J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 324–327

# Effect of ECH/ECCD on Sawtooth Oscillations in NB-heated Plasmas in JT-60U

ISAYAMA Akihiko, IDE Shunsuke, IKEDA Yoshitaka, SUZUKI Takahiro,
KAJIWARA Ken and JT-60 team
*Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Ibaraki 311-0193, Japan*

(Received: 11 December 2001 / Accepted: 4 June 2002)

## Abstract

Sawtooth period and amplitude during electron cyclotron (EC) wave injection to a neutral beam heated plasma are investigated. Significant decrease in sawtooth period is observed for EC injection inside the inversion radius in co-direction: the normalized sawtooth period $\tau_{ST}/T_e(0)^{1.5}$ reaches 1/10 of that in an ohmic heating phase, which shows a strong destabilization effect (here, $\tau_{ST}$ and $T_e(0)$ are sawtooth period and the central electron temperature, respectively). While time scale for the change in the sawtooth amplitude is comparable to that in the inversion radius, time scale for the change in the sawtooth period is much shorter than that in the inversion radius. This suggests that the change in the sawtooth amplitude is related to the current profile, and that the strong destabilization effect of the sawtooth period occurs independently of the change in the current profile.

## Keywords:

sawtooth oscillation, magnetohydrodynamic instability, electron cyclotron heating, electron cyclotron current drive, neutral beam, JT-60U, tokamak

## 1. Introduction

Sawtooth oscillation, which is a kind of magnetohydrodynamic instabilities in the central region of a plasma, has been observed in many devices since 1970s [1]. Although a number of experimental and theoretical research have been done, underlying physics of the sawtooth oscillations has not been fully understood yet.

In application to a fusion reactor, sawtooth oscillations are attractive since heat and particle in the core region can be expelled through a sawtooth crash. On the other hand, sawtooth oscillations can become undesirable since they can (a) limit the plasma performance through the flatting of the pressure profile, (b) form seed islands for neoclassical tearing modes, and (c) increase heat load at divertor plates to an intolerable level if a sawtooth crash is too large. Thus, to control the sawtooth oscillations — stabilization and destabilization — is an important issue.

Effects of additional heating and/or current drive tools on sawtooth oscillations have been investigated in many devices: For example, in JT-60/JT-60U, behavior of sawtooth oscillations during neutral beam (NB) injection, lower hybrid heating/current drive, ion cyclotron heating, and electron cyclotron heating (ECH)/ electron cyclotron current drive (ECCD) have been investigated [2-5]. In most cases, however, these experiment have been done from the viewpoint of stabilization.

In this paper, effects of ECH and ECCD on sawtooth oscillations in NB-heated plasmas in JT-60U are described. The difference between the results in this paper and those in ref. 5 is that EC wave was injected in ohmic heating (OH) plasmas in the latter case. We

*Corresponding author's e-mail: isayama@naka.jaeri.go.jp*

concentrate on the EC injection inside the inversion radius and investigate the destabilization effect by EC injection. After this introduction, experimental condition and results are described in Sec. **2**, and summary and discussion are described in Sec. **3**.

## 2. Experiment

### 2.1 Experimental setup

Since the period and amplitude of sawtooth oscillations are affected by discharge conditions, we perform this series of discharges under the following fixed conditions: plasma current $I_p$ = 1 MA, toroidal field $B_t$ = 3.7 T, major radius $R$ = 3.4 m, minor radius $a$ = 0.83 m, safety factor at the 95% flux surface $q_{95}$ = 5.6, plasma volume $V_p$ = 60 m$^3$, and line-averaged electron density $\bar{n}_e = 1.1 \times 10^{19}$ m$^{-3}$. Plasma configuration and the layout of heating and diagnostic systems are shown in Fig. 1. Two units of neutral beams, whose injection power and beam energy are respectively 2 MW and 80 keV, are tangentially injected to the hydrogen plasma in both co- and counter-directions. Electron cyclotron wave, whose frequency is 110 GHz, is injected from the low-field side. Electron cyclotron emission (ECE) diagnostics and motional Stark effect (MSE) diagnostics are used for measurement of electron temperature and current profiles, respectively. Profiles of electron temperature and safety factor during EC injection are shown in Fig. 2(a), and the change in the electron temperature profile during a sawtooth crash is shown in Fig. 2(b). In this series of discharges, inversion radius of a sawtooth oscillation is located at $\rho \gtrsim 0.15$. According to a Fokker-Planck code combined with a ray-tracing code, the peak position of the EC-driven current profile is located at $\rho \sim 0.1$. Thus, most of the injected EC wave is deposited inside the inversion radius. In order to discriminate between the effects of ECH and ECCD, behavior of sawtooth oscillations for co-ECCD and counter-ECCD cases are compared each other.

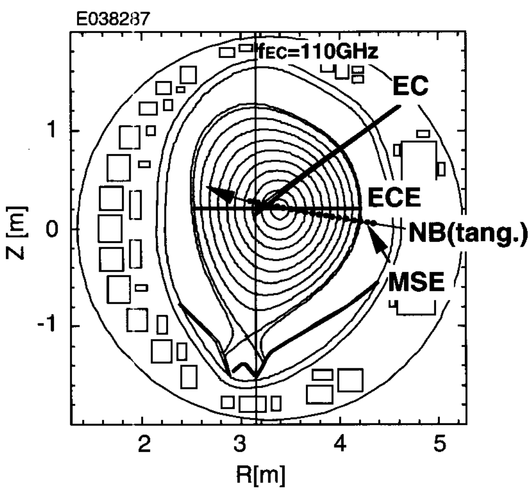


Fig. 1 Plasma shape and the layout of heating and diagnostic systems.

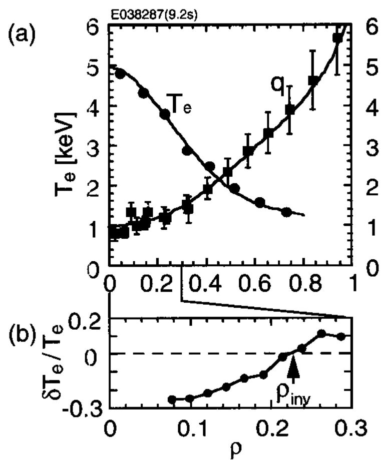


Fig. 2 (a) Profiles of electron temperature and safety factor; (b) Change in electron temperature during a sawtooth crash.

### 2.2 Experimental Results

Time evolution of the central electron temperature is shown in Fig. 3. Sawtooth oscillations appear before the NB injection, and sawtooth period is about 0.04 s. After the NB injection from $t$ = 8.0 s, the sawtooth period is extended to about 0.1–0.15 s. EC wave of 1.5

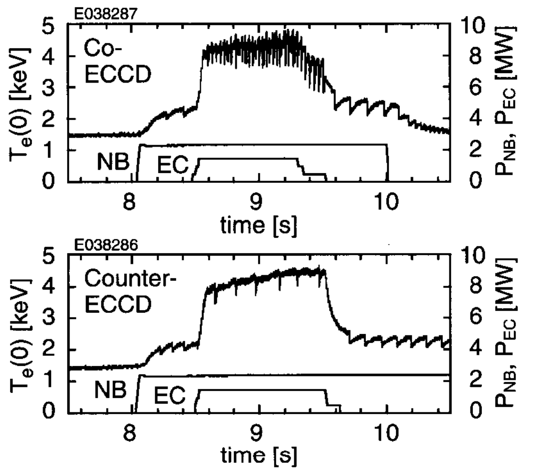


Fig. 3 Time evolution of the central electron temperature.

MW is injected from $t$ = 8.5 s. While the central electron temperature for the co-ECCD case is comparable to that for the counter-ECCD case, significant difference is observed in the behavior of the sawtooth oscillations: the sawtooth period decreases to about 0.02 s for the co-ECCD case, and it increases to 0.16 s for the counter-ECCD case. After the EC injection is quitted, the sawtooth period increases to about 0.12–0.13 s, which is comparable to that before the EC injection.

According to a theoretical analysis, sawtooth period increases with $T_e(0)^{1.5}$ [6]. It was reported that sawtooth period follows the scaling in NB-heated or EC-heated plasmas in JT-60/JT-60U [3,5]. In Fig. 4, time evolution of the sawtooth period is plotted as a function of the central electron temperature. For the co-ECCD case, the sawtooth period is much smaller than that from the scaling: the sawtooth period of 0.02 s obtained in the co-ECCD case is about 1/6 of that in the NB phase. By taking into account the increase in electron temperature during the EC phase, this shows that the sawtooth oscillations are strongly destabilized. For the counter-ECCD case, on the other hand, the experimental data are located near the scaling, which suggests that the increase in the sawtooth period during the EC injection is attributed to the increase in electron temperature.

The dependence of the normalized sawtooth period $\tau_{ST}[\mathrm{s}]/(T_e(0)[\mathrm{keV}])^{1.5}$ on EC injection power $P_{EC}$ is shown in Fig. 5. For the co-ECCD case, the normalized sawtooth period reaches 0.005 even for one-unit EC injection ($P_{EC}$ = 0.5 MW; 25% of NB power). When $P_{EC}$ = 1.5 MW, the value reaches about 0.002, which is about 1/10 of that in the OH phase. For the counter ECCD case, the normalized sawtooth period gradually decreases with EC power, and reaches about 0.15 when $P_{EC}$ = 1.5 MW.

In addition to the sawtooth period, sawtooth amplitude is another important parameter. Time evolution of the sawtooth amplitude is shown in Fig. 6. The sawtooth amplitude $A_{ST}$ is defined as follows:

$$A_{ST} = \left(T_e(0)^{\text{before}} - T_e(0)^{\text{after}}\right) \Big/ \left\{\left(T_e(0)^{\text{before}} + T_e(0)^{\text{after}}\right)/2\right\}$$

Here, $T_e(0)^{\text{before}}$ and $T_e(0)^{\text{after}}$ are the central electron temperature before and after a sawtooth crash, respectively. The value of $A_{ST}$ is 0.04 in the OH phase and increases to 0.08 in the NB phase. While $A_{ST}$ continuously increases to 0.26 for the co-ECCD case, it saturates at 0.12 for the counter-ECCD case. The value of $A_{ST}$ for the co-ECCD case is about twice as large as that for the counter-ECCD case.

Behavior of sawtooth oscillations can be affected by a current profile. Time evolution of inversion radius, which is a measure of the $q$ = 1 surface, is shown in Fig. 7. The inversion radius increases by ~0.05 in volume-averaged minor radius for the co-ECCD case, while no significant change in the inversion radius is observed for the counter-ECCD case. Similar result is also obtained in current profile: change in MSE angle is observed only for the co-ECCD case. While time scale for the change

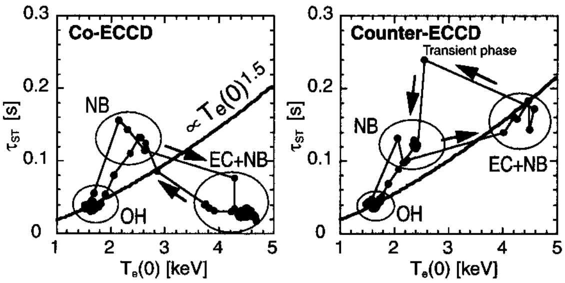


Fig. 4 Dependence of sawtooth period on the central electron temperature.

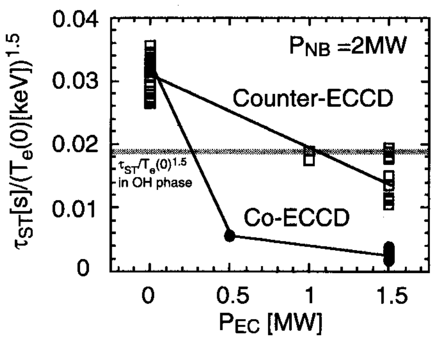


Fig. 5 Dependence of the normalized sawtooth period $\tau_{ST}/T_e(0)^{1.5}$ on EC injection power.

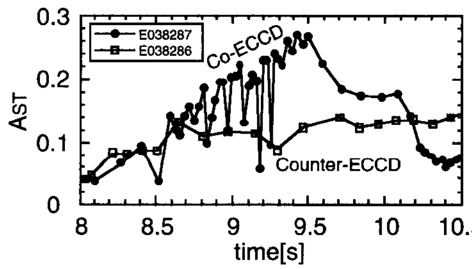


Fig. 6 Time evolution of sawtooth amplitude.

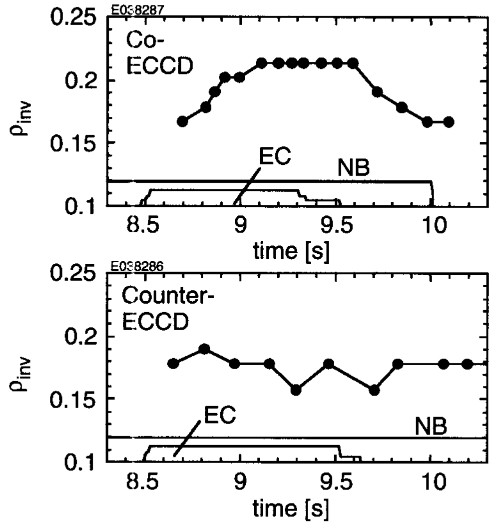


Fig. 7 Time evolution of sawtooth inversion radius.

in the sawtooth amplitude is comparable to that in the inversion radius, time scale for the change in the sawtooth period is much smaller than that in the inversion radius. This suggests that the change in the sawtooth amplitude is more closely related to the current profile, and that the strong destabilization effect by the co-ECCD case occurs independently of the change in the current profile.

## 3. Summary and Discussion

Effects of ECH/ECCD on sawtooth oscillations in NB-heated plasmas have been investigated. In this paper, we have investigated the destabilization effect by EC injection inside the inversion radius. It has been found that sawtooth period can be significantly decreased by injecting EC wave in co-direction. In this case, the normalized sawtooth period $\tau_{ST}/T_e(0)^{1.5}$ reaches 1/10 of that in the OH phase. The strong destabilization effect has not been observed for NB-heated or EC-heated plasmas in JT-60/JT-60U. Interaction between fast ions and EC wave may play an role, but the mechanism has not been clarified yet.

Unlike the sawtooth behavior, no significant difference in stored energy has been observed between the co- and counter-ECCD cases. One of the reasons is that energy released by a sawtooth crash is small since inversion radius is small in this series of discharges. While the reachable central electron temperature for the co-ECCD case is similar to that for the counter-ECCD case, the central electron temperature averaged over one sawtooth period for the co-ECCD case is lower than that for the counter-ECCD by several percents. This suggests that heat and particles in the core region can be effectively expelled by co-EC injection without serious confinement degradation.

## References

[1] S. von Goeler *et al.*, Phys. Rev. Lett. **33**, 1201 (1974).
[2] S. Ishida *et al.*, Nucl. Fusion **30**, 552 (1990).
[3] Y. Kamada *et al.*, Nucl. Fusion **33**, 225 (1993).
[4] H. Kimura *et al.*, *Radio Frequency Power in Plasmas* (AIP Conference Proceedings 289), (American Institute of Physics, New York, 1994) p. 52.
[5] A. Isayama *et al.*, Fusion Eng. Des. **53**, 129 (2001).
[6] W. Park *et al.*, Nucl. Fusion **30**, 2413 (1990).