II. Research Activities

1. Large Helical Device (LHD) Project

1-1. LHD Experiment

(1) Overview of LHD Experiment

The 16th experimental campaign of the Large Helical Device (LHD) experiment was completed successfully in the Japanese fiscal year 2012. During the 16th experimental campaign from Oct. 17th to Dec. 6th in 2012, the LHD produced more than 5,000 plasma discharges, which were used for diversified joint research. Parameter extension, in particular in ion temperature, as well as physics understanding, in particular, of the so-called 3 N's issues (Non-linear, Non-diffusive, Non-local) and 3-D issues have been advanced by making full use of the intrinsic physics and technological advantage of LHD.

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. The theme groups are reorganized every two years considering achievements and prospects. Before the 16th experimental campaign, the theme groups were re-organized into the following 8 groups; (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. These major changes have been done in order to promote acceleration of an interdisciplinary approach to solve issues and positive feed-back of a mission-oriented approach and exploration of physics. Typical change can be seen in the combination of steady-state-operation and plasma-wall interaction topics, and the integration of high electron and ion temperature into one group. In total, about 260 experiment proposals were made and experiment programs were executed based on these proposals.

Modification of the open helical divertor to a closed helical divertor has progressed in 2012. A Baffle-dome structure to accommodate a closed helical divertor configuration has been installed on 8 of the inboard sides among a total of 10 toroidal field periods. Provisional operation of a divertor cryo-pump has also started at one toroidal section. A new gyrotron with a frequency of 154 GHz and a power of 1 MW has been available. In parallel with the upgrade of major facilities like the closed helical divertor and the high-frequency gyrotron, the improvement of diagnostics and development of analysis tools have been greatly promoted in order to enable accurate physics discussions.

The results from the LHD experiment are described in the following chapters along with the above mentioned theme groups.

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. Physical understanding and parameter improvement have been stimulating each other. The current efforts are focused on the optimization of the plasma edge conditions to extend the operation regime towards higher ion temperature and more stable high density and high beta. 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.

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. ECH with up to 4.6 MW is remarkable in well-focused local heating and power modulation to generate a heat pulse, which are very useful for transport studies. The steady-state capability of ECH has been improved and 0.8 MW is available in steady-state. ICH with up to 2.4 MW plays the leading part in steady-state operations with the power of 1 MW.

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}=7.3 keV n_{eo}=1.2×10^{19} m^{-3}	10 keV at 2×10^{19} m^{-3}
Electron temperature	T_{e0}=13.5 keV n_{eo}=1.4×10^{19} m^{-3}	10 keV at 2×10^{19} m^{-3}
Long pulse	1,135 sec. (1 MW) T_{e0}=2.5 keV, n_{eo}=1×10^{19} m^{-3}	3,600 sec. (3 MW)

The extension of the high-ion-temperature regime has been emphasized in the recent experimental campaigns and the central ion temperature has exceeded 7.3 keV at the density of 1.2×10^{19}m^{-3}. Figure 1(a) shows the profiles in the plasma with this highest ion temperature. Wall conditioning by ICRF has been established and these high-ion temperature plasmas are now routinely reproduced. The new gyrotron with 154 GHz has extended the high-electron temperature regime and 13.5 keV of electron temperature has been achieved at the moderate density of 1.4×10^{19}m^{-3} (see Fig.1(b)). Electron heating in the density regime as high as $1\times10^{20}m^{-3}$ also has been demonstrated. Steady-state operation also has been extended to a higher heating power regime and consequently to a higher density and temperature regime than before. Steady-state operation and characterization of the modification of surface materials and the have contributed to each other.

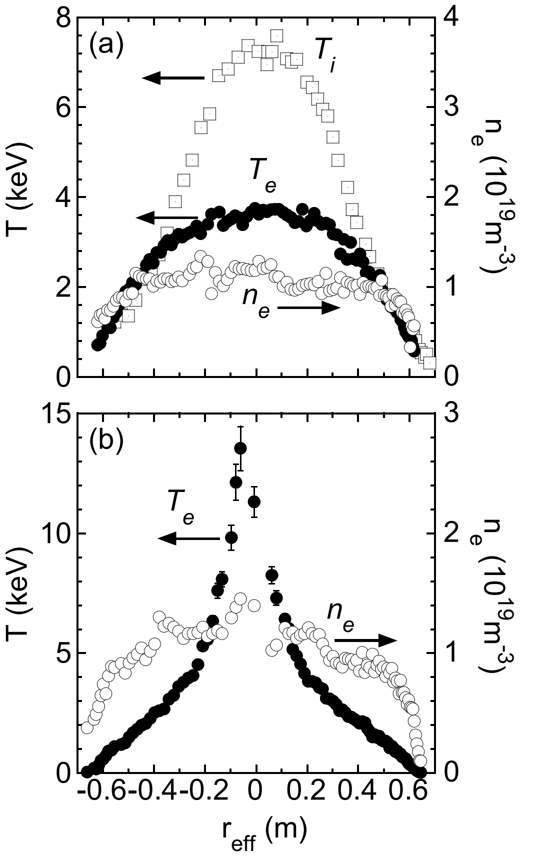

Fig.1 Typical plasma profiles of high-temperature plasmas. (a) Highest ion temperature. (b) High electron temperature.

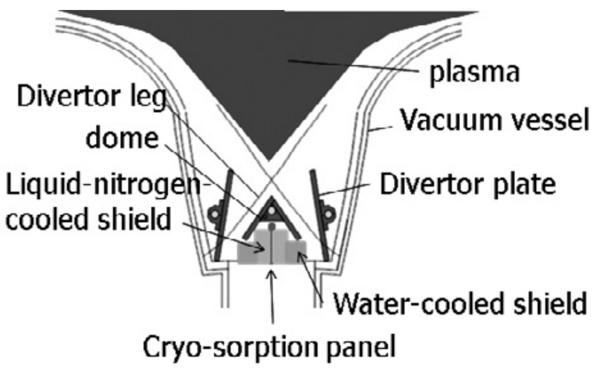

Fig.2 Horizontal cross-section of the equatorial plane of the closed helical divertor.

A closed helical divertor with an in-vessel cryo-sorption pump is being installed step-by-step. Figure 2 shows the horizontal cross-section of the closed helical divertor on the equatorial plane. It consists of divertor plates, dome and cryo-sorption pumps. The divertor plates and the dome are made of isotropic graphite. The carbon plates are tightly fixed with bolts sandwiching a SUS316L cooling pipe, and are actively cooled by water. The design of the baffle structure was carried out with a full 3D neutral transport code, EIRENE. The cryo-sorption pump consists of a helium-gas-cooled cryo-sorption panel, liquid-nitrogen-cooled chevron-type shields, and water-cooled louver-type shields.

Plasma dynamics specifically related to the 3-D geometry are a common important physics issue in toroidal plasmas. Beyond the intrinsic 3-D characteristics of heliotron plasmas, LHD has provided diversified cutting-edge physics insight into the plasma response in 3-D magnetic fields. In particular, topological change including the generation of magnetic islands and stochastization and its impact on plasma flow is highlighted. The effect of the stocahstization of the magnetic field on the plasma flow is one of the crucial issues to understand the mechanism of edge localized mode (ELM) suppression by magnetic perturbation. This is because the reduction of the plasma flow due to the stocahstization of the magnetic field should have a strong impact both on MHD stability and transport at the pedestal.

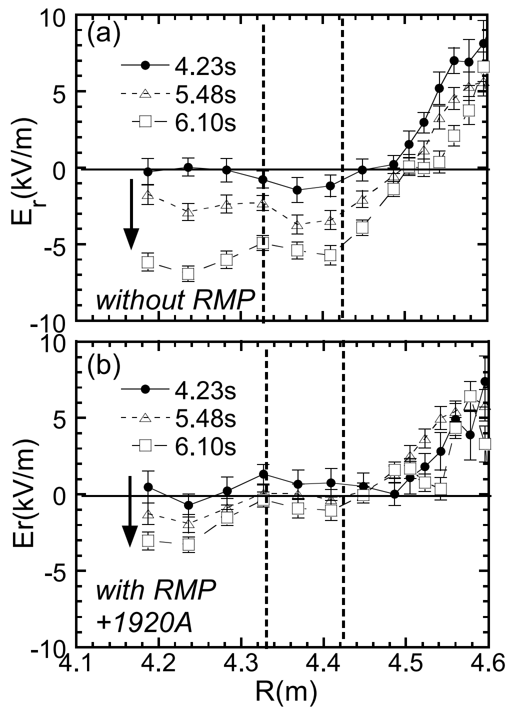

Fig.3 Radial profiles of radial electric field (a) without RMP and (b) with RMP in the discharges, where the direction of the NBI is switched from the co-direction to the counter-direction. Vertical dashed lines indicate the expected magnetic island by the RMP.

In order to distinguish the effect of a Resonant Magnetic Perturbation (RMP) on toroidal and poloidal rotation, tangential NBI are switched from co-injection to counter-injection. Figure 3 shows the comparison of the radial electric field without (a) and with (b) the RMP. Here, the direction of the NBI is switched at t = 4.3s. The radial electric field profile becomes strongly positive outside the last closed flux surface (LCFS at R = 4.55m) because electrons escape to the wall along the magnetic field. This comparison clearly shows the damping of flows due to the magnetic island. In contrast to this observation, in the region outside of the LCFS, the enhancement radial electric field shear at the LCFS is suggested in the plasma with an RMP because of the opposite effect of the RMP on the plasma flow inside and outside the LCFS.

Plasma response to perturbed magnetic fields has been investigated by many other experimental proposals. ELM mitigation in H-mode plasmas, penetration and screening of the RMP by the plasma, stabilization of a radiative divertor, influence of RMP on heat and particle transport and micro-turbulence, etc. have been studied and documented in this annual report.

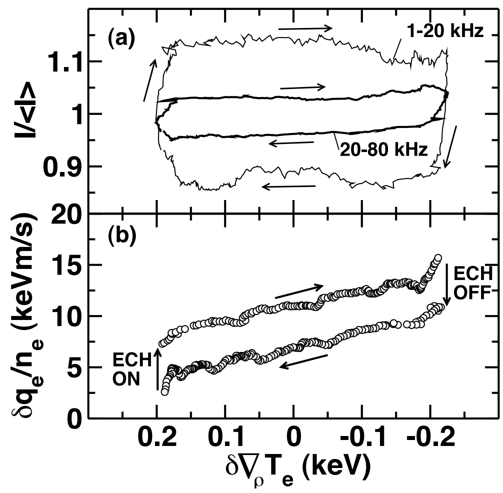

Fig.4 Non-linear electron-temperature gradient dependence of micro-fluctuation amplitudes and heat flux during ECH modulation. (a) Lissajous diagram of density fluctuation amplitudes and (b) gradient-flux relation. Arrows denote the direction of variation.

Another highlighted topic of new findings is the identification of the immediate change of heat flux prior to the change of the local temperature gradient. The small changes of electron temperature profiles and the amplitudes of density fluctuations are precisely evaluated by a conditional averaging technique with ECH modulation. Figure 4 shows the non-linear response (hysteresis) of the fluctuation amplitudes to the local electron temperature gradient and heat flux, which indicates a violation of Fick's law. The existence of hidden parameters and long-distance correlation of turbulence may be possible candidates for the cause of the observed hysteresis. It is a conjecture here that the on-off of the heating power at the center immediately influences the long range modes which couple with microscopic fluctuations at far distance.

The LHD project continues to pursue the maximization of plasma performance and comprehensive understanding of toroidal plasmas by the synergy of facility upgrades such as closed helical divertor and heating capability 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 17th experimental campaign in 2013.

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

(Yamada, H. for LHD Experiment Group)