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Observation of slow sawtooth reconnection in JET low-shear discharges

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1. Introduction

Tokamak discharges in the "hybrid" scenario, with a wide area of low magnetic shear and central safety factor close to one, have shown improved confinement and MHD stability at high beta [1]. The hybrid scenario is intermediate between the reference H-mode with central q well below one and the reversed shear scenario [1]. Neoclassical tearing modes (NTM) or fishbone modes occur in the hybrid scenario without degrading the confinement and possibly contribute to keeping the current profile stationary [2, 3]. One important issue for the validation of the hybrid scenario is the stability of the q≈1 region in the presence of dominant electron heating. Such a regime has been recently investigated in experiments at JET [1]. An MHD mode that provokes very slow temperature oscillations without affecting global performance has been found in these experiments (fig.1). The mode has the same spatial structure as the sawtooth precursor but it grows very slowly; for these reasons we will call it the "slow sawtooth". Slow sawteeth occur in 75% of hybrid JET discharges with dominant electron heating and in a few cases with dominant ion heating. The main characteristics of the slow sawtooth and its interaction with other modes are presented in the following sections.

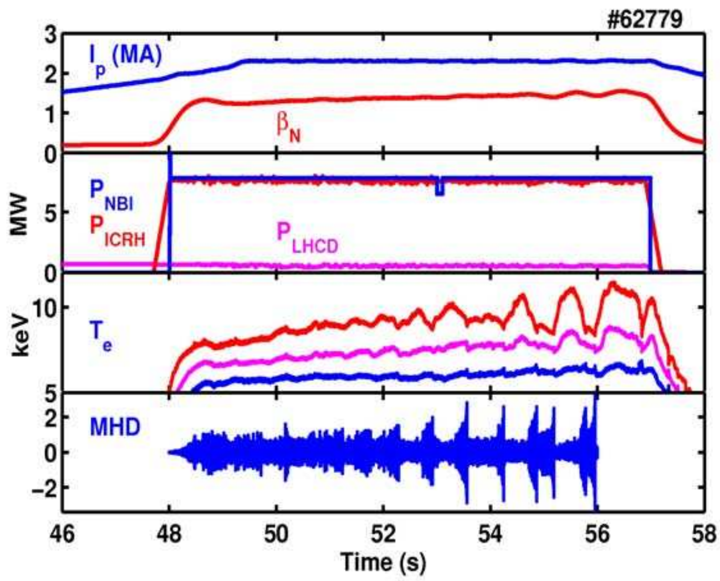


Figure 1. Time traces of a hybrid JET discharge with B=3.2T, I=2.3MA and dominant electron heating (T_i≈$0.6T_e$). T_e traces are given at R=3.15 m (red), 3.225 m (magenta) and 3.3 m (blue). MHD trace gives edge poloidal field oscillations between 2 and 10 kHz.

2. Slow sawtooth characteristics

During the discharge shown in fig. 1 slow sawteeth flare-up with 0.7 s repetition period. Magnetic oscillations have toroidal number n=1, constant or slightly increasing frequency below 7 kHz (fig.2) and exponentially growing amplitude with $\gamma=1.1\times10^{1}\ s^{-1}$ (Fig.3). During mode growth the electron temperature decreases around the plasma center and increases outside an inversion radius, as shown in fig. 4. This evolution resembles a sawtooth collapse (fig.5), but it is much slower (300 ms in a slow sawtooth, less than 1 ms in an ordinary one) furthermore a substantial temperature gradient remains at the end of each cycle, when the mode disappears or drops to small amplitude (fig.4). Coherence analysis of fast ECE data shows that the mode has internal kink structure, with top displacement of the order of 1 cm.

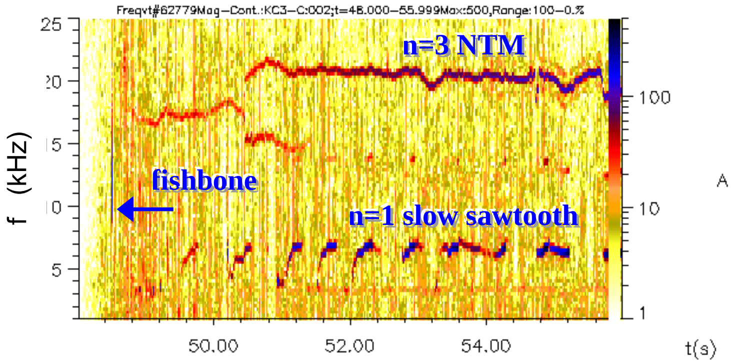


Figure 2. Spectrogram of magnetic oscillations below 25 kHz. Bursts between 4 and 7 kHz are n=1 slow sawteeth. The line near 20 kHz is an n=3 NTM. The intense, almost vertical line at t=48.6 s is a fishbone.

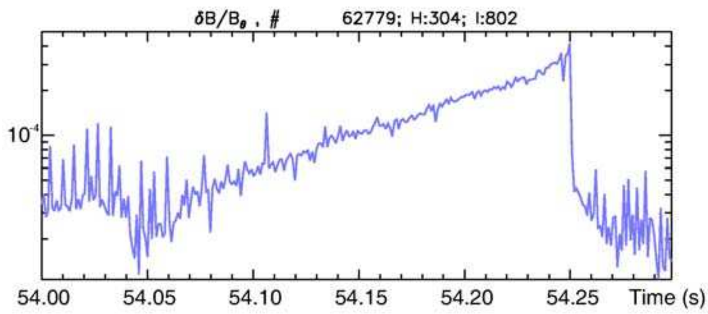
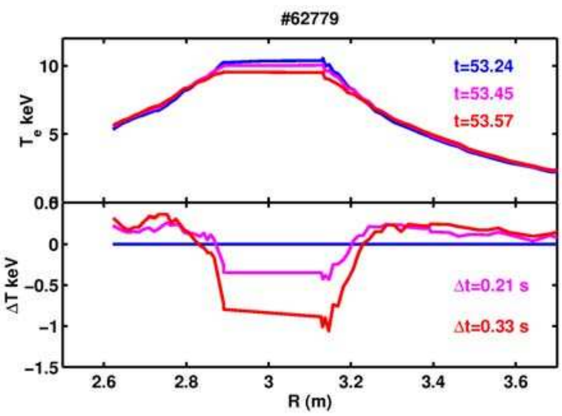


Figure 3. Amplitude of magnetic oscillations during a slow sawtooth cycle in lin-log scale. The e-folding time is 90 ms.



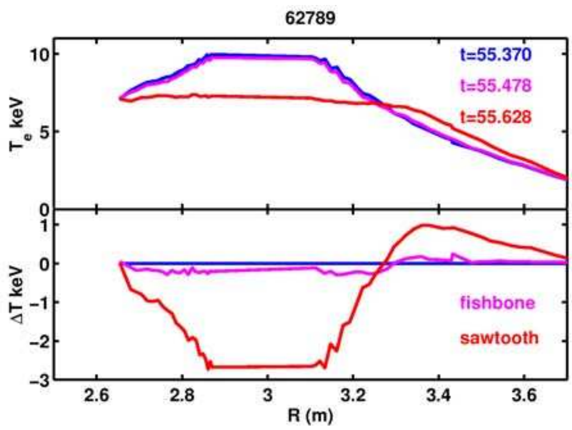


Figure 4. Profile evolution during a slow sawtooth. Red traces are at the top of mode amplitude.

Figure 5. Profile modification by a fishbone (magenta) and by an ordinary sawtooth (red).

3. Interaction with fishbones, NTMs and Alfvén Eigenmodes

Slow sawteeth coexisting with fishbones can be found in discharges with dominant NBI heating. Both modes have n=1 and kink-like structure, but the slow sawtooth develops on a much longer time scale and has slowly increasing frequency, while fishbones have rapidly decreasing frequency (fig.6). In all cases of coexistence, fishbones are spoiled as the slow sawtooth appears. In discharges with strong ICRH (fig.1), fishbones have much wider frequency chirping (30-5 kHz) and disappear before the onset of slow sawteeth.

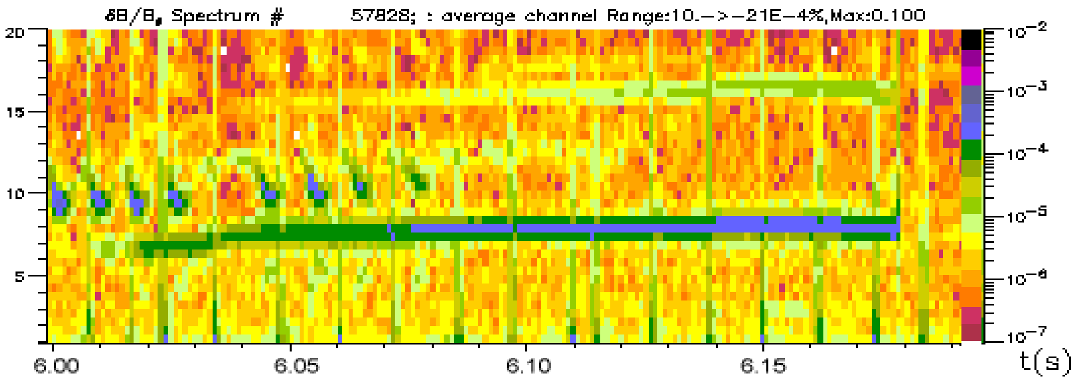


Figure 6. Spectrogram showing a direct comparison between a slow sawtooth (line below 8 kHz) and fishbones (modes with frequency chirp between 12 and 9 kHz). The line at 16 kHz is the m=2 second harmonic of the slow sawtooth.

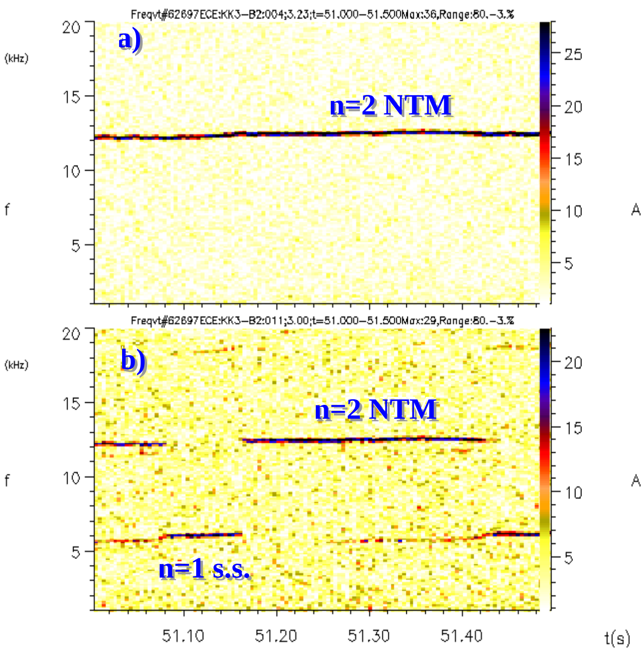


Figure 7. ECE spectrograms. a) R= 3.26 m showing the 3/2 NTM at 12 kHz. b) R=3 m showing the slow sawtooth at 6 kHz and the NTM expulsion from the central region at t=51.08 and 51.43 s.

All the discharges with slow sawteeth have NTM activity with n=2 or n=3. Neoclassical tearing modes with m/n=3/2 appear before the onset of slow sawteeth and saturate at small amplitude [1, 2]. Temperature oscillations at the NTM frequency extend throughout the q≈1 region; coherence analysis indicates that this is due to the existence of a 2/2 toroidal sideband. NTM oscillations disappear from the central region during a slow sawtooth (fig.7), possibly due to competition with the second harmonic of the n=1 mode.

Discharges with strong ICRH have two bands of spectral lines around 180 kHz and 550 kHz, while f_{TAE}=260/q kHz. The frequency of each line changes by about 3% during slow sawtooth cycles and intensity distribution within each band changes (fig.8). This indicates that the slow sawtooth interacts with AE by modulating the q profile and possibly by changing the distribution of high-energy ions.

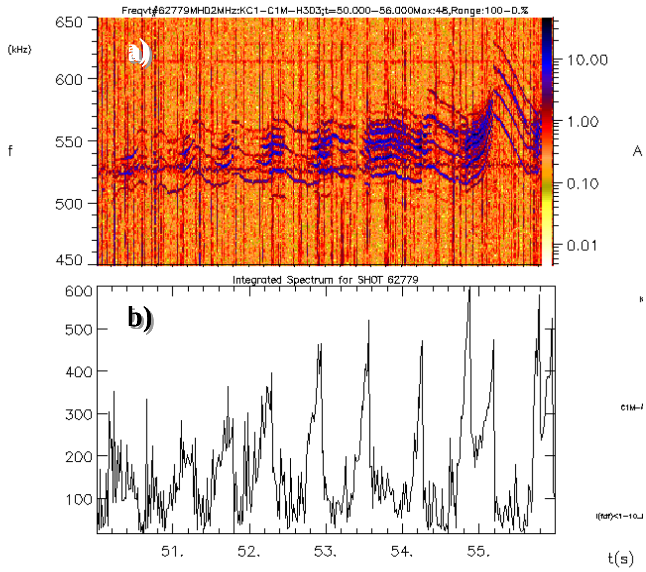


Figure 8. a) Magnetic spectrogram in the upper AE band. b) slow sawtooth mode amplitude.

4. Discussion

The slow sawtooth, a new form of MHD activity observed in JET hybrid discharges, appears as a sawtooth activity with strongly weakened reconnection rate. The low magnetic shear that characterizes hybrid discharges can reasonably explain such a weakening, in fact theoretical growth rates are proportional to the ratio between a "microscopic" length and the shear length L_S=R/s, where s=rq'/q is local magnetic shear. For example, taking the ion sound Larmor radius ρ as the microscopic length, the collisionless growth rate $\gamma_0=\rho s V_A/Rr$. In discharge 62779 (fig.1), we have Alfvén speed $V_A=9.9\times10^6$ m/s, ρ=5.7 mm, R=3 m, r=0.22 m and diamagnetic frequency $\omega^*=T/BrL_n=8.6\times10^3$ rad/s. For s < 0.1 the condition $\gamma_0<\omega^*$ is fulfilled and diamagnetic effects can reduce the actual growth rate (we recall that the experimental one is $\gamma=1.1\times10^1$ s^{-1}). This picture is confirmed by the observation that both slow sawtooth amplitude and its effect on central temperature increase in discharges with increasing magnetic shear.

Slow sawteeth have been found in more than 75% of hybrid JET discharges with dominant electron heating; it can then be expected that this kind of instability will be present in burning plasmas in the hybrid scenario.

References

[1] C. Gormezano et al., paper I5-01 this Conference.
[2] P. Belo et al., paper P1-170 this Conference.
[3] A.C.C. Sips et al., 30th EPS, St. Petersburg, Russia 7-11 July 2003.