§29. Study of High-performance Plasma Production using ICRF Heating in Heliotron J

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Main purpose of this study is to optimize fast ion confinement by using ICRF heating in a helical-axis heliotron device, Heliotron J on the basis of results of several helical devices. For the research of the fast ion confinement in a three dimensional magnetic field, fast ions are generated by ICRF minority heating in combination with NBI heating in Heliotron J (R_0 = 1.2 m, a = 0.1-0.2 m, $B_0 \leq$ 1.5 T). The energy range is extended from the injection energy of the NBI beam, 25 keV, to 60 keV during the ICRF pulse in the newly attempted low-ε_t configuration and medium density operation (1×10^{19} m^{-3}) [1]. This configuration is better in the fast ion generation and confinement than the high bumpiness configuration which is the best among the bumpiness scan. Here, the toroidicity and the bumpiness normalized by the helicity for the low-ε_t and the high bumpiness configurations are (0.77, -1.04) and (0.86, -1.16) in Boozer coordinates, respectively. They are key parameters in 1/ν regime of helical devices. The low-ε_t configuration is expected to have good confinement from the neo-classical theory. The Monte-Carlo calculation shows the advantage of the low-ε_t configuration for the generation and confinement of fast ions.

The fast ion generation and confinement are studied by using ICRF minority heating (H minority and D majority) for the simulation study of alpha particles, whose heating is essential for fusion reactors. In the previous study, the configuration dependence was investigated in the low-density condition (< 0.5×10^{19} m^{-3}). Fast ions were detected up to 35 keV in the high bumpiness configuration during ICRF pulse. To extend the energy range of fast ions, target plasmas are produced by EC + NBI heating with the line-averaged density of 1×10^{19} m^{-3}. ICRF heating is expected to accelerate NB injected ions further.

The measured energy spectra of minority hydrogen by the charge-exchange neutral particle analyzer (CX-NPA) are shown in Fig. 1. The injected hydrogen with energy E_0 in the NB is 24 keV. The injection power of ECH (70 GHz), NBI and ICRF (23.2 MHz) is 0.33 MW, 0.4 MW and 0.3 MW, respectively. The experiment is performed in the low-ε_t and the high bumpiness configurations and measured spectra are at 52° in pitch angle. In the bulk plasma, the minority ratio is about 0.1. In the energy spectrum without the ICRF pulse, the E_0, $E_0/2$ and $E_0/3$ peaks are observed in both cases. When the ICRF pulse is imposed, the high energy tail component is substantially increased up to 60 keV in the low-ε_t configuration. In the high bumpiness, the energy spectrum is different from the low-ε_t and limited within 35 keV. For the larger pitch angle (nearer to 90°), the high energy component becomes smaller. For example, the fast ions at the pitch angle of 62° in the high bumpiness are observed in the energy range below 20 keV during the ICRF pulse.

Using Monte-Carlo method with the experimental magnetic field and plasma parameters, the numerical calculation including orbit tracing, Coulomb collisions and ICRF acceleration is done in order to estimate the averaged behavior in whole torus for various configurations since the measurement area of the CX-NPA is limited. The test ions (protons) in the calculation, which represent the NBI particles, start at the middle point of the NB path in a plasma with the NB injection energy.

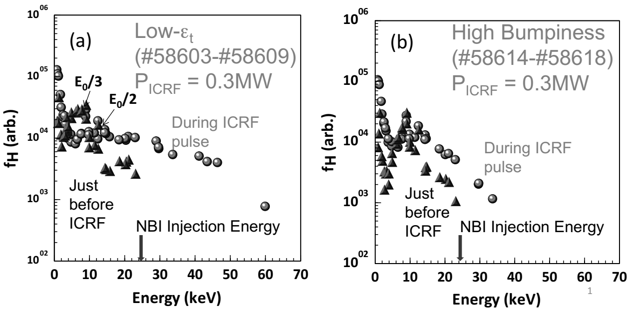

Fig. 1. The measured minority-hydrogen energy spectra of w/ and w/o ICRF pulse for (a) the low-ε_t configuration and (b) the high bumpiness configuration. The target plasma is produced by ECH (0.33 MW) and NBI heating (0.4 MW). The ICRF injection power is 0.3 MW. Measured flux is at the pitch angle of 52°.

Injected ions with the mono energy collide with bulk particles in a plasma and are accelerated or decelerated by the ICRF wave, then, ions spread in velocity space. The particles in the calculation are summed up during 0.5 ms after 1.5 ms from the beginning because of the statistical reason. At this timing, the high energy tail is formed near 60 keV in the low-ε_t. The high energy tail is formed along 55° in pitch angle for the low-ε_t and 45° for the high bumpiness. The energy tail spread more toward the high energy region in the low-ε_t and its direction is relatively narrow in comparison with the high bumpiness. The experimental and calculation results are explained partially by the loss region of fast ions for these configurations. The loss region is located near 90° in pitch angle and high energy area. The area is larger for the high bumpiness configuration.

1) H. Okada, et al., 20th International Stellarator-Heliotron Workshop (ISHW), Oct.5-9, 2015, Greifswald, Germany, P2S3-36.