

Influence of Poloidal Rotation of Plasma on Peeling-Ballooning Modes^{*}

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Abstract

Influence of the poloidal rotation of the plasma on Peeling-Ballooning modes (P-B modes) is studied with BOUT++ code. The results show that the poloidal rotation destabilizes P-B modes because of the effect of Kelvin-Helmholtz instability when the poloidal rotation is large enough and the shear is small, and the shear of the poloidal rotation can stabilize high-n P-B modes when the shear is increased.

Keywords: Plasma; Poloidal Rotation; Peeling-Ballooning Mode

1 INTRODUCTION

Edge localized modes (ELMs) are magnetohydrodynamic (MHD) instabilities occurring in fusion plasmas in high confinement regime (H-mode) of tokamaks. P-B modes which are driven by gradients of pressure and current in the pedestal are widely accepted as the instability triggering large ELMs [1-3]. The effect of the toroidal rotation of the plasma on ELM and P-B modes has been studied. For example, results from JT-60U showed that the toroidal rotation can reduce ELM size and increase ELM frequency [4]. The ELITE code [5,6] shows that high-n ideal P-B modes are stabilized by the shear of the toroidal rotation, while low-n P-B modes are destabilized. Results from BOUT++ in 2010 showed nonideal physics effects, such as diamagnetic drift, $\mathbf{E} \times \mathbf{B}$ drift, resistivity, and anomalous electron viscosity, are important to P-B modes [7]. Results from BOUT++ in 2012 showed the shear of the toroidal rotation can stabilize high-n P-B modes, and the Kelvin-Helmholtz instability which is caused by the shear of the toroidal rotation destabilizes P-B modes [8]. The above two articles have not taken into account the influence of the poloidal rotation on P-B modes.

In the absence of an external driving source, the poloidal rotation of the plasma in the Tokamak will be damped out because of magnetic pumping [9], so the influence of the poloidal rotation of the plasma on P-B modes or ELM is ignored generally. There is study showing that the electron cyclotron wave can drive the poloidal rotation of the plasma [9]. Meanwhile, experiments have found that the momentum of the injection can cause the poloidal rotation of the plasma when the supersonic molecular beam is injected along the tangential direction [10]. So it is necessary to figure out the influence of the poloidal rotation of the plasma on P-B modes and ELM. In this paper, we will study the influence of the poloidal rotation of the plasma on P-B modes with BOUT++ code, and the nonideal physics effects will be considered in our simulations.

2 SIMULATION EQUATIONS

In our simulations, we assume that the poloidal rotation of the plasma is existed without external driving source, so there isn't driving source term in three-field reduced MHD equations. Three-field equations describe the evolution of vorticity, pressure, and parallel vector potential with time. The flute perturbation model, $k_{\parallel} / k_{\perp} \ll 1$ is used in these

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equations

$$\frac{\partial \varpi_1}{\partial t} + \mathbf{v}_{\text{pol}} \cdot \nabla \varpi_1 + \mathbf{v}_{\text{E,dia0}} \cdot \nabla \varpi_1 + \mathbf{v}_1 \cdot \nabla \varpi_0 + \mathbf{v}_1 \cdot \nabla \varpi_1 = \mathbf{B}_0 \cdot \nabla_{\parallel} \mathbf{J}_{\parallel} + 2\mathbf{b}_0 \times \mathbf{k}_0 \cdot \nabla P \quad (1)$$

$$\frac{\partial p_1}{\partial t} + \mathbf{v}_{\text{pol}} \cdot \nabla p_1 + \mathbf{v}_{\text{E,dia0}} \cdot \nabla p_1 + \mathbf{v}_1 \cdot \nabla p_0 + \mathbf{v}_1 \cdot \nabla p_1 = 0 \quad (2)$$

$$\frac{\partial A_{\parallel 1}}{\partial t} = -\nabla_{\parallel} \Phi - \mathbf{v}_{\text{pol}} \cdot \nabla A_{\parallel 1} + \frac{\eta}{\mu_0} \nabla_{\perp}^2 A_{\parallel 1} - \frac{\eta_H}{\mu_0} \nabla_{\perp}^4 A_{\parallel 1} \quad (3)$$

$$\varpi_1 = \frac{\rho_0}{B_0} \left(\nabla_{\perp}^2 \phi_1 + \frac{1}{Z e n_0} \nabla_{\perp}^2 p_1 \right) \quad (4)$$

$$\varpi_0 = \rho_0 \mathbf{b}_0 \cdot \nabla \times \mathbf{v}_{\text{pol}} \quad (5)$$

$$\mathbf{J}_{\parallel} = \mathbf{J}_{\parallel 0} - \frac{1}{\mu_0} \nabla_{\perp}^2 A_{\parallel 1} \quad (6)$$

$$\Phi = \Phi_{\text{dia0}} + \phi_1 \quad (7)$$

In these equations, $\mathbf{v}_{\text{pol}}$ is poloidal rotation velocity. $\nabla_{\parallel} = \mathbf{b} \cdot \nabla = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$, $\tilde{\mathbf{b}} = \nabla A_{\parallel 1} \times \mathbf{b}_0 / B$, and $\mathbf{k}_0 = \mathbf{b}_0 \cdot \nabla \mathbf{b}_0$ is equilibrium magnetic field line curvature vector. ϕ_1 is perturbed electrostatic potential, Φ_{dia0} is electrostatic potential which can drive $\mathbf{E} \times \mathbf{B}$ drift velocity. $\mathbf{v}_{\text{E,dia0}}$ is $\mathbf{E} \times \mathbf{B}$ drift velocity which can balance ion diamagnetic drift velocity. η is resistivity, η_H is hyper-resistivity. In fact, In Eq. (5) $\varpi_0 = \rho_0 \mathbf{b}_0 \cdot \nabla \times \mathbf{v} = \rho_0 \mathbf{b}_0 \cdot \nabla \times (\mathbf{v}_{\text{E,dia0}} + \mathbf{v}_D + \mathbf{v}_{\text{pol}})$, but ion diamagnetic drift velocity $\mathbf{v}_D$ balances $\mathbf{E} \times \mathbf{B}$ drift velocity $\mathbf{v}_{\text{E,dia0}}$, so $\varpi_0 = \rho_0 \mathbf{b}_0 \cdot \nabla \times \mathbf{v}_{\text{pol}}$.

To meet the conditions of incompressible fluid, the poloidal rotation velocity is written artificially

$$\mathbf{v}_{\text{pol}} = C \mathbf{B}_p \quad (8)$$

$\mathbf{B}_p$ is poloidal magnetic field. Referring to the curve of poloidal rotation velocity in the Ref. [11], we define $C = C_0 (1 - \tanh(C_S (x - x_0)))$. Here, $x = (\psi - \psi_{\text{axis}}) / (\psi_{\text{sep}} - \psi_{\text{axis}})$ is normalized radial coordinate with poloidal magnetic fluxes, Ψ_{axis} and Ψ_{sep} are poloidal magnetic fluxes at the magnetic axis and separatrix, respectively. x_0 controls the location of the shear of poloidal rotation. C_0 controls the amplitude of the poloidal rotation, C_S controls the shear of the poloidal rotation.

3 SIMULATION RESULTS

We solve the three-field reduced MHD equations with BOUT++ code. In our simulations, the major radius on magnetic axis is $R_{\text{axis}} = 3.49\text{m}$. The magnetic field on axis is $B_0 = 1.94\text{T}$. In order to study the influence of the poloidal rotation and the shear of the poloidal rotation respectively, we give two different profiles of poloidal rotation velocity as shown in Fig. 1 and Fig. 2.

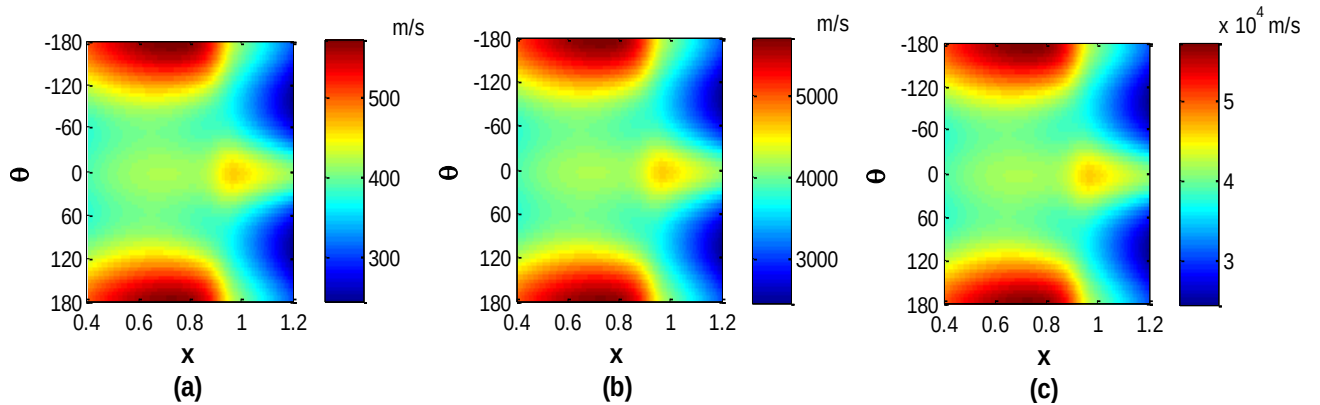


FIG. 1. $C_S = 0$, PROFILES OF THE POLOIDAL ROTATION VELOCITY FOR DIFFERENT C_0 . (A), (B), (C) CORRESPOND TO $C_0 = 1.5 \times 10^3$, 1.5×10^4 , 1.5×10^5 , RESPECTIVELY.

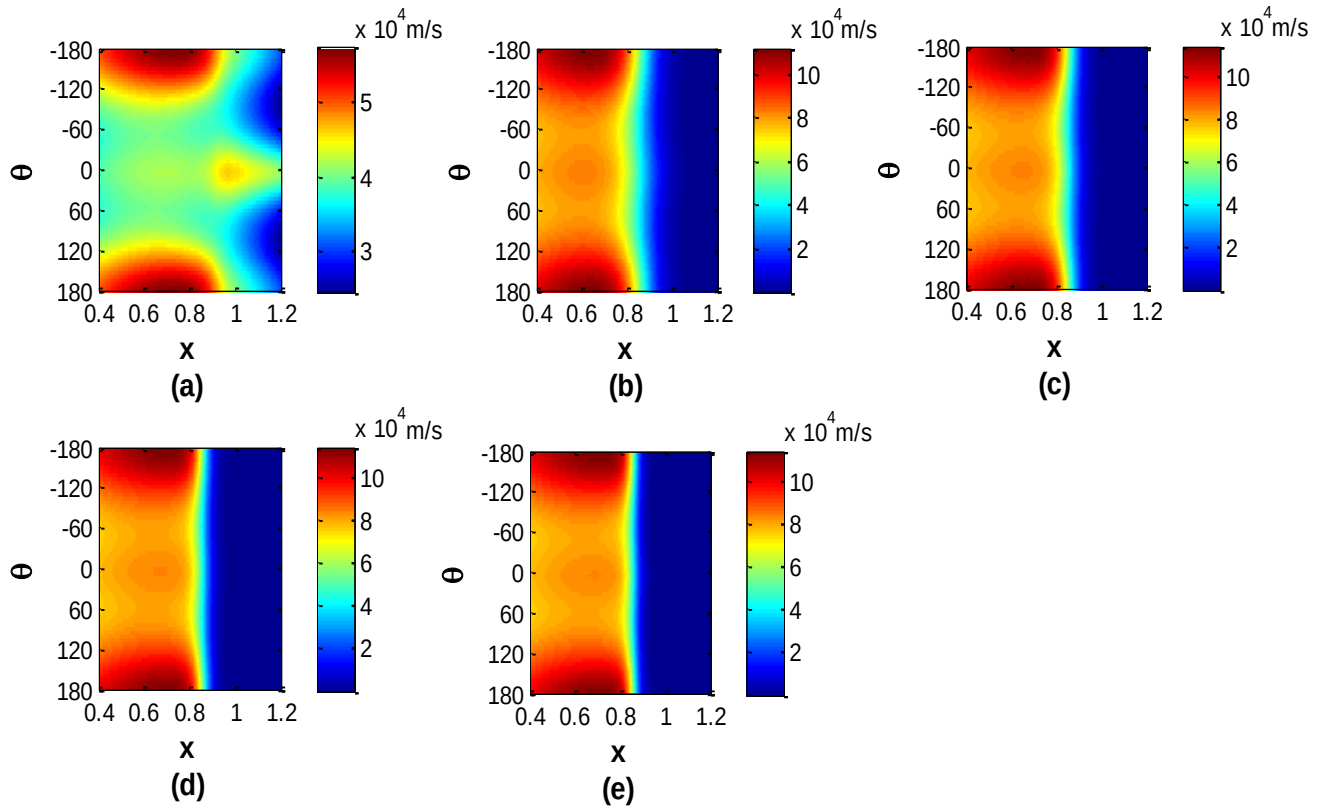


FIG. 2. $C_0=1.5 \times 10^5$, PROFILES OF THE POLOIDAL ROTATION VELOCITY FOR DIFFERENT C_s . (A), (B), (C), (D), (E) CORRESPOND TO $C_s=0, 10, 15, 20, 25$, RESPECTIVELY.

In Fig. 1, $C_s=0$ is invariant, the shear of the poloidal rotation is small and can be ignored, but the velocity gradient of the poloidal rotation will change with the amplitude of the poloidal rotation. In Fig. 2, $C_0=1.5 \times 10^5$ is invariant, the shear of the poloidal rotation becomes large when C_s is increased.

In Fig. 3 and Fig. 4, when the poloidal rotation is zero, the simulation result is consistent with the result in the Ref. [7]. In Fig. 3, the results show that the poloidal rotation increases the growth rates of P-B modes when the poloidal rotation is large enough and the shear of the poloidal rotation can be considered to be ignored. In Fig. 4, the results show the growth rates of high- n P-B modes is reduced when the shear of the poloidal rotation is increased.

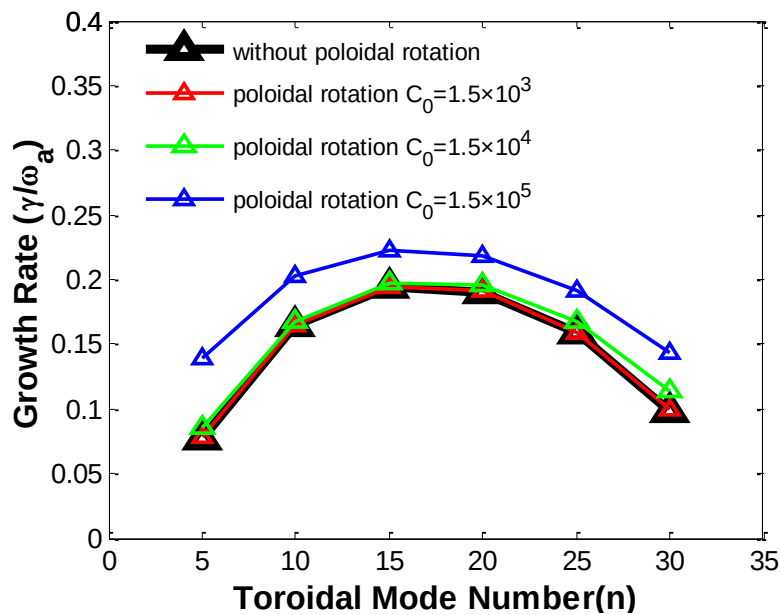


FIG. 3. $C_s=0$, GROWTH RATES OF P-B MODE VERSUS TOROIDAL MODE NUMBER n . THE GROWTH RATES ARE NORMALIZED TO THE ALFVEN FREQUENCY Ω_A . THE CURVES OF THE DIFFERENT COLORS CORRESPOND TO DIFFERENT C_0 .

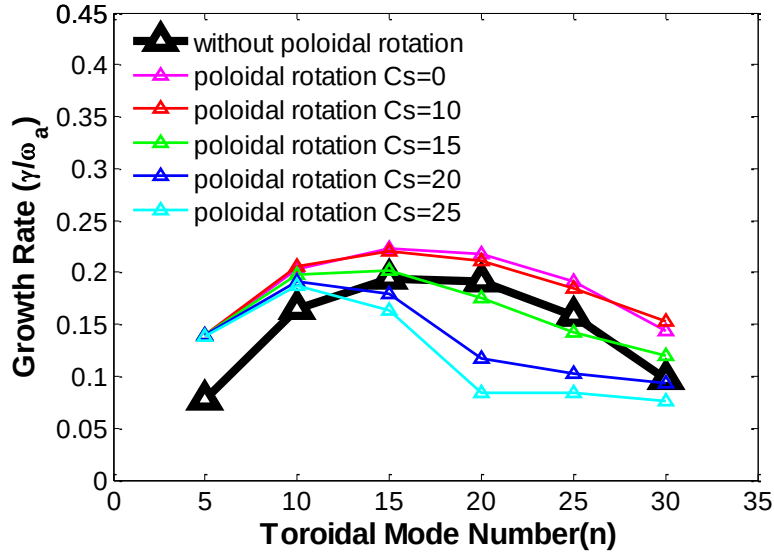


FIG. 4. $C_0=1.5 \times 10^5$, GROWTH RATES OF P-B MODE VERSUS TOROIDAL MODE NUMBER n . THE GROWTH RATES ARE NORMALIZED TO THE ALFVEN FREQUENCY Ω_A . THE CURVES OF THE DIFFERENT COLORS CORRESPOND TO THE DIFFERENT SHEAR PARAMETER C_S .

4 SUMMARY

The current results show the poloidal rotation of the plasma has a great influence on P-B modes. When the poloidal rotation of the plasma is large enough and the shear is small, the poloidal rotation of the plasma destabilizes P-B modes. When the shear of the poloidal rotation becomes large, the poloidal rotation of the plasma can stabilize high- n P-B modes. In our simulations, when $C_S=0$ is invariant, the velocity gradient of the poloidal rotation will change with the amplitude of the poloidal rotation, and the velocity gradient will lead to Kelvin-Helmholtz instability. The destabilizing effect of the poloidal rotation on P-B modes is caused by the Kelvin-Helmholtz instability.

The quantitative relationship between the external driving source and the poloidal rotation of the plasma and the self-consistent association with the plasma parameters are still not clear, so in this paper the formula of the poloidal rotation velocity has not yet reflected the self-consistent relationship between the poloidal rotation and the actual driving source as well as the plasma parameters. However, we can change the amplitude of the poloidal rotation and the shear of the poloidal rotation and the location of the shear by this formula. So our study on the influence of the poloidal rotation of the plasma on P-B modes is based on the assumption that the poloidal rotation of the plasma is existed in the Tokamak. In fact, the poloidal rotation in our paper is probable to be derived as mentioned in the section “Introduction”. The self-consistent relationship between the poloidal rotation and the actual driving source as well as the plasma parameters will be considered in a follow-up study.

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REFERENCES

- [1] Connor J W, Hastie R J, Wilson H R and Miller R L. “Magnetohydrodynamic stability of tokamak edge plasmas”[J]. Physics of Plasmas, 1998, 5: 2687
- [2] Snyder P B, Wilson H R, Ferron J R, et al. “Edge localized modes and the pedestal: A model based on coupled peeling–ballooning modes”[J]. Physics of Plasmas, 2002, 9: 2037
- [3] Snyder P B, Wilson H R, and Xu X Q. “Progress in the peeling-ballooning model of edge localized modes: Numerical studies of nonlinear dynamics”[J]. Physics of Plasmas, 2005, 12 056115

- [4] Oyama N, Sakamoto Y, Isayama A, et al. “Energy loss for grassy ELMs and effects of plasma rotation on the ELM characteristics in JT-60U”[J]. Nuclear Fusion, 2005, 45: 871-881
- [5] Wilson H R, Cowley S C, Kirk A, et al. “Magneto-hydrodynamic stability of the H-mode transport barrier as a model for edge localized modes: an overview”[J]. Plasma Physics and Controlled Fusion, 2006, 48: A71-A84
- [6] Snyder P B, Burrell K H, Wilson H R, et al. “Stability and dynamics of the edge pedestal in the low collisionality regime: physics mechanisms for steady-state ELM-free operation”[J]. Nuclear Fusion, 2007, 47: 961-968
- [7] Xu X Q, Dudson B, Snyder P B, et al. “Nonlinear Simulations of Peeling-Ballooning Modes with Anomalous Electron Viscosity and their Role in Edge Localized Mode Crashes”[J]. Physical Review Letters, 2010, 105 175005
- [8] Xi P W, Xu X Q, Wang X G, et al. “Influence of equilibrium shear flow on peeling-ballooning instability and edge localized mode crash”[J]. Physics of Plasmas, 2012, 19 092503
- [9] 刘才根, 钱尚介, 万华明. “电子回旋波驱动的托卡马克芯部等离子体极向旋转”[J]. 物理学报, 1998, 47: 1515
- [10] 陈程远. “HL-2A 装置上超声分子束注入的发展及其相关物理研究”[D]. 博士学位论文: 核工业西南物理研究院, 2016
- [11] Hinton F L, Kim J, Kim Y B, et al. “Poloidal Rotation near the Edge of a Tokamak Plasma in H Mode”[J]. Physical Review Letters, 1994, 72: 1216

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