Anisotropic Neutron Emission Spectrum and Its Utilization for Verification of Nuclear Elastic Scattering Effect in Proton-Beam-Injected Deuterium Plasmas

Hideaki Matsuura, Yasuko Kawamoto, Shota Sugiyama, and Shogo Kajimoto

***Abstract*— A possible scenario to observe a knock-on tail using anisotropic neutron emission spectrum in a proton-beam injected deuterium plasma is presented. On the basis of the ion trajectory analysis in ITER-like magnetic configuration, Boltzmann collision integral and Fokker–Planck simulation, the knock-on tail formation in deuteron distribution function due to nuclear elastic scattering, and the resulting modification of the "double differential" neutron emission spectrum are examined. As a result of the beam injection with a specific direction, the neutron emission spectrum is modified in 2-D phase space. It is shown that the ratio of neutron emission rate with >2.8-MeV energy to the 2.45-MeV peak is increased almost 10 times compared with the 1-D modified neutron emission spectrum integrated over the emission angle, which implies the improvement of the accuracy in the neutron measurement. By using the anisotropic neutron emission adjusting the relative positions between beam-injection port and the neutron detector, the possibility to catch the knock-on tail for various plasma conditions can be increased.**

***Index Terms*— ^{6}Li+d gamma-ray-generating nuclear reaction, D(d, n)^{3}He reaction, deuterium plasma, double-differential neutron emission spectrum, nuclaear elastic scattering (NES).**

I. Introduction

ENERGETIC ions in thermonuclear plasma play important roles in various stages of fusion reactor operation. The energetic ions slow down, deposit most of their energy via Coulombic collisions, and create energetic tails (non-Maxwellian components) in fuel-ion velocity distribution functions. It is well known that for suprathermal ions, the nuclear elastic scattering (NES) by thermal ions contributes to the slowing-down process. NES is a non-Coulombic, large-energy-transfer scattering process [1]. So far, energy-transfer process of fusion-produced ions via NES has been investigated for various plasmas. In D^{3}He plasma, several calculations have predicted that the fractional transferred power from energetic protons to bulk ions is enhanced almost 3 times due to NES compared with the case when we only consider the energy-transfer channel via Coulomb collisions [2], [3]. In such a case, the confinement parameter can be reduced significantly [4]. In Deuterium-Tritium (DT) plasmas, a knock-on tail formation in deuteron (triton) distribution functions owing to NES of α-particle and its effect on the emitted-neutron spectrum were examined by Fisher *et al.* [5] and Ballabio *et al.* [6]. The knock-on neutron emission has been observed in JET experiment [7], [8]. We have evaluated the NES effect for beam-injected DT plasma on the basis of the Boltzmann–Fokker–Planck analysis models [9]–[11]. The use of energetic ions for plasma diagnostic has also been studied [12], [13]. Ryutov [12] has pointed out that NES of alpha-particles significantly affects the distribution function of impurity ions and has suggested that the phenomenon can be utilized for diagnostics in thermonuclear plasmas.

The NES effect would appear always in the burning plasma operation and/or experiment. According to the plasma conditions, NES could determine important physics for reactor-grade burning plasma. It is important to experimentally ascertain the phenomena concerning plasma-heating process and validate the related numerical simulations for fusion plasma operation and control.

We have considered the scenarios to examine the NES effect in a deuterium plasma [14]–[16]. An observation scenario of knock-on tail due to NES by looking at the change of the γ-ray and neutron emission rates from ^{6}Li+d and D(d,n)^{3}He reactions in a proton-beam-injected deuterium plasma has been proposed and the experiment is just planning on large helical device at the National Institute for Fusion Science, Toki, Japan. We attempt to observe a knock-on tail in "deuteron" distribution function created by beam-injected "protons." To make sure that the change of the emission rates are caused by the knock-on tail formation in "deuteron" distribution function by NES, we choose not only "deuteron" but also "proton" beam. (If deuteron beam is injected, the emission rates are increased owing to the beam-created energetic tail formed in the deuteron distribution function.) The data concerning proton-created knock-on tail would also be useful to grasp the NES effects in D^{3}He plasmas.

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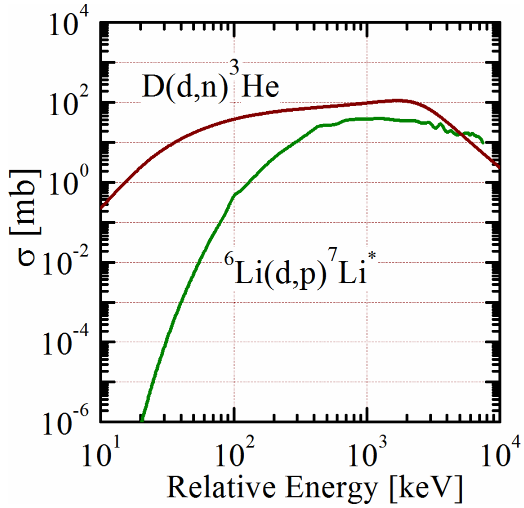

Fig. 1. D(d,n)^{3}He and ^{6}Li(d,pγ)^{7}Li cross sections as a function of relative energy of reactants.

In Fig. 1, the cross sections of the ^{6}Li(d,pγ)^{7}Li and D(d,n)^{3}He reactions are shown as a function of the relative energy of reactants [17], [18]. The cross section of the ^{6}Li(d,pγ)^{7}Li reaction rapidly increases with increasing relative energy. Owing to the existence of small fraction of knock-on tail component, "velocity-averaged" ^{6}Li(d,pγ)^{7}Li reaction rate coefficient would be significantly influenced. It is expected that by using the γ-ray generating reaction for various plasma conditions, we can quantitatively estimate the magnitude of the knock-on tail. On the other hand the cross section of the D(d,n)^{3}He reaction is somewhat gradually increases compared with the one for the ^{6}Li(d,pγ)^{7}Li reaction, and the relative increment due to knock-on tail is smaller. However, the higher neutron emission rate is expected compared with the γ-ray by the ^{6}Li(d,pγ)^{7}Li reaction.

Here, it should be noted that when knock-on tail is created in deuteron velocity distribution function by beam-injected protons, the neutron emission spectrum by the D(d,n)^{3}He reaction is also modified from Gaussian distribution function with enhancement of the neutron emission rate from the value for Maxwellian plasma. Previously many experiments to measure the fast-ion distribution function created by third harmonic ion cyclotron resonance frequency (ICRF) heating have been made by looking at the modified neutron emission spectrum [19]–[22]. Generally the knock-on tail created by NES of energetic ions is much smaller compared with the ones by ICRF heating, and thus we need to devise a way to measure it. When an intense proton beam is injected into the deuterium plasma with a specific direction, the neutron emission spectrum would be significantly modified from the Gaussian distribution anisotropically [23].

In this paper, we use proton beam with a specific direction to create an anisotropic knock-on tail in deuteron distribution function. To confirm the knock-on tail formation, the "double differential" neutron emission spectrum by D(d,n)^{3}He reaction is measured.

1) If the anisotropic neutron emission can be ascertained in the experiment for proton-beam injection with specific direction, it would be an evidence for anisotropic knock-on tail formation in deuteron distribution function.
2) In addition, by adjusting the relative positions between beam-injection port and the neutron detector, the possibility to catch the knock-on tail (accuracy of the measurement) may be increased.

The purpose of this paper is to newly propose a possible scenario of knock-on tail observation using anisotropic neutron emission spectrum in proton-beam injected deuterium plasmas.

II. Analysis Model

A. Estimation of Deuteron Distribution Function

We assume a proton-beam injected deuterium plasma confined in the ITER-like magnetic configuration. The proton distribution function is estimated by ion trajectory analysis using ORBIT code [24]. The equilibrium flux surfaces are determined according to the model developed by Yavorskij *et al.* [25], and radial profile of the safety factor assumed in the simulations is referred from the work of Green [26]. Here, radial profiles of temperature, ion, and electron densities are assumed as $T(r) = T(0) \times (1-(r/a)^2)$ and $n_j(r) = n_j(0) \times (1-(r/a)^2)^{0.05} (j = d, e, {}^6\text{Li})$, respectively [26]. The calculation to simulate the proton behaviors in the proton-beam-injected deuterium plasma follows 24 000 proton orbits for 170 000—840 000 toroidal transit time, i.e., 1.5—3.3 s, depending on beam-injection energy. In this paper, the absolute values of the proton distribution function is determined by comparing the 1-D proton distribution function, which is obtained by integrating $f_p(\vec{v}_p)$ for angular coordinates with the analytical solution of FP equation, i.e., so-called "slowing-down distribution [27]." Actually the neutral hydrogens are ionized with a spatial profile along with the beam injection line. The effect can be considered by superposing the results of the point source, which implies that all of the injected hydrogens are ionized at a spatial point in the plasma as a monoenergetic beam. When an attenuation of the neutral hydrogen beam is accounted, we consider the ionization reactions with background deuterons and electrons, and charge exchange reaction with deuterons.

As a next step, by using the obtained proton velocity distribution function, we evaluate the upscattered source of deuterons by energetic protons via NES. For this purpose, the following Boltzmann collision integral is carried out using the previously obtained proton distribution function at each radial point:

$$S_d^{\text{NES}}(\vec{v}_d) = \iint f_d(\vec{v}'_d) f_p(\vec{v}_p) P(\vec{v}'_d \to \vec{v}_d | \vec{v}_p) \, v'_r \sigma_{\text{NES}}(v'_r) d\vec{v}_p d\vec{v}'_d \quad (1)$$

where σ_{NES} is the cross section of NES. The data are taken from the work by Perkins and Cullen [28]. Here, $v'_r = |\vec{v}_p - \vec{v}'_d|$. P represents the probability that a deuteron velocity is changed from $\vec{v}'_d$ to $\vec{v}_d$ as a result of a collision with an energetic proton, which has velocity $\vec{v}_p$ in the laboratory system [29].

The equilibrium deuteron distribution function $f_d(v, \mu)$ is obtained by solving the following 2-D FP equation at each point in the magnetic configuration. In the calculation, previously obtained upscattered source of deuterons, i.e., (1), is used as a source term. The detailed model is presented in [30]. From the obtained deuteron distribution function, we can evaluate the D(d,n)^{3}He and ^{6}Li(d,pγ)^{7}Li reaction rate coefficients. The generation rates for 2.45-MeV neutron by the D(d,n)^{3}He reaction and 0.48-MeV ganma-ray ^{6}Li(d,pγ)^{7}Li reaction are obtained. Throughout the calculations, ^{6}Li is assumed to be Maxwellian and its density is assumed as $n_{6Li}(0) = 0.01\ n_d(0)$.

B. Estimation of Double Differential Neutron Emission Spectrum

The double differential neutron emission energy spectrum by the D(d,n)^{3}He reactions between deuterons which have velocity $\vec{v}_D$ and $\vec{v}'_D$ is written as

$$\frac{d^2N_n}{dEd\Omega}(E,\theta) = \frac{1}{2}\iiint f_D(\vec{v}_D) f_D(\vec{v}'_D)\frac{d\sigma}{d\Omega_c} \times \delta(E-E_n)\delta(\vec{\Omega}-\vec{\Omega}_n) v_r d\vec{v}_D d\vec{v}'_D d\Omega_c \quad (2)$$

where N_n is the D(d,n)^{3}He reaction rate (neutron emission rate), E_n is the emitted-neutron energy in the laboratory system [29], and $v_r = |\vec{v}_D - \vec{v}'_D|$

$$E_n = \frac{1}{2}m_n V_c^2 + \frac{m_\alpha}{m_\alpha + m_n}(Q + E_r) + V_c \cos\theta_c \sqrt{\frac{2m_n m_\alpha}{m_n + m_\alpha}(Q + E_r)} \quad (3)$$

where m_n is the neutron mass, V_c is the center-of-mass velocity of the colliding particles, θ_c is the angle between the center-of-mass velocity and the neutron velocity in the center-of-mass frame, Q is the reaction Q value, and E_r represents the relative energy given by

$$E_r = \frac{1}{4}m_D\left|\vec{v}_D - \vec{v}'_D\right|^2. \quad (4)$$

The θ represents the angle between the direction of emitted neutron and that of beam injection in the laboratory system, and $\vec{\Omega}_n$ is a unit vector in the direction of emission of the neutron in the laboratory system, which is determined using the classical kinematics as a function of $\vec{v}_D$, $\vec{v}'_D$, and θ_c [10]. Throughout the calculations, the differential D(d,n)^{3}He cross section is assumed to be isotropic in the center of frame [18].

III. Results and Discussion

In Fig. 2, we first show the volume-averaged proton distribution functions for tangential [Fig. 2(a)] and vertical [Fig. 2(b)] beam injections as a function of both parallel and vertical velocity components to the toroidal axis. The velocity variable is normalized to the deuteron speed $v_0 = (2T_0/m_d)^{1/2}$. Here, T_0 is taken as 60 keV. The neutral hydrogen beam is assumed to be ionized on the toroidal axis and energetic protons generate at the ionized place. In the calculation, deuteron density $n_d(0) = 10^{19}\text{m}^{-3}$, electron temperature $T_e(0) = 2$ keV, energy and particle confinement times $\tau_E = (1/2)\tau_p = 1$ s, beam-injection energy and power $E_{\text{NBI}} = 200$ keV,

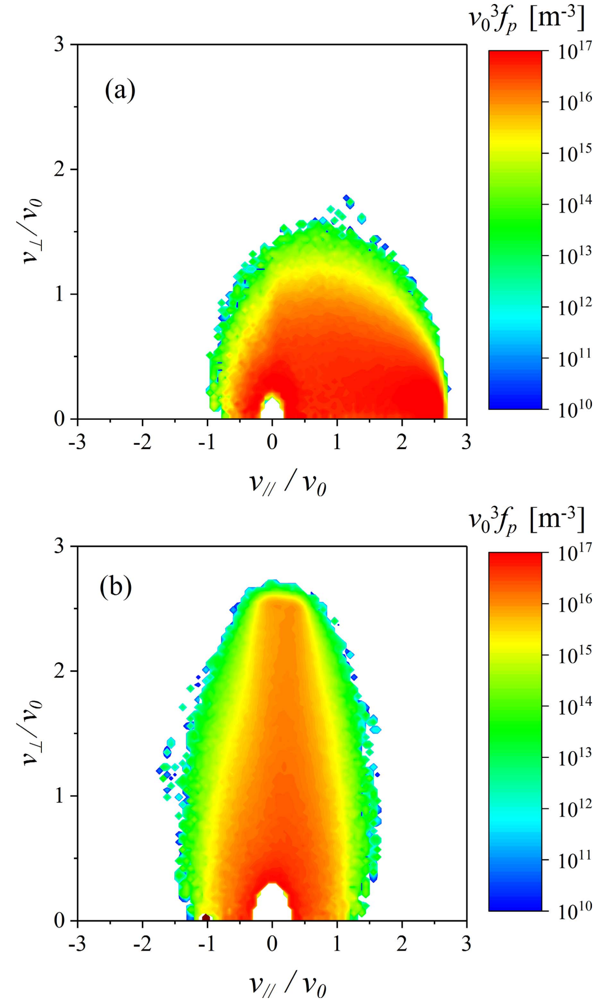

Fig. 2. Volume-averaged proton velocity distribution functions for (a) tangential and (b) vertical proton-beam injections.

$P_{\text{NBI}} = 33$ MW are assumed. It is found that the non-Maxwellian components are formed owing to the energetic beam injection almost along with the beam-injected direction, and the energetic protons slow down toward thermal energy range. In order to thermalize the injected protons perfectly so that Maxwellian component appears, it would be necessary much longer simulation (CPU) time. The purpose of this paper, however, is to examine the knock-on tail formation in deuteron velocity distribution function. Since the NES cross section of low-energy proton, i.e., less than ~100 keV, is considerably small, the distribution function shown in Fig. 2 would be sufficient to estimate the knock-on tail formation in deuteron distribution function via NES.

During the slowing-down process of beam-injected protons, the energetic protons knock up thermal deuterons to higher energy range via NES. The upscattered deuterons also slow down due to Coulomb collisions with background ions and electrons, NES by background ions, and finally reach the equilibrium state. Since the upscattered deuteron energy and the concentration are smaller compared with protons, NES of slowing-down deuterons is neglected in this paper. Thus, the equilibrium deuteron distribution function can be obtained

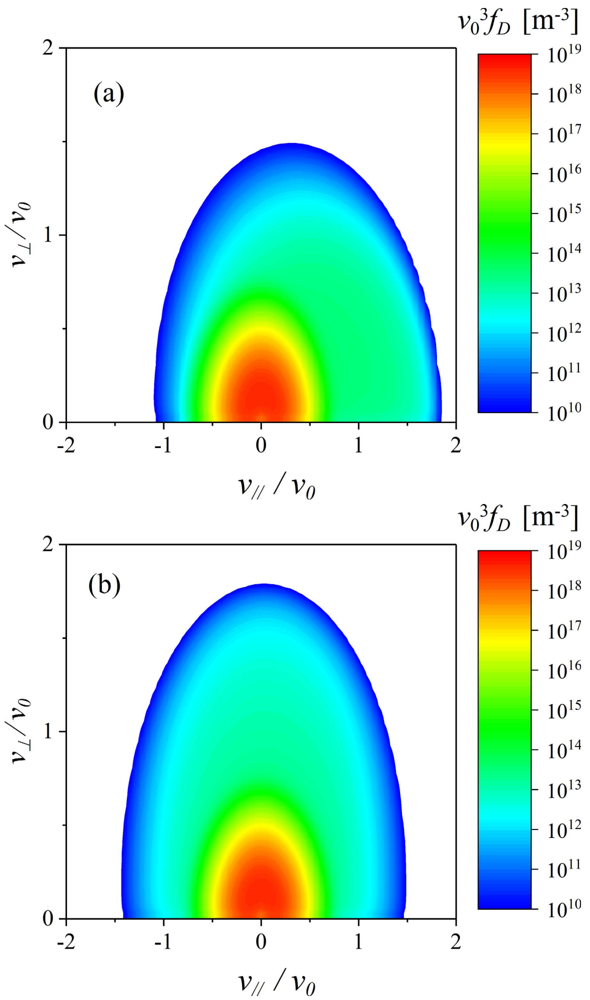

Fig. 3. Volume-averaged deuteron velocity distribution functions for (a) tangential and (b) vertical proton-beam injections.

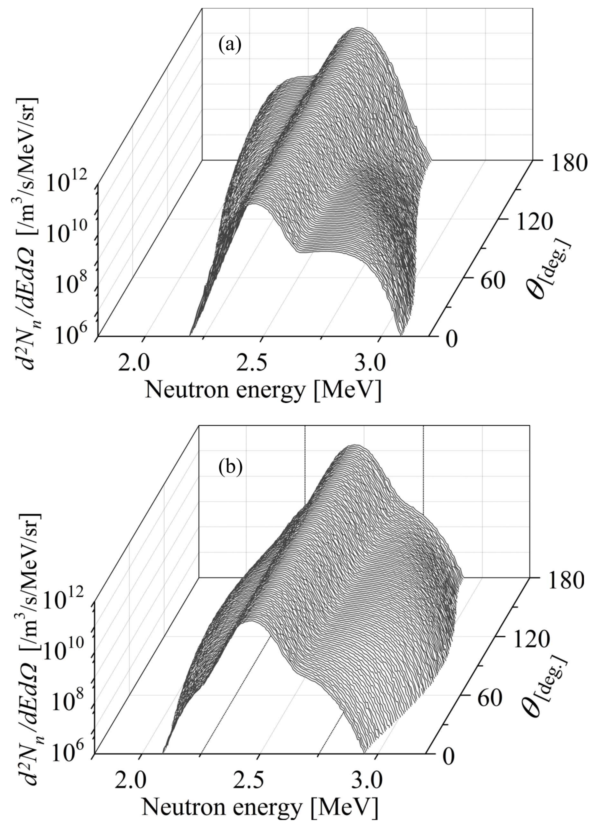

Fig. 4. Double differential neutron emission spectra for (a) tangential and (b) vertical proton-beam injections.

by solving FP equation using the upscattered deuteron source obtained as a source term for the FP equation. The equilibrium deuteron distribution functions for tangential [Fig. 3(a)] and vertical Fig. 3(b) proton injections are shown in Fig. 3 as a function of both parallel and vertical velocity components to the toroidal axis. The calculation condition is corresponding to tangential [Fig. 2(a)] and vertical [Fig. 2(b)] proton injections. We can understand that the knock-on tail appears almost along with the proton-beam injected direction. In the presented case, if we assume uniform ^{6}Li concentration with 1 % of deuteron density, the γ-ray emission rate by the ^{6}Li(d,pγ)^{7}Li reaction is almost two-order increases compared with the Gaussian case with $\sim 10^7$ s^{-1} count rate, as a result of the knock-on tail formation. The neutron generation rate by the D(d,n)^{3}He reaction is enhanced almost twice compared with the Gaussian case with $\sim 10^{11}$ s^{-1} count rate.

By using the obtained deuteron distribution function (see Fig. 3), we can evaluate the neutron emission spectrum by the D(d,n)^{3}He fusion reactions. In Fig. 4, the double differential neutron emission spectra formed by fusion-born neutrons are exhibited as a function of neutron energy and emission angle relative to the toroidal axis in the laboratory system for tangential [Fig. 4(a)] and vertical [Fig. 4(b)] proton injections. The calculation conditions are the same as those of Figs. 2 and 3. It is found that the neutron emission spectra are broadened toward both low- and high-energy ranges, and fraction of the neutrons born with more than 2.45-MeV energy increases compared with the case for Gaussian distribution function [19]–[22]. The shapes of the emission spectra have different features between tangential and vertical proton injections. When tangential injection to the toroidal axis, we can find that in the beam-injected direction, i.e., $\theta = 0$, the fraction of the energetic neutron component significantly increases. On the contrary in the opposite direction relative to injected-beam direction, i.e., $\theta = \pi$, the fraction of the energetic neutrons beyond 2.45 MeV significantly decreases. On the other hand for the vertical injection, the spectrum is broadened almost the same fraction toward both lower and higher energy ranges, especially around $\theta = \pi/2$ direction. Since injected-beam energy is much higher than the mean energy of the bulk-ion component, the center-of-mass velocity becomes larger compared with the averaged values, i.e., almost the same value as the injected-beam velocity. The neutron is produced almost isotropic direction in the center-of-mass frame, and hence the neutron, which is emitted toward beam-injected direction, i.e., $\theta = 0$ for tangential and $\theta = \pi/2$ for vertical injections, has considerably higher energy compared with the ones emitted other directions.

In Fig. 5, the energy spectra of neutrons in the $\theta = 0$ for tangential injection and $\pi/2$ for vertical injection are shown as well as the spectrum that is integrated along with

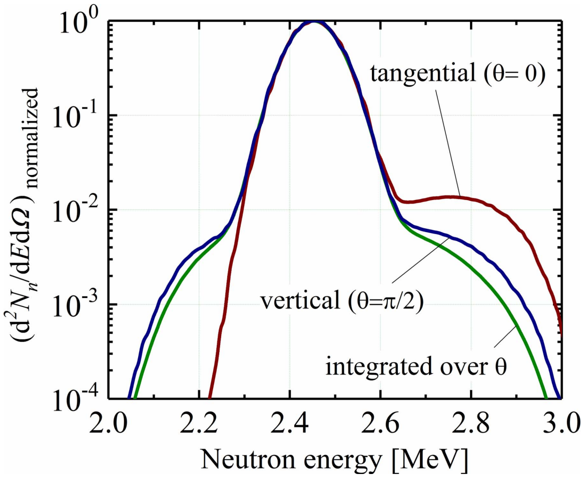

Fig. 5. Normalized neutron emission spectra of $\theta = 0$ component for tangential injection and $\theta = \pi/2$ component for vertical injection as well as spectrum integrated over θ.

θ directions. (The integrated spectrum is almost agree with the one obtained by 1-D calculation.) The calculation conditions are the same as those in Figs. 3 and 4. We can see that the spectrum has highly anisotropic distributions depending on the emission angle. Now it should be kept in mind again that the neutron emission spectrum is modified as a result of the knock-on tail formation in deuteron distribution function via NES. If the knock-on tail is not formed, we cannot observe the energetic neutrons beyond 2.5-MeV birth energy. Thus, we can ascertain the knock-on tail formation by looking at the energetic neutrons beyond 2.5-MeV energy. The idea to ascertain the knock-on tail formation by looking at the energetic neutrons has already been proposed previously [16], but the observation is considered to be difficult. This is because the population of the energetic neutron is considerably smaller compared with the Gaussian peak. From Fig. 5, we can find that the ratio for the integrated neutron emission spectrum, i.e., ~0.2% at 2.8-MeV neutron energy, is improved almost 10 times if we could detect the spectrum emitted toward $\theta = 0$ direction, i.e., ~1.5 % at 2.8-MeV neutron energy. In addition, if the "anisotropic neutron emission" itself due to proton-beam injection with specific direction can be ascertained in the experiment, it would be an evidence for anisotropic knock-on tail formation in deuteron distribution function.

IV. Conclusion

In this paper, we have proposed the knock-on tail observation scenario formed in deuteron distribution function using the "double differential" neutron emission spectrum in proton-beam injected deuterium plasmas. When deuteron density $n_d(0) = 10^{19}\mathrm{m}^{-3}$, electron temperature $T_e(0) = 2$ keV, energy and particle confinement times $\tau_E = (1/2)\tau_p = 1$ s, and beam-injection energy and power $E_{\mathrm{NBI}} = 200$ keV and $P_{\mathrm{NBI}} = 33$ MW are assumed, the fraction of 2.8-MeV neutron emission to Gaussian peak is improved almost one order. If we can use further high-energy beam, e.g., 1 MeV, the further improvement could be expected as well as large emission rates of both gamma rays and neutrons. In the measurement of the neutrons with a specific energy, the discrimination against the background noise may be necessary. The use of the neutron detector utilizing the threshold nuclear reactions may reduce the concerning problems. Throughout the calculations, the differential D(d,n)^{3}He cross section is assumed to be isotropic in the center-of-mass system. If we include the dependence of the cross section on the neutron emission angle, further improvement may be obtained. As a next step, more detailed studies for modification of the emission spectra would be required for various plasma and device conditions.

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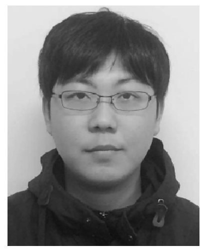

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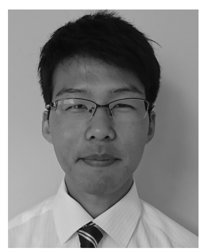

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