

Investigating a proton beam-based neutron source for BNCT using the MCNP simulation

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Abstract. Works in this project are focused on the design and optimization of a beam shaping assembly (BSA) for boron neutron capture therapy (BNCT) based on a 30 MeV proton beam generator. The aim was to maximize the epithermal neutron flux and to prevent the background radiation which are required for the BNCT designation. A set of material and geometry simulations of neutron multiplier, moderator, reflector, and collimator was examined. The final configuration consists of 0.5 cm of beryllium as a p-n converter, 15 cm in radius of uranium as a neutron multiplier, 44 cm of TiF_3 and 15 cm of Al_2O_3 as a first and second layer of moderator, 10 cm thickness of lead as a reflector, and lithium polyethylene as a collimator. According to the results of the calculation, the proposed cylinder BSA provides high epithermal neutron flux at the irradiation area.

1. Introduction

The Boron Neutron Capture Therapy (BNCT) is a technique with a high biological effectiveness and a promising therapeutic treatment of cancer. In BNCT, the ^{10}B is introduced into the cancer cell. Afterward, the neutron provided by a neutron source can induce $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction, and the resulting α particles can kill cancerous cells. The epithermal neutron is used due to efficient penetration in the human body. According to the recommendation of the International Atomic Energy Agency (IAEA), a high epithermal neutron flux of $\sim 0.5 - 1.0 \times 10^9 \text{ n cm}^{-2} \text{ s}^{-1}$, $\phi_{\text{epi}}/\phi_{\text{fast}} > 20$ and $\phi_{\text{epi}}/\phi_{\text{thermal}} > 100$ are required to complete the treatment [1, 2]. Different neutron sources such as a nuclear reactor, D-T neutron generator, proton accelerator, etc. are commonly used in the BNCT system. The nuclear reactor provides the required high epithermal neutron flux but the reactor is expensive and difficult to be realized in/near a hospital. Thus, the compact neutron generator based on a proton beam accelerator becomes a candidate for the BNCT system [2–5]. The design of the proton beam-based neutron source for the BNCT consists of the proton-neutron converter and the beam shaping assembly (BSA). The neutrons are produced through the (p, n) reaction by the proton beam stopped in thick targets of different materials such as tantalum [2], beryllium [6–8], lead [8] and carbon [4], etc. A wide range from low- to high- proton beam energy of 5 MeV to 600 MeV is used to irradiate the material targets. However, most of the neutrons source (based on nuclear reactor and D-T neutron generator) and the generated neutron from proton-neutron converter (based on a proton beam accelerator) have high energy in the range of fast neutron. To fulfill the recommended BNCT designed, by IAEA, the high epithermal neutron flux is needed. Therefore, the BSA which consist of neutron

multiplier, neutron moderator, reflector and collimator is designed to multiplier the number of neutron flux and to moderate the high energy neutron.

In this work, the appropriate design of proton beam-based neutron source for BNCT is studied. The neutronics calculations have been carried out using a Monte Carlo code MCNP[9]. The investigation medium-proton energy at 30 MeV is considered for the beryllium target. A suitable BSA and collimator for the high epithermal neutron flux are considered in this article. Additionally, the neutron energy deposition in the soft tissue is reported.

2. The proton-based neutron source design and result

Work in this paper deals with the design of a new cylinder BSA configuration based on a proton beam-based neutron source. Fast neutrons can be generated by the interaction of a proton beam with a thick target (so-called converter) in which the protons are completely stopped. The stopped length of a mono-energetic proton beam of 30 MeV in a beryllium target has been theoretically calculated as 0.425 cm. Moreover, the previous work in Ref.[10] shows that the neutron production is not effected by the target thickness.

A series of MCNP models have been set and a neutron production of the converter was calculated. Therefore, a 0.5 cm thick beryllium target (100% abundance of ^9Be) is used as the converter in this work. At 0° angular distribution, a wide range of neutron energy spectrum between zero and the incident proton energy (30 MeV) is produced due to a known reaction such as $^9\text{Be}(p,n)^9\text{B}$, $^9\text{Be}(p,p'n)^8\text{Be}$, $^9\text{Be}(p,pn\alpha)\alpha$, etc.[11] as shown in figure 1. As can be seen in the neutron spectrum, the ~ 1.6 MeV neutron peak is presented due to the smallest neutron binding energy of the ^9Be isotope. The ~ 6.8 MeV neutron peak is presented due to the first excited states neutron (p,n_1). The neutron spectrum calculated in this work agrees to the measurement one in Ref.[6]. However, the high energy neutrons (fast neutron) produced from the beryllium target must be moderated by the BSA.

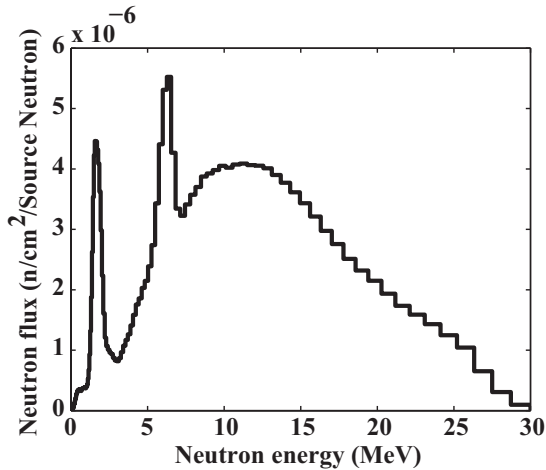


Figure 1. Generated neutron spectrum from the beryllium target bombarded by the 30 MeV proton beam.

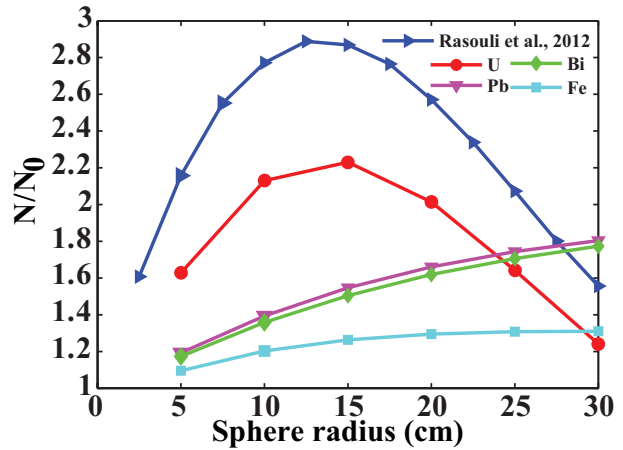


Figure 2. Number of neutron per number of initial neutrons versus different radii of spherical neutron multiplier.

3. The beam shaping assembly design and results

In this work, the new cylinder beam shaping assembly (BSA) is basically designed to generate a high epithermal neutron flux at the BNCT beam port and to reduce background radiation (thermal neutron, fast neutron and γ -rays). The design and optimization processes have been investigated for different materials and geometry configuration of the BSA system using the MCNP code. The uniform proton source (disk source) is applied in the model. It is placed

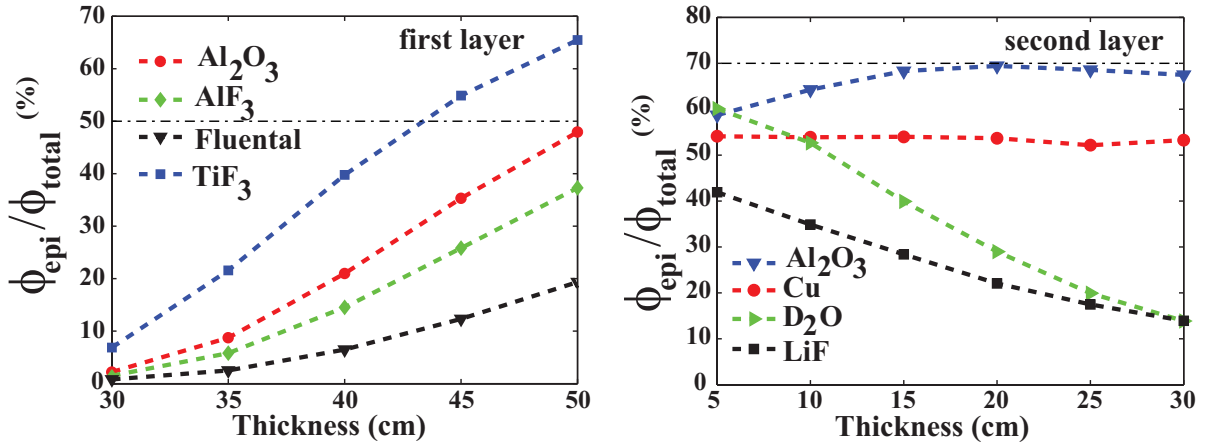


Figure 3. The ϕ_{epi}/ϕ_{total} for different thickness and materials as first and second layer of the moderators.

in the front of the p-n converter inside the neutron multiplier. The surface tally is set at the surface of the BSA assembly to measure the neutron flux. In addition, the point detector (F5 tally) is used to measure neutron flux at the end of the BSA collimator. The details of the new BSA structure are discussed in this section.

3.1. Neutron multiplier

The neutron multiplier is placed downstream of the converter. The aim is to increase the number of neutrons emitted from the converter. In Rasouli et al. work [12], it was found that the geometry (cylinder and sphere) played a minor role on the number of generated neutron in the neutron multiplier material. However, the neutron can be absorbed in the multiplier material. Therefore, to avoid the reduction of the neutron flux in different thickness (of the cylinder), the sphere is preferable. In this work, uranium has been considered as fission target due to its high fission cross section. In addition, the Pb, Bi and Fe have been considered due to the large cross section for the (n,2n) reaction. The sphere was simulated with different thicknesses of 5-30 cm in radius. Figure 2 shows the calculated number of neutron per number of initial neutron on the sphere surface versus its radius for different neutron multiplier materials.

The results in figure 2 show that by using the uranium with radius of 15 cm as a neutron multiplier, number of neutron per number of initial neutron (N/N_0) increases approximately two times where N is the number of generated neutron from the neutron multiplier and N_0 is the number of initial neutron generated from the p-n converter. However, the low energy neutron is absorbed when it passes through the multiplier material as can be seen the decreasing of N/N_0 at the higher radius of the uranium. Thus, the number of multiplied neutrons is lower than that generated from using fast neutrons from a neutron source, as reported by Rasouli et al. [12]. Additional, the number of neutrons per neutron source increased by increasing the radii of Pb, Bi and Fe which provide the maximum ratio at a radius of 30 cm for each material but lower than that using the uranium. Therefore, we choose a sphere of uranium with a radius of 15 cm due to the N/N_0 ratio reaching its maximum value.

3.2. Moderator

Two layers of the moderator have been designed in order to reduce the energy of fast neutrons generated by the neutron multiplier to the epithermal neutron. A series of MCNP simulations was performed to optimize the best material and thickness of the first and the second layer moderators. Four materials (Al₂O₃, AlF₃, Fluental, and TiF₃) with different thickness between 30 and 50 cm are determined as the first layer. Figure 3(left) shows the obtained ratio of epithermal neutron flux to total neutron flux (ϕ_{epi}/ϕ_{total}) of the first moderator materials. The

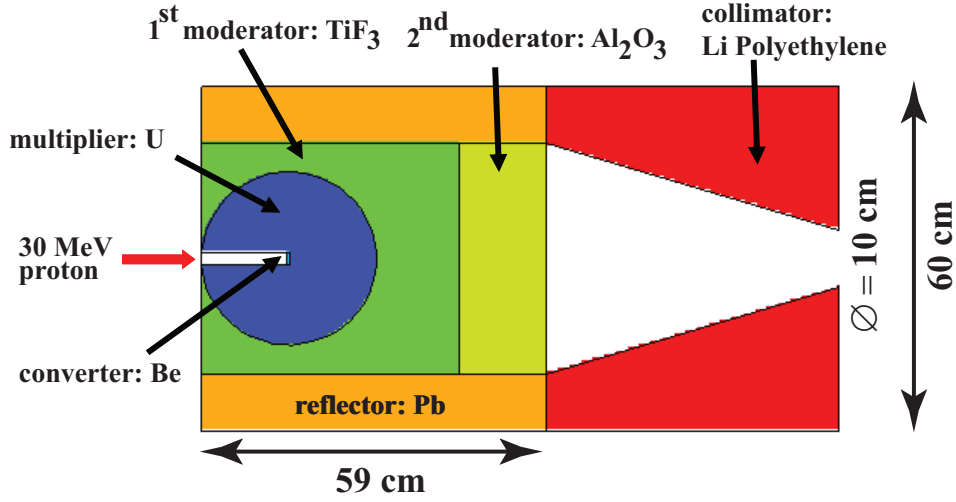


Figure 4. Cross section view of the designed BSA configuration based on a proton beam generator.

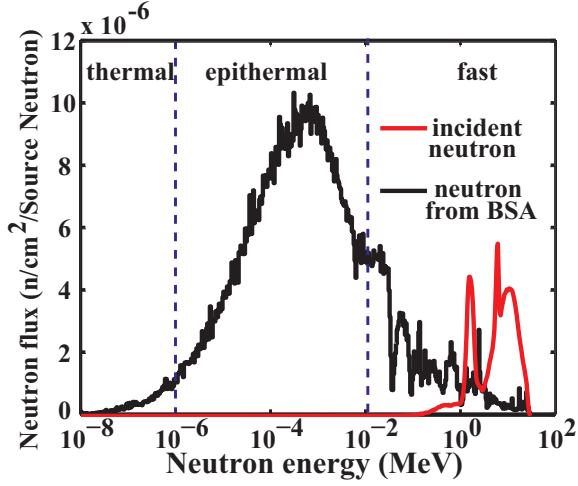


Figure 5. The neutron spectrum at the end of the designed BSA.

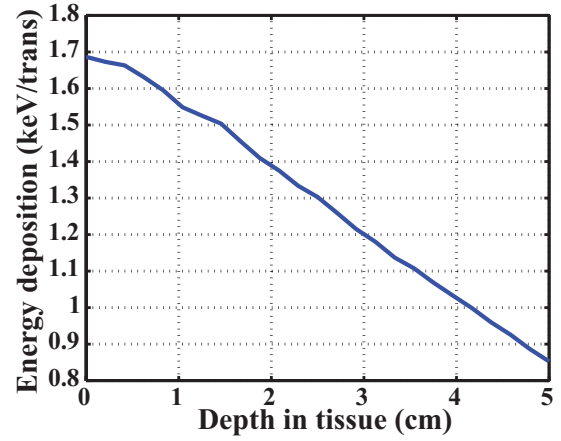


Figure 6. Energy deposition per transformation for different depths of simulated soft tissue.

44 cm of TiF_3 is selected in this work due to a 50% increase of the epithermal neutron flux. A second moderator material was added next to the 44 cm thick TiF_3 . Four different materials (Al_2O_3 , Cu, D_2O , and LiF) are considered. As can be seen in the results in figure 3(right), a Al_2O_3 moderator provides the highest $\phi_{\text{epi}}/\phi_{\text{total}}$ of 70% for the thickness above 15 cm and is considered to be the best material for the second layer of the moderator.

3.3. Reflector and collimator

The high elastic scattering and low absorption cross section materials have been considered as the reflector to capture the neutron from moderator. In this work, lead, beryllium oxide (BeO), and boranyloxyboron (B_2O) with the thickness of 10 cm have been tested as reflectors to determine their reflective capabilities. Due to the calculation results, lead has been used as a reflector due to it having the highest capabilities to generate epithermal neutron flux. In addition, a 50 cm length of lithium-polyethylene has been selected to be used as a neutron collimator. It is used to focus the output epithermal neutron beam from the BSA toward the soft tissue phantom.

Table 1. The elemental composition of a soft tissue [9].

Elements	Atomic fraction (%)
Hydrogen	10.454
Carbon	22.663
Nitrogen	2.49
Oxygen	63.525
Sodium	0.112
Magnesium	0.013
Silicon	0.03
Phosphorus	0.134
Sulfur	0.204
Chlorine	0.133
Potassium	0.208
Calcium	0.024
Iron	5e-3
Zinc	3e-3
Rubidium	1e-3
Zirconium	1e-3

4. Discussion

The schematic of the final configuration of the converter and BSA assembly is shown in figure 4. Figure 5 shows the neutron spectrum at the end of the collimator. It can be seen that by using the designed BSA, fast and thermal neutrons are decreased while epithermal neutrons are increased. With the commercial 30 MeV proton beam accelerator, the designed converter and BSA in this work generated epithermal neutron about 1.4 times higher than that presented in Ref.[3].

Moreover to estimate the BSA neutron beam performance, the energy deposition in the soft tissue with the density of 1.04 g/cm^3 was investigated in this work. The elemental composition of a soft tissue in the model shows in table 1. Figure 6 shows the total neutron energy deposition per transformation for different depth in soft tissue. The results show that, the energy deposition is higher than 1 keV per transformation up to 4 cm depth in soft tissue.

5. Conclusion

The Monte Carlo code MCNP was used with intention to optimization design parameters for a BNCT facility based on a proton beam generator. According to the MCNP simulations, the combination of 0.5 cm thick of beryllium as a p-n converter, 15 cm in radius of uranium as a neutron multiplier, 44 cm thick of TiF_3 and 15 cm thick of Al_2O_3 as a first and second moderator layers, 10 cm thick of lead as a reflector and 50 cm length of lithium-polyethylene as a collimator is considered as the best dimension for the cylinder BSA system. The designed in this work supplies epithermal neutron fluxes and reduces the background radiation (fast neutron and γ -rays) at the BSA output or the irradiated area. However, the proposed BSA in this work did not satisfy all the recommended design parameter criteria but it has the best epithermal neutron flux production for the BNCT facility based on the proton beam generator.

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