THE TESTING OF EPITHERMAL NEUTRON BEAMS PRODUCED BY THE DOUBLE LAYER BEAM SHAPING ASSEMBLY (DLSBA) ON A WATER PHANTOM USING PARTICLE HEAVY ION TRANSPORT SYSTEM (PHITS)

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Abstract. Design of double layer Beam Shaping Assembly (DLBSA) has been conducted. A Double Layer Beam Shaping Assembly (DLBSA) is designed to produce epithermal neutrons for BNCT purposes. The model of DLBSA was designed using the Particle and Heavy Ion Transport System (PHITS) in form of a double layer. The each component of the DLBSA, consisting of moderator, reflector, collimator, and filter were made of two materials. The DLBSA design produced the neutron beam with epithermal neutron flux values of 1.29×10^{9} n / (cm^2.s), the ratio of epithermal neutron flux (φ_{epi}) to thermal neutron flux (φ_{th}) and fast neutron flux (φ_{fast}) 705 and 56, and the dose rate ratio fast neutron absorption $\dot{D}_f$ and gamma dose ($\dot{D}_\gamma$) of epithermal neutron flux (φ_{epi}) are 1.51×10^{-13} Gy.cm^2 and 0.25×10^{-13} Gy.cm^2, respectively. The testing of epithermal neutron beams produced by the DLBSA and irradiated on a water phantom shows that epithermal neutron beams transform into thermal neutron upon entering the phantom. The thermal neutron can penetrate the phantom up to 2-8 cm deep. Therefore, the epithermal neutron beams produced by the DLSBA can be utilized for Boron Neutron Capture Therapy (BNCT) therapies of deeper located cancers.

1. Introduction

Boron Neutron Capture Therapy (BNCT) is a method in cancer therapy that causes minimal damage to normal tissues. This method utilizes the ability of Boron to capture neutron beams and subsequently kills cancer cells [1].

In the BNCT, highly lethal energetic particles (α,^{7}Li) are produced after the break up process of ^{11}B nuclei when ^{10}B atom captures a thermal neutron. The decay process of boron–neutron reaction is given below in equation 1 [2]:

$$
{}^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{11}_{5}B^{*} \rightarrow
\begin{cases}
{}^{4}_{2}He + {}^{7}_{3}Li + 2.79\ \text{MeV} & 6.1\% \\
{}^{4}_{2}He + {}^{7}_{3}Li^{*} + 2.31\ \text{MeV} & 93.9\% \\
\quad \hookrightarrow {}^{7}_{3}Li + \gamma(0.48\ \text{MeV}) &
\end{cases}
\tag{1}
$$

The products of this reaction have high linear energy transfer characteristics (α particle is approximately 150 keVμm^{-1},^{7}Li-nucleus is approximately 175 keVμm^{-1}). The path lengths of these particles in tissues are in the range of 4.5–10 μm: hence their energy deposition is limited to the diameter of a single cell.

Nuclear reactor neutron sources have been used for boron neutron capture therapy (BNCT) for a long time since high intensity neutron beams was supplied only by reactors. Furthermore, many of the reactors have been shut down and the number of reactors for BNCT decreases. Only few reactors are constructed recently for BNCT. On the other hand, accelerator-based neutron sources are becoming popular in neutron application fields [3]. Accelerators have several potential advantages in terms of safety, cost, and high neutron flux in the keV range, compared to reactor-based neutron sources for clinical radiotherapy [4].

One of the accelerators used in BNCT is in form of a cyclotron [5]. The resulting neutrons from the cyclotron are regulated such as to comply with the requirement set by the *International Atomic Energy Agency* (IAEA). Based on its criteria, the minimum beam intensity of the epithermal neutrons (1 Ev < E < 10 keV) should be 5×10^8 n.cm^{-2}.s^{-1}, the number for fast neutron (E >10 keV) dose rate per epithermal neutrons flux and gamma dose rate per epithermal neutron flux should be less than 2×10^{-13} Gy cm^2 and the minimum number for the ratio of the epithermal neutrons flux to the thermal neutrons (E <1 eV) flux should be 20 [6]. The part of the cyclotron that is capable of processing the neutron beam is the beam shaping assembly (BSA)**.**

Until now, most efforts for cyclotron-based BNCT have been focused on the design of the BSA, investigating the feasibility of clinical neutron beams having the desired characteristics for patient irradiation. To achieve this, many types of BSA have been designed using Monte Carlo N-Particle (MCNP) code and Particle and Heavy Ion Transport System (PHITS) [7,8]. The design is expected to produce neutrons that meet the IAEA standard of quality.

BSA designs used in neutron sources typically consist of moderator, filter, reflector, and collimator as their main components [9]. Each of the components is commonly designed with a single layer configuration, i.e. they only use one type of material. Such single-layer configuration has a weakness in that the components of BSA are not maximal in processing neutron radiation beams; hence the result is normally not optimal. To overcome the weakness, double layer and even multilayer, configurations have been developed [10]. Such configurations are yet to be optimized, to obtain better radiation beams, and tested, to find if the characteristics of the resulting beams that meet the requirements for BNCT [7,11,12]. In principle there are two ways to find the quality of beams for BNCT, i.e., by assessing their quality in the air and in a water phantom. Assessment of radiation beams in the air is an assessment that complies with the IAEA standard [13]. As for the assessment in a water phantom, the emphasis is on the ability of radiation beams to penetrate the phantom and the dose of neutron sustained by a tumor [14]. A water phantom is typically chosen as the testing material as 70% of the human body consists of water [15]. Indeed, this article reports some results of the testing of epithermal neutron beams produced by the DLBSA on a water phantom.

2. Methods

The proton source is modeled as 30 MeV protons impinging on ^{9}Be target with a diameter and thickness of 5 cm and 0.5 cm, respectively. High-energy neutrons are supposed to originate from ^{9}Be(p,n) reactions [16]. They are subsequently processed using Double Layer beam Shaping Assembly (DLBSA) to yield epithermal neutrons. The configuration of the intended DLSBA is shown in Figure 1, and a three-dimensional model is shown in Figure 2.

The materials used as the moderator in the design of DLBSA are aluminum (Al) and BiF_3. The reason for the selection of Al is their high scattering cross-section. Aluminum has a high cross-section at energies above 10 keV [17].

The materials for reflector are Pb and Ni. They have high density and are able to scatter fast neutron extremely well [8]. C (graphite) is also used as a reflector for its low cost. Apart from being cheap it also has high scattering cross-section and low absorption, particularly at energies above 1 MeV [18].

The collimator component under considerations is made of Ni and FeC materials. Ni is considered to be a stable element when it interacts with neutrons.

For fast neutron filter, FeC materials are used. The effectiveness of Fe as a high energy neutron filter owes to the ability of Fe to inelastically scatter high energy neutrons that pass through Fe. Fe materials are deemed superior in filtering fast neutrons. The ability of Fe to filter fast neutrons derives from its resonant cross-section which is above 10 keV [19].

Thermal neutrons are filtered using a material with high atomic number. Among atoms with high thermal neutrons absorption cross-section is Cd, which is frequently used as a thermal neutron filter. A cross-section of 20.600 barn is reasonably effective to absorb thermal neutrons. [19,20].

The material for shielding is Pb. Having a relatively constant attenuation coefficient, i.e., 0.05 cm^2/g, it can absorb gamma rays with energies of 1-10 MeV [18].

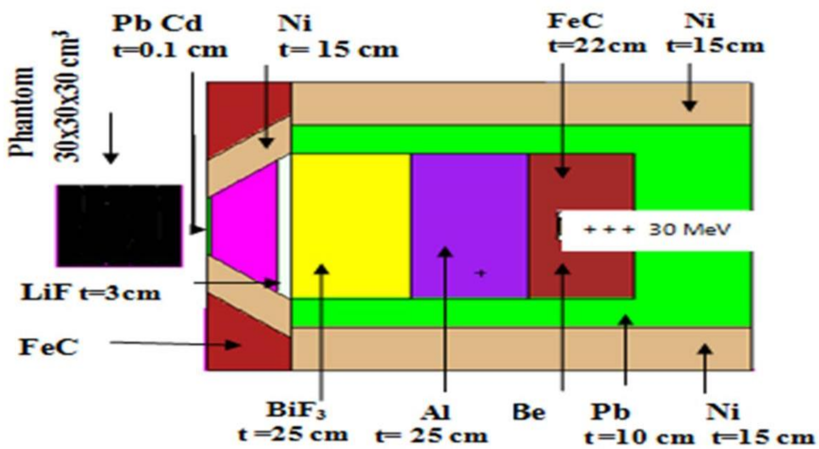

Figure 1. The configuration of DLBSA and water phantom

Epithermal neutrons leaving the DLSBA are subsequently imposed on the water phantom, shaped as a spherical ball, which is placed 1 cm in front of the DLSBA. The composition of the water phantom is 11.2% H atoms and 88.8% O atoms, with a density of 1000 kg/cm^3 [21].

The Particle and Heavy Ion Transport System (PHITS) code was utilized to design of double-layer beam shaping Assembly (DLBSA). These code were then used to calculate the distributions of epithermal neutron in the DLSBA and phantom, as well as testing the penetration of epithermal neutron beams on a water phantom. The track tally used in the PHITS calculation. To draw the particle track and visualize the geometry of DLBS, the ANGEL software used as a 3D-generated visual display. The transport is based on the cross-section data library JENDL-4.0 neutron and intra-nuclear cascade (INCL4.6) for proton [8].

3. Results and Discussion

3.1. Characteristics of Epithermal Neutron Beams from DLBSA

Figure 1 shows DLBSA as a system processing fast neutrons into epithermal neutrons and suppressing contaminants. DLBSA has four main components, i.e. moderator, reflector, collimator, and filter. Each of the components is formed of a combination of two materials. The moderator is formed of Al and BiF_3 materials, the reflector is formed of a combination of Pb and FeC, the collimator is formed of a combination of Ni and FeC, and the filter is formed of a combination of FeC and Cd materials. The use of two materials on every component of DLBSA is intended to enhance the contribution of each material.

Figure 2 shows the distribution of epithermal neutron in the double layer BSA. Epithermal neutrons are resulted from moderation of fast neutrons produced from interactions of 30 MeV protons with beryllium target [5]. Highest epithermal neutron fluxes are distributed around FeC filter and AL and BiF_3 moderator. Epithermal neutron flux in the vicinity of moderator and filter reaches 10^{11} n/cm^2.s. The ability of moderator in moderating fast neutrons into epithermal neutrons is accounted for by fluorine (F) in the BiF_3 material and aluminum (Al) as constituting components of the moderator. The effectiveness of Al and BiF_3 in producing epithermal neutron flux is due to Al that has high scattering cross section to energies of above 10 keV [22]. Interactions between neutrons and Al material produce epithermal neutrons through ^{27}Al(n,2n)^{26}Al reactions. With regard to the contribution of BiF_3 in moderating fast neutrons, it is because of the presence of fluorine (F) in the BiF_3 material. Fluorine is an element that has such high scattering cross section to fast neutrons that BiF_3 material also contribute to increasing the number of epithermal neutrons and reducing the number of thermal neutrons. Lastly, Bi contributes to reducing gamma radiations [23].

The quality of increasing epithermal neutrons is also sustained by the presence of the FeC filter placed in front of the moderator as a filter to high energy neutrons. The effectiveness of FeC as a high-energy neutron filter is attributed to the ability of FeC to in-elastically scatter high energy neutrons that pass through FeC material. Fe Material with 4 cm thickness is adequately effective in reducing energy of the order of MeV into that of an epithermal neutron [19].

Figure 3 shows the spectrum of neutron flux produced by the DLBSA calculated at the location of the aperture. The spectrum has a peak at the energy of 10 keV with maximum epithermal neutron flux of 1.0 x 10^9 n/cm^{2}s. Another researcher also found similar value of epithermal neutron flux [24]. Simulation results using the PHITS code suggest the following characteristics of neutron beams with epithermal neutron flux values of 1.29×10^9 n / (cm^2.s), the ratio of epithermal neutron flux (φ_{epi}) to thermal neutron flux (φ_{th}) and fast neutron flux (φ_{fast}) 705 and 56, and the dose rate ratio fast neutron absorption $\dot{D}_f$ and gamma dose ($\dot{D}_\gamma$) of epithermal neutron flux (φ_{epi}) are 1.51×10^{-13} Gy.cm^2 and 0.25×10^{-13} Gy.cm^2, respectively.

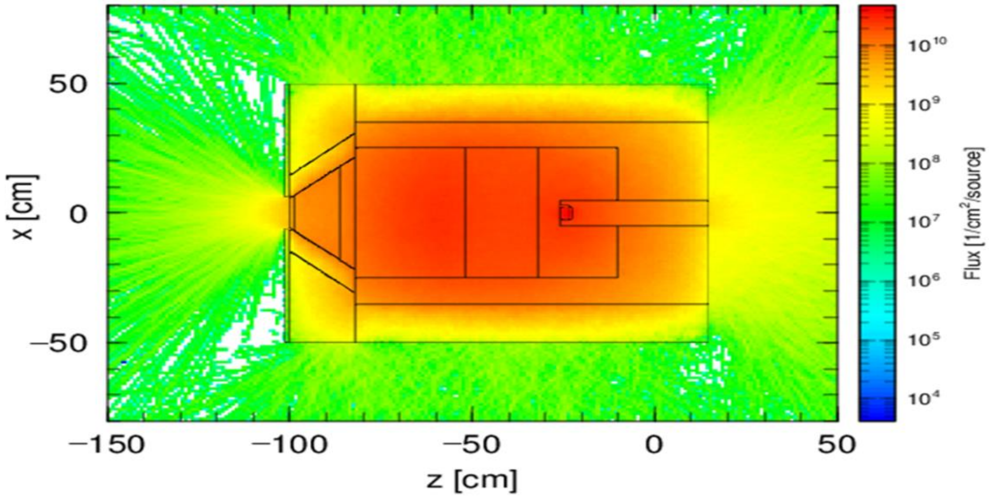

Figure 2: Distribution of epithermal neutron flux in the DLBSA

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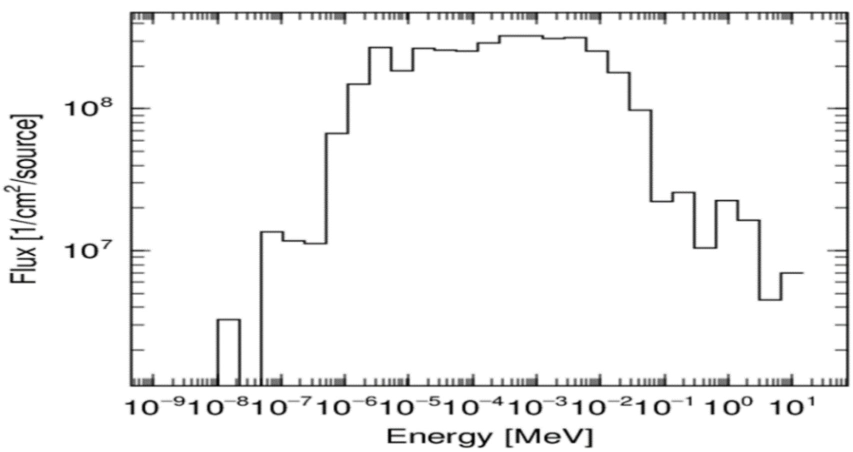

Figure 3: Spectrum of neutron beams at the end of DLBSA

3.2. Epithermal Neutron Flux in Water Phantom

Figure 4 shows the distribution of epithermal neutron in the DLBSA and phantom. Epithermal neutrons that enter the phantom continually decrease in energy (depicted by changes in color from yellow to blue in the phantom). The decrease in epithermal neutron flux is due to epithermal neutrons transforming into thermal neutrons during interactions with hydrogen atoms. This process is called thermalization [25].

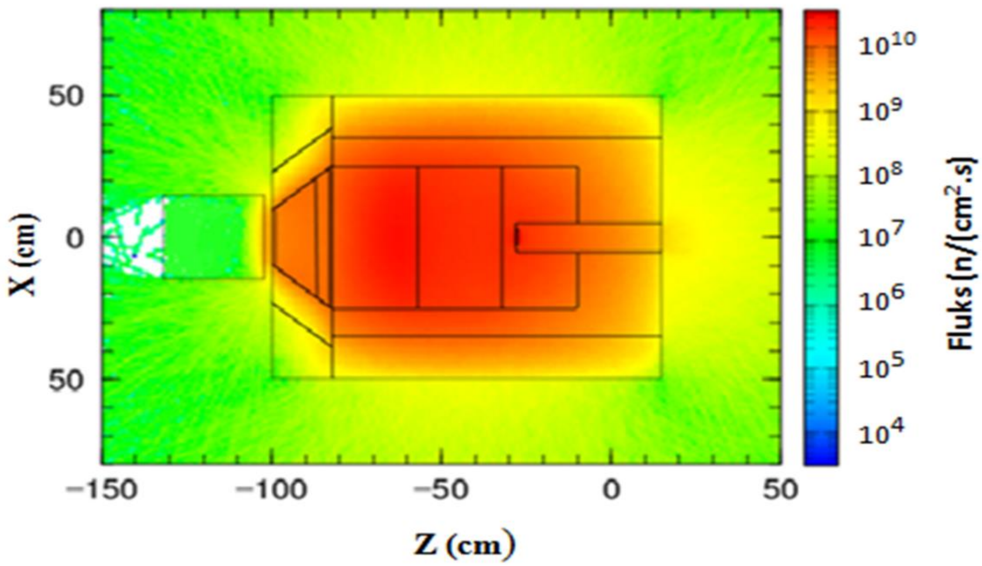

Figure 4. Distribution of epithermal neutron flux in DLBSA and water phantom.

Figure 5 shows thermal neutron flux in water phantom. The maximum value of thermal neutron flux is 1.1×0^9 n/cm^2.s, obtained at 2 cm deep from the surface of the phantom. Other researches also obtain similar result. [12,26]. The further deep epithermal neutron penetrate the phantom, the more increase in thermalization, causing the value of neutron flux to diminish. The value of thermal neutron flux at the depth of 5 cm and 12 cm reduce to 60 and 20%, respectively. The decrease in neutron flux is caused by thermalization of neturons with H. Such values of neutron flux are still acceptable as neutron source for therapies of deeply-located cancer [27].

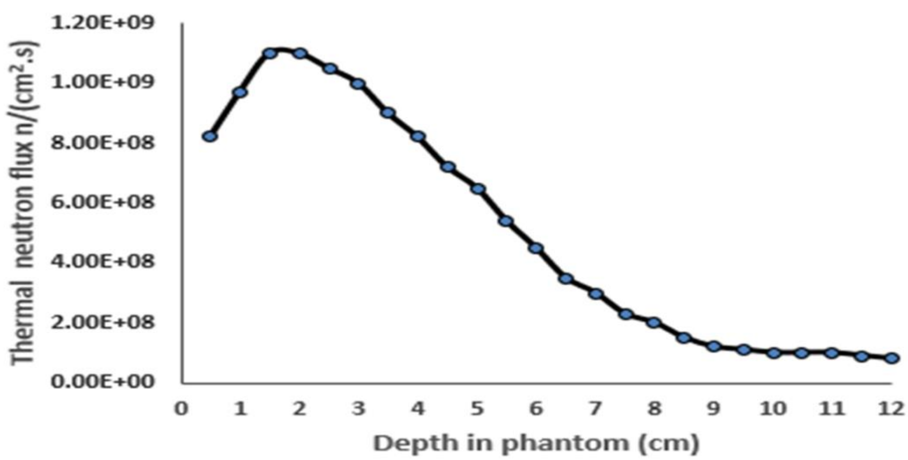

Figure 5. Neutron absorbed characteristic in water phantom.

Based on the characteristic of neutron in the phantom, the neutron beams produced by the DLBSA can be considered for neutron source for BNCT, particularly for therapies of cancer situated at 2-8 cm depth. Some of the types of cancers that can be treated using the neutron source are head and neck cancer, glioblastoma, lung cancer, breast cancer, pancreas, brain tumor and sarcoma [28].

4. Conclusion

A double layer beam shaping assembly is designed to produce epithermal neutrons for BNCT purposes. The spectrum of neutron beams calculated at the location of the aperture has the following characteristics: the epithermal neutron flux values of 1.29×10^9 n / (cm^2.s), the ratio of epithermal neutron flux (φ_{epi}) to thermal neutron flux (φ_{th}) and fast neutron flux (φ_{fast}) 705 and 56, and the dose rate ratio fast neutron absorption $\dot{D}_f$ and gamma dose ($\dot{D}_\gamma$) of epithermal neutron flux (φ_{epi}) are 1.51×10^{-13} Gy.cm^2 and 0.25×10^{-13} Gy.cm^2, respectively. The testing of epithermal neutron beams on a water phantom shows that epithermal neutron beams transform into thermal neutron upon entering the phantom. The thermal neutron can penetrate the phantom up to 2-8 cm deep. The characteristics of neutron beams produced by the DLBSA suggest that they are adequate as neutron source for BNCT, particularly for therapies of deeply-located cancers.

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