II. Research Activities

1. Large Helical Device (LHD) Project

1-1. LHD Experiment

(1) Overview of LHD Experiment

The 14th experimental campaign of the Large Helical Device (LHD) experiment has been completed successfully in the Japanese fiscal year 2010. Highlighted achievements can be seen in 3 directions, i.e., improvement of plasma parameters, demonstration of new ideas and deepening of understanding of physics processes. Ion and electron temperatures have increased to 6.4 keV and 20 keV, respectively. Compression of neutral pressure by a factor of 10 has been demonstrated by the baffle-structured helical divertor. A new antenna of Ion Cyclotron Range Frequency (ICRF) has shown efficient heating by the phase control. Detailed joint studies of experiment, theory and simulation have been promoted for the subjects of transport, MHD and energetic particles, etc.

In these 13 years since the initial operation in 1998, LHD has provided many occasions for experimental approaches to the clarification of physical processes in net-current free helical plasmas as well as the establishment of a comprehensive understanding of toroidal plasmas [1]. LHD is based on the heliotron magnetic configuration employing a pair of superconducting helical coils which configure a built-in divertor. The primary heating source is Neutral Beam Injection (NBI), and three tangential beam lines with the accelerating voltage of 180 keV and two perpendicular beam lines with that of 40-60 keV deliver 16 MW and 12 MW, respectively. Electron Cyclotron Heating (ECH) with 4 MW plays an important role in local heating and power modulation in transport studies. After a two-year hiatus, Ion Cyclotron Range Frequency (ICRF) heating has been used in the experiment with an improved antenna which is capable of the wave number control. LHD has a plan to maximize the plasma performance by three major upgrades, which are namely those of the heating capabilities, the closed helical divertor and the deuterium experiment, in the coming years. As the first step, the heating capability of the perpendicular NBI has been upgraded from 6MW to 12 MW. The divertor configuration has been partially modified to that with a baffle structure and the performance of this proto-type has been investigated in order to finalize the design of the closed helical divertor.

The LHD experiment group has advanced plasma parameters and deepened the understanding of plasma physics. Diversified experimental proposals were managed in the framework of four major mission-oriented theme groups (high density and related confinement improvement by divertor, extension of the high-temperature regime, steady-state operation of high-performance plasmas, and extension of the high-β regime) and five physics-oriented theme groups (core confinement physics, edge plasma physics and plasma wall interaction, MHD, physics of energetic particles, wave physics).

In total, about 250 experimental proposal have been executed in the 14th experimental campaign from Oct. 14th, 2010 to Jan. 27th, 2011. The results from the mission-oriented theme groups and the physics-oriented theme groups are described in the following chapters, 1-1.(2) and 1-1.(3), respectively.

The high ion temperature regime has been explored in the extended NBI heating capability. The plasma profiles in the plasma with the highest ion temperature are shown in Fig.1. The ion thermal diffusivity decreases to the level predicted by neoclassical transport, which exhibits the formation of an *Internal Transport Barrier*. The line averaged density and the magnetic field are $1.6\times10^{19}\mathrm{m}^{-3}$ and 2.85T, respectively. Here it is emphasized that very fine spatial resolution in the measurements is obtained and the profiles are projected on the reconstructed 3-D equilibrium. Base on the obtained database, characterization of high-ion temperature plasmas has progressed.

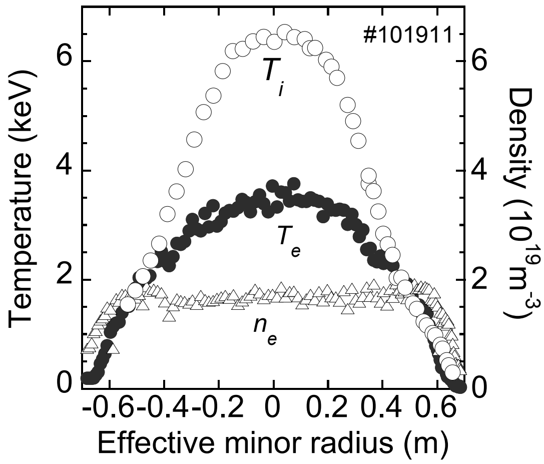

Fig.1 Profiles of ion and electron temperatures and electron density in the discharge with the highest central ion temperature. The signs of the effective minor radius a_{eff} denotes the inboard side (-) and the outboard side (+) with respect to the center.

The present divertor configuration in LHD is open with no facility for active pumping. The concept of the closed helical divertor has been maturing by the local island divertor and the consequent novel operational regime of *Super-Dense Core* due to an *Internal Diffusion Barrier*. A baffle-structured divertor with a dome was designed through a comparative study of numerical simulation and experiments. Two sections on the inboard side among 10 toroidal periods were modified to this configuration before the 14th experimental campaign. Compression of neutral pressure under the dome has been demonstrated successfully as the numerical simulation predicts (see Fig.2). A helical divertor system with a pump under the dome will be installed on the inboard side of the torus after the 15th experimental campaign and will be operational in 2012. This system is expected to have a pumping capability of 20Pam^3/s and to be able to withstand a heat load of more than 1.5MW/m^2 in steady state.

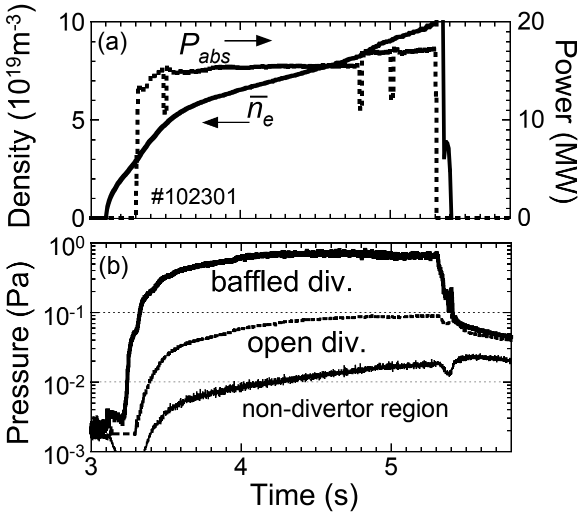

Fig.2 Waveforms of a typical gas-fuelled discharge. (a) Line averaged density and absorbed heating power. (b) Neutral pressures at different locations with regard to the divertor geometry.

Fig.3 ICRF antennas newly installed on the outboard side of the vacuum vessel. Faraday shields reflect the trajectory of the magnetic field lines.

One new pair of ICRF heating antennas was also installed before the 14th experimental campaign. Two antennas are arrayed in the toroidal direction and have a controllability of the wave number along the magnetic field line by changing the phase between them (see Fig.3). A higher wave number is preferable for reduction of the wave-particle interaction in front of the antennas. The operational density has reached 2.5×10^{19} m^{-3} at a power of 800 kW in the case of the antennas being out phase with each other while the sustained density by the previous poloidal array antenna was limited to 2.7×10^{19} m^{-3} at a power of 1.5 MW.

Together with these extensions of plasma parameters and demonstration of new ideas, diversified outcomes have been investigated by carefully arranged experiments and have been discussed with the theory and simulations towards a comprehensive understanding of the underlying physics.

In terms of transport, three "non"s, which are non-linear, non-diagonal and non-local, are targets to be documented. A non-linear process would be a key in the formation of an ITB and the life-time of the high-performance phase. Non-diagonal means off-diagonal terms in the transport matrix. *Impurity Hole* and *Intrinsic Rotation* have been heuristically identified being driven by the ion temperature gradient. A global correlation technique has been applied to observe long range fluctuations and this technique has revealed the existence of ballistic propagation in electron heat transport. Improved ion-temperature diagnostics (charge exchange spectroscopy) have identified a non-local ion temperature rise triggered by edge cooling.

Investigation of 3-D features has progressed in terms of MHD and edge plasma physics. Nowadays, 3-D physics is no longer specific to 3-D devices like a helical system but also is an emergent critical issue in tokamaks. The 3-D magnetic field is pronounced in magnetic islands and stochastization. Here it should be noted that the magnetic field in the plasma is not necessarily well predicted by the vacuum magnetic field. *Resonant Magnetic Perturbation* (RMP) and the control of the magnetic shear by NBI driven currents as well as by the confining magnetic field have been used to clarify the related plasma dynamics. Generation and healing of magnetic islands has been found to be correlated with the poloidal rotation. The penetration of an RMP easily occurs when the magnetic shear decreases. The boundary of the closed nested flux surfaces and the stochastic magnetic fields in the edge can be identified by the heat pulse propagation of ECH and the change of radial electric field. RMP has been also used for control of detachment onset and sustainment, which has demonstrated the availability of a new control knob on the stable divertor detachment.

Last but not least, LHD is a unique experimental platform for plasma wall interactions and atomic processes. In particular, studies on the retention of hydrogen and the characterization of reforming of high-Z material have progressed. Interdisciplinary studies on atomic processes have also progressed by using LHD as a light source.

All the detailed analyses of accumulated data and their integration of knowledge will lead to further investigation in the 15th experimental campaign in 2011.

Lastly, the excellent supporting work by the LHD operation group is greatly appreciated.

[1] Fusion Sci. Technol. **58**, "SPECIAL ISSUE ON LARGE HELICAL DEVICE (LHD)" (2010)

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