GTC linear simulations of tearing mode stabilization by ECCD in toroidal plasma

Jingchun Li¹,²,³, Chijie Xiao¹, Zhihong Lin⁵,¹, Dongjian Liu⁴ and Xiaoquan Ji⁵, Xiaogang Wang⁶

¹Fusion Simulation Center, Peking University, Beijing 100871, People’s Republic of China
²School of Physics, Nankai University, Tianjin 300071, People’s Republic of China
³University of California, Irvine, CA 92697, USA
⁴Sichuan University, Chengdu 610064, People’s Republic of China
⁵Southwestern Institute of Physics, Chengdu 610041, People’s Republic of China
⁶Harbin Institute of Technology, Harbin 150001, People’s Republic of China

E-mail: jingchnl@uci.edu

Abstract. Stabilization of tearing modes in tokamaks by localized electron cyclotron current drive (ECCD) has been studied using gyrokinetic code GTC coupled with ECCD ray tracing and Fokker-Planck GENRAY/CQL3D package. Linear gyrokinetic simulations using fluid-kinetic hybrid model find that the tearing modes can be fully stabilized by the ECCD with 1MW 68GHz X2-mode in HL-2A-like equilibrium, while the tearing modes in DIII-D tokamak are only partially stabilized with the same ECCD power. A helicon current drive is more efficient than a continuous ECCD to stabilize the tearing modes. Simulation results also indicate that, without external current drive, thermal ion kinetic effects could also reduce magnetic island width as well as growth rate of the tearing modes.

1. Introduction

Tearing mode instabilities (TM) can degrade plasma performance and may even lead to disruptions. Various methods for TM control have been established and verified in experiments, such as electron cyclotron current drive (ECCD), lower hybrid current drive, externally applied resonant magnetic perturbations, and neutral beam injection. Since ECCD can be highly localized and robustly controlled, it is considered to be an effective and successful method of controlling TMs. Experiments of ECCD as well as electron cyclotron resonant heating (ECRH) on many devices such as ASDEX Upgrade, DIII-D, and JT-60U has shown complete suppression of TMs or neoclassical tearing modes (NTM), a class of the tearing modes driving by bootstrap current. Moreover, DIII-D results also found that the stationary operation of hybrid scenario plasmas was successfully attained until the ECCD was turned off, suggesting tearing mode stabilization with ECCD is critical for the stable operation.
The TM stabilization condition have been achieved in the HL-2A tokamak\[16\], so this device is considered here as a typical case for the tearing mode suppression. Only TM stabilization by ECRH has been achieved in HL-2A experiments. Similar experiments also have been reported in TCV\[17\], TEXTOR\[18\], ASDEX Upgrade\[19\], etc. TM stabilization by ECCD requires a toroidal component to the EC injection. In DIII-D, R. J. La Haye et al. used active feedback to control the the neoclassical tearing mode. \[20\] Subsequently, the complete suppression of the m/n = 2/1 neoclassical tearing mode was achieved using ECCD to replace the missing bootstrap current in the island’s O-point\[21\].

Since the TMs and neoclassical tearing mode stabilization by ECCD are still under investigation, it is essential to conduct corresponding simulations in order to facilitate and test the design of real-time control system for TMs. Numerical studies of TMs stabilization with ECCD have been carried out using various numerical algorithms\[22, 23, 24, 25, 26, 27, 28\]. However, most of these algorithms are based on the reduced resistive MHD model\[29\] in slab or cylindrical geometries. A. M. Popov et al. have simulated the TM suppression by a radially localized toroidal current from ECCD\[30\] with full MHD code. Thomas G. Jenkins has calculated the TM stabilization with ECCD using the NIMROD code and demonstrated the complete suppression of the (2,1) tearing mode\[31\]. However, these works fell short of realizing a fully coupled, self-consistent model for ECCD/MHD interaction, including toroidal effects and kinetic effects.

In fusion plasmas, the ions can have a significant kinetic effects on the evolution of tearing modes. Analytically, Cai et al. found that the co-circulating energetic ions can stabilize the TMs\[32\]. Subsequently, they reported the effects of energetic particles on TMs from M3D-K simulations\[33\]. In their model, background thermal ions and electrons are treated as a single fluid, and the energetic ions are described by the drift kinetic equation. W A Hornsby et al. studied the nonlinear tearing mode evolution with the gyro-kinetic code GKW, and their self-consistent interaction with electromagnetic turbulence\[34, 35\]. The kinetic effects of thermal ions on the TM stabilization are an important area of study that has not been investigated thoroughly.

We have performed kinetic simulations of tearing modes and their suppression with localized current drive in tokamak plasmas by using the gyrokinetic toroidal code (GTC),\[36\] which has been extensively applied to study neoclassical transport,\[37\] energetic particle transport,\[38\] Alfven eigenmodes,\[39, 40\] microturbulence,\[41, 42\] as well as current driving instabilities including kink,\[43\] and tearing modes\[44, 45\]. In Ref.\[45\], we studied the effect of ECCD on magnetic island. However, the ECCD model used there is an analytical model and simulations were performed in cylinder.

In order to study the influence of ECCD on TM more precisely and guide the future experiments of TM stabilization on specific tokamaks, we carry out gyrokinetic simulations in toroidal geometry. The effect of ECCD on TM is investigated through the coupling between the GTC and GENRAY/CQL3D package\[46, 47\] with ECCD ray tracing and Fokker-Planck operators. The current GTC simulations find that the
stability of tearing modes depend sensitively on the magnetic shear. The TMs can be perfectly stabilized by 1MW 68GHz X2-mode in HL-2A-like tokamak, while instabilities in the DIII-D discharge are only partially stabilized with the 1MW 110GHz X2-mode ECCD due to inadequate power input. Our simulation find that a helicon current drive is more efficient than a continuous ECCD. These simulation results also indicate, both in HL-2A and DIII-D, that the presence of thermal ion kinetic effects can reduce the island width as well as the growth rate, and the kinetic effect of thermal ions on TM is more pronounced with higher ion temperature.

The remainder of this paper is organized as follows. The simulation model of TM suppression by ECCD is introduced in Sec. 2. The driven current characteristics and its mechanism for controlling the tearing mode as well as the ion kinetic effects on the TM stabilization in HL-2A are presented in Sec. 3. The kinetic simulation of TMs suppression by a radially localized toroidal current from ECCD in DIII-D are described in Sec. 4. Finally, brief conclusions are drawn in Sec. 5.

2. Physics model

In order to study the low-frequency MHD instabilities, such as resistive tearing mode, a massless electron fluid model can be coupled with gyrokinetic ions through the gyrokinetic Poisson’s equation and Ampere’s law[44]. In this work, we neglect the electron kinetic effects, which has been implemented in GTC using a fluid-kinetic hybrid electron model[48] and a conservative scheme for solving electron drift kinetic equation[49]. To study the effects of ECCD on TM, the ECCD current is obtained by employing GENRAY/CQL3D code, which solves ray-tracing and Fokker-Planck equations.

2.1. Gyrokinetic ion and massless electron fluid model

The gyrokinetic equation[50, 51] describing toroidal(magnetized) plasmas in the inhomogeneous magnetic field is given by:

$$\frac{d}{dt} f_\alpha(X, \mu, v_\parallel, t) = (\frac{\partial}{\partial t} + \dot{X} \cdot \nabla + \dot{v}_\parallel \frac{\partial}{\partial v_\parallel}) f_\alpha = (\frac{\partial}{\partial t} f_\alpha)_{\text{collision}}$$

$$\dot{X} = \frac{B}{B_0} v_\parallel + \frac{c b_0 \times \nabla \phi}{B_0} + \frac{v_\parallel^2}{\Omega_\alpha} \nabla \times b_0 + \frac{\mu}{m_\alpha \Omega_\alpha} b_0 \times \nabla B_0$$

$$\dot{v}_\parallel = -\frac{1}{m_\alpha B^*_\parallel} \cdot (\mu \nabla B_0 + Z_i \nabla \phi) - \frac{Z_\alpha}{m_\alpha c} \frac{\partial A_\parallel}{\partial t}$$

Here, index $\alpha = e, i$ stands for the particle species, electron or ion. $X, \mu, v_\parallel$ is the particle guiding center position, the magnetic moment and parallel velocity. $\phi, A_\parallel$ is the electrostatic potential, and parallel vector potential, respectively, and both are gyro-averaging for ion. $Z_\alpha$ is the particle charge, $m_\alpha$ and $\Omega_\alpha$ as the particle mass and cyclotron frequency, $B_0 \equiv B_0 b_0$ is the equilibrium magnetic field, $B^*_0 = B_0 + (B_0 v_\parallel/\Omega_\alpha) \nabla \times b_0$,
\[ B^* = b_0 \cdot B_0^*, \] and the expression of \( B^* \) can be found in Ref. [49]. \( B \equiv B_0 + \delta B \), which incorporates all the magnetic perturbation. For electron, a Krook collisional operator, \( \frac{\partial}{\partial t} f_{e0} = \eta (f_e - f_{e0}) \) is used to provide resistivity, where \( f_{e0} \) is the equilibrium distribution function. For ion, the collision operator \( \left( \frac{\partial}{\partial t} f \right)_{\text{collsion}} \) has been implemented in GTC, however, as in Ref. [45], we will omit it in this work.

To reduce particle noises, a perturbative \( \delta f \) simulation scheme has been used [52, 53]. Assuming a neoclassical solution for equilibrium distribution function \( f_{\alpha 0} \) that satisfies the equilibrium drift kinetic equation,

\[ L_0 f_{\alpha 0} = 0 \]  
(4)

Where \( L_0 = \frac{\partial}{\partial t} + (v_{\parallel} b_0 + v_d) \cdot \nabla - \frac{\mu}{m_\alpha} b_0 \frac{\partial}{\partial v_{\parallel}} \) is the equilibrium propagator. Subtracting Eq. (1) by Eq. (4), the equation for the perturbed distribution \( \delta f_\alpha \) is

\[ L \delta f_\alpha = - \delta L f_{\alpha 0} \]  
(5)

where \( \delta L = (v_{\parallel} \frac{\delta B}{B_0} + v_E) \cdot \nabla - \left( \frac{\mu}{m_\alpha} \frac{\delta B}{B_0} \nabla B_0 + \frac{q_\alpha}{m_\alpha} v_{\parallel} \frac{\partial \phi}{\partial v_{\parallel}} \right) \frac{\partial}{\partial v_{\parallel}} \). On the right side of Eq. (5), we use a shift maxwellian as an approximation of the neoclassical solution \( f_0 \).

Defining the particle weight as \( w_\alpha = \delta f_\alpha / f_{\alpha 0} \), we can rewrite Eq. (1) as the weight equation by using Eq. (5)

\[ \frac{dw_\alpha}{dt} = (1 - w_\alpha) \left[ -(v_{\parallel} \frac{\delta B}{B_0} + v_E) \cdot \nabla f_{\alpha 0} \right. \]
\[ \left. + \left( \frac{\mu}{m_\alpha} \frac{\delta B}{B_0} \cdot \nabla B_0 + \frac{q_\alpha}{m_\alpha} B^* \cdot \nabla \phi + \frac{q_\alpha}{c} \frac{\partial A}{\partial t} \right) \right] \times \frac{1}{m_\alpha f_{\alpha 0} \frac{\partial}{\partial v_{\parallel}}} \]  
(6)

The dynamic equation (Eq. (6)) together with the field equations (see following Eq. (11) and Eq. (12)) form the closed system of equations for the nonlinear gyrokinetic simulations. For ions, we use these standard gyrokinetic formulations. Note that we confine to linear simulation here, therefore, the nonlinear terms in Eq. (5) are not incorporated in this paper. For electrons, we integrate Eq. (1) to get the perturbed fluid continuity equation:

\[ \frac{\partial}{\partial t} \delta n_e + B_0 \cdot \nabla \left( \frac{n_{e0} \delta u_{\parallel e}}{B_0} \right) + B_0 \delta v_E \cdot \nabla \left( \frac{n_e}{B_0} \right) \]
\[ -n_{e0} (\delta v_{*e} + \delta v_E) \cdot \nabla B_0 \frac{\nabla}{B_0} + \delta B \cdot \nabla \left( \frac{n_{e0} \delta u_{\parallel e0}}{B_0} \right) \]
\[ + c \nabla \times B_0 \frac{B_0^2}{B_0^2} \cdot \left( - \frac{\nabla \delta p_e}{e} + n_{e0} \nabla \delta \phi \right) = 0 \]  
(7)

and the parallel momentum equation:

\[ n_{e0} m_e \frac{\partial}{\partial t} \delta u_{\parallel e} + n_{e0} m_e u_{\parallel e0} \cdot \nabla \delta u_{\parallel e} = -n_{e0} e \left( -\nabla \delta \phi - \frac{1}{c} \frac{\partial \delta A}{\partial t} \right) \]
\[ - \frac{\delta B}{B_0} \cdot \nabla p_{e0} - \nabla \delta p_e - n_{e0} m_e v_{e0} \delta u_{\parallel e} \]  
(8)
Here, the total electron density $n_e$, parallel flow $u_{\parallel e}$, and pressure $p_e$ are the sum of their equilibrium and perturbed parts, i.e., $n_e = n_{e0} + \delta n_e$, $u_{\parallel e} = u_{\parallel e0} + \delta u_{\parallel e}$, and $p_e = p_{e0} + \delta p_e$. The nonlinear terms in Eqs.(7, 8) have been dropped. Since this work is focused on the resistive tearing mode, we neglect the electron inertial term on the left hand side of Eq. (8). Furthermore, we treat the effect of the ECCD source enters as an additional force on the electron fluid, thereby reducing the massless electron momentum equation to the parallel force balance equation:

$$\frac{\partial \delta A_{\parallel}}{\partial t} = -c\mathbf{b}_0 \cdot \nabla \delta \phi + \frac{c}{n_{e0}e} \mathbf{b}_0 \cdot \nabla \delta p_e - c\eta (\delta j - \delta j_{eccd})$$

(9)

Here, $\delta j = -\frac{c}{4\pi} \nabla^2 \delta A_{\parallel}$, and $\delta j_{eccd}$ is the EC-driven current density.

In order to complete the fluid model, we use the gyrokinetic Poisson’s equation

$$\frac{4\pi Z_i^2}{T_i} (\delta \phi - \delta \tilde{\phi}) = 4\pi (Z_i \delta n_i - e\delta n_e)$$

(10)

and the parallel Ampere’s law

$$en_{e0} \delta u_{\parallel e} = \delta j + Z_i n_{i0} \delta u_{\parallel i};$$

(11)

$n_i$ and $u_{\parallel i}$ can be calculated from the standard gyrokinetic model for ions[48], namely, Eq. (1-6).

The gyrokinetic ions (1-6) and the fluid electrons (7-9) are coupled through equations (10) and (11). These equations form a closed system which can simulate the low frequency MHD instabilities.

2.2. Model for electron cyclotron current drive

The ECCD current is calculated by the GENRAY/CQL3D software package[46, 47]. The two principal equations solved in the package are ray-tracing equations and Fokker-Planck equation.

The ray-tracing equations are:

$$\frac{dR}{dt} = -\frac{c}{\omega} \frac{\partial D_0 / \partial N_R}{\partial \omega}$$

$$\frac{d\varphi}{dt} = -\frac{c}{\omega} \frac{\partial D_0 / \partial M}{\partial \omega}$$

$$\frac{dZ}{dt} = -\frac{c}{\omega} \frac{\partial D_0 / \partial N_Z}{\partial \omega}$$

(12)

(13)

(14)

Here we use cylindrical coordinates $R = (R, \varphi, Z)$, where $R$ is the major radius, $\varphi$ is the toroidal angle, and $Z$ is along the vertical axis. $N = Kc/\omega = (N_R, M = RN_\varphi, N_Z)$. $D_0$ is the dispersion function calculated using the magnetized cold plasma approximation and is given in Ref.[46]. In our calculations, the poloidal injection angle, $\alpha$, is defined with respect to the $Z=$constant plane at the source, with positive angles above the plane and negative below. The toroidal injection angle, $\beta$, is measured counterclockwise with
respect to the $Z$ axis. $\omega$ denotes wave frequency and the dispersion relation calculated with cold plasma approximation.

The 3-dimensional bounce averaged Fokker-Planck equation, 2-D in momentum space (slowing down, pitch-angle) and 1-D in configuration space (radial dimension) for the electron distribution function $f_e$ are given by:

$$\frac{\partial f_e}{\partial t} = \frac{\partial f_e}{\partial u} D_{EC} \frac{\partial f_e}{\partial u} + \hat{\mathcal{C}} f_e$$

(15)

where $D_{EC}$ is the diffusion coefficients of the electron cyclotron wave (ECW) in the velocity space, $u = p/m_e$ is the normalized momentum, and $\hat{\mathcal{C}}$ is the collision operator. Solving the Fokker-Planck equation, we obtain the distribution function. The driven current density can be calculated from:

$$\delta j_{eccd}(r) = -en_e c \int \frac{u_\parallel}{\gamma} f_e(r, u) du$$

(16)

Here, $\gamma$ is the electron relativistic factor. Once the ECCD current is obtained from GENRAY/CQL3D, the effect of the ECCD on tearing mode can be implemented in GTC through Eq. (9). If we use Eq. (16) as $\delta j_{eccd}$ in Eq. (9) directly, it means that we consider the continuous current drive by neglecting effects of magnetic islands. It is well known that the driven current at the O-point can suppress the tearing mode, while at the X-point, it leads to the destabilization of the tearing mode\[54, 55\]. In experiment, such a helical current has been generated by modulating continuous current drive, and better efficiency for suppressing tearing modes has been obtained\[55\]. Therefore, a helical driven current is also used to study the suppression of tearing modes. This kind of driven current density can be written as follows:

$$\delta j_{eccd} = \delta j_{eccd}(r)(1 + \cos(m\theta - n\xi))$$

(17)

It should be noted that due to time scale separations, the ray tracing and Fokker-Planck equation are not solved simultaneously with the hybrid model equation in GTC. Thus, the effect of the magnetic perturbations on the wave deposition and the source current profile is neglected. Finally, compared with the model in Ref. \[45\], the ECCD model used here is more realistic because this current drive is calculated by solving ray-tracing equations and Fokker-Planck equations in the GENRAY/CQL3D package. While in the former paper, the current term only applies an analytical formula without involving the RF-induced current.

3. GTC simulations of tearing modes in HL-2A-like equilibrium

We first simulate the tearing mode in HL-2A-like equilibrium with fluid model, namely treat both electron and ion as fluid\[44\] by suppressing ion kinetic effects. These results will be shown in section 3.1 and 3.2. In section 3.3, we use the gyrokinetic ion and massless electron fluid model, as described in section 2.1, to study the effect of kinetic ions.
3.1. Simulation of tearing mode without current drive

An HL-2A-like model equilibrium with circular cross section is chosen in our simulation, i.e., the major radius is $R_0 = 1.65m$, the minor radius is $a = 0.4m$ and on-axis magnetic field is $B_0 = 1.27T$. The equilibrium $q$ profile, electron density, and temperature profile utilized are shown in Figure 1. The electron density and temperature profile are from experimental data[56], while the $q$ profile is modified from EFIT-reconstruction, and circular-cross-section is assumed. Our calculation shows that it is the stronger magnetic shear that excites to the tearing mode in HL-2A. In the simulations, we use the number of grids $150 \times 350 \times 16$ in the radial, poloidal and parallel direction respectively. The equilibrium plasma current is $157kA$, the $q = 2/1$ surface is $r = 0.6a$, and the plasma resistivity is $\eta = 10^{-5}\Omega/m$. The resistivity is higher than the Spitzer resistivity ($\eta \sim 10^{-8}\Omega/m$ with the HL-2A parameter). This is because large time steps cause numerical errors in the finite difference model when the resistivity is very low. We have calculated the dependence of the linear growth rate on the resistivity and found that the dependence is similar to the theoretical resistivity scaling of tearing modes, i.e., $\eta^{3/5}$. The dependence of ECCD stabilization on $\eta$ is under investigation and not clarified in this paper.

We have verified the GTC capability of the resistive tearing mode simulation in Ref. [45], therefore we utilize this capability for the tearing mode simulation in HL-2A-like configuration. It is found that the mode amplitude oscillates in the early stage and then starts to increase linearly at $t = 1.7 \times 10^{-5}s$. The corresponding magnetic island width is about $0.169a$ at this time, and the growth rate is $0.13\omega_s$, where the normalized frequency is $\omega_s \equiv c_s/R_0$, $c_s \equiv \sqrt{T_e/m_i}$ and $T_e$ is calculated at the $q = 2$ rational surface. Note that the initial magnetic island width ($0.13a$ when $t=0$) given here is dependent on the initial parallel vector perturbation potential, which is given by
Figure 2. (a) Electron cyclotron wave trajectories on a poloidal plane with initial magnetic island, (b) ECCD current density versus major radius.

\[ A(r) = -0.658 \times 10^{-3} (r/a)^2 (1 - r/a)^2. \]

3.2. Tearing mode stabilization by stationary ECCD

A typical electron cyclotron current drive in HL-2A-like equilibrium is shown in Figure 2 for both continuous ECCD and helicon ECCD. Figure 2(a) shows the EC-wave trajectories on a poloidal plane, and Fig. 2(b) shows the current density versus major radius from the GENRAY/CQL3D calculations. In this case, the poloidal and toroidal injection angle is \( \alpha = 113^\circ \) and \( \beta = 190^\circ \), respectively, the wave power is 1MW, and the wave frequency is 68 GHz X2-mode. The total driven current here is 13 kA. The current ratio \( CR \equiv I_{ECCD}/I_0 = 0.08 \), the corresponding current ratio at the mode rational surface between the current density by external current drive and the perturbed current density is \( \delta j_{eccd}/\delta j = 1.6 \), with the radial deposition position located at \( r/a = 0.6 \), which is approximately at the rational surface of \( q = 2 \). The poloidal profiles of the TM perturbed current density and the helicon ECCD current density are shown in Fig. 3.

An example of the evolutions of tearing mode magnetic island width without ECCD, with continuous ECCD, and helicon ECCD is shown in Fig. 4. It can be seen that without ECCD, (2,1) TM amplitude increases after an initial oscillatory phase. In the case of ECW injection, width of the TM island decreases quickly and reduces to zero at about \( t = 3.5 \times 10^{-5} \) s. Moreover, the growth rate of TM is negative (damping rate of \( 0.10\omega_a \)), thus, the TM is indeed stabilized by ECCD. Finally, the helicon current drive is more efficient than the continuous ECCD. In comparison with continuous ECCD, the damping rate with helicon current drive is about \( 0.25\omega_a \). In summary, we find that 1MW ECW is sufficient to suppress the (2,1) tearing mode in a typical HL-2A equilibrium.

In general, the tearing mode in HL-2A is straightforward to suppress for this
Figure 3. The poloidal structure of TM perturbed current density (a) and helicon ECCD current density (b).

equilibrium parameter. Since the steering mirrors in the launcher allow the poloidal injection angle and the toroidal injection angle to be rotated between $-20^\circ \sim 20^\circ$, it is possible to inject the ECW off-axis, i.e., $r/a = 0.6$ in this case. The TM stabilization is closely related to the value of the current ratio CR ($CR \equiv I_{rf}/I_0$). A previous study found that the tearing mode can be completely suppressed when the current ratio CR is about 0.04. The equilibrium plasma current $I_0$ is low in this case. However, the total ECW power of 3MW is sufficient to suppress the TMs, even if $I_0$ reaches the highest value in HL-2A (450 kA). Finally, the dependence of TMs magnetic island width and growth rates on wave radial misalignment has been investigated in Ref. [45].

3.3. Ion kinetic effects on the tearing mode stabilization

We study the kinetic effects of thermal ions in the GTC simulations. In our simulation, the number of grids $150 \times 350 \times 16$ in the radial, poloidal and parallel direction are used. We adopt the same HL-2A parameters as in Section 3.1, and load 20 ions in every cell. Figure 5 shows the mode structure (a and b) and the magnetic island of TMs (c) without kinetic thermal ions (top), and with kinetic thermal ions (bottom). Both mode structure and magnetic island width shrink in the case with kinetic thermal ions given the same initial condition. Figure 5 (c) shows a clear difference in island width in these two cases. The island radial width of the TMs with kinetic ions is significantly
Figure 4. Time evolution of the width $w$ of tearing mode magnetic island without, with continuous ECCD, and helicon ECCD.

Figure 5. The mode structure (a)$\delta A_{||}$, (b)$\delta \phi$, and (c)the magnetic island, without thermal kinetic effect of ions (top panel), or with kinetic effect of thermal ions (the bottom panel).
smaller than that without kinetic ions at the same time, \( t = 1.9 \times 10^{-5} \text{s} \). The growth rate decreases to \(-0.12\omega_s\) when the ion kinetic effects are included. This indicates that the TM is damping when considering the ion kinetic effect. The phenomena is because that the magnetic shear of the modified \( q \) is still weak. The TMs could increase with a strong magnetic shear \( q \), even when we considering the kinetic effect of ion.

Moreover, with the kinetic ions added, we can see that the island has a weak clockwise rotation, which is in the same direction of ion diamagnetic drift direction. This rotation is more prominent when we calculate a case with \( q = 1.75 + 4.66(\psi/\psi_w)^2 \), where \( \psi \) is the poloidal magnetic flux, \( \psi_w \) is the poloidal magnetic flux of plasma edge, and the \( q = 2 \) rational surface shifts to inner plasma. And the calculated rotation frequency is 1.08KHz, which is very small in comparison with the ion diamagnetic drift frequency.

Figure 5 has shown that the radial mode width shrinks when kinetic thermal ions are added, and the net effect of kinetic ions on tearing modes is significant and stabilizing. We suspect that the kinetic ion interacts with the mode structure, and damp the edge region of it, and this damping finally leads to the decrease of the radial width of the magnetic island. To verify this argument, we further scan the temperature of thermal ions in order to study the kinetic effects of thermal ions. We also calculate the dependence of ion temperature on the island width and the growth rates of TM. It is found that the island radial width increases with decreasing ion temperature. The growth rate for the three cases, \( T_i = 0.01, 0.1, \) and \( 1T_e \), are \(-0.10\omega_s, -0.09\omega_s, -0.12\omega_s\), respectively. It can be concluded that when the ion temperature decreases, both the island radial width and the growth rates approach the values from fluid simulations. Therefore, this figure indeed confirms the ion thermal damping effect.

4. GTC simulations of tearing mode instability in DIII-D

The simulation of the tearing mode stabilization in DIII-D is presented in this section. The TM and its suppression by ECCD is shown in section 4.1 and 4.2. The effect of kinetic ion is calculated in Sec. 4.3.

4.1. Simulation of tearing mode without ECCD

Firstly, the equilibrium of DIII-D discharge 157402\[^{58}\] reconstructed from the EFIT code\[^{59}\] is used. This discharge has a prominent neoclassical tearing mode. However, this work is concentrated on the TM simulation and its suppression. Therefore, we ignore the effects of neoclassical bootstrap current (i.e., the bootstrap current terms in Eq.(9) were not incorporated) and consider only the 2D equilibrium profiles. The discharge parameters are given as follows: the major radius is \( R_0 = 1.78m \), the minor radius is \( a=0.58m \), the equilibrium plasma current is 790 kA, the \( q = 2/1 \) surface is \( r = 0.54a \), and the toroidal magnetic field strength is \( B_T = 2.06T \). In the simulations, we use number of grids \( 128 \times 512 \times 32 \) in the radial, poloidal and parallel direction
The configuration, equilibrium q profile, the electron density, and the temperature profile are shown in Figure 6. The resistivity is set to $\eta = 10^{-5} \Omega/m$.

Figure 7 shows the mode structures of the parallel vector potential and electrostatic potential, and the island structure at $t = 2.8 \times 10^{-5}$ s on the poloidal plane. The mode amplitude begins to increase linearly at this time, with the corresponding magnetic island width of about 0.127a at this time and the growth rate of 0.016$\omega_s$. Fig. 7 shows the (2, 1) tearing mode structures in DIII-D configuration. Our simulations show that tearing mode is unstable in this DIII-D discharge, which may provide the seed island for the neoclassical tearing mode.

### 4.2. Tearing mode stabilization by stationary ECCD

For equilibrium and plasma parameters used in Section 4.1, a 110 GHz electron cyclotron wave is launched with X-mode polarization from a port above the midplane, with the trajectories of the electron cyclotron wave shown in Figure 8(a). With 1MW ECW power injected, the corresponding profile of driven current density with a poloidal angle of 100° and a toroidal angle of 193° is shown in Figure 8(b). The absorption coefficient is 0.97 and the total driven current is 11 kA (CR = 0.013, the corresponding current density ratio, $\delta j_{eccd}/\delta j = 1.25$), with the radial deposition position located at $r/a = 0.5$ and a very narrow current drive profiles characteristic of ECCD, about 3.5 cm full width half maximum (FWHM), which is well suited for stabilizing TMs.
An example of the evolution of a TM magnetic island width with and without the ECCD in Fig. 8 (b) is shown in Figure 8 (c). Without ECCD, the TMs grow slowly and form a eigenmode. The stability is improved with ECCD since the magnetic island width decreases with ECCD, however, the island width does not decrease to zero in this case. The ECCD only reduces the growth the TMs, rather than fully stabilizing it. This is due to the low ECCD current (11 kA), significantly below the equilibrium current (790 kA), and that a higher input ECW power is required to entirely suppress the TMs. Indeed, if the value of CR is increased in the simulation, the tearing modes are almost suppressed when CR equals to 0.09 (as depicted by the orange line in Fig. 8 (c)). The island size decrease to very small width and corresponding damping rate is of $0.08\omega_s$.

4.3. Ion kinetic effects on the tearing mode stabilization

We carry out the GTC kinetic simulations by loading 20 ions in every cell in the DIII-D configuration. Figure 9 shows the mode structure (a and b) and the island map of tearing mode (c) without kinetic thermal ions (top), and with kinetic thermal ions (bottom). In both cases, we do not consider the effect of ECCD and assume the ion and electron temperature profiles are the same, namely, $T_i = T_e$. The radial width of the TM island with kinetic thermal ions is significantly smaller than that without kinetic thermal ions. When considering the ion kinetic effects, the growth rate decreases to $0.009\omega_s$, compared the growth rate of TM without kinetic ion, $0.016\omega_s$.

We conclude that kinetic effects of thermal ions can reduce the growth rate of the TMs in a tokamak plasma. This result is consistent with analytical calculations[32, 60], which show that the kinetic contribution tends to reduce $\Delta'$ for the toroidal equilibria, and can lead to the stability for tearing mode.
Figure 8. (a) Electron cyclotron wave packet trajectories with magnetic island, (b) ECCD current density versus normalized major radius, and (c) Time evolution of the width w of tearing mode magnetic island without ECCD, and with different ECCD powers in DIII-D tokamak.

5. Conclusions

In summary, we have investigated the influence of the electron cyclotron current drive on the m/n=2/1 tearing mode using gyrokinetic simulations in a HL-2A-like equilibrium and DIII-D configuration. The tearing mode evolution is calculated with a massless electron fluid model, and the ECCD current source is obtained by ray-tracing and the Fokker-Planck method. We find that the stability of tearing mode depends on the magnetic shear. The TMs are found to be perfectly stabilized by a continuous 1MW 68GHz X2-mode in HL-2A-like tokamak since the growth of TM becomes negative when we turn on the ECCD. Our simulation also find that a helicon current drive is more efficient than a continuous ECCD. In the DIII-D tokamak, the (2,1) TM is unstable with the real experimental data as the simulation input. The TM is only partially stabilized with the 1MW 110GHz X2-mode due to low current ratio, namely due to the inadequate power input.

The ion kinetic effect on the tearing mode stabilization is demonstrated. Analysis of the GTC simulation reveals, both in HL-2A-like and DIII-D equilibria, that the presence of ions can reduce the island width as well as the growth rate due to the interaction between the ions and the TMs. Furthermore, with the ions added, we can see that there is a weak rotation of modes structure due to diamagnetic flow. The kinetic effect of thermal ions on TM is found to be more pronounced with higher ion temperature.

Our simulations under a certain machine configuration will contribute to the design of the real-time control system of the TMs, and provide useful suggestions to TMs or
neoclassical tearing mode control experiments for fusion device, especially for HL-2A and DIII-D tokamaks. Meanwhile, the calculations is part of a longer term plan of building a first-principles model and a self-consistent simulation of the neoclassical tearing mode in fusion plasmas.

6. Acknowledgments

The authors would like to thank W.W. Heidbrink at UCI for providing EFIT equilibrium of DIII-D shot 157402, and Min Xu, and L. W. Yan, Jun Wang at SWIP, Lei Shi and Jian Bao at UCI, Youjun Hu at ASIPP for fruitful discussions. J. C. Li would like to thank S. Y. Liang at SWIP providing the experimental data in HL-2A. This work is supported by the ITER-China program (2014GB107004, 2013GB111000), NSFC (11375053), U.S. DOE SciDAC ISEP, and the China Postdoctoral Science Foundation No. 2017M610023.
7. References