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ТЕХНІКА ТА МЕТОДИ ЕКСПЕРИМЕНТУ
ENGINEERING AND METHODS OF EXPERIMENT

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Bilalodin[1,*], **A. Haryadi**[1], **Kartika Sari**[1], **Y. Sardjono**[2], **Rasito Tursinah**[3]

[1] *Department of Physics, Faculty of Mathematics and Natural Science,*
Jenderal Soedirman University, Purwokerto, Indonesia
[2] *Research Center for Accelerator Technology, National Research and Innovation Agency, Central Jakarta, Indonesia*
[3] *Research Center for Applied Nuclear Technology, Bandung, Indonesia*

*Corresponding author: bilalodin@unsoed.ac.id

DESIGN DEVELOPMENT OF DOUBLE-LAYER BEAM SHAPING ASSEMBLY USING EXTENSION NOZZLE TO INCREASE THE QUALITY OF EPITHERMAL NEUTRON BEAM AS A BORON NEUTRON CAPTURE THERAPY NEUTRON SOURCE

Double layer beam shaping assembly (DLBSA) is a system that moderates fast neutrons into epithermal neutrons. The epithermal neutrons that leave the aperture in the DLBSA system are broadened in the space, thereby reducing the intensity and homogeneity of the epithermal neutron beams. Therefore, it is necessary to improve the design. The development of the DLBSA design was carried out using an extension nozzle. The nozzles are designed using materials made in three configurations, namely Ni+LiF load polyethylene, Pb+LiF load polyethylene, and Bi+LiF load polyethylene. The simulation results show that the addition of a nozzle at the tip of the DLBSA can channel the beam more directionally with high intensity. The addition of nozzles with Ni+LiF load PE material produces an epithermal neutron beam that meets the IAEA standards.

Keywords: extension nozzle, double layer beam shaping assembly, epithermal neutron, boron neutron capture therapy.

1. Introduction

Boron neutron capture therapy (BNCT) is one of the cancer therapy methods currently developed. In BNCT therapy, a neutron beam is needed to induce the ^{10}B(n, α)^{7}Li reactions in cancer cells. The key to a successful cancer therapy using the BNCT method is determined by, among others, the accumulation of ^{10}B in cancer cells and the availability of an appropriate neutron source. The reaction produces alpha and lithium particles that can damage the cancer cells [1].

Initially, nuclear reactors were used as the source of neutrons. However nuclear reactors are constrained by several things, which include requiring very tight security, the presence of radiation waste from fission reactions, very high costs in the establishment, and difficulty in concession [2, 3]. Hence, more environmentally friendly neutron sources are developed in form of tandem accelerators and proton accelerators [4, 5]. A proton accelerator produces fast neutrons using beryllium or lithium targets [6].

One type of proton accelerator is the cyclotron. It has been developed in many countries, including Korea and Japan. Korea developed the accelerator-based boron neutron capture therapy (AB-BNCT) and Japan developed the cyclotron-based epithermal neutron source (C-BENS). C-BENS uses protons with an energy of 30 MeV and a beryllium target. The interaction of protons and beryllium targets produces fast neutrons through the reaction ^{9}Be(p, n)^{9}B. Fast neutrons produced by a C-BENS accelerator emit energy up to 28 MeV with a total flux of $1.9 \cdot 10^{14}$ n/s/mA^{-1} [7]. The neutrons emitted by the beryllium are highly energetic and need to be moderated into epithermal neutrons using beam shaping assembly (BSA) for BNCT. To fulfill epithermal neutrons as a neutron source for BNCT, a DLBSA model has been developed [8].

The DLBSA that has been developed is capable of producing an epithermal neutron flux close to the IAEA standard of 10^9 n/(cm^2·s). Epithermal neutrons flow through the aperture resulting in a neutron beam that radiates sideways (broadened in the space). As a result, the further away from the aperture the neutron beam decreases in intensity [9]. Therefore, it is necessary to have a new design of DLBSA that can reduce the neutron beam that spreads out from the aperture so that the epithermal neutrons are collected and channeled effectively. The approach in the new DLBSA design is by adding a nozzle channel at the end of the aperture. With this additional channel, it is expected that neutron beams complying with the requirement of the IAEA can be directed more conveniently toward the patient. In this article, the results of the development of the DLBSA design using additional nozzles and their effects on improving the quality of the epithermal neutron beam will be presented.

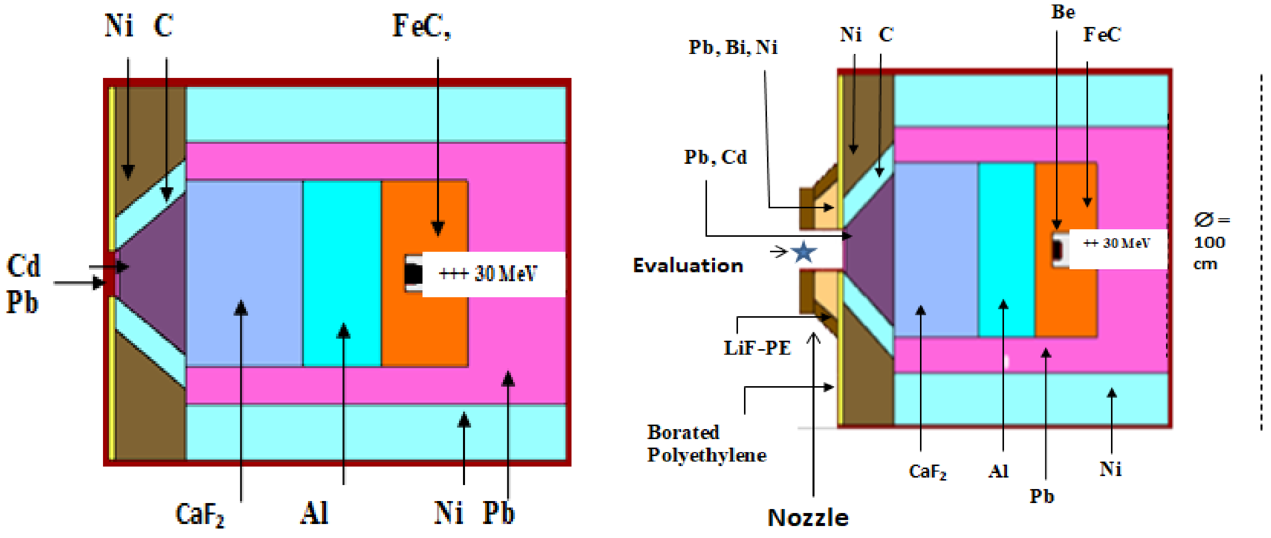
2. Materials and methods

2.1 Design of DLBSA

The proton source modeled in the DLBSA design is 30 MeV protons generated from a 30 MeV cyclotron type accelerator developed by the KURRI institute in Japan, namely C-BENS. 30 MeV protons impinge on ^{9}Be target producing fast neutrons with energy ranging from 0.01 to 28 MeV and total flux of $1.9 \cdot 10^{14}$ n/s/mA^{-1} [7]. The neutrons are subsequently processed using a DLSBA into epithermal neutrons.

DLBSA is modeled with four main components, namely moderator, reflector, collimator, and filter. Each component is formed from a combination of two materials. The moderator was chosen from a combination of aluminum and CaF_2 materials. The reflector is selected from a combination of plumbum with nickel material. The collimator is composed of nickel and carbon materials. The final stage is selecting a combination of fast neutron filters and thermal neutrons. The combination of fast and thermal neutron filters is materialized by combining FeC with cadmium material. Besides the cadmium filter, a gamma filter made of plumbum is installed [9]. At the end of the collimator, an additional channel is added in the form of a cylindrical nozzle.

The DLBSA design with additional nozzles is intended for usage in BNCT therapies, which is more efficient in delivering radiation beams onto patients. Additional nozzles are also intended to suppress beam spread as it exits the aperture. The position of the nozzle is placed at the output end of the aperture. The shape of DLBSA without nozzles (basic DLBSA) and with added nozzles is shown in Fig. 1. The nozzle material is made in three configurations, namely Ni+LiF load polyethylene, Pb+LiF load polyethylene and Bi+LiF load polyethylene. The length of the nozzle is 20 cm with a diameter of 12 cm. The evaluation of the neutron beam is carried out at the position of the output end of the nozzle.



a *b*

Fig. 1. DLBSA: *a* – basic DLBSA without the additional nozzle; *b* – DLBSA with nozzle extension. (See color Figure on the journal website.)

Neutron beam parameters for BNCT according to IAEA standard [11]

Parameter	Notation (unit)	IAEA recommendation
Epithermal neutron flux	φ_{epi}, n/(cm^2·s)	$\geq 1{,}0 \cdot 10^{9}$
Fast neutron dose rate / Epithermal neutron flux	D_f/φ_{epi}, Gy·cm^2	$< 2{,}0 \cdot 10^{-13}$
Gamma dose rate / Epithermal neutron flux	$D\gamma/\varphi_{epi}$, Gy·cm^2	$< 2{,}0 \cdot 10^{-13}$
The ratio of epithermal and thermal neutron flux	$\varphi_{epi}/\varphi_{th}$	> 100

An evaluation of the characteristics of the neutron beam coming out of the nozzle was carried out using the particle heavy ion transport version 3.2. code with nuclear data JENDL-4.0 [10]. The evaluation is carried out at the output tip of the nozzle as shown in Fig. 1. The characteristics of the neutron produced at the nozzle output tip are meant to comply with IAEA standards as shown in the Table.

3. Results and discussions

3.1. The characteristics of epithermal neutron flux

The development of the DLBSA design was carried out by adding a nozzle at the output end of the aperture. The resulting epithermal neutrons can expectedly reduce the scattering of the neutron beam and reduce the decrease in the epithermal neutron flux. The nozzle design combines metal and non-metallic materials. Metallic materials are intended to increase the reflectivity of epithermal neutrons. On the other hand, non-metals are used to absorb contaminants that accompany epithermal neutrons, such as thermal neutrons and fast neutrons.

The results of the evaluation of the spectral characteristics of the neutron emerging from the DLBSA without a nozzle are shown in Fig. 2. The spectrum of neutrons is shown in the basic spectrum of DLBSA. The neutron energy produced by DLBSA without a nozzle consists of thermal, epithermal, and fast neutrons with predominantly epithermal neutrons in the energy range 10^{-6} - 10^{-2} MeV. The total flux of epithermal neutrons before the nozzle is applied is $0.5 \cdot 10^9$ n/(cm^2·s) (Fig. 3). The value of the neutron flux is included in the category of low epithermal neutron flux because it is below the IAEA standard. Low flux causes cancer treatment time to be more than 1 h [12].

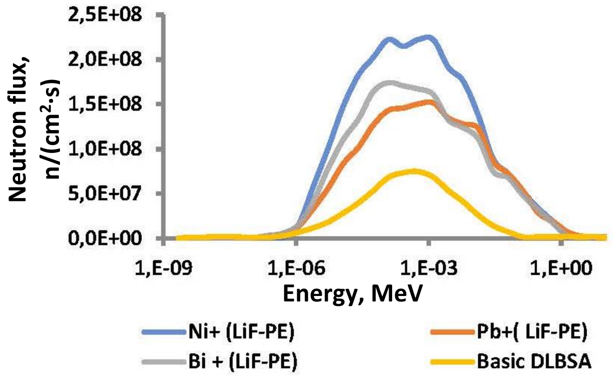


Fig. 2. The neutron flux spectrum of DLBSA output without and with nozzles.
(See color Figure on the journal website.)

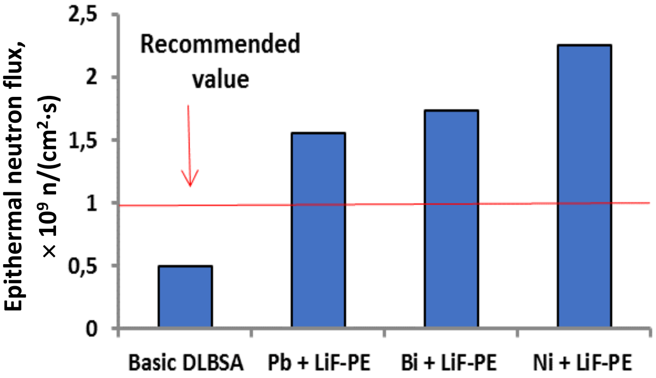


Fig. 3. The comparison of epithermal neutron flux of DLBSA output without and with nozzles.
(See color Figure on the journal website.)

The evaluation results of the epithermal neutron flux produced by DLBSA using nozzles are better than DLBSA without nozzles (basic DLBSA). The addition of nozzles with Pb+(LiF-PE), Bi+(LiF-PE), and Ni+(LiF-PE) materials can increase the epithermal neutron flux (see Fig. 2). The epithermal neutron flux produced following the addition of Pb+(LiF-PE), Bi+(LiF-PE) and Ni+(LiF-PE) nozzles is $1.55 \cdot 10^9$, $1.73 \cdot 10^9$, $2.25 \cdot 10^9$ n/(cm^2·s), respectively. The epithermal neutron flux output of DLBSA with nozzles is higher than without nozzles. The epithermal neutron flux agrees with the IAEA recommendation (see Fig. 3). The addition of nozzles from Ni+(LiF-PE) produces the highest epithermal neutron flux. Nickel material can transmit the highest epithermal neutron flux compared to plumbum and bismuth materials. This is because nickel has the highest elastic scattering cross-section: σs (Ni) = 26 b, σs (Pb) =11.11 b dan σs (Bi) = 9.156 b [13 - 15].

3.2. Neutron flux distribution

The distribution of epithermal neutron flux in DLBSA without a nozzle and using a nozzle is shown in Figs. 4 and 5. The distribution of epithermal neutron flux in DLBSA is represented by color intensity. Low epithermal neutron flux intensities are depicted in blue and high intensities are shown in red. The Figure shows that the epithermal neutron flux is spread out in the DLBSA. The epithermal neutron flux intensity is highest in the first filter with z = 0 (shown in red) and increases through the moderator, collimator, and decreases after passing through the filter with z > – 100 (shown in yellow). The decrease in epithermal neutron flux can be attributed to the change of epithermal neutrons into thermal neutrons due to collisions with the material it passes through [16]. The neutron flux produced by DLBSA without a nozzle was measured at a 20 cm distance from the aperture is $0.5 \cdot 10^9$ n/(cm^2·s). Without a nozzle, neutron flux tends to spread sideways after exiting the aperture (Fig. 4). This is due to the diffraction effect (deflection) of the neutron particles. The scattering of the epithermal neutron beam causes a decrease in the intensity of the neutron flux [17].

The distribution of epithermal neutrons in DLBSA using nozzles can channel more directed beams with greater intensity. Nickel, bismuth, and plumbum materials are very effective as reflectors on the nozzles so that (deflection in direction) of the neutron particles that spread to the side can be reduced. The use of nozzles can channel the epithermal neutron beam without a significant

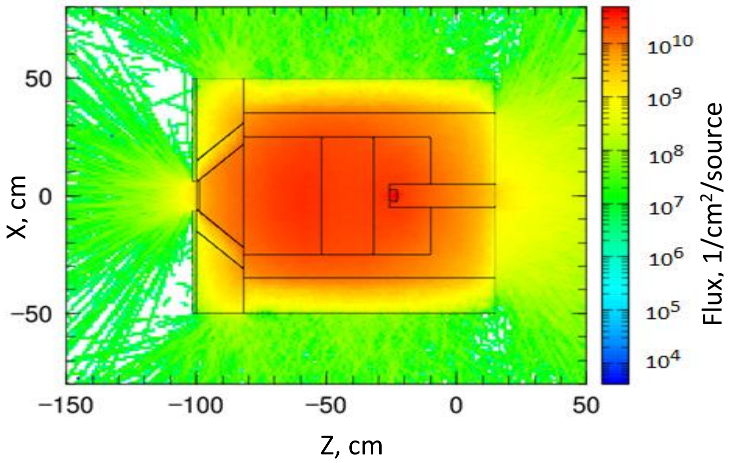


Fig. 4. Epithermal neutron distribution in basic DLBSA. X – wide of DLBSA; Z – length of DLBSA. (See color Figure on the journal website.)

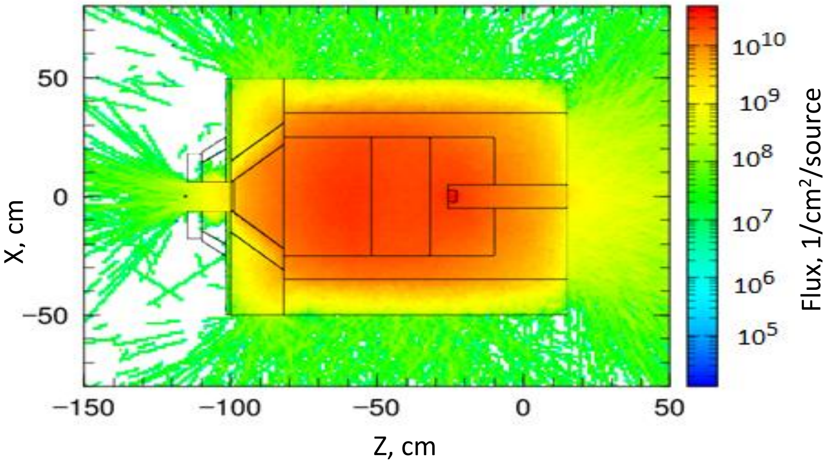


Fig. 5. Epithermal neutron distribution in DLBSA with Ni+LiF load polyethylene nozzle. X – wide of DLBSA; Z – length of DLBSA. (See color Figure on the journal website.)

decrease at a distance of 20 cm (Fig. 5). The effectiveness of the nozzle material in distributing the epithermal neutron beam is supported by the fact that the material has a high scattering cross-section and low absorption cross-section [13, 15].

3.3. Characteristics of contaminants

The neutron beam used in BNCT therapy requires low levels of contaminants that accompany epithermal neutrons. The IAEA sets the minimum standard for contaminants accompanying epithermal neutrons as follows. The ratio of epithermal neutron flux to thermal neutron $\varphi_{epi}/\varphi_{th} > 100$, the ratio of fast neutron dose rate to epithermal neutron flux $D_f/\varphi_{epi} < 2\cdot10^{-13}$ Gy·cm² and ratio of gamma dose rate to epithermal neutron flux $D_f/\varphi_{epi} < 2\cdot10^{-13}$ Gy·cm² [11].

Using nozzles in DLBSA can improve the quality of epithermal neutrons. The ratio of the epithermal neutron flux to the thermal neutron flux before the nozzle is applied is 50. The attachment of the nozzle increases the $\varphi_{epi}/\varphi_{th}$ ratio. The value of $\varphi_{epi}/\varphi_{th}$ after attachments of nozzles made of Pb+LiF load polyethylene, Bi+LiF load polyethylene, Ni+LiF load polyethylene are 173, 174, and 274 respectively. The addition of nozzles for the combination of bismuth and plumbum, and nickel metals with LiF load polyethylene materials can reduce the thermal neutrons that still escape the thermal filter cadmium. The decrease is caused by the lithium material, which has a high thermal neutron absorption cross-section [18]. Polyethylene material which is composed of carbon and hydrogenium elements also contributes to the decrease in thermal neutrons [19]. The value of the ratio of the epithermal neutron flux to the thermal neutron flux $\varphi_{epi}/\varphi_{th}$ has exceeded the IAEA criteria. The value of the ratio of the epithermal neutron flux to the thermal neutron flux is shown in Fig. 6.

Adding nozzles to DLBSA reduces contaminants caused by the presence of fast neutrons accompanying epithermal neutrons. Based on the calculation of the ratio of the fast neutron dose rate to the epithermal neutron flux, D_f/φ_{epi} decreased with the

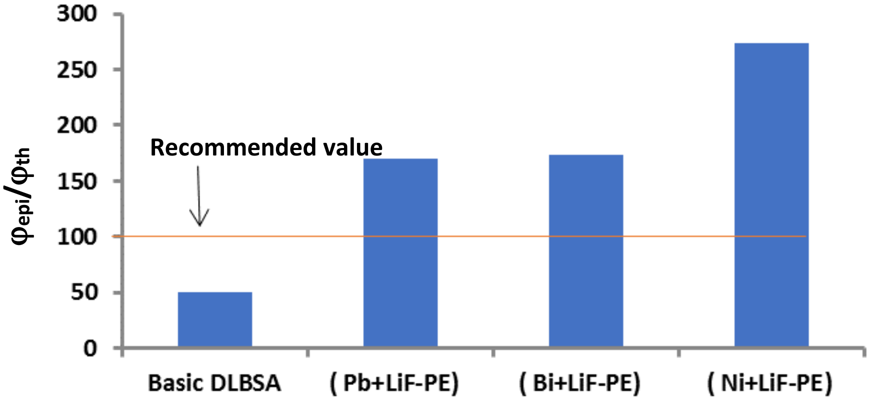


Fig. 6. The ratio of epithermal neutron flux to the thermal neutron flux.
(See color Figure on the journal website.)

attachment of the nozzle. The values of the fast neutron dose rate relative to the epithermal neutron flux using Pb+LiF load polyethylene, Bi+LiF load polyethylene, and Ni+LiF load polyethylene materials are respectively $4.35 \cdot 10^{-13}$, $1.50 \cdot 10^{-13}$ and $0.39 \cdot 10^{-13}$ Gy·cm^2. The decrease in the fast neutron dose rate is caused by fast neutrons still escaping the moderation process and will collide with the walls of the nozzle channel as a result, decreasing their energy to become epithermal neutrons [20].

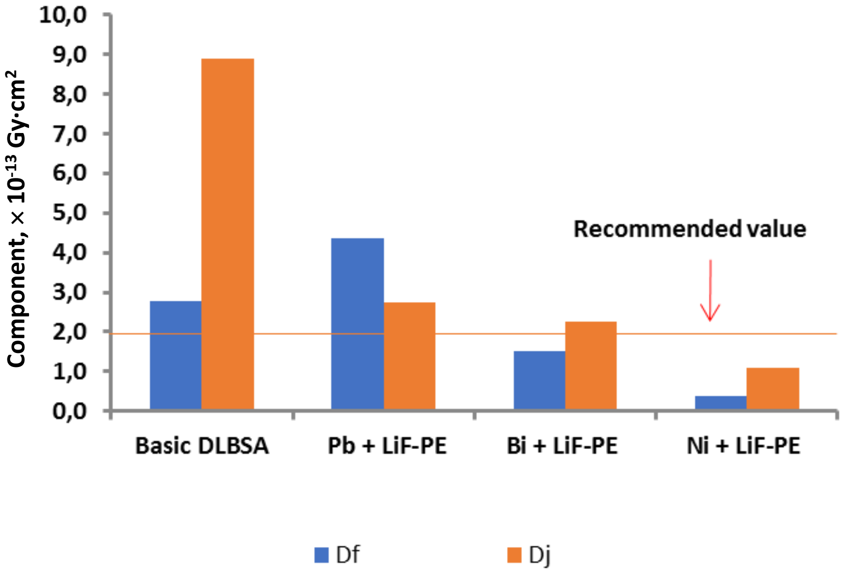


Fig. 7. The ratio of gamma dose rate (*D*γ) to the epithermal neutron flux without and with nozzles.
(See color Figure on the journal website.)

The addition of nozzles on DLBSA also affects of reduction gamma contaminants. Gamma dose rate over epithermal neutron flux D_γ/φ_{epi} resulting from the installation of Pb+LiF load polyethylene, Bi+LiF load polyethylene, and Ni+LiF load polyethylene materials are $2.74 \cdot 10^{-13}$, $2.26 \cdot 10^{-13}$ and $1.0 \cdot 10^{-13}$ Gy·cm^2 respectively. The gamma dose rate using Pb+LiF load polyethylene and Bi+LiF load polyethylene is still above the IAEA requirement (Fig. 7). This is because when plumbum and bismuth materials interact with neutrons, a neutron capture mechanism occurs. This mechanism produces gamma emission [15]. This is the cause of such high gamma dose rate in DLBSA using nozzles made of Pb+LiF load polyethylene and Bi+LiF load polyethylene materials. The gamma dose rate in DLBSA with nozzles made of Ni+LiF load polyethylene is the lowest because when neutrons interact with Ni material occurs elastic scattering without neutron capture [21].

4. Conclusion

A new DLBSA design has been developed with the addition of a nozzle at the end of the aperture. This addition is intended to reduce beam spread and decrease beam intensity. The result of adding a nozzle at the tip of the DLBSA is the ability to channel the beam more directionally with high intensity. The best nozzle for producing epithermal neutron beams is DLBSA with the addition of Ni+LiF load polyethylene material. DLBSA using Ni+LiF load polyethylene nozzles produces an epithermal neutron flux of $2.25 \cdot 10^9$ n/(cm^2·s), the ratio of the epithermal neutron flux to the thermal neutron flux ($\varphi_{epi}/\varphi_{th}$) 274, the value of the ratio of the fast neutron dose rate (D_f) and the rate of the gamma dose (D_γ) to the epithermal neutron flux is $0.39 \cdot 10^{-13}$ and $1.0 \cdot 10^{-13}$ Gy·cm^2, respectively. The epithermal neutron beam meets the IAEA standards.

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Білалодін[1,]*, А. Харьяді[1], Картіка Сарі[1], Ю. Сарджоно[2], Расіто Турсіна[3]

[1] *Кафедра фізики, факультет математики та природничих наук,*
Університет Джендерала Содірмана, Пурвокерто, Індонезія
[2] *Дослідницький центр прискорювальних технологій, Національне агентство досліджень та інновацій,*
Центральна Джакарта, Індонезія
[3] *Дослідницький центр прикладних ядерних технологій, Бандунг, Індонезія*

*Відповідальний автор: bilalodin@unsoed.ac.id

РОЗРОБКА КОНСТРУКЦІЇ ДВОШАРОВОЇ СИСТЕМИ ФОРМУВАННЯ ПУЧКА З ВИКОРИСТАННЯМ ДОДАТКОВОЇ НАСАДКИ ДЛЯ ПІДВИЩЕННЯ ЯКОСТІ ПУЧКА ЕПІТЕРМАЛЬНИХ НЕЙТРОНІВ ЯК ДЖЕРЕЛА НЕЙТРОНІВ ДЛЯ БОР-НЕЙТРОН-ЗАХОПЛЮВАЛЬНОЇ ТЕРАПІЇ

Двошарова система формування пучка (DLBSA) – це система, що перетворює швидкі нейтрони в епітермальні нейтрони. Епітермальні нейтрони, що залишають апертуру в системі DLBSA, розширюються в просторі, тим самим зменшуючи інтенсивність та однорідність пучків епітермальних нейтронів. Тому необхідно вдосконалити конструкцію. Розробка конструкції DLBSA проводилася з використанням додаткових насадок. Насадки розроблено з використанням матеріалів, виготовлених у трьох конфігураціях, а саме: поліетилен з додаванням Ni+LiF, поліетилен з Pb+LiF та поліетилен з Bi+LiF. Результати моделювання показують, що додавання насадки в DLBSA може каналізувати пучок більш спрямовано з високою інтенсивністю. Додавання насадок з поліетилену з Ni+LiF створює пучок епітермальних нейтронів, що відповідає стандартам МАГАТЕ.

Ключові слова: додаткова насадка, двошарова система формування пучка, епітермальний нейтрон, бор-нейтрон-захоплювальна терапія.

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