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Optimised BNCT facility based on a compact D-D neutron generator

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▶ ***Original article***

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ABSTRACT

Background: Boron Neutron Capture Therapy (BNCT) is a very promising treatment for patients suffering gliobastoma multiforme, an aggressive type of brain cancer, where conventional radiation therapies fail. Thermal neutrons are suitable for the direct treatment of cancers which are located at near-tissue-surface; deep-seated tumors need harder, epithermal neutron energy spectra. ***Materials and Methods:*** In this work a BNCT facility based on a compact D–D neutron generator, has been simulated using the MCNP4B Monte Carlo code. The materials considered, for the design of the facility, were chosen according to the EU Directive 2002/95/EC, hence, excluded the use of cadmium and lead. ***Results:*** An extensive set of calculations performed with MCNP4B Mote Carlo code have show that the combination of TiF_3 which integrates a conic part made of D_2O, then followed by a TiF_3 layer is the optimum moderator design. The use of BiF_3 as spectrum shifter and γ rays filter, Titanium as fast neutron filter and Lithium as thermal neutron filter is necessary in order to obtain an epithermal neutron beam with high quality. ***Conclusion:*** The simulations show that, even if the neutron flux is below the recommended value for clinical treatment, the proposed facility is a good alternative for clinics which cannot afford to build and maintain a small nuclear reactor.

Keywords: *Boron neutron capture therapy, epithermal neutron, MCNP4B, D–D neutron generator, ROHS directive.*

INTRODUCTION

Glioblastoma multiforme (GBM), is by far the most common and most malignant of the glial tumors. This type of tumor is extremely difficult to eliminate by surgery owing to its finger-like extensions that infiltrate the surrounding normal brain tissue [1, 2]. Thermal and epithermal neutrons play an important role in the efficiency of Boron Neutron Capture Therapy (BNCT). While thermal neutrons can easily reach cancers which are located at near-tissue-surface, epithermal neutrons is requested to treat deep seated tumors. Cancer cells are killed by α particles and ^{7}Li nuclei produced through the $^{10}B(n, \alpha)^{7}Li$ reaction. The ^{7}Li and α particle have a range 4.1 and 7.1 μm, which is less than the diameter of a cell nucleus. The chances are high that at least one of the nearby malignant cells will be destroyed [3-5].

The BNCT facilities that are currently operating are based on nuclear reactors. Nuclear reactors provide high-intensity neutron beams and reduce significant the treatment time [6, 7]. However, nuclear reactors are very expensive and too large to be used in hospitals. In addition the main questions about the nuclear reactors are the safety and authorization concerns that prevent its installation in a hospital environment in an urban area.

Accelerator-driven neutron sources could well be used to produce epithermal neutron beams, although have lower cost than reactors, are not cheap and usually need a series of ancillary systems which may occupy large areas. Isotropic neutron sources, such as ^{241}Am/Be and ^{252}Cf [8], although portable and relatively inexpensive, have low neutron intensity, with energies up to 10 MeV which would require adequate shielding [9].

This paper investigates the perspective to install a compact neutron generator in a hospital environment for BNCT purposes. Compact neutron generators, based on the D–D or D–T fusion reaction, have already considered for BNCT purposes for many researchers [4, 7, 10, 11]. In this work a therapeutic neutron beam based on a deuterium-deuterium(D–D) neutron generator is presented. In comparison to other facilities in the similar field (BNCT) the proposed unit is designed according to article 4 of the RoHS Directive 2002/95/EC, regarding the choice of materials. Hence, lead, cadmium and beryllium have been excluded from the design of a unit [12, 13]. Today similar legislation there is in many other countries e.g. China [14-16] or South Korea [17]. The facility was designed using the Monte Carlo MCNP version 4B, transport code [18-20].

MATERIALS AND METHODS

The neutron source

In the proposed unit the necessary epithermal neutron beam was derived from a compact D–D neutron generator. The D–D neutron generators produce neutrons with energy approximately equal to 2.5 MeV, have a compact size and offer an on/off switching of the emitted neutrons. They can produce relatively high neutron flux with logical cost. In this work, a coaxial RF-plasma D–D neutron generator was simulated. Neutrons in this generator are formed by using D–D fusion reaction. The deuterium gas mixture is ionized in an RF-driven plasma source. The ion beams are accelerated to ~120 keV energy using high current (350 mA), high voltage DC-power supply (120 kV) and neutrons are produced when the beams impinge on a titanium target [21-23].The neutron source has overall dimensions of 60 cm × 45 cm, with an extraction aperture composed of seven slits 1.5 mm wide and 75 mm in height [24-26]. The neutron spectrum used for such a work was derived by previous paper by Fantidis *et al.* [27], while the total neutron flux is 10^{11} ns^{-1}.

The MCNP facility modeling

Based on the data form literature Nickel (Ni) and graphite were selecting as reflector materials [28-30]. In the case of BNCT facility, the choice of the moderator is the first step in the design of the facility. The D–D neutron generator emits fast neutrons with a mean energy 2.5 MeV which should be moderated to the required epithermal energy range (1 eV–10 keV) using suitable moderator materials. The ideal moderator must have a low scattering cross section to epithermal energies, high scattering cross section at higher energies without induced gamma-rays from the interaction of the neutrons and the moderator material and last but not least has to possess a high absorption cross-section in all energies except to the epithermal range. Table 1 reports some recommended, by the IAEA, parameters for spectral ratios, fast neutron and γ ray doses at the beam port of a BNCT facility [31, 32].

In order to produce an epithermal beam the most suitable materials to moderate neutrons with different combinations and thickness were investigated by the Monte Carlo simulations.

Table 1. Recommended values in the beam exit window.

BNCT beam port parameters	Recommended value
$f_{epithermal}$ ($n\ cm^{-2}\ s^{-1}$)	~10^9
$f_{epithermal}/f_{fast}$	>20
$f_{epithermal}/f_{thermal}$	>100
$D_{fast}/f_{epithermal}$ ($Gy\ cm^2$)	<2×10^{-13}
$D_{\gamma}/f_{epithermal}$ ($Gy\ cm^2$)	<2×10^{-13}
Fast energy group (f_{fast})	E>10 keV
Epithermal energy group ($f_{epithermal}$)	1 eV ≤ E ≤ 10 keV
Thermal energy group ($f_{thermal}$)	E<1 eV

Ten different materials namely, Teflon (CF_2), heavy water (D_2O), Fluental, BiF_3, BiF_5, MgF_2, Al_2O_3, AlF_3, TiF_3 and CaF_2 were considered. After coming out of the moderators neutrons pass through filters in order to improve the quality of the neutron beams. An ideal neutron filter must absorb only the unwanted fast and thermal neutrons without producing γ rays. An absorber material, lithiated poliethylene (Poly-Li) at last included as delimited to get a collimated neutron beam.

RESULTS AND DISCUSSION

A wide set of computational studies were realized using the MCNP4B Monte Carlo code. The neutron flux and the dose rate were calculated at the exit of the facility across the 18 cm diameter window using the F2, Fm2 tallies and the DE, DF cards. Calculations were carried out with accuracy less than 1% in all cases. Ten different spectrum shifter materials to slow neutrons down to epithermal energy ranges, having different thickness, were therefore investigated. Figure 1 shows the epithermal neutron flux ($f_{epithermal}$) for the different materials considered. In figures 2 and 3 the $f_{epithermal}/f_{thermal}$ and $f_{epithermal}/f_{fast}$ ratios of candidate moderator materials versus their thickness, are plotted respectively. According to the results for thickness smaller than 17 cm the D_2O gives the higher $f_{epithermal}$ but at the same time has very small $f_{epithermal}/f_{thermal}$ ratio. Taking into account plots in figures 1, 2 and 3, it may be concluded that 18 cm thickness of TiF_3 provides the better balance among the $f_{epithermal}$, $f_{epithermal}/f_{fast}$ ratio and $f_{epithermal}/f_{thermal}$ ratio correspondingly. In order to improve the quality of the beam a second moderator should be used next to the TiF_3 moderator.

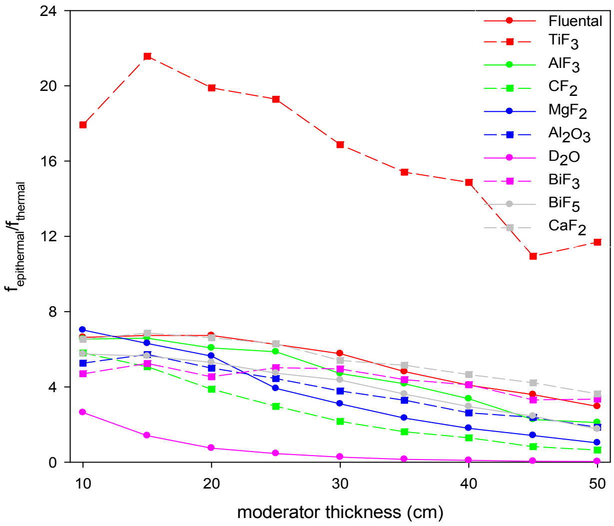

Figure 2. The $f_{epithermal}/f_{thermal}$ ratio for different thicknesses of moderators.

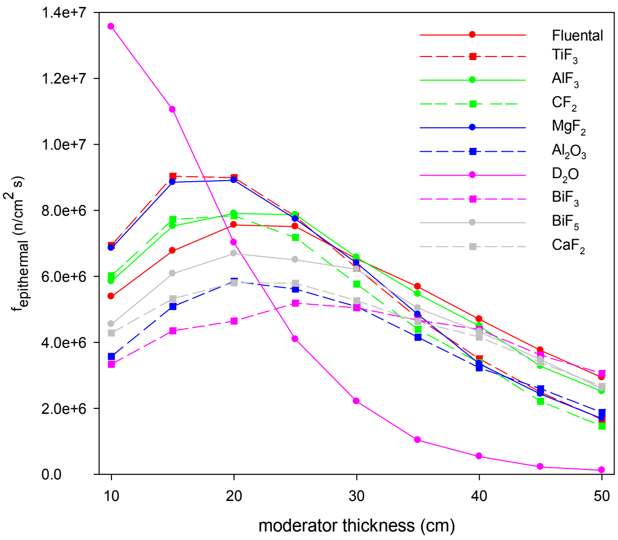

Figure 1. $f_{epithermal}$ for different thicknesses of moderators.

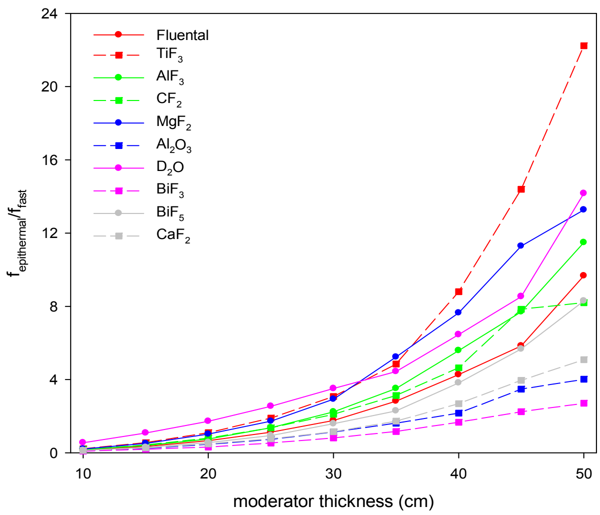

Figure 3. The $f_{epithermal}/f_{fast}$ ratio for different thicknesses of moderators.

Figures 4, 5 and 6 show the $f_{epithermal}$, the $f_{epithermal}/f_{thermal}$ and the $f_{epithermal}/f_{fast}$ ratios for a number of materials which have been selected as second spectrum shifter versus their thicknesses, whilst 18 cm TiF_3 has previously been selected as the first part of the moderator. Fluental and AlF_3 have similar values for $f_{epithermal}$ and $f_{epithermal}/f_{thermal}$ ratio but AlF_3 is a better choice because of superior values for $f_{epithermal}/f_{fast}$ ratio. Increasing the thickness of the AlF_3 have similar values for $f_{epithermal}$ and $f_{epithermal}/f_{thermal}$ ratio but AlF_3 is a better choice because of superior values for $f_{epithermal}/f_{fast}$ ratio. Increasing the thickness of the AlF_3 the $f_{epithermal}/f_{fast}$ ratio obtains higher values decreasing simultaneously the $f_{epithermal}$ and $f_{epithermal}/f_{thermal}$ ratio. Based on the results which depicted in figures 4, 5 and 6, 18 cm thickness of AlF_3 seems to be the better balance among $f_{epithermal}$, $f_{epithermal}/f_{fast}$ ratio and $f_{epithermal}/f_{thermal}$ ratio (configuration 1).

Usually in the BNCT facilities the γ rays attenuated using appropriate high-Z materials such as the Bi of Pb. Bi is commonly used, since it provides photon attenuation comparable to that from Pb, while limiting the absorption for the neutron beam. In this work instead of the Bi filter the use of BiF_3 is a better choice because the BiF3 not only reduces the γ flux (owing to the presence of Bi) but also is a good spectrum shifter. The $f_{epithermal}$ and the $D_\gamma/f_{epithermal}$ ratio versus different thicknesses of BiF_3 are presented in figure 7. For this reason a layer of BiF_3 with 9 cm thickness was chosen as γ rays filter and as third spectrum shifter (configuration 2).

However, from figures 1 and 4 is obvious that for small thicknesses the D_2O is able to provide the higher $f_{epithermal}$. With the aim to find out the best solution a huge number of configurations have been considered and the simulations show that the presence of truncated-cone-shaped made of D_2O in the first spectrum shifter is the optimum choice. The truncated-cone-shaped has a length of 6 cm and radii 5 and 4 cm with the larger radius close to the source (configuration 3). Table 2 shows how the $f_{epithermal}$, the $f_{epithermal}/f_{thermal}$ ratio and the $f_{epithermal}/f_{fast}$ ratio changes owing

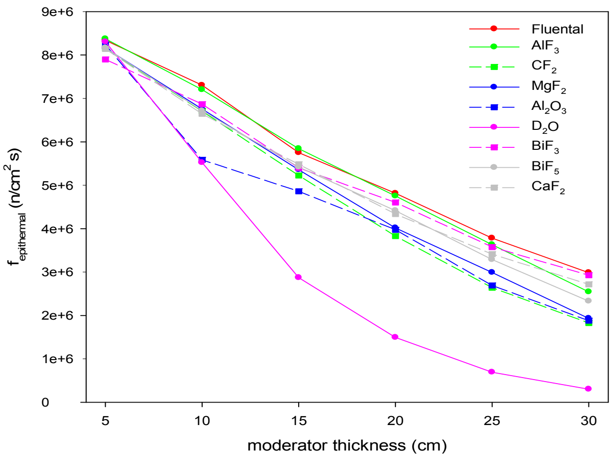

Figure 4. Epithermal neutron flux for different thicknesses of the second moderator and 18 cm thickness of TiF_3 as first spectrum shifter material selected.

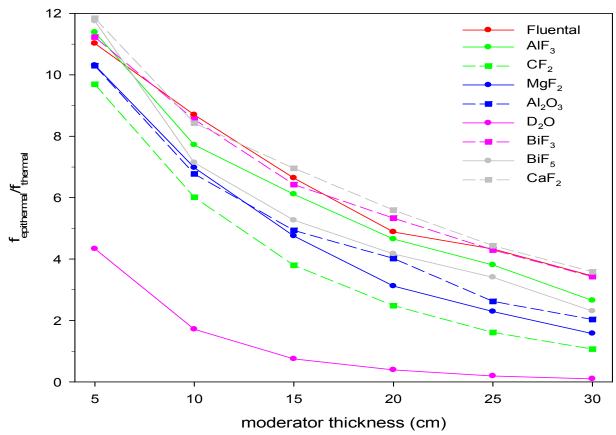

Figure 5. The ratio of epithermal/thermal neutron flux for different thicknesses of the second moderators and 18 cm thickness of TiF_3 as first spectrum shifter material selected.

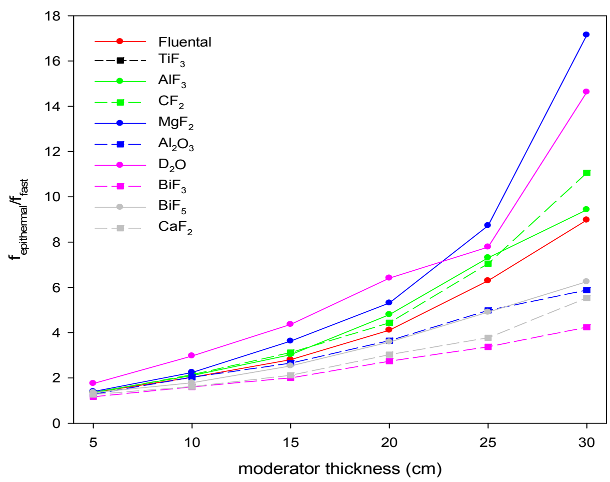

Figure 6. The ratio of epithermal/fast neutron flux for different thicknesses of the second moderators and 18 cm thickness of TiF_3 as first spectrum shifter material selected.

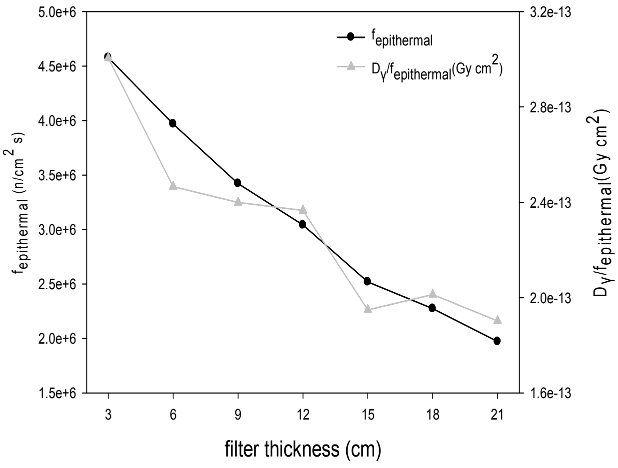

Figure 7. Epithermal neutron flux and $D_\gamma/f_{epithermal}$ ratio for different thicknesses of Ti fast neutrons filter.

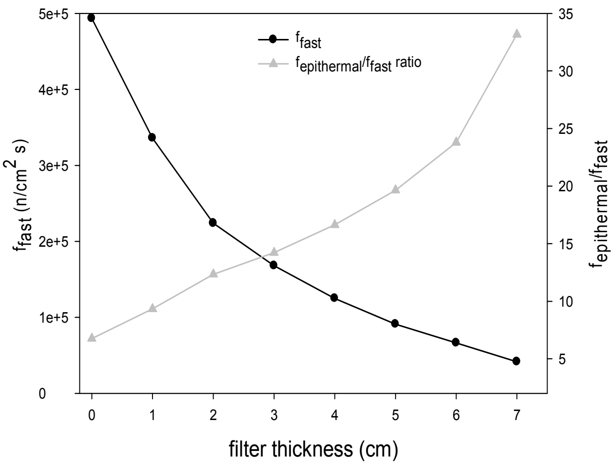

Figure 8. Fast neutron flux and $f_{epithermal}/f_{fast}$ ratio for different thicknesses of Ti fast neutrons filter.

Table 2. The $f_{epithermal}$, $f_{epithermal}/f_{thermal}$ ratio and $f_{epithermal}/f_{fast}$ ratio for configuration 1, 2 and 3.

	Configurations		
	Configuration 1	Configuration 2	Configuration 3
$f_{epithermal}$	5.33×10^6	3.20×10^6	3.34×10^6
$f_{epithermal}/f_{thermal}$ ratio	4.85	4.69	5.21
$f_{epithermal}/f_{fast}$ ratio	3.98	6.48	6.77

to the BiF_3 and D_2O.

The value of the $f_{epithermal}/f_{fast}$ ratio shows that is necessary the use of a fast neutron filter. Ti was selected as fast neutron filter and the Fig 8 illustrates the f_{fast} and the $f_{epithermal}/f_{fast}$ ratio versus different thicknesses of Ti. Based on the results which plot in figure 8, less than 6 cm thickness of TiF_3 provides $f_{epithermal}/f_{fast}$ ratio with values higher from the recommended level. The $f_{epithermal}/f_{thermal}$ ratio can be further raised up above the recommended level by using a thin layer of thermal neutron absorber. Just 2 cm of Lithium (Li) is indeed enough to absorb a large fraction of thermal neutrons with small part of epithermal ones (configuration 4). Neutron spectra of the proposed facility with and without Ti and Li filters are presented in figure 9 (configuration 5). The delimiter made of Poly-Li with thickness 3 cm is the last part of the proposed facility which is shown in figure 10.

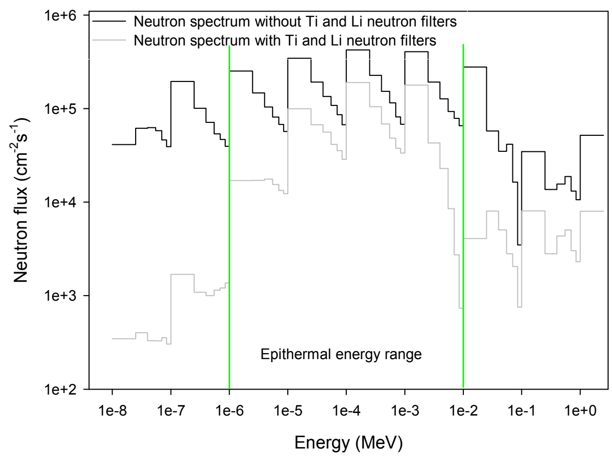

Figure 9. Final neutron spectra available at the exit of the optimized facility with and without filters.

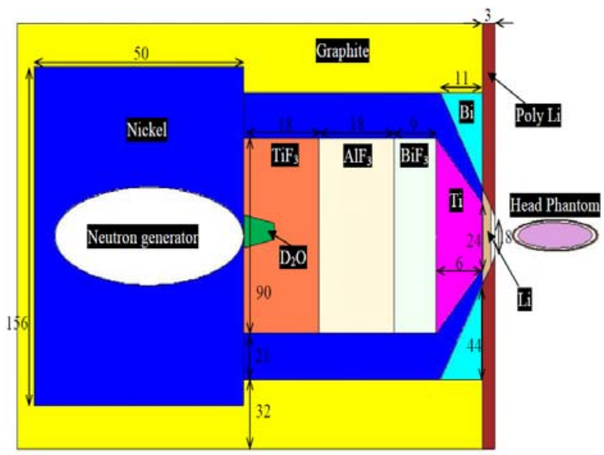

Figure 10. Geometric configuration of the BNCT system -not in scale (dimension in cm).

The proposed facility satisfies the free beam parameters which recommended parameters by IAEA except of the $f_{epithermal}$ owing to the low flux from the D–D neutron generator compared with nuclear reactors. However, this drawback is common in all BNCT portable facilities (10, 33, 34). In order to evaluate the proposed facility the results are compared with other published studies which are based on portable sources which requires light shielding (table 5). These results (unacceptable values are in italics letters) indicate that only the proposed facility meets all the recommended by IAEA criteria (except of the $f_{epithermal}$).As shown in Table 5 the proposed facility compared with the study from Durisi *et al.* using the same source, decrease the $D_{\gamma}/f_{epithermal}$ and the $D_{\gamma}/f_{epithermal}$ about four orders of a magnitude while at the same time the $f_{epithermal}$ only by a factor of ~1.6.

Table 4. Comparison of beam quality parameters between the proposed beam and the reference beam.

BNCT beam port parameters	Recommended value	Proposed facility
$f_{epithermal}$ (n cm^{-2} s^{-1})	~10^9	1.17×10^6
$f_{epithermal}/f_{fast}$	>20	20.81
$f_{epithermal}/f_{thermal}$	>100	128.81
$D_{Fast}/f_{epithermal}$ (Gy cm^2)	<2×10^{-13}	1.11×10^{-17}
$D_{\gamma}/f_{epithermal}$ (Gy cm^2)	<2×10^{-13}	2.32×10^{-17}

In order to study the profile of the $f_{epithermal}$ in the brain tissue, a head phantom was positioned at the exit of the proposed unit. The head phantom, which was derived by the MCNP samples files, consists of three ellipsoids for scalp, scull bone and brain. The dimensions and the chemical composition for an adult proceed from ICRU46 (35). The profile of the epithermal neutron flux on a perpendicular plane at the head is indicated in figure 11. The results show that epithermal and fast neutron fluxes have the maximum values at the scalp and reduce with the depth. Maximum thermal neutron flux occurs at a depth of 1.2 – 2.7 cm.

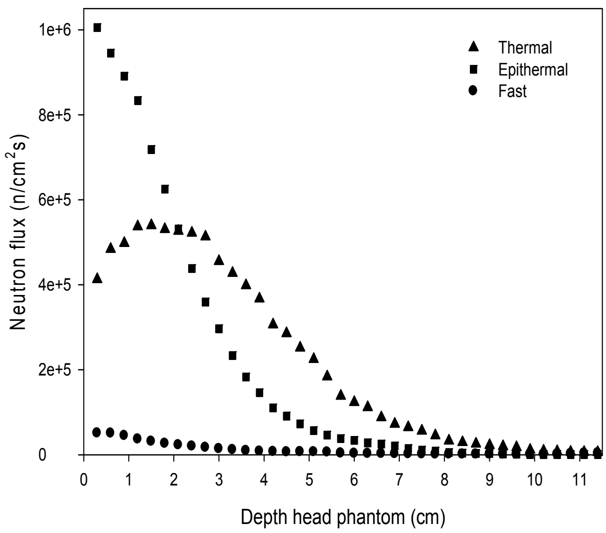

Figure 11. Distribution of the neutron fluxes on the head phantom.

Table 5. Comparison of the proposed facility with some published works (based on portable neutron sources).

Facility	Source	Neutron yield (n/s)	$f_{epithermal}$ (n/cm^{2}s)	$f_{epithermal}/f_{fast}$	$f_{epithermal}/f_{thermal}$	$D_{fast}/f_{epithermal}$ (Gy cm^2)	$D_{\gamma}/f_{epithermal}$ (Gy cm^2)
IAEA criteria			**>10^9**	**>20**	**>100**	**<$2*10^{-13}$**	**<$2*10^{-13}$**
Proposed facility	Compact D-D neutron generator	10^{11}	*$1.17*10^6$*	20.81	128.81	$1.11*10^{-17}$	$2.32*10^{-17}$
Durisi *et al.* (10)	Compact D-D neutron generator	10^{11}	*$1.87*10^6$*	–	–	*$1.82*10^{-12}$*	*$2.98*10^{-13}$*
El-moussaoui(33)	^{252}Cf radioisotope	$2.314*10^9$	*~$5.5*10^5$*	*3*	*18*	–	–
Ghassoun *(34)*	^{252}Cf radioisotope	$2.314*10^9$	*~$2*10^5$*	*~4*	~200000	–	–

CONCLUSION

MCNP4B Monte Carlo code was used with intention to calculate the optimum design parameters for a BNCT facility based on a portable D–D neutron generator. The materials considered were compatible with the European Union Directive on 'Restriction of Hazardous Substances' (RoHS) 2002/95/EC, hence excluding the use of cadmium, beryllium and lead. According to the MCNP4B simulations the combination of 18 cm TiF_3 and 18 cm of AlF_3 is the best moderator. A cone from D_2O with length 6 cm and radii 5 and 4 cm can improve the quality of the beam. With intention to further optimize the quality of the neutron beam the presence of filters is vital, so an arrangement of 9 cm BiF_3 as spectrum shifter and γ rays filter, 6 cm of Ti and 2 cm of Li offer the desired epithermal neutron beam for BNCT. According to the results obtained although similarly to the other facilities which based on portable neutron sources the neutron flux is below the recommended value for clinical treatment; the proposed facility meets all the other recommended by IAEA parameters and constitute an attractive alternative for centers wishing to install a simple BNCT facility.

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