AIP Advances

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Cite as: AIP Advances **9**, 015020 (2019); https://doi.org/10.1063/1.5080379
Submitted: 08 November 2018 . Accepted: 10 January 2019 . Published Online: 22 January 2019

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Submitted: 8 November 2018 • Accepted: 10 January 2019 •
Published Online: 22 January 2019

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ABSTRACT

The influence of modulated-ECCD on m/n=2/1 resistive tearing mode is investigated by a three-dimensional toroidal and non-reduced MHD code CLT. It is found that, after applying a modulated-ECCD, tearing mode instabilities are suppressed and magnetic islands are gradually reduced to a low level, then the width of the magnetic islands exhibit periodic oscillation with the time scale of ECCD modulation frequency. The minimum width of magnetic islands decreases with the decrease of ECCD modulation frequency and increases with the increase of the buildup time of the driven current.

I. INTRODUCTION

Tearing mode instabilities are often observed in tokamak experiments.[1–6] They are deleterious to tokamak performance as they can reduce core electron temperature,[7,8] degrade plasma energy confinement[9,10] or even cause disruptions.[11–14] Classical tearing modes are driven by unfavorable plasma current density gradient, which gives $\Delta' > 0$ (where Δ' indicates the discontinuity of radial derivative of magnetic perturbation across singular layer).[15–17] Neo-classical tearing modes (NTMs)[18,19] can be triggered by seed islands which lead to reduction of the bootstrap current inside magnetic islands, thus resulting in modification of the current profile and reinforcement of initial magnetic perturbations.

Classical and Neo-classical tearing modes are both dangerous for tokamak operation as they lead to large magnetic islands. When islands become so large that islands on different rational surfaces overlap, catastrophic plasma disruptions happen.[10,20,21] Much effort[22–35] has been made to control tearing modes and reduce the size of magnetic islands. One of the most successful methods is Electron Cyclotron Current Drive (ECCD). ECCD has localized energy and momentum deposition, which enables driven current to localize in magnetic islands.[36,37] This method has been widely used to control tearing modes in tokamaks, such as ASDEX upgrade,[8,27] JT-60U,[24,38] D-IIID,[25,26] and EAST.[39]

For stabilization of tearing mode using ECCD, the driven current should reduce the free energy of initial equilibrium (for classical tearing modes) or to replace the missing bootstrap current caused by the flattened pressure in the magnetic islands (for Neo-classical tearing modes). A continuous driven current can stabilize tearing mode as it can modify current profile and decrease Δ'.[40] From theoretical analysis,[36,41] we know that the driven current deposition around the O-point of magnetic island leads to a stabilizing effect while the driven current deposition around the X-point results in a destabilizing effect. It is found[42,43] that the efficiency of a continuous driven current is lower than a modulated one (a modulated ECCD means that the driven current deposits only around the O-point of the island), as the driven current around the X-point has a negative effect on suppressing the tearing modes.

To improve the efficiency of control of tearing modes by ECCD, it is wise to keep Electron Cyclotron Wave (ECW) locking on the O-point of magnetic islands.[43] The modulated-ECCD (i. e. the ECW keeps locking on the O-point) applied to control tearing modes in JT60U[24] and ASDEX Upgrade[27] had been reported, in which the O-point of the magnetic island is detected from electron temperature perturbation profile.[24] There is no similar study of the modulated-ECCD about EAST. Hence, we carry out a numerical simulation to investigate the influence of modulated-ECCD on tearing modes in EAST by the three-dimensional toroidal non-reduced MHD code CLT.[44–47]

II. MODULATED-ECCD MODEL

As we know, ECW interacts with electrons and almost has no influence on ions. Since the electron mass is assumed to be zero in the single-fluid MHD description, the driven current J_{cd} only appears in the Ohm's law.[48] As in large Tokamaks, the influence of current driven on tearing mode stabilization is much larger than that of heating.[49] Thus, the Resistive-MHD equations including driven current in CLT are given as follows:

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\mathbf{v}) + \nabla\cdot[D\nabla(\rho-\rho_0)] \quad (1)$$

$$\frac{\partial p}{\partial t} = -\mathbf{v}\cdot\nabla p - \Gamma p\nabla\cdot\mathbf{v} \quad (2)$$

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v}\cdot\nabla\mathbf{v} + (\mathbf{J}\times\mathbf{B}-\nabla p)/\rho + \nabla\cdot[\upsilon\nabla(\mathbf{v}-\mathbf{v}_0)] \quad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E} \quad (4)$$

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta(\mathbf{J}-\mathbf{J}_0-\mathbf{J}_{cd}) \quad (5)$$

$$\mathbf{J} = \nabla\times\mathbf{B} \quad (6)$$

where ρ, p, $\boldsymbol{v}$, $\mathbf{B}$, $\mathbf{E}$, and J denote the density, the pressure, the velocity, the magnetic field, the electric field, and the current density, respectively. The subscript "0" denotes the initial quantities. $\Gamma(=5/3)$ is the ratio of specific heat of plasma. The variables are normalized as follows: $\mathbf{B}/B_0 \to \mathbf{B}$, $\mathbf{x}/a \to \mathbf{x}$, $\rho/\rho_0 \to \rho$, $t/t_A \to t$, $\mathbf{v}/v_A \to \mathbf{v}$, $p/(B_0^2/\mu_0) \to p$, $\mathbf{J}/(B_0/\mu_0 a) \to \mathbf{J}$, $\mathbf{E}/(v_A B_0) \to \mathbf{E}$ and $\eta/(\mu_0 a^2/t_A) \to \eta$ where a is the minor radius, $t_A = a/v_A$ is the Alfvén time, and $v_A = B/\sqrt{\mu_0\rho}$ is the Alfvén speed. B_0 and ρ_0 are the initial magnetic field and the plasma density at magnetic axis, respectively.

To solve the closure problem,[42,50,51] the following equation for the driven current should be used to compute J_{cd}

$$\frac{\partial J_{cd}}{\partial t} = \nabla\cdot(\kappa_\parallel\nabla_\parallel J_{cd}) + \nabla\cdot(\kappa_\perp\nabla_\perp J_{cd}) + (J_s - J_{cd})/\tau_f \quad (7)$$

where $\kappa_\parallel$ and $\kappa_\perp$ are the parallel and perpendicular thermal conductivity, respectively. τ_f is the buildup time of the driven current and J_s is the current source. As shown in previous studies,[42,48,52–55] the driven current distribution determined by Equation (7) is always helical if all of the ECW is injected inside magnetic islands. In most experiments, the ECCD current deposition width is about 1~2cm that is much less than half of the magnetic island width.[25,27] Then we can assume the distribution of current source J_s due to electron cyclotron wave to be

$$J_s = J_{s0}\exp[-(\psi-\psi_{cd})^2/\delta^2][1+\cos(m\theta+n\phi)]\prod(h_0,\Delta h) \quad (8)$$

and

$$\frac{\partial J_{cd}}{\partial t} = (J_s - J_{cd})/\tau_f \quad (9)$$

where m and n are the poloidal and toroidal numbers of magnetic islands, respectively. $\psi_{cd} = \psi_O + \frac{1}{2}(\psi_O - \psi_X)(1+\cos(m\theta+n\phi))$ determines the location of the driven current, where ψ_O and ψ_X are the fluxes of the O-point and the X-point of the island, respectively. δ is the width of the driven current. The strengths of the current source and the driven current are defined as

$$f_s = J_{s0}[\oint\exp(-(\psi-\psi_0)^2/\delta^2)[1+\cos(m\theta+n\phi)]dS]/I_0 \quad (10)$$

$$f_{cd} = J_{cd}[\oint\exp(-(\psi-\psi_0)^2/\delta^2)[1+\cos(m\theta+n\phi)]dS]/I_0 \quad (11)$$

where I_0 is the total plasma current in the ϕ direction. The function $\prod(h_0,\Delta h)$ is defined as

$$\prod(h_0,\Delta h) = \begin{cases} 1, \mathit{for}\ |h-h_0| < \Delta h \\ 0, \mathit{elsewhere} \end{cases} \quad (12)$$

where $h = m\theta + n\phi$ is the helical angle and Δh is the wave deposition width along the helical angle. In tokamak experiments, the plasma rotates in both the toroidal and poloidal directions, but mainly in the toroidal direction. To compare with external driven current, effects of the plasma rotation on tearing mode dynamics can be neglected. For the sake of simplicity, we assume that there is no plasma rotation and the electron cyclotron wave rotates with the frequency Ω and its phase $h_0 = \Omega t$. This method is widely used.[42,53,54] In our future work, we will discuss the effects of plasma rotations on tearing mode control.

III. SIMULATION RESULTS

The geometry of EAST is chosen, i.e. the major radius $R_0 = 1.85m$, the minor radius $a = 0.45m$, the elongation E=1.9 and the triangularity $\sigma = 0.5$. The initial q profile is shown in Figure 1 and the most unstable mode is the m/n=2/1 tearing mode. $\mathbf{B_0}$ and $\mathbf{J_0}$ are obtained from the code NOVA.[56] Since the plasma pressure is not crucial in the dynamic evolution of tearing modes, we simply assume $\beta \sim 0$. Other normalized

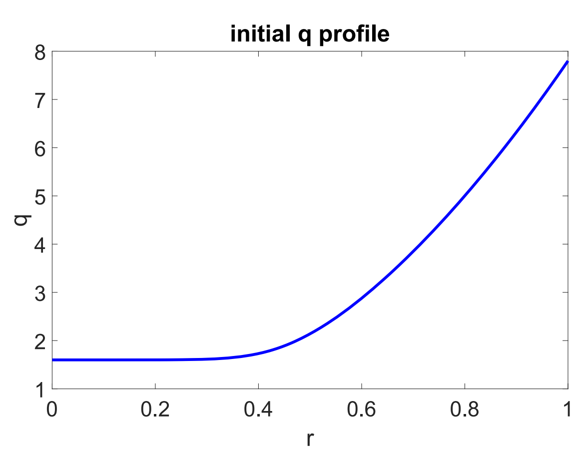

FIG. 1. Initial q profile.

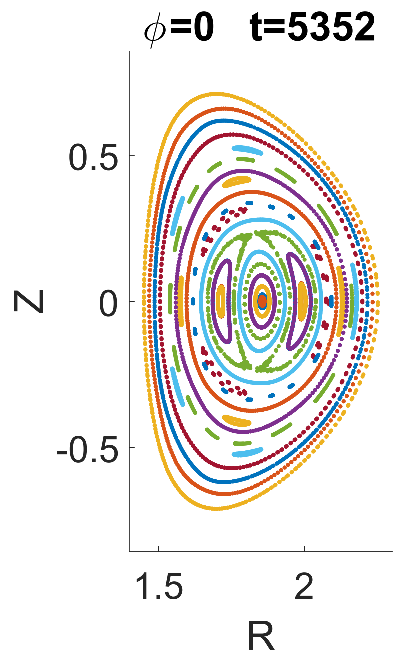

FIG. 2. Poincaré plots of the magnetic field at the ϕ = 0 cross-section in the saturation stage of the tearing mode.

parameters are chosen to be the resistivity $\eta = 1.0 \times 10^{-5}$, the viscosity $\nu = 1.0 \times 10^{-5}$ and the diffusion coefficient D = 1.0 $\times 10^{-4}$. The grids used in the simulations are 256 × 32 × 256 (R, ϕ, Z). In the simulations, the width of driven current is given as $\delta = 0.03$.

The system can self-consistently evolve into its saturation after the m/n=2/1 resistive tearing mode is triggered. The Poincaré plots of the magnetic field for the saturation stage of the tearing mode are shown in Figure 2. It is evident that the m/n=2/1 magnetic island is large and the width is ~10cm. Due to mode-mode coupling, there exist many magnetic islands with high m on other resonant surfaces.

After the tearing mode saturates, we start to turn on the modulated-ECCD with $\Delta h = \frac{\pi}{2}$. It means that the ECW only turns on when its phase locates in $-\frac{\pi}{2} < h - h_0 < \frac{\pi}{2}$. Thus, the amplitude of the driven current will oscillate periodically, instead of reaching a steady value. The evolution of the driven current is determined by three parameters, i. e. the rotation frequency of the plasma Ω (or the rotation frequency of ECW), the buildup time of driven current τ_f, and the strength of source f_s. The relationship of Ω and τ_f can be quite different in different tokamaks. Although in ASDEX-U[42] or EAST[57] $\Omega\tau_f > 1$, $\Omega\tau_f < 1$ could be satisfied in future fusion reactors.[52]

Figure 3 shows the evolution of driven current strengths with τ_f = 500, f_s = 0.012, and different rotation frequencies Ω (Ω = 0.005, Ω = 0.002, Ω = 0.001, and Ω = 0.0005). It indicates that for different Ω, the average driven current strengths in the late stage are almost the same value, that is about half of the strength of f_s. The minimum (maximum) strength of the driven current decreases (increases) with the decrease of Ω.

Spatial distributions of the driven current and Poincaré plots of magnetic field in the ϕ = 0 and $\phi = \pi$ cross sections are shown in Figure 4(a) and (b). It is evident that the driven current closely matches with the magnetic islands and is similar to that derived from the auxiliary frag/diffusion equation.[48]

The q profiles before and after applying modulated-ECCD with Ω = 0.005, τ_f = 500 and f_s = 0.012 are shown in Figure 5. Since the safety factor becomes flattened inside the magnetic islands, the width of the flattened q profile can be regarded as the width of the magnetic islands. Before applying the modulated-ECCD, the width of the m/n=2/1 magnetic islands is w_0 = 8.5cm (t=5441t_A). After the modulated-ECCD turns on at t=5500t_A, the magnetic island gradually shrinks and is finally reduced to w_1 = 5.7cm at t=8027t_A, which means that the width of the m/n=2/1 magnetic islands can be reduced about 30% by the modulated-ECCD. Due to mode-mode coupling, the magnetic islands on other resonant surfaces are also reduced as shown in Figure 5.

Figure 6 shows the evolutions of the perturbed radial magnetic field δB_r for τ_f = 500, f_s = 0.012, and different Ω (Ω = 0.005, Ω = 0.002, Ω = 0.001, and Ω = 0.0005). For the m/n=2/1 resistive tearing mode, the width of the magnetic island can be estimated by the radial perturbation of the magnetic field with $w \sim (\delta B_r)^{1/2}$. Thus, the evolution of δB_r is a good representation for the evolution of the magnetic island.

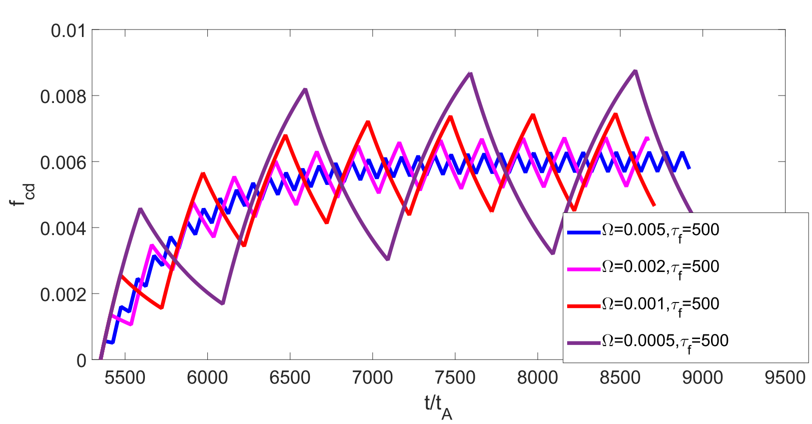

FIG. 3. Evolution of driven current strengths with τ_f = 500, f_s = 0.012, and different Ω (Ω = 0.005, Ω = 0.002, Ω = 0.001, and Ω = 0.0005).

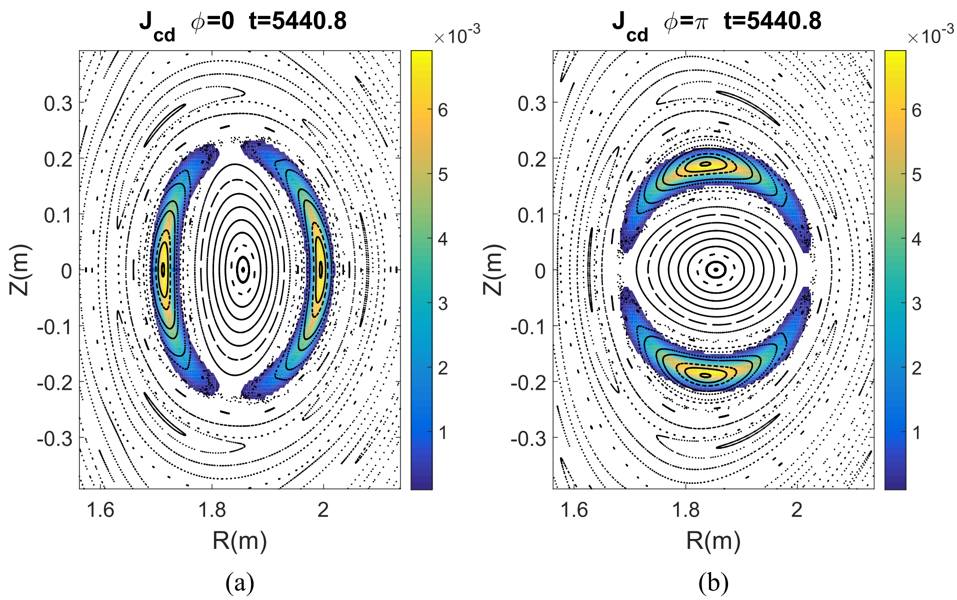

FIG. 4. Spatial distributions of the driven current and Poincaré plots of magnetic field in the (a) ϕ = 0 and (b) ϕ = π cross sections.

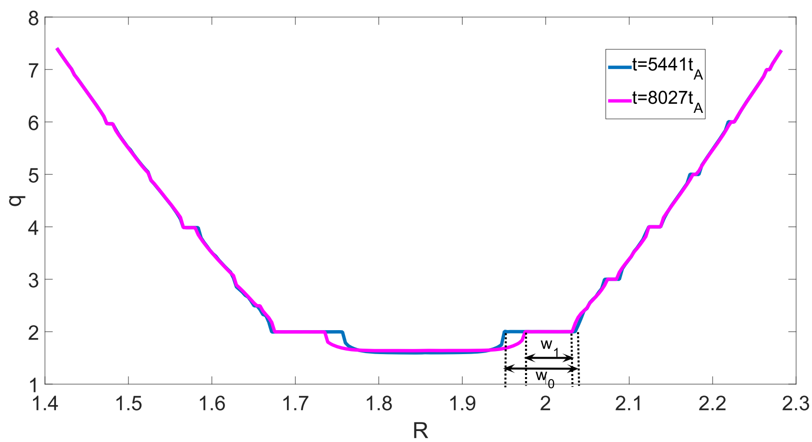

FIG. 5. Safety factor profile before (t=5441t_A) and after (t=8027t_A) applying ECCD. The safety factor q is derived from a trace-field line code. q is defined as $q = \frac{\Delta\phi}{\Delta\theta}$, where $\Delta\phi$ and $\Delta\theta$ are the changes of the toroidal angle and the poloidal angle of a tracing filed line, respectively.

Figure 6 shows that ECWs with different frequencies all well suppress tearing mode instabilities and reduce the width of the m/n=2/1 magnetic islands.

As an ECW with small Ω can drive a current with a large maximum density (shown in Figure 3), which can further reduce the magnetic islands. The minimum δB_r decreases

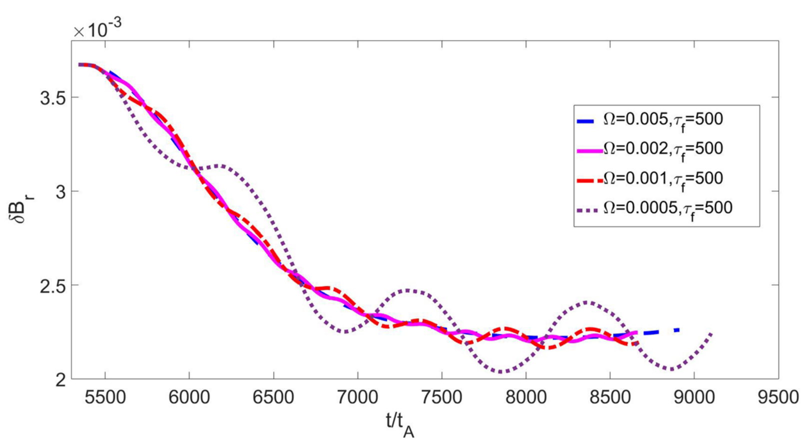

FIG. 6. Evolutions of the radial perturbation of the magnetic field δB_r for τ_f = 500, f_s = 0.012, and different rotation frequencies Ω (Ω = 0.005, Ω = 0.002, Ω = 0.001, and Ω = 0.0005).

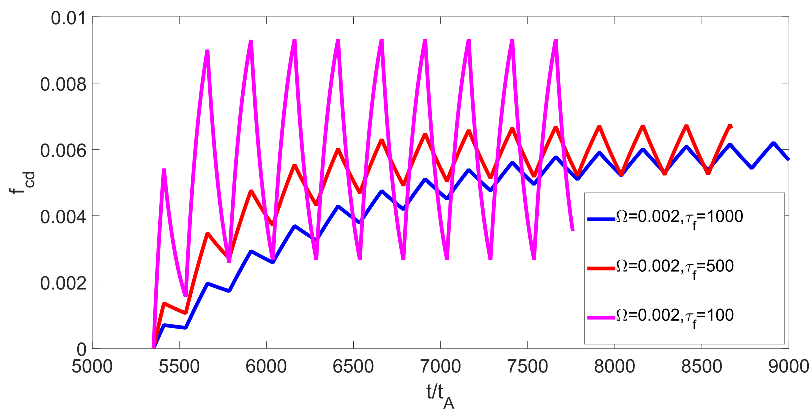

FIG. 7. Evolutions of the driven current with Ω = 0.002, f_s = 0.012, and different buildup times τ_f = 500 (τ_f = 1000, τ_f = 500, and τ_f = 100).

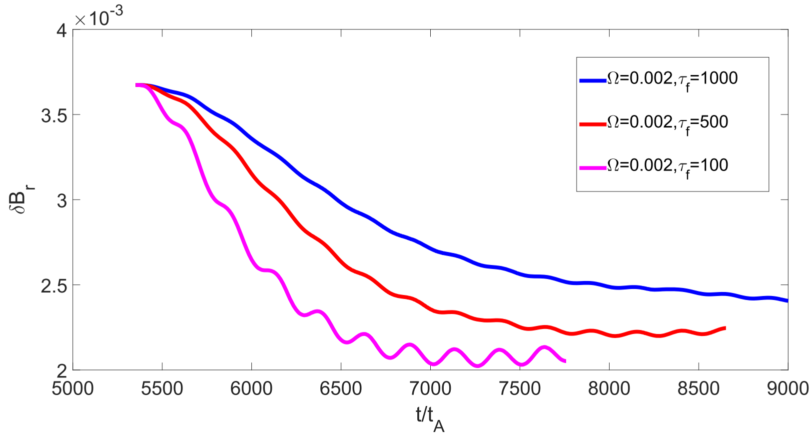

FIG. 8. Evolutions of the radial perturbation of the magnetic field δB_r for Ω = 0.002, f_s = 0.012, and different buildup times τ_f (τ_f = 1000, τ_f = 500, and τ_f = 100).

with decrease of Ω as shown in Figure 6. Since neoclassical tearing mode is linearly stable and nonlinearly unstable, the neoclassical tearing mode could be completely suppressed if the width of the magnetic islands is reduced to a critical value. Therefore, ECW with a small Ω could be helpful to control neoclassical tearing modes.[43]

The evolutions of the driven current with Ω = 0.002, f_s = 0.012, and different buildup times τ_f (τ_f = 1000, τ_f = 500, and τ_f = 100) are shown in Figure 7. The minimum (maximum) strength of the driven current decreases (increases) with the decrease of τ_f.

The evolutions of the radial perturbation of the magnetic field δB_r for Ω = 0.002, f_s = 0.012, and different buildup times τ_f (τ_f = 1000, τ_f = 500, and τ_f = 100) is shown in Figure 8. With a shorter buildup time, the strength of the driven current increases faster. Then the magnetic islands can be quickly reduced. If the simulations run long enough to reach a steady state, the sizes of magnetic islands for all cases will be the same.

IV. SUMMARY

The influence of modulated-ECCD on m/n=2/1 resistive tearing mode in EAST is investigated by a three-dimensional toroidal MHD code CLT. In the present paper, we systematically studied roles of modulated-ECCD with different rotation frequencies and current buildup times on m/n=2/1 resistive tearing mode. It is found that after applying modulated-ECCD, the tearing mode is reduced and the magnetic island gradually reduces to a low level, then the size of the magnetic island exhibits a periodic oscillation with the time scale of the plasma rotation frequency. The minimum width of the magnetic island decreases with the decrease of the plasma rotation frequency. For controlling neoclassical tearing modes, this effect can be more important as neoclassical tearing modes are stable when the widths of the magnetic islands are reduced to a critical value. For a shorter buildup time τ_f, the tearing mode is quickly controlled as the strength of the driven current increases more quickly.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China under Grant No. 11775188 and 41474123, Fundamental Research Fund for Chinese Central Universities.

REFERENCES

[1]Z. Chang, J. D. Callen, E. D. Fredrickson, R. V. Budny, C. C. Hegna, K. M. Mcguire, and M. C. Zarnstorff, Physical Review Letters **74**(23), 4663–4666 (1995).
[2]H. R. Wilson, M. Alexander, J. W. Connor, A. M. Edwards, D. Gates, O. Grüber, R. J. Hastie, C. C. Hegna, T. C. Hender, R. J. L. Haye, L. L. Lao, A. W. Morris, C. M. Roach, E. J. Strait, T. S. Taylor, M. Valovic, and H. Zohm, Plasma Physics and Controlled Fusion **38**(12A), A149 (1996).
[3]O. Sauter, R. J. L. Haye, Z. Chang, D. A. Gates, Y. Kamada, H. Zohm, A. Bondeson, D. Boucher, J. D. Callen, M. S. Chu, T. A. Gianakon, O. Gruber, R. W. Harvey, C. C. Hegna, L. L. Lao, D. A. Monticello, F. Perkins, A. Pletzer, A. H. Reiman, M. Rosenbluth, E. J. Strait, T. S. Taylor, A. D. Turnbull, F. Waelbroeck, J. C. Wesley, H. R. Wilson, and R. Yoshino, Physics of Plasmas **4**(5), 1654–1664 (1997).
[4]K. Hoshino, M. Mori, T. Yamamoto, H. Tamai, T. Shoji, Y. Miura, H. Aikawa, S. Kasai, T. Kawakami, H. Kawashima, M. Maeno, T. Matsuda, K. Oasa, K. Odajima, H. Ogawa, T. Ogawa, T. Seike, T. Shiina, K. Uehara, T. Yamauchi, N. Suzuki, and H. Maeda, Physical Review Letters **69**(15), 2208–2211 (1992).
[5]E. J. Strait, L. Lao, A. G. Kellman, T. H. Osborne, R. Snider, R. D. Stambaugh, and T. S. Taylor, Physical Review Letters **62**(11), 1282–1285 (1989).
[6]R. J. L. Haye, L. L. Lao, E. J. Strait, and T. S. Taylor, Nuclear Fusion **37**(3), 397 (1997).
[7]Z. Chang, E. D. Fredrickson, J. D. Callen, K. M. McGuire, M. G. Bell, R. V. Budny, C. E. Bush, D. S. Darrow, A. C. Janos, L. C. Johnson, H. K. Park, S. D. Scott, J. D. Strachan, E. J. Synakowski, G. Taylor, R. M. Wieland, M. C. Zarnstorff, and S. J. Zweben, Nuclear Fusion **34**(10), 1309 (1994).
[8]G. Gantenbein, H. Zohm, G. Giruzzi, S. Günter, F. Leuterer, M. Maraschek, J. Meskat, Q. Yu, ASDEX Upgrade Team, and ECRH-Group, Physical Review Letters **85**(6), 1242–1245 (2000).
[9]S. Günter, A. Gude, M. Maraschek, Q. Yu, and ASDEX Upgrade Team, Plasma Physics and Controlled Fusion **41**(6), 767 (1999).
[10]J. A. Snipes, D. J. Campbell, T. C. Hender, M. V. Hellermann, and H. Weisen, Nuclear Fusion **30**(2), 205 (1990).
[11]ITER Physics Expert Group on Disrup MHD and ITER Physics Basis Editors, Nuclear Fusion **39**(12), 2251 (1999).
[12]T. C. Hender, J. C. Wesley, J. Bialek, A. Bondeson, A. H. Boozer, R. J. Buttery, A. Garofalo, T. P. Goodman, R. S. Granetz, Y. Gribov, O. Gruber, M. Gryaznevich, G. Giruzzi, S. Günter, N. Hayashi, P. Helander, C. C. Hegna, D. F. Howell, D. A. Humphreys, G. T. A. Huysmans, A. W. Hyatt, A. Isayama, S. C. Jardin, Y. Kawano, A. Kellman, C. Kessel, H. R. Koslowski, R. J. L. Haye, E. Lazzaro, Y. Q. Liu, V. Lukash, J. Manickam, S. Medvedev, V. Mertens, S. V. Mirnov, Y. Nakamura, G. Navratil, M. Okabayashi, T. Ozeki, R. Paccagnella, G. Pautasso, F. Porcelli, V. D. Pustovitov, V. Riccardo, M. Sato, O. Sauter, M. J. Schaffer, M. Shimada, P. Sonato, E. J. Strait, M. Sugihara, M. Takechi, A. D. Turnbull, E. Westerhof, D. G. Whyte, R. Yoshino, H. Zohm, ITPA MHD, and Disruption and Magnet Group, Nuclear Fusion **47**(6), S128 (2007).
[13]A. Sykes and J. A. Wesson, Physical Review Letters **44**(18), 1215–1218 (1980).
[14]J. Wesson, R. Gill, M. Hugon, F. Schüller, J. Snipes, D. Ward, D. Bartlett, D. Campbell, P. Duperrex, and A. Edwards, Nuclear Fusion **29**(4), 641 (1989).
[15]H. P. Furth, J. Killeen, and M. N. Rosenbluth, The Physics of Fluids **6**(4), 459–484 (1963).
[16]R. White, Reviews of Modern Physics **58**(1), 183 (1986).
[17]H. P. Furth, P. H. Rutherford, and H. Selberg, The Physics of Fluids **16**(7), 1054–1063 (1973).
[18]C. C. Hegna, Physics of Plasmas **5**(5), 1767–1774 (1998).
[19]R. J. L. Haye, Physics of Plasmas **13**(5), 055501 (2006).
[20]B. Carreras, B. V. Waddell, H. R. Hicks, and S. J. Lynch, Physical Review A **18**(6), 2732–2734 (1978).
[21]B. V. Waddell, B. Carreras, H. R. Hicks, J. A. Holmes, and D. K. Lee, Physical Review Letters **41**(20), 1386–1389 (1978).
[22]J. A. Holmes, B. Carreras, H. R. Hicks, S. J. Lynch, and B. V. Waddell, Nuclear Fusion **19**(10), 1333 (1979).
[23]R. J. L. Haye, B. W. Rice, and E. J. Strait, Nuclear Fusion **40**(1), 53 (2000).
[24]A. Isayama, Y. Kamada, N. Hayashi, T. Suzuki, T. Oikawa, T. Fujita, T. Fukuda, S. Ide, H. Takenaga, K. Ushigusa, T. Ozeki, Y. Ikeda, N. Umeda, H. Yamada, M. Isobe, Y. Narushima, K. Ikeda, S. Sakakibara, K. Yamazaki, K. Nagasaki, and JT-60 Team, Nuclear Fusion **43**(10), 1272 (2003).
[25]D. A. Humphreys, J. R. Ferron, R. J. L. Haye, T. C. Luce, C. C. Petty, R. Prater, and A. S. Welander, Physics of Plasmas **13**(5), 056113 (2006).
[26]C. Petty, R. La Haye, T. Luce, D. Humphreys, A. Hyatt, J. Lohr, R. Prater, E. Strait, and M. Wade, Nuclear Fusion **44**(2), 243 (2004).
[27]ECRH Group, ASDEX Upgrade Team, M. Maraschek, G. Gantenbein, Q. Yu, H. Zohm, S. Günter, F. Leuterer, and A. Manini, Physical Review Letters **98**(2), 025005 (2007).
[28]Y. Yuan, X. Q. Lu, J. Q. Dong, X. Y. Gong, and R. B. Zhang, Physics of Plasmas **25**(1), 012510 (2018).
[29]B. Esposito, G. Granucci, M. Maraschek, S. Nowak, E. Lazzaro, L. Giannone, A. Gude, V. Igochine, R. McDermott, E. Poli, M. Reich, F. Sommer, J. Stober, W. Suttrop, W. Treutterer, H. Zohm, ASDEX Upgrade, and FTU Teams, Plasma Physics and Controlled Fusion **53**(12), 124035 (2011).
[30]W. Xiaoguang, Z. Xiaodong, Y. Qingquan, W. Bin, Z. Sizheng, W. Jinfang, Z. Yang, and W. Xiaojing, Nuclear Fusion **55**(9), 093024 (2015).
[31]M. Patrick, W. Fabien, F. Olivier, L. Hinrich, and G. Xavier, Plasma Physics and Controlled Fusion **60**(9), 095003 (2018).
[32]O. Février, P. Maget, H. Lütjens, and P. Beyer, Plasma Physics and Controlled Fusion **59**(4), 044002 (2017).
[33]D. Grasso, D. Borgogno, L. Comisso, and E. Lazzaro, Journal of Plasma Physics **84**(3), 745840302 (2018).
[34]E. Lazzaro, D. Borgogno, D. Brunetti, L. Comisso, O. Fevrier, D. Grasso, H. Lutjens, P. Maget, S. Nowak, O. Sauter, C. Sozzi, and EUROfusion MST1 Team, Plasma Physics and Controlled Fusion **60**(1), 014044 (2018).
[35]N. Bertelli, D. D. Lazzari, and E. Westerhof, Nuclear Fusion **51**(10), 103007 (2011).
[36]C. C. Hegna and J. D. Callen, Physics of Plasmas **4**(8), 2940–2946 (1997).
[37]H. Zohm, Physics of Plasmas **4**(9), 3433–3435 (1997).
[38]A. Isayama, Y. Kamada, S. Ide, K. Hamamatsu, T. Oikawa, T. Suzuki, Y. Neyatani, T. Ozeki, Y. Ikeda, K. Kajiwara, and JT-60 Team, Plasma Physics and Controlled Fusion **42**(12), L37 (2000).
[39]D. Hongfei, D. Siye, C. Jiale, W. Yifeng, L. Hui, X. Guosheng, Z. Xuemei, L. Haiqing, Z. Qing, L. Bo, D. Yanmin, Q. Jinping, and G. Xianzu, Nuclear Fusion **58**(6), 066011 (2018).
[40]A. Pletzer and F. W. Perkins, Physics of Plasmas **6**(5), 1589–1600 (1999).
[41]A. H. Reiman, The Physics of Fluids **26**(5), 1338–1340 (1983).
[42]Q. Yu, S. Günter, G. Giruzzi, K. Lackner, and M. Zabiego, Physics of Plasmas **7**(1), 312–322 (2000).
[43]B. Ayten and E. Westerhof, Physics of Plasmas **19**(9), 092506 (2012).
[44]S. Wang and Z. Ma, Physics of Plasmas **22**(12), 122504 (2015).
[45]S. Wang, Z. Ma, and W. Zhang, Physics of Plasmas **23**(5), 052503 (2016).
[46]W. Zhang, S. Wang, and Z. W. Ma, Physics of Plasmas **24**(6), 062510 (2017).
[47]W. Zhang, Z. W. Ma, and S. Wang, Physics of Plasmas **24**(10), 102510 (2017).
[48]T. G. Jenkins, S. E. Kruger, C. C. Hegna, D. D. Schnack, and C. R. Sovinec, Physics of Plasmas **17**(1), 355 (2010).
[49]D. D. Lazzari and E. Westerhof, Nuclear Fusion **49**(7), 075002 (2009).
[50]E. Westerhof and J. Pratt, Physics of Plasmas **21**(10), 102516 (2014).
[51]O. Février, P. Maget, H. Lütjens, J. F. Luciani, J. Decker, G. Giruzzi, M. Reich, P. Beyer, E. Lazzaro, S. Nowak, and ASDEX Upgrade Team, Plasma Physics and Controlled Fusion **58**(4), 045015 (2016).

[52] G. Giruzzi, M. Zabiégo, T. A. Gianakon, X. Garbet, A. Cardinali, and S. Bernabei, Nuclear Fusion **39**(1), 107 (1999).

[53] W. Xiaojing, Y. Qingquan, Z. Xiaodong, Z. Yang, Z. Sizheng, W. Xiaoguang, and W. Bin, Plasma Physics and Controlled Fusion **60**(4), 045004 (2018).

[54] Q. Yu, X. D. Zhang, and S. Günter, Physics of Plasmas **11**(5), 1960–1968 (2004).

[55] H. Zohm, G. Gantenbein, A. Gude, S. Günter, F. Leuterer, M. Maraschek, J. P. Meskat, W. Suttrop, Q. Yu, ASDEX Upgrade Team, and ECRH Group, Nuclear Fusion **41**(2), 197 (2001).

[56] C. Z. Cheng and M. S. Chance, Journal of Computational Physics **71**(1), 124–146 (1987).

[57] W. Xiaoguang, Z. Xiaodong, Y. Qingquan, W. Bin, Z. Sizheng, and H. Yemin, Physics of Plasmas **22**(2), 022512 (2015).