ЯДЕРНА ФІЗИКА ТА ЕНЕРГЕТИКА / NUCL. PHYS. AT. ENERGY 20 (2019) 070-075 ISSN 1818-331X

ТЕХНІКА ТА МЕТОДИ ЕКСПЕРИМЕНТУ
ENGINEERING AND METHODS OF EXPERIMENT

УДК 620.179.155.5, 621.039.556 https://doi.org/10.15407/jnpae2019.01.070

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# OPTIMIZATION AND ANALYSIS OF NEUTRON DISTRIBUTION ON 30 MeV CYCLOTRON-BASED DOUBLE LAYER BEAM SHAPING ASSEMBLY (DLBSA)

Design and optimization of double layer Beam Shaping Assembly (DLBSA) has been conducted using the MCNPX code. The BSA is configured to comply with such a construction having typically a double moderator, a reflector, a collimator, and a filter. The optimization of various combinations of materials that compose the moderator, reflector, and filter yields such quality and intensity of radiation beams that conform to the requirements for Boron Neutron Capture Therapy. The composing materials are aluminum and $BiF_3$ for moderator, lead and graphite for the reflector, nickel and polyethylene borate for the collimator, and iron and cadmium for the filter. Typical beam parameters measured at the exit of the collimator are epithermal neutron flux of $1.1 \cdot 10^9$ n/(cm$^2$·s), the ratio of epithermal neutron flux to thermal neutron and fast neutron flux 344 and 85, respectively, and the values of fast neutron and gamma dose to epithermal neutron flux $1.09 \cdot 10^{-13}$ Gy·cm$^2$ and $1.82 \cdot 10^{-13}$ Gy·cm$^2$, respectively. Analysis of epithermal neutron flux and neutron beam spectrum using the PHITS code reveals that the distribution of epithermal neutron spreads out in the DLBSA. The highest intensity is found in the moderator and decline downstream of the collimator and filter. The spectrum of neutron beams displays a narrow spike with that peaks at 10 keV.

*Keywords:* optimization of DLBSA, neutron particle distribution, MCNPX code, PHITS code.

## 1. Introduction

Boron Neutron Capture Therapy (BNCT) is a method for cancer therapy that combines irradiations using thermal neutron with that using $^{10}B$ isotope in a tumor. $^{10}B$ is highly probable to capture neutrons within the range of thermal energy (< 0.1 eV) and transforms into $^{11}B$. Due to its instability, $^{11}B$ immediately disintegrates, emitting alpha particle and $^7Li$. Li ion emits prompt gamma radiation, which is parasitic in BNCT as irradiates the normal tissue, cancer cell killing is mostly due to ions. The particle range is of order 4.5 - 10 μm such that energy is deposited in a single cell (5 - 15 μm in diameter) [1].

Neutrons can be produced using an accelerator, one of which is the cyclotron [2, 3]. Unfortunately, neutrons from Be(d, n) or Be(p, n) reactions produced using an accelerator cannot be directly utilized for BNCT purpose because they are fast neutrons and contain contaminants. In contrast, BNCT for particularly deep tumor requires epithermal neutrons [2].

A system that is capable of processing fast neutron beams into epithermal neutrons is Beam Shaping Assembly (BSA). The BSA typically consists of some components: moderator, reflector, collimator, filter [4 - 6]. The materials composing each component of the BSA are designed using a single layer configuration, where every component only uses one type of material. Such single-layer configuration has a deficiency, i.e. each component of the BSA does not function optimally, and thus gives a result that is below expectation. To overcome the deficiency a double layer configuration is developed.

Some components constructed in the form of double layer show better performance. The use of a double layer moderator can increase moderation up to 19.3 % [7]. A double layer filter can produce epithermal neutron beams that range from 1.5 to 10 keV [8]. Such is a range required in BNCT therapies.

The quality of a reflector can be improved by using the two-layer reflector. A combination of different materials such as tungsten and molybdenum can multiply neutron reflections to up to five times in comparison to using only tungsten. Other prescribed combinations to increase reflectivity are combinations of lead and BeO and graphite and boranyloxyboron ($B_2O$) [9].

A good collimator wall is made from a material that can reflect neutrons and absorb gamma rays (IAEA 2001). Such materials as plumbum and bismuth can be combined to make good collimator, owing to the characteristic of plumbum that reflect neutrons and Bi that absorbs gammas [10]. Other materials with neutron reflecting and gamma absorbing quality are lead and nickel and lead with BeO and graphite [9, 11].

Based on the above, BSA components configured in double layer form can increase quality of the BSA. The quality is even higher when optimization is carried out, particularly in regarding type, thickness, and composition of materials for the components. An optimized BSA tends to produce neutron beams with such characteristics adequate for BNCT purposes: epithermal neutron flux $\geq 1.0 \cdot 10^9$ n/(cm$^2$·s), the ratio of epithermal to thermal neutron flux >100, the ratio of epithermal to fast neutron flux of over 20, and fast neutron and gamma radiation contaminant below $2.0 \cdot 10^{-13}$ Gy·cm$^2$ [12].

In this article, a design of double layer BSA using two materials will be discussed. Optimization of DLBSA is carried out using MCNPX code [13] and analysis on particle distribution in the DLBSA using the PHITS code [14].

## 2. Materials and Methods

Incoming protons modeled in the design of DLBSA are produced by an accelerator of 30 MeV cyclotron type developed by KURRI institute of Japan, which is the C-BENS [2]. 30 MeV protons are impinging on $^9$Be target 5 and 0.5 cm in diameter and thickness, respectively, to produce fast neutrons that are going to be processed using double layer beam shaping assembly (DLBSA).

DLBSA has four main components, a moderator, a reflector, a collimator, and filter. Each component is formed of a combination of two materials. The moderator is chosen from a combination of aluminum and eight other materials, i.e, $Al_2O_3$, LiF, $AlF_3$, $MgF_2$, $CaF_2$, $BiF_3$, $PbF_2$, and $CF_2$. The reflector is chosen from combinations of lead and bismuth, FeC, nickel and graphite. Best moderator and reflector materials are combined with collimator materials composing of Ni and borated polyethylene. Materials for moderator, reflector, and collimator used as the components of DLBSA are picked based on their ability to produce the largest number of the epithermal neutrons. At the final stage, some combinations are selected for the filter of the fast and thermal neutrons. The combinations are obtained by combining iron with cadmium, Ti, Li, $B_4C$, and $^{10}$B. The best filter is selected by its ability to reduce fast and thermal neutrons. Also at the end of DLBSA a lead material is placed to reduce gamma rays [10].

The Monte Carlo Transport Code (MCNPX) 2.7 is utilized to carry out the optimization of Double Layer Beam Shaping Assembly (DLBSA) [13]. In obtaining parameters of thermal, epithermal, fast neutron flux, fast neutron dose and gamma radiation dose, the MCNPX code is run with particle history of $10^6$ and multiplication factor $6.25 \cdot 10^{15}$ n/s, in mode n p h and tally F5. The microscopic cross-section data for simulation uses ENDF/B-VII and Visual Editor for a visual creation of the MCNPX input.

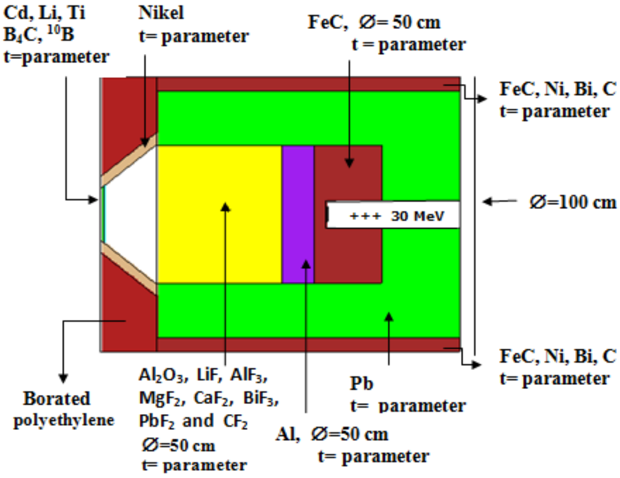

Fig. 1. The configuration of double layer BSA.
(See color Figure on the journal website.)

The distribution of epithermal neutron flux in DLBSA and the spectrum of outgoing neutron-flux on the aperture surface are determined using the Particle and Heavy Ion Transport System (PHITS) code [14]. The track length tally is used in the PHITS calculation. To draw the particle track and visualization geometry of DLBSA, the ANGEL software is used. The transport is based on the cross-section data library JENDL-4.0 for neutrons and photons, and intra-nuclear cascade (INCL4.6) for protons. The design of double layer BSA is shown in Fig. 1.

## 3. Results and Discussion

The neutrons used in DLBSA are originated from reactions of 30 MeV protons with the $^9$Be target. The $^9$Be material is chosen for its ability to produce high flux compared to other materials, such as $^7$Li and $^{181}$Ta. Another distinctive feature of $^9$Be is its melting point and boiling point which is higher than those of $^7$Li [15]. Therefore, $^9$Be is widely used as a fast-neutron producing target in a cyclotron system. High energy neutrons are conceived to result from $^9$Be(p, n)$^9$B reactions [16, 2]. Such neutrons are yet to be processed to achieve epithermal neutrons.

Table 1 lists fluxes of epithermal neutrons and their corresponding ratio to thermal neutron flux, produced by a BSA with double layer moderator. Combinations of aluminium material with eight different materials yield epithermal neutron flux of $2.6 \cdot 10^8$ n/(cm$^2$·s), at the lowest, and $1.27 \cdot 10^9$ n/(cm$^2$·s), at the highest, with a proton beam current of 1 mA. The highest ratio of epithermal to thermal neutron flux is achieved through a combination of aluminum and $BiF_3$ material. The optimization result corresponding to the thickness of aluminum and $BiF_3$ combinations is shown in Fig. 2. It suggests that the best combination of aluminum and $BiF_3$ is when aluminum is 20 cm, and $BiF_3$ is 30 cm in thickness, yielding a maximum epithermal flux of $1.2 \cdot 10^9$ n/(cm$^2$·s).

*Table 1.* **Epithermal flux from a combination of two moderators**

| Two-layer moderator | Epithermal neutron flux (n/(cm$^2$·s) | $Q_{epi}/Q_{ther}$ |
|---|---|---|
| Al + $Al_2O_3$ | $2.60 \cdot 10^8$ | 186 |
| Al + LiF | $8.40 \cdot 10^8$ | 142 |
| Al + $AlF_3$ | $5.50 \cdot 10^8$ | 141 |
| Al + $MgF_2$ | $5.10 \cdot 10^8$ | 146 |
| Al + $CaF_2$ | $9.50 \cdot 10^8$ | 103 |
| Al + $BiF_3$ | $1.27 \cdot 10^9$ | 300 |
| Al + $PbF_2$ | $7.20 \cdot 10^8$ | 129 |
| Al + $CF_2$ | $7.10 \cdot 10^8$ | 169 |

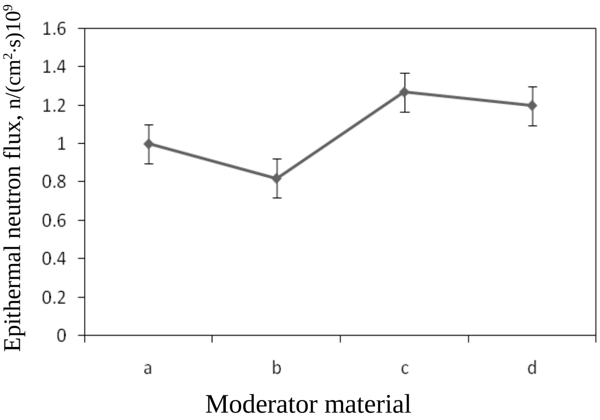

Fig. 2. Epithermal flux from a combination of Al + $BiF_3$ at a various thickness of moderator (cm) *a* = Al(40 cm) + + $BiF_3$(10 cm), *b* = Al(30 cm) + $BiF_3$(20 cm), *c* = Al(20 cm)+ + $BiF_3$(30 cm), *d* = Al(10 cm) + $BiF_3$(40 cm).

The success of aluminum and $BiF_3$ in producing high epithermal neutron flux is due to aluminum having a large cross section for neutron energy above 10 keV. [17]. Interactions of aluminum material with epithermal neutrons are predominantly through $^{27}Al(n, 2n)^{26}Al$ reactions [18]. As for $BiF_3$, its contribution to fast neutron moderation is due to the presence of fluorine element in $BiF_3$. Fluorine is an element that has a large scattering cross section for fast neutrons; hence $BiF_3$ also contributes to increase the number of epithermal neutrons and decreasing that of thermal neutrons. Finally, bismuth contributes to decreasing gamma radiations [19].

Fig. 3 shows the effect of double layer reflector on the epithermal flux in DLBSA. The double layer reflector is tested using the best moderator, i.e. Al (20 cm) + $BiF_3$ (30 cm). The simulation result shows that the combination of two reflectors is generally effective to increase epithermal neutron flux. Combination of lead and graphite suggests the highest epithermal neutron flux of $1.4 \cdot 10^9$ n/(cm$^2$·s). Such high epithermal neutron flux is due to the contribution of each combination of the reflector material. Lead as the main material for the reflector has high elastic scattering cross section for fast neutrons and low absorption cross-section for epithermal neutrons [9]. This characteristic of lead allows for fast neutrons are leaking out of the moderator to be directed back into the moderator for further moderation. Moderated fast neutrons increase the number of epithermal neutrons. The presence of graphite as secondary reflector also contributes to increasing epithermal neutrons, in addition to the contribution of as the main reflector [20].

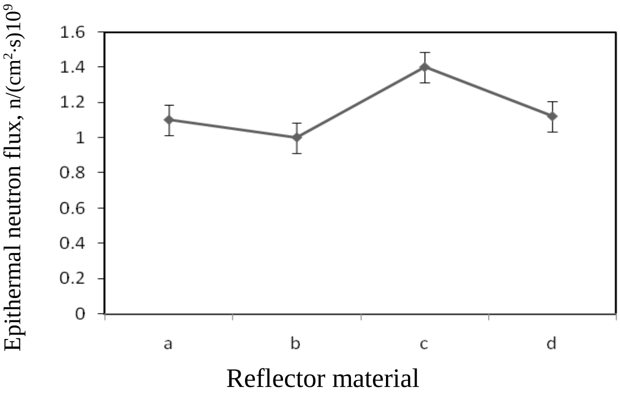

Fig. 3. Epithermal flux using double layer reflector material *a* = Pb + Bi, *b* = Pb + Ni, *c* = Pb + C, *d* = Pb + FeC.

Epithermal neutrons emanated from combinations of the best combination of moderator and reflector enter the collimator. The collimator made from nickel and borated polyethylene material can sustain high epithermal neutron flux. It is accounted for by nickel material having high reflectivity to epithermal neutrons [9].

To reduce fast and thermal neutrons in DLBSA, a filter is used. Table 2 shows the effect of combinations of fast and thermal neutrons filter material on the quality of the mixed gamma-neutron radiation field on an exit of the collimator of DLBSA. Based on the table the combination of iron and cadmium material is best in decreasing fast and thermal neutron flux. The effectiveness of iron as fast neutron filter is due to its ability to in-elastically scatter neutrons having the energy of higher than 14 MeV that pass through iron material [9]. Cadmium material is effective because of its largest absorption cross-section for thermal neutrons as compared to the rest four materials [10].

A simulation result for epithermal neutron flux distribution in DLBSA using the PHITS code is shown in Fig. 4. The distribution of epithermal neutron spreads out in the DLBSA. The intensity is highest inside the moderator and declines having to pass through collimator and filter. The decrease in epithermal neutron flux is possible due to the moderation of epithermal neutrons, turning them into the thermal neutrons. Epithermal neutron flux at the end of the collimator (aperture) is higher than $10^9$ n/(cm$^2$·s).

*Table 2.* **Effect of a combination of fast and thermal filter on the radiation beam leaving the DLBSA**

| Filter | Epithermal neutron flux, n/(cm$^2$·s) | $Q_{epi}/Q_{ther}$ | $Q_{epi}/Q_{fast}$ | $D_{fast}/Q_{epi}$, Gy·cm$^2$ | $D_\gamma/Q_{epi}$, Gy·cm$^2$ |
|---|---|---|---|---|---|
| Fe + Li | $1.10 \cdot 10^9$ | 688 | 23 | $4.64 \cdot 10^{-12}$ | $2.64 \cdot 10^{-13}$ |
| Fe + $B_4C$ | $1.35 \cdot 10^9$ | 38 | 22 | $3.48 \cdot 10^{-12}$ | $1.19 \cdot 10^{-13}$ |
| Fe + $^{10}B$ | $7.10 \cdot 10^9$ | 18 | 20 | $6.06 \cdot 10^{-12}$ | $3.10 \cdot 10^{-13}$ |
| Fe + Ti | $1.40 \cdot 10^9$ | 88 | 10 | $8.57 \cdot 10^{-12}$ | $5.93 \cdot 10^{-13}$ |
| **Fe + Cd** | **$1.10 \cdot 10^9$** | **344** | **85** | **$1.09 \cdot 10^{-13}$** | **$1.82 \cdot 10^{-13}$** |
| IAEA | > 1 | > 100 | > 20 | $< 2 \cdot 10^{-13}$ | $< 2 \cdot 10^{-13}$ |

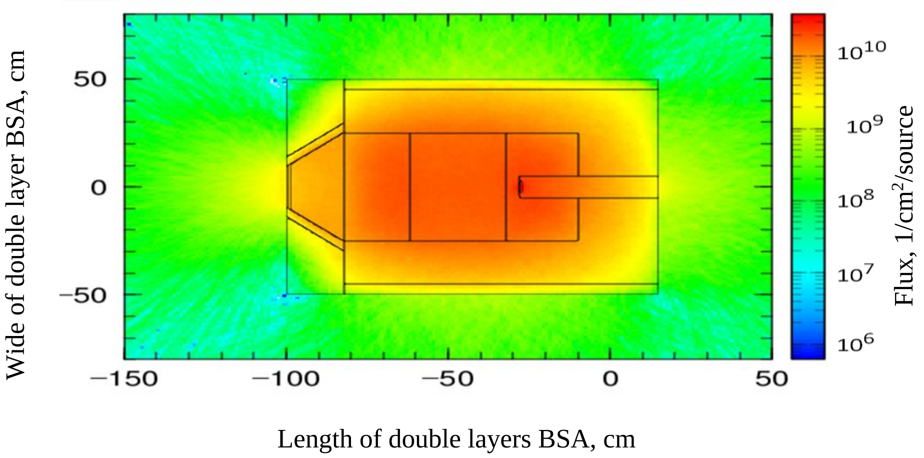

Fig. 4. Distribution of epithermal neutron flux in DLBSA
(See color Figure on the journal website.)

The spectrum of neutron beams produced by double layer BSA is shown in Fig. 5. Based on the figure, the spectrum of neutron beams demonstrates a narrow curve that peaks at 10 keV. It indicates that neutron beams leaving the end of the collimator (aperture) is dominantly epithermal neutrons. Such energy of neutrons is required for BNCT of deeply located cancer [21].

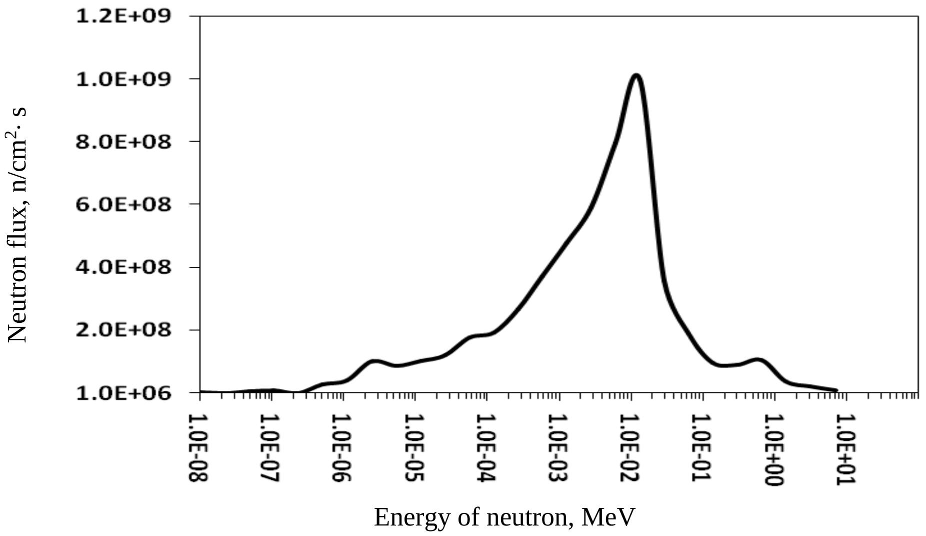

Fig. 5. The spectrum of neutron flux computed on the aperture surface.

The epithermal neutron flux produced by the DLSBA using iron and cadmium filter is $1.1 \cdot 10^9$ n/(cm$^2$·s). The ratio of epithermal neutron flux to fast neutron flux and thermal neutron flux are found to be 344 and 85. The values of the fast neutron and gamma dose to the epithermal neutron flux are found to be $1.09 \cdot 10^{-13}$ Gy·cm$^2$ and $1.82 \cdot 10^{-13}$ Gy·cm$^2$. The parameter of the neutron beam that is obtained is better than that of other workers, the epithermal neutron flux value of which is between $10^8$ and

$10^9$ n/(cm$^2$·s) [22] and $1.6\cdot10^8$ n/(cm$^2$·s) [23]. The dose of the contaminant of fast neutrons and gamma to the epithermal neutron flux is $5.56\cdot10^{-13}$ Gy·cm$^2$ and $1.0\cdot10^{-13}$ Gy·cm$^2$ [22]. The result shows that the intensity and quality of the neutron beam the DLSBA has generated leads to an agreeable neutron beam. It is highlighted by its high epithermal neutron flux and low entailing contaminants.

The parameters of neutron beam resulted by the DLBSA are in accordance with the IAEA standard. It shows that the double-layer configuration at each component, i.e. the moderator (aluminum and $BiF_3$), the reflector (lead and graphite), the collimator (nickel and polyethylene borate), and the filter (iron and cadmium) are able to optimize the function of the BSA.

## 4. Conclusion

A Double Layer Beam Shaping Assembly (DLBSA) was designed using the MCNPX code and its corresponding particle distribution in the DLBSA is analyzed using the PHITS code. Neutron source for the BSA is a 30 MeV cyclotron, and the component of the BSA comprises of a moderator, a reflector, a collimator, and a filter to provide neutron beam parameters suitable for BNCT of deep-seated tumors. Optimization results relating to various combinations of composing materials for moderator, reflector, collimator and filter that yield the best quality and intensity of radiation beams for BNCT are the following: the moderator is made of aluminum and $BiF_3$ material, the reflector is made of a combination of lead and graphite material, the collimator is made of a combination of nickel and polyethylene borate, and the filter is made of a combination of iron and cadmium material. The beam parameters produced at the end of collimator are epithermal neutron flux of $1.1\cdot10^9$ n/(cm$^2$·s), the ratio of epithermal to thermal neutron flux and epithermal to fast neutron flux of 344 and 85, respectively, and the ratio of fast neutron and gamma dose to epithermal neutron flux of $1.09\cdot10^{-13}$ Gy·cm$^2$ and $1.82\cdot10^{-13}$ Gy·cm$^2$ for accelerator proton beam current of 1 mA. Analysis of particle distribution using the PHITS code reveals that epithermal neutron distribution spreads throughout the DLBSA. The highest intensity is found in the moderator and decline having passed through collimator and filter. The magnitude of epithermal neutron flux at the exit of the collimator (aperture) is more than $1.0\cdot10^9$ n/(cm$^2$·s), with epithermal neutrons dominantly of 10 keV in energy. Such energy is appropriate for BNCT therapies treating deeply located cancers.

We thank the Ministry of Research, Technology and Higher Education for its BPPDN Scholarships and BATAN for its consent to use the MCNPX and PHITS codes, which allow this research to be conducted.

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## ОПТИМІЗАЦІЯ ТА АНАЛІЗ РОЗПОДІЛУ НЕЙТРОНІВ У ДВОШАРОВІЙ СИСТЕМІ ФОРМУВАННЯ ПУЧКА НА ЦИКЛОТРОНІ 30 МЕВ

Проектування та оптимізація пучка нейтронів за допомогою двошарової системи формування пучка (ДШСФП) проводилися з використанням коду MCNPX. Формування пучка здійснюється з конструкцією, яка зазвичай включає подвійний модератор, рефлектор, коліматор і фільтр. Оптимізація різних комбінацій матеріалів, що входять до модератора, рефлектора і фільтра, забезпечує якість і інтенсивність пучків, що відповідають вимогам бор-нейтронзахватної терапії. Для модератора використовуються алюміній і $BiF_3$, для рефлектора – свинець і графіт, для коліматора – нікель і поліетиленборат, для фільтра – залізо і кадмій. Типовими параметрами пучка, виміряними на виході з коліматора, є потік епітермальних нейтронів $1{,}1\cdot10^9$ н/см$^2$·с, відношення потоку епітермальних нейтронів до потоку теплових і швидких нейтронів відповідно 344 і 85, а також відношення дози від швидких нейтронів і гамма-квантів до потоку епітермальних нейтронів $1{,}09\cdot10^{-13}$ та $1{,}82\cdot10^{-13}$ Гр·см$^2$, відповідно. Аналіз потоку епітермальних нейтронів і спектра пучка нейтронів за допомогою коду PHITS показує, що розподіл епітермальних нейтронів розширюється в ДШСФП. Найбільша інтенсивність спостерігається в модераторі і знижується в коліматорі і фільтрі. Спектр нейтронного пучка має вузький викид із піком при 10 кеВ.

*Ключові слова*: оптимізація двошарового пучка нейтронів, розподіл нейтронів, код MCNPX, код PHITS.

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## ОПТИМИЗАЦИЯ И АНАЛИЗ РАСПРЕДЕЛЕНИЯ НЕЙТРОНОВ В ДВУХСЛОЙНОЙ СИСТЕМЕ ФОРМИРОВАНИЯ ПУЧКА НА ЦИКЛОТРОНЕ 30 МэВ

Проектирование и оптимизация пучка нейтронов с помощью двухслойной системы формирования пучка (ДССФП) проводились с использованием кода MCNPX. Формирование пучка осуществляется с конструкцией, которая обычно включает двойной модератор, рефлектор, коллиматор и фильтр. Оптимизация различных комбинаций материалов, входящих в модератор, рефлектор и фильтр, обеспечивает качество и интенсивность пучков, отвечающих требованиям бор-нейтронзахватной терапии. Для модератора используются алюминий и $BiF_3$, для рефлектора – свинец и графит, для коллиматора – никель и полиэтиленборат, для фильтра – железо и кадмий. Типичными параметрами пучка, измеренными на выходе из коллиматора, является поток эпитермальных нейтронов $1{,}1\cdot10^9$ н/(см$^2$·с), отношение потока эпитермальных нейтронов к потоку тепловых и быстрых нейтронов соответственно 344 и 85, а также отношение дозы от быстрых нейтронов и гамма-квантов к потоку эпитермальных нейтронов $1{,}09\cdot10^{-13}$ и $1{,}82\cdot10^{-13}$ Гр·см$^2$ соответственно. Анализ потока эпитермальных нейтронов и спектра пучка нейтронов с помощью кода PHITS показывает, что распределение эпитермальных нейтронов расширяется в ДССФП. Наибольшая интенсивность наблюдается в модераторе и снижается в коллиматоре и фильтре. Спектр нейтронного пучка имеет узкий выброс с пиком при 10 кэВ.

*Ключевые слова*: оптимизация двухслойного пучка нейтронов, распределение нейтронов, код MCNPX, код PHITS.

Надійшла 02.09.2018
Received 02.09.2018