ISOTOPE EFFECTS ON CONFINEMENT AND TURBULENCE IN ECRH PLASMA OF LHD

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Abstract

The positive isotope effects have been found in ECRH plasma of LHD. The enhancement factor of global energy confinement time ($\tau_E$) to ISS04 scaling in deuterium (D) plasma is about 17% better than in hydrogen (H) plasma. Clear reduction of ion energy transport was observed, while electron energy transport does not change dramatically. The global particle confinement is degraded in D plasma. More hollowed density profiles were observed. It was not due to the neutral or impurity source, but due to the difference of the transport. Ion scale density fluctuation were measured and compared with gyrokinetic linear calculation. Spatial structure and collisionality dependence was similar both in H and D plasma. Fluctuation level was higher in D plasma. Quicker reduction with increase of collisionality and e-dia. propagating in plasma frame is qualitatively agree with TEM characteristics.

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 character and lower H mode threshold power in D plasma than in H plasma were reported. Both tokamak scaling (ITER98y2) and helical scaling (ISS04) follow gyro-Bohm (GB) scaling with the exception of ion mass and ion charge number. While GB scaling predicts enhanced transport in D plasma, many experiments show better confinement (in tokamak) in D or comparable confinement (in medium-sized helical devices). In LHD, deuterium experimental campaign hast started from March 2017. Initial report about ECRH plasma with was reported in ref. 1 and 2. These results describe improvement in high power heating ECRH [1], scaling study and comparison with neoclassical transport [2] with some assistance of NB heating. This paper treats pure ECRH plasma, which are free from beam heating effects and describe the survey of particle transport and fluctuation characteristics in addition to energy transport.

2. ENERGY TRANSPORT

Figure 1 shows summary of global energy ($\tau_E$). $\tau_E$ was estimated from diamagnetic stored energy and power deposition calculated by LHDGAUSS[3]. In the dataset, the contamination of helium is less than 5% and the purity of the H and D are higher than 80%, respectively. In the dataset, the injection power was 0.6-3.9MW in D, 0.8-3.8MW in H, $n_e$ bar was 0.6-3.7x10^{19} m^{-3} in D, 0.3-3.8x10^{19} m^{-3} in H. The one path absorption power was 92+-4% of injection power both for H and D plasma. Only one path absorption power was used for the $\tau_E$ estimation. The magnetic axis ($R_{ma}$) was 3.6m and $B_t$ was 2.75T. The collisionality was normalized by the boundary between helical 1/8 and plateau regime at $\rho = 0.5$.

As shown in Fig.1 (a), $\tau_E$ is systematically higher in D. This is more apparent in the high collisionality regime. The improvement in D appears at $n_e^* \rightarrow 1$, where neoclassical contribution becomes smaller and anomalous contribution becomes higher. As shown in Fig.1 (b), the hydrogen data sets almost follow ISS04 [4] scaling, while deuterium dataset is systematically higher than ISS04 prediction. The averaged enhancement
Factors are $\tau_E / \tau_{E, ISS04} = 1.27^{+0.12} - 0.02$ in D and $1.09^{+0.02}$ in H plasma. Thus, improvement of $\tau_E$ in D to H is 17%.

However, as shown in Fig. 1 (c), the enhancement factor depends on $v_\theta^*$. The enhancement factor has a maximum at $v_\theta^* \sim 1.5$ both in H and D plasma. Finally, the scaling was deduced from the dataset of 2017 campaign.

$$\tau_{E, dia,ECH} \propto A^{0.24^{+0.01}_{-0.01}} \bar{n}_e^{0.50^{+0.01}_{-0.01}} P_{abs}^{-0.52^{+0.01}_{-0.01}}$$

(1)

Here, A is mass number (1 for H plasma, 2 for D plasma), $\bar{n}_e$ is the line averaged density, and $P_{abs}$ is the absorption power.

Local power balance analysis was carried out by using TASK3D code [5] for the data set of density scan with 2.5MW (1MW 77GHz and 1.5MW 154GHz) heating. Density was scanned shot by shot. About 2sec flat top was obtained. Perpendicular NB was injected for 20msec for every 400ms for Ti measurements using CXRS. This short pulse injection is not to change Ti profile. Analysis timing was selected just before NB injection. Presently, $n_e$ data of YAG laser Thomson scattering [6] is used for TASK3D. Figure 2 and 3 shows profiles of $n_e$, $T_e$, $T_i$ and $\chi_e, \chi_i$. As shown in Fig.2 (a) and Fig.3 (a), $n_e$ profiles are hollowed. This is widely seen in LHD [7]. Although, data points of Thomson $n_e$ profiles are scattered, density profile is hollower in D plasma.

In low density case, as shown in Fig.2 (b), $T_e$ 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 equitation heating is show by the following equation [8].

$$P_{el} \propto \frac{Z_i^2 n_e^2}{m_i T_i^2} (T_e - T_i)$$

(2)

Here, $Z_i$ is ion charge number, $m_i$ is ion mass. Thus, for same density and same temperature difference between electron and ion, $P_{el}$ in H plasma is twice of those in D plasma. Similar density and almost identical $T_e$, as shown in Fig. 2(a) and (b) result in lower $\chi_i$ in D plasma as shown in Fig. 2(c). While $\chi_e$ is almost identical in H and D plasma as shown in Fig.2 (c).

In high density case, $T_e$ is higher in D plasma, $T_i$ is almost identical, $n_e$ profiles are hollower and edge $n_e$ is higher in D region. These results in higher kinetic stored energy and better energy confinement in D plasma.

As well as in low density case, $\chi_i$ is lower in D plasma. In low density case, $\chi_i$ is lower than $\chi_e$ in almost entire region, on the other hands, in high density case, $\chi_i$ is higher than $\chi_e$ at $\rho > 0.5$. These are common observation both in H and D plasma.

Figure 4 shows collisionality dependence of $\chi_e, \chi_i$ at three radial locations. $\chi_e$ decreases with increase of $v_\theta^*$. Both $\chi_e$ in H and D plasma shows same trend. While, $\chi_i$ in D plasma is lower at all location and all $v_\theta^*$ regime of present experimental data. At $\rho = 0.5$ and 0.7, $\chi_i$ increases with increase of $v_\theta^*$. This is opposite tendency.
compared with $\chi_e$. This tendency becomes moderate at $\rho = 0.9$. The difference of $\chi_e$ and $\chi_i$ become larger at more outer locations.

3. PARTICLE AND IMPURITY TRANSFER

The global particle confinement time ($\tau_p$) is estimated by the ratio between averaged density and amount of particle source in steady state. Two different estimation was used for particle source. One is by using neutral pressure gauge. Neutral pressure is an indication of edge particle source. Neutral pressure gauge is located in main vacuum vessel. The other is by using spectroscopic measurements. In the analysis method using spectroscopic data, particle source was estimated by the sum of the intensity of H$\alpha$, D$\alpha$, and HeI lines. Then, $\tau_p$ was estimated for the data set of Fig.1 by using following equations.

$$\tau_p = \frac{N_e}{\chi_e - \frac{dN_e}{dt}} \approx \frac{n_{e\,\text{bar}}}{\text{Neutral Gas pressure}} + \frac{n_{e\,\text{bar}}}{I_{H\alpha,D\alpha} + 2\text{HeI}}$$

Figure 5 (a) and (b) shows collisionality dependence of $\tau_p$ by using two different method. As shown in Fig.5 (a), $\tau_p$ from pressure gauge is clearly higher in H plasma. This indicates that neutral pressure is higher for same line averaged density in D plasma. This is partly due to the higher recycling rate and partly due to the lower pumping speed in D plasma. The pumping speed of the cryo-sorption pump is inversely proportional to square root of the molecular mass [9].

While $\tau_p$ from spectroscopy does not show clear difference as shown in Fig.5 (b). However, the following scaling was obtained from regression analysis for the spectroscopic $\tau_p$.

$$\tau_{p\,\text{spec}} \propto A^{-0.33 \pm 0.02} n_e^{-0.52^{\pm 0.02}} P_{\text{abs}}^{-0.69^{\pm 0.02}}$$

It is big contrast that $\tau_{p\,\text{dia}}$ is 17% better in D plasma, $\tau_{p\,\text{spec}}$ is 20% worse for same $n_e$ and $P_{\text{abs}}$.

Figure 6 (a)–(d) shows comparison of $n_e$ and $T_e$ profiles in H and D plasma. Low and high density cases are shown. In Fig.6(a) and (c), $n_e$ profiles are from Abel inversion of multi-channel far infrared laser interferometer [10]. As shown in Fig. 6 (a)–(d), $T_e$ profiles are almost identical in H and Plasma, however, $n_e$ profiles are clearly different. Both in low and high density case, $n_e$ profiles in D plasma is hollower. Also edge peak position of hollowed profiles, which is shown by the arrow, is more outwardly in D plasma. The particle source rate profile calculated by 3D Monte Carlo simulation code EIRINE shows that peak of the particle source is at $\rho = 1.05$ where

$$\tau_{p\,\text{dia}} = 1.05$$

$FIG.4$ Collisionality dependence of $\chi_e$ and $\chi_i$ at (a) $\rho = 0.5$, (b) $\rho = 0.7$ and (c) $\rho = 0.9$

$FIG.5$ $\tau_p$ of collisionality dependence of (a) estimated from neutral pressure gauge, (b) estimated from spectroscopy, and (c) deduced scaling from spectroscopic $\tau_p$.

$FIG.6$ $n_e$ and $T_e$ profiles in (a),(b) low density, in (c),(d) high density and Particle source of D and H plasma.
is more outwardly of edge peak and the difference of neutral penetration is small as shown in Fig.5 (e). Thus, the difference of profile is not due to the difference of the neutral penetration of hydrogen or deuterium.

The effect of the impurity was investigated. The main impurity in core plasma of LHD is C6+. Main carbon source is carbon diverter plate. In D plasma, chemical and physical sputtering at divertor plate is enhanced. Then, In-flux of carbon is higher in D plasma than in H plasma [11]. Figure 7 (a) shows electron density from C6+ ions (n6, where n6 is C6+ density from charge exchange spectroscopy). n6 is higher in D plasma due to the larger carbon influx. As well as n6 profiles, n6 is hollower in D plasma. However, difference of n6 does not account for the difference of n6 profile. Because as shown in Fig.7 (b), in D plasma 139088, edge peak density is 0.22x10^19/m^3 lower than edge peak density of H plasma, however, edge 6nc is 0.062x10^19/m^3 higher. Thus, figure 6 and 7 indicate that hollower n6 profiles in D plasma is not due to the difference of particle source but due to the difference of transport.

Figure 6 (c) shows turbulence phase velocity measured by two dimensional phase contrast imaging (2D-PCI) [12,13]. ExB poloidal rotation speed profiles measured by charge exchange spectroscopy [14] are over plotted. 2D-PCI measures ploidal dominated wavenumber, thus measured phase velocity indicates fluctuation phase velocity Doppler shifted by ExB rotation. Thus, the measured phase velocity can be indicator of Er. As shown in Fig.6 (c), in D plasma, where 6nc is extremely hollowed, phase velocity is ion diamagnetic propagation in laboratory frame which suggests positive Er, if turbulence phase velocity is dominated by ExB rotation. While in H plasma, where 6n is not hallowed but flat, the phase velocity is electron diamagnetic propagation, which suggests negative Er. One possible interpretation of hollower 6nc is due to the neoclassical effects of positive Er, which transfer positively charged impurity ion outwardly.

Finally, density modulation experiments were performed in order to estimated diffusion coefficients and convection velocities. Modulation frequency was set to be 2.5Hz. The data set of a pair of comparison are shown in Fig.9 (a) ~ (c). The equilibrium profiles are hollower in D plasma as shown in Fig.9 (a). But the difference of modulation amplitude and phase is much clearer as shown in Fig.9 (b) and (c). This indicates that the density modulation is more sensitive to the difference of the particle transport than equilibrium profiles. However, flattening or reversal of the modulation phase, which is seen at ρ < 0.5 as shown in Fig.9 (c), make the determination of diffusion coefficients (Dmod) and convection velocity (Vmod) difficult. Presently, estimation are limited in edge region. The following scaling was obtained for D mod at ρ = 0.8-1.0.

![FIG.7 Comparison of (a) electron density profile ionized from C6+(6n), (b) n, and 6n, and (c) turbulence phase velocity, ExB, poloidal rotation velocity.](image1)

![FIG.8 Collisionality dependence of normalized density gradient.](image2)

![FIG.9 Density modulation experiments: Comparison of (a) equilibrium profile, (b)modulation amplitude, (c) modulation phase and (d) deduced scaling of modulation diffusion coefficient at ρ = 0.8 - 1.0.](image3)
D
\text{mod} is higher in D plasma for same n_e and T_e. This is qualitatively consistent with scaling of global particle confinement time shown by eq. (4).

3. TURBULENCE

Ion scale turbulence such as ITG or TEM can play a role on energy, particle and impurity transport. The 2D-PCI measures the turbulence of $k = 0.1 - 0.8 \text{ mm}^{-1}$ corresponding to $k \rho_i \sim 0.08 - 1.04$ for H and $0.12 - 1.6$ for D plasma, $f = 20 - 500 \text{ kHz}$ at $\rho \gg 0.4$. The CO_2 laser beam passes the vertically elongated cross section and measures turbulence from both the upper and the lower side relative to the equatorial plane.

Fig. 10 shows n_e, T_e, T_i and fluctuation profiles in low and high density D plasma. In Fig. 10 (a-5) and (b-5), $E \times B$, poloidal rotation velocity ($V_{E \times B}$), which is measured by HIBP [16] and CXRS[14], are over plotted. $V_{E \times B}$ in Fig (a-5) and (b-5) are projected components to the measured wavenumber of 2D-PCI. In low density case, as shown in Fig. 10 (a-5), dominant components exists at $\rho \sim 0.5$ and propagates toward the ion diamagnetic direction (i-dia.) in laboratory frame. At same location, $V_{E \times B}$ from HIBP shows further i-dia. propagation. This suggests that fluctuation at this location propagates toward the electron diamagnetic (e-dia.) direction in plasma frame. This is one of the characteristics of TEM.

In high density case, fluctuation profiles changes significantly. Core i-dia. components at $\rho = 0.4 - 0.7$ decreases, edge e-dia. at $\rho = 0.8 - 1.1$ components increases and edge i-dia. peak ($\rho \sim 1.05$) appears. Fluctuation phase velocity almost follows $V_{E \times B}$ from CXRS as shown in Fig. 10 (b-5). These spatial structure is similar both in H and D plasma. Presently, the measured peak wavenumber is almost identical, while ion Larmor is factor 1.4 higher in D plasma.

Figure 11 shows comparison of fluctuation behaviour in density ramp up plasma of H and D plasma. Density was ramped up from 1 to $4 \times 10^{19} \text{ m}^{-3}$ in D and from 1 to $3.5 \times 10^{19} \text{ m}^{-3}$ in H plasma. Change of the fluctuation spatial profiles with change of the density are clearly visible. In low density phase, core i-dia. fluctuation, of which peak position is $\rho \sim 0.7$ dominates. The core i-dia. components decreases with increase of the density. While edge e-dia.
components, of which peak is at $\rho \sim 1.0$ at initial stage, increases with increase of the density. The edge e-dia. components spreads toward the core region with increase of the density.

Figure 12 shows collisionality dependence of fluctuation level, which are fluctuation amplitude normalized by background density, in H and D plasma. The fluctuation components are total including both e-dia. and i-dia. components. The data of Fig.12 consists of density scan shot by shot in Fig. 4 and density ramp up data in Fig.11. All data are 2.5MW (1MW 77GHz, 1.5MW 154GHz) ECRH injection. As shown in Fig. 12 (a), core $(\rho = 0.5-0.8)$ fluctuation level decrease with increase of $v_{h}^*$ up to $v_{h}^*\sim 2$, then, core fluctuation level increases with increase of $v_{h}^*$. The former decreasing phase is decrease of core i-dia. components and latter increasing phase is increase and spreading edge e-dia. components as shown in Fig.11.

Present data set shows fluctuation level in D plasma is higher almost entire $v_{h}^*$ region. Core fluctuation level in D plasma decreases more rapidly up to $v_{h}^*\sim 2$, than in H plasma. Gyro kinetic analysis showed stronger collisionality stabilization of TEM in D plasma \[17\] and qualitatively consistent with observations.

Edge fluctuation also once decrease up to $v_{h}^*\sim 2$, then increases with increase of $v_{h}^*$. As well as core turbulence, former decreasing phase is due to the increase of i-dia. core components, latter increase is due to the increase of edge e-dia. components.

Gyrokinetic linear calculations were carried out by using GKV code. GKV is local flux tube gyrokinetic code. In present calculation, kinetic electron, collisionality effects are included. Ion species are only H and D. Detail results and calculation process are reported in ref. 18. Linear growth rate were calculated for low and high density in H and D plasma. These are same shot of Fig.2 and 3. But, density profiles by FIR laser interferometer was used. Gyrokinetic calculation is very sensitive to the density and temperature gradient, thus, all profiles ($n_e$, $T_e$ and $T_i$) are accumulated for 1 sec in order to use accurate profile. Fluctuation level was also accumulated for 1sec.

The results of low and high density cases are shown in Fig. 13, Fig.14 respectively. Calculated was performed for $k_\rho = 0.1-1.5$. The measured regions of $k_\rho$ are $k_\rho = 0.08-1.04$ for H and 0.12-1.6 for D plasma. Almost both calculation and measurements region correspond each other. In Fig.13 (d) - (g) and Fig.14 (d)-(g), growth rate is same unit both for H and D plasma. The hydrogen thermal velocity was used for the normalization. Hydrogen and deuterium mass was used for $\rho_i$ in H and D plasma respectively. The calculation was carried out at four different at $\rho = 0.36, 0.5, 0.7$ and 0.9.

As shown in Fig.13 (d) - (f), core fluctuation components in low density case at $\rho = 0.36-0.7$ are TEM and ITG, while experimentally the core components propagates e-dia. direction in plasma frame suggesting TEM characteristics. The growth rate is higher at $\rho = 0.36$ and 0.7 in H plasma and comparable at $\rho = 0.5$, while

FIG. 12 Collisionality dependence of fluctuation level at (a) $\rho = 0.5-0.8$ and (b) 0.8-1.1

FIG. 13 Profile in low density case of (a) $T_e$, (b) $n_e$, (c) fluctuation level and ( d)~(g) linear growth rate at $\rho = 0.36, 0.5, 0.7$ and 0.9 H 139080 ($t=4.4-5.4s$), D 143742 ($t=4.5-5.5s$). Red is D, Blue is H.
fluctuation level is higher in D plasma. The growth rate is the highest at $\rho = 0.36$, while the peak of the measured core fluctuation level is at $\rho = 0.6$.

Figure 13 (g) shows growth rate at $\rho = 0.9$, where e-dia. propagating edge components exist. TEM is dominant instability at this location. In D plasma, the region at $k_{ri} < 0.5$ is stable. At $k_{ri} > 0.5$, growth rate is higher in D plasma. Measured fluctuation level is higher at this location as well.

Figure 14 (d), $\rho = 0.36$ of high density case is hybrid of ITG and TEM. At this location, growth rate is clearly higher in D plasma. At $\rho = 0.5$, growth rate becomes comparable in H and D plasma as shown in Fig.14 (e), and location $\rho = 0.7$ becomes stable. At $\rho = 0.9$, dominant instability is TEM and growth rate is comparable in H and D plasma. While measured fluctuation level is higher in D plasma in all radial locations.

4. DISCUSSION AND SUMMARY

Extensive investigation of isotope effects were performed for ECRH plasma of LHD. Unlike tokamak, ELM and MHD activity such as sawteething do not appear and do not disturb plasma, thus, precise comparisons are possible. The data at analysis timing was free from beam heating effects. Thus, present data set is purely external electron heating plasma. Global energy confinement time is 17% higher in D plasma than in H plasma. Power balance analysis for density scan dataset with constant injection power showed comparable $\chi_e$ and reduced $\chi_i$ in D plasma. Ref.1 and Ref.2 reports that injection direction of tangential ECRH play a role on the isotope effects. This suggests that iota profile affects isotope effects. Recent analysis about NB heating plasma showed that $\tau_E$ does not show ion mass dependence [19]. This is clear contrast to the result of ECRH plasma described in this paper. This may suggests isotope effects varies on heating channel. Further investigation is necessary for the comprehensive understanding of isotope effects of LHD.

In ASDEX-U ECRH heating plasma, better confinement was observed in D than in H plasma. However, the observed difference is due to the difference of the equipartition heating. Higher equipartition heating in H plasma results in larger power degradation and enhanced transport [20]. In order to investigation of power degradation of ion and electron energy transport in LHD, kinetic confinement times was compared for the density scan data set. The results are shown in Fig. 15. The dataset of Fig. 15 is is same datasets of Fig. 4. Kinetic electron energy confinement time of H and D plasma overlaps in the same trends. While ion kinetic electron energy confinement time power does not overwrap. However, H and D data set lines also same trend. This observation suggests similar underlined mechanism exists to ASDEX-U results. Power degradation is stronger in ion channel.

Particle transport is enhanced in D plasma. This is confirmed by three different analysis technique ($\tau_p$ from neutral pressure gauge, $\tau_p$ from spectroscopy and edge diffusion coefficients from density modulation). This is

![FIG. 14 Profile in low density case of (a) Te, Ti,(b)ni,(c) fluctuation level and (d)-(g) linear growth rate at ρ=0.36, 0.5,0.7 and 0.9 H 139080 (t=4.4-5.4s), D 143742(t=4.5-5.5s . Red is D, Blue is H](image)

![FIG. 15 Power degradation of kinetic ion and electron energy confinement time](image)
clear contrast to the reduced global energy transport in D plasma. Density profiles are hollower in D plasma. But this is not due to the impurity but due to the difference of particle transport of bulk ions.

Ion scale turbulence was measured by using 2D-PCI. Two different components in core and edge region were found. Fluctuation spatial structure change with increase of density or collisionality. In low density, i-dia. propagating components dominates in core region at $\rho = 0.5$-0.8. This propagates e-dia. direction in plasma frame. Core i-dia. components decrease with increase of collisionality. With increase of the density, edge e-dia. propagating components at $\rho = 0.8$-1.1 becomes lager and spreading from edge to core region. These characteristics are in H and D plasma. Different fluctuation characteristics in core and edge region are also seen in NB heated plasma [21]. Present data set shows higher fluctuation level in D plasma.

Gyrokinetic linear analysis was performed. Experimentally, core i-dia. components shows characteristics of TEM. But correspondence to linear calculation is not clear. More detail parameter surveys are necessary both for experimental data and linear calculations.

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