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An Optimization Design of Collimator in The Thermal Column of Kartini Reactor For BNCT

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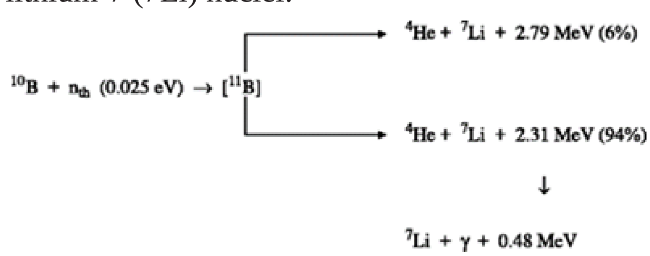
Abstract Studies were carried out to design a collimator which results in epithermal neutron beam for in vivo experiment of Boron Neutron Capture Therapy (BNCT) at the Kartini Research Reactor by means of Monte Carlo N-Particle (MCNP) codes. Reactor within 100 kW of thermal power was used as the neutron source. All materials used were varied in size, according to the value of mean free path for each material. MCNP simulations indicated that by using 6 cm thick of Natural Nickel as collimator wall, 65 cm thick of Al as moderator, 3 cm thick of Ni-60 as filter, 6 cm thick of Bi as γ-ray shielding, 3.5 cm thick of Li_2CO_3-polyethilene, with 2 cm aperture diameter. Epithermal neutron beam with maximum flux of 6.60 x 10^8n.cm^{-2}.s^{-1} could be produced. The beam has minimum fast neutron and γ-ray components of, respectively, 1.82 x 10^{-13}Gy.cm^2.n^{-1} and 1.70 x 10^{-13} Gy.cm^2.n^{-1}, minimum thermal neutron per epithermal neutron ratio of 0.041, and maximum directionality of 2,12. It did not fully pass the IAEA's criteria, since the epithermal neutron flux was below the recommended value, 1.0 x 10^9 n.cm^{-2}.s^{-1}. Nonetheless, it was still usable with epithermal neutron flux exceeding 5.0 x 10^8 n.cm^{-2}.s^{-1}. it is still feasible for BNCT in vivo experiment.

Keywords BNCT, Kartini reactor, Thermal Column, IAEA criteria.

INTRODUCTION

There were an estimated 14.1 million cancer cases around the world in 2012, of these. This number is expected to increase to 24 million by 2035 (Ferlay,2014). These facts lead to a consideration that eradicating the tumor cells as soon as possible is needed before it spreads to any nearby normal cells. There are several kinds of treatment to cure the disease or considerably prolong life while improving the patient's quality of life. Those treatments are, generally, sorted into 3 majors: surgery, radiotherapy, and systemic therapy. Neutron capture therapy (NCT) is a non-invasive method for the treatment of the malignant tumors like primary brain tumor and recurrent head and neck cancer. It is a selective or near to selective treatment with compare to any other methods.

In theory, boron neutron capture therapy (BNCT) selectively kills the cancerous cells and do not or little affect the normal cells. It works on the principle of the nuclear reaction, when the nonradioactive boron captures the neutron and getting unstable. In method, boron-10 (10B), which is a nonradioactive constituent of natural elemental boron, is irradiated with low-energy thermal neutrons to yield high linear energy transfer (LET) α particles (4He) and recoiling lithium-7 (7Li) nuclei:



For the success of the method first of all we have to selectively deliver required dose of the boron to the cancerous cells and the enough thermal neutrons must be absorbed by the boron, which is present in the cancerous cells. For the selective delivery of the boron we can use the antibody based selective rug delivery system or the any other selective drug delivery system (Barth, 2012). Because the high LET particles have limited path lengths in tissue (5-9 µm), the destructive effects of these high-energy particles is limited to boron containing cells.

Since BNCT method requires the source of the neutrons it requires the nuclear reactor or it can be performed in the hospitals where the alternative source of neutrons is available. A beam of epithermal neutrons penetrates the brain tissue, reaching the malignancy. Once there the epithermal neutrons slow down and these low-energy neutrons combine with boron-10 (delivered beforehand to the cancer cells by drugs or antibodies) to form boron-11, releasing lethal radiation (alpha particles and lithium ions) that can kill the tumor(Teruyoshi et al,2014).

In TRIGA MARK-II type research reactor in Yogyakarta, which has also been known as Kartini Research Reactor, the facility for BNCT is going to be built for an advanced study which uses tumor injected animals as the object. The thermal column of this reactor is planned to be implanted with a device which is capable of narrowing the neutron beam, called as collimator. Due to the tendency of epithermal neutron beams usage for BNCT, the collimator must contains materials needed to produce epithermal neutron beam which fulfill some particular characteristics recommended by the International Atomic Energy Agency (IAEA). Thus, a proper collimator has to be designed.(Chiragkumar et al,2015).

MATERIAL AND METHODS

This study was a simulation-basic experiment, using MCNP5 program. As the first step, it was needed to make a model of the reactor since it would be used as the neutron source. Several parts of the reactor, whose existence were considered to affect to the reactor criticality, were modelled, such as core, the radial reflector, rotary specimen rack, and piercing beam port. Reactor core configuration was made for thermal power of 100 kW. The thermal column was also built since it would become the point of interest; where the collimator would be built. Simulations was done to make sure that the criticality value was approximately 1, and the thermal neutron flux in the ring B was near (12.45 +0.23) x 1011 $n.cm^{-2}s^{-1}$. The result should be written (recorded) for the next collimator conceptual designing process.

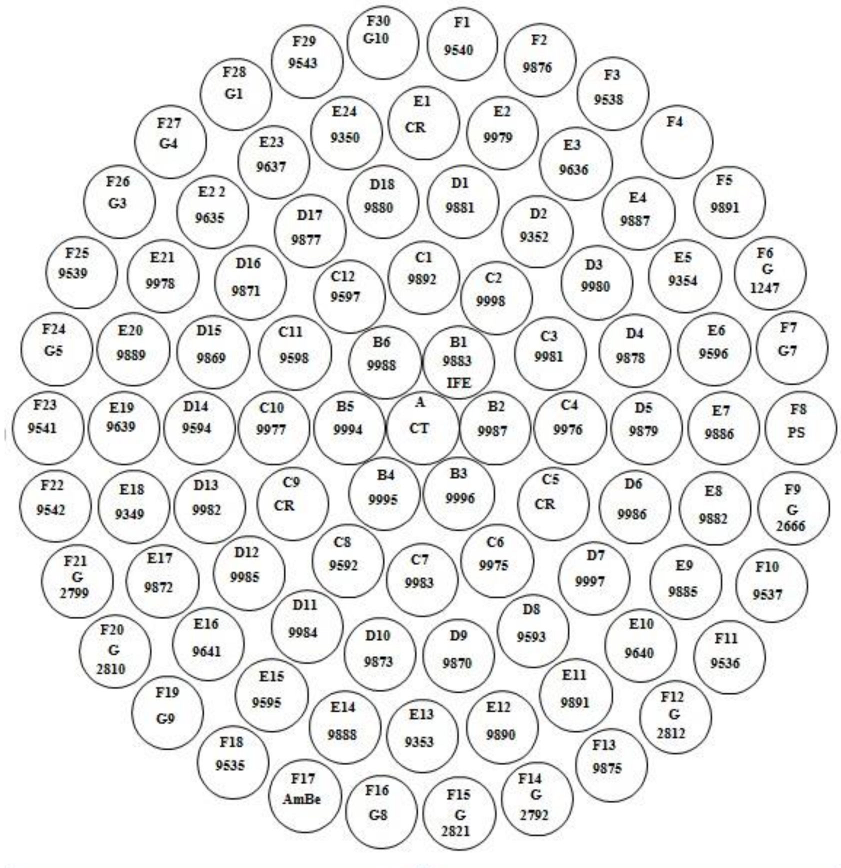


Figure.1. Core configuration of Kartini Reactor

In an MCNP input file, tallies are the information that a user wants to obtain by Monte Carlo calculation. According to the beam criteria in Table 1, the tallies needed were those for resulting fluxes and current data. Neutron and gamma fluxes were calculated using F4 tally and corresponding dose values were determined using fluence to kerma conversion factors reported in ICRU 63. Moreover, neutron current was calculated using F1 tally. Normalization factors for each tally were calculated, used for normalizing the tallies for a reactor within 100 kW thermal power.

Table 1 shows the beam criteria recommended by the IAEA. The energy limits of 5 x 10^{-7}, 10^{2}, and 20 MeV were used which, respectively, denoted the upper limit for thermal, epithermal, and fast neutrons energy spectrums. In this table, Φ_{epi}, Φ_{th}, and J are epithermal neutron flux, thermal neutron flux, and neutron current, respectively. Moreover, Df and Dγ stand for dose rates due to the fast neutrons and gamma rays.

Table 1. Beam criteria recommended by the IAEA (TECDOC-1223)

Parameter	**Nomenclature**
Epithermal beam intensity	Φ_{epi} (n.cm^{-2}.s^{-1})
Fast neutron dose per epithermal neutron	$\dot{D}_f/\Phi_{epi}$ (Gy.cm^{2}.n^{-1})
Gamma dose per epithermal neutron	$\dot{D}_\gamma/\Phi_{epi}$ (Gy.cm^{2}.n^{-1})
Ratio between thermal flux and epithermal flux	Φ_{th}/Φ_{epi}
Ratio between neutron current and neutron flux	J/Φ_{epi}

Several experiences in designing collimator for BNCT have been conducted both based on the materials selection and the geometry optimisation. A collimator consists of 5 components: collimator wall, moderator, filter, γ-ray shielding, and aperture.

Then, the collimator designing was conducted. A rough collimator design was made by using MCNP5 codes: 100 cm length of collimator, 54 cm of outer collimator diameter. Beam delimiter used was made of $^{6}Li_2CO_3$-polyethylene. In designing collimator, one should start with the varied size of collimator wall. Material used was Ni. The best thickness would be that the thickness which provided the highest epithermal neutron flux. Then, moderator, Al, was varied until the fast neutron component decrement no longer significant. In this point, ^{60}Ni as fast neutron absorber, which in fact also absorbed the thermal neutrons, was started to be used and varied until the fast and thermal neutron components desired reached. The next step was to employ Bi, as γ-ray shielding into the collimator and alter its thickness until the desired γ-ray component gained. The last parameter of beam quality, the directionality, was checked right after. If the directionality was less than desired, more beam delimiter would be added. The last step conducted was varying the aperture or the beam cross section size to find out the performance of the collimator design in different aperture size.

RESULT AND DISCUSSION

The Results and Discussion should be presented with clarity and precision. The results should be written in the past tense when describing findings in the author(s)'s experiments. Previously published findings should be written in the present tense. Results should be explained, but largely without referring to the literature. Discussion, speculation and detailed interpretation of data should not be included in the results but should be put into the discussion section and also should interpret the findings in view of the results obtained in this and in past studies on this topic. State the conclusions in a few sentences at the end of the paper. The Results and Discussion sections can include subheadings, and when appropriate, both sections can be combined.

3.1 Collimator Wall

All materials are recommended as a collimator wall tested by simulation using MCNP. The simulation results with variations in the thickness of 3 cm to 10 cm various materials shown in Figure 1.

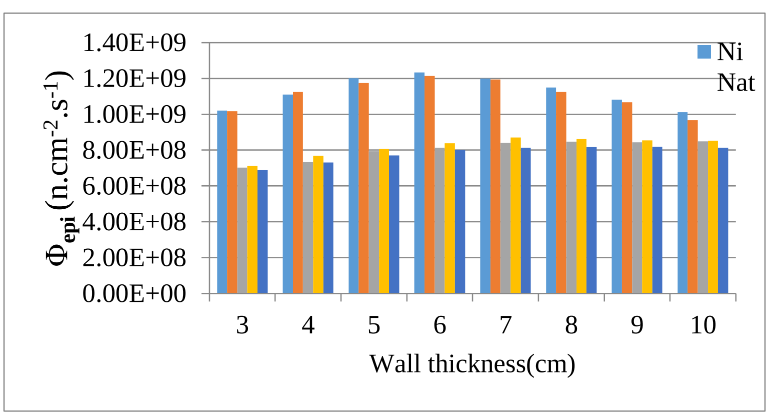


Figure.2. Epithermal flux comparison for various materials of collimator wall

3.2 Moderator

As shown as Figure.1 the best material to maintain the neutron is Nickel natural. Epithermal neutron flux which are reflected by the collimator wall material increased until an optimal thickness of 6 cm. This means that the thicker wall mounted collimator which means there will be more number of neutrons which are reflected. This increase is due to a shift in the neutron energy of fast neutrons into epithermal neutron. In the next thickness, epithermal neutron flux even more down. This is due to the thickness of the wall of a larger collimator makes the inside diameter of the smaller collimator causing more collisions between neutron collimator wall and causing a shift in the neutron energy growing up to run through the area of epithermal towards thermal area. Natural nickel is a very good material to be employed as a neutron collimator wall. Its atomic mass which is not too small, that would make too much energy decrement of neutrons, and yet not too high, that only would slightly shift.

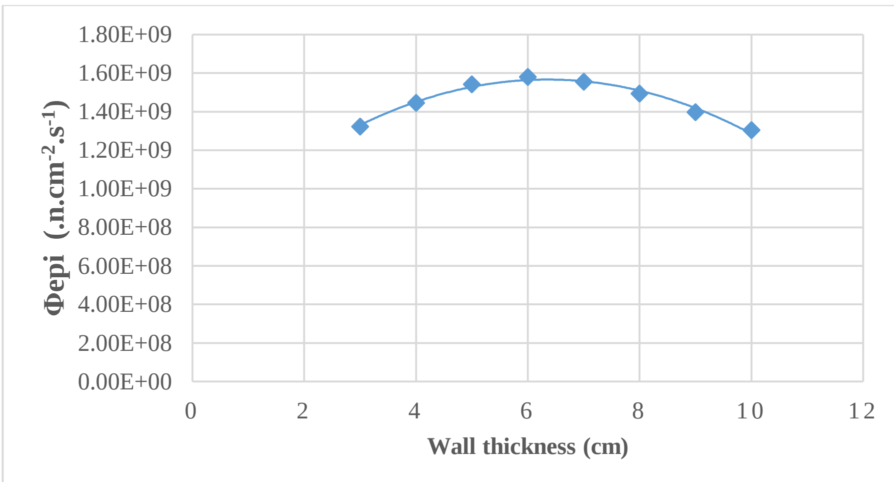


Figure.3. Epithermal neutron flux for various thickness of wall (Ni)

As shown in Figure 2, the flux increases when 3 to 10 cm of wall thickness is used. The thicker the collimator wall, the more neutrons would be reflected. The flux reaches its highest value (1.58 x 10^9 n.cm^{-2}.s^{-1}) in thickness of 6 cm.

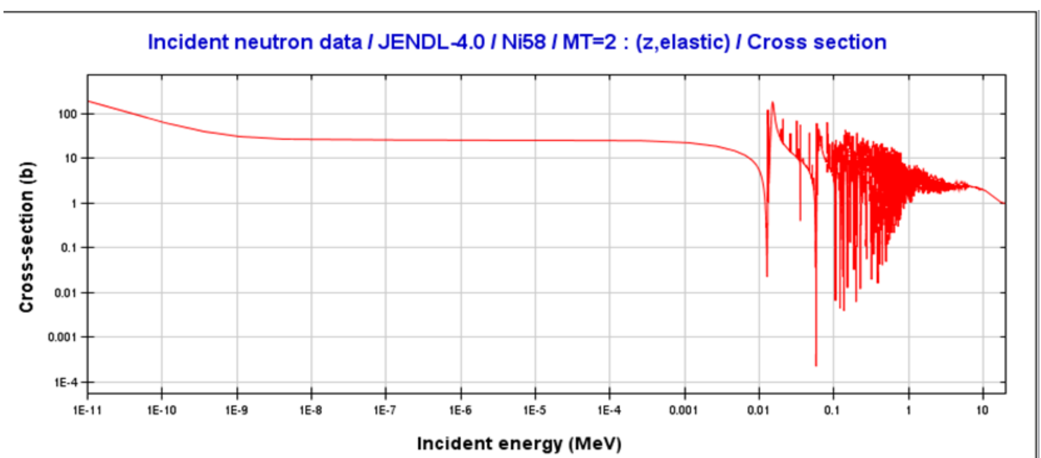


Figure.4. ^{58}Ni Scattering cross section (JANIS,2012)

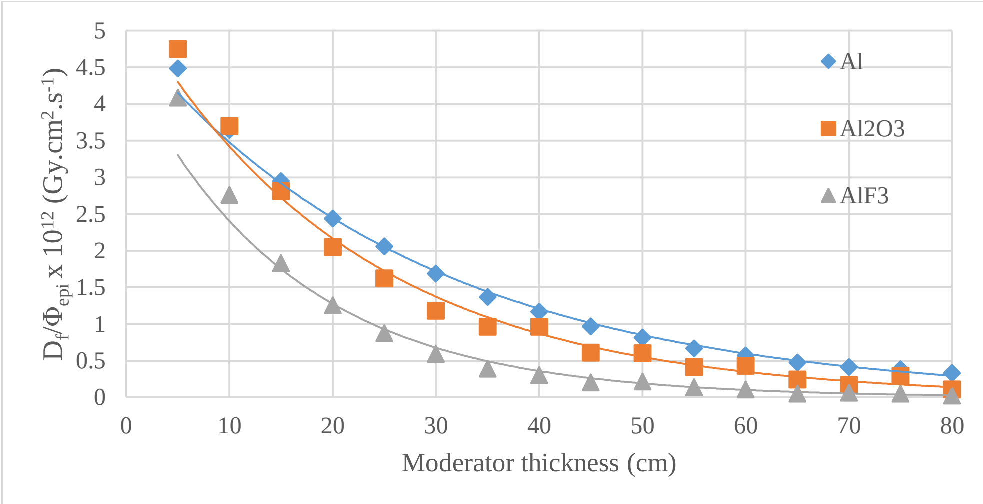


Figure.5. Fast neutron component for various material of moderator

From the graph we can see that the thicker the wall thickness will reduce the value of fast neutron component (Ḋf/Φepi). And we'll get that material AlF3 has the potential to moderate the fast neutrons is better than the material of Al and Al_2O_3. However, if we compare the number of epithermal neutron flux needed BNCT, look at the chart shows that the Al material better in epithermal neutron forward than the other two materials.

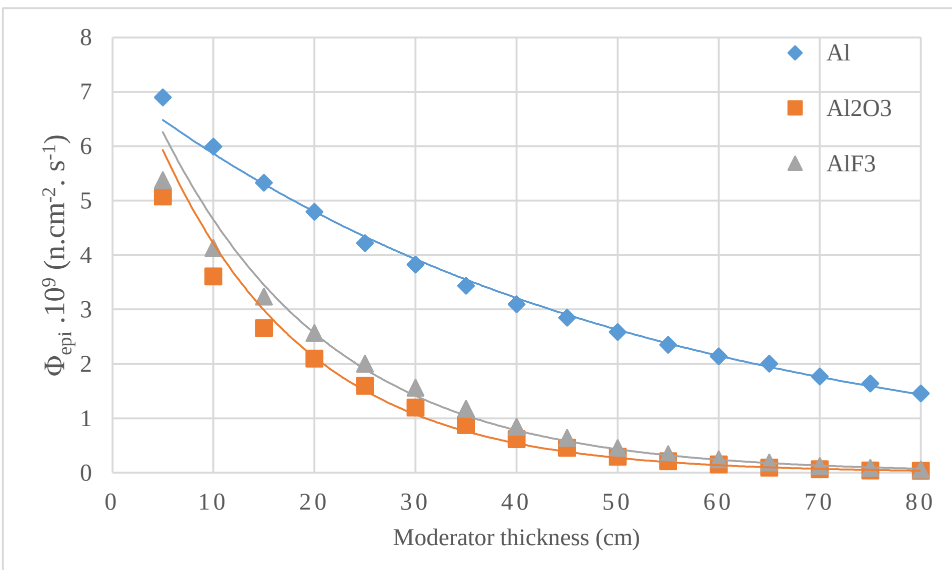


Figure.6. Epithermal flux for various material of moderator

Because of the IAEA requires epithermal flux minimum amount allowed is 10^9 n.cm^2.s^{-1}, the material Al_2O_3 and AlF_3 is not selected, resulting in the value of the thickness of the moderator is made of 35 cm, Φepi its value is below the minimum limit.

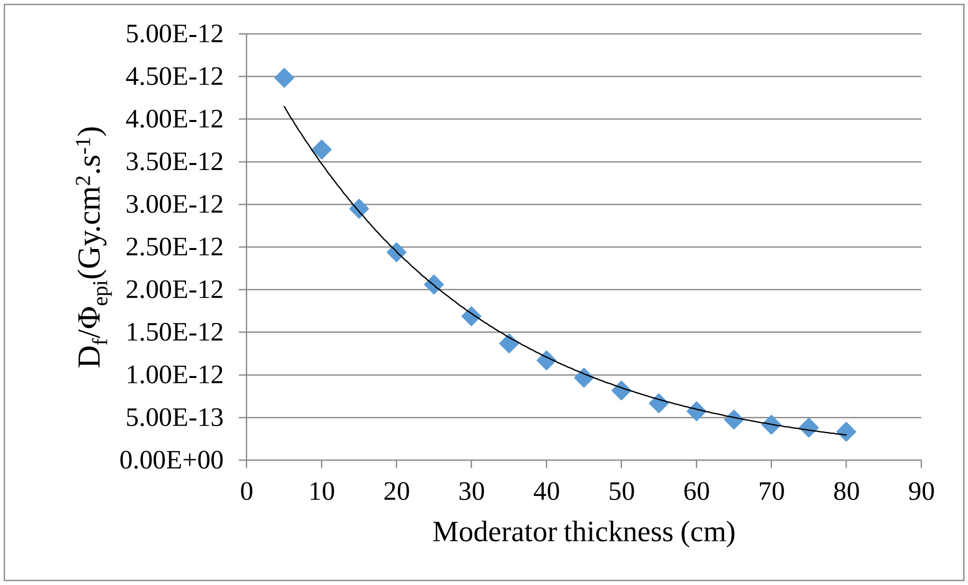


Figure.7. Fast neutron component for various thickness of moderator (Al)

From the above chart it is known that a decrease in fast neutron component decreased exponentially with the addition of material Al. For that we chose the moderator made of aluminum with a thickness of 65 cm for collimator which we design, because at this thickness and subsequent relatively stable.

3.3 Filter

By using Ni-60 material as a filter, obtained graph:

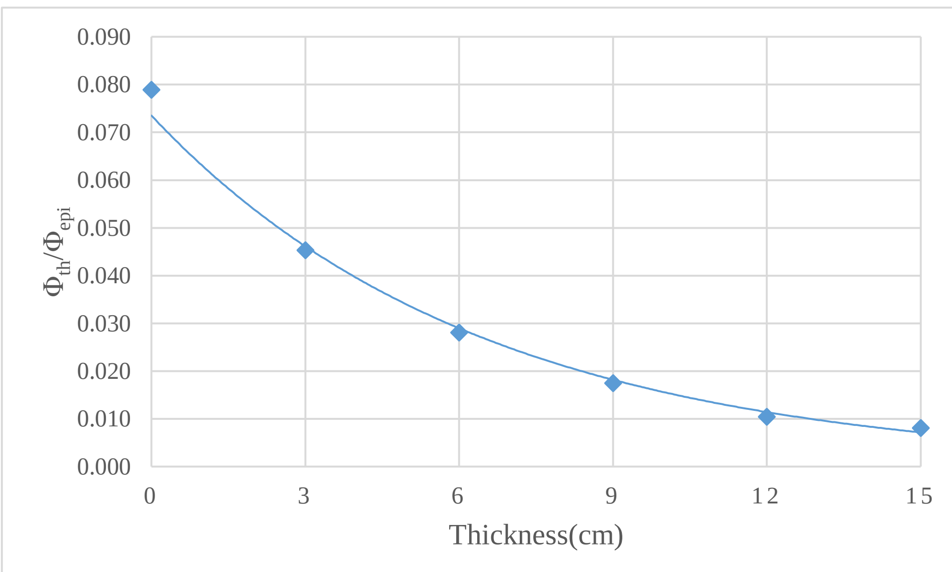


Figure.8. Fast neutron component for various thickness of filter (^{60}Ni) In Figure.6 shows that the Ni-60 Filter thickness of 3 cm was able to meet the requirements of the IAEA that the value Φth/Φepi already less than 0.05. The simulation results show that the value Φth/Φepi Ni-60 at a thickness of 3 cm which is equal to 0.0453.

3.3 Filter

Table.2. Results of γ-ray shielding (Bi) thickness variations.

Thickness	Φ_{epi}	$\dot{D}_f$	$\dot{D}_\gamma$	$\dot{D}_f / \Phi_{epi}$	$\dot{D}_\gamma / \Phi_{epi}$
1	1.02E+09	4.27E-04	5.45E-04	4.18E-13	5.33E-13
2	9.60E+08	3.79E-04	4.37E-04	3.94E-13	4.55E-13
3	9.36E+08	3.90E-04	3.47E-04	4.16E-13	3.71E-13
4	9.19E+08	3.81E-04	3.23E-04	4.15E-13	3.52E-13
5	8.95E+08	3.64E-04	2.89E-04	4.06E-13	3.23E-13
6	8.69E+08	3.42E-04	2.30E-04	3.94E-13	2.64E-13

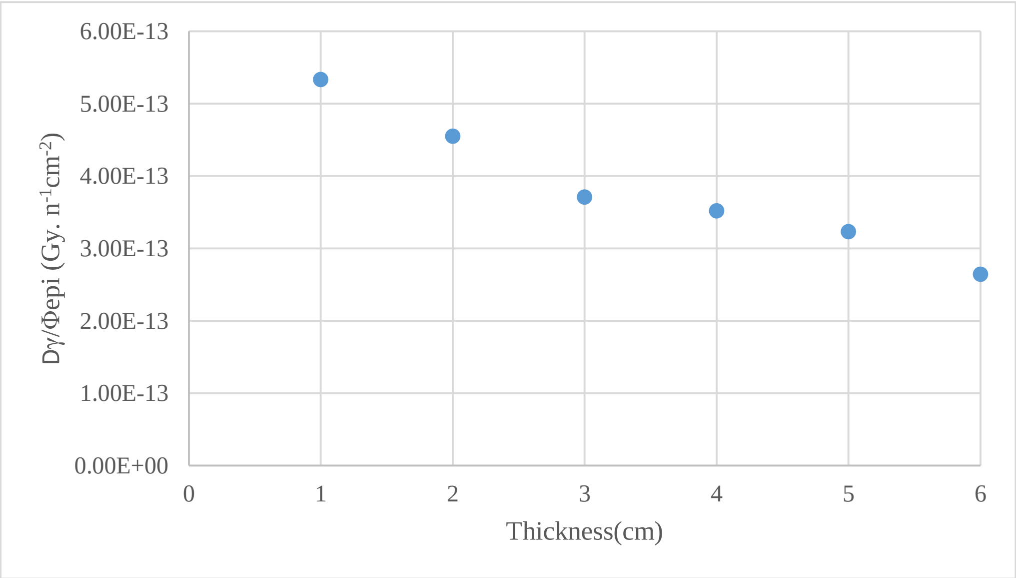


Figure.9. Gamma dose ratio per epithermal flux for various thickness of Bi Of all the gamma shield thickness variations, none of which meet the requirements of the IAEA (less than 2×10^{-13} Gy.n-^{1}cm^{-2}), therefore we chose 6 cm thick Bi material which has a value $\dot{D}\gamma/\Phi epi$ amounted to 2.64×10^{-13} Gy.n^{-1}cm^{-2}, the value of which is slightly greater than the maximum limit $D\gamma/\Phi epi$ required by the IAEA that is 2.0×10^{-13} Gy.n^{-1}cm^{-2}.

Table 5.2. Results of beam characteristics for various aperture diameter.

ϕ 61perture (cm)	3	4	5
Φ_{epi} (n cm^{-2} s^{-1})	6.86E+08	5.48E+08	6.97E+08
$\dot{D}_f / \Phi_{epi}$ (Gy.n^{-1} cm^{2})	1.55E-13	2.86E-13	3.02E-13
$\dot{D}\gamma / \Phi_{epi}$ (Gy.n^{-1} cm^{2})	3.89E-13	3.21E-13	1.65E-13
Φ_{th}/Φ_{epi}	0.0276	0.0758	0.0385
J/Φ_{epi}	0.736	1.5	2.1

This collimator design does not fully pass the IAEA's criteria, since the epithermal neutron flux is always below the recommended value of 1.0 x 10^9 $n.cm^{-2}.s^{-1}$. And the fast neutron component is above 2.0 x 10^{-13} $Gy.n^{-1}.cm^{-2}$. Furthermore, the optimization of the thickness of Li2CO3-polyethylene as follows:

Thick. (cm)	Φ_{epi} ($n\ cm^{-2}\ s^{-1}$)	$\dot{D}_f/\Phi_{epi}$ ($Gy.n^{-1}\ cm^2$)	$\dot{D}\gamma/\Phi_{epi}$ ($Gy.n^{-1}\ cm^2$)	Φ_{th}/Φ_{epi}	J/Φ_{epi}
0.5	6.78E+08	2.95E-13	1.88E-13	0.077	2.12
1	6.66E+08	3.35E-13	1.70E-13	0.056	2.15
1.5	6.99E+08	2.86E-13	2.18E-13	0.041	2.01
2	6.93E+08	3.12E-13	2.51E-13	0.045	2.10
2.5	**6.97E+08**	**3.02E-13**	**1.65E-13**	**0.038**	**2.10**
3	7.17E+08	2.34E-13	1.66E-13	0.052	2.08
3.5	**6.60E+08**	**1.82E-13**	**1.70E-13**	**0.041**	**2.12**
4	5.94E+08	4.59E-13	1.89E-13	0.047	2.24
4.5	5.77E+08	5.63E-13	1.85E-13	0.059	2.25

From the start delimiters thickness of 2.5 cm, the flux output parameter in the fast neutron component has improved such that can satisfy the IAEA recommendations at a maximum of 2 x10-13 $Gy.n^{-1}cm^{-2}$ at a thickness of 3.5 cm delimiter. Thus, the end result of the optimization is carried out as follows:

Parameter	Value	IAEA recomendation
Φ_{epi} ($n\ cm^{-2}\ s^{-1}$)	6.60 x 10^8	> 10^9
$\dot{D}_f/\Phi_{epi}$ ($Gy.n^{-1}\ cm^2$)	1.82 x 10^{-13}	< 2 x 10^{-13}
$\dot{D}\gamma/\Phi_{epi}$ ($Gy.n^{-1}\ cm^2$)	1.70 x 10^{-13}	< 2 x 10^{-13}
Φ_{th}/Φ_{epi}	0.041	< 0.05
J/Φ_{epi}	2.12	> 0.7

The final results of optimization that has been done shows there is one parameter that has not been achieved according to the IAEA recommendations epithermal flux value of 6.60 x 10^8 n cm^{-2} s-1 This value is below the recommended standard IAEA flux of more than 1 x 10^9 n cm^{-2} s^{-1}. Although it has not reached the criteria, the results are still eligible to be used for more than 5 x 10^8 $n.cm^2.s^{-1}$.

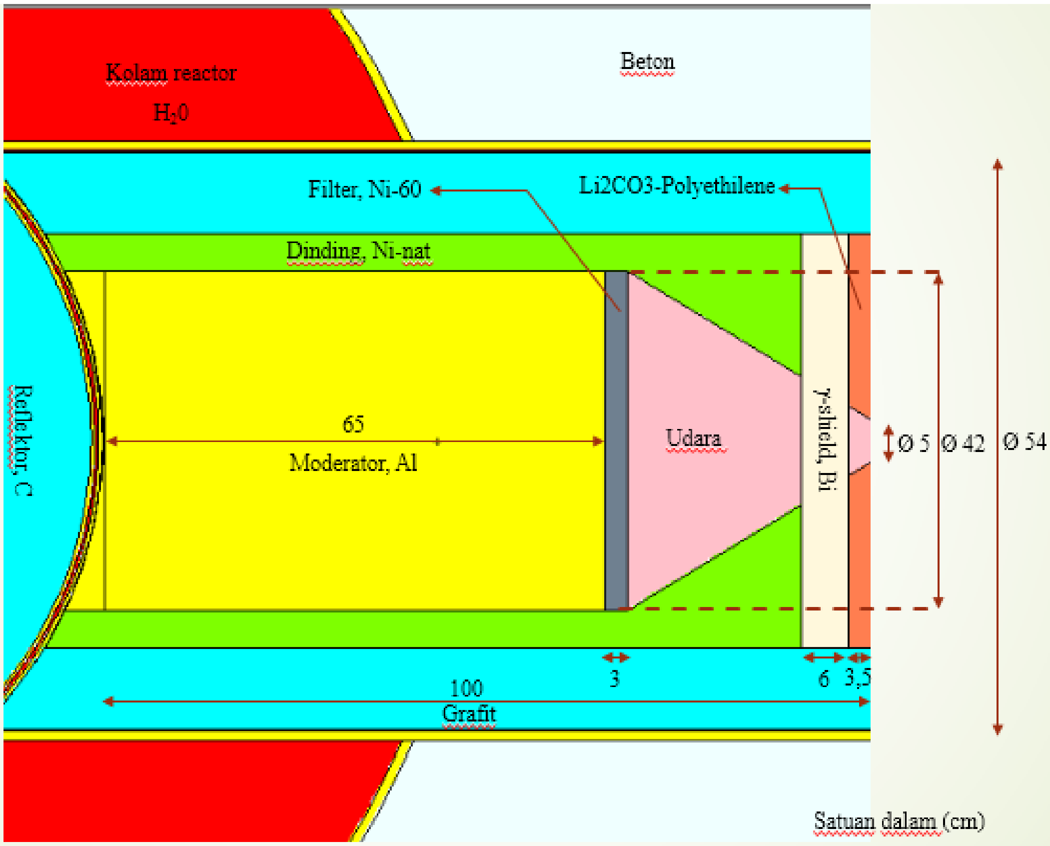


Figure.8. Collimator configuration

CONCLUSION AND REMARKS

The optimization is performed to produce:

1) Wall Collimator: Ni purity of 95% with a 6 cm thick
2) Moderator: Aluminium with a length of 65 cm
3) Filter: 60Ni with a thickness of 3 cm
4) Shield γ: Bi with optimum thickness of 6 cm.
5) Beam delimiters: Li2CO3 with a diameter of 5 cm and a diameter of 3.5

Output beam from the design shown in the following five parameters:

Φepi	: 6.60 x 10^8 $n.cm^{-2}$ s^{-1}
$\dot{D}$f/Φepi	: 1.82×10^{-13} $Gy.n^{-1}$ cm^2
$\dot{D}\gamma$/Φepi	: 1.70×10^{-13} $Gy.n^{-1}$ cm^2
Φth/Φepi	: 0.041
J/Φepi	: 2.12

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