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Conceptual Design of Collimator at Boron Neutron Capture Therapy Facility with 30 MeV Cyclotron and Target ^{9}Be as Neutron Generator Using Monte Carlo N-Particle Extended Simulator

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Abstract The optimization of collimator has been studied which resulted epithermal neutron beam for Boron Neutron Capture Therapy (BNCT) using Monte Carlo N Particle Extended (MCNPX). Cyclotron 30 MeV and ^{9}Be target is used as a neutron generator. The design criteria were based on recommendation from IAEA. Mcnpx calculations indicated by using 25 cm and 40 cm thickness of PbF_2 as reflector and back reflector, 15 cm thickness of TiF_3 as first moderator, 35 cm thickness of AlF_3 as second moderator, 25 cm thickness of ^{60}Ni as neutron filter, 2 cm thickness of Bi as gamma filter, and aperture with 20 cm of diameter size, an epithermal neutron beam with an intensity 1.21×10^9 n.cm^{-2}.s^{-1}, fast neutron and gamma doses per epithermal neutron of 7.04×10^{-13} Gy.cm^2.n^{-1} and 1.61×10^{-13} Gy.cm^2.n^{-1}, minimum thermal neutron per epithermal neutron ratio of 0.043, and maximum directionality of 0.58, respectively could be produced. The results have not passed all the IAEA's criteria in fast neutron component and directionality.

Keywords Collimator, BNCT, MCNPX, IAEA criteria.

I. INTRODUCTION

Cancer is one of the leading causes of death worldwide. Approximately 8.2 million deaths caused by cancer. Lung cancer, liver, stomach, colorectal, and breast cancer is the biggest cause of cancer deaths each year [1]. Approximately 70% of cancer deaths occur in developing countries, in Indonesia about 136 men and 109 women died for every 100.000 cases of cancer in 2008. An estimated deaths due to cancer in the world will increase beyond 13.1 million people in 2030 [2].

Several attempts treatment against cancer that has been intensified by surgery, chemotherapy, and radiotherapy. Radiotherapy is a type of therapy that typically use X-rays, gamma rays, and charged particles to destroy cancer cells and shrink tumors. Radiation uses high-energy dose that can cause ionization in the surrounding normal cells, and also the radiation is usually effective only when the characteristics of Linear Energy Transfer (LET) (53 keV.μm^{-1} or smaller) [3, 4, 5].

Boron Neutron Capture Therapy (BNCT) is a type of therapy for cancer using neutron as a source of radiation. A therapy is said to be good when the therapy is capable of destroying cancer cells without causing any harmful side effects to the surrounding normal cells. In the treatment process boron will be put into the patient's body with the help of boron delivery and then irradiation field to be irradiated with epithermal neutrons, and neutrons will be captured by the isotope ^{10}B and then this reaction will produce charged particles are particles of α (alpha) and ^{7}Li nucleus. Both of these particles have the same high LET (≥75 keV.μm^{-1}) and a short-range radiation (about 4.5 to 10 m) [6], so that the radiation is confined in cells [7].

In the years 1950 - 1994 beam that are used for facilities BNCT is a neutron thermal, but the beam of neutrons thermal has low penetration and its dose distributions are bad, then in 1994 neutron epithermal used the first time in the USA (Mitr-II and BMRR) [8]. Based on IAEA criteria for BNCT procedure epithermal neutron beam intensity is suitably more than 1×10^9 n.cm^{-2}.s^{-1} or more, but the epithermal neutron flux of 5×10^8 n.cm^{-2}.s^{-1} can still be used albeit with a longer irradiation time [9]. In order to produce the desired epithermal neutron flux, we need a method to filter and moderate the fast neutrons resulting from the reaction between beryllium targets with energy 30 MeV protons accelerated by a cyclotron HM-30. Collimator is a system that is designed to be able to filter and moderate the fast neutrons so that the output beam of neutrons produced in accordance with IAEA criteria.

In designing the collimator, there are two characteristics of the output beam concern, namely the intensity and quality. The intensity of the beam will be the determining factor for how long the iradiation time. Quality relates to the type, energy and other radiation intensity present apart from epithermal neutrons. The following epithermal neutron beam parameters recommended by the IAEA show in Table 1.

TABLE 1 BEAM PARAMETERS

Parameter	Nilai
Intensitas berkas sinar epitermal Φ_{epi} (n.cm^{-2}.s^{-1})	$>1{,}0\times10^{9}$
Dosis netron cepat per netron epitermal $\dot{D}_f / \Phi_{epi}$ (Gy.cm^2.n^{-1})	$<2{,}0\times10^{-13}$
Dosis foton per netron epitermal $\dot{D}_\gamma / \Phi_{epi}$ (Gy.cm^2.n^{-1})	$<2{,}0\times10^{-13}$
Rasio antara fluks netron termal dengan fluks netron epitermal Φ_{th} / Φ_{epi}	<0,05
Rasio antara arus netron dengan fluks netron total J / Φ_{total}	>0,7

Source: [9].

To get the criteria neutron beam for BNCT procedure as described above, then in designing the collimator needs to be optimized in dimensions and material selection right. A collimator is usually made up of five elements, namely:

1) *Reflector*

Collimator wall must be could either keep the neutrons remain in the moderation space and not leak to the outside. Materials commonly used as collimator wall is Pb, Bi, and PbF_2 [9].

2) *Moderator*

Best moderation of fast neutron can be achieved with a material that has a low atomic mass. Moderator or the selected filter material should not decompose at a high radiation field, nor produce moisture. All products of neutron activation should have a short life span. The suitable material candidate is Al, C, S, Al_2O_3, AlF_3, D_2O, and $(CF_2)_n$ [9].

3) *Gamma filter*

Materials such as Pb and Bi can be used to reduce the gamma rays from the reaction protons smashing into beryllium, however the addition of gamma filter can also reduce the intensity of neutrons. Bi is almost as good as the Pb for shielding gamma and let through more neutron epithermal. Despite Bi needs more attention in handling Bi irradiated neutrons due to the formation of ^{210}Po, alpha emitter which formed from the ^{209}Bi capture reaction and followed by beta decay of ^{210}Bi. Encapsulation of bismuth is strongly recommended [9].

4) *Neutron filter*

Filter materials for thermal neutrons require either elements with ^{6}Li, ^{10}B or Cd. Cd is most frequently used absorber due to the reason that Cd is an effective (n,γ) converter. Not only thermal neutrons, but also fast neutrons are very necessary to reduce. This can be done with natural or isotopically enriched materials, for which an interference minimum in the total neutron cross section exists in epithermal energy range. The total cross section of ^{60}Ni isotope has the deep and wide interference minimum in the energy range from several eV to 10 keV and therefore this material is useful for BNCT purposes [9].

5) *Aperture*

An aperture is usually made of a material that has a high absorption. Aperture serves to direct the beam to the target, so as not to endanger the patients when performed therapeutic procedures [10].

II. RESEARCH METHODOLOGY

A. Neutron Source Modelling

Neutron sources modeled in this study is 1 mA proton with energy of 30 MeV inducing target material 10Be with diameter and thickness of 19 cm and 0.55 cm. The (^{9}Be(p,n)^{9}B) reaction produce high-energy neutrons will then be moderated in the collimator for BNCT purposes.

B. Simulator

In this study, MCNPX is used for simulation. MCNPX input code consists of three parts, namely surface card, cell card, and the data card. The contents of the surface card is a surface type and dimensions followed by cell card that contains specifications covering the space between the surface density of the material, material number, importance cell, and the name of each cell. In the data card contains the definition of the radiation source used, the number of iterations, the number of sampling, material definition, and continued with the calculation tally.

TABEL 2 MCNPX TALLY TYPES

Mnemonic	Tally descriptions	Units
F1:<pl>	Particle current on *surface*	particle
F2:<pl>	Mean flux on *surface*	particle.cm^{-2}
F4:<pl>	Mean flux on cell	particle .cm^{-2}
F5a:N, F5a:P	Flux at certain point or ring shaped detector	particle.cm^{-2}
F6:<pl>	Mean energy deposition on cell	MeV.g^{-1}
+F6	Heating due to collision	MeV.g^{-1}
F7:N	Fission mean energy deposition on cell	MeV.g^{-1}
F8:<pl>	Energy distribution of pulse created in detector due to radiation	pulse
+ F8:<pl>	Deposition	charge

Source: [11].

The type of tally used is chosen according to the information which want to be obtained. In this study tally F1 and F2 are used to evaluate the value of the output collimator designed with the parameters that have been recommended by the IAEA.

At the time of writing the code, normalization factor or multiplier needed because the unit flux of calculation MCNPX tally different from the units used by the IAEA. It takes a proton source in units of particles per second with energy and current of 30 MeV and 1mA. Normalization factor can be obtained by the following calculation.

$$\frac{1 \times 10^{-3}\, {}^{C}/_{s}}{1{,}6022\ \times\ 10^{-19}\, {}^{C}/_{p}} = 6{,}2414 \times 10^{15}\, {}^{p}/_{s}$$

In the calculation of the dose based on the energy released by the radiation beam of neutrons and gamma photons in material, the reference used is a table of coefficients Kerma issued in the Dosimetry System 2002 (DS02) on ICRU report 63. For the calculation of neutron flux required limits for the classification of neutron energy so that it can distinguished neutron flux for thermal, epithermal and fast. In MCNPX we can put an upper limit on the neutron energy. Epithermal neutron energy range used in this study is 4 eV-40 keV, neutrons with energies below 4 eV is a thermal neutron, whereas neutrons with energies above 40 keV are fast neutrons.

III. RESULTS AND ALAYSIS

1) Reflector

3 candidates selected reflector material is Pb, PbF_2, and Bi. To get the best reflector material, each simulated reflector material with the same thickness and seen the value of the intensity of neutrons that exists in the moderation. It can be seen that the simulation results are presented in Figure 1.

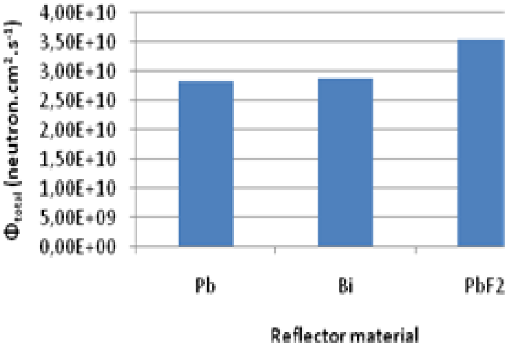

Figure 1. The effect of material types on the total neutron flux.

The result shows that the material PbF_2 is more superior than the other two. This is due to the scattering cross section of neutrons for materials PbF_2 is higher than the other two materials and also PbF_2 has a very low cross-section of neutron absorption. As a result, neutrons tend to be scattered back and very few neutrons that absorbed. To that end, PbF_2 material used as the reflector material on this collimator design.

Then, material PbF_2 simulated by varying the thickness of the reflector in two directions (side reflector and a back reflector) to get the value of the optimal thickness of the reflecto. The results of side reflector and back reflector thickness is presented in Figure 2 and Figure 3.

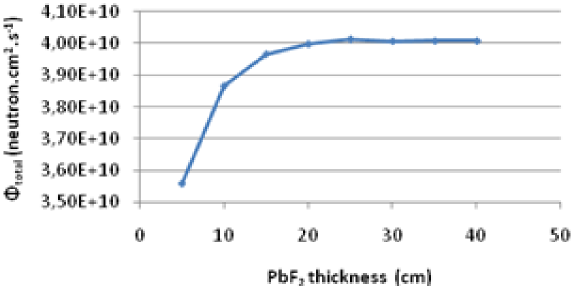

Figure 2. The effect of PbF_2 thickness on the total value of the neutron flux for the side reflectors.

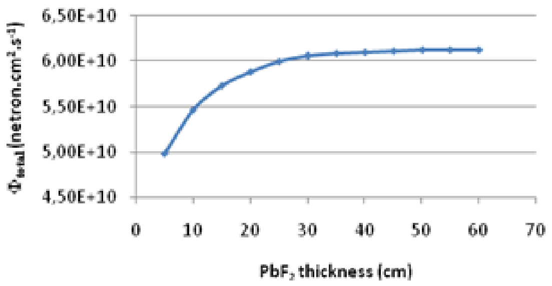

Figure 3. The effect of PbF_2 thickness to the total value of the neutron flux for the back reflectors.

From the simulation results can be seen that the neutron flux increases concurrently increasing the thickness of the reflector. The optimum thickness for the side reflector and a back reflector is achieved when the thickness are 25 cm and 40 cm respectively.

2) Moderator

In this design two moderators are used, 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. Materials candidate for moderator 1 is Al, AlF_3, Al_2O_3, and TiF_3.

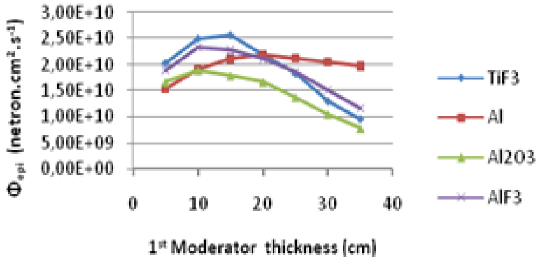

Figure 4. Moderator thickness effect on the value of epithermal neutron flux.

From the results of the graph in Figure 4 shows that TiF_3 material is superior compared to other materials. TiF_3 with a thickness of 15 cm is selected as moderator 1.

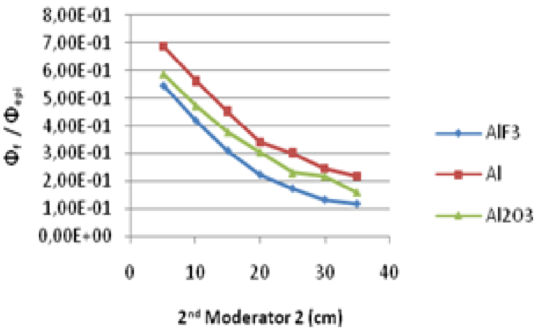

Figure 5. Moderator thickness effect on the value ratio between the fast neutron flux with epithermal neutron flux.

For second moderator material, the selected candidate is Al, Al_2O_3, and AlF_3. From the simulation results can be seen in the graph in Figure 5 shows that the material AlF_3 has a value of fast neutron flux ratio per epithermal neutron flux which is the lowest compared to the other materials. AlF_3 material with a thickness of 35 cm is selected as second moderator.

3) Neutron filter

It takes filters neutron due to the contaminations of fast neutron and thermal neutrons is still great. The material that being optimized is ^{60}Ni with 99.5% enrichment. Thickness variation performed to obtain optimal thickness, that is when the fast neutron dose impairment against epithermal neutrons are no longer significant.

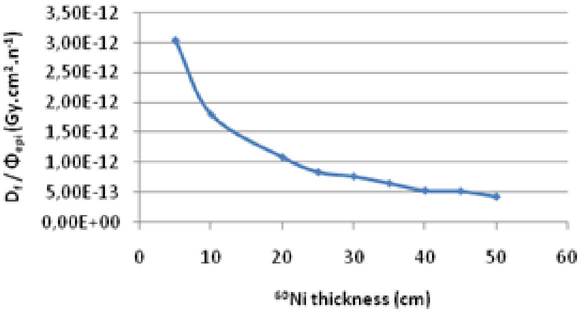

Figure 6. ^{60}Ni thickness influence on the value of the ratio between the dose of fast neutrons to epithermal neutron flux.

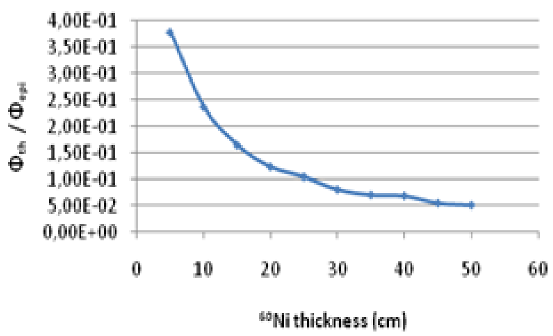

Figure 7. ^{60}Ni thickness influence on the value of the neutron flux thermal / epithermal neutron flux.

Graph the results can be seen in Figure 6. The selected optimal thickness is 35 cm, more than the decline that occurs is not significant.

4) Gamma filter

The material thickness to be optimized as gamma filter in this study is Bi.

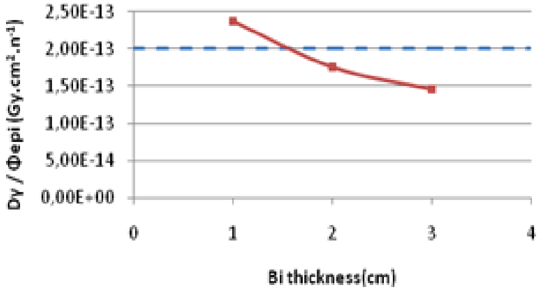

Figure 8. Bi thickness influence on the value of gamma dose/epithermal neutron flux.

From the results of the graph in Figure 7 is obtained 2 cm of Bi thickness is used so that the value of gamma dose/epithermal neutron flux is below the IAEA recommendation.

IV. CONCLUSION

Based on the research that has been done, get the results of the design collimator configuration as follows,

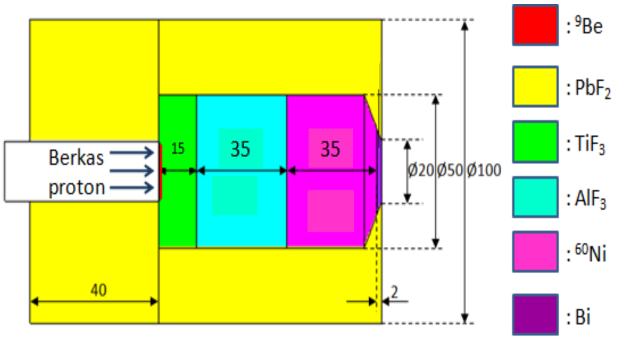

Figure 9. Configuration of colimator design result.

1. 25 cm and 40 cm thickness of PbF_2 as side reflector and back reflector.
2. 15 cm thickness of TiF_3 as first moderator.
3. 35 cm thickness of AlF_3 as second moderator.
4. 35 cm thickness of ^{60}Ni as neutron filter.
5. 2 cm thickness of Bi as gamma filter.

TABLE 3 PARAMETERS VALUE OF DESIGN RESULT

Units	Design Result	IAEA Recommendation
Φ_{epi} (n.cm^{-2}.s^{-1})	1,21 × 10^{9}	>1,00 × 10^{9}
$\dot{D}_f/\Phi_{epi}$ (Gy.cm^{2}.n^{-1})	7.04 × 10^{-13}	<2,00 × 10^{-13}
$\dot{D}_\gamma/\Phi_{epi}$ (Gy.cm^{2}.n^{-1})	1.61 × 10^{-13}	<2,00 × 10^{-13}
Φ_{th}/Φ_{epi}	0,043	<0,05
J/Φ_{total}	0,58	>0,7

There are still two parameters whose values do not meet the criteria of the IAEA which is on the fast neutron contamination and direcsionallity. Needs to be optimized in terms of election of material mainly the moderator to reduce contamination of fast neutrons. For the directionallity, need to be varied on the diameter moderation space and also on the diameter of the aperture in order to obtain the desired value of directionality.

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