Design of Neutron Spectrum-Shaping Assembly Around the Pneumatic Tube-End in the LHD Torus Hall for the Medical Research Application*)

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The designs of neutron spectrum-shaping assembly (NSSA) composed with various shielding materials with natural isotopic abundance were evaluated to construct the neutron field dominated with thermal neutron or epi-thermal neutron for the application of neutron filed in the torus hall of LHD toward the BNCT research. According to the neutron transport calculation by MCNP6, the fast neutron moderation efficiency was higher in polyethylene (PE) compared to lithium fluoride (LiF) and magnesium fluoride (MF), although LiF showed relatively large epi-thermal and thermal neutron absorption. This comparison showed that the thermal neutron field can be effectively achieved with using PE. For constructing the NSSA which can provide the neutron field dominated with epi-thermal neutron, several NSSA designs were evaluated with respect to fast neutron flux, epi-thermal neutron flux, and gamma-ray dose. The combination of MF, lead (Pb) and cadmium (Cd) can provide the good epi-thermal neutron field with the mitigations of fast neutron flux and gamma-ray dose, which is also suitable for BNCT research in the torus hall of LHD.

Keywords: neutron, BNCT, MCNP6, LHD

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1. Introduction

Deuterium experiment in the Large Helical Device (LHD) produces the neutron field in the torus hall [1–3]. In our previous studies [4–6], the neutron flux distribution in the torus hall was estimated by the activation foil method for the radiation safety point of view. There is a wide neutron flux/energy distribution in the LHD torus hall. In particular, fast neutron (0.1 MeV ∼ 14.1 MeV) is dominant near the LHD because the major virgin energy of neutron generated in the deuterium plasma is around 2.5 MeV. However, the components of epi-thermal neutron (0.55 eV ∼ 0.1 MeV) and thermal neutron (< 0.55 eV) increased with the distance from LHD increased. Also, the thermal neutron flux near the wall of the torus hall is almost uniform due to a lot of deceleration history of neutron by the wall, floor as well as components in the torus hall. According to the neutron flux and energy spectrum obtained in these studies, the radioactivity in the component such as the concrete wall of the torus hall was predicted.

These investigations of neutron flux distribution also showed that the neutron flux in the torus hall near LHD during plasma operation can achieve above 10^9 n cm^{-2} s^{-1}, which is close to the criteria of neutron source for the Boron Neutron Capture Therapy (BNCT) [7,8]. Therefore, the capability of fundamental researches for the development of BNCT has been considered. However, a wide neutron energy from thermal neutron to fast neutron in the torus hall is not suitable for BNCT. Fast neutron and thermal neutron should be excluded in BNCT. For fast neutron, the high radiation dose for patient is the disadvantage. Thermal neutron has large cross-section to be captured by ^{10}B. Therefore, thermal neutron seems effective for BNCT. However, thermal neutron cannot penetrate sufficiently into the human body because of the capture reactions by hydrogen and nitrogen near the surface region of human body. So, thermal neutron is unavailable for BNCT. On the other hand, epi-thermal neutron can penetrate into the deeper region of human body effectively, with low radiation dose. Also, epi-thermal neutron can decelerate into thermal neutron inside the human body, providing high efficiency of ^{10}B(n, α)^{7}Li reaction at the position of tumor. Therefore, the neutron spectrum-shaping assembly (NSSA) to generate the neutron field, where epi-thermal neutron is dominant, is necessary.

For the application of neutron in the LHD torus hall to

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fundamental BNCT research, the installation of pneumatic tube is carried out in FY2019 to expose the cancer cells to the neutron field. The experiments will be done with this pneumatic tube by transporting a cell samples into the LHD torus hall, and one will observe the damage in the cell by microscopes for the comprehensive understanding of the response of cancer cell to damage induced by BNCT as well as the radiation. For this application, the neutron field dominated with epi-thermal neutron is required because that neutron field should be used in the actual BNCT treatment as explained above. The research on the influence of epi-thermal neutron irradiation into cell, which will take place in the surface region of human body in BNCT treatment, can be done with this neutron field. Also, the control of neutron energy spectrum to epi-thermal neutron field by using NSSA can provide a knowledge about the neutron moderator/shielding capability of materials, helping to construct the NSSA in the actual BNCT facility. On the other hand, a small size of pneumatic tube is not able to moderate epi-thermal neutron to thermal neutron as like human body. Hence, the neutron filed dominated with thermal neutron, which should be produced inside the human body during the treatment, is also necessary to investigate the BNCT treatment efficiency.

Therefore, in this study, several designs of NSSA for the pneumatic tube-end were evaluated with respect to the neutron energy control and the gamma-ray shielding by using MCNP6 (General Mote Carlo N-Particle) code [9].

2. Installation of Pneumatic Tube

For BNCT research, a new pneumatic tube was installed in the LHD torus hall. In LHD, pneumatic tube system has been installed to perform the cross-check of the neutron yield evaluated by the neutron flux monitor (NFM) in the deuterium experiment [10]. A new pneumatic tube shares a part of that system. The sample in the capsule made of polyethylene (PE) can be transported by the pressurized air flow through pneumatic tube from the transport station placed in a room in the basement of LHD. The capsule can reach at the tube-end within 30 s. The maximum weight of capsule containing sample is about 10 g. The tube-end is placed near the 10-O port of LHD on the equatorial plane of plasma, which is 5.5 m of height from the floor level of the torus hall. The position of tube-end is shown in Fig. 1. The distance between the tube-end and the 10-O port is about 3 m. Figures 2 show the pictures of tube-end newly installed. The tube-end is a double tubing structure. The capsule containing the sample is transported to the inner tube-end before the deuterium plasma ignites. After the plasma operation, the capsule is returned to the transport station by the back flow which is supplied from the outer tube of tube-end. The support structure made by stainless steel is also prepared to set the NSSA around the tube-end.

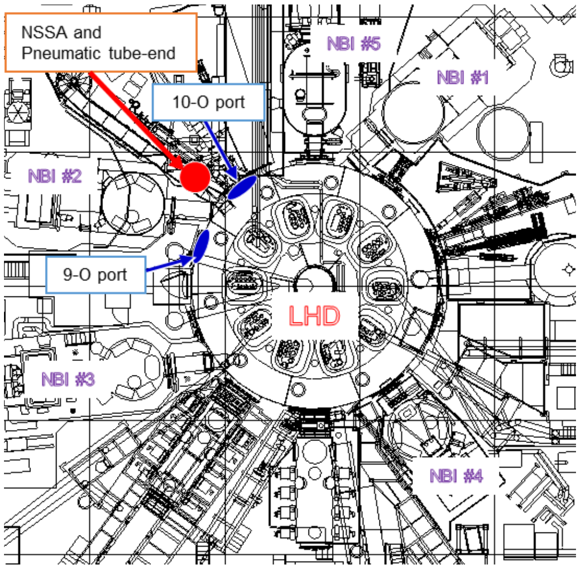

Fig. 1 Component layout in the LHD torus hall, and the position of NSSA and pneumatic tube-end.

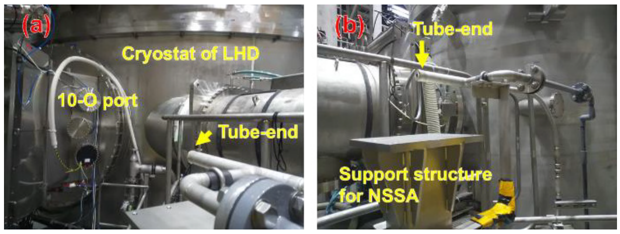

Fig. 2 The pneumatic tube-end newly installed in the LHD torus hall, observed (a) toward LHD, and (b) from LHD.

3. NSSA Designs and Radiation Transport Model by MCNP6

For designing NSSA for BNCT application, the selection of material is important first. The material in NSSA needs high efficiency for fast neutron deceleration, low capture rate for epi-thermal neutron, high/low capture rate for thermal neutron, and high efficiency of gamma-ray shielding, and so on. Also, the cost and weight, and residual radioactivity are important. In this study, lithium fluoride (LiF), magnesium fluoride (MF), and PE were selected as fast neutron decelerator due to their relatively low mass number and low capture rate for epi-thermal neutron. Cadmium (Cd) sheet and lead (Pb) were also selected by their characteristics of very high capture cross-section for thermal neutron and high gamma-ray shielding efficiency, respectively. The natural isotopic abundances of elements in these materials are considered. The size of the NSSA is $300 \times 300 \times 300\,\mathrm{mm}^3$ due to the space limitation in the torus hall.

In this study, NSSA was divided into 4 sections. The schematic configuration of NSSA is shown in Fig. 3. The tube-end is inserted into the center position of NSSA. The capsule is at the end position of tube. For the BNCT

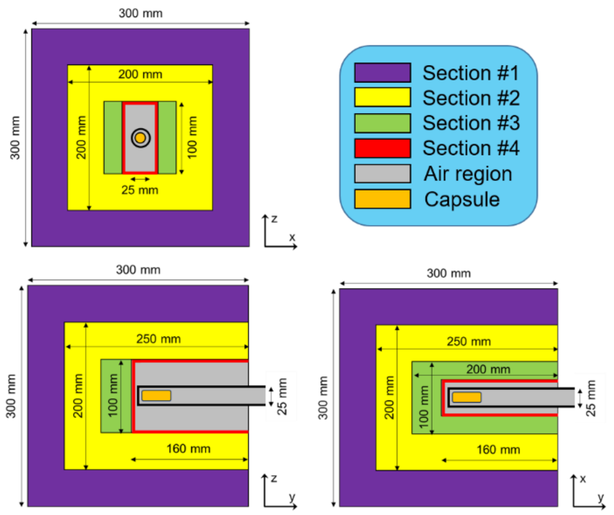

Fig. 3 Schematic configuration of NSSA for radiation transport calculation by MCNP6 in this work.

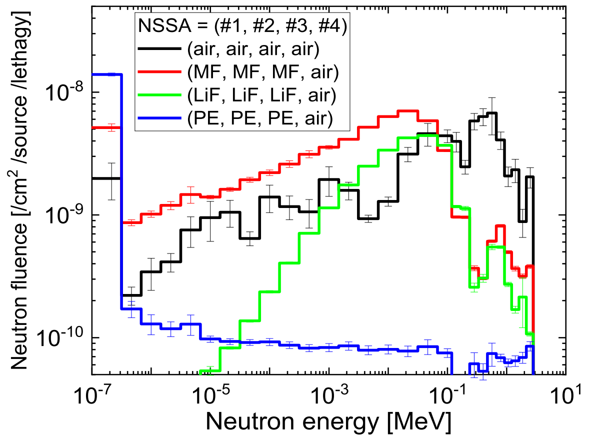

Fig. 4 Neutron energy spectra at the capsule in pneumatic tube-end with various NSSA designs.

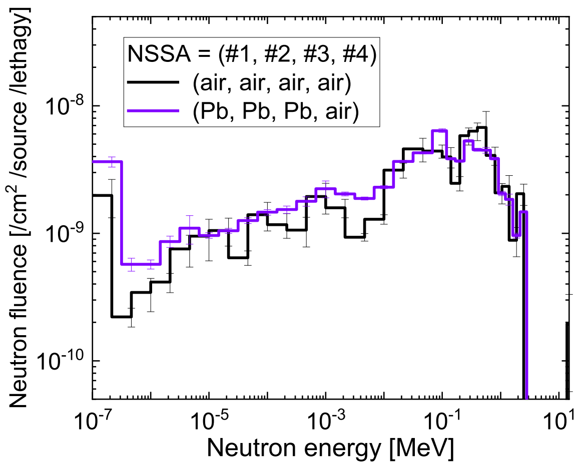

Fig. 5 Neutron energy spectra at the capsule in the tube-end surrounded by NSSA composed with Pb.

research, the cell samples are encapsulated with water. Therefore, it was assumed in the calculation that the capsule is filled with water. The section #4 is surrounding the tube-end as a sheet. The thickness of the section #4 is 1 mm.

The neutron flux, the neutron energy spectrum, the equivalent doses by neutron and gamma-ray at the sample were evaluated by the MCNP6 code. The model for MCNP6 calculation used includes the LHD body, the cryostat, the torus hall, and the basement of the torus hall as well as the pneumatic tube and the NSSA installed in this work. Pipes and ducts between the torus hall and the basement were also considered. This model for MCNP6 calculation has already been used in the calibration of NFM in the LHD [11]. With this model, the nuclear data library of ENDF/B-VII.1 was used [12]. For the calculation of equivalent dose, the neutron yield of 5.6×10^{16} n in a deuterium plasma discharge (shot) was assumed, which is a predicted maximum neutron yield in one shot in LHD [13].

4. Results and Discussion

Figure 4 shows the neutron energy spectra in the cases of NSSA designs composed with different fast neutron moderators. In the case without NSSA (NSSA composed with air), the peak at 2.45 MeV is clearly found. This neutron was almost directly transported to the sample from the deuterium plasma where 2.45 MeV neutrons dominantly generate. In this case, the fast neutron flux was relatively high compared to other cases. In the case of NSSA composed with LiF, the significant decrease of fast neutron flux was found. This is due to the collision processes of fast neutron with LiF. However, the thermal neutron flux and the epi-thermal neutron flux in the relatively lower energy region were clearly decreased. This should be caused by the ^{6}Li in LiF which exists about 7.5% in the natural abundance of lithium. The fast neutron moderates by LiF, then, thermal and epi-thermal neutrons were efficiently captured by ^{6}Li due to relatively high capture cross-section by ^{6}Li [14]. The case of NSSA with PE showed quite different energy spectrum. The neutron energy distribution is concentrated in the thermal neutron region. PE is the compound of carbon and hydrogen. Therefore, the fast neutrons were efficiently decelerated by hydrogen because the energy transfer from neutron to hydrogen is most effective due to the same mass of these particle. Therefore, the neutron field dominated by thermal neutron can be achieved by using PE. In the case of NSSA with MF, fast neutron flux was sufficiently decreased. Also, the epi-thermal neutron flux was relatively high compared to other designs. This result suggests that the NSSA composed with MF can provide the neutron field dominated with epi-thermal neutron by the additional reduction of thermal neutron flux.

Figure 5 shows the neutron energy spectra with NSSA composed by Pb and that without NSSA. It was found that the neutron energy spectrum slightly changed even more

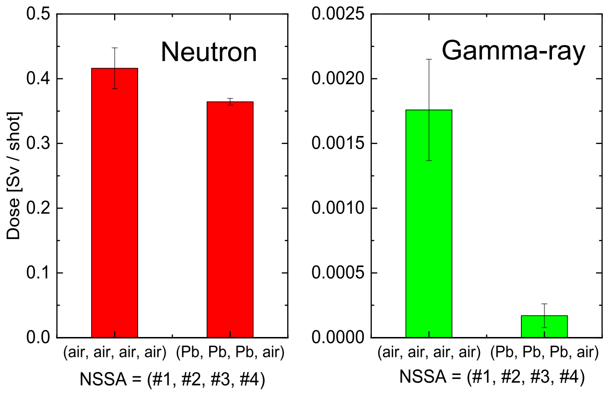

Fig. 6 The reduction of equivalent dose by neutron and gamma-ray by NSSA composed with Pb.

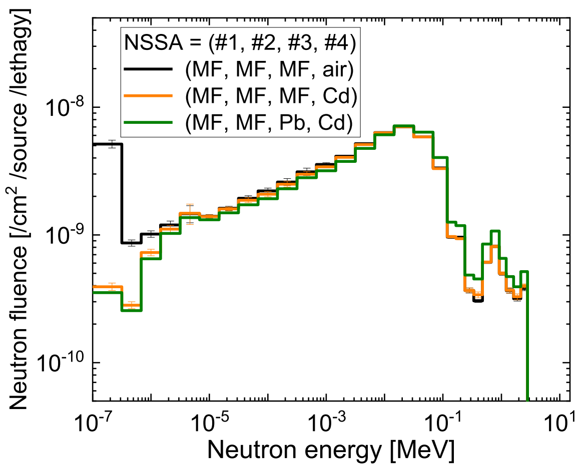

Fig. 7 The influence of Cd sheet in the section #4 of NSSA on neutron energy spectra.

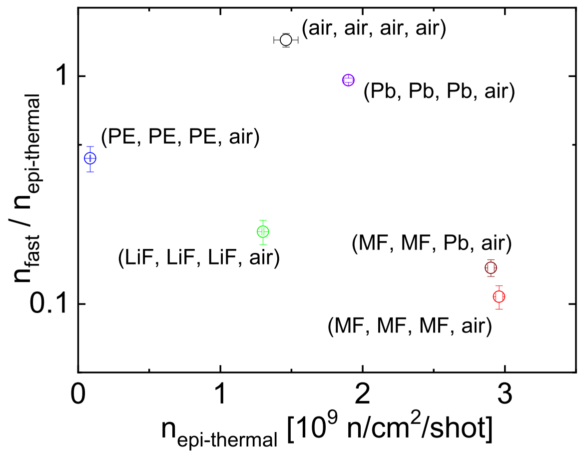

Fig. 8 The flux ratio of fast neutron to epi-thermal neutron with respect to the epi-thermal neutron flux in various NSSA designs.

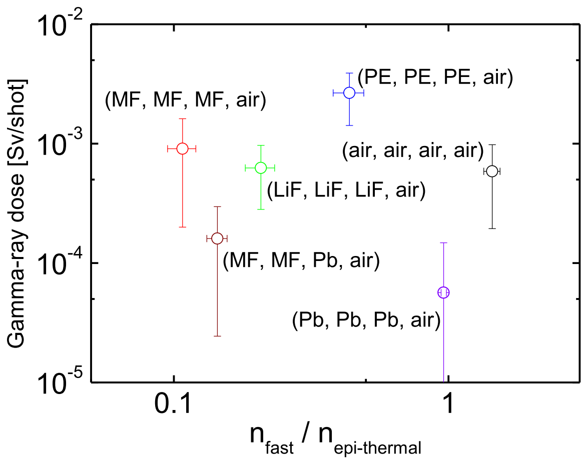

Fig. 9 The equivalent gamma-ray dose with respect to flux ratio of fast neutron to epi-thermal neutron in various NSSA designs.

than 10 cm-thick Pb covers the tube-end. The equivalent doses by neutron and gamma-ray in above two cases are displayed in Fig. 6. The dose by gamma-ray was significantly decreased by NSSA composed with Pb, although the dose by neutron was similar. Because of high electron density of Pb, the gamma-ray (photon) was effectively shielded. This result shows that Pb is effective for gamma-ray shielding although the heavy weight of Pb limits the acceptable volume of NSSA due to the load limit of support structure. In this work, 100 kg is a limit of support structure for NSSA. Therefore, Pb is only applicable in the section #3.

Figure 7 shows the effects of Cd in the section #4 in the case of NSSA composed with MF. As found in Fig. 7, the thermal neutron flux was one order of magnitude as low as that in the case without NSSA. Also, 1 mm-thick Cd slightly changed the neutron energy spectrum for epi-thermal neutron and fast neutron regions. This result clearly shows the contribution of Cd as thermal neutron absorber.

For constructing the neutron field dominated with epi-thermal neutron, all designs of NSSA were quantitatively evaluated with respect to (i) the epi-thermal neutron flux, (ii) the flux ratio of fast neutron to epi-thermal neutron, and (iii) the equivalent dose by gamma-ray. These parameters can evaluate the neutron source for BNCT research in which, (i) epi-thermal neutron flux is sufficiently high, (ii) fast neutron flux is sufficiently lowered, (iii) gamma-ray dose should be as low as possible. Figure 8 displays the flux ratio of fast neutron to epi-thermal neutron with respect to the epi-thermal neutron flux. Due to the criteria of (i) and (ii), the design located bottom-right side in Fig. 8 should be better. According to Fig. 8, it can be evaluated that the NSSA design with MF is better compared to others. Also, replacing MF in the section #3 to Pb slightly changes the performance of NSSA with respect to fast neutron shielding and epi-thermal neutron flux.

Figure 9 displays the equivalent dose by gamma-ray as a function of the flux ratio of fast neutron to epi-thermal neutron. Due to the criteria of (ii) and (iii), the design located bottom-left side in Fig. 9 should be a better design. The NSSA composed by MF with Pb in the section #3 showed one order of magnitude lower gamma-ray dose compared to NSSA fully composed with MF. Therefore, with the results of Figs. 8 and 9, the NSSA design adopting MF in the sections #1, #2 and Pb in the section #3 should be an effective design. With this selection of materials in the sections #1-3, the use of Cd in the section #4 is of help to exclude thermal neutron.

Finally, the NSSA design with MF in the sections #1 and #2, and Pb in the section #3, and Cd in the section #4 is employed for the epi-thermal neutron irradiation experiment to cell samples in the LHD torus hall. Also, the NSSA fully composed with PE is also employed for thermal neutron irradiation into cell samples. Toward these experiments, the benchmark test to quantify the neuron flux experimentally at the sample in the tube-end with NSSA designed in this work will be done with using activation foil method [15]. Then, the experiment with cell samples will be carried out in the LHD in the FY2021.

5. Conclusion

The designs of neutron spectrum-shaping assembly (NSSA) with various shielding materials were evaluated to construct the neutron field dominated with thermal neutron or epi-thermal neutron for the application of neutron filed in the torus hall of LHD toward the BNCT research. Neutron moderation efficiency was PE>LiF>MF, although LiF showed large thermal and epi-thermal neutron absorption. It was found that the neutron field dominated with thermal neutron can be produced by NSSA with PE. The effectiveness of Pb and Cd as gamma-ray and thermal neutron shielding, respectively, were confirmed by neutron transport calculation. Then, various NSSA designs were evaluated with respect to fast neutron flux, epi-thermal neutron flux, and gamma-ray dose. The combination of MF, Pb and Cd can provide the good epi-thermal neutron field for BNCT research in the torus hall of LHD.

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