Characterization of Isotope Effect on Confinement of NBI-Heated Plasmas on LHD

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1. Introduction

Energy confinement as well as thermal transport has been widely regarded as gyro-Bohm in tokamak as well as in stellarator-heliotron such as [1]

$\tau_E^{ISS04} / \tau_{Bohm} \propto \rho^{*-0.79} \nu^{*0.00} \beta^{-0.19} \iota^{1.06} A_p^{0.07}$,

where ρ*, ν*, β, and A_p are gyro radius normalized by plasma minor radius, collisionality normalized by bounce frequency in banana orbit, beta, rotational transform and aspect ratio. Thermal transport is also usually well documented by gyro-Bohm nature in a plasma consisting of a single kind of ion. However, this gyro-Bohm model predicts confinement degradation in deuterium(D) plasmas because of larger ρ* than in hydrogen(H) plasmas, which conflicts with major experimental observations. Robust confinement improvement in D plasmas has been confirmed in many tokamaks and no significant difference in energy confinement time of H and D stellarator-heliotron plasmas has been observed [2]. Here, it should be noted that equivalent energy confinement for H and D means even improvement in D over the gyro-Bohm model. This isotope effect is a long standing mystery in magnetic confinement fusion research. This study aims to quantify a peculiarity in dependence on ρ* in H and D plasmas in order to address this unresolved issue. The first deuterium plasma experiment in LHD is revealing definitive characteristics of isotope effect.

2. Methodology of Comparison of Dimensionally Similar Plasmas

This study focuses on three major non-dimensional parameters: ρ*, ν* and β. Since the operational freedom, which is associated with ρ*, ν* and β, is also 3 (heating power *P* instead of temperature, density *n* and magnetic field *B*), identical plasmas of H and D in terms of ρ*, ν* and β can be obtained by adjusting operational condition. Provided the gyro-Bohm nature except for mass dependence $\tau_E \propto \alpha n^{3/5} B^{4/5} P^{-3/5}$ is assumed for energy confinement time with using the confinement improvement factor of α (=τ_E^D/τ_E^H), which is unknown, the operational conditions to enable comparison of dimensionally similar plasmas with H and D are derived by the following relation with the mass ratio A (2 for D/H),

$$n_D = An_H,\ B_D = A^{3/4}B_H,\ P_D = A^{3/4}\alpha^{-5/2}P_H$$

and summarized in Table I. It should be note that gyro-Bohm corresponds to α of 1/√2. Comparison of H plasmas at 1.64T with D plasmas at 2.75T is highlighted. Difference of confinement (α) can be amplified by the power of 2.5 in required heating power. If transport is gyro-Bohm, 4 times larger heating power is needed for D to fulfil the dimensional similar condition.

Table I Operational ratios for dimensionally similar plasmas

α	1/√2	1	√2
Density n_D / n_H	2	2	2
Magnetic field B_D / B_H	1.68	1.68	1.68
Heating power P_D / P_H	4	1.68	0.71

3. Compilation of Database

169 NBI heated plasmas (54 for H and 115 for D) have been documented for the present study from the latest 19th experimental phase of LHD. Here, only uneventful ordinary discharges in quasi-steady state without transition, transport barrier, pellet injection, ECH and significant He contamination have been assessed. Magnetic geometry is fixed by the magnetic axis position of R_{ax}=3.6 m. Table II summarizes the ranges of operational parameters. TASK3D-a[3] / FIT3D[4] is used for analysis of heating power and power balance. It should be noted that electron heating is predominant (statistically, P_e/P_i=4.2±0.3 for H, 4.0±1.8 for D), consequently $T_e > T_i$ (statistically, T_e/T_i=1.5±0.3 for H, 1.7±1.8 for D). Purity of isotopes $n_D/(n_H+n_D)$, which is evaluated from the Hα and Dα emissions, is secured at the level of more than 0.77 for D plasmas and less than 0.20 for H plasmas (see Fig.1).

Table II Ranges in compiled database

Ion	Ave.	Min.	Max.	σ
		B (T)		
H	2.1	1.64	2.75	0.55
D	2.3	1.38	2.75	0.57
		n_e (10^{19}m^{-3})		
H	2.3	0.8	5.7	1.3
D	2.7	0.7	6.6	1.3
		P (MW)		
H	5.8	1.2	15.3	2.5
D	6.1	1.5	13.8	2.6

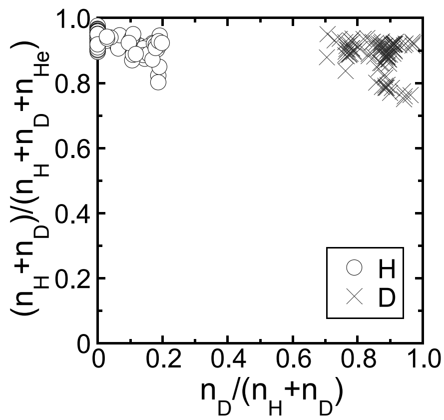

Fig.1 Concentration of ions in H/D data clusters

4. Energy Confinement Time

Confinement time of thermal energy has been assessed based upon well documented profiles by means of the Thomson scattering for T_e and n_e and the charge exchange recombination spectroscopy for T_i. Regression analysis has given the expression of

$$\tau_{E,th} \propto A^{0.15\pm0.02} B^{0.81\pm0.03} \overline{n}_e^{\,0.65\pm0.02} P_{abs}^{-0.75\pm0.02}$$
$$\propto A^{0.85} \rho*^{-1.39} \nu*^{0.36} \beta^{-0.46}$$

This positive isotope mass dependence indicates improvement of the energy confinement time by 10% in the absolute dimensional value in D compared with H, which contradicts with gyro-Bohm and is similar to the recent result from L-mode plasmas in JET-ILW[5]. Comparison with the ISS04 scaling $\tau_E^{th}/(\tau_E^{ISS04} f_{ren})$ [1] shows 0.67±0.07 for H and 0.75±0.09 for D, respectively.

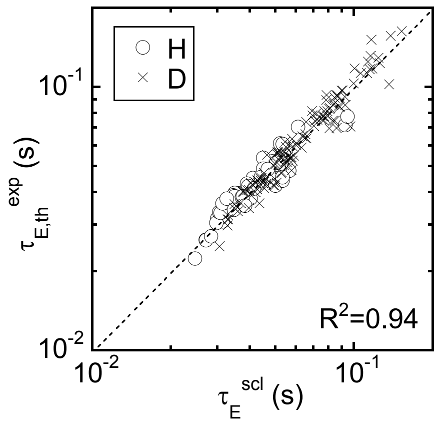

Fig.2 Comparison of thermal energy confinement time in experiment with the scaling expression.

5. Comparison of Dimensionally Similar Plasmas

Operational flexibility of B, $\overline{n}_e$, and P_{abs} in LHD enables adjustment of three major non-dimensional parameters, those being ρ*, ν* and β, in line with the description in Sec.2, and dimensionally similar plasmas of H and D in all these three parameters have been obtained. Figure 3 shows a typical pair of dimensionally similar (see (d)-(f)) plasmas. The required power P_D/P_H in this case is 1.05, which corresponds to α of 1.20. If gyro-Bohm nature predominates in these plasmas, thermal diffusivity normalized by Bohm diffusion should be the same. Nonetheless, both electron and ion loss channels are improved significantly in D plasmas. This improvement is seen in the entire radius by more than the magnitude to compensate for the gyro-Bohm factor (1/√2), which leads to the net improvement of as much as α of 1.20.

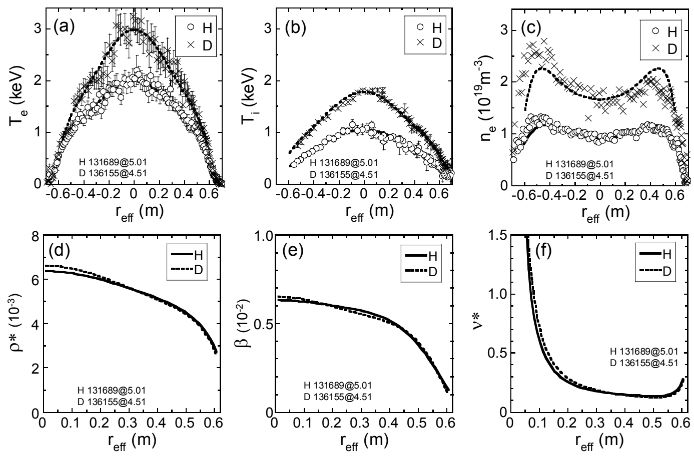

Fig.3 Profiles of a typical pair of dimensionally similar H (open circles / solid curves) and D (crosses / dashed curves) plasmas. (a) electron temperature, (b) ion temperature, (c) electron density, (d) normalized gyro radius, (e) normalized collisionality, (f) beta.

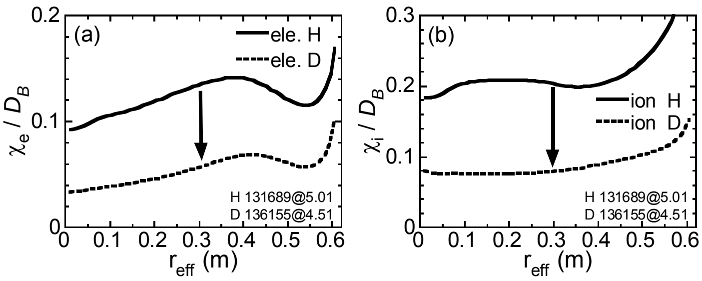

Fig.4 Comparisons of profiles (a) electron and (b) ion heat diffusivity for dimensionally similar H(solid curves) and D(dashed curves) plasmas. Diffusivity normalized by Bohm diffusion coefficient D_B.

Figure 4 shows comparison of heat diffusivity in dimensionally similar plasmas shown in Fig.3. If gyro-Bohm nature predominates in these plasmas, thermal diffusivity normalized by Bohm diffusion should be the same. Nonetheless, both electron and ion loss channels are improved significantly in D plasmas. This improvement is seen in the entire radius by more than the magnitude to compensate for the gyro-Bohm factor (1/√2), which leads to the net improvement. This improvement in D has been seen in entire radius.

Among the compiled database, 35 pairs of dimensionally similar plasmas have been identified. Required heating power to obtain these 35 pairs of dimensionally similar plasmas is statistically P_D/P_H of 1.47±0.54 which is less than 1.68 (see Table I) and corresponding to moderate net confinement improvement α = 1.06±0.39. However, it has been found that clear observation shown in Fig.4 is not universal. Figure 5 shows the ratio of normalized heat diffusivity (the ratio of solid and dashed curves in Fig.4) as a function of collisionality. Electron heat diffusivity robustly stays below 1 (solid horizontal line corrresponding gyro-Bohm) and is even lower than 1/√2 (dashed horizontal line: critical point of net improvement) while ion heat diffusivity degrades beyond 1 with increase of ν*. Correlation of this ratio with other non-dimensional parameters such as ρ* and β, and L_n (density scale length) has been also identified.

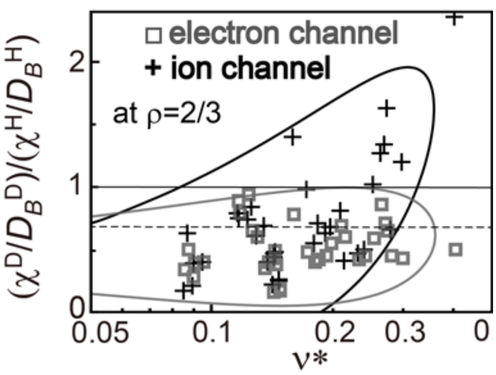

Fig.5 Ratio of normalized heat diffusivity of D and H plasmas for ions (plus symbols) and electrons (squares). Curves show 95% probability ellipses.

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