OVERVIEW OF THE FIRST DEUTERIUM EXPERIMENT IN LHD

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Abstract

In the first deuterium (D) experiment, LHD established one of the most important milestones towards the realization of the helical fusion reactor, ion temperature T_i of ~ 10 keV. This is the highest record among stellarator/heliotron devices. Clear reduction of the ion thermal diffusivity in both core and edge regions in D discharge from hydrogen (H) was identified, indicating the effect of the isotope mass. This experimental result was supported by the initial results from gyrokinetic simulations including multi-species of ion. By measuring the neutron flux from D plasma, energetic particle (EP) behavior trapped in the helical ripple could directly be estimated, which is quite important for heliotron devices, because demonstration of the EP confinement is essential to realize the burning condition. Precise measurement of the tritium exhaust demonstrated the tritium mass balance including the evacuation system.

1. INTRODUCTION

After 19 years of experiments with H plasma [1], the LHD started the D experiment on March 7, 2017. The main objectives of the LHD deuterium experiment, which is the first large-scale D experiment in stellarator/heliotron devices, are as follows: (1) achievement of high performance plasma through confinement improvement due to isotope effect, (2) clarification of the isotope effect by experimental and theoretical approaches, (3) demonstration of the confinement capability of EPs in heliotron configuration, and (4) study of isotope effect on plasma wall interactions. In this conference, initial results from the first D experiment aiming for the above objectives are reviewed.

2. EXPERIMENTAL SETUP

The LHD is one of the largest superconducting helical devices, with poloidal/toroidal period numbers of 2/10, and major and averaged plasma minor radius of 3.6 – 4.0 m and 0.6 m, respectively [1]. Preparing for the new experiment, some modifications and/or improvements were performed for instruments in the torus hall, e.g., heating devices, diagnostics, and safety systems [2]. Three negative-ion-based 180 keV neutral beams (NBI) are injected tangentially to generate and heat the plasma. It is available for these negative NBIs to be operated in the quasi steady-state mode, i.e., 10 minutes with 0.5 MW. Two positive-ion-based 40 keV NBs are also injected perpendicular to the plasma. The positive-ion-based NBIs are optimized for D, on the other hand, negative-ion-based NBIs are optimized for H. Thus, each heating power of those NBIs is different for different working gases. Heating power of each NBI for H and D is presented in Table 1. For additional heating, ion cyclotron range of frequency heating (ICH) with total heating power of ~ 3 MW (tentatively removed), and electron cyclotron resonance heating (ECH) with total heating power of ~ 5.4 MW are installed, and are sometimes utilized for the wall conditioning. The ECH can also be operated in the CW mode with 0.6 MW. For fuelling, the LHD is equipped with four gas puff valves and two pellet injectors for frozen H_2 and D_2. With these facilities, H, D, together with various impurity gases can be fed. The pellet injection can be varied from the single injection to the fast repetitive mode. Continuous injection can also be available.

Principal diagnostics in the LHD are routinely utilized in various experiments. The Thomson scattering system provides radial profiles of the electron temperature T_e and the electron density ne. The line averaged density is measured with the far infrared interferometer (FIR). Radiated power from impurities is measured with the bolometer array, and impurity densities with the charge exchange recombination spectroscopy system (CXRS). The visible and VUV spectroscopy systems are also employed to diagnose impurity ions and recycling particles. The plasma stored energy is measured with diamagnetic coils.

For the edge plasma control, the resonant magnetic perturbation (RMP) can be applied by using ten pairs of external coils installed on the up and the down sides of the torus.

TABLE 1. HEATING POWER OF NBI FOR HYDROGEN AND DEUTERIUM

# NBI		Power for H	Energy for H	Power for D	Energy for D
NBI#1	negative	6 MW	190 keV	3.5 MW	190 keV
NBI#2	negative	5 MW	180 keV	3 MW	180 keV
NBI#3	negative	5 MW	180 keV	3 MW	180 keV
NBI#4	positive	3 MW	40 keV	9 MW	60 keV
NBI#5	positive	3 MW	40 keV	9 MW	80 keV

3. EXPERIMENTAL RESULTS

To investigate the D plasma performance concerning the first objective, the high power operation was carried out [3]. The plasma was produced by electron cyclotron heating (ECH), and then maintained by two perpendicular D NBIs and three tangential H NBIs. The highest heating power of more than 30 MW (port through) could be extracted with this heating scheme. Intensive ECH wall conditioning and carbon pellet injection were performed to enhance the central power deposition. Figure 1 shows radial profiles of (a) ion and electron temperature, T_i, and T_e, and (b) electron density ne, respectively. It is found that T_i of ~ 10 keV was obtained, which is ~ 2 keV higher than that recorded in the former H experiment. Another important feature in D plasma is that n_e profile is more peaked and central ne is consequently higher, compared to H plasma. To estimate the confinement performance of such a high T_i discharge, the ion thermal diffusivity χ_i was calculated and compared with that of the H discharge [4]. It was found, in D plasma, that χ_i in the whole region decreased, especially in the core (~ 50 %), which is an opposite trend to the gyro-Bohm scaling. Similar improvement in the electron thermal diffusivity was also observed in the ECH D plasma, as shown in Fig. 2 [3,5,6].

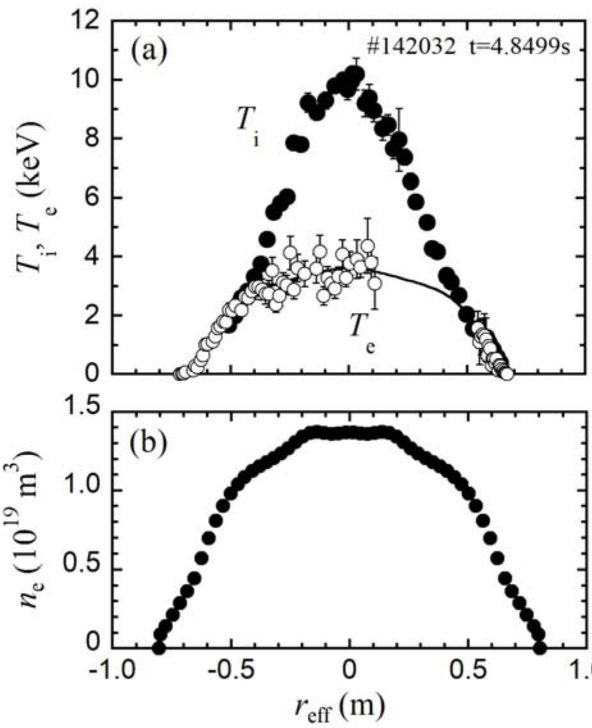

FIG. 1. Radial profiles of (a) T_i, T_e, and (b) n_e when the highest T_i was obtained.

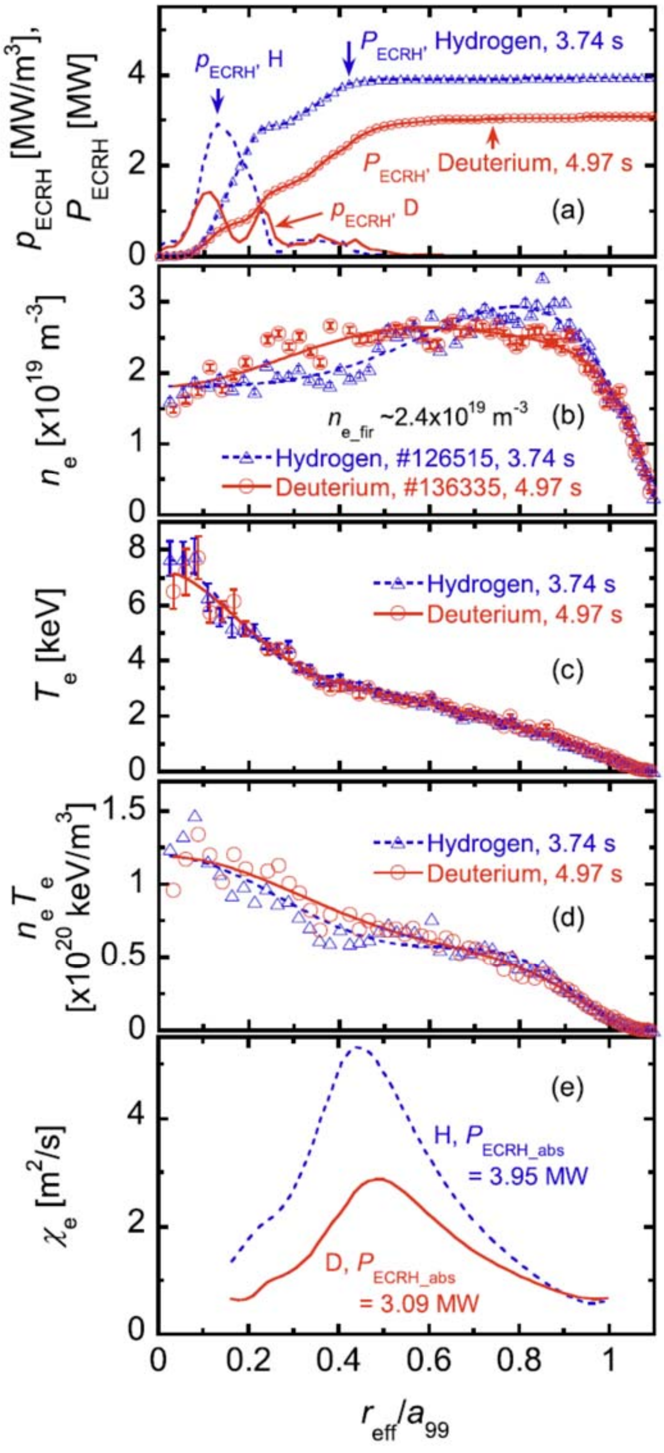

FIG. 2. Radial profiles of (a) power of ECH, (b) n_e, (c) T_e, (d) n_eT_e, and (e) χ_e for H and D with approximately the same n_{e_fir} and different ECH power.

Robust confinement improvement in electron loss channel in the D plasma with medium heating power was also observed, comparing between dimensionally identical H and D plasmas in terms of β^*, ρ^*, and β. These results obtained in the D experiment clearly indicate that the gyro-Bohm nature is violated in the comparison between H and D plasmas. In the T_{i0}- T_{e0} diagram depicted in Fig. 3, the extended operational regime of LHD by D experiment is summarized [7].

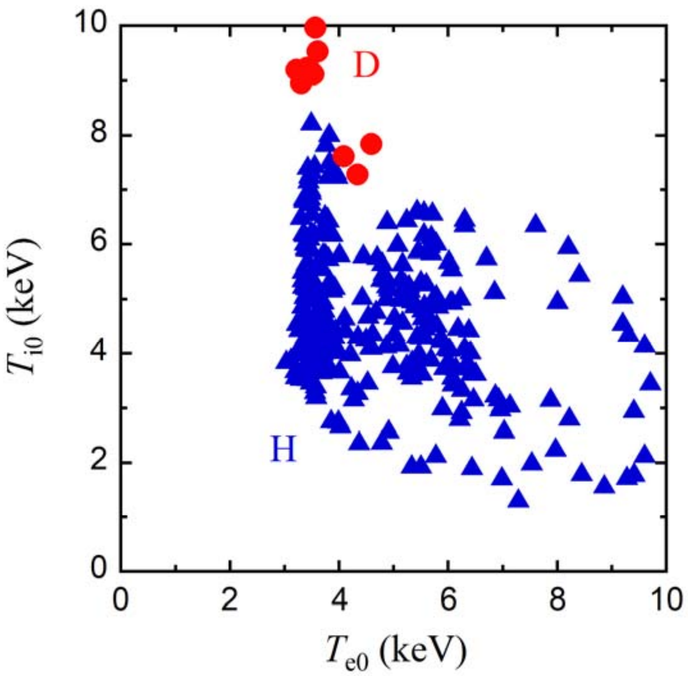

FIG. 3. Extended LHD operational regime by D experiment, where subscript 0 means center.

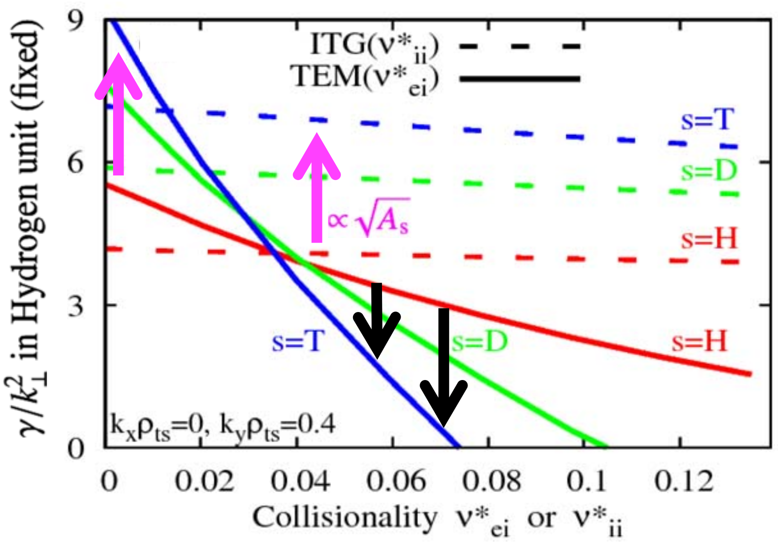

FIG. 4. Linear GK analysis predicts the improved confinement for TEM cases in a certain ν^*_{ei}-regime (ν^*ei > 0.04), beyond the Gyro-Bohm scaling.

In order to contribute to the clarification of the isotope effect, gyrokinetic simulations with the GKV code were performed [8], considering isotope effect on turbulent transport. It was found from the initial result that linear growth rates of the ion temperature gradient (ITG) mode in the core region and the trapped electron mode (TEM) in the edge region are smaller in D plasma, supporting described experimental results in D plasma.

As for the EP study, comprehensive neutron diagnostics installed for the D experiment were quite helpful. To estimate the confinement capability of EPs in each magnetic configuration, the triton burnup experiment was performed for the first time in stellarator/heliotron devices, measuring 2.5 MeV D-D and 14 MeV D-T neutron fluxes, simultaneously [9]. Figure 5 shows the measured triton burnup ratio as a function of the magnetic axis position R_{ax}. It is found that the ratio decreases with R_{ax}, indicating that better EP confinement is obtained in the inward shifted configuration.

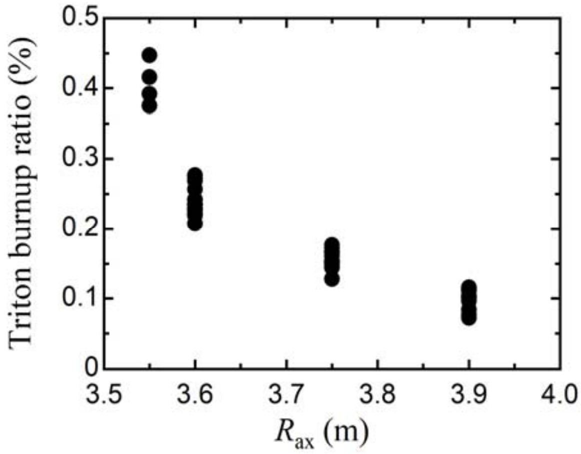

FIG. 5. Triton burnup ratio as a function of magnetic axis position.

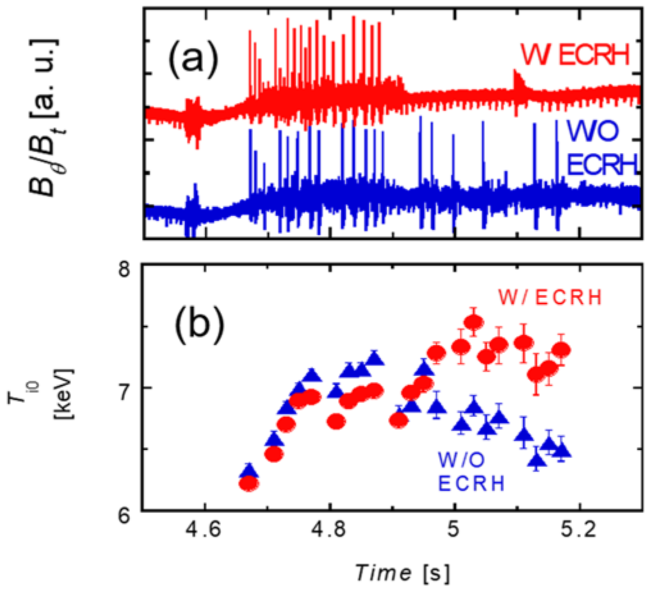

FIG. 6. Time evolution of (a) magnetic fluctuations and (b) central ion temperature. Red and blue correspond to with and without ECH during EIC, respectively.

Interactions between EPs and MHD modes called EIC are unfavorable for accessing the higher operational regime not only for LHD but also for future devices toward burning plasmas. Based on the precise observations with neutron diagnostics coupled with numerical calculations, details of the loss mechanism of EPs through the m/n = 1/1 interchange mode were revealed. It was also found that EIC can be stabilized by local heating with ECH [10,11] or application of resonant magnetic perturbations (RMPs).

4. SUMMARY

In the first D experiment performed in the large-scale stellarator/heliotron device, clear isotope effect on energy/particle confinement properties was observed. Thanks to new diagnostics for the D experiment, confinement characteristics of energetic particle in LHD could directly be observed in detail, which is a great advance. The LHD has proceeded to the new stage of the stellarator/heliotron research.

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REFERENCES

[1] Y. Takeiri et al., Nucl. Fusion 57 (2017) 102023.
[2] M. Osakabe et al., Fus. Sci. Technol. 72 (2017) 199-210.
[3] H. Takahashi et al., Nucl. Fusion 58 (2018) 106028.
[4] K. Nagaoka et al., IAEA-CN-258/EX/5-1.
[5] Felix Warmer et al., Nucl. Fusion 58 (2018) 106025.
[6] K. Tanaka et al., IAEA-CN-258/EX/P3-6.
[7] H. Yamada et al., IAEA-CN-258/EX/P3-5.
[8] M. Nakata et al., Phys. Rev. Lett. 118 (2017) 165002.
[9] M. Isobe, et al., Nucl Fusion 58 (2018) 082004.
[10] X. D. Du., et al., Phys. Rev. Lett. 118 (2017), 125001.
[11] S. Ohdachi, et al., IAEA-CN258/EX