§41. Sustainability and Controllability of High Performance Plasmas in LHD

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This collaborative research aim at establishing a control method for sustaining high performance plasma through coordinating wide range of research field which relate to the plasma science and engineering such as the divertor and boundary plasma physics, steady-state operation, plasma-wall interactions, atomic/molecular processes, and plasma heating physics. One of the most important task is formulation and implementation of experiments of the plasma physics and engineering group in LHD. Scheduled experimental plan, however, cannot be carried out, since the LHD experiments has been canceled in fiscal 2015. Therefore, main research activity is focused on the data analysis of the previous experiment campaign. Main results of the collaborative research are as follows.

1) Divertor and boundary plasma physics

Three types of divertor heat load mitigation operations with divertor detachment discharges, i.e. impurity gas-puffing, resonance magnetic perturbation, and massive fuel gas-puffing, has been established in LHD. Further radiative loss enhancement, however, is required. A comparative study with a theoretical simulation model, which takes into account the three-dimensional geometry is progressing.

The closed divertor with in-vessel cryo-sorption pump is continued to develop from the 2010. The final design of the divertor has been completed in 2015 and it will be installed in 2016. By optimizing structure of divertor and activated carbon adsorbent properties, the pumping performance has been improved. 80 m^3/s pumping speed has been attained for the deuterium experiment campaign which start at the end of fiscal 2016.

2) Steady-state operation and plasma-wall interactions

Dynamic change of the wall pumping rate and termination of the discharge with impurity mixing have been investigated in the ultra-long pulse discharges.

The microscopic modification, such as helium radiation damage and mixed-material deposition layers due to the PWI were formed on the first-wall surface. The carbon based mixed-material deposition layer seems to cause the continuous wall pumping capability. However, since the trapping energy of the helium into that deposition layer is weak and trapped helium is dramatically released even at near room temperature ($\sim$ 400 K). Desorbed helium from this trapping site likely causes the dynamic change of the wall pumping rate.

The carbon based mixed-material deposition layer was hard and brittle. Such material properties likely affected the exfoliation feature of the mixed-material deposition layer. Two kinds of exfoliation scenario were proposed, and its information is helpful for predicting the mixing scenario of the mixed-material deposition layer to plasmas.

3) Atomic/molecular processes

Space- and time-resolved spectral measurements for various charge-state tungsten ions have been performed over a wide wavelength range from visible to EUV.

EUV spectra for Zr, Pt, Au, Pb, and Bi have been measured for the purpose of development of the soft x-ray microscope.

4) Plasma heating physics

Since fiscal 2012, two high-power 154 GHz gyrotrons were newly installed in the ECH system, additionally to the previous three 77 GHz gyrotrons. Due to the higher frequency, effective heating of higher density plasmas up to 14.7×10^{19} m^{-3} was successfully demonstrated. The 154 GHz gyrotrons also worked well for the long pulse discharges.

In the ICH system, two new-type antennas named HAS and FAIT were applied. The EVITs (Ex-Vessel Impedance Transformer) installed in the transmission lines of the HAS antennas increased the injection power by a factor of 2. Then the EVITs were also installed for the FAIT antennas. Further increase in the power from the FAIT antennas are expected.

In the heating technique, major improvement of the ray-tracing code LHDGauss realized precise power deposition control of EC-waves and increase in the heating efficiency by referring to the real 3D equilibrium data of TSmap, considering the plasma region extended outside the last closed flux surface, and fast computing. Control of hydrogen/helium ratio H/(H+He) to the optimum value for ICH system, 15 %, reduced a fraction of high energy ion tail generated by ICH and contributed to the increase in the heating efficiency and stable long pulse discharges.

Owing to the improvements described above, significant achievements in the plasma parameters such as

- High electron temperature: $T_e(0) = 10.5$ keV at $n_e^{ave.} = 2 \times 10^{19}$ m^{-3}, with the ECH power of 5.4 MW
- High ion temperature due to ICH/ECH wall conditioning: $T_i(0) = 8.1$ keV by NBI
- Simultaneous achievement of high ion and electron temperatures: $T_i(0)$ =6.0 keV and $T_e(0) = 7.6$ keV
- Long pulse discharge by ICH and ECH: 48 min., $T_e(0) = T_i(0) = 2$ keV, $n_e^{ave.} = 1.2 \times 10^{19}$ m^{-3}, with the ICH+ECH power of 1.2 MW
- Long pulse discharge by ECH: 39 min., $T_e(0) = 2.5$ keV, $n_e^{ave.} = 1.1 \times 10^{19}$ m^{-3}, with the ECH power of 0.35 MW
- High β: $\beta = 4.1$ % at $B = 1$ T by NBI+ICH