(r)$) show growing oscillatory behaviour; (iii) the collapse phase, in which $n_e(r)$, $T_e(r)$ and SXR intensity fall rapidly to lower values. In ohmically heated Tokamaks the resulting modulations of $n_e(r,t)$ and $T_e(r,t)$ are less than 10% and the period of the complete cycle, τ_s, increases with the size of the device. In TEXTOR (major radius $R_0 = 1.75$ m) $\tau_s \simeq 20$ msec and in JET ($R_0 \simeq 3$ m) $\tau_s \simeq 100$ msec.

This review adopts a historical perspective to indicate how theoretical ideas and interpretation have developed in response to the increasingly detailed experimental data over the past two decades.

Initially, 1974, the only relevant theoretical calculations [2, 3] concerned the linear instability [2] and saturated amplitude [3] of the ideal MHD internal kink mode, with $m = n = 1$ (where m is the poloidal mode number and the toroidal mode number n is represented by $k_z R_0$ in a periodic cylinder model of a Tokamak), which occurs when the value of the safety factor, $q(r) = rB_\phi/R_0 B_\theta$, falls below unity on the magnetic axis; i.e. whenever the current profile, $j_\phi(r)$, becomes sufficiently peaked that the axial current density $j_\phi(0)$ exceeds the critical value $2B_\phi(0)/R_0$. The ideal internal kink instability in a toroidal plasma takes the form of a tilt and shift of the core plasma, (Figure 1(f)), in the region where the 'safety factor', q, is less than 1. The safety factor is a measure of the rate at which magnetic field lines wind around the symmetry axis as they pass around the magnetic axis ($r = 0$ in Figure 1(e)) i.e. field line tractories are defined by $d\phi/d\theta = q(r)$. Thus, on the magnetic surface where $q = 1$ all field lines close on themselves after just one toroidal (or poloidal) circuit (see Figures 1(c,e) for a characteristic $q(r)$ profile in a Tokamak and for a description of the magnetic coordinates (r, θ, ϕ)).

Using the theoretical results and understanding established in References 2 and 3, Kadomtsev [4, 5] proposed a mechanism for the complete sawtooth cycle. He

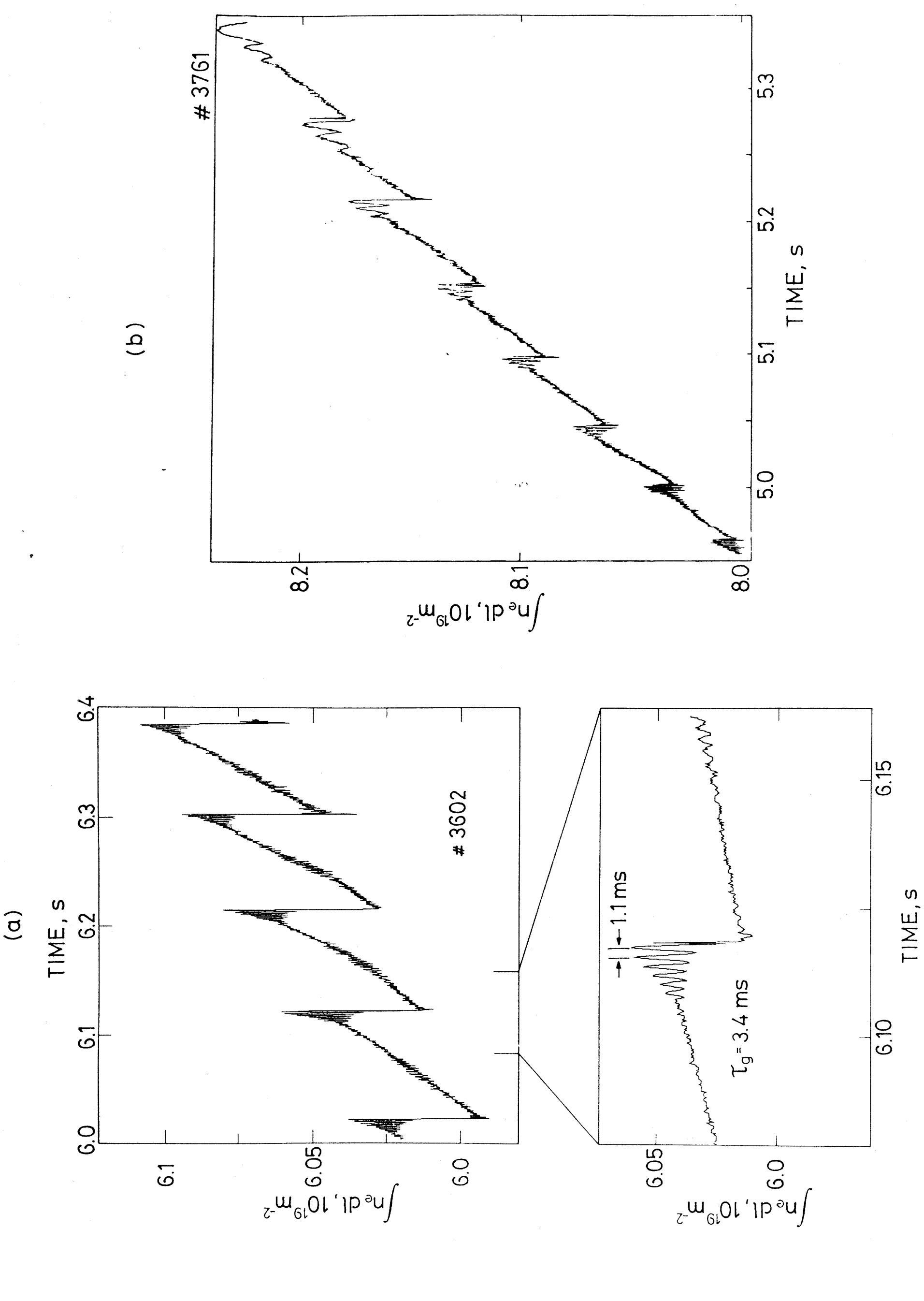

Figure 2. Typical interferometer data from early discharges on the JET Tokamak, showing the ramp, precursor oscillation and collapse phases of the Sawtooth instability.

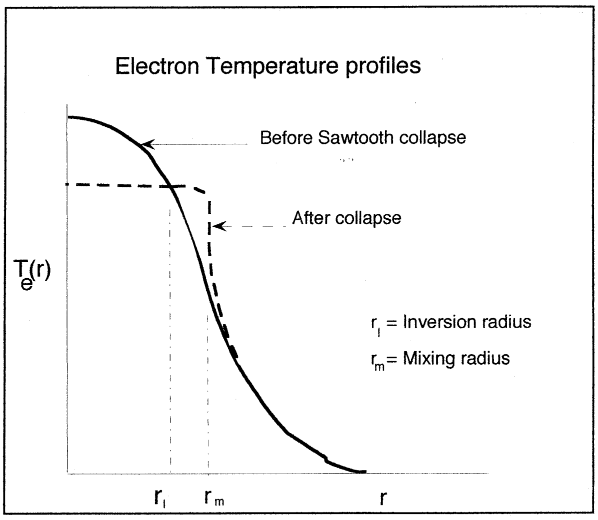

Figure 3. Typical electron temperatures $T_e(r)$, before and after the collapse phase of the Sawtooth instability. The mixing radius r_m defines the radial limit of the sudden change in $T_e(r)$, while the inversion radius r_I is defined as the point at which $\delta T = (T_{final} - T_{initial}) \simeq 0$.

visualised that the kink mode would drive magnetic reconnection of ψ^*, the flux through a helical ribbon bounded by the magnetic axis and a closed field line on the $q(r) = 1$ magnetic surface. Kadomtsev suggested that this reconnection process would continue until all $\psi^*(r) = \int_0^r r dr B_\theta(1-q) > 0$ was annihilated and a new, cylindrically symmetric, equilibrium was established with $q(0) > 1$. The final equilibrium state was calculated precisely in terms of the initial (at onset of the kink instability) state, and the time for the reconnection event to run to completion was estimated as $\tau_k \approx (\tau_\eta \tau_A^*)^{1/2}$ with $\tau_\eta = \mu_0 r_1^2/\eta$, $\tau_A^* = r_1(\mu_0\rho)^{1/2}/B_\theta(r_1)(1 - q_0)$, where $q(r_1) \equiv 1$. A consequence of this magnetic reconnection is that hot plasma near the magnetic axis ($r < r_1$) mixes with cooler plasma beyond the $q = 1$ surface ($r > r_1$), resulting in a flattened temperature (and pressure) profile (Figure 3) and a drop in $T(r = 0)$. It was then visualised that, during the succeeding ramp phase, ohmic heating in the new core plasma would cause temperature, and hence current, peaking so that $q(0, t)$ would fall below unity again and the cycle would repeat. One attraction of this elegant explanation is that it involves only a single mechanism; the weakness that, since there is no linear stability threshold for the $m = n = 1$ kink mode in cylindrical geometry if $q_0 < 1$, the quiescent ramp phase of the Sawtooth cycle is difficult to explain, and its duration is outside the scope of the model.

Following this proposed mechanism, numerical simulations [6, 7] (see Figure 4) were published and confirmed that a resistive MHD fluid in cylindrical equilibrium with $q(0) < 1$ did reconnect in such a fashion. Careful analysis of the soft X-ray emission from the TFR Tokamak during the precursor oscillation and collapse,

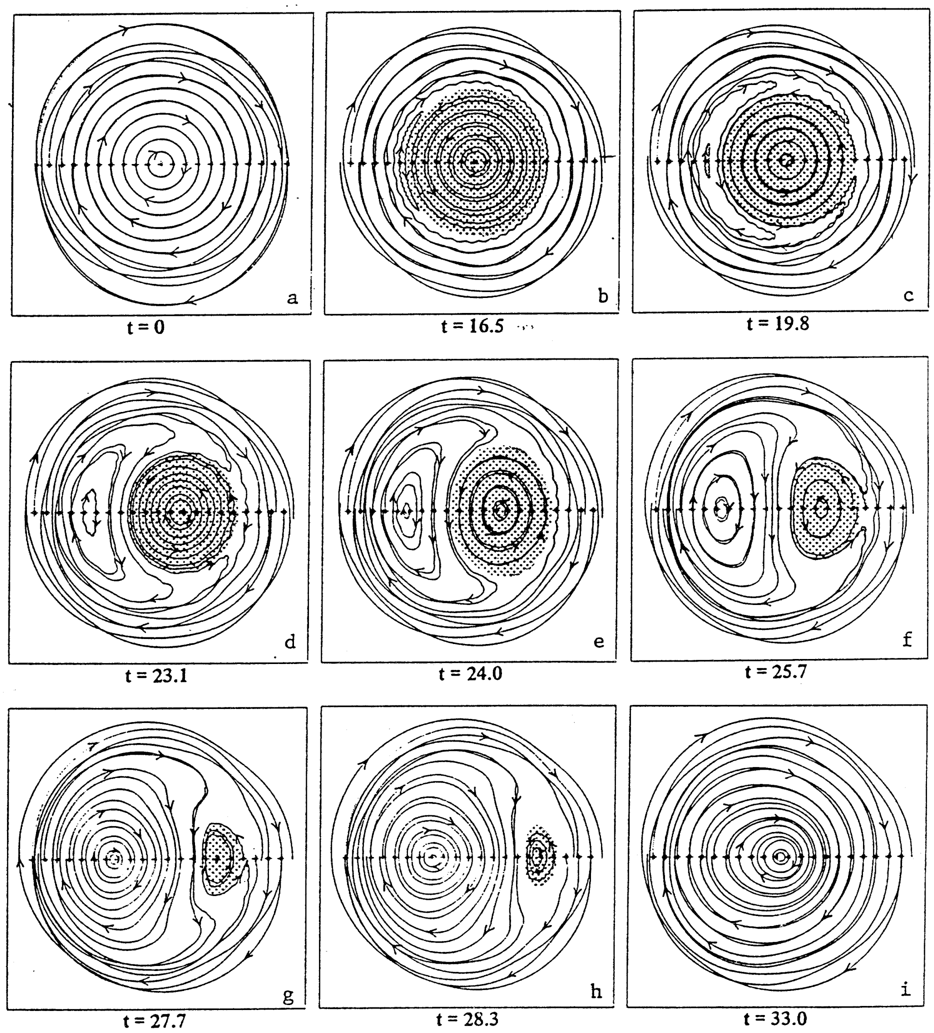

Figure 4. Approximate structure of magnetic surfaces during the reconnection process, showing growth of the, crescent-shaped, magnetic island, shrinking of the hot core plasma, until the island takes its place and a new cylindrically symmetric equilibrium is established (from Reference 6).

however, led Dubois et al. [8, 9, 10] to the conclusion that, although a reconnection process involving a change of magnetic topology, with $m = n = 1$ island growth, does commence as Kadomtsev suggested, this process appears to be interrupted by the sudden thermal collapse in the core when the magnetic island is still relatively small. These authors, therefore, proposed that a rapidly growing secondary instability is responsible for the observed thermal collapse, and concluded that it is uncertain whether or not the reconnection process proceeds to completion ($q(0) > 1$).

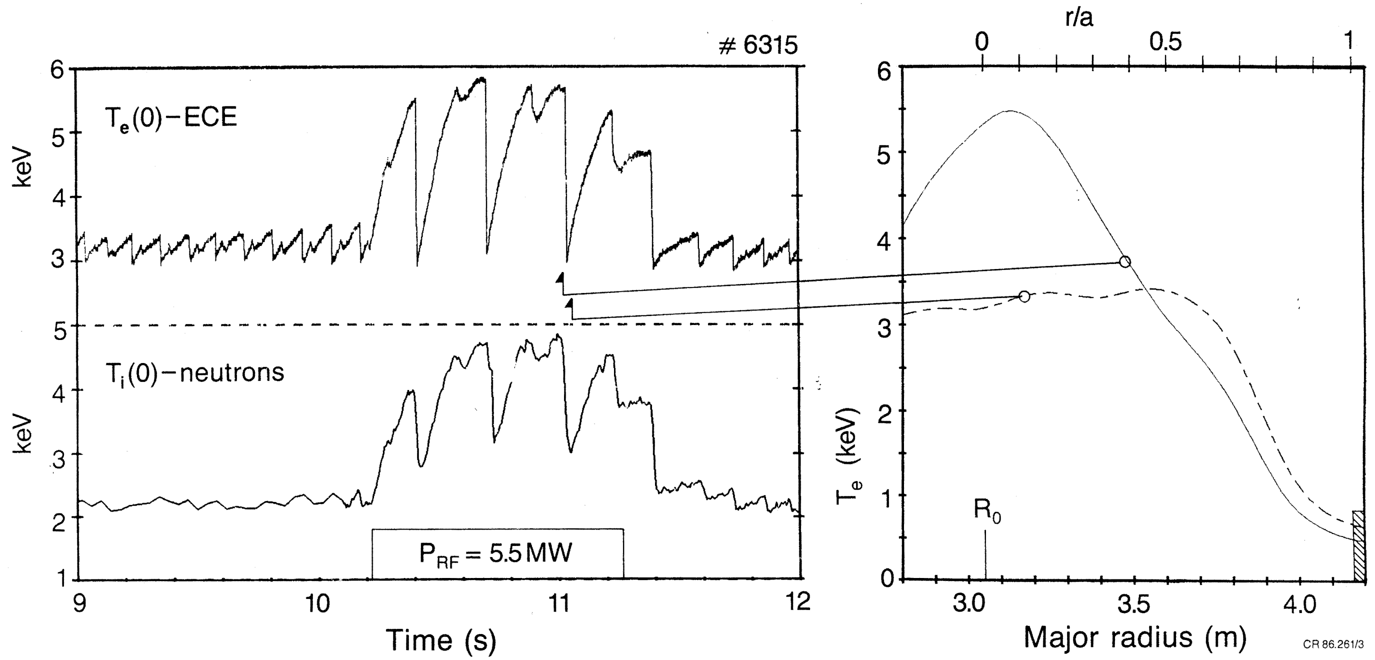

Figure 5. Longer Sawtooth periods after auxiliary heating is switched on suggest that the kink mode is not driven unstable by plasma pressure. Also note the dramatic collapse (50%) of the central electron temperature T_e in this JET discharge with auxiliary heating (ICRH).

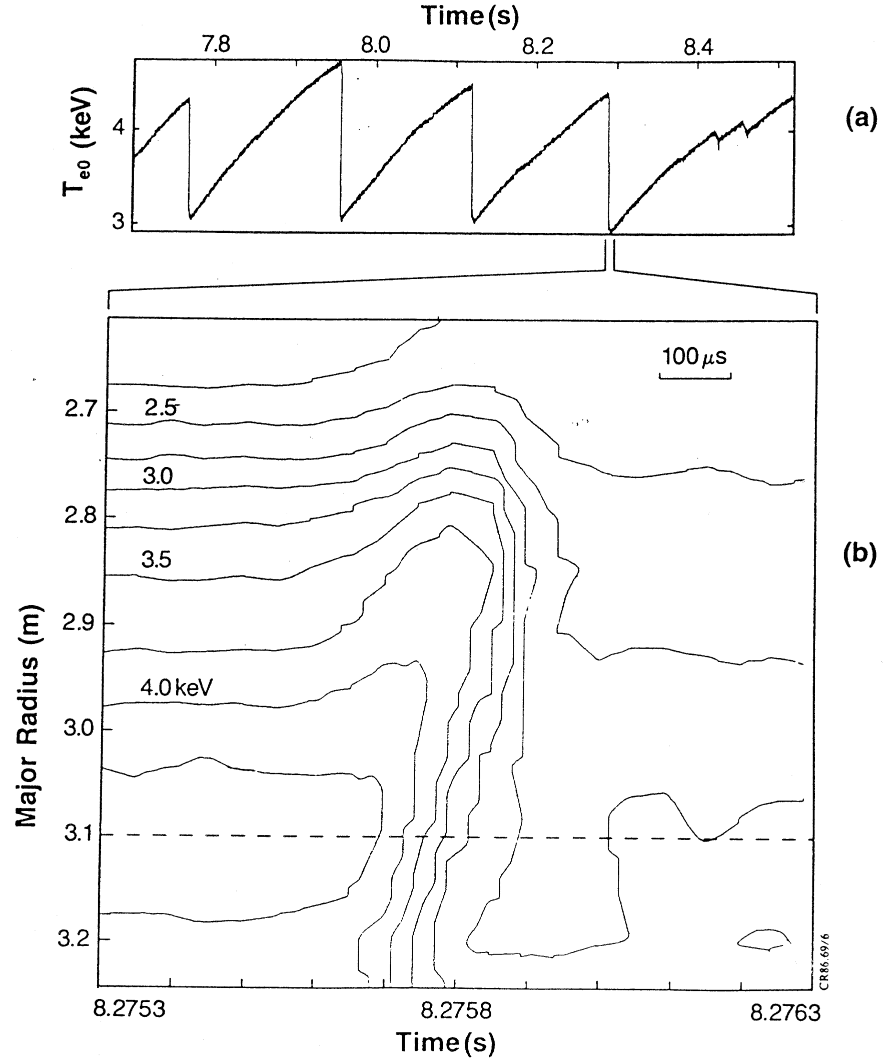

Figure 6. Fast Sawtooth collapse events without a precursor oscillation. The kink displacement of the plasma core is still a feature (Figure 6b), but occurs on the same 100μsec timescale as the thermal collapse. Figure 6b shows the electron temperature as a function of major radius R, and time t.

During the 1980's a new generation of large Tokamaks began operating and revealed new variations in Sawtooth behaviour which stimulated further theoretical activity. Partial, or compound, Sawteeth [11] were reported on the DIII Tokamak where, although the repetition period, τ_s, remained the same, normal Sawteeth collapse events alternated with events in which the thermal redistribution was localised to an off axis region, and the magnetic axis was largely unaffected. Parail and Pereversev [12] had suggested a modification of the Kadomtsev model in-

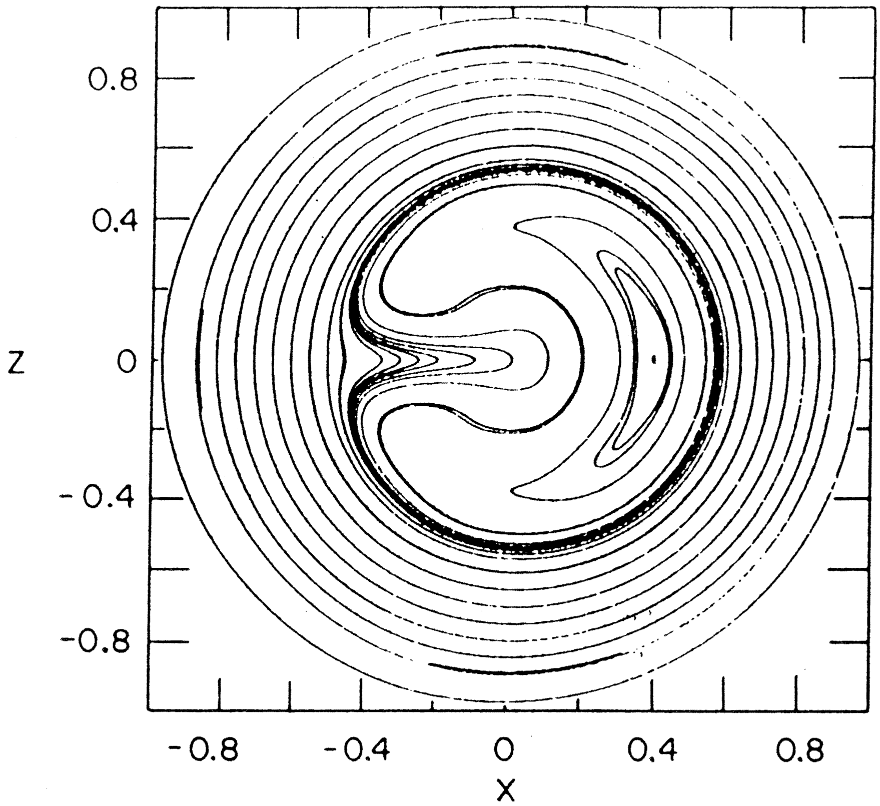

Figure 7. Magnetic surface shapes in the non-linear phase of the $m = n = 1$, Ideal MHD kink instability, when $q \sim 1$ in the plasma core. There is no reconnection. The hot core plasma distorts to a crescent shape and is pushed aside; a bubble of cooler plasma is drawn into the concave side of the crescent, in a 'quasi-interchange' motion.

volving a non-monotonic profile of $q(r)$ with two $q(r) = 1$ surfaces and Pfeiffer [11] extended this in an attempt to explain the new observations. In JET [13] auxiliary heating (both neutral beam injection, NBI, and ion cyclotron resonance heating, ICRH) resulted in a more rapid rise of temperature and pressure during the Sawtooth ramp, but longer Sawtooth repetition times. This suggests that the destabilisation of the MHD kink mode is not caused by plasma pressure ($\beta = 2\mu_0 p/B^2$), but by a 'magnetic trigger' (Wesson [14]), i.e. by some property of the current profile $j_\phi(r)$ or of the $q(r)$ profile. JET also reported Sawteeth in which the slowly growing precursor oscillation is absent [15] (Figure 5) so that the $m = n = 1$ kink instability appears suddenly with rapidly increasing growth rate γ ($\gamma^{-1} \approx 100$ μsec, at maximum growth rate, and rising to that value in 100 μsec). These observations in the mid 1980's led Wesson [15] to suggest that the MHD kink instability seen at the collapse phase might be of ideal MHD character (hence the fast growth). However, to make such instability possible in an ideal MHD model

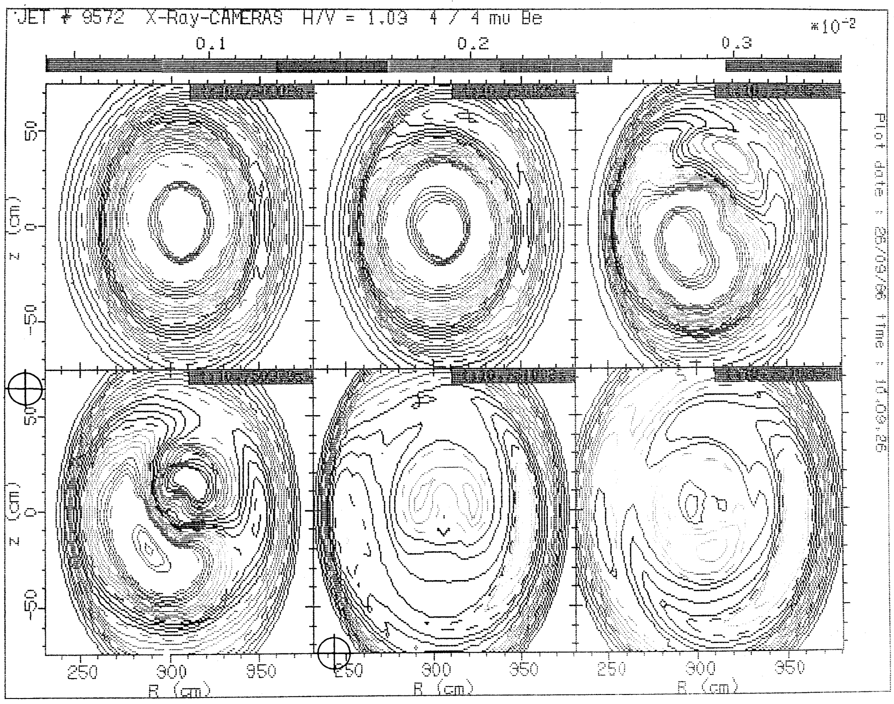

Figure 8. Contours of constant SXR emission during a Sawtooth collapse in the JET Tokamak, displaying the 'hot-crescent, cold-bubble' or 'quasi-interchange' structure.

at relatively low β, it is necessary that $q(r) \simeq 1$ in the entire core region to a high accuracy. In a region where the safety factor $q(r) \equiv 1$, the helical pitch of the magnetic field coincides exactly with the pitch of an $m = n = 1$ kink displacement and no magnetic field line bending occurs. Even a small deviation of $q(r)$ from unity requires significant field line bending energy in a kink displacement and consequent MHD stability. Thus Wesson was led to postulate that $q(r)$ is flat in the core and $q(r) = 1$. Non-linear MHD simulations (see Figure 7) show that the nature of the plasma displacement in such an ideal MHD instability differs considerably from that in a $q(0) < 1$ reconnecting instability. Magnetic surfaces are strongly distorted so that the hot plasma core becomes crescent shaped and a 'bubble' of cold plasma is drawn into the concave crescent. This 'hot crescent, cold bubble' structure, which Wesson called a 'quasi-interchange', contrasts markedly with the cool island (crescent shaped), hot core (circular shape) of the Sykes-Wesson [6] reconnection simulation (Figure 4). During the 1980's, analysis of the SXR emission from Tokamaks became more sophisticated and tomographic methods using up to three SXR cameras and many chordal measurements were employed. Reconstruction of the contours of constant SXR emission on JET (Figure 8) [16] revealed the 'hot crescent, cold bubble' structure predicted by Wesson for kink instability in a $q(r) \simeq 1$ equilibrium.

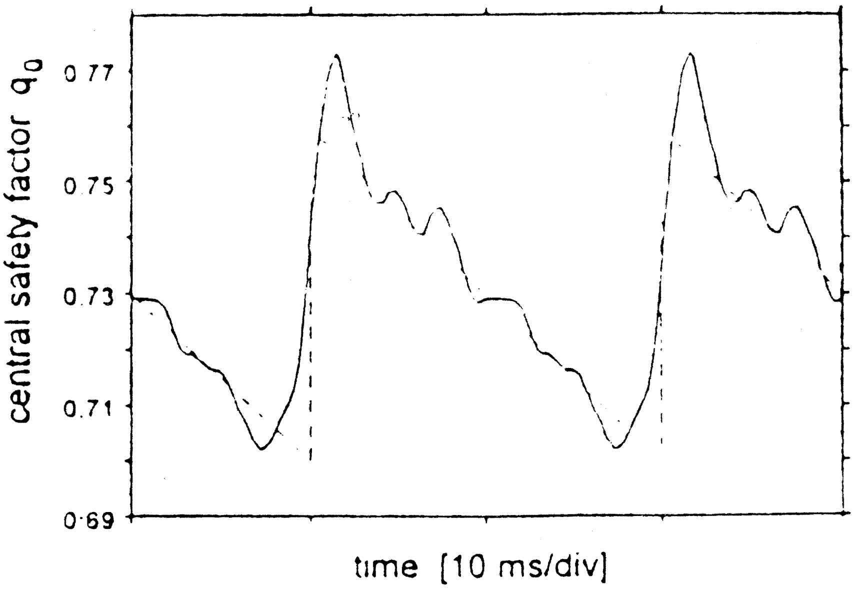

Figure 9. Behaviour of $q(0)$, during a Sawtooth on TEXTOR. The axial value of q never rises above 0.8. Box-car averaging techniques were used to sum the signals from many similar Sawteeth, and enable the $\sim$ 5% sudden changes in q_0 to be monitored.

Thus by 1986 three sawtooth mechanisms had been proposed.

1. Magnetic reconnection driven by the $m = n = 1$ kink instability.
2. Interrupted reconnection, with secondary instability causing the thermal collapse.
3. Quasi-interchange instability in a $q(r) \simeq 1$ core region.

Meanwhile, a new generation of numerical simulations was being published. First, in cylindrical geometry, Denton, Drake and Kleva [17] had convincingly produced many complete sawtooth cycles and shown that strongly anisotropic thermal conductivity is necessary for this. Aydemir et al. [18] and Park et al. [19] extended the studies to toroidal equilibria. In all cases complete reconnection occurred, with $q(0) > 1$ immediately after each thermal collapse. The reconnection process proved to be rather slow in these simulations, broadly agreeing with the Kadomtsev estimate, τ_k, which is an order of magnitude longer than that observed in the high temperature plasmas of large auxiliary heated Tokamaks like JET, TFTR and DIII-D. Many theorists now turned their attention to investigating physical effects leading to faster reconnection. Electron inertia (linear [20] and non-linear [21]), Hall terms [22, 23], anomalous electron viscosity [24] and neo-classical parallel viscosity [25] have all been added to the conventional resistive Ohm's law, and all these effects speed up reconnection.

The 1980's, however, also brought the first reported attempts to measure the poloidal magnetic field in Tokamaks and hence directly measure the profile of the

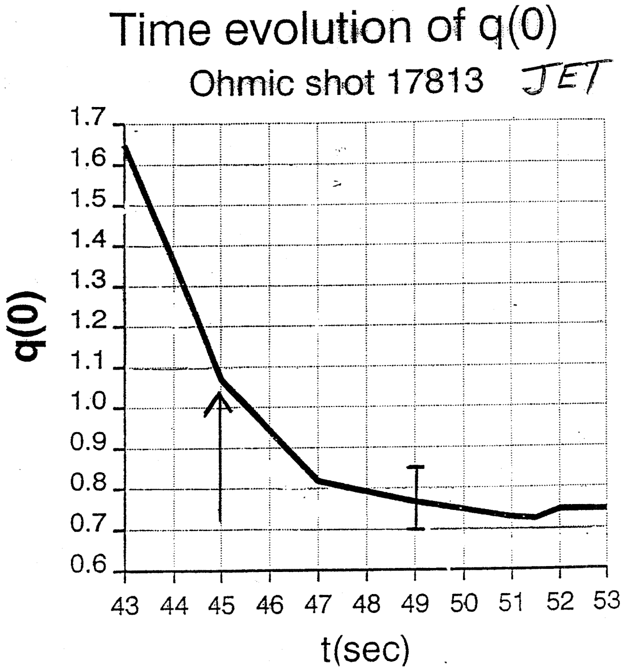

Figure 10. Evaluation of $q(0)$ in a JET ohmic discharge. $q(0)$ continues to decrease after Sawtoothing commences at $t = 45$. Averaging smoothes out the small modulations which occur at each Sawtooth event, which are consequently not visible (from Reference 28).

safety factor $q(r)$. A pioneering measurement by electron scattering of laser light in the DITE Tokamak was reported by Forrest *et al.* [26] in 1978, and indicated that $q(0)$ might fall significantly below unity. The first routinely accurate measurements were carried out on TEXTOR by Soltwisch et al. [27] by measuring the Faraday rotation of a plane polarized FIR micro-wave beam. Blum et al. [28] employed similar methods on JET, while the motional Stark effect (MSE) was used [29, 30] to determine $q(r)$ in DIII-D and TFTR. Figures (9–12) show results of those measurements on TEXTOR [31], JET [28] and TFTR [32]. In each case $q(0) \simeq 0.75$, and varies by $\simeq$ 5% at each collapse event before slowly declining during the succeeding ramp period. These surprising observations indicate that at no time during a Sawtooth cycle does the axial value of the safety factor, q_0, rise above unity. This appears to rule out both the Kadomtsev and Wesson models for the Sawtooth and raises many new questions, some of which will be examined in the remainder of this review.

‘THE TRIGGER PROBLEM’

The polarimity or MSE measurements of $q(r)$, together with measurements of $n_e(r,t)$, $T_e(r,t)$, $T_i(r,t)$ make it possible to construct a detailed picture of the Tokamak equilibrium and its evolution during Sawtoothing. In particular one can

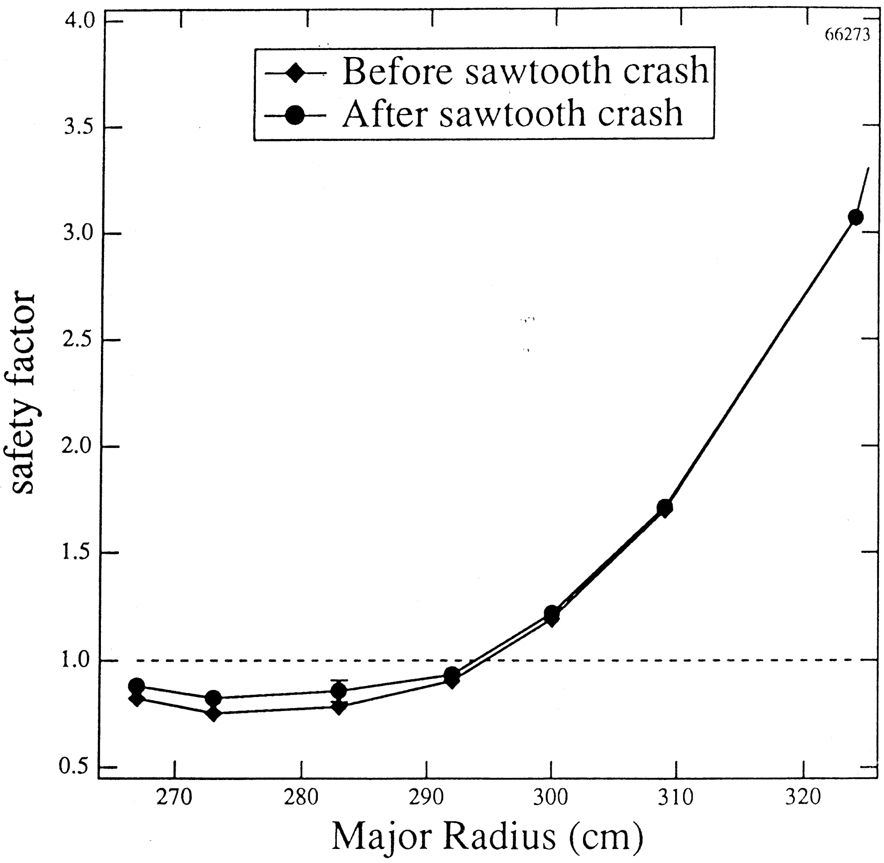

Figure 11. $q(r)$ profiles just before, and just after, a Sawtooth collapse on the TFTR Tokamak, measured using the Motional Stark Effect (from Reference 32).

seek to correlate equilibrium properties at the onset of the $m = 1$ instability (which initiates the collapse phase of Sawteeth) with the crossing of a theoretical stability boundary for the internal kink mode. The theoretical boundary differs, of course, as additional physical effects are introduced into the linearized 'MHD' equations. In increasing complexity, one can assess: (1) Ideal, single fluid, MHD, (2) Resistive single fluid MHD, (3) Two fluid, resistive equations incorporating diamagnetic effects (i.e. $\omega \lesssim \omega_*$ with $\omega_* \approx \rho_i v_i/a^2$ being the diamagnetic frequency), (4) Two fluid plus kinetic treatment of a collisionless high energy ($E \gg kT_i$) population of ions.

The results of such comparisons have been disappointing.

1. The ideal MHD theory of the internal kink mode yields the stability criterion

$$\delta W_{\text{mhd}} > 0 \tag{1}$$

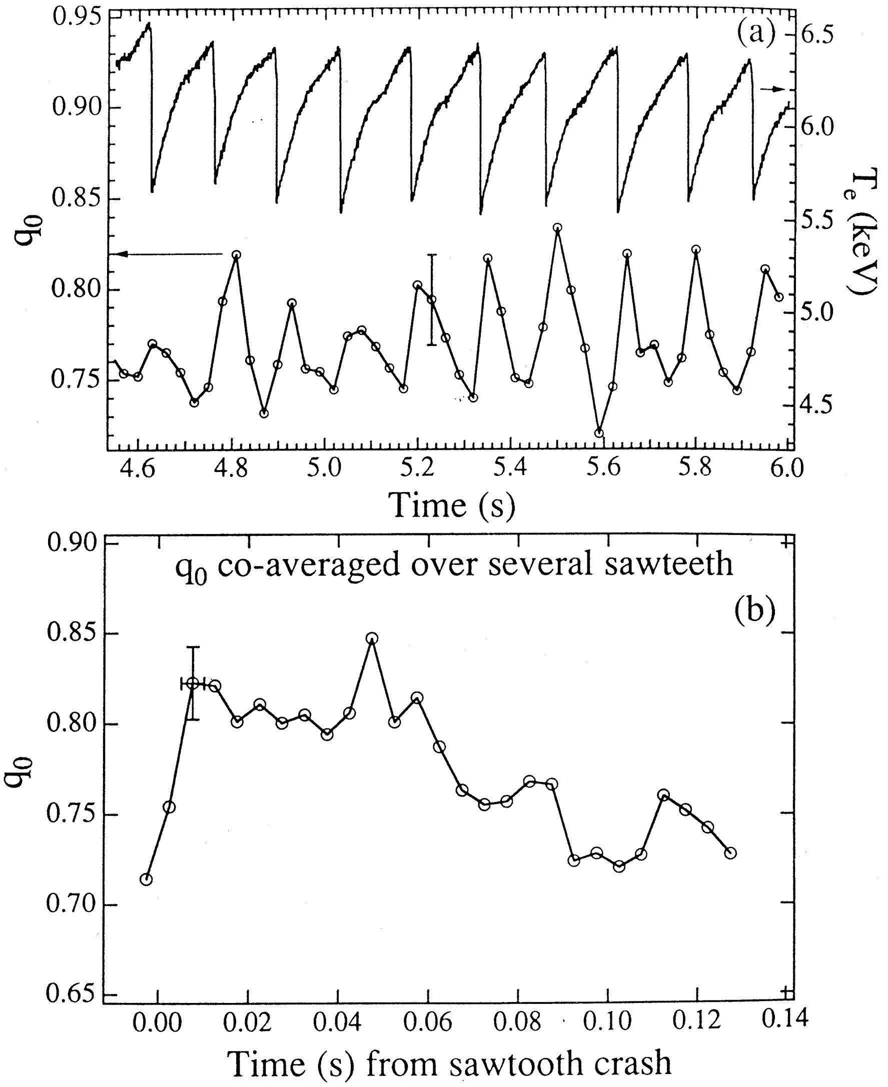

Figure 12. (a) q_0 measurements using MSE during Sawtoothing on the TFTR Tokamak. (b) q_0 evolution during a Sawtooth period, obtained by averaging 9 consecutive Sawtooth events (from Reference 32).

where δW_{mhd} is the potential energy required to perturb the plasma by an $m/n = 1/1$ displacement, with coupling to 0/1, 2/1 and more remote poloidal harmonics induced by the 2-D nature of a toroidal Tokamak equilibrium. In an elegant short paper Bussac et al. [33] calculated the analytic form for δW_{mhd}

for a toroidal equilibrium in the limit of large aspect ratio, $R/a \gg 1$, obtaining the result,

$$\delta W_{\rm mhd} = 2\pi^2 \varepsilon_1^4 \xi_0^2 R_0 B_0^2 \delta \hat{W}_{\rm mhd}, \psi \tag{2}$$

with ξ_0 being the amplitude of the kink displacement and

$$\delta \hat{W}_{\rm mhd} = \delta W_0 - \beta_p \delta W_1 - \beta_p^2 \delta W_2, \psi \tag{3}$$

where

$$\beta_p = -\frac{2}{B_\theta^2(r_1)} \int_0^{r_1} \frac{r^2}{r_1^2} \frac{dp}{dr} dr$$

is a measure of the poloidal beta confined within the magnetic surface where $q(r) = 1$, $\varepsilon_1 = r_1/R$ with $q(r_1) \equiv 1$ and the 'poloidal' beta is the ratio of the plasma pressure p to the magnetic pressure of the poloidal component of the field (Figure 1(e)). In particular Bussac et al. showed that the ideal kink energy of a toroidal plasma is crucially dependent on the toroidal curvature of the equilibrium and is quite different from that of a straight (cylindrical) plasma with the same $p(r)$, $q(r)$ and $j(r)$ profiles.

The coefficients δW_n in Equation (3) depend on the global current profile (or equivalently the $q(r)$ profile). The calculation showed that the δW_n are positive, implying stability ($\delta \hat{W}_{\rm mhd} > 0$) for $\beta_p \to 0$, and that for typical current profiles in Tokamaks the critical value of β_p above which instability should appear is $\sim 0.2 - 0.3$. The 2-D linear stability computer codes which were developed during the following decade have revealed that the Bussac et al. [33] calculation, although asymptotically correct for $R/a \to \infty$, is rather inaccurate when applied at values of the aspect ratio ($R/a \sim 3$ or 4) which are typical of most Tokamaks. Nevertheless, such computer codes still predict [34] ideal mhd stability at values of β_p below $0.15 \sim 0.2$ for realistic Tokamak equilibria. In conflict with this prediction, Tokamak discharges, in which the only plasma heating is ohmic heating, regularly display Sawtoothing activity at much smaller values of β_p (~ 0.05), implying that the 1/1 kink instability observed at each Sawtooth collapse is not of ideal MHD character.

The single fluid resistive MHD model [35, 36] is also unsuccessful in accounting for Sawteeth. This model predicts linear instability at any value of β_p, when $q(0) < 1$. There are two forms of reconnecting instability in an Ideal mhd stable plasma, ($\delta \hat{W}_{\rm mhd} > 0$), when $q(0) < 1$. One is known as the resistive kink mode, with growth rate,

$$\gamma \tau_A = s_1^{2/3} S^{-1/3}, \psi \tag{4}$$

where $s_1 = r_1 q'(r_1)$ is the shear of the magnetic field lines at the $q = 1$ surface, and $S = \tau_\eta/\tau_A$ is the Lundquist number, with $\tau_A = \sqrt{3} R_0/V_A$ and $V_A = B/\sqrt{\mu_0 \rho}$ is the Alfven speed. The other is the tearing instability with growth rate,

$$\gamma \tau_A = 0.55 s_1^2 (\varepsilon_1^2 \delta \hat{W}_{\rm mhd})^{-4/5} S^{-3/5} \tag{5}$$

The tearing instability scaling, $\gamma \tau_A \propto S^{-3/5}$, applies if $\varepsilon_1^2 \delta \hat{W}_{\rm mhd} > s_1^{5/3}/S^{1/2}$ and the growth rate increases as Ideal marginal stability is approached,

($\delta\hat{W}_{\text{mhd}} \rightarrow 0+$). The resistive kink scaling applies when $\delta\hat{W}_{\text{mhd}}$ is small. Larger, Alfvenic, growth is predicted when $\delta\hat{W}_{\text{mhd}} < 0$. Since the resistive fluid model predicts an unstable plasma during the ramp phase when $q(0) < 1$, with linear growth time of order 5–10 msec, it cannot explain the quiescent ramp phase of the Sawtooth cycle, during which no mhd activity is observed and which can have a duration of many seconds (many hundreds of e-folding times of the resistive instability) in large Tokamaks with auxiliary heating. One possible explanation of the stable ramp phase in this model involves subtle distortions of the current profile close to the $q = 1$ radius. Such equilibria have been investigated by several authors [37–39] and the existence of resistively stable equilibria, with $q_0 < 1$, has been demonstrated. However, such equilibria have locally non-monotonic current densities, $j_\phi(r)$, and transport simulations of Tokamak discharges show that resistive diffusion ought to render them short lived, if they exist at any time.

Two fluid plasma models have also been explored [40, 22] and show more promise. The physics of the reconnecting layer at r_1 is now complicated by Hall terms in Ohm's law and gyro-viscous effects in the ion stress tensor, which appear as diamagnetic frequency terms, $\omega_* \propto \rho_i v_i / r L_n$ (ρ_i = ion Larmor radius, v_i = ion thermal speed, $L_n^{-1} = d \ln n_e/dr$) which greatly exceed τ_η^{-1} and strongly modify the single fluid resistive dispersion relation. Asymptotic matching of layer solutions to those of the outer ideal region leads to a dispersion relation of the (symbolic) form [40],

$$\delta\hat{W}_{\text{mhd}} = \delta\hat{W}_{\text{layer}}(s_1, \omega_*\tau_\eta, \ldots)\,\psi \tag{6}$$

where $\delta\hat{W}_{\text{layer}}$ also has complicated dependence on the density and temperature gradients at r_1. Analysis of this dispersion relation [40] has revealed stable regions of parameter space which might account for quiescence during the Sawtooth ramp. When $\delta\hat{W}_{\text{mhd}} \approx 0$ (i.e. for β_p near to its critical value for ideal instability) a relatively simple stability criterion for reconnecting instabilities may be derived from (6), namely [41, 42]

$$s_1 < 1.4\left(\beta^2 \frac{R^3}{L_n^2 L_p}\right)^{\frac{1}{3}} \tag{7}$$

for stability, where $L_p^{-1} = d \ln p/dr$. Studies of Sawteeth on the TFTR Tokamak [42] comparing two different types of discharge (known as 'supershots' and 'L-modes') found that in discharges where this criterion was satisfied no Sawtoothing occurred, while in those which violated the inequality (7), (the L-modes in fact), normal Sawtoothing was present. Remarkably, however, the supershot discharges, in which no Sawteeth were seen, had very high values of β_p ($\approx 1-2$), greatly in excess of the critical value for ideal instability ($\beta_p \sim 0.2$). This led Levinton et al. [42] to conjecture that ideal unstable equilibria may behave as though they are marginally stable and that Sawtoothing is controlled by the two-fluid dynamics of the reconnecting layer under these conditions (i.e. by inequality (7)). This idea is very plausible. In essence it

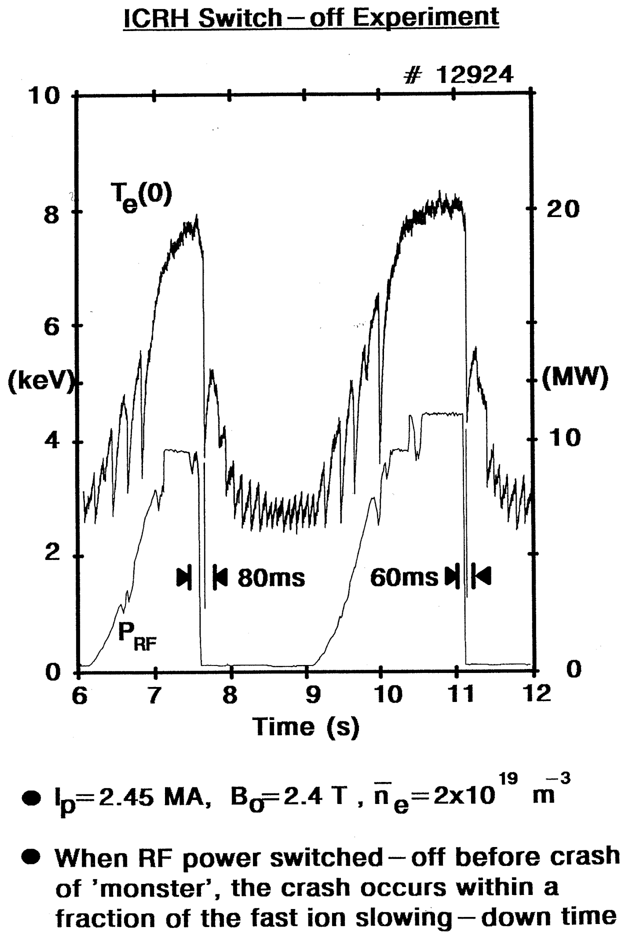

Figure 13. Stabilising effect of energetic ions demonstrated by switch-off of ICRH. This triggered a Sawtooth collapse in 60 - 80 msec, a delay comparable to the slowing down time of the trapped energetic ions generated by the ICRH.

suggests that an ideal unstable equilibrium, with $\delta\hat{W}_{\rm mhd} < 0$, merely adjusts by kinking slightly in the core, $r < r_1$, region. The resulting field line bending energy in the new, slightly distorted but topologically unchanged, equilibrium returns $\delta\hat{W}_{\rm mhd}$ to zero. A precise calculation of this process in an ideal mhd plasma [3] showed that the amplitude of the kink displacement is, in practice, extremely small.

2. In experiments [43] with auxiliary heating, long Sawtooth periods were terminated by a Sawtooth collapse that followed switch off of ICRH with a time lag of $\sim 60 - 80$ ms – comparable to the slowing down time of the energetic ions (Figure 13). This suggests that a collisionless kinetic theory may be re-

quired. In such a theory the potential energy $\delta\hat{W}$ in Equation (6) acquires two additional terms, so that with collisionless ion dynamics (6) becomes

$$\delta\hat{W}_{\text{total}} \equiv \delta\hat{W}_{\text{mhd}} + \delta\hat{W}_{ki} + \delta\hat{W}_{kE} = \delta\hat{W}_{\text{layer}} \tag{8}$$

where [44]

$$\delta\hat{W}_{ki} \simeq \varepsilon_1^{-3/2}\beta_i \tag{9}$$

with

$$\beta_i = \frac{5}{2}\int_0^1 dx x^{3/2}\frac{2p_i(x)}{B_0^2}, \quad x \equiv r/r_1$$

and [45]

$$\delta\hat{W}_{kE} \simeq \varepsilon_1^{-\frac{1}{2}}\beta_E^* \tag{10}$$

with

$$\beta_E^* = -\frac{2}{B_\theta^2(r_1)}\int_0^1 x^{3/2}\frac{dp_E}{dx}dx$$

and p_i, p_E are the thermal ion and energetic ion pressures, respectively.

The physical mechanism underlying these additional, stabilising, contributions to the potential energy is the compression of magnetically trapped ions by the kink displacement.The differing expressions (9) and (10) arise from different limits of a common dynamical response of thermal and high energy ions.

The complex dispersion relation (8) contains elements which may account for the wide range of Sawtooth ramp times in differing Tokamaks. According to the Levinton [42] conjecture, energetic ions will be irrelevant if $\delta\hat{W}_{\text{total}} < 0$ (ideal instability even with energetic ions present). In this case stability of the Sawtooth is determined by the plasma parameters at r_1 (inequality (7)). If, however, $\delta\hat{W}_{\text{total}} > 0$ due to the presence of a population of energetic ions, the stability criterion is modified [40] by the (positive) ideal energy $\delta\hat{W}_{\text{total}}$. Recently stability criteria based on these ideas and results have been incorporated in a transport code in an attempt to predict the Sawtooth repetition time τ_s for a D-T plasma in the proposed ITER device. It was found [46] that the alpha particles produced by D-T fusion had a significant effect in lengthening τ_s. The electron and ion dynamics of the reconnecting layer are, however, even more complex than has been assumed in the derivation of (7). In current Tokamak experiments a long mean-free-path analysis, $\lambda_{mfp} \gg R_0$, incorporating magnetic trapping effects is required. Work on this topic has recently been reported [47–49].

Any linear stability analysis, however complex, will predict the emergence of a slowly growing mode – a precursor oscillation – as a linear stability boundary is crossed by a slowly evolving Tokamak equilibrium. The experimental observation of precursorless Sawteeth, in which the initial kink perturbation has a large growth rate, appears to require a non-linear instability mechanism to explain it. Work on this topic is also under development in the form of ‘small island’ stability theory. This seeks to describe a non-linear regime in which some magnetic reconnection has occurred and the resulting magnetic island at the $q = 1$ surface has become wider than the narrow layer of linear theory, in which non-ideal effects, such as resistivity, control plasma dynamics.

At this point, the predictions of linear and non-linear calculations differ because the change of magnetic topology, implicit in the non-linear island, permits rapid longitudinal particle motion (in kinetic theory) or longitudinal transport (in fluid theory) from one side of the 'layer' to the other. In linear theory this role can only be performed by cross field drifts, (or cross field transport processes in fluid theory).

Now, in high temperature Tokamaks the linear layer width is predicted to be of the order of a few mm, and magnetic perturbations associated with islands of this width are difficult to detect. Thus, the first detectable kink perturbation seen during a precursorless Sawtooth event may already be in a non-linear phase of its dynamics. Consequently one possible explanation of the sudden growth of the $m/n = 1/1$ kink in precursorless Sawteeth, may lie in the differing stability boundaries of 'linear' and 'small-island' stability theory. In the event that the linear stability boundary is higher (e.g. a larger value for the critical β_p) than the 'small island' stability boundary, a plasma evolving slowly, from a linearly stable to linearly unstable state, could pass to a strongly unstable non-linear state before any perturbations were detected experimenally. In such a scenario, it is the linear stability boundary which determines the 'trigger' for the Sawtooth event, but the subsequent dynamic evolution is controlled by non-linear effects. Zakharov et al. [41] have investigated such a situation using the two fluid equations and found that, in contrast to single fluid theory, rapid exponential growth is predicted in the non-linear phase with

$$\gamma \tau_A \propto s_1 \frac{\rho_i}{r_1} \tag{11}$$

Before turning to other interesting experimental observations, it may be useful to summarise this section.

Since the Sawtooth collapse is *invariably* accompanied by a 1/1 kink displacement, much work has been carried out on the linear stability of this mode. The calculations involve asymptotic matching at a critical layer where $q = 1$. Relatively simple calculations, neglecting inertia and dissipation, are used to calculate a measure of the potential energy, $\delta \hat{W}_{\text{total}}$, available in the outer regions of the plasma (away from the narrow reconnecting layer at $q = 1$) to drive instability. The appropriate model for this relies on collisionless ion dynamics, and treats energetic ions in a different limit from thermal ions when calculating the compressional energy.

The complementary calculation, within the layer, in the simplest possible limit, involves only inertia. Realistically, however, the layer calculations need to take account of long mean-free-path transport processes [47–49], of toroidal geometry, of finite Larmor radius (FLR) averaging effects and of the diamagnetic frequency effects which Hall terms and gyro-viscosity generate in two fluid calculations. Reconnection is predicted by single fluid theory, but the diamagnetic corrections of two fluid theory suppress reconnection under certain conditions (inequality (7)).

Linear stability calculations may correctly determine the marginal stability boundary, and hence the Sawtooth 'Trigger' condition, but they fail to account for the sudden appearance of 1/1 displacements with large (100 μsec^{-1}) growth rates. For this 'small island' stability theory [41] is required. This topic is not yet highly developed in the context of Sawteeth, but it offers the possibility of an explanation for sudden growth.

SOME MISCELLANEOUS OBSERVATIONS

A number of other experimental observations throw light on the sawtooth phenomenon. A few are briefly outlined below.

'Snakes' Pellet injection in JET quite frequently results in the creation of a high density closed tube of plasma (the Snake) [50] on the $q = 1$ surface when a pellet of sufficient size reaches the core. Snakes are long lived phenomena aligned to the closed magnetic field lines of the $q = 1$ surface. They survive many sawtooth collapses, with the thermal and density redistribution taking place around them. At each Sawtooth event, the radial position of the Snake suddenly decreases slightly, to increase slowly during the subsequent ramp phase of the Sawtooth. The Snake appears to be a reliable 'marker' for the $q = 1$ surface so that these observations have been taken as further evidence that a Kadomtsev reconnection is not taking place at each collapse, and that $q(r)$ experiences relatively small changes.

Magnetic shear at $q = 1$. Pellet injection in JET also furnishes a novel and elegant means of estimating the magnetic shear $s = rq'/q$, at the $q = 1$ surface [51]. Light emitted by the ablating pellet, shows a pronounced dip as the pellet passes through $q = 1$ where field lines close on themselves after just one circuit of the Tokamak. At this point the source of electrons impinging on the pellet is much reduced (since the pellet effectively passes through its own 'shadow') resulting in reduced emission. Close to the $q = 1$ surface this mechanism remains partially operative and, by measuring the width (in time) of the reduced emission, Gill et al. [51] were able to calculate the shear s_1. The method yields a rather indirect measurement of s_1 and one might suspect that other physics (ablation instabilities) might produce similar effects. However, accepting the geometric interpretation of the reduced emission, the results are surprising. Gill et al. deduced $s_1 \simeq 1{-}2\times10^{-2}$ with no correlation between the measured value and the time within the Sawtooth ramp (early, mid, or late) that the pellet was injected (Figure 14). For comparison, a simple parabolic $q(r)$ with $r_1/a \sim 1/3$ yields a value of $s_1 \approx 0.16$ (an order of magnitude larger).

Sawtooth suppression. Over the years a number of methods of suppressing Sawteeth in Tokamaks have been discovered experimentally, and these may throw some light on aspects of the sawtooth, and certainly on the 'Trigger mechanism'. The following are three examples:

1. By localised ECRH/ECCD (Electron cyclotron resonance heating and current drive) tuned to resonance at $r = r_1 + \delta$, $(\delta/r_1 \ll 1)$ i.e. just outside the

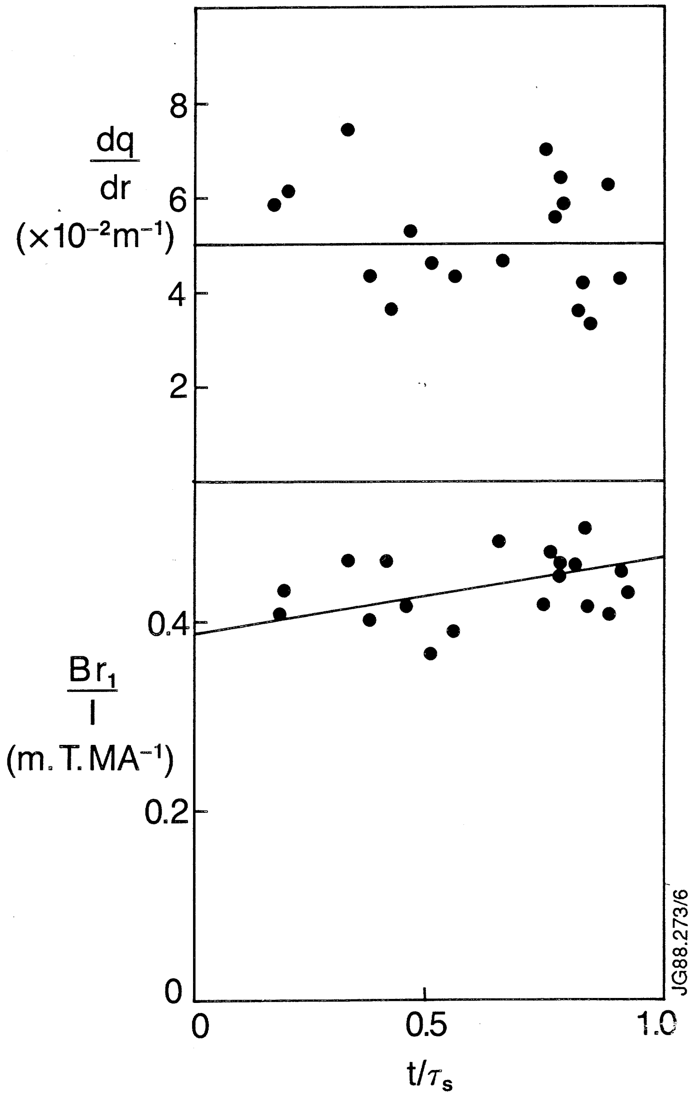

Figure 14. Magnetic shear, $s_1 = r_1 \frac{dq}{dr}(r_1)$ at the $q = 1$ surface as inferred from light emitted as a pellet passes through $q = 1$. Note the lack of correlation between values of $q'(r_1)$ and the time elapsed since the last Sawtooth collapse (from Reference 51).

$q = 1$ surface [52]. Evidently the mechanism involves linear stabilisation of the $m = n = 1$ internal kink mode (ideal or resistive) by current profile control. Calculations showing the stabilising effect of local perturbations in the current prolile have been published [37–39].

2. By generation of energetic trapped ions. A combination of NBI and ICRH appears to be most effective, and Sawtooth periods in excess of 8 secs have

been obtained on JET [53] by this means. In this case, linear stability theory shows that an energetic trapped ion population can stabilise the $m/n = 1/1$ ideal internal kink at moderate values of $1 - q(0)$, but whether this mechanism could be responsible for complete Sawtooth suppression, or merely lengthening of the Sawtooth period is not clear.

3. By application of externally generated resonant magnetic perturbations (RMPs) with $m = 2$, $n = 1$. The RMP is generated by coils external to the plasma, and creates a magnetic island at the $q = 2$ surface which exerts a drag on the plasma at that radius. A sufficiently large RMP brings the plasma to rest at $q = 2$ (the toroidal rotation of the plasma is suppressed) and when this occurs Sawteeth are suppressed [54]. Reduction of the amplitude of the RMP (reducing the drag) results in spin up of the plasma and resumption of normal Sawtoothing. The way in which this mechanism suppresses the kink mode is not understood but it points to the importance of (sheared) plasma rotation in the stability of the kink mode: a neglected subject.

Impurity transport during a Sawtooth collapse. One explanation for the rapid transport during a Sawtooth collapse has received considerable attention [55, 56, 57] and deserves a special mention. In this model it is proposed that the $m = n = 1$ helical magnetic perturbation, interacting with the axisymmetric equilibrium fields of the Tokamak, causes stochastic break up of the regularly nested magnetic surfaces in the plasma core. Magnetic field lines 'wander' radially as they circuit the torus and, it is argued, rapid longitudinal transport (parallel to B) is responsible for the sudden thermal collapse of the core plasma.

A recent experiment [58] on the JET device has a bearing on this suggestion. In the experiment a small amount of heavy impurity (Nickel) was introduced at the plasma edge. The Nickel ionized and was transported toward the core but, for reasons that are not understood, the Nickel ions did not penetrate beyond a radius of about $r/a \approx 1/3$, comparable to the radius of the $q = 1$ surface. However, at the next Sawtooth event the Nickel impurity was observed to suddenly invade the core region on the same 50 μsec timescale as the thermal collapse. Wesson et al. [58] point out that on this timescale, whereas electrons with an energy of around 5 keV travel about 1500 metres (equivalent to nearly 100 transits of the JET torus), the massive Nickel ions cover a longitudinal distance of only 5 metres (less than one transit of the machine). It follows that the sudden radial influx of Nickel ions from $r/a > 1/3$ into the axis cannot be explained in terms of magnetic stochasticity. Instead, Nickel ions must be drifting *across* the magnetic field.

A possible explanation, which still involves magnetic stochasticity, runs as follows. At sufficiently large amplitude of the $m = n = 1$ magnetic perturbations, magnetic stochasticity may indeed become significant. This will permit rapid (on ~ 100 μsec timescale) exchange of passing electrons (up to 50% of the electrons are magnetically trapped and cannot follow wandering field lines to different radii) between the axial region $r \ll r_1$ and the surrounding, $r \sim r_1$ region. Unequal electron densities and/or trapping fractions in these two regions may cause the

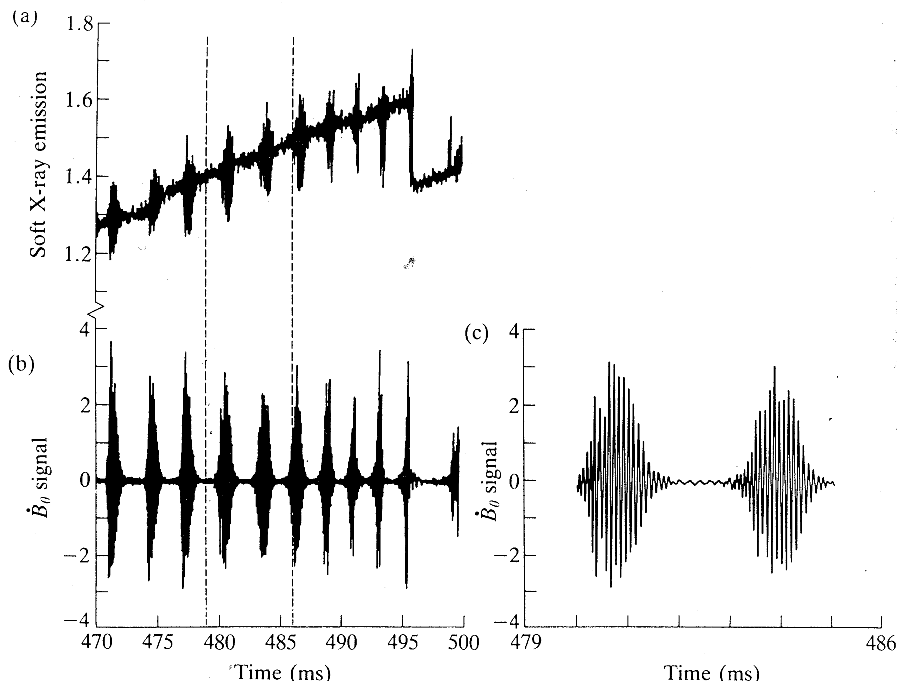

Figure 15. (a,b) Regular bursts of fishbone activity on PDX as seen on soft X-ray emission and magnetic fluctuations. (c) Characteristic signature of the magnetic fluctuation signal for the Fishbone instability on the PDX Tokamak (from Reference 60).

build up of electrostatic potentials with $e\phi/T_e \lesssim 0(1)$. Under the influence of such electrostatic potential, ions, impurities and magnetically trapped electrons will $\mathbf{E} \times \mathbf{B}$ drift together across the magnetic field in a large scale convective motion. Such a detachment of plasma from the magnetic field might explain the 'quasi-interchange' structure of the SXR emission contours noted earlier [25] and would not require flat, $q(r) = 1$, equilibria in the Tokamak core. Magnetic stochasticity remains an essential element in this scenario, with the other element being the different longitudinal mobility of electrons and ions.

However other observations on JET [59] cast doubt on this suggestion also. Duperrex et al. [59] made detailed measurements of the magnetic perturbations outside the plasma and found that their evolution matched very closely that of the distortions in the SXR emission from the plasma core. They concluded that the core displacements are of a purely electromagnetic character, rather than of an electrostatic character.

The Fishbone instability. In 1983 a new form of $m = n = 1$ internal kink instability was observed on the PDX experiment [60]. Like the precursor oscillation of the Sawtooth instability, the Fishbone instability appears as a slowly growing, oscillating, signal on the SXR emission and other diagnostics, and can be attributed to a growing $m = n = 1$ kink displacement of the core plasma, rotating in the toroidal direction. Unlike the Sawtooth instability, no rapid thermal collapse in the core is observed. Instead, the oscillatory signal first grows and then decays in amplitude, giving the characteristic signal (Figure 15) which led to the terminology 'Fishbone instability'. Periods of quiescence alternate with bursts of Fishbone activity (Figure 15) in a fairly regular manner.

A good qualitative theoretical understanding of the instability, which has stood the test of time, was quickly provided [61]. The unique feature of the PDX device which caused it to exhibit the instability so clearly, lay in the fact that the angle of neutral beam injection (NBI) was nearly perpendicular to the main toroidal field. Consequently, most of the high energy ions became magnetically trapped. Like the mirror trapped particles of the Earth's Magnetosphere, which precess around the earth in the equatorial direction, magnetically trapped ions in a Tokamak precess in the toroidal direction. The Fishbone instability was explained in terms of a magnetic perturbation whose toroidal phase velocity is in Landau resonance with the precessional velocity of the energetic NBI ions and which draws on their energy to grow. Because the relevant frequency is relatively low it occurs within the spectrum of the Alfvén continuum, so that Alfvén continuum damping must be overcome. Because of this there must be a sufficiently high pressure of the trapped energetic ions, and previous experiments with NBI did not have sufficient auxiliary heating power, or the necessary perpendicular injection geometry, to exceed the threshold for instability.

Much theoretical work quickly followed. Some of this focused on the new Fishbone instability, and in particular on the possibility that the mode is a discrete eigenmode, weakly damped in the absence of energetic ions, within a gap in the Alfvén continuum [62]. However, since it had become clear that a relatively low pressure of trapped energetic ions could be responsible for the new kink instability, attention now also focused on the effect of such ions on the MHD (ideal or resistive) internal kink mode which had been thought to be responsible for the Sawtooth instability. As a result it is now accepted that quantitative predictions of Sawtooth characteristics must necessarily take account of the collisionless dynamics of energetic ion populations. Where these have been created by external heating schemes, such as NBI or ICRH, the relevant ion distribution functions are neither Maxwellian in energy nor isotropic in pitch angle ($\theta = \cos^{-1}(v_\parallel/v)$). In such cases the resulting stability calculations are complicated. Simpler calculations, and possibly more robust predictions, are possible when the energetic ions are the α-particles produced by D-T fusion. Here the distribution is isotropic and the calculations more tractable [63, 64]. A comprehensive review of the theoretical work on energetic ion effects in Sawteeth and Fishbones has been given by Porcelli [65].

The absence of sudden thermal collapse events during Fishbone activity provides another clue to the mechanism involved in the thermal collapse events in Sawteeth. According to the theory of Fishbones the frequency of such modes is such that they should cause little or no magnetic reconnection. This suggests that a change in magnetic topology may be an essential ingredient in the fast thermal collapses of Sawteeth, where a transition from a mildly unstable linear phase to a more strongly unstable, small island, phase may be crucial. In contrast, non-linear effects in the Fishbone 1/1 kink tend to be stabilising since the mode expels the energetic ions which provide the drive.

Summary and Conclusions

The understanding of the Sawtooth instability in Tokamak plasmas is improving but is nevertheless still incomplete. Early explanations in terms of a single magnetic reconnection phenomenon now appear to be untenable. Instead the Sawtooth collapse phase appears to require at least two ingredients: the initial growth of an MHD internal kink instability causing some magnetic reconnection in the vicinity of the $q = 1$ surface, together with a secondary event which is responsible for the very rapid collapse of the core density $n_e(r = 0)$ and temperatures $T_j(r = 0)$. The precise nature of this secondary event remains unclear. It may be a pressure driven instability as has been suggested by, e.g., Bussac et al. [66], Gimblett et al. [67], or it may be sudden stochastization of the magnetic field structure at a critical amplitude of the kink perturbation as suggested by, e.g., Mercier [55], Lichtenberg et al. [56, 57].

Observations on TORE-SUPRA [68] showing a sudden burst of increased density fluctuations (in the frequency range 500 kHz–1 MHz) during the thermal collapse give strong support for the former explanation. It has also been suggested [69, 70] that Sawteeth may be triggered by a critical level of turbulence unconnected with the $m = n = 1$ kink mode (whose appearance, in this model, is a consequence rather than a cause of the collapse event).

In the case of the, so-called, precursorless Sawteeth, the very rapid onset of the $m = n = 1$ kink perturbation cannot be reconciled with slow evolution of an equilibrium through marginal stability but might be explained by a transition to a more unstable, ‘small island’, non-linear regime.

Some progress has been made in correlating the linear stability boundary for the $m = n = 1$ kink mode with experimental observations of the equilibrium at onset of the kink, but this requires a two fluid treatment of the inertial layer at the $q(r) = 1$ surface, and a calculation of the collisionless dynamics of any high energy ions (with $E \gg kT_e, kT_i$) which are present in the core plasma.

The measurements, using polarimetry or the motional Stark effect, which indicate that the axial value of the safety factor, $q(r = 0)$, never rises to, or above, unity at any time during the Sawtooth cycle, cannot be reconciled with the non-linear fluid MHD simulations in which the initial Kadomtsev reconnection process invariably continues to completion, resulting in a $q(0) > 1$, post collapse, state. However, if these measurements indicating that $q(0) < 1$ could be discarded most of the other observations become mutually compatible and compatible with non-linear simulations of discharges in which $q(r)$ is flat and close to unity. In addition, it is a fact that, on certain Tokamak devices, the measurements of $q(r)$ have suggested values which are indeed very close to unity. McCormick et al. [71] used Zeeman splitting of radiation from injected Lithium atoms to measure $q(0) \approx 1$ in the ASDEX Tokamak and recent MSE measurements on DIII-D [72] gave $q(0) = 0.96$ before and $q(0) = 1.02$ after a Sawtooth collapse. In such cases a hybrid Kadomtsev/Wesson picture, in which plasma flow patterns have some quasi-interchange structure but reconnection also takes place, becomes possible (See Aydemir et al. [18] for simulations of such Sawteeth). The rapidity of the reconnection event can rather readily be explained by one of the accelerating mechanisms discussed earlier. We conclude that it is possible that somewhat different dynamics controls Sawteeth in different Tokamaks and that $q(0) \approx 1$, with Kadomtsev Sawteeth, in some, while $q(0) \lesssim 0.75$ in others. In the latter cases it appears that the hot plasma ($T \sim 1$–10 keV) in the core of these Tokamaks is not well described by MHD single fluid equations.

When, eventually, a better understanding of the dynamics of Sawteeth is achieved it may throw light on many other phenomena in Tokamak plasmas (such as the disruptive instabilities which sometimes terminate a discharge and the instabilities of the plasma boundary known as Edge Localised Modes, ELMs), but also perhaps on fast reconnection events in the Magnetosphere, the Solar Corona and elsewhere.

Finally, the interested reader should consult the four excellent review articles [14, 65, 73, 74] which cover different aspects of Sawtooth phenomena.

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