

O-X-B Heating of Overdense Plasmas by 54.5 GHz Electron Cyclotron Waves in CHS

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An evident increase in the plasma stored energy by applying 54.5 GHz electron cyclotron (EC) waves has been observed in plasmas sustained by neutral beam injection (NBI) with line-averaged electron density of above $3.8 \times 10^{19} \text{ m}^{-3}$, that is, the cut-off density of the 54.5 GHz waves, in the Compact Helical System (CHS). The heating effect can be seen even for high-density over $8 \times 10^{19} \text{ m}^{-3}$: more than twice the cut-off density. The 54.5 GHz EC-wave beam is obliquely injected to high-density plasmas. The scanning of the EC-wave beam direction gives the evident increase in the stored energy at the beam direction where the leakage EC-wave power from the CHS vacuum vessel becomes almost the minimum. The most possible cause for this heating mechanism is an electron Bernstein wave heating via an Ordinary – eXtraordinary – Bernstein (O-X-B) mode conversion process.

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Electromagnetic (EM) plasma waves such as ordinary (O) or extraordinary (X) mode waves suffer cut-off in high-density plasmas, and EM plasma waves cannot contribute to electron heating over the cut-off density. Electron Bernstein (B) waves, on the other hand, have advantages of no density limit and strong absorption even in low temperature plasmas. Since the B-waves are a kind of electrostatic waves in plasmas, they have to be excited through mode conversion processes from injected EM-waves. Three types of mode conversion processes are considered, so called fast X-B, slow X-B and O-X-B. Among them, the O-X-B mode conversion technique is the most promising way to heat overdense plasmas by using existing electron cyclotron heating (ECH) systems in tokamaks and helical systems considering the required power sources and steerable beam injection systems from the low field side. If the injection angle of the O-mode wave satisfies a critical condition [1], the O-mode wave is mode-converted into the slow X-mode wave at the cut-off layer, and then the slow X-mode wave is mode-converted into the B-wave at the upper hybrid resonance layer through kinetic processes. However, despite many theoretical and experimental investigations, so far the phenomena related to the O-X-B mode conversion were clearly demonstrated only in W7-AS [2–4] due to the narrow mode conversion window.

In this paper recent experimental results are presented,

which show an evidence of O-X-B heating in the Compact Helical System [5]. A 54.5 GHz ECH system in CHS is equipped with a two-dimensionally steerable beam injection mirror antenna, which enables us to find the optimum injection condition experimentally. Using this antenna system, EC-wave power of 415 kW was obliquely injected in the toroidal direction twice during a discharge. The first one was for plasma generation, and the second one was applied to high-density plasmas sustained with 860 kW neutral beam injection (NBI). The magnetic field on the magnetic axis was set at 1.9 T, slightly below the resonant magnetic field 1.95 T. Figure 1 shows a typical time evolution of O-X-B heating. Here, the O-mode cut-off density for the 54.5 GHz waves is $3.8 \times 10^{19} \text{ m}^{-3}$. A clear increase in the plasma stored energy of more than 30% was observed by the second EC-wave power, and the stored energy was kept high until the end of the EC-wave application. On these discharges, intensive gas-puffing was continuously applied, resulting in the monotonic increases of the density. At the end of the second EC-wave application, the density reached over $8 \times 10^{19} \text{ m}^{-3}$. Without the EC-wave application after 112 ms, the NBI power could not sustain this high-density plasma, and the radiation collapse occurred. During the second EC-wave application, the radiation power from the plasma was reduced probably due to the suppression of radiation losses at the peripheral region by slightly increasing or keeping the electron tem-

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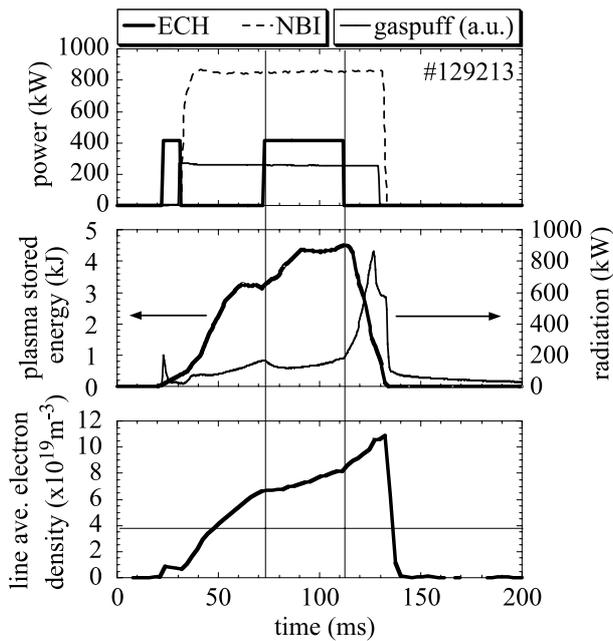


Fig. 1 Time traces of a discharge of O-X-B heating. A significant increase in the stored energy was obtained by application of EC-waves to a high-density plasma over the cut-off. A horizontal thin line on the bottom column denotes the cut-off electron density for the waves of frequency 54.5 GHz.

perature all over the plasmas, and/or a reduction of accumulation of impurities.

By scanning the EC-wave beam direction, the leakage EC-wave power from the CHS vacuum vessel varied systematically as seen in Fig. 2. The leakage power level is considered as a measure of mode conversion and/or power absorption efficiency. The toroidal angle θ_{tor} scan was performed by keeping the radial beam position at the equatorial plane fixed at $R = 92.1$ cm where the magnetic axis was set. Here both the beam steering mirror and the detector for leakage power measurement were set at the poloidal cross section of $\theta_{\text{tor}} = 0$ deg. Beam direction scanning in the radial direction also resulted in the variation of leakage power having a minimum. Around the beam direction where the leakage power reached the minimum, the stored energy showed evident increases. The increments of the stored energy are also plotted in Fig. 2. Among the 4 variations (left-hand and right-hand circular, two orthogonal directions of linear) in polarization with the beam direction optimized, the left-hand circular polarization which is supposed to contain a high fraction of O-mode showed the

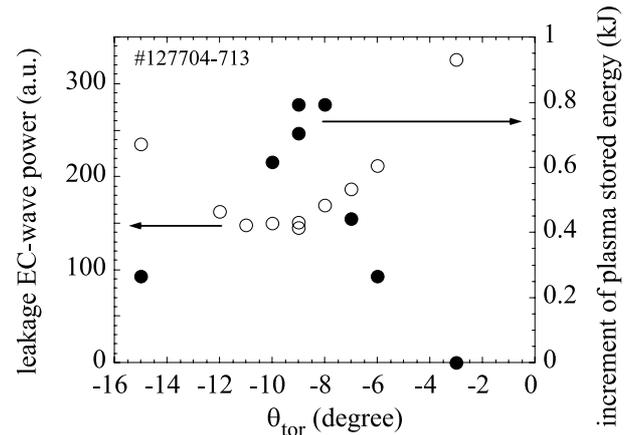


Fig. 2 Variations of leakage power of EC-waves from the CHS vacuum vessel and the maximum increment of plasma stored energy during the second EC-wave application as functions of the EC-wave beam injection direction. The leakage power was averaged over the period of the second EC-wave application.

best performance. The discharge shown in Fig. 1 was performed with the optimized beam direction ($\theta_{\text{tor}} = -9$ deg. and $R = 92.1$ cm) and the left-hand circular polarization.

No heating effect was observed for normal beam injections ($k_{\parallel} = 0$ with $\theta_{\text{tor}} = 0$) with O-mode aiming at the fundamental resonance heating layer at the plasma peripheral region where the density was less than the cut-off. Therefore, the significant increase in the stored energy observed with oblique incidences should be attributed to the O-X-B heating at the core plasma region and the resultant decrease in the radiation losses, not to the cyclotron resonance heating at the peripheral region. Theoretical investigations on power deposition of the O-X-B heating under the experimental conditions are now underway.

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