§11. Optimization of Third Harmonic ECH Scenario to Extend a Heating Plasma Parameter Range

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The 3rd harmonic electron cyclotron heating by the extraordinary mode injection (X3 heating) can enlarge a possible heating region up to the higher density region than the 2bd harmonic X mode heating . So far we successfully performed X3 EC heating experiment at 168 GHz, 84 GHz and 77 GHz frequency region [1, 2].

The objective of the 3rd harmonic heating experiment in this experimental campaign is to obtain a data set of the target plasma with wide plasma density and electron temperature ranges, because the absorption efficiency of the harmonic heating strongly depends on them. The X3 heating experiment was conducted using three 77 GHz gyrotrons. The cut-off density is $5 \times 10^{19}\mathrm{m}^{-3}$. We selected the magnetic field strength of 0.95 T so that the position of the magnetic axis coincided with ECR, when the Shafranov shift was taken into account. A target plasma was produced by tangentially injected NBI, and it was sustained by perpendicularly injected NBI without plasma current. The millimeter-wave power of 77 GHz was injected from 2O-r, 9.5U-in and 5.5U-out antennas. Typically, the absorption rates and the electron temperature values at the ECH turn-on and -off timings are plotted for the 5.5U-out antenna case as a function of the line-averaged electron density in Fig. 1. The maximum absorption rate of about 40% was obtained around the density of $1.5 \times 10^{19}\ \mathrm{m}^{-3}$ with $T_e \sim 1.2$ keV at the ECH off timing. The ray-trace calculation (TRAVIS-code) results of the absorption rate for the same injection configuration in the experiment show that the density dependence of the absorption rate agrees well with the experimental results shown in Fig. 2.

Superposed stepwise injection from three gyrotrons with totally 3 MW increased the central electron temperature to about 3.5 times of the initial target plasma temperature of 0.6 keV, which is shown in Fig. 3. This clearly shows that the temperature increase improves the absorption rate of the subsequent power injection.

These results show that the X3 mode ECH can be expected as methods with sufficient absorption, when the EC beam is injected (1) along the ECR over a long distance (U-antenna case) and (2) through the saddle point of the magnetic field strength between two ECR layers (O-antenna case). It is shown also that the high harmonic ECH has a potential to extend the heating regime of higher density and higher β fusion-relevant plasmas utilizing optimized injection condition and magnetic configurations with a long-distance resonance.

1) T Shimozuma, et al. :, Plasma and Fusion Research, 3 (2008) S1080-1 – S1080-5.
2) T Shimozuma, et al. :, Plasma and Fusion Research, 8 (2013) 2402073-1 – 2402073-5.

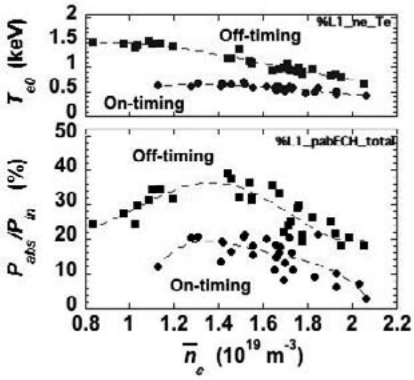

Fig. 1: Dependence of X3 (U-out antenna) absorption rate estimated at ECH turn-on timing (circles) and -off timing (squares) on the line-averaged density (bottom). Density dependence of electron temperature at the center is also plotted (top).

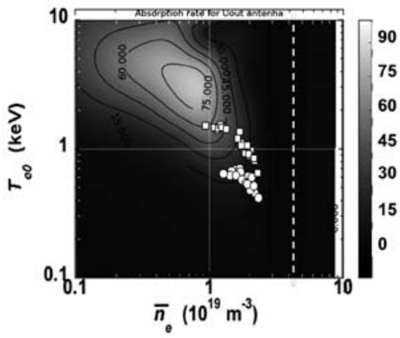

Fig. 2: Calculated absorption rate of X3-mode (U-out antenna) is mapped in T_{e0} - line-averaged n_e space. Density and temperature profiles are assumed to be $n_e(\rho) = n_{e0}(1-\rho^8)$ and $T_e(\rho) = T_{e0}(1-\rho^2)^3$, which approximate the profiles in the experiments. A dashed-line shows a line-averaged cut-off density of X3 (=8/9 n_{e0_cutoff}). Data points of T_{e0} in Fig. 1 (top) are also over-plotted.

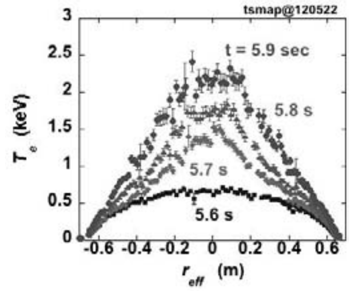

Fig. 3: The electron temperature profiles during X3 ECH. 5.6s:just before ECH, 5.7s:1 gyrotron-, 5.8s: 2 gyrotron-, 5.9s: 3 gyrotron-injection