ISOTOPE EFFECT ON IMPURITY AND BULK ION PARTICLE TRANSPORT IN THE LARGE HELICAL DEVICE

K. IDA$^{1,2}$
$^1$National Institute for Fusion Science, National Institutes of Natural Sciences
Toki, Gifu, Japan
$^2$SOKENDAI, Department of Fusion Science
Toki, Gifu, Japan
Email: ida@nifs.ac.jp

R. SAKAMOTO$^{1,2}$, Y. YOSHINUMA$^{1,2}$, K. YAMAZAKI$^3$, T. KOBAYASHI$^{1,2}$, AND LHD EXPERIMENT GROUP
$^1$National Institute for Fusion Science, National Institutes of Natural Sciences
Toki, Gifu, Japan
$^2$SOKENDAI, Department of Fusion Science
Toki, Gifu, Japan
$^3$Research Institute for Applied Mechanics Kyushu University,
Kasuga, Fukuoka, Japan

Abstract

Isotope effects of the ion particle transport both for carbon impurity and bulk ions are investigated in Large Helical Device (LHD) in a condition decoupled from electron particle transport. Better particle confinement for both impurity and bulk ions are observed in deuterium plasma than in hydrogen plasma. The following findings are presented in this paper. 1) Carbon impurity density gradient is negative (peaked profile with inward convection) inside the internal transport barrier (ITB) region in the deuterium (D) plasma, while it is positive (hollow profile with outward convection) in the hydrogen (H) plasma. 2) The decay time of H and D ion density measured with bulk charge exchange spectroscopy inside the plasma after the H and D pellet injections are comparable, while the isotope ratio of the edge density is strongly influenced by the recycling isotope ratio.

1. INTRODUCTION

The LHD is a heliotron-type device for magnetic confinement of high-temperature plasma. The radial profiles of carbon impurity density and bulk ion density (fraction of H and D ion density) are measured using charge exchange spectroscopy. In order to investigate the isotope effect on impurity and bulk ions, two experiments are performed. One is the carbon pellet injection into the hydrogen and deuterium plasma with ITB and the other is the H and D pellet injection into the D-H mixture plasma. It should be noted that the transport study in the D-H mixture plasma is essential in order to resolve degeneration between ion particle transport and electron particle transport due to the quasi-neutralization condition. In the case of impurity transport, the impurity transport is always independent from electron transport because the electrons provided by impurities are negligibly small. In this paper, the isotope effect on impurity and its secondary effect on heat transport are described in section 2. The hydrogen and deuterium density profile measurements and the isotope effect of recycling on the particle ion transport after the pellet injection are discussed in section 3.
2. ISOTOPE EFFECT ON IMPURITY AND HEAT TRANSPORT

The carbon pellet injection is applied to trigger the formation of ion-ITB in the plasma with the magnetic axis of 3.6m magnetic field strength 2.85T, NBI power of \( \sim 30 \) MW, and line averaged electron density of \( 1 \times 10^{19} \text{ m}^{-3} \).

During the decay phase of carbon density after the carbon pellet injection, the ion temperature \( (T_i) \) starts to increase from 5 keV to 7-9 keV, while the carbon density decreases by one order of magnitude. Differences of ion temperature profiles in Fig.1 (a) and (c) show improvement of confinement within a certain radius such as an ITB plasma. Therefore, the radius is referred to as the ITB-foot and inside the radius is referred to as the ITB region. The isotope effect is observed in the carbon density gradient inside the ITB region \( (r_{\text{eff}}/a_{99} < 0.55-0.65) \).

The carbon density gradient is positive in the H-plasma, while it is negative in the D-plasma. However, there is no difference in the electron density profiles between H and D-plasmas. The carbon density profile just after the pellet injection is flat for both H and D-plasmas. However, the carbon density profile becomes hollow inside the ITB region in H-plasma, while the carbon density profile becomes peaked inside the ITB region in the D-plasmas. This behavior indicates the difference in convection velocity of impurity transport between H and D-plasmas due to the friction force between impurity and bulk ions. It should be noted that the absolute carbon density is even lower in the deuterium plasma because of the smaller size of the carbon pellet injected.

Therefore, this result shows that the carbon density gradient (not the carbon density concentration) is a key parameter for the achievement of higher ion temperature. The sustainment of ITB state in the deuterium plasma is longer than that in the hydrogen plasma in LHD. Therefore, the achieved ion temperature is comparable just after the formation of ITB, and the ion temperature in the deuterium plasma becomes higher than that in the hydrogen plasma later phase of ITB state [1].

![FIG.1 Radial profiles of ion temperature and carbon density after the carbon pellet injection in the hydrogen and deuterium plasmas. The carbon density gradient is positive in the hydrogen ITB plasma, while it is negative in the deuterium ITB plasma.](image-url)
Figure 2 shows the time evolution of the ratio of central carbon density to the carbon density at ITB-foot and central ion temperature. In the hydrogen plasma, the central ion temperature starts to decrease after $t = 4.74$ sec due to the degradation of confinement after the carbon density ratio decrease below unity (positive carbon density gradient). The carbon density ratio decreases to 0.5 which shows the formation of impurity hole characterized by the hollow impurity density profile. In contrast, carbon density ratio stays above unity (negative carbon density gradient) due to the mitigation of impurity hole and there is no decrease of central ion temperature observed in the deuterium plasma. The longer sustainment of ion-ITB state in deuterium plasma is due to the mitigation of impurity hole (postponement of the appearance of positive impurity gradient).

Figure 3 shows the relation between the central ion temperature as an indicator of improvement of heat transport and the ratio of central carbon density to the carbon density at the ITB-foot. In both hydrogen and deuterium plasmas, the central ion temperature increases as the density ratio increased (density profile is peaked). No clear difference between hydrogen and deuterium plasma for the given carbon density gradient is observed. The correlation between the central ion temperature and the gradient of carbon density in the ITB region suggests that the positive carbon density (hollow carbon density profile) enhances the ion transport and prevents the steady-state sustainment of ion-ITB, where the impurity formation occurs due to the increase of the ion temperature gradient.
It is expected theoretically that the positive impurity gradient destabilizes the ITG turbulence [2, 3, 4, 5, 6]. After the formation of ITB, the ITG turbulence becomes un-stable due to the increase of the ion temperature gradient because the density profile is flat. In the hydrogen plasma, the ITG turbulence is expected to be destabilized due to the formation of impurity hole (hollow impurity profile) and to cause the degradation of ion confinement. However, in the deuterium plasma, the ITG turbulence is expected to be stabilized due to the negative impurity density gradients and contributes to the sustainment of the steady-state ITB (no decrease of central ion temperature). This hypothesis is consistent with simultaneous decreases of carbon density ratio and central ion temperature in the hydrogen plasma plotted in figure 2 and the dependence of central ion temperature on carbon density peaking factors plotted in figure 3.

3. ISOTOPE EFFECT ON BULK ION TRANSPORT

Hydrogen or deuterium pellet is injected into the D-H mixture plasma and hydrogen and deuterium density profiles are measured with charge exchange spectroscopy. As seen in figure 4, the density profile becomes hollow after the pellet injection and the increase of the density of pellet injection peaks at $R = 4.5$ m ($r_{	ext{eff}}/a_{99} = 0.91$). Although the deposition of the pellet is near the plasma periphery, the core density increases after the pellet injection due to the inward convection of the particle fueled by the pellet.

![Figure 4](image-url)

FIG. 4 Radial profile of electron density before (5.233 sec) and after (5.266 sec) the hydrogen and deuterium pellet injection. The radial profiles of the increments of electron density due to pellet injection are also plotted.

Bulk charge exchange spectroscopy system has been installed in LHD to measure the radial profiles of $n_0/(n_{H}+n_D)$ and $n_0/(n_{H}+n_D)$ in the plasma from $H_\alpha$ and $D_\alpha$ lines emitted by the charge exchange reaction between the bulk ions and the neutral beam injected [7, 8]. The hot component due to the active charge exchange reaction with the neutral beam is smaller than the cold component emitted in the edge by one order of magnitude. In order to subtract the cold component of the $H_\alpha$ and $D_\alpha$ charge exchange lines, beam modulation technique is applied.

Charge exchange lines are fitted by 4 Gaussian of H and D cold components and H and D hot components ($I_{H\text{cold}}, V_{H\text{cold}}, T_{H\text{cold}}, I_{D\text{cold}}, V_{D\text{cold}}, T_{D\text{cold}}, I_{H\text{hot}}, V_{H\text{hot}}, T_{H\text{hot}}, I_{D\text{hot}}, V_{D\text{hot}}, T_{D\text{hot}}$; 12 free parameters). Here $I$, $T$, and $V$ are intensity, flow velocity, and ion temperature, respectively. In order to reduce the number of the free parameters, the flow velocity, ion temperature, and D/H ratio of cold component ($V_{H\text{cold}} = V_{D\text{cold}}, T_{D\text{cold}} = T_{H\text{cold}}$...
I_{D\text{hot}}/I_{H\text{cold}} ; 5 \text{ parameters}) \text{ are given by fitting the spectrum at beam off timing. The flow velocity of hot component is derived from the rotation velocity measurements of carbon impurity (V_{H\text{hot}}=V_{D\text{hot}}=V_{Chot} ; 3 \text{ parameters}) and equal ion temperature between hydrogen and deuterium is assumed (T_{H\text{hot}}=T_{D\text{hot}} ; 1 \text{ parameter}).}

Although the assumption of equal toroidal flow velocity between carbon and bulk ions is invalid in the pedestal region where the ion pressure gradient is large, this assumption is valid in the plasma core region [8]. In addition, the wavelength separation between hydrogen and deuterium is 0.18nm and corresponds to the Doppler shift of bulk ions with the flow velocity of 80 km/s, which is much larger than the velocity difference between carbon and bulk ion expected by the neoclassical theory. The amplitude of hot and cold components, ion temperature, and D/H ratio of the hot components (I_{D\text{hot}}/I_{H\text{hot}}, T_{H\text{hot}}=T_{D\text{hot}}, I_{D\text{hot}}+I_{H\text{hot}}, I_{D\text{cold}}+I_{H\text{cold}} ; 4 \text{ parameters}) are selected as the free parameters to be fitted.

In order to investigate the isotope effect on ion particle transport, the decay time of deuterium and hydrogen ions (not the electron density) are measured using H_{a} and D_{a} bulk charge exchange spectroscopy after the H pellet and D pellet injections. Before the pellet injection, the ratio of hydrogen to deuterium is roughly unity. Figure 5 shows the spectrum of H_{a} and D_{a} lines after subtracting the spectrum at beam-off timing from the spectra at
beam-on timing for the discharge with H and D pellet injection. Although most of the cold components of the charge exchange lines are subtracted by the beam modulation, there still remain cold components comparable to the hot components as seen in the spectra of bulk charge exchange lines. The most significant differences between these two spectra appear at the red wing of the spectrum. This is because both the red shift and wider Doppler shift of H hot component contribute to the increase of red wing, while their effect cancels each other in the blue wing. The intensity of H hot component is larger than that of D hot component in the discharge with H pellet, while the intensity of D hot component is larger than the intensity of H hot component in the discharge with D pellet.

Figure 6 shows the time evolution of radial profiles of hydrogen density 5 ms before and after the hydrogen pellet injection and deuterium density 5 ms before and after the deuterium pellet injection. Although ablation of the pellet is near the plasma periphery, significant increases of ion density of the pellet are observed 25 ms after the pellet injection. Hydrogen and deuterium density increase by 2.5 times due to the particle fueling of hydrogen and deuterium pellet, respectively. Then the ion density gradually decreases towards the level before the pellet injection. Hydrogen density decay is saturated at 85 ms because of the recycling, while the deuterium density keeps decreasing even 95 ms after the pellet injection.

Figure 7 shows the decay of hydrogen density after the hydrogen pellet and deuterium density after the deuterium pellet injection at $r_{\text{eff}}/a_{99} = 0.91$ for the wall condition of 1:1 isotope recycling ratio and high deuterium recycling.

$FIG. 7$ Decay of hydrogen density after the hydrogen pellet and deuterium density after the deuterium pellet injection at $r_{\text{eff}}/a_{99} = 0.91$ for the wall condition of 1:1 isotope recycling ratio and high deuterium recycling.

The decay time of hydrogen density is 18 ms and that of deuterium is 20 ms, and the saturation level of hydrogen density is 0.66 and that of deuterium is 0.61 when the recycling isotope ratio between hydrogen and deuterium is roughly 1:1. However, when the wall is saturated in deuterium, the saturation level of hydrogen density is 0.17 and the saturation level of hydrogen density is 0.69, while the decay time of hydrogen density is 27 ms, which is comparable to that of deuterium of 26 ms. This is because the saturation level is determined by the isotope ratio of the recycling. In these discharges, there are no significant isotope differences in transport of hydrogen and deuterium ions. However, the isotope ratio of the edge density is strongly influenced by the recycling isotope ratio.
4. DISCUSSION AND SUMMARY

This paper reports important findings on isotope effect on particle transport. First, isotope effect on the sign of the convection of impurity transport and impurity density gradient has a secondary effect on ion heat transport. Second, isotope density ratio near the plasma edge is strongly influenced by the isotope ratio of the recycling in the H- D mixture plasma, which implies the importance of the difference in D and T particle transport in the fusion plasma in future.

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