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High-Field Side Injection of EC-Waves for Electron Bernstein Wave Heating in LHD

LHDにおける電子バーンシュタイン波加熱のためのEC波高磁場側入射

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To realize an excitation of electron Bernstein waves via mode conversion from X-mode waves injected from high magnetic field side (HFS), new inner-vessel mirrors were installed close to a helical coil in the large helical device. 77 GHz electron cyclotron (EC) wave beams injected from an existing EC-wave injection system toward the new mirror are reflected on it so that the beams are injected to plasmas from HFS. Evident increases in electron temperature at the plasma core region and plasma stored energy have been observed by the HFS beam injection to the plasmas with the line-average electron density higher than the plasma cut-off density of 77 GHz EC-waves, 7.35×10^{19} m^{-3}. The heating efficiency evaluated from the change in the time derivative of the plasma stored energy reached up to 70%.

1. Introduction

Electron Bernstein wave (EBW) heating is considered as a very promising electron cyclotron heating (ECH) scheme to heat plasmas with the density higher than the EC-wave's cut-off density, that is, overdense plasmas. To realize EBW heating, so-called O-X-B and X-B techniques have been investigated [1-9].

The helical systems such as Compact Helical System (CHS) and Large Helical Device (LHD) provide good opportunities to investigate the slow X-B heating scenario, in which an X-mode wave is injected to plasmas from the high magnetic field side (HFS), through a fundamental resonance layer (FRL). The X-mode wave reaches at an upper hybrid resonance (UHR) layer and is mode-converted to an EBW, and then the EBW is expected to be absorbed at Doppler-shifted FRL.

Since the plasma confining magnetic field is generated with a pair of helical coils, the magnetic field configurations of these devices have two X-B access windows in a poloidal cross section. In a vertically elongated poloidal cross section, one window exists at the inner side of the torus while the another one at the outer side. In a horizontally elongated poloidal cross section, two windows open at the upper and the lower sides. There is no enough space at the inner side of the torus, similar to tokamaks. On the other hand, at the upper, lower or outer sides of the torus, a wider space is available for installing a mirror to reflect EC-wave beam for HFS injection.

By installing a mirror inside the CHS vacuum vessel, slow X-B experiments have been performed and effective heating in overdense plasmas was observed [7, 8]. Also in LHD, slow X-B experiment using newly installed inner-vessel mirrors was started.

2. Experimental Setup

LHD is a helical device with the toroidal period number m = 10 and the polarity l = 2. The magnetic field structure with the rotational transform for plasma confinement is generated totally by the external superconducting magnets such as a couple of helical coils and three pairs of poloidal coils. The major radius R_{ax} of LHD plasma can be varied in a range of 3.42 ~ 4.1 m. In the case of R_{ax} = 3.6 m, the averaged minor radius is 0.6 m.

As for the ECH system used in this study, the frequency of EC-waves is 77 GHz, that is, the fundamental resonant magnetic field is 2.75 T. In the conventional ECH scheme, the EC-waves are injected from the low-field side (LFS): from a horizontal outside port of LHD. The FRLs of 2.75 T exist at the upper and lower parts of the plasma. The EC-wave beams are injected from LFS toward the FRLs in the horizontally elongated poloidal cross section or toward the FRL in the neighboring vertically elongated poloidal cross section by toroidally oblique beam injection.

In addition to the existing EC-wave beam injection system described above, a set of new plane mirrors was installed inside the vacuum vessel between plasma and an upper helical coil. By directing EC-wave beams from the existing injection system to the new mirror, a beam injection of 77 GHz EC-wave from HFS becomes possible.

3. Experimental results in the EC-wave HFS injection experiment

An experiment of 77 GHz EC-wave beam HFS injection in LHD was performed to investigate the possibility of realizing the slow X-B heating scheme for overdense plasmas. An example of the waveforms of the plasma stored energy W_p in the discharges is seen in Fig. 1. The target high-density plasmas were generated with 300 ms ECH, and the plasmas were heated and sustained with 4 neutral beam injection (NBI) systems. Gas-puffing was applied to increase the electron density, and the high-density plasmas were sustained with one of the NBIs from 4.5 s to 5.5 s, with the power of 5 MW. Four ECH pulses of 25 ms pulse width with 25 ms intervals were injected from 5.203 s to 5.378 s, to the high-density target plasmas. The line-average electron density $n_{e\text{-ave}}$ was ~7.5×10^{19} m^{-3}, while the cut-off density of the 77 GHz waves is 7.35×10^{19} m^{-3}. The injection power was 775 kW. The heating efficiency evaluated from the change in the time derivative of W_p reached up to 70%.

Figure 2 shows the electron temperature T_e distributions at two timings of 5.2 s: just before the start of EC-wave injection period and 5.4 s: just after the period. A hollow electron density distribution at 5.2 s is also plotted. Although the plasma core region is surrounded with overdense plasma with the density higher than the 77 GHz cut-off, T_e at the core region increased by ~ 40 eV.

4. Conclusions

An injection of EC-wave from HFS using newly installed inner-vessel mirror, to realize EBW heating, was performed. So far, distinction of the heating effects by fundamental X-mode heating and X-B heating is not clear, but the increases in the stored energy, with the heating efficiency of ~70%, and electron temperature at the core region of overdense plasmas were observed. Those heating effects show an effectiveness of the EC-wave HFS injection for the plasma heating over plasma cut-off.

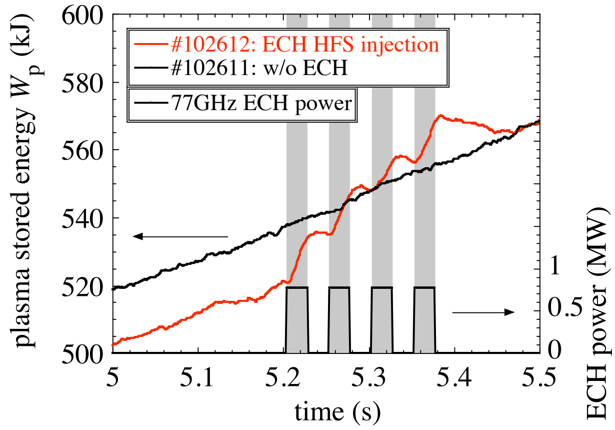

Fig.1 Waveforms of the plasma stored energy in the cases of with and without ECH pulses

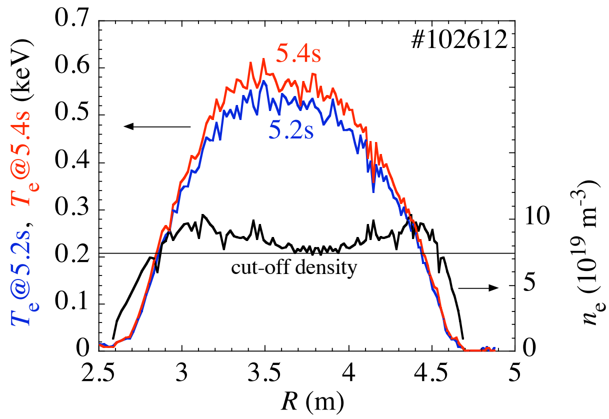

Fig.2 Electron temperature and density distributions just before and after the ECH pulses

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