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Profile Effects of Plasma Rotation Velocity on Instability at Tokamak Internal Transport Barrier

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Abstract

The peaked profile of perpendicular/parallel plasma rotation velocity at internal transport barrier (ITB) is modelled by a Gaussian distribution. Its stabilizing or destabilizing effects on the sheared slab η_i instability are analyzed in the finite and weak magnetic shear regions in detail. It is found that the peaked profile of a counter-toroidal rotation at ITB contributes to the formation and maintenance of ITB in the tokamak discharges with negative magnetic shear.

Keywords:
plasma rotation profile, Gaussian distribution, slub η_i instability, internal transport barrier (ITB)

1. Introduction

Negative central magnetic shear (NCS) operation provides a new channel to the core confinement improvement for tokamak discharges. One of remarkable achievements is the formation of the internal transport barrier (ITB) [1-3]. ITB is characterized by a radial thin layer with reduced transport rate. It is located in the region with negative and weak magnetic shear near the minimum–q surface. At ITB, it has been observed that the ion/electron temperature and density gradients become sharply steep, and the plasma rotation forms a peaked, even "notch", profile in the ion diamagnetic drift direction for the perpendicular component and in the counter-toroidal direction for the parallel one. Previously, effects of local rotation shear on the slab η_i ($\eta_i = d\ln T_i/d\ln n$) stability have been intensively discussed in the core and edge plasmas [4,5]. Recently, the curvature effects of the rotation velocity have also been explored [6,7]. However, when the eigen mode width is comparable to or larger than that of the rotation profile, the local characteristic quantities, such as the rotation shear and curvature, are not enough to describe the radial variation features of the velocity profile at ITB. In this work, considering that the slab mode might be dominant in the weak magnetic shear region near the minimum–q surface and the toroidal model is rather complicated when the rotation velocities are included (here the ballooning symmetry is broken), we temporarily employ the sheared slab η_i instability to further study the effects of rotation profile.

2. Basic Model and Eigen Equation

In the weak magnetic shear region near the minimum–q surface, the conventional sheared slab model should be expanded to include the radial variation effects of the magnetic shear. The equilibrium magnetic field can be written as [8,9]

$$\vec{B} = B_0\,[\,\hat{e}_z - (x/L_s + x^2/L_B^2)\,\hat{e}_y\,] \qquad (1)$$

Here $\hat{e}_z$ and $\hat{e}_y$ correspond to the toroidal and poloidal directions. $x = r - r_0$, $L_s = Rq_0/\hat{s}$ and $L_B^2 = (2R/r_0)(q^2/q_0'')$ with $\hat{s} = r_0 q_0'/q_0$. When r_0 approaches the minimum–q surface ($r_0 \rightarrow r_{\min}$), $L_s \rightarrow \infty$, only the variation of the

*Corresponding author's e-mail: E-mail:lijiquan@hotmail.com magnetic shear is dominant [8]. Otherwise, it degenerates to the conventional sheared slab model [4,5].

According to the neoclassical estimate, the rotation velocity is proportional to the ion temperature or pressure gradient [10]. Experimentally, the rotation velocities, including the poloidal and toroidal, have been observed to form a peaked profile at ITB [11,12]. So we assume the perpendicular/parallel rotation velocity at ITB has a Gaussian distribution form, *i.e.*,

$$\upsilon_{\perp,//} = \hat{\upsilon}_{p,//} \exp\left[-(x - x_\upsilon)^2 / L^2_{\perp,//}\right] \qquad (2)$$

Here $L_{\perp,//}$ and x_υ represent the characteristic width scale of the profile and the possible small deviation of the position with velocity peak from the mode resonant surface (assuming $x_\upsilon^2 << L^2_{\perp,//}$). Near the rational surface, $\upsilon_{\perp,//}$ can be approximately written as $\upsilon_{\perp,//} \approx \hat{\upsilon}_{p,//}\,[1 + 2x_\upsilon x/L^2_{\perp,//} - x^2/L^2_{\perp,//} + ...]\exp(-x_\upsilon^2/L^2_{\perp,//})$. This profile at least includes the contributions of the velocity shear and curvature. Note that the appearance of a larger x_υ also means the effect of rotation shear is dominant near the reference surface. For the smaller x_υ, this expression is almost same as the profile modelled by Sen, *et al* [7]. However, $\upsilon_{\perp,//}$ in Eq. (2) decreases quickly and tends to be negligible with x increasing, like the experimental observation [11,12]. Hence, this modelled profile appears to be more reasonable at ITB.

Using the fluid description, the electrostatic slab η_i eigen equation can be derived as [4,5,8]

$$\mathrm{d}^2\hat{\phi}/\mathrm{d}x^2 + U(x,\Omega)\,\hat{\phi} = 0, \qquad (3)$$

with the potential function

$$U(x,\Omega) = -k_y^2 + \frac{1 - H\Omega}{H\Omega + K} + \frac{(k_{//} L_n / k_y)^2}{(H\Omega)^2 - (\Gamma/\tau)(k_{//} L_n / k_y)^2} - \frac{H\Omega \cdot k_{//} \upsilon'_{//} L_n^2 / k_y}{(H\Omega + K)\,[(H\Omega)^2 - (\Gamma/\tau)(k_{//} L_n / k_y)^2]} .$$

Here $\Omega = \omega/\omega_{*e}$, $H = 1 - L_n(\upsilon_\perp + k_z\upsilon_{//}/k_y)/\Omega$, $k_{//} = k_z - k_y(x/L_s + x^2/L_B^2)$. $\upsilon_\perp < 0$ means the perpendicular rotation is along the ion diamagnetic drift direction. Meanwhile, $\upsilon_{//} < 0$ indicates the parallel rotation is in the counter-toroidal direction. Note that the profile effect of perpendicular rotation mainly causes a generalized Doppler frequency shift, which depends on the velocity profile, including its shear and curvature effects. It can also lead the dilatation of the eigenmode structure and a wave-flow resonance [6]. Meanwhile, the parallel rotation profile produces a small Doppler frequency shift for non-zero k_z as well. Most importantly, the parallel rotation couples with the ion transit motion and may drive or damp the drift wave perturbation.

3. Stability Analysis and Discussion

Equation (3) can be numerically solved for the lowest order slab η_i mode by using the shooting code based on the method of invariant embedding [8]. In the following calculations for two cases by taking typical ITB parameters, we only display the dependence of the growth rates on velocity profiles under considering that

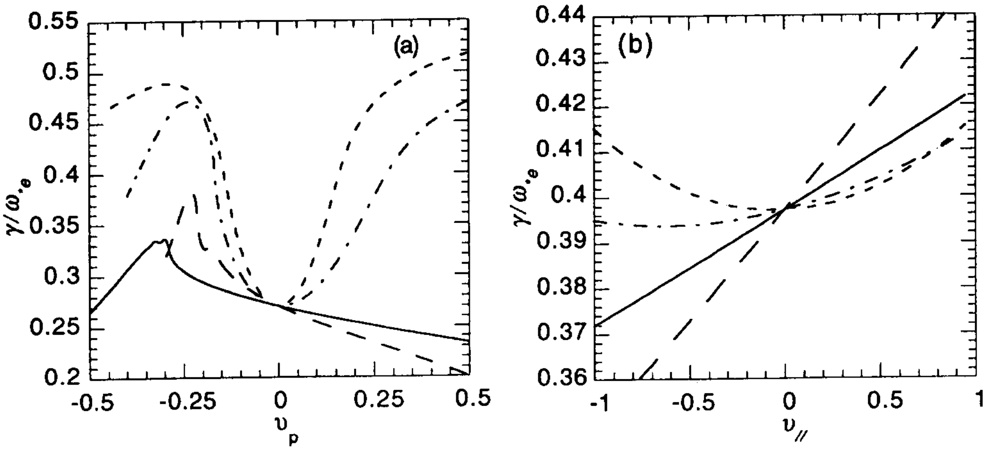

Fig. 1 Normalized growth rate versus perpendicular (a) and parallel (b) rotation velocity profile in the finite magnetic shear region. The solid curve is for $L^2_{\perp,//} = 100$, $x_\upsilon = 0$, the dashed for $L^2_{\perp,//} = 50$, $x_\upsilon = 0$, the dot-dashed for $L^2_{\perp,//} = 100$, $x_\upsilon = 5$, the dot-dotted for $L^2_{\perp,//} = 50$, $x_\upsilon = 5$. $\hat{\upsilon}_{//} = 0$, $\Gamma = 1$ in Fig. 1a and $\hat{\upsilon}_p = 0$ and $\Gamma = 0$ in Fig. 1b. The other parameters are $\eta_i = 1.1$, $\tau = 0.75$, $L_n = 10$, $L_s = 50$, $L_B \to \infty$, $k_y = 0.3$.

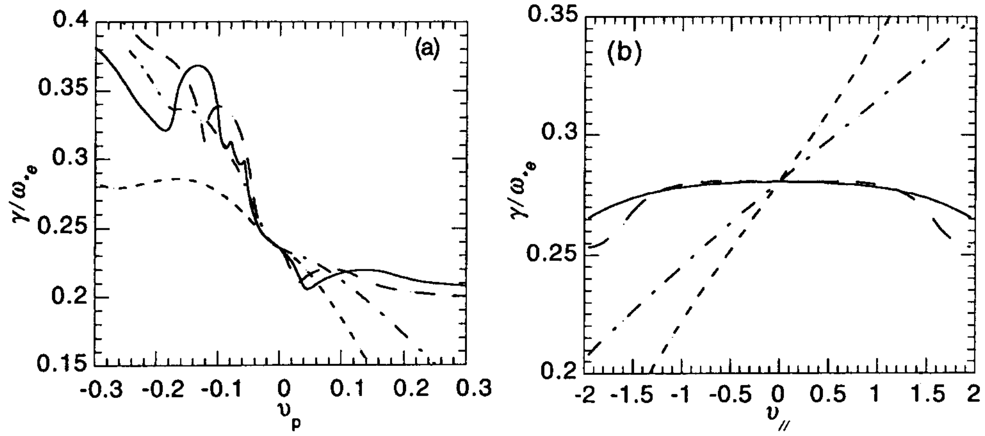

Fig. 2 Normalized growth rate of the global branch versus perpendicular (a) and parallel (b) rotation velocity profile in the weak magnetic shear region. The corresponding curves and parameters are the same as in Fig. 1 except $L_B = 50$, $L_s \to \infty$, $k_z = 0.005$.

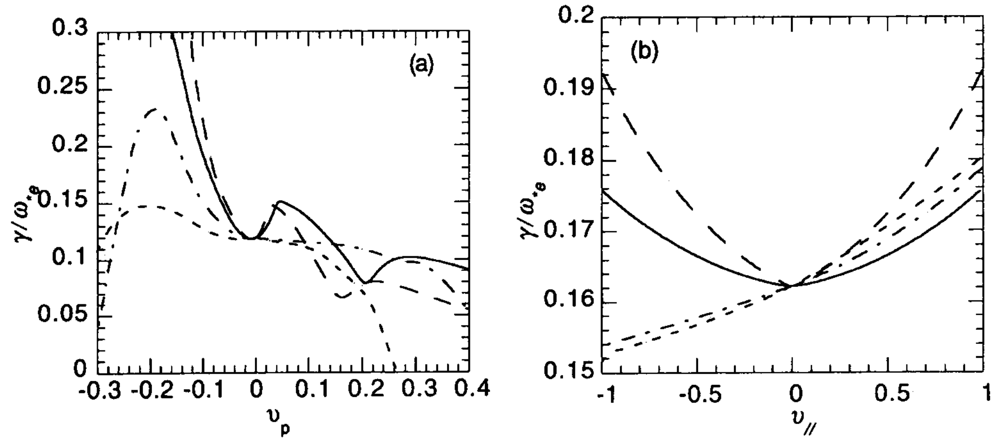

Fig. 3 Normalized growth rate of the double branch versus perpendicular (a) and parallel (b) rotation velocity profile in the weak magnetic shear region. The corresponding curves and parameters are the same as in Fig. 2.

the real frequency and their signs are obviously influenced by the Doppler frequency shift.

One case is that the ITB is located in the finite and negative shear region far off the minimum–q surface. Fig. 1a shows that when $\upsilon_\perp < 0$, the peaked profile has a destabilizing role for smaller perpendicular rotation and a stabilizing role for the larger one. The former role results from the mode coupling with the higher radial harmonics and the latter is caused by a wave-flow resonant absorption when the rotation velocity increases. For $\upsilon_\perp > 0$, the peaked profile always stabilizes the slab η_i mode and the rotation shear plays a destabilizing role. The perturbation analysis shows that the stability of the slab η_i mode is apparently independent of the sign of the rotation shear, but the eigen perturbation can "feel" the direction of rotation curvature. Meanwhile, for the parallel rotation profile, its shear ($x_\upsilon \neq 0$) always destabilizes the slab η_i mode as shown in Fig. 1b. This displays its enhanced effects to the η_i driving mechanism due to the parallel rotation profile coupling with the parallel ion compression motion. However, its peaked profile ($x_\upsilon = 0$) in the counter-toroidal direction can dilate the eigenmode structure and has a strongly stabilizing role. It indicates the peaked profile of the parallel rotation along the counter-toroidal direction can be conducive to suppress the slab η_i instability in the finite magnetic shear region.

The other is the ITB is located near the minimum–q

surface, where the magnetic shear is weak and its radial variation effect is dominant. In this case, there exist two branches of the lowest order sheared slab η_i instability, called the global (G) and double (D) modes [8,9]. Fig. 2 and Fig. 3 display the dependence of their growth rates on the perpendicular and parallel velocity profiles. Comparing Fig. 2a and Fig. 3a with Fig. 1a, we can see that the profile effects of perpendicular rotation on the global and double modes are very complex. On the whole, the peaked profile of perpendicular rotation in the ion diamagnetic drift direction destabilizes the two branches and stabilizes them for the larger rotation in the reverse drift direction in the weak magnetic shear region. For the parallel rotation, its peaked profile weakly stabilizes the global branch and strongly destabilizes the double one regardless of the rotation direction as shown in Fig. 2b and Fig. 3b. However, its shear in the counter-toroidal direction plays a strongly stabilizing role to the two branches in the weak magnetic shear region, similar to the effects of its peaked profile in the finite magnetic shear region. This is because the parallel rotation profile strongly couples with the ion transit motion along the equilibrium field line, and the shear of parallel rotation and the magnetic shear have an equitable role to the eigen perturbation. In brief summary, the complex dependence of the stability of sheared slab η_i mode on the perpendicular and parallel rotation profiles is dominated by the eigenmode structure, the rotation direction and q profile (magnetic field structure).

An interesting result can be noted by comparing Fig. 1b with Fig. 2b and Fig. 3b. For the parallel rotation along the counter-toroidal direction ($\upsilon_{//} < 0$), its peaked profile in the finite magnetic shear region and its shear in the weak magnetic shear region (near the minimum–q surface) identically have a strongly stabilizing role to the sheared slab η_i modes regardless of their eigenmode structure. Experimental results observed in JT-60U [3] have shown that a peaked, even "notch", counter-toroidal rotation profile emerges at ITB and its outside edge approaches the minimum–q surface. It is obvious that the effects of rotation profile should be dominant at the center of ITB where the magnetic shear is negative and finite ($-2 < \hat{s} < -1$) and the shear of the parallel rotation plays a major role in the weak magnetic shear region near the minimum–q surface. This means that the peaked profile of the counter-toroidal rotation at ITB can consistently suppress the linear growing of η_i instability. It indicates the peaked profile of the counter-toroidal rotation is good for the formation and maintenance of ITB in tokamak plasmas with strongly negative magnetic shear.

4. Summary

A stability analysis on the profile effects of the perpendicular and parallel rotation on the sheared slab η_i instability at ITB has been carried out. The profile of rotation velocity at ITB has been modelled by a Gaussian distribution following the neoclassical theory and the experimental observation. Numerical calculations show that the stabilizing or destabilizing roles of the perpendicular and parallel velocity profiles depend on the regime with finite or weak magnetic shear, on the direction of plasma rotation along the ion or electron diamagnetic drift, and on the perturbation structure of the eigen mode. It is found that the peaked profile of a counter-toroidal rotation at ITB contributes to the formation and maintenance of ITB in the tokamak discharges with negative magnetic shear.

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