Control of neoclassical tearing mode by synergetic effects of resonant magnetic perturbation and electron cyclotron current drive in reversed magnetic shear tokamak plasmas

Weikang Tang (汤炜康)©, Zheng-Xiong Wang (王正汹), Lai Wei (魏来)©, Jialei Wang (王佳磊)© and Shuangshuang Lu (路爽爽)

Key Laboratory of Materials Modification by Laser, Ion, and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, Dalian 116024, People’s Republic of China

E-mail: zxwang@dlut.edu.cn

Received 1 September 2019, revised 10 December 2019
Accepted for publication 13 December 2019
Published 16 January 2020

Abstract
Synergetic effects of resonant magnetic perturbation (RMP) and electron cyclotron current drive (ECCD) on stabilizing neoclassical tearing mode (NTM) in reversed magnetic shear (RMS) tokamak plasmas are numerically investigated based on a set of reduced MHD equations. For the moderate separation, it is found that the explosive burst induced by the fast reconnection of double tearing mode (DTM) in the RMS configuration can be completely suppressed by externally applied RMPs. Zonal flows with strong shear induced by a rotating RMP play an important role in this suppression process. Moreover, turning on ECCD in advance is essential to mitigate the NTM. For the large separation without the explosive burst, two strategies, i.e. a continuous ECCD with static RMP and a modulated ECCD with rotating RMP, are separately investigated. It is shown that when the NTM is decelerated by a relatively slow rotating RMP, the modulated ECCD can have a better stabilizing effect. In addition, the ECCD deposition widths in both radial and helical angle directions, as well as the ECCD on-duty time, are analyzed in detail. The best effectiveness of ECCD is obtained and the relevant physical mechanisms are discussed.

Keywords: neo-classical tearing mode, reversed magnetic shear, resonant magnetic perturbation, electron cyclotron current drive

(Some figures may appear in colour only in the online journal)
DTM with a moderate separation between two resonant surfaces has a linear growth rate proportional to $S^{-3/5}$, which is much higher than that of the single tearing mode, $\gamma \propto S^{-3/5}$, where $S$ is the Lundquist number. Moreover, in the case of the moderate separation, a structure driven fast reconnection phase was found to cause an explosive burst [6–8], which is closely related to the major disruption in JT-60U experiments. Taking the bootstrap current into consideration, Wang et al. discovered that even in a large separation, the explosive burst can still be induced by neo-classical double tearing mode with a high bootstrap current fraction [9]. For future advanced fusion reactors with RMS configuration, such as ITER, JT60-SA and CFETR, the excitation of DTM is inevitable. The understanding of DTM and their control are therefore of great importance to be studied [10].

Resonant magnetic perturbation (RMP) [11] or error field (EF) [12, 13], for another thing, is found to be vital for neo-classical tearing mode (NTM) physics [14–16], since RMP can bring about additional stabilizing or destabilizing effects on NTM and influence its frequency. To be specific, in the presence of a static RMP with a sufficiently large amplitude, NTM will be decelerated and finally ‘caught’ by RMP, called locked mode [17]. For a rotating RMP, it can be used for unlocking the magnetic islands locked by intrinsic EFs and sustaining its toroidal and poloidal rotations [18]. Due to its great significance, many researches were carried out to study the dependence of locked mode threshold on plasma parameters [19], to understand its penetration process and screening mechanism [20, 21], and to explore its potential on NTM suppression [22]. Majority of the existing researches, though, was based on monotonic $q$ profiles. The effects of RMP on DTM with two same resonant surfaces, therefore, remain to be discovered.

To stabilize NTM, electron cyclotron current drive (ECCD) is the most widely used and straightforward method [23–28]. By emitting radio frequency electron waves localized at the magnetic islands, it can compensate the loss of bootstrap current caused by the flattening of pressure profile and modify the local plasma current gradient [29]. The non-inductive current drive deposited at the O-point of the magnetic islands along the plasma current direction can have a stabilizing effect on NTM, whereas it will destabilize NTM if the deposition is at the X-point. Consequently, extensive research efforts have been devoted to the modulated ECCD [30]. Due to the nonuniformity of the plasma rotation, high definition of diagnostic device and feedback control system are essential to ensure the accuracy of the modulated ECCD. However, because of the technical limitation, those criteria are hard to reach in some circumstances, especially when the frequency of NTM is large. Accordingly, externally applied RMP coils, as an auxiliary method, are put forward to help adjust the mode frequency and locate the O-point of the island in very recent investigations. Volpe et al. used static three-dimensional fields to align the O-point of islands at the deposition of injected waves [31]. In this way, locked islands were suppressed for the first time by combination of applied static RMP and localized ECCD in experiment. Wang et al. showed that the stabilizing effect of ECCD can be enhanced if the RMP with a small amplitude is applied at the position where the phase difference of RMP and deposition of ECCD is half period along the helical angle [32]. One third of input ECCD can be saved if a proper RMP amplitude is used. Hence, the combined use of ECCD and RMP is an emerging and promising technology to control the NTM.

Motivated by the above reasons, in this paper, an ECCD model coupled with a set of reduced MHD equations is established to investigate the synergetic effects of RMP and ECCD on DTM in RMS tokamak plasmas. It is found that the explosive burst in the RMS configuration can be effectively prevented by applying a rotating RMP with large frequency. Mitigation of DTM by static RMP with continuous ECCD and by rotating RMP with modulated ECCD are separately studied and compared. In addition, the optimal control strategy and underlying physical mechanisms are analyzed and discussed.

The rest of this paper is organized as follows. In section 2, the modeling equations used in this work are introduced. In section 3, numerical results and physical discussions are presented. Finally, the paper is summarized and conclusions are drawn in section 4.

## 2. Simulation model

A set of reduced MHD equations, including the evolution of the vorticity, magnetic flux, and plasma pressure, is adopted to study the nonlinear evolution of NTM in this work. The normalized equations in a cylindrical geometry ($r, \theta, z$) can be written as

\[
\frac{\partial \psi}{\partial t} = \left[\psi, \phi\right] - \frac{S_\parallel}{S_\perp} (j - j_b) + E_\theta, \quad (1)
\]

\[
\frac{\partial \varphi}{\partial \theta} = \left[\varphi, \psi\right] + \frac{\sqrt{\gamma} R^{-1}}{\sqrt{\gamma} R^{-2} + \frac{\partial p}{\partial r}} p + \frac{\partial p}{\partial z} + S_\theta, \quad (2)
\]

\[
\frac{\partial p}{\partial r} = \left[p, \phi\right] + \chi_\parallel \nabla_\parallel^2 p + \chi_\perp \nabla_\perp^2 p + S_\phi, \quad (3)
\]

where $\phi$ and $\psi$ are the stream function and magnetic flux, respectively. $u = \nabla_\perp \phi$ and $j = -\nabla_\perp \psi$ are the vorticity and plasma current density along the axial direction, respectively. $p$ is the plasma pressure. $j_b = -f_0 \frac{\sqrt{\gamma} R^{-2}}{\sqrt{\gamma} R^{-2} + \frac{\partial p}{\partial r}}$ is the bootstrap current. $R_0$ is the inverse aspect-ratio.
and $B_0$ is the poloidal magnetic field. The radial coordinate $r$, time $t$ and velocity $v$ are normalized by the plasma minor radius $a$, Alfvén time $\tau_a = \sqrt{\mu_0 \rho a^2}/B_0$ and Alfvén speed $v_A = B_0/\sqrt{\mu_0 \rho}$, respectively. $R = r/\tau_a$ and $S_\lambda = \tau_\eta/\tau_\lambda$ in equations (1) and (2) are, respectively, the Reynolds number and the magnetic Reynolds number, where $\tau_\nu = a^2/\nu$ is the viscosity diffusion time, $\tau_\eta = a^2 \mu_0/\eta$ the resistive diffusion time, $\nu$ the plasma viscosity and $\eta$ the resistivity. $\chi_\parallel$ and $\chi_\perp$ are the parallel and perpendicular transport coefficients, respectively, which are normalized by $a^2/\tau_\nu$. Source terms $E_{\phi,0} = S_\lambda \delta f_{\phi,0} = S_\lambda ^{-1} (j_{\phi,0} - j_0)$ and $S_0 = -\chi_\parallel \nabla^2 \rho_0$ in equations (2) and (3) are chosen to balance the diffusions of the initial profiles of Ohm current $j_{\phi,0}$ and pressure $\rho_0(r)$ respectively, where $j_{\phi,0}$ and $j_0$ are the $z$-component of the initial bootstrap and total current density, respectively. The Poisson brackets in equations (1)–(3) are defined as

$$[f, g] = \nabla f \times \nabla g \cdot \hat{z} = \frac{1}{r} \left( \frac{\partial f}{\partial \theta} \frac{\partial g}{\partial \phi} - \frac{\partial f}{\partial \phi} \frac{\partial g}{\partial \theta} \right).$$ (4)

Each variable $f(r, \theta, z, t)$ in equations (1)–(3) can be written in the form $f = f_0(r) + \tilde{f}(r, \theta, z, t)$ with $f_0$ and $\tilde{f}$ being the time-independent initial profile and the time-dependent perturbation, respectively. By applying the periodic boundary conditions in the poloidal and axial directions, the perturbed fields can be Fourier-transformed as

$$\tilde{f}(r, \theta, z, t) = \frac{1}{2} \sum_{m,n} \tilde{f}_{m,n}(r, t) e^{i(m \theta - nz/R_0)}.$$ (5)

with $R_0$ being the major radius of the tokamak.

The EC waves can produce a perturbation in velocity space around the resonant parallel velocity, creating a velocity space ‘hole’ at small perpendicular velocities and a ‘bulge’ at high perpendicular velocities. This perturbation is convected along the magnetic field lines with the parallel velocity of the resonant electrons. The velocity space hole is filled in more quickly than the bulge diminishing due to the velocity dependence of collision frequency, which will result in a net current effect [33, 34]. According to above mechanism, the ECCD can be described in the form of

$$\frac{\partial j_{\phi 1}}{\partial t} = -j_{sc} - \nu_{sc} j_{\phi 1} + v_{pres} \nabla_{\parallel} j_{\phi 1},$$ (6)

$$\frac{\partial j_{\phi 2}}{\partial t} = j_{sc} - \nu_{sc} j_{\phi 2} + v_{pres} \nabla_{\parallel} j_{\phi 2},$$ (7)

$$\tilde{j}_d = j_{\phi 1} + j_{\phi 2}.$$ (8)

The EC current in the model originates in the Fisch–Boozer effect. Considering the perpendicular excursion in velocity of a group of electrons with the parallel velocity $v_{pres}$, these resonant electrons are accelerated to higher energy location, higher perpendicular velocity, in velocity space. As a result, perturbations of the distribution function $\delta f_e$ and $-\delta f_e$ are generated in the high $v_\perp$ side and low $v_\perp$ side respectively, due to the conservation of the particles. Then two driven current densities with opposite signs can be obtained from calculation of the first moment of the perturbations as

Figure 2. Nonlinear evolution of the island width, magnetic and kinetic energy versus time for moderate separation (left) and large separation (right).
Figure 3. Contour plots of helical magnetic flux $\psi_*$ during the explosive burst.

Figure 4. Mode frequency and island width in a burst avoidance case (blue lines) compared with the case without RMP (pink lines). The input parameters are set as $\omega_{\text{rmp}} = -9.6 \times 10^{-2}$, $\psi_{\text{rmp}} = 5 \times 10^{-4}$ and $\omega_{\text{ntm}} = -6 \times 10^{-3}$. The process can be divided into four parts. (I) Without RMP, the mode rotates at its natural frequency. (II) After RMP turning on, mode frequency locks to RMP soon. (III) Mode frequency starts to oscillate and the structure of magnetic islands are broken. (IV) Mode frequency maintains at lower level than RMP with little oscillation. Typical contour plots of helical magnetic flux $\psi_*$ with RMP in different regimes (II) $t = 2200$, (III) $t = 4500$ and (IV) $t = 12000$ are given in the lower pictures.
Assuming the collision is Krook-type, which declines as $v^{-3}$, the collision frequency at high velocity $\nu_2$ is smaller than the collision frequency at low velocity $\nu_1$. The collisional relaxation process symmetrizes the high energy electrons more slowly than it fills the lower energy location they came from, leading to a net current $j = j_1 + j_2$.

For self-consistent calculation of the source term, a ray tracing code, such as TORAY [35] and GENRAY [36], is needed to be coupled with our RMHD code and ECCD model. In this work, owing to the computational limitation, the source term of ECCD $j_{sc}$ is provided to be the Gaussian distribution as

$$j_{sc} = j_0 \exp\{ -4\left[\left(\frac{r - r_0}{\Delta r_d}\right)^2 + \left(\frac{\chi - \chi_0}{\Delta \chi}\right)^2\right]\}.$$  \hspace{1cm} (10)

where $(r_0, \chi_0)$ is the center of the Gaussian distribution with a peak value $j_0$. $\Delta r_d$ is the half deposition width in the radial direction, and $\Delta \chi$ is the half deposition width in the helical angle direction, normalized by $m/2\pi, m = 3$.

The effect of RMP with $m/n$ is taken into account by the boundary condition

$$\tilde{\psi}_{in, n}(r = 1) = \psi_n(t)e^{i(mn - nz)/R_0}.$$  \hspace{1cm} (11)

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 $(n/m)(r/R)$ times smaller than that in toroidal direction, and the speed in toroidal direction should be $(m/n)(R/r_s)$ 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 $[(m/n)(R/r_s)]^2$.

Given the initial profiles of $\phi_0, \psi_0,$ and $p_0$, equations (1)–(3) can be solved by an initial value code: MDC (MHD@Dalian Code) [37–39, 45, 46]. The two-step predictor-corrector method is applied in the time advancement. The finite difference method is used in the radial direction and the pseudo-spectral method is employed for the poloidal and the toroidal directions ($\theta, \zeta = -z/R_0$).

3. Numerical results

To begin with, a pair of nonmonotonic $q$ profiles with the same magnetic shear value are adopted in this work as shown in figure 1. In the RMS discharges of advanced tokamaks such as JT-60U, the minimum safety factor $q$ is usually larger than 2. Thus, two types of separations between inner and outer $q = 3$ resonant surfaces are considered. One is a moderate separation with $d_s = 0.286$, and the other is a large separation with $d_s = 0.408$. The normalized initial pressure profile with large inner pressure gradient is set as $p_0(r) = (1 - r^2)^6$. The
poloidal shear flow is considered by setting $v_0(r) = \Omega_0(r - r_3)$ with $\Omega_0 = 3 \times 10^{-3}$. The plasma parameters are set as follow, $\varepsilon = 0.25$, $S_A = 10^6$, $R = 10^7$, $\chi_\parallel = 10$ and $\chi_\perp = 10^{-6}$. The frequency of NTM $\omega_{\text{ntm}}$ at the outer rational surface $r = 0.623$ is set as $-6 \times 10^{-3}$, where the negative sign indicates that the direction of rotation is clockwise. The ECCD parameters are set as follows. Collision frequencies are $\nu_1 = 2.5 \times 10^{-3}$, $\nu_2 = 5 \times 10^{-4}$, $\Delta_\nu = 0.05$, $\Delta_\chi = 0.2$, $r_0 = 0.567$ and $\chi_0 = 0.5$.

The ECCD on tokamak should be very large, here, the $v_{\text{pres}} = 0.4$ is close to but slightly lower than its real value due to the computational limitation. Ensured the fast electrons can propagate along the magnetic field lines promptly when rotating, we set the $v_{\text{pres}}$ as large as possible. In our simulation, since the island keeps rotating, the $\chi_0$ is not important and is fixed as $\chi_0 = 0.5$. Exceptionally, when the island is locked by the static RMP, we make the location of the O-point of the island is just right at the $\chi_0 = 0.5$. Taking the bootstrap current into account, the modified Rutherford equation can be written as

$$\tau_R \frac{dw}{dr} = \Delta' - 2 \varepsilon^{1/2} \frac{v_0}{B_0^2} \frac{dp}{dr} \frac{L_q}{w}$$

(12)

where $L_q = q/(dq/dr)$ is the magnetic shear length. It is worth noting that as the magnetic shear is positive (negative) at the outer (inner) rational surface, the bootstrap current has a destabilizing (stabilizing) effect on tearing mode at the outer (inner) rational surface in the RMS configuration. For the q-profile adopted in this work, the strongly destabilizing effect at the outer rational surface can overwhelm the relatively weak stabilizing effect at the inner rational surface. Thus, the ECCD is aimed at the outer rational surface, and
only the width of outer island is plotted in this work. For the large separation, two kinds of strategies are studied separately: (a) use static RMP to lock the NTM and then launch a continuous ECCD to suppress it; (b) use rotating RMP to lock the NTM and then launch a modulated ECCD with the same frequency. Owing to the existence of explosive burst in the moderate separation, the control strategy should be different from that in large separation. For the moderate separation, a static or low frequency RMP can only accelerate the process of the explosive burst. However, it is discovered that a high frequency RMP can suppress the explosive burst. Moreover, to stabilize the NTM, a ECCD turned on at the early stage is necessary in this situation.

3.1 Control of NTM with RMP and ECCD in the moderate separation

In the absence of RMP, the nonlinear evolution of island width, magnetic energy and kinetic energy of the system for different separations are given in figure 2. For the moderate separation, the explosive burst [4, 6, 7] takes place at around \( t = 7600 \), which can be identified by the rapid ascent and descent of the island width, magnetic and kinetic energy. Note that the mode does not self disappear in this process. Instead, considerable energy releases at the same time, may leading to a major disruption [40]. For the large separation, however, no explosive burst is observed. The whole process of this explosive burst with the moderate separation is shown in figure 3. In the beginning \( (t = 7150) \), the inner and outer magnetic islands grow near the original resonant surfaces. As the islands become larger \( (t = 7550) \), they start to squeeze each other and the inner one is gradually deformed to a triangular shape. This sharp triangularity in the magnetic structure results in an intense current point, which greatly enhances the magnetic reconnection \( (t = 7650) \). Finally \( (t = 7700) \), massive magnetic energy is released converting into kinetic energy, which leads to subsequent internal disruptions.

In the previous researches [38, 41], it is found that flows, such as shear flow and diamagnetic flow, can play an important role in stabilizing this kind of explosive burst. Inspired by this rationale, equivalently, a rotating RMP can induce flows and affect the frequency of NTM. Thus, the influence of rotating RMP is studied, and it turns out to be useful. In figure 4, the blue lines gives a burst avoidance case with the help of rotating RMP. The RMP is turned on at \( t = 2000 \) and saturates at \( t = 2500 \) with the amplitude of \( \psi_{\text{rmp}} = 5 \times 10^{-4} \). After the RMP is switched on, the NTM locks to the frequency of RMP quickly. As the magnetic islands gradually grow, the frequency starts to oscillate, and the island structure is broken by the RMP induced flows, as shown in the lower center picture of figure 4. Ultimately, reaching a new balance, the NTM and RMP rotates at their own frequencies separately without burst occurring. Note that the frequency of NTM is eventually at a frequency that is different from the frequency of RMP with little oscillation, which is distinct from the general locked mode where the two frequencies should be equal. This behavior is similar to the slight suppression regime for static RMP [42, 43], where \( \omega_{\text{ntm}} \) is suppressed with oscillation. The corresponding radial profiles of \( \mathbf{E} \times \mathbf{B} \) flow at different time are illustrated in the upper picture of figure 5. It is interestingly found that after turning on RMP, a strong sheared zonal
flow is produced and approaches the $q = 3$ resonant surface with time, accounting for the broken island structure in figure 4 (III).

Scanning of the amplitude and frequency of RMP is further carried out to find out where the burst avoidance regime is. It can be seen, from figure 6, that the explosive burst can be avoided only if the amplitude and frequency of RMP are both large enough. From the lower picture of figure 5, we can find that for a small amplitude of RMP with the same frequency, the flows cannot penetrate and reach the resonant surface, indicating that a large enough amplitude of RMP is needed. Since the frequency of RMP can directly affect the strength of flows, a high enough frequency of RMP is necessary for suppressing the explosive burst. Secondly, the NTM will be locked if the frequency of RMP is relatively small, which can destabilize the NTM and then induce the explosive burst. Furthermore, the effectiveness of three different turn-on time of RMP, $t = 2000$ (linear phase), $t = 4000$ (Rutherford phase) and $t = 6000$ (a little before fast reconnection phase), are studied. It is found that only when RMP is applied at $t = 2000$, the explosive burst can be prevented. Since the growth of DTM is very fast and some time for RMP to penetrate is needed, the feedforward control is necessary.

The effectiveness of ECCD after the burst suppressed by rotating RMP is further studied. However, it is still very hard to eliminate the NTM in this circumstance. The explosive burst can be easily triggered after the ECCD is turned on because of the strong zonal field and the coupling of the two islands. It is found that, to stabilize the NTM in the moderate separation, it is pivotal to launch the ECCD at the early stage long before the explosive burst, which is different from the pre-emptive ECCD that is applied before the onset of the NTM [44]. In figure 7, it is clearly shown that only the ECCD turned on at $t = 2000$ with $I_{cd}/I_p = 7.8\%$ can mitigate the NTM. In contrast, other cases can merely postpone the explosive burst.

3.2. Control of NTM with RMP and ECCD in the large separation

To study the synergetic effects of RMP and ECCD on NTM, it is necessary to investigate the locked mode of NTM in this situation. It is found that the NTM can be locked to the RMP of a moderate amplitude without burst occurring, since in the large separation the interaction between magnetic islands located at two rational surfaces is weak. However, if the amplitude of RMP is further increased the explosive burst can still be induced, indicating that the penetration threshold is larger than the mode locking threshold in the RMS scenario.

First, synergetic effects of static RMP and continuous ECCD are studied. The ECCD is turned on at $t = 15,000$ after the NTM is totally locked. Figure 8 gives the evolution of island width and mode frequency versus time. The NTM can be nearly fully suppressed when the ratio of driven current to total plasma current $I_{cd}/I_p$ is 7.0%. For smaller $I_{cd}/I_p$, the island width can be mitigated to different amplitude levels. The blue lines in figure 9 show the evolution of inner and outer island widths of the case in figure 8 with $I_{cd}/I_p = 7.0\%$, compared by the case without ECCD. The inner island shrinks spontaneously if the outer island is mitigated by the ECCD, as suggested before, due to the stabilizing effect of the

Figure 10. Evolution of island widths with time for different radial deposition $r_0$ of ECCD, where $I_{cd}/I_p = 5.4\%$ (upper). Other parameters are set as $\nu_1 = 2.5 \times 10^{-3}$, $\nu_2 = 5 \times 10^{-4}$, $\Delta_{rd} = 0.05$, $\Delta_{r} = 0.2$ and $\chi_0 = 0.5$. Saturated island widths for different radial deposition (lower).

Figure 11. The process of NTM slowing down and locking to rotating RMP. The rotating RMP is turned on at $t = 10,000$ with $\psi_{rmp} = 3 \times 10^{-4}$ and $\omega_{rmp} = -2 \times 10^{-3}$. The saturated island widths for the case in figure 8 with $I_{cd}/I_p = 7.0\%$, compared by the case without ECCD. The inner island shrinks spontaneously if the outer island is mitigated by the ECCD, as suggested before, due to the stabilizing effect of the
negative magnetic shear at the inner rational surface. By contrast, without the application of ECCD, the inner and outer islands saturates independently like the single tearing mode. The influence of radial misalignment can be also observed, as illustrated in figure 10. Optimal effectiveness can be attained if the deposition of driven current is slightly inside the initial resonant surface. This is due to the strong interaction between the inner and outer magnetic islands, which makes the island structure greatly deformed. Consequently, the O-point of the outer magnetic islands move inward slightly.

As discussed above, using static RMP accompanied with continuous ECCD can be an effective way of controlling NTM. However, it is well recognized that plasma rotation is beneficial to steady state operation of the tokamak devices. Another method, utilizing a rotating RMP and modulated ECCD, is therefore studied in the rest of this subsection. For modulated ECCD, the situation will be more complicated. It mainly results from different time scales between three physical quantities, i.e. rotation frequency \( \omega_{\text{ntm}} \), collision frequency of fast electrons \( \nu \) and parallel velocity of fast electrons \( v_{\text{pres}} \), which will be discussed later.

Next, synergetic effects of rotating RMP and modulated ECCD are studied. Figure 11 shows the mode slowing down and locking to the rotating RMP with \( \omega_{\text{imp}} = -2 \times 10^{-3} \). After the RMP is turned on at \( t = 10000 \), the phase of NTM jumps to the phase of RMP in few rotation periods and then locks to it smoothly. Later after the NTM is locked to the rotating RMP, the modulated ECCD is turned on at \( t = 15000 \). Figure 12

Figure 12. Evolution of island width (upper left) and mode frequency (upper right) versus time for different RMP frequencies and the corresponding driven current fraction \( I_{\text{cd}}/I_p \) versus time (lower). The RMP is turned on at \( t = 10000 \) and ECCD is switched on at \( t = 15000 \) after the islands are totally locked by rotating RMP. Other parameters are set as \( \nu_1 = 2.5 \times 10^{-3}, \nu_2 = 5 \times 10^{-4}, r_0 = 0.603, \chi_0 = 0.5, \Delta \chi = 0.05 \) and \( \Delta \chi = 0.20 \).

Figure 13. Comparison of the evolution of island width (upper) and driven current (lower) versus time for modulated and continuous ECCD. Higher collision frequencies \( \nu_1 = 7.5 \times 10^{-3} \) and \( \nu_2 = 1.5 \times 10^{-3} \) are adopted here. Other parameters are set as \( \Delta \chi = 0.15, \Delta \chi = 0.03, r_0 = 0.603, \chi_0 = 0.5 \) and \( \omega_{\text{imp}} = -2 \times 10^{-3} \).
displays the evolution of island width versus time for different RMP frequencies. It is seen that a modulated ECCD can effectively mitigate the NTM. Moreover, it is noted that the stabilizing effect decreases with the increase of RMP frequency. Through analyzing the evolution of driven current fraction, it is found that for a lower RMP frequency, the driven current can rise and fall rapidly in a modulated period in response to the approach and moving away of the O-point of island. For a large RMP frequency, however, it almost keeps the same with slight oscillation due to the turn-on and turn-off of the ECCD. Therefore, a relatively small ratio of rotation frequency to collision frequency \(|\omega_{\text{rpm}}/\nu|\) can strengthen the stabilizing effect.

Effects of modulated ECCD and continuous ECCD are compared in figure 13 with a higher collision frequency, indicating a smaller slowdown time of fast electrons, the driven current can quickly saturate and fade in a modulated period, resulting in a better suppression effect. Because of the faster time scale for fast electrons to fade away, the ‘flip’ effects will be stronger when turning off the ECCD compared with the low collision frequency cases. In a modulated period, the stabilizing effect is stronger than the destabilizing effect for turning off the ECCD. Therefore, a net stabilizing effect is still can be obtained. Figure 14 demonstrates the spatial distribution of driven current at different time. For a continuous ECCD, the driven current can be deposited at arbitrary poloidal location and transported through the magnetic field lines when the magnetic islands rotate, leading to dispersion of driven current. For a modulated ECCD, on the contrary, the driven current can
The NTM can be mitigated to different extent or nearly islets by static RMP are studied in the large separation. and coupling of the two islands in RMS. mitigate the NTM in the moderate separation, it is necessary a difference can prevent NTM from being locked. Besides, to quency of RMP is needed for two reasons. One is due to the surface. To implement this method, an extremely large fre- can be produced by the rotating RMP. A larger amplitude large amplitude and frequency. Zonal flows with strong shear can be fully suppressed by a rotating RMP with sufficiently angle can reinforce the stabilizing effect. On the other hand, the stabilizing effect cannot be further enhanced if the deposition is beyond a critical value. Moreover, the optimal on-duty ratio is found to be in the range of 60%–70% for modulated ECCD. In conclusion, the best strategy is, using a relatively slow rotating RMP to slow down NTM, to aim the ECCD at the inward side of initial resonant surface with a broad enough deposition width and on-duty ratio of 60%–70%.

4. Summary and discussion

In this paper, control of NTM in RMS by ECCD and RMP is numerically investigated based on a set of reduced MHD equations. Main points can be summarized as follows. First, in the moderate separation, it is found that the explosive burst induced by the fast reconnection of DTM in RMS can be fully suppressed by a rotating RMP with sufficiently large amplitude and frequency. Zonal flows with strong shear can be produced by the rotating RMP. A larger amplitude of RMP can enhance the penetration of the generated zonal flows, otherwise, it cannot propagate and reach the resonant surface. To implement this method, an extremely large frequency of RMP is needed for two reasons. One is due to the velocity of produced zonal flows is proportional to the frequency of applied RMP. The other is that large frequency difference can prevent NTM from being locked. Besides, to mitigate the NTM in the moderate separation, it is necessary to apply a ECCD at the early stage due to the strong zonal field and coupling of the two islands in RMS.

Next, effects of continuous ECCD on locked magnetic islands by static RMP are studied in the large separation. The NTM can be mitigated to different extent or nearly fully stabilized according to different fraction of ECCD. The optimal radial deposition of ECCD is at the inward side of the initial resonant surface, in consequence of the deformation of the island structure by interaction between the outer and inner islands.

Finally, synergetic effects of rotating RMP and modulated ECCD on NTM are investigated in the large separation. Rotation frequency $\omega_{ntm}$, collision frequency of fast electrons $\nu$ and parallel velocity of fast electrons $v_{pes}$ play important roles in the effectiveness of ECCD. It is found that smaller $|\omega_{ntm}/\nu|$ can enhance the stabilizing effects of ECCD, since the driven current can rise and fall swiftly in response to the approach and away of the O-point of island. In our simulation, considering the Alfvén time is about $10^{-6}$ s in today’s tokamak, a typical $|\omega_{ntm}|$ is chosen as $6 \times 10^{-3}$, i.e. 6kHz. The $|\omega_{ntm}|$ is 5–10 times larger than $\nu$ in experiments. Therefore, to gain a better stabilizing effect for modulated, a rotating RMP with $|\omega_{ntm}| = 0.1–1$kHz can be utilized to slow down the NTM. Besides, a broader deposition width of radial and helical angle can reinforce the stabilizing effect. On the other hand, the stabilizing effect cannot be further enhanced if the deposition is beyond a critical value. Moreover, the optimal on-duty ratio is found to be in the range of 60%–70% for modulated ECCD. The best effectiveness. Besides, further increasing the on-duty time over 70% can reduce the stabilizing effect.

4. Summary and discussion

In this paper, control of NTM in RMS by ECCD and RMP is numerically investigated based on a set of reduced MHD equations. Main points can be summarized as follows. First, in the moderate separation, it is found that the explosive burst induced by the fast reconnection of DTM in RMS can be fully suppressed by a rotating RMP with sufficiently large amplitude and frequency. Zonal flows with strong shear can be produced by the rotating RMP. A larger amplitude of RMP can enhance the penetration of the generated zonal flows, otherwise, it cannot propagate and reach the resonant surface. To implement this method, an extremely large frequency of RMP is needed for two reasons. One is due to the velocity of produced zonal flows is proportional to the frequency of applied RMP. The other is that large frequency difference can prevent NTM from being locked. Besides, to mitigate the NTM in the moderate separation, it is necessary to apply a ECCD at the early stage due to the strong zonal field and coupling of the two islands in RMS.

Next, effects of continuous ECCD on locked magnetic islands by static RMP are studied in the large separation. The NTM can be mitigated to different extent or nearly fully stabilized according to different fraction of ECCD. The optimal radial deposition of ECCD is at the inward side of the initial resonant surface, in consequence of the deformation of the island structure by interaction between the outer and inner islands.

Finally, synergetic effects of rotating RMP and modulated ECCD on NTM are investigated in the large separation. Rotation frequency $\omega_{ntm}$, collision frequency of fast electrons $\nu$ and parallel velocity of fast electrons $v_{pes}$ play important roles in the effectiveness of ECCD. It is found that smaller $|\omega_{ntm}/\nu|$ can enhance the stabilizing effects of ECCD, since the driven current can rise and fall swiftly in response to the approach and away of the O-point of island. In our simulation, considering the Alfvén time is about $10^{-6}$ s in today’s tokamak, a typical $|\omega_{ntm}|$ is chosen as $6 \times 10^{-3}$, i.e. 6kHz. The $|\omega_{ntm}|$ is 5–10 times larger than $\nu$ in experiments. Therefore, to gain a better stabilizing effect for modulated, a rotating RMP with $|\omega_{ntm}| = 0.1–1$kHz can be utilized to slow down the NTM. Besides, a broader deposition width of radial and helical angle can reinforce the stabilizing effect. On the other hand, the stabilizing effect cannot be further enhanced if the deposition is beyond a critical value. Moreover, the optimal on-duty ratio is found to be in the range of 60%–70% for modulated ECCD. In conclusion, the best strategy is, using a relatively slow rotating RMP to slow down NTM, to aim the ECCD at the inward side of initial resonant surface with a broad enough deposition width and on-duty ratio of 60%–70%.

Acknowledgments

The authors acknowledge the Super-computer Center of Dalian University of Technology for providing computing resources. This work was supported by the National Natural Science Foundation of China (Grant No. 11675083), the National Key R&D Program of China (Grant Nos. 2017YFE0301900 and 2017YFE0301100), the Fundamental Research Funds for the Central Universities (Grant Nos. DUT18ZD101 and DUT17RC(4)54), and the Dalian Youth Science and Technology Project Support Program (Grant No. 2015R01).

ORCID iDs

Weikang Tang https://orcid.org/0000-0002-8406-8349
Lai Wei https://orcid.org/0000-0003-2224-2038
Jialei Wang https://orcid.org/0000-0002-8678-8075

References

[1] Strait E.J. et al 1995 Phys. Rev. Lett. 75 4421–4
[2] Levinton F.M. et al 1995 Phys. Rev. Lett. 75 4417–20
[3] Fujita T., Ide S., Shirai H., Kikuchi M., Naito O., Koide Y., Takeji S., Kubo H. and Ishida S. 1997 Phys. Rev. Lett. 78 2377–80
[4] Janvier M., Kishimoto Y. and Li J.Q. 2011 Phys. Rev. Lett. 107 195001
[5] Zhang W., Ma Z.W., Zhu J. and Zhang H.W. 2019 Plasma Phys. Control. Fusion 61 075002
[6] Wang Z.X., Wang X.G., Dong J.Q., Lei Y.A., Long Y.X., Mou Z.Z. and Qu W.X. 2007 Phys. Rev. Lett. 99 185004
[7] Ishii Y., Azumi M. and Kishimoto Y. 2002 Phys. Rev. Lett. 89 205002
[8] Ishii Y., Azumi M., Kurita G. and Tuda T. 2000 Phys. Plasmas 7 4477–91
[9] Wang Z.X., Wei L. and Yu F. 2015 Nucl. Fusion 55 043005
[10] Bierwage A., Toma M. and Shinohara K. 2017 Plasma Phys. Control. Fusion 59 125008
[11] Hender T. et al 1992 Nucl. Fusion 32 2091–117
[12] Wang H., Wang Z., Ding Y. and Rao B. 2015 Plasma Sci. Technol. 17 539–44
[13] Fitzpatrick R. 2014 Phys. Plasmas 21 092513
[14] La Haye R.J. 2006 Phys. Plasmas 13 055501
[15] Bardóczi L., Rhodes T.L., Bañón Navarro A., Sung C., Carter T.A., La Haye R.J., McKee G.R., Petty C.C., Chrystal C. and Jenko F. 2017 Phys. Plasmas 24 056106
[16] Maraschek M. 2012 Nucl. Fusion 52 074007
[17] Hu Q., Du X., Yu Q., Logan N., Kolemen E., Nazikian R. and Jiang Z. 2018 Nucl. Fusion 59 016005
[18] Elgriw S. et al 2017 Fusion Eng. Des. 123 148–52
[19] Yu Q. and Günter S. 2008 Nucl. Fusion 48 065004
[20] Ivanov N.V. and Kakurin A.M. 2017 Nucl. Fusion 7 16021
[21] Becoulet M. et al 2012 Nucl. Fusion 52 054003
[22] Yu Q., Günter S. and Lackner K. 2018 Nucl. Fusion 58 054003
[23] Gantenbein G., Zohm H., Giruzzi G., Günter S., Leuterer F., Maraschek M., Meskat J. and Yu Q. 2000 Phys. Rev. Lett. 85 1242–5
[24] Giruzzi G., Zabiego M., Gianakon T., Garbet X., Cardinali A. and Bernabei S. 1999 Nucl. Fusion 39 107–25
[25] Grasso D., Borgogno D., Comisso L. and Lazzaro E. 2018 J. Plasma Phys. 84 745840302
[26] Fèvrier O., Maget F., Lütjens H., Luciani J.F., Decker J., Giruzzi G., Reich M., Beyer P., Lazzaro E. and Nowak S. 2016 Plasma Phys. Control. Fusion 58 045015
[27] Hegna C.C. and Callen J.D. 1997 Phys. Plasmas 4 2940–6
[28] Lazzaro E. and Comisso L. 2011 Plasma Phys. Control. Fusion 53 054012
[29] Yu Q., Günter S., Giruzzi G., Lackner K. and Zabiego M. 2000 Phys. Plasmas 7 312–22
[30] Maraschek M., Ganzenbein G., Yu Q., Zohm H., Günter S., Leuterer F. and Manini A. 2007 Phys. Rev. Lett. 98 135–6
[31] Volpe F.A., Hyatt A., La Haye R.J., Lancerot M.J., Lohr J., Prater R., Strait E.J. and Welander A. 2015 Phys. Rev. Lett. 115
[32] Wang X., Zhang X., Yu Q., Wu B., Zhu S., Wang J., Zhang Y. and Wang X. 2015 Nucl. Fusion 55 053024
[33] Westerhof E. and Pratt J. 2014 Phys. Plasmas 21 102516
[34] Pratt J., Hujsmans G.T.A. and Westerhof E. 2016 Phys. Plasmas 23 102507
[35] Matsuda K. 1989 IEEE Trans. Plasma Sci. 17 6–11
[36] Harvey R.W., Smirnov A.P., Prater R. and Austin M.E. Electron cyclotron heating, current drive, and emission applications of the GENRAY ray tracing code
[37] Wei L., Wang Z.X., Wang J. and Yang X. 2016 Nucl. Fusion 56 106015
[38] Wang J., Wang Z.X., Wei L. and Liu Y. 2017 Nucl. Fusion 57 046007
[39] Liu T., Wang Z.X., Wang J. and Wei L. 2018 Nucl. Fusion 58 076026
[40] Takeji S. et al 2002 Nucl. Fusion 42 5–13
[41] Ye C., Wang Z.X., Wei L. and Hu Z.Q. 2019 Nucl. Fusion 59 096044
[42] Hu Q., Yu Q., Rao B., Ding Y., Hu X. and Zhuang G. 2012 Nucl. Fusion 52 083011
[43] Tang W., Wei L., Wang Z., Wang J., Liu T. and Zheng S. 2019 Plasma Sci. Technol. 21 065103
[44] Sauter O., Henderson M.A., Ramponi G., Zohm H. and Zucca C. 2010 Plasma Phys. Control. Fusion 52 025002
[45] Yang S.X et al 2018 Nucl. Fusion 58 046016
[46] Han M.K., Wang Z.-X., Dong J.Q. and Du H. 2017 Nucl. Fusion 57 046019