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Evidence of Electron Bernstein Wave Heating on the TST-2 Spherical Tokamak

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Electron Bernstein wave heating experiments based on the X-mode to Bernstein mode mode-conversion scenario were performed on the Tokyo Spherical Tokamak -2 (TST-2). Up to 140 kW of microwave power at 8.2 GHz was injected perpendicularly from the low-field side. Evidence of electron heating was observed as increases of the stored energy (by about 15%) and soft X-ray ($h\nu$ > 1 keV) emission.

Keywords:

mode-conversion, electron Bernstein wave, spherical tokamak, heating

The electron Bernstein wave (EBW), which has no density cutoff and is strongly absorbed by electron cyclotron damping, is an attractive candidate for heating a spherical tokamak (ST). A key issue for EBW heating is to identify the optimum mode-conversion (MC) scenario, given that the externally injected electro-magnetic wave must be mode-converted to excite an electro-static EBW. The high-field side X-mode injection scenario [1] demonstrated on conventional tokamaks is not applicable to ST. O-mode injection from the low-field side, the so-called OXB scenario [2], is a possible candidate. In addition, the ST configuration with a low toroidal field offers the possibility of a unique MC scenario: low-field side perpendicular X-mode injection [3]. In the third scenario, the launched X-mode encounters a triplet consisting of the R-cutoff, the upper hybrid resonance, and the L-cutoff. Efficient MC is predicted when a suitably steep density gradient (small density scale length, L_n) in the triplet region is realized. Advantages of this scenario include a simple launcher design and the possibility of L_n control independent of the core plasma.

Thus far, only low power EBW receiving experiments have been reported using this scenario [4,5]. In order to examine its feasibility for heating ST plasmas, TST-2 (R = 0.38 m, a = 0.25 m, B_t = 0.3 T, I_p = 0.14 MA) [6] was temporarily moved to Kyushu University, where high power microwave sources (200 kW @ 8.2 GHz) are available.

In this experiment, a launcher consisting of 8 waveguide horn antennas and a movable local limiter surrounding the antennas were installed on the low field side of the torus, below the midplane, and up to 140 kW of microwave power was injected perpendicular to the magnetic surface. The local limiter was used to change L_n in front of the antennas and could be moved in the range R = 625 mm to 665 mm (the antenna aperture was located at R~750 mm). An RF leakage monitor, measuring the power leaking through a vacuum window, was also installed and used as an indicator of RF power that was neither absorbed by the plasma nor reflected back to the launcher.

In some discharges, a possible indication of EBW heating was observed. Figure 1 shows an example of such a discharge. The first RF pulse was used for pre-ionization, during which the line-integrated density $n_e l$ was low (< 1×10^{18} m^{-2}) and the RF leakage was large, suggesting poor absorption. During the second RF pulse, used for heating, the density was higher than the cut-off density ($n_e l$ > 4×10^{18} m^{-2}, l ~ 0.7 m) and the RF leakage became negligibly small.

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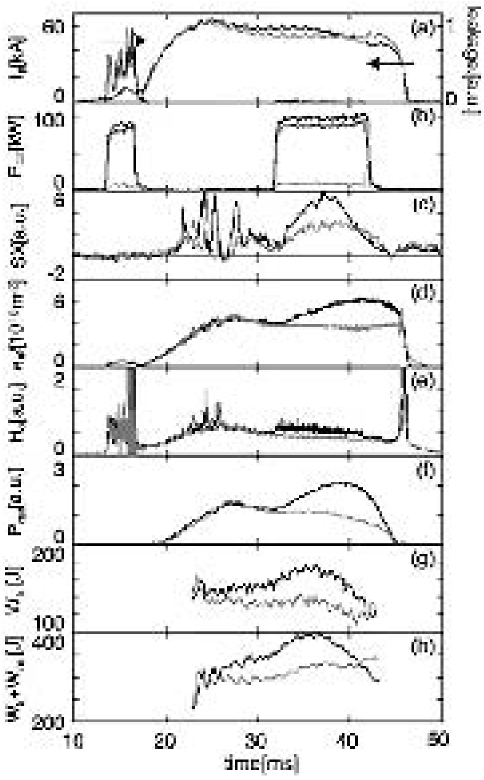

Fig. 1 Time evolutions of (a) plasma current and RF leakage power, (b) forward, reflected, and net RF powers, (c) SX emission (1–10 keV), (d) $n_e l$ (R = 0.38 m), (e) H_α, (f) P_{rad} (broadband radiation over the range 0.01 eV ~ 7 keV), (g) kinetic stored energy, and (h) kinetic plus poloidal magnetic with (black) and without (gray) RF.

$n_e l$, H_α, radiated power P_{rad} (measured by an absolute extreme ultraviolet detector), and soft X-ray (SX) emission (1–10 keV) measured by a surface barrier diode with a Be filter increased after RF turn-on. The increase of SX emission indicates that high energy electrons are generated by EBW injection at the beginning of RF injection, though a direct electron temperature measurement was not available (note that the previous measurement of plasmas with ~100 kA plasma current using X-ray pulse height analysis showed T_e was ~ 400 eV). P_{rad} continued to increase after SX turned over, suggesting that the loss of heating is caused by increased radiation. A step-function like response observed in H_α emission (rise time ~ 0.6 ms) indicates that some power is deposited directly in the plasma edge.

In Figs. 1 (g) and (h), the representative parameters calculated by equilibrium reconstruction are shown. The plasma kinetic energy (W_k) increased from 150 to 170 J, and the total (kinetic plus poloidal magnetic) energy ($W_{tot} = W_m + W_k$) increased by 15% (from 340 to 390 J), suggesting the possibility of current drive in addition to heating (note the increase in I_p over the same time scale as the stored energy increased). The timing of the stored energy turn-over was approximately same as the SX signal turn-over, suggesting that the high energy electrons contribute to the stored energy increase.

In the discharge, the net injected RF power was 90 kW, whereas the ohmic input power was approximately 120 kW. The calculated stored energy increase is rather small compared to the ratio of RF and ohmic heating powers. If 50% of the injected RF power were assumed to be absorbed, an L-mode type energy confinement time scaling would predict a stored energy increase of 17%, which is not inconsistent with the observation. However, the absorbed power estimated from the break-in-slope analysis of the stored energy was only about 6 kW from $\Delta dW_k/dt$ (and 15 kW from $\Delta dW_{tot}/dt$). A significant portion of the injected power may have been absorbed before reaching the plasma core. The power decay length by collisional damping, a possible candidate for such an absorption, is calculated to be shorter than the minor radius only when the electron temperature is low (< 10 eV), but Langmuir probe measurements showed T_e ~ 10 eV at R = 620 mm. Details will be discussed in a subsequent paper.

In summary, results of the first X-B EBW heating experiment on TST-2 are reported. Evidences of possible electron heating are obtained as increased SX radiation and stored energy, although the absorbed power seems to be low.

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