

Experimental Observation of MHD Precursor to Sawteeth in Tore Supra

V.S. Ushintsev, J.-L. Ségui, M. Ottaviani, G. Giruzzi, P. Maget, T. Aniel,
J.F. Artaud, M. Goniche, G. Huysmans, D. Mazon, R. Sabot, A. Sirinelli,
L. Vermare and the Tore Supra Team
*Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache,
F-13108 St. Paul-lez-Durance, France*

1. Introduction

Sawtooth oscillations in the tokamak plasma are often preceded by a fast MHD precursor with $m/n = 1/1$ as the dominant mode. The most famous model to explain the sawtooth crash as a periodic magnetic reconnection of plasma inner regions with different magnetic helicity has been introduced by B.B. Kadomtsev [1]. Later, a few experimental features that contradict the Kadomtsev model, have been found. Several explanations have been put forward to clarify these discrepancies. However, so far no reliable model for the internal disruption in general and for the sawtooth oscillation in particular has been found.

On the Tore Supra tokamak, series of experiments have been conducted to shed some light on the fast $m/n = 1/1$ mode topology and its influence on transport properties in the plasma center. It is suggested that the $m = 1$ mode cannot be described as an ideal kink only, and resistive effects play an important role in development of the mode. Possible mechanisms that influence the $m = 1$ mode behaviour prior and after the sawtooth crash and their links to the evolution of the central q -profile will be discussed in this paper.

2. Diagnostic set-up

The Tore Supra tokamak ($R_0 = 2.40$ m, $a = 0.72$ m, $B_T \approx 3.8$ T, circular cross-section) is equipped with a 32-channel ECE radial heterodyne radiometer (sampling rate ≤ 100 kHz) [2]. A set of fast/slow soft X-ray (SXR) cameras allows for a poloidal reconstruction of the plasma region ± 60 cm above and below the midplane. An X-mode heterodyne density fluctuation reflectometer and two X-mode density profile reflectometers are being used to study fast (up to 500 kHz) MHD phenomena throughout the plasma cross-section [3].

3. Experimental observation of $m/n = 1/1$ mode in plasmas with sawteeth

On Tore Supra, the $m/n = 1/1$ mode behaviour in sawtooth plasmas has been studied for ICRH, LHCD and purely Ohmic regimes. In the literature, the $m/n = 1/1$ mode activity prior to or after the sawtooth crash is often called as *pre-* or *post-*cursor. In reality, it is a very sketchy classification, because oscillations may survive the crash and continue with the same frequency and amplitude for a long time after it. Therefore, we suggest to speak about different $m = 1$ mode manifestations during sawtooth activity, and will use words “*precursor*” and “*post-cursor*” only for reasons of clarity.

In Ohmic and ICRH phases of Tore Supra shots with a strong sawtooth activity (typical densities $3.0 - 5.5 \times 10^{19} \text{ m}^{-3}$, plasma current 1.2 MA , P_{ICRH} up to 1.7 MW), two general types of the $m = 1$ mode are distinguished. The first one is similar to typical sawteeth with a “classical” precursor, with relatively small amplitude of oscillations steadily increasing or constant prior to the crash. In many cases, these oscillations do not disappear after the crash, but continue with the same frequency and amplitude for some time after (Fig. 1,*a*).

The second type is shown in Fig. 1,*b*. It manifests itself by a sudden and marginal increase in the mode amplitude (phase II), sometimes even with saturation, and appears on ECE time traces as two heat pulses, one before the sudden increase (actual crash), and one after the oscillation phase. This large amplitude oscillation phase can last for a few *ms*, or up to tens of mode periods. After the second heat pulse (phase III), no visible temperature oscillations are observed by ECE (with a few exceptions that will be discussed later

in this paper). Different $m = 1$ mode activity types in ICRH and Ohmic plasmas may be observed even in two successive sawteeth.

If LHCD is applied with the power of 2.1 – 3.2 MW, the second type of the $m = 1$ mode activity (as “precursor”) has never been observed. The influence of LHCD on the central q -profile and its role in the $m = 1$ mode behaviour will be discussed in Section 7.

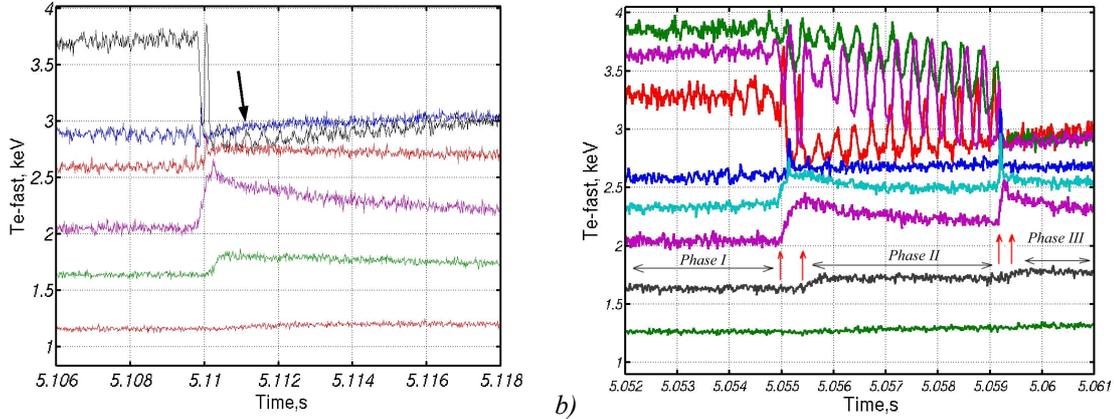


Figure 1. (a) – the first type of $m = 1$ activity before and after the sawtooth crash for shot 32766 with ICRH; (b) – the second precursor type at the successive sawtooth (crash times are indicated by red arrows).

4. Topology of the $m = 1$ mode during the crash

At Tore Supra, the topology of the $m = 1$ mode has been studied by means of ECE and SXR diagnostics. In order to create the poloidal 2D reconstruction of the $m = 1$ precursor out of ECE, the projection of the toroidal mode rotation on poloidal cross-section for a single period has been taken. A very simple equilibrium has been assumed. Figure 2(left) shows the $m = 1$ mode topology for three successive phases (a-c), as defined in Fig. 1,b. It appears that the hot core maintains continuously its temperature and density during the phase I, starts to shift off the magnetic axis and to change its shape from circular into the crescent-like in the end of the phase. The fast displacement of the hot core occurs in the beginning of phase II, and reshaping into the hot crescent-like structure is finally completed. Near the former magnetic axis, a bubble with the colder plasma is formed. This “cold” island takes the place of the former hot core. During transition from phase II to phase III, the heat from the displaced hot core quickly dissipates, and no visible oscillations are detected after the crash.

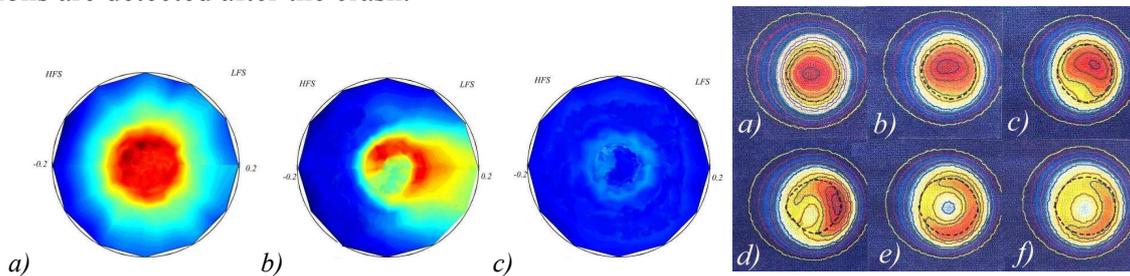


Figure 2. Poloidal reconstruction of the $m = 1$ topology out of ECE (left) and SXR (right) diagnostics.

As can be seen from the mode topology in phase II, the shift of the hot spot is larger at the LFS, compared to the HFS direction. This effect is due to the large pressure gradient in the hot spot that forces it to shift toward the direction of negative field curvature, which is in the LFS direction, and is similar to the ballooning mode mechanism [4].

Observations by SXR at Tore Supra for discharges similar to that in Fig. 2(left) do confirm the formation of the hot crescent out of the former core (Fig. 2(right)) [5]. It has been detected that the sudden radial shift (as observed in the poloidal cross-section) of the circular hot core takes place just during 50 μ s, with a radial velocity of 2–3 km/s (b-c), and accom-

panied by a strong change in central density. The formation of the hot crescent is in contradiction with measurements done at TFTR and DIII-D (where the circular hot core in the pre-crash phase and the radially elongated one in the crash phase have been observed [4,6]) but in agreement with measurements done on WT-3 [7] and TEXTOR [8].

5. Typical crash times

Estimations of crash times were done for both $m = 1$ precursor types in Tore Supra. Because ECE time traces inside the $q = 1$ radius are highly modulated by the oscillating precursor, an inverted sawtooth rise has been used to determine the crash time (see Fig. 1,*b*). Typical times for the first precursor type are found to be about 300 – 350 μs , for the second type about 350 – 400 μs . For a typical Alfvénic time $\tau_A \approx 2 \times 10^{-7} \text{ s}$, and a resistive time $\tau_R \approx 1 \text{ s}$ (for $r \leq r_{q=1}$), a theoretically calculated (according to Kadomtsev model) crash time for Tore Supra is $\tau_{Kad} \approx \sqrt{\tau_A \tau_R} \approx 450 \mu\text{s}$. A difference in crash times between two $m = 1$ mode types can be explained by incomplete magnetic reconnection process [9] that is taking place for the first type. This would explain why post-cursor oscillations are still present after the crash (the first type), as observed by ECE and reflectometers. For the second precursor type, however, full or almost full (Kadomtsev) reconnection occurs. During the “second crash”, after oscillations with large amplitude, intensive heat dissipation takes place, most likely due to ergodisation of the outer magnetic surfaces of the hot crescent. This process takes place in a layer between the $q = 1$ surface and the surface at the mixing radius. A typical “second crash” time is twice as shorter as for the first crash.

As we have mentioned in Section 3, there are a few exceptions in which $m = 1$ mode oscillations, reduced in amplitude, are still present after the crash with the second precursor type. Figure 3,*a* shows oscillation as measured by the fluctuation reflectometer and ECE immediately after the second crash type. Both diagnostics show a frequency component that is twice as high as the frequency of the $m = 1$ prior to the crash. A secondary density and temperature peaking inside the “cold island” can explain this effect. On the other hand, a certain pressure (and, therefore, density and temperature) gradient still remains in the displaced crescent-like former hot core, implying that incomplete reconnection has occurred.

6. Compound crash and evidence for transport barrier at the $q = 1$ surface

Another interesting observation of the central electron temperature behaviour has been made for a “single” or a “double” (Fig. 3,*b*) compound crash. It can be seen that, unlike the “main” crash, electron temperature on the magnetic axis may not be affected by the compound crash, and continue to rise. However, channels that measure more closely to the $q = 1$ radius, have showed the crash event. This observation implies that the reconnection process of a few flux surfaces takes place in a layer close to the $q = 1$ radius. The central part is therefore excluded from the reconnection.

An evidence for internal transport barrier associated with the $q = 1$ rational surface has been obtained in Tore Supra. It can be seen as a sudden change in the electron temperature gradient during the temperature rise prior to the compound crash (Fig. 3,*c*). In this time window, the radius of the $q = 1$ surface shrinks and passes through several neighbouring ECE channels. Central temperature rises during the same time period. Because large oscillations have just disappeared prior to the change in temperature gradient but q_0 remains below 1, one would expect the local magnetic shear to be low in this phase, which favours the trigger of a barrier.

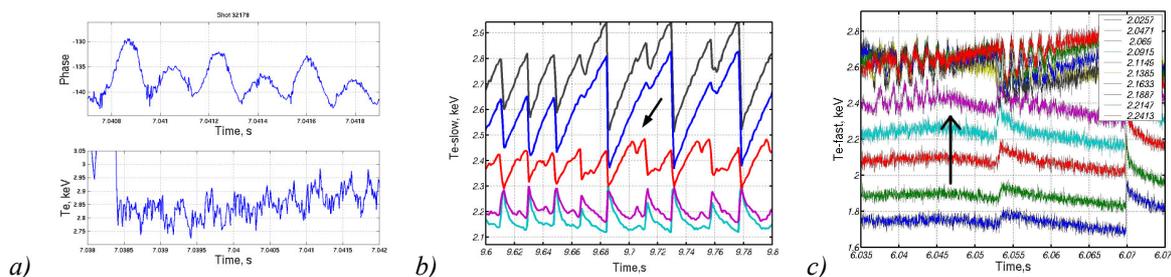


Figure 3. (a) – oscillations after the crash with second precursor type (an “exception”); (b) – “double” compound crash (ECE, slow acquisition); (c) – evidence for the transport barrier at the $q = 1$ surface, after the oscillation phase (black arrow) and before the compound crash.

7. Simulations of the q -profile during sawtooth activity in Tore Supra

In order to make a proper estimate for the q -profile evolution during various crash types at Tore Supra, simulations with the integrated modelling code CRONOS have been performed [10]. Figure 4 shows reconstruction of the q and magnetic shear profiles for two shots, with LHCD (first precursor type) and ICRH (second type). Unfortunately, because real plasma profiles were taken with relatively large time steps (tens of ms), and because error bars for the q values can be considerable, there is no possibility to follow fast changes in q -profiles, and only qualitative analysis can be done.

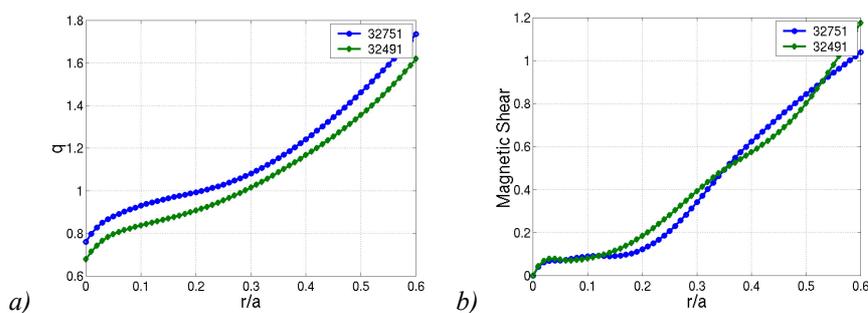


Figure 4. CRONOS simulations for $q(r/a)$ (a) and shear(r/a) (b) prior to the sawtooth crash with different $m = 1$ mode activity types (first type: green; second type: blue).

It can be seen that, in both cases, the magnetic shear is low near the plasma centre, however, the low shear region is smaller for the shot with LHCD. The second type of precursor exists in the shot with q_0 closer to 1 prior to the crash, compared to the first type. The most plausible, although still speculative, explanation for the second type of the precursor activity, is that the q_0 value prior to the crash is much closer to 1 than for the first type of precursor. During reconnection process, a bifurcation of the central q -profile takes place and the resulting q_0 value after the crash may exceed 1 or, sometimes, remain below. That is why oscillations similar to those shown in Fig. 3,a, may be present. For the first type of precursor activity, in contrast, the $q_0 = 1$ condition does never occur, and only incomplete reconnection takes place.

8. Future plans

In coming experimental campaigns at Tore Supra, dedicated studies of plasma transport properties in the vicinity of $q = 1$ surface will be done. Plasma turbulence measurements in different heating regimes (LHCD, ICRH, and ECRH) will be done by means of density fluctuation reflectometer and correlation ECE. Motional Stark Effect (MSE) diagnostic will also be available for a proper estimation of the q -profile.

References [1] B. Kadomtsev, Sov. J. Plasma Phys. **1**, 389 (1976) [2] J.-L. Ségui *et al.*, in Proc. of the EC-13 Workshop, Nizhny Novgorod, Russia (2004) [3] R. Sabot *et al.*, This Conf., P4-112 (2004) [4] W. Park *et al.*, Phys. Fluids B**3**, 507 (1991) [5] P. Cristofani, PhD-Thesis, University of Provence (1996) [6] Y. Nagayama *et al.*, Phys. Plasmas **3** (5), 1647 (1996) [7] S. Yamaguchi *et al.*, PPCF **46**, 1163 (2004) [8] V.S. Udintsev *et al.*, in Proc. of the 30th EPS Conf., St.-Petersburg, ECA **27A**, P-2.314 (2003) [9] F. Porcelli *et al.*, PPCF **38**, 2163 (1996) [10] V. Basiuk *et al.*, Nucl. Fusion **43**, 822 (2003)