Effect of the pressure gradient in the connection region on the PBM stability

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Introduction

The width of the plasma edge pedestal formed by the transport barrier and the pressure at the top of the pedestal strongly affect performance of tokamak fusion plasmas. In previous studies [1, 2], the pressure gradient at the centre of pedestal was mainly considered as a major factor that determines the pedestal stability. However, the edge instabilities are non-local [3, 4] so that the pressure gradient and current profile in other regions can also affect the stability [5, 6] and the structure of the pedestal. For this reason, we have investigated the dependence of pedestal properties such as the pedestal height and the pedestal width on α_i which represents the pressure gradient in the connection region.

We have used a fixed boundary code, HELENA [5] to construct the plasma equilibrium and MHD stability code, MISHKA [6] to calculate the edge MHD instability. The edge predictive model EPED1 [7] was also used to predict and to understand the behaviour of the edge pedestal in terms of α_i. Based on these results, we suggested the possible mechanism of the interaction between the edge pedestal and the core profile through Shafranov shift and α_i.

Simulation setup

To investigate the effect of α_i on the edge stability, the stability analysis of the peeling-ballooning mode (PBM) [8] is carried out in terms of α_i. We used α_i as normalised pressure gradient α [9] at $\psi_N = 0.9 \simeq 1 - 2.5W_{ped}$ for simplicity in this study, where

$$\alpha = -\frac{2\mu_0 \partial V/\partial\psi}{(2\pi)^2}\left(\frac{V}{2\pi^2 R_c}\right)^{\frac{1}{2}}\frac{\partial P}{\partial\psi}. \quad (1)$$

Here, V is the plasma volume contained by the poloidal flux surface (ψ), R_c is the geometric center of the poloidal flux contour, and P is the plasma pressure. A JET-like discharge is selected as a reference equilibrium for the stability calculation whose major parameters are as following; major radius $R_0 = 2.91$, aspect ratio $A = 3.15$, plasma current $I_p = 1.38$ MA, toroidal field $B_0 = 1.69$ T), upper elongation $\kappa_{up} = 1.58$, lower elongation $\kappa_{low} = 1.73$, upper triangularity $\delta_{up} = 0.37$, lower triangularity $\delta_{low} = 0.36$, normalized beta $\beta_N = 2.25$, density at the top of the pedestal $n_{e,ped} = 3.36 \times 10^{19}$ m^{-3}, and carbon impurity with effective charge number $Z_{\rm eff} = 1.36$. We used the same

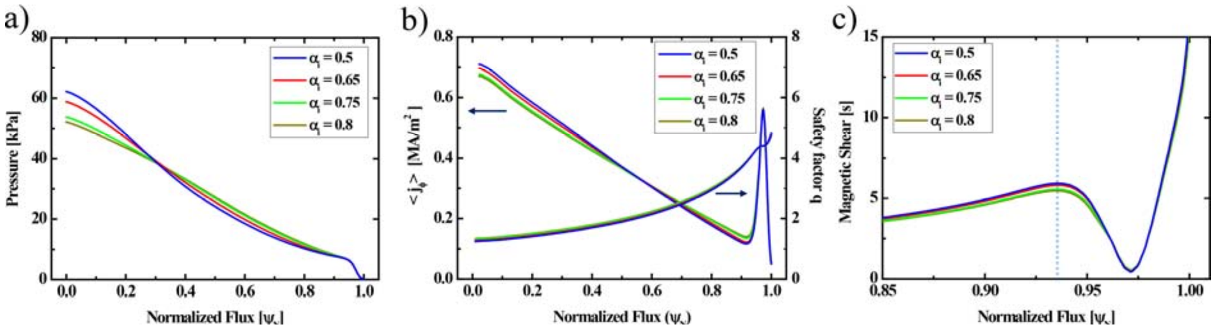

Figure 1. Profiles of (a) pressure, (b) current, safety factor, and (c) magnetic shear ($\hat{s}$). The gold, green, red and blue lines show the profiles in cases whose α_i values are 0.5, 0.65, 0.75, and 0.8, respectively.

I_p and boundary shape as the reference while pressure profiles were adjusted to change α_i while keeping the current density and pressure profiles in the pedestal region fixed to remove their effect on the PBM stability. To modify the pressure profile, we used temperature and density profile form as Eq. (2)

$$T(\psi_N) = \alpha_{t1}\left(1-\left(\frac{\psi_N}{1-W_{ped}}\right)^{\beta_{t1}}\right)^{\beta_{t2}} H(\psi_N - 1 + W_{ped}) + \alpha_{t2}\tanh\left[\frac{2(\psi_N - 1 + W_{ped}/2)}{W_{ped}}\right] + \alpha_{t0}. \quad (2)$$

In Eq. (2), $\mathrm{W_{ped}}$ is the pedestal width in the normalized poloidal flux coordinate (ψ_N) set to be 0.04, H is the unit step function, α_{t0} is the temperature at the separatrix, and the first and the second term describe the core and the pedestal profile, respectively. The electron density profile, $n_e(\psi_N)[10^{19}m^{-3}]$ was defined in the same form as Eq. (2) with $\alpha_{n0} = 0.8$, $\alpha_{n1} = 3.6$, $\alpha_{n2} = 1.4$, $\beta_{n1} = \beta_{n2} = 1.1$. Lastly, $T = T_e = T_i$ is assumed and the current profile was constructed with the Sauter's bootstrap current model with Ohmic contributions [10]. We reconstructed the plasma equilibrium and calculated the PBM stability under these conditions.

Effect of α_i on the PBM stability

To calculate the effect of α_i on the growth rate of PBM, we produced four equilibria, where α_i changes from 0.5 to 0.8 (see Fig.1). We controlled α_{t1} and β_{t2} of the temperature profile in Eq. (2) to adjust α_i while other plasma parameters including Shafranov shift and α profile in the pedestal region were fixed. Results of the stability calculation are shown in Fig. 2. As α_i increases, PBM is destabilised and the growth rate increases for all n values. For example, the growth rate of n = 12 has increased from 0.042 to 0.05 as α_i changes from 0.5 to 0.8. To understand the effect of α_i, we examined the variation of mode structure according to α_i . Figure 3 shows the mode structure or

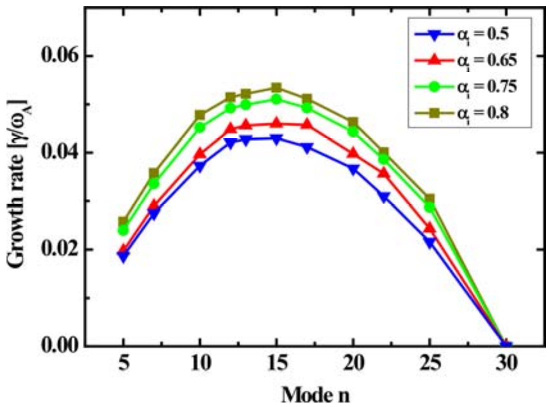

Figure 2. Growth rate (γ/ω_A) of PBM versus the mode number. Gold, green, red, and blue lines are for α_i = 0.5, 0.65, 0.75, and 0.8, respectively.

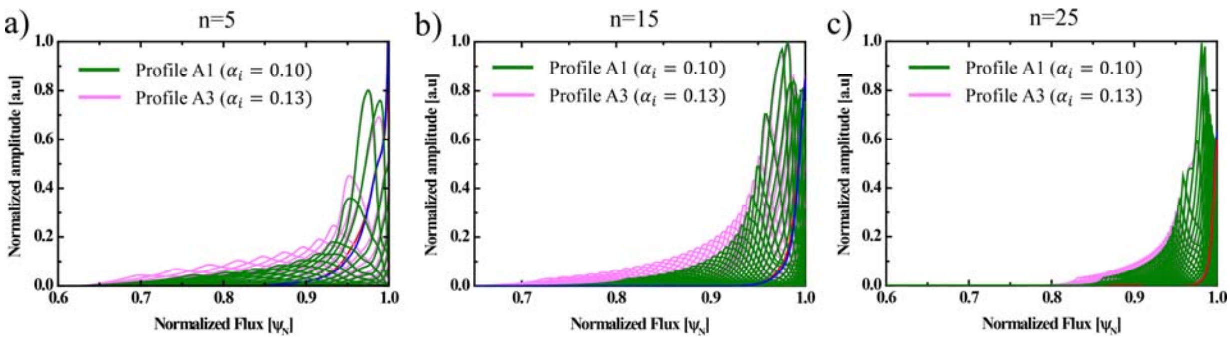

Figure 3. Eigen mode structure of PBM for a) n = 5 b) n = 15, and c) n = 25. The pink and the green lines show the mode structures for $\alpha_{\mathbf{i}}$ = 0.65 and 0.8, respectively. The red and the blue lines show the mode structure of the dominant peeling mode for α_{i} = 0.65 and 0.8, respectively.

eigenfunction of n = 5 (Fig. 3(a)), n = 15 (Fig. 3(b)) and n = 25 (Fig. 3(c)) for two equilibria, one with $\alpha_i = 0.65$ (green) and the other with $\alpha_i = 0.8$ (pink). The width of the mode is shown to increase with α_{i}. As the amplitude of the mode in the connection region increases, width of the mode envelope becomes wider. When α_i increases, the ballooning component in the connection region becomes destabilized due to increase in the pressure gradient and consequently, the relative amplitude of the mode increases. Since PBM components in the connection region and the edge regions are coupled, increase in the mode component at the inner region can result in destabilization of PBM.

Destabilising effect of α_i on PBM depends on the mode number n as shown in Fig. 2. When α_i changes from 0.5 to 0.8, PBM growth rate with intermediate n tends to be more affected by α_i than that with lower and higher n. For low n cases where the peeling part is dominant, the peeling component whose destabilizing source is the pedestal current density is less likely to be affected by α_i, since α_{i} is the destabilizing source of the ballooning component. For high n cases (n=25), the width of the mode envelope of PBM is smaller than lower n modes (n=5, 15) in Fig.3. As the PBM component in the connection region normalized to its maximum near the edge is already small in higher n, the effect of α_i in this region is also small. Therefore, coupling between the connection region and the edge region is relatively reduced for high n. For this reason, the stability of PBM can be less sensitive to α_i in high n PBM. It can be also found in Fig.3 that the mode structure of n=25 is less sensitive to α_{i} than that of n=5 and n=15.

Effect of α_i on the pedestal structure

To understand the effect of α_i on the pedestal structure, we applied EPED1 to the edge predictive analysis. Here, we changed not only α_i but also Shafranov shift Δ'_{ped} to investigate their effect on the edge pedestal together. Results from the predictive analysis is shown in Fig.4. The temperature (T_{ped}) at pedestal top which is predicted by EPED is drawn on the contour where x- and y- axis correspond to Δ'_{ped} and α_i, respectively.

EPED analysis on the reference equilibrium shows that T_{ped} improves with Δ'_{ped} while it deteriorates as α_i increases. For example, when Δ'_{ped} changes from 0.3 to 0.33, T_{ped} increases by 13%. This behaviour of T_{ped} is due to the stabilization of PBM by Δ'_{ped}. It is also consistent to the previous studies [11-12]. When α_i increases from 0.4 to 0.55, T_{ped} decreases by 15% as shown in Fig. 4. The effect of α_i on T_{ped} is also related to the destabilising effect of α_i on PBM. Furthermore, we expect that the edge pedestal whose MHD stability is peeling- or ballooning- dominant will be less affected by α_i as PBM with low and high n are less sensitive to α_i.

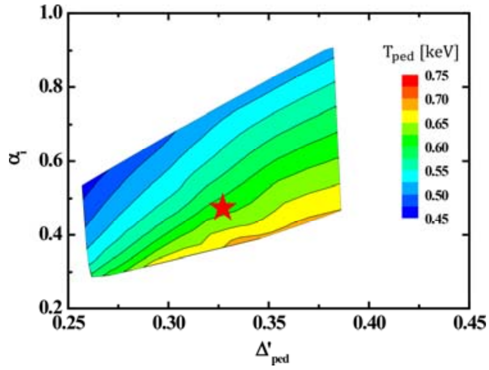

Figure 4. Pedestal height (T_{ped}) from EPED prediction results in $\Delta'_{ped} - \alpha_i$ space. Red star indicates the reference equilibrium point.

Conclusion

In this study, we analysed the effect of the pressure gradient in the connection region on the edge MHD stability. We compared the PBM stability of various equilibria with different α_i, and found that large α_i destabilizes PBM. The mode structure widens as α_i increases. Destabilization of PBM with α_i was related to the increment of the destabilizing source of the pressure gradient in the connection region and coupling between the connection region and the edge region. Also, decrease of $\hat{s}$ in the connection region due to increase in the bootstrap contribution to j_ϕ with α_i further acts to destabilize PBM. The EPED prediction shows that as Δ'_{ped} increases or as α_i decreases, the pedestal height improves. This is because the PBM stability has improved allowing enhancement of the edge pedestal. This highlights the importance of modelling the core accurately when the pedestal is predicted as increasing the core pressure can either decrease (through α_i) or increase (through Δ'_{ped}) the predicted pedestal height.

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