Study on ion cyclotron emission excited by DD fusion produced ions on JT-60U

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1. Introduction

On JT-60U, ion cyclotron emissions (ICEs) which are related to deuterium-deuterium (DD) fusion produced fast ^{3}He (ICE(^{3}He)), T and H ions were detected [1, 2]. The previous work shows that the magneto-acoustic cyclotron instability (MCI) is a possible emission mechanism for the ICE(^{3}He) observed in JT-60U [3]. The MCI can be driven by the bump-on tail structure and strong anisotropy on the ion velocity distribution [4]. In spite of relatively high DD fusion neutron emission rates, a disappearance of the ICE(^{3}He) was often observed on JT-60U [1]. There is a possibility that the mechanism for the disappearance is a change of the fast ^{3}He ion velocity distribution. Investigating characteristics of the fast ion velocity distribution that excites the ICE can contribute to understanding its emission mechanism. In this study, to investigate the characteristics of the distribution, we have evaluated the fast ^{3}He ion velocity distribution by using OFMC code [5] under the realistic conditions and compared the distribution between the cases with and without the ICE(^{3}He) observation. In addition, we have developed a wave dispersion code that can solve the dispersion for an arbitrary distribution function in order to take into account characteristics of the fast ^{3}He ion distribution obtained from the above evaluation. We have calculated the linear growth rate of the MCI by using the wave dispersion code.

2. Evaluation of the fast ^{3}He ion velocity distribution

A plasma edge on the low field side would be a region where the ICE(^{3}He) is excited because the ICE(^{3}He) is often observed in the frequency near ^{3}He ion cyclotron frequencies there. We evaluated the fast ^{3}He ion distributions at the midplane edge of the plasma on the low field side in a typical discharge (E48473) where the disappearance of the ICE(^{3}He) is observed in spite of the relatively high neutron emission rate. Figure 1 shows the evaluated energy and pitch-angle distribution of the fast ^{3}He ions (a) before and (b) during the disappearance of the ICE(^{3}He). Both distributions have strong pitch-angle anisotropy. In the

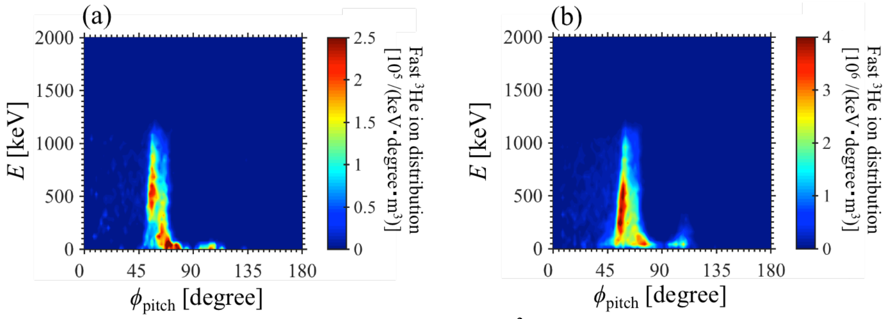

Fig.1. Energy E and pitch-angle $\phi_{\rm pitch}$ distribution of the fast ^{3}He ions at the midplane edge of the plasma on the low field side (a) before and (b) during the ICE(^{3}He) disappearance in E48473.

case with the ICE(^{3}He) excitation, a steep bump-on tail structure in the energy direction is formed. On the other hand, the distribution in the case without the excitation has an almost flat structure in the energy direction. The evaluation results imply that the formation of the steep bump-on tail structure is necessary to excite the ICE(^{3}He).

3. Calculation of the growth rate of the MCI

The evaluated distributions at the plasma edge on the low field side are non-Maxwellian as shown in Fig. 1. Thus, we developed the wave dispersion code that can solve the dispersion for the arbitrary distribution function. In the wave dispersion code, we assumed the linear theory and a model for a homogeneous plasma as a local approximation. The dielectric tensor for the plasma with the arbitrary distribution function $f_{s0}(v_\parallel, v_\perp)$ is given by,

$$\boldsymbol{\varepsilon}_{i,j} = \delta_{i,j}\left(1-\sum_s \frac{\omega_{ps}^2}{\omega^2}\right)+\sum_{s,n}\frac{\omega_{ps}^2}{\omega^2}\int \frac{\left[\boldsymbol{H}_{s,n}\right]_{i,j}}{\omega - k_\parallel v_\parallel - n\Omega_s}\left(\frac{n\Omega_s}{v_\perp}\frac{\partial f_{s0}}{\partial v_\perp}+k_\parallel \frac{\partial f_{s0}}{\partial v_\parallel}\right)\frac{1}{n_{s0}}d^3v \quad (1)$$

where the subscript s is charged particle species, Ω_s is a cyclotron angular frequency, ω_{ps} is a plasma angular frequency and n_{s0} is a density. $v_\parallel$ and $v_\perp$ are parallel and perpendicular velocity components to the magnetic field line, respectively. $k_\parallel$ and $k_\perp$ are parallel and perpendicular wavenumbers, respectively. n is an integer. Tensor $\boldsymbol{H}_{s,n}$ is defined as,

$$\boldsymbol{H}_{s,n} = \begin{bmatrix} \frac{n^2\Omega_s^2}{k_\perp^2}J_n^2 & iv_\perp \frac{n\Omega_s}{k_\perp}J_n J'_n & v_\parallel \frac{n\Omega_s}{k_\perp}J_n^2 \\ -iv_\perp \frac{n\Omega_s}{k_\perp}J_n J'_n & v_\perp^2 J'^2_n & -iv_\parallel v_\perp J_n J'_n \\ v_\parallel \frac{n\Omega_s}{k_\perp}J_n^2 & iv_\parallel v_\perp J_n J'_n & v_\parallel^2 J_n^2 \end{bmatrix} \quad (2)$$

where J_n is the Bessel function and its argument is $k_\perp v_\perp/\Omega_s$. J'_n is the derivative of J_n. Here, we define $\boldsymbol{C}(v_\parallel)$ as,

$$\boldsymbol{C}(v_{\parallel}) = 2\pi \frac{\omega_{ps}^2}{\omega^2} \int v_{\perp} \boldsymbol{H}_{s,n} \left(\frac{n\Omega_s}{v_{\perp}} \frac{\partial f_{s0}}{\partial v_{\perp}} + k_{\parallel} \frac{\partial f_{s0}}{\partial v_{\parallel}} \right) \frac{1}{n_{s0}} dv_{\perp} \quad (3)$$

Then, the second term in the right side of Eq. 1 can take the form of,

$$\boldsymbol{I}_{s,n} = \int \frac{\boldsymbol{C}(v_{\parallel})}{\omega - k_{\parallel} v_{\parallel} - n\Omega_s} dv_{\parallel} \quad (4)$$

An issue is known that we can not calculate $\boldsymbol{I}_{s,n}$ by using only a simple trapezoidal integration method for the solution with Im (ω) $\leq$ 0 for the arbitrary distribution function because of the existence of a pole at $\omega = n\Omega_s + k_{||}v_{||}$. A numerical calculation method with linear tent functions has been used to resolve the issue [6]. In this method, approximating $\boldsymbol{C}(v_{||})$ as a sum of the tent functions, $\boldsymbol{I}_{s,n}$ can be numerically calculated even when Im (ω) $\leq$ 0. Here, we define the uniform parallel velocity mesh as $v_{\parallel j} = v_{\parallel j\text{-}1} + \Delta v_{\parallel}$. Then, the approximation of $\boldsymbol{C}(v_{\parallel})$ with the linear tent function T_j is given by,

$$\boldsymbol{C}(v_{\parallel}) = \sum_j \boldsymbol{C}(v_{\parallel j}) T_j \quad (5)$$

and

$$T_j = \begin{cases} 1 - \dfrac{\left| v_{\parallel} - v_{\parallel j} \right|}{\Delta v_{\parallel}} & \text{if} \left| v_{\parallel} - v_{\parallel j} \right| \leq \Delta v_{\parallel}, \\ 0 & \text{otherwise.} \end{cases} \quad (6)$$

Here, we define the parallel velocity $v_{||l}$ at the mesh point l as $v_{||l} = (\omega - n\Omega_s) / k_{||}$. Then, $\boldsymbol{I}_{s,n}$ is given by,

$$\boldsymbol{I}_{s,n} = \sum_j \frac{\boldsymbol{C}(v_{\parallel j})}{-k_{\parallel}} K_{j-l} = \sum_j \frac{\boldsymbol{C}(v_{\parallel j+l})}{-k_{\parallel}} K_j \quad (7)$$

where K_j is given by,

$$K_j = \int_{-1}^{1} \frac{1 - |X|}{X + j} dX = \begin{cases} \ln\left(\dfrac{j+1}{j-1} \right) - j \ln\left(\dfrac{j^2}{j^2 - 1} \right) & |j| > 1, \\ \pm \ln 4 & j = \pm 1, \\ i\pi & j = 0. \end{cases} \quad (8)$$

where $X = (v_{\parallel} - v_{\parallel j})/\Delta v_{\parallel}$. Substituting $\boldsymbol{I}_{s,n}$ of Eq. 7 for the second term in the right side of Eq. 1, we can numerically calculate the dielectric tensor for the arbitrary distribution function. We adopted the numerical calculation method with the tent functions in the wave dispersion code.

We used a following function as the fast ^{3}He ion velocity distribution to calculate of the dispersion of the MCI.

$$f_{3\mathrm{He}} = C_{\mathrm{d}} \exp\left[-\frac{\left\{ \left(v_{\parallel} - v_{0\parallel} \right)\cos\phi_0 + \left(v_{\perp} - v_{0\perp} \right)\sin\phi_0 \right\}^2}{\delta v_{\mathrm{E}}^2} \right] \exp\left[-\frac{\left\{ -\left(v_{\parallel} - v_{0\parallel} \right)\sin\phi_0 + \left(v_{\perp} - v_{0\perp} \right)\cos\phi_0 \right\}^2}{\delta v_{\mathrm{p}}^2} \right] \quad (9)$$

where $v_{0\parallel}$ and $v_{0\perp}$ are velocities at the center of the velocity distribution of the fast ^{3}He ions in parallel and perpendicular directions to the magnetic field line, respectively. ϕ_0 is a pitch angle defined as $\phi_0 = \cos^{-1}(v_{0\parallel}/v_0)$. δv_E is a velocity spread in the energy direction at $\phi_{pitch} = \phi_0$. On the other hand, δv_p is a velocity spread in the pitch-angle direction at $E = E_0$ where E_0 is the energy at $v = v_0$. C_d is a normalization constant for the distribution function.

The parameters used for the calculation of the MCI are as follows. The magnetic field strength is 1.8 T. The density and temperature of the bulk D plasma are 2×10^{18} m^{-3} and 300 eV, respectively. The minority ^{3}He ion density is 10^{10} m^{-3}. Here, we assumed the wave propagation angle θ_k = 100 degree, $v_0 = 5.65\times10^6$ m/sec, ϕ_0 = 56 degree, $v_{0\parallel} = v_0 \cos\phi_0$, $v_{0\perp} = v_0 \sin\phi_0$ and $\delta v_p = 0.05\times10^6$ m/sec. Figure 2 shows calculated results of linear growth rates Im (ω / Ω_{cD}) of the MCI. The growth rate decreases as δv_E increases, indicating that the growth rate is higher when the distribution has the steeper bump-on tail structure. The tendency of the δv_E dependence of the growth rate is qualitatively consistent with the relation between the ICE(^{3}He) excitation and the characteristics of the evaluated distribution.

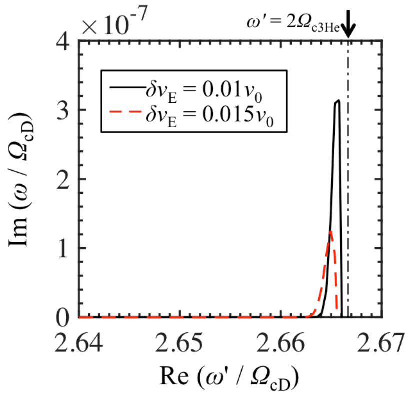

Fig.2. Im (ω / Ω_{cD}) as a function of Re (ω' / Ω_{cD}) of the MCI. Here, ω' is defined as $\omega' = \omega - k_\parallel v_{0\parallel}$. Solid and dashed lines indicate the linear growth rates with δv_E = 0.01 v_0 and 0.015 v_0, respectively.

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