Effects of resonant magnetic perturbation on locked mode of neoclassical tearing modes

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Abstract
The effects of externally applied resonant magnetic perturbation (RMP) on the locked mode of the neoclassical tearing mode (NTM) are numerically investigated by means of a set of reduced magnetohydrodynamic equations. It is found that, for a small bootstrap current fraction, three regimes, namely the slight suppression regime, the small locked island (SLI) regime and the big locked island (BLI) regime, are discovered with the increase of RMP strength. For a much higher bootstrap current fraction, however, a new oscillation regime appears instead of the SLI regime, although the other regimes still remain. The physical process in each regime is analyzed in detail based on the phase difference between the NTM and the RMP. Moreover, the critical values of the RMP in both SLI and BLI regimes are obtained, and their dependence on key plasma parameters is discussed as well.

Keywords: neoclassical tearing mode, resonant magnetic perturbation, locked mode

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

1. Introduction
The neoclassical tearing mode (NTM), one of the very dangerous macroscopic magnetohydrodynamic (MHD) instabilities, can substantially damage an equilibrium magnetic configuration and contribute to a significant degradation of plasma confinement [1–3]. In general, a ‘seed island’ [4, 5] is needed to excite the NTM, which can be induced by various kinds of instabilities, such as the edge localized mode (ELM) [6–8], the tearing mode (TM) [9, 10] and fishbone [11–13]. The loss of bootstrap current, caused by the flattening of the pressure profile in the inner region of magnetic islands, can further result in a destabilization of magnetic islands and even lead to major disruptions [14, 15]. Although achieving a high poloidal beta $\beta_p$ [16, 17] is important for improved H-mode scenarios in advanced tokamaks, the saturated island width of the NTM is proportional to the $\beta_p$. Therefore, it is very necessary to control the NTM islands in tokamak experiments, because they can seriously restrict the improvement of plasma parameters and limit the performance of tokamak devices.

Resonant magnetic perturbation (RMP) has different effects on the TM or the NTM, adjusting its rotation velocity [18], driving magnetic reconnection [19] and stabilizing the tearing modes [20]. Many experiments and simulation investigations of RMP effects on the TM/NTM were carried out in previous decades [21–23]. Yu et al showed that the NTM can be stabilized by an externally applied helical field of a different helicity if the field magnitude is sufficiently large [24]. Hu et al found that the suppression of the TM by RMP with moderate amplitude is possible and that a small locked island (SLI) regime was identified clearly [25, 26], which was also observed in recent study using two-fluid equations [27]. However, Hu’s work was based on a classical tearing mode model and some neoclassical effects were not considered. Wang et al found that the required RF (radio frequency) current for mode stabilization is reduced by about one third if an appropriate RMP is applied [28]. Very recently, Choi et al applied a rotating RMP to slow the mode rotation down at a low frequency, and then applied the electron cyclotron current drive (ECCD) modulated at the same frequency, so that the avoidance of plasma disruption...
and the re-establishment of the high confined mode were achieved in DIII-D [29].

On the other hand, when the magnitude of a static RMP or residual error field is sufficiently large, the mode frequency of the NTM can be ‘arrested’ and become the same as the frequency of the RMP (error field), called the locked mode (LM) [30–32], which is especially dangerous in experiments. These magnetic perturbations can impose electromagntic torques to brake and ultimately stop the normal rotation of the saturated internal magnetic islands that are present in most tokamak plasmas [33]. Consequently, the resultant non-rotating magnetic islands can rapidly grow to large amplitude and ultimately lead to disruption. Aiming to avoid the LM induced disruption, Fitzpatrick et al theoretically and numerically investigated the effect of RMP on the basis of nonlinear simulations. In particular, the nonlinear process of the LM of the NTM is quite limited. Therefore, it is very necessary to have a clear understanding on the effects of RMP on the LM of the NTM are numerically given. The physical processes that are present in most tokamak plasmas are drawn in section 4.

Motivated by the above reasons, in this work, the effects of RMP on the NTM are numerically investigated based on a set of reduced magnetohydrodynamic equations. A big locked island (BLI) regime and a SLI regime are discovered and the scalings of the critical value of the LM of the NTM is quite different. Therefore, it is very necessary to have a clear understanding on the effects of RMP on the LM of the NTM on the basis of nonlinear simulations. In particular, the critical value of the LM of the NTM should be highly valued.

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The time-dependent RMP $\psi_a(t)$ in equation (6) is set as

$$ \psi_a(t) = \begin{cases} \frac{d\psi}{dt} & 0 < t \leq T_1 \\ \psi_{\text{RMP}} & T_1 < t \leq T_2, \\ 0 & t > T_2. \end{cases} $$

where $T_1$ is the time when turning on the RMP, and $d\psi/dt$ is the growth rate of the RMP. In our simulation, we keep the growth rate of the RMP as a constant and modulate the amplitude of RMP by changing the flattop value of the RMP, as figure 1(b) illustrates. It should be pointed out that, in a real tokamak, the toroidal rotation is prevailing and much stronger than the poloidal one, whereas only the poloidal rotation is considered in this work due to the large aspect ratio approximation. The electromagnetic force exerted in the poloidal direction is $(n/m)\sqrt{r_i/R}$ times larger than that in toroidal direction, and the speed in toroidal direction should be $(n/m)\sqrt{r_i/R}$ times larger than the poloidal one for having an equivalent rotation frequency. Therefore, the locking threshold in the toroidal direction can be estimated by multiplying such a factor $[(n/m)\sqrt{r_i/R}]^2$. 

3. Numerical results

3.1. Effects of RMP amplitude

For a comprehensive understanding of the effects of RMP on NTMs, the effects of different RMP amplitudes on NTMs are investigated in this section. The common parameters are set as $f_b = 0.1, R^{-1} = 1 \times 10^{-4}, S \chi^2 = 5 \times 10^{-5}, \chi_0 = 10$ and $c \omega = 1 \times 10^{-6}$. The nonlinear evolution of the NTM without RMP is given in figure 2 as a baseline case. It is seen in figure 2(a) that the $m/n = 2/1$ magnetic island saturates at around $t = 20000$ and the saturate island width is about 0.2. During the whole evolution, the average island width $\bar{w}$ is 0.206.
Firstly, a small bootstrap current fraction $f_b = 0.1$ is taken into account. Figure 2(b) gives the average island widths in the presence of different RMP amplitudes. It is found that with the increase of RMP value, $w_{fi}$ first decreases, indicating a stabilizing effect of RMP. However, once $\psi_{RMP}$ exceeds a threshold, $w_{fi}$ immediately increases again. The processes associated with the relation between $w_{fi}$ and $\psi_{RMP}$ can be divided into three regimes, which are illustrated in figure 3 and discussed in detail as follows.

(i) Slight suppression regime: when the RMP is turned on at $t = 10000$, the island width and the mode frequency start to oscillate due to the electromagnetic torque applied by the boundary magnetic perturbation. As a result, the NTM can be slightly stabilized for a low $\psi_{RMP}$, such as $\psi_{RMP} = 8.1 \times 10^{-4}$.

(ii) Small locked island regime: for a moderate RMP, the NTM can be further stabilized and the island width is reduced to 0.13. The mode frequency drops slowly and then is suddenly locked to the RMP when the plasma rotation has been reduced to one half of its original value.

(iii) Big locked island regime: for a sufficiently large RMP, the field penetration occurs accompanied with an explosive growth of island width, and the mode frequency is locked to the static magnetic field, which is known as the so-called locked mode.

Secondly for a higher bootstrap current fraction, however, the regimes determined by different RMP amplitudes are different. As shown in figure 4, there are also three typical regimes for $f_b = 0.25$: (i) slight suppression regime; (ii) oscillation regime; (iii) big locked island regime. Although the (i) and (iii) regimes are almost the same as those of $f_b = 0.1$, a new oscillation regime (ii) appears instead of the small locked island regime (ii) of $f_b = 0.1$.

To understand the effects of RMP on the NTM in more depth, phase analysis has been carried out. Figure 5 gives the phase of the NTM, the island width and the mode frequency in the early suppression period, which can be observed in all

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Figure 3. The three typical processes for a small bootstrap current fraction $f_b = 0.10$: (a) slight suppression, (b) small locked island, (c) big locked island. The corresponding RMP amplitudes are $8.1 \times 10^{-4}$, $9.8 \times 10^{-4}$ and $9.9 \times 10^{-4}$, respectively.

Figure 4. The three typical processes for a large bootstrap current fraction $f_b = 0.25$: (a) slight suppression, (b) oscillating phase, (c) big locked island. The corresponding RMP amplitudes are $9.0 \times 10^{-4}$, $9.6 \times 10^{-4}$ and $9.8 \times 10^{-4}$, respectively.
regimes mentioned above. The phase of NTM is equal to the phase difference between the NTM and the RMP, since the phase of the static RMP is zero. In figures 5(a)–(c), the gray line is the phase of the NTM, the blue line is the island width, and the red line is the mode frequency. The yellow horizon lines are \( \pi/2 \) and \(-\pi/2\) respectively. When the phase difference is at \( \Delta \Phi < |\pi/2| \) (pink area), the RMP has a destabilizing effect on the NTM. Oppositely, for \( \Delta \Phi > |\pi/2| \) (white area), the RMP has a stabilizing effect. Moreover, the mode frequency of the NTM also changes periodically. The RMP has a decelerating effect on the mode frequency when \( \Delta \Phi < |\pi/2| \) (pink area). For \( \Delta \Phi > |\pi/2| \) (white area), the RMP has an accelerating effect. It can be clearly noted in figure 5(c) that time interval \( t_2 \) in the white area is longer than \( t_1 \) in the pink area, leading to a net stabilizing effect on the island in an entire period. On the other hand, \( t_1 < t_2 \) also indicates that the average mode frequency in the pink area is larger than that in the white area. As the amplitude of RMP gets higher, the electromagnetic torque becomes much bigger, which can be judged from the slopes of the mode frequency growth shown in figure 5. Once the electromagnetic force exceeds a threshold, the direction of the rotation can reverse. Then the mode can no longer travel through the whole phase region and the angular velocity is slowly damped, hence the SLI in the (ii) regime finally occurs, as shown in figure 6(a).

It should be noted in figures 6(a) and (b) that the phase of the SLI is locked to \(-0.52\pi\), which is essentially different from the BLI regime where the phase is locked to \(-0.10\pi\) (almost the phase of the static RMP). For the SLI, the phase difference is in \( \Delta \Phi > |\pi/2| \), where the RMP has a stabilizing effect on the NTM. But for the BLI, the phase difference is in \( \Delta \Phi < |\pi/2| \), where the RMP has a destabilizing effect on the NTM. That is the reason why there are two kinds of locked mode with significantly different island widths for the SLI and BLI.

Figure 7 shows the evolution of the perturbed magnetic flux of the BLI in figure 6(b). Figures 7(a)–(d) give continuous motion slices of perturbed magnetic flux in one entire phase period. It can be found that when the NTM and the RMP are in the same phase, the RMP can enhance the magnetic reconnection, as shown in figures 7(b) and (c). But when they are in anti-phase, the RMP can prevent the magnetic reconnection, as shown in figures 7(a) and (d). Hence the magnetic island width periodically changes while the mode is rotating. Then the SLI occurs at about \( t = 27000 \), and the island width is still small, as shown in figure 7(e), in which the NTM is static in the anti-phase of the RMP. But during \( t = 29000 \)–\( 31000 \), as shown in figure 7(f), the NTM is dragged to the same phase of the RMP by the electromagnetic torque, which leads to an explosive growth of the island width due to the continuous strong magnetic reconnection by the RMP.

3.2. The dependence of critical value of LM and plasma parameters

In this section, we analyze the critical RMP values in both the SLI and the BLI. Figure 8 shows the critical value \( \psi_c \) versus \( f_b \), where the blue and yellow lines represent the critical values for the BLI and the SLI, respectively.

The \( \psi_c \) of the BLI decreases with the increase of \( f_b \) due to the destabilizing effect of the bootstrap current. Since for a larger \( f_b \), the NTM becomes more unstable and the island width becomes larger, so that a lower RMP value is needed to lock the NTM. Interestingly, it is noticed that the \( \psi_c \) of the SLI increases with the increase of \( f_b \).

To clarify the \( \psi_c \) dependence difference, the nonlinear evolution of magnetic island widths are compared for different \( f_b \) values. In figure 9(a), it can be seen that for the same RMP amplitude of \( \psi_{\text{RMP}} = 8.8 \times 10^{-4} \), the case of \( f_b = 0.15 \) is still in the slight suppression regime, while the case of \( f_b = 0.10 \) enters the SLI regime. Here for \( f_b = 0.10 \), \( \psi_{\text{RMP}} = 8.8 \times 10^{-4} \) is the critical value of SLI, as shown in

Figure 5. (a) Magnetic island widths together with the phase difference and (b) mode frequency together with the phase difference in the early suppression period (c) magnification of three phase periods in (b). The yellow horizon lines are \(-\pi/2\) and \(\pi/2\) respectively. The input parameters are set as \( f_b = 0.10 \), \( \psi_{\text{RMP}} = 9.8 \times 10^{-4} \).
The scaling of the BLI with viscosity is numerically studied in simulations and J-TEXT experiments [25]. Because a larger RMP value is required to suppress the island width to a small level, the critical value of the SLI increases with the increase of $f_b$. For an even larger $f_b$, however, the SLI has occurred before the island width is suppressed to the level for triggering the SLI. Finally, the SLI disappears with the increase of $f_b$, and thus only the BLI remains.

Dependence of critical value of locked mode on plasma viscosity is discussed, since the plasma viscosity is a key parameter affecting the mode locking. Figure 10 gives $\psi_c$ versus plasma viscosity $\nu$. It is seen that for both the BLI and the SLI, $\psi_c$ increases with the increase of $\nu$. It is reasonable that the large viscosity denotes a large viscous torque, which can balance the electromagnetic torque. Therefore, a larger electromagnetic force generated by RMP is needed to lock the NTM in the large viscosity region. Besides, it is noted that the SLI appears only in the large viscosity region. On the other hand, the scaling of the BLI with viscosity is numerically obtained as $\psi_{crit} \sim \nu^{0.56}$, which is very close to the theoretical one $\psi_{crit} \sim \nu^{7/12}$ [35].

Figure 11 illustrates $\psi_c$ versus the ratio of parallel to perpendicular transport coefficient $\chi_///\chi_\perp$, since $\chi_///\chi_\perp$ is very important for determining the saturated width of the NTM island. Because the increase of $\chi_///\chi_\perp$ normally increases the saturated island width, $\psi_c$ of the BLI decreases. On the other hand, the SLI can only appear in the small $\chi_///\chi_\perp$ region. In fact, the effect of $\chi_///\chi_\perp$ on $\psi_c$ is similar to that of bootstrap current fraction $f_\theta$ shown in figure 8. Finally, it is indicated in figures 8, 10 and 11 that the SLI tends to occur, when the NTM is in less unstable regimes.

4. Summary

In summary, the effects of externally applied static RMP on the LM of the NTM are numerically investigated by means of a set of reduced magnetohydrodynamic equations. A small locked island (SLI) regime and a big locked island (BLI) regime are discovered. Effects of some significant plasma parameters on the properties of the SLI and BLI are analyzed in detail. The main results can be summarized as follows.

(i) For the NTM with a small bootstrap current fraction $f_\theta$, three regimes, namely the slight suppression regime, the SLI regime and the BLI regime, are found with the increase of RMP amplitude. In the case with a low RMP amplitude, the NTM can be always stabilized. With an increase of RMP strength, two kinds of locked mode with qualitatively different properties are observed. In the SLI/BLI regime, the stabilized/destabilized islands of NTMs are locked to the RMP with phase difference $\Delta \Phi$ being greater/less than $\pi/2$.

(ii) For the NTM with a large bootstrap current fraction $f_\theta$, islands of the NTM can be slightly suppressed with a low RMP amplitude, which is the same as the result in the small $f_\theta$ case. However, for a moderate RMP amplitude, an oscillating regime appears instead of the SLI regime. For a sufficiently large RMP amplitude, the BLI occurs. Thus, there are also three regimes, namely slight suppression regime, oscillation regime and BLI regime.
Dependence of the critical value of RMP $\psi_c$ for the BLI and the SLI on the bootstrap current fraction $f_b$, plasma viscosity $\nu$, and the ratio of parallel to perpendicular transport coefficient $\chi_P/\chi_\perp$ are further discussed. It is found that the $\psi_c$ of the BLI decreases as $f_b$ increases, since the electromagnetic force is proportional to the amplitude of the NTM which increases with the increase of $f_b$. However, the $\psi_c$ of the SLI unexpectedly increases with the increase of $f_b$. This is due to the fact that, in this work, there is a critical value of island width for the SLI, a higher RMP strength is needed to suppress the NTM to a necessarily small amplitude to trigger the SLI. For plasma viscosity $\nu$, $\psi_c$ of both the SLI and the BLI increase with the increase of $\nu$, since the viscous torque, to a great extent, can balance the electromagnetic torque. And only in the large $\nu$ region, the SLI occurs. Finally, like the effects of $f_b$, the $\psi_c$ of the BLI/SLI decreases/increases with the increase of $\chi_P/\chi_\perp$. The SLI can only be found in the small $\chi_P/\chi_\perp$ region. It is found through the above results that SLI tends to occur when the NTM is in less unstable regimes.

Figure 7. Perturbed magnetic flux in the process of figure 6(b). The four pictures with arrows are the perturbed magnetic flux in an entire phase period before mode locked and the arrows indicate the direction where it moves. The two pictures with crosses show the perturbed magnetic flux after the locked mode, which means the mode is static.
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Figure 9. Comparison of the nonlinear evolution of island widths for different $f_b$. $8.8 \times 10^{-4}$ and $9.5 \times 10^{-4}$ are the critical RMP values of SLI for $f_b = 0.10$ and $f_b = 0.15$ respectively as shown in figure 8.

Figure 10. Dependence of the plasma viscosity $\nu$ and the critical value of locked mode $\psi_c$. All scans are carried out with $f_b = 0.2$, $S_{\lambda}^{-1} = 5 \times 10^{-3}$, $\chi_{\parallel} = 10$, $\chi_{\perp} = 1 \times 10^{-4}$.

Figure 11. The critical value of locked mode $\psi_c$ versus the ratio of the parallel transport coefficient to perpendicular transport coefficient $\chi_{\parallel}/\chi_{\perp}$. All scans are conducted with $f_b = 0.2$, $R^{-1} = 1 \times 10^{-4}$, $S_{\lambda}^{-1} = 5 \times 10^{-3}$. 

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