II. Research Activities

1. Large Helical Device (LHD) Project

1-1. LHD Experiment

(1) Overview of LHD Experiment

The 13th experimental campaign of the Large Helical Device (LHD) experiment has been completed successfully in the Japanese fiscal year 2009. LHD is based on the heliotron employing a pair of superconducting helical coils. The primary heating source is Neutral Beam Injection (NBI) with a heating power of 23 MW, and Electron Cyclotron Heating (ECH) with 3.5 MW plays an important role in local heating and power modulation in transport studies. In parallel with parameter improvement, important physics processes of transport and MHD for fusion energy development have been identified and assessed by the analyses based on profile diagnostics with fine spatial resolution and numerical computation to cope with a real 3-D geometry. In these days, the demand for 3-D modeling is becoming inevitable for accurate and detailed studies in tokamaks as well as in helical systems. Both toroidal systems share common 3-D related physics issues such as documentation of 3-D equilibria, transport in a stochastic magnetic field, plasma response to a *Resonant Magnetic Perturbation* (RMP) and divertor physics.

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, high β, steady state, and high ion temperature) and five physics oriented theme groups (core confinement physics, scrape-off layer and divertor physics including plasma material interaction, MHD, physics of energetic particles, wave physics). The research initiative of trilateral elements; extension of plasma parameters, identification of correlation and causality, and new discoveries, which all stand on the foundation of accurate diagnostics and theoretical modeling, is emphasized to accelerate research. The progress in understanding net-current free helical plasmas and innovative approaches towards a comprehensive understanding of toroidal plasmas is described in the following two chapters.

The highlighted achievements in plasma parameters are the quasi-steady-state maintenance of a *Super-Dense-Core* (SDC) due to an *Internal Diffusion Barrier* (IDB) for 3 s by the feedback control of pellet fueling, high electron temperature of 15 keV by the intensive Electron Cyclotron Heating (ECH) (see Fig.1), the central β of 10 % at a moderate magnetic field of 1.5 T and a steady-state high temperature discharge with the central electron temperature of 3 keV for 400 s.

The central density of $3\times10^{20}\mathrm{m}^{-3}$ with a highly peaked density profile is maintained for $35\tau_E$ by feedback control of pellet injection with the heating power of 10 MW as shown in Fig.2. Duration is limited by the NBI capability. Nonetheless, enhanced recycling increases edge density, and consequently degrades an IDB and global confinement. Particle control by a closed divertor in plan will resolve this unfavorable condition.

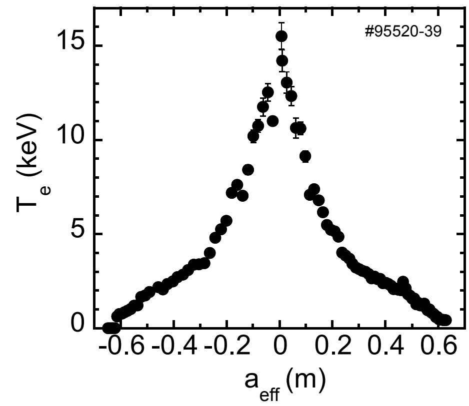

Fig.1 Electron temperature profile in the discharge with the highest central electron temperature. The signs of the effective minor radius a_{eff} denotes the inboard side (-) and the outboard side (+) with respect to the center. The power of ECH and the averaged electron density are 2.7 MW and $2.3\times10^{18}\mathrm{m}^{-3}$, respectively.

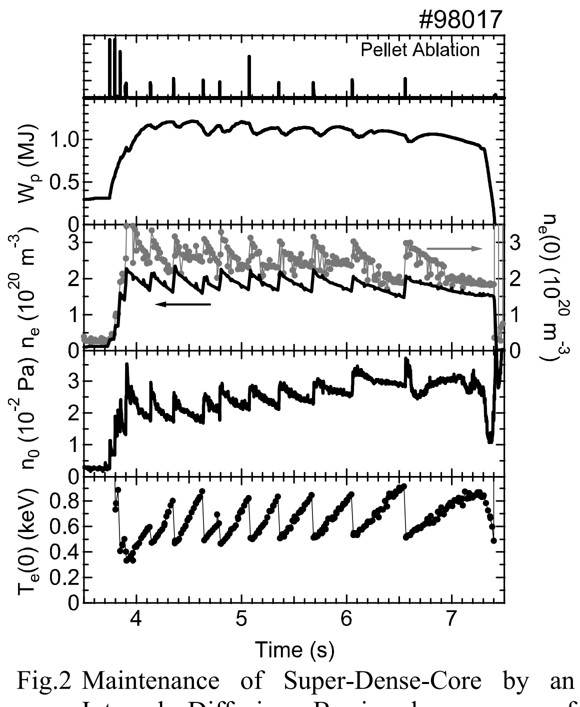

Fig.2 Maintenance of Super-Dense-Core by an Internal Diffusion Barrier by means of feedback control of pellet refueling.

An RMP with m/n=1/1, which has resonance in the plasma periphery, has demonstrated the radial expansion of a super-dense-core surrounded by an IDB through the density reduction in the mantle outside the IDB. Detachment physics also has been investigated by applying an RMP to high density plasmas. Localization of the radiation at the induced magnetic island X-point leads to stable detachment.

A high central β plasma due to an IDB often exhibits a large-scale relaxation event called *Core Density Collapse* (CDC). The loss of the core density and consequent lost pressure reaches 50 %. While the stability analysis indicates that a low–n MHD mode is stable in the core due to magnetic well, the pressure–driven high–n ballooning mode is destabilized in the magnetic hill in the periphery with a large pressure gradient.

The plasma with a central ion temperature reaching 5.6 keV exhibits the formation of an *Internal Transport Barrier* (ITB). The ion thermal diffusivity decreases to the level predicted by neoclassical transport. Micro-turbulence with a wave-number of 0.1-1mm^{-1}and a frequency of 20-500kHz, which is measured by two dimensional phase contrasting imaging, does not change as a temperature/pressure gradient develops to form the ITB while the increase of turbulence is observed in the outer region of the ITB. The measurement of the radial electric field by the heavy-ion-beam-probe (HIBP) diagnostic indicates that the radial electric field is negative (ion root) in the ion ITB region in contrast to the large positive radial electric field (electron root) in the electron ITB referred to as *Core Electron Root Confinement* (CERC). With regard to CERC in the case of central ECH, fluctuations with long distance correlation have been investigated at frequencies up to 10 kHz by ECE and reflectrometry to clarify the relation between meso-scale turbulence and non-local transport. An analysis of the transient response to edge cooling has revealed that the large scale coherent structure connecting the edge and the core regions invokes the non-local T_e rise.

The ion ITB is accompanied by spontaneous toroidal rotation and an *Impurity Hole* which generates an impurity-free core. An Impurity Hole is derived from an extremely hollow profile of carbon impurities which develops with the increase of the ion temperature gradient. This phenomenon is due to a large outward convection of carbon impurities in spite of the negative radial electric field which has been confirmed by the HIBP. The magnitude of the Impurity Hole is enhanced in the magnetic configuration with larger helical ripples and for higher Z impurities as shown in Fig.3. Another mechanism to suppress impurity contamination is impurity screening at the plasma edge with a stochastic magnetic field. The ratio of carbon line emissions reflecting the penetration and source indicates that the screening effect is enhanced by an increase of density. The 3-D simulation of edge plasma by the EMC3-EIRENE code has reproduced experimental observations and clarified the friction-force role in driving impurities downstream towards the divertor.

The study of magnetic-island dynamics with an RMP has clarified that a poloidal flow develops prior to the transition from growth to healing of the magnetic island. Electron cyclotron current drive has been used for control of rotational-transform profile and a GAM induced by energetic particles accompanied by a reversed-shear Alfvén eigenmode has been identified by the HIBP.

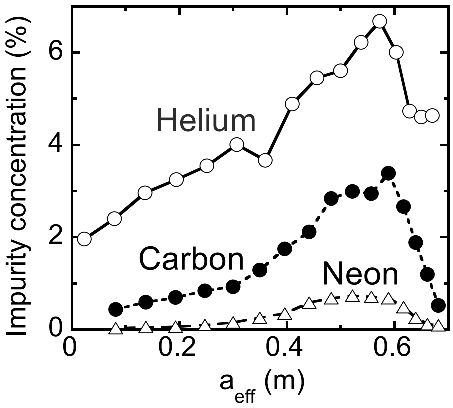

Fig.3 Profiles of impurity concentration for He, C and Ne in the plasma with an Impurity Hole. These impurities are injected intentionally and decrease to the shown level.

4 divertor tiles among 2,000 tiles have been replaced with graphite tiles coated with tungsten by using a vacuum plasma spray (VPS) method with a thickness of 100 μm to investigate the PWI properties of tungsten. All VPS tiles sufficiently withstood a single experimental campaign without any macroscopic damage. The deposition dominant area covered by C dominant deposits retains ten times more hydrogen than that of the erosion dominant area.

Radial electric field control by electrode biasing has been investigated for the first time in a large-scale helical plasma. The electrode current showed a decrease with the increase in the electrode voltage. The electrode characteristics with negative resistance have shown hysteresis and transition.

It should be noted that remarkable achievements are obtained by synergy of a strategic plan and sufficient preparation for new discovery. For example, the central electron temperature of 15 keV is a combined product of the development of a high-power gyrotron, optimization of confinement by reduced helical ripples and radial electric field, and improvement in the accuracy of Thomson scattering measurement. Identification of the atomic dependence of Impurity Hole is attributed to the combination of perpendicular NBI favorable to ion heating, confinement improvement leading to high ion temperature, improvement in accuracy of charge exchange recombination spectroscopy and quantitative evaluation based on an atomic database.

All the detailed analyses of accumulated data and their integration of knowledge will lead to further investigation in the 14th experimental campaign in 2010. Lastly, the excellent supporting work by the LHD operation group is greatly appreciated.

(Yamada, H. for LHD Experiment Group)