II. Research Activities

1. Large Helical Device (LHD) Project

1-1. LHD Experiment

(1) Overview of LHD Experiment

The 15th experimental campaign of the Large Helical Device (LHD) experiment was completed successfully in the Japanese fiscal year 2011. During the 15th experimental campaign, the LHD produced more than 7,000 plasma discharges, which were used for diversified joint research. In total, about 260 experimental proposals were executed from Jul. 28th, 2010 to Oct. 20th in 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 LHD has shown the advantages of a heliotron plasma from the operational point of view, not only 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 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 multi-dimensional geometry with high space and time resolutions, enable us to challenge the 3 N's (Non-linear, Non-diagonal, Non-local) and 3-D 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 Ion Cyclotron Heating : ICH (25-100MHz). The primary heating source is provided by NBI with up to 29 MW. ECH with up to 3.7 MW is remarkable in well-focused local heating and power modulation to generate a heat pulse, which are very useful for transport studies. ICH with up to 2MW plays the leading part in steady-state operations.

The extension of the high-ion-temperature regime has been emphasized in the recent experimental campaigns and the central ion temperature has exceeded 7 keV at the density of $1.5\times10^{19}\mathrm{m}^{-3}$. Figure 1 shows the profiles in the plasma with this highest ion temperature. Thermal transport in the core plasma is improved in the ion channel, which exhibits a broad internal transport barrier. Wall conditioning by ICRF is effective as it decreases the edge electron density during high power NBI heating and improves the beam absorption at the plasma center.

The provisional experiment of a closed divertor has been advanced where 20 % of the inboard side divertor was modified to a baffled structure. Modification that will increase to 80 % with a cryo-pump and reduced recycling, which is preferable for the high-ion-temperature approach as well as for high-density and steady-state scenarios, is foreseen in the next experimental campaign.

The LHD has already demonstrated the volume averaged beta value of 5.1 % and sustainment of the high beta state over 4.5% for longer than 100 times of the energy confinement time. Since this high beta was achieved at low magnetic field of 0.425T, the plasma lies in the collisional regime due to low temperature. Therefore, extension of high beta plasma to the higher magnetic field has been promoted. Consequently, 4.1 % and 3.4 % have been achieved at 0.75 T and 1 T, respectively. The database of high beta plasmas has been extended to the collisionless regime.

Achieved plasma parameters to date are summarized in Table 1 with targets of the LHD project.

Table 1 Achieved and targeted plasma parameters

Parameter	Achieved	Target
Ion temperature	7 keV at $1.5\times10^{19}\,\mathrm{m}^{-3}$	10 keV at $2\times10^{19}\,\mathrm{m}^{-3}$
Electron temperature	20 keV at $0.2\times10^{19}\,\mathrm{m}^{-3}$	10 keV at $2\times10^{19}\,\mathrm{m}^{-3}$
Density	$1.2\times10^{21}\,\mathrm{m}^{-3}$ with 0.25 keV	$4\times10^{20}\,\mathrm{m}^{-3}$ with 1.3 keV
Beta	5.1 % at 0.425 T 4.1% at 0.75 T 3.4% at 1 T	5% at 1-2 T
Long pulse	3,268 sec. (0.5 MW) 800 sec. (1 MW)	3,600 sec. (3 MW)

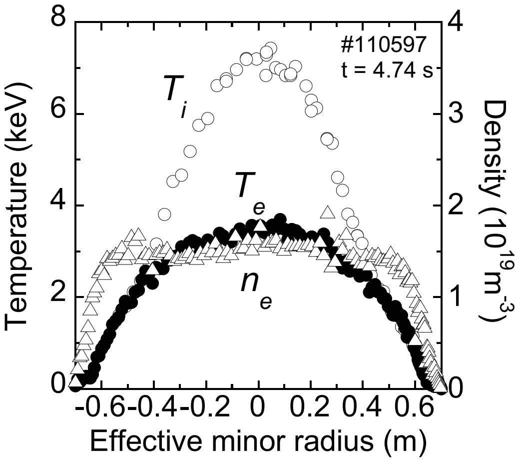

Fig.1 Profiles of ion (open circles) and electron (closed circles) temperatures and electron density (triangles) in the plasma with the highest central ion temperature. The signs of the effective minor radius denote the inboard side (-) and the outboard side (+) with respect to the center.

Assessment of 3-D effects based on diagnostics with fine special resolution and numerical models to cope with a real 3-D geometry has remarkably progressed. In particular, a Resonant Magnetic Perturbation (RMP) with m/n=1/1, which has resonance in the plasma periphery, has been applied to the experiments of divertor detachment, ELM mitigation, and magnetic island dynamics. The RMP has a stabilizing effect on detached plasmas by changing the radiation pattern in the edge. With RMP, enhancement of radiation power is enhanced at low density and regimes where radiation power does not depend on density appear (see Fig.2). Consequently radiating plasmas with divertor heat load reduced by factor of 3-10 can be sustained stably. Blob-like intermittent plasma transport characterizes non-diffusive cross-field transport in detached plasmas. It is noted that even in the case where the accumulation of high-Z impurity is observed in the core plasma, the concentration level of iron remains at the order of 10^{-5}. This low contamination is attributed to screening against impurity influx by the ergodic layer surrounding nested flux surfaces.

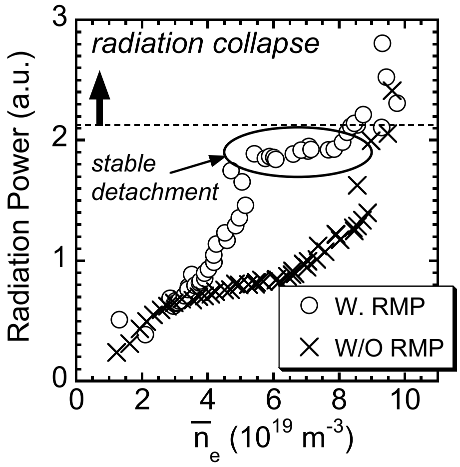

Fig.2 Radiation as a function of density with (circles) and without (crosses) RMP.

In LHD H-mode, large ELMs often expel up to 20 % of the total stored energy. It should be noted that these ELMs are thought to be induced by interchange modes destabilized at the edge while peeling ballooning modes causes ELMs in tokamaks. Applications of the RMP has clearly reduced the ELM amplitude and increased the ELM frequency (see Fig.3). In the mitigated phase, the energy loss by an ELM decreases to a few % of the total stored energy. Identification of stochasticity of magnetic fields is a key element in terms of a generic 3-D MHD model as well as for this specific ELM mitigation. Since open field lines generate positive radial electric field, the position of the enhanced shear of the radial electric field indeed moves due to a change in the topology of the magnetic fields. Heat pulse propagation also shows a convincing observation of a change in topology. The screening tolerance against the RMP depends on magnetic shear, and penetration easily occurs as the plasma loses magnetic shear and/or is put in a magnetic hill.

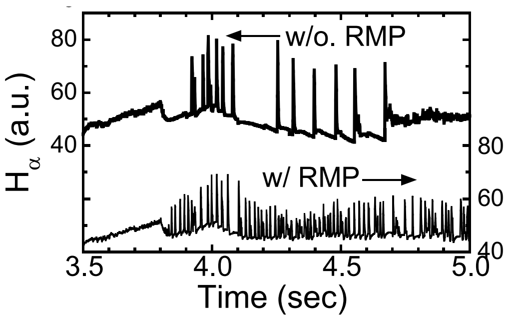

Fig.3 Typical waveforms of Hα, which reveals ELM mitigation by RMP.

Novel wave heating schemes have been advanced. A new dipole antenna for ICRF heating can control toroidal phase and excite a fast wave with large wavenumbers. It shows better heating efficiency at higher density than the conventional monopole antenna as expected, and consequently a steady-state operation scenario with high density will be planned. With regard to the physics of energetic particles, fast ion losses induced by TAE changes from a convective nature to a diffusive nature for different magnetic configurations, which has been explained by numerical analysis of orbits in 3-D. An interesting phenomenon is that bulk-ion heating by the energetic particle driven n=0 mode has been suggested.

The non-diffusive nature attracts interests in new pictures of thermal and momentum transport in magnetically confined toroidal plasmas. In particular, two types of intrinsic toroidal rotation have been identified in the LHD. One is intrinsic rotation in the ctr-direction driven by the positive radial electric field near the plasma periphery, and the other is that in the co-direction driven by the ion temperature gradient at half of the plasma minor radius especially in the improved confinement regime with a large temperature gradient above a threshold. The existence of non-linearity in the intrinsic rotation strongly suggests the driving mechanism is Reynolds stress due to turbulence not the neoclassical viscosity. Dynamic response of micro-turbulence to ECH modulation has been studied in terms of the long distance radial correlation of turbulence, which is expected to be the most possible candidate for causing the non-local transport. The amplitude of micro-turbulence is found to be not proportional to the local temperature gradient, which suggests a significant contribution of non-locality in the heat transport.

All the detailed analyses of accumulated data and their integration of knowledge will lead to further investigation in the 16th experimental campaign in 2012.

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

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