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

H. Urano\textsuperscript{1}, T. Takizuka\textsuperscript{2}, M. Kikuchi\textsuperscript{1}, T. Nakano\textsuperscript{1}, T. Fujita\textsuperscript{1}, N. Hayashi\textsuperscript{1}, N. Oyama\textsuperscript{1}, Y. Kamada\textsuperscript{1}, and the JT-60 Team\textsuperscript{1}

\textsuperscript{1} Japan Atomic Energy Agency, Naka, Ibaraki 311-0193 Japan
\textsuperscript{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 \cite{1, 2}. For all discharge types the energy confinement increased with isotope mass $\tau_{th} \propto M^\zeta$ with the exponent $\zeta$ 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.

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 $W_{th}$ as a function of the loss power $P_L$. The $W_{th}$ values increase continuously with $P_L$ for both cases at approximately the same scale, as expected from the empirical law $W_{th} \propto P_L^{0.31}$ \cite{3}. However, $W_{th}$ or $\tau_{th}(=W_{th}/P_L)$ is larger by a factor of 1.2 – 1.3 for deuterium in comparison with that for hydrogen at a given $P_L$. A pair of hydrogen and deuterium plasmas were chosen along the gray line in Fig. 1, which

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Dependence of $\tau_{th}$ on $P_L$ for conventional H-mode plasmas.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Profiles of $T_i$, $T_e$, $n_e$, $V_T$, $Q_i$, and $\chi_i$ which correspond to the hydrogen and deuterium discharges with the same $W_{th}$ of 0.75MJ.}
\end{figure}
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 $\chi_i$ 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 $\nabla T_i$ 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 $\nabla T_i$ is less significant as $P_L$ is raised, indicating that $\chi_i$ increases gradually with the heating power for both hydrogen and deuterium. In further detail, the increase in $\nabla T_i$ 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 $\nabla T_i$ of $\approx 2.1$keV/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 $\chi_i$ 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 \( \nabla T_i / T_i \) (or \( R / L_{Ti} \)) at \( r / a = 0.6 \). It can be seen in this figure that \( Q_i \) increases rapidly with \( \nabla T_i / T_i \) 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 \( \chi_i \), at \( r / a = 0.6 \) is two times as large for hydrogen than for deuterium with the same \( \nabla T_i / T_i \) of \( \sim 2.0 \text{m}^{-1} \) (or \( R / L_{Ti} \) \( \sim 7.0 \)). On the other hand, the \( \nabla T_i / T_i \) values required for a given \( Q_i \) clearly increased by a factor of \( \sim 1.2 \) for deuterium in comparison with those for hydrogen; this result is indicative of a decrease in the \( L_{Ti} \) 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 \( s / q, T_i / T_e \), and \( \epsilon \) where \( s \) and \( \epsilon \) denote the magnetic shear and the inverse aspect ratio, respectively. The operation with a fixed magnetic geometry enables \( s / q \) and \( \epsilon \) to remain nearly constant. In addition, \( T_i / T_e \) 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 \( Q_i \) 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 \( L_{Ti} < L_{Tip} \). While the \( L_{Ti} \) values in the sufficiently heated phase are clearly smaller for deuterium than those for hydrogen, it is hard to identify whether the ITG threshold \( L_{Tip} \) becomes certainly smaller for deuterium in this series of experiments.

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 \( \sim 6.5 \text{MW} \) (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 \( P_L = 7.3 - 7.4 \text{MW} \), which corresponds to \( P_{sep} \) of \( \sim 6.5 \text{MW} \) 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 \( \sim 1.5 \) than for hydrogen. Note that the total poloidal beta \( \beta_p^{TOT} \) of 0.9 for deuterium is larger than \( \beta_p^{TOT} \) of 0.6 for hydrogen.
4 Discussion

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 $\beta_p$ improving the edge stability limit [8–11]. Fig. 5 shows the relationship between $\beta_p^{\text{TOT}}$ and the pedestal poloidal beta $\beta_p^{\text{ped}}$ for hydrogen and deuterium plasmas at 1MA and 2T chosen from the JT-60 confinement database. The $\beta_p^{\text{ped}}$ is increased linearly with the increased $\beta_p^{\text{TOT}}$ 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 $\beta_p^{\text{TOT}}$ and $\beta_p^{\text{ped}}$ is almost identical [12]. This result suggests that the increase in $\beta_p^{\text{ped}}$ is strongly affected by the increase in $\beta_p^{\text{TOT}}$ regardless of the difference of the isotope species. In other words, higher pedestal pressure observed for deuterium can be obtained by higher $\beta_p^{\text{TOT}}$. A smaller $L_T$ for deuterium is one of the keys leading to higher $\beta_p^{\text{TOT}}$. 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 $\beta_p^{\text{TOT}}$ for deuterium.

5 Conclusions

Energy confinement properties for hydrogen and deuterium H-mode plasmas were examined in this paper. The $\tau_{\text{th}}$ value becomes larger by a factor of $\sim 1.2 - 1.3$ for deuterium than for hydrogen at a given $P_L$. When $W_{\text{th}}$ 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 $W_{\text{th}}$ value that was two times as large for hydrogen. Hence, the $\chi_i$ values for hydrogen were higher, explicitly throughout the minor radius, than those for deuterium at the same $L_T$. The $\nabla T_i/T_i$, or the inverse of $L_T$, required for a given $\chi_i$ increased by a factor of $\sim 1.2$ for deuterium compared with that for hydrogen. These results lead to the conclusion that the $L_T$ is shrunk with hydrogen isotope mass in H-mode plasmas. The relation between $\beta_p^{\text{TOT}}$ and $\beta_p^{\text{ped}}$ 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 $\beta_p^{\text{TOT}}$.

References