§10. Exploration of Advanced Plasma Heating Scenarios in the Large Helical Device

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In FY2014, significant progresses on heating systems were accomplished. In regard to ECH system, one additional high power 154 GHz gyrotron (154 GHz #2) became available for LHD experiments. Together with the existing three 77 GHz gyrotrons and a 154 GHz #1, the total injection power to LHD was increased up to 5.4 MW in the 18th experimental campaign, while it was 4.6 MW in the 17th campaign. Two new antennas were installed on 2-O port. One (2-OUL) is used for 154 GHz #2, and the other (2-OUR) is used for one of the three 77 GHz gyrotrons.

In regard to ICH system, additional impedance transformers were installed on the transmission lines of HAS antennas, to decrease the maximum voltage on the transmission line so that higher injection power can be achieved. A Faraday shield on lower PA antenna was removed to decrease the risk of arcing at the Faraday shield during high power operation. Note that the Faraday shield for the upper PA antenna had been already removed. Due to these modifications, together with a pair of FAIT antennas, the total injection power to LHD was also increased from 3.4 MW (in the 17th campaign) to 4.5 MW (in the 18th campaign).

Applying the high powers from ECH, ICH and NBI, parameters of the LHD plasmas were enhanced significantly as follows: high central electron temperature T_{e0} of 10 keV at line average electron density n_{e_ave} of 2×10^{19} m^{-3}, high T_{e0} of 7.6 keV and high central ion temperature T_{i0} of 6 keV simultaneously, and high beta value of 4.1 % at the magnetic field strength of 1.0 T.

Using the improved heating systems, various physics experiments were performed. Power absorption efficiencies η of EC-waves injected from top port (5.5-U) and horizontal port (2-O) were precisely evaluated at various n_{e_ave}, while the vacuum EC-wave beams were directed toward and focused at the vacuum magnetic axis. η in the case of U-port injection decreases with n_{e_ave}, while in the case of O-port injection, the dependence is weak. These results agree with prediction of the EC-wave ray tracing code, LHDGauss. Rays and power depositions are calculated by the code under the temperature and density profiles based on the measured ones. According to the code, EC-waves are refracted by plasmas significantly at a high density regime, and the effect on heating becomes serious for the U-port injection. Using the results of LHDGauss, EC-wave beam direction of the antenna at 5.5-U was optimized, and T_{e0} increased from 6 keV to 7.5 keV when n_{e_ave} was about 1.3×10^{19} m^{-3}.

Trial and preparation of feedback control of EC-wave beam direction and polarization were performed for the first time. Direction of EC-wave beams injected from 2-OUL (77 GHz) antenna was feedback controlled referring to an ECE signal. It was found that further experiments are required to make the result noticeable. In addition, polarization angle α, measured from toroidal direction, of EC-wave beams injected from 77 GHz 5.5-U antenna was scanned quickly in the angle range 25 - 65 deg. within ~1 s (i.e., during a discharge), keeping ellipticity β at nearly 0 deg. The highest η of ~95 % was obtained at α~45 deg. These angles (α~45, β~0 deg) coincide with the values used in the previous exp. campaigns, showing that the quick polarization scan is reliable.

ICH was applied to low B plasmas intended to achieving a high total beta β_{total}. In the experiment with B = 1.375 T, injection of 4.5 MW ICH power caused clear increase in plasma stored energy W_p and β_{total}. From the changes in W_p, η was evaluated as ~40 %. The heating mechanism is considered to be second harmonic resonance heating of applied IC-waves at the frequency of 38.5 MHz.

Applying ICH power to the plasmas with lower B of 1.0 T, we have successfully obtained the highest β_{total} value (4.1 %) of LHD plasmas at B = 1.0 T. Plasmas were generated and sustained with high power NBIs up to 27 MW in total. A number of ice hydrogen pellets were injected to the plasma to increase the density and β_{total}. ICH power of 3 MW was applied at around the timing when the highest density was obtained. After the timing of the density maximum, the density starts to decrease, while β_{total} increased and shows a peak about 100 ms later. Although the effect of ICH was not noticeable in each discharge, improvement by ICH becomes clear when we analyze many discharges, and compare β_{total} for the cases with and without ICH.

Furthermore, research on the following issues were performed: reliable plasma start up by 77 GHz ECH powers injected from 2-O port, trials of OXB heating and BXO radiation measurement, intense ECCD by use of two 2-O 77 GHz antennas, dependences of η of 3rd harmonic X-mode ECH on n_{e_ave} and beam aiming direction, dependence of η of ICH on phase difference between voltages on the paired antennas, sustainment of high density plasmas by high power ICH, investigation on heat transport by harmonic components of ECH power modulation, and so on.

Acknowledgements

The authors would like to express their thanks to NIFS staff for performing the LHD experiments. This work was supported by the LHD project (NIFS ULRR701, 703, 801, 804, 806, KLPR016, 030, KUGM051).