Electron Bernstein Wave Heating through Slow X-B Mode Conversion in CHS

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Evident increases in plasma stored energy have been observed in the Compact Helical System (CHS) by injecting nearly X-mode-polarized 54.5 GHz electron cyclotron (EC) waves from the high-field side. An additional plane mirror that enabled the high-field side injection of the EC waves was installed. The centrally peaked and increased electron temperature distributions with the X-mode wave directions which are not aimed at the fundamental resonance layer at the plasma core region strongly suggest that the heating effects occurred due to the excitation of the electron Bernstein waves via mode conversion from the X-mode waves injected from the high-field side.

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 angle range of beam injection through a fundamental resonance layer from high-field side, i.e., the so-called "X-B access window", is much wider than the angle range for the O-X-B process. When injected through 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. 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]. The Compact Helical System [8] provides a good opportunity to investigate the slow X-B heating scenario experimentally, since due to its two helical coils 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.

This paper presents recent experimental results that show evidence of direct slow X-B heating in the CHS. A new plane mirror was installed inside the vacuum vessel between plasma and an outer helical coil. By directing the beam from the existing antenna system to the new mirror, an injection of 54.5 GHz EC-waves from the high-field side became possible. The beam is reflected upward and steered in the toroidal direction by this new mirror. The experimental configuration is schematically drawn in Fig. 1.

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 about 50 degrees upward. The wave
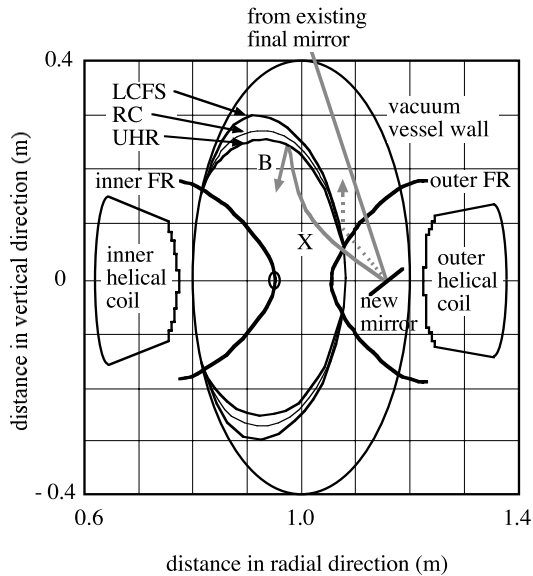
Fig. 1 Experimental configuration for X-B heating drawn based on the data taken at 110 ms of the discharge plotted in Fig. 2. The abbreviations LCFS, RC, UHR, FR, X, and B indicate the last closed flux surface, right-hand cutoff, upper-hybrid resonance, fundamental resonance (1.95 T magnetic field for 54.5 GHz waves), X-mode wave, and electron Bernstein wave, respectively. The EC-wave beam path which suffers right-hand cutoff (gray dashed line) and that for X-B mode conversion (gray line) are also drawn, though the beam path within the plasma region is not based on analytical or numerical calculations.
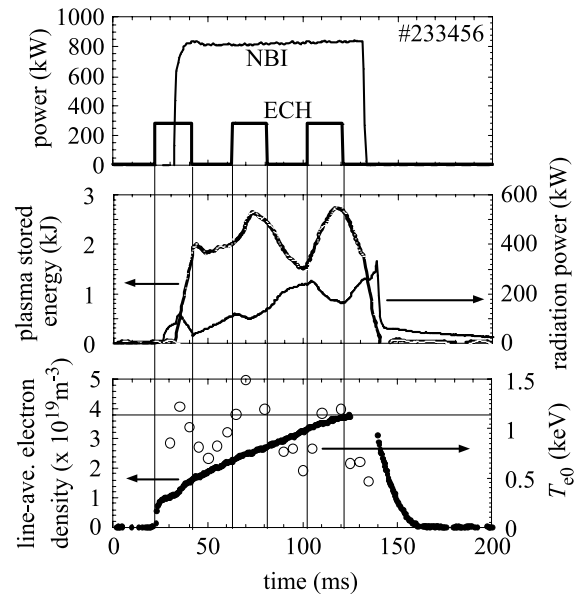

Fig. 2 Time traces of a discharge of X-B heating. The top column shows the ECH and NBI injection timings, the middle column shows the plasma stored energy (bold line) and the radiation power from the plasma (thin line), and the bottom column shows the line-average electron density (closed circles) and central electron temperature (open circles). The horizontal line in the bottom column denotes the O-mode cutoff density 3.8×10^{19} m^{-3} for the 54.5 GHz waves. Density data around 130 ms are not available due to the "fringe-jump".

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.

At the third injection timing of this discharge, the line-average electron density reached close to the O-mode cutoff density of 3.8×10^{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,
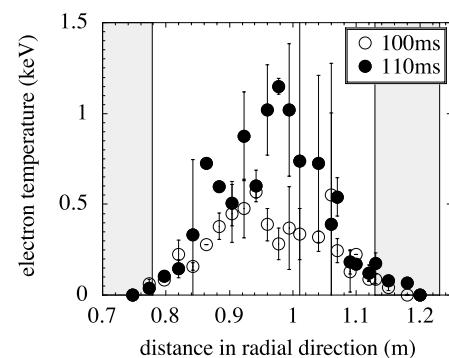

Fig. 3 Electron temperature profiles during (at 110 ms, closed circles) and just before (at 100 ms, open circles) the third ECH power injection. The gray regions correspond to the range of plasma minor radius where the outer fundamental resonance layer exists. Here, note that the horizontal axis of this figure denotes the distance in the radial direction at the horizontally elongated poloidal cross section, so that it does not directly correspond to the horizontal axis in Fig. 1 for the vertically elongated poloidal cross section.

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 con-

dition but the presence of another fundamental resonance layer in the plasmas in front of the new mirror (X-B access window) 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 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, the X-B access window moves upward and "opens" for beams injected counterclockwise.

Though there is a possibility of fundamental X-mode heating as a cause of the increases in plasma stored energy, the rather upward EC-wave beam directions which do not aim at the inner fundamental resonance layer and the measured centrally increased electron temperature distributions deny both the on-axis X-mode heating at the inner

fundamental resonance layer and off-axis X-mode heating at the outer fundamental resonance layer. This strongly suggests that significant plasma heating occurs through the slow X-B mode conversion. Precise numerical calculations to confirm the realization of slow X-B heating in the experimental configuration should be performed in the future.

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