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Optimization of the fission-converter and filter set-up for the boron-neutron capture therapy (BNCT)

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Abstract

The paper presents the third step of the numerical modeling of the fission-converter-based epithermal neutron source designed for the Polish Boron Neutron Capture Therapy (BNCT) facility to be located at the Polish research nuclear reactor MARIA at Świerk. The optimization of the fission converter has been carried out again. The epithermal neutron flux has increased 240 % comparing with the variant proposed previously while the number of fuel rods was significantly reduced. The specific photon and fast neutron doses meet the requirements of the therapy. Optimization of the reflector surrounding the filter/moderator as well as collimator shape, length and liner has been also carried out. Configuration of the filter/moderator has remained the same. Criticality calculations show that k_{eff} of the fission converter filled with light water is below 1. The MCNP code has been used during computations.

1. Introduction

The paper presents the final step of Monte Carlo calculations concerning design of the BNCT (Boron Neutron Capture Therapy) facility to be located at the MARIA nuclear reactor at Świerk. The previous computations were described in the IFJ reports issued in the last two years [1, 2]. The BNCT [3, 4] is the up-to-date method to treat some kinds of cancer (mainly glioblastoma multiforme) which, due to their character, are hard to be extracted with surgical methods. Adequately large number of thermal neutrons, which cause the nuclear reaction, delivered in suitable time is an important factor in the BNCT. It is estimated [4] that time of irradiation is not longer than 10 ÷ 15 minutes when the epithermal neutron flux incident patient's skin is at least 10^{10} n/cm^2·s.

The MARIA nuclear reactor is to be used as the neutron source. The aim of the authors is to design the BNCT facility to obtain the maximum possible epithermal neutron flux. Since neutrons at the outlet of the reactor duct are too slow – mainly thermal energies – it is essentially to use a neutron converter that contains fissionable material. Fast neutrons from the ^{235}U fission are to be slowed down to the thermal energies using a filter/moderator set-up. Because fast neutrons and photons, present in the radiation beam, affect both healthy and tumor tissues the same way, they are useless for therapy purposes. Hence, photon and fast neutron doses should be suitably reduced with some filters so that they not exceed 10 % of epithermal neutron dose [2].

The previous computations enabled to select the optimal variant of the fission converter [1, 5] and the filter/moderator set-up [2]. Optimization of the collimator and the reflector surrounding the filter is presented. Although the configuration of the fission converter was claimed to be finished [2] further investigations have been taken up in order to achieve a better performance of the therapeutic beam.

The research presented in the paper has been conducted using the MCNP code [6].

2. Reflector

In the previous simulations the 10 cm lead reflector was assumed [2]. Since the material and its thickness were selected arbitrary is it essential to optimise also this part of the filter/moderator arrangement. Two materials, lead and bismuth, has been taken into account due to their high atomic mass and high scattering cross sections for epithermal neutrons. Thickness of both materials has been changed in the range 0 ÷ 18 cm with 2 cm increment.

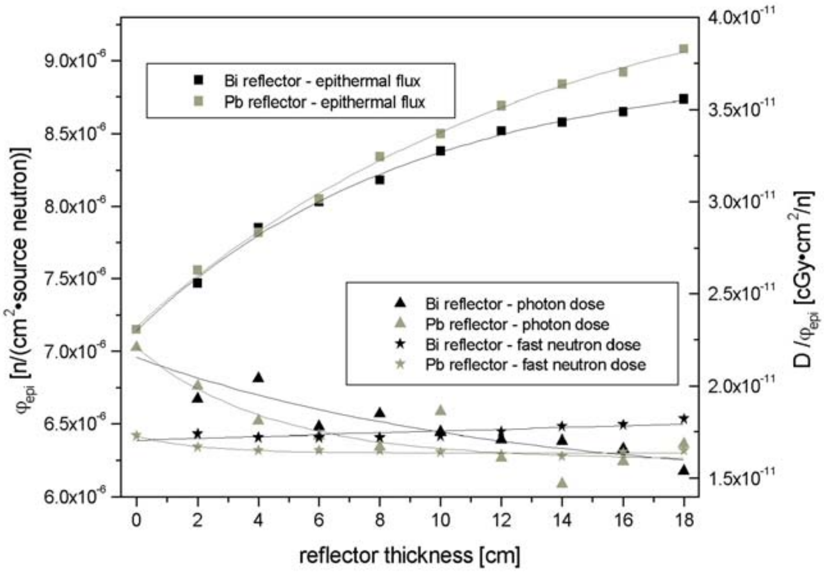

Fig.1. Epithermal neutron flux and the specific photon and fast neutron doses *vs*. Bi and Pb reflector thickness.

As it is presented in Fig. 1 the epithermal neutron flux increases with the thickness of the reflector. Lead proves a better material and differences are more significant for thicker reflectors. Contaminations of the therapeutic beam (photons and fast neutrons) for reflectors thicker than 4 cm are below the recommended value $2\cdot10^{-11}$ $cGy\cdot cm^2/n$.

Although the 18 cm lead reflector provides the largest epithermal neutron flux the lead reflector of 10 cm has been used in further computations because a large mass of the thick reflector may cause structural problems. However, the use of a thicker reflector should be considered if it does not cause any danger to safety.

3. Optimisation of the fission converter

The second step of the modelling brings optimisation of the fission converter, which seemed to be finished [2]. After all, further effort has been made to achieve better performance of the therapeutic beam. The expected epithermal neutron flux may be not intense enough to meet the needs of BNCT.

First of all the filter/moderator system has been shifted 15 cm toward the fission converter to minimise distance between them. Moreover the rectangular shape of the fission

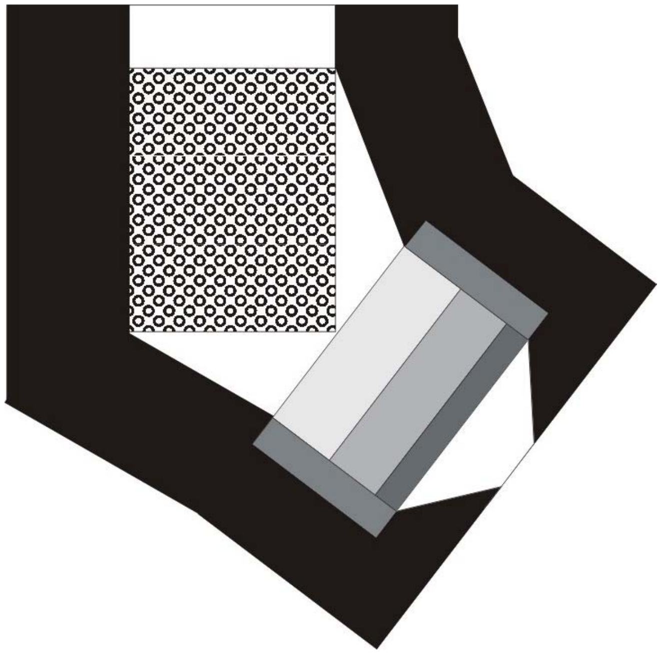

Fig.2. Fission converter and filter/moderator arrangement with the filter shifted as close as possible toward the converter.

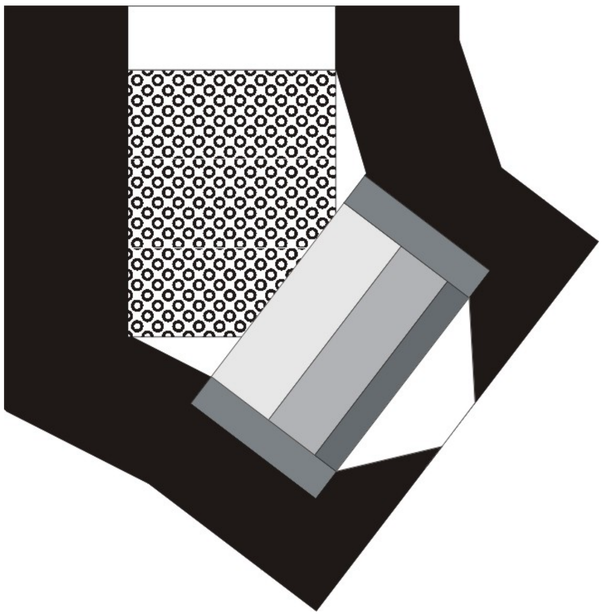

Fig.3. Fission converter and filter/moderator arrangement with the filter shifted of 20 cm toward the reactor duct outlet.

converter has been abandoned. In the first calculated case the filter/moderator system has adjoined the rectangular fission converter (Fig. 2) then the filter has been gradually moved (2, 4, 8, 12, 16 and 20 cm) and simultaneously the number of uranium rods in the fission converter has been changed (Fig. 3). The initial number of rods (780) has been decreased to 778, 775,

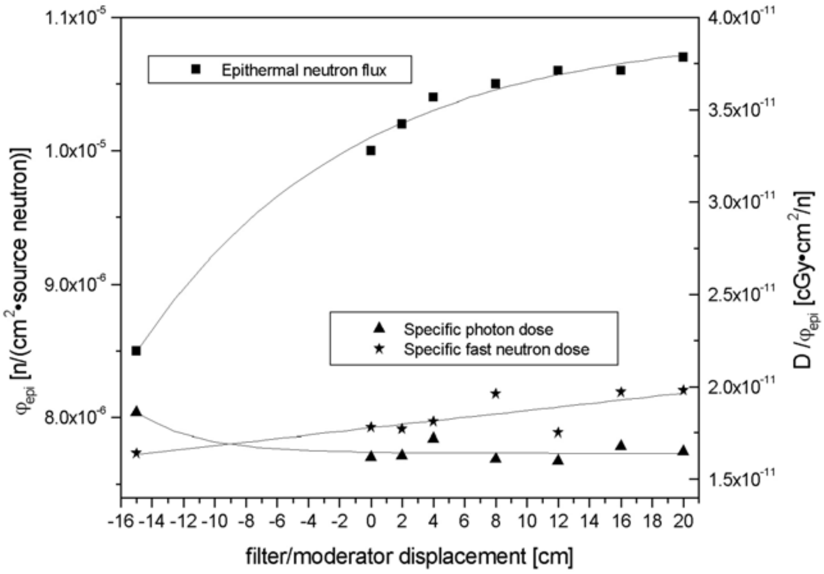

Fig.4. Epithermal neutron flux and the specific photon and fast neutron doses *vs*. filter/moderator displacement.

765, 749, 728 and 702, respectively. Fig. 4 shows results of calculations. The epithermal neutron flux increases when the filter is moved - up to $1.07 \cdot 10^{-5}$ n/cm^2 for the filter shifted of 20 cm – though the total uranium mass in the fission converter decreases. The difference with the "basic" case (-15 cm in Fig. 4), when the epithermal neutron flux is $8.50 \cdot 10^{-6}$ n/cm^2, is significant. Specific photon and fast neutron doses are still below required limits.

The foregoing results indicate that geometrical effects predominate performance of the therapeutic beam. Thus, another modifications of the set-up have been investigated. The filter/moderator location has been the same like in Fig. 2, when it adjoined the fission converter, but the fuel rods have been arranged in the entire accessible space. Because it is expected that rods situated closer to the filter/moderator provide larger contribution to the neutron flux, the uranium rods have been distributed irregularly. Number of rods has been gradually reduced, starting from 768 to 377, in order to select their optimal number. There have been two rods' zones: the first one "dense" has comprised of the constant number of 143 uranium rods and has been situated alongside the filter/moderator. The second zone "sparse" has been located closer to the reactor duct outlet. The rods in the second zone have been gradually removed – usually two rows of the fuel rods at a time. Fig. 5 presents the arrangement for 441 fuel rods. Results of calculations - showed in Fig. 6 – imply that uranium rods situated in the left-top

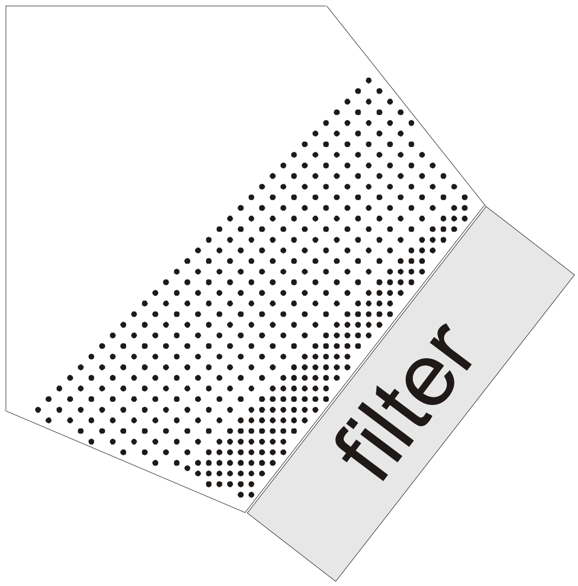

Fig.5. Fission converter arrangement (441 rods) with two rod zones.

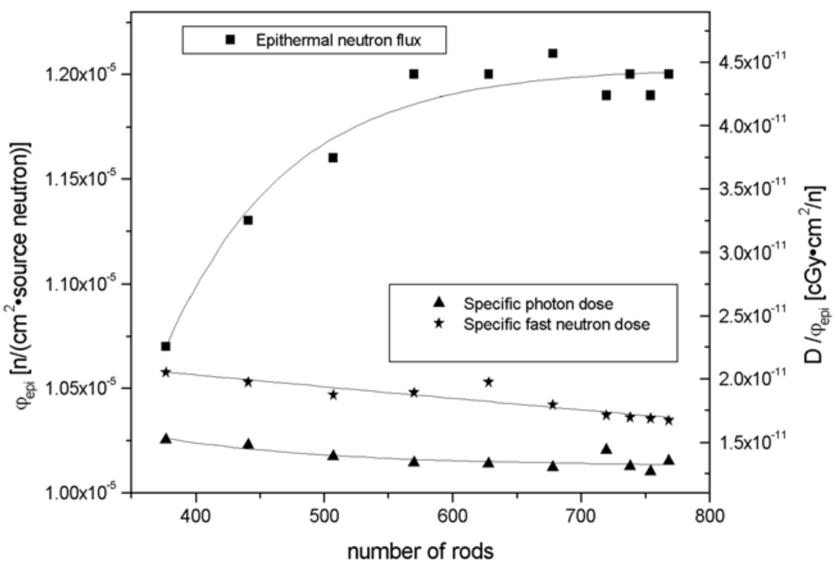

Fig.6. Epithermal neutron flux and the specific photon and fast neutron doses *vs.* number of rods arranged in two zones.

corner of the fission converter region are useless. The epithermal neutron flux reaches plateau for 570 rods and its value is almost stable ($1.19 \div 1.21 \cdot 10^{-5}$ n/cm^2) when the number of rods increases. Moreover, geometrical arrangement of the uranium rods seems more important than the total mass of ^{235}U in the converter due to self-absorption [2]. Also the distance between the filter/moderator and the reactor duct outlet ought to be minimized.

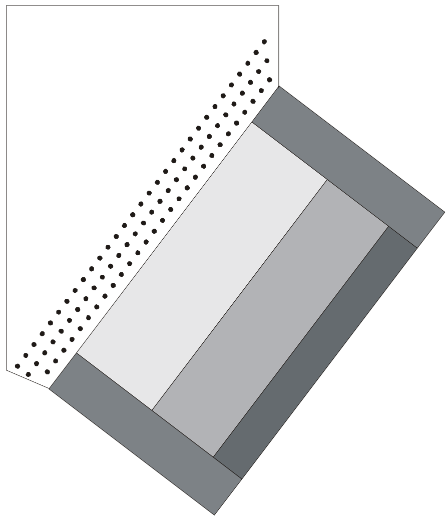

Fig.7. Fission converter with 89 rods arranged in 3 cm grid. The filter/moderator shifted 40 cm toward the reactor duct outlet.

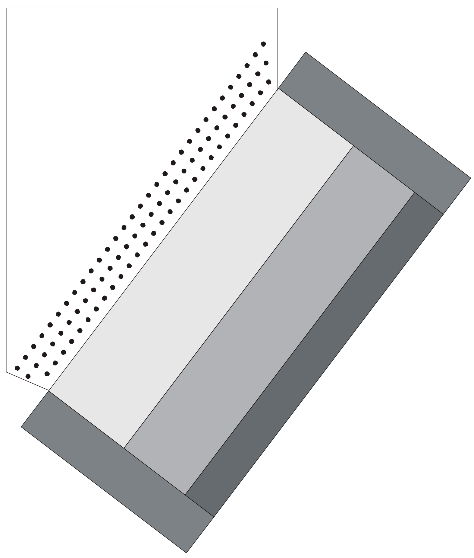

Fig.8. Fission converter with 89 rods arranged in 3 cm grid. The filter/moderator shifted 40 cm toward the reactor duct outlet and widened of 20 cm.

The next major change has consisted in a displacement of the filter/moderator system as far as possible (40 cm) toward the reactor duct. The fuel rods have been arranged in the 3 cm grid (distance between adjacent rods) as it is shown in Fig. 7. In order to better utilize neutrons from fission the filter/moderator has been extended to 84 cm – initially it was 64 cm wide (Fig. 8). Comparison of both filter widths has been carried out (Fig. 9) for various numbers of the uranium rods. In each case the epithermal neutron flux is higher for the wider filter/moderator. It should be noticed that its value reaches $1.41 \cdot 10^{-5}$ n/cm^2 (259 and 299 rods) though the number of rods is lower than for the previous arrangement presented in Fig. 5. Therefore, the filter – reactor duct interval seems to be the key factor from the point of view

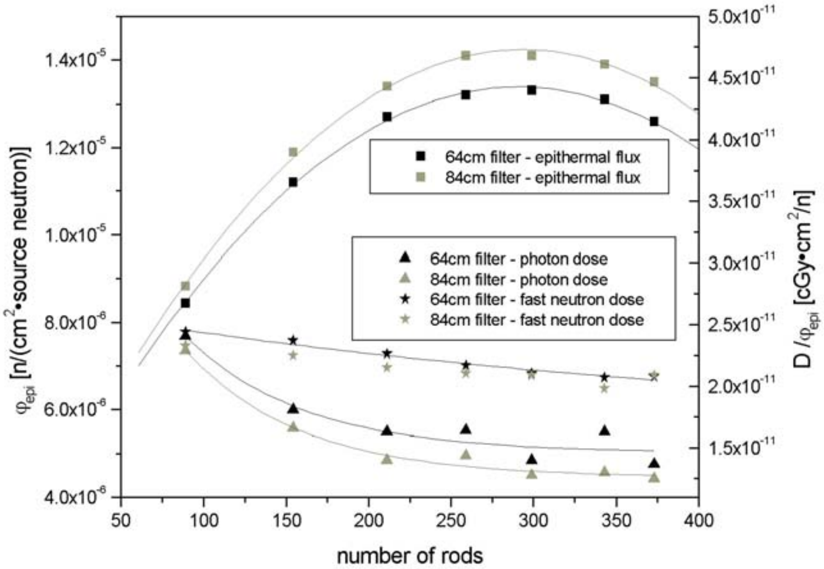

Fig.9. Epithermal neutron flux and the specific photon and fast neutron doses *vs.* number of rods in 3 cm grid for two widths of the filter/moderator.

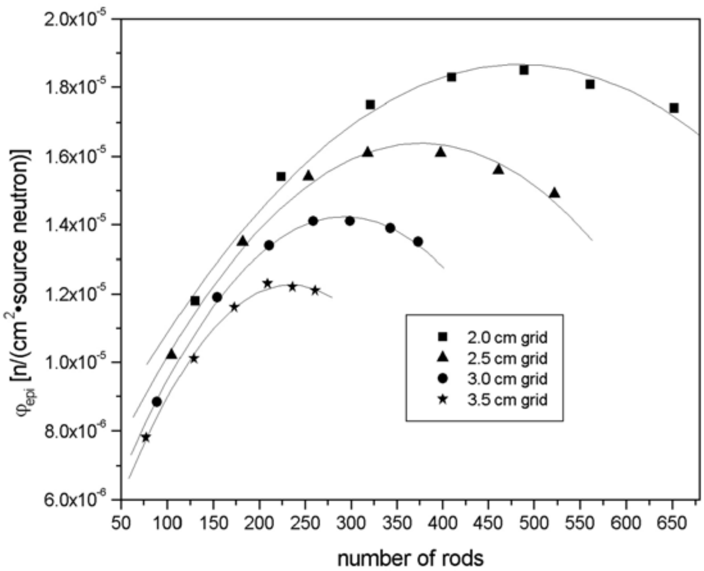

Fig.10. Epithermal neutron flux *vs*. number of rods arranged in 2, 2.5, 3 and 3.5 cm grids for the filter/moderator width of 84 cm.

of the maximization of the epithermal flux. On the other hand, the fast neutron specific dose exceeds slightly $2\cdot10^{-11}$ cGy·cm^2/n but its values are still acceptable.

Another arrangements of the uranium rods have been also investigated: 2 cm, 2.5 cm and 3.5 cm grids (Fig. 10). In all cases the filter/moderator width has been assumed 84 cm since it brings a better performance of the therapeutic beam. The 2 cm grid ensures the maximal epithermal neutron fluxes even when the number of rods is comparable with other grids. In case of 489 rods (2 cm grid) the epithermal neutron flux reaches maximum $1.85\cdot10^{-5}$ n/cm^2.

4. Collimator

In the previous calculations a graphite 20 cm conical collimator was modelled. Both its length and a material to line the collimator should be optimised. The shape will be discussed in the next chapter of this paper. Materials to be used as a liner should meet similar requirements like in selecting the reflector. Lead, bismuth and nickel have been investigated in the configuration with 489 rods arranged in 2 cm grid and the 84 cm wide filter. Thickness of each material has been changed in the range 1 ÷ 20 cm with irregular increment (1, 2, 3, 4, 5, 7, 10, 15 and 20 cm). Results of calculations are shown in Fig 11. Nickel provides even worse performance of the therapeutic beam than graphite. From among two other materials

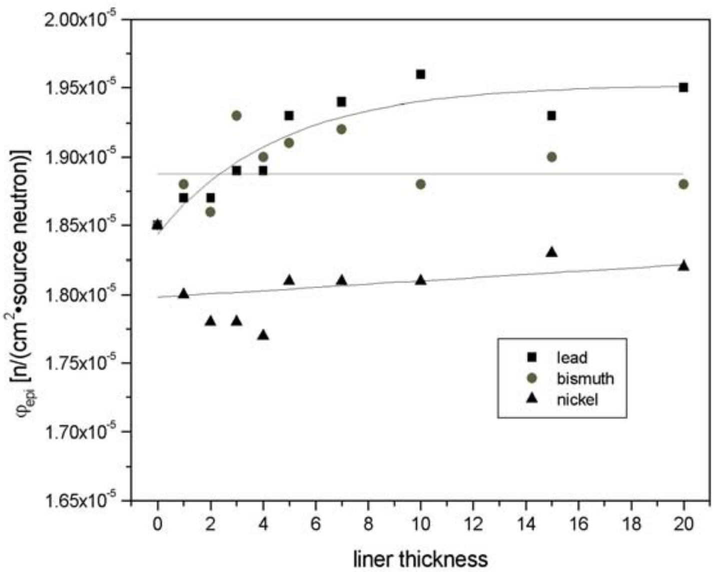

Fig.11. Epithermal neutron flux *vs*. liner thickness (lead, bismuth and nickel) for 20 cm conical collimator.

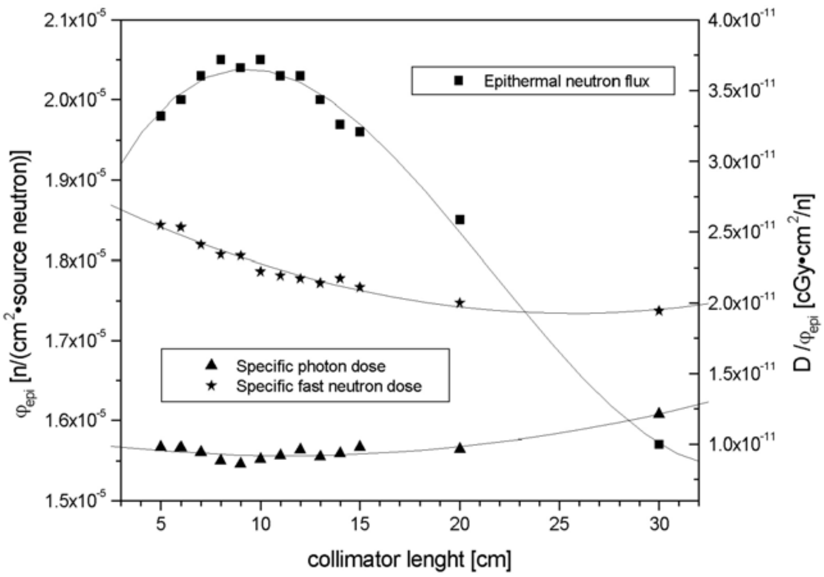

Fig.12. Epithermal neutron flux and the specific photon and fast neutron doses *vs.* collimator length with no liner.

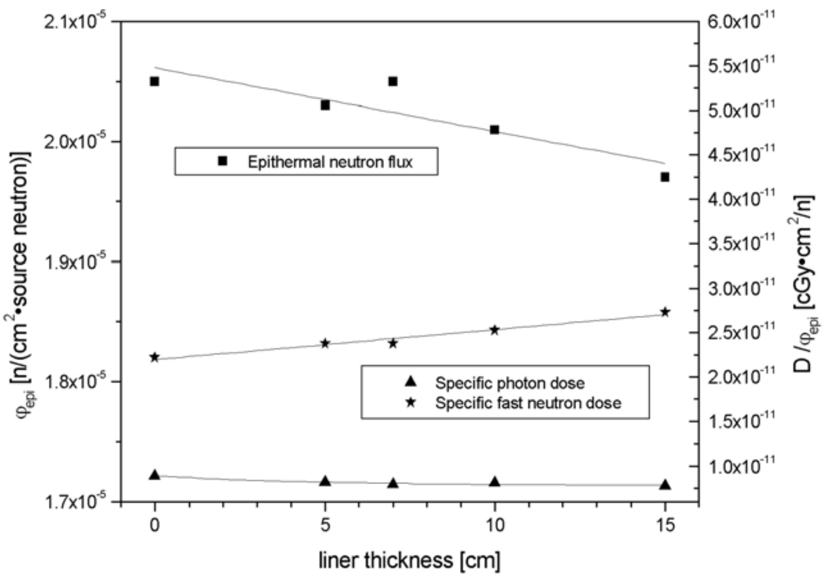

Fig.13. Epithermal neutron flux and the specific photon and fast neutron doses *vs.* liner thickness for 10 cm conical collimator.

lead supplies better results. The use of 5 ÷ 10 cm lead liner brings increase of the epithermal neutron flux of 4 ÷ 6 %.

Optimisation of the collimator length has been carried out for the graphite without any liner. The length has been changed from 5 cm up to 30 cm (Fig.12). The highest epithermal neutron flux ($2.05\cdot10^{-5}$ n/cm^2) has been obtained for 10 cm collimator while the specific fast neutron dose has been $2.22\cdot10^{-11}$ cGy·cm^2/n. On the other hand, the specific photon dose is very small ($8.94\cdot10^{-12}$ cGy·cm^2/n) and compensates in excess the specific fast neutron dose.

In the light of the results of the collimator liner optimization it has been expected to obtain even better results when the collimator is lined with lead. Results of simulations for 10 cm collimator with 0, 5, 7, 10 and 15 cm lead liner are presented in Fig. 13. In defiance of expectations and results for 20 cm cone graphite, the use of the lead liner does not bring benefits in case of the shortened collimator.

5. Criticality and final optimisation of the fission converter

In the chapter 3 the fission converter with 489 rods arranged in the 2 cm grid has been selected as the optimal one. Unfortunately, criticality calculations for the foregoing configuration have showed that k_{eff} is 1.00 when the fission converter is filled with water. For the 2.5 cm grid with 398 rods, in analogous situation, k_{eff} is 0.92. Another, “mixed” grid has been investigated (Fig. 14). The fuel rods have been arranged in 1.8 cm grid (245 rods in 5 rows) alongside the filter/moderator and in 2.5 cm grid (244 rods in 8 rows). Thus, the total number of rods has been the same. In this configuration k_{eff} is 0.98 when the converter is accidentally filled with light water.

In order to compare performance of the converter with the mixed grid vs. 2 cm and

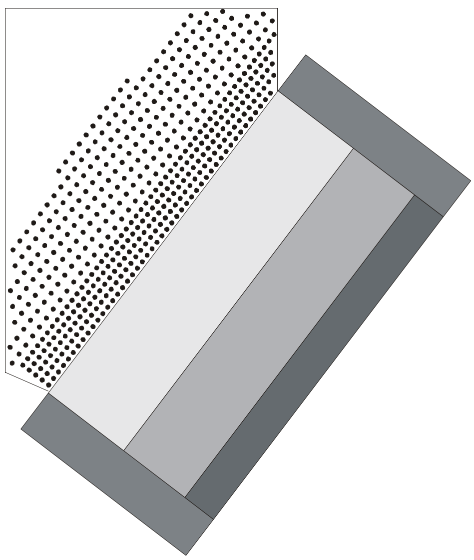

Fig.14. Fission converter with 489 rods arranged in mixed 1.8 and 2.5 cm grid. The filter/moderator width is 84 cm.

2.5 cm grids, calculations for 20 cm conical collimator without liner and the 84 cm wide fil

ter/moderator have been carried out. The epithermal neutron flux for the mixed 1.8+2cm grid is $1.80 \cdot 10^{-5}$ n/cm^2. This is less than for the 2 cm grid ($1.85 \cdot 10^{-5}$ n/cm^2) but noticeably more than the maximum result in case of the 2.5 cm grid: $1.61 \cdot 10^{-5}$ n/cm^2 (see Fig. 10) when 318 or 398 uranium rods were used.

Table 1. Epithermal neutron flux and specific doses „in-air".

configuration	ϕ_{epi} [10^{-5} n/cm^2] per source neutron	D_γ/ϕ_{epi} [10^{-11} cGy·cm^2/n]	D_{fn}/ϕ_{epi} [10^{-11} cGy·cm^2/n]
84 cm filter/moderator 20 cm conical collimator	1.80	1.23	2.03
84 cm filter/moderator 10 cm conical collimator	1.98	0.93	2.25
84 cm filter/moderator 10 cm pyramid collimator	2.02	0.90	2.30
101 cm filter/moderator 10 cm pyramid collimator	2.04	0.81	2.19

According to results of collimator optimization, the conical collimator (without liner) has been shortened to 10 cm. The epithermal neutron flux has increased, as it was expected, to $1.98 \cdot 10^{-5}$ n/cm^2. Because the conical shape of the collimator is hard to be constructed the 10 cm collimator of a square cross-section (truncated pyramid shape) has been modeled. This shape of the collimator has proved more efficient and the epithermal neutron flux has been $2.02 \cdot 10^{-5}$ n/cm^2. Finally the filter/moderator has been widened to 101 cm (Fig. 15) what brings a small improvement of the set-up. The fuel rods (the same total number - 489) have been also arranged in 1.8 cm (270 rods in 5 rows) and 2.5 cm grid (219 rods in 7 rows). The results are collected in Table 1.

The specific fast neutron dose is slightly exceeded but this should not bring any harm from the therapeutic point of view. Moreover, the specific photon dose is much below recommended value ($2 \cdot 10^{-11}$ cGy·cm^2/n). Therefore, the 10 cm collimator with the square cross section as well as 101 cm filter/moderator should be used since this arrangement provides the best performance of the beam.

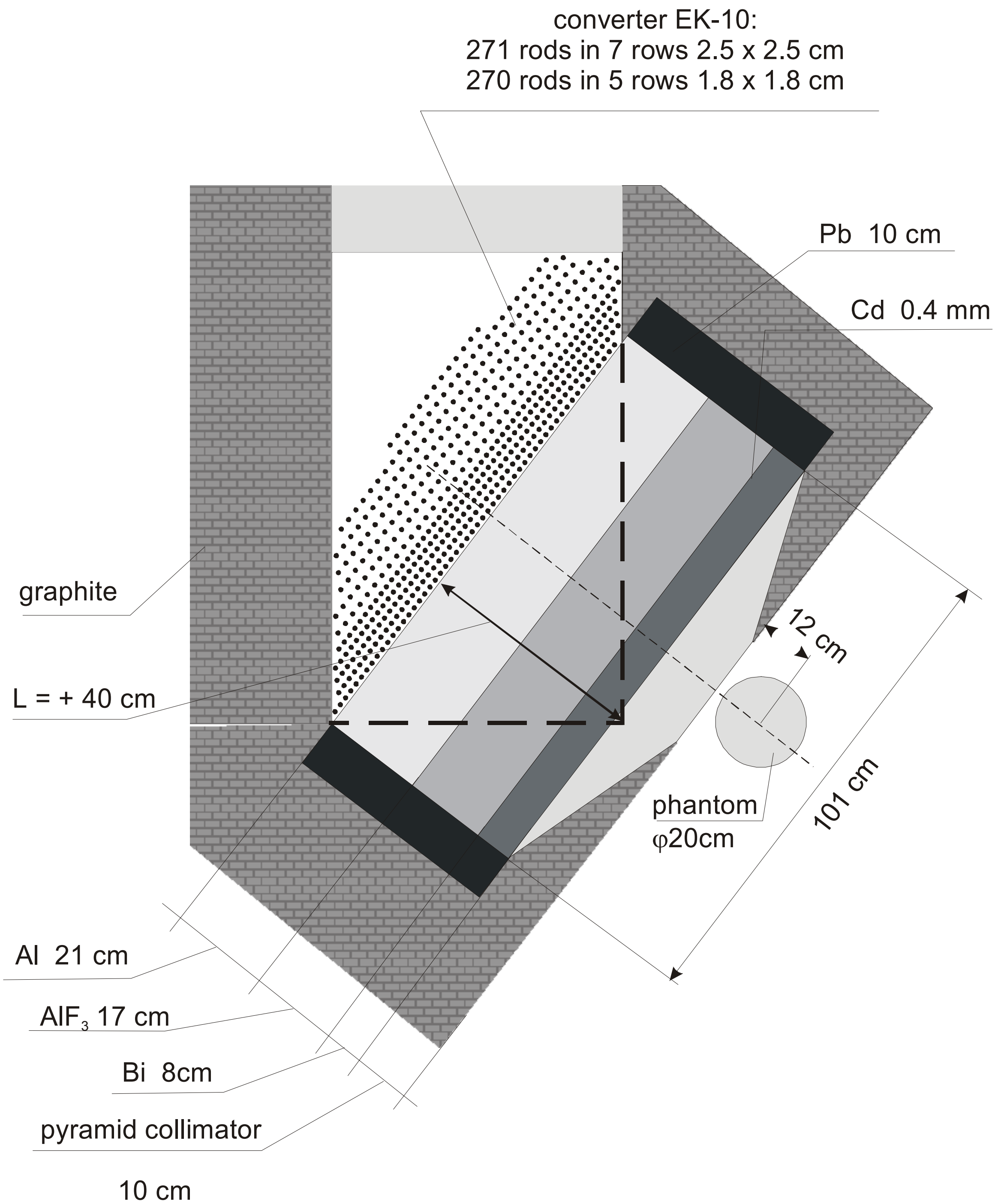

Fig.15. Fission converter with 489 rods arranged in mixed 1.8 and 2.5 cm grid. The filter/moderator width is 101 cm.

6. Conclusions

The arrangement of the fission converter has been noticeably improved comparing with the variant proposed previously [2] when the maximum epithermal neutron flux was $8.50\cdot10^{-6}$ n/cm^2. The epithermal neutron flux has increased to $1.80\cdot10^{-5}$ n/cm^2 when the filter/moderator system has been shifted toward the reactor duct outlet, the filter has been widened to 84 cm and the fuel rods have been located in the mixed grid. The further improvements concerning collimator shape and length as well as broadening of the filter up to 101 cm bring the epithermal neutron flux $2.04\cdot10^{-5}$ n/cm^2 per one source neutron. The optimization reduces the number of the fuel rods from 780 to 480 – the total ^{235}U mass decreases from 6.275 kg to 3.934 kg. This should facilitate piping away of heat from the converter. The uranium rods should be placed in the mixed grid 1.8+2.5 cm, which ensures safety since k_{eff} is below 1 when converter is filled with light water. The proposed arrangement consists of 270 fuel rods in 5 rows placed in the 1.8 cm grid and 219 rods in 7 rows placed in the 2.5 cm grid. The corresponding filter/moderator width is 101 cm (Fig. 15). It is suggested to use 10 cm graphite collimator (without liner) of a square cross section. In the foregoing set-up the specific fast neutron dose exceeds the recommended value (Table 1) but this should not have significance during therapy. Furthermore the specific photon dose is very small and compensates surplus of the fast neutron specific dose.

The optimization has been carried out with 10 cm lead reflector. In the light of the results presented in the Chapter 2 the use of a thicker lead reflector should be considered.

The filter/moderator system remains unchanged *i.e.* comprises of 21 cm of aluminum and 17 cm of AlF_3 (neutron moderator) as well as 0.4 mm of cadmium (thermal neutron filter) and 8 cm of bismuth (photon filter) surrounded with reflector [2]. The lateral graphite shield (36 cm) should enclose the entire arrangement.

References

1. Woźnicka U., Tracz G., Dworak D., Symulacje komputerowe konwertera uranowego jako źródła neutronów dla terapii borowo-neutronowej (BNCT). INP Report 1886/AP. 2001. Kraków. (in Polish). http://www.ifj.edu.pl/reports/2001.html
2. Tracz G., Woźnicka U., Optimization of the fission-converter and the filter/moderator arrangement for the boron-neutron therapy (BNCT). INP Report 1913/AP. 2002. Kraków. http://www.ifj.edu.pl/reports/2002.html
3. Nigg D.W., Some Recent Trends and Progress in the Physics and Biophysics of Neutron Capture Therapy. Progress in Nucl. Energy. 35(1). (1999). 79-127.
4. Kiger III W.S., Sakemoto S., Harling O.K., Neutronic Design of a Fission Converter-Based Epithermal Neutron Beam for Neutron Capture Therapy. Nucl. Sci. Eng. 131. (1999). 1-22.
5. Pytel K., Dąbkowski J., Optymalizacja konwertera uranowego dla potrzeb BNCT w reaktorze MARIA. Założenia do obliczeń. 2001. Internal report. Warszawa. (in Polish)
6. Briesmaister J.F., MCNP – A General Monte Carlo N-Particle Transport Code. Version4C. Los Alamos National Laboratory. LA-13709-M. 2000.