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Experimental characterisation of sawtooth crash precursors on ASDEX Upgrade via Soft X-Ray tomography

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Introduction Magnetic reconnection in the core of tokamak plasmas is responsible for a quasi-periodic relaxation process that significantly affects energy and particle confinement [1, 2]. Named *sawtooth crashes* - after the characteristic shape they entail on the time traces of the core electron temperature and Soft X-Ray (SXR) measurements - this type of event has become both a classic of tokamak operation and a subject of continued theoretical and experimental interest. Indeed, the exact mechanisms governing the reconnection time and the triggering of the crash remain partially unexplained [3, 4], and the recent addition of heavy impurities in some Tokamaks complicates further both the physics and the data interpretation [5].

In an effort to provide both return on experience for tokamak control and experimental input for MHD model validation, this paper describes the systematic quantitative characterisation, using SXR tomography, of approximately 50 sawtooth crash precursors drawn from 9 shots of the ASDEX Upgrade database. In particular, the time evolution of the growth rate of the internal m=1 kink mode is robustly estimated up to the crash. The growth rate is found to remain relatively constant during a preliminary phase of a typical duration of 5000-30000 times the poloidal Alfven time scale $\tau_A = \frac{r_1\sqrt{\rho\mu_0}}{B_P(q=1)} = 0.2-0.4\ \mu s$, (where r_1 is the $q=1$ surface minor radius) at a value around or below 0.1 % of $\frac{1}{\tau_A}$. It then surges in less than 2000 τ_A to values which are typically of the 0.2-0.5 % of $\frac{1}{\tau_A}$ (but the error bars in this short phase are larger). Also observed (but not quantitatively characterised) is the systematic absence of phase shift (i.e. poloidal position) of the SXR hot core at the time of the crash as would be expected from complete reconnection and redistribution of all impurities with plasma flux, and the existence of a post-cursor after the collapse, that keeps on rotating as though it were a diminished continuation of the precursor.

In the following, the criteria governing the selection of the presented cases are briefly explained, then a brief description of the methodology of analysis is provided and exemplified in a particular case, and finally the results of the systematic analysis of all the crashes are presented and discussed.

Data selection and methodology The zoology of the effects of sawtooth crashes on SXR measurements is large, and in order to stick to cases that can be interpreted beyond reasonable doubt, we dismissed all cases for which trajectory of the SXR maximum was not thought to give a reasonable estimation of the trajectory of the initial hot core. Hence, cases like hollow or flat profiles, profiles flattened by visible locked modes, very asymmetric profiles, compound crashes or very slow crashes were all dismissed. Even for peaked profiles, the SXR maximum may be significantly shifted from the hot core in high rotation plasmas due to tungsten [5]. This may cause a phase shift on the line-integrated measurements, but it should not affect significantly the estimation of the displacement growth rate since the trajectory is shifted but not significantly distorted.

The methodoly of analysis, inspired from [6], is as follows: SXR tomographic inversions are performed for all time steps of a 200 kHz-sampled interval encompassing the sawtooth precursor and collapse. At each time step the position of the profile maximum is robustly determined by calculating the center of mass of the top 5 % of the profile. Several different regularisation methods have been tested, ranging from 1st order linear regularisation to linearised minimum Fisher regularisation, and two different mesh sizes were tried. While the shape of the profile may be significantly affected by the regularisation method (the minimum Fisher being more prone to reconstructing peaked profiles), the position of the profile maximum was found to be a quite robust feature, with typical differences below the mesh size.

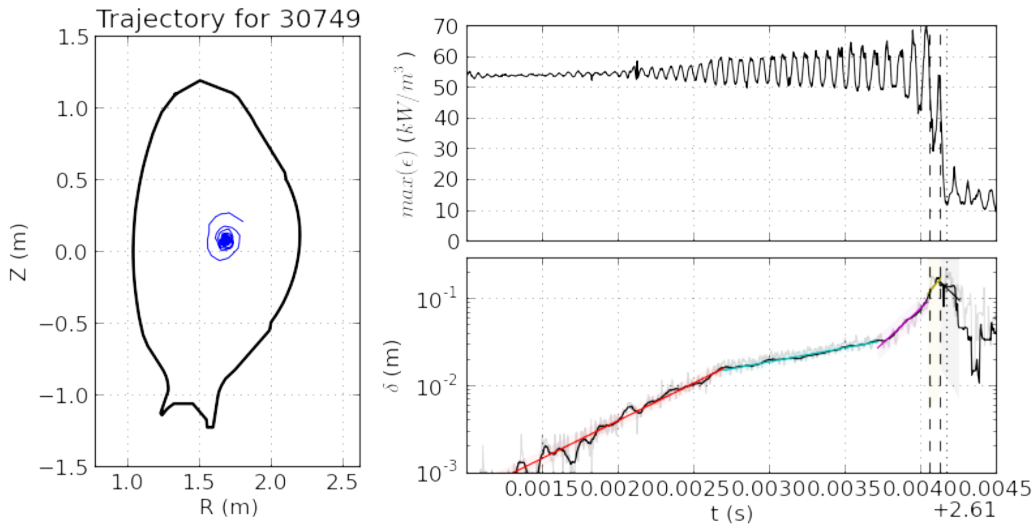

Figure 1: *(left) Trajectory in the poloidal cross section of the hot core during the precursor oscillations (upper right) time trace of the SXR emissivity inside the hot core (lower right) time trace of the estimated displacement, in semilog scale, from which piece-wise constant growth rate can be derived. The temporary dampening of the growth rate in the intermediate phase may be due to fishbones*

From the maximum trajectory tracking, which reveals an outward spiraling hot core, the mode frequency can be estimated and then used to compute a robust estimate of the time evolution of the core displacement using a geometrical method based on a one-period averaging of the trajectory. The time trace of the displacement can then be fitted by exponentials - since it can be seen in 1 that the growth rate is piece-wise constant. Both the displacement and the growth rate can then be normalised by the poloidal Alfven time scale to facilitate comparisons with literature [7].

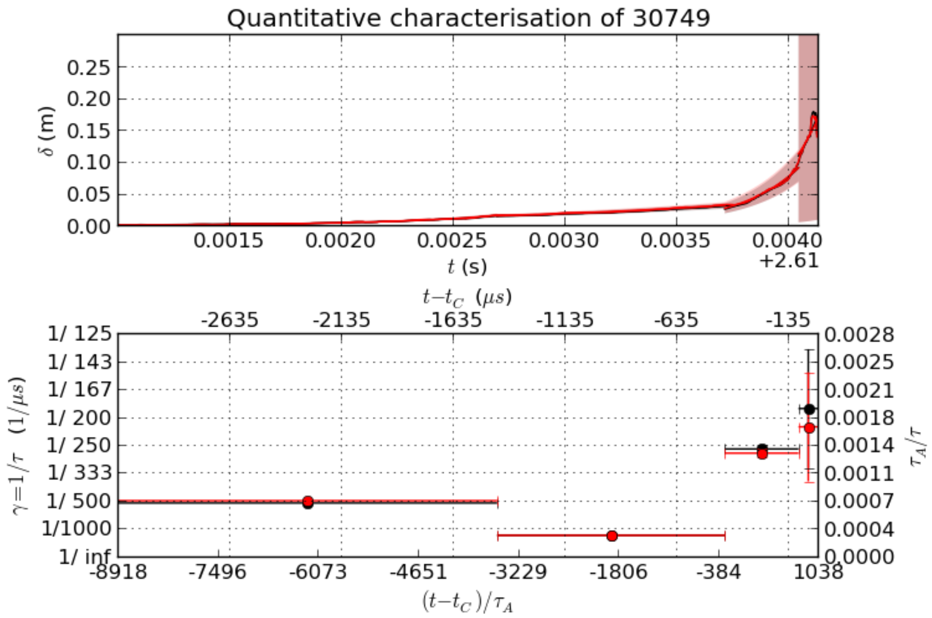

Figure 2: *(top) Time trace of the core displacement, computed with two different regularisation functionals (black and red). Shaded areas indicate the fit quality (bottom) Associated estimated piece-wise constant growth rates, with horizontal error bars showing the fitting interval, and vertical error bars indicate the fitting quality. Axis are doubled to show absolute and normalised values*

Systematic analysis Applying this methodology to the other crashes reveals good reproducibility of the features observed in the previous example. Indeed, one can clearly identify a long preliminary phase of slow and relatively constant growth and a second much shorter phase of sudden increase of the growth rate. The quantitative agreement of the normalised displacements and growth rates in fig.3 is also remarkable. Indeed, these shots have significantly varying plasma parameters, since the central elecron temperature is $1.5-3.5\ keV$, the electron density $0.4-1.10^{20}\ m^{-3}$, the plasma rotation $100-250\ km/s$, the plasma current $0.8-1\ MA$ and the toroidal magnetic field $1.8-2.8\ T$. One can see that once normalised they all offer a quite similar picture. Some points show a large intial growth rate. They correspond to rare cases for which the beginning of the growth could be clearly seen and these cases are not numerous enough, in the presented results, to check the reproducibility of this behaviour.

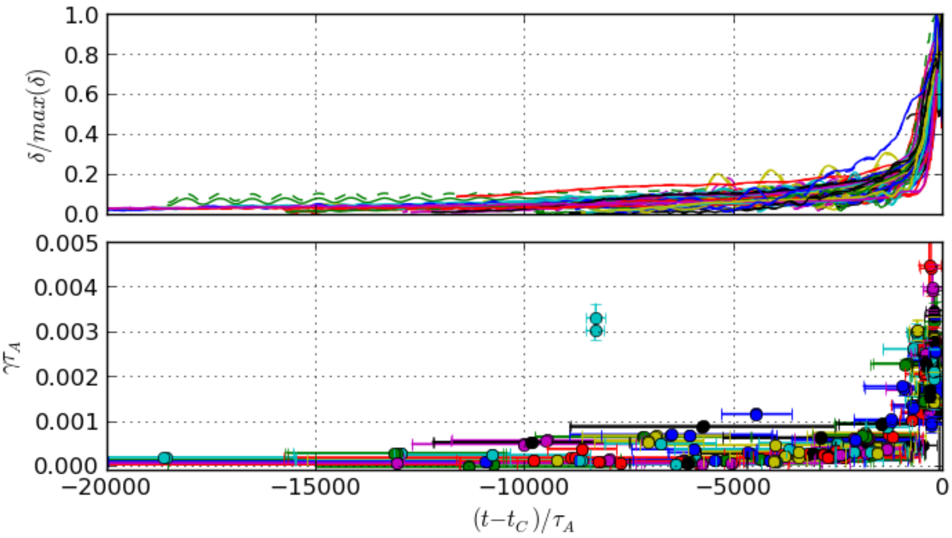

Figure 3: *(top) Time trace of the normalised core displacement for all the crashes (bottom) Associated estimated piece-wise constant growth rates*

Though the quantitative characterisation of the postcursor will not be shown here, it must be said that all the crashes presented here do have a postcursor structure which, on the SXR at least, resembles a diminished continuation of the precursor (no phase shift is observed at the collapse time). Also, the methods and hypotheses (regarding W redistribution during the mode growth [5]) used for this analysis do not permit to guarantee that a growth rate superior to the mode frequency can be correctly quantified, hence, all such cases were removed from the presented results.

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