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Investigation and simulation of gamma-neutron shielding for nuclear-pumped lasers

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HIGHLIGHTS

- We have simulated a shielding system for Nuclear-pumped lasers by using the MCNPX code.
- We have obtained a suitable protection compound as Fe_2B-BPE-Pb for such lasers.
- The total dose rate due to neutrons and gamma in the arrangement of different materials in compounds was calculated.

ABSTRACT

Nuclear-pumped lasers (NPL) are lasers in which excited active laser environment caused by nuclear reaction. Such lasers need ionizing radiation shielding for mixed neutron and gamma fields. In this work, a shielding system for NPL was designed for an NPL that uses $^{10}B(n,\alpha)^7Li$. In fact, we have used MCNPX 2.6.0 Monte Carlo code and the thermal neutron flux as 1×10^{16} n.cm^{-2}.s^{-1} for excitation reaction. Such a large neutron flux can be obtained from a reactor source or a heavy ion accelerator. For this work, 10B fuel is covered on the surface of a rectangular cube aluminum shell by using the Monte Carlo method. In the design of the shielding, combinations with different materials have been used with various arrangements in three layers. According to the simulation, the arrangement of Fe_2B-BPE-Pb is a suitable protection compound for such lasers.

KEYWORDS

Nuclear-pumped lasers
Gamma-neutron shielding
Monte Carlo method
Neutron flux

HISTORY

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1 Introduction

Fission energy is widely employed for various purposes such as electricity generation and heat supply. Currently, in this field, all sorts of nuclear reactors are under development. Despite the fantastic advantage of these reactors, we can find limitations to their performance: for instance reactor efficiency and temperature limitations. The development of a fresh nuclear energy system that has a more effective utilization of energy and is free from temperature limitations will expand the field of nuclear energy use in the future. Therefore, such problems may be resolved by extending laser manufacturing technology that uses excitation reaction (Karelin et al., 1997; Hu et al., 2020; Xu et al., 2022).

Nuclear-pumped lasers (NPL) are lasers in which the exciteed active laser environment are prepared by nuclear reaction. These lasers are instruments that have a straight conversion of nuclear into optical energy, and lasing is carried out by nuclear energy. Since these reactions are best used in a nuclear reactor, the NPL utilizing a nuclear reactor is frequently called a reactor- pumped laser. Here, however, we refer to this type of laser as NPL (Fig. 1) (Gulevich et al., 2000).

When we go back to the history and origin of this type of laser, Karelin and his colleagues were among the pioneers in this field (Karelin et al., 1997). According to the studies, Xe-Kr lasers are one of the good candidates for this type of lasers, namely NPL. Naturally, problems such as low efficiency and so on arise, which can probably be caused by the presence of impurities in the gas. Because, the impurity of gas lasers causes fluctuations in the laser (Tomizawa et al., 2000).

Anyway, to initiate nuclear reactions, most NPLs use thermal neutrons. One of the sources of these neutrons is pulsed nuclear reactors. The used neutron sources that can produce the highest power density in direct energy conversion applications can be mentioned as: radioisotopes, light ion accelerators, high energy photo-neutron or photo-fission sources, and spallation neutron sources (Prelas, 2016). The nuclear-produced ion source can be one of several types of surface, volume or multiphase

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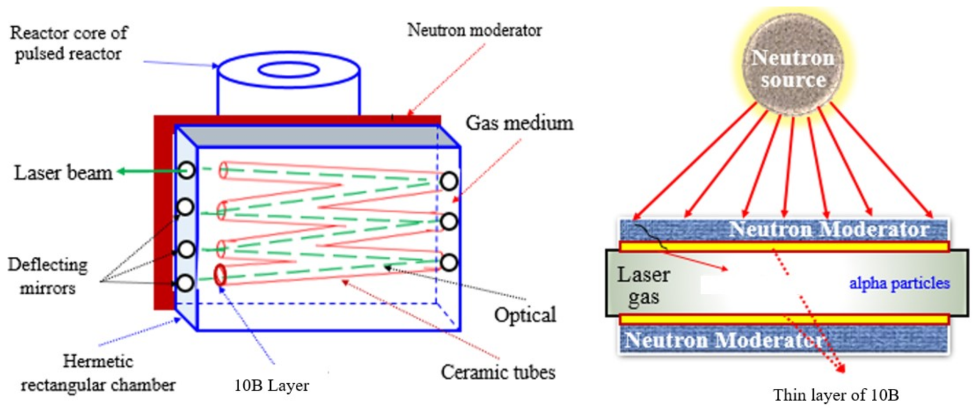

Figure 1: A schematic of a nuclear pumping laser in which a thin layer of B-10 is used in two views (Melnikov et al., 2015; Prelas, 2016).

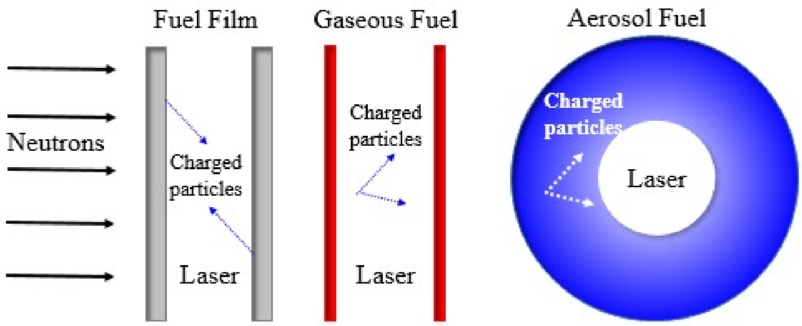

Figure 2: Types of sources used in laser with sources of as Surface (left), Volume (middle), and Aerosol (right) (Prelas, 2016).

sources that can be seen in Fig. 2.

Specifically, ions may be produced by converting thermal or fast neutron flux, through nuclear reactions, into a source of energetic ions. Normally, reactions caused by neutrons, which are of interest in NPLs, are as follows:

$$^{3}\mathrm{He} + n \rightarrow T + p + 0.76\ \mathrm{MeV} \quad (1)$$

$$^{10}\mathrm{B} + n \rightarrow ^{7}\mathrm{Li} + ^{4}\mathrm{He} + 2.35\ \mathrm{MeV} \quad (2)$$

$$^{235}\mathrm{U} + n \rightarrow ff_h + ff_l + \nu_n + 200\ \mathrm{MeV} \quad (3)$$

According to the mechanism of NPLs, we have various types of particles such as neutrons and photons, and to protect people and devices near the laser, we need suitable shielding. Interactions between neutrons and target nuclei can be divided into inelastic scattering, elastic scattering, absorption and trapping. Therefore, the purpose of shield design is to protect people from radiation by reducing the energy of particles, absorbing particles and their secondary radiation. The energy of fast neutrons is mainly reduced by inelastic scattering, and when the energy of fast neutrons reaches below the threshold value of inelastic scattering, the energy of neutrons is greatly reduced by elastic scattering until the energy of neutrons reaches the thermal neutron region, and then thermal neutrons can be easily absorbed (Hu et al., 2020).

For gamma rays, shielding mainly depends on three ways of interaction of gamma rays with shielding materials: photoelectric absorption, Compton scattering and pair production (Prelas, 2016).

Anyway, all nuclear energy systems need shields that first have good protection performance and then, if possible, light weight. It has been found that multi-layer shields can be effective in realizing such features. For the successful design of such protection, achieving the suitable composition and arrangement (in terms of absorption, shield weight, cost, etc.) is essential (Xu et al., 2022).

Nowadays, commonly used shielding materials for nuclear facilities are often composed of hydrogen, heavy metal elements, neutron absorbers, and an effective shield is always multilayer. Barnhart first came up with the concept of a multilayer shielding structure in 1955. He investigated the shielding properties of radiation shields composed of concrete, paraffin, and steel (Xu et al., 2022; Barnhart and Anderson, 1989). In the early stage of shield design, the concept of perfect shield was proposed by authors that, the shield contains three layers: a moderator that reduces the energy of the neutrons, an absorber that stops the degraded neutrons and the last layer that absorbs the gamma-rays, and the super shield is constructed in accordance with the characteristics of neutrons and gamma-rays, which allows each layer to perform its function in the shielding at its best. It can be seen that a multilayer radiation shield with an optimal combination of structure parameters can improve the shielding performance, otherwise, the result may deteriorate (Hu et al., 2020; Xu et al., 2022).

Anyway, it is clear that protection is the major part

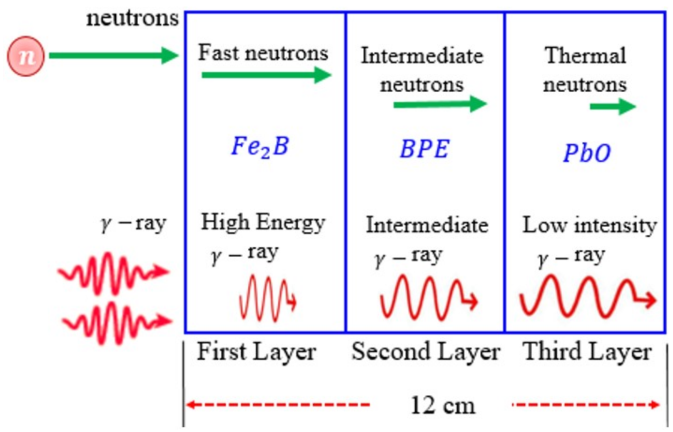

Figure 3: Three-layer mixed shielding for gamma-ray and neutron beam.

of the work and always takes up most of the volume and weight of the nuclear system. The optimum design of the structure and suitable protection components can improve the efficiency of the device.

In this research, we use the Monte Carlo code of MCNPX 2.6.0 to simulate radiation shielding for NPLs. In this simulation, we use different types of materials and propose an optimal multi-layer shield for surface sources in nuclear pump lasers.

2 Materials and Methods

As we know, due to the different interactions of neutrons and gamma rays with materials, it is necessary to choose suitable materials and compounds in the design of the desired protection. Regarding the selection of three layers for our protection, we should note that when the energy of neutrons is high (fast neutrons, energy about 1 keV to 10 MeV), elements such as W, Pb, Fe and Cu are used in the first layer, having a high inelastic cross-section (Hu et al., 2020). In fact, because the elastic scattering cross-section of light elements with fast neutrons is low, heavy and high Z materials are used. When the energy of neutrons reaches the threshold value, elements with high elastic cross-section, such as H and C, are selected as the second layer. We did not use water and paraffin, because paraffin is flammable and water maintenance due to leakage and evaporation is difficult. B, Li and Gd elements, which have high thermal neutron absorption cross-section (Xu et al., 2022; Mughabghab, 2003), will be selected as the second layer. Although cadmium has a very large cross-section, we did not use cadmium because after absorbing a thermal neutron, it emits a photon with an energy of about 9 MeV (McParland, 2010; Tsoulfanidis and Landsberger, 2021).

We propose three-layer mixed shielding for gamma-ray and neutrons in these lasers (Fig. 3) and according to the provided explanations, suitable materials should be placed in each layer and its shielding properties should be examined. For this purpose, the arrangement of several components including polyethylene borated (BPE 5% WT boron), B_4C, Pb, PbO, Fe, Fe_2B, WO_3, stainless steel 304, and concrete (H, O, Si, Al, Na, Ca, Fe) have been used in different arrangements to make several different shielding compounds.

The studied Fe_2B (iron boride) alloy consists of an iron composition with boron between 8 and 10%. Boron is an element with high absorption cross-section for slow neutrons (Xu et al., 2022; Mughabghab, 2003). Also, iron is a good shielding material against high-energy neutrons due to the suitable Z but it is relatively transparent for neutrons below 1 MeV (Sariyer, 2020).

In this research, the overall thickness of the shielding is considered to be 12 cm and thickness of each layer is 4 cm.. The thickness of 12 cm is chosen experimentally, and the same thickness of each layer is due to the comparison of the effectiveness of the shielding composition. In this case, the total dose rate of neutrons and gamma rays are measured and the data related to the dose rate of neutrons and gamma rays are calculated using the suitable tally cards.

To calculate the dose rate, tally type 4 is used along with the dose function (DF) card (Pelowitz et al., 2005). This dose rate is calculated inside the human phantom, which is in front of the right side of the laser perpendicular to the y-axis. The simple human phantom used is made of water in a body of PMMA. Due to the closeness of the density and compounds in water with the body tissue, the simulation of determination of dosimetry parameters takes place in the water phantom. The size of the phantom is equal to the size of a normal human.

As a result, in order to better attenuate neutrons and gamma rays, the appropriate composition of materials in these three layers is selected. The ion source used is a surface source of B-10, which is covered on an aluminum surface as a rectangular cube. In these lasers, only the thermal neutron flux as 1×10^{16} n.cm^{-2}.s^{-1} are used for nuclear reaction. An image of the simulated geometry is shown in Fig. 4.

In this work, we investigate the shielding system of NPL that uses B-10 fuel. For this work, we will use the thermal neutron flux as a suitable source for nuclear reaction which is covered on the surface of a rectangular cube aluminum shell. In shielding design, combinations of

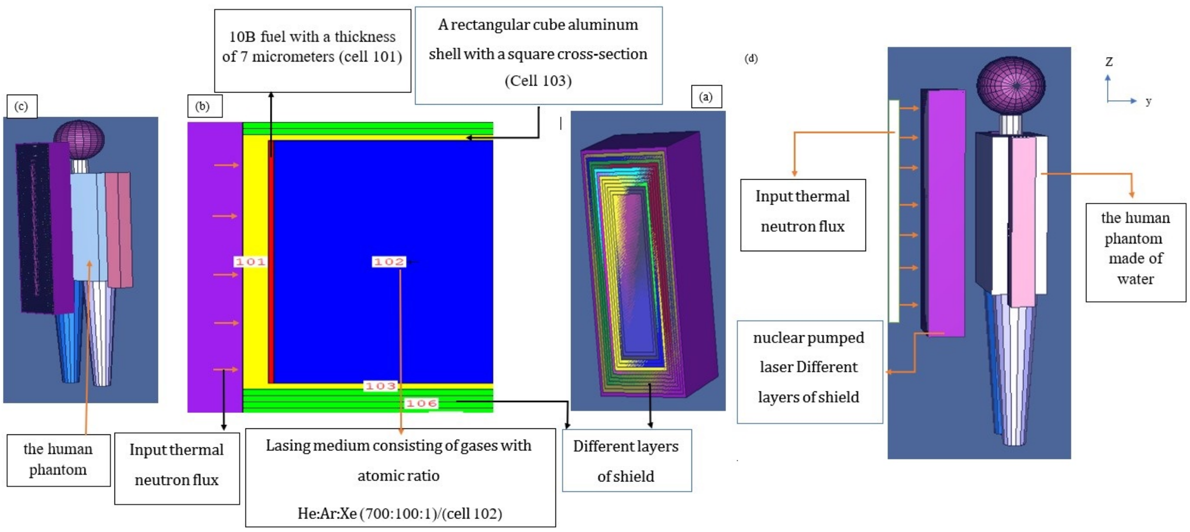

Figure 4: The image of the simulated geometry of the problem is a) three-dimensional, b) two-dimensional and c) a three-dimensional figure placed in front of the human phantom in MCNPX 2.6.0 d) An overview of the geometry of the problem.

Table 1: Dose rate of photons and neutrons in two groups (Unit: $Sv.h^{-1}$ per single particle of source).

Group I					Group II				
Compound	Photon dose rate	Relative error	Neutron dose rate	Relative error	Compound	Photon dose rate	Relative error	Neutron dose rate	Relative error
BPE-Fe-Pb	2.913E-15	0.015	1.648E-14	0.025	B_4C-Steel-WO_3	5.565E-15	0.011	1.771E-14	0.022
BPE-Pb-Fe	3.070E-15	0.014	1.659E-14	0.025	B_4C-WO_3-Steel	5.697E-15	0.010	1.774E-14	0.022
Fe-BPE-Pb	9.641E-14	0.002	1.539E-14	0.022	Steel-B_4C-WO_3	2.219E-13	0.002	1.833E-14	0.021
Fe-Pb-BPE	1.061E-13	0.002	1.529E-14	0.025	WO_3-B_4C-Steel	1.900E-13	0.002	1.771E-14	0.022
Pb-BPE-Fe	2.554E-14	0.004	1.617E-14	0.023	WO_3- Steel-B_4C	2.788E-13	0.001	1.657E-14	0.022
Pb-Fe-BPE	5.520E-13	0.001	1.626E-14	0.023	Steel-WO_3-B_4C	2.461E-13	0.001	1.829E-14	0.021

materials with different arrangements in three layers are checked to get the most suitable combination for each layer that has the lowest dose around these lasers in comparison with the other arrangements.

3 Results and discussion

First, we investigate six different materials in the form of two groups in different arrangements. The results related to the photon and neutron dose rate for a group consisting of three different compounds including BPE (5%wt B), Fe, Pb and another group with combinations of steel, WO_3, and B_4C materials are shown in Table 1.

The obtained results are due to the single source neutron. Also, the graph related to the photon dose rate of these two groups is shown in Fig. 5. Considering the photon dose in different compounds and the fact that the last layer is placed to protect against photons, it is clear that the dose is lower for elements such as lead, iron and tungsten.

According to Table 1 and Fig. 5, the use of elements such as lead, iron and tungsten compared to boron carbide and polyethylene in the third layer for protection against photons is better and more efficient. Therefore, it is more appropriate to use such materials in the third layer.

The energy of fast neutrons must first be reduced to become thermal neutrons and then absorbed. The dose rate related to these neutrons for two groups of materials is shown in Table 1 and Fig. 6. The data relating to the neutron dose rate show that the use of materials with high inelastic cross-section is suitable for slowing down neutrons. In fact, first two layers are dedicated to protection against neutrons, and the obtained data showed that placing lead, iron, steel and materials with a high inelastic cross-section in the first layer is appropriate.

When neutrons are slowed down, neutron absorption must be carried out. Placing materials containing boron caused the absorption of thermal neutrons. To absorb thermal neutrons, materials with a high absorption cross-section such as boron or compounds containing boron are used. Gd or water and paraffin can also be used; But Gd emits gamma rays with high energy after absorbing thermal neutrons, water has a risk of leakage and paraffin is flammable, so the use of boron is much more appropriate.

Now, we simulate the different arrangements of compounds and get the neutron and photon dose rate of each compound. These results are summarized in Table 2.

Figure 7 shows the neutron and photon dose rates separately, and Fig. 8 shows the total photon and neutron dose rates. According to the data given in Table 2 and Figs. 7 and 8, it can be concluded that when we used Fe_2B in the first layer against fast neutrons and high-energy photons, we obtained good results, which showed that among the materials used, Fe_2B is the most suitable material for the first layer.

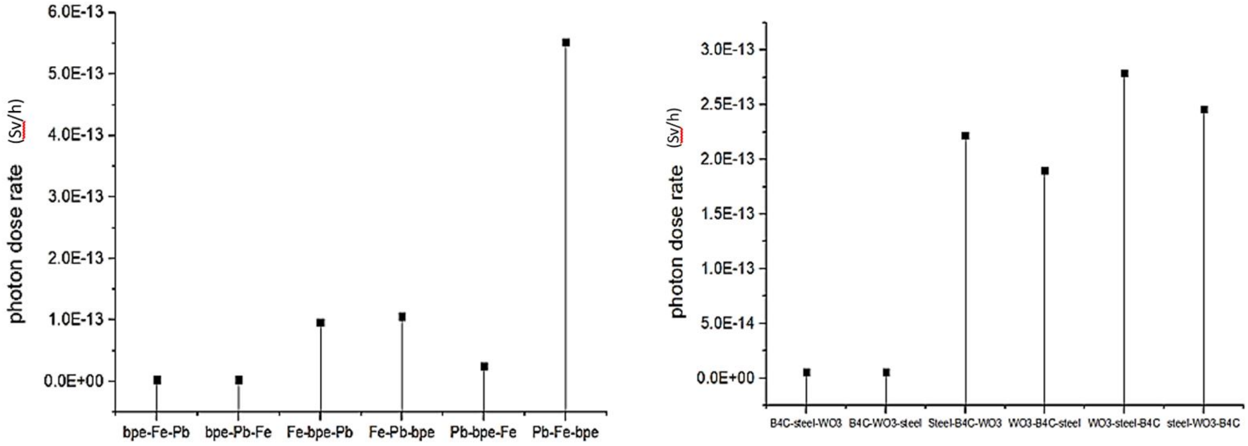

Figure 5: Left) The dose rate of photons in the arrangements of different materials in compounds of group I and, right) group II.

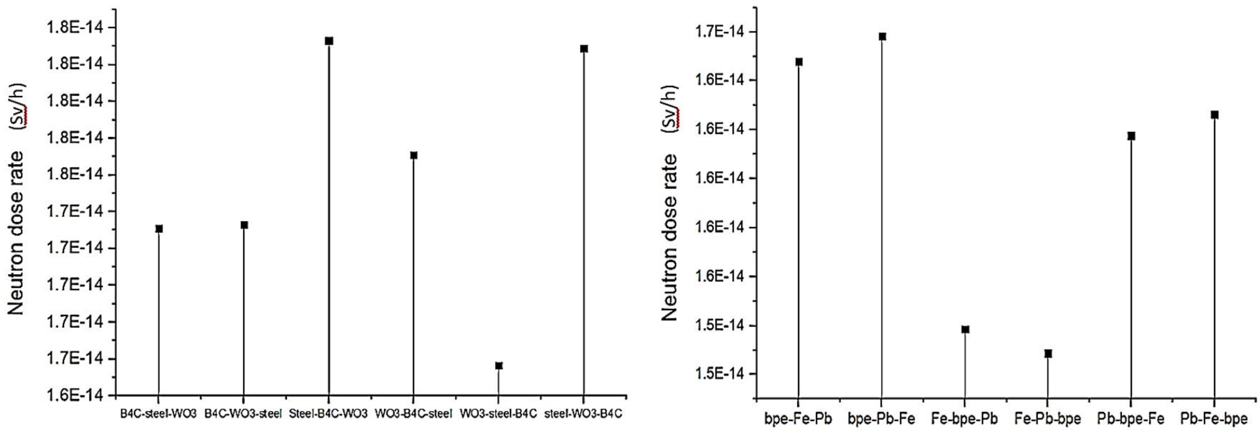

Figure 6: Right) Dose rate of neutrons in arrangements of different materials in compounds of group I and, left) group II.

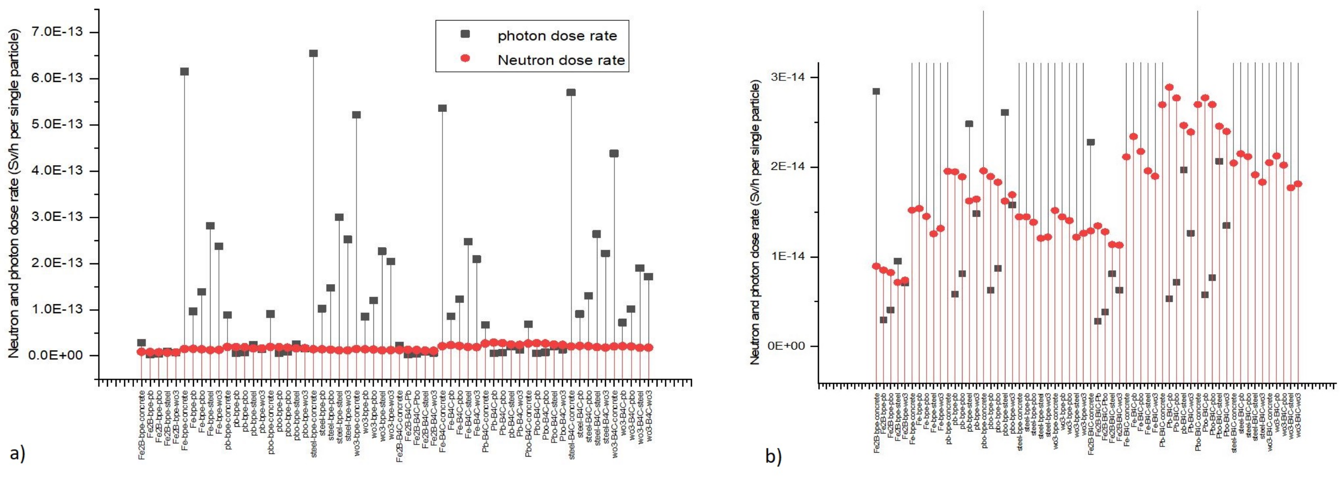

Figure 7: (a) The total dose rate due to neutrons and photons in the arrangement of different materials in compounds (b) Since neutron dose rate data are not distinguishable quantitatively, the neutron dose rate area is zoomed (Unit: $Sv.h^{-1}$ per single particle of source).

The combination of Fe_2B with B_4C or BPE performed the best. In general, the arrangements that use BPE compared to B_4C in the second layer record a lower dose rate output and these combinations have much better performance. BPE had less weight and better performance.

Table 2: Photon and neutron dose rate and total dose rate for different materials in the arrangements (Unit: $Sv.h^{-1}$ per single particle of source).

Group I				Group II			
Compound	Photon dose rate	Neutron dose rate	Total dose rate	Compound	Photon dose rate	Neutron dose rate	Total dose rate
Fe_2B-B_4C-Concrete	2.280E-14	1.289E-14	3.569E-14	Fe_2B-BPE-Concrete	2.846E-14	8.959E-15	3.742E-14
Fe_2B-B_4C-Pb	2.792E-15	1.347E-14	1.626E-14	Fe_2B- BPE-Pb	2.968E-15	8.527E-15	1.149E-14
Fe_2B-B_4C-PbO	3.828E-15	1.280E-14	1.663E-14	Fe_2B- BPE-PbO	4.079E-15	8.248E-15	1.233E-14
Fe_2B-B_4C-Steel	8.107E-15	1.138E-14	1.948E-14	Fe_2B-BPE-Steel	9.523E-15	7.137E-15	1.666E-14
Fe_2B-B_4C-WO_3	6.299E-15	1.130E-14	1.760E-14	Fe_2B-BPE-WO_3	7.051E-15	7.397E-15	1.445E-14
Fe-B_4C-Concrete	5.357E-13	2.115E-14	5.568E-13	Fe-BPE-Concrete	6.156E-13	1.521E-14	6.308E-13
Fe-B_4C-Pb	8.562E-14	2.343E-14	1.090E-13	Fe-BPE-Pb	9.640E-14	1.538E-14	1.118E-13
Fe-B_4C-PbO	1.229E-13	2.176E-14	1.447E-13	Fe-BPE-PbO	1.390E-13	1.451E-14	1.535E-13
Fe-B_4C-Steel	2.474E-13	1.960E-14	2.670E-13	Fe-BPE-Steel	2.819E-13	1.257E-14	2.945E-13
Fe-B_4C-WO_3	2.093E-13	1.899E-14	2.282E-13	Fe-BPE-WO_3	2.378E-13	1.316E-14	2.509E-13
Pb-B_4C-Concrete	6.747E-14	2.696E-14	9.443E-14	Pb-BPE-Concrete	8.864E-14	1.955E-14	1.082E-13
Pb-B_4C-Pb	5.310E-15	2.892E-14	3.422E-14	Pb-BPE-Pb	5.836E-15	1.949E-14	2.533E-14
Pb-B_4C- PbO	7.181E-15	2.772E-14	3.490E-14	Pb-BPE-PbO	8.087E-15	1.893E-14	2.702E-14
Pb-B_4C-Steel	1.971E-14	2.466E-14	4.437E-14	Pb-BPE-Steel	2.483E-14	1.623E-14	4.106E-14
Pb-B_4C-WO_3	1.264E-14	2.393E-14	3.657E-14	Pb-BPE-WO_3	1.481E-14	1.644E-14	3.125E-14
Pbo-B_4C-Concrete	6.908E-14	2.774E-14	9.608E-14	PbO-BPE-Concrete	9.088E-14	1.960E-14	1.105E-13
Pbo-B_4C-Pb	5.734E-15	2.700E-14	3.348E-14	PbO-BPE-Pb	6.309E-15	1.895E-14	2.526E-14
Pbo-B_4C- PbO	7.696E-15	2.699E-14	3.468E-14	PbO-BPE-PbO	8.733E-15	1.832E-14	2.705E-14
Pbo-B_4C-Steel	2.067E-14	2.457E-14	4.524E-14	PbO-BPE-Steel	2.611E-14	1.622E-14	4.233E-14
Pbo-B_4C-WO_3	1.349E-14	2.399E-14	3.748E-14	PbO-BPE-WO_3	1.578E-14	1.693E-14	3.272E-14
steel-B_4C-Concrete	5.701E-13	2.046E-14	5.905E-13	Steel-BPE-Concrete	6.549E-13	1.446E-14	6.694E-13
Steel-B_4C-Pb	9.078E-14	2.151E-14	1.123E-13	Steel-BPE-Pb	1.022E-13	1.446E-14	1.167E-13
Steel-B_4C-PbO	1.304E-13	2.118E-14	1.516E-13	Steel-BPE-PbO	1.471E-13	1.386E-14	1.609E-13
Steel-B_4C-Steel	2.636E-13	1.916E-14	2.827E-13	Steel-BPE-Steel	3.001E-13	1.207E-14	3.121E-13
Steel-B_4C-WO_3	2.218E-13	1.833E-14	2.401E-13	Steel-BPE-WO_3	2.521E-13	1.222E-14	2.643E-13
WO_3-B_4C-Concrete	4.379E-13	2.050E-14	4.584E-13	WO_3-BPE-Concrete	5.216E-13	1.517E-14	5.367E-13
WO_3-B_4C-Pb	7.193E-14	2.126E-14	9.319E-14	WO_3-BPE-Pb	8.508E-14	1.446E-14	9.954E-14
WO_3-B_4C-PbO	1.012E-13	2.022E-14	1.214E-13	WO_3-BPE-PbO	1.203E-13	1.404E-14	1.344E-13
WO_3-B_4C-Steel	1.900E-13	1.771E-14	2.076E-13	WO_3-BPE-Steel	2.267E-13	1.220E-14	2.389E-13
WO_3-B_4C-WO_3	1.713E-13	1.815E-14	1.895E-13	WO_3-BPE-WO_3	2.040E-13	1.263E-14	2.167E-13

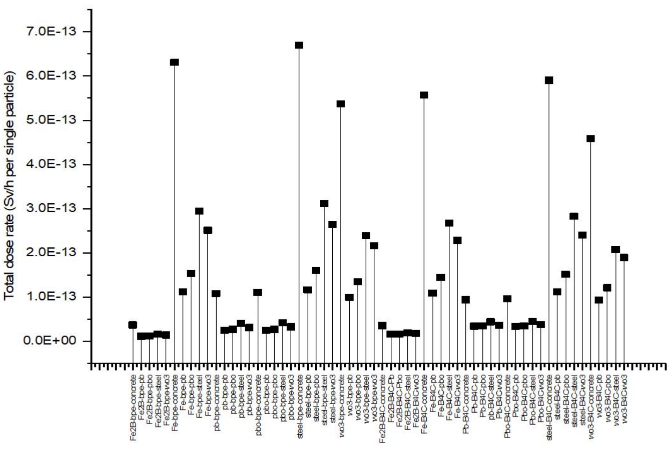

Figure 8: The total dose rate due to neutrons and photons in the arrangement of different materials in compounds (Unit: $Sv.h^{-1}$ per single particle of source).

4 Conclusions

In order to protect the radiation, it is necessary to use a shield consisting of several layers when working with the nuclear laser system.

In this research, to protect against the mixed radiation of photons and neutrons, compounds with different arrangements of materials were used. The use of Fe_2B material in the first layer in different arrangements has a more acceptable performance than other materials and they record a lower neutron dose rate. The use of BPE (5% wt B) compared to boron carbide (B_4C) significantly improves the protection performance. Therefore, compounds that use BPE as a neutron absorber have more suitable efficiency. The results show that the use of the Pb-interlayer-Fe_2B arrangement has the best performance. Therefore, the use of the Fe_2B-BPE-Pb arrangement shows the overall dose rate as 1.14948×10^{-14} $Sv.h^{-1}$ per single particle; and the Fe_2B-BPE-PbO arrangement will have a dose rate of 1.23276×10^{-14} $Sv.h^{-1}$ per single particle, which has increased the dose rate by about 7.25%.

Due to the toxicity of lead, tungsten can be used instead of lead, but the use of Fe_2B-BPE-WO_3 has an increase of about 25.69% compared to the arrangement of Fe_2B-BPE-Pb for the dose rate. In the case of Fe_2B-BPE-steel approximately 44.94% increase in dose was observed; and if concrete is used, an increase of about 225.55% will be observed. Using BPE instead of B_4C in the second layer has a much better performance. In this way, the Fe_2B-BPE-Pb arrangement is used. Comparing this arrangement with Fe_2B-B_4C-Pb shows, something about 41.45% lower dose rate can be achived.

Therefore, considering the beginning of the development of technological progress in the field of NPL, it is necessary to provide useful information about the design of radiation protection for this type of laser.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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