Isotope effects on energy, particle transport and turbulence in electron cyclotron resonant heating plasma of the Large Helical Device

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Abstract
Positive isotope effects have been found in electron cyclotron resonant heating plasma of the Large Helical Device (LHD). The global energy confinement time ($\tau_E$) in deuterium (D) plasma is 16% better than in hydrogen (H) plasma for the same line-averaged density and absorption power. The power balance analyses showed a clear reduction in ion energy transport, while electron energy transport does not change dramatically. The global particle confinement time ($\tau_p$) is degraded in D plasma; $\tau_p$ in D plasma is 20% worse than in H plasma for the same line-averaged density and absorption power. The difference in the density profile was not due to the neutral or impurity sources, but rather was due to the difference in the transport. Ion scale turbulence levels show isotope effects. The core turbulence ($\rho = 0.5–0.8$) level is higher in D plasma than in H plasma in the low collisionality regime and is lower in D plasma than in H plasma. The density gradient and collisionality play a role in the core turbulence level.

Keywords: isotope effects, turbulence, LHD, transport

(Some figures may appear in colour only in the online journal)

1. Introduction
The transport of different hydrogen isotopes is an important issue for predicting the performance of ITER and the future reactor operation. In a tokamak, improved transport characteristics and lower H-mode threshold power in deuterium (D) plasma than in hydrogen (H) plasma were reported. Both tokamak scaling (ITER98y2 [1]) and helical scaling (ISS04...
[2]) follow gyro-Bohm (GB) scaling. GB scaling predicts that $\tau_E$ scales with $A^{0.5}$, where $A$ is the ion mass number (1 for H, 2 for D), then GB scaling enhanced transport in D plasma. However, many experiments show better confinement in tokamaks in D or comparable confinement in medium-sized helical devices.

In JET with an ITER-like wall, $\tau_E$ scales with $A^{0.15}$ in the L-mode and $\tau_E$ scales with $A^{0.4}$ in the H-mode [3]. In the JT-6U tokamak, clear improvements in ion thermal confinement were observed. Only one half of the heating power was necessary in D plasma compared with the heating power in H plasma to obtain the identical density and temperature profiles in neutral beam (NB)-heated H mode with a carbon wall. The higher edge pedestal improved core confinement due to the ion temperature stiffness [4]. In ASDEX-U electron cyclotron resonant heating (ECRH) L-mode plasma, $\tau_E$ scales with $A^{0.7}$. The results show that the better $\tau_E$ in D plasma than in H plasma is not due to the improvement in the transport, but is due to the difference in equipartition heating ($P_{ei}$) from the electron to the ion. A higher $P_{ei}$ in H plasma results in degraded $\tau_E$ due to the power degradation [5]. These results in tokamaks suggest that confinement improvements in D plasma mainly come from the edge pedestal.

On the other hand, the results of the hydrogen isotope effects are very limited in the stellarator/heliotron. In an early study of a medium-sized stellarator/heliotron (Heliotron-E, ATF, W-7AS), the global energy confinement time of the ECRH plasma was almost comparable. The scaling study showed a modest improvement in D plasma compared to that in H plasma, but the difference was within the uncertainty [6]. In NB-heated plasma of the Compact Helical System, $\tau_E$ was worse in D plasma than in H plasma in the low collisionality regime, and the global confinement time ($\tau_p$) was comparable. However, density modulation experiments showed lower diffusion, and more inwardly directed convection velocity in the low-density regime were reported [7]. In Heliotron-J, density modulation experiments were performed in D and H plasma with ECRH. Comparable diffusion coefficients and convection velocities were reported [8]. In a stellarator/heliotron, due to the limits of the datasets, a comprehensive picture of the isotope effects has not yet been obtained.

In the Large Helical Device (LHD), the deuterium experimental campaign started from March 2017 [9]. This paper treats pure ECRH plasma, which is free from beam-heating effects, and presents the survey of particle transport in addition to energy transport. Initial reports regarding ECRH plasma were published in [10, 11]. These results describe improvement in high power heating ECRH [10], scaling studies and comparison with neoclassical transport [11] with the assistance of NB heating. In [11], the datasets of ECRH plasma include different injection directions of tangential ECRH. The tangential ECRH induces electron cyclotron current drive and affects ion profiles. This can affect transport, and can affect the stochasticity of magnetic topology [10, 12]. Thus, in this paper, for the investigation of isotope effects, the injection direction was mainly a balanced injection to prevent the change in the iota profile and formation of a stochastic region. With ECRH it is possible to adjust the total deposition power in H and D plasma, although in NBI, it is not technically easy. Thus, a clear and simple comparison became possible from the dataset analyzed in this publication.

Figure 1 shows a summary of global energy confinement time ($\tau_E$). The $\tau_E$ was estimated from diamagnetic stored energy and power deposition calculated by LHDGAUSS [13]. In the dataset, the contamination of helium was less than 10% and the purity of the H and D was higher than 80%, respectively. In the dataset, the injection power was 0.6–3.9 MW in D and 0.8–3.8 MW in H. The line-averaged density ($n_\text{bar}$) was $0.6–2.8 \times 10^{19} \text{ m}^{-3}$ in D, and $0.3–2.8 \times 10^{19} \text{ m}^{-3}$ in H. The one-path absorption power was 91% ± 3% in D and 93% ± 3% in H plasma. Only one-path absorption power was used for the $\tau_E$ estimation. The magnetic axis position ($R_{\text{ax}}$) was 3.6 m, and the magnetic field strength at the magnetic axis ($B_\phi$) was 2.75 T. The magnetic axis position at $R_{\text{ax}} = 3.6$ m is most widely operated in the LHD. This is because the confinement was the best compared with other outer shifted configurations [2].

The normalized collisionality $\nu_i^n$ is defined as $\nu_i^n = \nu_i/e^{1/2} \nu_T/qR_{mj}$. Here, $\nu_i$ is the electron–ion collision frequency, $\nu_T$ is the electron thermal velocity, $q$ is the safety factor, $R_{mj}$ is the major radius, and $e^{1/2}$ is an effective helical ripple [14, 15]. The total collision frequency is the sum of $\nu_{ei}$ and $\nu_i$ (ion–ion collision frequency). For H or D ions, $\nu_{ei}$ is approximately one order of magnitude larger than $\nu_i$ in ECRH plasma, thus, $\nu_i$ is used as a representative value.

Here, $\nu_i^n = 1$ corresponds to the boundary of $1/\nu$ and the plateau regime in the helical/stellarator [16], which
corresponds approximately to the banana regime and plateau regime in a tokamak with the same aspect ratio as the LHD. The \( \nu'^* \) at \( \rho = 0.5 \) was used as a representative value.

As shown in figure 1(a), \( \tau_E \) is systematically higher in D. This is more apparent in the high collisionality regime. The improvement in D appears at \( \nu'^* > 1 \). As shown in figure 1(b), the H data sets almost follow ISS04 [2] scaling, while the D dataset is systematically higher than ISS04 prediction. The averaged enhancement factors are \( \tau_{E} / \tau_{E,ISS04} = 1.19 \pm 0.11 \) in D and \( 1.04 \pm 0.15 \) in H plasma. However, as shown in figure 1(c), the enhancement factor depends on \( \nu'^* \). The enhancement factor has a maximum at \( \nu'^* \sim 1.5 \) in both H and D plasma. Finally, the scaling was deduced from the dataset of the 2017 campaign.

\[
\tau_{E_{\text{dia,ECH}}} \propto A^{0.22 \pm 0.01} \overline{n}_e^{0.60 \pm 0.01} P_{\text{abs}}^{-0.51 \pm 0.01}.
\]

(1)

Here, \( A \) is the mass number (1 for H plasma, 2 for D plasma), \( \overline{n}_e \) is the line-averaged density and \( P_{\text{abs}} \) is the absorption power. For the same \( \overline{n}_e \) and \( P_{\text{abs}} \), \( \tau_E \) in D plasma is 16% better than in H plasma.

Local power balance analysis was carried out by using the TASK3D code [17] for the data set of the density scan with 2.5 MW (1 MW 77 GHz and 1.5 MW 154 GHz) heating. Density was scanned shot by shot. An approximately 2 s flat top was obtained. A perpendicular NB was injected every 400 ms for \( T_i \) measurements using charge exchange spectroscopy (CXRS). This short pulse injection does not change \( T_i \). Analysis timing was selected just before NB injection.

Density profile data from YAG laser Thomson scattering [18] is used for TASK3D power balance analysis. Figures 2 and 3 show the profiles of \( n_e, T_e, T_i \) and \( \chi_e, \chi_i \). As shown in figures 2(a) and 3(a), the \( n_e \) profiles are hollowed. This is widely seen in NB-heated plasma of the LHD [16].

In the present analysis, charge exchange loss and convection loss are not included. This is because absolute neutral density profiles of H and D were not measured. The charge exchange loss can reduce absorption power in the plasma peripheral region. As described in the next section, global particle confinement is worse in D plasma. This indicates that neutral density is higher in D plasma than in H plasma for the same density. Higher neutral density in D plasma reduces absorption power in the peripheral region and reduces \( \chi_e \) and \( \chi_i \) in D plasma compared with H plasma.
In the low-density case, as shown in figure 2(b), the $T_e$ and $T_i$ profiles are almost identical. Ion heating is only due to the heat transfer from electron to ion. This heat transfer, which is equipartition heating, is shown by the following equation

$$ P_{ei} \propto Z_i^2 n_e^2 \left( T_e - T_i \right). \quad (2) $$

Here, $Z_i$ is the ion charge number and $m_i$ is the ion mass. Thus, for the same density and same temperature difference between an electron and ion, $P_{ei}$ in H plasma is twice that in D plasma.

Similar density and almost identical $T_e$, $T_i$, as shown in figures 2(a) and (b), results in lower $\chi_i$ in D plasma, as shown in figure 2(c). This is because $P_{ei}$ is lower in D plasma than in H plasma. Here, $\chi_e$ is almost identical in H and D plasma, as shown in figure 2(c). This is partly because absorption energy to the electron is not very different in H and D plasma.

In the high-density case, as shown in figure 3, $T_e$ is higher in D plasma, $T_i$ is almost identical, the $n_e$ profiles are hollower and the edge $n_e$ is higher in D plasma. These differences in profiles result in higher stored energy and better energy confinement in D plasma than in H plasma. Here, $\chi_i$ is lower in D plasma than in H plasma as well as in the low-density case. In the low-density case, $\chi_i$ is lower than $\chi_e$ in almost the entire region. On the other hand, in the high-density case, $\chi_i$ is higher than $\chi_e$ at $\rho > 0.5$.

The ion heating power increases in the high-density case compared with the low-density case. This can result in enhancement of transport due to the effects of power degradation. Power degradation is higher in H plasma due to the higher $P_{ei}$ than in D plasma. Such effects are reported in the ECRH L mode plasma of ASDEX-U [5].

The neoclassical values of $\chi_e$ and $\chi_i$ were estimated for the shots in figures 2 and 3 by using the GSRAKE code [20]. Figure 4 shows the neoclassical estimation in the low-density case. In figure 4(a), the radial electric field ($E_r$) measured using CXRS [21] is shown. The neoclassical solutions
are multiple at $\rho < 0.9$. The CXRS data show a positive $E_r$ at $\rho = 0.7–0.9$ in both shot 143742 and 139080. The turbulence phase velocity measured by 2D phase contrast imaging (2D-PCI) [22, 23] shows ion diamagnetic propagation at $\rho = 0.5–0.8$. The ion diamagnetic propagation in the laboratory frame suggests a positive $E_r$, based on the assumption that the phase velocity is dominated by $E_r \times B$ poloidal rotation. Thus, it is likely that $E_r$ at $\rho = 0.45–0.9$ in 143742 and $\rho = 0.55–0.9$ in 139080 are positive and the neoclassical root is the electron root. Therefore, the neoclassical $E_r$, $\chi_e$ and $\chi_i$ in the electron root are shown in figures 4(a) and (b). Both neoclassical $\chi_e$ and $\chi_i$ are almost the same in D plasma shot 143742 and in H plasma shot 139080. This indicates that there are no isotope effects of neoclassical transport in electron-root plasma.

Figure 5 shows the neoclassical estimation in the high-density case. In H plasma shot 143750, the neoclassical root is a single ion root at $\rho > 0.35$. In D plasma shot 139088, the neoclassical root is a single ion root at $\rho > 0.4$. Neoclassical $\chi_e$ is almost identical, however, neoclassical $\chi_i$ is higher in D plasma at $\rho < 0.9$.

Figure 6 shows a comparison between the experimental and neoclassical $\chi_e$ and $\chi_i$ in the low-density case. As shown in figure 6(a), both the neoclassical and experimental $\chi_e$ are almost identical. The neoclassical contribution in $\chi_e$ is less than 30%. The electron transport is dominated by an anomalous process, and there are no isotope effects. As shown in figure 6(b), the neoclassical contribution in $\chi_i$ is also less than 30% at $\rho < 0.9$. Ion transport is also dominated by an anomalous process.

As shown in figure 6(b), the neoclassical $\chi_i$ is identical in H and D plasma in the low density case. However, experimental $\chi_i$ is lower in D plasma than in H plasma. Thus, the anomalous contribution is lower in D plasma. Ion transport has an isotope effect in the low density case.

Figure 7 shows a comparison between the experimental and neoclassical $\chi_e$ and $\chi_i$ in the high-density case. As shown
Both the neoclassical and experimental $\chi_e$ are almost identical in the high density case as well as in the low density case. However, at $\rho < 0.85$ in H plasma and at $\rho < 0.8$ in D plasma, the neoclassical $\chi_e$ becomes comparable with the experimental $\chi_e$. This indicates that core electron transport is accounted for by the neoclassical transport. Only edge regions ($\rho > 0.85$ in H, and $\rho > 0.8$ in D plasma) are dominated by the anomalous process. The amount of anomalous contribution to $\chi_e$ in the edge region is almost comparable in H and D plasma, indicating no isotope effects.

As shown in figure 7(a), both the neoclassical and experimental $\chi_e$ are almost identical in the high density case as well as in the low density case. However, at $\rho < 0.85$ in H plasma and at $\rho < 0.8$ in D plasma, the neoclassical $\chi_e$ becomes comparable with the experimental $\chi_e$. This indicates that core electron transport is accounted for by the neoclassical transport. Only edge regions ($\rho > 0.85$ in H, and $\rho > 0.8$ in D plasma) are dominated by the anomalous process. The amount of anomalous contribution to $\chi_e$ in the edge region is almost comparable in H and D plasma, indicating no isotope effects.

As shown in figure 7(b), the neoclassical $\chi_i$ at $\rho < 0.6$ of H plasma exceeds the experimental $\chi_i$, and the neoclassical $\chi_i$ at $\rho < 0.85$ of D plasma exceeds the experimental $\chi_i$. These regions should be interpreted as showing that transport is dominated by the neoclassical process. Then, the anomalous process plays a role at $\rho > 0.6$ in H plasma and $\rho > 0.85$ in D plasma. In H plasma, a wider region is dominated by the anomalous process than in D plasma.

Figure 8 shows the collisionality dependence of $\chi_e$ and $\chi_i$ at three radial locations. Here, $\chi_e$ decreases with the increase in $\nu^*_h$. In both H and D plasma, $\chi_e$ shows almost the same value. On the other hand, $\chi_i$ in D plasma is lower at all locations. At $\rho = 0.5$ and $0.7$, $\chi_i$ increases with the increase in $\nu^*_h$. This is an opposite tendency compared with $\chi_e$. This tendency becomes moderate at $\rho = 0.9$. The difference between $\chi_e$ and $\chi_i$ become larger at more outer locations.

$P_e$ has strong proportionality to density ($n_e^2$), as shown in equation (2), thus, in the dataset of the density scan of figure 8, $P_e$ increases with collisionality. Thus, absorption power to the ion increases with collisionality. On the other hand, absorption power to the electron decreases with the increase in collisionality. The opposite collisionality dependence of absorption power to the electron and ion results in opposite collisionality dependence in $\chi_e$ and $\chi_i$.

The present data set from the power balance analysis showed there are no isotope effects in electron heat transport. There is an isotope effect in ion heat transport: $\chi_i$ is lower in D plasma than in H plasma.

3. Particle transport

The global particle confinement time ($\tau_p$) is estimated by the ratio between the averaged density and the amount of particle source in steady state. Two different estimations were used for the particle source. The first uses the neutral pressure gauge. Neutral pressure is an indication of the edge particle source. The neutral pressure gauge is located in the main vacuum vessel. The other method uses spectroscopic measurements. In the analysis method using spectroscopic data, the particle source was estimated from the sum of the intensity of H$\alpha$, D$\alpha$ and HeI lines. Then, the $\tau_p$ was estimated for the data set of figure 1 by using the following equations.
τ_p = \frac{N_e}{S_e - \frac{dS_e}{dt}} \propto n_{e\text{ bar}} \propto \text{Neutral gas pressure} \propto \frac{n_{e\text{ bar}}}{\mu_{\text{He,D}} + 2\mu_{\text{He}}} . \tag{3}

The τ_p from both methods is estimated in arbitrary units. This is because the absolute value of the particle source is unknown, and only the relative change in the particle source can be used for the comparison of τ_p. Figures 9(a) and (b) show collisionality dependence of the τ_p using two different methods. As shown in figure 9(a), the τ_p from the pressure gauge is clearly lower in D plasma. This indicates that neutral pressure is higher in D plasma than in H plasma at the same line-averaged density. This is partly due to the higher recycling rate and partly due to the lower pumping speed in D plasma than in H plasma. The pumping speed of the cryosorption pump is inversely proportional to the square root of the molecular mass [24]. Thus, neutral pressure becomes higher in D plasma than in H plasma.

The τ_p from spectroscopy does not show a clear difference, as shown in figure 9(b). However, the following scaling was obtained from regression analysis for the spectroscopic τ_p-

τ_p\text{ spec} \propto A^{-0.33 \pm 0.02} n_e^{0.52 \pm 0.02} P_{\text{eabs}}^{0.69 \pm 0.02} . \tag{4}

This is a significant contrast between the larger τ_E dia and smaller τ_p spec in D plasma than in H plasma for the same n_e and P_{abs}.

Figures 10(a)–(d) show comparisons of the n_e and T_e profiles in D and H plasma. Low- and high-density cases are shown. In figures 10(a) and (c), the n_e profiles are from Abel inversion of a multi-channel far-infrared laser interferometer [25]. As shown in figures 10(a)–(d), the T_e profiles are almost identical in H and D plasma. However, the n_e profiles are clearly different. In both low- and high-density cases, the n_e profiles in D plasma are hollower than in H plasma. Also, the edge peak positions of the hollowed profiles, which are shown by the arrow, are more outwardly positioned in D plasma than in H plasma. The
particle source profile calculated by the 3D Monte Carlo simulation code EIRENE shows that peaks of the particle source are at $\rho = 1.05$ in both D and H plasma, as shown in figure 10(e). These peak positions are the outer edge peak of the density profile. Also, the difference in neutral penetration is small in H and D plasma. Thus, the differences in $n_e$ profiles are not due to the difference in the neutral penetration of H or D.

The effect of the impurity was investigated. The main impurity in the core plasma of the LHD is $C^+_6$. The main carbon source is a carbon divertor plate. In D plasma, chemical and physical sputtering at the divertor plate is enhanced. Then, the influx of carbon is higher in D plasma than in H plasma [26]. Figure 11(a) shows electron density profiles from $C^+_6$ ions ($6n_e$, where $n_e$ is $C^+_6$ ion density from charge exchange spectroscopy). The $6n_e$ is higher in D plasma due to the larger carbon influx. The $6n_e$ profile is hollower in D plasma than in H plasma. However, the difference in $6n_e$ profiles does not account for the difference in the $n_e$ profile. As shown in figure 11(b), the edge peak of D plasma at $\rho = 0.8$ is $0.22 \times 10^{19}$ m$^{-3}$ lower than the edge peak of H plasma at $\rho = 0.7$. However, the edge peak of $6n_e$ density of D plasma at $\rho = 0.8$ is $0.062 \times 10^{19}$ m$^{-3}$ higher than the edge of $6n_e$ density of H plasma at $\rho = 0.7$, as shown in figure 11(a). Thus, figures 10 and 11 indicate that the hollower $n_e$ profiles in D plasma are not due to the difference in impurity profile, but rather to the difference in transport.

Figure 11(c) shows turbulence phase velocity measured by 2D-PCI [22, 23]. The $E_x \times B_i$ poloidal rotation speed profiles measured by CXRS [21] are over plotted. The 2D-PCI measures the poloidally dominated wavenumber; thus, the measured phase velocity indicates fluctuation phase velocity Doppler shifted by $E_x \times B_i$ rotation. Thus, the measured phase velocity can be an indicator of $E_x$.

As shown in figure 11(c), in D plasma, where the $6n_e$ profile is extremely hollowed, phase velocity is ion diamagnetic propagation in the laboratory frame. This suggests $E_x$ is positive. The neoclassical root is suggested to be the electron root. On the other hand, in H plasma, where the $6n_e$ profile is flat, the phase velocity is electron diamagnetic propagation. This suggests negative $E_x$. The neoclassical root is suggested to be the ion root. One possible interpretation of hollower $6n_e$ profiles is that the neoclassical effects of positive $E_x$ transfer positively charged impurity ions outwardly.

Detailed analysis of the particle transport were investigated by using density modulation experiments. Analysis is now underway.

4. Turbulence

Turbulence plays a role in transport. Therefore, turbulence can play a role in isotope effects as well, when transport is dominated by the anomalous process. Gyrokinetic simulation predicts favorable isotope effects in the case where the trapped electron mode (TEM) governs the transport. The stabilization effects due to collision between the charged particles is higher in D plasma than H plasma [27]. These are direct isotope effects. In addition, the density profile can affect the linear stability, in both TEM and ion temperature gradient mode (ITG). A lower negative gradient ($-\frac{1}{n} \frac{dn}{dr}$) reduces the linear growth rate of TEM and the ITG [28]. Thus, if there is a systematic difference between the density profiles of H...
K. Tanaka et al and D plasma, isotope effects can appear due to the difference in density profiles.

In the 19th (in the year 2017) and the 20th (in 2018–2019) LHD experimental campaigns, electron density turbulence was measured by 2D-PCI [22, 23]. The measured frequency and wavenumber regions were $20 < 500 \text{kHz}$ and $0.1 < k < 0.8 \text{mm}^{-1}$. In the present dataset, $k_{\text{perp}}/\rho_i$ is 0.1–1, where, here, $k_{\text{perp}}$ is the perpendicular wavenumber and $\rho_i$ is the ion Larmor radius. These wavenumber regimes are ITG and TEM ion scale turbulence.

Figure 12 shows the measured cross-sectional view of 2D-PCI. The measurement quantity of 2D-PCI is line-integrated fluctuation along the injected beam. With the use of magnetic shear and the strong asymmetry of the turbulence wavenumber between perpendicular and parallel to the magnetic field, local measurements of the fluctuation become possible from the analysis of the line-integrated 2D turbulence picture [22, 23]. The measured $k$ is perpendicular to the beam axis and magnetic field. Both radial and poloidal components contribute the signal. In most of this case, the signal is dominated by poloidal components.

The 2D-PCI is a type of laser scattering technique using a CO$_2$ laser. The signal intensity is a linear function of electron density turbulence amplitude. However, signal intensity is also affected by the laser power. Thus, it is essential to keep the laser stable to avoid changing the signal due to the change in the laser power. In particular, this is important to compare the signal from a different experimental day. In the 20th campaign (2018–2019), the CO$_2$ laser was carefully tuned and stabilized. Also, the change in the laser power and wavelength were monitored. In the dataset analyzed in this paper, the difference in power on different experimental days are maximum 3%, and the difference in the wavelength is maximum 0.1%. The small differences in the power were also calibrated for the estimation of the turbulence level. Thus, precise comparison of fluctuation amplitude became possible, and systematic comparison of the ion scale turbulence was carried out.

Figure 13 shows the time trace of H (shots 15249, 152264, 152270) and D (shots 147826, 147824, 147829). The heating is 2 MW 154 GHz second harmonic on axis heating. One-path deposition is more than 88% of the injection power. In the dataset, there is 5~10% He contamination, but the other portions are pure H and D ions. The configuration was $R_{\text{ax}} = 3.6 \text{ m}$, $B_t = 2.75 \text{ T}$.

As shown in figures 13(a–1)–(c–1), the line-averaged density was adjusted for both H and D plasma.
and (a-3)–(c-3) show line-integrated fluctuation signals for 20–200 kHz and 200–500 kHz. The 20–200 kHz and 200–500 kHz signals are approximately core and edge fluctuation, respectively. The fluctuation amplitude of 20–200 kHz is higher in D plasma than in H plasma at low and middle density, but lower in D plasma than in H plasma at high density. On the other hand, the fluctuation amplitude of 200–500 kHz is lower in D plasma at all density regimes, and the difference becomes larger at higher density. As shown in figures 13(a-4)–(c-4), the central $T_e$ is almost identical at low density in both H and D plasma, and the central $T_e$ becomes higher in D plasma than in H plasma at higher density. On the other hand, the central $T_i$ is almost identical in both H and D plasma. Figure 13 indicates that turbulence characteristics are different for identical density and heating power in H and D plasma. These are turbulence isotope effects.

In figures 14–16, the $n_e$, $T_e$, $T_i$ and fluctuation spatial profiles are shown for low, middle and high density. Profiles are 0.5 s accumulated to obtain good quality profiles. The turbulence spatial structures are different in three density regimes.

As shown in figure 14, in the low-density regime, dominant turbulence amplitude exists at $\rho < 0.8$ in both D and H plasma. Figures 14(a-3)–(a-5) and (b-3)–(b-5) suggest that turbulence expands $\rho < 0.4$, where 2D-PCI is not accessible. The turbulence at $\rho = 0.4–0.8$ propagates toward the ion diamagnetic direction in the laboratory frame both in H and D plasma. The small peak is seen at $\rho = 1.0$, which propagates toward the ion diamagnetic direction in the laboratory frame as well. The spatial structure is similar; however, the fluctuation amplitude is larger in D plasma than in H plasma. As shown in figures 14(a-5) and (b-5), phase velocities of the turbulence follow $E_r \times B_t$ poloidal rotation velocity measured by CXRS.

As shown in figure 15, in the middle density, the peaks of the fluctuation amplitude are $\rho = 0.6–0.8$ in both D and H plasma. These components propagate toward the ion diamagnetic direction in the laboratory frame. The peak at $\rho = 1.0$ becomes clearer compared with the low-density case. In D plasma, as shown in figure 15(a-5), there are two peaks at $\rho = 1.0$ and 1.1. The former and latter propagate toward the electron and ion diamagnetic direction in the laboratory frame, respectively. As shown in figures 15(a-5) and (b-5), the $V_{E_r \times B_t}$ also shows the changes the same way. The turbulence phase velocities follow $V_{E_r \times B_t}$ in both D and H plasma. The spatial structure is similar in D and H plasma. However, the fluctuation amplitude is clearly higher in D plasma than in H plasma as shown in figures 15(a-3) and (b-3).

As shown in figure 16, in the high-density plasma, the electron density turbulence profiles are clearly different in D and H plasma. As shown in figures 16(a-3) and (b-3), the
turbulence amplitude is clearly smaller in D plasma than in H plasma. In D plasma, the peak of the turbulence is at $\rho = 1.0$. On the other hand, in H plasma, the peak of the turbulence is around $\rho = 0.7$. In addition, in H plasma, turbulence exists over a wider region compared with D plasma. In low and middle density, the turbulence spatial structures are similar in H and D plasma; however, the turbulence amplitude is larger in D plasma than in H plasma. This indicates that the unstable region is the same in D and H plasma, but the saturation level is different. On the other hand, in the high density case, different spatial structures are clear in addition to turbulence amplitudes. These indicate that the unstable spatial region is different in H and D plasma. In D plasma, the turbulence phase velocities follow $V_{E\times B}$, as shown in figure 16(a-5). On the other hand, in H plasma, the turbulence phase velocity is further toward the electron diamagnetic direction compared with $V_{E\times B}$ at $\rho \sim 0.7$, as shown in figure 16(b-5). This observation suggests that the turbulence propagates toward the electron diamagnetic direction in the plasma frame at $\rho > 0.7$ in H plasma.

Figure 17 shows the collisionality dependence of the turbulence level and normalized gradients. The turbulence level was turbulence amplitude normalized by electron density. The turbulence level was averaged for the core ($\rho = 0.5$–0.8) and edge ($\rho = 0.8$–1.1). This is because the turbulence structure is different at the core ($\rho = 0.5$–0.8) and edge ($\rho = 0.8$–1.1), as shown in figures 14–16. The collisionality and normalized gradient was averaged for the core ($\rho = 0.5$–0.8) and edge ($\rho = 0.8$–1.1). The $n_e$ profiles are fitted by the eighth order polynomial function, and the $T_e$ and $T_i$ profiles are fitted by the sixth order polynomial function for $\rho = 0$–1.0. This is because fitting becomes inappropriate when including the data at $\rho > 1.0$ due to the scattering of the data of profiles. On the other hand, the turbulence has a large component at $\rho > 1.0$; thus, the edge turbulence peak was estimated at $\rho = 0.8$–1.1. Also, the turbulence level was estimated for the upper side of the equatorial plane and the lower side of the equatorial plane. Both sides show similar dependence. However, there is asymmetry between the upper and lower side in some cases.

As shown in figure 17(a), the core turbulence level has a V-shaped dependence on the $\nu^*_h$. The turbulence level decreases with $\nu^*_h$ up to $\nu^*_h = 4$; then, the turbulence level increases with $\nu^*_h$ at $\nu^*_h > 4$. At $\nu^*_h < 2$, the turbulence level is lower in H plasma than in D plasma. Then, at $\nu^*_h > 4$, the turbulence level is higher in H plasma than in D plasma. As shown in figure 17(b), the normalized $T_e$ and $T_i$ gradients are almost constant at $\nu^*_h < 2$. 

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**Figure 16.** Profiles in D plasma (a-1)–(a-5) and H plasma (b-1)–(b-5) of high-density plasmas. (a-1) and (b-1) $n_e$, (a-2) and (b-2) $T_e$ and $T_i$ profiles, (a-3) and (c-3) the electron density fluctuation amplitude, (a-4) and (d-4) contour plots of the fluctuation amplitude $k$ spectrum and (a-5) and (b-5) contour plots of fluctuation amplitude phase velocity in the laboratory frame. In (a-5) and (b-5), the blue lines indicate the $E_e \times B_t$ poloidal rotation velocities measured by CXRS.
Only the normalized density gradient is reducing. Thus, the normalized density gradient is likely to be the driving term. However, it should be noted that the normalized density gradient is lower in D plasma at $\nu^*_h < 2$, although the turbulence level is higher in D plasma. The magnitude relationship of the turbulence level between H and D plasma exchanges at $\nu^*_h \sim 3$. This observation qualitatively agrees with theoretical expectations, where the TEM has stronger collisionality stabilization effects in D plasma than in H plasma [27].

On the other hand, at $5 < \nu^*_h < 10$, the all-normalized gradient increases with the increase in $\nu^*_h$ in both H and D plasma. Experimentally, the driving term is not clear in this regime.

In the ATF, in which magnetic configuration is similar to the LHD, it was reported that the measured core turbulence was dissipative trapped electron mode (DTEM) [29]. The linear growth rate of DTEM increases with the increase in collisionality. The increase in the turbulence level with the increase in the collisionality was reported. Qualitatively, the observation in the ATF is similar to the results at $\nu^*_h > 4$ in the LHD. However, more detailed analysis using gyrokinetic simulation is necessary to identify the turbulence.

Figures 17(c) and (d) show $\nu^*_h$ dependence of the edge turbulence level and normalized gradient. Clear exchanges of the magnitude relationship of the turbulence level between H and D plasma are not observed. The turbulence level is comparable at $\nu^*_h < 2$ and becomes lower in D plasma at $\nu^*_h > 2$. The turbulence level is the lowest at $\nu^*_h = 2–5$ in H plasma, and is the lowest at $\nu^*_h = 2–10$ in D plasma. The normalized gradient does not change clearly. As well as the core region, at a higher $\nu^*_h$, the turbulence level becomes clearly lower in D plasma. But the $\nu^*_h$ dependence and normalized gradient dependence is not as clear as the core turbulence. More detailed arguments are necessary.

5. Discussion and summary

Extensive investigation of isotope effects was performed for ECRH plasma of the LHD. Unlike in tokamaks, edge-localized mode and magnetohydrodynamical activity, such as sawtoothing, do not appear and do not disturb the plasma, thus, precise comparisons are possible. The data at analysis timing was free from beam-heating effects. Thus, the present data set is purely external electron-heating plasma. The global energy confinement time is 16% better in D plasma than in H plasma. Power balance analysis for the density scan dataset with constant injection power showed a comparable $\chi_e$ and reduced $\chi_i$ in D plasma. References [1, 2] report that the injection direction of tangential ECRH plays a role in the isotope effects. This suggests that a change in the iota profile affects the isotope effects. However, in the dataset analyzed in this paper, tangential ECRH were almost balanced; thus, the effects of tangential injection of ECRH do not affect isotope effects.

Local power balance analyses were performed. The $\chi_i$ increased with $\nu^*_h$ and $\chi_e$ decreased with $\nu^*_h$. The opposite $\nu^*_h$ dependence is likely to be the effects of the equipartition heating power. The equipartition heating power...
increases with the increase in $\nu^*_h$. Then, the increase in $\nu^*_h$ results in a decrease in the electron-heating power, and then, $\chi_e$ reduces. On the other hand, an increase in $\nu^*_e$ results in an increase in the ion heating power. Then, $\chi_i$ increases, possibly with power degradation effects. Comparable $\chi_e$ and reduced $\chi_i$ in D plasma rather than in H plasma were found. Experimentally, isotope effects were seen only in the ion energy channel in the present dataset of power balance analyses. Thus, the improvement in the global energy confinement is likely to be due to the improvement in the ion energy confinement.

Neoclassical estimations were performed for low- and high-density cases. In the low-density case, the neoclassical root was the electron root. There are no isotope effects in the neoclassical $\chi_e$ and $\chi_i$, while the experimental $\chi_i$ is lower in D plasma than in H plasma. This indicates that the anomalous contribution of $\chi_i$ is lower in D plasma. In high density, the neoclassical root was the ion root. There are no isotope effects in the neoclassical $\chi_e$, but isotope effects appear in $\chi_i$. The neoclassical $\chi_i$ is higher in D plasma than in H plasma, although the experimental $\chi_i$ is lower in D plasma than in H plasma. Thus, the anomalous contribution of $\chi_i$ is lower in D plasma.

Global particle confinement is enhanced in D plasma. This is confirmed by the $\tau_p$ from the neutral pressure gauge and the $\tau_p$ from spectroscopy. Density profiles are more hollowed in D plasma than in H plasma. This is not due to the difference in neutral penetration or impurity sources, but rather due to the difference in the transport.

Ion scale turbulence was measured by 2D-PCI. Precise comparisons are performed from the monitoring of the probe laser. The isotope effects were found in ion scale turbulence. In the core region ($\rho = 0.5–0.8$), the turbulence level is lower in H plasma at $\nu^*_h < 2$, and the turbulence level is higher in D plasma at $\nu^*_h > 2$. The core turbulence level decreases with the increase in $\nu^*_h$ at $\nu^*_e < 4$. The driving term of the turbulence at $\nu^*_h < 4$ is likely to be the normalized density gradient. The exchange of the magnitude relationship qualitatively agrees with the gyrokinetic prediction of the TEM [27]. At $\nu^*_h > 4$, the core turbulence level increases with $\nu^*_h$ in both H and D plasma. The driving term is not clear in this collisionality region.

In the edge region ($\rho = 0.8–1.1$), the turbulence level is comparable at $\nu^*_h < 2$ in H and D plasma, and the turbulence level is lower in D plasma than in H plasma at $\nu^*_h > 2$. The driving term is not clear since the normalized gradient was almost constant in the present dataset. Isotope effects of the turbulence are different in the spatial region and collisionality region. For the next step, a comparison with gyrokinetic simulation is necessary for further understanding.

Isotope effects of ECRH plasma in the LHD are different in ion energy transport, electron energy transport and particle transport. Recent analysis regarding NB-heated plasma showed that the $\nu^*_e$ does not show ion mass dependence [30]. This is in clear contrast to the results from ECRH plasma described in this paper. This suggests that isotope effects vary in heating channels as well. Also, comparison with He plasma will also provide additional knowledge of ion mass and charge number effects. This is performed for H and He plasma with NB heating [31]. Experiments in He plasma with ECRH are expected.

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