Nuclear Engineering and Technology 52 (2020) 1002–1007

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

A feasibility study of the Iranian Sun mather type plasma focus source for neutron capture therapy using MCNP X2.6, Geant4 and FLUKA codes

M. Nanbedeh [a], S.M. Sadat-Kiai [b,*], A. Aghamohamadi [a], M. Hassanzadeh [c]

[a] Department of Physics, Sanandaj Branch, Islamic Azad University, Sanandaj, Iran
[b] Plasma and Nuclear Fusion Research School, Nuclear Science and Technology Research Institute (NSTRI), AEOI, Tehran, Iran
[c] Reactor and Nuclear Safety Research School, Nuclear Science and Technology Research Institute (NSTRI), AEOI, Tehran, Iran

ARTICLE INFO

Article history:
Received 1 February 2019
Received in revised form
21 September 2019
Accepted 22 October 2019
Available online 22 October 2019

Keywords:
IS plasma focus device
Beam-shaping assembly
Neutron therapy
GEANT4
MCNPX2.6
FLUKA

ABSTRACT

The purpose of the current study was to evaluate a spectrum formulation set employed to modify the neutron spectrum of D-D fusion neutrons in a IS plasma focus device using GEANT4, MCNPX2.6, and FLUKA codes. The set consists of a moderator, reflector, collimator and filters of fast neutron and gamma radiation, which placed on the path of 2.45 MeV neutron energy. The treated neutrons eliminate cancerous tissue with minimal damage to other healthy tissue in a method called neutron therapy. The system optimized for a total neutron yield of 10^9 (n/s). The numerical results indicate that the GEANT4 code for the cubic geometry in the Beam Shaping Assembly 3 (BSA3) is the best choice for the energy of epithermal neutrons.

1. Introduction

Because it is almost neutral in terms of electrical charge, neutron can penetrate more in-depth than other fundamental particles in various materials, including the human body. This characteristic of neutrons used to treat deep tumors or large tumors. One of the most effective and advanced methods for control land treatment of cancer is radiation therapy, which today is used for treatment of 50% of cancer patients. Neutron Capture Therapy (NCT) is a potentially effective treatment for highly invasive tumors, such as melanoma. At present, only neutron sources for NCTs are research reactors. Many efforts been made to optimize reactors for NCT. The purpose of this study is to design a neutron source that can easily installed in a medical facility and used for treatment. In this method, soft tissue irradiated by a beam of epithermal neutrons. The emitted neutrons cannot used directly for treatment and should optimized the energy and intensity, as well as the neutron beam contamination. It should be minimized in order to achieve these constraints, a set of different materials, called the Beam Shaping Assembly (BSA), is placed in the path of neutrons so that the beam of the extracted neutrons is suitable for treatment. The spectrum-forming complex consists of a moderator, collimator, reflector and filter [1–3]. To achieve this aim MCNPX, FLUKA and GEANT4 codes used to examine the maximum neutron flux in collimator outputs. In addition, taking into account the geometric features and appropriate radiation protection strategy that is in accordance with the radiological protection rules [4]. Goldhaber proposed the concept of treatment with neutron capture, for the first time, after the discovery of a neutron, in 1934. Neutrons do not have an electromagnetic interaction due to their neutrality and, with their nuclear interactions, energize their environment, since neutrons have effects including destruction on the nucleus of atoms and the possibility of repairing the cells that damaged in this way is very low. The neutrons, by their transferring energy to the atomic nucleus and repulsion of them, and in some cases generating high-energy fragmentation, cause biological changes in the treatment region. Today neutron therapy performed without surgery by using epithermal neutrons. In fact, epithermal neutrons can be converted to thermal neutrons by crossing various tissues (head and neck) when they reach the tumor [1,5].

---

[*] Corresponding author.
E-mail address: sadatkiai@yahoo.com (S.M. Sadat-Kiai).

https://doi.org/10.1016/j.net.2019.10.016

2. Methods and materials

In this study, the GEANT4 simulation software used to obtain the maximum uniform neutron flux in collimator output. This code, which is one of the strongest Monte Carlo simulation codes that are able to cross section simulate the most complex geometries and particle tracking. The advantage of the GEANT4 code is compared to other multi-agent simulation software, one of which being open source, i.e., by free access to libraries, it can simulate the geometry of the software, and then import it into the software. This software has the ability to simulate electric and magnetic fields and able to perform different energy particle sizes that the FLUKA and MCNPX codes cannot simulate. In other words, the particle in addition to the particle mode in the state a wave also tracked. For there more, the GEANT4 code has a DNA packet that can simulate chromosomal and dosimetry failure on a micro nanoscale. In GEANT4, with the definition of CELLFLUX, it is feasible to calculate the neutron flux from D-D fusion in soft tissue for 10^9 n/s particles. GEANT4 is a free tool for simulating particle paths in matter and is a reference simulation engine for LHC experiments at CERN and high-energy labs around the world [1,4]. The geometric representation of the spectrum formulation set by GEANT4 code given in Figs. 1 and 2 in two cylindrical and cubic geometries. The image of the simulated Iranian Sun (IS) device using this code is shown in Fig. 5 [6]. This simulation was performed for the first time in order to calculate and optimize the spectrum of epithermal neutron flux for treatment through an IS plasma focus device by this code.

It was also used two MCNPX2.6 and FLUKA codes to examine the results of the BSA. MCNPX2.6, which has a very precise and extensive cross-sectional library to simulate the geometry of desired cells, source, soft tissue. The FLUKA code has a wide application in the field of high-energy particle physics and cosmic particle studies. The benefits of this code compared to other Monte Carlo codes can is that it easily define the graphical interfaces as well as the user's access to the Fortran-written programs and its ability to interfere with them. A geometric view of the source using the, MCNPX2.6, FLUKA codes, shown in Figs. 3 and 4 [9].

The materials for moderating, filtering, and reflecting listed in Tables 1–3. This set includes a moderator, a reflector, a collimator, and a filter for thermal neutrons and gamma radiation. The moderator reduces the energy of fast neutrons to reach the proper energy. The reflector prevents the exodus of the dispersed neutrons from the system and returns them to the system. The cone-shaped collimator plays the role of focusing the outlet neutrons on the target. Filters, by absorbing fast neutrons and gamma rays, do not allow them to pass through and reduce the radiation dose [7,8]. It should be noted that in Table 2, without changing their thickness,

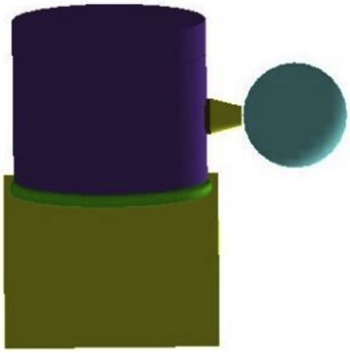

Fig. 1. Soft tissue image and IS geometry simulated by GEANT4 code to calculate neutron flux in cylindrical geometry.

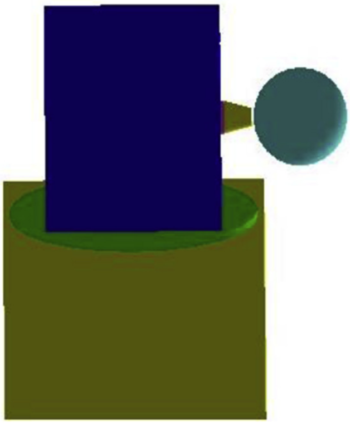

Fig. 2. Soft tissue image and IS geometry simulated by GEANT4 code to calculate neutron flux in cube geometry.

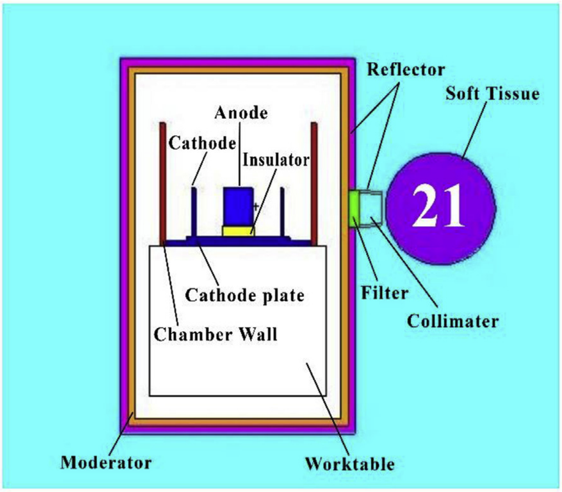

Fig. 3. Soft tissue image and IS geometry simulated to calculate the neutron flux by MCNPX2.6 code.

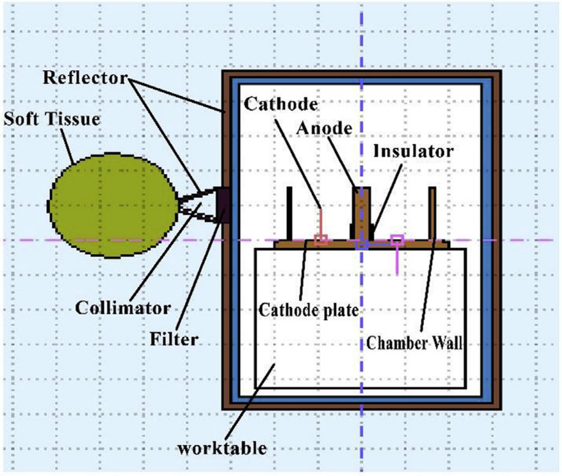

Fig. 4. Soft tissue image and IS geometry simulated to calculate the neutron flux by the FLUKA code.

Fig. 5. Simulated IS geometry image.

Table 1
Materials used in BSA1.

Cell	Material	Thickness (cm)	Density (g/cm^3)
Reflector	H_2O	2	1
Collimator	Air	9	0.001205
Filter	Bismuth	3	9.78
Moderator	Fe	2	0.669

Table 2
Materials used in BSA2.

Cell	Material	Thickness (cm)	Density (g/cm^3)
Reflector	Pb	2	11.34
Collimator	Pb	9	11.34
Filter	Bismuth	3	9.78
Moderator	Fe	2	0.669

Table 3
Materials used in BSA3.

Cell	Material	Thickness (cm)	Density (g/cm^3)
Reflector	Pb	2	11.34
Collimator	Pb	9	11.34
Filter	Bismuth	3	9.78
Moderator	Al	2	2.70

they changed the reflecting material and lead (Pb) was replaced by H_2O and air in a collimator shell, and in Table 3, the material was replaced by a moderating agent and aluminum was replaced by iron. It should be noted that the number of particle histories for all codes are 10^9 (n/s) and the total error is less than 1% for the neutron flux parameter in the current paper.

3. Results and discussion

In this study, using GEANT4, the flux of neutrons flowing from the soft tissue surface in two cubic and cylindrical geometries are shown in Figs. 4 and 5 which obtained by GEANT4 code. Figs. 6 and 7 illustrate the neutron flux at two intervals of thermal and epithermal neutrons, respectively. Fast neutron energy spectrum ($E > 0.1$ MeV), epithermal neutrons (0.1 MeV $> E > 0.625$ eV) and thermal neutrons ($E \leq 0.625$ eV).

In selecting materials, they must have a mass close to the neutron mass and have a low absorption cross section for epithermal neutrons and a high scattering cross section for fast neutrons. They should not break down or release toxic substances in the event of high-intensity radiation. As such, the low mass number of slowing materials causes the neutrons to slowing down rapidly. However, if the material mass is too low, it can cause very high contamination to thermal neutrons. On the other hand, if the mass number is large, the neutron energy does not reach the epithermal region, so the optimal state considered. Therefore, as neutron therapy commonly used to treat epithermal neutron fluxes, it is very important to select the appropriate material for the spectrum set. Therefore, given that neutron therapy usually used for the treatment of epithermal neutron flux, Figs. 6 and 7 are the best choices for this neutron energy range with respect to BSA3 materials. In addition, according to the results presented in these figures, the cube geometry can be a better choice for increasing neutron flux. This difference is mainly due to the difference in the cubic and cylindrical geometries. In large, the neutron energy does not reach the epithermal region and therefore the optimal state should considered. Therefore, given that neutron therapy usually used for the treatment of epithermal neutron flux, Fig. 3 is the best choice for this neutron energy range with respect to BSA3 materials. Moreover, according to the results obtained from these figures, cube geometry can be a better choice for increasing neutron flux. This difference is mainly due to the difference in the cubic and

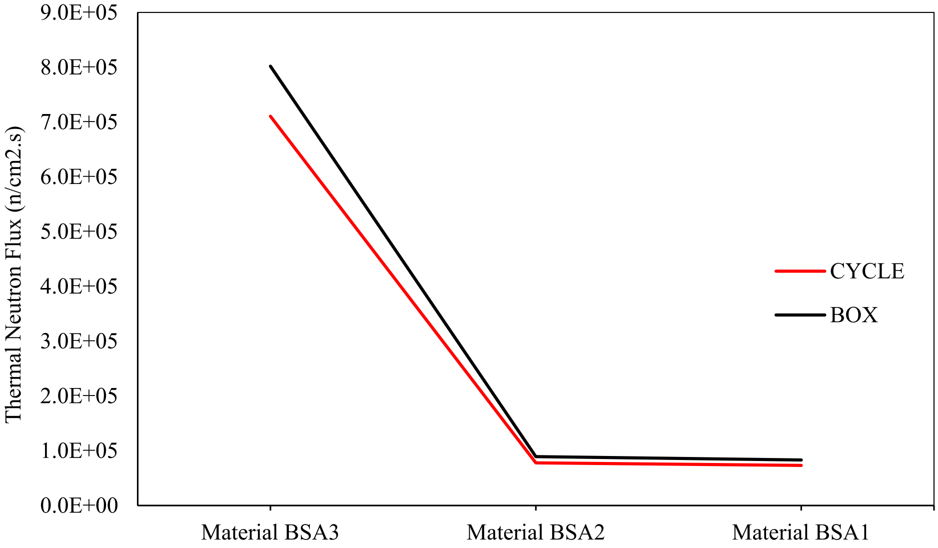

Fig. 6. Comparison of thermal neutron fluxes in BSA2, BSA2 and BSA3 in two cylindrical and box geometries using GEANT4 code derived from D-D fusion.

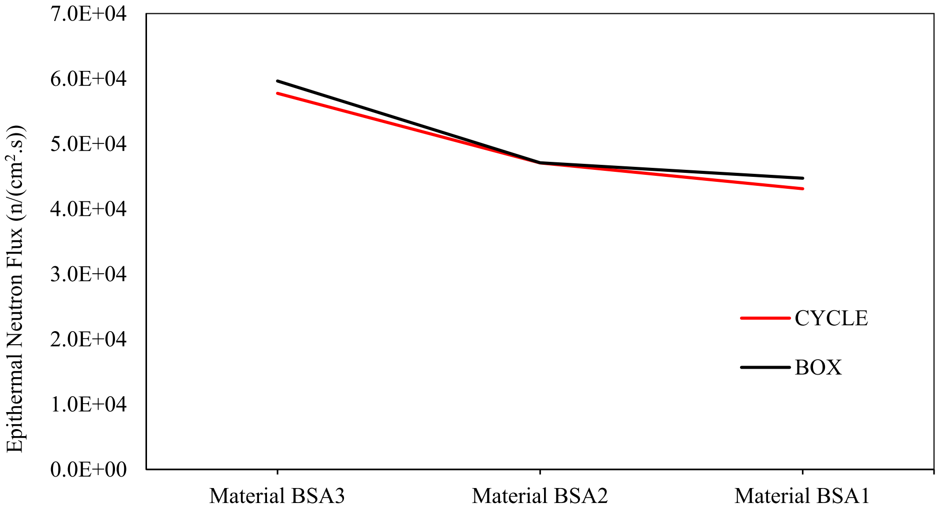

Fig. 7. Comparison of the Fluxes of Epithermal Neutrons in BSA2, BSA2 and BSA3 in Two Cylindrical and box Geometries Using the GEANT4 Code Derived from the D-D Fusion.

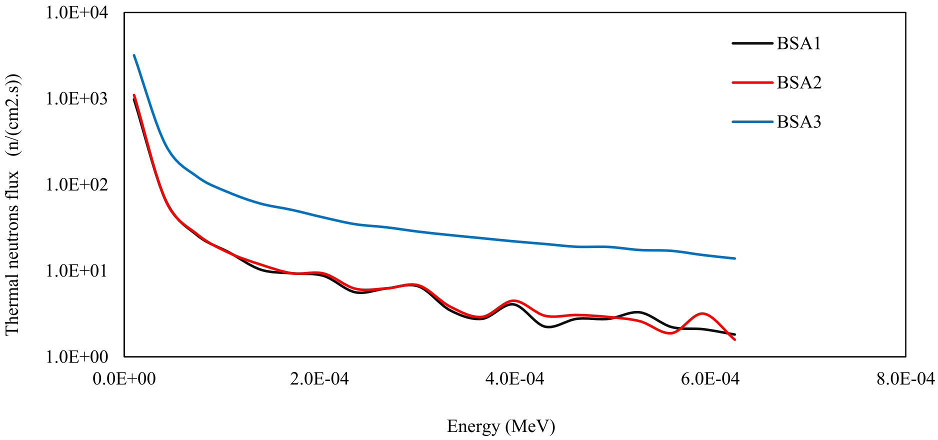

Fig. 8. Comparison of thermal neutron fluxes in BSA1, BSA2 and BSA3 using the D-D fused MCNPX code.

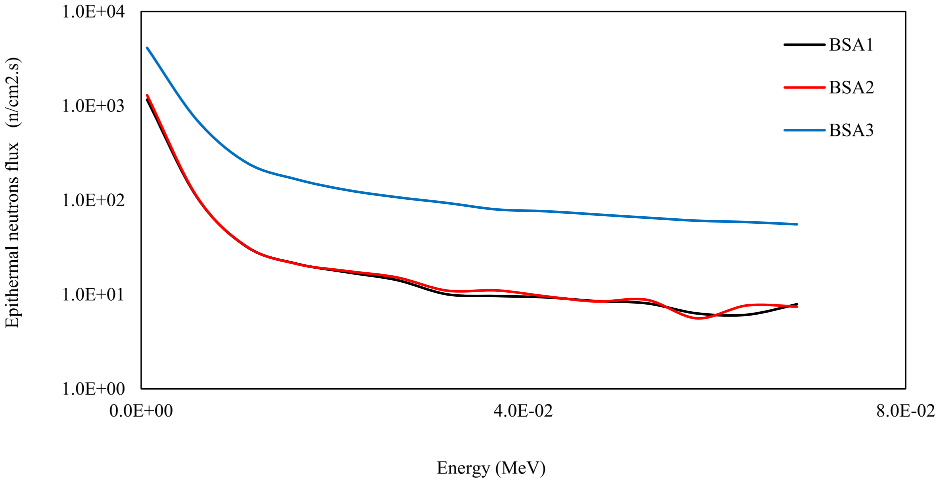

Fig. 9. Comparison of epithermal neutron fluxes in BSA1, BSA2 and BSA3 using the D-D fusion-coupled MCNPX code.

cylindrical geometry.

With regard to the results presented in Figs. 8 and 9, which obtained by MCNPX code, BSA3 is the best choice for this energy range of neutrons.

These results were also examined in the FLUKA code, and were examined in a series of epithermal and thermal neutrons, as shown

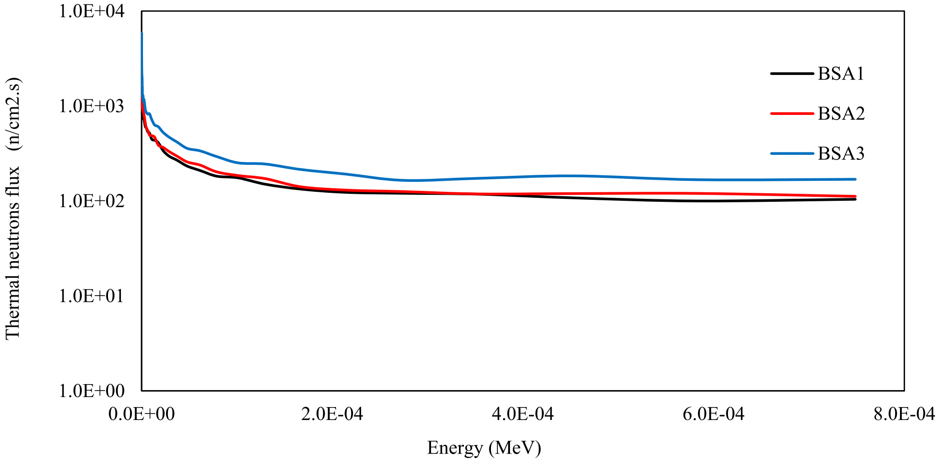

Fig. 10. Comparison of thermal neutron fluxes in BSA1, BSA2 and BSA3 using the FLUKA code derived from D-D fusion.

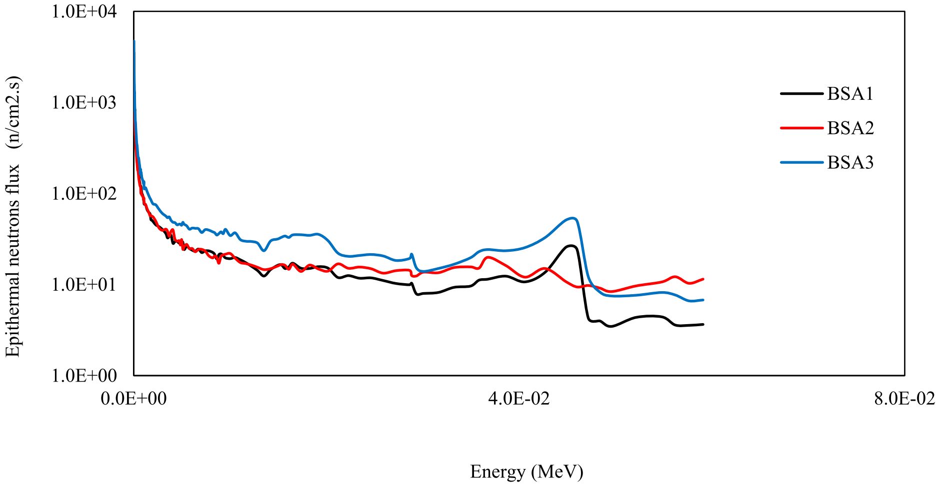

Fig. 11. Comparison of epithermal neutron fluxes in BSA1, BSA2 and BSA3 using FLUKA code derived from D-D fusion.

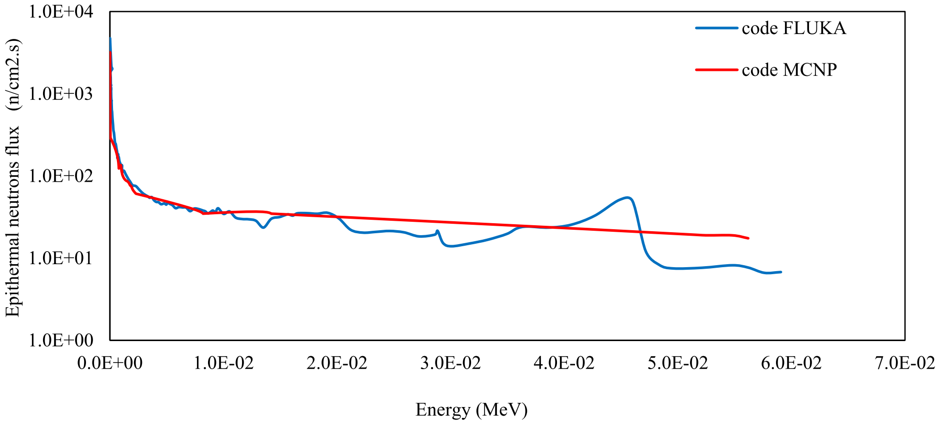

Fig. 12. The epithermal neutron flux in BSA3 using the FLUKA and MCNPX2.6 codes derived from the D-D fusion.

in Figs. 10 and 11, and confirm the results in two GEANT and MCNPX codes on the selection of BSA3.

The results of two FLUKA and MCNPX codes in the epithermal neutron interval shown in Fig. 12. As shown this figure, good agreement and the reason is the difference in obtained results between the two codes libraries.

The absorbed dose defined as the absorbed energy of any type of radiation in the unit mass of each target substance. The unit of measurement of absorbed dose in the SI system is (Gy).

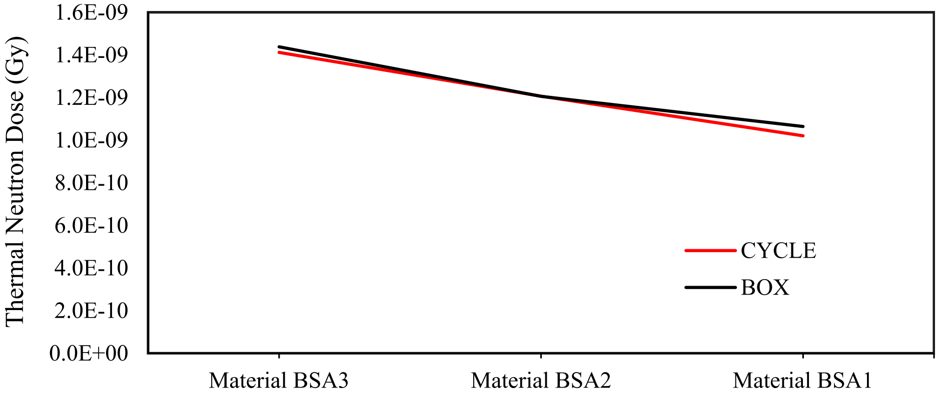

Fig. 13. Comparison of absorbed soft tissue thermal neutron doses in BSA1, BSA2 and BSA3 in two cylindrical and box geometries using GEANT4 code derived from D-D fusion.

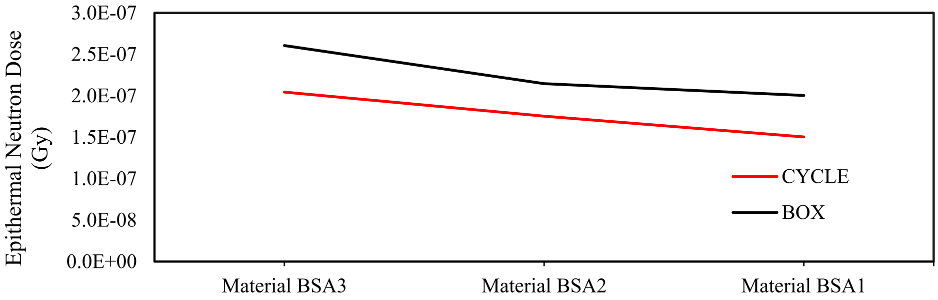

Fig. 14. Comparison of absorbed soft tissue epithermal neutron doses in BSA1, BSA2 and BSA3 in two cylindrical and box geometries using GEANT4 code derived from D-D fusion.

$1\text{Gy} = 100\ \text{rad},\ 1\text{Gy} = 1\ \text{j/Kg}$

Using the Geant4 code, the doses are calculated in two cubic and cylindrical geometries and in the BSA spectrum, whose results are presented in three intervals of thermal and epithermal neutrons in Fig.s 13 and 14.

4. Conclusion

In this paper, beam shaping assembly3 (BSA3) is designed and simulated to optimize the spectrum of epithermal neutron fluxes for treatment via IS plasma focus device coded by GEANT4, MCNPX2.6 and FLUKA codes. Many parameters contribute to the optimization of the beam shaping assembly, including the geometric shape. The spectrum set was simulated by the GEANT4 code in two cylindrical and box geometries of the IS device and according to the geometry simulation results A box could be a better choice for increasing neutron flux. Using the code GEANT4, the dose calculated in two box and cylindrical geometries as well as in three beam shaping assembly (BSAs). The results of which in the two intervals of thermal and epithermal neutrons continue BSA3 and box geometry for neutron capture therapy. However, based on these results, the IS plasma focus device can be a suitable tool for the neutron source in NCT applications.

Declaration of competing interest

There is no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.10.016.

References

[1] S.E. Binney, General Considerations for Neutron Capture Therapy at a Reactor Facility, 2001. No. IAEA-TECDOC–1223.
[2] M. Catterall, R.D. Errington, D.K. Bewley, Fast neutrons in the treatment of locally advanced breast cancer, Eur. J. Surg. Oncol.: the journal of the European Society of Surgical Oncology and the British Association of Surgical Oncology 13 (4) (1987) 315–319.
[3] P. Binns, K. Riley, et al., Dosimetric comparison of six epithermal neutron Beams using an ellipsoidal water phantom, Res. Develop. Neutron Capture Therapy (2002) 405–410.
[4] Geant4 Collaboration, Introduction to GEANT4 User Documentation, 2009.
[5] Robert S. Stone, John C. Larkin Jr., The treatment of cancer with fast neutrons, Radiology 39 (5) (1942) 608–620.
[6] M. Clemencic, et al., The LHCb simulation application, Gauss: design, evolution, and experience, J. Phys. Conf. Ser. 331 (3) (2011). IOP Publishing.
[7] SM Sadat Kiai, et al., Design a 10 kJ IS mather type plasma focus for solid target activation to produce short-lived radioisotopes 12 C (d,n) 13 N. J. Fusion Energy 29 (5) (2010) 421–426.
[8] Jérôme M. Verbeke, Jasmina L. Vujic, Ka-Ngo Leung, Neutron beam optimization for boron neutron capture therapy using the DD and DT high-energy neutron sources, Nucl. Technol. 129 (2) (2000) 257–278.
[9] C.M. Lavelle, et al., Neutronic design and measured performance of the Low Energy Neutron Source (LENS) target moderator reflector assembly, Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 587 (2–3) (2008) 324–341.