Sawtooth control via *n*=1 applied magnetic perturbation in tokamak

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Abstract

This paper reports about a novel and simple technique to control sawteeth in tokamak, which has been experimentally found in RFX-mod used as tokamak. Experiments in RFX-mod demonstrate that an externally applied and feedback-controlled n=1 magnetic perturbation – of the order of 0.05% of the average toroidal field – causes a strong reduction of the sawtooth amplitude. Experimental findings are described and explained by simulations performed with the visco-resistive non-linear MHD code PIXIE3D.

The experiments described in this paper have been performed in RFX-mod [1] ohmic circular tokamak plasmas, with 150 kA plasma current and safety factor at the edge q_{edge}<2. RFX-mod is born and typically runs as RFP, but it is capable to run also as a tokamak, though at lower current than as a RFP – where it can reach 2 MA - due to the limited available toroidal field B_t. Target plasmas have q_{edge}<2 and are obtained via feedback control of the (2,1) resistive wall mode. Feedback control is successful and allows for robust operation at q_{edge}<2, with discharge duration only limited by power supplies [1]. Typical waveforms of plasma current I_p and q_{edge} are shown in Fig.1. With complete suppression of the edge magnetic perturbation due to the (2,1) RWM – the discharge corresponding to black traces in Fig. 1 - the usual sawteeth are observed (Figs. 1-c and 1-d).

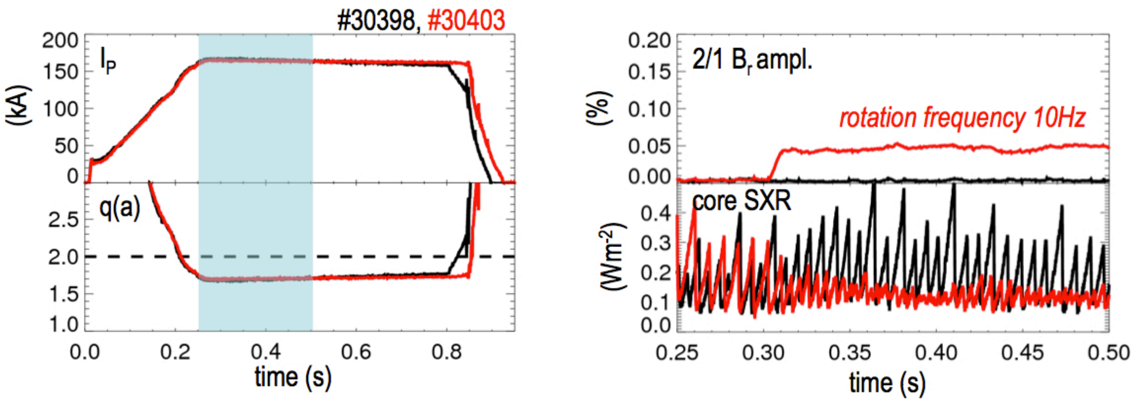

Figure 1

When the amplitude of the (2,1) edge perturbation is kept at small, but non-zero level ($\approx 5\text{x}10^{-4}$ B_t) – the case that in Fig. 1 corresponds to red traces -, the sawtooth amplitude strongly decreases. The sawtooth amplitude and frequency are correlated with the perturbation amplitude, as shown in Fig. 2. Indeed the amplitude of sawteeth decreases with the (2/1) perturbation amplitude, while their frequency increases – leading therefore to an overall mitigation of their effect. No major deleterious effects on confinement are observed, even if at the moment experimental data on confinement are limited.

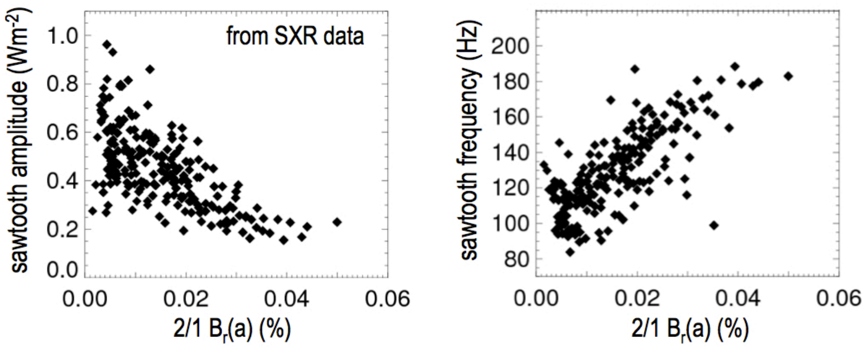

Figure 2

Interesting, sawtooth reduction is observed also when a (1,1) perturbation is applied to the same q_{edge}<2 plasmas, as shown in Fig. 3. In this case we note that a double ramp of (1,1) perturbation – first increasing and then decreasing – is applied between 0.35 and 0.80 s, while the (2,1) mode stays at a much lower amplitude (interestingly, not exactly zero, though in principle it should be actively controlled).

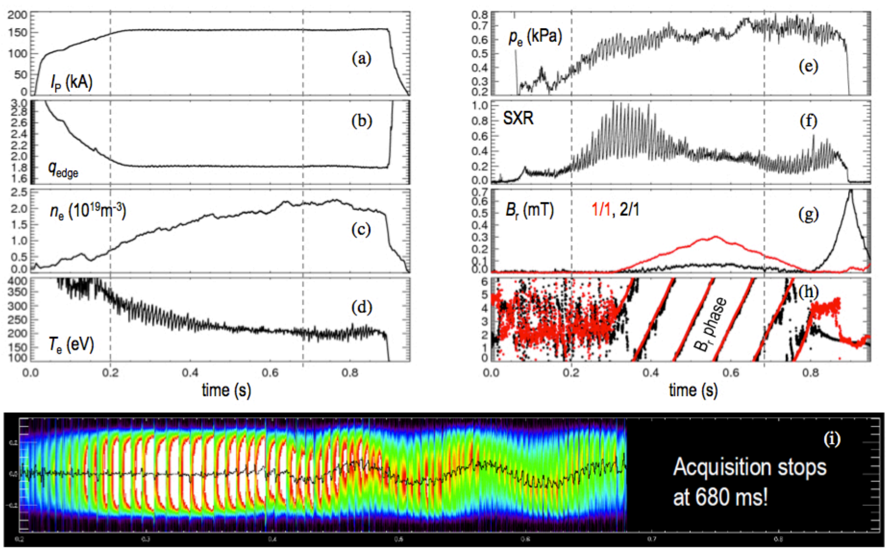

Figure 3

SXR measurements show that when the perturbation is applied and sawteeth are suppressed, a helical equilibrium is present in the plasma core. The helical structure – shown in Fig.3-i - rotates with the same frequency of the applied perturbation (Fig. 3-h). This is consistent with equilibrium calculation performed with the VMEC code [2].

The transition to a helical nature of the plasma core is predicted and reproduced by the visco-resistive non-linear MHD code PIXIE3D [3].

PIXIE3D simulations are summarized in Figure 4. The temporal evolution of (a) $q(0)$ and (b) on-axis amplitude of the (1,1) internal kink mode b_r component are shown for a set of visco-resistive MHD simulations in toroidal geometry with Lundquist number $S=10^5$, Prandtl number $P=30$ and initial axysimmetric equilibrium with on-axis safety factor $q(0)=0.8$ and $q_{edge}=1.8$. Different amplitudes and periodicities of the external magnetic perturbation are applied at the wall located at position b such that $b/a=1.1$, with a plasma radius. Interestingly, the code shows that the key feature is the $n=1$ character of the perturbation.

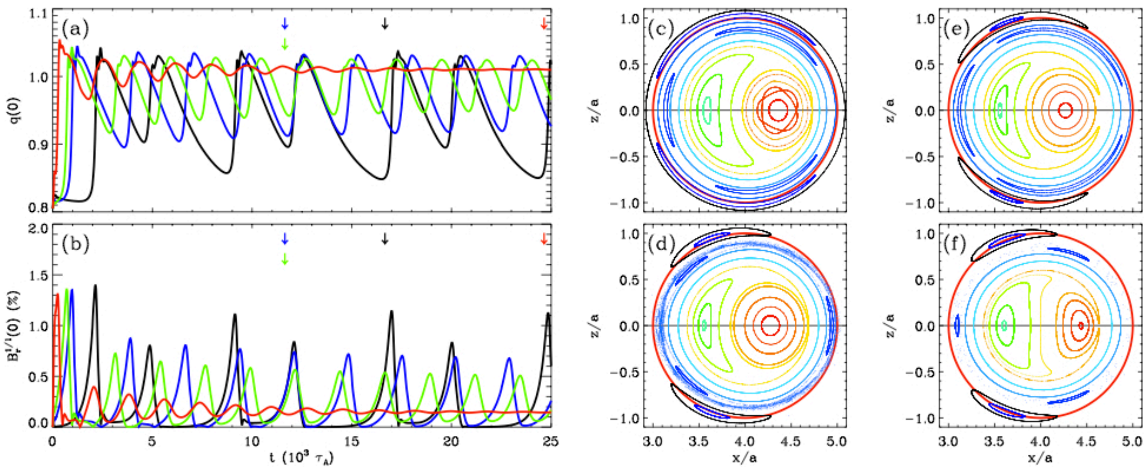

Figure 4

No external perturbation is applied for the black case, resulting in the typical sawtooth dynamics and a narrow (2,1) island at the edge due to the toroidal coupling between the (1,1) and the (2,1) modes (see Poincaré plot in panel c). A (2,1) external perturbation with 0.1% amplitude relative to the edge toroidal field is applied for the blu case, providing a reduction of both sawtooth period and the range of oscillation of $q(0)$. The (2,1) island is wider due to the applied magnetic perturbation and the overlap with the (3,2) island produces a chaotic layer at the edge (panel d). A magnetic perturbation with the same amplitude but with (1,1) periodicity is applied in the green case. The (1,1) periodicity – in the numerical simulation - turns out to be more efficient for the mitigation of the sawtooth oscillations. This is expected due to the direct action on the (1,1) internal kink mode. It is worth noting that in the experiment a larger efficiency of the (1,1) applied perturbation with respect to the (2,1) is not observed at the moment. In addition, in the (1,1) numerical case chaos does not develop in the edge region (panel e). Finally, the red case corresponds to a (1,1) external perturbation with 0.3% amplitude, which completely suppresses sawtooth oscillations, yielding a steady-state configuration with helical core (panel f). A stochastic layer is observed in this last case, again due to the (2,1) island produced by toroidal coupling with the (1,1) perturbation.

The key factor to reproduce the measurements is the full non-linear and toroidal mode coupling, which is self-consistently taken into account in the three-dimensional code.

The results presented in this paper show that an applied external magnetic perturbation with a n=1 nature - (m=2,n=1) and (m=1,n=1) have been tested in RFX-mod – interacts with the sawteeth behaviour, and eventually leads to a very strong mitigation of them when the safety factor at the edge is below 2. Interaction between external magnetic perturbation and sawtooth was reported in Compass [4]. In the present RFX-mod experiments the flexibility of the real-time system for the feedback control of MHD stability [5], the possibility of clean and reproducible experiments and the outcome of visco-resistive non-linear MHD simulation allow for building a broad database on this sawtooth control technique. Because of its effectiveness and simplicity, of the possibility to easily fine tuning its effects, and of the capability to numerically reproduce and predict it, this technique has the potential to be used in a broad range of tokamak plasma scenarios. If results where confirmed also in larger D-shaped tokamaks and at higher q_{edge} - where needs to be extensively tested-, in principle it may became a useful and general tool to control sawteeth and complement other techniques already used, as those based on electromagnetic waves injected into the plasma.

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References

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