Effect of shear equilibrium flow in Tokamak plasma on resistive wall modes*

Li Li(李 莉)† and Liu Yue(刘 悦)

Key Laboratory of Materials Modification by Laster, Ion and Electron Beams, Ministry of Education, School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, *China*

(Received 5 November 2012; revised manuscript received 4 December 2012)

A code named LARWM with non-ideal magnetohydrodynamic equations in cylindrical model is used to describe the instability in Tokamak plasma surrounded by a conducting wall with finite resistivity. We mainly take three factors related to the shear equilibrium plasma flow into consideration to study the stabilizing effect of the shear flow on the resistive wall modes (RWMs). The three factors are the velocity amplitude of flow, the shear rate of flow on plasma surface, and the inertial energy of equilibrium plasma flow. In addition, a local shear plasma flow is also calculated by the LARWM code. Consequently, it is found that the inertial energy of the shear equilibrium plasma flow has an important role in the stabilization of the RWMs.

Keywords: Tokamak plasma, shear equilibrium flow, resistive wall modes

PACS: 52.30.Cv, 52.35.Py, 52.65.Kj **DOI:** 10.1088/1674-1056/22/7/075203

1. Introduction

One of the most dangerous modes is the external kink mode for high-pressure and bootstrap current tokamaks because of its global structure, which can be excited when the plasma pressure exceeds the no-wall beta limit.[1] Fortunately, according to the linear magnetohydrodynamic (MHD) theory,[2] the external kink mode can be stabilized absolutely when the plasma is surrounded by a perfect wall, which means that the wall diffusion time τ_w approaches infinity, so that perturbations cannot penetrate the wall. However, there is always finite resistivity on the actual conducting wall, which can make the perturbative energy run out of the wall into the outer vacuum, thereby exciting a new instability called the resistive wall mode (RWM). Though the growth rate of RWM is significantly smaller than the external kink mode, it is still dangerous when the discharge time of the device exceeds the wall diffusion time.

Theoretical[3–8] and experimental[9–12] work suggests noticeable stabilizing effect of the uniform equilibrium plasma flow on the RWMs, when the dissipative effects are taken into consideration.[13] It can be seen easily that the effect of the velocity amplitude of the uniform plasma flow on the stabilized RWMs. At the same time, the inertial energy taken into plasma by the equilibrium plasma flow is also changed, so that it may be another factor of stabilized RWMs. It is well known that there is obvious effect of the shear plasma flow on stabilization of many MHD modes.[14–19] For the tearing mode, the shear rate of the plasma flow on the plasma resonance surface plays an important role.[14,15] For the RWMs, there are also some studies[16–19] on the influence of the shear plasma flow. However, most of previous publications focus on the effect of different types of the plasma flow profiles[17–19] or the shear rate of the plasma flow on the resonance surface.[16] In fact, the shear rate on a plasma surface also plays a key role in stabilization of the RWMs, especially in the plasma without a resonance surface. In this work, we focus on the effect of the equilibrium shear plasma flow on the RWMs, and mainly take three factors into consideration, including the velocity amplitude, the shear rate of the plasma flow on the plasma surface, and the inertial energy of the equilibrium plasma flow.

We simply introduce the model used in this work and the benchmark of the LARWM code in Section 2. In Section 3, we analyze the numerical results of the stabilization of RWMs with the global equilibrium shear plasma flow. We consider the case of the local shear plasma flow in Section 4. Section 5 ends with the conclusions of this paper.

2. Model and benchmark

The LARWM code[20] is used to describe the instabilities in the system, where plasma is surrounded by a conducting wall in the cylindrical model. The configuration of this model is shown in Fig. 1, where a and b are the position of the plasma surface and the conducting wall, respectively.

In this code, the linearized non-ideal MHD equations with plasma viscosity are used to describe the plasma, and the thin wall approximation is applied on the resistive wall. All variables in above equations are scaled with the length by a, magnetic field by the toroidal field $B_{0\phi}$, and density by ρ_0 which is

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11105065 and 11275041) and the National Basic Research Program of China (Grant Nos. 2008CB717801, 2008CB787103, 2009GB105004, and 2010GB106002).

†Corresponding author. E-mail: lil@mail.dlut.edu.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

uniform, so that the dimensionless viscosity and plasma conductivity can be written as the Reynolds number R_e and the Lundquist number S. The space step is assumed to be 10^{-3}, so that the time step is fixed to be 10^{-4}, in order to ensure the numerical stability.

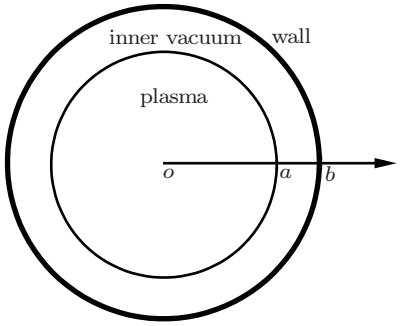


Fig. 1. Geometry of the cylindrical model.

An equilibrium can be modeled by $\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}$ and $\boldsymbol{J} \times \boldsymbol{B} = \nabla p$, where the equilibrium toroidal magnetic filed $B_{0\phi}$ and density ρ_0 are all uniform in a one-dimensional cylindrical tokamak configuration, so that the distribution of equilibrium current can be obtained as

$$J_{0\phi} = \frac{4}{q_a R_0}(1 - r^2),$$

which is the same as the one mentioned in Ref. [8], where q_a indicates the safe factor on the plasma surface.

As we know, the wall diffusion time τ_w means the conductivity of the resistive wall. For the RWMs, there is a close relationship between the growth rate of RWMs and the wall diffusion time. Therefore, we show the growth rate $\gamma\tau_w$ of instability calculated by the LARWM code versus the wall diffusion time τ_w in Fig. 2. Powerful evidence can be found that the value of the growth rate approaches a constant when $\tau_w \geq 10^5$, which means the instability is just the RWMs when the wall diffusion time is larger than 10^5. Therefore, the wall diffusion time is assumed as 10^5.

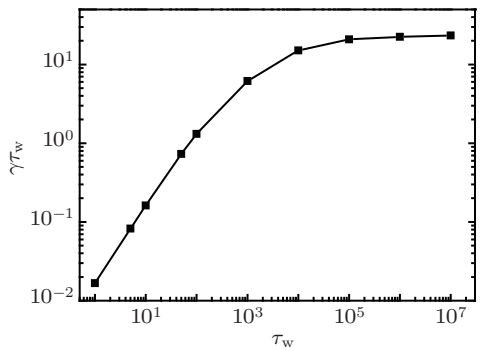


Fig. 2. The value of $\gamma\tau_w$ as a function of the wall diffusion time τ_w with $R_e = 10^5$ and $S = 10^4$.

Some previous theoretical work[16–19] indicated that the RWMs can be stabilized by the plasma rotation with the plasma viscosity, which can also be testified by the LARWM code. Assuming a uniform equilibrium plasma flow, the growth rate of RWMs versus the position of conducting wall with different velocity amplitudes is plotted in Fig. 3. When the velocity amplitude exceeds a certain critical value, a stable window can be found, where the RWM become stabilized. The critical stable positions of the resistive wall are denoted by b_{cL} and b_{cR}, respectively, and Δb indicates the width of the stable window. For fixed position of the resistive wall $b = 1.2a$, the inset in Fig. 3 shows the growth rate of the RWM as a function of the velocity amplitude of the uniform equilibrium plasma flow, so that the RWMs with stabilized critical velocities of $v_c = 0.012 v_A$ can be obtained.

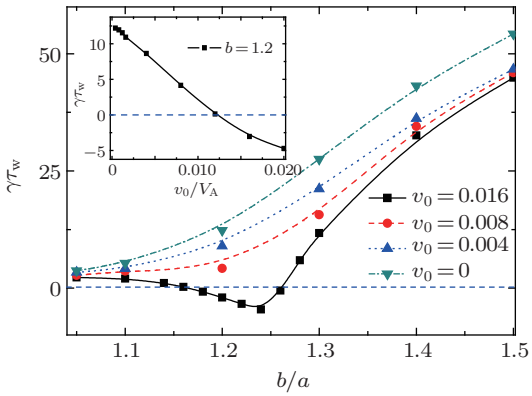


Fig. 3. (color online) The growth rate of the resistive wall mode as a function of the position of conducting wall for different velocities of the uniform flow.

3. Global shear equilibrium plasma flow and RWMs

The stabilizing effect of the uniform plasma flow on the RWMs seems to be due to the inertial energy taken by the equilibrium plasma flow into the plasma, as well as the amplitude or the shear rate of this flow on the plasma surface. We assume that the inertial energy W_I of the equilibrium plasma flow can be written as

$$W_I = \frac{1}{2}\int_{r=0}^{r=a} \rho_0 v_0^2 r \, dr, \quad (1)$$

where v_0 is the velocity amplitude of the equilibrium plasma flow. On the other hand, some theoretical studies demonstrated that the shear rate of the plasma flow on the resonance surface is crucial for stabilization of the MHD modes. However, for RWMs with a global structure, the stabilizing effect of the shear rate on the plasma surface cannot be neglected, especially for the plasma without the resonance surface. Then, we will present the results of three factors associated with the stabilization of RWM.

3.1. Effect of the velocity amplitude on the plasma surface

For studying the effect of the velocity amplitude on the plasma surface, we fix the inertial energy of the equilibrium plasma flow as $E_I = 6.4 \times 10^{-5}$, and the shear rate on the

plasma surface is zero, so a series of shear equilibrium plasma flow profiles can be devised as

$$v_0 = V_{\rm uni}(a_{\rm v} r^3 + b_{\rm v} r^2 + c_{\rm v}), \tag{2}$$

where $a_{\rm v}$, $b_{\rm v}$, and $c_{\rm v}$ are the parameters for carrying out the profiles, $V_{\rm uni} d_{\rm v}$ is the velocity amplitude of the equilibrium plasma flow on the plasma surface, $d_{\rm v} = a_{\rm v} + b_{\rm v} + c_{\rm v}$, and $V_{\rm uni} = 0.008 v_{\rm A}$. After simple calculation, we obtain a series of equilibrium plasma flow profiles with the same inertial energy and shear rate, but with different velocity amplitudes on the plasma surface, as shown in Fig. 4.

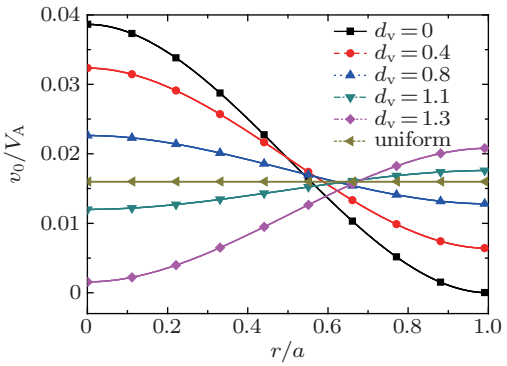


Fig. 4. (color online) A series of plasma flow profiles with different velocity amplitudes of the equilibrium shear flow on the plasma surface for fixed shear rate on the plasma surface $s_{\rm p} = 0$, and fixed inertial energy of the equilibrium flow $E_{\rm I} = 6.4 \times 10^{-5}$.

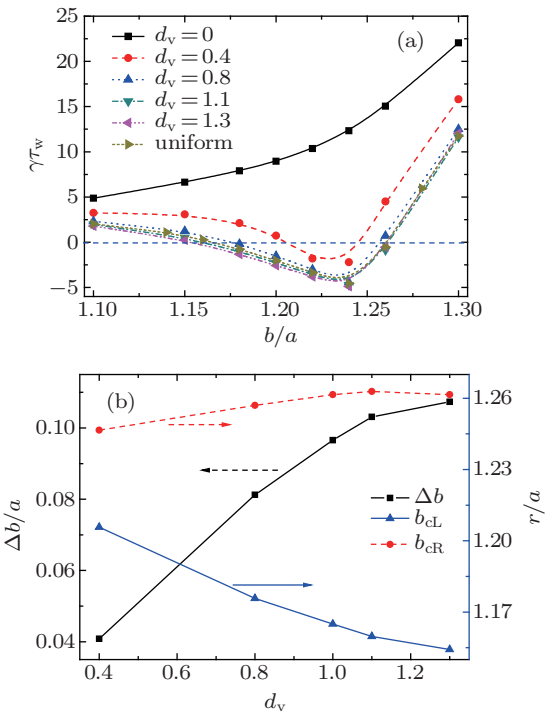


Fig. 5. (color online) Effect of the velocity amplitude of the equilibrium plasma flow on the plasma surface on the stabilization of the RWMs. (a) The growth rate of the RWMs as a function of the position of the resistive wall with different velocity amplitudes; (b) the crucial stable position of the resistive wall $b_{\rm cL}$ and $b_{\rm cR}$, and the width of the stable window Δb versus the velocity amplitude of the equilibrium plasma flow on the plasma surface.

Figure 5(a) shows the growth rate of RWMs versus the position of the resistive wall with a series of equilibrium plasma flow profiles shown in Fig. 4. The numerical results indicate that the stable window becomes thinner with decreasing velocity amplitude ($d_{\rm v}$) on the plasma surface, and even disappears, but the position of the stable window is not changed. In order to see this more clearly, we plot the critical stable positions of the resistive wall and the width of the stable window as functions of the velocity amplitude on the plasma surface in Fig. 5(b). It suggests that, compared to the case of the uniform plasma flow, there is a significant destabilizing effect of series of shear flows on the RWMs when decreasing the velocity amplitude. It can also be found that the stable window becomes appreciably wider when increasing the velocity amplitude.

3.2. Effect of the shear rate at the plasma surface on the RWMs

We assume a series of shear equilibrium plasma flow profiles as

$$v_0 = V_{\rm uni}(a_{\rm s} r^{c_{\rm s}} + b_{\rm s} r^{d_{\rm s}}). \tag{3}$$

For fixed velocity amplitude on the plasma surface $v_0(r = a) = 0.014 V_{\rm A}$, equation (3) can be written as

$$a_{\rm s} + b_{\rm s} = 1. \tag{4}$$

According to the inertial energy of the equilibrium plasma flow $E_{\rm I} = 6.4 \times 10^{-5}$, there exists a relationship given by

$$\frac{1}{2}\int_{r=0}^{r=a} [V_{\rm uni}(a_{\rm s} r^{c_{\rm s}} + d_{\rm s} r^{d_{\rm s}})]^2 r {\rm d}r = E_{\rm I}. \tag{5}$$

Then, the shear rate on the plasma surface can be written as

$$s_{\rm p} = V_{\rm uni}(a_{\rm s} c_{\rm s} + d_{\rm s} b_{\rm s}), \tag{6}$$

where $a_{\rm s}$, $b_{\rm s}$, $c_{\rm s}$, and $d_{\rm s}$ are the coefficients for adjusting the distribution of the plasma shear flow, and $s_{\rm p}$ is the shear rate of the shear plasma flow. According to Eqs. (3)–(6), we can obtain other coefficients by assuming the power r, and then can obtain the distributions of the plasma shear flow with different shear rates on the plasma surface, as shown in Fig. 6.

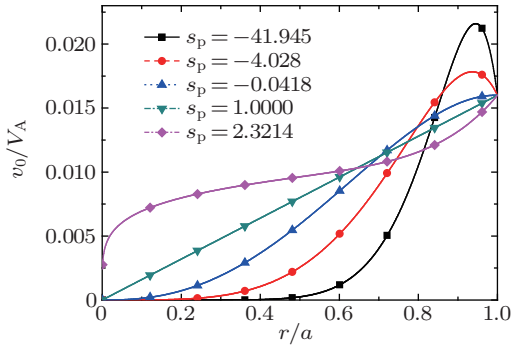


Fig. 6. (color online) A series of equilibrium shear plasma flow profiles with different shear rates on the plasma surface, for fixed $v_0(r = a) = 0.016 V_{\rm A}$ and fixed inertial energy of the equilibrium plasma flow $E_{\rm I} = 6.4 \times 10^{-5}$.

We calculate the RWM with the above series of equilibrium plasma flow profiles using the LARWM code, and plot the growth rate as a function of the position of the resistive wall in Figs. 7(a) and 7(b) for the cases of $s_p < 0$ and $s_p > 0$, respectively. The numerical results illuminate that the stable window will move away from the plasma while increasing the absolute value of the shear rate when $s_p < 0$. However, there is no obvious stabilizing effect of the positive shear rate on the RWMs.

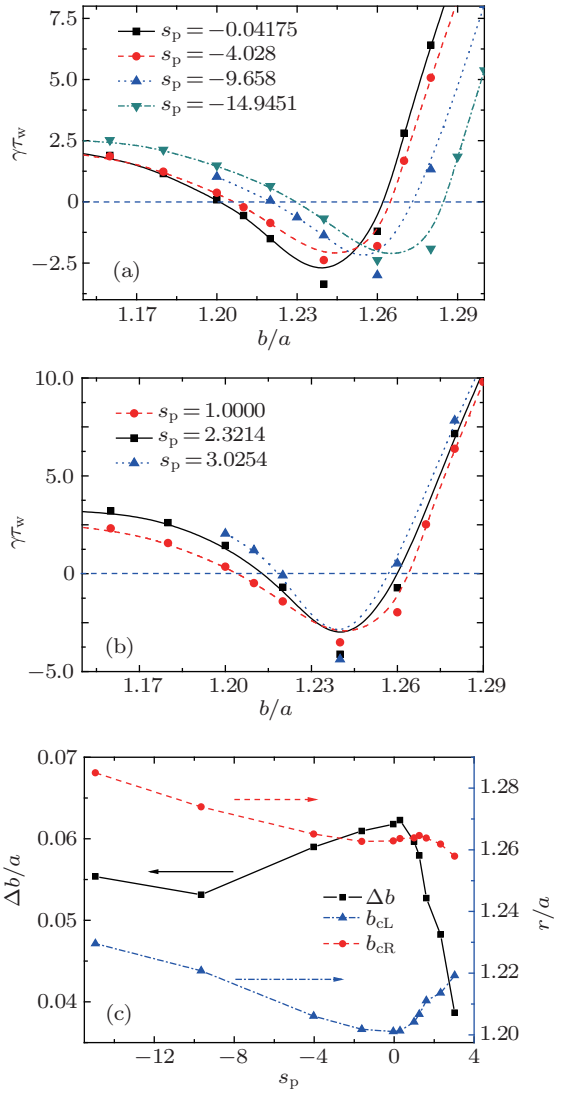


Fig. 7. (color online) Effect of the shear rate of the equilibrium plasma flow on the plasma surface on the stabilization of the RWMs. (a) The growth rate of the RWMs as a function of the position of the resistive wall with different shear rates on the plasma surface with $s_p < 0$. (b) The growth rate of the RWMs versus the position of the resistive wall with different shear rates on the plasma surface with $s_p > 0$. (c) The crucial stable position of the resistive wall b_{cL} and b_{cR} as well as the width of the stable window Δb versus the shear rate of the equilibrium plasma flow on the plasma surface.

Figure 7(c) shows the width of the stable window and the critical stabilizing position of the resistive wall versus the shear rate of the equilibrium flow on the plasma surface. For the case of $s_p < 0$, though b_{cL} and b_{cR} are all far away from the plasma, the stable window still keeps the width fixed while changing the absolute value of the shear rate. Therefore, this result demonstrates that there exists an effect of the shear rate of the equilibrium plasma flow on the stabilization of the external kink mode, but no effect on the stabilization of the RWMs. When the shear rate at the plasma edge increases, the growth rate of the external kink mode will increase gradually, because the velocity shear can supply instability with free energy. For the positive shear rate, the width of the stable window slightly decreases with increasing shear rate, but its position does not change. Consequently, the above phenomena suggest that there is destabilizing effect of the positive shear rate of the equilibrium plasma shear flow on the RWMs.

3.3. Effect of the inertial energy of the equilibrium plasma flow on the RWMs

A series of the shear equilibrium plasma flow profiles are designed as

$$v_0 = V_{uni}(a_E r^2 + b_E r + c_E), \tag{7}$$

where a_E, b_E, and c_E are the coefficients used to justify the distributions of the plasma flow, and $V_{uni} = 2\sqrt{E_I}$. Here, E_I is the inertial energy of the uniform plasma flow V_{uni}. Therefore, according to Eq. (1), the inertial energy can be expressed as

$$\begin{aligned} W_I = {} & E_I(a_E{}^2/3 + 4a_E b_E/5 + a_E c_E \\ & + b_E{}^2/2 + 4b_E c_E/3 + c_E{}^2). \end{aligned} \tag{8}$$

For fixed shear rate on the plasma surface $s_p = 0$, the plasma flow $v_0(r)$ satisfies

$$2a_E + b_E = 0. \tag{9}$$

In order to keep the velocity amplitude on the plasma surface same with the uniform plasma flow $V_{uni} = 0.016V_A$ in this case, the coefficients can be written as

$$a_E + b_E + c_E = 1. \tag{10}$$

After setting the velocity amplitude of the profiles in the center of plasma, we can obtain all coefficients, and carry out the distributions of the equilibrium plasma shear flow with different inertial energies, which are shown in Fig. 8(a). Then, in Fig. 8(b), we plot the width of the stable window Δb and two critical stabilizing positions b_{cL} and b_{cR} versus the inertial energy of the equilibrium plasma flow. Notably, it can be seen that b_{cL} get close to the plasma, but b_{cR} is almost at rest when increasing the inertial energy W_I, so that the width of the stable window gradually increases. Consequently, there is stabilizing effect of the inertial energy of the equilibrium plasma flow on the RWMs in non-resonance surface plasma.

However, it can also be found from Fig. 8(a) that there is a noticeable change in the shear rate in the center of plasma while increasing the inertial energy of the shear equilibrium plasma flow, so that we need to testify whether there is the

effect on the stabilization of the RWMs in the above case, by changing the shear rate in the center of plasma. Hence, another series of shear equilibrium plasma flow profiles are assumed as follows:

$$v_{0\phi} = V_{\rm uni}[d_{\rm E}(\cos(\pi r)+1)+1], \tag{11}$$

where $V_{\rm uni}d_{\rm E}$ denotes the velocity amplitude of the shear flow in the center of plasma, and $V_{\rm uni} = 0.016v_{\rm A}$. When $d_{\rm E} < 0$, there is an inverse plasma rotation in the core plasma.

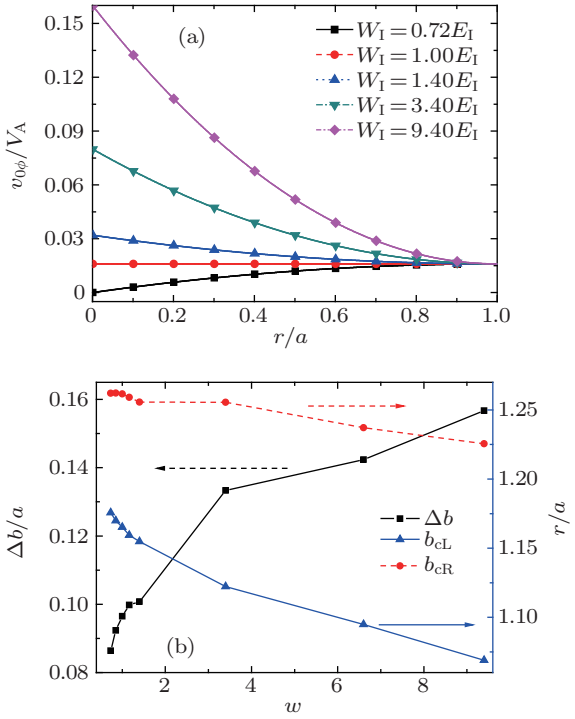


Fig. 8. (color online) (a) A series of equilibrium shear plasma flow profiles with different inertial energies for fixed velocity amplitude $v_0(r=a) = 0.016V_{\rm A}$ and fixed shear rate $s_{\rm p}(r=a) = 0$ on the plasma surface, without considering the shear rate in the core plasma. (b) The crucial stable position of the resistive wall $b_{\rm cL}$ and $b_{\rm cR}$ as well as the width of the stable window Δb versus the inertial energy of the equilibrium plasma flow.

These equilibrium flow profiles are plotted in Fig. 9(a), and figure 9(b) shows the parameters Δb, $b_{\rm cL}$, and $b_{\rm cR}$ versus the inertial energy of the shear equilibrium plasma flow. It can be seen that the tendency of all curves is the same with the above case, and this phenomenon indicates that there is no effect of the shear rate in the center of plasma on the stabilized RWMs. Figure 9(b) also indicates that the width of the stable window becomes smaller, or even disappears when decreasing $W_{\rm I}$. On the other hand, there is destabilizing effect of the equilibrium plasma flow in the reverse direction on the RWMs.

Consequently, the higher the velocity amplitude on the plasma surface is, the better RWMs can be stabilized, and the larger the inertial energy at the edge plasma is. Compared with the positive shear rate on the plasma surface, the stable window is wider when the shear rate is negative. At the same time, the inertial energy is larger. Hence, the results in the above three parts illuminate that, the inertial energy of the shear equilibrium plasma flow at the edge plasma plays a key role in stabilized RWMs.

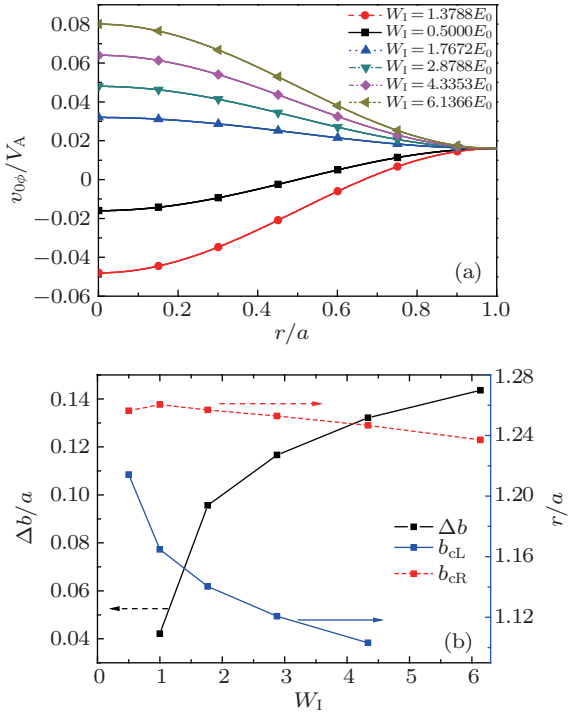


Fig. 9. (color online) A series of equilibrium shear plasma flow profiles with different inertial energies for fixed velocity amplitude $v_0(r=a) = 0.016V_{\rm A}$ and fixed shear rate $s_{\rm p}(r=a) = 0$ on the plasma surface, with the shear rate in the core plasma $s_{\rm p}(r=0) = 0$ considered. (b) Crucial stable positions of the resistive wall $b_{\rm cL}$ and $b_{\rm cR}$ as well as the width of the stable window Δb versus the inertial energy of the equilibrium plasma flow.

4. Local shear plasma flow and the RWMs

As shown in the above section, there is no obvious effect of the shear rate in the core plasma on the stabilized RWMs. Hence, we assume a series of equilibrium plasma flow profiles with local shear structures as follows:

$$v_{0\phi} = \begin{cases} V_{\rm uni}, & (0 \le r < r_0), \\ V_{\rm uni}\left(\frac{d_{\rm v}-1}{2}\cos\left(\frac{\pi}{1-r_0}(r-r_0)\right)+\frac{d_{\rm v}+1}{2}\right), & (r_0 \le r \le 1), \end{cases} \tag{12}$$

where $V_{\rm uni}$ is the velocity of the uniform plasma flow in the core plasma, $V_{\rm uni}d_{\rm v}$ is the velocity amplitude on the plasma surface, and r_0 is the width of the uniform plasma flow.

In Fig. 10(a), we show a series of distributions of the equilibrium plasma flow with negative shear rate at the edge plasma with $v_0(r=0) = 0.016V_{\rm A}$, $s_{\rm p}(r=a) = 0$, and $d_{\rm v} = 0$. The growth rate as a function of the position of the resistive wall with different widths of the shear flow layer is plotted in Fig. 10(b) for the cases of $r_0 = 0.6$, 0.7, 0.8, and 0.9. It can be found that, except for the case of $r_0 = 0.9$, the width of the stable window decreases while increasing the thickness of the shear flow layer, and even becomes zero. The reason for

this phenomena is that the inertial energy of the equilibrium plasma flow grows down when decreasing r_0. Therefore, the inertial energy plays an important role in stabilizing effect of the plasma shear flow on the RWMs. However, for the case of $r_0 = 0.9$, although the inertial energy of this shear flow is much larger than other ones, its stable window is the thinnest. The reason is the great velocity gradient at the plasma edge, which is taken into by the shear flow layer, so that the instability driven by the plasma flow can be excited.

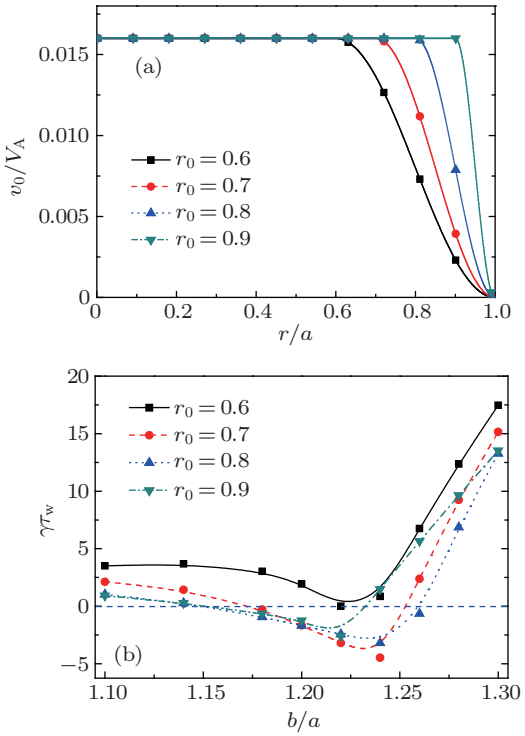


Fig. 10. (color online) Effect of the width of the local equilibrium shear plasma flow layer on the stabilization of the RWMs at the edge plasma, for the negative gradient of the velocity in the layer. (a) Profiles of the local equilibrium shear plasma flow with $v_0(r = a) = 0.016V_A$, $s_p(r = a) = 0$, and $d_v = 0$. (b) Growth rate of the RWM versus the position of the resistive wall with different widths of the shear plasma flow layer.

To prove the above conclusion, figure 11(a) shows the growth rate versus the position of the resistive wall with different velocity amplitudes on the plasma surface in the case of $r_0 = 0.7$. The critical positions of the resistive wall and the width of the stable window as functions of d_v are plotted in Fig. 11(b). It can be found that, for positive shear rate, the width of the stable window increases when raising the shear rate. At the same time, the inertial energy of the equilibrium plasma flow becomes larger and larger. However, for the negative shear rate, the stable window becomes thinner when increasing the absolute value of the shear rate, or decreasing the inertial energy of the equilibrium plasma flow. Therefore, the inertial energy of the equilibrium plasma flow plays an important role in the stability effect of the shear flow on the non-resonance RWMs.

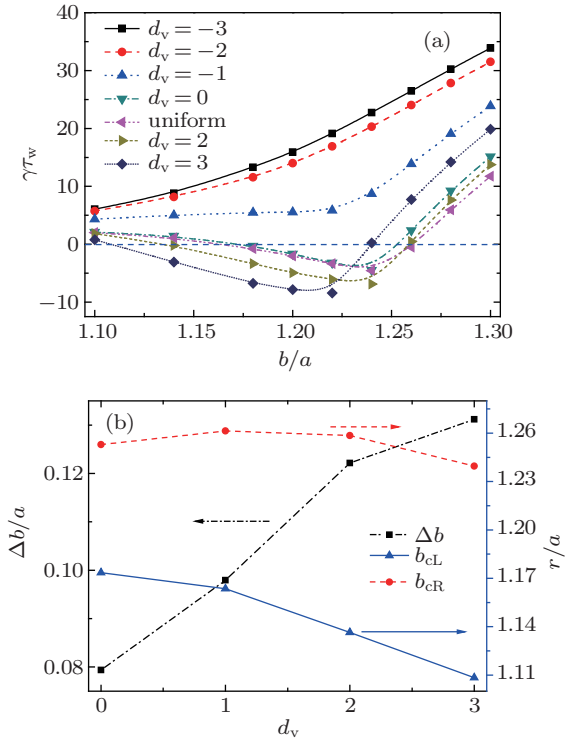


Fig. 11. (color online) (a) The growth rate of the RWM as a function of the position of the resistive wall for the case of $r_0 = 0.7$ and different d_v. (b) The critical stable positions of the resistive wall and the width of the stable window.

5. Conclusion and discussion

In this work, we start with non-ideal MHD equations with plasma viscosity and use a code which describes plasma surrounded by a conducting wall with finite resistivity in a cylindrical model to investigate the RWMs in a tokamak plasma without a resonance surface.

After the benchmark of our code, the stable window can be found when the uniform plasma flow is taken into consideration and fast enough. The stabilizing effect may be induced by two factors of the equilibrium plasma flow: the inertial energy and the velocity amplitude on the plasma surface. In addition, for the RWMs without resonance surfaces in plasma, the shear rate on the plasma surface may play an important role in stabilization of the RWMs.

Therefore, we take three factors into consideration to investigate the effect of the shear flow on the growth rate of the RWMs. They are the velocity amplitude, the shear rate, and the inertial energy of the equilibrium plasma flow. For fixed inertial energy and shear rate on the plasma surface, there exists a significant effect of the velocity amplitude on the destabilization of RWMs when decreasing the velocity amplitude on the plasma surface. At the same time, the inertial energy will also decrease. For fixed inertial energy and velocity amplitude on the plasma surface, the stable window driven by the shear plasma flow will move away from the plasma when increasing the absolute value of the shear rate on the plasma surface from zero, because the velocity gradient increases gradually. When

the shear rate is positive, there is unnoticeable displacement of the stable window, but its width decreases dramatically. The reason is that the inertial energy at the edge plasma become smaller. Hence, the negative shear rate on the plasma surface is better for the stabilization of the RWMs in these conditions. For fixed velocity amplitude and shear rate on the plasma surface, the stable window will become wider gradually when increasing the inertial energy of the equilibrium plasma. However, there is no obvious effect of the shear rate in the core plasma on the stabilization of the RWMs.

Moreover, in the case of the local shear plasma flow, it is more clearly seen that the crucial factor which can affect the stabilization of the RWMs is the inertial energy taken into the plasma by the equilibrium plasma flow. However, there is another instability driven by the velocity gradient of the plasma flow, when the shear flow layer is thin enough. This also illuminates that there is no stabilizing effect of the shear rate of the equilibrium plasma flow in the core plasma on the RWMs.

Some heating methods can also supply a large torque for tokamak plasma in experiments,[22,23] such as neutral beam injection (NBI) and wave heating. The velocity amplitude and the shear rate of the flow on the plasma surface can be adjusted through changing the angle of the NBI, and the power of the NBI is in direct proportion to the inertial energy of the equilibrium plasma flow, on the basis of which, we study and testify the effects of these factors on the RWMs.

References

[1] Troyon F, Gruber R, Saurenmann H, Semenzato S and Succi S 1984 *Plasma Phys. Controlled Fusion* **26** 209

[2] Freidberg J P 1987 *Ideal Magnetohydrodynamics* (New York)

[3] Bondeson A and Ward D J 1994 *Phys. Rev. Lett.* **72** 2709

[4] Betti R and Freidberg J P 1995 *Phys. Rev. Lett.* **74** 2949

[5] Gimblett C G 1986 *Nucl. Fusion* **26** 617

[6] Boozer A H 1995 *Phys. Plasmas* **2** 4521

[7] Smith S P, Jardin S C, Freidberg J P and Guazzotto L 2009 *Phys. Plasma* **16** 084504

[8] Wesson J 2004 *Tokamaks* (3rd edn.) (Oxford: Oxford University Press)

[9] Strait E J, Taylor T S, Turnbull A D, Ferron J R, Lao L L, Rice B, Sauter O, Thompson S J and Wróblewski D 1995 *Phys. Rev. Lett.* **74** 2483

[10] Okabayashi M, Pomphrey N, Manickam J, Warda D J, Bell R E, Hatcher R E, Kaita R, Kaye S M, Kugel H W, LeBlanc B, Levinton F M, Roberts D W, Sesnic S, Sun Y and Takahashi H 1996 *Nucl. Fusion* **36** 1167

[11] Takeji S, Tokuda S, Fujita T, et al 2002 *Nucl. Fusion* **42** 5

[12] Reimerdes H, Garofalo A M, Jackson G L, et al 2007 *Phys. Rev. Lett.* **98** 055001

[13] Guo S C, Freidberg J P and Nachtrieb R 1999 *Phys. Plasmas* **6** 2868

[14] Coelho R and Lazzaro E 2007 *Phys. Plasmas* **14** 012101

[15] Wang X Q, Wang X, Xu W B and Wang Z X 2011 *Phys. Plasmas* **18** 012102

[16] Chu M S, Greene J M, Jensen T H, Miller R L, Bondeon A, Johnson R W and Mauel M E 1995 *Phys. Plasmas* **2** 2236

[17] Reimerdes H, Garofalo A M, Okabayashi M, Strait E J, Betti R, Chu M S, Hu B, In Y, Jackson G L, La Haye R J, Lanctot M J, Liu Y Q, Navratil G A, Solomon W M, Takahashi H, Groebner R J and DIII-D Team 2007 *Plasma Phys. Controlled Fusion* **49** 349

[18] Taylor J B, Connor J W, Gimblett C G and Wilson H R 2001 *Plasma Phys.* **8** 4062

[19] Guazzotto L, Betti R, Manickam J and Kaye S 2004 *Plasma Phys.* **11** 604

[20] Li L, Liu Y, Xu X Y and Xia X N 2012 *Plasma Sci. Technol.* **14** 14

[21] Finn J M 1995 *Phys. Plasmas* **2** 198

[22] Strait E J, Garofalo A M, Jackson G L, Okabayashi M, Reimerdes H, Chu M S, Fitzpatrick R, Groebner R J, In Y, LaHaye R J, Lanctot M J, Liu Y Q, Navratil G A, Solomon W M, Takahashi H and the DIII-D Team 2007 *Phys. Plasmas* **14** 056101

[23] Gao J M, Liu Y, Li W, Cui Z Y, Zhou Y, Huang Y and Ji X Q 2010 *Chin. Phys. B* **19** 115202