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RESEARCH

# Beam Shaping Assembly Optimization for Boron Neutron Capture Therapy Facility Based on Cyclotron 30 MeV as Neutron Source

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ABSTRACT A design of beam shaping assembly (BSA) installed on cyclotron 30 MeV model neutron source for boron neutron capture therapy (BNCT) has been optimized using simulator software of Monte Carlo N-Particle Extended (MCNPX). The Beryllium target with thickness of 0.55 cm is simulated to be bombarded with 30 MeV of proton beam. In this design, the parameter regarding beam characteristics for BNCT treatment has improved, which is ratio of fast neutron dose and epithermal neutron flux. $TiF_3$ is replaced to 30 cm of $^{27}Al$ as moderator, and 1.5 cm of $^{32}S$ is combined with 28 cm of $^{60}Ni$ as neutron filter. Eventually, this design produces epithermal neutron flux of $2.33 \times 10^9$, ratio between fast neutron dose and epithermal neutron flux of $2.12 \times 10^{-13}$,ratio between gamma dose and epithermal neutron flux of $1.00 \times 10^{-13}$, ratio between thermal neutron flux and epithermal neutron flux is 0.047, and ration between particle current and total neutron flux is 0.56.

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## 1. INTRODUCTION

Cancer is the second leading cause of death globally. The World Health Organization revealed that 8.2 million people die each year from cancer, an estimated 13% of all deaths worldwide. With lung cancer being the leading cause of cancer deaths in 2015, at approximately 1.7 million deaths from 8.8 million (WHO 2017). In 2014, 1.5 million people died due to cancer in Indonesia. 21.4% of these cases were due to breast cancer, which was the most frequent form experienced by women, and 21.8% of these cases were lung cancer in men, which was the most frequent type experienced by males (WHO 2014). It is predicted that will increase to 24 million cases in 2035 (Ferlay et al. 2015).

Some types of cancer treatment that are often done includes chemotherapy, radiotherapy and surgery, which has been used as a method of tumor treatment for more than 130 years (Benjamin 2014). While these treatments have proven to cure and even completely eliminate the cancer in the body, these three such treatments still have some shortcomings, mainly its influence on other healthy cells located around the cancer cells. The radiation dose given for radiation therapy and chemotherapy drugs are intended to kill or stop the growth of cancer cells, but can lead to cessation of division in normal cells (Marín et al. 2015). Therefore, cancer treatment with high selectivity is important to minimize the side effect.

Boron Neutron Capture Therapy (BNCT) is a type of radiation therapy for cancer which employs non-radioactive nuclide, $^{10}B$ to capture thermal neutron. Its nuclear reaction produce alpha and lithium, which are used to destroy the cancer cell. This advanced technology works effectively with high accuracy on tumor cell selection since the energy deposition is just limited to the diameter of a single cell (Karaoglu et al. 2018)

BNCT can be operated in a nuclear reactor facility or a hospital with an alternative neutron source, such as a compact neutron generator (CNG) or cyclotron which should meet the required epithermal neutron flux of $1 \times 10^9$ $n/cm^2/s$ (Benjamin 2014; Ferlay et al. 2015; Masoudi et al. 2017). Compared with nuclear, the advantages of the cyclotron as a neutron source are simply size and affordability in maintenance.

The cyclotron accelerator HM-30 1 mA has been manufactured by Sumitomo Heavy Industries, with a 30 MeV proton beam. When the HM-30 hydrogen negative ions are accelerated and protons up to 30 MeV are produced by charge conversion in a carbon foil stripper. A beam transport system is used for focusing the proton beam on a beryllium target (Tanaka et al. 2009).

Regarding efficacy, the neutron beam should meet the requirements of IAEA which has five parameters (Kasesaz et al. 2015). Accordingly, to reach all of the parameters written above, it needs a BSA as the collimator to filter and moderate fast neutron produced by the reaction of beryllium and high energy proton. A BSA collimator has been designed by Isyan et al. (2017) to produce epithermal neutron for BNCT based on cyclotron 30 MeV using a beryllium target. The value of IAEA's parameters and the value of Isyan's BSA design is shown in Table 1 (Isyan et al. 2017)

The two shaded columns show the parameters which have not already met the requirements of IAEA. Therefore,

TABLE 1. The output of previous BSA by Isyan et al. (2017).

| Parameter | Recommendation by IAEA | Isyan's design |
|---|---|---|
| $(\Phi_{epi})$ | $> 1.0 \times 10^{9}\ (n/cm^2.s)$ | $1.21 \times 10^{9}$ |
| $(\dot{D}_{fast}/\Phi_{epi})$ | $< 2.0 \times 10^{-13}\ Gy.cm^2/n$ | $7.04 \times 10^{-13}$ |
| $(\dot{D}\gamma/\Phi_{epi})$ | $< 2.0 \times 10^{-13}\ Gy.cm^2/n$ | $1.61 \times 10^{-13}$ |
| $(\Phi_{th}/\Phi_{epi})$ | $< 0.05$ | 0.043 |
| $(J/\Phi_{total})$ | $< 0.70$ | 0.580 |

this research is aimed to optimize that BSA design for BNCT facility using cyclotron 30 MeV.

There are four main parameters which should be considered in designing the BSA of BNCT: reflector, moderator, gamma filter, and neutron filter. Burlon et al. (2004) was doing research to prove that Pb is the appropriate material for the reflector. Comparing Pb with graphite, it shows that Pb has better results as a reflector than graphite (Burlon et al. 2004). Additionally, Pb was also employed for a reflector in D-T neutrons design (Burlon et al. 2004), despite spectra calculations having similar results when using a Bi collimator. Rasouli and Masoudi (2012) have investigated 16 different materials to be used as moderators: $TiF_3$, Fluental, $AlF_3$, $Al_2O_3$, $MgF_2$, BeO, Fe, Al, $H_2O$, $CF_2$, Mn, $PbF_2$, LiF, Co, Cu and $PbF_4$ with cylindrical geometry. de Boer (2008) studied moderator near the beam exit using material $Al_2O_3$ or $AlF_3$. It has shown that $AlF_3$ was the proper material as moderator with neutrons energies less than 10 keV while $Al_2O_3$ was excellent for fast neutrons with energies higher than 10 keV.

For the gamma filter, lead, glass or concrete material are usually employed as gamma shielding material since the appropriate gamma shielding materials require a high atomic number (Güngör et al. 2018). Bismuth (Bi) is a good material for the gamma filter in BNCT collimator which has atomic number of 83 (Hassanein et al. 2018; Jia et al. 2018).

For the neutron filter, $^{60}Ni$ is effective in reducing fast neutron group in energy range of 10 keV – 30 keV (Hassanein et al. 2018). Nickel is also an appropriate material as a reflector for epithermal neutrons in BNCT facility (Durisi et al. 2007). Thermal neutron and fast neutron can be moderated by adding a sulfur layer. Additionally, from the economy aspect, sulfur is more affordable compared with $TiF_3$ and $MgF_2$ (Warfi et al. 2016).

## 2. MATERIALS AND METHODS

### 2.1 Experimental methods

The research is simulated by means of Monte Carlo N-Particle Extended (MCNPX) codes. MCNP is a tool based on a computer code which is used to simulate the probability of neutron, photon, and electron as well as their interactions, including fission reaction, scattering, and absorption (Xoubi 2016). The research is started by collecting data of the previous BSA design, then studying the material that is needed as references for optimizing the beam shaping assembly.

### 2.2 Source modelling

Neutron source is represented in MCNPX as sdef, which contains information about characters of radiation generated by cyclotron. The multiplier factor is required to normalize neutron flux with the real condition. It needs the proton as particle per second with an energy of 30 MeV and current of 1 mA. The normalization factor of neutron and gamma with Be target for dose calculation is obtained from the neutron yield and gamma-ray yield:

$$1 \times 10^{-3} C/s \div 1.6022 \times 1^{-19} C/p = 6.2414 \times 10^{15}$$

### 2.3 Geometry modelling

The previous BSA design of Isyan et al. (2017) is shown in Figure 1. In this research we focus on optimizing the BSA design especially in two parameters; those are the ratio of gamma dose rate and epithermal neutron flux, and the ratio of particle current and total flux. In this case, a study about the characteristics of material when it interacts with neutron is important to consider in making a design. Accordingly, the ability of the chosen materials is also simulated by MCNPX.

The tally of F1 is used for measuring the particle current; the tally of F2 is used for measuring flux over the surface. To convert flux into a dose with the unit of Sv/s, kerma coefficient is needed which is cited from Dosimetry System 2002.

## 3. RESULTS AND DISCUSSION

The new BSA design after optimization is shown in Figure 2. The quality of the beam is determined by four parameters: neutron filter, moderator, gamma filter, and reflector.

### 3.1 Neutron filter

In this research, we focus on improving the ratio of fast neutron dose and epithermal neutron flux, which is included in the neutron filter parameter. Selecting material and geometry of this design is based on testing material's ability

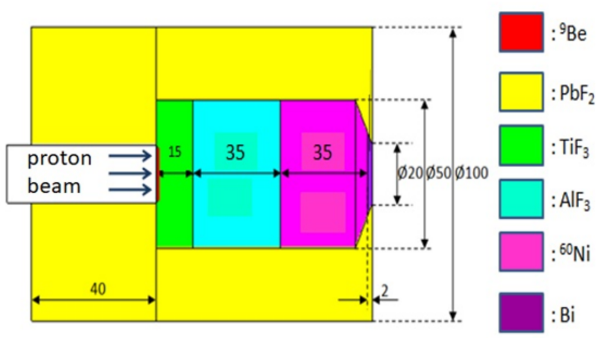


FIGURE 1. BSA designed by Isyan et al. (2017).

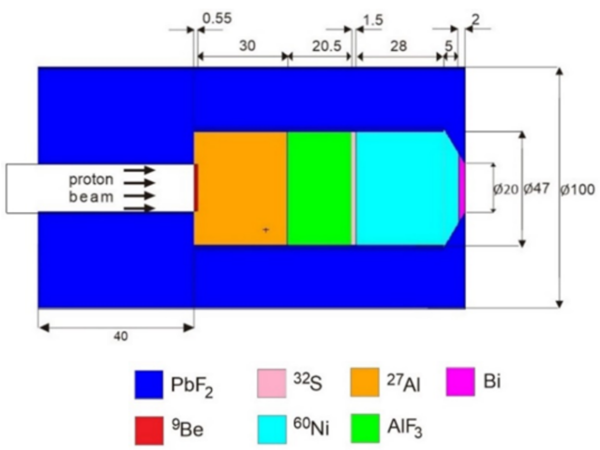


FIGURE 2. Beam Shaping Assembly (BSA) design after optimization.

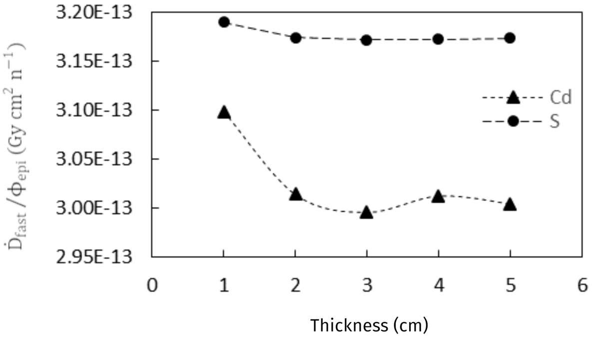


FIGURE 3. Cd and S thicknesses affecting ratio of fast and epithermal neutron flux.

to meet each BNCT BSA's requirements. Fast neutron filter materials that can reduce the fast component flux will produce high epithermal flux neutrons. Variation of thicknesses of cadmium and sulfur are simulated by MCNP to test their ability as a neutron filter.

As Figure 3 shows, sulphur has an outstanding ability in reducing fast neutron flux. Therefore, 1.5 cm of sulphur is combined with 28 cm of nickel as a neutron filter since nickel has a good ability in reducing thermal neutron flux (Masoudi et al. 2017).

### 3.2 Moderator

A moderator is used to decrease beam energy while keeping the neutron flux. In addition, if the material of the moderator has a high absorption cross section, it will cause too many neutrons that may be absorbed before it reaches the patient and will result in high gamma contamination. In this design, two moderators are used. The first moderator focused on getting the highest epithermal neutron flux while the second moderator focused on the least of fast neutron flux decline per epithermal neutrons value. Aluminium, deuterium, carbon, and aluminium oxide are examined to test the potential as a moderator.

In Figure 4, the moderator thicknesses effect on the value of epithermal neutron flux can be seen. The results in the chart show that the aluminium material is superior compared with the other materials in producing epithermal neutron. Besides producing epithermal neutron flux, other selected materials are important in decreasing fast neutron flux. It has been by simulation proved that $AlF_3$ has a good effect on the value ratio between fast neutron flux with epithermal neutron flux (Masoudi et al. 2017). Eventually, aluminium is chosen as moderator 1 and $AlF_3$ as moderator 2 with a thickness of 30 cm and 28 cm, respectively.

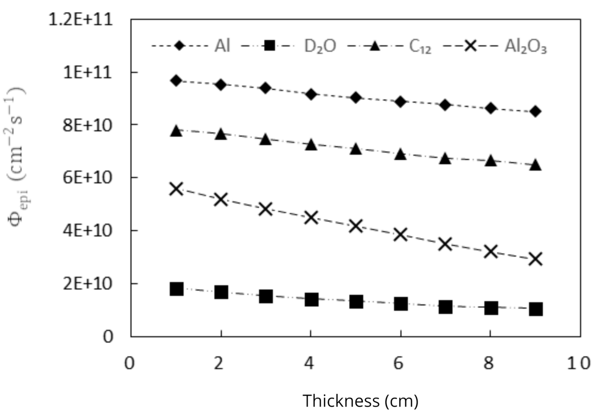


FIGURE 4. Cd and S thicknesses affecting ratio of fast and epithermal neutron flux.

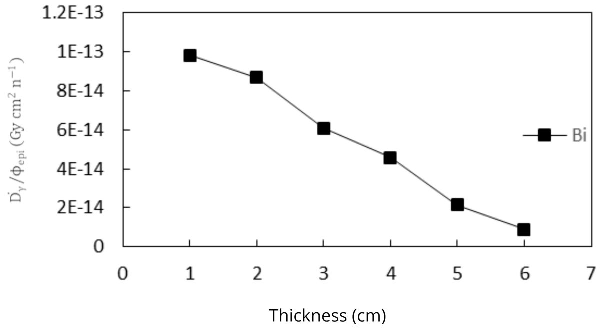


FIGURE 5. Ability of bismuth as a gamma filter depending on thicknesses.

TABLE 2. The output of the new BSA.

| Parameter | Recommendation by IAEA | New design |
|---|---|---|
| $(\Phi_e pi)$ | $> 1.0 \times 10^9$ $(n/cm^2.s)$ | $2.33 \times 10^9$ |
| $(\dot{D}_{fast}/\Phi_{\text{epi}})$ | $< 2.0 \times 10^{-13}$ $Gy.cm^2/n$ | $2.12 \times 10^{-13}$ |
| $(\dot{D}\gamma/\Phi_{\text{epi}})$ | $< 2.0 \times 10^{-13}$ $Gy.cm^2/n$ | $1.00 \times 10^{-13}$ |
| $(\Phi_{\text{th}}/\Phi_{\text{epi}})$ | $< 0.05$ | 0.047 |
| $(J/\Phi_{\text{total}})$ | $< 0.70$ | 0.560 |

### 3.3 Gamma filter

The material to be employed as a gamma filter is bismuth. The effect of thickness on the ratio between gamma dose and epithermal flux is shown in Figure 4. The gamma filter or gamma shielding is intended to reduce gamma radiation from nuclear reactions and neutron capture interactions with materials that occur in the BSA.

### 3.4 Reflector

PbF2 is chosen as a reflector based on Isyan's design (Isyan et al. 2017). It performs well in reflecting the neutron beam. A good reflector must have low absorption cross section and high elastic scattering cross section for epithermal energies (Kiger et al. 1999). Reflector material also must have a large mass number with no energy lost when each elastic collision occurs (Kiger et al. 1999). It is important to produce more neutron flux due to high-scattered neutron but less-absorbed neutron. In this design, the thickness of $PbF_2$ is increased to 26 cm to obtain more neutron flux, and as a consequence the diameter of aluminium, $AlF_3$, sulphur, and nickel are decreased.

## 4. CONCLUSIONS

After optimization, the current BSA design produces an output with the characteristics shown in Table 2.

In this design, $TiF_3$ is replaced by 30 cm of 27Al as the moderator, and 1.5 cm of 32S is combined with 28 cm of $^{60}$Ni as the neutron filter, and $PbF_2$ as side reflector thickness, is increased from 25 cm to 26 cm to produce more neutron flux. In this research, the second parameters of IAEA $(\dot{D}_{fast}/\Phi_{\text{epi}})$ have been improved.

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