The Effect of Toroidal Plasma Rotation on Sawtooth Activity in KSTAR

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Abstract. It has been found that toroidally rotating plasmas exhibit beneficial effects such as suppression or reformation of magnetohydrodynamic (MHD) instabilities. In KSTAR plasmas, it is found that sawtooth period lengthens significantly as the toroidal rotation speed increases. Stability analysis reveals the critical rotation speed and the rotation shear to reach the marginal stability, suppressing the growth of the ideal internal kink instability.

1. Introduction

Sawtooth instability is a fundamental phenomenon which is a periodic internal disruption occurred in various tokamak plasmas. One of the important parameters describing a sawtooth is the period. Since sawtooth period is determined as the time difference between sawtooth crashes, growth of the instability (n=1 internal kink mode) causing a crash event should be understood and controlled. Many attempts have been paid for controlling sawteeth [1], and there are two primary schemes to control the sawtooth. First way is to destabilize the sawtooth. Destabilization decreases the sawtooth period to make small sawteeth. The reason for destabilization is to avoid big rational surface (e.g. large q=1 surface) that can couple to the modes at outer rational surfaces (e.g. q=3/2 or 2/1) [2, 3]. Another reason is to expel the impurity accumulated in the core region by the small and frequent sawteeth. This scheme has employed the ion-cyclotron resonance heating (ICRH) and/or the co- and counter-NBI on JET and TEXTOR [4-7]. Destabilization of the sawtooth can also be done with the electron-cyclotron current drive (ECCD) that changes the magnetic shear at the q=1 surface. Small sawteeth would be beneficial to study the control of the amount of the high-Z core impurities that will be produced from the tungsten plasma-facing components in ITER. The opposite control scheme is to lengthen the sawtooth period which is several times longer than the energy confinement time [8-10]. Main purpose of keeping a long quiescent time between crashes is to study core plasma behavior without disturbance such as sawtooth oscillation. It is also expected that study on the increase of the fusion yield for long energy confinement time in the absence of the big collapses in the core plasmas can be an advantage for the next-step devices. Experimental efforts using ICRH and NBI to study the sawtooth instability have been devoted in JET, TEXTOR, MAST and so on [10-12]. Both the toroidal momentum and the fast-ion population supplied by the NBI and the ICRH are known to be an important factor to stabilize the sawtooth instability.
It is known that toroidal momentum input driving a rotation gives a favorable effect on the magnetohydrodynamic instabilities like internal, external, resistive modes in tokamak plasmas \[13, 14\]. The works addressed in this paper are based on the investigation of the relationship between toroidal rotation speed and sawtooth period for the NBI-heated plasmas in KSTAR. In section 2, experimental observations of extension of sawtooth period are described. Stability analysis of the internal kink instability was done by the simple analytic formula. The effect of the toroidal plasma rotation on the stability is described in section 3. Besides the increase of the sawtooth period, observation and explanation of the disappearance of the sawtooth are given in section 4. Finally, further discussion and conclusion are presented in section 5 and 6.

2. Increase of sawtooth period by toroidal rotation drive

Sawtooth period is sensitive to the various plasma parameters such as current profile, pressure, \(m/n=1/1\) mode amplitude/frequency and so on. It is observed in KSTAR H-mode discharges that besides these parameters, toroidal rotation has a key role to determine the sawtooth period. Co-current toroidal rotation extends the sawtooth period, and it can be identified by NBI whose power is 1.5 MW. As depicted in Figures. 1 and 3, it is clear that the sawtooth period lengthens as the rotation speed increases. Toroidal rotation speed is measured by the tangential x-ray crystal spectrometer detecting Doppler shifted spectral lines of argon impurity ions \[15\]. As soon as the NBI is turned on at \(t=2\)sec, sawtooth period as well as toroidal rotation speed increases immediately. At the second stage (~ 2.4 sec in Figure. 1) of which sawtooth period is increasing, discharge is in the H-mode phase and the sawtooth period depends mainly upon the increase of the toroidal rotation not upon the poloidal beta and the density with high rotation speed.

**FIG. 1.** Changes in sawtooth period and core rotation speed in the NBI-discharge.

**FIG. 2.** Toroidal rotation profiles measured by the x-ray crystal spectrometer are plotted in time. The curve at \(t=1.946\)sec represents the rotation profile before NBI. As soon as the NBI is applied \((t=2.061\)sec\), rotation level increases, and the profile shows core rotation becomes peaked near the center as NBI continues. Rotation shear also increases as toroidal rotation speed increases. \(t=2.758\)sec and \(3.136\)sec represent the times at the last sawtooth before suppression and the sawtooth-free phase respectively.
Figure 3 shows the relationship between the core rotation speed and the sawtooth period from the selected NBI H-mode discharges. Sawtooth period is saturated at about 100 msec which is limited by the size of the plasma or the q=1 surface. Maximum size of the q=1 surface in NBI-heated KSTAR plasmas is about 15 – 18 cm, estimated from the electron cyclotron emission (ECE) signals.

In addition, it is also worthy of noting that the clear decrease of sawtooth period is seen while the on-axis ECRH is applied, causing a significant core rotation drop [16] (Figure. 4 (a)). On the contrary, ECRH is deposited at the outside (z=60cm) of the q=1 surface, rotation drop in the core region is weak, and thus high-speed co-rotation driven by NBI is still dominant and the sudden decrease of sawtooth period is not observed (Figure. 4 (b)). This exhibits that the change in the sawtooth period is governed by the change in the core rotation speed, not by the rotation outside the q=1 surface.

3. Stabilization of n=1 internal kink mode by the toroidal rotation

On the onset of the sawtooth crash, the precursor such as the m/n=1/1 magnetic perturbation is seen on the vicinity of the q=1 surface. If the n=1 internal kink mode does not grow, it will not lead to the catastrophic event such as a crash.

Stability of the n=1 internal kink mode can be significantly influenced by toroidal plasma rotation [12, 17-18]. In order to investigate the effect of the plasma rotation on the stability of the n=1 internal kink mode, analytic formula based on a large aspect-ratio expansion of the MHD equations including toroidal plasma flow has been used [14, 18].

It is found that toroidal rotation can change the stability condition to delay or not to cause the crash event. Growth rate ($\gamma_0$) of the n=1 internal kink mode taking a sheared rotation into account can be expressed as [17, 18]:

$$\gamma_0 = \text{expression}$$
\[
\frac{\gamma_i}{\omega_A} = -\frac{\pi r_f}{\sqrt{3} |s_i| R_0^2} \delta W_i
\]
\[
\delta W_i = 3 r \left| s_i \right| \left( \frac{13}{144} - \beta_p^2 \right) + \left( \frac{2}{\epsilon_x^2} - \frac{1}{\epsilon_p^2} \right) \left( \frac{v_{q0}}{v_A} \right)^2
\]

where \( R_0, r_f, s_1, \omega_x, \omega_A, \epsilon_x, \epsilon_p, \) and \( v_{q0} \) are the major radius, the radius of the q=1 surface, the magnetic shear \( s = r/q \frac{dq}{dr} \) at the q=1 surface, the Alfvénic frequency \( \omega_A^2 = B_0^2/\mu_0 \rho_0 R_0^2 \), the Alfvén velocity \( v_A^2 = B_0^2/\mu_0 \rho_0 \), the scale length of the toroidal rotation profile, the scale length of the density profile and the core toroidal rotation speed respectively. To determine the radial scale lengths of the rotation and the density, rotation profile is obtained by quartic polynomial fitting with the measured data from the x-ray crystal spectrometer. Electron density profile is regarded as almost flat in the core region, and q-profile from the EFIT calculation is reconstructed to a monotonic profile with two constraints which are the edge safety factor \( q_{95} = 5 - 7 \) and the radial position of the q=1 surface.

Poloidal beta \( (\beta_p) \) in the first term (Bussac part of the potential energy \( \delta W \)) in Eq. (2) can be modified to include the centrifugal effect [19] due to strong rotation. If the centrifugal force becomes effective, density profile becomes no longer a flux function and has a poloidal asymmetry leading to GAM (geodesic acoustic mode) or density stratification [20]. However, since sonic Mach number \( \left( M = \sqrt{\frac{3}{5} \rho v_{q0}^2 / S P} \right) \), where 3/5 is adiabatic constant, is below 0.2 in spite of the fast rotation whose value is up to \( \sim 200 \) km/sec, contribution of the GAM frequency to the stabilization can be vanished and the change in the pressure term in the \( \beta_p \) can be neglected. Therefore \( \beta_p \) in Eq. (2) can be regarded as an experimentally measured value which does not include the centrifugal force term. The second term in the potential energy \( (\delta W) \) gives the apparent toroidal rotation effect, and the strong rotation speed and the rotation shear at the q=1 surface makes \( \delta W \) larger, resulting in reduction of growth rate. Then, the n=1 internal kink mode is stabilized and the quiescent time between crashes becomes long (Figure 1). Another important factor to stabilize the mode is the scale length of the rotation profile. Figure 2 shows a set of rotation profiles taken at five different time points. A noticeable point in this figure is that toroidal rotation shear at the q=1 surface while the NBI is applied, and thus the radial scale length of the toroidal rotation decreases. It means that higher rotation shear at the q=1 surface leads to the increase of the potential energy \( (\delta W) \), and reduces the growth rate of the n=1 internal kink mode, which is a function of the toroidal rotation speed at the q=1 surface, obtained by the analytic theory with the flat density profile and the quartic rotation profile. For instance, the critical speed to stop growing internal kink mode (shot# 5511), which is marginally stable, is about 170 km/sec.
rate. However, the effect of the rotation level is somewhat stronger than that of the rotation shear.

4. Suppression of the sawtooth by the toroidal rotation

Disappearance of sawtooth has been reported in several papers, and various explanations have been introduced to describe the mechanism of this phenomenon. It is known that there are several causes to suppress the internal kink mode. Firstly, suppression of sawtooth was observed in ohmic discharges in ASDEX-Upgrade [21]. Neoclassical calculation showed the central safety factor \(q_0\) is above the unity during sawtooth-suppression phase. Change in \(q_0\) in this case is due to broadening of core current density profile owing to influx of the impurity injected during the experiment. Secondly, long quiescent time, which is about 3 – 5 times longer than the confinement time, between sawtooth crashes was observed in ICRH-dominated plasmas in JET [10]. Main cause of this phenomenon is fast-ion population generated by both ICRH and NBI in the core plasma. Fast-ions inside the q=1 surface lead to the diamagnetic wells so as to increase the plasma internal energy and the internal kink mode becomes stable not to cause the sawtooth crash with \(q_0\) well below the unity.

Stability analysis based on the analytic formula (Eq. (1) and (2)) shows the growth rate of the n=1 mode becomes zero at the critical rotation speed as depicted in Figure. 5. In KSTAR, even though its aspect ratio is not tight (\(\varepsilon \sim 3.6\)), toroidal rotation speed in the core is up to about 200 km/sec due to the beam-path on the well-aligned on-axis tangent. It is found in typical H-mode discharges that sawtooth is disappeared when toroidal rotation speed and shear exceed critical levels, making the instability growth suppressed. For instance, critical speed calculated with the parameters such as rotation speed, rotation profile, modeled density profile and q-profile at the time near the sawtooth suppression in case of shot# 5511 is about 170 km/sec as depicted in Figure. 5. Critical speed can be varied by the change in the shape of the profiles of the parameters such as toroidal rotation, density, and so on. Analytic stability analysis by using Eq. (1) and (2) sometimes presents a somewhat larger critical rotation speed to reach marginal stability than that measured speed. It means that it represents an upper bound on the marginal flow speed. Rotation level suppressing the sawtooth in KSTAR H-mode discharges ranges from 160 km/sec to 190 km/sec, depending on the profiles of the rotation shear and the electron density. Radius of q=1 surface \(r_1\), which is identified by the ECE data, decreases gradually as the rotation speed increases. \(r_1\) just before the disappearance of the sawtooth is about 10 cm and the finite \(r_1\) implies \(q_0\) is still below than unity at the last crash before the sawtooth suppression. Fast toroidal rotation seems to maintain the stabilization not to cause the crash under the condition of \(q_0\) below than the unity.

As depicted in Figure. 6, internal inductance and \(r_1\) decrease, and the edge safety factor increases while sawtooth period increases in the H-mode phase. This implies the broadening of the plasma current profile at the core region. However, change in the magnetic shear in the core region is not observed, therefore the broadened current profile does not affect to the internal kink mode stability.

Both the extended sawtooth period and the sawtooth suppression are observed in H-mode NBI discharges in KSTAR, however suppression is not seen in the L-mode NBI discharges. This means that the differences of the plasma profiles between two phases (L- and H-modes) have a role to modify the internal kink mode stability. Density profile would not show the significant change between L-mode and H-mode at the core plasma. However, rotation level and shear in the H-mode phase are higher than those in the L-mode, hence the stabilization effect on the internal kink mode can be strong, leading to suppression of the sawtooth.
5. Discussion

Toroidal rotation-induced sawtooth stabilization does not show the giant sawtooth, unlike the stabilization by the ICRH-induced energetic ions. Radius of the $q=1$ surface decreases as the sawtooth period increases, and it suggests low possibility of triggering the tearing modes at outside of the $q=1$ surface. Besides toroidal rotation effect, kinetic effect to stabilize the internal kink mode can be considered. However, kinetic contribution of the energetic (fast) ions does not seem to be dominant on the internal kink mode stability in KSTAR H-mode discharges. To examine the energetic ion effect indirectly, variation of the electron density can be used as an important parameter. It has been reported that sawtooth period in presence of energetic ion yields the inverse density scaling [22]. The amount of the energetic ion decreases in the high-density plasma because it experiences the strong slowing-down of the kinetic energy, and thus the stabilization of the internal kink mode becomes weak. However, sawtooth period in KSTAR NBI plasmas exhibited in this paper does not obey the inverse density scaling when the variations of the electron temperature and the plasma shape are not significant. Exponent of the scaling is about 1.07 ($\tau_{ST} \sim <n_e>^{1.07}$), which is calculated from the linear regression fitting. The relationship between the density and the sawtooth period shown in Figure. 7 does not imply the significant role of the fast-ion population on the sawtooth stabilization. Heating employed in the discharges in this paper is the NBI whose power is 1.5MW. Assessment of the kinetic effect on the sawtooth suppression will have to be investigated in future work with both the ICRH and the NBI having higher heating power. Furthermore, L-mode NBI discharge has higher energetic ion fraction ($\beta_{\text{fast}}$), however sawtooth period in H-mode NBI discharge with higher rotation speed is apparently longer than in the case of L-mode.

Poloidal asymmetry of density profile and GAM due to strong toroidal rotation may have to be investigated with the consistent calculation including centrifugal effect. Centrifugal effect may be effective at higher rotation level which is comparable to the ion sound speed. This is beyond the work described in this paper, and will be addressed in future work.
6. Conclusion

Strong core toroidal rotation driven by NBI observed in KSTAR H-mode plasmas has a primary role to stabilize the ideal internal kink mode and to extend the sawtooth period. Stability analysis using analytic formula confirms the effect of the toroidal rotation on the sawtooth stabilization. Rotation change during NBI by applying on-axis ECRH provided both the rotation drop and the instant decrease of the sawtooth period. Besides the increase of the sawtooth period, disappearance of the sawtooth is observed while the strong rotation is maintained at the rotation speed above the critical level even with low power NBI ($P_{\text{NBI}} \sim 1.5$ MW). The rotation speed exceeding the critical level in conjunction with high rotation shear at the core plasma, which makes the instability marginally stable, stabilizes the sawtooth. Moreover, it seems $q_0$ is below unity during sawtooth-free phase although there is no sawtooth activity. Finally, population of the fast ions in the core region can be considered as a stabilizing source, however, density scaling of the sawtooth period does not obey the inverse relation in NBI ($P_{\text{NBI}} \sim 1.5$ MW) discharges in KSTAR. It implies that fast-ion population does not have a significant role in the stabilization compared with the toroidal rotation effect. Active change in the flow effect such as toroidal rotation can be a knob to control the internal MHD mode stability to maintain the burning plasma reaction without the disturbance in the core region for a long time, which is several times longer than energy confinement time or alpha-particle slowing-down time, in the next step fusion devices.

References