§54. Ray-trace Study of the Third Harmonic EC Heating in LHD

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Efficient heating at the third harmonic electron cyclotron resonance was observed by injection of millimeter-wave power with 84 GHz frequency range at the magnetic field strength of 1 T in LHD. Electron temperature at the plasma center clearly increased and the increment of the temperature reached 0.2 – 0.3 keV.

Absorbed power was estimated by the increment of the plasma stored energy dW_p/dt before and after ECH on-timing, assuming that the other plasma parameters did not change quickly. The dependences on the focal point R_{foc} of the upper-port antennas (82.7 GHz) and on line-averaged density were examined and shown in Fig. 1 (a) and (b), respectively. The closed circles denote experimentally obtained data. The maximum absorption rate was obtained on the antenna focal position R_{foc}=3.7m, which was smaller than the 3rd harmonic ECR layer (3.78m) shown in Fig. 1 (a). The absorption rate, however, is rather low, because the temperature and density of the target plasma was fairly low. The density dependence of the absorption rate is plotted for $R_{foc} = 3.7$ m in Fig. 1 (b).

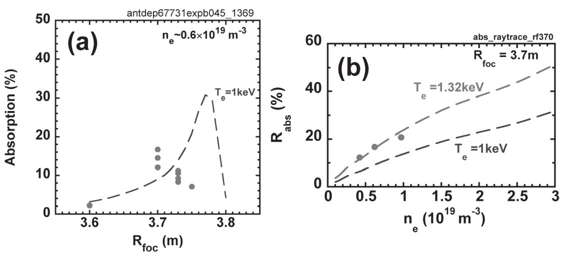

Fig. 1: Efficiency of absorbed power for 82.7GHz. (a) Antenna focal point on the equatorial plane R_{foc} dependence(closed circles) for the density of $0.6 \times 10^{19} \mathrm{m}^{-3}$. (b) Electron density dependence for $R_{foc} = 3.7$ m. The dashed lines show the calculation results by ray-tracing.

Ray-tracing calculation was performed in the realistic three-dimensional magnetic configuration of LHD to compare the experimental results and calculated ones. In these figures, dashed lines represent the results by ray-tracing calculations. In the calculations, the dispersion relation of a cold plasma was assumed for ray trajectory calculations, and the weekly relativistic effect was included for the absorption calculations[1]. The polynomial fitted data of electron temperature and density profiles were used.

There is a great difference between experimental data and ray-tracing calculations in the focal position dependence. The calculation results reflect strong single-pass absorption around ECR which corresponds to $R \simeq 3.78$ m. In order to examine the dependence of the single-pass absorption rate on the electron temperature T_e and density n_e, the ray tracing calculation was expensively performed over two order of magnitude in the $T_e - n_e$ space. Because the optical thickness scales as $\tau \sim n_e \cdot T_e^2$, a little temperature change possibly leads to fairly large difference of the absorption rate.

In parallel, the ray-tracing code, "TRAVIS (IPP)", was applied to the 3rd harmonic heating experiment in LHD[2]. The basic ray-tracing equations include weakly relativistic formulation for Hamiltonian with taking into account possible anomalous dispersion effects. The wave absorption can be calculated in fully relativistic formulation. The power deposition is decomposed to passing and trapped electrons contributions.

In Fig. 2, the configuration of calculation is illustrated with mod-B counters, flux surfaces with 0.33 % plasma β value and wave rays. The 3rd harmonic electron cyclotron resonance is also depicted. Calculated ray trajectories from the upper-port antenna in Fig. 2 (a) and lower-port antenna in (b) are typically shown. No relativistic and anomalous effects are found in the trajectories in such a low temperature and density plasma, and the trajectories follow almost straight line paths. The focal point dependence of the wave absorption rate was agreed with the previous calculation results, meaning a little full relativistic effect on the absorption.

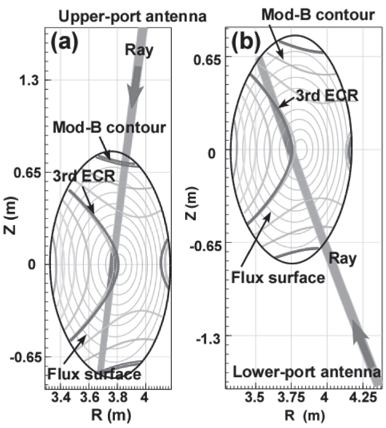

Fig. 2: Ray trace calculation together with ECR, mod-B contours and flux surfaces. (a) Upper-port antenna injection. (b) Lower-port antenna injection.

1) S. Kubo, T. Shimozuma et al., Plasma Phys. Control. Fusion, **47**, A81, 2005.
2) N. B. Marushchenko et al., Plasma and Fusion Research, **2**, S1129, 2007.