II. Research Activities

1. Large Helical Device (LHD) Project

1-1. LHD Experiment

(1) Overview of LHD Experiment

The 17th experimental campaign of the Large Helical Device (LHD) experiment was completed successfully in the Japanese fiscal year 2013. During the 17th experimental campaign from Oct. 2nd to Dec. 25th in 2013, the LHD produced 7,300 plasma discharges, which were used for diversified joint research. Parameter extension, in particular in ion temperature and steady-state operation, as well as physics understanding, in particular, of 3-D physics issues and the so-called 3 N's issues (Non-linear, Non-diffusive, Non-local) have advanced by making full use of the intrinsic physics and technological advantage of LHD. The LHD has shown the advantages of a heliotron plasma from the operational point of view, having not only characteristics such as disruption free and steady state operation, but also high density and stable high beta operation.

The LHD experiment is organized by the LHD Experiment Board and theme groups, which the LHD Experiment Board defines, are responsible for the execution of the research. Eight theme groups are (1) divertor and edge plasma physics, (2) high-β and MHD physics, (3) extension and exploration of high temperature regime, (4) steady-state operation and plasma-wall interaction, (5) transport physics, (6) atomic and molecular processes, (7) heating physics and (8) device engineering. In total, about 270 experiment proposals were made and experiment programs were implemented based on these proposals. The results from the LHD experiment are reported in this chapter along with those from these theme groups.

LHD employs three heating schemes; Neutral Beam Injection:NBI (180 keV for tangential beams and 40keV for perpendicular beams), Electron Cyclotron Heating : ECH (77GHz and 154GHz) and Ion Cyclotron Heating : ICH (25-100MHz). The primary heating source is provided by NBI with up to 29 MW. Before the 17th experimental campaign, a new antenna for ICH was installed and the heating capability of ICH has been upgraded from 2.4 MW to 3.5 MW. In total, LHD has 6 antennas for ICH, which has enabled mitigation of the local heat load. ECH with up to 4.6 MW is remarkable in its well-focused local heating and power modulation to generate a heat pulse, which is very useful for transport studies. Combined heating by ICH and ECH together with improvement of particle control by means of gas-puff and boosting ECH has extended the steady-state operational regime significantly. Particle control is also important for high-ion temperature operation. A wall conditioning scheme by long-pulse ICH and ECH plasmas has matured, which has greatly improved its reproducibility and availability as well as the ion temperature itself of high-ion temperature plasmas.

Parameter extension and physical understanding have stimulated each other. Developed diagnostics and numerical codes, which can manage the multi-dimensional geometry with high space and time resolutions, enable us to challenge advanced plasma physics.

Newly achieved plasma parameters in the 16th experimental campaign are summarized in Table 1 with the targets of the LHD project.

Table I Newly achieved and targeted plasma parameters

Parameter	Achieved	Target
Ion temperature	T_{i0}=8.1 keV (T_{e0}=3.5 keV) n_{eo}=1.0×10^{19} m^{-3}	10 keV 2×10^{19} m^{-3}
Simultaneous achievement of high temperature	T_{i0}=6.1 keV T_{e0}=5.8 keV n_{eo}=1.1×10^{19} m^{-3}	
Long pulse	2,859 sec. (1.2 MW) T_{i0}=2.0 keV T_{e0}=2.0 keV $\overline{n}_e$=1.2×10^{19} m^{-3}	3,600 sec. (3 MW)
High beta	3.7 % at 1 T	5 % at 1-2T

The extension of the high-ion-temperature regime has been emphasized in the recent experimental campaigns and the central ion temperature has exceeded 8.1 keV at the density of 1.0×10^{19}m^{-3}. Figure 1 shows the profiles in the plasma with this highest ion temperature. The plasma with high-ion temperature exhibits an Internal Transport Barrier (ITB) in the ion channel and lies in the ion root with lower electron temperature than ion temperature. The integration of high ion and electron temperatures also has been successful by application of central ECH to the plasma with an ion ITB in the 17th experimental campaign (see Fig.2) and 6keV of both temperatures has been achieved simultaneously. It should be noted that this plasma lies in the electron root with a positive electric field, which suggests that the ion ITB is not specific to the ion root.

The analysis of high-ion temperature has progressed remarkably. The suppression of neutrals in the plasma core due to wall conditioning has been quantified by the Hα measurement with extremely high dynamic range and the time evolution of the discharge has been simulated by the time dependent transport code TASK-3D with precise heat deposition evaluation including a non-stationary distribution function and impurities. Improvement of reproducibility and availability has enlarged the physics database significantly and the resulting observation of impurity hole and plasma flows has been explored in more detail than before.

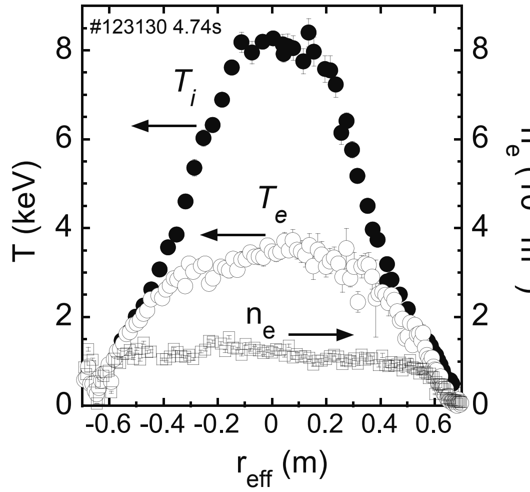

Fig.1 Typical plasma profiles in the plasmas with the highest ion temperature.

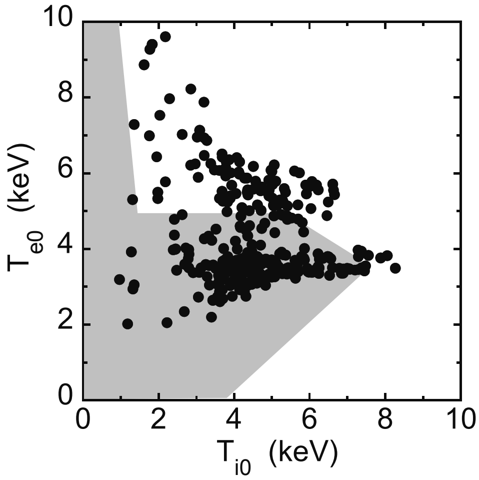

Fig.2 Operational regime on the central electron and ion temperatures. Gray hatched region is the regime achieved before the 17th experimental campaign. Closed circles are data obtained in the 17th experimental campaign.

The steady-state operational regime has been greatly extended. A plasma with a temperature of 2 keV and a density of 1×10^{19} m^{-3} has been maintained in steady state for 48 minutes (see Fig.3) by the combined heating of ICH and ECH of 1.2 MW. The total input heating energy throughout the discharge has reached 3.4 GJ, which doubles the previous world record of 1.6 GJ. Characterization and understanding of the modification of surface materials has been accelerated by these long pulse discharges. For example, helium gas fueling is needed even for the 48-min. long discharge. The trapping of helium in developing co-deposition layers is a potential player to change the wall pumping.

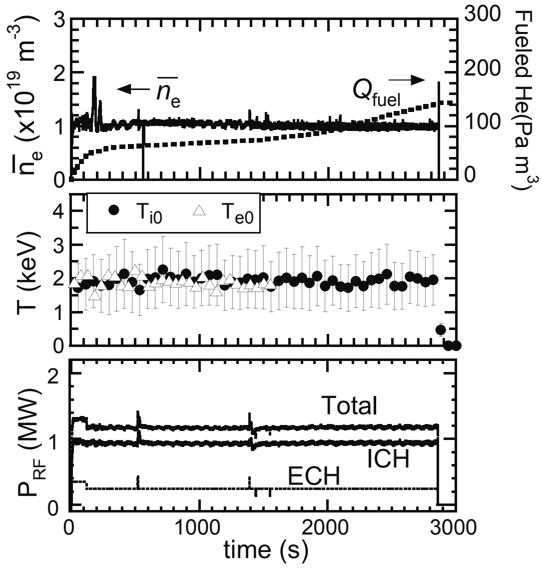

Fig.3 Waveforms of 48-min. long discharge with the heating power of 1.2 MW. Top:Line averaged density and fueling rate of He. Middle: Central ion and electron temperatures. Bottom: Heating power.

With regard to the divertor and edge plasma study, the progress in control and understanding of detached plasma is highlighted. Injection of impurity gasses such as helium, nitrogen and krypton, and the effect of a Resonant Magnetic Perturbation (RMP) have been explored experimentally and compared with the 3-D simulation (EMC3-EIRENE).

Besides stabilizing a detached plasma, the RMP has been widely used to investigate the plasma response to a 3-D magnetic field, in particular, with regard to the magnetic islands and magnetic stochastization. For example, the penetration condition of the RMP into the plasma has been assessed systematically in terms of the magnetic shear, magnetic well and the Mercier criterion.

Exploration of the 3N's has also proceeded, in particular, in the subjects of spontaneous rotation, non-local heat transport and bifurcation of magnetic topology. Last but not least, LHD has provided a unique platform for the study of atomic and molecular processes. Spectroscopy ranging from visible, EUV to soft X-ray spectrum of high-Z elements covers the fields of not only fusion such as the tungsten issue, but also astrophysics, EUV lithography and biological microscopy of a water window.

The LHD project continues to pursue the maximization of plasma performance and a comprehensive understanding of toroidal plasmas by the synergy of facility upgrades and the positive feedback of new findings. All the detailed analyses of accumulated data and their integration of knowledge will lead to further investigation in the 18th experimental campaign in 2014.

Lastly, all contributions from collaborators and the excellent supporting work by the LHD operation group are greatly appreciated.

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