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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 Δ_{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 ρ_{pol}^*, β_{pol} and ν^* 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 Δ_{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 Δ_{ped} scales as the normalized poloidal Larmor radius of thermal ions ρ_{pol}^*, i.e. $\Delta_{ped} \propto \rho_{pol}^*$ [1]. Later analysis showed the weaker dependence of Δ_{ped} on ρ_{pol}^* [2]. In the DIII-D tokamak, $\Delta_{ped} \propto (\rho_{pol}^*)^{0.66}$ or $\Delta_{ped} \propto \beta_{pol}^{0.4}$, where β_{pol} ($\propto nT / I_p^2$) 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 ρ_{pol}^* and β_{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 ν^* ($\propto n / T^2$) fixed in a single deuterium discharge, then we can find that ρ_{pol}^* ($\propto \sqrt{mT} / I_p$) varies in proportion to $\beta_{pol}^{5/6}$. To distinguish these variables, a pair of experiments in hydrogen and deuterium plasmas are conducted in this study. Explicit difference between ρ_{pol}^* and β_{pol} is the mass dependence of ρ_{pol}^* ($\propto m^{0.5}$) in contrast with no mass dependence in β_{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 ρ_{pol}^* dependence of Δ_{ped} is investigated conducting the dedicated mass scan experiments using hydrogen and deuterium plasmas. In addition, the β_{pol} dependence of Δ_{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 β_{pol} H-mode performed during the period 2000-2003.

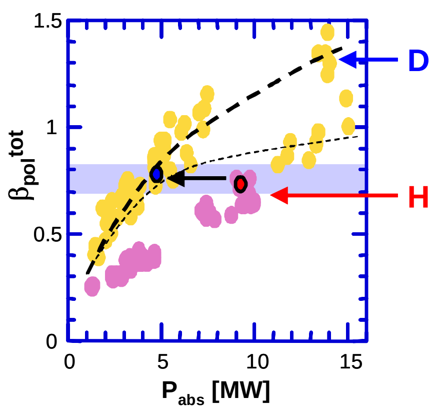

Figure 1. Relation between P_{abs} and β_{pol}^{tot} for hydrogen and deuterium discharges.

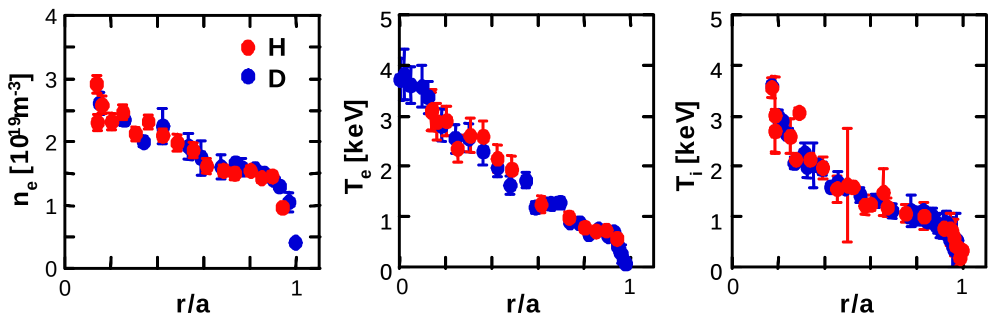

Figure 2. Profiles of n_e, T_e and T_i which correspond to the deuterium and hydrogen discharges operated at the same β_{pol}^{tot} (see highlighted data points shown in figure 1).

For comparison of the spatial profiles between hydrogen and deuterium discharges, the dependence of β_{pol}^{tot} (total β_{pol}) on P_{abs} for the discharges operated at I_p = 1MA, B_T = 2T, q_{95} ~ 4, κ ~ 1.4 and δ ~ 0.3 is shown in figure 1. It is seen that β_{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 β_{pol} in hydrogen plasmas, we can select a pair of discharges operated at the same β_{pol}, ν* 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 β_{pol} and $\bar{n}_e$ fixed, which correspond to the data points highlighted in figure 1. The power required to sustain β_{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 ρ_{pol}* dependence of Δ_{ped} is weak.

3. Experiment on ρ_{pol}* dependence in type-I ELMy H-mode plasmas

The experiments were conducted at fixed B_T = 2.4T, κ = 1.4, δ = 0.34 and ε = 0.27 for deuterium and hydrogen discharges. To keep a sufficient range of ρ_{pol}* and β_{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 β_{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.

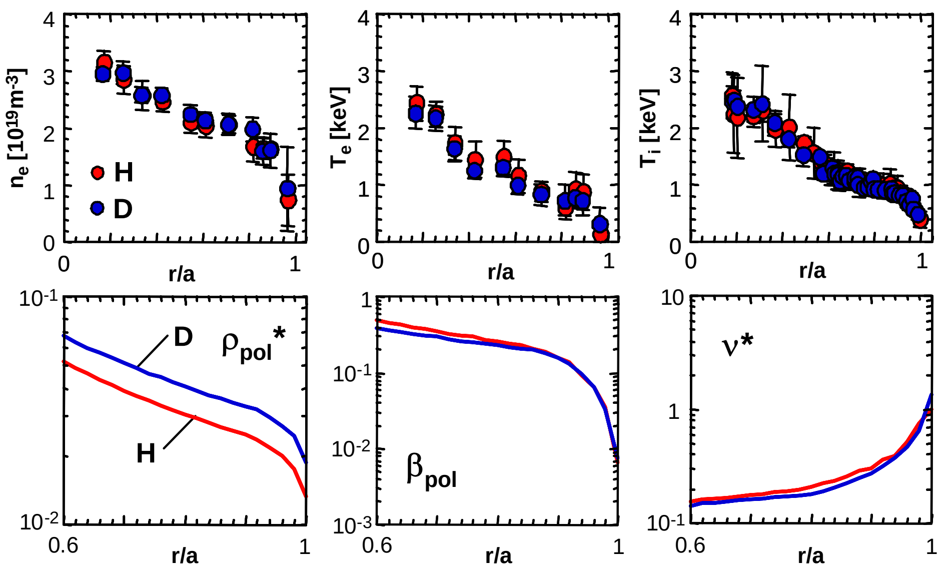

Figure 3. Profiles of n_e, T_e, T_i for deuterium and hydrogen discharges. Edge profiles of ρ_{pol}*, β_{pol} and ν* are also shown.

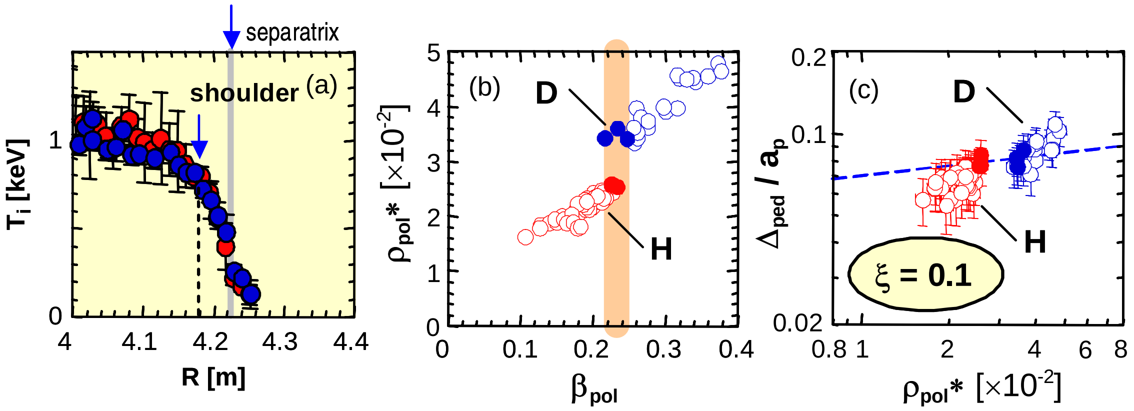

Figure 4. (a) Pedestal T_i profiles for deuterium and hydrogen plasmas at the same β_{pol} and ν^*. (b) Data area in β_{pol}-ρ_{pol}^* space of the experiments. (c) Relation between ρ_{pol}^* and Δ_{ped}/a_p. The exponent of ρ_{pol}^* in the log-linear regression at fixed β_{pol} is $\xi = 0.1$.

If Δ_{ped} is dependent on ρ_{pol}^*, it would be impossible to match the pedestal height for both plasmas at the same edge pressure gradient. In this case, since Δ_{ped} in deuterium plasmas becomes larger than that in hydrogen plasmas by the factor of ~ 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 Δ_{ped} is determined by β_{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, ρ_{pol}^*, β_{pol} and ν^* for hydrogen and deuterium discharges. The required power in the hydrogen plasma is ~ 2 times larger than that in deuterium plasma to sustain the same β_{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 β_{pol}–ρ_{pol}^* space in this series of experiments. A strong correlation between β_{pol} and ρ_{pol}^* is seen in each species. At β_{pol} ~ 0.24 in the pedestal region, the ρ_{pol}^* scan is possible comparing H/D plasmas. Figure (c) shows the relation between ρ_{pol}^* and Δ_{ped}/a_p. By keeping β_{pol} fixed, it is seen that the ρ_{pol}^* dependence of Δ_{ped} is weak, satisfying $\Delta_{ped}/a_p \propto \rho_{pol}^{*0.1}$.

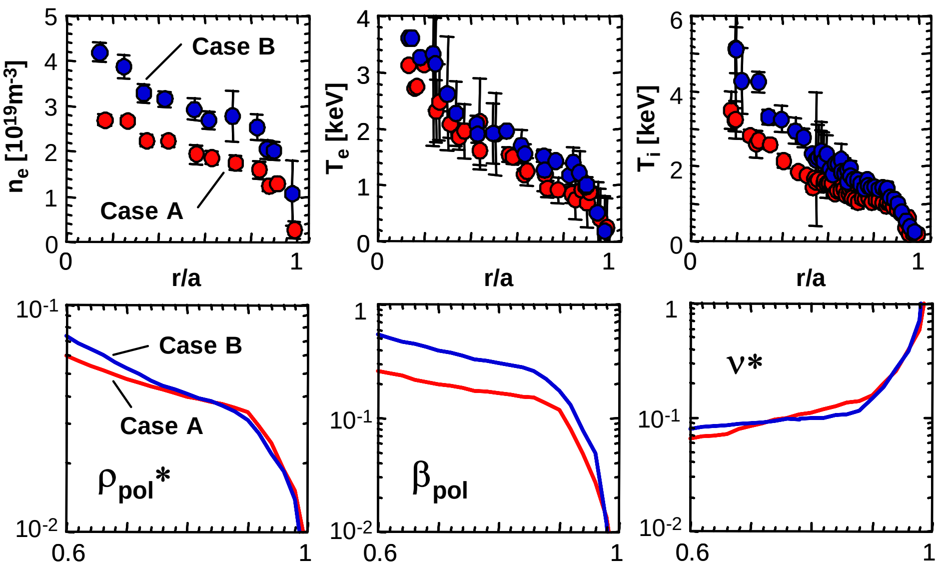

Figure 5. Profiles of n_e, T_e, T_i for β_{pol} scan experiments. Edge profiles of ρ_{pol}^*, β_{pol} and ν^* are also shown.

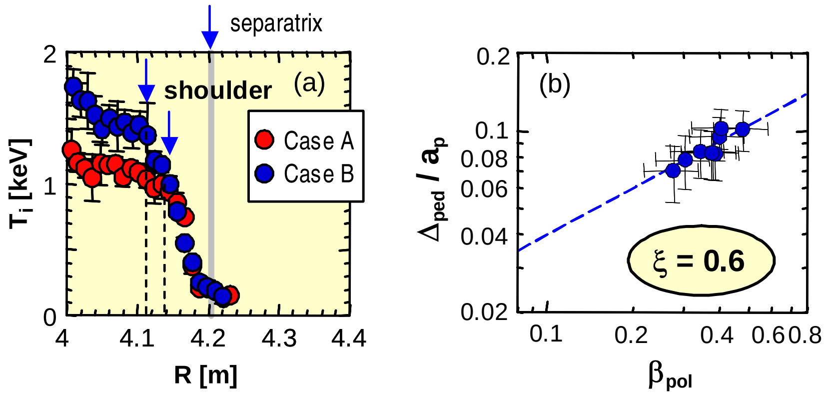

Figure 6. (a) Pedestal T_i profiles for the β_{pol} scan at the same ρ_{pol}* and ν*. (b) Relation between β_{pol} and Δ_{ped}/a_p at ρ_{pol}* ~ 4.5x10^{-2}. The exponent of β_{pol} in the log-linear regression at fixed ρ_{pol}* is $\xi = 0.6$.

4. Experiment on β_{pol} dependence in ELMy H-mode plasmas

Power scan of satisfying $\beta_{pol} \propto I_p^4$ at the pedestal with controlling $n \propto I_p^4$ gives the variation of β_{pol} at fixed ρ_{pol}*. Based on this rule, the experiments were conducted at fixed q_{95} = 3.6, κ = 1.4, δ = 0.35 and ε = 0.27 in deuterium plasmas. The spatial profiles of the n_e, T_e, T_i, ρ_{pol}*, β_{pol} and ν* for a pair of H-mode plasmas in β_{pol} scan are shown in figure 5. The case (A) indicates a 'low' β_{pol} plasmas performed at I_p = 0.96MA and B_T = 2.1T while the case (B) indicates a 'high' β_{pol} plasmas performed at I_p = 1.15MA and B_T = 2.5T. As shown in figure 5, the edge β_{pol} is scanned while ρ_{pol}* and ν* are kept constant. From the edge T_i profiles shown in figure 6(a), the case (A) of the higher β_{pol} plasma has higher pedestal T_i value accompanied by wider pedestal width in spite of the almost identical ρ_{pol}* at the pedestal. Figure 5(b) shows the relation between β_{pol}* and Δ_{ped}/a_p while keeping ρ_{pol}* fixed at ~ 4.5x10^{-2}. Then, it is seen that Δ_{ped} depends strongly on β_{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 ρ_{pol}* and β_{pol} at the pedestal in addition to the log-linear fitting deviation. In JT-60U, the relation between edge ρ_{pol}* and β_{pol} is expressed as $\rho_{pol}{*} \propto \beta_{pol}^{0.7\pm0.1}$. 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 ρ_{pol}* reacts to that of β_{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 ρ_{pol}*. Identical profiles of the edge T_i which were obtained in the experiments suggested that the pedestal width depended on β_{pol} more strongly than ρ_{pol}*. The experiment on β_{pol} scan was also performed. Higher β_{pol} plasma had higher pedestal T_i value accompanied by wider pedestal width in spite of the almost identical ρ_{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

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