§16. Study of Optimization of the ICRF Heating in Heliotron J

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Main purpose of this study is to optimize ICRF heating in a helical-axis heliotron device, Heliotron J on the basis of results of several helical devices. In the previous experiment, good confinement of fast minority ions and high-efficiency of ICRF heating for a high bumpiness have been achieved in the minority heating using hydrogen and deuterium as a minority and a majority, respectively. In STD configuration, the heating position effect has been investigated by changing an ICRF frequency. In these experiments, the minority heating and bulk heating efficiency are evaluated by the energy spectra of hydrogen and deuterium measured by a charge-exchange neutral particle energy analyzer (CX-NPA).

The minority cyclotron resonance layer is located on-axis or at the inner position of the torus in the experiment. In on-axis heating, minority effective temperature is higher than that in the inner heated case. On the contrary, the increase of bulk temperature is larger in the inner heated case. These results are not consistent from the heating mechanism of the minority heating. It seems that the localized fast ions caused by the generation and loss mechanism affect the measured energy spectrum. It is difficult to estimate the overall effect of the loss region structure on fast-ion confinement because the structure varies with the position in a plasma column. In addition, the CX-NPA has a limited observation area. Numerical analysis using Monte-Carlo simulation is useful for establishing a physical model for the energy spectra in the three-dimensional magnetic field of Heliotron J.

The numerical model includes orbit tracing, Coulomb collisions, and acceleration by ICRF heating. Minority protons are used as test particles and heating is simulated by the velocity kick in the perpendicular direction in velocity space when ions cross the cyclotron layer. In this calculation, the acceleration term for ICRF heating is proportional to the ICRF electric field amplitude, which is an input parameter. The electric field amplitude is determined from the input power for ICRF heating. Although it is possible to determine the heating profile as a function of the magnetic field, plasma parameters, and wave frequency, it is not simple to calculate the rf electric-field structure and the absorption profile for the magnetic configuration of Heliotron J. Here, the rf electric-field profile was assumed to be parabolic, as in previous calculations for Heliotron E plasmas. The initial test ion distribution is uniform in the toroidal and poloidal directions and parabolic in the radial direction. The initial ion energy is randomly selected from the Maxwell distribution characterized by the bulk ion temperature.

Using 500,000 particles, the velocity distributions of the minority protons were calculated for the three bumpinesses. The plasma parameters are $T_e(0)$ = 0.7 keV, $T_i(0)$ = 0.3 keV, $n_e(0) = 0.5 \times 10^{19}$ m^{-3}, and $Z_{eff} = 3.0$. The input rf field is adjusted so that the input power is about 100 kW in each case. Orbit tracing with acceleration and collisions is performed for 2 ms. Under these conditions, the velocity distribution reaches steady state within 1 ms. From these measurements, the dependence of the energy spectra on the pitch angle was obtained for bumpinesses (defined as B_{04}/B_{00}, where B_{04} is the bumpy component and B_{00} is the averaged magnetic field strength) of 0.01 (low), 0.06 (medium) and 0.15 (high) at $\rho = 0.67$. The ICRF frequency is 23.2 MHz for the high bumpiness and 19 MHz for the medium and low bumpinesses.

Figures 1(a)-(c) show typical calculated energy spectra at a pitch angle of 120° for the three bumpinesses. In these figures, the vertical axes show the logarithm of the particle counts. This pitch angle (120°) gives the largest energy tail observed in the CX-NPA measurements. The calculated and experimental values are indicated by solid and open symbols, respectively. The calculation reproduces the high-energy tail up to 20 keV, which was measured only in the high bumpiness case (see Fig. 1(a)). No detectable data was obtained in the CX-NPA measurements for energies above 6 and 8 keV for the medium and low bumpinesses, respectively. The measured and calculated energy spectra are identical at energies below 10 keV for the medium and low bumpinesses..

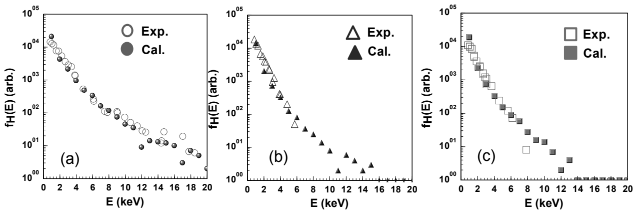

Fig. 1 The energy spectra calculated by Monte-Carlo method for three bumpiness cases are illustrated by solid symbols. The pitch angle range is 120±5°. The experimental energy spectra obtained by CX-NPA measurements at 120° are indicated by open symbols. Results are shown for the (a) high, (b) medium, and (c) low bumpinesses.

The dependence of the energy spectra on pitch angles is investigated using effective temperature defined as the slope in the range from 1 to 7 keV for the experimental and calculated data. The effective temperature for the high bumpiness has two peaks at 60 and 120° in pitch angle and it is the highest for the three bumpinesses at almost all pitch angles. The effective temperature for the low bumpiness is the lowest for the three bumpinesses. It has peaks at 70 and 110° and decreases near 90°, just as for the high bumpiness. The calculation results are consistent with the experimental results. The model used in the Monte-Carlo code is considered to be useful for analyzing fast ions in Helitoron J plasmas.

1) H. Okada, et al., “Numerical Analysis of ICRF Minority Heating in Heliotron J”, PRF volume 6 (2011, in press).