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Analysis of Toroidal Rotation Effects of the Ion Polarization Current on the Neoclassical Tearing Mode

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Abstract

A model of the polarization current, which would be associated with the excitation of the Neoclassical Tearing Mode (NTM), was investigated. In this paper, the model of the polarization current term which includes the effects of the toroidal rotation and the pressure gradient was evaluated using JT-60U experimental data. Destabilization and stabilization by the polarization current term with the observed toroidal rotation were analyzed to be consistent with the excitation and suppression of the NMT. When the toroidal rotation has a destabilizing effect on the NTM, the NTM will grow rapidly without a seed island by both effects of the bootstrap current term and the polarization current term.

Keywords:

neoclassical tearing mode, plarization current, toroidal rotation, pressure gradient, mode frequency

1. Introduction

The neoclassical tearing mode (NTM) is considered to reduce the β-limit in low collisional plasmas and cause confinement degradation in tokamaks. Hence, it is important to prevent the occurrence of the NTM and clarify the nonlinear mechanisms for excitation of the NTM. It is accepted that the polarization current is necessary to resolve the nonlinear mechanisms for excitation of the NTM. The role of the polarization current in the nonlinear island evolution has been analyzed theoretically [1-5] and experimentally [5-6]. One of the authors (A.I.S.) has shown that the generalization of the theory of drift effects could give rise to stationary small-scale magnetic islands rotating in the poloidal direction with a frequency on the order of the diamagnetic drift frequency [1,2]. In this paper, the polarization current term model, including the toroidal rotation and the pressure gradient, was analyzed using experimental data from JT-60U.

2. Modified Rutherford Equation

The modified Rutherford equation [1-3,5,7] is a commonly used analytical method for evaluating the NTM growth. It is written as follows:

$$\tau_{\mathrm{R}} \frac{d}{dt}\left(\frac{w}{r_{\mathrm{s}}}\right) = r_{\mathrm{s}}\Delta'(w) + k_1 r_{\mathrm{s}} \sqrt{\varepsilon_{\mathrm{s}}}\, \beta_{\mathrm{ps}} \frac{L_{\mathrm{q}}}{L_{\mathrm{p}}} \frac{w}{w^2 + w_{\mathrm{d}}^2} + \frac{k_2 r_{\mathrm{s}}}{w^3} g(\nu_{\mathrm{i}}, \varepsilon) L_{\mathrm{s}}^2 \frac{(\omega - \omega_{\mathrm{E}})(\omega - \omega_{\mathrm{E}} - \omega_{*\mathrm{i}})}{k_\theta^2 v_{\mathrm{A}\theta}^2}. \quad (1)$$

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Here, subscript s denotes the rational surface, r is the minor radius, w is the full island width, $w_d \simeq 5 (\chi_\perp/\chi_\parallel)^{1/4} [r_s L_q q/(\varepsilon m)]^{1/2}$ [7] is the critical island width that will lead to an incomplete flattening of the pressure profile within the island for small w, $L_q = -(\mathrm{d} \ln p/\mathrm{d}r)^{-1}$, $L_q = (\mathrm{d} \ln q/\mathrm{d}r)^{-1}$, $L_s = qL_q/\varepsilon_s$. ω is the mode rotation frequency, ω_E is the plasma rotation frequency which is induced by the radial electric field, ω_{*i} is the ion diamagnetic drift frequency. $k_\theta = m/r_s$ is the poloidal wave number, $v_{A\theta} = B_\theta(\mu_0 n_i m_i)^{-1/2}$ is the poloidal Alfvén velocity, $\tau_R = \mu_0 r_s^2/\eta_{nc}$ is the resistive field diffusion time, η_{nc} is the neoclassical resistivity, $\beta_p = 2\mu_0 p/B_\theta^2$ is the poloidal beta. The strength function $g(\nu_i, \varepsilon)$ takes the asymptotic value $\varepsilon^{3/2}$ and 1, when $\nu_i \ll \varepsilon\omega_{*e}$ and $\nu_i \gg \varepsilon\omega_{*e}$, respectively. The first term on the right-hand side is the contribution of the equilibrium current profile, characterized by the stability parameter $\Delta'(w)$. The second term describes the bootstrap current drive. The last term is the contribution of the polarization current based on the theory of Refs. [1,2]. This term has the stabilizing effect in the case of $\omega_{*i} < \omega - \omega_E < 0$. In the following section, the effects of the toroidal rotation and the pressure gradient were examined for the polarization current term in the modified Rutherford equation.

3. Evaluation of the Polarization Current Term

The polarization current term was evaluated using the data of two discharges [6]. The discharge condition is the same except with and without the negative ion based NBI (N-NBI) injection into the discharge. The 2/1 mode was observed in the discharge where the N-NBI was not injected, while in the other discharge with N-NBI, the mode was not observed though the beta value was rather higher. Differences of parameters in the two discharges are the toroidal velocity and the pressure gradient at the $q = 2$ surface. The total pressure gradient is 1.36×10^5 Pa/m and 8.9×10^4 Pa/m in the discharges with NTM and without NTM [6], respectively. Figure 1 shows the toroidal velocity profiles, whose values are about 1.0×10^4 m/s and 4.9×10^4 m/s in the discharges with NTM and without NTM, respectively. The mode rotation frequency, ω, was estimated from the observed frequency, ω_{Mirnov} ($= 2\pi f_{\mathrm{Mirnov}}$), by ECE and Mirnov coils. Since the toroidal rotation was small at the rational surface, we assumed that the poloidal component of the mode rotation was dominant and $\omega \sim \omega_{\mathrm{Mirnov}}$. The mode started at a frequency of 4 kHz and the frequency reduced to 2 kHz in the discharge with NTM as shown in Fig. 2. The mode rotation was in the direction of the ion diamagnetic drift.

In order to evaluate the effect of the polarization current term, the function of f is considered as a figure merit of the polarization current term:

$$f = \frac{(\omega - \omega_E)(\omega - \omega_E - \omega_{*i})}{k_\theta^2 v_{A\theta}^2}. \tag{2}$$

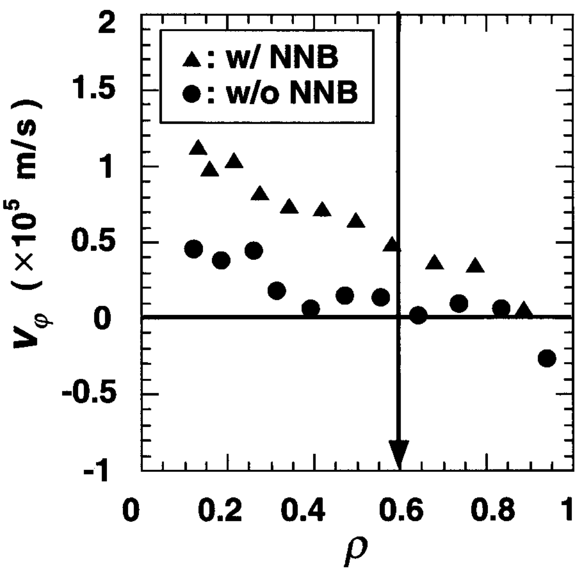

Fig. 1 Toroidal velocity profiles for the discharges with and without N-NBI. The vertical line indicates the location of the $q = 2$ surface.

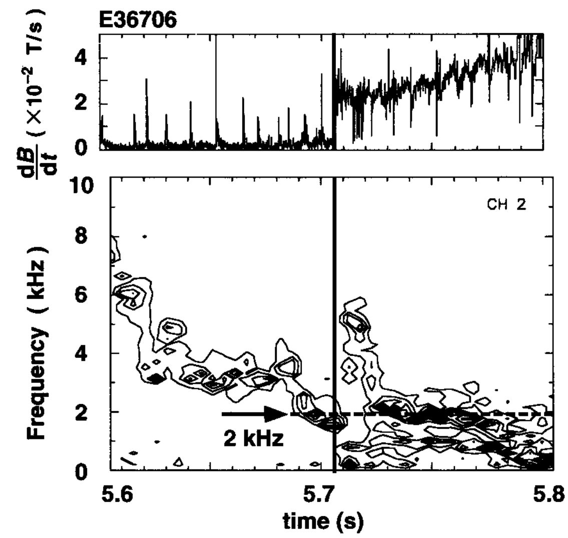

Fig. 2 Time evolutions of the Mirnov oscillation amplitude and the mode frequency measured by ECE in the discharge with NTM.

The drift frequency by the radial electric field ω_E and the ion diamagnetic drift frequency ω_{*i} are expressed as follows, respectively:

$$\omega_E = -\frac{m}{r_s B_\phi}\left(\frac{1}{Z_{imp} e n_{imp}} \frac{dp_{imp}}{dr} - v_\theta B_\phi + v_\phi B_\phi\right) \quad (3)$$

$$\omega_{*i} = -\frac{m}{r_s} \frac{1}{Z_i n_i e B_\phi} \frac{dp_i}{dr} \, . \quad (4)$$

Here, B_ϕ is the toroidal magnetic field, Z_{imp} and n_{imp} are impurity effective charge number and the impurity density, respectively. v_θ is the poloidal rotation velocity and v_ϕ is the toroidal rotation velocity. In the case of $\omega_{*i} < \omega - \omega_{*i} < 0$, the sign of f is negative, by which the polarization current term has a stabilizing effect on the NTM. The mode frequency, f_{Mirnov}, was not measured in the discharge with N-NBI, since the mode was not observed. Hence, it is assumed that the mode frequency is the same with the discharge without N-NBI in the analysis.

The effect of the toroidal rotation was evaluated on the value of f for the above two discharges in Fig. 3. In this analysis, ω was fixed, and ω_E was varied with the pressure gradient dp_i/dr and the toroidal velocity v_ϕ. The value of observed toroidal velocity was outside the stabilizing range ($f > 0$) when the NTM set in, and the value of the toroidal velocity existed inside the stabilizing range ($f < 0$) when the NTM was not observed. As a result, the effect of the toroidal rotation appears to be consistent with the excitation and suppression of the NTM.

In order to evaluate sensitivity of the polarization current term, the dependence of f on the toroidal rotation and the pressure gradient was investigated. And further, the dependence on the mode frequency was evaluated for 1 kHz, 2 kHz and 4 kHz, because the mode started at a frequency of ~4 kHz and slowed down to ~2 kHz in the discharge with NTM, and the mode frequency was assumed to be 2 kHz in the discharge without NTM. The results are shown in Fig. 4. When $-\omega_{*i}$ is low, the stabilizing region against the toroidal velocity is so narrow that adequate toroidal rotation is required to have a stabilizing effect on the NTM. However, as $-\omega_{*i}$ increases, the stabilizing region expands. Accordingly higher $-\omega_{*i}$ is preferable to extend the stabilizing region against the toroidal velocity. Figure 4 also indicates that the stabilizing region shifts with the mode frequency. If the mode frequency is 1 kHz, the polarization current term has a stabilizing effect on the NTM in the discharge with NTM, by contrast, in the discharge without NTM, the polarization current term has a

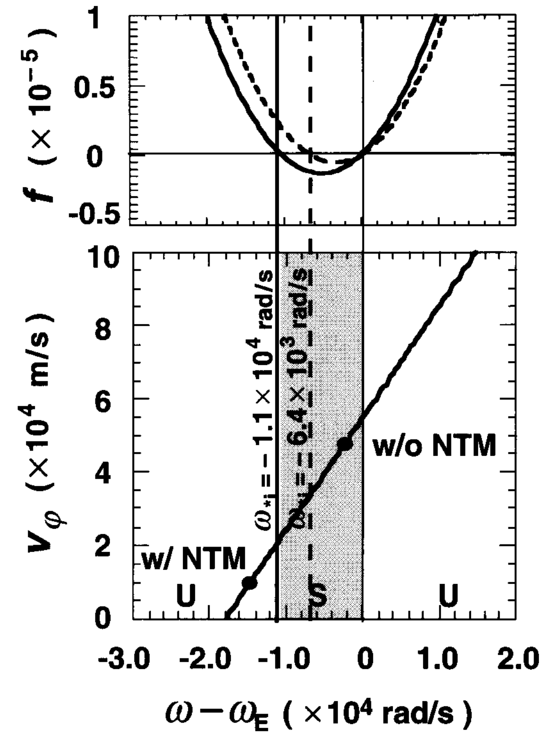

Fig. 3 Stabilizing ($f < 0$) effect ranges of $\omega - \omega_E$ together with the relationship with v_φ for discharges with and without NTM. The vertical solid line and broken line denote the value of ω_{*i} of the discharge with NTM and without NTM, respectively. 'S' and 'U' stand for the stabilizing range and the destabilizing range, respectively.

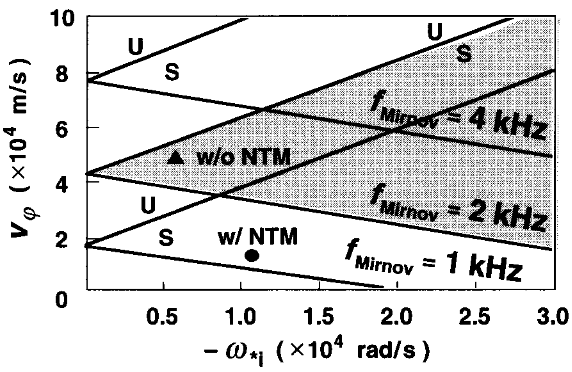

Fig. 4 Negative and positive sign regions of f plotted in the domain of the ion diamagnetic drift frequency and the toroidal velocity. The stabilizing effect region shifts with the mode frequency. The dotted area indicates the stabilizing region when $\omega_{Mirnov}/2\pi = 2$ kHz.

destabilizing effect. For 2 kHz, the result is consistent with the experimental results. For 4 kHz, the plasma with and without NTM are outside of the stabilizing region. Consequently, the stabilizing effect region is sensitive to the mode frequency.

The 2/1 island growth was examined with the bootstrap current term and the polarization current term in the modified Rutherford equation. The pressure gradient affects both terms. Figure 5 shows the effect of the bootstrap current term alone. The growth rate of the discharge without NTM is smaller than the other, since the pressure gradient in the discharge without NTM is lower than the other. However, the results are not clear to explain the drive mechanisms of the NTM. Both effects of the polarization current term and bootstrap current term were evaluated in Fig. 6. Results are drastically changed since the NTM will grow rapidly without a seed island in the case of the discharge with NTM.

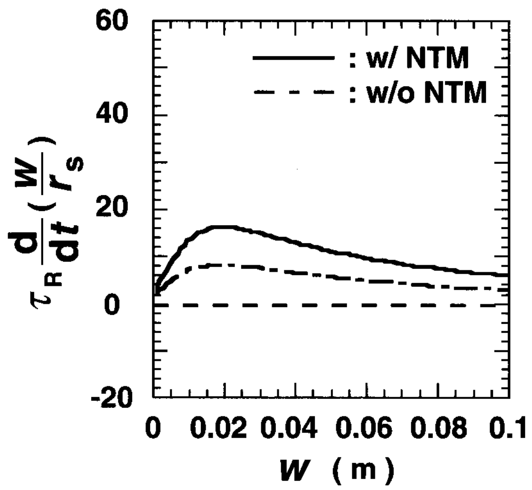

Fig. 5 The growth rate against the island width by the bootstrap current effect.

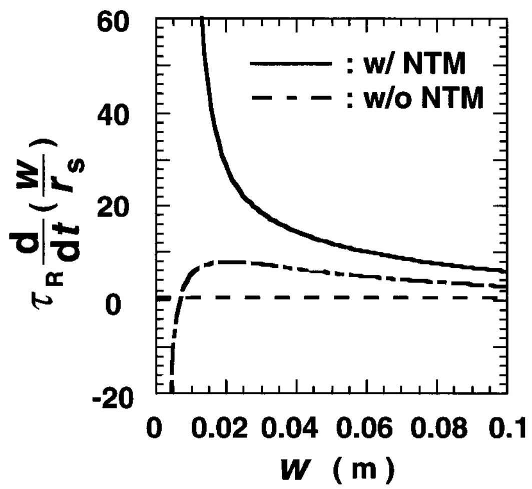

Fig. 6 The growth rate against the island width taking account of both effects of the bootstrap current and the polarization current.

4. Summary

The model of the polarization current term which includes the effect of the toroidal rotation and the pressure gradient [1,2] were evaluated using experimental data from JT-60U. Results show that the effect of the toroidal rotation appears to be consistent with the excitation and suppression of the NTM when the mode frequency, ω, is equal to 2 kHz. However, the stabilizing effect of the polarization current term is sensitive to the mode frequency. Stabilizing region against the toroidal velocity expands with an increase in $-\omega_{*i}$, thus higher $-\omega_{*i}$ is preferable. The effect of the pressure gradient through the bootstrap current term in the modified Rutherford equation is not clear to explain the trigger of the NTM. However, both the polarization current term with a destabilizing effect and the bootstrap current term are important to explain the excitation of NTM without a seed island.

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