Influence of energetic ions on neoclassical tearing modes

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Abstract

In addition to their effect on the linear stability of tearing modes, energetic particles can influence the nonlinear evolution of a magnetic island through an uncompensated cross field current due to the effect of charge separation when the orbit width of an energetic particle is much larger than the island width. The corresponding return parallel current may compensate the loss of bootstrap current in the magnetic island. This nonlinear effect depends on the island’s propagation frequency (the rotation frequency of the island relative to the plasma), the density gradient of energetic ions and magnetic shear. If the island’s propagation frequency is positive, the effect of the uncompensated current plays a stable role on neoclassical tearing modes. When the magnetic shear is sufficiently small, this effect becomes significant and can partially cancel or even overcome the destabilizing effect of the perturbed bootstrap current. In ITER this provides a possibility of using energetic ions to suppress the neoclassical tearing mode for the steady state and hybrid scenarios with weak magnetic shear.

1. Introduction

Neoclassical tearing modes (NTMs) have been observed in major tokamaks, and they can negatively and significantly impact the performance of magnetically confined plasmas[1-4]. These modes are driven by the perturbed helical bootstrap current due to the pressure flattening across the island. They can increase the local radial transport, degrade plasma confinement and even lead to the disruption in high β plasma, resulting in a limit on maximum achievable β[5]. Thus, understanding the physics of NTMs in tokamak plasmas is one of the critical problems of present and future devices for achieving steady-state and high confinement plasmas, such as International Thermonuclear Experimental Reactor (ITER)[6]. To achieve high β and steady operation plasmas, scenarios with a weak magnetic shear configuration were proposed and successfully realized in some large tokamaks[7]. Hence, it is important to explore the physics of NTMs in the operation scenarios with weak magnetic shear configuration.

Energetic particles are inevitably produced in burning plasma or during auxiliary heating (such as neutral beam injection) in tokamak. They can interact with plasma instabilities effectively. Much work has been devoted to investigating the interaction between energetic particles and ideal MHD instabilities[8-11], such as the internal kink and Alfven eigenmodes. However, the study on the interaction between energetic particles and resistive instabilities of m>1 modes (such as NTMs) has just begun. Recently, the effective interaction between NTMs (including tearing modes) and energetic ions has been shown in some experiments and theories[12-23]. The redistribution and loss of energetic ions due to NTM and beam ion effects on NTM onset threshold during neutral beam injection (NBI) have been observed in the experiments[12-15]. In DIII-D[14], it was shown that the onset threshold increases with co-injected beam. Hegna et. al.[17] showed that energetic ions can stabilize nonlinear tearing modes by the perturbed beam ion parallel current in the island region. This beam ion parallel current is due to the deformation of particle distribution function by the magnetic island. However, this stabilizing effect is expected to be small when the orbit width of energetic ions is much larger than island width because the responses of energetic ions to perturbation in the island region is weakened by orbit averaging. In this case, energetic ions can affect the linear stability of tearing modes through their interaction with tearing modes in the outer region[18-21,23]. Furthermore, Mirnov et. al.[24] recently pointed out that the effects of energetic ions in the inner region of linear tearing modes can not be neglected even when their orbit width is large for a RFP plasma. It was shown that an uncompensated cross field current is produced due to the charge separation effect, and the effect of this uncompensated current is stabilizing for linear tearing modes. The uncompensated current comes from a net ExB current because the beam ion ExB current is significantly reduced by orbit averaging effect in the limit of large orbit width. In this work, we investigate the effect of the uncompensated current on the nonlinear evolution of NTM. We will show that the effect is significant when magnetic shear is weak and is stabilizing when the mode frequency is positive in plasma frame.

2. Influence of energetic ions on NTM

The detailed calculation can be referred to the paper [25]. By a series of derivation, we can obtain the evolution of NTMs including energetic ions, as

$$\frac{8\pi}{\eta c^2} I_1 \frac{dw}{dt} = \Delta' + \Delta'_b + \Delta'_\pi + \Delta'_u \tag{1}$$

where $\Delta'_b, \Delta'_\pi, \Delta'_u$ result from the contribution of bootstrap current, neoclassical polarization current and uncompensated cross field current, respectively, as

$$\Delta'_b = G_1 \sqrt{\varepsilon_s} \frac{r_s}{sL_n} \frac{\beta_{\theta i}}{w}, \tag{2}$$

$$\Delta'_\pi = -1.64 \varepsilon_s^{3/2} G_2 \frac{r_s^2}{s^2 L_n^2} \frac{\rho_{\theta i}^2}{w^2} \frac{\beta_{\theta i}}{w} \frac{\omega'(\omega' - \omega_{*i})}{\omega_{*i}^2}, \tag{3}$$

$$\Delta'_u = -G_3 \frac{r_s^2}{s^2 L_n^2} \frac{\beta_{\theta i}}{w} \frac{\omega'}{\omega_{*i}} \frac{L_{ni}}{L_{nh}} \frac{n_h}{n_i}. \tag{4}$$

Here, the numerical coefficients $I_1 \sim 0.83, G_1 \sim 2.31, G_2 \sim 1.42, G_3 \sim 1.58$, ω_{*i} is the ion diamagnetic current, L_{ni}, L_{nh} are the scale lengths of ion density and energetic ion density, respectively. ω' is determined by the torque balance, which is still an open debate. Here, it is needed to point out that the contributions of energetic ions are reflected in both Δ'_u and the stability criterion Δ' (one can refer the detail in **Ref**.[19]. From Eq.(4), it can be seen that the effect of uncompensated cross field current from energetic ions depends on the magnetic shear, propagation frequency of the island and the density gradients of ions and energetic ions at resonance surface. It plays a stable role for $\omega' > 0$ if density gradients of ions and energetic ions at resonance surface have the same sign. This is different from the effect of neoclassical polarization current, which is stabilizing for $\omega' < 0$ or $\omega' > \omega_{*i}$. Although the density of energetic ions is much smaller than the ion density, Δ'_u may become significant for weak magnetic shear, like in one of the scenarios of high β and steady state and hybrid operations in ITER[26] and some large tokamaks[7], where a lot of steady operation discharges have been realized with a zero or weak magnetic shear configuration. For weak magnetic shear, the effect of uncompensated cross field current from energetic ions can be comparable with the contribution of the perturbed bootstrap current, and would enhance the onset threshold of NTMs or suppress the NTMs. For the typical tokamak like JT-60U, the main parameters $R_0 \sim 3.2, a \sim 0.8,$ and the energetic ion density can be up to $0.02n_i$ during neutral beam injection[30]. Given $\omega' \sim \omega_{*i}$, $\varepsilon_s \sim 1/8$, $L_h \sim 0.16m$, $L_{ni} \sim 0.7m$, the ratio of $|\Delta'_u / \Delta'_b|$ against n_h / n_i is shown in **Fig**.1. From **Fig**.1, it can be seen that $|\Delta'_u / \Delta'_b|$ increases with n_h / n_i increasing or s decreasing. For the weak magnetic shear and large fraction of energetic ion density, $|\Delta'_u| \sim |\Delta'_b|$, even $|\Delta'_u| > |\Delta'_b|$. Namely, the contribution of uncompensated cross field current from energetic ions becomes significant, and its stabilizing effect can partially cancel or overcome the destabilizing effect of the perturbed bootstrap current. Then, NTMs will be suppressed.

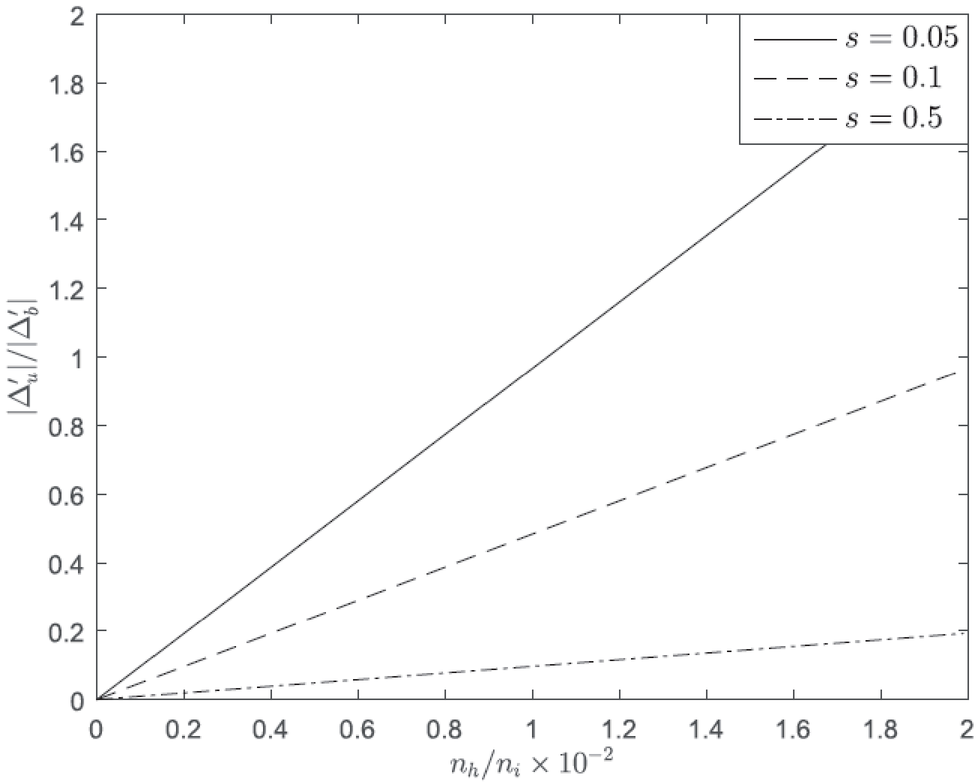

Figure 1. The ratio between the contributions of uncompensated cross field current due to energetic ions and bootstrap current, $|\Delta'_u|/|\Delta'_b|$, against the fraction of energetic ion density n_h/n_i with different values of magnetic shear $s = 0.05,\ 0.1,\ 0.5$.

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