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# Efficiency of the layered BSA model for BNCT of deep tumors based on photoneutron sources

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HIGHLIGHTS

- Photoneutron sources of 25 MeV and 30 MeV have been considered for BNCT of deep tumors.
- A layered reflector/moderator BSA model has been designed to be used for electron linac photoneutron sources.
- The IAEA criteria have been considered to optimize the BSA cells.
- The results show considerable effect of the layered model on improving the in-air parameters for photoneutron sources.

ABSTRACT

Due to the selectively treating tumors and largely sparing normal neighboring cells, Boron Neutron Capture Therapy (BNCT) continues to be of special significance and interest for wide groups of researchers. One of the most important challenges in this context is to design an optimized beam based on an appropriate neutron source. The recent studies, focused on investigating neutron sources as alternatives for nuclear reactors, revealed the high potential of electron linac-based photoneutron sources to improve the efficiency of this treatment method. Inquiring about the efficiency of a layered model of beam shaping assembly (BSA) for photoneutron sources to be used in BNCT of deep tumors is the main subject of this simulation study. This model, unlike the traditional BSA in which the reflector surrounds the whole moderator, includes many concentric cylinders of reflectors and moderators. The MCNPX simulations for various primary energies show that the layered model results in more appropriate beam characteristics compared with that of the common geometry. Moreover, the parameters governing the beam properties such as the thickness of the layers, moderator/reflector and collimator lengths, and the thickness of the surrounding reflector have been investigated. The results are encouraging and offer new ways to accomplish more researches in studies on the BNCT technique.

KEYWORDS
BNCT
Photoneutron source
BSA designing
IAEA criteria
Monte Carlo simulation

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## 1 Introduction

The underlying principle of Boron Neutron Capture Therapy (BNCT), as one of the prominent methods for treatment of tumors, is straightforward. It is based on delivering thermal neutrons to the cancer cells which contain much more B-10, the boron stable isotope with a large cross-section for absorption of them, than those of the surrounding healthy cells. Due to the interaction of neutrons with B-10, high-energy particles are produced that, in principle, can deposit their energy into the cell and kill them. Though the healthy surrounding tissues receive a lower dose because of the lower concentration of B-10, perfect sparing of these tissues is not possible in real treatment. It is mainly because of unwanted doses due to the proton recoil reaction of fast neutrons, the dose due to the thermal neutron capture by nitrogen, and the dose due to the primary and secondary generated gamma rays. These undesired doses need to be managed so that do not exceed the maximum allowable dose to the healthy tissues. To control the treatment quality, there are two set of criteria that should be satisfied: The criteria for the performance of the beam in the phantom/patient's body, and the criteria for the beam befor reaching the tissue. The IAEA has recommended a set of parameters (IAEA, 2001), known as in-air parameters, that can be considered as the criteria in designing the beam for the BNCT method. As a result, one of the key steps to reach an acceptable treatment is to design an appropriate beam shaping assembly (BSA) to deliver low neutron and gamma contaminations to the tissue.

There are worthy documents devoted to the design and

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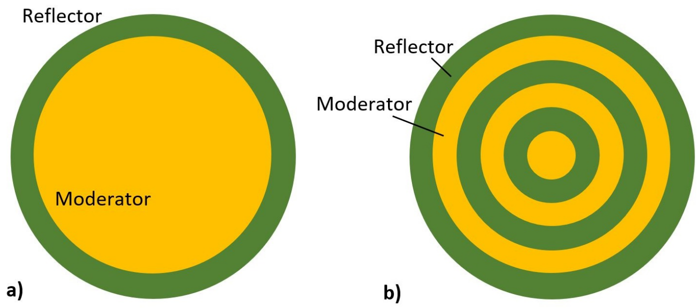


**Figure 1:** The schematic cross-sectional view of the models suggested for BSA. a) the traditional geometry. b) The layered reflector/moderator model.

optimization of BSAs based on various suggested neutron sources including nuclear reactors (Kasesaz et al., 2014; Kiger III et al., 1999), fusion D-D and D-T reactions (Durisi et al., 2007; Cerullo et al., 2002; Rasouli and Masoudi, 2012), accelerator-based sources (Ganjeh and Masoudi, 2014; Yue et al., 1997; Capoulat et al., 2011), and photoneutron electron linac-based sources (Rahmani and Shahriari, 2011; Torabi et al., 2013, 2014; Pazirandeh et al., 2011; Masoudi et al., 2018). Because of different properties, a designed BSA for a typical neutron source may not be appropriate for another chosen source. It is important due to the fact that the IAEA criteria cover the parameters to take into account both the quality and intensity of the beam. Therefore, not only is the dominant energy of the neutrons in the beam spectrum important, but its intensity also plays a considerable role to be so that the irradiation can be performed in less than 1 hour (IAEA, 2001). However, advantages such as requiring less space, the high safety, ease of operation, and the practical aspects of utilizing the photoneutron sources based on electron linacs have encouraged the researchers to consider them as important potential candidates as neutron sources for BNCT.

In the work presented by Kasesaz et al. (Kasesaz et al., 2015), a reflector/moderator geometry including multilayer and hexagonal lattice designs for a typical neutron source of Watt fission energy spectrum with uniform spatial distribution has been suggested. The results show that these new geometries are more effective compared with the common traditional BSA models which include the reflector layer that covers the moderator(s). The challenge, however, is whether layer design is also effective for photoneutron sources. In the present work, the MCNPX Monte Carlo code (version 2.6) has been used to design a layered reflector/moderator geometry for BSA based on an electron linac-based photoneutron source. The number of layers and dimensions have been optimized based on satisfying the IAEA recommended criteria.The results have been compared with those of traditional BSA designs.

## 2 Materials and Methods

### *2.1 Simulation tool*

Because of its high flexibility and ability to solve problems that deal with the transport of particles in complicated geometries, the Monte Carlo method provides an appropriate tool to simulate the optimized configurations for generating the beam for BNCT of either shallow or deep tumors. In the present work, simulations and particle tracking in the medium are carried out using the well-known Monte Carlo N-Particle eXtended code (MCNPX). The details of the simulations and models we used are as presented in the following subsections. The number of histories in all steps have been chosen so that the uncertainties are less than 2%.

### *2.2 IAEA in-air criteria*

BNCT can be used for either shallow or deep tumors. Owing to that the recommended IAEA in-air criteria are different for treatment of these two types of tumors (IAEA, 2001), knowing the depth of the tumor is important in beam designing. In the present work, the BSA is designed for the treatment of deep tumors, and therefore, the ability to generate epithermal neutrons (1 eV $\leq$ E $\leq$ 10 keV) with the sufficient neutron intensity of larger than $5 \times 10^8$ n.cm$^{-2}$.s$^{-1}$ is vital. Moreover, the target number for fast neutron dose rate and gamma dose rate per epithermal neutron, denoted respectively by $\dot{D}_{fast}/\Phi_{epi}$ and $\dot{D}_{\gamma}/\Phi_{epi}$, is $2 \times 10^{-13}$ Gy.cm$^2$. Also, the ratio of the epithermal neutron flux to the thermal neutron flux, shown by $\Phi_{epi}/\Phi_{thermal}$, should be greater than 20, and the maximum beam size aperture is 12 to 14 cm.

### *2.3 Neutron Source*

In this work, the photoneutron source has been chosen to be used for BSA designing. In such sources, the incidence of accelerated electrons to the appropriate high-Z target leads to the generation of a cascade shower of lesser-energy electrons and photons. W, Pb, Ag, Re, Ta, and Th are a number of suggested materials to be responsible for $(e, \gamma)$ reaction (Rahmani and Shahriari, 2011; Torabi et al., 2013, 2014; Jallu et al., 1999; Eshwarappa et al., 2005). The generated photons incident a second target, known as photoneutron target or photon converter, to generate neutrons. Among a number of materials investigated in published studies, tungsten is the most appropriate candidate to be responsible for $(\gamma, n)$ reaction (Torabi et al., 2013).

With the aim of avoiding complicated designing for targets, in a previously published work (Masoudi and Rasouli, 2015), we have shown that tungsten has the potential to be used as both a photon converter and electron target. Moreover, this cell slows down the produced neutrons toward the desired energy range while keeping their number as constant as possible, the factors that are important for BNCT. Considering these results, the spherical tungsten of 6 cm radius (Masoudi and Rasouli, 2015) has been chosen as the target. The study has been performed for two primary electron energies of 25 and 30 MeV. The current of the beam has been considered to be 1 mA.

### *2.4 BSA geometry*

In this work, we have investigated the efficiency of layered model for reflector/moderator in BSA design (Kasesaz et al., 2015), and have compared the results with those of traditionally used geometry. A schematic cross-sectional view of these geometries has been shown in Fig. 1. As typical materials commonly used in BSA designs (Rasouli et al., 2012; Koivunoro et al., 2004), Fluental and Pb have been considered as moderator and reflector, respectively. In order to investigate the effect of the energy of neutrons on the results, these models have been tested for typical isotropic neutron sources with energies ranged between 6 MeV to 14 MeV, with steps of 2 MeV. In both models, BSAs are cylinders with the fixed length of 70 cm, and the radius is 50 cm. In the layered model, the thickness of concentric cylinders is 5 cm.

In the next step, a collimator of 10 cm length has been used to reduce the beam port to a circular surface of 6 cm radius. Figure 2 shows a schematic of this configuration. In order to investigate the effect of the number of layers on the results, the BSAs with the various number of layers, and therefore various thicknesses, have been simulated. These thicknesses range between 0.5 to 30 cm. Moreover, the optimized lengths of the moderators and collimator, and the optimized thickness of the surrounding reflector have been selected. The final results have been compared with some other published works with traditional BSA geometries.

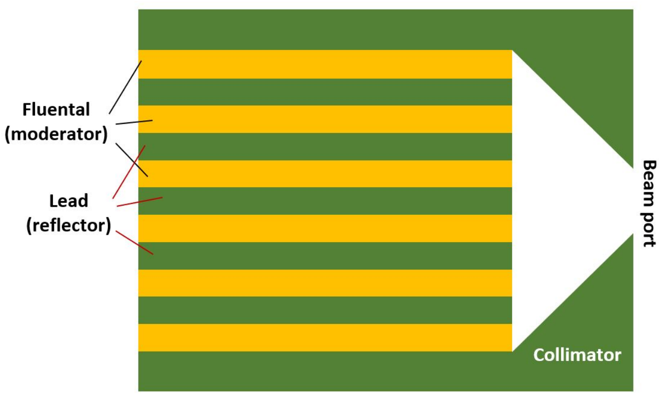


**Figure 2:** The schematic cross-sectional view of the layered reflector/moderator model including a collimator.

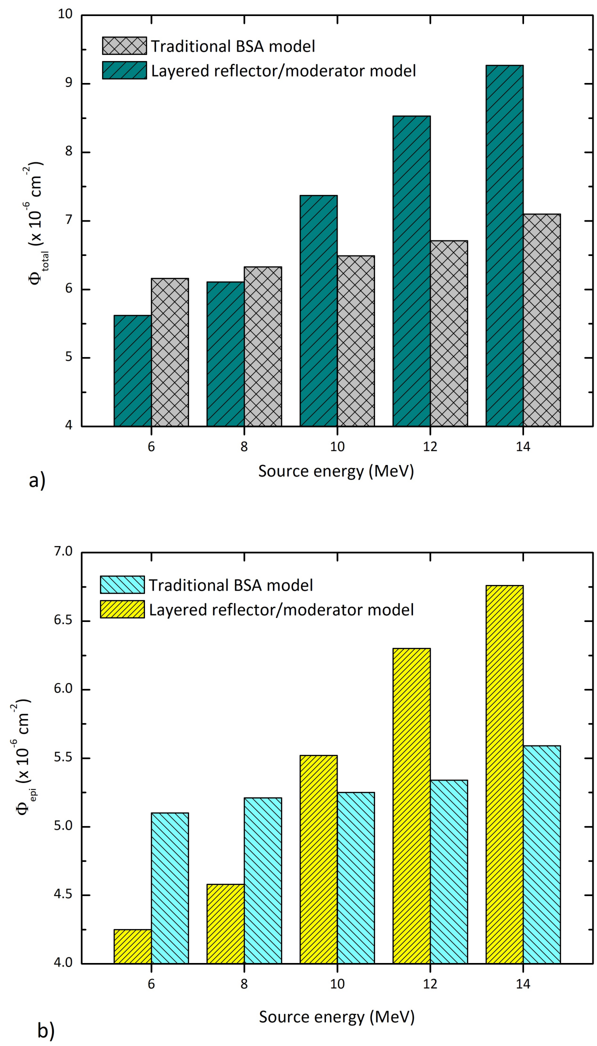


**Figure 3:** a) Total neutron flux, and b) epithermal neutron flux for two suggetsed models as a function of the energies of the typical isotropic neutron sources. The values have been reported per source particle.

## 3 Results and Discussion

Figure 3 shows the epithermal and the total neutron flux for two suggested models as a function of the energies of the typical isotropic neutron sources. The aim was to investigate the sensitivity of the layered model to the energy of the neutron source, regardless of its type. As the results show, the total and epithermal neutron flux corresponding to the layered reflector/moderator model is higher than those of the traditional model for energies greater than 10 MeV. By increasing the neutron source energy, the differences become larger. Strictly speaking, the total neutron flux calculated at the beam port of the layered model deviates from that of the traditional model by about 13.5% and 30.5% for the primary energies of 10 MeV and 14 MeV, respectively (Fig. 3-a). According to Fig. 3-b, these values are about 5% and 21% for epithermal neutron flux. Moreover, increasing the beam energy leads to the increment of the neutron flux in the layered model so that the epithermal neutron flux corresponding to the primary energy of 14 MeV deviates from that of 6 MeV by about

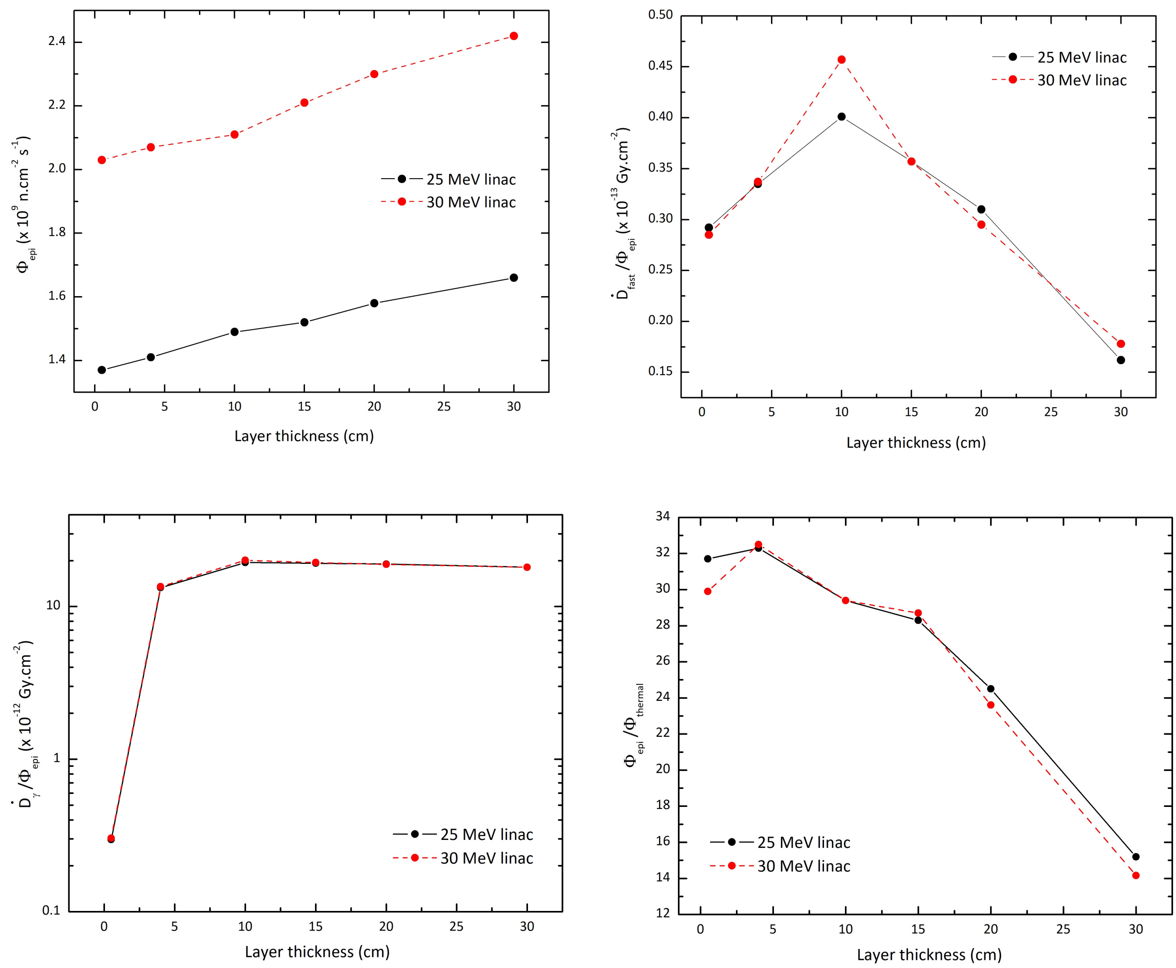


**Figure 4:** The IAEA in-air criteria for various thicknesses of layers in the layered reflector/moderator BSA model for two different 1 mA primary electron beams of 25 MeV and 30 MeV. The lines are to guide eyes.

60%. This deviation is 9.6% for the traditional model. It can be inferred that the layered model can be considered as an appropriate choice for sources with higher energies.

Figure 4 shows the IAEA criteria for various thicknesses of the cylinders in the layered reflector/moderator model (See Fig. 2) for two different 1 mA primary electron beams of 25 MeV and 30 MeV. To select the optimized thickness, all these factors should be taken into account. Though the results show that for both linacs, the epithermal neutron flux decreases by the increment of the layer thickness, it can be found that $\dot{D}_\gamma/\Phi_{epi}$ and $\Phi_{epi}/\Phi_{thermal}$ decrease. Therefore, a trade-off between the larger beam intensity and the smaller beam contaminations should be considered. For example, for primary energy of 25 MeV (30 MeV), the epithermal neutron flux for thickness layer of 0.5 cm decreases by only about 17.5% (16.1%) compared with that of 30 cm thickness. However, $\dot{D}_\gamma/\Phi_{epi}$ increases about 98.4% (98.3%) by increment the layer thickness from 0.5 cm to 30 cm for 25 MeV (30 MeV) linac. Moreover, $\Phi_{epi}/\Phi_{thermal}$ for 0.5 cm layer thickness is 108.5% (111.1%) larger than that of 30 cm for beam energy of 25 MeV (30 MeV). Therefore, to consider the overall effect of these criteria, the layered model with 0.5 cm thickness has been chosen.

In order to find the optimized length of the reflector/moderator in this model, different values have been investigated. Table 1 presents the calculated IAEA criteria at the beam port for lengths of 40 to 55 cm for two given primary electron energies. According to these results, 55 cm has been chosen as the optimized length for both energies. It is worthy to note that the larger thicknesses do not improve the desired IAEA criteria significantly, and therefore, have not been reported in the table.

The collimator length is also an effective factor on the results. Table 2 presents the in-air parameters for three various lengths of this cell. As the results show, the 20 cm length provides the most appropriate values for the ratio of gamma dose rate per epithermal neutron flux. Furthermore, according to the results of the investigation of various thicknesses for the surrounding reflector, the optimized value of 30 cm has been chosen.

Figure 5 shows the schematic view of the final designed configuration. The neutron spectrum at the beam port for two given electron beam energies have been reported in Fig. 6. As the curves show, passing through designed BSA moderates the high energy neutrons of the source and shifts the spectrum to the desired epithermal energy range.

**Table 1:** The calculated IAEA in-air criteria at the BSA beam port of layered model for four reflector/moderator lengths. The primary electron energies are 25 MeV and 30 MeV.

| Electron beam energy | Length (cm) | $\Phi_{epi}$ ($\times 10^9$ n.cm$^{-2}$s$^{-1}$) | $\Phi_{epi}/\Phi_{thermal}$ | $\dot{D}_{fast}/\Phi_{epi}$ ($\times 10^{-13}$ Gy.cm$^2$) | $\dot{D}_\gamma/\Phi_{epi}$ ($\times 10^{-13}$ Gy.cm$^2$) |
|---|---|---|---|---|---|
| 25 MeV | 40 | 1.88 | 55.1 | 0.792 | 6.85 |
| | 45 | 1.60 | 38.7 | 0.530 | 4.22 |
| | 50 | 1.37 | 31.7 | 0.292 | 2.97 |
| | 55 | 1.12 | 24.2 | 0.230 | 2.01 |
| 30 MeV | 40 | 2.74 | 57.6 | 0.805 | 7.07 |
| | 45 | 2.41 | 40.77 | 0.475 | 4.63 |
| | 50 | 2.03 | 29.9 | 0.285 | 3.03 |
| | 55 | 1.69 | 23.7 | 0.187 | 2.40 |

**Table 2:** The calculated IAEA in-air criteria at the BSA beam port of layered model for various lengths of the collimator for two primary electron energies, 25 MeV and 30 MeV.

| Electron beam energy | Length (cm) | $\Phi_{epi}$ ($\times 10^9$ n.cm$^{-2}$s$^{-1}$) | $\Phi_{epi}/\Phi_{thermal}$ | $\dot{D}_{fast}/\Phi_{epi}$ ($\times 10^{-13}$ Gy.cm$^2$) | $\dot{D}_\gamma/\Phi_{epi}$ ($\times 10^{-13}$ Gy.cm$^2$) |
|---|---|---|---|---|---|
| 25 MeV | 10 | 1.12 | 24.2 | 0.230 | 2.01 |
| | 15 | 1.20 | 20.60 | 0.164 | 1.94 |
| | 20 | 1.18 | 20.65 | 0.154 | 1.91 |
| 30 MeV | 10 | 1.69 | 23.7 | 0.187 | 2.40 |
| | 15 | 1.71 | 22.7 | 0.177 | 2.28 |
| | 20 | 1.72 | 21.06 | 0.162 | 2.18 |

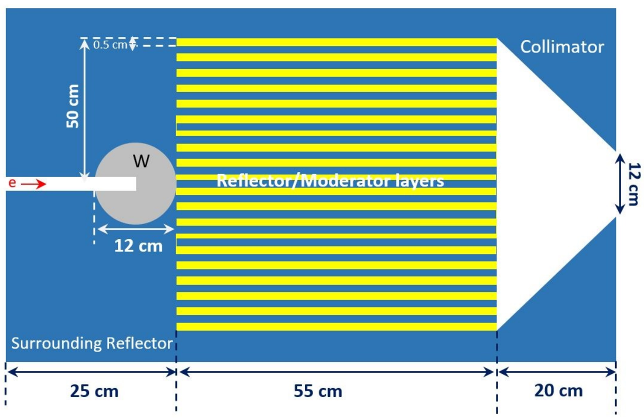


**Figure 5:** The schematic cross-sectional view of the final designed configuration. The dimensions have also been shown.

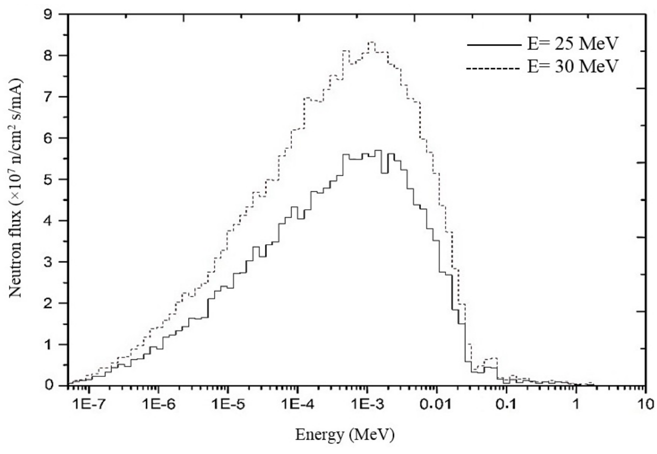


**Figure 6:** The neutron spectrum at the beam port for two primary electron energies.

Table 3 compares the calculated IAEA in-air parameters for the designed configuration based on electron linacs of primary beams of 25 MeV and 30 MeV with those of some other published works with traditional BSAs. According to the results, the optimized layered reflector/moderator model for BSA satisfies all recommended criteria and has the potential to be considered for beam designing for BNCT based on photoneutron sources.

## 4 Conclusion

Among the alternatives for nuclear reactors as neutron sources for BNCT, electron linac based photoneutron sources are the most prominent facilities for in-hospital treatments, minimizing technical complexities. In addition to the appropriate neutron source, achieving a compact, optimized, and geometrically simple BSA configuration is fundamental to generate a standard treatment beam. In the present simulation study, we have managed to investigate the efficiency of the layered reflector/moderator model based on an electron linac for BNCT of deep tumors. The electron target and photon converter have been chosen based on our previously published study (Masoudi and Rasouli, 2015).

The layered model has been tested for two different primary electron energies, and the results have been compared with those of the traditional design for the BSA model in which the reflector surrounds the whole moderator(s). Here we have considered well-known materials of Fluental and lead as typical options for moderator and reflector, respectively. The results show that by increasing the beam energy, the epithermal neutron flux in the layered model increases significantly; quantitatively, the

**Table 3:** The calculated IAEA in-air criteria at the BSA beam port for the designed configuration and some other published works.

| Facility | $\Phi_{epi}$ ($\times 10^9$ n.cm$^{-2}$s$^{-1}$) | $\Phi_{epi}/\Phi_{thermal}$ | $\dot{D}_{fast}/\Phi_{epi}$ ($\times 10^{-13}$ Gy.cm$^2$) | $\dot{D}_\gamma/\Phi_{epi}$ ($\times 10^{-13}$ Gy.cm$^2$) |
|---|---|---|---|---|
| This work (30 MeV-1 mA) linac | 2.31 | 26.8 | 0.157 | 1.78 |
| This work (25 MeV-1 mA) linac | 1.61 | 27.7 | 0.156 | 1.61 |
| Potoneutron source (20 MeV-72 kW) (Rahmani and Shahriari, 2011) | 0.82 | 3830 | 7.98 | 1.18 |
| Potoneutron source (25 MeV-1 mA) (Torabi et al., 2013) | 0.72 | 55.5 | 0.296 | 0.865 |
| Potoneutron source (25 MeV-2.5 mA) (Masoudi and Rasouli, 2015) | 1.06 | 62.5 | 0.395 | 2.23 |
| D-T source ($5 \times 10^{12}$ n.s$^{-1}$) (Rasouli et al., 2012) | 1.04 | 20.2 | 0.67 | 5.79 |

epithermal neutron flux corresponding to the primary energy of 14 MeV deviates from that of 6 MeV by about 60%. However, this deviation is 9.6% for the traditional BSA designing. Moreover, the total neutron flux at the beam port of the layered model from that of the traditional model deviates by about 30.5%. It can therefore be concluded that the results corresponding to the layered reflector/moderator model are encouraging, and can be considered as a potential geometry for BSA designing.

Trying to investigate the parameters governing the beam characteristics for the layered model, various factors have been considered. The results of studying different thicknesses of the concentric cylinders show that while by the increment of the layer thickness, the desired epithermal flux increases, two other important parameters of $\Phi_{epi}/\Phi_{thermal}$ and $\dot{D}_\gamma/\Phi_{epi}$ get worse. Therefore, by taking into account a trade-off between the acceptable intensity and higher beam quality, the thickness of 0.5 cm has been chosen. Moreover, by examination of various lengths for the moderator/reflector and the collimator as well, the optimized values of 55 cm and 20 cm have been chosen, respectively. The thickness of the surrounding reflector has also been optimized.

The IAEA in-air parameters are convenient factors for estimating the performance of the designed beam for BNCT. These parameters have been calculated for the final designed BSA, and have been compared with those of other related published works. The results exhibit the considerable effect of using the new geometry model on improving the in-air criteria for electron-linac based sources. It is worthy to mention that the present results can be extended to simulation of a wider span of moderator and reflector materials, and other possible neutron sources to accomplish more researches in simulation-based studies on the BNCT beam designing.

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