II. Research Activities

1. Large Helical Device Project

1-1. LHD Experiment

(1) Overview of LHD Experiment

The 18th experimental campaign of the Large Helical Device (LHD) started on November 6th, 2014 and ended on February 5th, 2015, in the Japanese fiscal year 2014. Following the engineering experiment for 2 days, 44 days were allotted for the plasma experiment. During the period, 228 experiments based on the collaboration proposals were systematically performed. The total number of the discharge (shots) was more than 6400.

The experiment was carried out by newly organized four experimental theme groups, i.e., three plasma physics groups and one engineering science group. The first plasma physics group named “Plasma Improvement Group” deals with mission-oriented themes, aiming at the deuterium experiment which is expected to start in 2017. The group explores the extended plasma parameter regimes, e.g., highest ion and electron temperatures, highest beta values, etc., by confinement improvement. Preparatory experiments and drawing up plans for the deuterium experiment are also performed by the group. The experimental proposals concerning the edge plasma physics, plasma-wall interactions, steady-state operation, atomic and molecular physics are assigned to the second “Plasma Physics and Engineering Group”. The third group called “Core Plasma Physics Group” deals with plasma transport, MHD and high energy particles. The group is also in charge of the 3-D physics and resonant magnetic perturbation (RMP) experiments. The “Engineering Science Group” conducts the engineering studies to improve the reliability of the superconducting coils and the cryogenic system to be used in the deuterium experiment.

Every research theme is proposed on the domestic and international collaboration programs. All groups have their leaders from both NIFS and universities. A leader from abroad is sometimes assigned, according to the experimental theme. The experimental schedule is arranged and finally determined in the board meeting of the experimental groups, consisting of group leaders. The board meeting is responsible for the all LHD experiment.

In this annual report of NIFS, each report from four experimental theme groups is distributed to following subsections from 1.1-1(2) to 1.1-1(9). Some reports in section 1.1-2 are closely related to the Plasma Improvement Group and Core Plasma Physics Group.

The LHD is the world largest superconducting heliotron device of which major and minor radii are 3.42 – 4.10 m and 0.63 m, respectively. Maximum toroidal magnetic field strength is 3 T. For the plasma heating, three negative neutral beam injectors (n-NBI, 180 keV, 16 MW) and two positive neutral beam injectors (p-NBI, 40-50 keV, 12 MW), ion cyclotron heating system (ICH, 20-100 MHz, 3 MW) and electron cyclotron heating system (ECH, 77, 82.7, 84, 154 GHz, 5.4 MW) are equipped. The power of NBI and ECH can be modulated to study the energy transport. Especially for ECH, a quite narrow focusing area is useful to see the heat pulse propagation from the designated position in the core region. In the 18th experimental campaign, a 154 MHz gyrotron (1.0 MW, 5 s or 0.5 MW, CW) was additionally installed in LHD, which has been developed by NIFS and Tsukuba University on the Bidirectional Collaboration Research Program. The new gyrotron greatly contributed to extend the operational regime of LHD, as follows.

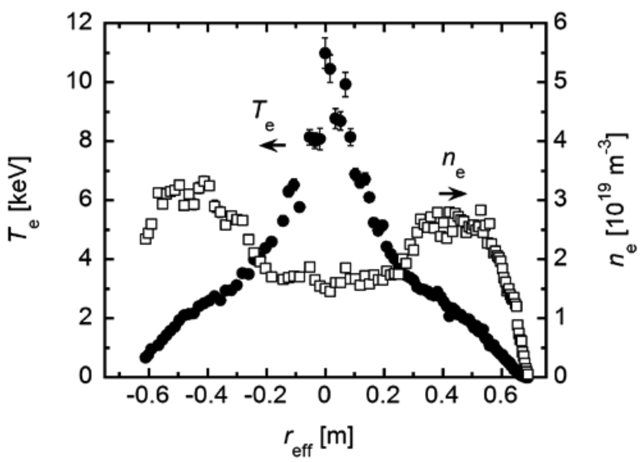

Fig. 1 Electron temperature and density profiles during strongly heated discharge with ECH.

Figure 1 shows electron temperature T_e and density n_e profiles obtained with highest electron temperature T_e of 10 keV. As is seen in the figure, T_e profile is so peaked, on the other hand, n_e profile is quite hollow. Therefore the central electron density is relatively low as 1.6×10^{19} m^{-3}. Since our target value is 2×10^{19} m^{-3} at the center, we should find the way to get better profile. This result really owes the increased heating power to the electron by the newly installed 154 GHz gyrotron whose power is ~ 1 MW. In addition, optimization of the microwave injection scheme also contributed to improve the heating efficiency of ECH. First, main four microwave launchers for 77 and 154 GHz were gathered in the horizontal port. With the horizontal injection, microwaves of 77 and 154 GHz always meet resonant surfaces along their path, even if the plasma column moves outward due to the Shafranov shift when the beta values increases. On the other hand, with the vertical injection, microwaves sometimes don't intersect any resonant surfaces. Another improvement for microwave injection was performed. The injection direction for microwaves were slightly changed from the vacuum condition to the finite beta condition, considering the ray to refract in the high density plasma. The ray tracing in the finite beta plasma were performed with the LHD Gauss code combined with profile data (T_e, n_e) from Thomson scattering and the equilibrium data by the VMEC code. With this numerical scheme, the microwave launcher can be set to be the optimal position.

The optimized high power ECH also contributed the high ion temperature (T_i) trial. After the exhaustive wall conditioning between shots (discharges), ECH was superimposed on the high power neutral beam heated plasma. In the discharge, after the carbon pellet injection, high T_e and T_i of more than 6 keV were obtained simultaneously. History of high T_i experiment is shown in Fig. 2, as a T_i-T_e diagram. It is clearly found that the optimization of the injection scheme is quite effective to achieve the new operational regime, in addition to the increase of the ECH power.

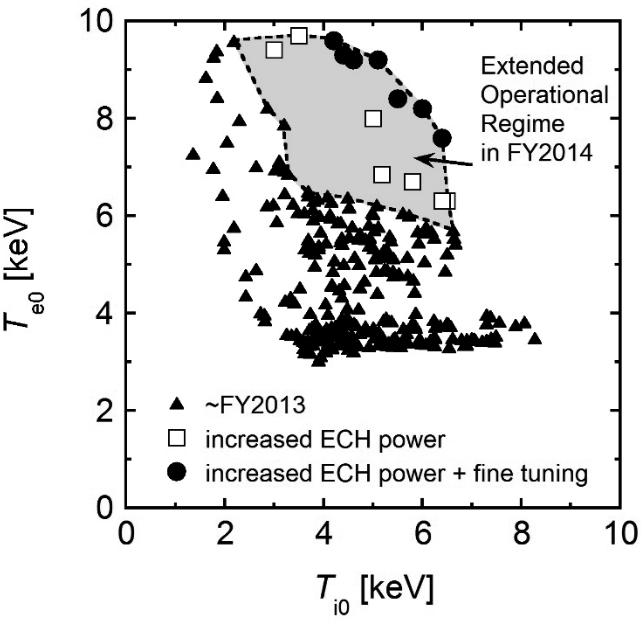

Fig. 2 Relationship between central electron temperature T_{e0} and central ion temperature T_{i0}. Open squares and closed circles are obtained in last experimental campaign in FY 2014.

Another extension of the LHD operational regime was accomplished. In the high beta trial, the volume averaged beta value $<\beta>$ of 4.1 % was achieved. Objectives of the experiment are to obtain a stable high beta plasma in the heliotron configuration, showing its high potential for the confinement property. Therefore it is important to obtain the high beta plasma with conditions closer to the reactor plasma. For this purpose, in the 18th experimental campaign, we tried to achieve the high beta plasma in the low collisionality regime, i.e., with relatively high toroidal magnetic field of 1 T. During high beta discharges, some MHD activities were observed in the core and edge regions. Detailed observations and/or discussions are described in following subsections.

In the 18th experimental campaign, steady progress was made towards the final goal of the LHD project, as described above. Finally, achieved plasma parameters up to the 18th experimental campaign are finally summarized in Table 1 with the targets of the LHD project.

Table 1 Achieved and targeted plasma parameters. New data obtained in the 18th experimental campaign are written in bold.

parameter	achieved	target
Ion temperature	8.1 keV at n_{e0} = 1 × 10^{19}m^{-3}	10 keV at 2 × 10^{19}m^{-3}
Electron temperature	**10 keV** at n_{e0} = 1.6 × 10^{19}m^{-3}	10 keV at 2 × 10^{19}m^{-3}
Simultaneous achievement of high T_i, T_e	T_{i0} = 6.0 keV T_{e0} = 7.6 keV at n_{e0} = 1.2 × 10^{19}m^{-3}	
Long pulse	47 min. 30 sec. P = 1.2 MW T_{i0} = 2.0 keV T_{e0} = 2.0 keV at n_{e0} = 1 × 10^{19}m^{-3}	1 hour P = 3 MW
beta	**4.1 %** at B_T = 1 T	5 % at B_T = 1-2 T

The LHD experiment group is now facing the forthcoming deuterium experiment, where the confinement improvement is expected. In the deuterium experiment, it is quite important to study the isotope effect in stellarator/heliotron devices, in order to provide a useful knowledge for the reactor design activities. In addition to the preparation for the experiment, e.g., installation of new diagnostics, facilities, safety system, etc., summary and documentation in hydrogen experiments should be completed by the end of the next campaign in 2016.

Lastly, all contributions from domestic and international collaborators, and excellent support by engineering and operation group in NIFS are greatly appreciated.

(Morisaki, T. for LHD Experiment Group)