Control of Growth of Neoclassical Tearing Mode by Central Co-ECCD in JT-60U

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Growth of a neoclassical tearing mode (NTM) with a poloidal mode number $m = 3$ and a toroidal mode number $n = 2$ has been controlled by electron cyclotron current drive (ECCD) in the same direction as the plasma current (co-ECCD) in the central region away from the NTM island. By using ECCD at a fraction of about 10% of the plasma current, the amplitude of the $m/n = 3/2$ NTM is limited to about 1/5 of that without ECCD. The frequency spectrum of magnetic perturbations shows that the frequency of the $m/n = 3/2$ NTM is modulated by a sawtooth crash. The beta value, which is the ratio of the plasma pressure to the magnetic pressure, is higher by 6% than that without ECCD at the same input power. This operational scenario is quite different from that for conventional NTM stabilization in which the ECCD location is accurately adjusted at the mode rational surface and is thus off-axis. This result shows the compatibility of sawtooth oscillations and a small-amplitude 3/2 NTM, and suggests the possibility of a new and easier operational scenario for NTM control.

Keywords: neoclassical tearing mode, sawtooth oscillation, electron cyclotron current drive, plasma instability, JT-60U

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In a fusion reactor such as the International Thermonuclear Experimental Reactor (ITER), plasma operation with a high fraction of bootstrap current is expected to reduce externally driven current. In such plasmas, however, neoclassical tearing modes (NTMs) would be excited. Since NTMs degrade plasma performance and sometimes cause a disruption, it is critically important to establish a scenario to control the NTMs. Stabilization of the NTM by electron cyclotron current drive (ECCD) at the mode rational surface, which is typically located at a half of the minor radius, has been successfully performed in ASDEX-U [1], JT-60U [2], and DIII-D [3].

Among a number of instabilities, sawtooth oscillations are considered beneficial in controlling heat and particles at the core region. In JT-60U, it was demonstrated that the amplitude and period of sawtooth oscillations can be controlled by optimizing the location and direction of the ECCD. In particular, ECCD in the same direction as the existing plasma current (co-ECCD) inside the sawtooth inversion radius can enhance sawtooth oscillations [4]. However, in relation to the NTM, sawtooth oscillations are considered harmful since a large sawtooth crash triggers an NTM at a low-β regime [5] (β is the ratio of the plasma pressure to the magnetic pressure). Thus, it is important to clarify the interaction between the NTM and sawtooth oscillations and to develop a scenario for controlling the NTM.

Controllability of an NTM having a poloidal mode number $m = 3$ and a toroidal mode number $n = 2$ through the use of central co-ECCD has been investigated in JT-60U. Figures 1 (a) and (b) show the temporal evolution of the normalized beta β_N and the injection power of neutral beams (NBs) and the electron cyclotron (EC) wave, respectively. Here, $\beta_N \equiv \beta[\%]/(I_p[\mathrm{MA}]/a[\mathrm{m}]B_t[\mathrm{T}])$, I_p is the plasma current, a is the plasma minor radius, and B_t is the toroidal magnetic field. Typical plasma parameters are as follows: $I_p = 1.5$ MA, $B_t = 3.7$ T, major radius $R = 3.22$ m, $a = 0.78$ m, safety factor at 95% flux surface $q_{95} = 3.8$. In this discharge, ~20 MW of NBs are injected from $t = 4.8$ s, and the value of β_N reaches 1.8. At $t = 5.5$ s, the line-averaged electron density is 3.4×10^{19} m^{-3}, and the electron and ion temperatures at the plasma center are 7 keV and 17 keV, respectively. Prior to the NB injection, 4-units of O-mode EC waves, whose power and frequency are 2.4 MW and 110 GHz, respectively, are injected to the central region. Figure 2 shows the plasma cross section and the ray trajectory of the EC wave. The EC wave is injected from the low-field side and fully absorbed by the fundamental resonance before reaching the cold resonance location ($R = 3.0$ m) due to the Doppler shift. A Fokker-Planck code shows that the peak position of the ECCD profile is located at 0.1 in the normalized minor radius ρ with a full-width at half-maximum of ~0.1 in ρ, and that EC-

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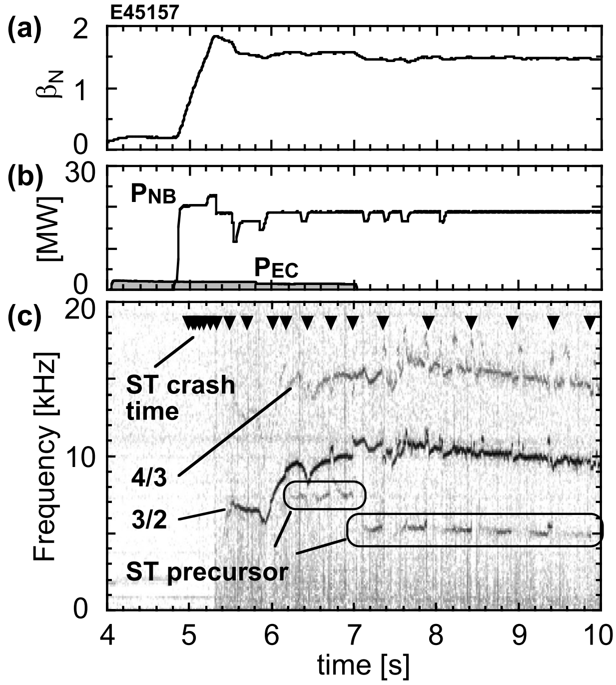

Fig. 1 Temporal evolution of (a) the normalized beta, (b) injection power of NB ($P_{\rm NB}$) and EC waves ($P_{\rm EC}$), and (c) frequency spectrum of magnetic perturbations. Triangles in (c) indicate the time of sawtooth (ST) crash.

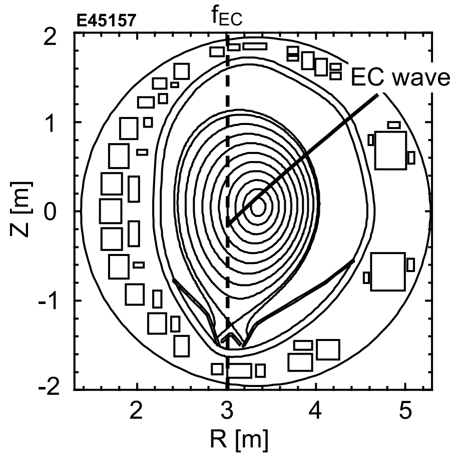

Fig. 2 Plasma cross section seen in the experiment. The contour lines are drawn at intervals of 0.1 in ρ. Also shown are the cold resonance surface of 110 GHz ($f_{\rm EC}$) and the ray trajectory of the EC wave.

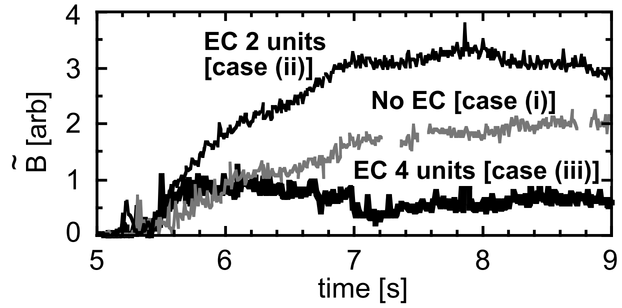

Fig. 3 Temporal evolution of magnetic perturbation in a frequency range of 5.5 to 13 kHz for cases of no ECCD, 2-unit ECCD, and 4-unit ECCD.

driven current is 130 kA at t = 5.5 s, which is about 10% of $I_{\rm p}$.

Figure 1 (c) shows the frequency spectrum of magnetic perturbations. An NTM with $m/n = 3/2$ appears at t = 5.4 s and persists throughout the NB phase. Electron temperature perturbations measured using an electron cyclotron emission (ECE) diagnostic show that the center of the magnetic island associated with the NTM is located at $\rho \sim 0.4$, and that the width of the magnetic island at the saturated phase, $t \sim 5.5$ s, is about 10 cm. In Fig. 1 (c), the time of sawtooth crash is also indicated by a triangle. After the EC wave injection at t = 4.0 s, sawtooth oscillations appear at t = 5.0 s. The ECE diagnostic shows that the inversion radius of the sawteeth increases in time until $t \sim 6.4$ s and remains at ~0.22 in the minor radius. For a 2-unit ECCD case, the inversion radius is smaller than that in the 4-unit ECCD case by about 0.06 in ρ. Sawtooth oscillation does not appear before and during the NB phase without EC wave injection. In the 4-unit ECCD case, a precursor of the sawtooth oscillations can be clearly seen in the frequency spectrum of the magnetic perturbation shown in Fig. 1 (c). The precursor exists even after the EC wave injection is turned off at t = 7.0 s while the frequency decreases after turn-off. The ECE diagnostic shows that the $m/n = 3/2$ and 4/3 modes persist throughout the NB phase, and thus the modes with ~10 and ~15 kHz seen in Fig. 1 (c) are mainly from the 3/2 and 4/3 modes, respectively. The ECE signals measuring around the $q = 1.5$ surface, where perturbations from the 3/2 and 4/3 modes are simultaneously observed, show that the change in the mode frequency by a sawtooth crash cannot be explained simply by the change in the toroidal rotation. It is most likely that the frequency modulation is caused by the change in the mode frequency itself. This modulation was not observed in the 2-unit ECCD case, possibly due to smaller sawtooth amplitude and inversion radius.

The temporal evolution of magnetic perturbations in the cases of (i) no ECCD, (ii) 2-unit ECCD, and (iii) 4-unit ECCD is shown in Fig. 3 (Case (iii) is the same discharge as that seen in Fig. 1). For cases (i) and (ii), a 3/2 NTM appears and grows continuously. On the other hand, for case (iii), while the initial growth of the 3/2 mode ($t \lesssim 5.7$ s) is similar to that of case (ii), the growth is suppressed and the amplitude is kept low (~1/5) throughout the rest of the NB phase even after the EC wave injection is turned off. It should be noted that in cases (i) and (ii) the saturated mode amplitude is similar while the growth rate of case (ii) is about two-fold faster than that of case (i). The reasons for this difference are thought to be attributed to the difference in current and pressure profiles, and also to the sawtooth oscillations. The value of β_N in case (iii) is higher than that in case (ii) by 6% at the same injection power, suggesting an improvement of the beta value and confinement by the NTM control. This result shows the compatibility of sawtooth oscillations and a moderate 3/2 NTM without large confinement degradation. This operational scenario is quite different from that for NTM stabilization in that the EC wave is deposited far outside the mode rational surface, and the above preferable result suggests that it can provide a new and easier scenario for NTM control.

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