Stabilization and Onset of Sawteeth in TFTR

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(Received 2 December 1993)

Measurements from the Tokamak Fusion Test Reactor (TFTR) of the q profile using motional Stark effect polarimetry and the pressure profiles have allowed detailed comparison of both supershots and L-mode discharges to theoretical models describing the stability of sawteeth. In TFTR supershots sawteeth are usually absent, whereas in L-mode discharges they are generally present, and in both cases $q(0)$ is less than 1. It has been found that the ω^*-stabilization criterion of the two-fluid collisionless $m = 1$ reconnection mode agrees very well with the presence or absence of sawteeth in TFTR and no beta limits to the sawtooth stabilization have been observed.

PACS numbers: 52.55.Fa, 52.30.Jb, 52.35.Py

Sawtooth oscillations [1] are characterized by a periodic collapse of the pressure in the plasma core. They have been the subject of extensive experimental and theoretical investigations because of their relation to several fundamental properties in plasmas, such as magnetohydrodynamic (MHD) phenomena, magnetic reconnection, and perhaps plasma disruptions. There are several theoretical models [2,3] which predict that when the central safety factor, $q(0)$, is less than 1, the plasma is unstable to the $m = 1/n = 1$ reconnection mode which is responsible for observed sawteeth. A similar result is obtained for the ideal $m = 1$ internal kink, with the modification that $q(0) < 1$ and $\beta_{1,\mathrm{pol}}$ must exceed some threshold value [4] before the mode becomes unstable. Various theories are distinguished by the evolution or change in $q(0)$ after a sawtooth crash, the criteria for stabilizing the mode, and the dynamics of the magnetic reconnection during the crash.

Stabilization of sawteeth has been observed on several devices [5–8]. A number of mechanisms for stabilization have been suggested, but no clear understanding has emerged. In this Letter we present a comparison of data to the two-fluid model for sawtooth stabilization, for discharges both with and without sawteeth, that have $q(0) < 1$. We have found that for the one-fluid ideal and resistive MHD models the $m = 1/n = 1$ mode is always unstable, contradicting the experimental data. However, the two-fluid collisionless $m = 1$ reconnection model [9,10], which is a resistive internal kink in the high temperature regime, has an ω^*-stabilization effect that agrees very well with data from TFTR during neutral beam heating if we neglect the effect of the ideal mode.

Only recently, with routine q-profile measurements, has a quantitative comparison of theoretical sawtooth models with experimental data become possible. On the Tokamak Fusion Test Reactor (TFTR) [11], a multichannel motional Stark effect (MSE) polarimeter [12,13] can measure the local magnetic field pitch angle, $\tan(\gamma_p) = B_p/B_t$, in the midplane at 10 spatial locations with a time resolution of ≥ 3 ms. The circular geometry of TFTR simplifies the conversion of pitch angle to $q(R)$ [13] and equilibrium reconstruction, making a more accurate comparison to theoretical models possible. The temperature and density profiles, which are also essential for stability analysis, are measured using charge exchange recombination spectroscopy (CHERS) for ion temperature profiles, electron cyclotron emission (ECE), and Thomson scattering for electron temperature profiles, multichord FIR interferometry, and Thomson scattering for electron density profiles, and visible bremsstrahlung for Z_{eff} profiles. The fast ion pressure due to neutral beam injection (NBI) is calculated with a Monte Carlo simulation in a $1\frac{1}{2}$D transport code TRANSP [14], which utilizes the kinetic and magnetics data to determine the equilibria. The MSE data, along with the kinetic profile data, have been incorporated into a fixed boundary equilibrium solver [15] to calculate the current density and q profile.

The data from TFTR either have sawteeth, are sawtooth stable, or make a transition between the two states. The sawteeth can be clearly identified with the ECE diagnostic which is very sensitive to temperature fluctuations and sawtooth activity. Our experience on TFTR has been that when sawteeth are present, $q(0)$ is less than 1. However, the converse is not true: when $q(0) < 1$, sawteeth are not necessarily present. Shown in Fig. 1 is an example of the evolution of $q(0)$ during the neutral beam heating phase for both a supershot without sawteeth and an L-mode discharge with sawteeth. In both cases $q(0)$ is less than 1 with no discernible difference in its evolution. Sawteeth are present during the Ohmic phase, but disappear shortly after the neutral beams are turned on for the supershot example. In both discharges the plasma current was 1.8 MA and auxiliary neutral beam input power was 17 MW for 1.5 s. The line averaged density for the supershot was 25% lower, and had a factor of 2 larger peak pressure. Both discharges also have similar $m = 1/n = 1$ MHD modes, about 15 cm in width, which in the sawtoothing discharge appears as a precursor to a sawtooth crash, and in the nonsawtoothing supershot is a

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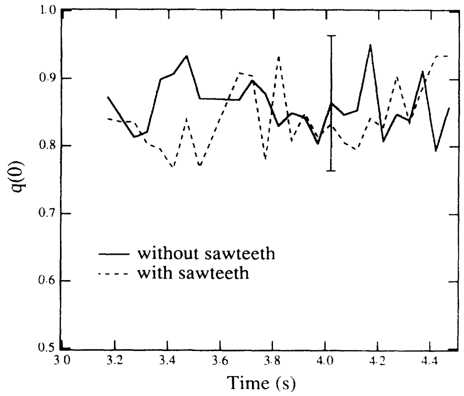

FIG. 1. The $q(0)$ evolution for both a supershot without sawteeth (solid line) and an L-mode discharge with sawteeth (dashed line). Neutral beam heating is from 3.0 to 4.5 s.

saturated $m = 1/n = 1$ mode for the last half of the NBI phase of the discharge. During the first half of the NBI phase there is no $m = 1$ MHD mode present. All the sawtooth stable discharges in this series have $q(0) < 1$ with little or no MHD activity. When the $m = 1$ mode is present it is saturated at a low level. It is also noteworthy that even when sawteeth are present, $q(0)$ remains below 1 throughout the discharge. The small measured change in the q profile and $q(0)$ during the sawtooth crash implies that a full magnetic reconnection cannot occur, which is contrary to many sawtooth models such as the Kadomtsev model [2]. These results are described in more detail in Ref. [13].

We have also looked for small-scale structure ($\sim$ 1–2 cm) in the q profile, such as a low shear region near the $q = 1$ radius which has been predicted theoretically [16] to stabilize the $m = 1$ mode. This was suggested as the mechanism responsible for the sawtooth stabilization observed in the TEXTOR [17] tokamak. Low shear in the q profile and flat spots in the electron temperature profile could be observed in TFTR by moving the plasma radially several centimeters, which would allow structures of order 1–2 cm to be observed [13,18]. This technique allows the gradient to be measured by a single detector which removes systematic uncertainties and greatly improves the spatial resolution. The results from this study do not show any flattening or other structure near the $q = 1$ radius, whether or not sawteeth are present.

Sawtooth stabilization by fast particles, as has been observed for rf heated plasmas [19], is not likely since the neutral beams are injected tangentially and would produce few trapped ions for fast particle stabilization [20–22].

Supershot data are characterized by peaked pressure profiles, and they are usually sawtooth free. L-mode discharges typically have sawteeth with a broader pressure profile and a lower peak pressure. These tendencies are the opposite of what one would expect based on linear ideal or resistive MHD theories, where pressure gradients are more destabilizing to the $m = 1/n = 1$ mode. For typical sawtooth stable supershots the central $\beta_{1,\mathrm{pol}}$ is $\sim$ 1–2, which is much higher than the theoretical threshold of 0.3, derived by Bussac [4], for excitation of the ideal MHD $m = 1$ mode, where $\beta_{1,\mathrm{pol}}$ is defined as

$$\beta_{1,\mathrm{pol}} = \frac{8\pi[\langle p\rangle - p(r_1)]}{B_\theta^2(r_1)}.$$

Here, $\langle p\rangle$ is the total plasma pressure averaged over the volume inside the $q = 1$ radius and $B_\theta(r_1)$ is the poloidal field at $r = r_1$, where r_1 is the radius at the $q = 1$ surface. Both the L-mode and supershot discharges are calculated to be unstable to the ideal $m = 1$ mode using both the analytic Bussac criterion as well as a numerical stability calculation with the PEST code [23].

In TFTR, with electron temperatures of 5–12 keV and ion temperatures of $\leq$ 35 keV the single-fluid resistive MHD model is questionable. The ion Larmor radius ($\sim$ 5 mm) as well as the collisionless skin depth, $d_e = c/\omega_{pe}$ ($\sim$ 0.8 mm) are larger than the resistive singular layer, $\Delta_\eta \sim r_1\tau_{\mathrm{rec}}/4\tau_\eta \sim 0.02$ mm, where τ_{rec} is the reconnection time and τ_η is the resistive diffusion time. In this regime the $m = 1$ mode is in the modified [24] collisionless regime and can be described by a kinetic [25] or two-fluid model [9,10]. Both result in diamagnetic effects that can stabilize the collisionless $m = 1$ reconnection mode due to the relative motion between the magnetic perturbation and the plasma that provides additional inertia for stabilization. The resulting stability criterion can be written in a symbolic form,

$$r_1 q'_{\mathrm{cr}} > r_1 q'_1, \tag{1}$$

where $r_1 q'_1$ is the shear at the $q = 1$ radius and $r_1 q'_{\mathrm{cr}}$ is the critical shear for stabilization, which depends on the local gradients and pressure at the $q = 1$ surface and the ideal mode characteristic singular layer width, λ_H.

In the analysis, $r_1 q'_{\mathrm{cr}}$ has been calculated numerically by solving the dispersion relation of the two-fluid MHD model [9]. To be consistent with the fluid model we include the beam particles in the ion species. If the linear ideal MHD mode is included in the dispersion relation for the growth rate [cf. Eq. (26) of Ref. [9] with $\lambda_H \neq 0$] the $m = 1$ mode is found to be always unstable, contradicting the experimental data. But, if we assume that the perturbation due to the $m = 1$ mode nonlinearly saturates and can neglect for that reason the ideal kink mode ($\lambda_H = 0$), then the criterion in Eq. (2) below is consistent with the experimental data. Indeed, the $m = 1$ mode is observed experimentally to saturate at low amplitude when it is present at all. Then with $\lambda_H = 0$ the criterion in Eq. (1) is approximately [cf. Eq. (39) of Ref. [10]]

$$r_1 q'_{\mathrm{cr}} \simeq 1.4 \left(\frac{m_i}{2m_p Z_{\mathrm{eff}}}\right)^{1/6} \beta_1^{2/3} \left(\frac{|n'_e|R}{n_e}\right)^{2/3} \left(\frac{|p'|R}{p}\right)^{1/3} > r_1 q'_1. \tag{2}$$

All quantities are evaluated at r_1, and β_1 is the toroidal beta at r_1, n_e the electron density, m_p the proton mass, R the major radius, p the total plasma pressure, including the fast ion pressure, and $q_1' = dq(r)/dr|_{r=r_1}$. Note that for $T_i' = T_e' = 0$, the criterion in Eq. (1) corresponds to the condition $\omega_i^* > \gamma_0$ of Ref. [25]. In contrast to ideal MHD theory for the $m = 1$ mode, the pressure gradient in Eq. (2) is stabilizing while the shear is destabilizing.

In the analysis, the measured kinetic profiles and the calculated fast ion pressure from the TRANSP code are used to calculate the parameter $r_1 q_{\rm cr}'$, while the MSE data are used to determine the q profile and shear. The estimated uncertainty of $r_1 q_1'$ and $r_1 q_{\rm cr}'$ is $\sim 0.05 - 0.1$. This is based on the propagation of the systematic and statistical uncertainties in the MSE data in the equilibrium reconstruction.

The stability criterion in Eq. (2) is in good agreement with all data analyzed to date. Shown in Fig. 2 is the time evolution of the shear, $r_1 q_1'$, and the critical shear, $r_1 q_{\rm cr}'$, from Eq. (2), for three discharges. The first discharge, with a plasma current of 1.8 MA and NBI power of 10 MW, has sawteeth throughout its duration [Fig. 2(a)]. The critical shear, $r_1 q_{\rm cr}'$, is less than the measured shear, $r_1 q_1'$, which correctly predicts this discharge to have sawteeth. Figure 2(b) depicts a similar discharge to that shown in Fig. 2(a), except the plasma current was reduced to 1.4 MA. This resulted in a more peaked pressure profile and broader q profile, as shown by the quantities $r_1 q_{\rm cr}'$ and $r_1 q_1'$. This discharge was correctly predicted to be sawtooth stable. In another case, a 1.4 MA supershot was purposely degraded to L mode with a large puff of helium gas during the NBI phase of the discharge. The plasma was sawtooth free until shortly after the helium was added at 4.2 s, after which the confinement deteriorated and sawteeth began to occur. The time evolution of $r_1 q_{\rm cr}'$ and $r_1 q_1'$ is shown in Fig. 2(c). The stability criterion predicts a stable discharge between $t = 3.8$ s and 4.33 s. This is consistent with the data, which have the last sawtooth after the Ohmic phase at 3.76 s and are stable until the sawteeth begin again at 4.47 s. In this example, the last sawtooth after the Ohmic phase occurs before the stability criterion changes from unstable to stable. The time delay is less than one sawtooth period, which is typically 0.15–0.3 s during the NBI phase. Similarly, the stability criterion changes from stable to unstable before the sawteeth resume, and again, the difference in time is less than one sawtooth period. This suggests that even though the mode is unstable there is a finite period of time, consistent with the sawtooth period, that is required to trigger the sawtooth crash. An analysis of many shots for the entire evolution of the NBI phases of the discharge has been performed on the TFTR data where both the MSE and kinetic data are available for calculation of the stability criterion. The data include cases with $q(0)$ in the range of 0.7–0.95 for both L-mode and supershot conditions, and plasma currents of 1.4–2.0 MA and neutral beam power of 10–18 MW. The results are shown in Fig. 3. The region in the upper part of the graph, with $r_1 q_{\rm cr}' > r_1 q_1'$, should be sawtooth stable, while the region below the line should be sawtooth unstable. The data points are plotted according to their calculated values of $r_1 q_{\rm cr}'$ and $r_1 q_1'$, and their symbols indicate whether or not there were sawteeth at the time. All the data agree very well with the criterion within the uncertainty of the calculated quantities. One data point which stands out that is calculated to be stable when it is not is interesting because it is the only case that has "fishbone" bursts, that is, high frequency bursts observed on the external magnetic coils, which are often accompanied by a loss of fast ions [26,27]. This may not be too surprising, since the calculation of the fast ion pressure does not allow for the loss of the ions due to the fishbone mode. At r_1, the fast ion pressure is calculated to be 40% of the total pressure. If the fast ion loss were included the pressure would be reduced, lowering the data point closer to or perhaps below the stability boundary.

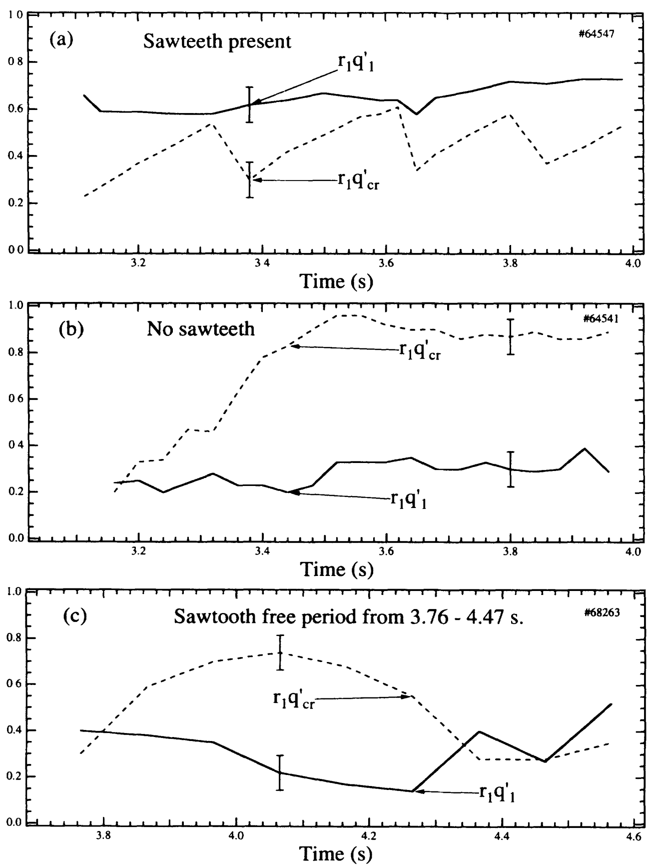

FIG. 2. The critical shear, $r_1 q_{\rm cr}'$, and shear, $r_1 q_1'$, for three cases. In (a) is an L-mode discharge with sawteeth. In (b) is a supershot without sawteeth. In (c) the discharge starts off as a supershot without sawteeth and is spoiled to an L mode with sawteeth. The discharge is sawtooth free from $t = 3.76$ s to 4.47 s.

In conclusion, we have observed stabilization of saw-

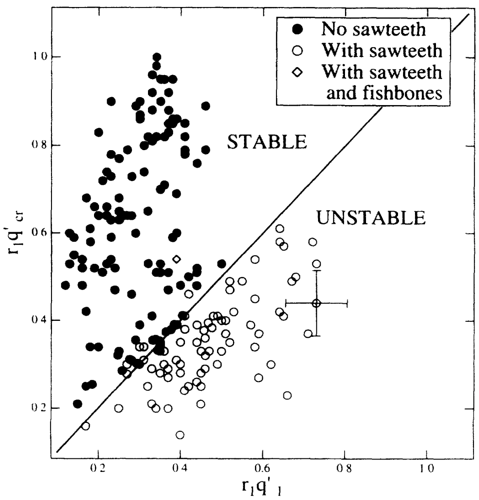

FIG. 3. The critical shear, $r_1q'_{cr}$, and shear, $r_1q'_1$, from several discharges, each at several different times during a discharge. The data consist of both L mode and supershots with $q(0) < 1$. Cases where sawteeth are present have open circles and where absent have solid circles.

teeth that are not due to fast particles or small-scale structure in the q profile, such as low shear near the $q = 1$ radius. Based on the extremely good agreement of the stabilization criterion of Eq. (2) with the presence, absence, or onset of sawteeth, we can conclude that the m=1 two-fluid collisionless reconnection mode is responsible for sawtooth oscillations observed in tokamak plasmas. We have a set of data covering a wide region of operational parameter space in which the model works, when the ideal mode is ignored, including both sawtoothing and sawtooth-free discharges for the entire NBI phase (up to 2 s). In contradiction to linear ideal MHD theory we see no beta limit to sawtooth stabilization. In all cases the linear ideal and resistive single-fluid theories predict the mode to be unstable, including many examples which are sawtooth stable.

There are still several outstanding issues that have not been addressed in this model, such as the sawtooth period and the change in the central current density or $q(0)$. Measurements in TFTR have shown that the change in $q(0)$ after a sawtooth crash is small (≤ 0.1), and $q(0)$ remains below 1 throughout the sawtooth evolution [13]. This implies that the reconnection is only partial; perhaps some mechanism prevents the full reconnection of flux. This has to be reconciled with the observation that the flattening of the pressure profile after a sawtooth crash extends to the plasma center. These results may help guide theory and lead to a better understanding of reconnection phenomena, MHD stability, and perhaps plasma disruptions in high temperature plasmas.

The authors would like to thank E. Fredrickson, B. Grek, H. Park, A. Ramsey, E. Synakowski, G. Taylor, and the TFTR staff for their support and operation of the tokamak. This work was supported by United States Department of Energy Contract No. DE-AC02-76-CHO-3073.

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