CONCEPTUAL DESIGN OF COMPACT-MULTICHANNEL NEUTRON MODERATOR FOR ACCELERATOR-BASED BNCT SYSTEM

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Abstract

This study aims to develop a compact-multichannel neutron moderator to provide a high flux epithermal neutron beam source using an accelerator to support the new cancer treatment Boron Neutron Captured Therapy (BNCT). Typical accelerator-based BNCT neutron generators are delivering only a certain type of neutron spectrum through only one channel. However, in this study, new design of accelerator-based moderator system is proposed to deliver neutron spectrums at several different channels, while maintaining the minimum epithermal neutron flux of 10^9/s/cm^2 as suggested by IAEA. Several different materials were chosen and investigated in detailed. Out of the materials studied, Fe, AlF_3 and Teflon were chosen to be the final options for the configuration of moderators. Besides moderators, other aspects including the target, gamma shield, collimator as well as the thermal analysis of the target system were also performed to complete the study. A preliminary stage of experiment of this study was also performed to confirm the feasibility of the conceptual-design of this system in clinical accelerator-based BNCT.

INTRODUCTION

Since neutron capture reaction was proposed by Locher to be a potential cancer treatment in 1936 [1], Boron Neutron Captured Therapy (BNCT) had been one of the popular research interest. However, for an effective treatment, BNCT neutron source must contain high epithermal neutron flux of at least 10^9 cm^{-2} s^{-1}, while maintaining low contamination by other components. Some researchers had proven the possibility of using a nuclear reactor to provide epithermal beam [2]. Since this decade, an Accelerator-Based BNCT (AB-BNCT) which can be easily handled in a hospital was proposed to be a good alternative to a nuclear reactor. There are several projects currently running in Russia, UK, Italy, Japan, Israel, and Argentina to develop AB-BNCT. To date, most of the facilities are implementing Li and Be as the primary target to generate epithermal neutron beam [3]. However, the weak mechanical strength and the blistering effects of the target consequently raised other challenges for its clinical feasibility. Thus, in this study, AB-BNCT using a neutron spallation reaction is proposed as another possible source because of the mechanical strong target and its high neutron beam intensity, which is of at least one order higher than the fission does at the same power [4]. As neutron beam is expensive, this high intensity neutron source can also be fully utilized for multi-BNCT or radioisotope production in a hospital. Thus, this work aims to investigate the conceptual study of a compact multi-channel neutron moderator well suited for spallation-AB-BNCT.

SPALLATION TARGET

Target material

The total neutron yield for several target materials are calculated using PHITS code ver. 2.87 developed by JAEA, RIST and KEK [5]. From Figure 1, spallation neutron yield for all targets increases most significantly of almost an order from 10^{-7} to 10^{-6} n/cm^2/source when the input proton energy was increased from 20 MeV to 50 MeV. However, this increase slows down as the energy is further increased beyond 50 MeV. Thus, 50 MeV could be an optimum energy for practical use. The total neutron yield for the densest W metal is the highest for any proton energy. This suggests that a dense heavy metal should be a good option for target.

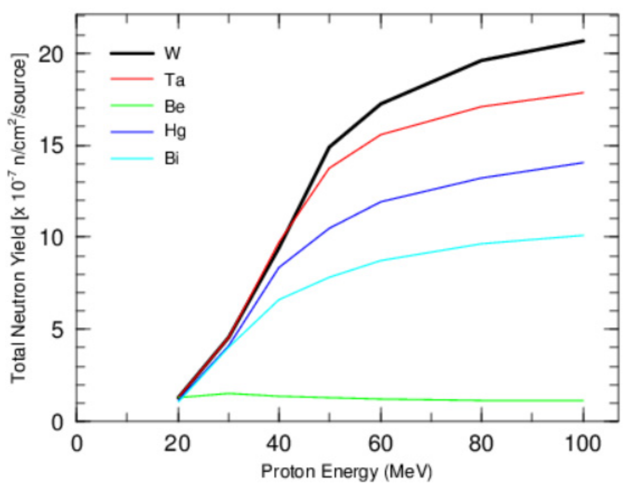

Figure 1: Total neutron yield for different spallation targets at 1 m away from the target

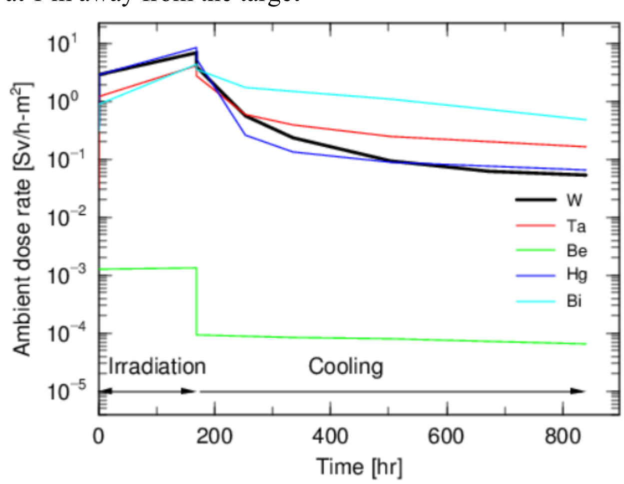

Figure 2: The ambient dose equivalent at 1 m away for different target materials after 1-week irradiation.

On top of this, the activation of the target is calculated using DCHAIN-SP in PHITS [6]. The ambient dose equivalent of the activated target for 1-week irradiation is shown in Figure 2. All the heavy targets have relatively higher ambient dose owing to the production of long-half-life residual nuclei. Thus, for clinical implementation, a robotic target replacement system should be used to handle the activated target carefully. As for this study, W which has a strong mechanical structure and produces the most flux is chosen.

Thermal analysis

In order to keep the W target below its melting point, a simple water-cooling system is necessary to dissipate the heat deposited to the target. In order to obtain a realistic cooling system, the heat transfer coefficient (h) of the flowing water should be determined. However, h of a real turbulent water flow in the cooling tube is chaotic and complicated. Assuming the temperature of the flowing water is consistent at the center, a steady-state model could be implemented. Hence, in this study, the Dittus-Boelter turbulent model is used as the steady-state model of the flowing cooling water to obtain h.

The flow of Dittus-Boelter model is described by:

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \qquad (1)$$

where Nusselt number, $Nu = \frac{hD}{k}$, is a dimensionless quantity to describe the heat transfer rate, D is the effective diameter of the pipe, k is the thermal conductivity of water (0.657 W/m-K). Reynold number is defined by $Re = \frac{Dv\rho}{\mu}$, v is the average velocity of water and ρ is water density (998.2 kg/m^3), μ is the dynamic viscosity. Prandtl number is given by $Pr = \frac{\mu C_p}{k}$, with C_p as the specific heat capacity (4182 J/kg-K).

The pressure drop is described by:

$$\Delta P = \frac{f \rho v^2}{2D}(x_2 - x_1) \qquad (2)$$

where (x_2-x_1) is the length of the flow, f is the friction factor for the pipe:

$$f = (0.79 \ln Re - 1.64)^{-2}$$

Using Eq. (1) and (2), the pressure drop and heat transfer coefficient for different water velocity are obtained.

Taking an average water velocity of 30 m/s, the heat transfer coefficient from Dittus model is 93 kW/m^2/K. In a flow length of 1 m, the pressure required to maintain the flow was about 1 MPa. This is practically realizable.

Using the heat transfer coefficient of 93 kW/m^2/K, thermal analysis is performed using ANSYS Workbench 18.0. The W target was assumed to be a cylindrical plate with radius of 40 mm and thickness of 2.4 mm. It has a backing Cu plate of thickness 10 mm with water flowing in the rectangular opening of (10x5) mm^2. The heat flow onto the W target is assumed to be uniform at 15 kW. Other surfaces are assumed to be adiabatic. The inlet water temperature is taken as 30 ºC. The temperature distribution of the whole target system is as shown in Figure 3.

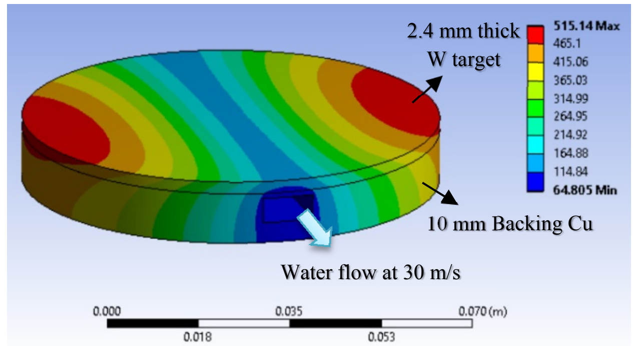

Figure 3: Temperature distribution of the target system.

From Fig. 3 the maximum temperature on the target is about 515 ºC. This is far below the melting point of W at 3422 ºC. As for the temperature of water coolant, the temperature of the inner wall of Cu containing water has a maximum value of 65 ºC. This is below the boiling point of the flowing water. Thus, we can conclude that the cooling system is feasible.

MODERATOR ASSEMBLY

Moderator materials

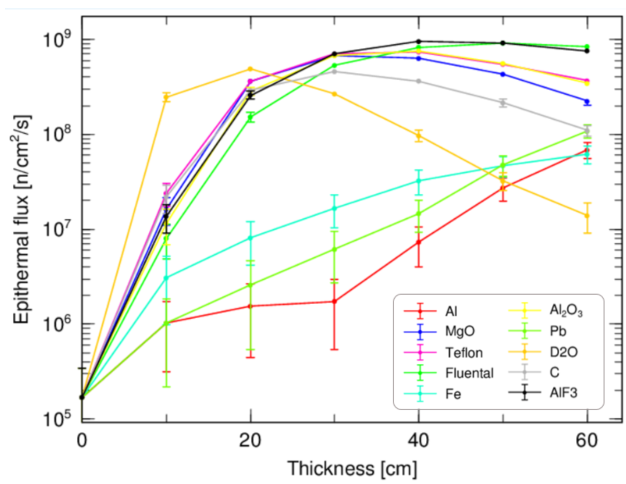

Figure 4: The perpendicular epithermal flux of different materials at 1 m away from the W target.

Several materials are studied independently in PHITS to determine their moderating effect. Each material is made into a cylindrical shape, with W target locating at the center of the cylinder. The epithermal neutron flux is then obtained at 90º ± 10º at 1 m away from the W target. The relationship between the epithermal neutron flux and the thickness of some materials is shown in Figure 4. Among all, AlF_3 is the most effective epithermal beam moderator producing the highest epithermal flux with lowest fast-neutron contamination. As Fluental is a moderator made from AlF_3 and its high price, it is not used in this study despite of its effectiveness. Fe, AlF_3, Teflon and LiF are used in the final moderator assembly. Fe is used to moderate fast neutron with energy greater than 1 MeV, whereas AlF_3 and Teflon are used as the epithermal beam shaper, LiF is chosen to absorb the excessive thermal neutrons. These four materials form a whole moderator assembly to obtain the optimum BNCT neutron beam.

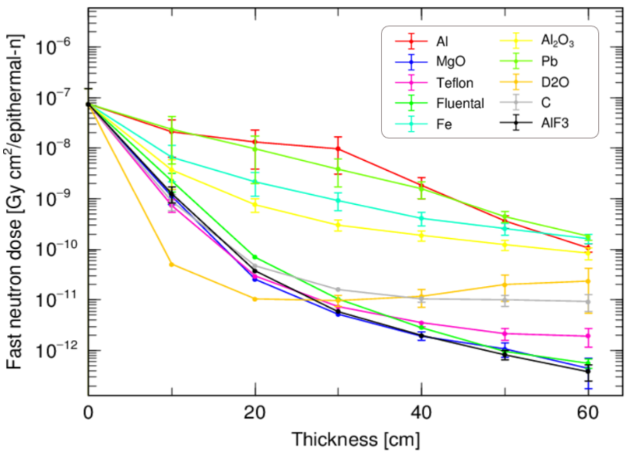

Figure 5: Fast neutron dose of different materials at 1 m away from the W target.

Moderator Sequence

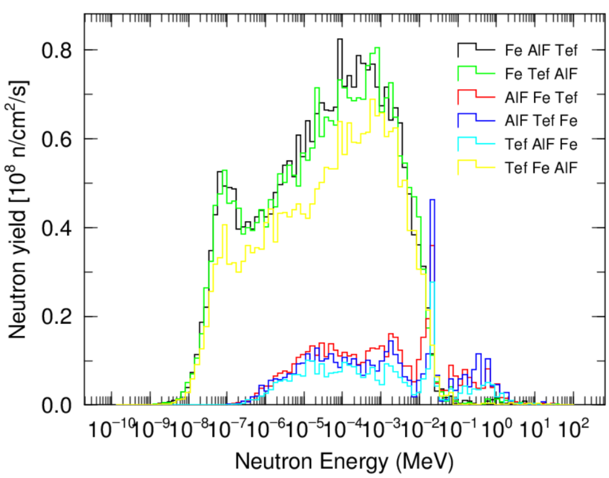

Figure 6: The perpendicular neutron spectrum at 1 m away from the W target when different moderator materials are combined with different sequences.

The sequential effect when combining different materials is also studied in order to optimize the neutron beam quality. From Fig. 6, the black and green lines show that the sequence of Fe, AlF_3, Teflon and Fe, Teflon and AlF_3 produce the most epithermal flux, with minimal fast neutron contamination. Thus, the sequence showed by the black-coloured line (Fe→AlF_3→Teflon) is then used, with an additional 0.5 cm of LiF after Teflon to absorb the undesired thermal neutrons produced.

Beam Shaping Assembly (BSA)

Table 1: The Specification Details of the BSA

Input Power	15 kW (50 MeV 300 μA)
Beam Type	Proton
Target (Thickness/Radius)	W (0.24 cm/4 cm)
Target Backing Plate (Thickness)	Cu (1 cm)
Moderator Material (Thickness)	Fe; AlF_3; Teflon; LiF (20; 39; 2; 0.5 cm)
Reflector (Thickness)	Pb (15 cm)
Gamma Shield (Thickness)	Bi (4 cm) – At Beam Exit Pb (5 cm) – Outermost Shield
Neutron Shield (Thickness)	5% Borated Polyethylene (5 cm)

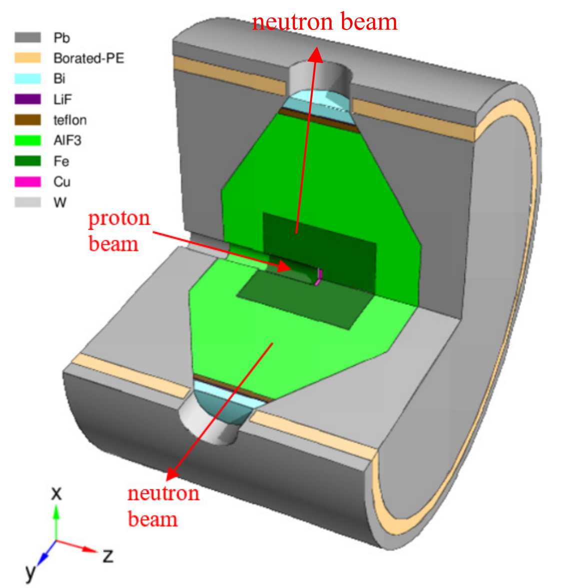

Figure 7: The conceptual design of the Beam Shaping Assembly (BSA).

After deciding the moderating materials and sequence, the thickness of each component is then optimized. Pb reflector and Bi gamma shield are also added. A layer of Borated polyethylene with a layer of Pb are used as the final layer to shield unwanted neutrons and gamma rays at places else than the beam exit. The 3D drawing of the conceptual design is as shown in Fig. 7. The neutron spectrum obtained at the exit planes is as shown in Fig. 8. The calculated thermal (<0.5 eV), epithermal (0.5 eV – 10 keV) and, fast neutron (> 10 keV) fluxes at the 20 cm diameter exit planes at 300μA are $(7.98 \pm 0.64) \times 10^7$ n/cm²s, $(1.17 \pm 0.06) \times 10^9$ n/cm²s and $(3.94 \pm 0.95) \times 10^7$ n/cm²s. The undesired fast neutron dose and gamma dose are $(1.84 \pm 0.45) \times 10^{-13}$ Gy-cm²/epithermal-n and $(2.46 \pm 0.69) \times 10^{-13}$ Gy-cm²/epithermal-n respectively. The collimation of the beam is 0.73 ± 0.05.

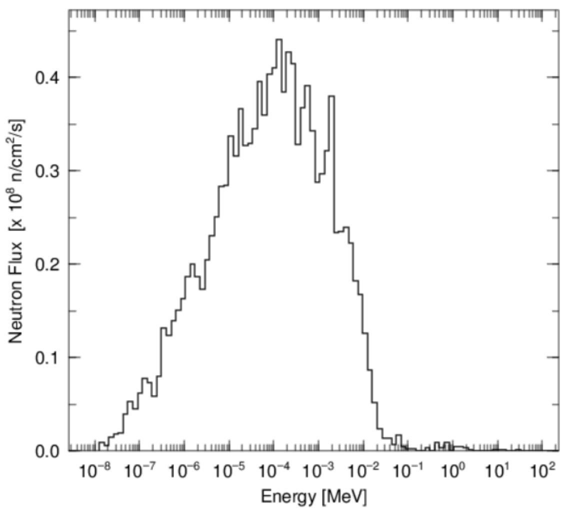

Figure 8: The neutron spectrum obtained at the aperture of the BSA.

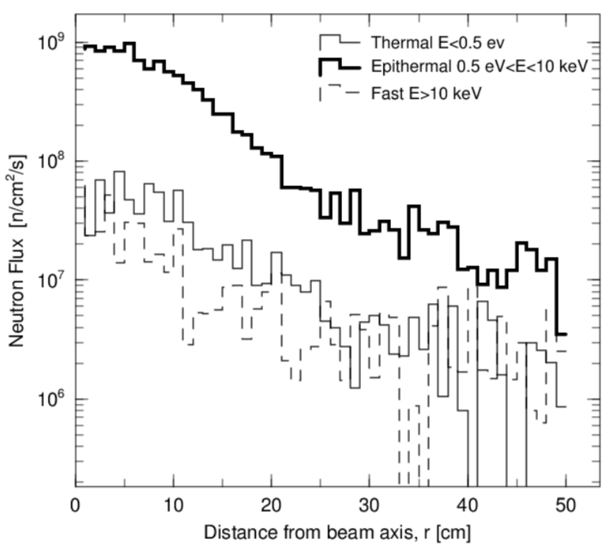

Figure 9: Radial beam intensity profile from the beam axis at 5 cm plane from the aperture of the BSA.

CONCLUSION

The results from PHITS calculations had proven the feasibility of the proposed compact-multichannel neutron moderator for simultaneous BNCT as all the beam quality parameters obey the standard suggested by IAEA [7]. In order to further confirm its clinical practicality, several phases of experiments are progressing currently in RCNP. Further investigation regarding the shutter system, the target handling system as well as the customization of various neutron energy spectra to different depths of tumour will also be performed as future study.

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