Neoclassical Tearing Mode Control with ECCD and Magnetic Island Evolution in JT-60U

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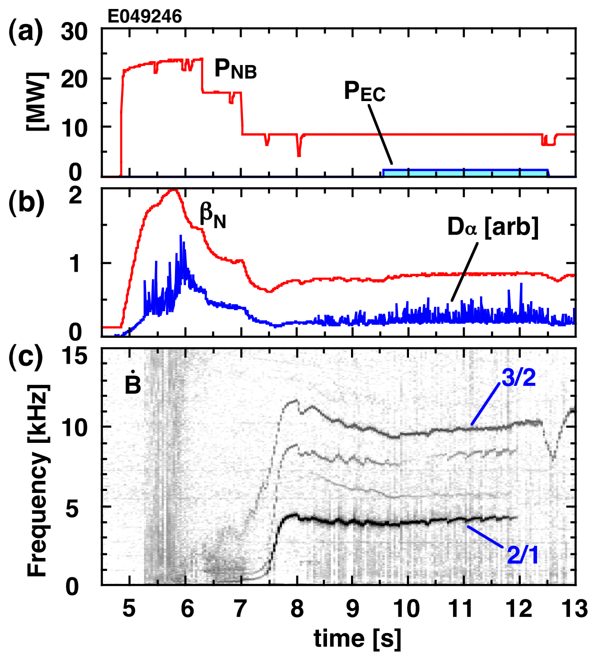
Abstract. Results of stabilization of neoclassical tearing modes (NTMs) with electron cyclotron current drive (ECCD) in JT-60U are described with the emphasis on effective stabilization: (1) identification of the minimum electron cyclotron (EC) wave power for complete stabilization, (2) stabilization by modulated ECCD in synchronization with mode rotation, (3) modelling of NTM behavior using the modified Rutherford equation (MRE) and comparison of the coefficients in the MRE between JT-60U and ASDEX-U. For unmodulated ECCD, minimum EC wave power for complete stabilization of an m/n=2/1 NTM has been experimentally identified as $0.2<j_{\rm EC}/j_{\rm BS}<0.4$ for $W_{\rm sat}/d_{\rm EC}\sim3$ and $W_{\rm sat}/W_{\rm marg}\sim2$, and $0.35<j_{\rm EC}/j_{\rm BS}<0.46$ for $W_{\rm sat}/d_{\rm EC}\sim1.5$ and $W_{\rm sat}/W_{\rm marg}\sim2$. Here, m and n are poloidal and toroidal mode numbers; $j_{\rm EC}$ and $j_{\rm BS}$ are EC-driven current density and bootstrap current density at the mode rational surface; $W_{\rm sat}$, $W_{\rm marg}$ and $d_{\rm EC}$ are full island width at saturation, marginal island width at which the island spontaneously decays and full width at half maximum of ECCD profile, respectively. Stabilization of a 2/1 NTM with modulated ECCD in synchronization with mode rotation at about 5 kHz has been performed. It has been experimentally found that modulated ECCD has about twice stronger stabilization effect than unmodulated ECCD for O-point ECCD. Degradation of the stabilization effect has been observed as the phase difference between the modulated ECCD and island O-point increases. For modulation out of phase, which corresponds to X-point ECCD, NTM amplitude increased, showing destabilization effect. In addition, evolution of magnetic island associated with an $m/n=3/2$ NTM has been compared in JT-60U and ASDEX-U based on the modified Rutherford equation. It has been found that the value of the coefficient describing the contribution from bootstrap current is in the order of unity in both devices.

1. Introduction

To sustain a high-beta plasma with positive magnetic shear, for example the ITER standard operation and Hybrid operation, control of NTMs is essential since they degrade plasma performance and sometimes cause disruption. In particular, an NTM with the poloidal mode number $m=2$ and the toroidal mode number $n=1$ is needed to be suppressed since its effect on plasma is serious: as shown later, the degradation of the beta value typically 30-50% in JT-60U experiments.

In JT-60U, two scenarios for NTM suppression have been developed. One scenario is NTM avoidance, where the onset of NTM is avoided by optimizing current and pressure profiles. In previous JT-60U experiments, long-duration sustainment of high-beta plasma was demonstrated [1, 2]. Although this scenario is advantageous in that only neutral beam (NB) is required, the optimization is not necessarily consistent with other factors such as current drive. The other scenario is stabilization by localized current drive. NTM stabilization using EC wave is considered to be most promising due to its ability of highly localized current drive. In JT-60U, experiment on NTM stabilization using ECCD has been performed since the installation of the first gyrotron in 1999, and several innovative stabilization techniques have been demonstrated such as stabilization by real-time steering of EC mirror [3], *preemptive* stabilization [4] etc. In addition, simulation of NTM evolution using the TOPICS code has been also performed [5–7], and the island evolution was reproduced by determining the undermined coefficients from experimental data. However, detailed research on effective stabilization, which is an important issue also in ITER, was remained as future work.

This paper describes results of active control of an $m/n=2/1$ NTM using localized ECCD at the mode location in JT-60U and comparative study of NTM simulation using the modified Rutherford equation in JT-60U and ASDEX-U. In Section 2, result of the identification of the minimum required



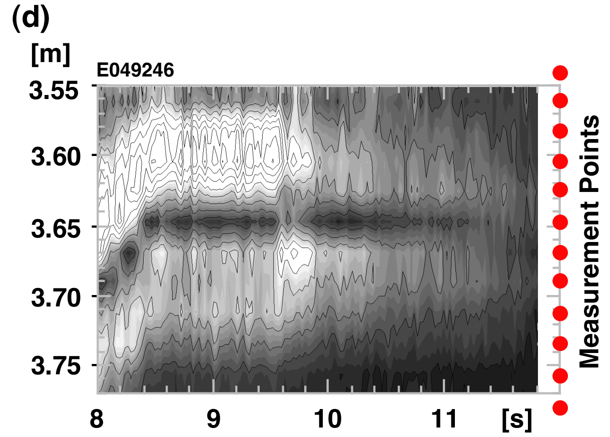


FIG. 1. Typical discharge for a 2/1 NTM stabilization with ECCD : (a) injection power of NB (P_{NB}) and EC wave (P_{EC}), (b) Normalized beta (β_N) and intensity of D_α line, (c) frequency spectrum of magnetic perturbation, and (d) contour plot of electron temperature perturbations. At $t = 9.5$ s. the island center is located at $R \sim 3.65$ m ($\rho \sim 0.6$).

EC wave power to completely stabilize a 2/1 NTM is described. In expedients, the minimum power in two different regimes with the toroidal magnetic field of 3.7 T and 1.7 T, has been investigated. In Section 3, result of NTM stabilization with modulated ECCD is described. EC wave power was modulated in synchronization with the mode rotation frequency ($\sim$ 5 kHz). Effect of the phase difference between magnetic perturbations and modulated EC wave has been investigated. Comparison with unmodulated ECCD is also described. In Section 4, result of comparative study of a 3/2 NTM in JT-60U and ASDEX-U is described. And finally, summary of this paper is described in Section 5.

2. Minimum EC Wave Power for Complete Stabilization

As shown in the previous section, NTM stabilization using ECCD has been extensively preformed in JT-60U. However, as in other devices, NTMs were *overstabilized* in most cases, where EC wave power was larger than the minimum required power. Although NTMs should be stabilized with less EC wave power in ITER, it is still uncertain how much EC wave power is required at the minimum. Thus, identification of the minimum required EC wave power is an important issue. To clarify the minimum required power, stabilization of an $m/n = 2/1$ NTM with reduced EC wave power was performed. A part of these experiments was done remotely from Max-Planck-Institut für Plasmaphysik (IPP) using a newly developed remote experiment system, where experimental condition was set at IPP and sent to the JT-60 control room under high security [8].

Experiments were performed in two different regimes with different toroidal field at 3.7 T (‘case 1’) and 1.7 T (‘case 2’). Typical waveform of the experiment at high field (case 1) is shown in Fig. 1, where plasma current $I_p = 1.5$ MA, toroidal field $B_t = 3.7$ T, safety factor at 95% flux surface $q_{95} = 4.1$, major radius $R = 3.18$ m, minor radius $a = 0.80$ m, triangularity at the separatrix $\delta_x = 0.20$. The toroidal field was fixed in time throughout this and all other discharges. In this series of discharge, neutral beams of about 25 MW was injected and the normalized beta β_N increased to about 2. An NTM with $m/n = 2/1$ appeared at $t \sim$5.7 s, and the value of β_N decreases to about 1.4. Since the mode locked soon after the onset, the behavior is not clear from the frequency spectrum in Fig. 1(c). At $t = 7$ s, NB power was decreased and the direction of the tangential NBs was changed from balanced injection to counter injection to raise the mode frequency. The 2/1 NTM started to rotate in the counter direction at $t = 7.5$ s, and the mode frequency saturated at about 4-5 kHz as shown in Fig. 1(c). Electron cyclotron wave with the frequency of 110 GHz was injected at $t = 9.5$ s by up to 3 gyrotrons. By changing the power and combination of the gyrotrons, various injection power becomes possible. Injection angle of EC wave, i.e. ECCD location, was fixed during the ECCD in

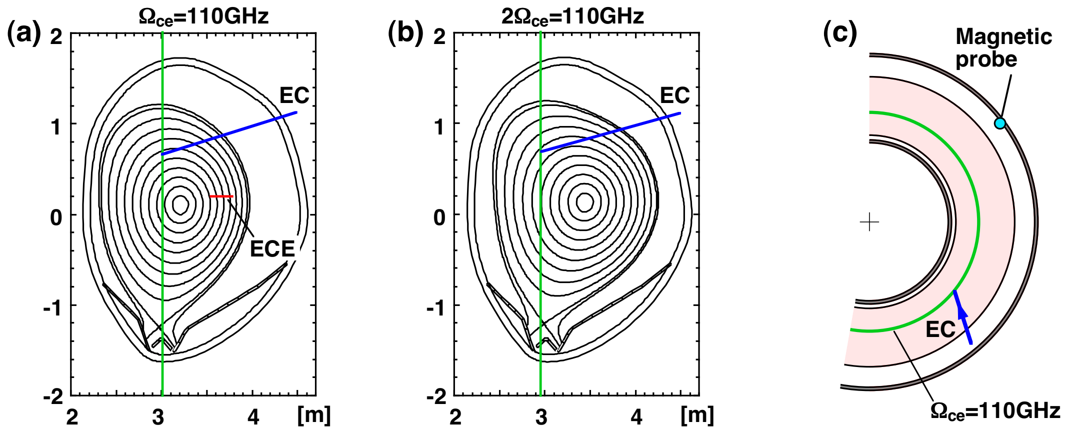


FIG. 2. Plasma cross section for (a) case 1 (B_t = 3.7 T) and (b) case 2 (1.7 T). (c) Top view of plasma configuration for the case 1.

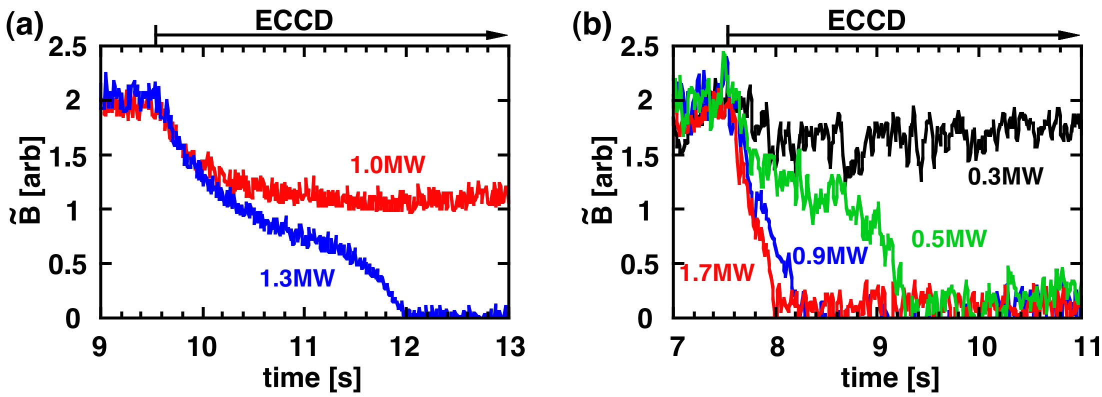


FIG. 3. Temporal evolution of magnetic perturbation amplitude near the threshold EC power for (a) case 1 and (b) case 2.

all discharges after the optimum injection angle was determined. Temporal evolution of the structure of magnetic island measured with electron cyclotron emission (ECE) radiometer with the channel separation of about 2 cm, which corresponds to ~0.02 in the volume averaged minor radius (ρ), is shown in Fig. 1(d). The two bright peaks correspond to the separatrix of of the island, and the dark region between the two peaks correspond to the center of the island. Note that in this discharge the major radius was shifted inward by 4 cm at t =8.0-8.5 s. The shift is clearly seen in the contour plot. As shown in this figure, the center position of magnetic island is unchanged during the ECCD, and shot-to-shot difference of the island center is less than the channel separation of the ECE radiometer. The mode location, ρ_s, is about 0.6, and the full island width before ECCD, W_{sat}, is 0.12 (The value is normalized by the plasma minor radius.). After the ECCD, the distance between the two peaks in Fig. 1(d), which corresponds to the full island width, decreases, and the 2/1 NTM was completely stabilized at $t = 12.0$ s.

Similar experiments were done at lower field with the second harmonic X-mode ECCD ('case 2'). Typical plasma parameters are as follows: $I_p = 0.85$ MA, $B_t = 1.7$ T, $R = 3.38$ m, $a = 0.88$ m, $q_{95} = 3.5$, $\delta_x = 0.37$. Discharge scenario is similar to the case 1: an $m/n = 2/1$ NTM was first destabilized at $\beta_N \sim 3$ by high-power NB, and then the power was stepped down to 1.5. The values of ρ_s and W_{sat} are $\sim$ 0.6 and 0.15, respectively.

Plasma configurations of the two discharge regimes are shown in Figs. 2(a) and 2(b). The cold resonance surface of 110 GHz EC wave with the fundamental O-mode and the second harmonic X-mode is located at 3.02 and 2.95 m in the configuration, respectively. Since the EC wave is injected tangentially to the flux surface, narrow ECCD deposition width is obtained. The poloidal injection angles for the case 1 and 2 are 16° and 13°, respectively (The angle is as the depression angle). The toroidal

	case 1	case 2
I_p [MA]/B_t [T]	1.5 / 3.7	0.85 / 1.7
β_N^{onset}	~ 2	~ 3
β_N^{sat}	0.9	1.5
β_N^{marg}	0.4	0.8
W_{sat}	0.12	0.15
W_{marg}	0.06	0.08
d_{EC}	0.08	0.05
$(j_{EC}/j_{BS})_{min}$	0.35–0.46	0.2–0.4

TABLE 1. Parameters for for the two configurations. The values of W_{sat}, W_{marg} and d_{EC} are normalized by the plasma minor radius.

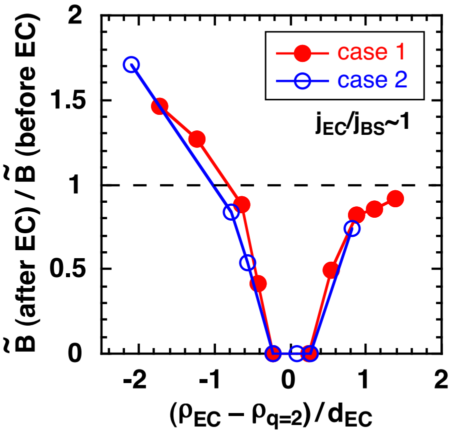


FIG. 4. Magnetic perturbation amplitude after ECCD normalized by that before ECCD for different ECCD locations.

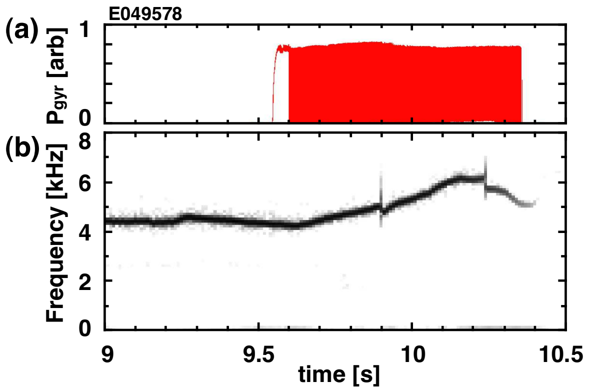
injection angle is $\sim 22°$ in these configurations. Profile and amount of EC-driven current were calculated by a Fokker-Planck code, EC-Hamamatsu. The full-width at half maximum of ECCD deposition width, d_{EC}, is 0.08 for the case 1 and 0.05 for the case 2.

Figure 3 shows temporal evolution of magnetic perturbation amplitude, $\tilde{B}$, near the minimum EC wave power for complete stabilization. For the case 1, while the 2/1 mode was completely stabilized for EC wave power P_{EC}=1.3 MW, it was not completely stabilized for P_{EC}=1.0 MW. Thus, the minimum EC wave power is located between 1.0 and 1.3 MW in this experimental condition. For the case 2, the stabilization effect becomes weak with decreasing EC wave power, and complete stabilization was not achieved for P_{EC}=0.3 MW. Thus, the minimum EC wave power is located between 0.3 and 0.5 MW in this experimental condition.

It can be seen from both experimental regimes that the island evolution is similar: the island first decays and then slows down and finally rapidly decays. The behavior is consistent with the description of the modified Rutherford equation, and it was also observed in previous NTM experiments [7]. The width at which the final rapid decay begins is referred to as the marginal island width (the full width of the marginal island width is described as W_{marg} hereafter), and cross-machine comparison of W_{marg} of an $m/n = 3/2$ NTM was done before [9]. In Fig. 3, $\tilde{B}$ reaching the marginal island width corresponds to ~ 1.2 for the case 1 and ~ 1.8 for the case 2, which correspond to $W_{marg} = 0.06$ and 0.08, respectively. The marginal island width can be also estimated roughly by stepping down the NB power and investigating the beta value at which the NTM spontaneous decays. For the case 1 and 2, the marginal β_N value, β_N^{marg}, is 0.4 and 0.8, respectively. By assuming that the island width is proportional to the beta value, which is reasonable assumption for NTM, this result is roughly consistent with the result of the above marginal island width.

In NTM stabilization with ECCD, the ratio of EC-driven current density (j_{EC}) to bootstrap current density (j_{BS}) at the mode rational surface is an important parameter. In addition, ECCD deposition width with respect to the marginal island width is another important parameter because EC-driven current inside the island O-point decreases as the NTM is stabilized if ECCD deposition width is comparable or wider than the marginal island width, which is the case for most experimental conditions in JT-60U and also in ITER. According to the results from ACCOME and EC-Hamamatsu code calculations, The range of the value of j_{EC}/j_{BS} $0.35<j_{EC}/j_{BS}<0.46$ for the case 1 and $0.2<j_{EC}/j_{BS}<0.4$ for the case 2. In previous JT-60U experiments, an m/n=2/1 NTM was completely stabilized at $j_{EC}/j_{BS} = 0.5$ with fundamental O-mode ECCD, but the minimum value of required EC-driven current could not be identified [7]. The previous result is consistent with the above new result. The parameters in these two regimes are summarized in Table 1.

Since the ECCD deposition width with respect to the saturated island width is different between the two operation regimes, the effect of misalignment on NTM was also investigated. Although the effect



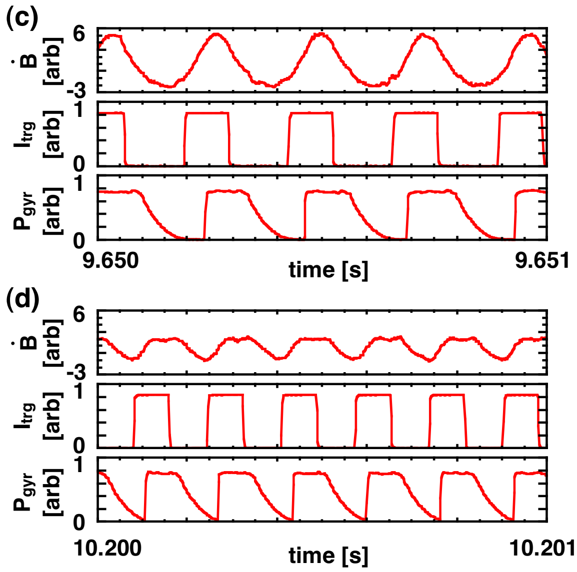


FIG. 5. Typical discharge of NTM stabilization with modulated ECCD. (a) Power from a gyrotron (P_{gyr}), (b) frequency spectrum of magnetic perturbations. Magnetic probe signal ($\dot{B}$), trigger signal at the gyrotron (I_{trig}) and power from the gyrotron at (c) t =9.65 s and (d) 10.2 s.

of ECCD deposition width on NTM stabilization was previously investigated by TOPICS simulation [7], experimental verification has not been performed yet. Figure 4 shows amplitude of magnetic perturbation after ECCD as a function of ECCD location relative to the mode rational surface. The value of the vertical axis is normalized to magnetic perturbation amplitude before ECCD, and the value of the horizontal axis is normalized by d_{EC}. The closed symbols correspond to the case 1, and the open symbols correspond to the case 2. In both cases, $j_{EC}/j_{BS}{\sim}1$ and $W_{sat}/W_{marg}{\sim}2$. It can be seen that similar V-shape profile is obtained for both cases. It is also found that the dependence of the stabilization effect on misalignment becomes similar by using the normalized parameter while without the normalization, allowable misalignment decreases with decreasing ECCD deposition width.

3. Stabilization of 2/1 NTM by Modulated ECCD

Stabilization of NTMs with modulated ECCD is thought to be more effective than with unmodulated ECCD. In experiments, stabilization of an $m/n = 3/2$ NTM by modulated second harmonic X-mode EC wave was previously performed in ASDEX-U [10, 11]. Since adding an ability to modulate EC wave at several kHz imposes significant changes in designing gyrotrons, it is important to perform stabilization of a more dangerous 2/1 NTM and clarify whether modulated ECCD is actually more effective and how much the superiority is. In addition, issues in performing the modulated ECCD should be clarified in order to make NTM stabilization in ITER reliable.

In JT-60U experiments, power modulation at several tens of Hz has been done to investigate heat wave propagation since the initial phase of the first gyrotron operation [12]. Although the modulation frequency had been increased year by year, the EC wave was not injected to a plasma because the frequency is rather low for NTM stabilization experiments, where modulation frequency of about 5 kHz is required. In 2008, the control system of gyrotrons was modified to achieve higher modulation frequency up to $\sim$ 7 kHz, and fast power down at each power modulation [13]. To synchronize the EC wave with NTM rotation, signal from a magnetic probe was sent to the control system of gyrotrons. The magnetic probe is located 13.5° below the horizontal midplane and 87° apart from the EC antenna in the toroidal direction (See Fig. 2(c)). The toroidal angle between the magnetic probe and the intersection of the EC ray trajectory and the cold resonance surface is about 78°.

In these experiments, the mode frequency as well as the mode location stays almost constant in the steady state phase ($t \sim 9$ s in this discharge condition; see Fig. 1 for example). However, in general, mode frequency can change in time. In the modulation system, mode frequency is monitored in real time, and the trigger signal for the modulation is generated accordingly [13]. The effectiveness was experimentally demonstrated as shown in Fig. 5, where plasma configuration and discharge scenario are the same as in Fig. 1. In this discharge, the mode frequency changed from 4.3 to 6.1 kHz during

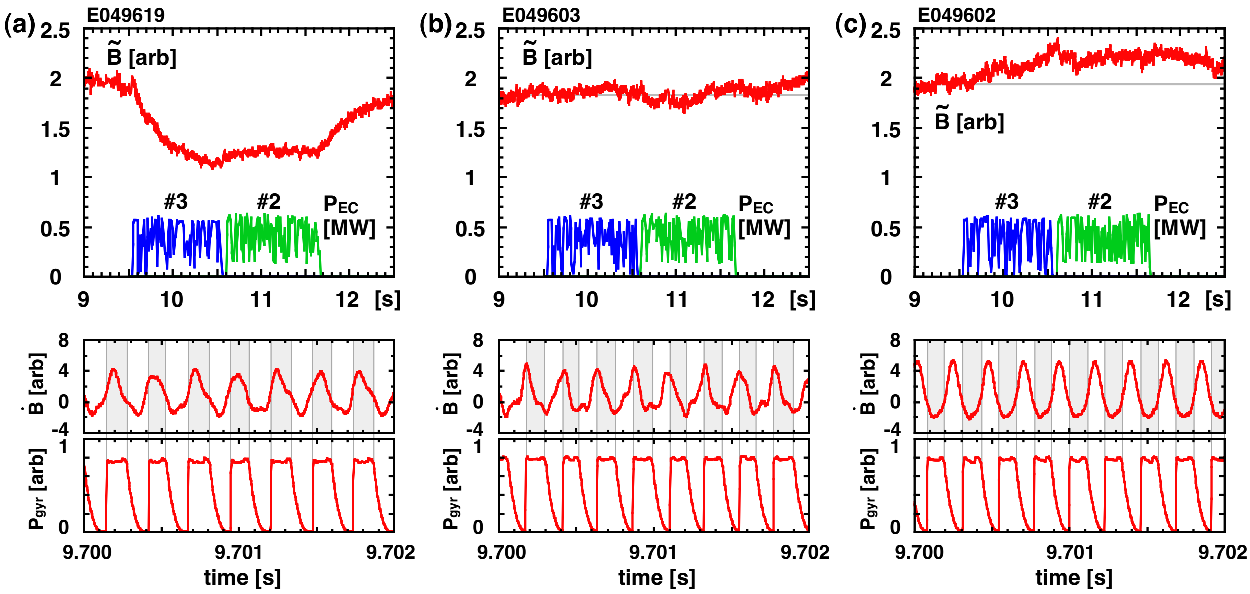


FIG. 6. Temporal evolution of magnetic perturbation amplitude, EC wave power, magnetic probe signal and gyrotron power for (a) 0°, (b) 90 ° and 180° phase differences.

ECCD. As can be seen in this figure, the trigger signal was successfully generated in synchronization with the magnetic perturbations. Note that in the modulation system the trigger signal is generated by taking into account the delay time of the actual power down from the trigger. In this discharge, the $2/1$ NTM was completely stabilized at $t = 10.4$ s.

In modulating ECCD, phase difference between modulated EC wave and magnetic perturbation signal is important: stabilization effect reaches the maximum when the phase difference is the one corresponding to O-point ECCD; stabilization effect weakens and even becomes negative (i.e. destabilization) as the phase difference increases. Although calculation of the stabilization effect can be done based on a numerical model, experimental verification is essential to make a better prediction of NTM stabilization in ITER. To investigate the effect of the phase difference, the delay time was scanned. Figure 6 shows temporal evolution of magnetic perturbation amplitude for the phase differences of 0°, 90° and 180°. Note that the value of the phase difference is defined just as the phase difference between the raw signals. The injected power of EC wave from gyrotron #3 and #2 is both 0.6 MW. The power is modulated as 0-100% for #3 and 20-100% for #2 with respect to the peak power. (Note that the EC wave power in the top figures of Fig. 6 does not reflect the real waveform due to slow data sampling.). Duty cycle of the modulated ECCD is 50%, that is, 50% on-time and 50% off-time as shown in this figure. For the 0° case, stabilization effect is seen during ECCD, and the magnetic perturbation amplitude increases after the turnoff of the EC wave injection. For the 90° case no clear effect of ECCD is seen. As shown in the expanded waveforms of the magnetic perturbation and EC wave, the phase of modulation is actually shifted as expected. And for the 180° case, the magnetic perturbation amplitude slightly increases, and it decreases after the turnoff the EC wave injection, showing a destabilization effect.

Figure 7 shows the dependence of the initial decay time, τ_{decay}, on the phase difference around zero. Here, τ_{decay} was obtained by fitting the magnetic perturbation amplitude as $\sim \exp[-t/\tau_{\mathrm{decay}}]$ by using the initial 300 ms data from the start of modulation in order to see the ECCD effect alone. As seen from this figure, the decay time reach a minimum at about $-10°$, which corresponds to O-point ECCD. For unmodulated ECCD with the same peak power, the decay time is about 4 s, which is much larger than the above cases, showing the superiority of modulated ECCD at (or near) the island O-point. The offset of the minimum phase difference can be explained by the difference in the toroidal and poloidal angles between the ECCD location and the magnetic probe by taking into account the phase variation by $n\varphi + m\theta$ with $\varphi \sim 78°$, $\theta \sim 120 + 13.5°$, $m = 2$ and $n = 1$. Similar example showing the superiority of O-point ECCD is shown in Fig. 8. In this discharge, modulated ECCD

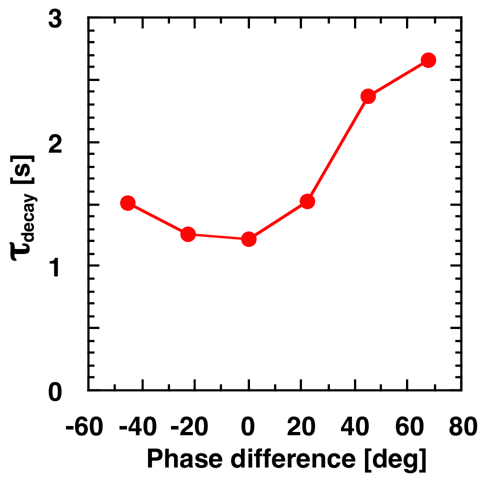


FIG. 7. Dependence of decay time of magnetic perturbation amplitude on phase difference.

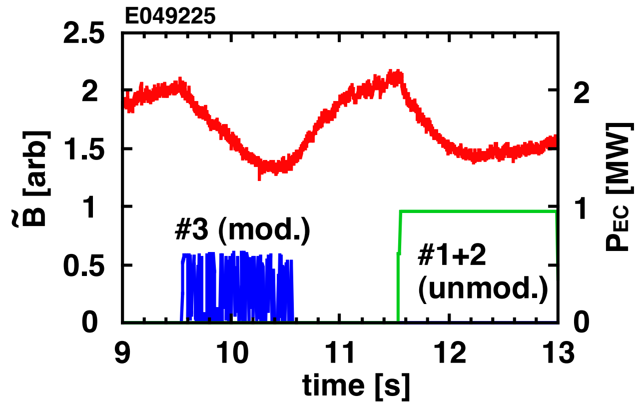


FIG. 8. Temporal evolution of magnetic perturbation amplitude for modulated ECCD (#3) followed by unmodulated ECCD (#1+2).

with one gyrotron was followed by unmodulated ECCD with two gyrotrons. The phase difference of the modulated ECCD is about $-65°$. Decay time of the modulated ECCD and unmodulated ECCD is 1.9 s and 1.5 s, respectively. As seen from this figure, the stabilization effect is similar in spite of higher unmodulated power and unperfect O-point ECCD.

In a theoretical model, stabilization efficiency is described by integrating the current profile on the island flux surface [14, 15]. The efficiency η_{EC} is a function of full island width (W), misalignment of ECCD location ($\Delta\rho_{EC}$), ECCD deposition width. For modulated ECCD, the duty ratio (τ_{duty}) and the center phase of the modulation (α_c) enter the η_{EC} function. The value of η_{EC} is 0.43 for $W/d_{EC} = 0.15$, $\Delta\rho_{EC}/d_{EC} = 0.25$, $\tau_{duty} = 0.5$ and $\alpha_c = 0$, which are the values in the modulated ECCD experiments. The value of η_{EC} for unmodulated ECCD is 0.15 ($W/d_{EC} = 0.15$, $\Delta\rho_{EC}/d_{EC} = 0.25$), showing that the model is consistent with the experimental results.

It will be useful to discuss technical issues we met in performing the modulated ECCD experiments. As shown above, the EC wave was modulated by referring a magnetic perturbation signal since in JT-60U a signal-to-noise ratio of the magnetic perturbation signal is better than ECE signal. In some of the NTM experiments, an instability other than an $m/n = 2/1$ mode was observed, such as 3/2 mode. Although the amplitude was much smaller than the 2/1 mode at the saturation phase, it could not be negligible as the 2/1 mode was stabilized by ECCD. In such situation, the trigger signal was not generated as we expected, where the frequency of the trigger signal was higher than the frequency of the 2/1 mode in most cases. In our modulation system, a protection circuit was added, where modulation is stopped if the mode frequency deviates from a certain range. In addition, sharp pulses due to an ELM could affect the magnetic probe signal. Perturbation by ELM was not so serious in the JT-60U NTM experiments because the 2/1 mode frequency ($\sim$ 5 kHz) was much higher than the ELM frequency (several tens of Hz), and the amplitude of an ELM was small due to relatively small NB power. However, in general, such ELM effect will not be negligible in a higher power (i.e. high beta) regime. Thus, for future experiments, development of pre-processing scheme of magnetic probe signals will be important.

4. Comparison of NTM Evolution between JT-60U and ASDEX-U

Evolution of magnetic island associated with NTMs is described by the modified Rutherford equation (MRE). Since the MRE contains undetermined coefficients for the contribution from different physics such as the effect of bootstrap, the Glasser-Greene-Johnson (GGJ) effect. Determination of the range of the coefficients is important to predict the behavior of NTMs in ITER and establish scenarios for the control the NTMs. Although fitting of experimental data with the MRE and simulation of NTM stabilization were previously performed independently in JT-60U [5–7] and ASDEX-U [16, 17], the form of the MRE was not identical. To understand the NTM physics in a wider parameter range, comparison of the coefficients between ASDEX-U and JT-60U for an $m/n = 3/2$ NTM has been performed by using the same form of the MRE and the same analysis method [18].

The MRE used in this comparison is as follows: $(\tau_s/r_s)(dW/dt) = r_s\Delta' + c_{sat}(r_s\Delta'_{GGJ} + r_s\Delta'_{BS})$. Here, τ_s, r_s and Δ', are the resistive timescale, minor radius at the mode rational surface and the tearing parameter, respectively. Δ'_{BS} and Δ'_{GGJ} stand for contribution from bootstrap current and the GGJ effect, respectively, and they are evaluated by using parameters at the mode rational surface. The coefficients c_{sat} can be estimated by evaluating the full island width at the mode saturation ($dW/dt = 0$) as $c_{sat} = \Delta'/(\Delta'_{BS} + \Delta'_{GGJ})$. Figure 9 shows a plot of c_{sat} versus local β_p value at the mode rational surface. The plasma parameters in JT-60U are $I_p = 1.5$ MA, $B_t = 3.7$ T, $R = 3.24$ m, $a = 0.76$ m, $q_{95} = 3.8$, $\beta_N^{sat} \sim 1.5$, and those in ASDEX-U are $I_p = 0.8$ MA, $B_t = 2.2$ T, $R = 1.65$ m, $a = 0.49$ m, $q_{95} = 4.5$, $\beta_N^{sat} \sim 2$. It can be seen that the value of c_{sat} is about unity while plasma parameters are quite different in JT-60U and ASDEX-U.

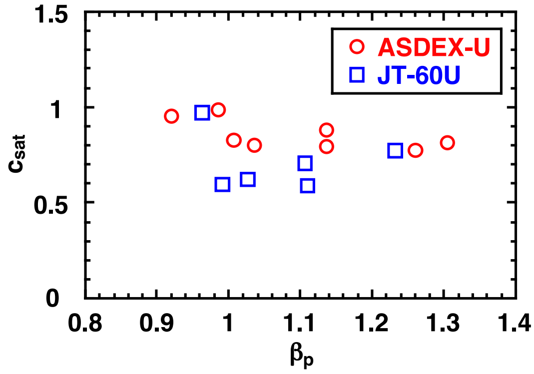


FIG. 9. Plot of c_{sat} in JT-60U and ASDEX-U.

5. Summary

In JT-60U, effect of localized ECCD on an $m/n = 2/1$ NTM has been performed with an emphasis on effective stabilization. In this paper, three topics which are important issues also in ITER have been described: minimum EC wave power for complete stabilization, stabilization with modulated ECCD and modelling and comparison of NTM using the MRE in JT-60U and ASDEX-U. The range of the minimum EC wave power has been investigated at $B_t = 3.7$ T and 1.7 T using the fundamental O-mode ECCD and the second harmonic X-mode ECCD, respectively. For the former case, the minimum EC-driven current is located at j_{EC}/j_{BS} =0.35-0.46 under the condition of $W_{sat} = 0.12$, $W_{marg} = 0.06$ and $d_{EC} = 0.08$. For the latter case, the minimum EC-driven current is located at j_{EC}/j_{BS} =0.2-0.4 under the condition of $W_{sat} = 0.15$, $W_{marg} = 0.08$ and $d_{EC} = 0.05$. Stabilization with modulated ECCD in synchronization with magnetic perturbations has been performed successfully. It has been experimentally demonstrated that modulated ECCD has roughly twice stronger stabilization effect than unmodulated ECCD if the modulation center is located at the island O-point. Increase in the decay time was observed with increasing the deviation from the O-point ECCD, showing the degradation of the stabilization effect. On the other hand, destabilization effect was first observed for ECCD near the island X-point. Comparison of the behavior of an $m/n = 3/2$ NTM between JT-60U and ASDEX-U has been made by using the same MRE and analysis method. The coefficients describing the saturated island width, c_{sat}, has been found to be about unity in both devices.

References

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