34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-4.150 (2007)

ANALYSIS OF FAST IONS DURING ICRF HEATING IN HELIOTRON J

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1. Introduction

The high-energy particle confinement is one of key issues of a helical-axis heliotron device, Heliotron J as an advanced helical device.[1-2] The design concept of Heliotron J is that confinement of high-energy particles is controlled by using one of Fourier components of the magnetic field, the bumpiness. It is also an important subject for Heliotron J to seek the guiding principle for optimizing the confinement-field structure. The device parameters of Heliotron J are: the major radius of the torus R = 1.2 m, the minor radius of the plasma a = 0.1~0.2 m, the helical-coil pole number L = 1, the pitch number M = 4, the pitch modulation $\alpha = -0.4$, the rotational transform $\iota/2\pi$ = 0.3~0.8, the edge well-depth of 1.5%, and the magnetic field on the axis $B_0 \leq 1.5$ T.

Fast ions were generated in the ion cyclotron range of frequencies (ICRF) heating experiment using a deuteron majority and a proton minority in Heliotron J[3] in order to study fast ion confinement for various field configurations. The dependence of the fast neutral fluxes on the bumpiness was observed by using the charge-exchange neutral particle energy analyzer (CX-NPA). It can be scanned in the toroidal direction from -10 to +18 deg and in poloidal direction from -3 to 10 deg in order to observe ions in the wide range of the velocity distribution. Three configurations are selected; the bumpy ratio (B_{04}/B_{00}, where B_{04} and B_{00} are the bumpy component and the averaged magnetic-field strength, respectively) are 0.01, 0.06 and 0.15 at the normalized minor radius ρ = 0.67. In this experiment, it was found that the fast ion confinement and the bulk heating efficiency are better in the high bumpy case. The pitch angle dependence of the fast ion energy spectra was also investigated. The fast ion tail in the velocity space is prolonged in the direction of 20 – 30 deg from the perpendicular although the acceleration of fast ions by the ICRF heating is perpendicular.

2. Calculation Model

For analysis of fast ions in the experiments, we use a Monte-Carlo calculation code including an ICRF heating model, orbit losses and Coulomb collisions with background plasma particles. In this code, minority protons are regarded as test particles. The orbit calculation and the change of momentum and energy by the collision with bulk particles obey the model of Booze and Kuo-Petravic[4]. Concerning the interaction of the test particles and ICRF wave, the radio-frequency (rf) electric field amplitude and its spatial distribution are given as input parameters. When a test particle passes through the ion cyclotron resonance layer, its velocity is increased by[5]

$$\Delta v_{\perp} = \frac{qE_{RF}}{2m}\left(\frac{2\pi}{n|\dot{\Omega}|}\right)^{\frac{1}{2}} J_{n-1}(k_{\perp}\rho_i)\exp(-in\phi_0),$$

where q is the electric charge of an ion, m is the ion mass, n is the cyclotron harmonic number, $k_{\perp}$ is the perpendicular wave number, ρ_i is the ion gyro-radius, E_{RF} is the strength of the left-handed polarized electric field, J_{n-1} is a Bessel function of the first kind, $\dot{\Omega}$ is the time derivative of the cyclotron frequency seen by drifting ions in the vicinity of the resonant layer and ϕ_0 is a random variable representing the phase of ICRF waves when ions pass through the resonance layer. We used $J_{n-1} = 1$, $k_{\perp}\rho_i << 1$ as in this calculation. For minority protons, the cyclotron layer corresponds to fundamental resonance, then, n is 1. Here, E_{RF} is determined to match the input power. Many standing waves of the rf-electric field appear, caused by the ICRF wave in the plasma cross-section in the usual fast wave heating. The heating profile depends on the plasma parameters and wave frequency. The wave calculation has not done yet, so we assume that the wave profile is parabolic as in the previous calculation for Heliotron E plasmas[5].

3. Loss regions for three bumpy configurations

The orbit loss region under the no collision condition is calculated for the comprehension of fast ion confinement for the first step. The starting point of protons is selected at the point of (ρ, θ, ϕ) = (0.3, 0.0, 0.0) where ρ is the normalized minor radius, θ is the poloidal angle and ϕ is the toroidal angle. This location (ϕ = 0) is in the corner section of the plasma where the ICRF antennas are installed. In this section, the helical coil is positioned in the innermost position in the major radial direction. The poloidal angle θ = 0 corresponds

perpendicular direction. This deviation is consistent with the experimental observation in the pitch angle scan experiment in Ref. 3.

The calculated energy spectra are shown in Fig. 3. The particle loss ratios are 0.45, 0.57 and 0.54 for the high, medium and the low bumpy cases, respectively. It is supposed that this tendency is caused from the loss area shown in Fig. 1. However, the order is not same for the medium and low bumpy cases in Fig. 1 (a). It seems that the difference of loss ratio is little since the averaged difference of loss region is not as large for these two cases as shown in Fig 1 (a) and (b).

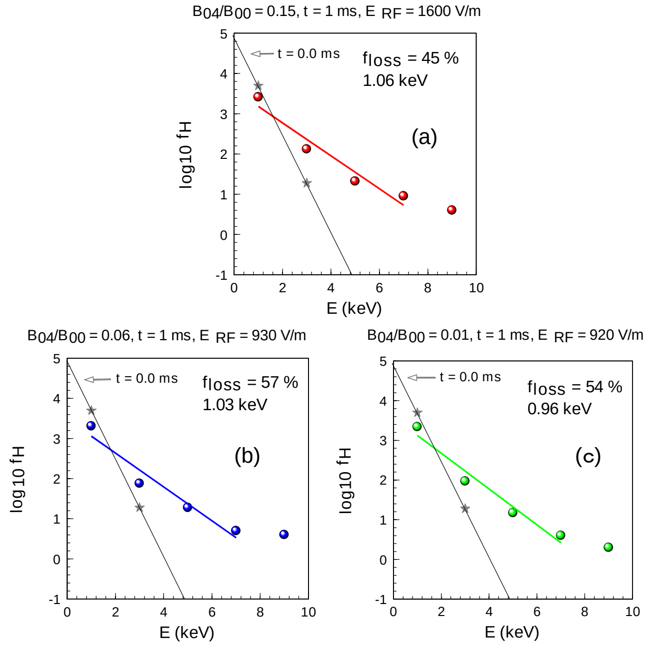

Fig. 3. Calculated energy spectra by a Monte-Carlo mothod for (a) high, (b) medium and (c) low bumpy cases, respectively.

The tail temperatures estimated from the energy spectra from 1 to 7 keV are in the same range as the experimental data except the low bumpy case. The tail temperature is largest in the high bumpy case although the difference is not as large as the experimental data in Ref. 3. The loss particle ratio is smallest in the high bumpy case. The bulk heat source, which is delivered mainly to ions in these cases, is also largest in the high bumpy case. The bulk ion heating power in the high bumpy case is 20% larger than two other cases.

By using Monte Carlo method, the velocity distribution of fast ions and energy spectra are discussed. It is found that the loss region near the perpendicular direction is changed by the bumpiness and it affects the energy spectra. The effects of the radial electric field and the rf field profiles will be discussed for the next step.

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