Development of high-power, long-pulse gyrotrons and its application for high electron temperature, EBWH and ECCD experiments on LHD

Y. Yoshimura, S. Kubo, T. Shimozuma, H. Igami, H. Takahashi, M. Nishiura, S. Ito, S. Kobayashi, Y. Mizuno, K. Okada, Y. Takita, T. Mutoh, H. Yamada, A. Komori, T. Kariya[1)], T. Imai[1)]
National Institute for Fusion Science, Toki, Japan
[1)]University of Tsukuba, Tsukuba, Japan

To sustain plasmas with higher temperature and density, and with longer pulse duration in LHD, ECH system has been upgraded for recent years. The first high-power, long-pulse 77 GHz gyrotron was introduced to the ECH system in 2007. The second one was introduced in 2008 and the third one in 2009, by replacing with the existing pulse-operational (up to 1 s) 168 GHz gyrotrons. The designed output power and operation duration time are over 1 MW for several seconds and 0.3 MW for continuous operation, respectively. Owing to the upgrade of gyrotrons and improved power supply operation procedure, total injection power of EC-waves (by three 77 GHz, one 84 GHz and one 82.7 GHz gyrotrons) to LHD increased up to 3.7 MW at the last LHD experimental campaign in 2010.

Application of the high-power in focused EC-wave beams to the center of plasma with low line-average electron density n_e of ~0.2×10^{19} m^{-3} causes highly steep electron temperature profile and the central electron temperature T_{e0} reached up to 20 keV, which highly exceeds the former record of 15 keV. At higher n_e region of 1×10^{19} m^{-3}, T_{e0} reached 8.6 keV.

Additional EBWHs: O-X-B and slow X-B heatings, with up to 1.08 MW by one 77 GHz ECH system caused clear increase in plasma stored energy even for the high-density plasmas over plasma cutoff (>7.35×10^{19} m^{-3}) sustained with higher-power NBI (up to 5 MW). For the O-X-B scenario, the 77 GHz EC-wave was obliquely injected from low-field side (LFS) in O-mode polarization, aiming at the point where high-mode conversion efficiency was expected in previously performed calculations. For realizing slow X-B scenario, a new inner-vessel mirror was installed in LHD just close to a helical coil, that is, at the high-field side (HFS) region. The new HFS mirror reflects the EC-wave beam injected from existing LFS mirror so that an X-mode EC-wave beam injection from HFS (slow X-mode wave injection) is realized. The ray tracing analysis using the experimental density and temperature profiles provides the heating scenario mentioned below. The X-mode wave propagates through the fundamental resonance layer, where some fraction of the wave is absorbed. The residual power is mode-converted to the Bernstein wave at the UHR layer then propagates toward the Doppler-shifted ECR layer and is absorbed there.

Also, oblique injection of long-pulse 0.77 MW/8 s 77 GHz wave with various $N_{//}$ clearly demonstrated ECCD in LHD. The EC-driven current changes its direction with the sign of $N_{//}$, and the highest EC-driven current reached up to 42 kA.

A long-pulse discharge of 120 s duration, with n_e of 0.2~0.3×10^{19} m^{-3} and T_{e0} of 4 keV, was sustained with ~0.6 MW EC-wave power from three 77 GHz and one 84 GHz gyrotrons.

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