Simulation of the effect of ECH/CD on sawtooth period

D. Kim, O. Sauter, F. Felici and T.P. Goodman

Ecole Polytechnique Fédérale de Lausanne (EPFL) - Centre de Recherches en Physique des Plasmas (CRPP), Association EURATOM, Confédération Suisse, CH-1015 Lausanne, Switzerland

Abstract

Sawteeth in tokamak plasmas are periodic fast relaxations, followed by slower recovery of the plasma parameters in the central region [1]. A long sawtooth period can create a seed island triggering NTMs in the TCV experiment [2]. It is also able to change the β limit for NTM onset by more than a factor of 2 and trigger NTMs at low β_N [3]. In burning plasmas such as ITER, it is predicted that long sawtooth periods will be produced by energetic α-particles [1]. Therefore, control of the sawtooth period is crucial to avoiding NTMs and other instabilities.

ECH/CD can be used as a sawtooth period control method because it affects the evolution of shear at q=1 surface. ECH/CD can lengthen or shorten sawtooth periods depending on the deposition position and the direction of current drive [4]. Recently pacing [5] and locking [6, 7] of sawteeth have been shown to be two efficient ways to control the sawtooth instability using ECH/CD power pulses rather than the slower deposition location control provided by adjusting the antenna mirror. The on/off timing of ECH/CD provides the sawtooth period control through a rapid change in the evolution of the magnetic shear. The sawtooth period can also be affected by the ECH/CD deposition width. When the beam width decreases, ECH/CD becomes very localised and makes the sawtooth period even longer when deposited in a stabilising location.

Physics model

In this work, all the simulations are conducted with the ASTRA code [8] and a standard sawtooth model [1, 9] is employed. This model has one free parameter c governing when the crash occurs and follows the generic condition: $\gamma > c\gamma_{crit}$, which can be converted to $s_1 > s_{1,crit}(c)$. For the predictive simulation, a new automatically scaled electron heat conductivity(χ_e) model has been developed, which depends on q profile and power deposition position. This χ_e is simply proportional to q^2 outside the $q = 1$ surface while it has a constant value inside $q = 1$ surface. This model takes into account the scaling not only caused by changes in power levels (through an H factor related to standard scaling laws) but also caused by changes in the deposition position, since it is known that off-axis deposition is less effective than on-axis [10]. The scaling factor for deposition position is dependent on q profile and is defined as

$$scaling = 1 - 0.3[1 - exp\{-(q^2 - 1)^2\}] \quad (1)$$

For the case of reversed shear q profile, we try to keep only one q=1 surface by modifying the q profile. If the sawtooth crash criteria is satisfied on the most off-axis q=1 position, inside this radius q is modified with $q = min(q, 0.998)$. This modification allows the simulation to apply the conventional reconnection model and has little effects on the post-crash profiles.

Sawtooth pacing and locking at a stabilising deposition location

The pacing [5] and locking [6, 7] of sawteeth with external heating power are two efficient ways to control the sawtooth instability. Experimentally, the feasibility of pacing and locking of sawtooth period have been demonstrated in the TCV tokamak [5, 7]. In particular both methods were carried out at deposition location where the EC power stabilises (lengthens) sawteeth.

Sawtooth pacing relies on real-time detection of the sawtooth crash and subsequent control actions. The control action is to step-increase the EC power for a given time (stabilising), decrease it until the next sawtooth crash is detected, then repeat. With this pulsed ECH/CD, the sawtooth period is paced. In the simulation, we use 0.5MW of ECH as a baseline heating and add another 0.5MW for pacing, in the same way as the TCV experiment [7]. Figure 1 shows the resulting sawtooth period and the evolution of shear and critical shear at the q=1 surface. The ECH/CD high power "on-time" τ_{set} is changed from 10 ms to 35 ms and in all cases the sawtooth period is paced with some delay, as observed experimentally. The delay decreases as the tau_{set} is increased. The overall shape of $s_1(t)$ is related to the shape of $j(\rho)$ as $\rho(q$=1) is increasing. Due to the off-axis j_{ECCD}, j has a local maximum which induces a minimum in $s(\rho)$. While $\rho(q$=1) increases, $s_1(t)$ also shows a mininum when the q=1 surface moves across the minimum of $s(\rho)$. For 10 ms to 25 ms cases, at the time when the EC is turned off, $\rho(q$=1) is smaller than the position of the minimum of shear. Since the time evolution is accelerated up to the next crash, $s_1(t)$ shows a rapid minimum first before reaching s_{1crit} and it makes part of the different delays, which are quantitatively comparable to the experimental results.

Sawtooth locking is basically the same as sawtooth pacing, but sawtooth locking does not use real-time sawtooth detection. The EC pulse-train is set in feedforward, as a modification with a given amplitude, period and duty cycle(ratios of on-time to period). Under certain conditions, the sawtooth period locks to the τ_{set}. Figure 2 gives an example of locking simulation results. Figure 2a displays the sawtooth period and duty cycle and Figure 2b shows the locking range as obtained with the simulation. Full power makes 46.7 ms sawtooth period, but for the comparison to the experiment result, this maximum sawtooth period is normalised to 40 ms. With

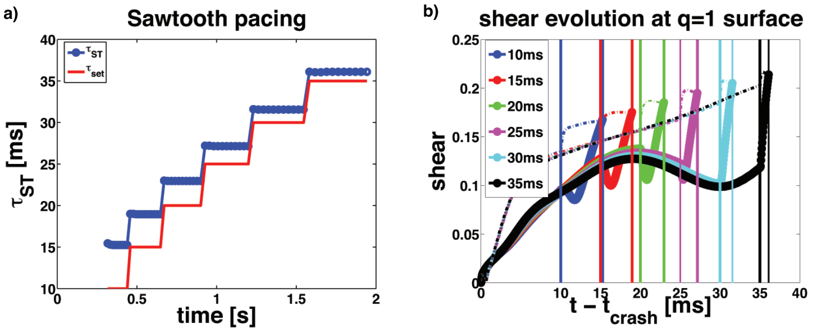

Figure 1: a) Sawtooth period(blue) is well paced by modulated ECH/CD period (red) with delay. b) Evolution of shear at q=1 surface for each ECH/CD period

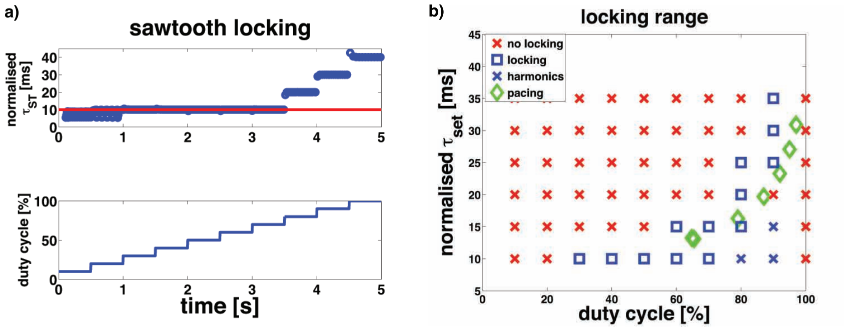

Figure 2: a) Sawtooth period is locked by ECH/CD (red line, period: 10 ms, duty cycle: 30% ˜ 70%). b) Sawtooth period is locked when ECH/CD is in blue area

the ECH/CD period set to 10 ms and 30% ˜ 70% duty cycle the sawtooth period is locked. For the 80% and 90% cases, the sawtooth periods are the 2nd and 3rd harmonics of the ECH/CD period. In the experiment [7] the sawtooth period is locked on wider range than seen in the simulation. Nevertheless, both pacing and locking can be simulated and used for the prediction of the sawtooth responses to localised power deposition for different plasmas and different tokamaks, since these simulations have been performed with our predictive χ_e model.

Effects of ECH/CD beam width and deposition position on sawtooth period

In a recent TCV experiment, we unexpectedly generated a fully stabilised sawtooth, the cause of which is not very well understood. Since sawtooth period can be also affected by the beam width [4], we investigated the effect of beam width on sawtooth period, in simulation, as one possible source of the discrepancy. In addition we focused on the deposition location(ρ_{dep}) since the maximum sawtooth period depends on the deposition position relative to the q=1 surface. We examined the sawtooth period of three beam widths (w=0.1, 0.075, 0.05 in normalized ρ) with fixed ρ_{dep} and real-time controlled fixed relative position with TCV experimental data of 43687(ECH power: 0.5MW, I_{CD}:3.1kA). Real-time controlled (RTC) ρ_{dep} is defined as [11]

$$\rho_{\mathrm{dep}} = \rho_{\mathrm{q=1}} + \eta w_{\mathrm{EC}} \tag{2}$$

where η is used to determine ρ_{dep}. As shown in [4], sawtooth period increased when beam width decreased for both ρ_{dep} options (fixed and RTC). For w = 0.1, 0.075 cases, fixed ρ_{dep} yields longer sawtooth period(13.5, 18.7ms versus 11.8 and 16.3ms for the RTC) while for w=0.05, we have longer period with RTC ρ_{dep}(28.26ms versus 25.2ms with fixed). Although fixed ρ_{dep} can have longer sawtooth period, RTC ρ_{dep} is still useful, since one needs to be within $w/2$ of the q=1 position. In plasmas $\rho_{q=1}$ can change by a larger amount, due to a change in plasma current, density or confinement. However, if we fix the relative position of ρ_{dep}, it can move together with $\rho_{q=1}$ and still give the desired effect. With RTC ρ_{dep} sawtooth is fully stabilised (with 1.0MW and 6.2kA) in this simulation while a sawtooth crash occurs for fixed ρ_{dep} case.

Summary

In the sawtooth crash criteria, shear at q=1 surface plays a critical role, therefore it is very important to control the shear evolution for lengthening or shortening sawtooth period. In this simulation work, the effect of ECH/CD on shear evolution is investigated with predictive electron heat conductivity and safety factor modification model. The shear evolution is highly affected by ECH/CD. Depending on the deposition position and the current drive dirrection, the speed of shear evolution is determined. Also by controlling the on/off time of ECH/CD as a real-time feedback (pacing) or feedforward method (locking), we can control the speed of shear evolution and can extend the sawtooth period at fixed power, consistent with the experimental results. In addition, by decreasing the beam width, the sawtooth period can be increased. Since it is a very localised effect, it is also important to fix the deposition position relative to q=1 surface. With narrow beam width, sawtooth can be fully stabilised by controlling the relative deposition position.

This work is supported in part by the Swiss National Science Foundation.

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