Evaluation of Neutron Emission Rate with FIT3D-DD Code in Large Helical Device*)

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We compared the experimentally measured neutron emission rate with the emission rate calculated by using the simple Fokker-Planck equation with the experimental temperature and density profiles, and the deuteron density evaluated by a spectroscopy in peripheral region in LHD. The neutron emission rates evaluated by the FIT3D-DD code are approximately two times higher than experimental results in the typical magnetic configuration of LHD. In the case of low fast-ion confinement, the calculations are approximately four times higher than experimental measurements.

Keywords: neutron emission rate, simple and fast Fokker-Planck analyses, FIT3D-DD, LHD

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1. Introduction

In the Large Helical Device (LHD), deuterium experiments have been performed by using tangentially-injected neutral beams (NBs) with the ~180 keV deuterium and perpendicularly-injected NBs with the 60 - 80 keV deuterium [1–4]. In the deuterium experiments, the 2.45 MeV neutrons are generated by the D-D nuclear fusion. The neutron emission rate is measured by the neutron flux monitor in the LHD [5, 6]. Since the main component of the neutron emission is the fusion reaction due to fast deuteron produced by NBs in the LHD, the neutron emission rate reflects the fast-ion density in the plasma. It is therefore important for the investigation of a fast-ion confinement to compare the neutron emission rate of the measurements with the numerical calculation.

We have developed a neutron emission evaluation code, FIT3D-DD, with a simple and fast Fokker-Planck analysis. In the LHD, the neutron emission rate before the start of the deuterium experiment is evaluated by using the database of the neutron emission rate with the FIT3D-DD code. The FIT3D-DD code and the database are described in Sec. 2.

It is important for evaluation of neutron emission rate with considering the practical plasma profile and the ratio of deuteron in plasma. To introduce the FIT3D-DD code to the transport analysis suite, TASK3D-a [7], we designed a new neutron emission rate evaluation tool with the experimental temperature and density profiles and the bulk deuteron density evaluated by a spectroscopy in the peripheral region. The new emission rate evaluation tool was applied to the deuterium experiments. The calculated neutron emission rate is compared with the experimental results. In addition, the effective normalized minor radius for neutron emission rate is evaluated in order to investigate the slowing down time dependence.

2. Neutron Emission Evaluation Code Based on the FIT3D Code

2.1 FIT3D-DD code

A neutron emission evaluation code, FIT3D-DD, has been developed from the FIT3D code. The FIT3D code [8] is the heating power profile and fast-ion pressure evaluation code with a simple analytical solution of the Fokker-Planck equation. The code is constructed by the combination of the HFREYA, MCNBI, and FIT codes (Fig. 1). In this section, these codes are briefly explained. An evaluation method of the neutron emission rate introduced to the FIT code is described.

The HFREYA code can calculate the fast-ion deposition profile of NB with the Monte-Carlo method. In the HFREYA code of the FIT3D code, the position and the simple shape of the ion source of NBs and the focus position of the beam lines are considered. The plasma shape and the density and temperature profiles are evaluated from a mapping with the equilibrium data of the Boozer coordinates. The large number of fast neutral particles are traced from the vacuum region to the end of their path length cal-

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culated by using a random number and the cross section of beam ionization including the charge exchange reaction. As a result, the ionization points of fast-ions are calculated. The cross section fit by Suzuki *et al.* [9] was introduced to the HFREYA code by P. Vincenzi for application of the deuterium experiments [10].

The MCNBI code is an orbit tracing code with the guiding center equation in the Boozer coordinates. In the MCNBI code of the FIT3D code, many fast-ions are traced for 20 μs (five times the toroidal transit time of a 180 keV fast proton produced by tangentially-injected NB) without considering the collision and charge exchange loss. As a result of the short orbit tracing, the deposition profile is changed due to the prompt loss and the initial orbit width.

The FIT code evaluates the heating power profile and the fast-ion pressure by using the simple analytical solution of the Fokker-Planck equation. The electron and ion heating ratio are expressed by

$$G_e = \frac{2}{v_{f0}^2}\int_{v_{th}}^{v_{f0}} \frac{v^3}{v^3+v_c^3} v\mathrm{d}v, \tag{1}$$

and

$$G_i = \frac{2}{v_{f0}^2}\int_{v_{th}}^{v_{f0}} \frac{v_c^3}{v^3+v_c^3} v\mathrm{d}v, \tag{2}$$

respectively. Here v_{f0} and v_{th} are the initial velocity of fast-ions and the velocity of the thermal ions, respectively. $v_c = \sqrt{2E_c/m_f}$, E_c is the critical energy, and m_f is the mass of fast-ions. The critical energy is calculated by

$$E_c[\mathrm{keV}] = \mathrm{Te}[\mathrm{keV}]\left(\frac{9\pi}{16}\frac{m_f}{m_e}\right)^{1/3}\left(\frac{m_f}{m_p}Z_1\right)^{2/3}, \tag{3}$$

and

$$Z_1 = \sum_i \frac{z_i^2 n_i}{A_i n_e}, \tag{4}$$

where m_e and m_p is mass of electron and proton, respectively. T_e is electron temperature, and n_e and n_i are electron and ion densities. Z_i and A_i denote the ion charge and mass number, respectively. The density of the fast-ion is calculated by

$$N_f = \frac{w_{dep}\tau_s}{E_0}\int_{v_{th}}^{v_{f0}} \frac{v^2}{v^3+v_c^3}\mathrm{d}v, \tag{5}$$

where w_{dep} is deposition power density and E_0 is the initial energy of fast ions. The slowing down time is expressed by

$$\tau_s = 0.12\frac{T_e[\mathrm{keV}]^{3/2}}{z_f^2 n_e[10^{19}\mathrm{m}^{-3}]}\frac{m_f}{m_p}, \tag{6}$$

where Z_f is the charge of fast ions. In the FIT code of the FIT3D code, w_{dep} is calculated by the HFREA code and the MCNBI code. The FIT3D code evaluates the heating power profile by using the three codes.

The neutron reaction of beam-bulk D-D reaction is introduced to the FIT code. The neutron emission rate evaluation code, FIT3D-DD, has been developed. In the FIT3D-DD, the neutron emission rate is evaluated with the density of fast ion produced by NB [Eq. 5] as follows.

$$\Delta R_{neut} = \Delta V\frac{w_{dep}\tau_s}{E_0}\int_{v_{th}}^{v_{f0}}\int \sigma_{dd}\left|\mathbf{v}_{i\_th}-\mathbf{v}\right| \times n_d \mathbf{f}_{Maxwell}(\mathbf{v}_{i\_th})\mathrm{d}\mathbf{v}_{i\_th}\frac{v^2}{v^3+v_c^3}\mathrm{d}v, \tag{7}$$

where σ_{dd} is the cross section of the D-D fusion reaction described in Ref. [11]. In the FIT3D-DD, the cross section is calculated with the relative speed between a bulk deuteron and a beam deuteron.

2.2 Database of neutron emission rate by using FIT3D-DD

Before the deuterium experiments, the prediction of the neutron emission rate is required for safely conducting experiments in the LHD. Therefore, the database of the neutron emission rate was made by the FIT3D-DD code. Figure 2 shows a sample of the neutron emission rate database. In this database, the typical magnetic configuration in LHD (R_{ax} = 3.6 m, γ = 1.254) is used and

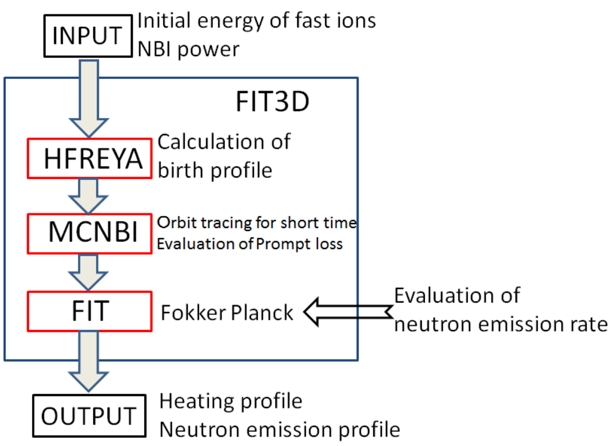


Fig. 1 Outline of FIT3D-DD code.

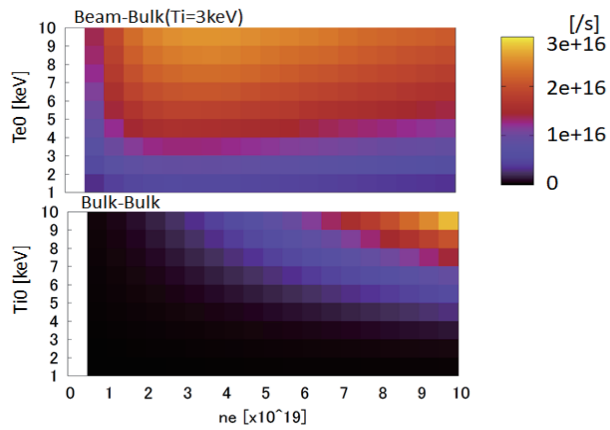


Fig. 2 Sample of database of neutron emission rate. The color represents the neutron emission rate.

the field strength is set to be 2.85 T. The pure deuterium plasma is assumed. The temperature and density profiles are given by

$$T_{e,i} = T_0(1 - \rho^8),\ [T_0 = 1, \cdots, 10\,\mathrm{keV}], \tag{8}$$

and

$$n_e = n_0(1 - \rho^2),\ [n_0 = 0.5, 1, \cdots, 10 \times 10^{19}\,\mathrm{m}^{-3}]. \tag{9}$$

From Fig. 2, the neutron emission rate of beam-bulk D-D fusion has maximum value near the $n_e = 3 \times 10^{19}\,\mathrm{m}^{-3}$. The neutron emission rate decreases in the higher density region than $\sim 3 \times 10^{19}\,\mathrm{m}^{-3}$. It is seen in Fig. 2 that the neutron emission rate increases with the increase in the electron temperature.

3. Evaluation of Neutron Emission Rate by Using FIT3D-DD

It is important for the investigation of a fast-ion confinement to compare the neutron emission rate of the measurements with the numerical calculation based on the experimental temperature and density profiles. Therefore, the FIT3D-DD code is introduced to the transport analysis suite, TAKS3D-a. In the TASK3D-a, the equilibrium magnetic field is identified by using the experimental electron temperature and density profiles. The densities of proton, deuteron, and helium ion are evaluated by using a spectroscopy. The experimental value of the port-through power and the injection energy of NB is used in the FIT3D-DD code of the TASK3D-a. Figure 3 shows the outline of the FIT3D-DD code introduced to the TASK3D-a.

We compare the neutron emission rate calculated by the FIT3D-DD code of the TASK3D-a with measurements at the maximum value of the neutron emission rate. Figure 4 shows the comparison of the neutron emission rate between the FIT3D-DD code and the neutron flux monitor in the case of magnetic axis $R_{\mathrm{ax}} = 3.6\,\mathrm{m}$. It is found in Fig. 4 that the neutron emission rates evaluated by FIT3D-DD are approximately two times higher than the experimental measurements. This overestimate occurs because the impurity carbon ion is ignored. In this case, the density of the bulk deuteron is overestimated because a typically effective ion charge is 2 - 3 in the LHD plasma. The density of impurity carbon ion will be introduced in the near future. In addition, the fast-ion loss for a slowing down process is not included in FIT3D-DD. Therefore, the neutron emission rate calculated by the FIT3D-DD code tends to be higher than experimental results.

Next, we compare the FIT3D-DD results with experiments in the case of magnetic axis $R_{\mathrm{ax}} = 3.75\,\mathrm{m}$ and $R_{\mathrm{ax}} = 3.9\,\mathrm{m}$, in which the low confinement of the fast-ion is pointed out [12]. It is found in Fig. 5 that the neutron emission rates evaluated by the FIT3D-DD code are approximately four times higher than the experimental measurements in the case of low confinement of fast-ion. The

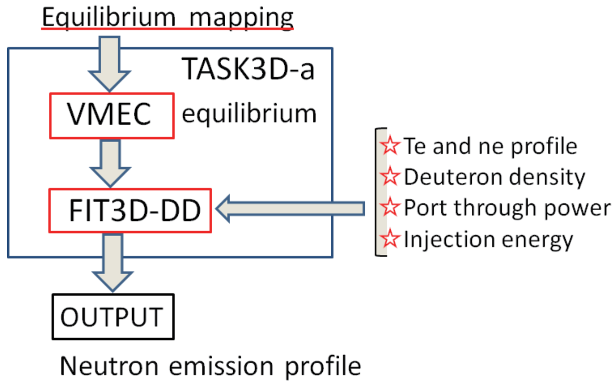


Fig. 3 Neutron emission evaluation tool in the TASK3D-a.

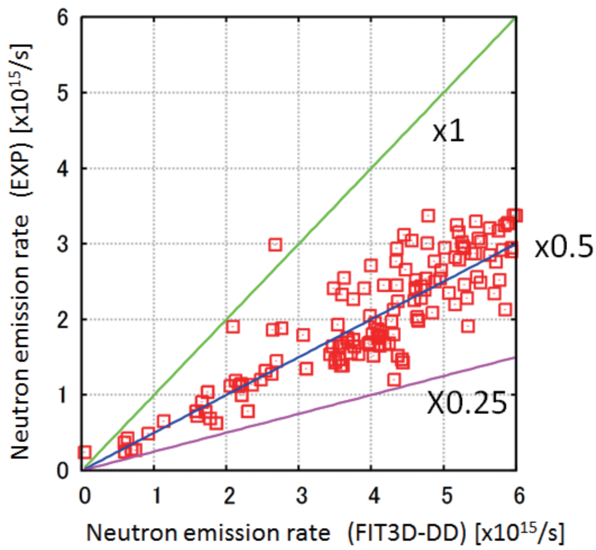


Fig. 4 Comparison of the neutron emission rate between FIT3D-DD results and neutron flux monitor measurements.

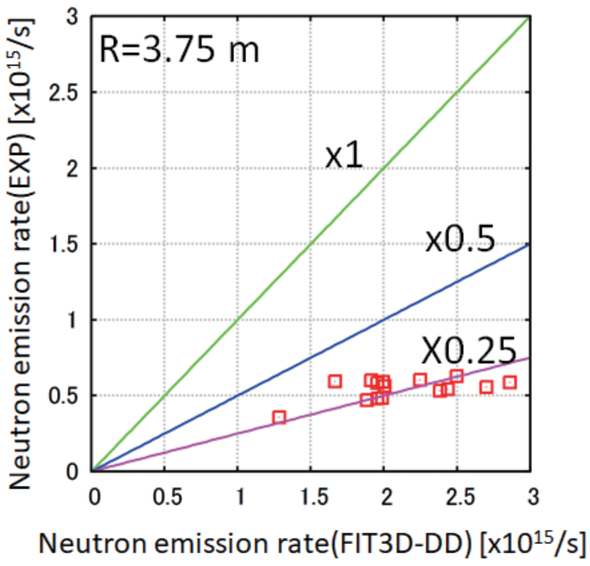
overestimation of the neutron emission rate becomes larger than that in the $R_{ax} = 3.6\,\mathrm{m}$. It is more important for evaluation of the neutron emission rate to include the orbit effect properly in the case of the low fast-ion confinement, especially for fast-ions produced by perpendicular NBs. One of these overestimate is caused by fast-ions produced by perpendicular NB. The effect of the orbit tracing time on evaluation of neutron emission rate is discussed in Sec. 4.2.

4. Discussion

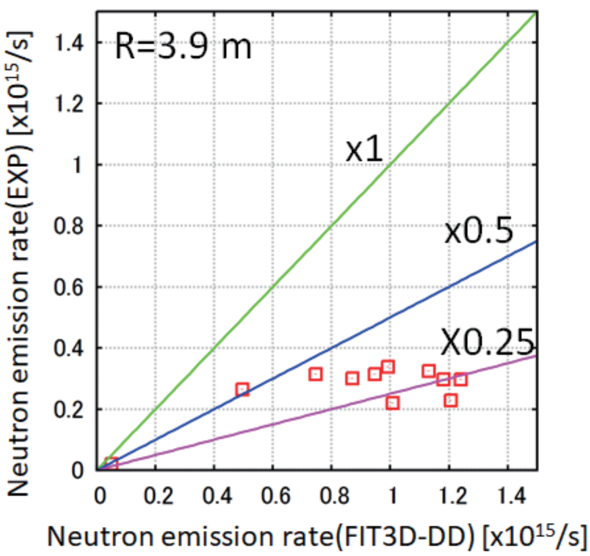
4.1 Slowing down time dependence

The neutron emission rate reflects the fast-ion density in the plasma. The difference of the neutron emission rate between the FIT3D-DD and the measurements implies the orbit loss and/or the loss due to the MHD instabilities. We investigated the difference of the neutron emission rate by changing the slowing down time.

In order to calculate the slowing down time, the effec-

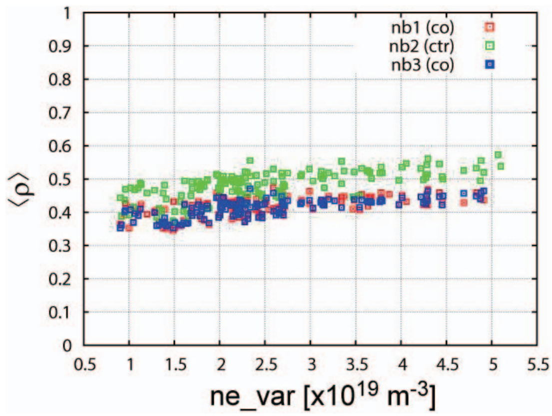


(a) R_{ax} = 3.75 m

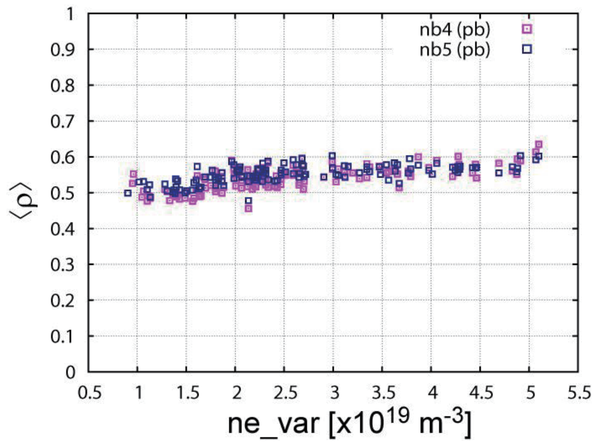


(b) R_{ax} = 3.9 m

Fig. 5 Comparison of the neutron emission rate between FIT3D-DD results and neutron flux monitor measurements in the case of the low confinement of the fast-ion.



(a) Tangential NB



(b) Perpendicular NB

Fig. 6 Effective normalized minor radius for neutron emission rate in the case of (a) tangential NB and (b) perpendicular NB.

tive normalized minor radius for the neutron emission rate is evaluated from neutron emission rate profiles calculated by the FIT3D-DD code as follows.

$$\langle\rho\rangle_{\rm neut} = \frac{\int \rho \times \Delta R_{\rm neut} d\rho}{\int \Delta R_{\rm neut} d\rho}, \qquad (10)$$

where ρ denotes the normalized minor radius. $\Delta R_{\rm neut}$ is the neutron emission rate in $\Delta\rho$. Figure 6 shows the effective normalized minor radius in the cases of tangential NB and perpendicular NB. The effective normalized minor radius increases in the higher density region because the number of the fast-ions produced in the peripheral region becomes large. The effective normalized minor radius in the case of the ctr-tangential NB is approximately 0.5 in the 2×10^{19} m^{-3}. The effective normalized minor radius in the case of the co-tangential NB becomes smaller than in the ctr-tangential NB case. In addition, the effective normalized minor radius in the case of the perpendicular NB is approximately 0.55 in the 2×10^{19} m^{-3}.

Using the effective normalized minor radius, we investigate the dependence of the slowing down time in the neutron emission rate in the typical magnetic configuration of LHD. In Fig. 7, the difference between the FIT3D-DD results and neutron flux monitor measurements become larger in the low collision regime. In the low collision regime, there is a possibility that the overestimate of FIT3D-DD is caused by fast-ion-driven instabilities because the fast-ion density becomes higher. In the future, the neutron emission rate including the instabilities will be evaluated.

4.2 Effect of orbit tracing time for evaluating the prompt loss

In the FIT3D-DD code, the fast-ions are traced for a short time in order to evaluate the prompt loss and the initial orbit width. However, there is a possibility that the

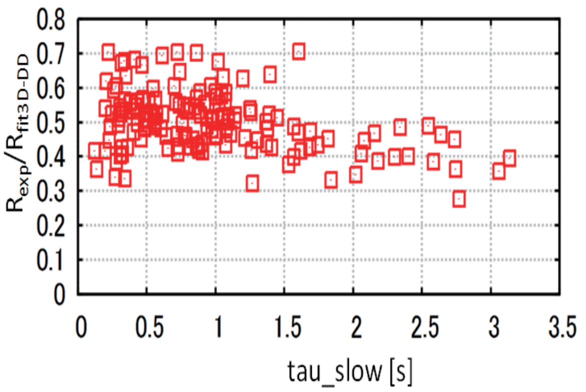


Fig. 7 Slowing down time dependency in the difference between FIT3D-DD results and neutron flux monitor measurements.

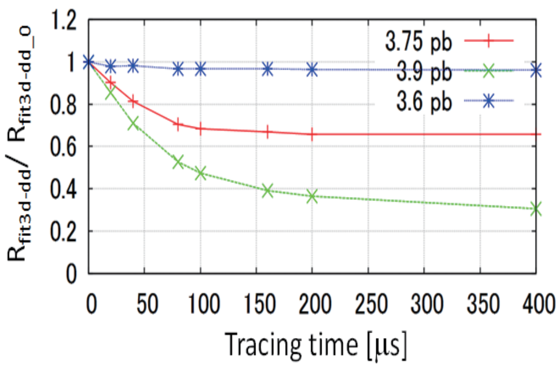


Fig. 8 Neutron emission rate in terms of orbit tracing time in the case of perpendicular NB. Blue, red, and green lines show the neutron emission rate in the case of R_{ax} = 3.6 m, R_{ax} = 3.75 m, and R_{ax} = 3.9 m, respectively.

prompt losses of fast-ions produced by perpendicular NB could not be properly evaluated because the poloidal transit time of trapped fast-ions is much longer than the toroidal transit time of fast-ion produced by tangential NB.

We investigate the effect of orbit tracing time on the neutron emission rate. Figure 8 shows the neutron emission rate in terms of orbit tracing time in the case of perpendicular NB. In the case of R_{ax} = 3.6 m, the orbit tracing time barely affects the neutron emission rate. On the other hand, in the case of R_{ax} = 3.75 m and R_{ax} = 3.9 m, the neutron emission rate largely decreases until ~200 µs. The neutron emission rate in the case of 20 µs is approximately two times higher than that in the case of 200 µs. On the other hand, it is pointed out that re-entering fast ion and the charge exchange loss should be considered in the case of the low fast ion confinement [13]. These effects on the neutron emission rate will be investigated in the near future. In the case of tangential NB, the neutron emission rate rarely changes independent of the magnetic axis position.

5. Summary

The neutron emission rate measured in LHD is compared with the emission rate calculated by using simple Fokker-Planck equation with the experimental temperature and density profiles, and the deuteron density evaluated by using a spectroscopy in peripheral region.

Since only the prompt loss is considered and the impurity carbon ion is ignored in the FIT3D-DD code, the calculated neutron emission rate tends to be higher than the experimental results. The neutron emission rate evaluated by the FIT3D-DD code is approximately two times higher than the neutron flux monitor measurements in the typical magnetic configuration of LHD. In the case of low fast-ion confinement, the calculations are approximately four times larger than the experimental measurements.

In order to calculate the slowing down time dependence, the effective normalized minor radius for neutron emission rate is evaluated from the results of the IT3D-DD code. It is found that the effective normalized minor radius is approximately 0.5.

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