Sawtooth precursors in ASDEX Upgrade

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Introduction

The sawtooth oscillation is a periodic collapse phenomenon widely observed in tokamaks. It develops in the plasma core when the safety factor (q) on-axis is below 1. In the core, the temperature and density ramp up slowly – also exhibiting oscillations – over most of the sawtooth period, and then suddenly crash down. During the crash phase there is an intensive density- and heat transport outwards [1]. The sawtooth phenomenon is important for different reasons. It can help remove helium ash form the core, and on the other hand it can trigger neoclassical tearing modes degrading plasma confinement. For these reasons, significant effort has been placed by the fusion community in observing, controlling and understanding the sawtooth instability. Although the physical processes that govern sawtooth oscillations in fusion plasmas remain only partially understood, the knowledge of how to control sawteeth has improved significantly in recent years [2]. Despite the success of the control attempts, the details of the crash mechanism itself still need to be revealed.

A low frequency sawtooth precursor (LFSP)

Most of the control methods rely on influencing the $(1,1)$ internal kink mode, which is a well known sawtooth precursor characterized by $(m,n) = (1,1)$ spatial structure, where m and n are the poloidal and toroidal mode numbers, and the vast majority of the models only take this mode into account. However, just before the crash, other modes have been shown to appear, and the stochastic model relies on these. The importance of higher order harmonics, namely the $(2,2)$ and $(3,3)$ has been investigated on ASDEX Upgrade [3, 4] and HT-7 [5], and recent results on ASDEX Upgrade [6–8] and HT-7 [9] showed, that a low frequency signal component is visible on the central SXR signals, and it gains energy just before the sawtooth crash. Observations of a second, lower amplitude and lower frequency n=1 mode have also been reported on JET [10].

Recently, properties of this low frequency sawtooth precursor (LFSP) have been studied in detail in NBI heated ASDEX Upgrade discharges with pronounced sawtooth activity based on soft X-ray (SXR) measurements [8, 11]. In these discharges the enhanced toroidal rotation raises the frequency of the modes in the laboratory frame, and thus relieves the separation of the (1,1) and LFSP modes. An example of such a sawtooth crash is shown in figure 1. The measured frequency ratio of the LFSP and the (1,1) kink mode is varying in the range 0.5-0.7.

The appearance of the low frequency component is usually visible several tens of milliseconds before the crash, but the power of the component is very low (10^{-2} – 10^{-3} times the power of the (1,1) kink mode) during most of the precursor phase. The low-energy phase lasts for 10-40 ms and is followed by a swift energy gain ∼5 ms before the sawtooth crash. The ramp-up of the low frequency component is very uniform from the amplitude growth point of view. The average amplitude growth rate is $\gamma_A = (407\ 1/\mathrm{s} \pm 3\%)$. The component in average reaches 10% of its maximal power $\tau_{10\%} = (-4.4\ \mathrm{ms} \pm 13\%)$ before the crash, and saturates at about ~ 2 ms before it.

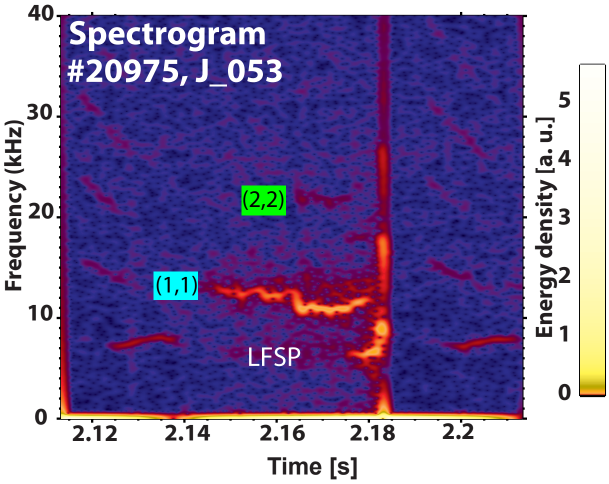

Figure 1: The (1,1) mode and its harmonics are clearly visible before the crash. Another signal component, identified as the LFSP appears with a frequency lower than the (1,1) mode.

Mode structure of the LFSP was determined form the SXR signals by a method based on the phase of the wavelet decomposition and wavelet coherence [12]. LFSP was found to have the same mode structure as the (1,1) kink mode, also propagating in the ion diamagnetic drift direction [8].

Interaction of sawtooth precursor modes

The interaction of the (1,1) and the LFSP may play a key role in the mechanism of the sawtooth crash [6, 8]. This interaction was indicated already in the low power stationary precursor phase by the bandpower correlation results [11], that was confirmed recently by a bicoherence analysis [8].

The bicoherence plot shown on figure 2 was calculated for a time window ending 15 ms before the crash, well before the ramp-up phase of the LFSP. The (1,1) kink mode and its (2,2) harmonic gives the highest bicoherence, but despite the low energy of the LFSP that is barely visible on the autospectrum, there is also a significant, 0.6 bicoherence

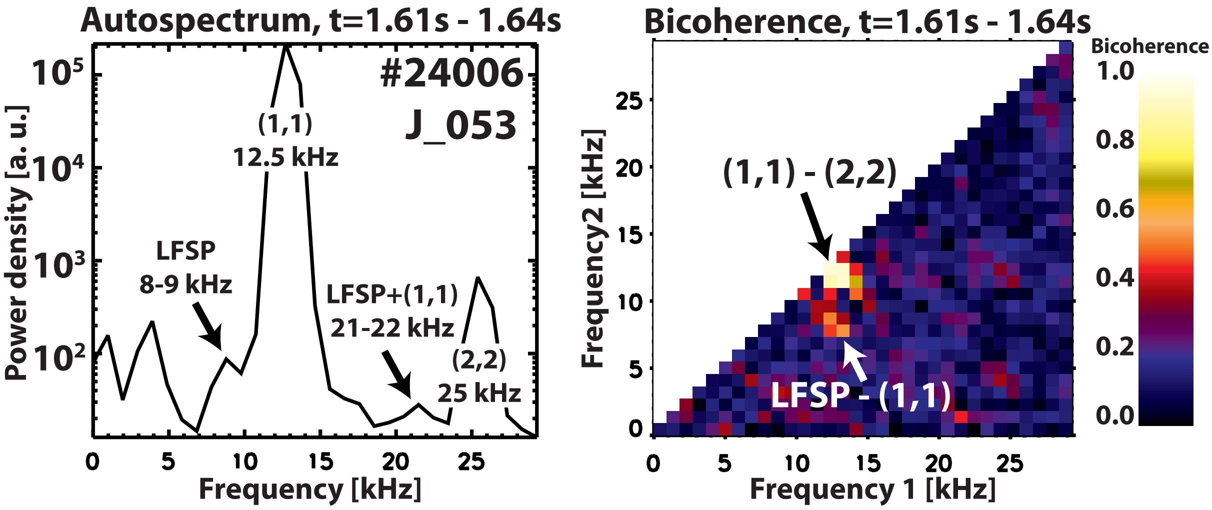

Figure 2: Autospectrum and bicoherence calculated for the time interval t=1.61 s – 1.64 s for the crash in #24006 at 1.6537 s.

between the (1,1) and the LFSP. This suggests the existence of a nonlinear interaction between the two modes already in the low-energy phase of the LFSP, in agreement with the bandpower-correlation analysis.

Discussion

A potential explanation of the experimental results is the following. If the (1,1) kink mode already exists in the plasma, it provides a strong periodic driving force that can excite other modes (directly via e.g. magnetic coupling; or indirectly through the change of the profiles [13]). The mode numbers of the LFSP was found to be identical to the (1,1) internal kink mode, and energy transfer is indicated by bandpower-crosscorrelation, and the high value of bicoherence.

It has been shown previously that upper harmonics can contribute to the stochastization of the plasma core [3, 4]. Following the same logic, a lower frequency component with commensurate spatial structure can create a relatively broad stochastic layer near the (1,1) island separatrix and especially at the X point. This coincides with the 2D ECE measurements of the crash phase [14]. The model implies very little change of the q profile that is also consistent with the measurements [1]. The interaction of the LFSP and the (1,1) kink implies a partial reconnection procedure that agrees with the observations that heat comes out from the central core region through the X-point of the (1,1) island and the (1,1) island might survive the crash [14]. The sudden onset of the crash, the rapidity of the temperature collapse and the incomplete relaxation of the current profile can also be explained by the interaction of modes with commensurate spatial structure [4].

The difference in the observed frequencies is possibly due to the difference of the mode types. The LFSP is most probably a resistive mode according to the growth rate of $\gamma_A \sim 400$ 1/s [8, 15]. The internal kink, on the other hand, is often characterized as an ideal mode before the crash [16]. An ideal mode cannot be responsible for changes in the magnetic topology – reconnection – while a resistive can be [17]. In the ASDEX Upgrade the presence of a (1,1) island is indicated after the crash, but not before [14].

We understand the LFSP as a secondary instability driven by the (1,1), that causes, or contributes to the crash. During the years, several different crash models have been proposed, each with experimental support [2]. The LFSP can play a role, as outlined above, in the models involving field line stochasticity, chaos or partial magnetic reconnection [1]. There are indications that the sawtooth crash might be governed by different mechanisms in the various devices [18], or by a mixture of the possible mechanisms. One of the latter is the possibility that the aforementioned magnetic reconnection process excites secondary ideal MHD instabilities during the crash [13], that would explain the rapidity of the collapse.

Acknowledgments

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References

[1] V. Igochine et al. In *same conference*, P2.079. 2011.
[2] I. T. Chapman. Plasma Physics and Controlled Fusion **53**(1):013001, 2011.
[3] V. Igochine et al. Nuclear Fusion **47**(1):23, 2007.
[4] O. Dumbrajs et al. Nuclear Fusion **48**(2):024011 (7pp), 2008.
[5] X. Xu et al. Plasma Physics and Controlled Fusion **52**(1):015008, 2010.
[6] V. Igochine et al. Nuclear Fusion **48**(6):062001 (5pp), 2008.
[7] V. Igochine et al. In *23st IAEA Fusion Energy Conference*, vol. EX/P9-10. 2008.
[8] G. Papp et al. Plasma Physics and Controlled Fusion **53**(6):065007, 2011.
[9] Y. Sun et al. Plasma Physics and Controlled Fusion **51**(6):065001 (11pp), 2009.
[10] R. Buttery et al. Nuclear Fusion **43**(2):69, 2003.
[11] G. Papp et al. In *Europhysics Conference Abstracts*, vol. 33E, P1.157. 2009.
[12] G. Pokol et al. In *Europhysics Conference Abstracts*, vol. 34A, P5.129. 2010.
[13] I. T. Chapman et al. Phys. Rev. Lett. **105**(25):255002, 2010.
[14] V. Igochine et al. Physics of Plasmas **17**(12):122506, 2010.
[15] R. J. Hastie et al. Physics of Fluids **30**(6):1756, 1987.
[16] A. Letsch et al. Nuclear Fusion **42**(9):1055, 2002.
[17] C. G. Gimblett et al. Plasma Physics and Controlled Fusion **36**(9):1439, 1994.
[18] R. Hastie. Astrophysics and space science **256**(1-2):177, 1998.