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A mechanism of neoclassical tearing modes onset by drift wave turbulence

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Abstract

The evolution of neoclassical tearing modes (NTMs) in the presence of electrostatic drift wave turbulence is investigated. In contrast with anomalous transport effect induced by turbulence on NTMs, a new mechanism that turbulence-driven current can affect the onset threshold of NTMs significantly is suggested. Turbulence acts as a source or sink to exchange energy with NTMs. The turbulence-driven current can change the parallel current in magnetic islands and affect the evolution of NTMs, depending on the direction of turbulence intensity gradient. When the turbulence intensity gradient is negative, the turbulence-driven current enhances the onset threshold of NTMs. When the turbulence intensity gradient is positive, it can reduce or even overcome the stabilizing effect of neoclassical polarization current, leading to a small onset threshold of NTMs. This implies that NTMs can appear without noticeable magnetohydrodynamics (MHD) events.

Keywords: neoclassical tearing modes, turbulence, onset threshold

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

Neoclassical tearing modes (NTMs), driven by the perturbed helical bootstrap current due to the pressure flattening across magnetic islands can form large scale islands, degrade plasma confinement, and even lead to disruption if the islands are large enough in high β plasma ($\beta = 8\pi p/B^2$, where p and B are plasma pressure and magnetic field, respectively), resulting in a β limit. Thus, understanding the physics of NTMs is one of critical issues for present and future fusion devices, such as International Thermonuclear Experimental Reactor (ITER) [1].

Many studies have been devoted to the physics of NTMs [2–4], however there are still some critical issues that are not resolved, such as onset threshold of NTMs, the origin of seed islands, the interaction with small scale turbulence, and so on. Microturbulence is ubiquitous in tokamak plasma, which is responsible for anomalous transport that seriously degrade plasma confinement. Previous theories and experiments have showed that the interaction between magnetic islands and turbulence can be effective [5–24]. In [5], an ad-hoc model of turbulence effects through anomalous electron viscosity is used to study the growth rate and nonlinear property of tearing modes. Turbulence is artificially modelled as a stochastic source in the Rutherford equation to analyze the behavior of NTMs in [6]. In 2006, Mcdevitt *et al* [9] proposed a minimal self-consistent model based on wave kinetics and adiabatic theory to study the interaction between tearing modes and drift wave turbulence. They showed that the turbulence induces an anomalous negative viscosity and affects the linear growth rate of tearing modes. Some numerical works [11–21] studied the interaction between turbulence and magnetic island, where it was shown that magnetic islands could change the nature of turbulence and turbulence could affect the dynamics of magnetic islands and drive the growth of magnetic island correspondingly. In [12], the generation and enhanced growth of the magnetic island due to the nonlinear beating of the interchange turbulence was presented. Some experiments have found that NTMs were triggered without the existence of an MHD triggering event [25–27], which implied the importance of microturbulence triggering the onset of NTMs. In the recent DIII-D experiment [24], it was observed that edge localized modes

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(ELMs) resulted in peaking of the temperature in the magnetic island, and narrowing of the island width. Afterwards the turbulence accelerated the recovery of NTM magnetic island. It is evident that turbulence can accelerate NTMs. Previous theoretical studies on the effects of turbulence on NTMs were based on the anomalous perpendicular heat transport and anomalous electron or ion viscosity induced by turbulence. Recently, theory of turbulence-driven current was proposed [28–30]. It has been estimated that this turbulence-driven current can be comparable to bootstrap current in the low collisionality [29]. The turbulence-driven current results from residual electron stress, turbulence acceleration and resonant scattering by turbulence. The residual electron stress, acting like residual ion stress which contributes to the ion momentum flux and can drive plasma flow, can drive electron momentum flux and lead to a turbulence-driven current. Turbulence acceleration relies on the exchange of momentum between ions and electrons, which can also accelerate electrons and drive a current. These two mechanisms are similar to those of ions [31, 32], which result from the symmetry breaking of turbulence spectrum. Therefore, the turbulence-driven current can affect the parallel current in the island regime, and change the evolution of NTMs correspondingly. In this work, we will consider the effect of turbulence-driven current on NTMs. It is shown that the onset threshold of NTMs is affected by turbulence significantly.

To understand the underlying physics, a heuristic interpretation is given here. In general, NTMs can be affected by the stresses and fluxes driven by turbulence via mean-field theory. On the other hand, turbulence can be affected by the large scale flow associated with NTMs [33]. As pointed out above, with turbulence-driven current, the perturbed modified Ohm's Law can be written as $\delta J_\parallel = \sigma_{\rm sp}\,\delta E_\parallel + \delta J_{\rm bs} + \delta J_{\rm tur}$, where the first term on the right hand of the expression denotes the perturbed Ohm's current density, $\delta J_{\rm bs}$ is the perturbed bootstrap current density, $\delta J_{\rm tur}$ is the perturbed turbulence-driven current, affected by the large scale $E\times B$ drift flow realted to NTMs. So that $\delta J_{\rm tur}\propto\delta\phi^{\rm ntm}$ can be obtained, where $\delta\phi^{\rm ntm}$ is the electrostatic potential of NTMs. Therefore, turbulence-driven current may affect NTMs via parallel Ohm's law, while the large scale flow of NTMs reacts on turbulence-driven current. There is a nonlinear coupling between NTMs and turbulence-driven current.

Now, the details of our derivation are given. The magnetic field can be written as $\mathbf{B} = I\,\nabla\zeta + \nabla\zeta\times\nabla(\psi+\delta\psi^{\rm ntm})$, where the toroidal geometry is assumed to be axisymmetric. ζ is the toroidal angle, ψ is the equilibrium poloidal flux, $\delta\psi^{\rm ntm} = \delta\hat{\psi}^{\rm ntm}\cos\xi$ is the perturbed poloidal flux, where $\xi = l_m\,\theta - l_n\,\zeta - \omega_{\rm ntm}\,t$, and the constant $\delta\hat{\psi}^{\rm ntm}$ approximation is made. θ and ζ are the poloidal and toroidal angles, respectively. l_m and l_n are the poloidal and toroidal mode numbers, respectively. $\omega_{\rm ntm}$ is the rotation frequency of the island relative to the plasma. Then, based on the generalized Rutherford theory, the evolution equation of NTMs can be obtained

$$\Delta' = \frac{4\sqrt{2}\,q_{\rm s}}{q'_{\rm s}\,\psi'_{\rm s}\,w}\,\frac{4\,\pi\,R_0}{c}\int_{-1}^{\infty}{\rm d}\Omega\langle\delta J_\parallel\,\cos\xi\rangle, \tag{1}$$

where $q_{\rm s} = l_m/l_n$ is the safety factor at the rational surface (the prime denotes the derivative with respect to r), $w = 2\sqrt{q_{\rm s}\,\delta\hat{\psi}/(q'_{\rm s}\,\psi'_{\rm s})}$ is the island width and R_0 is the major radius. Here, the island coordinate is introduced, as $\Omega = 2\,x^2/w^2 - \cos\xi$, $x = r - r_{\rm s}$. The operator $<\ldots>=\oint{\rm d}\xi/(2\,\pi)\,(\ldots)/\sqrt{\Omega+\cos\xi}$.

We decompose the electron distribution function into a mean part and a fluctuating part due to mircoturbulence, as $f_{\rm e} = \bar{F}_{\rm e} + \delta F_{\rm e}^{\rm tur}$, satisfying $\overline{\delta F_{\rm e}^{\rm tur}} = 0$ ($\overline{(\ldots)}$ denotes a temporal average), then the drift kinetic equation for the mean distribution can be obtained

$$\begin{aligned} &v_\parallel\,\mathbf{b}\cdot\nabla\bar{F}_{\rm e} + \mathbf{v}_d\cdot\nabla\bar{F}_{\rm e} - e\,v_\parallel\,E_\parallel\frac{\partial\bar{F}_{\rm e}}{\partial\varepsilon} + \overline{\delta\mathbf{v}_E^{\rm tur}\cdot\nabla\delta F_{\rm e}^{\rm tur}} \\ &- \overline{e\,v_\parallel\,\delta E_\parallel^{\rm tur}\frac{\partial\delta F_{\rm e}^{\rm tur}}{\partial\varepsilon}} = C(\bar{F}_{\rm e}), \end{aligned} \tag{2}$$

where only the electrostatic fluctuation is considered for simplicity. It is pointed out that the electromagnetic effect in the drift wave turbulence may become important in high β plasma, so that the effect of electromagnetic on NTMs may be significant. It was shown that the Maxwell stress counteracts with the Reynolds stress when turbulent fluctuations excite low wavenumber flow and islands in electromagnetic turbulence [34]. Then, it is convenient to separate $\bar{F}_{\rm e} = F_b + F_c$, where F_b is caused by magnetic drift [35]. F_c satisfies

$$\begin{aligned} &\oint\frac{q\,R\,{\rm d}\theta}{v_\parallel}\left(\overline{\delta\mathbf{v}_E^{\rm tur}\cdot\nabla\delta F_{\rm e}^{\rm tur}} - \overline{e\,v_\parallel\,\delta E_\parallel^{\rm tur}\frac{\partial\delta F_{\rm e}^{\rm tur}}{\partial\varepsilon}} - e\,v_\parallel\,E_\parallel\frac{\partial F_M}{\partial\varepsilon}\right) \\ &= \oint\frac{q\,R\,{\rm d}\theta}{v_\parallel}C(F_c). \end{aligned} \tag{3}$$

Furthermore, to obtain the expression F_c resulting from turbulence, the Krook model for collision operator is assumed, as $C(F_c) = -\nu_{\rm e}\,F_c$, $\nu_{\rm e}$ is the electron–ion collision frequency. Then, it can be obtained from equation (3) as

$$F_c = -\frac{1}{\nu_{\rm e}}\left(\overline{\delta\mathbf{v}_E^{\rm tur}\cdot\nabla\delta F_{\rm e}^{\rm tur}} - \overline{e\,v_\parallel\,\delta E_\parallel^{\rm tur}\frac{\partial\delta F_{\rm e}^{\rm tur}}{\partial\varepsilon}} - e\,v_\parallel\,E_\parallel\frac{\partial F_M}{\partial\varepsilon}\right), \tag{4}$$

where the electrons are assumed to be passing, since trapped electrons do not directly contribute to the current, the scattering effect is neglected, and the collisionless bootstrap current [29] is not considered. Without collision term, the electron momentum transport equation including turbulence in steady state can be also derived, then the turbulence-driven current is obtained. One can refer the detail in [29, 31]. Thus, the Ohm's law including electrostatic turbulence can be written as

$$\sigma_{\rm sp}\,E_\parallel = J_\parallel - J_{\rm bs} - J_{\rm tur}, \tag{5}$$

where the current is assumed to be carried by electrons,

$$J_{\rm tur} = \frac{e}{m_{\rm e}\,\nu_{\rm e}}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\Pi_{\parallel,{\rm e}}\right) + M_{\parallel,{\rm e}}\right), \tag{6}$$

$$\Pi_{\parallel,{\rm e}} = 2\,\pi\,m_{\rm e}\int{\rm d}\mu\,B_0/m_{\rm e}\int{\rm d}v_\parallel\,v_\parallel\,\overline{\delta\mathbf{v}_E^{\rm tur}\cdot\nabla r\,\delta F_{\rm e}^{\rm tur}}, \tag{7}$$

$$M_{\parallel,\mathrm{e}} = 2\,\pi\,e\int \mathrm{d}\mu\,B_0/m_\mathrm{e}\int \mathrm{d}v_\parallel\,\overline{\delta E_\parallel^{\mathrm{tur}}\,\delta F_\mathrm{e}^{\mathrm{tur}}}. \tag{8}$$

Here, $\Pi_{\parallel,\mathrm{e}}$ is an electron momentum flux, and $M_{\parallel,\mathrm{e}}$ results from electron–ion momentum exchange. As noted in [28, 29], $\Pi_{\parallel,\mathrm{e}} = -\chi_\phi\,\partial\bar{u}_{\parallel,\mathrm{e}}/\partial r + V\,\bar{u}_{\parallel,\mathrm{e}} + \pi_{\parallel,\mathrm{e}}$ can be written, where the first term is anomalous electron viscosity, the second term is a pinch of electron momentum, and the last term refers to electron residual stress. The effect of anomalous electron viscosity on tearing modes has been studied in [5], while the pinch of electron momentum term has no effect on tearing modes. Here i focus on the effect of electron residual stress, so that the centered Maxwellian distribution can be used. The effects of magnetic drift and collision are also not considered. Then, the expression of $\delta F_\mathrm{e}^{\mathrm{tur}}$ can be obtained from the linearized drift kinetic equation. Substituting the expression of $\delta F_\mathrm{e}^{\mathrm{tur}}$ into equation (8), and keeping transit resonances only, one can obtain [29]

$$\pi_{\parallel,\mathrm{e}} = \sqrt{\pi/2}\,n_\mathrm{e}\,m_\mathrm{e}\,\sqrt{m_\mathrm{e}/m_\mathrm{i}}\,\rho_\mathrm{i}\sum_{m,n}\frac{m}{r}\,\frac{\omega}{k_\parallel}\,\frac{\omega-\omega_{*\mathrm{e}}}{|k_\parallel|} \times\exp\left(-\frac{m_\mathrm{e}\,\omega^2}{2\,T_\mathrm{e}\,k_\parallel^2}\right)|\frac{e\,\delta\phi_{m,n}^{\mathrm{tur}}}{T_\mathrm{e}}|^2, \tag{9}$$

where $\rho_\mathrm{i} = c_\mathrm{s}/\Omega_{\mathrm{ci}}$ is the Larmor radius of ion, $c_\mathrm{s} = \sqrt{T_\mathrm{e}/m_\mathrm{i}}$, $k_\parallel = (m - n\,q)/(q\,R)$, m and n are the poloidal and toroidal mode numbers of turbulence, respectively. ω is the frequency of turbulence mode, $\omega_{*\mathrm{e}} = c\,T_\mathrm{e}/(e\,B\,L_n)\,(1/2 + m_\mathrm{e}\,\omega^2/(2\,T_\mathrm{e}\,k_\parallel^2))\,m/r$, $L_n = -(\mathrm{d}\ln n_\mathrm{i}/\mathrm{d}r)^{-1}$. Similarly, one can obtain $M_{\parallel,\mathrm{e}}$. Then, the parallel Ohm's law including turbulence-driven current is obtained. It has been shown that the turbulence-driven current can be comparable to the bootstrap current [28, 29]. Consequently, it affects the evolution of NTMs significantly. From equation (9), it is pointed out that the effect of turbulence-driven current depends on the frequency of turbulence, namely the effect could be opposite for different turbulence.

Now we consider the self-consistent evoution of $|\delta\phi_{m,n}^{\mathrm{tu}}|^2$ in the presence of NTMs. It is convenient to introduce a wave kinetic equation (WKE) [9] for the evolution of drift wave action density as

$$\frac{\partial N_k}{\partial t} + \frac{\partial}{\partial\mathbf{k}}\left(\omega_k + \mathbf{k}\cdot\mathbf{v}^{\mathrm{ntm}}\right)\cdot\frac{\partial N_k}{\partial\mathbf{x}} - \frac{\partial}{\partial\mathbf{x}}\left(\mathbf{k}\cdot\mathbf{v}^{\mathrm{ntm}}\right)\cdot\frac{\partial N_k}{\partial\mathbf{k}} = S, \tag{10}$$

where $N_k = (1 + k_\perp^2\,\rho_\mathrm{i}^2)\,|e\,\delta\phi_{m,n}^{\mathrm{tu}}/T_\mathrm{e}|^2$, ω_k is the frequency of drift wave, $\mathbf{v}^{\mathrm{ntm}} = c\,\mathbf{b}\times\nabla\delta\phi^{\mathrm{ntm}}/B_0$ is the electrostatic flow of NTMs, and the effect of zonal flow is not considered [20]. $S = \gamma_k\,N_k - \Delta\omega_k\,N_k^2$ is the source term, where the first term denotes the linear drive of drift waves in the presence of NTMs, the second term represents the nonlinear like-scale interaction. Here, it is assumed that the self-interaction of small-scale turbulence fields is small compared to the interaction between turbulence and NTMs. Considering small deviation from the equilibrium drift wave spectrum N_{k0}, we have

$$\delta N_k \sim \frac{\gamma_k}{\gamma_k^2 + (\mathbf{l}\cdot\mathbf{v}_g)^2}\,k_\theta\,\frac{\partial N_{k0}}{\partial k_r}\,\frac{c}{B_0}\,\frac{\partial^2\delta\phi^{\mathrm{ntm}}}{\partial r^2}, \tag{11}$$

where $\mathbf{v}_g = \partial\omega_k/\partial\mathbf{k}$, and the ordering $a\,\partial\ln\delta\phi^{\mathrm{ntm}}/\partial r \gg 1$ (a is the minor radius) for NTMs is used. Then, based on equations (6)–(8) and (11), the turbulence-driven current perturbed by NTMs can be obtained

$$\delta J_{\mathrm{tur}} \sim \sqrt{\pi/2}\,\frac{n_\mathrm{e}\,e^2}{m_\mathrm{e}\,\nu_\mathrm{e}}\,\mu_{\parallel,\mathrm{e}}\,a^2\,\frac{\partial^3\delta\phi^{\mathrm{ntm}}}{\partial x^3}, \tag{12}$$

where

$$\mu_{\parallel,\mathrm{e}} = \left(\frac{m_\mathrm{e}}{m_\mathrm{i}}\right)^{3/2}\int \mathrm{d}\mathbf{k}\,\frac{k_\theta^2\,\rho_\mathrm{i}^2}{k_\parallel\,|k_\parallel|\,a^2}\,\frac{\rho_\mathrm{i}}{L_n}\,\frac{\omega-\omega_{*\mathrm{e}}}{\omega_{*\mathrm{e}}}\,\exp\left(-\frac{m_\mathrm{e}\,\omega^2}{2\,T_\mathrm{e}\,k_\parallel^2}\right) \times\frac{1}{(1+k_\perp^2\,\rho_\mathrm{i}^2)^2}\,k_\theta\,\frac{\partial N_{k0}}{\partial k_r}\,\frac{\gamma_k\,\omega}{\gamma_k^2 + (\mathbf{l}\cdot\mathbf{v}_g)^2}, \tag{13}$$

the current from $M_{\parallel,\mathrm{e}}$ is not included in equation (12), since it is an odd function and has no effect on NTMs based on equation (1). Now, following the procedure in [4], equation (1) can be obtained as

$$\frac{8\,\pi\,I_1}{c^2\,\eta}\,\frac{\mathrm{d}w}{\mathrm{d}t} = \Delta' + \frac{G_1\,\sqrt{\epsilon_\mathrm{s}}\,r_\mathrm{s}}{s\,L_n}\,\frac{\beta_\theta}{w}\left(\frac{w^2}{w^2 + w_\chi^2} - \frac{w_{\mathrm{pol}}^2}{w^2} + \frac{\sigma\,w_{\mathrm{tur}}^2}{w^2}\right), \tag{14}$$

where

$$w_{\mathrm{pol}}^2 = \sqrt{G_2}\left(\frac{r_\mathrm{s}}{s\,L_n}\right)^{1/2}\sqrt{\epsilon_\mathrm{s}}\,\rho_{\theta\mathrm{i}}, \tag{15}$$

$$w_{\mathrm{tur}}^2 = \frac{G_3}{\sqrt{\epsilon_\mathrm{s}}}\,\frac{\tau_\mathrm{R}}{\tau_\mathrm{A}}\,\frac{r_\mathrm{s}\,d_\mathrm{i}}{q_\mathrm{s}}\,|\mu_{\parallel,\mathrm{e}}|, \tag{16}$$

σ denotes the sign of the turbulence intensity gradient or the shear flow gradient, which both lead to the symmetry breaking of turbulence spectrum. The numerical coefficients $G_1 \simeq 2.31$, $G_2 \simeq 9.32$, $G_3 = 41.96$. w_χ is a critical scale width determined by the ratio between perpendicular and parallel transport coefficients [3]. $d_\mathrm{i} = c/\omega_{\mathrm{pi}}$ is the ion inertial length, s is the magnetic shear, τ_R and τ_A are the resistive diffusion time and Alfvén time, respectively. $\mathrm{d}\beta_\theta/\mathrm{d}r = -\beta_\theta/L_n$ is scaled. The values of parameters in equation (14) are defined at the rational surface. w_{tur} is the turbulence-driven current term. Although the effect is proportional to $(m_\mathrm{e}/m_\mathrm{i})^{3/2}$ and turbulence intensity, it could be significant, since it is also proportional to $\tau_\mathrm{R}/\tau_\mathrm{A}$ and $1/w^3$. From the expression (13), $\partial N_{k0}/\partial k_r < 0$ is always satisfied, then it can be shown that the effects of turbulence-driven current on NTMs depend on the $k_\parallel$ symmetry breaking. Whether it plays a stabilizing role or destabilizing role depends on the $k_\parallel$ symmetry breaking mechanisms, like shear flow [36], the turbulence intensity gradient [37]. Considering the drift wave turbulence, the expression (16) can be rewritten as

$$w_{\mathrm{tur}}^2 = \frac{G_3}{\sqrt{\epsilon_\mathrm{s}}}\,\frac{\tau_\mathrm{R}}{\tau_\mathrm{A}}\left(\frac{m_\mathrm{e}}{m_\mathrm{i}}\right)^{3/2}\frac{r_\mathrm{s}^3\,d_\mathrm{i}\,\rho_{\theta\mathrm{i}}^2}{q_\mathrm{s}\,s^2\,L_n\,|L_I|\,a^2}\,I_{\mathrm{tur}} \tag{17}$$

where $k_\theta\,\rho_\mathrm{i} \sim 1$ and the turbulence mode width $w_{\mathrm{tu},k} \sim \rho_\mathrm{i}$ are chosen, $I_{\mathrm{tur}} = \sum_{m,n}|e\,\delta\phi_{m,n}^{\mathrm{tur}}/T_\mathrm{e}|^2$ is the turbulence intensity at the spectrum peak, $L_I = (\mathrm{d}\ln I_{\mathrm{tur}}/\mathrm{d}r)^{-1}$ is the scale length of turbulence intensity. Here, the symmetry breaking mechanism from turbulence intensity gradient is considered. The

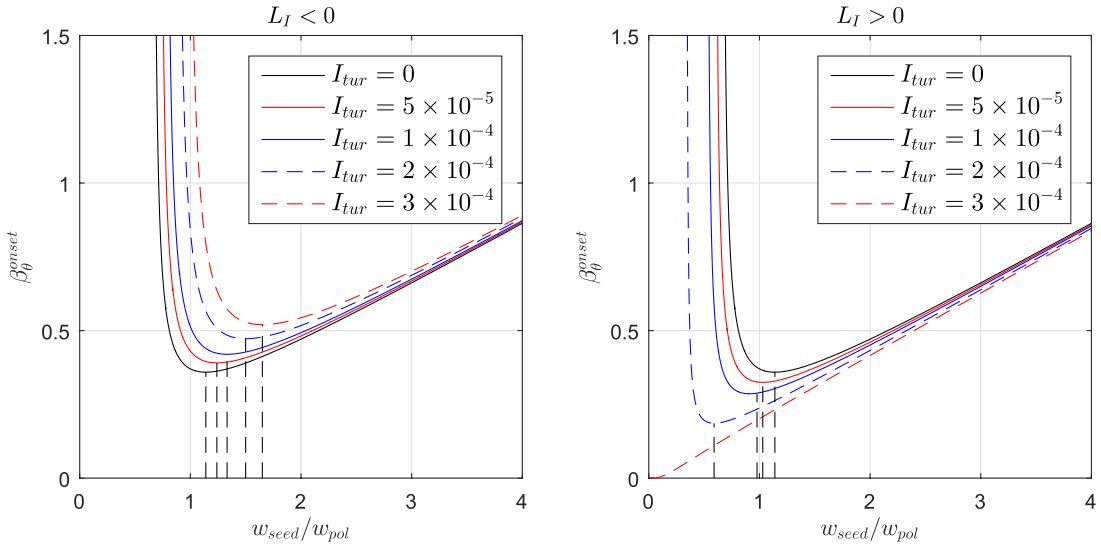


Figure 1. The dependence of $\beta_\theta^{\rm onset}$ on $w_{\rm seed}/w_{\rm pol}$ for $L_I < 0$ and $L_I > 0$, respectively.

turbulence intensity gradient always changes its sign between the turbulence drive. In the simulation, the peak of turbulence intensity can deviate from the rational surface of magnetic island [18, 20], so that turbulence intensity gradient near the island has relation to the location of the peak of turbulence intensity. In the tokamak experiment, the positive turbulence intensity gradient is likely [38]. From the expressions (16) and (17), the effect of turbulence-driven current is similar to that of neoclassical polarization current. It would change the onset threshold of NTMs. The effect is proportional to ρ_*^2 (where $\rho_* = \rho/a$), so that the effect would become less significant in larger tokamak. The effect also scales strongly with magnetic shear. For the steady state and hybrid scenarios with weak magnetic shear in ITER, the effect would become more significant. Based on equation (14), the onset threshold $\beta_\theta^{\rm onset}$ against the critical seed island width $w_{\rm seed}$ (given by $\mathrm{d}w/\mathrm{d}t = 0$) can be derived as

$$\beta_\theta^{\rm onset} = -r_{\rm s}\,\Delta' \left(G_1\,\sqrt{\epsilon_{\rm s}}\,\frac{r_{\rm s}}{s\,L_n}\right)^{-1} \frac{w_{\rm pol}}{r_{\rm s}} \times \left[\frac{\hat{w}_{\rm seed}}{\hat{w}_{\rm seed}^2 + w_\chi^2/w_{\rm pol}^2} - \frac{1}{G_1\,\hat{w}_{\rm seed}^3}\left(1 - \frac{\sigma\,w_{\rm tur}^2}{w_{\rm pol}^2}\right)\right]^{-1}, \tag{18}$$

where $\hat{w}_{\rm seed} = w_{\rm seed}/w_{\rm pol}$. It can be shown that the effect of turbulence-driven current on onset threshold of NTMs depends on the ratio $w_{\rm tur}^2/w_{\rm pol}^2$ and the direction of turbulence intensity gradient σ. If $\sigma > 0$, the effect of turbulence-driven current enhances the onset threshold of NTMs. If $\sigma < 0$, it reduces or overcomes the stabilizing effect of neoclassical polarization current, and can trigger NTMs. It can be estimated that the ratio $w_{\rm tur}^2/w_{\rm pol}^2 \sim O(1)$ for typical parameters in tokamak, namely the effect of turbulence-driven current is significant. It would dramatically change the onset threshold of NTMs. For a typical tokamak like DIII-D, the parameters are given as $B = 1.6$ T, $a = 0.61$ m, $R = 1.7$ m, $T_{\rm i} = T_{\rm e} = 2$ keV, $n_{\rm i} = 2 \times 10^{19}$, $r_{\rm s}\,\Delta' = -3$, $q_{\rm s} = 2$, $s = 1$, $\epsilon_{\rm s}^{1/2} = 0.5$, $L_n = |L_I| = 0.5\,a$, and $w_\chi = 0$ is set for simplicity, then the onset threshold $\beta_\theta^{\rm onset}$ against $\hat{w}_{\rm seed}$ can be plotted in figure 1, where the dotted dark lines denote the lowest threshold $\beta_{\theta,\rm min}$ (below which NTMs can not exist), corresponding to w_c. $I_{\rm tur} \sim 10^{-4}$ is very likely in tokamaks. Then, it can be easily shown that the effect of turbulence-driven current affects the onset threshold of NTMs significantly. For $L_I < 0$, $\beta_{\theta,\rm min}$ and w_c increases with $I_{\rm tur}$ increasing, namely the turbulence-driven current plays a stabilizing role, and enhances the onset threshold. For $L_I > 0$ (It is always satisfied in typical tokamkas), $\beta_{\theta,\rm min}$ and w_c decreases with $I_{\rm tur}$ increasing. If $I_{\rm tur}$ is large enough, $\beta_{\theta,\rm min}$ and w_c would be reduced to zero (Here, it is needed to pointed out that the above results are valid for $w \gg w_{{\rm tu},k}$). This means that the effect of turbulence-driven current is destabilizing, and cancels the stabilizing effect of neoclassical polarization current. In this way, turbulence-driven current would lead to a reduction of onset threshold of NTMs and can trigger NTMs. Actually, in the DIII-D experiment [24], it was observed that ELMs resulted in peaking of the temperature in the magnetic island and reduction in the island width. Afterwards the turbulence accelerated the recovery of NTM island. It was clearly shown that NTM can be accelerated by turbulence. In this experiment, $I_{\rm tur} \sim 10^{-4}$. This is consistent with our prediction of the effect of turbulence-driven current on NTMs. Some other experiments showed that NTMs do not always correlate with triggering MHD events [25–27]. For example, NTMs appeared without noticeable triggering MHD events in about 80% of the discharges in JT-60U [25]. Our results indicate that turbulence-driven current may provide a new mechanism for the onset of NTMs without triggering MHD events. Some simulation works showed that turbulence can drive tearing modes [19, 21] or double tearing modes [18], where the Ohm's law used did not include turbulence-driven current pointed out here. In the simulation [21], it was shown that turbulence can contribute to polarization current, and drive the growth of magnetic island.

In conclusion, the evolution of NTMs including turbulence-driven current term is derived. A new mechanism that turbulence-driven current can affect NTMs significantly is proposed.

The turbulence-driven current would modify Ohm's law, and alter the parallel current in the island. Correspondingly, it would modify the evolution of NTMs. It is shown that the effect of turbulence-driven current on NTMs is comparable to that of neoclassical polarization current. Furthermore, the effect of turbulence-driven current on NTMs depends on the direction of turbulence intensity gradient at the resonance surface and the amplitude of turbulence. When drift turbulence intensity gradient at the resonance surface is negative, the onset threshold of NTMs increases as turbulence intensity increases, and NTMs become harder to be triggered. On the other hand, when the turbulence intensity gradient is positive, the effect of turbulence-driven current can reduce or overcome the stabilizing effect of neoclassical polarization current, and reduce the onset threshold of NTMs. In this way the turbulence can accelerate NTMs dramatically. Our results show that the onset threshold of NTMs can be affected significantly by turbulence. The triggering of NTMs by turbulence depends on type of turbulence and the symmetry breaking mechanism of turbulence spectrum. When the turbulence intensity gradient is positive, the effect of turbulence-driven current may explain the recent experimental results in DIII-D [24]. It also implies NTMs can appear without noticeable MHD events.

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