EFFECT OF IMPURITY DISTRIBUTION ON THE STABILITY OF NEOCLASSICAL TEARING MODE

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The neoclassical tearing mode (NTM) stabilization due to variations in impurity distribution has been observed for the first time. For the 2/1 NTM in the high beta stational H-mode of HL-2A, a qualitative agreement with experimental results was obtained using the kinetic Rutherford equation by carefully considering the impact of impurity and fast ion profiles on the main deuterium ion profile. The results indicate that impurity distribution significantly influences NTM stability. Specifically, the higher the impurity gradient in phase with the electron density gradient at the rational surface where the NTM is located, the lower the ion bootstrap current drive term, which favors NTM stabilization. This result is exciting for International Thermonuclear Experimental Reactor (ITER), as it suggests that the originally separate tasks of NTM suppression and medium-Z impurities injection enhancing radiation may have the potential to produce beneficial coupling effects. This has significant and beneficial implications for ITER activities.

In tokamaks, tungsten impurity accumulation in the core can lead to rapid plasma cooling, triggering major disruptions [1], while impurity injection has been shown to improve plasma confinement [2]. Impurities can also affect the stability of tokamak plasmas. The NTM is a common magnetohydrodynamic instability in high-performance plasmas, primarily driven by the bootstrap current term [3, 4]. It is generally believed that impurities unstablize NTM instability by causing radiative cooling and increasing resistivity [5]. The impact of impurity distribution on temperature gradient (ITG) turbulence has been studied [6], however, the effect of impurity distribution on NTM has not yet been reported.

The stability of NTM was analyzed using the kinetic Rutherford equation [7]. This model considers the effects of rotating magnetic island and kinetic effects, but does not account for plasma rotation, rotational shear, and other factors [8, 9]. However, since the rotation frequency and rotational shear of vary slightly during the NTM eruption, and the shaping such as elongation, and triangularity in HL-2A high β plasma are relatively weak, we consider it appropriate to conduct qualitative analysis using this equation. For the low collision frequency regime HL-2A high β plasma, the kinetic Rutherford equation in collisionless polarization current regime is as follows :

$$\frac{\mu_0}{1.22\eta_{\rm nc}}\frac{\mathrm{d}w}{\mathrm{d}t} = \Delta' + \Delta_{bs} + \Delta_{pc} = \Delta \tag{1}$$

$$\Delta_{bs} = 18.396\,\frac{\epsilon^{1/2}}{1+\tau^{-1}}\frac{\beta_\theta}{w}\frac{L_q}{L_n}\left[1+\frac{\eta_e}{4}+\tau^{-1}\left(1-\frac{\eta_i}{2}\right)\right] \tag{2}$$

$$\Delta_{pc} = -74.456\,\frac{\epsilon^{3/2}\tau}{1+\tau^{-1}}\left(\frac{\rho_{\theta \rm i}}{w}\right)^2\left(\frac{L_q}{L_n}\right)^2\frac{\beta_\theta}{w}\frac{\omega(\omega-\omega_{*\rm pi})}{\omega_{*\rm e}^2} \tag{3}$$

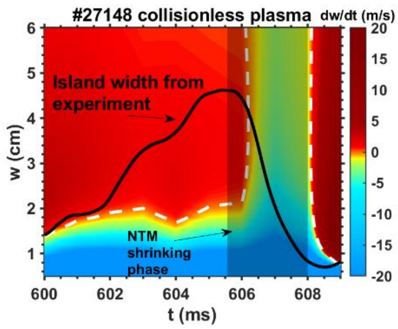

Fig. 1. The results of the kinetic Rutherford equation analysis of the evolution time period of the NTM in shot 27148, showing w and its growth rate. The solid black curve represents the experimental data, while the dashed white curve represents the contour curve where the growth rate is 0. The black shaded area represents the shrinking phase of the NTM.

The parameter w is scanned as the sole variable, and the evolution of the magnetic island width over time is plotted together for comparison, as shown in Fig. 1. From the figure, especially during the phase of NTM spontaneous stabilization, the kinetic Rutherford equation provides qualitatively consistent results. The differences in time may arise from diagnostic errors and the fact that the calculation interval of the kinetic

Rutherford equation time axis is 1 ms, while the time resolution of magnetic probe measurements is much higher. Nevertheless, the qualitative consistency suggests that the kinetic Rutherford equation can explain the phenomenon of NTM spontaneous stabilization and supports further instability analysis.

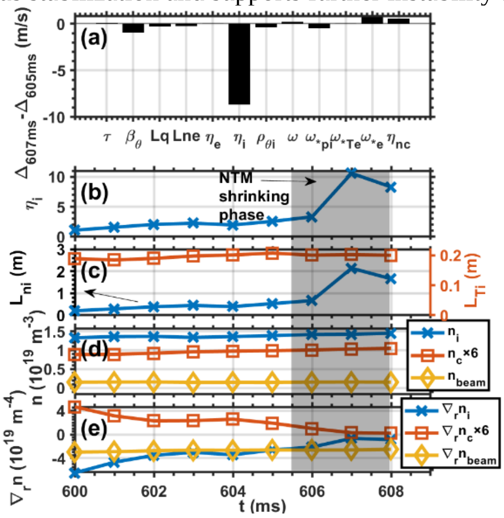

Fig. 2. (a) Qualitative analysis of the contributions of various parameters in the kinetic Rutherford equation to the NTM stabilization results. Changes in relevant physical quantities related to η_i *during NTM evolution: (b)* η_i*, (c)* L_{ni} *and* L_{Ti}*, (d)* n_i*,* n_c *times 6, and* n_{beam}*, radial gradient (e)* $\nabla_r n_i$*,* $\nabla_r n_c$ *times 6,* $\nabla_r n_{beam}$*. The black shaded area represents the shrinking phase of the NTM.*

By varying the parameters at different time points, a convenient comparison between the magnetic island growth stage at 605 ms and the NTM stabilization stage at 607 ms can be made to analyze the contribution of each parameter to NTM spontaneous stabilization. For example, the contribution of η_i can be calculated as $\Delta_{607ms} - \Delta_{605ms} = \Delta(\eta_i(607), w(605), \omega(605) \ldots) - \Delta(\eta_i(605), w(605), \omega(605) \ldots)$. The results indicate that η_i contributes the most to NTM stabilization, as shown in Fig. 2(a).

The time evolution of quantities related to η_i is shown in Fig. 2(b), (c), (d), and (e). The increase in η_i is primarily due to the increase in L_{ni} as depicted in Fig. 2(c). L_{ni} is mainly influenced by the equilibrium impurity distribution. As shown in Fig. 2(d) and (e), the equilibrium quantities do not change significantly, primarily because the impurity gradient decreased, resulting in an increase in L_{ni}. Therefore, changes in impurity transport state lead to an increase in η_i, ultimately stabilizing the NTM. It is worth noting that the radiation can destabilize NTM [10], but during the NTM stabilization phase, the radiation on the 2/1 rational plane increased, so the NTM stabilization is independent of the radiation.

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