External RMP effect on locked-mode-like instability in helical plasmas

Y. Takemura\textsuperscript{1,2}, K.Y. Watanabe\textsuperscript{1,3}, S. Sakakibara\textsuperscript{1,2}, S. Ohdachi\textsuperscript{1,4}, Y. Narushima\textsuperscript{1,2}, K. Ida\textsuperscript{1,2}, M. Yoshinuma\textsuperscript{1,2} and LHD Experiment Group

\textsuperscript{1} National Institute for Fusion Science, National Institutes of Natural Science, Toki, Gifu 509-5292, Japan
\textsuperscript{2} The Graduate University for Advanced Studies, SOKENDAI, Toki, Gifu 509-5292, Japan
\textsuperscript{3} Nagoya University, Graduate School of Engineering, Chikusa, Nagoya 464-8603, Japan
\textsuperscript{4} The University of Tokyo, Graduate School of Frontier Sciences, Kashiwa, Chiba 277-8561, Japan

E-mail: takemura.yuki@nifs.ac.jp

Received 13 July 2020, revised 30 October 2020
Accepted for publication 10 November 2020
Published 22 December 2020

Abstract
The slowing-down mechanism of the locked-mode-like instabilities with and without an island structure is investigated through the effects of an external RMP (resonant magnetic perturbation) on the instabilities. For both instabilities, the slowing-down duration decreases with the increase in the external RMP, and the RMP dependence is consistent with the braking model of the $j \times B$ force due to the interaction between the instabilities and the external RMP. Moreover, the relationship between the amplitude and the frequency of both locked-mode-like instabilities during the slowing down is consistent with the force balance model between the $j \times B$ force due to the external RMP and a viscous force. These results suggest that the slowing down of both locked-mode-like instabilities with finite external RMP occurs due to the $j \times B$ force driven by the external RMP.

Keywords: MHD instability, plasma rotation, RMP, LHD, locked mode, slowing-down, mode structure

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

1. Introduction

In the LHD (large helical device), a reactor-relevant plasma with a volume-averaged beta value of 5\% can be stably maintained for more than ten times as long as the confinement time [1]. On the other hand, collapse events due to various MHD instabilities observed in different operational regimes cause serious degradation of confinement property: the torus-outward magnetic axis shift configuration ($R_{ax} > 3.75$ m) with a peaked pressure profile [2], the torus-inward shifted configuration ($R_{ax} < 3.60$ m) [3] and the standard magnetic axis configuration ($R_{ax} = 3.60$ m) with a low magnetic shear. In particular, in low magnetic shear discharges, the frequency of the precursor decreases, and the collapse occurs. This event is called the locked-mode-like instability [4]. In high beta discharges of the LHD, the plasma pressure gradient is maintained without the collapse events even if linear MHD analysis predicts that the interchange mode is unstable. In a helical plasma, investigating the physical mechanism of the collapse and the relationship between the index of linear MHD instability and the collapse is useful for reflecting MHD stability characteristics of the high beta LHD discharges on the design of a helical fusion plasma.

Two types of locked-mode-like instabilities whose precursors have different radial mode structures are observed in different regimes of a magnetic shear and a beta value of the LHD [4–6]. Regarding the radial profile of internal fluctuations, the precursor of the first type has the odd-type structure with respect to the resonant surface. This structure is similar to the tearing mode, which is considered to have the large magnetic island (type-I, tearing-type locked-mode-like instability). The other instability has the even-type structure, similar to the interchange mode which is considered to not have the large magnetic island (type-II, interchange-type locked-mode-like instability).
In locked mode discharges of tokamaks [7] and RFPs [8], it is demonstrated that the disruption is escaped by maintaining the rotation of a precursor of the locked mode by using a rotating external RMP [9] and/or tangential NBIs. These results suggest that the slowing down of the precursor could be related to the trigger mechanism of the collapse.

In the LHD, in order to establish the method of avoiding the collapse, the slowing-down mechanism of the MHD fluctuations due to the locked-mode-like instability has been investigated. From the comparison between the frequency of the precursor and the \( E \times B \) flow at the resonant surface during the slowing down phase, the precursor’s frequency is almost the same as the \( E \times B \) flow around the resonant surface [5]. It is found that the decrease in the \( E \times B \) flow around the resonant surface occurs through the following two stages [5]. The slowing-down of the first stage (\( \Delta t_{\text{first}} \)) is caused by the movement of the resonant surface to the plasma core region with a small \( E \times B \) flow due to increasing the plasma current in the codirection because the plasma current in the codirection enhances the increase of the core rotational transform. The slowing down of the second stage (\( \Delta t_{\text{second}} \)) occurs due to the decrease of the plasma flow around the resonant surface but the resonant surface moves slightly. The above two stages are observed in both of the two types of instabilities [6]. Figure 1 shows the time evolution of (a) the amplitude of the magnetic fluctuation due to the \( m/n = 1/1 \) mode measured by a magnetic probe, (b) the mode frequency, (c) the radial magnetic fluctuation amplitude measured by saddle coils, (d) the plasma current and (e) the radial profile of an \( E \times B \) flow and the radial location of the \( \nu/2\pi = 1 \) resonant surface in the interchange-type locked-mode-like instability discharge. Here, \( m \) and \( n \) denote the poloidal and the toroidal mode number, respectively. Furthermore, it is found that the duration of the slowing-down phase (\( \Delta t_{\text{first}} + \Delta t_{\text{second}} \)) decreases with the increase of the external RMP amplitude in interchange-type locked-mode-like discharges [6]. However, the reason for the decrease of an \( E \times B \) flow in \( \Delta t_{\text{second}} \) is unclear.

In the locked mode of tokamaks, several slowing-down models are proposed [10]. The well-known slowing-down force is the \( j \times B \) force. Two types of \( j \times B \) forces are considered depending on what induces \( R: F_{\text{rw}} \) and \( F_{\text{RMP}} \). The former is the slowing-down force due to the interaction between the toroidal perturbed current (\( \delta j_t \)) due to the instability and the perturbed magnetic field due to the eddy current flowing in the resistive wall of the vacuum vessel. The latter is the force due to the interaction between \( \delta j_t \) and the perturbed magnetic field due to the external RMP coils. In the JT-60U tokamak, the relationship between the magnetic fluctuation amplitude and frequency of the precursor during the slowing-down phase is consistent with the prediction of the \( F_{\text{rw}} \) model, suggesting that the contribution of \( F_{\text{rw}} \) to the slowing down is large [11].

In this paper, when an amplitude of the imposed external RMP is changed, the duration time of the slowing-down phase, and the relationship between the magnetic fluctuation amplitude and frequency of the precursor are obtained in locked-mode-like instability with different internal mode structures.

![Figure 1. Typical waveform of the interchange-type locked-mode-like instability with \( j_{\text{RMP}}/B_0 = 100 \text{ A/T} \). (a) Amplitude of a magnetic fluctuation due to the \( m/n = 1/1 \) mode measured by a magnetic probe, (b) mode frequency (closed circles) and the \( E \times B \) flow at \( \nu/2\pi = 1 \) (open circles), (c) radial magnetic fluctuation amplitude measured by saddle loops, (d) plasma current, and (e) radial profile of an \( E \times B \) flow and the radial location of the \( \nu/2\pi = 1 \) resonant surface in the interchange-type locked-mode-like instability discharge. Here, \( m \) and \( n \) denote the poloidal and the toroidal mode number, respectively. Furthermore, it is found that the duration of the slowing-down phase (\( \Delta t_{\text{first}} + \Delta t_{\text{second}} \)) decreases with the increase of the external RMP amplitude in interchange-type locked-mode-like discharges [6]. However, the reason for the decrease of an \( E \times B \) flow in \( \Delta t_{\text{second}} \) is unclear. The experiment results are compared with the \( F_{\text{rw}} \) and \( F_{\text{RMP}} \) models.

This paper is organized as follows. In section 2, the experimental setup is explained. In section 3, the experiment results regarding the locked-mode-like instability are analyzed. In section 3.1, the effects of the external RMP on the slowing-down duration time of the interchange-type instability are shown. In section 3.2, the RMP dependence of the slowing-down duration is compared with the slowing-down models considered in tokamaks. In section 3.3, the experiment results of the tearing-type instability are shown and the effect of the internal structure of the instability on the slowing down is discussed. In section 3.4, the relationship between the magnetic fluctuation amplitude and the frequency of a precursor of both instabilities is shown. The summary and discussion are presented in section 4.

2. Experimental setup

The locked-mode-like instability typically occurs in low magnetic shear plasmas of the LHD. When the plasma aspect ratio \( A_p \) increases, the magnetic shear in the whole region of a plasma decreases [12]. In this experiment, \( A_p \) is set to 7.1, which is higher than the configurations with \( A_p = 5.8–6.6 \), where the reactor-relevant high beta discharges are achieved in the LHD.
For the production and heating of plasmas, two tangential NBIs are used. The plasma current increases during discharges due to two tangential NBIs with the same direction and the core rotational transform increases, leading to the decrease in the magnetic shear. Perpendicular NBIs are modulated for measurement of an $E \times B$ flow by a charge exchange spectroscopy.

The toroidal and poloidal mode number of magnetic fluctuations are identified by a toroidal array with six magnetic probes and a helical array with 15 probes outside a plasma [13]. For evaluation of the amplitude and frequency of a magnetic fluctuation, one of the toroidal array probes located $\sim 0.3$ m away from the $i/2\pi = 1$ surface is used. The slowly changing radial magnetic fluctuation amplitude is measured by two arrays of saddle loops with a large cross-sectional area. The effective area through which the radial magnetic flux passes is $\sim 0.4 \text{m}^2$. The averaged distance between the saddle loop and the $i/2\pi = 1$ surface is $\sim 0.5$ m.

The definition of $\Delta I_{\text{first}}$ is the duration when the $i/2\pi = 1$ surface largely decreases, and that of $\Delta I_{\text{second}}$ is when the $i/2\pi = 1$ surface does not largely change but the $E \times B$ flow velocity at the $i/2\pi = 1$ surface decreases. Therefore, accurate evaluation of the radial location of the $i/2\pi = 1$ surface is important. During the slowing-down phase in the locked-mode-like instabilities, the small flattening region in the radial electron temperature profile appears due to the $m/n = 1/1$ precursor. The Thomson scattering system with high spatial resolution can observe the time evaluation of the flattening.

The RMP coil system in the LHD, which has ten vertical pairs of coils at the top and the bottom, can calibrate the intrinsic error field. According to measurement of the magnetic surface mapping in vacuum [14], there is an $m/n = 1/1$ magnetic island due to the intrinsic error field, which is almost corrected by the external RMP with an RMP coil current ($I_{\text{RMP}}/B_t$) of 110 A/T. Namely, the magnetic island due to the intrinsic error field shrinks to a smaller size. In this paper, $I_{\text{RMP}}/B_t$ is changed from 0 to 100 A/T. As $I_{\text{RMP}}/B_t$ increases, the corrected error field amplitude decreases, which means that a positive sign of $I_{\text{RMP}}/B_t$ corresponds to the opposite phase to the error field. It should be noted that $I_{\text{RMP}}/B_t$ and the error field amplitude have a negative correlation.

3. Experiment results

3.1. External RMP effect on interchange-type locked-mode-like instability

Figure 1 shows a typical waveform of the interchange-type locked-mode-like instability discharges where the intrinsic error field is almost cancelled by imposing an external static RMP of $I_{\text{RMP}}/B_t = 100$ A/T. Next, when the amplitude of the imposed external RMP is changed, behaviours of the $m/n = 1/1$ mode as the precursor are explained. Figure 2 shows typical waveforms with an $I_{\text{RMP}}/B_t$ of 30 and 15 A/T: (a) and (e) radial magnetic fluctuation amplitude measured by saddle loops, (b) and (f) mode frequency, (c) and (g) magnetic field signal and (d) and (h) radial location of the $i/2\pi = 1$. Here, the blue and red hatched regions correspond to the first and second stages of the slowing-down phase, respectively.

Figure 3 shows the external RMP dependence of (a) $\Delta I_{\text{first}}$ and (b) $\Delta I_{\text{second}}$. Circles display several discharges of the same $I_{\text{RMP}}/B_t$ and cross symbols correspond to the averaged value of the discharges of each $I_{\text{RMP}}/B_t$. There is no clear dependence of the slowing-down phase, respectively. It should be noted that the timing/amount of gas puffing, the magnetic configuration and the heating condition are almost the same as those in figure 1 except for $I_{\text{RMP}}/B_t$. In figures 1 and 2, the error field amplitude increases when $I_{\text{RMP}}/B_t$ decreases. From figures 1 and 2, it is found that $\Delta I_{\text{first}}$ is not largely changed, but $\Delta I_{\text{second}}$ decreases as the error field increases.

Figure 3 shows the external RMP dependence of (a) $\Delta I_{\text{first}}$ and (b) $\Delta I_{\text{second}}$. Circles display several discharges of the same $I_{\text{RMP}}/B_t$ and cross symbols correspond to the averaged value of the discharges of each $I_{\text{RMP}}/B_t$. There is no clear dependence
of $\Delta t_{\text{first}}$ on the amplitude of the external RMP in the 0 to 100 A/T region. On the other hand, $\Delta t_{\text{second}}$ decreases as $I_{\text{RMP}}/B_1$ decreases. It is found that the external RMP dependence of the duration of the slowing-down phase ($\Delta t_{\text{slowing}} = \Delta t_{\text{first}} + \Delta t_{\text{second}}$) as reported in reference [6] reflects the external RMP dependence of $\Delta t_{\text{second}}$. It is interesting that $\Delta t_{\text{first}}$ for $I_{\text{RMP}}/B_1 = 100$ A/T is different from the other cases. The duration $\Delta t_{\text{first}}$ is determined by the change rate of the current profile and the time when the radial movement of the resonant surface stops. The effect of the external RMP on the change rate and the time as shown in the above is outside the scope of this paper and is a topic for future research.

3.2. Comparison between slowing-down models and experimental observation of locked-mode-like instability

In tokamaks, the slowing-down of the precursor of the locked mode is considered by $j \times B$ forces [10], as shown in section 1. There are two types of $j \times B$ forces, $F_{\text{rw}}$ and $F_{\text{RMP}}$, due to a perturbed magnetic field induced by an eddy current on the resistive wall of a vacuum vessel ($B_{\text{eddy}}$) and by the external coils ($B_{\text{RMP}}$), respectively. Assuming that $B_{\text{eddy}}$ is proportional to a perturbed current due to the precursor, $\delta I_t$, and its rotation angular frequency $\omega$, 

$$F_{\text{rw}} \propto \delta I_t^2 \frac{\omega_{\text{rw}}^2}{1 + \omega_{\text{rw}}^2 \tau_{\text{rw}}^2} \approx \delta b_r^2 \frac{\omega_{\text{rw}}^2}{1 + \omega_{\text{rw}}^2 \tau_{\text{rw}}^2}.$$  

Figure 3. External RMP dependence on (a) $\Delta t_{\text{first}}$ and (b) $\Delta t_{\text{second}}$ of the interchange-type locked-mode-like instability. Cross symbols correspond to the averaged value at each $I_{\text{RMP}}/B_1$.

Here, $\delta I_t$ is assumed to be proportional to the radial magnetic fluctuation amplitude $\delta b_r$, measured outside a plasma and $\tau_{\text{rw}}$ is the wall time constant. Assuming that $B_{\text{RMP}}$ is proportional to $I_{\text{err}}/B_1 - I_{\text{RMP}}/B_1$ and the penetration of the external RMP into a plasma is shielded due to the rotation of the external RMP in the frame of the precursor, $F_{\text{RMP}}$ is expressed as

$$F_{\text{RMP}} \propto \frac{\omega_{\text{RMP}}^2}{1 + (\omega_{\text{RMP}}^2 \tau_{\text{rec}}^2)} \delta I_t \times \left( I_{\text{err}}/B_1 - I_{\text{RMP}}/B_1 \right)$$

$$\approx \frac{\omega_{\text{RMP}}^2}{1 + (\omega_{\text{RMP}}^2 \tau_{\text{rec}}^2)} \delta b_r \times \left( I_{\text{err}}/B_1 - I_{\text{RMP}}/B_1 \right).$$  

Here, $I_{\text{RMP}}/B_1$ of 110 A/T corresponds to the compensation coil current for the intrinsic error field, as shown in section 2. In addition, $\omega_{\text{RMP}}$ is the slip frequency on the external RMP frame and $\tau_{\text{rec}}$ is the typical reconnection timescale [10]. In this study, $\omega = \omega_{\text{RMP}}$ because the external RMP does not rotate in the laboratory frame.

As mentioned above, $\delta b_r$ plays an important role in both $F_{\text{rw}}$ and $F_{\text{RMP}}$. Therefore, the dependence of $I_{\text{RMP}}/B_1$ on $\delta b_r$ time-averaged during $\Delta t_{\text{second}}$ of the interchange-type locked-mode-like instability is shown in figure 4. It is clearly found that $\delta b_r$ increases with $I_{\text{RMP}}/B_1$ in the 0 to 100 A/T region. Note that $\delta b_r$ is the amplitude of the minor radial component of the magnetic fluctuation due to the $\text{mode}=1/1$ mode measured by a magnetic probe and the time-averaged value of $\delta b_r$ during $\Delta t_{\text{second}}$ cannot be evaluated if $\Delta t_{\text{second}} = 0$.

Figure 5 shows relationships between $\Delta t_{\text{second}}$ and (a) $F_{\text{rw}}$ and (b) $F_{\text{RMP}}$. The forces are the time-averaged value during the second stage of the slowing-down phase. When a force strongly contributes to the slowing down, the slowing-down time decreases with the increase of the force. In other words, the correlation between the force and the slowing-down time is negative. From figure 5, $\Delta t_{\text{second}}$ increases with $F_{\text{rw}}$, but $\Delta t_{\text{second}}$ decrease with the increase in $F_{\text{RMP}}$. These results suggest the contribution of $F_{\text{RMP}}$ to the slowing down is large against $F_{\text{rw}}$. Here, $\tau_{\text{rw}}$ is assumed to be 1 ms. Since $\tau_{\text{rw}}$ is the resistive skin time of the vacuum chamber, it is not changed by
Figure 5. Dependence of (a) $F_{rw}$ and (b) $F_{RMP}$ time-averaged during $\Delta t_{\text{second}}$ on $\Delta t_{\text{second}}$.

3.3. Effect of internal mode structure of locked-mode-like instabilities on slowing-down mechanism

The previous sections show experiment results of the interchange-type locked-mode-like instability. From here, the results of the tearing–type locked-mode-like instability are shown. The tearing-type instability appears in the region of a higher magnetic shear and a lower volume-averaged beta value than the parameter region where the interchange-type instability appears [6]. In order to clarify the slowing-down mechanism of the tearing-type locked-mode-like instability, the external RMP dependences of the slowing-down time of the tearing-type locked-mode-like instability are investigated.

Figure 6 shows the external RMP dependences of $\Delta t_{\text{first}}$ and $\Delta t_{\text{second}}$. Similar to the interchange-type locked-mode-like instability, $\Delta t_{\text{first}}$ of the tearing-type locked-mode-like instability does not depend on $I_{\text{RMP}}/B_t$, but $\Delta t_{\text{second}}$ increases with $I_{\text{RMP}}/B_t$.

Figure 7 shows the dependence of $I_{\text{RMP}}/B_t$ on $\delta b$ of the tearing-type locked-mode-like instability, together with the experimental data of the interchange-type instability as already shown in figure 4. For the tearing-type instability as well as the interchange-type instability, $\delta b$ increases with $I_{\text{RMP}}/B_t$. It is interesting that $\delta b$ of the interchange-type instability is larger than that of the tearing-type instability at the same $I_{\text{RMP}}/B_t$. The external RMP drives the locked mode in tokamaks, while it suppresses the tearing mode appearing before the mode locking. Similarly, in the locked-mode-like instability discharges, the suppression of the precursor during the slowing-down by the external RMP is also observed. However, the suppression mechanism is a future work.

Figure 8 shows (a) the $F_{rw}$ dependence and (b) the $F_{RMP}$ dependence of $\Delta t_{\text{second}}$ for the tearing-type locked-mode-like instability together with the interchange-type locked-mode-like instability. Similar to the interchange-type locked-mode-like instability, $\Delta t_{\text{second}}$ increases as $F_{rw}$ increases, but $\Delta t_{\text{second}}$ decreases as $F_{RMP}$ increases. This result suggests that $F_{RMP}$
has a large contribution to the slowing-down regardless of the internal mode structure of the instability, that is, the size of the magnetic island of the instability. However, quantitatively, it can be seen that $\Delta t_{\text{second}}$ of the tearing-type instability is shorter than that of the interchange-type instability at the same $F_{\text{RMP}}$. In order to understand the reason for the quantitative difference, additional data and more systematic analyses are required in future.

3.4. Relationship between amplitude and frequency of precursor during slowing-down phase

Next, the relationship between the frequency ($f$) and magnetic fluctuation amplitude ($\delta b/B_t$) of the precursor during the slowing-down phase is investigated. According to the JT-60U tokamak experiment study, the relationship between $f$ and $\delta b/B_t$ of the tearing mode, which is the precursor of the locked mode, is almost consistent with the equation of the $F_{\text{RMP}}$ model [11]. This result suggests that the contribution of $F_{\text{RMP}}$ to the slowing-down of the precursor of the locked mode is large. The $\delta b/B_t$-$f$ relationship of the interchange-type instability during the sum of $\Delta t_{\text{first}}$ and $\Delta t_{\text{second}}$ has already been reported [6]. However, there was no conclusive result. Here, the $\delta b/B_t$-$f$ relationship only during $\Delta t_{\text{second}}$ is focused upon, and is compared with the relationship based on the following force balance models.

In the force balance model of $F_{\text{tw}}$ and a viscous force ($F_{\text{vc}}$), the relationship between the mode frequency and the magnetic fluctuation amplitude of the mode is expressed in [10]. The viscous force is expressed as

$$F_{\text{vc}} \propto (f_0 - f),$$  \hspace{1cm} (3)

where $f_0$ corresponds to the rotation frequency due to the neoclassical flow. The force balance between $F_{\text{tw}}$ and $F_{\text{vc}}$ is

$$F_{\text{tw}} = - F_{\text{vc}}.$$  \hspace{1cm} (4)

Substituting equations (1) and (3) into equation (4) yields

$$f = \beta_{\text{tw}} \sqrt{1 + \frac{\alpha_{\text{tw}}}{\alpha_{\text{vc}}} (\delta b/B_t)^2}.$$  \hspace{1cm} (5)

In addition, the $\delta b/B_t$-$f$ relationship based on the force balance of $F_{\text{RMP}}$ and $F_{\text{vc}}$ is also derived.

$$F_{\text{RMP}} = - F_{\text{vc}}$$  \hspace{1cm} (6)

$$f = - \alpha_{\text{RMP}} \frac{\delta b}{B_t} \times \left( \frac{I_{\text{err}}}{B_t} - \frac{I_{\text{RMP}}}{B_t} \right) + \beta_{\text{RMP}}.$$  \hspace{1cm} (7)

Here, $\omega \tau_{\text{rec}} \gg 1$ is assumed since $\omega$ is several $\text{rad s}^{-1}$ and $\tau_{\text{rec}} \sim 0.2 \text{ s}$ in the typical LHD plasma parameters.

On the other hand, if the external RMP is completely penetrated, $F_{\text{RMP, no-slip}}$, and the $\delta b/B_t$-$f$ relationship based on the $F_{\text{RMP, no-slip}}$ model is derived as follows [10].

$$F_{\text{RMP, no-slip}} \propto \delta b \times \left( \frac{I_{\text{err}}}{B_t} - \frac{I_{\text{RMP}}}{B_t} \right).$$  \hspace{1cm} (8)

$$f = - \alpha_{\text{RMP, no-slip}} \frac{\delta b}{B_t} \times \left( \frac{I_{\text{err}}}{B_t} - \frac{I_{\text{RMP}}}{B_t} \right) + \beta_{\text{RMP, no-slip}}.$$  \hspace{1cm} (9)

It should be noted that the $\delta b/B_t$-$f$ relationship based on the no-slip model of $F_{\text{RMP}}$ has the same dependence with the one based on the slip model in the limit of $\omega \tau_{\text{rec}} \gg 1$. Here, $\alpha_{\text{tw}}$, $\beta_{\text{tw}}$, $\alpha_{\text{RMP}}$, $\beta_{\text{RMP}}$, $\alpha_{\text{RMP, no-slip}}$ and $\beta_{\text{RMP, no-slip}}$ are free parameters. Note that $\alpha_{\text{tw}}$, $\alpha_{\text{RMP}}$, $\alpha_{\text{RMP, no-slip}}$ (each $\beta$) are related with the proportionality constant of $F_{\text{tw}}$, $F_{\text{RMP}}$ and $F_{\text{RMP, no-slip}} (F_{\text{vc}})$ except $\delta b$ and $f$, respectively.

Figure 9(a) shows the $\delta b/B_t$-$f$ relationship of the interchange-type locked-mode-like instability with the external RMP of $I_{\text{RMP}}/B_t = 50 \text{ A/T}$ during $\Delta t_{\text{second}}$. Black and grey symbols correspond to the typical behaviour and a transient behaviour of $\delta b/B_t$ and $f$, respectively. The transient behaviour is observed for a short time just after the precursor suddenly appears. The intermittent appearance of the precursor is often observed in discharges with external RMP as shown in [6]. The blue dash-dotted lines display the equations of the $F_{\text{RMP, no-slip}}$ model with ($\alpha_{\text{RMP}}$, $\beta_{\text{RMP}}$) = ($1.0 \times 10^8$, 0.8) and ($2.5 \times 10^7$, 0.8), and the red dashed line displays the equations of the $F_{\text{RMP}}$ model with ($\alpha_{\text{RMP}}$, $\beta_{\text{RMP}}$) = ($6.6 \times 10^4$, 1.7). The $\delta b/B_t$-$f$ relationship is consistent with $F_{\text{RMP}}$, but it is not consistent with the $F_{\text{tw}}$ model. This result suggests that the $F_{\text{RMP}}$ model is closer to the experimental data when comparing the two models.

Figure 9(b) shows the $\delta b/B_t$-$f$ relationship of the tearing-type instability with the external RMP of $I_{\text{RMP}}/B_t = 50 \text{ A/T}$, which coincides with the $F_{\text{RMP}}$ model of ($\alpha_{\text{RMP}}$, $\beta_{\text{RMP}}$) = ($6.6 \times 10^3$, 1.4). These results suggest that the $F_{\text{RMP}}$ model is
how the duration of the second stage changes by imposing the external RMP, and the RMP dependence of the duration of the second stage is compared with the slowing-down models for a precursor of the locked mode in tokamaks: $F_{\text{rw}}$ and $F_{\text{RMP}}$. The former is the $j \times B$ force caused by the interaction between a perturbed current due to the instability and an RMP field created by its eddy current, and the latter is the $j \times B$ force caused by the interaction between the perturbed current and an RMP field due to the external coils at the resonant surface. In addition, $F_{\text{RMP}}$ with the complete penetration of the external RMP into the resonant surface ($F_{\text{RMP,no-slip}}$) is also considered.

It is found that the duration of the second stage decreases as the effective external RMP amplitude increases. The duration time of the second stage has a negative correlation with $F_{\text{RMP}}$, but a positive correlation with $F_{\text{rw}}$. Thus, the above results suggest that $F_{\text{RMP}}$ make a large contribution to the slowing down of the precursor.

Furthermore, the relationship between the magnetic fluctuation amplitude of the precursor and its frequency during the second stage with the external RMP is not consistent with that predicted by the $F_{\text{rw}}$ model, but it is consistent with the $F_{\text{RMP}}$ model. This result supports the statement that the contribution of $F_{\text{RMP}}$ to the slowing down is larger than $F_{\text{rw}}$.

The above are the experimental results of the interchange-type locked-mode-like instability, which has a magnetic island with a small width. The same qualitative results for the tearing-type locked-mode-like instability are obtained. These results suggest that the slowing down of the precursor is mainly caused by the $j \times B$ force driven by the external RMP regardless of the size of the magnetic island of the instability.

According to an early work, it is reported that the penetration of the external RMP into a plasma is shielded when the external RMP rotates in the frame of the precursor, and that the $B_{\text{RMP}}$ is reduced at the resonant surface and $F_{\text{RMP}}$ is smaller than that $F_{\text{RMP,no-slip}}$ in the complete penetration case. The $\Delta t_{\text{second}}$ dependence on $F_{\text{RMP}}$ shown in figure 5(b) and 8(b) is almost the same against $F_{\text{RMP,no-slip}}$ in the limit of $\omega \tau_{\text{ec}} \gg 1$. The evaluation of experimental $B_{\text{RMP}}$ at the resonant surface during the shielding of the penetration of the external RMP is a future research topic.

From the quantitative aspect, the duration of the second stage of the tearing-type locked-mode-like instability looks shorter than that of the interchange-type instability at the same $F_{\text{RMP}}$. Here, $\delta j_t$ is assumed to be proportional to $\delta b_t$ observed outside a plasma. The interchange-type locked-mode instability is expected to have an odd-function-type $\delta j_t$ profile, which would have larger $|\delta j_t|$ around the resonance surface than in the tearing-type instability for the same $\delta b_t$. The improvement in the quantitative accuracy for $F_{\text{RMP}}$ of the interchange-type locked-mode-like instability is a future task.

In this study, it is found that the contribution of the electromagnetic force due to the external RMP to the slowing down of the precursor is large, from the dependence of the slowing-down time on the external RMP. On the contrary, even in the discharges with small external RMP ($I_{\text{RMP}}/B_i = 100$ A/T), the precursor frequency decreases for finite $\Delta t_{\text{second}}$. According to a previous work on the external RMP effects on the
locked-like mode instability, the locked location of the precursor is consistent with the phase of the error field when the finite error field exists. On the other hand, the locked locations of the precursor are not fixed when the error field is almost compensated [15]. The behaviour suggests that the slowing-down mechanism on the precursor of the locked-mode-like instability in the case without the error field is different from that with the error field. The slowing-down mechanism in the discharges with the small external RMP should be resolved in future.

Acknowledgments

The authors are grateful to the LHD Operation Group for their excellent technical support. One of the authors (YT) would like to thank Dr. S. Nishimura (Housei University), Dr. A. Isayama (QST) and Dr. M. Furukawa (Tottori University) for useful discussions. This work was supported in part by NIFS under contract NIFS07KLPH004 and by a dispatch grant from the Future Energy Research Association.

ORCID iDs

Y. Takemura  https://orcid.org/0000-0003-3754-897X
Y. Narushima  https://orcid.org/0000-0002-3541-6298
K. Ida  https://orcid.org/0000-0002-0585-4561

References

[1] Sakakibara S. et al 2008 MHD study of the reactor-relevant high-beta regime in the Large Helical Device Plasma Phys. Control. Fusion 50 1–10

[2] Ohdachi S. et al 2017 Observation of the ballooning mode that limits the operation space of the high-density super-dense-core plasma in the LHD Nucl. Fusion 57 066042

[3] Sakakibara S. et al 2002 Effect of MHD activities on pressure profile in high-β plasmas of LHD Plasma Phys. Control. Fusion 44 A217–23

[4] Takemura Y. et al 2012 Mode locking phenomena observed near the stability boundary of the ideal interchange mode of LHD Nucl. Fusion 52 102001

[5] Takemura Y. et al 2017 Experimental Study on Slowing-Down Mechanism of Locked-Mode-Like Instability in LHD Plasma Fusion Res. 12 1402028

[6] Takemura Y. et al 2019 Study of slowing down mechanism of locked-mode-like instability in helical plasmas Nucl. Fusion 59 066036

[7] Snipes J.A., Campbell D.J., Hugon M., Lomas P.J., Nave M.F.F., Haynes P.S., Hender T.C., Lopes Cardozo N.J. and Schüller F.C. 1988 Large amplitude quasi-stationary MHD modes in JET Nucl. Fusion 28 1085–97

[8] Frassinetti L., Memmuir S., Olofsson K.E.J., Brunsell P.R. and Drake J.R. 2012 Tearing mode velocity braking due to resonant magnetic perturbations Nucl. Fusion 52 103014

[9] Okabayashi M. et al 2017 Avoidance of tearing mode locking with electro-magnetic torque introduced by feedback-based mode rotation control in DIII-D and RFX-mod Nucl. Fusion 57 016035

[10] Fitzpatrick R. 1993 Interaction of tearing modes with external structures in cylindrical geometry (plasma) Nucl. Fusion 33 1049–84

[11] Isayama A., Matsunaga G., Ishii Y., Sakamoto Y., Moriyama S., Kamada Y. and Ozeki T. 2010 Effect of magnetic island associated with neoclassical tearing modes on plasma rotation in JT-60U Plasma Fusion Res. 5 037

[12] Watanabe K.Y., Suzuki Y., Sakakibara S., Yamaguchi T., Narushima Y., Nakamura Y., Ida K., Nakajima N. and Yamada H. 2010 Characteristics of MHD equilibrium and related issues on LHD Fusion Sci. Technol. 58 160–75

[13] Sakakibara S. and Yamada H. (Group LHDE) 2010 Magnetic measurements in LHD Fusion Sci. Technol. 58 471–81

[14] Morisaki T., Shoji M., Masuzaki S., Sakakibara S., Yamada H. and Komori A. 2010 Flux surface mapping in LHD Fusion Sci. Technol. 58 465–70

[15] Sakakibara S. et al 2013 Response of MHD stability to resonant magnetic perturbation in the Large Helical Device Nucl. Fusion 53 043010