Triggering of Neoclassical Tearing Mode by Error Field Penetration

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We conduct the first simulation study of the neoclassical tearing mode (NTM) triggered by error field penetration. A series of processes including the error field penetration, formation of seed islands, and the triggering of the NTM occurs, when the plasma flow and the electron diamagnetic drift approximately cancel out each other. The excited NTM is the born-locked mode, which is locked from the beginning. In the case where the plasma flow and the electron diamagnetic drift completely cancel out each other, a vacuum island width necessary for triggering the born-locked NTM is much smaller than a seed island width necessary for triggering the original NTM. This tendency is consistent with a theoretical prediction. Thus, whether the born-locked NTM is excited depends on both the plasma flow velocity and the error field amplitude.

Keywords: neoclassical tearing mode, error field, plasma flow, perturbed bootstrap current, forced magnetic reconnection

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In tokamaks, magnetic islands driven by the neoclassical tearing mode (NTM) reduce the achievable β value, and the locking of the magnetic island rotation by resistive wall or error fields occasionally triggers disruptions of plasma discharges. To avoid locked magnetic islands is a particularly important technical issue. The NTM is a nonlinear instability destabilized by the perturbed bootstrap current [1]. For triggering the NTM, finite-amplitude perturbations called seed islands are necessary. The error field is caused by positioning errors of the main coil system. The error field induces the forced magnetic reconnection [2], even when the NTM is stable. The forced magnetic reconnection is prevented by plasma flows, i.e., the error field is shielded by plasma flows [3]. The formation of magnetic islands due to error fields is called the error field penetration. In experiments in JET, born-locked modes, which are the NTM locked at its onset, have been observed, where the error field penetration triggers the NTM [4–6]. Using a modified Rutherford equation, possibility of excitation of the born-locked NTM in ITER is pointed out [1]. However, the seed island formation by error field penetration and the consequent evolution of the NTM have not been fully investigated. In preceding works, it is found that the error field penetration occurs, when the plasma flow and the electron diamagnetic drift approximately cancel out each other [7–9]. In those works, an effect of the perturbed bootstrap current is not taken into account. However, the stability of the NTM becomes a problem in high β regime. In this paper, we consider the error field penetration as a seeding mechanism of the NTM.

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We consider tokamak plasmas with the minor radius a, the major radius R_0, and the toroidal magnetic field B_0. We introduce a reduced set of two-fluid equations [10], where the bootstrap current is phenomenologically introduced. We assume that the quasi-neutral density is constant in time and space, and the pressure is proportional to the temperature. The normalized reduced two-fluid equations are

$$\frac{\partial U}{\partial t} + [\phi + \delta\tau p, U] = \delta\tau\,[\nabla_\perp\phi; \nabla_\perp p] + \nabla_\parallel j_\parallel + \mu\nabla_\perp^2 U, \quad (1)$$

$$\frac{\partial\psi}{\partial t} = -\nabla_\parallel(\phi - \delta p) - \eta_\parallel\left(\tilde{j}_\parallel - \tilde{j}_{\rm bs}\right), \quad (2)$$

$$\frac{\partial p}{\partial t} + [\phi, p] = \epsilon^2\chi_\parallel\nabla_\parallel^2 p + \chi_\perp\nabla_\perp^2 p, \quad (3)$$

with $U = \nabla_\perp^2\phi$ and $j_\parallel = -\nabla_\perp^2\psi$, where U is the vorticity, ϕ is the electrostatic potential, $j_\parallel$ is the parallel current density, $\tilde{j}_\parallel$ is the parallel current density perturbation, $\tilde{j}_{\rm bs}$ is the bootstrap current perturbation, ψ is the magnetic flux, p is the electron pressure, μ is the perpendicular viscosity coefficient, $\eta_\parallel$ is the parallel resistivity, $\chi_\parallel$ is the parallel thermal diffusivity, $\chi_\parallel$ is the perpendicular thermal diffusivity, δ is the ion skin depth, $\epsilon = a/R_0$, τ is the ratio of the ion temperature to the electron tempearture, $\{\nabla_\perp, \nabla_\parallel\}$ are the perpendicular and parallel spatial differential operators, respectively, and the bracket with the semicolon in Eq. (1) is the spatial differential operator defined in Ref. [10]. The time is normalized by $\tau_{\rm A} = R_0/v_{\rm A}$, where $v_{\rm A}$ is the Alfvén velocity, and $\{\nabla_\perp, \nabla_\parallel\}$ are normalized by a and R_0, respectively. Our simulation set up is shown as follows. Assuming single-helicity modes resonant at the rational surface,

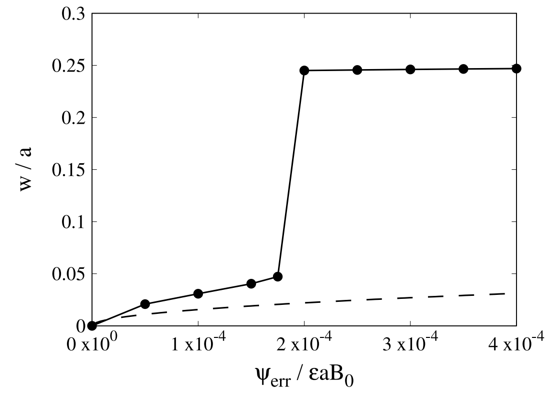

Fig. 1 Dependence of saturated island widths on $\psi_{\rm err}$. The vacuum island width is shown by a dashed line.

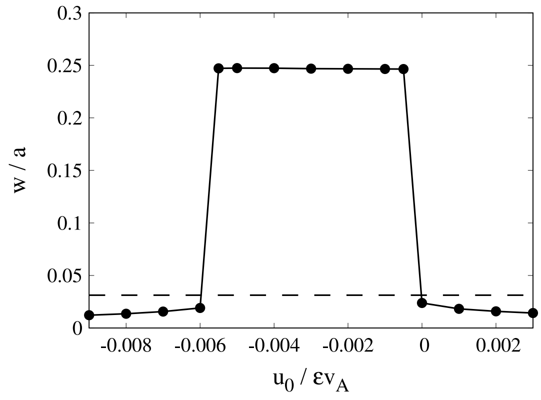

Fig. 2 Dependence of saturated island widths on u_0. The vacuum island width is shown by a dashed line.

we only consider spacial profile of variables in the two-dimensional coordinates (x, y), where x is the radial position and y is the poloidal position. The box size in the $x-y$ space is $L_x \times L_y = 1 \times \pi$, where the radial and poloidal boundaries are located at $x = 0, 1$ and $y = 0, \pi$, respectively. The bootstrap current perturbation is given by $\tilde{j}_{\rm bs} = -(f_{\rm bs} q_{\rm s}/2\sqrt{\epsilon})\partial_x \tilde{p}$, where $f_{\rm bs} = 1.46$ and $q_{\rm s}$ is the safety factor at the rational surface. The equilibrium quantities are given by $U_0 = 0$, $\phi_0 = u_0 x$, $\psi_0 = \ln[\cosh(x - x_{\rm s})]$, $p_0 = (\beta/\epsilon)[1 - (x - x_{\rm s})/(1 - x_{\rm s})]$, where $x_{\rm s} = 0.5$ is the radial position of the rational surface, and u_0 is the equilibrium poloidal flow velocity constant in space. Boundary conditions of perturbation in the y direction are periodic, and those in the x direction are fixed. The error field is applied in terms of the magnetic flux perturbation as $\tilde{\psi}(t, x, y)\big|_{x=1} = \psi_{\rm err}\cos(k_y y)$, where $\psi_{\rm err}$ is the amplitude, m_0 is the poloidal mode number of the error field, and $k_y = 2\pi m_0/L_y$. In addition, the relative magnitude of the error field is evaluated as $B_{\rm r}/B_0 = \epsilon k_y \psi_{\rm err}$, where $B_{\rm r}$ is the radial component of the error field at $x = 1$. In simulations, the following parameters are fixed: $\tau = 1, \beta = 0.02, \delta = 0.02$, $\epsilon = 0.3$, $q_{\rm s} = 2$, $m_0 = 2$, $\tau = 1$, $\eta_\parallel = 10^{-5}$, $\chi_\perp = 10^{-5}$, $\mu = \chi_\perp/4$, and $\epsilon^2\chi_\parallel = 1$. For consistency with the single-helicity assumption, only perturbations with poloidal mode numbers $m = 0, 2, 4, \ldots$ are considered. The tearing mode stability parameter for the $m = 2$ mode is $\Delta' = -7.86$. In addition, the electron diamagnetic drift velocity is given by $v_{*\rm e} = -\delta(dp_0/dx) = 2\delta\beta/\epsilon = 2.67 \times 10^{-3}$. In simulations, u_0 and $\psi_{\rm err}$ are used as control parameters.

First, nonlinear stability analysis of the NTM is performed. Using $u_0 = 0$ and $\psi_{\rm err} = 0$, time evolution of magnetic island widths for various seed island widths w_0 is simulated. It is found that the magnetic island grows to a large size $w_{\rm sat} = 0.24$, only when the seed island width exceed a critical value $w_0^{\rm crit} = 0.08$, and damps in other cases. Next, we consider cases where the NTM and the error field coexist. In the following part of this paper, w_0 is sufficiently small. In simulations, $u_0 = -v_{*\rm e} = -2.67 \times 10^{-3}$ is chosen. Figure 1 shows the error field amplitude dependence of saturated widths of magnetic islands which are locked from the beginning. It is shown that sudden transition occurs between $\psi_{\rm err} = 1.75 \times 10^{-4}$ and $\psi_{\rm err} = 2 \times 10^{-4}$, and the born-locked NTM is triggered in the large $\psi_{\rm err}$ regime. Note that the critical vacuum island width for triggering the born-locked NTM is about $w_{\rm v}^{\rm crit} = 0.02$, which is much smaller than $w_0^{\rm crit}$. A theoretical analysis based on the modified Rutherford equation predicts $w_{\rm v}^{\rm crit}/w_0^{\rm crit} = 2/(3\sqrt{3}) = 0.384\ldots$ [1], which roughly agrees with the simulation result $w_{\rm v}^{\rm crit}/w_0^{\rm crit} = 0.25$. Finally, we consider shielding effects of plasma flows in the presence of the electron diamagnetic drift. Figure 2 shows the dependence of saturated magnetic island widths on the value of u_0 for $\psi_{\rm err} = 4 \times 10^{-4}$. In the regime not far from $u_0 = -v_{*\rm e} = -2.67 \times 10^{-3}$, the born-locked NTM is triggered, while, suppression of the born-locked NTM following the error field shielding occurs in other regime.

In summary, we confirmed that the born-locked NTM is triggered, when the error field amplitude exceeds a critical value, and when plasma flows and the electron diamagnetic drift approximately cancel out each other.

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