Plasma Density Suppression by Electron Cyclotron Wave in Lower Hybrid Wave Driven TST-2 Spherical Tokamak Plasma

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For successful plasma current (I_p) ramp-up by the lower hybrid wave (LHW), the plasma density must be kept at a low level. In the TST-2 I_p ramp-up experiment using the LHW, the application of the electron cyclotron wave (ECW) was found to reduce the plasma density by about 10%. This allowed for further I_p ramp-up later in the discharge.

Keywords: lower hybrid wave, electron cyclotron wave, spherical tokamak plasma, density suppression

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In order to use the spherical tokamak (ST) configuration for burning fusion reactors, it is essential to demonstrate a reliable method to start and ramp-up the plasma current without using the central solenoid. Plasma current ramp-up by the LHW, leading to an advanced tokamak discharge having a very large bootstrap current fraction, was demonstrated on the JT-60U tokamak [1]. Effects of the ECW in LHW driven plasmas were observed on the WT-2 and WT-3 tokamaks [2, 3]. In WT-2, the ECW caused a plasma current increase and a density decrease when the EC resonance was positioned on the outboard side of the magnetic axis. Conversely, the plasma current decreased and the density increased when EC heating was applied to the bulk electrons. Thus, the ECW can help LHW current drive if the EC resonance layer is positioned appropriately. In an ST with its low toroidal magnetic field, successful plasma current ramp-up by the LHW can be achieved only when the plasma density is kept at a low enough level, since a high density plasma prevents the LHW from penetrating to the plasma core.

The effects of the ECW (2.45 GHz) on plasmas produced and ramped up by LHW (200 MHz) current drive were investigated on the TST-2 spherical tokamak (R = 0.38 m, a_0 = 0.25 m). The ECW was launched into deuterium plasmas with the O-mode polarization (the wave electric field parallel to the confining magnetic field) and with the fundamental EC resonance located at the nominal plasma center ($R \approx 0.38$ m, $P_{EC} \simeq 2$ kW). The LHW power injected by the CCC antenna [4] was gradually increased to 30 kW. The LHW power was fifteen times larger than the ECW power at the end of the LHW pulse. A microwave interferometer measured the line integrated density ($n_e l$) along a vertical chord through the nominal center of the plasma. The D_α line emission was measured from the outboard midplane.

In order to evaluate the effect of the ECW, only the ECW pulse length was varied in the three discharges shown in Fig. 1. In the discharge shown by the black line, the ECW power was turned off at 70 ms. The plasma current was increased successfully to 12.6 kA. Plasma current ramp-up continued while the vertical field (B_v) was being increased. Note that $n_e l$ was kept below 0.21×10^{18} m^{-2} throughout the discharge. For the case in which the ECW injection ended at 70 ms, the decline of the plasma current was caused by insufficient B_v. In the discharge shown by the red line, the ECW was turned off at 60 ms. Although the plasma current ramp-up rate remained the same after ECW turn-off, the rate of increase of both $n_e l$ and D_α emission increased abruptly after a delay of a few ms, and the plasma current started to decline after reaching 11.9 kA, and $n_e l$ increased to 0.24×10^{18} m^{-2} from 0.21×10^{18} m^{-2}. In the discharge shown by the blue line, the ECW was turned off at 50 ms. The $n_e l$ and D_α increase started earlier and the plasma current started to decline after reaching 10.8 kA. The density increase is thought to be caused by outgassing from the antenna or the first wall of the vacuum vessel, because there is no additional gas puffing after the initial plasma formation.

The plasma current ramp-up rate is not directly affected by the low power ECW. Rather, the $n_e l$ and D_α increases which are observed in the absence of ECW are

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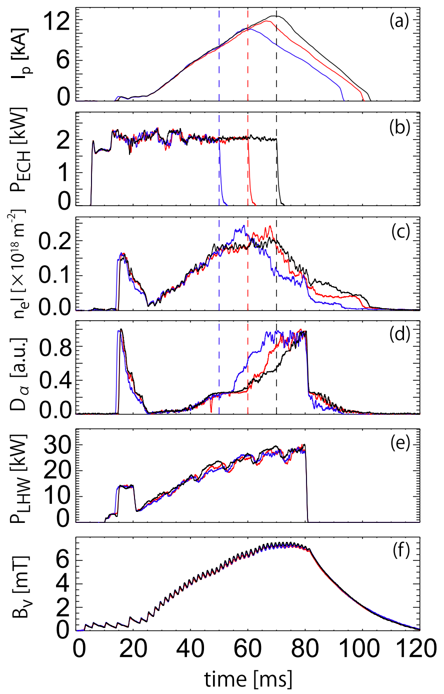

Fig. 1 Waveforms of (a) plasma current, (b) ECW injected power, (c) LHW injected power, (d) line integrated density through the central vertical chord (path length ~ 0.5 m), (e) D_α line emission, (f) vertical field at the plasma center. Only the ECW pulse length is different in the three discharges shown.

suppressed by ECW injection. Thus, ECW is effective in reducing the plasma density in spite of the low power. The decrease in $n_{\rm e}l$ (more precisely, the suppression of a $n_{\rm e}l$ increase) is approximately 10%. Note that the density suppression occurred when the EC resonance layer was located at the plasma center. It remains to be seen what whould happen if the EC resonance layer were placed off-axis.

Many discharges were studied to investigate the reason for the effect of the low power ECW on the current drive. The current drive seems to be affected indirectly through the density increase. The maximum plasma current and $n_{\rm e}l$ at the time of the maximum plasma current are plotted in Fig. 2. According to this figure, the maximum plasma current is achieved only when $n_{\rm e}l$ is less than $0.25 \times 10^{18}\,\mathrm{m}^{-2}$. Higher $n_{\rm e}l$ is observed in the low current region $I_{\rm p} \leq 2\,\mathrm{kA}$, but in this region the plasma current is dominated by the pressure driven current, not by wave driven current [4]. It can be concluded that there is a density limit around $n_{\rm e}l \simeq 0.25{\times}10^{18}\,\mathrm{m}^{-2}$ ($\overline{n}_{\rm e} \simeq 0.5{\times}10^{18}\,\mathrm{m}^{-3}$) for LHW current drive in TST-2. The decline of the plasma

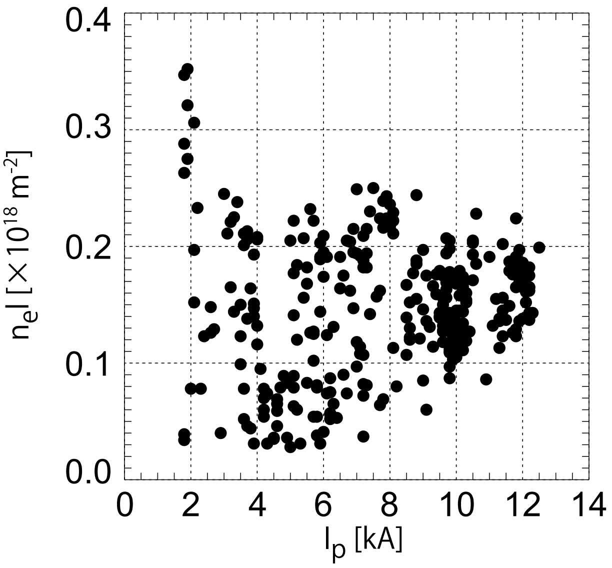

Fig. 2 Relationship between the maximum plasma current and $n_{\rm e}l$. There is a density limit around $n_{\rm e}l \simeq 0.25 \times 10^{18}\,\mathrm{m}^{-2}$ except in the low plasma current region ($I_{\rm p} \leq 2\,\mathrm{kA}$), where the plasma current is dominated by the pressure driven current.

current in Fig. 1 for the discharges shown in blue and red is caused by the density limit. Thus, in order to keep ramping up the plasma current, it is essential to keep the density below this limit. Low power ECW injection may be a useful tool to achieve such density control.

There are several possible causes for the observed density limit. In TST-2, the LH resonance frequency $[f_{\rm LH} \approx \omega_{\rm pi}/2\pi\,(1+\omega_{\rm pe}^2/\Omega_{\rm e}^2)^{0.5}]$ is approximately 40 MHz at the plasma center, which is much lower than the 200 MHz used in this experiment. Therefore, it is unlikely that the limit is due to mode conversion to the ion plasma wave or to a parametric decay instability. Other possibilities include reduced accessibility (by mode conversion to the fast wave), increased radiation loss, or edge absorption and enhanced fast electron loss. More detailed density, hard x-ray, and soft x-ray profile data are necessary to determine the dominant cause of the density limit.

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