EPJ Web of Conferences **87**, 02016 (2015)
DOI: 10.1051/epjconf/ 20158702016

Demonstration of sawtooth period control with EC waves in KSTAR plasma

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Abstract. The sawtooth period control in tokamak is important issue in recent years because the sawtooth crash can trigger TM/NTM instabilities and drive plasmas unstable. The control of sawtooth period by the modification of local current profile near the q=1 surface using ECCD has been demonstrated in a number of tokamaks [1, 2] including KSTAR. As a result, developing techniques to control the sawtooth period as a way of controlling the onset of NTM has been an important area of research in recent years [3]. In 2012 KSTAR plasma campaign, the sawtooth period control is carried out by the different deposition position of EC waves across the q=1 surface. The sawtooth period is shortened by on-axis co-ECCD (destabilization), and the stabilization of the sawtooth is also observed by off-axis co-ECCD at outside q=1 surface. In 2013 KSTAR plasma campaign, the sawtooth locking experiment with periodic forcing of 170 GHz EC wave is carried out to control the sawtooth period. The optimal target position which lengthens the sawtooth period is investigated by performing a scan of EC beam deposition position nearby q=1 surface at the toroidal magnetic field of 2.9 T and plasma current of 0.7 MA. The sawtooth locking by the modulated EC beam is successfully demonstrated as in [3-5] with the scan of modulation-frequency and duty-ratio at the low beta (β_N~0.5) plasma. In this paper, the sawteeth behavior by the location of EC beam and the preliminary result of the sawtooth locking experiments in KSTAR will be presented.

1 Introduction

In tokamaks, plasmas are confined by toroidal (B_φ) and poloidal magnetic fields (B_θ) and the safety factor $q(r)$ is defined as the number of toroidal turns to complete one poloidal turn. Tokamak plasmas with $q(r=0)<1$ feature a periodic crash and reorganization of the plasma core temperature and density which is known as the sawtooth instability [6]. The crashes can form the seed island in the plasma. Therefore, Neoclassical tearing modes (NTMs) which deteriorate the energy confinement [7] or lead to disruptions [7, 8] can be triggered and driven unstable caused by the formation of seed island. As a result, developing techniques to control the sawtooth period as a way of controlling the onset of NTMs has been an important area of research in recent [9]. The two approaches to sawtooth period control are either to delay the sawtooth crash for as long as possible (stabilization) or to decrease the sawtooth period to reduce the likelihood of triggering other MHD instabilities (destabilization) by small and frequent sawtooth crashes. Sawtooth period control can be achieved by changing the radial profiles of the plasma current density and pressure near q=1 surface which is associated with the magnetic shear defined as $s = r/q\ \mathrm{d}q/\mathrm{d}r$. For controlling sawteeth using ECCD, the main consideration is when the plasma conditions have been met in order for a sawtooth crash to occur and the most relevant criterion for determining the onset of the sawtooth crash can be written as [10]

$$s_1 > s_{1,crit} \tag{1}$$

where s_1 is magnetic shear at q=1 surface. It was found that the sawtooth period was highly sensitive to the location of the EC deposition with respect to the q=1 surface [11-13]. When ECH is applied to the plasma,

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changes in the local current density occur due to the increase of electron temperature and subsequently change in the conductivity. For example, by driving co-current inside the q=1 surface, the magnetic shear (s) inside the q=1 surface will decrease and the magnetic shear at the q=1 surface will be increased and thus result in more frequent sawtooth crashes by considering equation (1). Conversely, counter-ECCD inside q=1, the magnetic shear at q=1 surface will be decreased and thus result gives rise to destabilization [14-17].

Benefits of a long period sawteeth provide the improved performance of plasma with gradients build-up and the increase of stored energy. However, the long sawtooth period can create a seed island by the giant sawtooth crash caused by big degradiation of electron temperature and density in the core region, and it can trigger secondary long-lasting MHD activity such as NTM which causes confinement degradation or disruption. It means that the sawtooth period control in ITER is very important because a very long sawtooth period is expected due to large fusion-born alpha particle population in the core [9]. Therefore, the sawtooth period control by the ECH will be needed to avoid NTM in ITER and it is well demonstrated in many tokamak devices that ECH system can stabilize and destabilize sawtooth depending on power deposition position (summarized in [2]). In KSTAR, the different sawtooth period behaviors with different ECH injection conditions are also observed during the 2012 campaign [18]. The sawtooth period is shortened by on-axis co-ECCD in NB-heated plasmas (KSTAR shot #8053) and the stabilization of the sawtooth is also observed by off-axis co-ECCD outside q=1 surface. This means that the sawtooth period can be controlled in accurate way by various EC beam injection conditions on KSTAR.

In recent, new experiments on TCV have shown that the sawtooth period can also be controlled by periodic forcing of EC waves such as sawtooth pacing and sawtooth locking [3-5]. Reference [3] demonstrated that on TCV the sawtooth period can be paced by gyrotron power modulation of the ECCD. The sawtooth period can lock to the gyrotron power modulation period [4], i.e. the sawtooth period converges towards the modulation period. So, during the 2013 KSTAR plasma campaign, a new type of sawtooth period control methods of injection-locking is demonstrated using the periodic forcing of EC waves nearby the q=1 surface to active control the sawtooth period. To this experiments are performed, where the deposition location is held fixed, while the gyrotron power is modulated (on and off) relatively fast with a period in the same order of magnitude as the sawtooth period. In section 2.2, the sawtooth control by the different injection locations of ECH in KSTAR is summarized, and then in section 2.3, the preliminary results of sawtooth locking experiments in KSTAR is followed.

2 Experimental results

2.1 Experimental setup

Two different ECH systems of 110 GHz X2 and 170 GHz X2 are used to sawtooth control experiments in KSTAR. The second harmonic resonance layer of 110 GHz lies at 1.8 m for B_φ=2.0 Tesla and R=1.74 m for B_φ=3.0 Tesla, respectively. The launchers are installed on the equatorial plane and the final section of launcher system has front steering mirror which can control the EC deposition position. The pivot position of steerable mirror is not located at the center but is located at 300 mm down from the center [19].

2.2 Sawtooth period control by the different deposition position of EC waves

The first sawtooth period control experiments in KSTAR carried out by the different EC beam deposition location across the q=1 surface because the sawtooth period is highly sensitive to the current profile at the inversion radius which is dominantly affected by EC deposition location [11-13]. Figure 1 shows the period of sawtooth destabilization by the on-axis EC heating inside q=1 surface in NB heated plasma. Here the X2 0.4 MW of ECH is directed on-axis to inject EC beam inside the q=1 surface. The sawteeth are regular with an average sawtooth period of 100 ms with 2.4 MW NBI heated plasmas and it is shortened to 20 ms by additional co-ECCD beam as shown in figure 1(a). The grassy sawtooth is also obtained with on-axis ECH in NBI (1.2 MW)-heated plasma as shown in figure 1(b). Since the heating acts like co-ECCD, the efficient destabilization occurs with on-axis ECH inside the q=1 surface.

On the other hand, the sawtooth period stabilized (lengthen) with almost same amplitude is observed by off-axis co-ECCD as shown in figure 2(a). The deposition position of the off-axis co-ECCD is about ρ=0.4 which is just outside the inversion radius of ρ=0.2 as shown in figure 2(b). The beam deposition is calculated using Toray-GA ray tracing code and the inversion radius is calculated from the ECE channels. As a result, the sawtooth period increased from 110 ms to 200 ms by the co-ECCD injection just outside the q=1 surface. Such behavior is demonstrated in many other machines as well.

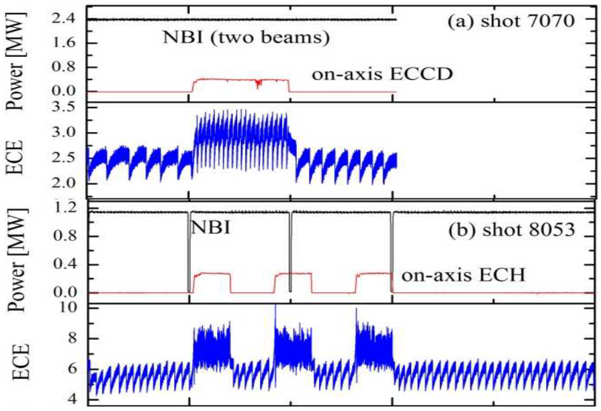

Figure 1. Sawtooth destabilization by on-axis ECH (inside the q=1 surface) in NBI-heated plasma in KSTAR. (a) co-ECCD and (b) perpendicular injection with respect to the toroidal magnetic field (ECH) is used for sawtooth destabilization experiments.

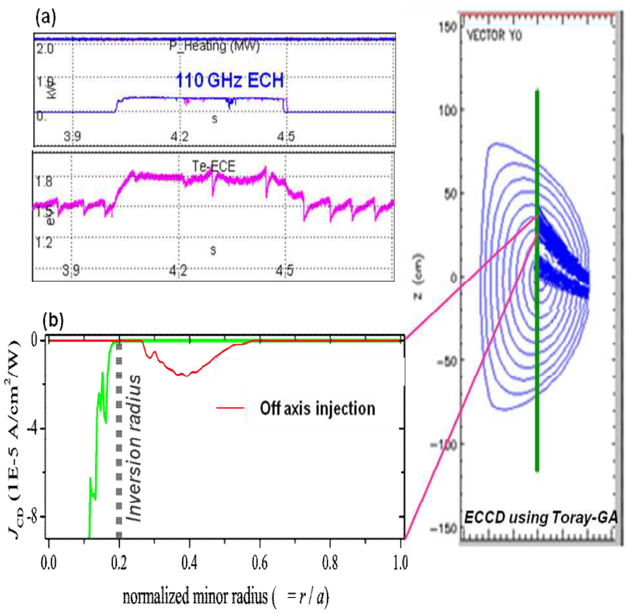

Figure. 2. (a) Sawtooth stabilization by the co-ECCD injection just outside the q=1 surface in KSTAR off-axis co-ECCD in NBI-heated plasma in KSTAR. (b) The EC beam deposition position of off-axis which is calculated using Toray-GA code at the toroidal magnetic field of 2.0 Tesla with the parameters of $T_e(0)$=5.0 keV and $n_e(0) = 5.0 \times 10^{19}$m^{-3}.

2.3 Sawtooth period control experiments by periodic forcing of EC waves

For the sawtooth control experiments in 2013 KSTAR plasma campaign, 170 GHz EC beam is used with a maximum power of 0.8 MW. For the second harmonic X-mode with the frequency of 170 GHz, the cold resonance lies at R=1.69 m in KSTAR with a toroidal magnetic field of 2.9 T. The plasma current I_p = 0.7 MA and the line-averaged electron density is maintained about $n_e \sim 2 \times 10^{19}$ m^{-2}. The optimal location of EC deposition position for maximizing the sawtooth period was determined by performing a scan of EC beam across q=1 surface in an L-mode plasma with fixed B_φ at constant q and plasma shape. The EC beam is scanned from the plasma core to outward of q=1 surface. Figure 3(a) shows the ECE signals for the electron temperature of the core plasma and the EC-deposition position is changed in poloidally during a pulse (KSTAR shot number 9145) at the same resonance layer position with B_φ = 2.9 T and I_p = 0.7 MA as shown in figure 3(b). At the beginning of poloidal scan shot, the base line of the sawtooth period is destabilized (shortened) from 20 ms to 10 ms by the co-ECCD injection inside the q=1 surface with the duration of 2.5 sec < t < 4.5 sec in accordance with equation (1). And then, the sawtooth period is extended by the sweeping of EC deposition position through the q=1 surface and it is maximized at t = 5.7 sec with 100 msec by the co-ECCD injection just outside the q=1 surface. The optimized deposition position of the sawtooth control experiment is decided at z=25 cm from the mid-plane which has the maximized sawtooth period as shown in figure 3(c).

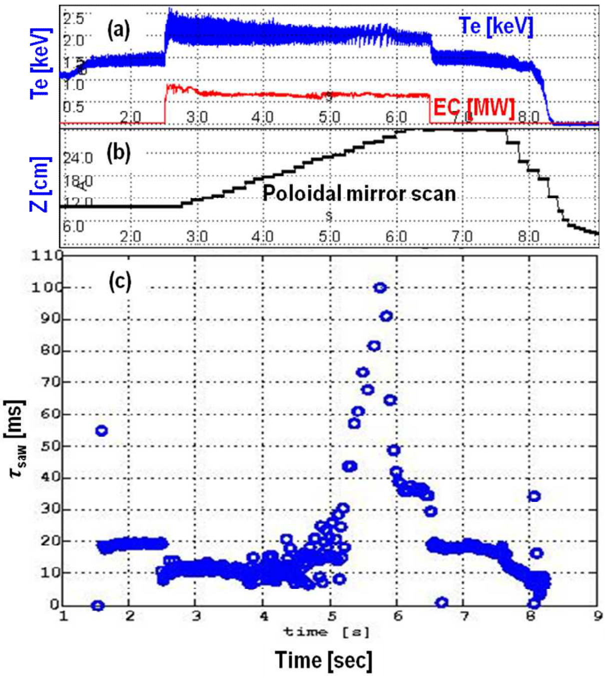

Figure. 3. The sawtooth period according to EC deposition position across q=1 surface (#9145). The sawtooth period decreased (destabilized) by the EC beam injection inside the q=1 surface at the beginning of the pulse from τ_{saw} = 20 msec to τ_{saw} = 10 msec. However, as increase of EC deposition position with polidal, sawtooth period increased upto $\tau_{saw,\,max}$ = 100 msec at the EC deposition of z=25 cm from the mid-plane. The sawtooth period is measured by ECE diagnostics.

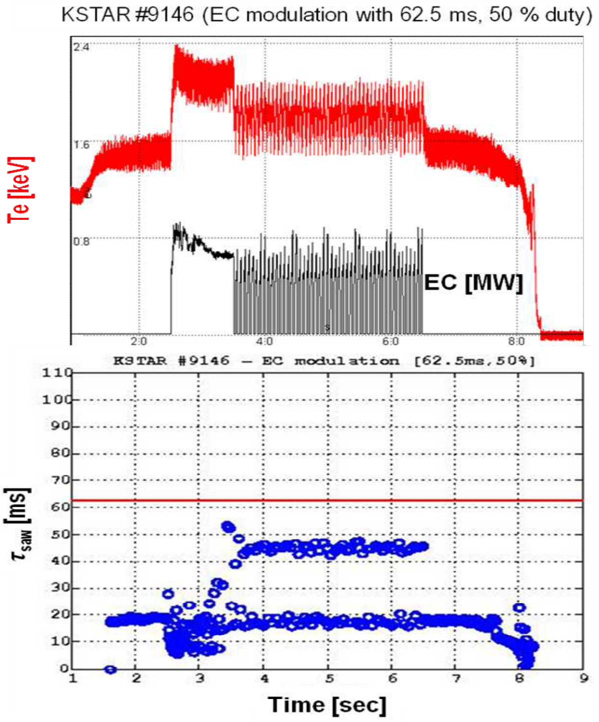

Figure 4. Sawtooth locking experiment with periodic forcing of EC waves (KSTAR shot #9146). EC beam started at t=2.5 sec and the EC beam modulation is enabled at t=3.5 sec to 6.5 sec (#9146). EC beam deposition position is fixed at z=26 cm from the mid-plane. During the modulation phase, the modulation period is maintained at τ_{set} = 62.5 msec (16 Hz) with the duty ratio of 50 %. At t=3.7 sec, an alternating period is observed for which the sum of the two successive periods matches the modulation period.

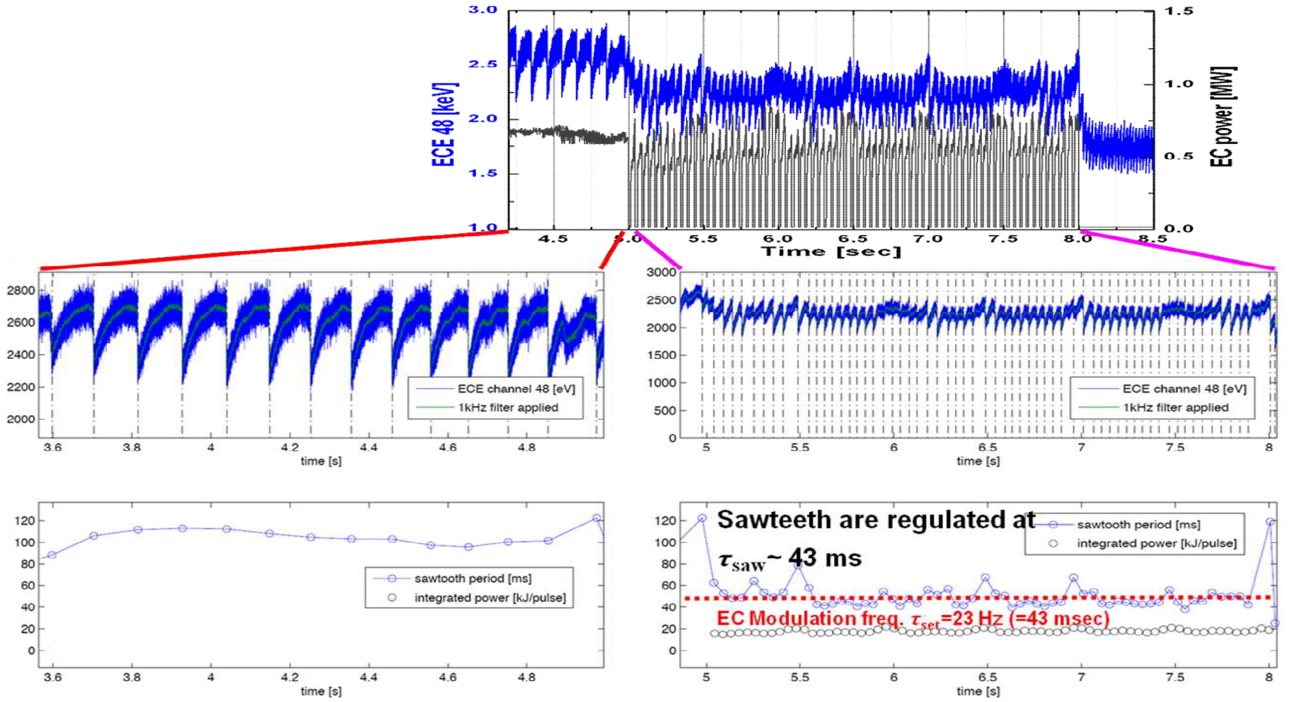

Figure 5. EC beam started at *t*=3.0 sec and the EC beam modulation is enabled at *t*=5.0 sec to 8.0 sec (#9215). EC beam deposition position is fixed at *z* = 26 cm from the mid-plane. During the CW injection phase, the sawtooth period is fully extended with $\tau_{\text{saw, max}}$ = 100 msec and then during the modulation phase, the sawtooth period locks to the modulation period of τ_{saw} = 43 msec (23 Hz) with the duty ratio of 70 %. 1

Subsequently, the sawtooth locking experiment is commenced by injecting modulated power. The modulation period is fixed at constant to investigate the locking of the sawtooth period. The power level, duty cycle (ratio of power 'on' to modulation period) and period of the modulating gyrotron are also fixed during a shot. In all experiments, a constant RF power from the gyrotron of 0.8 MW is deposited on the optimum position to increase the base line of the sawtooth period from 20 msec (the ohmic period) to 100 msec. During the experiment of #9146 as shown in figure 4, the co-ECCD injection is started at 2.5 sec and the power modulation is started at 3.5 sec. The power modulation period is set in τ_{set} = 62.5 ms (16 Hz) considering of sawteeth period according to EC beam injection conditions (= [$\tau_{\text{saw, max}}$+ $\tau_{\text{saw, No ECCD}}$] / 2) and its duty cycle is 50 %. The sawtooth period alternates between two values of which the smallest is the baseline value 20 ms and the larger one is regulated at the τ_{set} = 43 msec. It is due to the long EC-off time which is longer than ohmic sawtooth period and the sum of two values is equal to the modulation period of injected EC beam. This result means that the power modulation can make the sawtooth period behavior regular, even when it is not locked.

Considering this result, the combinations of period and duty cycle have been changed to τ_{set} = 43 msec with the duty ratio of 70 % for application in an open loop sawtooth period control. The results, figure 5, show that the sawtooth period locks to the modulation period and follows the changing modulation period well. Therefore, robust sawtooth period control can be achieved using the locking phenomenon in KSTAR. This control method has the advantage (compared with pacing [3] or aiming control) that it does not need any real-time measurements of the sawtooth period, so it is immune to missing or noisy diagnostic measurements and signals derived from them (i.e. sawtooth detection). On the other hand, the locking region must first be known in order to design a successful controller. So, the other sawtooth locking experiments at different injection conditions should be continued in next campaign to find the sawtooth locking region in KSTAR.

3 Conclusions

Sawtooth locking experiments have been carried out successfully on KSTAR using a feed-forward (open-loop) control in which the sawtooth period follows the modulation period of an externally applied high power EC wave source. The characteristics on the sawtooth period of modulation period and duty cycle have been investigated. The experimental dependence of locking on modulation frequency and duty cycle shows that it can be successfully used in an open loop sawtooth period controller. The sawtooth period control has been demonstrated at τ_{set} = 43 msec with the duty ratio of 70 % which is optimized experimental conditions. This opens the possibility of open-loop control for sawtooth period without real-time measurement of sawtooth period which is used for sawtooth pacing. Above all, however, prior knowledge of the locking range in KSTAR should be carried out by the variation of modulation frequency and duty ratio. And then, this locking range can be used to the locking phenomenon in a feedback-loop control to avoid of TM/NTM mode triggering in burning plasma.

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