Characterization of H-mode pedestal width based on hydrogen and deuterium discharges in JT-60U

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1. Introduction

In the H-mode plasmas, the edge pedestal structure determines the boundary condition of the heat transport of the plasma core. Therefore, it is of primary importance to understand the physical processes determining the edge pedestal structure. The structure of the H-mode pedestal is composed of a spatial width in which a steep pressure gradient is formed. In this region, the periodic expulsion of energy and particles is commonly observed due to the existence of the MHD instabilities (ELMs) caused by a steep pressure gradient or a large bootstrap current. However, the dependence of the pedestal width on local and global plasma parameters is not clearly known.

Particularly, knowledge of the pedestal width \( \Delta_{\text{ped}} \) based on non-dimensional parameters is of great help for the extrapolation towards next step device. In this paper, the non-dimensional parameters such as \( \rho_{\text{pol}}^* \), \( \beta_{\text{pol}} \) and \( v^* \) are the values evaluated at the pedestal shoulder unless otherwise specified. The shoulder of the H-mode pedestal is determined by the linear fit of the edge \( T_i \) profile on the outer midplane. Several empirical scalings of \( \Delta_{\text{ped}} \) have been proposed with the use of the non-dimensional parameters. However, these scalings vary from machine to machine and with the operational regime. In the JT-60U tokamak, it has been reported that the pedestal width \( \Delta_{\text{ped}} \) scales as the normalized poloidal Larmor radius of thermal ions \( \rho_{\text{pol}}^* \), i.e. \( \Delta_{\text{ped}} \propto \rho_{\text{pol}}^* \) [1]. Later analysis showed the weaker dependence of \( \Delta_{\text{ped}} \) on \( \rho_{\text{pol}}^* \) [2]. In the DIII-D tokamak, \( \Delta_{\text{ped}} \propto (\rho_{\text{pol}}^*)^{0.66} \) or \( \Delta_{\text{ped}} \propto \beta_{\text{pol}}^{0.4} \), where \( \beta_{\text{pol}} \) \((\propto nT/Ip^2)\) denotes the ratio of the edge kinetic pressure to the poloidal magnetic pressure [3]. This disagreement can be caused by the existing strong co-linearity between \( \rho_{\text{pol}}^* \) and \( \beta_{\text{pol}} \), which is hard to separate out in the peripheral region. In practice, the edge pressure imposed by the stability boundary for ELMs scales empirically as \( nT \propto I_p \) in JT-60U. If we keep the collisionality \( v^* \) \((\propto n/T^2)\) fixed in a single deuterium discharge, then we can find that \( \rho_{\text{pol}}^* \propto \beta_{\text{pol}}^{5/6} \). To distinguish these variables, a pair of experiments in hydrogen and deuterium plasmas are conducted in this study. Explicit difference between \( \rho_{\text{pol}}^* \) and \( \beta_{\text{pol}} \) is the mass dependence of \( \rho_{\text{pol}}^* \) \((\propto m^{0.5})\) in contrast with no mass dependence in \( \beta_{\text{pol}} \). The investigation of the mass dependence of the pedestal width can reveal the dependence of the H-mode pedestal width on the edge non-dimensional parameters.

In this study, the \( \rho_{\text{pol}}^* \) dependence of \( \Delta_{\text{ped}} \) is investigated conducting the dedicated mass scan experiments using hydrogen and deuterium plasmas. In addition, the \( \beta_{\text{pol}} \) dependence of \( \Delta_{\text{ped}} \) is also examined by conducting the non-dimensional transport experiments.

2. ELMy H-mode confinement database in JT-60U

The dataset is restricted to hydrogen and deuterium discharges of standard H-mode, high density H-mode and high \( \beta_{\text{pol}} \) H-mode performed during the period 2000-2003.

Figure 1. Relation between \( P_{\text{abs}} \) and \( \beta_{\text{pol}}^\text{HF} \) for hydrogen and deuterium discharges.
For comparison of the spatial profiles between hydrogen and deuterium discharges, the dependence of $E_{pol}^{tot}$ (total $E_{pol}$) on $P_{abs}$ for the discharges operated at $I_p = 1$MA, $B_T = 2$T, $q_{95} \sim 4$, $\kappa \sim 1.4$ and $\delta \sim 0.3$ is shown in figure 1. It is seen that $E_{pol}^{tot}$ for deuterium plasmas is larger by a factor of two than that for hydrogen plasmas at fixed $P_{abs}$. In other words, the energy confinement time in deuterium plasmas is two times longer than that in hydrogen plasmas. In the accessible range of $E_{pol}$ in hydrogen plasmas, we can select a pair of discharges operated at the same $E_{pol}$, $Q^*$ and the plasma density.

Shown in figure 2 are the profiles of $n_e$, $T_e$ and $T_i$ for hydrogen and deuterium discharges with keeping $E_{pol}$ and $\n_\phi$ fixed, which correspond to the data points highlighted in figure 1. The power required to sustain $E_{pol}$ equivalent to that obtained in the deuterium discharge is larger by a factor of two for the case of the hydrogen discharge. However, it is clear that the resultant profiles of $n_e$, $T_e$ and $T_i$ are almost identical over the wide radial range between these plasmas. This result implies the $U_{pol}^{*}$ dependence of $\Delta_{ped}$ is weak.

3. Experiment on $\rho_{pol}^*$ dependence in type-I ELMy H-mode plasmas

The experiments were conducted at fixed $B_T = 2.4$T, $\kappa = 1.4$, $\delta = 0.34$ and $\varepsilon = 0.27$ for deuterium and hydrogen discharges. To keep a sufficient range of $\rho_{pol}^*$ and $\beta_{pol}$ value, a set of discharges was performed with different $I_p = 0.90$, 1.08 and 1.25MA, each of which were tuned by varying the NB injection power $P_{NB}$ so that $\beta_{pol}$ can be matched for both species. Note that the plasmas in this experiment are the H-modes without the ITB in the plasma core.

Figure 2. Profiles of $n_e$, $T_e$ and $T_i$, which correspond to the deuterium and hydrogen discharges operated at the same $E_{pol}^{tot}$ (see highlighted data points shown in figure 1).

Figure 3. Profiles of $n_e$, $T_e$, $T_i$, for deuterium and hydrogen discharges. Edge profiles of $\rho_{pol}^*$, $\beta_{pol}$ and $v^*$ are also shown.
If $\Delta_{\text{ped}}$ is dependent on $\rho_{\text{pol}}^*$, it would be impossible to match the pedestal height for both plasmas at the same edge pressure gradient. In this case, since $\Delta_{\text{ped}}$ in deuterium plasmas becomes larger than that in hydrogen plasmas by the factor of $\sim 1.4$ (which is the square root of the mass ratio), the pedestal height in deuterium plasmas should be larger than that in hydrogen plasmas at fixed pressure gradient. On the other hand, if $\Delta_{\text{ped}}$ is determined by $\beta_{\text{pol}}$, edge pedestal profiles which are defined by the pedestal width and height would become identical for both plasmas.

Figure 3 shows the spatial profiles of the $n_e$, $T_e$, $T_i$, $\rho_{\text{pol}}^*$, $\beta_{\text{pol}}$ and $\nu^*$ for hydrogen and deuterium discharges. The required power in the hydrogen plasma is $\sim 2$ times larger than that in deuterium plasma to sustain the same $\beta_{\text{pol}}$ at the plasma edge. As seen in figure 4(a), the edge $T_i$ profiles are obviously almost identical in H/D plasmas. In both cases, clear type-I ELMs are observed while the ELM frequency for the hydrogen plasma is higher than that for the deuterium plasma. Figure 4(b) shows the data area in $\beta_{\text{pol}}$-$\rho_{\text{pol}}^*$ space in this series of experiments. A strong correlation between $\beta_{\text{pol}}$ and $\rho_{\text{pol}}^*$ is seen in each species. At $\beta_{\text{pol}} \sim 0.24$ in the pedestal region, the $\rho_{\text{pol}}^*$ scan is possible comparing H/D plasmas. Figure (c) shows the relation between $\rho_{\text{pol}}^*$ and $\Delta_{\text{ped}}/\alpha_p$. By keeping $\beta_{\text{pol}}$ fixed, it is seen that the $\rho_{\text{pol}}^*$ dependence of $\Delta_{\text{ped}}$ is weak, satisfying $\Delta_{\text{ped}}/\alpha_p \propto \rho_{\text{pol}}^*$.0.1.

Figure 5. Profiles of $n_e$, $T_e$, $T_i$ for $\beta_{\text{pol}}$ scan experiments. Edge profiles of $\rho_{\text{pol}}^*$, $\beta_{\text{pol}}$ and $\nu^*$ are also shown.
4. Experiment on $\beta_{pol}$ dependence in ELMy H-mode plasmas

Power scan of satisfying $\beta_{pol} \propto I_p^n$ at the pedestal with controlling $n \propto I_p^\kappa$ gives the variation of $\beta_{pol}$ at fixed $\rho_{pol}^*$. Based on this rule, the experiments were conducted at fixed $q_{gy} = 3.6$, $\kappa = 1.4$, $\delta = 0.35$ and $\varepsilon = 0.27$ in deuterium plasmas. The spatial profiles of the $n_e$, $T_e$, $T_i$, $\rho_{pol}^*$, $\beta_{pol}$ and $v^*$ for a pair of H-mode plasmas in $\beta_{pol}$ scan are shown in figure 5. The case (A) indicates a ‘low’ $\beta_{pol}$ plasmas performed at $I_p = 0.96$MA and $B_T = 2.1$T while the case (B) indicates a ‘high’ $\beta_{pol}$ plasmas performed at $I_p = 1.15$MA and $B_T = 2.5$T. As shown in figure 5, the edge $\beta_{pol}$ is scanned while $\rho_{pol}^*$ and $v^*$ are kept constant. From the edge $T_i$ profiles shown in figure 6(a), the case (A) of the higher $\beta_{pol}$ plasma has higher pedestal $T_i$ value accompanied by wider pedestal width in spite of the almost identical $\rho_{pol}^*$ at the pedestal. Figure 5(b) shows the relation between $\beta_{pol}$ and $\Delta_{ped}/a_p$ while keeping $\rho_{pol}^*$ fixed at $\sim 4.5 \times 10^{-2}$. Then, it is seen that $\Delta_{ped}$ depends strongly on $\beta_{pol}$, satisfying $\Delta_{ped}/a_p \propto \beta_{pol}^{0.6}$.

5. Discussion and summary

In this series of experiments on the non-dimensional parameter scan, we obtain the scaling of the pedestal width, which is expressed as $\Delta_{ped} \propto a_p \rho_{pol}^{*0.1} \beta_{pol}^{0.6}$. We should be careful for the error evaluation of the scaling under the existence of strong co-linearity between $\rho_{pol}^*$ and $\beta_{pol}$ at the pedestal in addition to the log-linear fitting deviation. In JT-60U, the relation between edge $\rho_{pol}^*$ and $\beta_{pol}$ is expressed as $\rho_{pol}^* \propto \beta_{pol}^{0.7+0.1}$. Then, the pedestal width scales as $\Delta_{ped} \propto a_p \rho_{pol}^{*0.1+0.15} \beta_{pol}^{0.6+0.11}$. The deviation of $\rho_{pol}^*$ reacts to that of $\beta_{pol}$ and vice versa.

In this study, the characteristics of the pedestal width were investigated in hydrogen and deuterium plasmas. Both the database analysis and the dedicated experiments on the mass scan indicated that the pedestal width depend very weakly on the plasma particle species or $\rho_{pol}^*$. Identical profiles of the edge $T_i$ which were obtained in the experiments suggested that the pedestal width depended on $\beta_{pol}$ more strongly than $\rho_{pol}^*$. The experiment on $\beta_{pol}$ scan was also performed. Higher $\beta_{pol}$ plasma had higher pedestal $T_i$ value accompanied by wider pedestal width in spite of the almost identical $\rho_{pol}^*$ at the pedestal. Based on the non-dimensional experiments, the scaling of the pedestal width was evaluated as $\Delta_{ped} \propto a_p \rho_{pol}^{*0.1+0.15} \beta_{pol}^{0.6+0.11}$.

References