Velocity Distribution of Fast Ions Generated by ICRF Heating in Heliotron J

H. Okada 1), S. Kobayashi 1), H. Takahashi 2), S. Mihara 2), D. Katayama2), T. Mutoh 3), T. Mizuuchi 1), K. Nagasaki 1), Y. Nakamura 2), S. Yamamoto 1), H. Arimoto 2), G. Motojima 3), S. Watanabe 2), K. Mukai 2), H. Matsuoka 2), Y. Kowada 2), K. Hosaka 2), S. Konoshima 1), K. Hanatani 1), K. Kondo 2) and F. Sano 1)

1) Institute of Advanced Energy, Kyoto Univ., Gokasho, Uji, Kyoto 611-0011, Japan
2) Graduate School of Energy Science, Kyoto Univ., Gokasho, Uji, Kyoto 611-0011, Japan
3) National Institute of Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan

e-mail contact of main author: okada@ iae.kyoto-u.ac.jp

Abstract Fast ion velocity distribution is investigated using ICRF minority heating in Heliotron J with special emphasis on the effect of the toroidal ripple of magnetic field strength. The effect of the magnetic configuration on the fast ion confinement is one of the most important issues in helical devices. Here, the pitch angle dependences of energy spectra for three bumpy cases are measured for the first time, then, the fast ions up to 34 keV are observed in the high bumpy case during ICRF heating in Heliotron J. The configurations used in this study are as follows; the bumpiness (B_{04}/B_{00}, where B_{04} is the bumpy component and B_{00} is the averaged magnetic field strength) are 0.15 (high), 0.06 (medium) and 0.01 (low) at the normalized radius of 0.67. The configuration of B_{04}/B_{00} = 0.06 corresponds to the standard configuration in Heliotron J. In high bumpy cases, the higher energy flux is measured near 120 deg in pitch angle although the ions are considered to be accelerated in the perpendicular direction by ICRF heating. To understand experimental results, Monte Carlo calculation is performed. The numerical model consists of orbit tracing, Coulomb collisions and acceleration by the ICRF heating. Minority protons are regarded as test particles and the heating is simulated by the velocity kick in the perpendicular direction in velocity space when ions cross the cyclotron layer. The calculation results using Monte Carlo method represents that the accelerated ion distribution has its peak in the range between 20 deg and 30 deg from the perpendicular direction. This result is considered to be caused mainly due to the existence of the loss region around the perpendicular direction.

1. Introduction

The effect of the magnetic configuration on the fast ion confinement is one of the most important issues in helical devices. In this paper, fast ion formation and confinement are studied using ion cyclotron range of frequency (ICRF) heating in the minority heating scheme in Heliotron J [1, 2, 3], a low-shear helical-axis heliotron (R_0 = 1.2 m, a = 0.1-0.2 m, $B_0 \leq$ 1.5 T) as shown in Fig. 1. Fourier components of the magnetic field in Boozer coordinates can be controlled by using five sets of coil systems. The bumpiness can be changed by the ratio of the coil current of Toroidal coil A to that of Toroidal coil B. The effect of the bumpiness, which is the toroidal field ripple, on fast ion confinement and heating efficiency were discussed in the previous papers [4, 5, 6]. The configurations used in these studies were as follows; the bumpiness (B_{04}/B_{00}, where B_{04} is the bumpy component and B_{00} is the averaged magnetic field strength) are 0.15 (high), 0.06 (medium) and 0.01 (low) at the normalized radius of 0.67. The configuration of B_{04}/B_{00} = 0.06 corresponds to the standard configuration in Heliotron J. The bumpiness is one of key parameters for improving the confinement in

Heliotron J configuration [3].

The good confinement of fast ions and the high efficiency of ICRF heating in the high bumpy case were reported [6]. However, the energy spectra of minority protons were measured only at the fixed pitch angle except for the medium bumpy case [5]. The highest effective temperature of the high energy tail was observed at the pitch angle different from the perpendicular to the magnetic field in the medium bumpy case although the acceleration of minority ions by the ICRF heating is perpendicular. In this paper, the energy spectra for various pitch angles in three bumpy cases mentioned above are observed widely in velocity space by using charge-exchange neutral particle analyzer (CX-NPA) to clarify velocity distribution under the existence of ICRF heating source. Then, orbit calculation and Monte Carlo analysis with ICRF heating term and collisional damping term are carried out to clarify the effect of the bumpiness on the formation and confinement of fast ions.

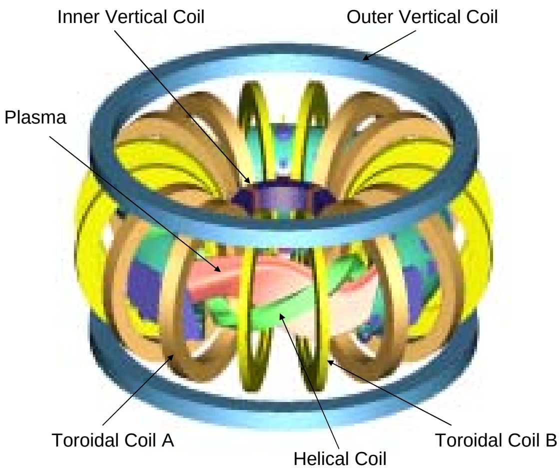

Fig.1. A schematic view of Heliotron J device and its coil system. The major radius of the torus is 1.2 m. The main vertical coil is not illustrated since it has a large radius (3.5 m).

2. Experimental Setup

Two ICRF loop antennas are installed on the low-field side of Helitoron J as shown in Fig. 2. Each antenna is fed by an independent transmitter. This section corresponds to the corner section of a Heliotron J plasma, where the mod-B surface has a tokamak-like structure. The cyclotron-resonance layer is located near the axis with a frequency of 19 MHz in the STD configuration. The frequency is changed so that the resonance layer is shifted to the selected position. The ICRF wave is radiated from the antenna on the low-field side to ECH target plasmas. The phase between the two antenna currents can be controlled by a phase shifter at the first stage oscillators. The two loop antennas are used for the experiment under almost equally powered condition. Plasmas are generated by using a 70 GHz ECH beam injected vertically from the upper port in the straight section of Heliotron J. The power of ECH is from 300 to

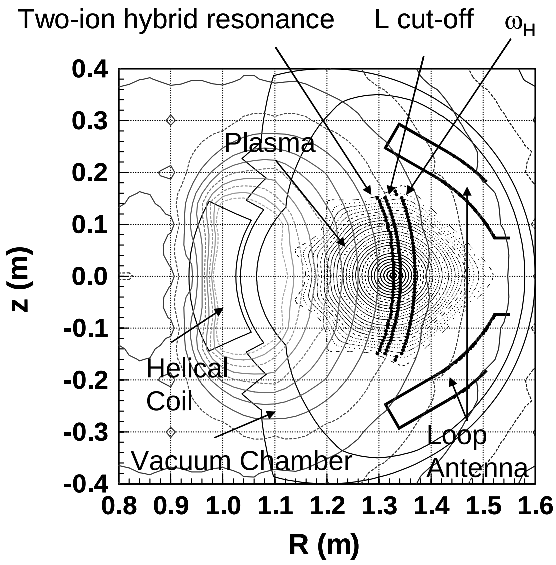

Fig. 2. A schematic view of two antenna loops, the plasma shape, the proton cyclotron-resonance layer (ω_H), the left-hand cut-off layer, the two-ion hybrid resonance layer, and the mod-B surface in the poloidal cross-section at the corner section of Heliotrn J. The cutoff and resonance layers are calculated with the parameters: ICRF frequency = 19 MHz, density = 0.5 x 10^{19} m^{-3}, B_0 = 1.32 T, minority ratio = 0.1, and $k_{//}$ = 0.53 m^{-1}.

350 kW. For keeping the ECH resonance condition, the magnetic field strength adjusted to be constant in the ECH injection position. Therefore, the magnetic strength in the poloidal cross section of the ICRF antenna is changed for different bumpy configuration. The frequency of the injected ICRF wave is adjusted so that the resonance layer is positioned near the magnetic axis: 23.2 MHz for the high bumpiness and 19 MHz for the medium and low bumpy cases. An ICRF pulse of 23.2 MHz or 19 MHz is injected into an ECH target plasma where $T_i(0)$ = 0.2 keV, $T_e(0)$ = 0.7-0.8 keV and $\bar{n}_e$ = 0.4 x 10^{19} m^{-3}. ICRF injection power is in the range from 250 kW to 300 kW. The minority heating mode is selected to generate fast ions with deuterium as the majority species and hydrogen as the minority.

A CX-NPA is equipped to analyze the energetic ions, which has the ability of scanning in the toroidal and poloidal directions in order to research ions in the wide range of the velocity distribution. The CX-NPA has 10 channels for hydrogen and 10 channels for deuterium. The type of the analyzer is *E//B*. The energy range is from 0.4 to 80 keV for hydrogen and from 0.2 to 40 keV for deuterium with the energy resolution in the range from 4 to 10%. 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 charge-exchange neutrals in the wide range of the velocity distribution. The origin is the normal direction to the torus for the toroidal angle and the horizontal direction for the poloidal angle. For the poloidal direction the CX-NPA is determined so that the line of sight of the CX-NPA crosses the magnetic axis for every toroidal angle in this experiment.

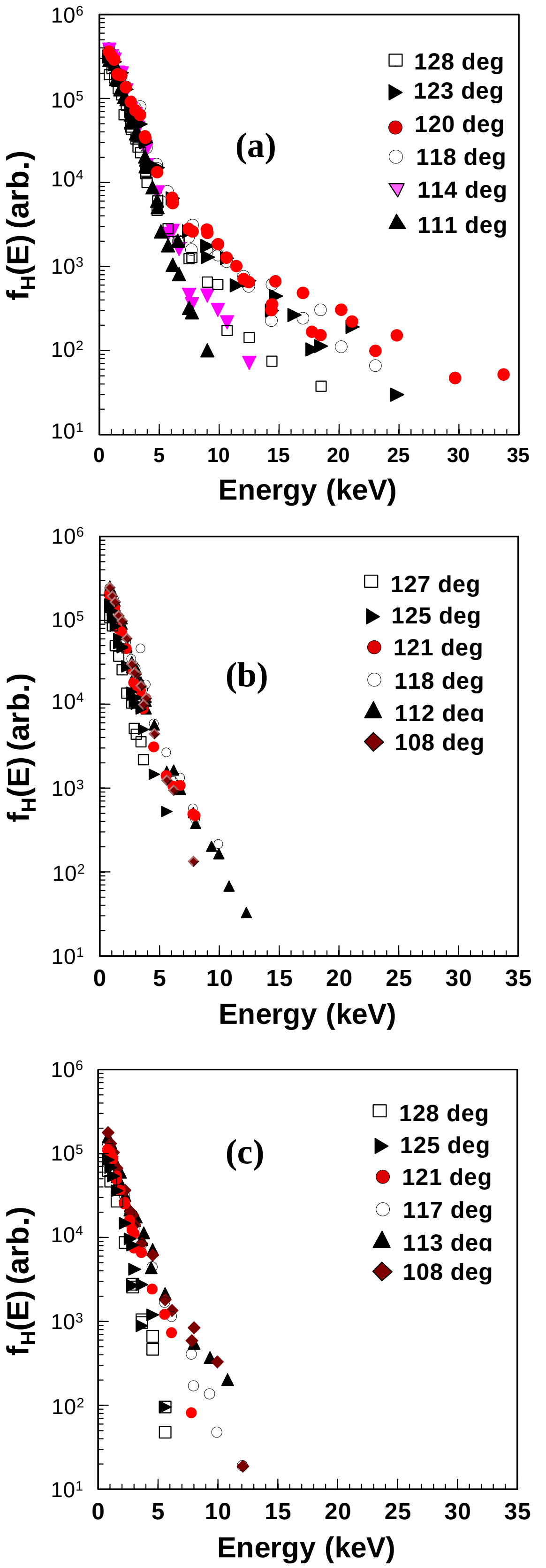

Fig. 3. Minority hydrogen spectra for various pitch angles in the high bumpy (a), the medium bumpy (b) and the low bumpy (c) configurations. By changing the toroidal and poloidal angles of CX-NPA, the energy spectra were measured. The line of sight of the CX-NPA crosses the magnetic axis for all cases.

3. Measured velocity distributions

Figure 3 shows measured minority hydrogen energy spectra for various pitch angles by changing toroidal angle of a CX-NPA for three bumpy cases mentioned above. In high bumpy

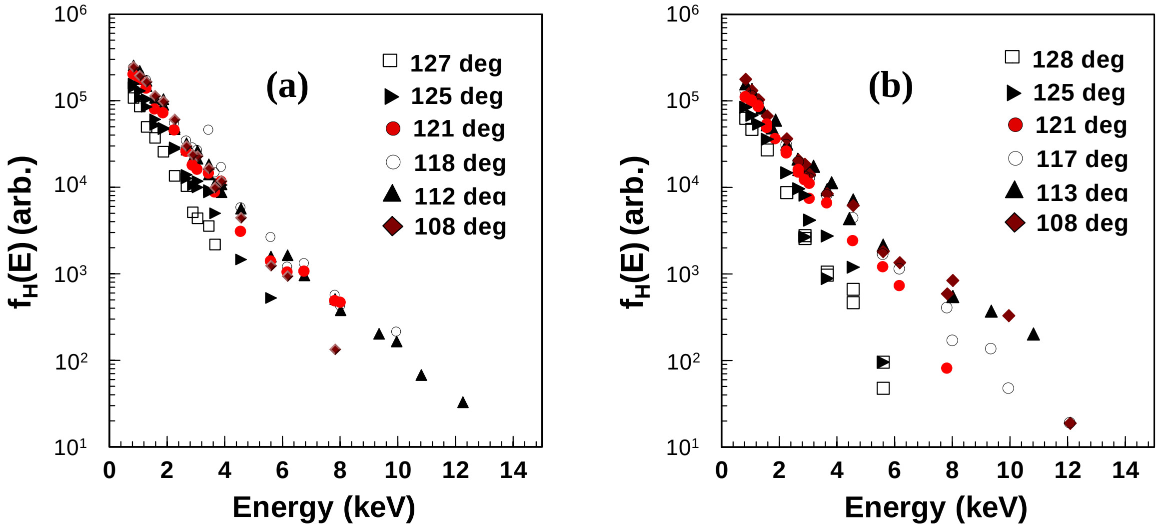

Fig. 4. Minority hydrogen spectra for various pitch angles in the medium bumpy (a) and low bumpy (b) configurations. These figures are expanded in energy range from Figs. 3(b) and 3(c).

case (a), the ion flux is observed up to 34 keV at the pitch angle of 120 deg. Such high energy particles cannot be observed in the medium and low bumpy configurations. The angle where the highest tail is observed is about 30 deg from the perpendicular direction to the magnetic field. Toward 90 deg, the tail component decreases shown in Fig. 3(a). The tail decreases from the angle of 120 deg as the pitch angle increases as well, since there is no acceleration mechanism in the parallel direction to the magnetic field.

In medium and low bumpy cases, there is no fast ion observed over 15 keV as shown in Fig. 3(b) and (c). The dependence of the energy spectrum on the pitch angle is also different from the high bumpy case. The figures of these cases are expanded in energy as shown in Fig. 4 to see the structures well. In the range from 108 deg to 121 deg, the slope in Fig. 4(a) is gentle and the abundant high energy fluxes are observed. Then, the slope becomes steeper in the angles of 125 deg and 127 deg. In the low bumpy case (Fig. 4 (b)), the energy spectra at the pitch angles of 108 and 113 are almost same. Then, the slope becomes steeper continuously with the pitch angle. The dependences of the velocity distributions on pitch angle have different characteristic for three bumpy cases. Among them, the high bumpy case is recognized as the most preferable configuration for the fast ion formation and confinement in ICRF minority scheme.

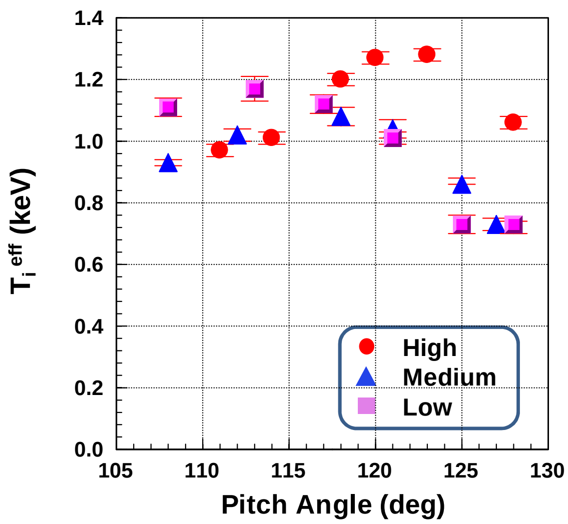

Fig. 5. Effective temperature estimated in the energy range below 7 keV for each energy dpectrum.

The effective temperature for the minority protons is estimated from the slope of the energy spectra below 7 keV. The effective temperature clearly represents the changes in the velocity space for three bumpy cases as shown in Fig. 5. It is already known that there is large loss region in the outside region of the torus at the corner section, where the ICRF antennas are installed. It is expected that the existence of the loss region affects the fast ion distribution in velocity space. However, it is difficult to estimate the effect of the loss region structure on the fast ion confinement, because it is different at each position. The numerical analysis using Monte Carlo method is useful to reproduce such conditions in the complicated field structure like Helitoron J magnetic field.

4. Monte Carlo Analysis

To understand experimental results, Monte Carlo calculation is performed. The numerical model consists of orbit tracing, Coulomb collisions [7] and acceleration [8] by the ICRF heating. Minority protons are regarded as test particles and the 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 by ICRF heating is proportional to the ICRF electric field amplitudes and this field is given as an input parameter. The field amplitude is determined to match the input power by the ICRF heating. Various 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. Here, the rf-electric field profile is assumed to be parabolic as in the previous calculation for Heliotron E plasmas [8]. The initial distribution of test ions is uniform in the toroidal and poloidal directions, and parabolic in the radial direction. The initial energy of ions is chosen randomly due to the Maxwell distribution characterized by the bulk ion temperature. Examples of the orbit of trapped ion with energy of 1 keV in Boozer coordinates are shown in Fig. 6 for two configurations under the same initial conditions. The ion in Fig. 6(a) is trapped in one toroidal segment due to high bumpiness and confined in the plasma. The ion in Fig. 6(b), where the bumpiness is weaker, is barely trapped, then, lost finally.

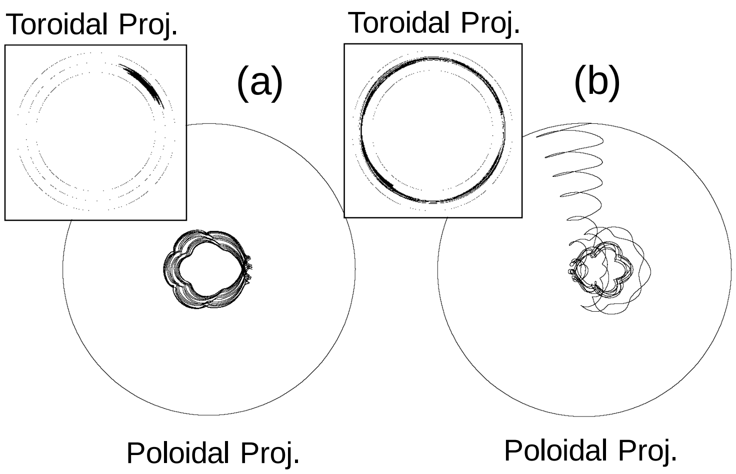

Fig. 6. Trapped ion orbits starting in the straight section for the high bumpy case (a) and the medium bumpy case (b). The toroidal projection (the smaller one) and the poloidal projection of the orbit are illustrated in each case.

Using 5000 particles, the velocity distributions of the minority protons for three bumpy cases are calculated. The plasma parameters are: $T_e(0)$ = 0.7 keV, $T_i(0)$ = 0.3 keV, $n_e(0)$ = 0.5 x 10^{19} m^{-3} and Z_{eff} = 3.0. The input rf-field is adjusted so that the input power should be about 100 kW for each case. The orbit tracing with acceleration and collisions is continued during 2 ms. The velocity distribution is saturated within 1 ms in this condition. All figures show the distribution at 1 ms, since the particle number is gradually decreased by loss. The calculated particles are summed for some bounded area in velocity space. The bounded area is characterized as particle energy and pitch angle in this calculation. In Figure 7, the calculated results for three bumpy cases are presented, where the vertical axis corresponds to the logarithm of the ion counts in the area defined due to the energy and the pitch angle.

Figure 7(a) shows the relation of calculated energy spectra to the pitch angle in the high bumpy case. The high energy tail is largest among the three configurations. The high energy ions are generated between 60 deg and 70 deg and between 110 deg and 120 deg in pitch angle. It is noted that the particle with the pitch angle from 5 deg to 15 deg is represented as "10 deg", here. There are high energy ions at 90 deg; however they are not so large. The asymmetry against the pitch angle of 90 deg can be found in Fig 7(a). The tail near 60 deg is larger than that near 120 deg. In the experiment, the high energy tail is observed in the high bumpy case and it has a peak near 120 deg. However, the tail is decreased rapidly as the decrease of the pitch angle in the experiment.

There is little tail in the medium bumpy case as shown in Fig. 7(b). The asymmetry at the 90 deg is also weak. The fast ion distribution is almost same from 70 deg to 120 deg. The difference of the energy spectra

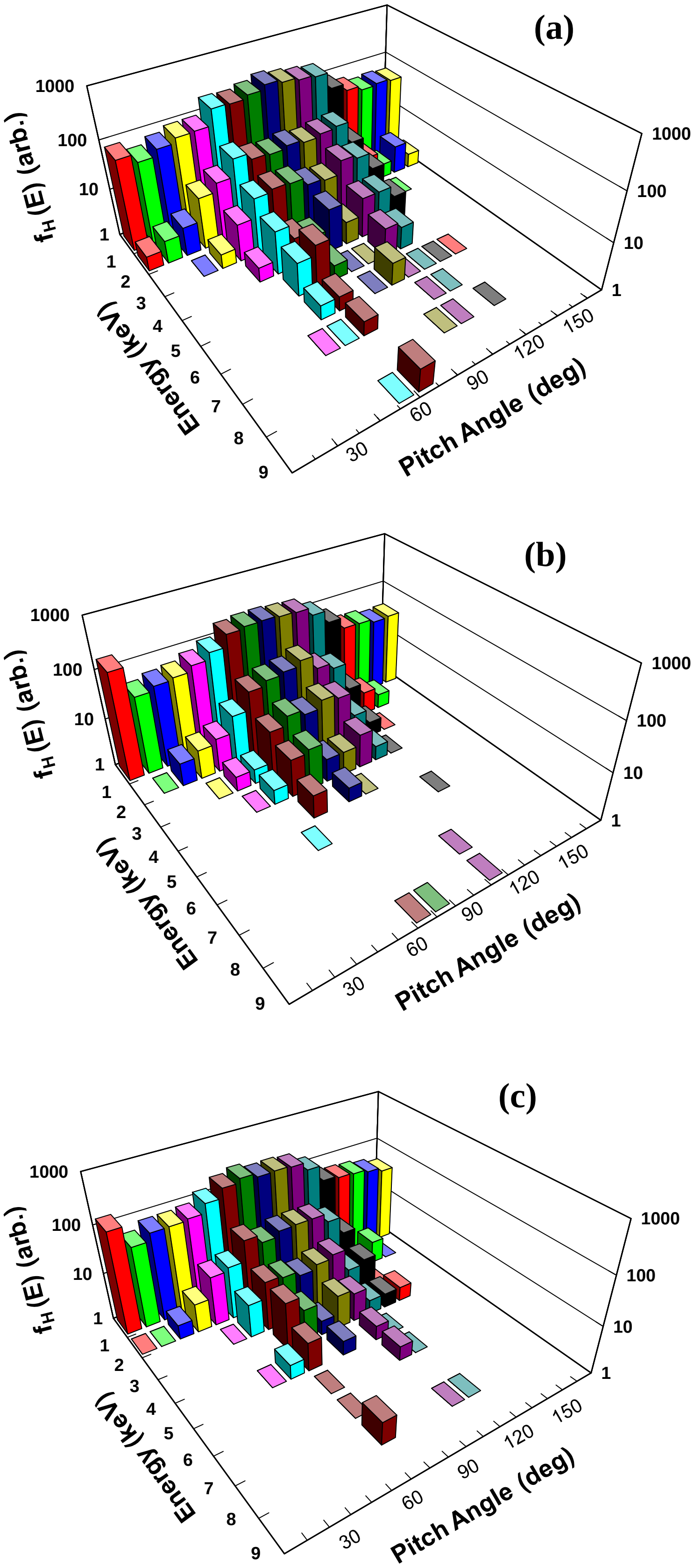

Fig. 7. Calculated pitch angle dependence of energy spectra in the high bumpy case (a), the medium bumpy case (b) and the low bumpy case (c). Five thousands particles are used for each calculation.

among this pitch angle range in experiment is also very small as shown in Fig. 4(a) and Fig. 5. The tail is observed in the low bumpy case shown in Fig. 7(c) although it is smaller than that in the high bumpy case. The tail component is observed at the angles of 70 deg, 110 deg and 120 deg. The high energy component is decreased little towards the perpendicular direction and it is decreased rapidly towards the parallel direction. In the experiment results shown in Fig. 4(b) and Fig 5, the fast ions is increased towards 90 deg and almost constant from 108 deg to 117 deg. Both results agree well.

The calculation results using Monte Carlo method represents that the accelerated ion distribution has its peak in the range between 20 deg and 30 deg from the perpendicular direction in the high and low bumpy cases and there is little tail in the medium bumpy case. This result is considered to be caused mainly due to the existence of the loss region around the perpendicular direction [6]. On the outer side of the torus in the cross section of the corner section, the loss region is largest for all cases. Therefore, the structure of the loss region at this position is very important to improve the fast ion confinement. However, integrated analysis is needed to understand the experimental results since Coulomb collisions and acceleration by the ICRF heating are also important for the fast ion formation and confinement. Using Monte Carlo calculation, the dependences of the high energy tail distribution on the pitch angle and on the field configuration (bumpy component) are reproduced and they agree with the experimental results qualitatively.

5. Summary

Fast ion velocity distribution is investigated using ICRF minority heating in Heliotron J with special emphasis on the effect of the toroidal ripple of magnetic field strength. The effect of the magnetic configuration on the fast ion confinement is one of the most important issues in helical devices. The pitch angle dependences of energy spectra for three bumpy cases are measured. In the high bumpy case, the fast ions up to 34 keV are observed for the first time during ICRF heating in Heliotron J. In the energy spectra of the minority protons, high energy tail can be found in the high and low bumpy cases. The tail is largest in the high bumpy case, then, the high bumpy configuration is most preferable for the fast ion formation and confinement. The direction of the high energy tail formation is not perpendicular to the magnetic field and has the deviation of 20 -30 deg. This result is considered to be caused mainly due to the existence of the loss region around the perpendicular direction. When the effective temperature is estimated in the high energy component, the dependences on the pitch angle among three bumpy cases are different from each other.

To understand experimental results, Monte Carlo calculation is performed. The numerical model consists of orbit tracing, Coulomb collisions and acceleration by the ICRF heating. Minority protons are regarded as test particles. The calculation results using Monte Carlo method represents are as follows: (1) The high bumpy configuration is the most favorable for the fast ion acceleration and confinement, (2) The tail is created at the pitch angle between 20 deg to 30 deg away from the perpendicular direction, (3) The pitch angle dependence of the energy spectra is very weak in the medium bumpy case. (4) There exists the asymmetry of the energy spectra on the pitch angle against 90 deg. These results except (4) agree with the experimental results. There is no experimental data for the result of (4). It is found that Monte Carlo procedure is very useful to estimate the fast ion formation and confinement in the complex field structure like Heliotron J magnetic field. From the result of (4), it is expected that the larger tail would be exist in the high and low bumpy configurations on the opposite side against perpendicular direction to the side where the energy spectra are observed by a CX-NPA in the experiment. For the next step, better configuration in the relation to the fast ion confinement will be sought by using ICRF heating and numerical calculation.

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