Investigating a cyclotron HM-30 based neutron source for BNCT of deep-seated tumors by using shifting method

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Abstract We have successfully proposed a simulation of a neutron beam-shaping assembly using MCNPX Code. This simulation study deals with designing a compact, optimized, and geometrically simple beam shaping assembly for a neutron source based on a proton cyclotron for BNCT purpose. Shifting method was applied in order to lower the fast neutron energy to the epithermal energy range by choosing appropriate materials. Based on a set of MCNPX simulations, it has been found that the best materials for beam shaping assembly are 3 cm Ni layered with 7 cm Pb as the reflector and 13 cm AlF_3 the moderator. Our proposed beam shaping assembly configuration satisfies 2 of 5 of the IAEA criteria, namely the epithermal neutron flux 1.25×10^9 n.cm^{-2} s^{-1} and the gamma dose over the epithermal neutron flux is 0.18×10^{-13} Gy.cm^{2} n^{-1}. However, the ratio of the fast neutron dose rate over neutron epithermal flux is still too high. We recommended that the shifting method must be accompanied by the filter method to reduce the fast neutron flux.

1. Introduction

Neutron Capture Therapy (NCT) is not a new technique of neutron cancer therapy. The concept of NCT was first published by Locher in 1936, who proposed the use of slow neutrons with strong neutron absorbers (e.g. boron, gadolinium) injected into tissue for selective destruction of cancerous tissues. To date, only boron has been used in NCT clinical trials and the method is known as Boron Neutron Capture Therapy (BNCT)[1].

BNCT provides a way to selectively destroy malignant cells and spare normal cells. It is based on the nuclear capture reaction that occurs when ^{10}B, which is a nonradioactive constituent of natural elemental boron, is irradiated with low energy thermal neutrons ($E < 1$eV) to yields high linear energy transfer α particles and recoiling ^{7}Li nuclei. In order for BNCT to be successful, a sufficient amount of ^{10}B must be selectively delivered to the tumor and enough thermal neutrons must be absorbed by them to sustain a $^{10}B(n,\alpha)^{7}Li$ capture reaction. The high Linear Energy Transfer of α particles have limited path lengths in soft tissue (5-9 μm). Since biological cells posses size of 12-13 μm, the destructive effects of these high-energy α particles is limited to boron containing cancer cells [2].

As stated above, the boron capture reaction occurs with thermal neutrons. The treatment of deep-seated tumors, such as glioblastoma multiforme, requires beams of neutrons in the epithermal energy range. Such a beam, if accompany with the least amount of gamma contamination, can be served for treatment of deep tumors. The recommended criteria for the optimal beam for BNCT, including the beam intensity and beam quality, are given in a document published by the IAEA at Table 1.

In order to satisfy the IAEA recommended neutron beam intensity, various neutron sources have been suggested so far. The advantage of epithermal neutrons with respect to thermal ones is widely accepted. At present time, almost neutron sources for BNCT currently are limited to nuclear reactors. However, the availability of neutron flux from the reactors is not high enough. For an example, we have reported that the epithermal neutron flux at the end of the Ring Pierce Beamport of the Kartini reactor at PSTA BATAN Yogyakarta is about 1.06×10^8 n/cm^2/s when operated at 100 kW power [3]. Due to this lack of neutron flux, reactor-based neutron sources practically are no longer available for use. Indonesian BNCT researches are now interested to use accelerator-based neutron sources.

Proton accelerators based neutron sources generate polyenergetic neutrons. The primary neutrons produced from the cyclotron cannot be used directly for BNCT treatment. Suitable beam shaping assembly (BSA) is required to moderate the primary neutrons into the epithermal energy range. While the main purpose of this assembly is to moderate neutrons to epithermal energy range, other considerations are needed to achieve the successful BNCT treatment [4-8].

In this paper we report the feasibility study of designing such a BSA and achieving an optimized beam for BNCT of deep tumors using shifting method. The neutron beams were assumed generated by a HM-30 proton cyclotron, developed by the *Sumitomo Heavy Industries*, Ltd for the *Kyoto University Research Institute* (KURRI).

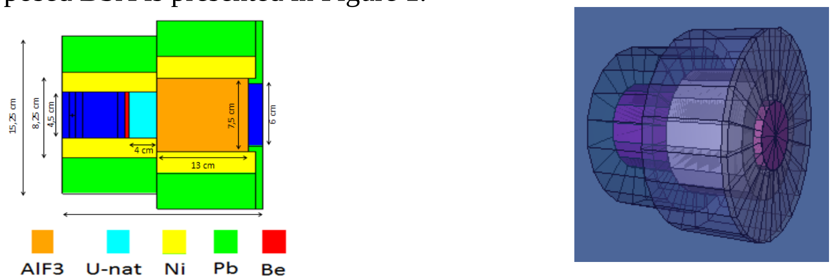
2. Experiment Method

The specifications of the HM-30 proton cyclotron can be obtained elsewhere [6,7]. In this report, the HM-30 cyclotron was assumed produces 30 MeV monoenergetic proton beams with 1 mA current. The target material was ^{9}Be without cooling system and its temperature was assumed constant at room temperature. The reflector materials were Pb and Ni. The reflector thickness was varied from 0.5 to 4.0 cm with a 0.5 cm step. As moderator materials, we used AlF_3, CaF_2 and MgF_2. A 4 cm thickness disk of uranium nature as a neutron multiplier, attached behind the Be target. The neutronic simulations in this study were carried out with the general purpose particle transport Monte Carlo computer code, MCNPX.

The results reported in this work have been carried out with adequate number of histories so that the relative errors to be less than 1%. The parameters IAEA recommended criteria, were tallied at the BSA beam port. The neutron flux, gamma radiation and neutron current were tallied using F4:n, F4:p and F1:n, respectively. The dose rate was tallied by employing the DE and DF tallies. The normalization factors are respectively 1.4677×10^{14} /s for neutron and 4.8398×10^{13} /s for photon, corresponds to the 1 mA proton current.

3. Results and discussion

Our proposed BSA is presented in Figure 1.



(a) (b)

Figure 1. Our BSA model in (a) two, and (b) three dimensional view.
The symbol U-nat stands for natural uranium.

Figure 2 depicts the simulation results of the neutrons energies spectrum produced by the ^{9}Be(p,n)^{9}B reaction. Is can be seen that the HM-30 produces neutrons almost in fast energy region, with a maximum energy of 28.62 MeV. As a comparison, Tanaka *et al* [5] reported that the same cyclotron yields 28 MeV neutrons maximum energy, in good agreement with us.

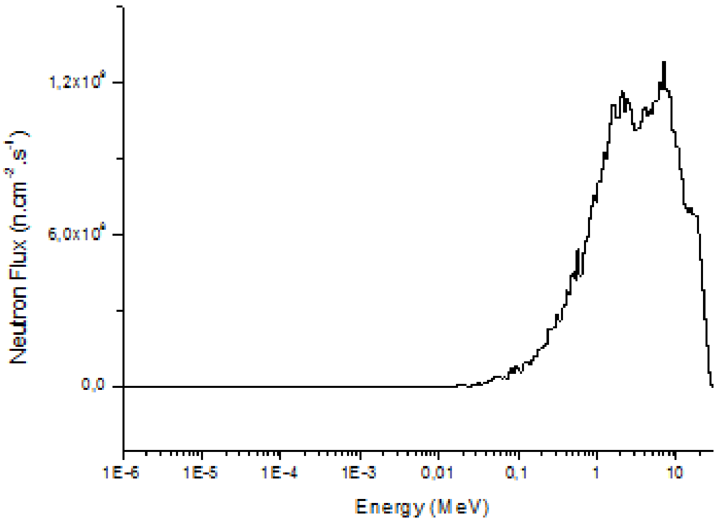


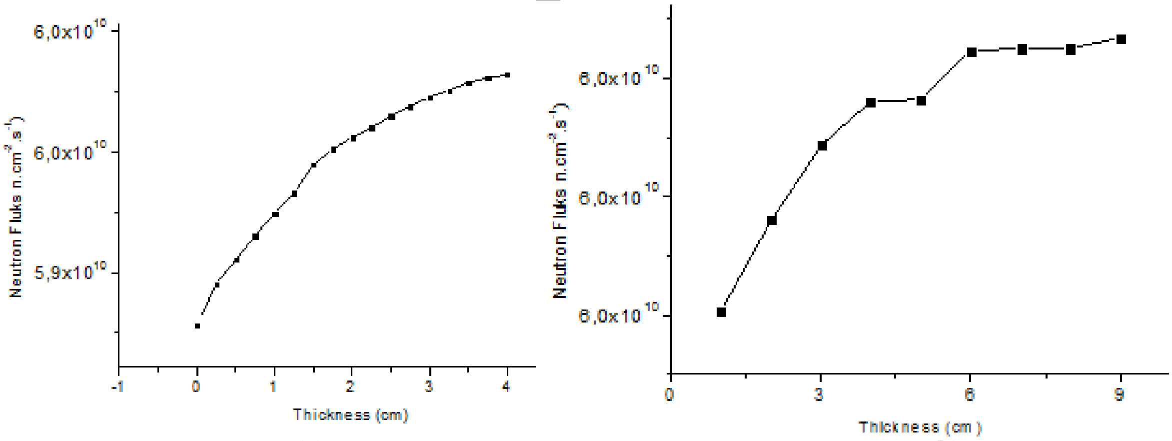
Figure 2. Neutron energy spectrum produced by 1 mA 30 MeV protons through the ^{9}Be(p,n)^{9}B reaction

According to the results presented in Figure 2, almost all the neutrons belong to the fast energy range. Shifting-down the energy of neutrons to the epithermal range is possible by means of neutron interaction with a set of materials mounted in the beam path. Our BSA is responsible for slowing-down the neutrons emitted from the source, and filtering/removing undesired fast and thermal neutrons and gamma contamination as well.

We have calculated the neutron flux of each reflector thickness. In Figure 3 (a) we show the dependence of the neutron flux to the thickness of the Ni reflector. It can be seen clearly the total neutron flux increases significantly. When the reflector thickness is 3.75 cm, the flux of the epithermal neutron raise about 37.08 % when compared to the flux without the Ni reflector. Furthermore, the Ni reflector also raises the fast neutron flux about 4.78 %, compared to that without reflector. We choose the 3.75 cm as the optimized Ni reflector thickness size.

In order to more increase the neutron flux, we layered the 3.75 cm Ni reflector with Pb. We varied the thickness of Pb layer from 1 to 9 cm with 1 cm step. In Figure 3 (b) we show the dependence of the total neutron flux when the Ni reflector is layered with several Pb thicknesses. It can be seen, the neutron flux increase monotonically with the thickness of the Pb layer. When the thickness of Pb layer is 7 cm, the epithermal neutron flux increased by about 21.7%, whereas the flux of the fast neutron decreased although not significantly, just only 0.23%.

In order to maximize neutron yields, we used a natural uranium disk attached behind the Be target. The thickness of the U-nat disk is about 4 cm. We expected that the fast neutron produced by the ^{9}Be(p,n)^{9}B reaction will react with ^{238}U under fission process to yield 2~3 neutrons. In other words, the U-nat acts as a neutron multiplier. In Figure 4 we show the spectrum of neutron, with and without U-nat neutron multiplier, at the BSA beam port. It can be seen, the total neutron flux does not increase. Instead, the fast neutron flux decreased significantly, whereas the flux of the epithermal neutron increases slightly. Most probably, this phenomenon is caused by the amount of the U-nat in the disk is not enough to support fission reaction. The thickness of the U-disk is shorter than the mean free path of neutron in uranium. Consequently, the fast neutrons are moderated by the uranium disk. Therefor the U-nat disk material doesnot act as neutron multiplier but as a moderator from our BSA design.



(a) (b)

Figure 3. Total neutron fluxes as a function of the thickness of (a) Ni, (b) Ni (3.75 cm) + Pb

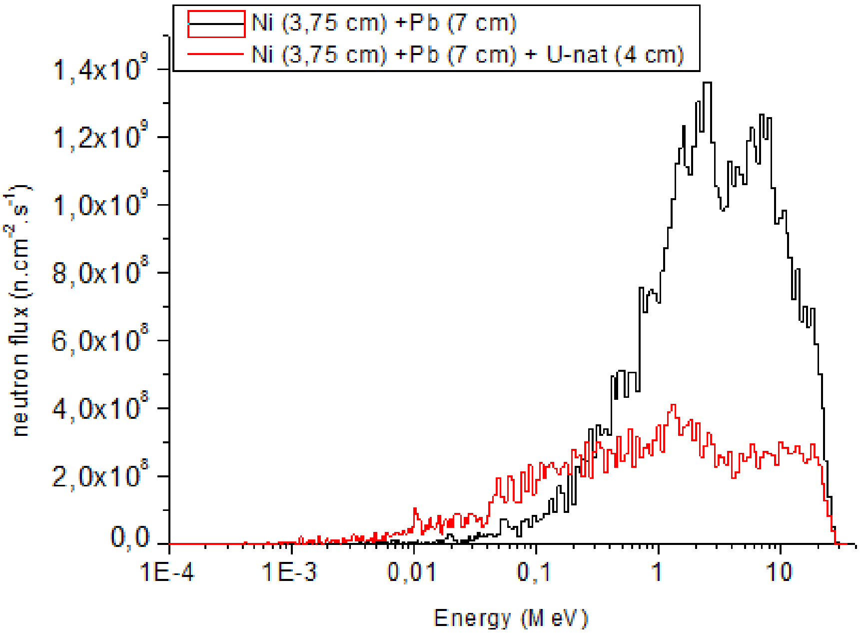


Figure 4. Neutron spectrum at the BSA beam port generated by attaching the U-nat disk and without the addition of the U-nat disk.

In order to find the most appropriate material as moderator, a number of materials have been suggested. We have looked for a moderator which not only increase the number of epithermal neutrons per cm^2, but also remove high-energy neutrons as much as possible. Finally, we decided to use four moderator materials, namely AlF_3, CaF_2, Al_2O_3 and MgF_2 and calculate the neutron flux for each material. Figure 5 depicts the effect of moderator materials to the neutron flux.
The superiority of the AlF_3 moderator among the others is obvious. It can be seen clearly in Figure 5(a), this moderator yields the highest epithermal neutrons flux. In Figure 5(b) we show the ratio of the fast neutron flux over the epithermal neutron flux. Again, the supremacy of the AlF_3 moderator is apparent. It possesses the least ratio number. Although at 13 cm thickness, the advantage of the AlF_3

moderator is still evident, as shown at Figure 5(c). At that thickness or thicker, the fluxes of fast neutron and epithermal are both almost the same.

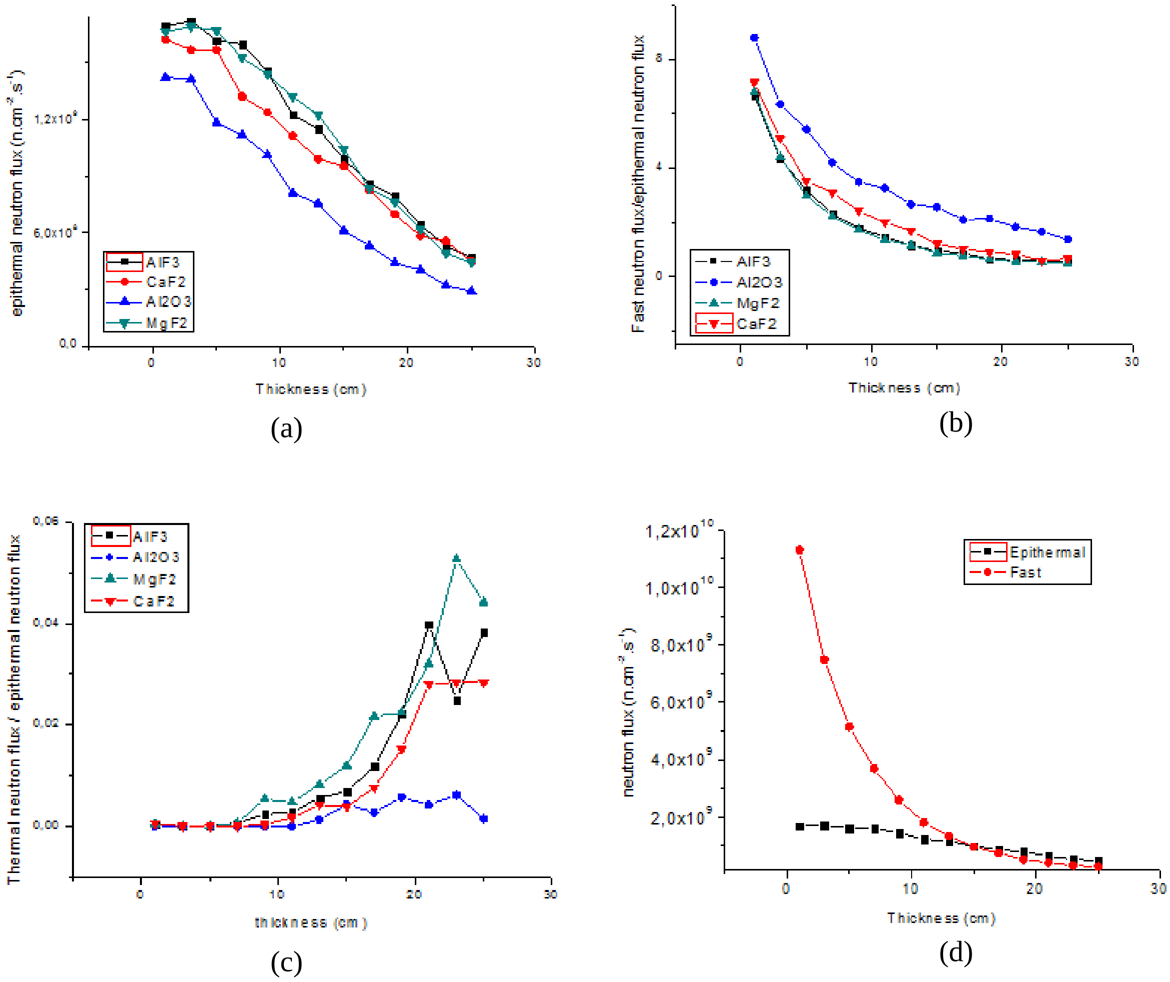


Figure 5. (a) Epithermal neutron flux, (b) ratio of the fast over the epithermal neutron flux, (c) ratio of the thermal over epithermal neutron flux of different moderators, and (d) fast and epithermal neutron fluxes of the AlF_3 moderator.

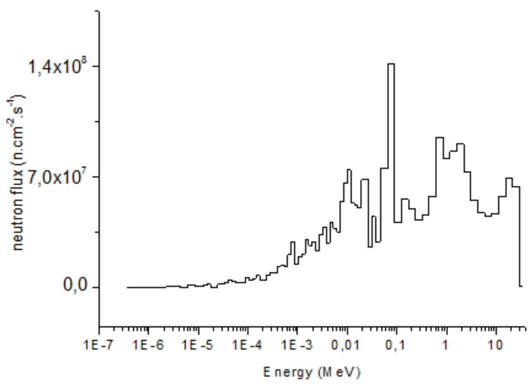


Figure 6. Neutron energy spectrum at our BSA when the AlF_3 moderator is mounted.

Table 1. Characteristics of neutron flux at the end of the BSA

Parameters	unit	IAEA	Result
Φ_{epit}	$n.cm^2s^{-1}$	$>10^9$	1.25×10^9
Φ_{th}	$n.cm^2s^{-1}$	-	5.71×10^6
Φ_{th}/ Φ_{epit}	-	<0.05	0.0045
Φ_{fast}	$n.cm^2s^{-1}$	-	1.37×10^9
$\dot{D}_{fast}/\Phi_{epit}$	$Gy.cm^2n^{-1}$	$< 2 \times 10^{-13}$	2.85×10^{-11}
$\dot{D}_{\gamma}/\Phi_{epit}$	$Gy.cm^2n^{-1}$	$< 2 \times 10^{-13}$	0.18×10^{-13}

Journal of Physics: Conference Series **776** (2016) 012063 doi:10.1088/1742-6596/776/1/012063

Based on the characteristic of the moderators, AlF_3 is an interesting material to be used as neutron moderator [9]. Knowing these results was our motivation to study on feasibility of utilizing this material as a neutron moderator produced by accelerator based neutron generator for BNCT purpose. An apperture with a radius of 6 cm is added to the end of beam port. Finally, at Figure 6 we show the neutron energy spectrum at our BSA beam port when the 13 cm AlF_3 moderator is applied. It can be seen, the fast neutron flux reduced significantly and the energy shifts to the epithermal energy range.

4. Conclusion and Suggestions for further work

Critical issues that must be addressed include the use for more selective collimator and moderator materials. Our BSA, composed of 3.75 cm Ni layered Pb with 7 cm reflector and 13 cm moderator AlF_3 only meets 2 of 5 of IAEA criteria. Therefore, our BSA design must be redesign by filtering the fast neutron. Furthermore, the using of U-nat as neutron multiplier have to be reassessed.

5. Acknowledgements

This research was supported by the grant under The Maintenance Research Group scheme of Sebelas Maret University.

6. References

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