Effects of Plasma Rotation on the Neoclassical Tearing Mode in JT-60U

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Introduction

It is important to clarify stabilizing or destabilizing effects of the polarization current term in the Rutherford equation. Here, we consider the effect of plasma rotation on the neoclassical tearing mode (NTM) through the polarization current term using JT-60 experimental data. Quasi-steady state high $\beta_p$ H-mode discharges were performed in JT-60U. Sustainable beta and duration of quasi-steady state high $\beta_p$ H-mode plasmas are limited by low-n tearing modes such as m/n=3/2 and 2/1 modes. Here, m and n are poloidal and toroidal mode numbers, respectively. These modes are considered to be NTM, and the normalized beta at the observation of NTM scales as $\nu e^{0.36}\rho_i^*$[1]. However, in the discharge with the negative ion based NBI injection (N-NBI), NTM was not observed and critical beta was exceeded, though in the discharges without N-NBI NTMs occurred for lower plasma beta, as shown in Fig. 1. These two discharges are different in the rotation and the pressure profiles. Therefore, in this paper effects of plasma rotation on the stabilization of NTM are investigated. Effect of plasma rotation enters the dynamics of NTM modes via the modification of the polarization term.

NTM Equation

The NTM is evaluated using the modified Rutherford equation [2-4]:

$$\tau_r \frac{d}{dt} \left( \frac{w}{r_S} \right) = \Delta'(w)r_S + \Delta_{nero} + \Delta_{pol}$$

$$= \Delta'(w)r_S + k_1r_S\sqrt{\nu_e}\beta_p \frac{L_q}{L_p} \frac{w}{w + w_d} + \frac{k_2r_S}{w^3} g(\nu_e, \epsilon) L_2 \left( \omega - \omega_E \right) \left( \omega - \omega_E - \omega_{\alpha} \right) \frac{1}{k_0^2 v_{A0}^2}$$

Fig. 1 Time evolution of normalized beta for discharges with and without NNB
The third term of the right hand side is the polarization current term which is stabilizing for 
\( \omega_{\varepsilon} > \omega - \omega_{E} > 0 \). Here, \( L_p = -\left( \frac{\partial \ln p}{\partial r} \right)^{-1} \), \( \beta_0 = 8\pi p / B_0^2 \), \( \varepsilon = r_s / R \), \( \nu_{A0} = \nu_{A0}^2 / q^2 R^2 \), 
\( \omega, \omega_{E} \) and \( \omega_{\varepsilon} \) is mode rotation, plasma rotation and the ion diamagnetic drift frequency, respectively. In the N-NBI injected plasma, the strong momentum input near the plasma center creates large toroidal flow near the q=2 rational surface (at r/a~0.6 in Fig.2). At the same the pressure gradient near the q=2 rational surface becomes lower. The suppression of NTM in NBI plasma may be associated with the enhanced effect of the ion polarization current due to large plasma velocity.

![Graph showing toroidal rotation profile for discharges with (E36715) and without NNBI (E36706)](image)

**Comparison of the discharges with and without N-NBI**

To consider effects of rotation, first we check each frequency on the polarization current term. Mode frequency was measured by the ECE and Mirnov coils as shown in Fig. 3. The mode rotates in the direction to the ion diamagnetic direction, the mode starts at the frequency ~5kHz and the fluctuations become larger at the frequency of ~2kHz for the discharge of E36706. Then, \( \omega \) of E36706 is -1.34 x10^4 [1/s] and we assumed \( \omega \) of E36715 is same frequency since the mode was not observed in E36715. Based on the neoclassical theory, \( \omega_{E} \) is obtained from the pressure gradient and the toroidal rotation of Carbon by the CXRS measurements, using the transport code TOPICS. The ion pressure gradients are not very much different in both discharges, but the toroidal rotation is different even at the q=2 rational surface (r/a~0.6), as shown in Fig.2. The obtained \( \omega_{E} \) is 3.4 x10^3 [1/s] for E36706 and \( \omega_{E} \) is -9.8 x10^3 [1/s] for E36715. The ion diamagnetic drift frequency \( \omega_{\varepsilon} \) is -1.1 x10^4 [1/s] for both discharges.

**Dependency of stabilizing effect of the polarization current**

Using the above values, the parameter \( f \) is -1.3 x10^{-6} [1/s] for E36715 and 5.7 x10^{-6} [1/s]
for E36706. Here, $f$ is a figure of merit of the polarization current term:

$$f = \left( \omega - \omega_E \right) \omega - \omega_E - \omega_s \frac{k_0^2 v^2}{\alpha}.$$  

Then, the polarization current term of E36706, which the mode emerged, is destabilizing. To consider the parameter dependency, the value of $f$ was obtained for the pressure gradient and the toroidal velocity, as shown in Fig.4. Here, $\omega$ is fixed, and $\omega_E$ is scaled as...
\[ \omega_E = -\frac{m}{\rho B} E_r \quad \text{and} \quad E_r = \frac{\nabla p}{Z_i e n_i} - V_i B_0 + V_0 B_0 \]

using the parameter of E36715 as a reference. \( V_0 \) is also scaled as \( \nabla p \). Results clearly show the larger pressure gradient and larger \( \omega_{\ast i} \) increase the stable region \( (f<0) \), however, the difference of these two discharges are not clear. If we consider the observed frequency in Fig.3, the mode starts at 4kHz. The dependency of the mode frequency on the \( f \) value is shown in Fig.5, where the frequencies of \( \omega - \omega_E \) and \( \omega_{\ast i} \) are plotted against the toroidal velocity, for each mode frequency of \( \omega \), fixing the pressure gradient. The arrow shows the estimated trajectory of each discharges. \( f \) is negative (stabilizing) when \( \omega - \omega_E \) is from -1.1 x10^4 to 0 [1/s] for each discharges. For the frequency \( \omega \) correspond to ~2-4kHz, the value of \( f \) is remained a positive value (destabilizing) for the discharge of E36705 where the mode emerged. Therefore, it is plausible possibility that the mode appear by the destabilizing effect of the polarization current term for the discharge of E36706. On the other hand, by the toroidal rotation, in the mode with lower frequency \( (\omega < 3.5kHz) \), the polarization current acts as a stabilizing effects, resulting in no NTM mode.

Summary

The mode in JT-60U rotates in the ion diamagnetic direction. When the toroidal rotation is low, the polarization current acts as a destabilizing, however, the larger toroidal rotation can change the polarization current to the stabilizing term. This is illustrated in Fig.6 where the mode growth rate is shown as a function of the magnetic island for these two cases.