Experimental conditions for electron Bernstein wave heating by use of EC waves injected from high-field side in CHS

Y. Yoshimura, K. Nagasaki[a], S. Ferrando-Margalet, T. Akiyama, M. Isobe, A. Shimizu, C. Suzuki, C. Takahashi, K. Nagaoka, S. Nishimura, T. Minami, K. Matsuoka, S. Okamura, CHS group, S. Kubo, T. Shimozuma, H. Igami, H. Takahashi, and T. Mutoh

National Institute for Fusion Science,322-6 Oroshi-cho, Toki 509-5292, Japan

[a] Institute of Advanced Energy, Kyoto University, Uji 611-0011, Japan

In the Compact Helical System (CHS), electron heating by electron Bernstein waves was experimentally investigated to study a technique for the high-density plasma heating over cutoff. The EBWs are excited through mode conversion process from X-mode waves injected to plasmas from the high-field side. In the experiment, within a range of oblique EC wave beam injection angle, evident heating effect was observed. Dependences of the heating effect on the wave's polarization and the toroidal injection angle show that the absorption of the mode-converted EBWs should be the cause of the plasma heating effect.

Keywords: electron Bernstein wave, EBW, slow X-B, high-density plasma heating, high-field side injection, ECH, CHS

1. Inroduction

Electromagnetic (EM) plasma waves such as ordinary (O) or extraordinary (X) mode waves suffer cutoff in high-density plasmas, and the EM plasma waves cannot contribute to electron heating over the cutoff density. Electron Bernstein (B) waves, on the other hand, have the advantages of an absence of density limit and a strong absorption even in low-temperature plasmas. Since the B-waves are a kind of electrostatic wave in plasmas, they have to be excited by means of mode conversion processes from injected EM-waves. Three types of mode conversion process are considered: the so-called fast X-B, slow X-B, and O-X-B. Among them, the O-X-B mode conversion technique [1] has been considered the most promising way to heat overdense plasmas because ECH systems including steerable beam injection antennas from the low-field side are technically available on existing tokamaks and helical systems [2-6].

Compared to the O-X-B process, the slow X-B process can more simply and easily realize mode conversion to B-waves, since the difficulty of achieving high O-X mode conversion efficiency does not exist. When injected through a fundamental resonance layer from the high-field side (so called the X-B access window), the X-mode EC-waves propagate into the plasmas and are mode converted into the B-waves at the upper hybrid resonance (UHR) layer. The B-waves are absorbed at the Doppler-shifted electron cyclotron resonance, resulting in plasma heating. When injected away from the X-B access window, the X-mode EC-waves suffer right-hand cutoff and cannot heat the plasmas effectively.

So far in the WT-3 tokamak, using an O-X polarization twister installed at the high-field side, B-wave heating was performed by injecting O-mode EC-waves to avoid the right-hand cutoff of X-mode waves [7]. Also in the COMPASS-D tokamak, electron heating and current drive by the high-field side X-mode injection were demonstrated [8]. However, generally speaking, EC wave injection from the high-field side (that is, from the inner side of the torus) is accompanied with difficulties due to insufficient available space for installing an EC-wave injection antenna system or a reflection mirror.

The Compact Helical System [9] provides a good opportunity to investigate the slow X-B heating scenario experimentally, since due to its two helical coils generating plasma confining magnetic field, it has two X-B access windows in the poloidal cross section. In the vertically elongated poloidal cross section, one window is at the inner side of the torus in a position similar to tokamaks, while the other is at the outer side where a wider space is available for installing an elaborate structure such as the movable mirror for beam direction scan, as seen in Fig. 1. Installing a mirror inside the CHS vacuum vessel, the slow X-B experiments were performed [10]. In this paper, the dependences of the slow X-B heating effect on the wave's polarization and the beam direction are presented as follows. The experimental setup such as CHS and the EC wave injection system are described in Sec. 2. The slow X-B experimental results are presented in Sec. 3. Then Sec. 4

author's e-mail: yoshimura.yasuo@LHD.nifs.ac.jp

summarizes the contents of this paper.

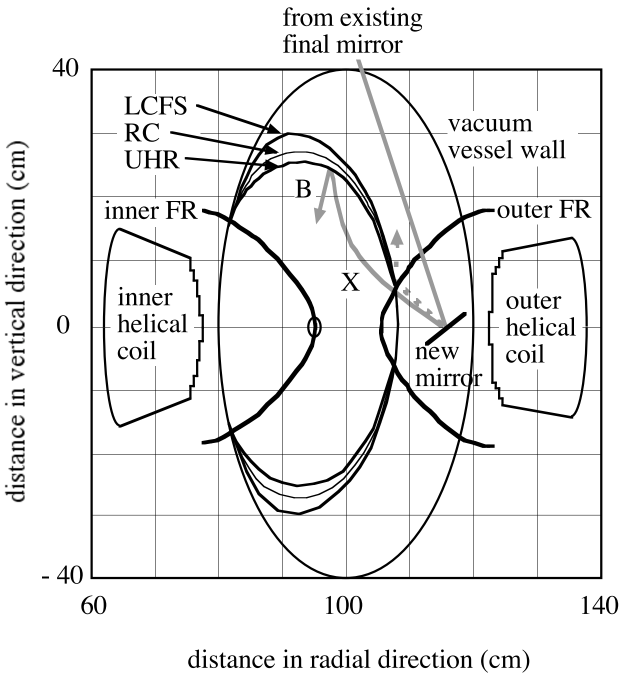

Fig. 1 Experimental configuration for slow X-B experiment.

2. Experimental Setup

The CHS is a helical device with the toroidal period number m = 8 and the polarity l = 2. The magnetic field structure with the rotational transform for plasma confinement is generated totally by the external coils such as a couple of helical coils and three pairs of poloidal coils. The major radius of CHS plasma is about 1.0 m and the averaged minor radius is 0.2 m, so that the aspect ratio is 5. The magnetic field at the plasma axis can be set up to about 2.0 T.

The ECH system on CHS furnishes two gyrotrons. The operating frequency of one of them is 54.5 GHz and that of another one is 106.4 GHz. The slow X-B experiments described in this paper were performed with the 54.5 GHz one. The transmission line for the 54.5 GHz waves was constructed as a quasi-optical Gaussian beam transmission system using 12 mirrors, three of them inside the CHS vacuum vessel and two of them l/4 and l/8 grating polarizers. The three inner-vessel mirrors are installed on the top port and the final plane mirror can be tilted 2-dimensionally so that the injected EC-wave beam direction can be scanned in both the poloidal and toroidal directions. The beam injections from the top port result in the injections from the low-field side. The injected EC-wave beams are circularly focused having the beam size (1/e radius of the electric field amplitude) of 22 mm at the equatorial plane. Using the two polarizers, the polarization of EC-wave beams can be varied arbitrarily. The total length between the gyrotron output window and the CHS plasma center is about 17 m. The maximum injection power and pulse length of the 54.5 GHz waves to the CHS vacuum vessel are 415 kW and 100 ms, respectively.

In addition to the existing EC-wave power injection system described above, a new plane mirror was installed inside the vacuum vessel between plasma and an outer helical coil. By directing the EC-wave beam from the existing antenna system at the top port to the new mirror, an injection of 54.5 GHz EC-wave from the high-field side becomes possible. The beam is reflected 39 degrees upward and can be steered in the toroidal direction by tilting this new mirror toroidally. The experimental configuration is schematically drawn in Fig. 1.

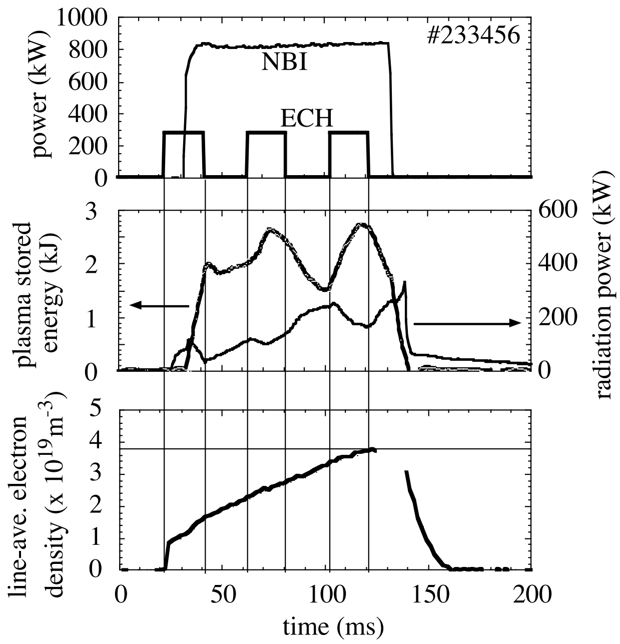

Fig. 2 Waveforms in the slow X-B discharge.

3. Dependences of heating effect on the EC-wave beam direction and the polarization

Figure 2 shows a typical time evolution of a discharge of the slow X-B heating. An EC-wave power of 275 kW was obliquely injected in three pulses during the discharge at incidence angles of 20 degrees counterclockwise in the toroidal direction and 39 degrees upward. The wave polarization was set at nearly the X-mode. The first pulse was for plasma generation, and the second and the third ones were applied to the plasmas sustained with 845 kW neutral beam injection (NBI). The plasma stored energy significantly increased with the second and the third injections of ECH power. The central electron temperature increased from about 1.0 to 1.5 keV by the second injection and from about 0.6 to 1.2 keV by the third injection, while the line-average electron density linearly increased during the plasma duration. The increases in the plasma stored energy were then caused by increases in the electron temperature. The electron temperature profiles measured using Thomson scattering measurement during and just before the third ECH power injection are plotted in Fig. 3. It can be clearly seen that the electron heating occurred at the plasma core region, not at the peripheral region where the outer fundamental resonance layer exists. The heating effect is considered to be a result of the B-wave heating, and the resultant improvement in NBI heating efficiency and reduction in radiation power from the plasma.

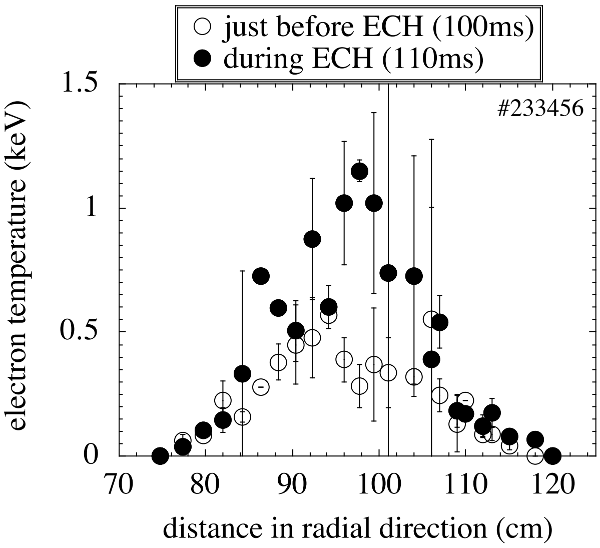

Fig. 3 Electron temperature profiles just before EC-wave injection and during injection measured using Thomson scattering measurement.

At the third injection timing of this discharge, the line-average electron density reached close to the O-mode cutoff density of $3.8\text{x}10^{19}$ m^{-3} for the 54.5 GHz EC-waves. In other discharges, the heating effect was also observed for plasmas even with the density over the O-mode cutoff. The magnetic field on the plasma axis was set at 1.95 T, that is, the fundamental resonance magnetic field of the 54.5 GHz EC-waves. Here, an essential point regarding the magnetic field setting is not the on-axis resonance condition but the presence of another fundamental resonance layer in the plasmas (X-B access window) in front of the new mirror as seen in Fig. 1.

In the toroidal scan of the EC-wave beam direction, effective plasma generation and significant plasma heating occurred only at the counterclockwise injection. Otherwise, the plasmas could not overcome the radiation barrier. This dependence can be understood as follows. Due to the rather upward (39 deg) beam reflection from the new mirror, the beam path is beyond the range of the X-B access window when the beams are injected with a toroidal incidence angle of around 0 degrees or clockwise. However, because the helical coil winding of the CHS is left-handed, that is, the vertically elongated poloidal cross section rotates counterclockwise around the magnetic axis with the toroidal angle, the X-B access window moves upward and “opens” for beams injected counterclockwise.

In the polarization scan of the injected EC-waves, it was confirmed that the heating effect degraded when the polarization was set at nearly O-mode. Figure 4 shows the variation of the direction of the magnetic field along an EC-wave beam path which aims at the magnetic axis and is injected perpendicularly to the flux surfaces. The beam path is on the equatorial plane. The definition of the angle is as follows. Looking from outside of the torus, the toroidal direction in the right side is 0 deg, and the angle increases counterclockwise. At the LCFS, the direction is -13 deg. In the perpendicular injection case, the O-mode injection is realized by setting the linear polarization with the electric field oscillation in the direction of -13 deg, and the X-mode in the 77 deg.

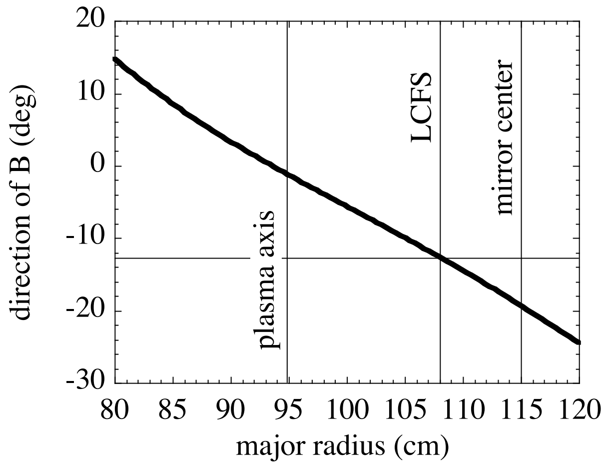

Fig. 4 Variation of the magnetic field direction along a beam path perpendicular to the flux surfaces.

The dependence of the heating effect on the linear polarization direction is plotted in Fig. 5. The heating effect is evaluated with the value of the plasma stored energy during EC-wave injection divided by that just before injection. Only at the polarization direction of -10 deg, the heating effect vanished. In the slow X-B experiment the EC-waves were injected obliquely, then the linear polarization with the direction of -13 deg does not mean the pure O-mode but the O-mode purity is considered high. This plot shows that the X-mode component is important for the heating, and that the mode conversion to the B-wave would be the key for the plasma heating. Setting pure O- and X-mode polarization by the elliptical polarization would make the dependence clearer.

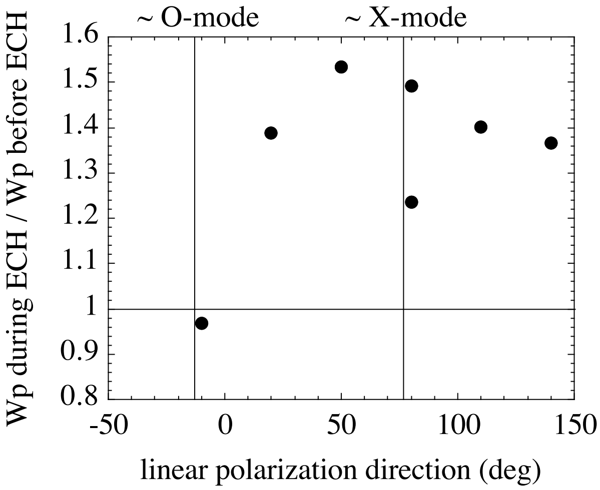

Fig. 5 Dependence of the heating effect on the polarization of the EC-waves.

The numerical calculations to confirm the realization of slow X-B heating in the experimental configuration are under investigation. Some of the results can be seen in this conference [11].

4. Conclusions

In CHS, the slow X-B heating technique was investigated by using an inner-vessel mirror which enables the EC-wave beam injection to plasmas from the high-field side through the fundamental resonance layer. As a result of the beam direction scanning, the increases of the plasma stored energy and the electron temperature were performed only when the EC-wave beams were injected through the X-B access window. The polarization scanning experiment showed that nearly O-mode polarization had no heating effect. Those results and dependences show that the slow X-B heating was realized in CHS.

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