Extension of the operational regime of the LHD towards a deuterium experiment

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As the finalization of a hydrogen experiment towards the deuterium phase, the exploration of the best performance of hydrogen plasma was intensively performed in the large helical device. High ion and electron temperatures, $T_i$ and $T_e$, of more than 6 keV were simultaneously achieved by superimposing high-power electron cyclotron resonance heating on neutral beam injection (NBI) heated plasma. Although flattening of the ion temperature profile in the core region was observed during the discharges, one could avoid degradation by increasing the electron density. Another key parameter to present plasma performance is an averaged beta value $\langle \beta \rangle$. The high $\langle \beta \rangle$ regime around 4% was extended to an order of magnitude lower than...
than 48 min are highly valued. Although these parameters have a high beta value of 5.1%, and long pulse discharges of more than 3600 s with heating power of 3 MW. With great effort, and contributions not only from domestic collaborators but also from all over the world, the LHD has produced many important results since the first plasma obtained in 1998. In particular, achievement of a high ion temperature plasma of 8.1 keV, a super dense core mode with central electron density of $1.2 \times 10^{21}$ m$^{-3}$, a high beta value of 5.1% [4], and long pulse discharges of more than 48 min [5] are highly valued. Although these parameters were not obtained simultaneously, each result is a world record in non-tokamak magnetic fusion devices, which is evidence that the LHD has led the stellarator/heliotron community as the world’s largest superconducting net-current free heliotron. A summary of the parameters achieved is presented in table 1.

In addition to those achievements obtained by continuous effort to optimize plasma control and upgrade the heating devices, some important discoveries and progress in plasma physics, plasma–wall interactions, and material science have been obtained. In particular, featuring the heliotron configuration, the three-dimensional (3D) effect on core and edge plasma transport has been clearly demonstrated [6], and its mechanism can be explained by numerical simulation [7].

In order to achieve the final goal of the LHD, a deuterium experiment started in March 2017. The deuterium plasma is expected to have better energy and particle confinement than the hydrogen plasma, which is clearly seen in tokamaks, but is not always obvious in helical devices. Thus it is worthwhile seeing whether or not such an isotope effect exists in helical plasmas. For this study, it is essential to know the marginal performance of the hydrogen plasma before the deuterium experiment starts. Intensive experiments were performed to expand the operational regime. In this paper, an overview of the recent progress in the LHD experiment is given, taking the forthcoming deuterium experiment into consideration.

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 radii of 3.6–4.0 m and 0.6 m, respectively [8]. Three negative-ion-based 180 keV neutral beams (NBs) with a total heating power of ~5.4 MW are injected tangentially to generate and heat the plasma. It is possible for these negative neutral beam injectors (NBIs) to be operated in the quasi-steady-state mode, i.e. 10 min with 0.5 MW. Two positive-ion-based 40 keV NBs with a total heating power of ~12 MW are also injected perpendicular to the plasma. For additional heating, ion cyclotron range of frequency heating (IC) with a total heating power of ~3 MW and electron cyclotron resonance heating (ECH) with a 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 continuous wave (CW) mode with 0.6 MW. For fuelling, the LHD is equipped with four gas puff valves and two frozen H$_2$ pellet injectors. With these facilities, hydrogen, together with various impurity gases, can be fed. The pellet injection can be varied from single injection to a fast repetitive mode. Continuous injection is also 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 $n_e$. The line averaged density is measured with a far infrared interferometer. Radiated power from impurities is measured using a bolometer array, and impurity densities are measured using a charge exchange recombination spectroscopy system. Visible and VUV spectroscopy systems are also employed to diagnose impurity ions and recycling particles. The plasma stored energy is measured using diamagnetic coils.

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

3. Recent experimental results

3.1. High beta experiment

Production of high beta plasma [9] is one of the most important issues in toroidal confinement systems for realizing an economical fusion reactor. The LHD has explored the potential of stellarator/heliotrons to realize high beta plasma. The beta value has increased every year with increasing heating power. Optimization of the magnetic configuration has also contributed to it.
Former high beta experiments were done in a low magnetic field of 0.425 T, which is in the low temperature, i.e. high collisional, regime. To investigate the collisionality dependence of plasma confinement, high beta experiments with a higher magnetic field of 1 T were performed, which realized higher electron temperatures, i.e. lower collisionality. It is expected that the increase in the temperature raises the magnetic Reynolds number, $S$, which contributes to suppressing the low-$n$ resistive interchange mode.

The history of the high beta experiment is shown in figure 1. A volume averaged beta value $\langle \beta \rangle$ of more than 4% was successfully obtained in an order of magnitude lower collisional regime than that of the former experiment where the highest $\langle \beta \rangle$ of 5.1% was achieved [10]. Such a low collisional regime was realized by increasing the magnetic field up to 1 T, which produced a high temperature plasma. In this situation, transition to the improved particle confinement mode was observed when $\langle \beta \rangle$ increased. It is considered that the magnetic topology, especially in the edge region, was modified by the increase in $\langle \beta \rangle$ stabilizing or destabilizing the MHD modes [11]. The spontaneous appearance of rational surfaces plays an important role. In order to realize the further extension of the plasma parameters to the reactor relevant regime, control of the edge magnetic topology to suppress the MHD instability is indispensable.

### 3.2. Exploring the high temperature regime

In the LHD, each major plasma parameter, e.g. $T_i$, $T_e$, $\langle \beta \rangle$ and $n_e$, has independently developed since the first plasma in 1998. In order to satisfy the reactor-relevant conditions, however, comprehensive progress is necessary. Recently, improvement of plasma heating devices and control techniques has led the LHD plasma to the advanced stage towards the reactor-relevant conditions [12].

In recent years, mega-watt-class 77 GHz and 154 GHz gyrotrons have been installed to increase $T_e$ in the higher density regime. In the experiment, fine tuning of microwave launching was performed to optimize the power deposition on the appropriate resonant surface, using a newly developed ray-tracing code. This upgrade of the ECH scheme realized efficient central heating, which resulted in the highest $T_e$ of 10 keV with the formation of an electron internal transport barrier (e-ITB) in the relatively high averaged electron density regime of $\sim 2 \times 10^{19} \text{m}^{-3}$.

For ion heating, improvement of the perpendicular NBIs and ICH antennas, together with the ICH wall conditioning technique, increased $T_i$ up to 8.1 keV. The highest $T_i$ and $T_e$ mentioned above were obtained in different discharges [2]. On the other hand, in the burning plasma, where electron heating is dominant, $T_i$ and $T_e$ are expected to be comparable. Therefore, the experimental condition where $T_i$ and $T_e$ are simultaneously...
high is essentially required for future helical plasma studies. Superimposing the upgraded ECH on the NBI heated plasma, the ion internal transport barrier (i-ITB) and the e-ITB could simultaneously be formed in the high temperature plasma where both \( T_i \) and \( T_e \) are more than 6.0 keV. Figure 2 shows the history of the operational regime of \( T_i \) and \( T_e \). It is clearly shown that the operational regime was extended by the increase in the ECH power (green squares), and the optimization of the launching scheme (red circles) [13]. Note that most of the data points in figure 2 especially above 6 keV, were obtained in the narrow density range between \( 1 \times 10^{19} \text{ m}^{-3} \) and \( 2 \times 10^{19} \text{ m}^{-3} \).

For discharges with simultaneous achievement of high \( T_i \) and \( T_e \), it is important to investigate core/edge thermal transport. Figure 3 shows the time evolution of (a) port through power of NBI and ECH, (b) line-averaged electron density, (c), (d) gradient of \( T_e \) and \( T_i \) at \( r_{\text{eff}}/a = 0.31 \) and 0.98, and (e) kinetic energy of electrons and ions. On-axis electron cyclotron resonance heating (ECRH) was superposed stepwise up to ~5 MW on the NBI-sustained plasma. According to the ray trace calculation, more than 90% of the ECRH power was absorbed inside \( r_{\text{eff}}/a = 0.2 \) at 4.74 s. It was found that \( T_e \) and its gradient increased with increasing ECRH power both in the plasma core and the edge. On the other hand, the \( T_i \) gradient decreased in the plasma core with increasing ECRH power, as depicted in figure 3(d).

However, the core \( T_i \) can be increased by on-axis ECRH, if \( n_e \) is high, as is seen in figure 3(i). This feature is quite beneficial for the high \( T_i \) scenario in high density plasmas such as DEMO, where electron heating is dominant.

### 3.3. Impurity transport

In the high \( T_i \) and \( T_e \) discharges shown in the previous subsection, it is typically observed that the carbon impurity is exhausted when high \( T_i \) and \( T_e \) are obtained with the formation of i-ITB and e-ITB. This phenomenon, called an ‘impurity hole’, is not easy to understand because conventional modeling based on the neoclassical theory cannot simply explain the experimental result. That is, the electric field is always negative and the direction of the impurity flux is ‘inward’ with this experimental condition.

In order to understand such an unusual phenomenon, the impurity behaviour in hydrogen discharges with NBI heating was classified, as shown in figure 4, with the plasma parameters \( n_e, T_e \) at the last closed flux surface (LCFS) [14]. In this classification, ‘accumulation’ is evaluated as an increase in core radiation \((dS_{\text{rad}}/dt > 0)\). Physical studies on the critical
of a C3$^+$ impurity flow evaluated from the Doppler shift of the second order of CIV line emission (2$^\text{+}$ line) at a horizontally elongated plasma position of the LHD. The observation range of the VUV spectroscopy [20] is also illustrated in figure 5(b). The two arrows in figure 5(a) correspond to each observation chord depicted by two solid arrows in figure 5(b). The measured flow velocity in figure 5(a) is a projection of the flow along the observation chord, which can approximately be considered to be the direction of the plasma major radius. Figure 5(c) shows the flow at the top and bottom edges of the stochastic layer as a function of density, indicating that the flow velocity increases with the density.

A synthetic profile of the simulated flow is depicted in figure 5(a) with solid line, together with experimental result obtained by integrating the Doppler-shifted CIV intensities along the observation chord. Excellent agreement between experiment and simulation can be seen, which offers the conclusion that the parallel flow in the stochastic layer can be well explained by the presently used theoretical modelling on the edge impurity transport.

In conclusion, it can be said that the impurity parallel flow is mainly determined by the momentum balance along the magnetic field line. In particular, the friction force between impurity and bulk ions, and the ion thermal force driven by the ion temperature gradient, are dominant terms in the momentum balance. The calculated friction force has a maximum value at the top and bottom edges of the stochastic layer where the impurity parallel flow also takes a maximum value. The impurity screening driven by the friction force is more effective in the higher electron density regime, as depicted in figure 5(c).

3.4. Global particle balance over a long pulse discharge

Exhausted particles moving through the stochastic region reach the divertor. As the final and then the first transport process
for particles, the global particle balance (recycling process) should be clarified to achieve steady-state operation for high performance plasma. The history of the steady-state operation research is summarized in figure 6. Intensive efforts have been paid to realizing steady-state operation [5], and knowledge of particle recycling in the LHD has been accumulated.

In the LHD, the wall retention has been investigated for steady-state long pulse discharges [21, 22]. As for the plasma facing components in the LHD, stainless steel and graphite are employed for the first wall and diverter, respectively. The surface areas of the first wall and the diverter plate are approximately 650 m² and 50 m², respectively. The first wall temperature was maintained below 370 K, even in the baking, for wall conditioning. The temperature on the surface diverter was approximately 500 K at maximum.

Analysis of the global particle balance was conducted in the long-pulse helium discharge heated by ICH + ECH (1.2 MW × 48 min = 3.4 × 10⁹ MJ), as shown in figure 7(a). The heating energy injected into the plasma was a new world record in toroidal plasmas [5]. The line-averaged electron density was 1.2 × 10¹⁹ m⁻³, and electron and ion temperatures of 2 keV were obtained, as shown in figure 7(b). In the discharge, the global particle balance analysis was conducted. The gas balance analysis depends on the measurement of the injected and pumped particle fluxes during and after the plasma discharges. Therefore, identification of supplied and exhausted particles was undertaken carefully. The wall retention was evaluated by subtracting pumped particles from fed particles. Figure 7(c) shows the temporal evolution of the wall retention in the long pulse discharge. The dynamic change of the helium wall retention is observed. The inventory can be mainly separated into three phases. In the first phase, defined from 0 to 300 s, quite high wall inventory occurs. In this phase, more than 80% of the puffed helium is retained in the wall. After the first phase, the wall inventory shows modest decline. However, the high wall inventory appears again in the third phase. The physics of the phased retention is discussed based on a simple assumption that there are two kinds of helium reservoir, ‘first wall with stainless’ and ‘diverter plate with graphite’.

4. The LHD as an advanced academic platform

The LHD has also been the platform for advanced academic research to facilitate high-temperature plasma physics and its contribution to wide-ranging academic fields.

Abrupt flow damping was found in the LHD due to the magnetic stochasticization induced by the change in the magnetic shear through the toroidal current control by means of switching co- and counter-NBIs [23]. Figure 8(a) shows the radial profiles of the delay time of heat pulse produced by the modulated electron cyclotron heating (MECH) at three timings after switching the beam (at t = 5.3 s). The topology of the magnetic field can be identified through the characteristics of the delay time [24] as the nested magnetic surfaces (t = 5.75 s), stochastic (t = 6.25 s) and magnetic island (t = 6.73 s), respectively. The central rotational transform measured by motional stark effect (MSE) spectroscopy [25] increases, and the magnetic shear at the rational surface with \( \kappa/2\pi = 0.5 \) decreases during this period to reach the steady-state value of 0.5 at t = 5.8 s. The toroidal flow velocity measured by charge exchange spectroscopy [26] is shown in figure 8(b), where the abrupt damping of the toroidal flow at the central region is found to be associated with a transition from nested magnetic surfaces to a stochastic magnetic field. The physics mechanism for this abrupt flow damping has not been clarified, but candidates were proposed in [23], such as the change in the non-diffusive term of the toroidal momentum transport and the toroidal momentum pinch as a direct electro-magnetic effect. This newly found breaking mechanism of the
plasma flow associated with magnetic stochastization may also be relevant to astrophysics research.

A new excitation phenomenon of a geodesic acoustic mode (GAM) has been discovered through measuring the electric potential fluctuation and density fluctuation using a heavy ion beam probe [27], the poloidal magnetic field fluctuation using a Mirnov coil array, and the energy distribution function of ions using a neutral particle analyser [28]. Although the GAM is normally stable, it is abruptly excited with a time scale of approximately 1 ms when the chirping frequency of an energetic particle-driven GAM (EGAM) approaches twice the GAM frequency. The experimental results indicate the nonlinear growth of the abruptly excited GAM and the mode coupling between the GAM and the initially excited EGAM.

In order to interpret the abrupt phenomena, a model taking into account both kinetic nonlinearity and fluid nonlinearity has been proposed [29, 30]. According to the model, the abrupt excitation phenomenon can be interpreted as a subcritical instability of the GAM. A simulation based on the model with experimental parameters successfully reproduces the time scale, the amplitude, and the timing of the excitation. Because a subcritical instability is a working hypothesis for understanding of the trigger problem of the abrupt phenomena, this observation in the LHD will show an experimental path to resolve the trigger problem. Recently, a simulation based on the first principle has been developed [31], and a direct comparison between the experiment and the simulation will give better understanding of the abrupt excitation phenomenon in the near future.

From the viewpoint of atomic physics, the LHD can be regarded as a unique light source for spectroscopic studies on impurity ions because of the wide parameter ranges, low opacity and high tolerance for the impurities. In addition, impurity pellet injection systems and reliable diagnostic tools are routinely available in the LHD. Therefore, we have exploited the LHD to produce an experimental database of extreme UV (EUV) spectra from a variety of heavy ions including tungsten, tin and lanthanides. Until now, we have systematically investigated more than half of the elements with atomic numbers

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**Figure 8.** (a) Radial profiles of the delay time of the heat pulse produced by MECH at three timings, and (b) toroidal flow velocity measured by MSE spectroscopy at three radial positions with the three timings in (a) clearly indicated.

**Figure 9.** EUV spectra observed in (a) high and (b) low electron temperature discharges.
higher than 50. For example, figure 9 shows the measured temperature dependence of the EUV spectrum from terbium (Tb) ions, one of the candidates for the next-generation light sources for semiconductor lithography [32]. Thanks to the maximum capability to control the electron temperature in the LHD, we could successfully observe a drastic change in the spectral feature from discrete to quasi-continuum as the temperature decreases. The discrete feature at the high temperature case (figure 9(a)) originates mainly from higher charge states around Cu-like Tb$^{36+}$ ions, while the quasi-continuum features in the low temperature case (figure 9(b)) consist of contributions from lower charge states. The isolated lines at 7.203 and 8.796 nm in the high temperature case are identified as the transitions of Cu-like Tb$^{36+}$ ions, which have been found for the first time in the LHD. In a similar way, we identified some of the isolated lines from neodymium (Nd), holmium (Ho) and thulium (Tm) ions for the first time [33]. The experimental database developed in the LHD will be helpful for verification of atomic models of tungsten emissions in ITER [34] as well as plasma light sources for industrial applications.

5. Summary

The deuterium experiment will start in March 2017. Before that, the finalization and summarization of the hydrogen experiment towards the deuterium phase were performed.

In the high beta trial, experiments with relatively high magnetic field of 1 T were performed, expecting an increase in $T_e$. The high $\langle \beta \rangle$ regime around 4% was extended to an order of magnitude lower collisional regime than before. In this situation, transition to the improved particle confinement mode was observed during the increase in $\langle \beta \rangle$.

In the high temperature experiment, high ion and electron temperatures, $T_i$ and $T_e$, of more than 6 keV were simultaneously achieved by superimposing high power ECH on the NBI heated plasma. It was found that $T_e$ and its gradient increased with an increase in ECH power both in the plasma core and on the edge. On the other hand, the $T_i$ gradient decreased in the plasma core with an increase in the ECH power. However, the core $T_i$ can be increased by on-axis ECH, if $n_e$ is high. This feature is quite beneficial for the high $T_i$ scenario in high density plasmas such as DEMO, where electron heating is dominant.

Impurity behaviour in hydrogen discharges with NBI heating was classified with the plasma parameters ($n_e$, $T_e$) at the LCFS. It was found that there exists no impurity accumulation regime where the high performance plasma is maintained with high power heating ($P_{\text{NBI}} > 10$ MW), which is favourable for realizing fusion plasmas. Wide parameter scan experiments suggest that toroidal rotation and turbulence are the candidates for exhausting impurities from the core region. In the edge stochastic region, impurity flow properties experimentally obtained agree well with those obtained in theoretical modelling. This result suggests that the impurity parallel flow is mainly determined by the momentum balance along the magnetic field line.

Global particle balance was studied. It was found that there exists dynamic change in the helium wall retention. The inventory can mainly be separated into three phases. In the first phase, quite high wall inventory occurs. After the first phase, the wall inventory shows modest decline. However, the high wall inventory appears again in the third phase. The physics of the phased retention can be discussed based on a simple assumption that there are two kinds of helium reservoir, ‘first wall with stainless’ and ‘divertor plate with graphite’.

Based on the results of the hydrogen experiment mentioned above, the LHD is about to enter the next stage. In the deuterium experiment, high-performance plasmas through confinement improvement are expected, which promote the scientific research in more reactor-relevant conditions. In addition, clarification of the isotope effect on confinement is also an important theme, since it has been a long-standing mystery in fusion research. Physics understanding is crucially important to accurately predict the behaviour of the burning plasma. Demonstration of the confinement capability of energetic ions is also a crucial issue for the LHD to promote reactor studies in helical devices.

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