Energy confinement characterization of hydrogen and deuterium H-mode plasmas in JT-60U tokamak

H. Urano[1], T. Takizuka[2], M. Kikuchi[1], T. Nakano[1], T. Fujita[1], N. Hayashi[1], N. Oyama[1], Y. Kamada[1], and the JT-60 Team[1]
[1] *Japan Atomic Energy Agency, Naka, Ibaraki 311-0193 Japan*
[2] *Osaka University, Suita, Osaka, 565-0871 Japan*

1 Introduction

Knowledge of the influence of the plasma isotopic composition on the heat conduction in the steady H-mode plasma has important consequences from both the physics and the engineering point of view. The effects of the isotope mass M on the energy confinement have been extensively studied [1, 2]. For all discharge types the energy confinement increased with isotope mass $\tau_{\rm th} \propto M^{\zeta}$ with the exponent ζ greater than 0. However, little is known about the process responsible for the energy confinement by varying the isotopic composition. In this paper, dependence of hydrogen isotopes on heat transport and pedestal structure is characterized using hydrogen and deuterium H-mode plasmas in JT-60U tokamak.

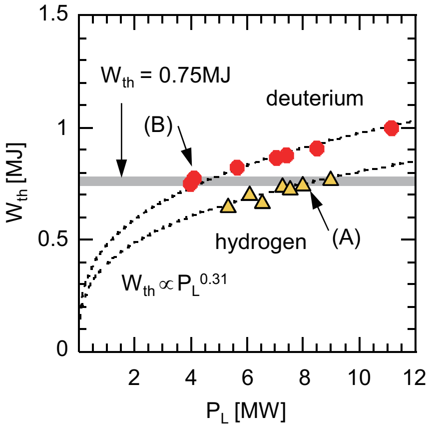

FIG. 1: Dependence of $\tau_{\rm th}$ on $P_{\rm L}$ for conventional H-mode plasmas.

2 Heat transport properties in hydrogen and deuterium H-mode plasmas

The experiments were conducted for hydrogen and deuterium H-mode discharges at 1.08MA/2.4T. Fig. 1 shows the thermal stored $W_{\rm th}$ as a function of the loss power $P_{\rm L}$. The $W_{\rm th}$ values increase continuously with $P_{\rm L}$ for both cases at approximately the same scale, as expected from the empirical law $W_{\rm th} \propto P_{\rm L}^{0.31}$ [3]. However, $W_{\rm th}$ or $\tau_{\rm th}(= W_{\rm th}/P_{\rm L})$ is larger by a factor of $1.2 - 1.3$ for deuterium in comparison with that for hydrogen at a given $P_{\rm L}$. A pair of hydrogen and deuterium plasmas were chosen along the gray line in Fig. 1, which

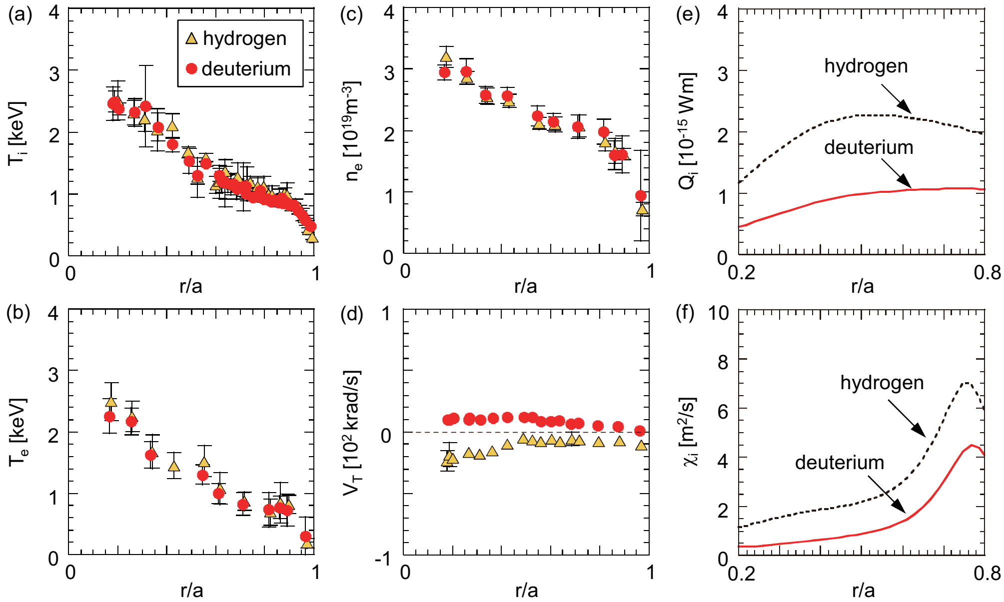

FIG. 2: *Profiles of* $T_{\rm i}$, $T_{\rm e}$, $n_{\rm e}$, $V_{\rm T}$, $Q_{\rm i}$, *and* $\chi_{\rm i}$ *which correspond to the hydrogen and deuterium discharges with the same* $W_{\rm th}$ *of* 0.75*MJ.*

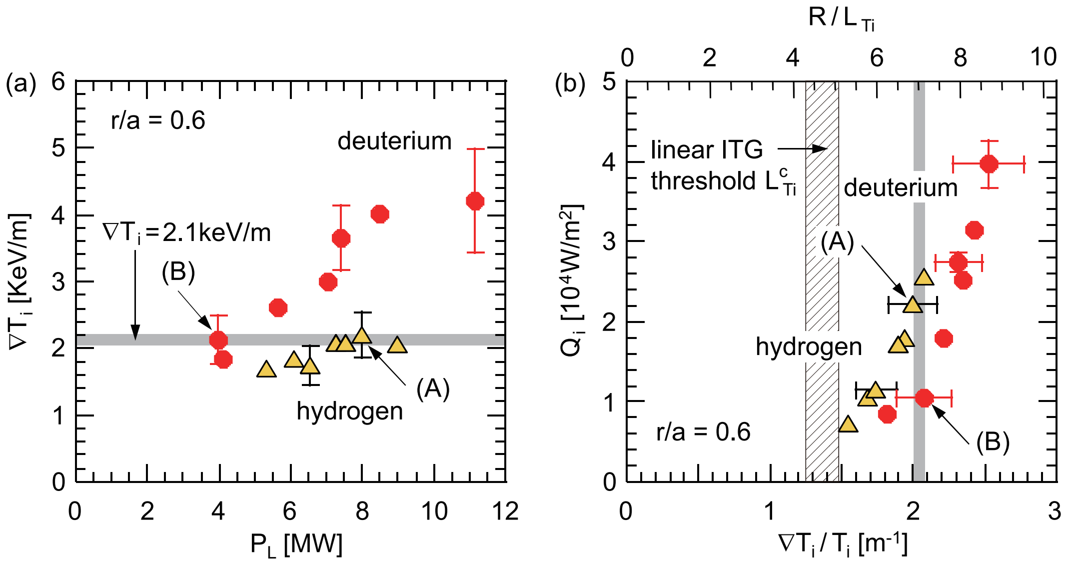

FIG. 3: (a) Relationship betwwen ∇T_i and P_L evaluated at $r/a = 0.6$. The data for hydrogen and deuterium with the same W_th of 0.75MJ are indicated as (A) and (B), respectively. (b) Ion conductive heat flux Q_i as a function of $\nabla T_\mathrm{i}/T_\mathrm{i}$ (or R/L_{T_i}) at $r/a = 0.6$ for hydrogen and deuterium H-mode plasmas.

indicates the constant thermal energy W_th (= 0.75MJ) at a steady state, as indicated by (A) and (B), respectively. The power required to sustain the same W_th was greater for hydrogen (P_L = 8.0MW) than for deuterium (P_L = 4.0MW) by a factor of two, resulting in the τ_th value of 0.1s for hydrogen, which was half that for deuterium (τ_th = 0.2s).

The results of the heat transport analyses for these two cases are shown in Fig. 2. In the figure, the spatial profiles of T_i, T_e, and n_e become obviously identical, indicating that the spatial profiles of the thermal pressures p_th also becomes approximately identical. The ion conductive heat flux Q_i for hydrogen becomes approximately two times that for deuterium, which corresponds to the result that two times as much heating power is required for hydrogen. Hence, the χ_i values for hydrogen are explicitly higher throughout the minor radius compared with those for deuterium. In this comparison, higher P_NBI was applied for hydrogen plasma using the perpendicular NB to adjust W_th to a similar value. This operation leads to a larger ripple loss of fast ions, which enhances the V_T for hydrogen toward the counter direction as shown in Fig. 2(d). However, this difference of V_T is much smaller than that in the previous experiment on the V_T scan in which the reduction of L_{T_i} due to V_T is not clearly present [4].

Fig. 3(a) shows the ion temperature gradient ∇T_i as a function of P_L evaluated at $r/a = 0.6$, where the influence of the local heat transport on the overall energy confinement becomes significant in standard H-mode plasmas. The increase in ∇T_i is less significant as P_L is raised, indicating that χ_i increases gradually with the heating power for both hydrogen and deuterium. In further detail, the increase in ∇T_i with the heating power is more rapid for deuterium than for hydrogen, suggesting a reduced energy confinement for hydrogen plasmas at a given P_L. In this figure, the data points (A) and (B) with the same W_th of 0.75MJ are plotted along the same ∇T_i of $\simeq$ 2.1keV/m at $r/a = 0.6$ because of the identical T_i profiles as shown in Fig. 2(a). The P_L value increases for hydrogen compared with that for deuterium by a factor of two, resulting in a χ_i value that is two times as large for hydrogen at the approximately identical density profiles as well as the effective ion charge number Z_eff values of $\sim$ 1.5 which are also nearly the same for both cases.

Fig. 3(b) shows the relationship between Q_i and $\nabla T_\mathrm{i}/T_\mathrm{i}$ (or $R/L_{\mathrm{T_i}}$) at $r/a = 0.6$. It can be seen in this figure that Q_i increases rapidly with $\nabla T_\mathrm{i}/T_\mathrm{i}$ for both the hydrogen and deuterium plasmas, indicating the profile stiffness in the ITG unstable region for the variation of the heating power in this experiment. This figure also shows the pair of data points (A) and (B) with the same W_th of 0.75MJ. As expected from the identical T_i profiles shown in Fig. 2, the Q_i, or χ_i, at $r/a = 0.6$ is two times as large for hydrogen than for deuterium with the same $\nabla T_\mathrm{i}/T_\mathrm{i}$ of $\sim 2.0\mathrm{m}^{-1}$ (or $R/L_{\mathrm{T_i}} \sim 7.0$). On the other hand, the $\nabla T_\mathrm{i}/T_\mathrm{i}$ values required for a given Q_i clearly increased by a factor of ~ 1.2 for deuterium in comparison with those for hydrogen; this result is indicative of a decrease in the $L_{\mathrm{T_i}}$ value with increasing hydrogen isotope mass.

A region of the linear ITG threshold predicted in Refs. [5] and [6] is also indicated in Fig. 3(b). This threshold value depends on the s/q, $T_\mathrm{i}/T_\mathrm{e}$, and ϵ where s and ϵ denote the magnetic shear and the inverse aspect ratio, respectively. The operation with a fixed magnetic geometry enables s/q and ϵ to remain nearly constant. In addition, $T_\mathrm{i}/T_\mathrm{e}$ also remained at a nearly constant value of $1.1 - 1.3$ at $r/a = 0.6$ for both the hydrogen and deuterium plasmas as Q_i was varied. Accordingly, there is no expected difference in the linear ITG threshold between hydrogen and deuterium. All the experimental data are above the threshold value for the ITG unstable region at $L_{\mathrm{T_i}} < L^\mathrm{c}_{\mathrm{T_i}}$. While the $L_{\mathrm{T_i}}$ values in the sufficiently heated phase are clearly smaller for deuterium than those for hydrogen, it is hard to identify whether the ITG threshold $L^\mathrm{c}_{\mathrm{T_i}}$ becomes certainly smaller for deuterium in this series of experiments.

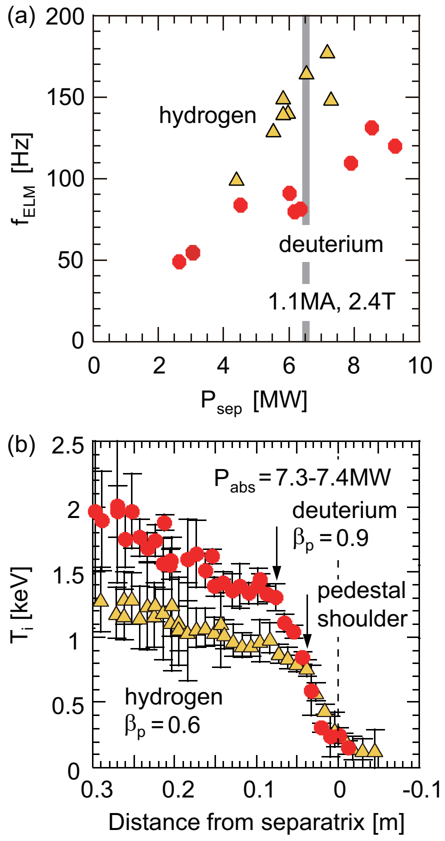

FIG. 4: (a) Dependence of f_ELM on P_sep. (b) Edge T_i profiles at P_sep of $7.3 - 7.4$MW.

3 Edge pedestal characteristics

The edge pedestal condition plays a significant role in determining the overall confinement quality in H-mode plasmas. It is therefore important to analyze the energy confinement in hydrogen and deuterium H-mode plasmas by focusing the edge pedestal characteristics. Fig. 4(a) shows the ELM frequency f_ELM as a function of the power crossing the separatrix P_sep. Linear increase of f_ELM with P_sep for both cases indicates a typical feature of type-I ELMy H-mode plasmas. At a given P_sep of ~ 6.5MW (see gray line in Fig. 4(a)), f_ELM for hydrogen becomes approximately two times as large for deuterium. The ELM frequency f_ELM for the case of hydrogen becomes 165Hz while f_ELM for the case of deuterium becomes 80Hz. Fig. 4(b) shows the edge T_i profiles for hydrogen and deuterium plasmas at $P_\mathrm{L} = 7.3 - 7.4$MW, which corresponds to P_sep of ~ 6.5MW indicated in Fig. 4(a). Despite a given P_L, the T_i value at the pedestal shoulder becomes higher for deuterium by a factor of ~ 1.5 than for hydrogen. Note that the total poloidal beta $\beta_\mathrm{p}^\mathrm{TOT}$ of 0.9 for deuterium is larger than $\beta_\mathrm{p}^\mathrm{TOT}$ of 0.6 for hydrogen.

4 Disucussion

In the present understanding, H-mode confinement is determined by the relation of two physics processes: (i) the increase of the pedestal temperature as a boundary condition affecting the reduction in the core heat transport through the profile stiffness, (ii) the increase of total β_p improving the edge stability limit [8–11]. Fig. 5 shows the relationship between β_p^{TOT} and the pedestal poloidal beta β_p^{ped} for hydrogen and deuterium plasmas at 1MA and 2T chosen from the JT-60 confinement databse. The β_p^{ped} is increased linearly with the increased β_p^{TOT} for both cases. A significant result seen in this figure is that despite the two types of isotope species of hydrogen and deuterium the relationship between β_p^{TOT} and β_p^{ped} is almost identical [12]. This result suggests that the increase in β_p^{ped} is strongly affected by the increase in β_p^{TOT} regardless of the difference of the isotope species. In other words, higher pedestal pressure observed for deuterium can be obtained by higher β_p^{TOT}. A smaller L_{T_i} for deuterium is one of the keys leading to higher β_p^{TOT}. As other possibility, the fast ion energy depends on the slowing down time of high energy ions which is proportional to $M^{1/2}T^{3/2}/n$, which may also contribute to raise β_p^{TOT} for deuterium.

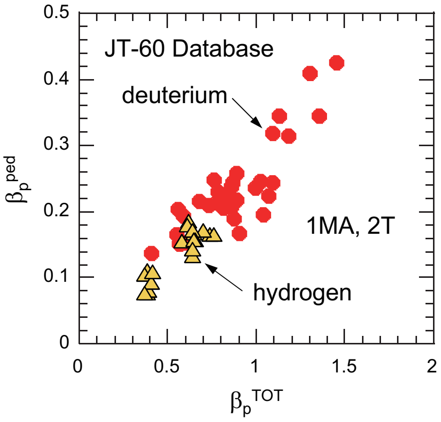

FIG. 5: The relationship between β_p^{TOT} and β_p^{ped} at 1MA and 2T.

5 Conclusions

Energy confinement properties for hydrogen and deuterium H-mode plasmas were examined in this paper. The τ_{th} value becomes larger by a factor of $\sim 1.2 - 1.3$ for deuterium than for hydrogen at a given P_L. When W_{th} was fixed, the profiles of n_e, T_e and T_i became identical for both cases while higher heating power was required for hydrogen. The ion conductive heat flux Q_i for hydrogen became approximately two times that for deuterium, corresponding to a required heating power to sustain the same W_{th} value that was two times as large for hydrogen. Hence, the χ_i values for hydrogen were higher, explicitly throughout the minor radius, than those for deuterium at the same L_{T_i}. The $\nabla T_i/T_i$, or the inverse of L_{T_i}, required for a given χ_i increased by a factor of ~ 1.2 for deuterium compared with that for hydrogen. These results lead to the conclusion that the L_{T_i} is shrunk with hydrogen isotope mass in H-mode plasmas. The relation between β_p^{TOT} and β_p^{ped} was almost identical regardless of the difference of the isotope species, suggesting that higher pedestal pressure observed for deuterium H-modes be obtained through higher β_p^{TOT}.

References

[1] Sabbagh, S. A., et al., in Plasma Physics and Nuclear Fusion Research 1994 (Proc. 15th Int. Conf. Seville, 1994) vol. 1, IAEA, Vienna (1994) 663.
[2] Cordey, J. G., et al., Nucl. Fusion **39** (1999) 301.
[3] ITER Physics Basis, Nucl. Fusion **39** (1999) 2175.
[4] Urano, H., et al., Nucl. Fusion **48** (2008) 085007.
[5] Guo, S. C. and Romanelli, F., Phys. Fluids B **5** (1993) 520.
[6] Jenko, F., et al., Phys. Fluids B **8** (2001) 4096.
[7] Urano, H., et al., Nucl. Fusion **48** (2008) 045008.
[8] Kamada, Y., et al., Plasma Phys. Control. Fusion **48** (2006) A419.
[9] Maggi, C. F., et al., Nucl. Fusion **47** (2007) 535.
[10] Snyder, P. B., et al., Nucl. Fusion **47** (2007) 961.
[11] Leonard, A. W., et al., Phys. Plasmas **15** (2008) 056114.
[12] Urano, H., et al., Nucl. Fusion (in press).