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A Calculation of the Distribution Function of ICRF Heated Plasma in LHD using a Bounce-Averaged Fokker-Planck Equation

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Abstract

High-energy ions produced by the ion cyclotron range of frequency (ICRF) heating were observed on the Large Helical Device (LHD). The dependence of the count number of high-energy particles on pitch-angle was studied using the time-of-flight neutral particle analyzer (TOF-NPA) in the LHD. The angle of the line-of-sight was scanned at five successive discharges sustained by ICRF heating only. A unique "rabbit-ear" structure with a large population of high-energy ions at a certain pitch-angle, was observed. A bounce-averaged Fokker-Planck equation was applied to the LHD plasma in the helical magnetic configuration in order to explain the structure of the measured distribution function. The calculation successfully reproduced the "rabbit-ear" structure.

Keywords:

ICRF heating, LHD, high-energy ions, bounce-averaged Fokker-Planck equation

1. Introduction

Ions are accelerated perpendicularly to the magnetic line of force near the ion cyclotron resonance layer by the ion cyclotron range of frequency (ICRF) heating, resulting in an increase in the population of trapped particles. The high-energy ions are accelerated until they do not across the ion cyclotron resonance layer. Therefore, the particles with a pitch-angle of 90° have the largest population near the ion cyclotron resonance layer. The peak of the distribution function is shifted to a lower angle as these particles are observed at the location with lower magnetic field strength than that of the cyclotron resonance layer. This distribution has a so-called "rabbit-ear" ("butterfly") structure [1-4].

In order to investigate the effect of ICRF heating in helical systems, the dependence of the distribution function on pitch-angle was studied using the time-of-flight neutral particle analyzer (TOF-NPA) [5] on the large helical device (LHD). A bounce-averaged Fokker-Planck equation was applied to the ICRF heated plasma on the helical magnetic configuration in order to explain the experimental result.

2. Experimental Result

The angle of the line-of-sight with respect to the magnetic axis, ϕ, was changed as shown in Fig. 1, and it was scanned from 40.4° to 93.9° at five successive

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plasma discharges sustained by ICRF heating in the minority heating regime in the He plasma having H minority. The magnetic field strength on the axis B_0 was 2.75 T and the applied frequency f was 38.47 MHz. Plasma parameters and an ICRF injection power were kept constant: $\bar{n}_e = 0.9 \times 10^{19}$ m^{-3}, $T_{e0} = 1.5$ keV and $P_{ICRF} = 1.2$ MW.

Figure 2 shows the contour of the neutral particle flux shown in polar coordinate with the angle ϕ and the modulus $\sqrt{2E/m_H}$, where E is particle energy. The labels $v_{//} = \sqrt{2E/m_H}\cos\phi$ and $v_\perp = \sqrt{2E/m_H}\sin\phi$ on the abscissa and the ordinate are parallel and perpendicular velocity to the magnetic axis, respectively. In order to compensate for the difference of viewing volume, which depends on the line-of-sight, fluxes are normalized on the assumption that the distribution function was isotropic at the energy range of 6 keV (lowest channel of the TOF-NPA). It was found that the flux of high-energy neutral particles was largest at the angle of $\phi \cong 70°$. It was thought that this was related to the so-called "rabbit-ear" structure of the distribution function.

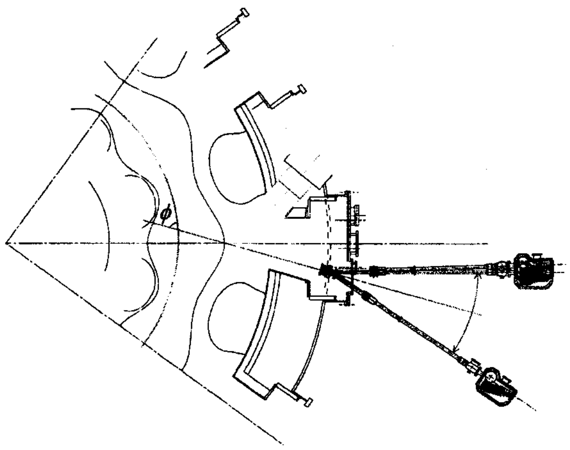

Fig. 1 The TOF-NPA. The angle of the line-of-sight with respect to the magnetic axis, ϕ, was scanned from 40.4° to 93.9°.

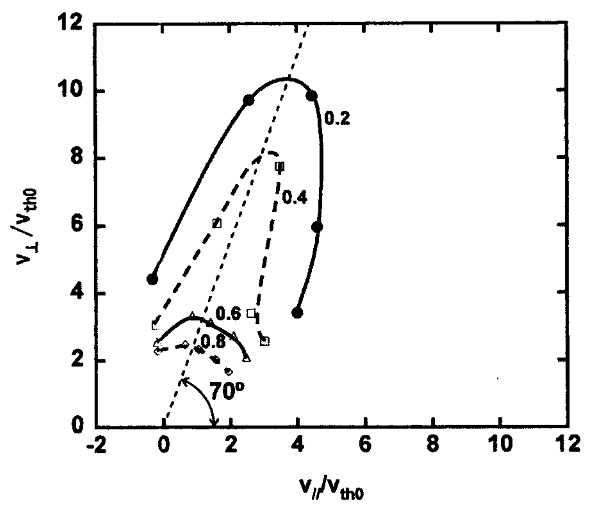

Fig. 2 Contour of count number of neutral particles detected with the TOF-NPA. The contour of the count number is shown in a polar coordinate (ϕ, $\sqrt{2E/m_H}$).

3. Calculation of Fokker-Planck Equation

The bounce-averaged Fokker-Planck equation is as follows [3]:

$$\frac{\partial f_0}{\partial t} = \bar{C}(f_0) + \bar{Q}(f_0)$$

The distribution function f_0 is independent of l, a length along the magnetic line of force. The collision term, $C(f_0)$, and the quasi-linear diffusion term for ion cyclotron heating, $Q(f_0)$, are averaged along the magnetic line of force weighted by $1/v_{//}$ and divided by the bounce period, τ_b:

$$\bar{C}_0(f_0) = \frac{1}{\tau_b}\int \frac{dl}{v_\parallel} C(f_0) = \frac{1}{V^2} mv\left(\frac{\partial}{\partial E} + \frac{\mu}{E}\frac{\partial}{\partial \mu}\right) \times \left\{ -\alpha V^2 f_0 + \frac{1}{2} mv\left(\frac{\partial}{\partial E} + \frac{\mu}{E}\frac{\partial}{\partial \mu}\right)\left(\beta V^2 f_0\right)\right\} + \frac{m\gamma}{2v^2\tau_b}\frac{\partial}{\partial \mu}\tilde{c}\mu\frac{\partial f_0}{\partial \mu}$$

$$\bar{Q}(f_0) = \frac{1}{\tau_b}\int \frac{dl}{v_{//}} Q(f_0) = \frac{2\pi m q^2}{\tau_b} L_{res}\tilde{q}L_{res} f_0$$

where,

$$\tau_b = \int \frac{dl}{v_{//}}, \quad \tilde{c} = \int \frac{v_{//}}{B} dl\,,$$

$$\tilde{q} = \sum_{res} \frac{\mu B}{8\left|\left(v_{//} - k_{//}\mu/q\right)\left(d\Omega/dl\right)\right|}\left|E_{left} J_0\left(\frac{k_\perp v_\perp}{\Omega}\right)\right|^2,$$

$$L_{res} = \frac{1}{m}\left(\frac{\partial}{\partial E} + \frac{q}{m\omega}\right), \quad \alpha = \langle \Delta v_{//}\rangle + \frac{1}{2v}\left\langle \left(\Delta v_{//}\right)^2\right\rangle,$$

$$\beta = \left\langle \left(\Delta v_{//}\right)^2\right\rangle, \quad \gamma = \left\langle \left(\Delta v_\perp\right)^2\right\rangle,$$

where $\langle \Delta v_{//}\rangle$, $\langle(\Delta v_{//})^2\rangle$, and $\langle(\Delta v_\perp)^2\rangle$ are the Coulomb diffusion coefficients, and m and q are the mass and charge of the resonant particle, respectively. ω and Ω are the applied frequency and an ion cyclotron frequency of the resonant particle, respectively. E and μ are the energy and the magnetic moment of the resonant particle, respectively, and $E_{\rm left}$ is a left hand component of the radio frequency (RF) electric field. The summation $\sum_{\rm res}$ is taken at the resonant point on the magnetic line of force, i.e.,

$$\begin{cases} \omega - k_{/\!/} v_{/\!/} - \Omega = 0 \\ E = \mu B + \dfrac{1}{2} m v_{/\!/}^2 \end{cases}$$

Coefficients $\tau_{\rm b}$, $\tilde{c}$, and $\tilde{q}$ are calculated along the magnetic line of force using plasma parameters.

In the helical magnetic configuration, there are many helical ripples along the magnetic line of force. The coefficients $\tau_{\rm b}$, $\tilde{c}$, and $\tilde{q}$ must be calculated at each helical ripple. The particle trapped in one helical ripple is transferred to the other ripples via drift motion. Therefore, the calculation of drift orbits was required in order to deduce the number of bounces in i-th ripple, n_i. The coefficients $\tau_{\rm b}$, $\tilde{c}$, and $\tilde{q}$ were weighted by n_i:

$$\tau_{\rm b} = \sum_i n_i \tau_{{\rm b}i} / \sum_i n_i$$

$$\tilde{c} = \sum_i n_i \tilde{c}_i / \sum_i n_i$$

$$\tilde{q} = \sum_i n_i \tilde{q}_i / \sum_i n_i$$

The magnetic line of force at the normalized minor radius ρ = 0.75 was employed in the following calculation of the distribution function. Figure 3(a) shows the magnetic line of force and the contour of the magnetic field strength in the plane, where an abscissa and an ordinate are a toroidal angle φ and a poloidal angle θ. The bottoms of each helical ripple are indicated by solid circles. The magnetic field is obtained by solving the Biot-Savart equation. Figure 3(b) shows the drift orbit of the particle which passes the position (ρ, θ, φ) = (0.75, 0°, 18°) with an energy of 100 keV and a pitch-angle of 70°. The poloidal angle is divided into twelve regions separated by dashed lines as shown in Fig. 3(a). The trapped particles at the i-th region in Fig. 3(b) behaves as the particles on the magnetic line of force in the i-th ripple in Fig. 3(a), and the bounce number is given by

$$n_i = t_i / \tau_i,$$

where t_i is the staying-time in the i-th region.

Figure 4 shows the contour lines of a calculated

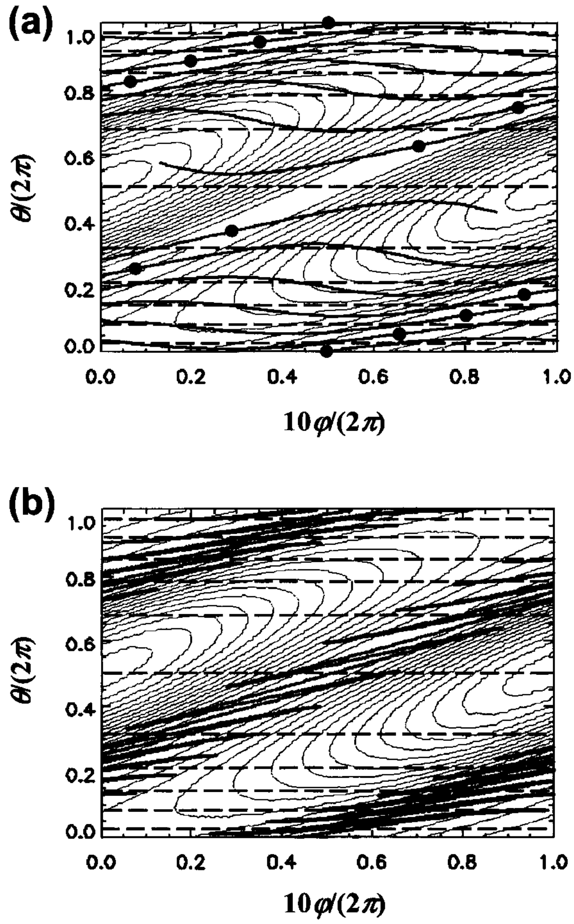

Fig. 3 Contour of magnetic field strength with (a) the magnetic line of force and (b) the drift orbit of the particle which passes (ρ, θ, φ)=(0.75, 0°, 18°) with an energy of 100 keV and a pitch-angle of 70°. The abscissa is toroidal angle φ and the ordinate is poloidal angle θ. The solid circles are locations of the ripple bottoms. The area is divided into twelve regions by dashed lines.

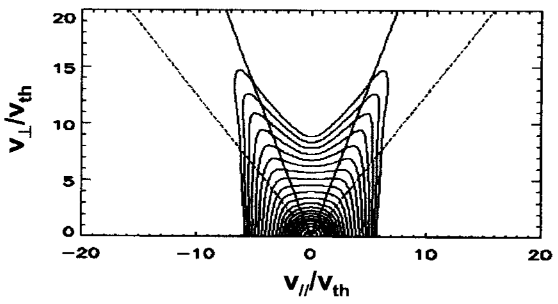

Fig. 4 Contour of the calculated distribution function by solving the bounce-averaged Fokker-Planck equation. $v_{/\!/}$ and $v_{\perp}$ are normalized to $v_{\rm th}$, the thermal velocity of hydrogen calculated with $T_{\rm H}$ = 0.75 keV at ρ = 0.75.

steady state distribution function in the velocity space at (ρ, θ, φ) = (0.75, 0°, 18°) in which the magnetic field strength is lowest. The solid lines indicate a pitch-angle of 70°, and the particles on the solid lines are reflected at the ion cyclotron resonance layer. The dashed lines are the boundary between passing and trapped particles, above which particles are trapped. In the calculation of $\tilde{q}$, the left hand component of the RF electric field was deduced from the elements of the dielectric tensor, assuming a uniform RF electric field strength in the propagating region. In the evanescent region, the electric field was put at zero. The distribution function depended on the power density. The power density was employed at 60 kW/m^3 with $n_e = 1 \times 10^{19}$ m^{-3}, $n_H = 5 \times 10^{17}$ m^{-3}, and $T_e = T_{He} = 0.75$ keV in this calculation.

A large fraction of the particles are in the trapped region, and the particles whose banana tips are near the ion cyclotron resonance layer have the largest population; the calculated "rabbit-ear" structure of the distribution function is similar to the experimental result shown in Fig. 2. However, the angle of the largest population is a little lower than that of the solid line. A left-hand component of the RF electric field is small in the ion cyclotron resonance layer, but at slightly higher magnetic field strength it increases in the minority heating regime. Particles with slightly smaller pitch-angle than that of particles on the solid line can reach the strong absorption region. Therefore, the angle of the largest population is slightly smaller than that of the solid line. The particles with a pitch-angles of 90° cannot cross the ion cyclotron resonance layer, but their number increases via pitch-angle scattering. The employment of a smaller ρ than 0.75 would reproduce the distribution function that has the maximum population at a larger pitch-angle. Since the pitch-angle is close to the line-of-sight angle with respect to the magnetic axis, employing ρ = 0.75 is reasonable in comparison to the experimental result.

4. Summary

In order to observe the anisotropy of the distribution function, the line-of-sight of the fast neutral particle analyzer was scanned. The signal had a peak at a certain angle. The result was compared with analysis using the bounce-averaged Fokker-Planck equation. In this calculation, the bounce-averaged Fokker-Planck equation was modified in order to adapt it to the helical system, which has toroidal and helical ripples. The calculation successfully simulated the "rabbit-ear" structure.

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