Influence of modified neutron emission spectrum on tritium production performance in blanket systems with NBI-heated deuterium plasma

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\section*{A B S T R A C T}

In high-temperature plasma sustained by neutral beam injection heating, the emission spectrum of the neutrons produced by fusion reactions is known to have a modified Gaussian distribution. In this study, neutron transport simulation is carried out for a plasma source that emits neutrons with a modified spectrum and the influence of this modified neutron emission spectrum on the tritium production performance is investigated. The results show that in tritium production using D(d,n)\textsuperscript{3}He reactions, the rate of the \textsuperscript{9}Be(n,2n)\textsuperscript{7}Be neutron multiple reactions, which has a threshold energy of 2.0 MeV, is significantly enhanced compared with that when a source with a Gaussian neutron emission spectrum was assumed. In addition, the influence of the blanket composition on the tritium production performance is discussed.

\section*{1. Introduction}

In the interest of creating a nuclear fusion DEMO reactor, research and development of a blanket system have been conducted all over the world. Recently, solid and liquid breeder blankets have been investigated. A water-cooled solid blanket, DEMO-JP has been proposed as one of the conceptual designs for a nuclear fusion DEMO reactor in Japan \cite{1}. In the blanket system, beryllium or a beryllium compound is used as a neutron multiplier material and a lithium compound is used as the tritium breeding material. Liquid breeder blankets have also been studied; various candidates have been used as the coolant, such as water, He and He and water dual-cooling methods have also been proposed in the system in the EU \cite{2}. In this system, lithium–lead is mainly used as a neutron multiplier and tritium breeder. Recently, a blanket system has been proposed in which beryllium is used in the water-cooled lithium–lead as a neutron multiplication material to attain a higher TBR \cite{3}.

In the nuclear design process for a blanket system, neutron transport calculations are performed \cite{4,5}. To characterize the performance of the blanket system, a mono-energetic neutron spectrum has been assumed in most studies. However, when high-temperature plasma is sustained by neutral beam injection (NBI) heating, an energetic non-Maxwellian component is formed in the velocity distribution function of the beam-injected ion species. Owing to the increase in the population of fast ions, the ratio of the fast neutrons (produced by fusion reactions) to total neutron emission rate is increased. Thus, the neutron emission spectrum is modified from a Gaussian distribution function \cite{6}. In addition, owing to the increase in the fractional fast ion population, the total neutron emission rate (from the D(d,n)\textsuperscript{3}He reactions) also increases.

A method to start up a fusion reactor while producing tritium by D(d,n)\textsuperscript{3}He reactions using NBI heating has been proposed \cite{7}. In the plasma produced in this approach, significant modification of neutron emission spectrum would appear. This modification in the emission spectrum would cause an increase in the reaction rate of the threshold reaction, such as neutron multiplier \textsuperscript{9}Be(n,2n)\textsuperscript{7}Be reaction, and affect the nuclear characteristics in the blanket system.

In this study, we consider deuterium plasma sustained by NBI heating and evaluate the influence of the modified neutron emission spectrum on tritium production performance in (a) water-cooled solid blanket and (b) water-cooled lithium–lead with beryllium blanket.

\section*{2. Theoretical model}

\subsection*{2.1. Calculation of the neutron emission spectrum}

In this study, we consider the neutrons that are produced by D(d,n)\textsuperscript{3}He reactions from the deuterium plasma sustained by NBI heating as described in Ref. \cite{8}. In Fig. 1, the velocity distribution functions of deuterons are shown for several beam injection energies (E_{\text{beam}}) and powers (P_{\text{NBI}}). The deuterons are assumed to be present at a density of $6.0 \times 10^{19} \text{ m}^{-3}$. The solid lines show the velocity distribution functions.
of the deuterons in the plasma sustained by NBI heating and the dotted line shows a Maxwellian distribution. When \( P_{\text{NBI}} \) is increased from 80 to 160 MW, the injection rate of the energetic particles increases, which causes an increase in the fraction of the energetic particles in the distribution functions. When \( E_{\text{ENBI}} \) is increased from 1.0 to 2.0 MeV, the fraction of high-energy (reactive) particles increases.

The neutron emission spectrum can be described as follows:

\[
\frac{dN_n}{dE}(E) = \frac{1}{2} \int \frac{f_\nu f_d}{\delta(E - E_n) v_n v_r} d\Omega
\]

where \( N_n \) represents the neutron generation rate, \( \frac{d\sigma}{d\Omega} \) is the differential cross-section of the \( \text{D(d,n)}^3\text{He} \) reaction, \( v_r \) is the relative velocity between deuterons, and \( E_n \) represents the neutron energy in a laboratory system.

An expression for \( E_n \) has been derived in Ref. [9,10]:

\[
E_n = \frac{1}{2} m_n v^2 + \frac{m_3}{m_n + m_3} (Q + E_r) + V_c \cos \theta, \quad \sqrt{\frac{2m_n m_3}{m_n + m_3} (Q + E_r)},
\]

where \( m_3 \) is the mass of a neutron (helium-3), \( V_c \) is the center-of-mass velocity of colliding particles, \( \theta \) is the angle between the direction of the center-of-mass velocity and the neutron velocity in the center-of-mass frame. \( E_r \) represents the relative energy between the deuterons.

2.2. Blanket model

2.2.1. Blanket concept

In this paper, two blankets were considered in the simulations: (a) a water-cooled solid breeder and (b) a water-cooled lithium–lead with beryllium. Fig. 2 shows the computational schema of the blanket systems. A one-dimensional analysis model with a rectangular blanket shape and a neutron incident surface with an area of 4900 cm² were used. Perfect reflection conditions were assumed at the boundary areas and the breeder zone was assumed to be homogeneous. The materials of the breeder zone are shown in Table 1. In addition, the neutrons from the neutron source were incident vertically relative to the FW.

2.2.2. Material information

To produce the 2.45 MeV neutrons by a \( \text{D(d,n)}^3\text{He} \) reaction, lithium–lead is not effective as a neutron multiplier because of the threshold energy. So, in this study, lithium–lead is used as a breeder material. In the coolant, sub-critical water condition of 23 MPa and 290 °C were assumed. For the \( \text{Li}_2\text{TiO}_3 \), the density was assumed to be 85% of the theoretical density, i.e., 2.92 g/cm³ and \( ^6\text{Li} \) enrichment was assumed to be 90%. For the \( \text{Li}_2\text{TiO}_3 \), the temperature of this material in the breeder zone was assumed to be about 750 K and the \( ^6\text{Li} \) enrichment was assumed to be 90%.

2.3. Evaluation of tritium production performance

In this study, we examine the influence of the modified neutron emission spectrum on the tritium production performance, which corresponds to the \( ^6\text{Li}(n,\alpha)\text{T} \) reaction rate. In addition, we add increase in total neutron emission rate of the beam incidence in comparison with a case of the Maxwellian, and examine the influence on tritium production performance.

Neutron flux is calculated using the 3D Monte Carlo neutron transport code MVP [11] using the nuclear date library JENDL-4.0 [12]. Reaction rates of the \( ^6\text{Li}(n,\alpha)\text{T} \) and \( ^9\text{Be}(n,2n)\alpha \) reactions were calculated using the obtained neutron flux.

3. Results and discussion

3.1. Neutron emission spectrum

Fig. 3 shows the neutron emission spectra calculated using the...
deuteron velocity distribution functions shown in Fig. 1. The following characteristics were observed depending on the beam injection power and energy. When $P_{\text{NBI}} = 160 \text{ MW}$ and $E_{\text{NBI}} = 1.0 \text{ MeV}$, the total number of neutrons emitted with energies more than 2.45 MeV increases by a factor of 1.61 compared to the case where $P_{\text{NBI}} = 80 \text{ MW}$ and $E_{\text{NBI}} = 1.0 \text{ MeV}$. When $P_{\text{NBI}} = 80 \text{ MW}$ and $E_{\text{NBI}} = 2.0 \text{ MeV}$, the energy range of neutron emission spectrum also becomes broader compared to the case where $P_{\text{NBI}} = 80 \text{ MW}$ and $E_{\text{NBI}} = 1.0 \text{ MeV}$. The modifications of the neutron emission spectrum from the Gaussian distribution were found to have almost the same tendency as those in the energetic tails of the velocity distributions functions (see Fig. 1). Due to the modification of the neutron emission spectrum, the percentage of neutrons emitted with energies exceeding 2.45 MeV increases by a factor of 1.35 times compared to the case in which the neutron emission spectrum was a Gaussian distribution. And, the increase in total neutron emission rate of the beam incident is 1.7–2.1 times in comparison with a case of the Maxwellian. This is because the cross-section of the D(d,n)$^3\text{He}$ reaction increases with increasing deuteron energy.

### 3.2. Influence of the modified emission spectrum on the tritium production performance

In this chapter, we investigate the influence of the modification of the neutron emission spectrum on the tritium production performance. For this purpose, the neutron emission spectra were normalized as shown in Fig. 3 and used as the source in the neutron transport calculations. Here, for example, a water-cooled solid blanket model is assumed as in the DEMO-JP design [1,3]. In these conditions, the volume fraction of contents for Li$_2$TiO$_3$, Be$_{12}$Ti, He gas, water, and F$_8$2H were modeled as 10%, 54%, 16%, 6%, and 14% respectively.

In Fig. 4, the neutron fluxes obtained using the MVP simulations are shown. The data shows that, as a result of the modified neutron emission spectra, the neutron flux is also modified toward the high-energy side. It was found that the energy range where energetic neutrons appear conspicuously depends on the plasma conditions.

In Fig. 5, the neutron multiplier for the $^9\text{Be}(n,2n)^2\alpha$ reaction rate is shown for several plasma conditions. The results indicate that the reaction rate of the $^9\text{Be}(n,2n)^2\alpha$ reaction increases dramatically due to the modification of the emission spectrum from the Gaussian distribution, especially in the energetic region beyond 3.0 MeV. This is because the $^9\text{Be}(n,2n)^2\alpha$ reaction has the threshold around a neutron energy of 2.0 MeV, as shown in Fig. 6.

Further, the rate of the $^9\text{Be}(n,2n)^2\alpha$ reaction increases by a factor of 4.3–7.1 depending on the plasma conditions. Fig. 7 shows the $^6\text{Li}(n,\alpha)^7\text{T}$ reaction rate as a function of the neutron energy. By integrating the reaction rate over the energy range and in all breeder zone domains, the total tritium production rate, $R_T$, was estimated. To examine the effects of the spectrum modification on the $R_T$ value, the $\eta$ parameter is defined as follows:

$$\eta = \left( \frac{R_T \text{ with beam}}{R_T \text{ without beam}} - 1 \right) \times 100 \ [%].$$  

Fig. 8 shows the influence of the beam energy and the power on the $\eta$ parameter. The $\eta$ parameter is much more sensitive to the beam energy than to the beam power. It is found that the tritium production performance, and thus the $^6\text{Li}(n,\alpha)^7\text{T}$ reaction rate, is enhanced by 1.6–4.0% with the use of the modified neutron emission spectrum compared to when a Gaussian distribution is assumed.
3.3. Influence of the blanket composition on the tritium production performance

In this chapter, we discuss the influence of the blanket composition on the tritium production performance and $\eta$ parameter for various material compositions of the tritium breeder, the neutron multiplier, the coolant, and the structure. To express the volume fraction of the multiplier material, the BMR parameter was defined as the ratio of the total volume of the breeder ($V_{\text{Breeder}}$), multiplier ($V_{\text{Multiplier}}$), and tritium recovery ($V_{\text{recovery}}$) materials that extract tritium to the total volume of all material in the breeder zone:

$$\text{BMR} \equiv \frac{V_{\text{Breeder}} + V_{\text{Multiplier}} + V_{\text{recovery}}}{\text{All materials in breeder zone content}} \times 100\%.$$  (4)

In the case of a lithium–lead blanket, it is not necessary to load other materials in order to extract tritium; thus, $V_{\text{recovery}}$ was set as zero. In the case of a water-cooled solid blanket model, the ratio of $V_{\text{recovery}}$ to the sum of $V_{\text{Breeder}}$, $V_{\text{Multiplier}}$, and $V_{\text{recovery}}$ was adjusted to keep it at 20%. In the case of a water-cooled solid blanket, non-breeder material (which except the breeder, multiplier and tritium recovery in the breeder zone) is composed 30% Water and 70% F82H. In the case of a water-cooled lithium-lead, that is composed 25% Water, 20% F82H and 55% SiC/SiC. The volume fraction of the non-breeder material to all material in breeder zone content is set to $$(100 - \text{BMR})\%.$$ 

To express the volume fractions of the breeder materials, the TBMR parameter was defined as the ratio of $V_{\text{Breeder}}$ to the sum of $V_{\text{Breeder}}$, $V_{\text{Multiplier}}$, and $V_{\text{recovery}}$:

$$\text{TBMR} \equiv \frac{V_{\text{Breeder}}}{V_{\text{Breeder}} + V_{\text{Multiplier}} + V_{\text{recovery}}} \times 100\%.$$  (5)

When the BMR is increased, the volume fraction of beryllium (or the beryllium compound) increases and the volume fractions of the coolant and the structure decrease. Further, when the TBMR is increased, the volume fraction of beryllium (or the beryllium compound) decreases and the volume fraction of breeder material increases.

Two models were considered for when $P_{\text{NBI}} = 80$ (160) MW and $E_{\text{NBI}} = 1.0$ (2.0) MeV, (a) a water-cooled solid blanket and (b) a water-cooled lithium-lead–with beryllium, and the results are shown in Figs. 9 and 10, respectively. In Fig. 9, the $\eta$ parameter is shown as a function of the TBMR for several BMRs. The results show that $\eta$ increases when the BMR increases and the TBMR decreases due to the change of the quantity of beryllium (or beryllium compound) loading, which increases the $^9\text{Be}(n,2n)^{12}\text{C}$ reaction rate. Thus, the influence of the increase in the $^9\text{Be}(n,2n)^{12}\text{C}$ reaction rate on the tritium production performance due to the modification of the neutron emission spectrum becomes remarkable. When $P_{\text{NBI}} = 160$ MW and $E_{\text{NBI}} = 2.0$ MeV, the tritium production performance was found to be enhanced by 0.5%–6.5% depending on the blanket composition compared to when a Gaussian distribution is assumed. However, while $\eta$ parameter increases, the tritium production performance which corresponds to the $^6\text{Li}(n,\alpha)^3\text{He}$ reaction rate itself decreases when the TBMR decreases. It is because that quantity of lithium compound loading decreases while the quantity of beryllium (or beryllium compound) loading increases.

Fig. 10 shows the $\eta$ parameter for the water-cooled lithium-lead with beryllium blanket as a function of the TBMR for several BMRs. Although a similar tendency to the one seen for the water-cooled solid blanket (Fig. 9), influence of the volume fraction of breeding material (TBMR) is somewhat week. The tendency is caused by the difference of amount of beryllium including in the blanket. Since the material composition is different between two types of the blanket, amount of the beryllium including in the breeder zone is different (even if the BMR and TBMR have the same values). The amount of the beryllium included in the water-cooled solid blanket tends to be larger than that in the water-cooled lithium-lead blanket with beryllium. When $P_{\text{NBI}} = 160$ MW and $E_{\text{NBI}} = 2.0$ MeV, the tritium production performance was found to be enhanced by about 2.8%–7.5% depend on the blanket composition compared to when a Gaussian distribution is assumed.

4. Concluding remarks

In this study, we considered the deuterium plasma sustained by NBI
heating and evaluated the influence of the modified neutron emission spectrum on the tritium production performance.

In the Sections 3.2 and 3.3, we normalized the neutron emission spectra shown in Section 3.1 to focus on the modification of the neutron emission spectrum and examined the influence of this modification on the tritium production performance in the blanket. The results show that, with the use of the modified neutron emission spectrum, the $^9\text{Be} (n,2n)^2\alpha$ reaction rate increases by a factor of 4.3–9.0 and the tritium production performance (i.e., $^6\text{Li}(n,\alpha)^3\text{T}$ reaction rate) is enhanced by 1.6–4.0% relative to those values in the case of a Gaussian neutron emission spectrum. The influence of the modified neutron emission spectrum is most significant when the beam power and beam energy are high. When the amount of beryllium in the blanket system is high, the influence of the modified emission spectrum on tritium production performance tends to be enhanced. Specifically, the modification of the neutron emission spectrum increases the tritium production performance by 0.5–7.5% depending on the blanket composition compared to when a Gaussian distribution is assumed.

In addition, when we add increase in total neutron emission rate of the beam incident in comparison with a case of the Maxwellian, the reaction rate of the $^9\text{Be}(n,2n)^2\alpha$ reaction is increased 7.5–19.1 times, and the tritium amount of production is increased 1.7–2.2 times.

It is well known that if a mono-energetic beam is injected at a certain angle to the magnetic axis, the neutron emission spectrum has an anisotropic shape [9]. However, with the deuterium plasma considered in this study, the influence of the anisotropy of the neutron emission spectrum and/or the blanket arrangement on the tritium production performance would appear conspicuously. Thus, the influence of an anisotropic neutron emission spectrum should be examined further in further studies.

References