II. Research Activities

1. Large Helical Device (LHD) Project

1-1. LHD Experiment

Overview of LHD Experiment

FY2015 was the final year before starting the deuterium experiment. Although the LHD experiment was not performed, many collaborations with universities and research institutes were carried out, utilizing the accumulated experimental results and the database. Numerical codes were, of course, combined with data analyses. Some important results were obtained, as expressed below.

Towards the deuterium experiment, a preparatory research to investigate the effect of mass difference upon the plasma performance was performed. In the experiment, helium was used in place of deuterium, which has four times the mass of hydrogen. A composite gas of hydrogen and helium was employed, and the plasma was generated and heated by neutral beam injection. Ion temperature (intrinsic carbon impurity) was measured with charge exchange recombination spectroscopy, changing the composition ratio as expressed in Fig. 1. It is found that the greater the amount of helium in the plasma, the higher the ion temperature we achieved. (See the closed squares.) On the other hand, the numerical simulation with the TASK3D code was conducted in parallel with this experiment. It was demonstrated that the ion temperature was nearly constant irrespective of the helium composition. (See the open circles.)

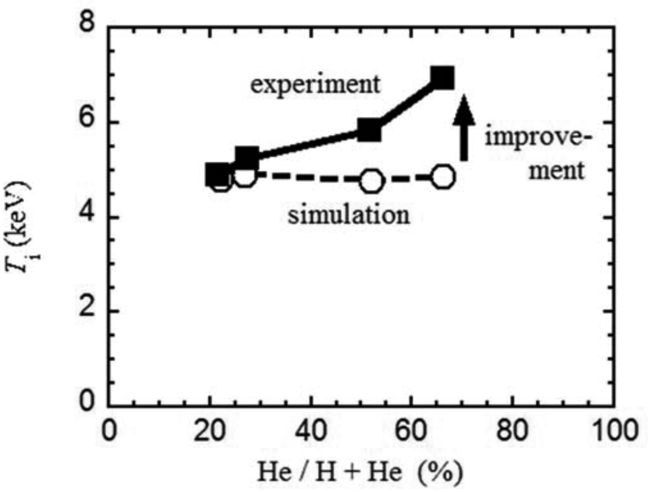

Fig. 1 Ion temperature (closed squares), as a function of helium composition ratio. Numerical result is also depicted (open circles).

The result in which the temperature obtained by experiment is higher indicates the possibility that heretofore hidden factors for the confinement improvement (the isotope effect) may be found in plasma. These experimental and numerical results are quite encouraging, although it is not the perfect simulation for the mass effect since the electric charge of helium is also different. (Nagaoka, K., Murakami, S.)

Steady progress was made in the impurity transport study. In order to explain the drastic suppression of impurity accumulative behavior during high power NBI heating, so called impurity hole, a database of carbon density profiles from steady state hydrogen discharges without impurity accumulation is constructed. It was found that the hollowness of carbon profile becomes stronger with decreasing the background ion collisionality. The radial electric field also increases with decreasing the ion collisionality and becomes positive so as to drive the impurities outward. However, the neoclassical impurity flux density due to E_r is too low to explain the strong outward convection at around mid-radius. A strong correlation is visible between the ion temperature gradient and the logarithmic gradient of carbon density. Since temperature gradients are the primary quantity in determining the characteristics of turbulent modes, the correlation provide a strong signature that turbulence is important in the impurity transport. One of most probable candidates for anomalous impurity transport is turbulence such as the ITG mode, which can be driven in high temperature plasmas in LHD, and drives the impurities outward. (Nakamura, Y.)

As for the impurity transport in the edge stochastic region, so called “impurity screening”, has been studied in LHD. The theoretical modelling explains that the parallel momentum balance on impurity ions in the stochastic region determines the direction and quantity of the impurity flow, which can be the key mechanism driving the impurity screening. In the last experimental campaign, precise profile measurements of the impurity flow were performed with the space-resolved VUV spectroscopic technique. Fig. 2 shows a full vertical profile of C^{3+} impurity flow evaluated from Doppler shift of the second order of CIV line emission (2 × 1548.20 Å) for a hydrogen discharge with $n_e = 6.0 \times 10^{19}$ m^{-3} and P_{NBI} = 10 MW. The horizontal axis, Z (mm), is the vertical position of observation chords at R = 3.6 m. The measured flow velocity in Fig. 2 is the projection of the flow along the observation chord which can be approximately considered to be the direction of the plasma major radius. It is found that the carbon flow at the top and bottom edges in the stochastic region has the same direction toward the outboard side along the major radial direction. The simulation result of C^{3+} impurity flow parallel to the magnetic field lines calculated with a three-dimensional simulation code, EMC3-EIRENE is also plotted with a dashed line in Fig. 2. It indicates that the major radial component of the flow has the same direction toward the outboard side at the top and bottom edges in the stochastic region. The experiment and the simulation agree well with each other quantitatively, which concludes that the parallel flow in the stochastic region can be well explained by the presently used theoretical modelling. (Oishi, T.)

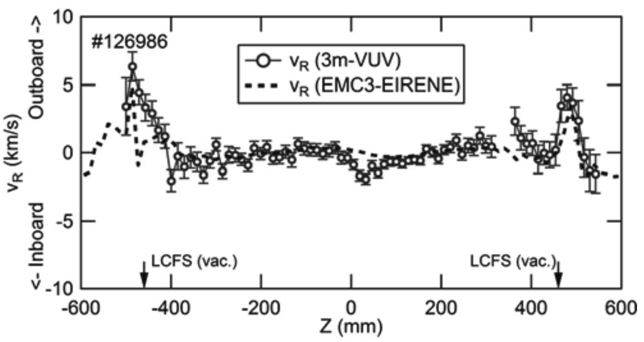

Fig. 2. Vertical profile of C^{3+} impurity flow measured by VUV spectroscopy. A synthetic profile of the C^{3+} flow simulated with EMC3-EIRENE code is also plotted with a dashed line.

Using the LHD high temperature plasma, fundamental study of atomic physics in highly charged ions of lanthanide elements (Z=57–71) was performed, where relativistic effects and multi-electron correlation play an important role. In spite of growing interest not only in pure atomic process study but also in industrial application for the next generation light sources of EUV lithography, the spectroscopic data and atomic process models for these elements are still insufficient. In this study, EUV spectra from highly charged ions of lanthanide elements with Z=60–70 were dealt with. Lines of Tb (Z=65), Ho (Z=67) and Tm (Z=69) observed in this study have not been experimentally identified in former studies. Consequently, the present study gives the first experimental identification of the spectral lines of Cu-like ions for these elements. The wavelengths for other elements are in excellent agreement with those in the former study. (Suzuki, C.)

Along with the new experimental results described above, other essential results concerning the preparatory activities for the deuterium experiment were obtained. On December 10, 2015, the domestic meeting about experiment planning for the LHD deuterium experiments was held at NIFS in order to facilitate discussions on it. More than 90 researchers participated. After the reports on basic plans, safety management, and diagnostics capabilities in the deuterium experiment, presentations on physics topics (major targets of deuterium experiment) such as isotope effect, energetic particles confinement, plasma-wall interaction, steady state operation, and the neutron applications were made from collaborators in universities and NIFS staffs. Based on and following the domestic meeting, the international workshop on the LHD deuterium experiment was held on February 9 and 10, 2016 at NIFS, to share the past progress and present status, and then to discuss future directions with international collaborators. In order to increase understandings and clarifications of the isotope effect, necessity of cutting-edge diagnostics, theory and simulation were mentioned. Suggestions for comprehensive research including atomic and molecular dynamics, deuterium experiment plans in the experimental facilities in Asian region and its collaboration possibilities with LHD were also reported. In the summary session, it was agreed by participants that further continuous discussions should be promoted to maximize the outcome of the LHD deuterium experiment. From the LHD experiment board, establishment of the LHD international program committee (IPC) for the LHD deuterium experiment was suggested, and it was also fully agreed.

The LHD is almost ready to start the deuterium experiment. Necessary facilities and devices for the experiment and safety management have been equipped. In November in 2016, the absolute calibration for neutron detectors will be done, and the experiment will start with hydrogen from February in 2017, then switch to deuterium in March.

Finally, achieved plasma parameters with hydrogen up to the 18th experimental campaign are summarized in Table 1 with the targets of the LHD project.

Table 1 Achieved and targeted plasma parameters. New data obtained in the 18th experimental campaign are written in bold.

parameter	achieved	target
Ion temperature	8.1 keV at $n_{e0} = 1 \times 10^{19}\mathrm{m}^{-3}$	10 keV at $2 \times 10^{19}\mathrm{m}^{-3}$
Electron temperature	**10 keV** at $n_{e0} = 1.6 \times 10^{19}\mathrm{m}^{-3}$	10 keV at $2 \times 10^{19}\mathrm{m}^{-3}$
Simultaneous achievement of high T_i, T_e	T_{i0} = 6.0 keV T_{e0} = 7.6 keV at $n_{e0} = 1.2 \times 10^{19}\mathrm{m}^{-3}$	
Long pulse	47 min. 30 sec. P = 1.2 MW T_{i0} = 2.0 keV T_{e0} = 2.0 keV at $n_{e0} = 1 \times 10^{19}\mathrm{m}^{-3}$	1 hour P = 3 MW
beta	**4.1 %** at B_T = 1 T	5 % at B_T = 1-2 T

Lastly, all contributions from domestic and international collaborators, and excellent support by engineering and operation group in NIFS are greatly appreciated.

(Morisaki, T. for LHD Experiment Group)