Effect of equilibrium properties on the structure of the edge MHD modes in tokamaks

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Abstract. Effects of the pressure profile and the current density profile inside the top of the pedestal and that of the plasma shape on the expansion of the structure of the unstable edge MHD mode are investigated numerically. The structure of the edge MHD mode is expanded by spreading the envelope of the edge ballooning mode structure due to the increase of the pressure gradient inside the top of the pedestal, and by decreasing the toroidal mode number of the most unstable mode due to the increase of the current density inside the top of the pedestal. In strongly shaped plasmas, the pressure gradient inside the top of the pedestal can approach to the ballooning mode stability boundary and the current density increases enough to reduce the toroidal mode number of the most unstable mode. These increases of the pressure gradient and the current density destabilize the edge MHD mode and expand the structure of this mode.

1. Introduction
For realizing a economical fusion reactor, H-mode operation is suitable due to a good confinement property near the plasma edge[1]. However, in the H-mode tokamak plasmas, edge localized modes (ELMs) sometimes occur, and constrain the maximum pressure gradient in the edge pedestal[2]. Since the so-called ‘Type-I ELM’ leads a large heat load on the divertor and reduces a life time of the divertor, the quantitative analysis about the amount of the energy loss due to the Type-I ELM is important for ITER and future devices.

Recent theoretical and experimental researches have shown that the Type-I ELM is triggered by ideal MHD modes (a peeling mode, a ballooning mode, and a coupled peeling-ballooning mode), and some numerical codes realize to analyze the linear stability of these MHD modes[3, 4, 5, 6, 7]. From the experimental analysis with such linear stability codes, the width of the eigenfunction of the edge MHD mode is sometimes related to the amount of the ELM energy loss[1, 4].

By comparing some experimental results, it has been found the amount of the energy loss by the Type-I ELM in JT-60U without Ferritic steel tiles tends to be smaller than that in JET and DIII-D[8]. The reason of such a difference of the ELM energy loss between JT-60U and JET/DIII-D needs to be revealed for reducing the amount of the ELM energy loss. In comparison between these devices, we can see that some equilibrium properties which have impacts on the edge MHD stability are different. From the viewpoint of the maximum pressure gradient at the pedestal, the difference of the shape of the plasma cross-section is crucial. In JET/DIII-D, the plasma shape can be optimized by changing shaping parameters (a ellipticity $\kappa$, a triangularity $\delta$, a squareness[9], a sharpness[7] etc.) in wide range, and a pressure gradient near the pedestal can be improved due to stabilizing edge MHD modes. On the other hand, in JT-60U, since the
optimization of the plasma shape is restricted by the layout of the magnetic coils, the maximum pressure gradient near the pedestal tends to be smaller than those in JET/DIII-D.

Moreover, we can see that there is a difference in the pressure profile not only near the pedestal but also inside the top of the pedestal among JT-60U, JET, and DIII-D. In particular, the pressure profile in JT-60U is more gradual than those in JET/DIII-D. The effect of the difference of the pressure profile inside the top of the pedestal on the amount of the ELM energy loss has been discussed numerically with the integrated simulation code TOPICS-IB, and Hayashi et al. have clarified that the pressure profile inside the top of the pedestal is important for the amount of the ELM energy loss due to the expansion of the width of the eigenfunction of the unstable MHD mode[10].

In this paper, we investigate numerically that the effect of the equilibrium properties on the width of the eigenfunction of the edge MHD modes by the MARG2D stability code[11, 12]. In particular, we pay attention to the effect of the pressure profile and the current density profile inside the top of the pedestal and the plasma shape on the expansion of the structure of the unstable edge MHD mode.

2. Stability analysis in different shape equilibria

2.1. Equilibria

In this paper, we investigate numerically the stability of edge MHD modes in the equilibria which have two kinds of the shape of the plasma cross-section as shown in figure 1. Figure 1(a) is the JT-60U (shot No. is 43075 and 5.5 sec.) like shape whose $A = 3.91$, $\kappa_{up} = 1.28$, $\kappa_{low} = 1.62$, $\delta_{up} = 0.16$, $\delta_{low} = 0.35$, and figure 1(b) is the ITER-like shape which will be realized in JT-60SA[13] whose $A = 3.12$, $\kappa_{up} = 1.66$, $\kappa_{low} = 2.03$, $\delta_{up} = 0.37$, $\delta_{low} = 0.60$. Here $A$ is an aspect ratio, a subscript $up$ ($low$) expresses the upper (lower) value. The plasma current is about 1.08MA (JT-60U) and 2.20MA (ITER like), which is slightly adjusted for fixing the edge safety factor as about $q_a = 6.4$, and the toroidal magnetic field is 3.11 (JT-60U) and 2.46 (ITER-like). The electron density $n_e$ and electron temperature $T_e$ profiles are determined artificially, the ion temperature $T_i$ profile is assumed as $T_e = T_i$, and the effective charge $Z_{eff}$ is given as 2.3. The current density profile, including a ohmic current, a bootstrap current, and additional (NBCD etc.) currents, is calculated by the ACCOME code[14].

Figures 2 and 3 show the profiles of (a) $n_e$ and $T_e$, (b) the plasma pressure $p$, and (c) the parallel current density $(\mathbf{j} \cdot \mathbf{B})/(\mathbf{B}^2$) and the safety factor $q$ in the JT-60U shape (figure 2) and the ITER-like shape (figure 3) equilibria, respectively. To investigate the effect of the pressure gradient inside the top of the pedestal on the structure of the edge MHD modes, the $T_e (= T_i$)
profile is changed as shown in figure 2(a) (J1)-(J3) and figure 3(a) (I1)-(I3), but the \( n_e \) profile is unchanged. The profiles of \( T_e \) near the pedestal are changed linearly to identify the marginally stable condition, and these profiles in the plasma core region \( (\rho \leq 0.5) \) is adjusted to reduce the change of the poloidal beta value \( \beta_j \) in each equilibrium, where \( \rho \) is the minor radius defined as \( \rho = \sqrt{V(\psi_N)/V_{total}} \), \( V(\psi_N) \) is the volume at each magnetic surface, \( V_{total} \) is the volume of the plasma, and \( \psi_N \) is the poloidal magnetic flux normalized as \( \psi_N = 0 \) at the magnetic axis and \( \psi_N = 1 \) at the surface. As the result, \( \beta_j \) of each equilibrium is (J1) 0.76, (J2) 0.79, (J3) 0.82 in the JT-60U shape case, and (I1) 0.78, (I2) 0.80, (I3) 0.83 in the ITER-like shape case. The position of the top of the pedestal is fixed as \( \rho_{ped} = 0.948 \) in each equilibrium. Since the pressure gradient inside the top of the pedestal becomes larger, the bootstrap current at this region also increases as shown in figure 2 (c) and figure 3 (c), and the current density profile in the plasma core region \( (\rho \leq 0.5) \) is adjusted to maintain the \( q \) value at the magnetic axis \( q_0 > 1.0 \).

2.2. JT-60U shape case

We analyze numerically the ideal MHD stability of the equilibria shown in the previous subsection. The range of the toroidal mode number \( n \) of the analyzed MHD mode is from 1 to 20. Figure 4 shows the result of the stability analysis in the JT-60 shape case on the \((n, \lambda_0)\) plane and the \((n, \gamma_{IM})\) plane, where \( \lambda_0 \) is the eigenvalue of the eigenvalue problem associated with the two-dimensional Newcomb equation[11]

\[
\mathcal{N} Y = -\lambda_0 \mathcal{R} Y,
\]

\( \mathcal{N} \) is the Newcomb operator, \( \mathcal{R} \) is the diagonal operator whose components are \( \mathcal{R}_{m,m} \propto (m-nq)^2 \), \( m \) is the poloidal mode number, and \( \gamma_{IM} \) is the growth rate of the MHD mode under the
incompressible assumption normalized with the toroidal Alfvén frequency at the axis. Both $\lambda_0$ and $\gamma_{IM}$ are calculated by the MARG2D code[11, 12]. The eigenvalue problem equation (1) realizes to identify explicitly whether the plasma is stable or unstable by determining the sign of the eigenvalue $\lambda_0$, and the $\lambda_0$ dependence on $n$ roughly shows whether the plasma tends to be stable or unstable as $n$ increases. In the case shown in figure 4, the most unstable mode is the $n = 8$ peeling-ballooning mode in each equilibrium, and the dependence of the edge MHD stability on $n$ are similar to each other.

The structures of the poloidal Fourier harmonics of the eigenfunction $Y$ are shown in figure 5 ((a) the real part and (b) the imaginary part), and the displacements in the radial direction $\xi_r$ at $\theta = 0$ are also shown in figure 5(c), where the red, green, and blue lines show the eigenfunctions in cases (J1), (J2), and (J3), respectively. These figures indicate that the structure of the eigenfunction extends slightly to the plasma core region as the pressure gradient inside the top of the pedestal increases. To discuss a change of the width of the edge MHD mode, we define the width of $\xi_r(\theta = 0)$ as $w(\xi_r(\theta = 0)) = 1.0 - \rho(\xi_r(\theta = 0))$. Since the width of $\xi_r$ is mainly determined by the ballooning mode structure in the plasma, $\xi_r(\theta = 0)$ is normalized as the top of the edge ballooning mode envelope is unity as shown in figure 5(c). Afterward, $\xi_r$ means $\xi_r(\theta = 0)$. Figure 5 (d) shows the dependence of $w/w_{\text{org}}$ at $\xi_r = 0.3$ (red line), 0.2 (green line), and 0.1 (blue line) on the normalized pressure gradient at $\psi_N = 0.87$ ($\rho \simeq 0.87$), $\alpha_{87}$, where $w_{\text{org}}$ is the $w$ value of case (J1), $\alpha$ is defined as $\alpha = -[\mu_0/(2\pi^2)](dp/d\psi)(dV/d\psi)(VR/2\pi)^{0.5}$, $\mu_0$ is the permeability in the vacuum, $\psi$ is the poloidal magnetic flux, $R$ is the major radius, and the subscript 87 expresses the value at $\psi_N = 0.87$. Since the ballooning mode becomes unstable first near $\psi_N = 0.87$ when the pressure gradient inside the top of the pedestal increases, we pay attention to the dependence of $w$ on $\alpha_{87}$. As shown in this figure, the width at $\xi_r = 0.3$ is almost unchanged in spite of that $\alpha_{87}$ increases from 0.20 to 0.68, but the $w/w_{\text{org}}$ value becomes slightly larger as $\xi_r$ decreases. This means that the tail of the edge ballooning mode envelope extends to the plasma core region as the pressure gradient inside the top of the pedestal increases, but the amount of variation of $w/w_{\text{org}}$ is less than 20%.

### 2.3. ITER-like shape case

In this subsection, the edge MHD stability in the ITER-like shape equilibrium is investigated. The $n$ dependence of $\lambda_0$ shown in figure 6 indicates that the $n$ number of the unstable MHD mode tends to decrease as the pressure gradient inside the top of the pedestal increases, and as the result, the $n$ number of the most unstable mode decreases from $n = 9$ (case (I1) and case (I2)) to $n = 6$ (case (I3)). Figure 7 shows the structures of the poloidal Fourier harmonics of (a) $\text{Re}(Y)$ and (b) $\text{Im}(Y)$ and (c) the structure of $\xi_r$, where red, green, and blue lines show the structures of the most unstable mode in cases (I1), (I2), (I3), and the purple line shows that of
Figure 5. Profiles of the poloidal Fourier harmonics of (a) Re($Y$) and (b) Im($Y$), where $Y$ is the eigenfunction of the eigenvalue problem equation (1), and (c) the displacement at $\theta = 0$, $\xi_r(\theta = 0)$ in JT-60U shape equilibria. The red, green, and blue lines show the results in cases (J1), (J2), and (J3), respectively. (d) Dependence of the width $w(\xi_r)$ normalized with $w_{\text{org}} = (w$ of (J1)) on $\alpha_{87}$. The red, green, and blue lines show $w/w_{\text{org}}$ at $\xi_r = 0.3, 0.2, \text{ and } 0.1$, respectively.

Figure 6. Dependence of $\lambda_0$ (solid line) and $\gamma_{IM}$ (broken line) on $n$ in ITER-like shape equilibria. The red, green, and blue lines show $\lambda_0$ and $\gamma_{IM}$ of (I1), (I2), and (I3), respectively.

the $n = 9$ mode in case (I3). In this ITER-like shape case, the extension of $\xi_r$ to the plasma core region is larger than that in the JT-60U shape case as shown in figure 7 even when the $n$ number of the mode is unchanged as $n = 9$. Moreover, in case (I3), the decrease of the $n$ number of the most unstable mode from 9 to 6 expands the structure of $\xi_r$. These results can be described with $w$ normalized with $w_{\text{org}} = (w$ of (I1)) as shown in figure 7 (d), where the red, green blue lines shows $w/w_{\text{org}}$ at $\xi_r = 0.3, 0.2, \text{ and } 0.1$, respectively. In particular, at $\xi_r = 0.1$, the width of $\xi_r$ becomes about twice as $\alpha_{87}$ increases from 0.42 to 1.49.

3. Effect of the pressure profile and the current profile inside the top of the pedestal

In the previous section, not only the pressure gradient but also the current density profile inside the top of the pedestal becomes larger due to increasing the bootstrap current density. In this section, we identify separately the effect of the pressure gradient and the current density on the structure of the edge MHD mode.

3.1. Effect of the pressure profile

First, we investigate the effect of the pressure gradient. In this study, we change the pressure profile but fix the current density profile as shown in figures 8 (a), (b) (JT-60U shape) and figures 8 (c), (d) (ITER-like shape), respectively. The $p$ and $\langle j \cdot B \rangle / \langle B^2 \rangle$ profiles in case (Jp1), and those in case (Ip1) are same as those in case (J1) in figure 2 and those in case (I1) in figure 3.
The results of the stability analysis in JT-60U shape equilibria in figure 9 (a) show that the n dependence of the edge MHD stability changes little and the n number of the most unstable mode is same as n = 8 though the pressure gradient inside the top of the pedestal increases from \( \alpha_{87} \) = (Ip1) 0.20 to (Ip2) 0.43, (Ip3) 0.59, and (Ip4) 0.80, where red, green, blue, and purple lines express the results in cases (Ip1), (Ip2), (Ip3), and (Ip4), respectively. This result is almost same as that in subsection 2.2. On the other hand, in ITER-like shape case, the result of the stability analysis shown in figure 9 (b) indicates the n number of the most unstable mode is also unchanged as n = 9 though the \( \alpha_{87} \) value increases as (Ip1) 0.41, (Ip2) 0.91, (Ip3) 1.22, and (Ip4) 1.60. This result is different from that in subsection 2.3 (both profiles of p and \( \langle j \cdot B \rangle / \langle B^2 \rangle \) are changed), and in comparison between this result and that discussed in subsection 2.3, we reveal that the increase of the pressure gradient inside the top of the pedestal is not important for changing the n number of the most unstable mode.

Next, we compare the structure of \( \xi_r \) in figure 10. As shown in figure 10 (a), the expansion of \( \xi_r \) is relatively small in JT-60U shape case, and this result is similar to that shown in figure 5. On the other hand, the extension of \( \xi_r \) in ITER-like shape case shown in figure 10 (b) goes deeper to the plasma core region as \( \alpha_{87} \) increases than that in JT-60U shape case. To discuss the expansion of the width due to the increase of the pressure gradient, the \( \alpha_{87} \) dependence of \( w/w_{\text{org}} \) at \( \xi_r = 0.3, 0.2, \) and 0.1 are shown in figures 10 (c) (JT-60U shape case) and (d) (ITER-like shape case), where \( w_{\text{org}} \) is the \( w \) value in case (Ip1) in figure 10 (c) and that in case (Ip1) in figure 10 (d). Here the solid line in figure 10 (c) expresses \( w/w_{\text{org}} \) of \( \xi_r \) shown in
Figure 9. Dependence of $\lambda_0$ (solid line) and $\gamma_M$ (broken line) on $n$ in (a) JT-60U shape equilibria and (b) ITER-like shape equilibria. The red, green, blue, and purple lines show $\lambda_0$ and $\gamma_M$ in cases (Jp1), (Jp2), (Jp3), (Jp4) in figure (a), and those in cases (Ip1), (Ip2), (Ip3), (Ip4) in figure (b), respectively. In these cases, the $p$ profile is changed, but the $\langle \mathbf{j} \cdot \mathbf{B} \rangle / \langle \mathbf{B}^2 \rangle$ profile is fixed as shown in figure 8.

Figure 10. Profiles of $\xi_r$ in (a) JT-60U shape equilibria and (b) ITER-like shape equilibria. The red, green, blue, and purple line show the profiles in cases (Jp1), (Jp2), (Jp3), (Jp4) in figure (a), and those in cases (Ip1), (Ip2), (Ip3), (Ip4) in figure (b), respectively. Dependence of $w/w_{org}$ in (c) JT-60U shape equilibria and (d) ITER-like shape equilibria, where $w_{org}$ is the $w$ value in case (Jp1) in figure (c) and that in case (Ip1) in figure (d), respectively. The red, green, and blue lines show $w/w_{org}$ at $\xi_r = 0.3$, 0.2, and 0.1.

As shown in figure 10 (c), the $w/w_{org}$ of $\xi_r$ whose $n = 8$ shown in figure 5 (c), and that in figure 10 (d) expresses $w/w_{org}$ of $\xi_r$ whose $n = 9$ shown in figure 7 (c); in these cases, both $p$ and $\langle \mathbf{j} \cdot \mathbf{B} \rangle / \langle \mathbf{B}^2 \rangle$ profiles are changed. In comparison between these solid and broken lines, we find that the width of $\xi_r$, whose $n$ number is unchanged as $n = 8$ in JT-60U shape case and $n = 9$ in ITER-like shape case, expands due mainly to the increase of the pressure gradient inside the top of the pedestal. Particularly, in ITER-like shape case, though the $n$ number of the most unstable mode changes from 9 to 6 when both $p$ and $\langle \mathbf{j} \cdot \mathbf{B} \rangle / \langle \mathbf{B}^2 \rangle$ profiles are changed as discussed in subsection 2.3, the $\alpha_{St}$ dependence of $w/w_{org}$ of the $n = 9$ mode at $\xi_r = 0.3$, 0.2, 0.1 can be represented without the increase of the current density inside the top of the pedestal as shown in figure 10 (d).

3.2. Effect of the current density profile

In this subsection, we investigate the effect of the increase of the current density inside the top of the pedestal on the expansion of $\xi_r$. As shown in figure 10(c), since the increase of the pressure gradient can explain approximately the expansion of $\xi_r$ in JT-60U shape case, we discuss the current density effect only in ITER-like shape case. In this study, we change the reference
current density profile from (I1) to (I3) in figure 3. Figure 11 shows the profiles of (a) $p$ and (b) $q$ and $(\mathbf{j} \cdot \mathbf{B})/\langle \mathbf{B}^2 \rangle$, respectively. As already mentioned, the $p$ and $(\mathbf{j} \cdot \mathbf{B})/\langle \mathbf{B}^2 \rangle$ profiles of (Ij1) in figure 11 is referred to those of (I3) in figure 3. The $\alpha_{87}$ value is 0.40 (Ij1), 0.76 (Ij2), and 1.49 (Ij3), respectively. By comparing the stability analysis results in these equilibria and those in the equilibria shown in figures (a) and (b), we can discuss the effect of the current density inside the top of the pedestal on the expansion of $\xi_r$.

The results of the stability analysis in figure 11 (c) show that the $n$ number of the unstable mode tends to increase as the pressure gradient inside the top of the pedestal decreases, and as the result, the $n$ number of the most unstable mode changes from $n = 6$ in case (Ij1) to 7 in case (Ij2), and 9 in case (Ij3). As shown in figure 11 (d), $\xi_r$ extends to the plasma core region as the pressure gradient inside the top of the pedestal increases. This expansion of $\xi_r$ is thought to be caused by both increasing the pressure gradient inside the top of the pedestal and decreasing the $n$ number of the most unstable mode. As shown in figure 11 (c), the increase of the bootstrap current density is necessary for decreasing $n$ of the most unstable mode, and in combination with such a increase of the current density, the increase of the pressure gradient can help to decrease the $n$ number of the mode.

### 4. Effect of the Plasma Shape

In this section, we discuss the reason that the plasma shape affects the expansion of the displacement of the unstable mode due to the increase of the pressure gradient and the current density inside the top of the pedestal. Figures 12 (a) and (b) show the stability diagram of the ideal MHD mode in JT-60U shape case on the $(s, \alpha)$ plane at (a) $\psi_N = 0.87 (\rho \simeq 0.87)$ and (b) $\psi_N = 0.97 (\rho \simeq 0.97)$ when the $p$ profile is changed but the $(\mathbf{j} \cdot \mathbf{B})/\langle \mathbf{B}^2 \rangle$ profile is fixed discussed in subsection 3.1, where $s$ is the magnetic shear defined as $s = 2V/q(dq/dV)$. The black line is the stability boundary of the $n = \infty$ ballooning mode, the red, green, blue and purple lines show those of the peeling/kink mode and the peeling-ballooning mode, and the red, green, blue, and purple points show the $(s, \alpha)$ point of the equilibria in cases (Jp1), (Jp2), (Jp3), and (Jp4), respectively. These equilibria access to the second stability region of ballooning mode at the pedestal $(\psi_N = 0.97)$, but still exist in the first stability region inside the top of the pedestal $(\psi_N = 0.87)$. In this case, the maximum pressure gradient at the pedestal $(\psi_N = 0.97) \max(\alpha_{87})$ and the stable region against ideal MHD modes are almost unchanged though $\alpha_{87}$ increases about four times. These results and the result that the change of $\xi_r$ is small as shown in figure 10 (a) imply that the increase of the pressure gradient inside the top of the pedestal affects little on the edge MHD stability in JT-60U shape case.
Figure 12. (a), (b) Stability diagram of the ideal MHD mode in JT-60U shape case discussed in subsection 3.1 on the \((s, \alpha)\) plane at (a) \(\psi_N = 0.87\) and (b) \(\psi_N = 0.97\). (c), (d) Stability diagram of the ideal MHD mode in ITER-like shape case discussed in subsection 3.1 on the \((s, \alpha)\) plane at (c) \(\psi_N = 0.87\) and (d) \(\psi_N = 0.97\). In both cases, the \(p\) profile is changed but the \((\mathbf{j} \cdot \mathbf{B})/\langle \mathbf{B}^2 \rangle\) profile is fixed. The black line is the stability boundary of the \(n = 1\) ballooning mode. The red, green, blue and purple lines show the stability boundaries of the peeling/kink mode and the peeling-ballooning mode, and the red, green, blue, and purple points show the \((s, \alpha)\) points of the equilibria in cases (Jp1), (Jp2), (Jp3), and (Jp4) in figures (a) and (b), and those of the equilibria in cases (Ip1), (Ip2), (Ip3), and (Ip4) in figures (c) and (d), respectively.

On the other hand, in ITER-like shape case shown in figures 12 (c) and (d), the \(\alpha_{87}\) decreases about 10% and the stable region against ideal MHD modes becomes narrower as the pressure gradient inside the top of the pedestal increases about four times. Moreover, in figure 12 (c), the \(\alpha_{87}\) value approaches to the stability boundary of the ballooning mode. These results and the result that the change of \(\xi_r\) is visible as shown in figure 10 (b) imply that the increase of the pressure gradient inside the top of the pedestal changes the edge MHD stability due to approaching the ballooning mode stability boundary inside the top of the pedestal. From these results, we find the reason of the difference in the expansion of the structure of \(\xi_r\) in the different shape equilibria as follows. In a strongly shaped plasma, the pressure gradient and the current density near the pedestal can increase due to stabilizing the ideal ballooning mode and the peeling-ballooning mode. However, since the shaping effect becomes weaker in the plasma core region, the pressure gradient inside the top of the pedestal can approach to the stability boundary of the ideal ballooning mode as shown in figure 12 (c). This approach changes the edge MHD stability, and expands the structure of the edge MHD mode.

Finally, we investigate the reason why the \(n\) number of the most unstable mode changes when both the \(p\) and \((\mathbf{j} \cdot \mathbf{B})/\langle \mathbf{B}^2 \rangle\) profiles are changed in ITER-like shape case as discussed in subsection 2.3. Figure 13 shows the \((s, \alpha)\) stability diagram of the equilibria shown in figure 3 at (a) \(\psi_N = 0.87\) and (b) \(\psi_N = 0.97\). In this case, the \((s_{87}, \alpha_{87})\) point of the equilibria approaches to the ballooning mode stability boundary, but the trajectory of \((s_{87}, \alpha_{87})\) does not pass across the ballooning mode stability boundary due to accessing the second stability region unlike in the fixed \((\mathbf{j} \cdot \mathbf{B})/\langle \mathbf{B}^2 \rangle\) case. At \(\psi_N = 0.97\) shown in figure 13 (b), the stability boundaries of the peeling/kink mode and the peeling-ballooning mode straiten the stable region and the \(\max(\alpha_{87})\) decreases over 30%, because the relatively low-\(n\) \((n = 4 \sim 6)\) peeling-ballooning modes and the low-\(n\) \((n = 1 \sim 3)\) kink-ballooning modes are destabilized due to the increase of the current density inside the top of the pedestal.

In comparison between figures 12 (c) and (d) and figure 13, the difference of the edge MHD stability with/without the increase of the current density inside the top of the pedestal is in evidence. When the current density profile is fixed, since only the pressure driven component in the plasma potential energy becomes larger, the expansion of the eigenfunction is caused by making the pressure driven ballooning mode to be unstable as shown in figure 12 (c). When the
Figure 13. Stability diagram of the ideal MHD mode on the \((s, \alpha)\) plane at (a) \(\psi_N = 0.87\) and (b) \(\psi_N = 0.97\) when both the \(p\) and \((\mathbf{j} \cdot \mathbf{B})/\langle \mathbf{B}^2 \rangle\) profile are changed in ITER-like shape case discussed in subsection 2.3. The black line is the stability boundary of the \(n = \infty\) ballooning mode. The red, green, blue and purple lines show the stability boundaries of the peeling/kink mode and the peeling-ballooning mode, and the red, green, blue, and purple points show the \((s, \alpha)\) point of the equilibria (I1), (I2), and (I3), respectively.

The current density inside the top of the pedestal increases shown in figure 13, on the other hand, since not only the pressure driven component but also the current driven component become larger, the peeling-ballooning mode tends to be unstable and the maximum pressure gradient at the pedestal decreases. The reason of this destabilization is thought as the coupling between the peeling-ballooning mode localized near the pedestal and that localized inside the top of the pedestal, and the structure of the peeling-ballooning mode extends to the plasma core region as shown in figure 7.

5. Summary
In this paper, effects of the pressure profile and the current density profile inside the top of the pedestal and that of the plasma shape on the expansion of the structure of the unstable edge MHD mode are investigated numerically. The numerical results of the stability analyses showed that the pressure and the current density profiles inside the top of the pedestal is important for determining the structure of the eigenfunction of the edge MHD mode, and the expansion of the displacement of the unstable mode is enhanced in a strongly shaped plasma. From the results under the fixed current density profile assumption, it is revealed that the increase of the pressure gradient is essential for the expansion of the edge MHD mode due to spreading the envelope of the edge ballooning mode. On the other hand, the increase of the bootstrap current density is necessary for decreasing the toroidal mode number of the most unstable mode. Since the decrease of the toroidal mode number generally expands the structure of the edge MHD mode, both the pressure profile and the current density profile inside the top of the pedestal has an impact on the structure of the edge MHD mode. The expansion of the edge MHD mode is induced by making the ballooning mode or the peeling-ballooning mode to be unstable inside the top of the pedestal. The ideal ballooning mode is strongly stabilized by the plasma shaping but this stabilizing effect of the plasma shaping becomes weak in the plasma core region. In a strongly shaped equilibrium, the pressure gradient and the current density inside the top of the pedestal can increase largely and destabilize the edge MHD mode due to approaching to the ballooning mode stability boundary. This destabilization expands the structure of the edge MHD mode.

The numerical results in this paper showed that not only the pressure gradient but also the current density inside the top of the pedestal is important for discussing the structure of the edge MHD mode. This result implies that the global safety factor profile, in other words, the total
plasma current, also affects the structure of the edge MHD mode by changing the ballooning mode and the kink/peeling mode stability on the \((s, \alpha)\) plane. This will be discussed in near future.

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