

X-Ray Tomography of Sawtooth Activity During Intense Electron Cyclotron Heating Experiments on TCV

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INTRODUCTION

Although sawtooth (ST) instabilities have been observed and studied for many years in all tokamaks, the understanding of the underlying physical mechanism is still incomplete. Furthermore, recent experiments have shown that the usual, triangular shaped, Ohmic sawteeth can exhibit a range of shapes during auxiliary Electron Cyclotron Resonance Heating (ECRH). Different types of sawtooth shapes have been observed on TCV (Tokamak à Configuration Variable) with ECRH depending on the plasma and ECRH launching configuration and parameters [1].

The TCV is currently equipped with 3 second harmonic gyrotrons (82.7GHz, 500kW each). Both the poloidal and toroidal mirror angles can be swept for EC heating and non-inductive current drive. This system, together with the unique ability of TCV to produce a wide variety of plasma shapes, allows a detailed study of the influence of various heating scenarios on sawteeth. High temporal resolution is required to resolve the dynamics of the ST collapse phase which, in TCV plasmas, can be faster than 100 μ s. The TCV soft X-ray tomographic system, which consists of ten 20 channel pinhole cameras, (47 μ m Be filter), placed in a single poloidal plane, has been recently upgraded with a fast acquisition system with 13 μ s time resolution. This diagnostic, together with 4 toroidally equispaced Si photodiodes (50 μ m Be filter, 250kHz time resolution), is used to monitor the poloidal structure of the soft X-ray emission and to determine the toroidal mode number ($n = 1, 2$). MHD activity is also monitored by toroidal and poloidal arrays of Mirnov coils, with sampling rate up to 1MHz.

In this paper, we report observations of non-standard sawtooth behaviour during ECRH obtained with these high temporal resolution diagnostics. A tentative interpretation of the results is presented on the basis of a recently developed theoretical model [2].

SAWTOOTH BEHAVIOUR RESPONSE TO ECRH POWER DEPOSITION

The soft X-ray and electron density response to a sweep of the EC injection angle are shown in Fig. 1. Plasma parameters are: $\delta_{95} = 0.15$, $\kappa_{95} = 1.28$, $I_p = 192$ kA, $P_{\text{ECRH}} = 500$ kW. The EC resonance position is moved through the plasma along a vertical direction with a velocity of 3.5cm / 100ms with a constant plasma shape, albeit with a varying resonance incidence angle and beam width.

The sawtooth shape and period are seen to depend on the sweep position with the longest sawtooth period obtained with power deposition close to the $q = 1$ surface. The EC resonance location is calculate using the TORAY ray tracing code, while the position of the $q = 1$ surface is obtained from the TCV magnetic equilibrium reconstruction. A large difference in both the

sawtooth period and shape is observed between heating on the $q = 1$ surface either above or below the magnetic axis. This up-down asymmetry can be attributed to the difference in the local ECRH power density near the $q = 1$ surface caused by the wave beam divergence [3].

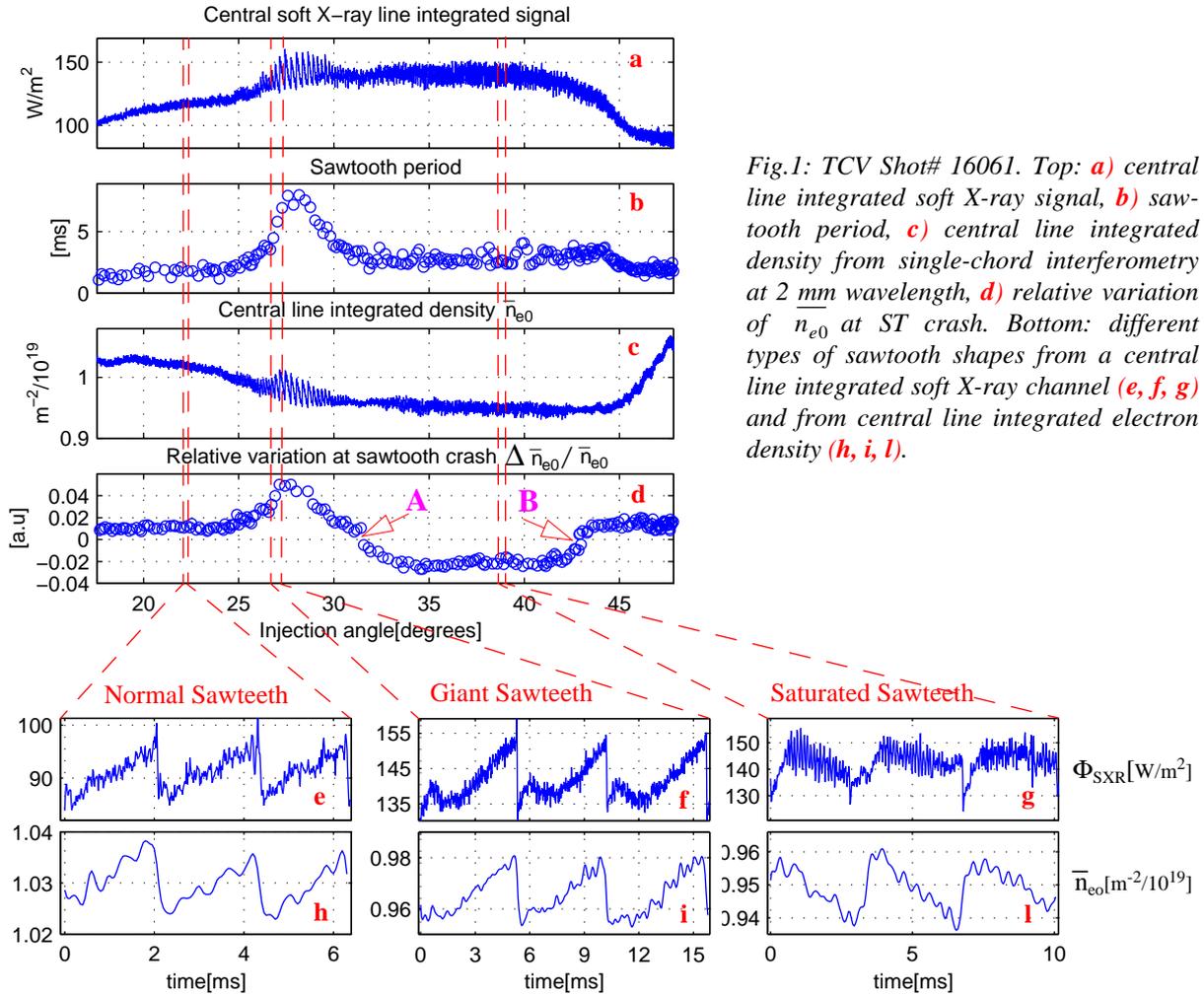


Fig.1: TCV Shot# 16061. Top: **a)** central line integrated soft X-ray signal, **b)** sawtooth period, **c)** central line integrated density from single-chord interferometry at 2 mm wavelength, **d)** relative variation of \bar{n}_{e0} at ST crash. Bottom: different types of sawtooth shapes from a central line integrated soft X-ray channel (**e, f, g**) and from central line integrated electron density (**h, i, l**).

The time behaviour of the central line integrated electron density \bar{n}_{e0} (monitored by a 2 mm single-chord interferometer) strongly depends on the EC resonance position. For injection angles in the interval [A,B] on Fig. 1.d, corresponding, within experimental uncertainties, to power deposition inside the ST inversion radius, \bar{n}_{e0} decreases between two subsequent ST crashes (Fig. 1.l), resulting in central line-integrated soft X-ray traces which show partial, or even inverted, ST behaviour. The decrease of \bar{n}_{e0} results from a flattening of the electron density profile, which is measured by multichord FIR interferometer. With ECRH power deposition outside the ST inversion radius, \bar{n}_{e0} shows normal (i.e. triangular) sawtooth behaviour.

MHD activity is different when heating either inside or outside the $q = 1$ surface. With central ECRH, partially saturated, saturated and inverted sawteeth are observed on the soft X-ray traces. For these sawteeth, the reheating ramp can be partially or completely interrupted by a phase of oscillations which show frequency doubling on some photodiode channels. These oscillations are caused by a $m/n = 1/1$ mode, rotating in the electron diamagnetic drift direction at a frequency of ~ 6 kHz (Fig. 2, SVD-Topos# 2, 3), coupled to a $m/n = 2/2$ structure (Fig. 2, SVD-Topos# 4, 5), resulting in the frequency doubling. During the saturated phase, coupled $m \geq 2, n=1$ modes are also seen by the Mirnov coils. With ECRH power deposition outside the

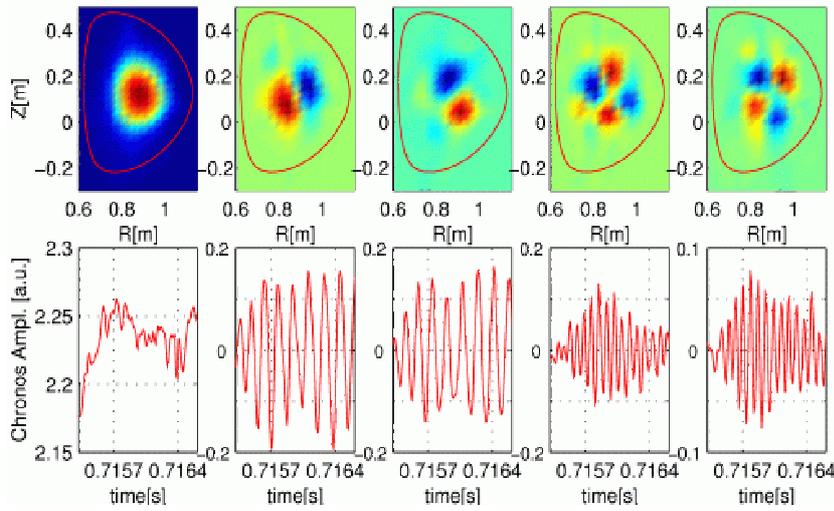
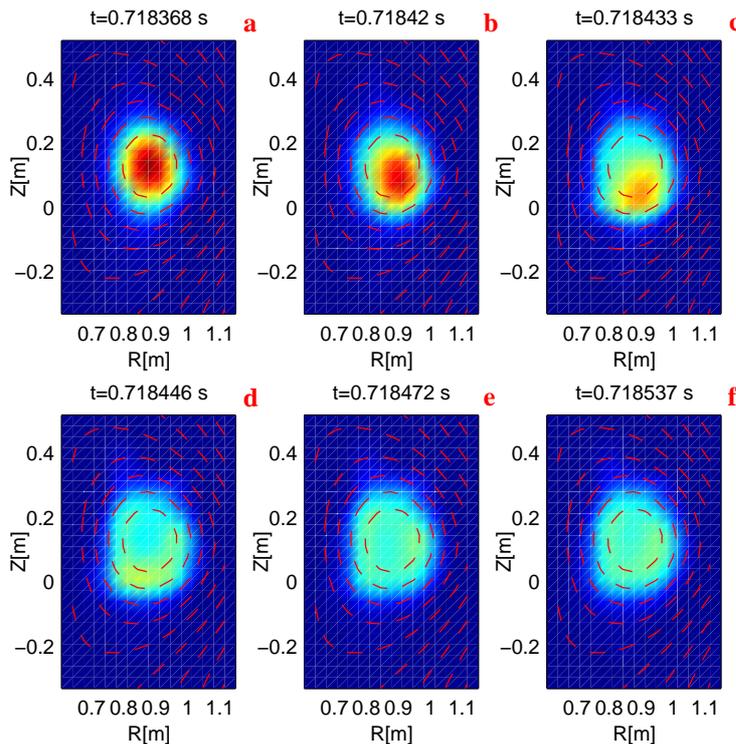


Fig. 2: TCV Shot# 14386. Shot parameters: $\delta_{95} = 0.34$, $\kappa_{95} = 1.33$, $q_{95} = 3.4$, $n_{e0} = 1.1 \cdot 10^{19} \text{ m}^{-2}$, $P_{ECRH} = 500 \text{ kW}$ (on-axis heating). SVD analysis of tomographically reconstructed soft X-ray emissivity distribution during the saturated phase. The figure shows the Topos with the LCFS (top) and the corresponding Chronos (bottom). SVD-Topos# 2, 3 show the $m/n = 1/1$ mode, while SVD-Topos# 4, 5 show the coupled $m/n = 2/2$ rotating structure.

$q = 1$, mode activity consists of brief $m/n = 1/1$ precursors or postcursors of the ST crash, which are not observed during the sawtooth reheating ramp.

Highly peaked soft X-ray emissivity profiles at the end of the ST ramp have been observed with on-axis ECRH power deposition (Fig. 3.a). Here, the fast relaxation phase is preceded by a $m/n = 1/1$ precursor which typically grows over several hundreds microseconds. At the sawtooth crash, the soft X-ray emissivity peak moves outwards (Fig. 3.c) and tends to redistribute



forming a hot ring localized near the inversion radius (Fig. 3.f).

The formation of a hot ring, and the subsequent hollow emissivity profiles, can be sustained during the sawtooth ramp with very localized ECRH power deposition near the $q = 1$ surface, as shown in Fig. 4 for TCV Shot# 15278. In this experiment the EC resonance is placed near the high field side of the $q=1$ surface which results in the highest ECRH power density. The hollow emissivity profile following the ST crash is maintained for $\sim 3\text{ms}$ until a slow $m/n = 1/1$ instability develops.

Fig. 3: For the same TCV shot of Fig. 2 an expanded view of the sawtooth relaxation phase. The soft X-ray emissivity is shown together with flux surfaces (in red).

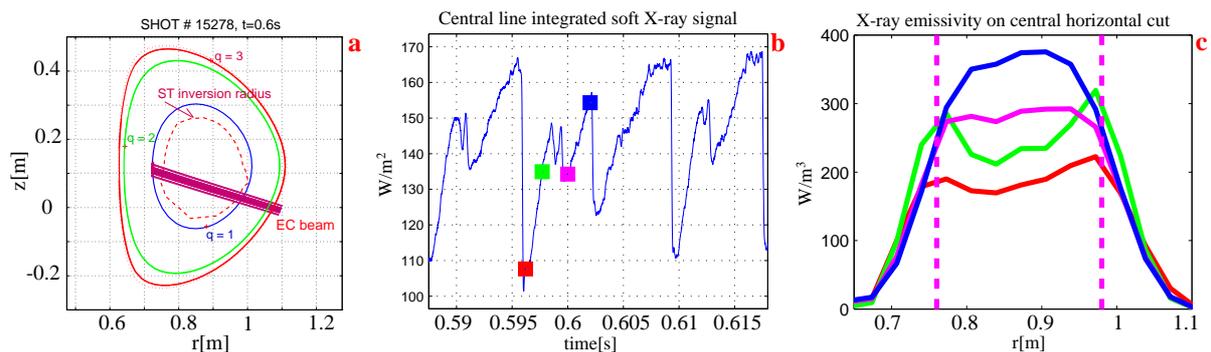


Fig. 4: TCV Shot# 15278. Shot parameters: $\delta_{95} = 0.4$, $\kappa_{95} = 1.42$, $q_{95} = 2.5$, $n_{e0} = 0.9 \cdot 10^{19} m^{-2}$, $P_{ECRH} = 500kW$. **a)** Rational flux surfaces with EC resonance position and ST inversion radius. **b)** Giant sawteeth on a central soft X-ray channel. **c)** Reconstructed emissivity profiles along horizontal cut at different times.

This instability appears to mix the plasma close to the $q = 1$ surface with the plasma core, resulting in a peaking of the soft X-ray emissivity profile, whilst the electron temperature profile remains flat [4].

SAWTOOTH MODELLING

A numerical code, based on a theoretical model recently developed [2], has been used to simulate the different ST behaviours. The combined effects of a $m/n = 1/1$ magnetic island dynamics, a localised heat source, a large parallel heat diffusivity and plasma rotation are included. Non-standard ST features, like the formation of a hot ring near the $q = 1$ surface and frequency doubling, are reproduced by the model, in qualitative agreement with the experimental data.

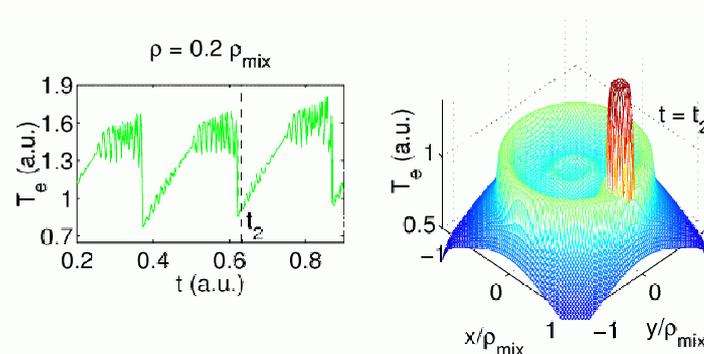


Fig. 5: Simulation of saturated partially sawteeth with central ECRH power deposition [5]. Right: temporal evolution of the central electron temperature. Left: 2D temperature profile after the ST crash.

Acknowledgments

This work was partly funded by the Swiss National Science Foundation.

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