COMPARISON STUDY OF BERYLLIUM AND LITHIUM TARGET SYSTEM FOR BEAM SHAPING ASSEMBLY USED IN BORON NEUTRON CAPTURE THERAPY

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Abstract

Boron neutron capture therapy (BNCT) is a selective targeting cancer therapy method which is by radiating epithermal neutron beams to a tumor which has been injected by boron-10 compound. The implementation of this method requires 2 (two) key elements, namely the boron-10 compound and the irradiating neutron beam of epithermal energy level. The neutron source used in this research was 13 MeV 1mA cyclotrons which have been developed by Indonesia National Nuclear Energy Agency. This paper was preoccupied in beam shaping assembly (BSA) target system. BSA target system is used to convert the proton produced by cyclotron into neutron. IAEA generated a recommendation for BNCT neutron beam quality, one of them was epithermal neutron flux which is higher than 10^9 n/cm^2. To fulfill this requirement it is definitely crucial that the neutron flux in the target system produces the possible highest neutron flux before moderation. In this paper, simulation was conducted to find the best target system and thickness for cyclotron 13 MeV that can produce the highest neutron flux before moderation using MCNPX. From the simulation, beryllium was evidenced to yield higher neutron flux compared to lithium. Beryllium neutron flux peaked at 1250 μm with neutron flux of 4.87E+12 n/cm^2 and lithium neutron flux peaked at 4000 μm with flux of 3.53E+12 n/cm^2.

Keywords: bnct, cyclotron, beam shaping assembly, target, mcnpx.

Presenting Author's biography

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1. Introduction

Cancer is the second most common cause of death in the world after heart disease. From the data published by International Agency for Research on Cancer (IARC) in 2012, there were 14 million new cases of cancer per year [1]. This data indicated a significant increase of new cases compared to those in 2008 of 12.7 million new cases with 7.6 million total number of death in the world [2, 3].

Despite the increasing number of the case, several methods of cancer treatment have been developed enormously including surgery, brachytherapy, chemotherapy, and radiotherapy. Surgery is the oldest and most common method used to treat cancer. This method is considered to be effective, because the cancerous tumor can be removed completely from the patient body, yet there are several cases where this method cannot be applied. The risks and potential side effects of surgery can cause huge deterrents, for example, when the tumor is located around critical organ such as brain or main blood vessel. Apart from that, there is a possibility of the remaining cancerous cells in the patient's body. As a result, after surgery the patient is usually given an adjuvant therapy with radiotherapy and chemotherapy as an option [4, 5, 6].

Unfortunately, the adjuvant therapy methods of radiotherapy and chemotherapy have a considerable flaw. They are inadequately selective in killing the cancer cells as they destroy both cancer cells and healthy cells in the body [7, 8, 9]. Nevertheless, a new selective targeting cancer treatment method is being developed around the world called **Boron Neutron Capture Therapy** (BNCT).

$$^{10}_{5}B + ^{1}_{0}n_{th} \rightarrow \begin{cases} ^{4}_{2}He(1.47MeV) + ^{7}_{3}Li(0.84MeV) + \gamma(0.48MeV) & (93.7\%) \\ ^{4}_{2}He(1.78MeV) + ^{7}_{3}Li(1.01MeV) & (6.3\%) \end{cases}$$

Fig. 1 BNCT reaction inside cancer cell

BNCT is a cancer therapy method working by radiating epithermal neutron beams to a tumor which has been injected by boron-10 compound. When the boron-10 that accumulates in the cancer cells inside tumor capture the epithermal neutron, it then quickly transformed into boron-11 and disintegrates into alpha particle and recoiling lithium nuclide that has a high linear energy transfer (LET). This reaction can be seen in detail on fig. 1. The destructive effects of these high energy particles are only limited into the cells that contain boron-10. These two particles deposit their energy in a range of about 5-9 µm which is in the same with a one cell dimensions (<10 µm). This method can accurately kills cancerous cells in the body without damaging any other healthy cells [10, 11]. The irradiated neutrons have a very low probability to interact with healthy cells in the body that does not contain boron-10 compound, this is mainly caused by the large boron-10 thermal neutron absorption cross section. Boron-10 has a thermal neutron absorption cross section of 3840 barns, for comparison the cross sections for hydrogen and nitrogen (two highest concentrations of atoms in tissue) is 0.33 barns and 1.70 barns respectively [12].

There are two key elements for this method to work, the first element is the boron-10 compound that can accumulate in the cancer cell and not in a healthy cell and the second element is the irradiating neutron beam used must be at epithermal or thermal energy level depending on the depth of tumor [13].

The neutron source used in this research is a 13 MeV cyclotron which is still being developed by the Center of Science and Accelerator Technology of the Indonesia National Nuclear Energy Agency (PSTA-BATAN) in Yogyakarta. Cyclotron is preferred to be used as a neutron source because it is much more practical in size and safer compared to a research reactor. A compact neutron source like this can be installed directly in a hospital.

Beam shaping assembly (BSA) is a component that is installed on the cyclotron beam port. It has multiple functions, it is used to convert the proton produced by the cyclotron into neutron, reduces the produced neutron energy, and directing the neutron to converge on the radiated tumor [14, 15].

This paper focuses in the part of the BSA called the target. The target is a component that converts the proton from the cyclotron into neutron. There are two materials that are commonly used as a cyclotron target, they are beryllium and lithium. Both materials can produce neutron but at a different amount. The target system in this paper will be made by a copper coin coated with a thin layer of beryllium and lithium (one material at a time, not layered to each other). This thin layer of beryllium or lithium reacts with the proton produced by the cyclotron and produces neutrons. These produced neutrons are then to be moderated into epithermal or thermal energy level so that it can be used in BNCT therapy.

International Atomic Energy Agency (IAEA) produces a recommendation on neutron beam quality standard that must be fulfilled in BNCT therapy. This recommendation can be seen on tab.1. One of the beam parameter is the epithermal neutron flux that must be above $10^9\ n/cm^2$ per second. To fulfill this requirement, it is absolutely crucial that the BSA has a high neutron flux from the beginning (before moderation) so that the obtained epithermal neutron flux in the end of the BSA is higher than the IAEA recommendation. The higher the epithermal neutron flux the better it is for BNCT.

Tab. 1 BNCT in-air neutron beam parameter [16]

BNCT Neutron Beam Parameters	Requirements
ϕ_{epi} (cm^{-2}s^{-1})	$> 1\times10^9$
ϕ_{epi}/ϕ_{fast}	> 20
$\dot{D}_{fn}/\phi_{epi}$ (Gy cm^2)	$< 2\times10^{-13}$
$\dot{D}_{\gamma}/\phi_{epi}$ (Gy cm^2)	$< 2\times10^{-13}$
J/ϕ_{epi}	> 0.7

This research was conducted with a simulation using a program called MCNPX. This program was used to determine the best possible target thickness and material for 13 MeV cyclotron so that it could produce the highest neutron flux before moderation. The result of this research can be used as a reference to fabricate a BSA target system for 13 MeV 1mA cyclotron.

2. Materials and methods

Program

In this research the targets was simulated using Monte Carlo N-Particle Transport Code Extended (MCNPX) version 2.6.0 which was developed by Los Alamos National Laboratory (LANL) in New Mexico. MCNPX has a lot of different applications, one of the main features of MCNPX is to simulate and calculate a particle transport and its interactions with other particle [17].

To use the MCNPX to simulate the targets, first the front part of the BSA (front collimator and target) geometry was created in the program. Then all of the parameters and setup were configured through the input files, the last step was conducting the simulation and changing the materials and thickness.

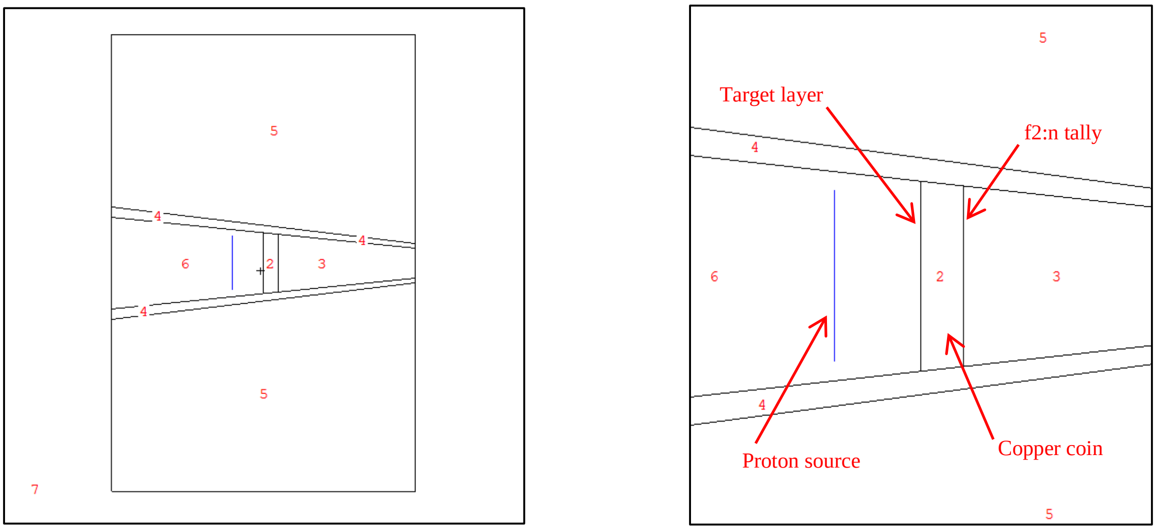
Target geometry and simulation

The front part of the BSA geometry can be seen in fig. 2. The blue line in the figure is the location of the proton source, and the target is an area with the index number 2. The beryllium and lithium thin layers are located on the left side of target surface facing the proton source. The neutron flux is measured on the right side of the target (opposite to the beryllium or lithium layer) with the f2:n tally which is the average neutron flux that cross through the right surface.

The simulated copper coins have a diameter and thickness of 5 cm and 0.5 cm respectively, the beryllium and lithium target has the same diameter of 2.5 cm. The target thickness will be varied initially from 500 μm to 5000 μm with 500 μm interval. This initial data with high interval is used to identify the neutron flux peak, after the neutron flux peak is located then more simulations will be done near the peak location but with smaller interval to accurately find the highest neutron flux.

This research is conducted to layer thickness of 5000 μm, although a thick layer of target can degrades the produced neutron energy [18] it won't cause any negative side effect on the BSA because in the end the neutrons produced from this BSA will be moderated into epithermal energy range for BNCT.

Others area in the geometry are as follows, area indicated with the number 3 is air, number 4 is a nickel shaped into a cone used to funnel the protons from the cyclotron beam line onto the target. Area number 5 is paraffin used as a shield that absorbs any particle escaped from the nickel reflectors, and finally area labeled 7 is a void area which tells the MCNPX not to calculate or simulate any particle in this area.



(a) (b)

Fig. 2 (a) BSA front collimator and target geometry (b) Target geometry in details

Proton source

The proton beam used in this research comes from PSTA-BATAN's cyclotron. The endpoint of this cyclotron beam line has a 2 cm diameter and it is put directly 1 cm from the target layer. This cyclotron output is assumed to have a uniform proton distribution on its output line. This cyclotron produces 13 MeV protons and has 1mA of current.

3. Results and Discussions

The target simulation results can be seen fig. 3. From fig. 3 we can see that with the increase of target thickness, the neutron flux also increases for beryllium and lithium but at a different gradient. Both neutron fluxes kept increasing until it reaches its peak. At first, beryllium has a very steep incline but only after around 1200 μm the neutron flux decreases steadily, whilst lithium has a steady incline and peaks at around 4000 μm.

Beryllium produces higher neutron flux compared to lithium up to 3800 μm thickness level. This is mainly caused by the proton absorption cross section of beryllium that is higher than lithium. Beryllium cross section at 13 MeV is around 145 milibarn compared to lithium that is only around 75 milibarn [19].

This results is consistent with the theoretical neutron production formula in Eq. (1), where F is the neutron yield flux (neutron/sec), N is the number of target nuclei per square centimeter of target, σ is the target (beryllium and lithium) absorption cross section for 13 MeV proton (in cm^2) and ϕ is the incident particle rate of protons [20].

$$F = N\sigma\phi \tag{1}$$

The particle rate relates to the cyclotron beams current and calculated dividing the current with proton charge. Eq. (1) is the formula for a very thin target. When the target has a thickness x the formula changed into Eq. (2).

$$dF = \sigma\phi\left(\frac{\rho N_a}{A}\right)dx \tag{2}$$

Where ρ is the density of the target (beryllium or lithium), N_a is Avogadro's number, A is the gram-atomic weight of the target and dx is the target thickness.

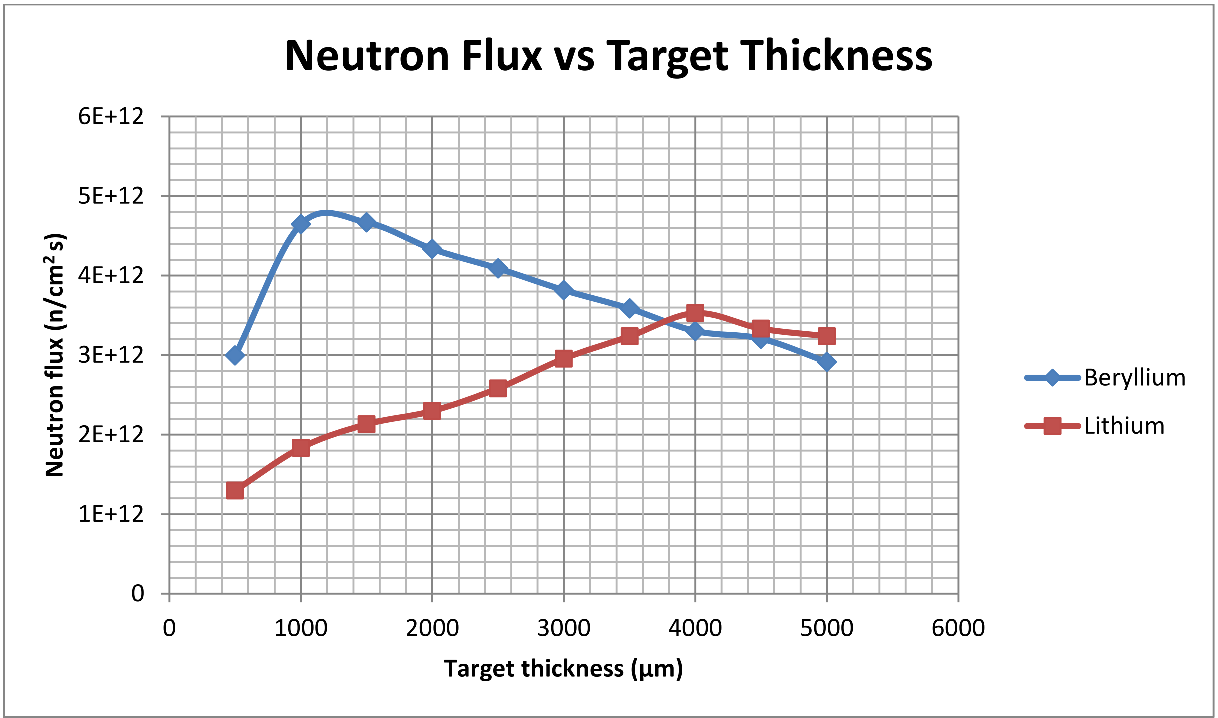


Fig. 3 Neutron flux vs target thickness graph

From fig. 3 it can be seen that after the neutron flux reaches its peak both target started to decrease in neutron flux. This is mainly caused by the energy of incident proton and the proton beam current. Incident proton energy defines the proton 'stopping power' into the target material, which translates into the ability of proton to penetrate into the target, with higher proton energy the deeper the proton can penetrate into the target. The proton beam current defines the amount of proton particle that bombarded the target. Higher current means there is more proton particles that incident to the target, this higher current increases the probability of the target to capture the proton.

These two elements combined with the target thickness played a key role in neutron production, after the proton beam entered the target there are two probabilities that can hinder the neutron flux produced. First the proton energy is not sufficient to penetrate deep inside the target, thus the neutron is only produced by the front part of the target. This front produced neutron is subjected into the rest of the target that hasn't reacted with the proton, this target 'left-over' can alter the neutron produced by reducing its energy and the neutron can react with the target resulting a loss. This phenomenon can be seen by comparing to the research done by B. N. Lee in 2011 [21], in his research he determined the best neutron flux produced by lithium target from 2.5 MeV 2 mA cyclotron. It can be seen that the neutron flux peaks at only around 100 µm, whilst in this research for lithium it peaks at 4000 µm. The second probability, the proton beam current is not high enough, a low proton beam means there is less proton that can react with the target even though the proton has enough energy to penetrate deeply inside the target. This less amount of proton means the probability for the proton to react with the target is lower, thus the reductions in neutron flux.

With the information obtained in fig. 3, more simulation is conducted around the targets peak. For beryllium target it is simulated from 1050 µm until 1450 µm, and 3800 µm until 4200 µm for lithium both target is simulated with 50 µm intervals. The results can be seen in fig. 4 and 5 below.

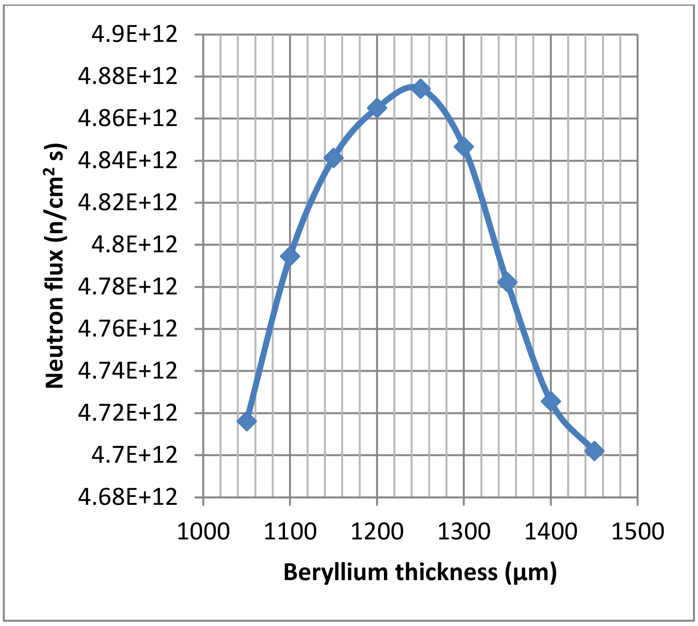


Fig. 4 Neutron flux vs beryllium thickness graph

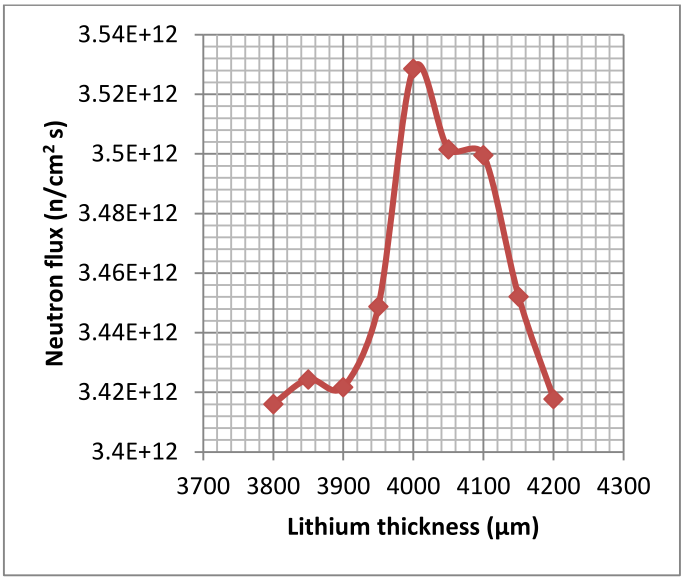


Fig. 5 Neutron flux vs lithium thickness graph

From fig. 4 it can be seen in detail that the maximum neutron flux produced by beryllium is at around 1250 µm with the neutron flux produced 4.87E+12 n/cm^2s, while from fig. 5, the maximum neutron flux produced by lithium is at around 4000 µm with neutron flux 3.53E+12 n/cm^2s.

Melting point consideration

Beryllium melts at 1287 degrees Celsius while lithium has a very low melting point of 180.50 degrees Celsius [22]. This melting point contributes directly to cooling systems that need to be applied to the target system. Lithium low melting point can be a problem, because it require a high cooling power to keep its temperature well below the melting point, whilst beryllium require less cooling power to maintain its integrity.

Melting point also play a key part in the target fabrication process, with a very low melting point, lithium can be easily fabricated by evaporation method like what have been done by Vanleeuw in 2014 [18]. Beryllium with its high melting point cannot be fabricated by evaporation easily, as it requires a lot of heat to evaporate. Beryllium, require a more complex process to fabricate.

4. Conclusion

1. Beryllium produced higher neutron flux compared to lithium. Beryllium neutron flux peaked at 1250 um with neutron flux of 4.87E+12 n/cm^2s and lithium neutron flux peaked at 4000 um with flux of 3.53E+12 n/cm^2s.
2. Beryllium had a higher melting point, thus, less cooling power to prevent the target from melting was required. In addition, lithium required a high cooling power to maintain the target integrity from melting.
3. Beryllium was evidenced to be better for a target, but it was much more difficult to fabricate the target system using evaporation method. Because of the high melting point, beryllium required a lot of heat to evaporate. It was easier to fabricate lithium target system with the evaporation method.

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