Study of Inverted Sawtooth Activities in EAST Plasma*  

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Abstract On the EAST tokamak, during whole off-axis LHCD (low hybrid current drive) limiter discharge, inverted sawteeth oscillations on the SXR (soft X-ray camera) signals appear continuously, and no positive sawtooth is observed. It is thought that this phenomenon is caused by the curvature pinch, though it could partly be explained by the electron temperature profile observed on the PHA (soft X-ray pulse height analyzer) system. The off-axis LHCD and Ohmic heating generate a non-monotonic $q$ profile. According to the curvature pinch effect, this $q$ profile leads to a special electron density profile that has a valley ring. The non-monotonic $q$ profile and the special electron density profile lead to this interesting phenomenon.  

Keywords: soft X-ray camera, inverted sawtooth, LHCD  

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(Some figures may appear in colour only in the online journal)  

1 Introduction  

Sawtooth oscillation, which was first observed on the ST tokamak [1], is an important MHD instability in toroidal magnet confined fusion devices. Since this observation, a variety of sawtooth phenomena have been reported on various devices, including single sawteeth, double sawteeth, and inverted sawteeth [1–5].  

As reported [4,5], the inverted sawtooth is a phenomenon associated with particle transport, and both electron and impurity transport can induce this phenomenon. Investigations on the TCV tokamak showed that the deposition position of electron cyclotron power played an important role in the appearance of inverted sawteeth. This work suggest that the inverted sawteeth on the TCV tokamak were due to outward electron transport [4]. Inverted sawtooth activity was also observed on the HL-2A tokamak, and was caused by impurity injection [5].  

The inverted sawtooth phenomenon was observed with soft X-ray cameras on the EAST tokamak, meanwhile, the signals from the electron cyclotron emission system (ECE) system confirmed the phenomenon. Sometimes, the inverted sawtooth is accompanied by a weak normal sawtooth on the signals of the central channels. Experimental observations are presented in section 2, the mechanism of this phenomenon is discussed in section 3, and finally, a conclusion is drawn in section 4.  

2 Experimental observations  

The main parameters of the EAST tokamak are as follows: major radius $R=1.7-1.9$ m, minor radius $r=0.4$ m, aspect ratio 4.25, elongation 1.2-2. The distribution of the SXR (soft-X ray) system is shown in Fig. 1. The SXR system is composed of a vertical camera and two horizontal cameras. The vertical camera has one photodiode array with 46 elements. The two horizontal arrays observe, respectively, the upper and lower region with some overlapping area, which may occupy 1/4 of the total area. The thickness of the beryllium foil is 12.5 $\mu$m, and the detectors are sensitive to photons in the energy range of 1-10 keV. The time resolution of the SXR cameras is 100 $\mu$s, and the space resolution is about 2.5 cm.  

Fig. 1 The arrangement of the soft X-ray cameras on the EAST tokamak  

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During EAST tokamak LHCD limiter discharges, the inverted sawtooth phenomenon is observed with SXR cameras. Shot No. 23760 is one typical discharge with this phenomenon. The plasma current, loop voltage, LHW (low hybrid wave) power and soft X-ray camera signal of the central chord are shown in Fig. 2(a). The central chord-averaged electron density is $1.8 \times 10^{19} \text{m}^{-3}$; the central electron temperature is 1.5 keV (the result of the soft X-ray PHA system); and the plasma centre is at $R=1.88 \text{m}$. The inverted sawtooth always appears continuously. It starts at the ramp-up phase of the plasma current, lasts for the whole flat-top phase, and disappears in the decreasing phase. In a stable shot, the inverted sawteeth can last for about 4 s. The main feature of this phenomenon is that there is a sudden rise in the SXR signals in the crash phase; no positive sawtooth is observed on any of the SXR channels, and in contrast all of the SXR signals decrease slowly during the relatively stable phase. Hereafter, positive and negative crash means the sudden decrease and increase in soft X-ray or ECE intensity, respectively. Positive and negative sawtooth refers to the signal waveform of the soft X-ray or ECE signals, respectively. The signals of the SXR and ECE for two sawtooth periods are presented in Fig. 2(b). On the SXR signals there is no large positive sawtooth crash, while a weak positive and negative sawtooth crash can be found in the middle of a full sawtooth period. On the ECE signals there are negative sawteeth in the central plasma and positive sawtooth in the outer plasma. The reverse radius could be inferred from the ECE signals, which is around $r=20 \text{cm}$.

The inverted sawtooth is accompanied by MHD oscillations from the beginning to the end of each sawtooth period. The $(m, n) = (1, 1)$ oscillations are common phenomena during sawteeth periods. All of the pre-cursor oscillations, post-cursor oscillations and mid-oscillations appeared during the full sawtooth period. The double sawteeth phenomenon was also observed on SXR signals. Sometimes a weak normal sawtooth exists during a full sawtooth period. The weak normal sawtooth could last for several inverted periods. SVD [6] is used to analyze this phenomenon using the upper array of the horizontal camera, and the result is shown in Fig. 3. The left column of the figure is the temporal eigenvector and the right column is the spatial eigenvector.

**Fig. 2** The waveform of the main discharge parameters. (a) Main discharge parameters, (b) SXR and ECE signals in two inverted sawteeth periods

**Fig. 3** The SVD results of the inverted sawteeth phenomenon using the upper array (covers the upper half of the plasma) of the horizontal cameras. The left column shows the temporal eigenvectors and the right the spatial eigenvectors. The second biorthogonal component shows the inverted sawtooth and the weak normal sawtooth, and the third biorthogonal component shows the $m = 1$ mode during a sawtooth period.
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Using the C3PO/LUKE code [7, 8], the deposition location of the off-axis LHW and the LHCD current density are shown in Fig. 4. Since the loop voltage has not dropped to zero, the current density presented in Fig. 4(b) is not the total current density distribution of the plasma.

The total current profile may have two peaks. One is caused by the Ohmic heating in the core region, and the other by LHCD, as shown in Fig. 4. This implies a non-monotonic $q$ profile which may have two valleys. The weak sawtooth crash in a full sawtooth period can be explained using this non-monotonic profile with two $q = 1$ surfaces, as proposed by Pfeiffer’s model [3].

3 Results and discussion

It is well known that SXR intensity is influenced by three plasma parameters: electron density, electron temperature and impurity content. Inverted sawteeth caused by impurity injection have been reported [5]. The impurity is injected during the normal sawtooth phase, and then the inverted sawtooth appears immediately. During the inverted sawtooth phase, the SXR intensity increases dramatically and lasts for several sawtooth periods, after which normal sawteeth appear again. It is shown that the inverted sawtooth caused by impurity transport is not a stable phenomenon. As for the inverted sawtooth in shot No. 23760, there are two features that exclude impurity transport from explanations of this phenomenon. Firstly, SXR intensities do not rise continually in a sawtooth period. Secondly, the inverted sawtooth in shot No. 23760 is a stable phenomenon. These observations are inconsistent with the features of inverted sawteeth caused by impurity transport. Fig. 5 shows that the soft X-ray energy spectrum before and after this inverted sawteeth phenomenon appears (at about 1.88 s) by PHA diagnostics. There is no obvious variation in impurity emission shown in this figure, which implies that the appearance of inverted sawteeth is not caused by impurity transport.

The inverted sawtooth phenomenon associated with density behavior was observed on the TCV tokamak, and is driven by off-axis ECH. The hollow electron density profile is observed using Thomson scattering measurements [4]. During the stable phase of the inverted sawtooth, the electrons are ceaselessly transported outwards, and then a hollow electron density profile is shaped. During the crash phase, the inner core mixes with the outer part, resulting in a flattened emission distribution. As for the inverted sawtooth phenomenon observed on EAST, the electron density may be peaked in the core region when a small crash occurs since the weak crash is a normal sawtooth crash. It is also reasonable to assume a global hollow density profile as a
big crash happens. Considering the weak normal crash and large inverted crash, a schematic electron density profile with a valley ring is shown in Fig. 7. The curvature pinch model \cite{9} could explain the formation of this density profile. The curvature pinch is caused by inward anomalous particle transport, which is considered as the main factor causing the peaked particle profile in the normal case, and it strongly depends on the safety factor $q$ profile. It claims that in the transport process, while maintaining $J$ ($J$ is the second adiabatic invariant constant) a constant, the collisionless trapped electrons experience anomalous transport and gain energy from the interaction with the electrostatic turbulence via electric draft. Because electric draft is related to the magnetic field, and the magnetic field decides the $q$ value, the $q$ profile affects the electrostatic turbulence causing anomalous transport and consequently curvature pinch. Therefore, the resulting electron density profile caused by curvature pinch depends on the $q$ profile. It is stated that the particle density caused by curvature pinch decreases monotonically with the increase in $q$. The resulting particle profile will peak where $q$ is low, and vice versa. A schematic diagram of the $q$ profile corresponding to the analysis results at the end of section 3 is shown in Fig. 7.

The inverted sawtooth is explained in the following way. During the stable phase of a sawtooth period, the electron density profile, as shown in Fig. 7, is shaped due to the curvature pinch. When a sawtooth crash takes place due to magnetic reconnection (the magnetic field reconnection process is shown in Fig. 8(d)-(f), particles diffuse to both sides of each density peak. This explanation is consistent with the analysis results of SXR tomography and channel-to-channel time delay, as shown below.

![Fig. 6](image1)

**Fig. 6** The temperature profile measured from the soft X-ray PHA system. The time instant is 3.075 s and the time resolution is 150 ms, which is about eight times the inverted sawtooth period.

![Fig. 7](image2)

**Fig. 7** A schematic diagram of the $q$ profile and the electron density profile.

![Fig. 8](image3)

**Fig. 8** Tomography result of the inverted sawtooth phenomenon. (a) The waveform of the central channel SXR signal in one inverted sawtooth period, where time ‘a’ and ‘b’ are the analyzed time instants. The tomography results are shown in (b) and (c). The magnetic field reconnection process is shown in (d)-(f).
The tomography results before and after the sawtooth crash are shown in Fig. 8. Fig. 8(a) shows the central channel SXR signal in one inverted sawtooth period, and Fig. 8(b) and (c) are the tomography results at certain times before and after the sawtooth crash, respectively. Obviously, before the crash there is a relatively hot ring on the SXR emission distribution whose minor radius is about \( r = 15 \text{ cm} \). The formation of this hot ring is consistent with the assumption of the globally hollow density profile. When the crash is finished, the hot emission ring is flattened, and the emissivity of the central plasma is increased.

Fig. 9 shows the time evolution of the SXR signals (channels 10-18) for one inverted sawtooth period. The left column shows the original signals (3.13-3.135 s), while in the right column the signals are normalized by the maximum value of each channel in the duration. In the right column it is easy to see that signal intensity increasing of channel SXC15U (\( r = 13.5 \text{ cm} \)) maximizes is delayed compared with signals SXC10U (central channel \( r = 1.1 \text{ cm} \)) and SXC18U (\( r = 20.9 \text{ cm} \)). This indicates that the main particle diffusion is from a radial location to both sides.

Fig. 9 The SXR signals of one inverted sawtooth period from channel 10 to channel 18. The left column shows the original signals, and on the right the signals are those normalized by the maximum value of each channel in this period.

4 Conclusion

The inverted sawtooth was observed with the SXR system during LHCD discharge on the EAST tokamak. The inverted sawtooth is always accompanied by a weak normal sawtooth during a full sawtooth period. The off-axis LHCD causes a special \( q \) profile that is non-monotonic and has more than one \( q = 1 \) surface. The inverted sawtooth phenomenon suggests that a special electron density profile may be formed during the stable phase of an inverted sawtooth period due to curvature pinch. The density profile has two peaks located at the centre and outside. Due to magnetic reconnection when the sawtooth crash occurs, the electrons at the density peaks diffuse to both sides, and then the sawtooth is inverted.

As the density profile is so important for the explanation of the inverted sawtooth on EAST plasma, and this profile was not measured in these shots, the measurement of this profile will be included in the investigation of this phenomenon in future work.

References

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