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Improved performance of ECRH by real-time deposition location control and perpendicular injection in LHD

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To improve the performance of ECRH, a real-time control system for the deposition location of ECRH was newly developed to compensate the effect of refraction in standard oblique injection of ECRH on LHD. By the control absorption power higher than that without control was maintained under line-averaged electron density $n_{\mathrm{e,avg}} \simeq 3 \times 10^{19}$ m^{-3}. In addition to that, a method of perpendicular injection was developed in order to be more insensitive to the effect of refraction. The achieved central electron temperature in the case of perpendicular injection was about 2 keV higher than that in the case of standard oblique injection for $n_{\mathrm{e0}} \sim 1 \times 10^{19}$ m^{-3} by 1 MW injection. With such improved performance of ECRH, high density ECRH plasma of $n_{\mathrm{e0}} \sim 8 \times 10^{19}$ m^{-3} was successfully sustained after multiple pellet injection.

In tokamak and helical fusion plasmas, adjustments of launcher settings of ECRH are necessary to produce high-performance plasma, to realize desired power deposition profiles, to decrease the stray radiation level in the vessel, and to prevent damages of in-vessel components from unabsorbed power during high-power long-pulse injection. The precise evaluation of deposition profiles is also essential for transport studies [1]. For such purposes, two heating methods have been developed to improve performance of ECRH in LHD: (i) real-time deposition location control and (ii) perpendicular injection.

The real-time control system for the deposition location was newly developed with a fast field programmable gate array (FPGA) [2]. Appropriate settings for a steerable launcher were obtained by evaluating deposition profiles for various n_{e} profiles using the ray-tracing code *LHDGauss*. Figure 1 shows a typical demonstrated result of the real-time deposition location control in order to obtain and to sustain high absorption power under the EC wave refracted by time-varying n_{e}. The vertical target position Z_{f} was controlled according to a gradual increase in n_{e} profiles. Since a deposition location can be controlled mainly by changing Z_{f} with the launcher on an equatorial outer port of LHD, the toroidal target position was fixed almost at -0.4 m, which is a standard toroidally-oblique injection setting. Under $n_{\mathrm{e,avg}} \simeq 2 \times 10^{19}$ m^{-3} at 5 s, the deposition location in the case with the control was maintained at $r_{\mathrm{eff}}/a_{99} \sim 0.3$, while the deposition location in the case without the control shifted outward, which indicates that heating in the plasma core region was maintained longer due to the control. After 5 s, the absorption power in the case without the control gradually decreases due to refraction of the EC wave by a gradual increase of n_{e}, while higher absorption power was maintained longer due to the control under $n_{\mathrm{e,avg}} \simeq 3 \times 10^{19}$ m^{-3}. At higher densities, a decrease in absorption power was observed even in the case with the control. The absorption power level was almost the same as that in the case without the control, which suggests that the effect of multi-pass absorption is expected to be dominant in the experimentally-evaluated absorption power.

The above-mentioned situation led to the necessity of perpendicular injection (i.e., perpendicular to the ECR layer) because it is expected to be more insensitive to the effect of refraction. It is a similar heating method in tokamaks and W7-X, and will be also used in a helical DEMO reactor FFHR-c1. When 77-GHz EC waves are injected from the outside of the horizontally-elongated cross section, on-axis ECRH with perpendicular injection is available only in the magnetic field increased with sub-cooled helical coils. Figure 2 shows comparisons of the T_{e} responses between perpendicular injection and oblique injection in power-modulated ECRH. The perturbation amplitude of T_{e0} in the case of perpendicular injection was higher than that in the case of oblique injection. Perpendicular injection showed better central heating than oblique injection, although the absorption power were almost the same in both cases. Refraction and Doppler-shifted absorption in oblique propagation of the EC wave caused broadening of the deposition profiles, in particular at high density, even with the real-time deposition location control. This result clearly demonstrated that perpendicular injection is more insensitive to refraction and Doppler effects than oblique injection as expected.

Achieved T_{e} profiles were compared between the two kinds of injection of 1 MW without modulation. Plasmas were sustained by other two 154-GHz gyrotrons with 1 MW injection power each. T_{e0} increased from 4 keV to over 6 keV by perpendicular injection for $n_{\mathrm{e,avg}} \simeq 1 \times 10^{19}$ m^{-3}. The achieved T_{e0} is about 2 keV higher than that in the case of oblique injection.

Such an improved ECRH performance has opened up a new operational region in ECRH plasmas. As shown in Fig. 3, high density plasma with $n_{\mathrm{e0}} \sim 8 \times 10^{19}$ m^{-3} was successfully sustained after injection of three consecutive deuterium pellets for the first time in ECRH plasmas of LHD. Hollow n_{e} profiles by gas puffing changed to peaked profiles after the pellet injection. Equipartition heating was significant in the high-n_e region: $T_{i0} \sim T_{e0} \sim 1$ keV were obtained. The new high-n_e region in ECRH plasmas will contribute to comparative studies in transport between W7-X and LHD and to helical reactor designs.

These two techniques for efficient first-pass absorption in the plasma core region are beneficial not only for preventing damages of in-vessel components during long-pulse operations but also for extending high-T_e and high-n_e operational regimes and precise transport studies.

[1] K. Tanaka *et al.*, Nucl. Fusion **59** (2019) 126040.
[2] T. Ii Tsujimura *et al.*, Fusion Eng. Des. **131** (2018) 130.

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