https://doi.org/10.46813/2024-151-124

A CLINICAL-BASED NEUTRON SOURCE FOR NUCLEAR MEDICINE AND NEUTRON-CAPTURE THERAPY APPLICATIONS

***V.Y. Kasilov*[1], *V.V. Tsyats'ko*[1], *Yu.G. Kazarinov*[1,2], *V.O. Grigorenko*[1], *S.G. Karpus*[1,2], *G.D. Kovalenko*[1], *S.S. Kochetov*[1], *E.V. Tsyats'ko*[1]**

[1]NSC "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine;

[2]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine

E-mail: stek@kipt.kharkov.ua

The most promising method for generating high-density neutron fluxes for BNCT and nuclear medicine using delayed fission neutrons has been proposed. Estimated fluxes densities of therapeutic neutrons of the order of $4.4 \cdot 10^{13}$ n/(cm^2·s) for radiosurgery and $1.44 \cdot 10^{11}$ n/(cm^2·s) for BNCT are presented, which significantly exceeds existing world analogues. Proposals for a design solution for a clinical-based neutron source device are presented. A study was conducted of the capabilities of NSC KIPT as a potential participant in the international center of nuclear medicine.

PACS: 61.72.Cc, 61.80.Hg, 78.20.Ci, 87.80.+s, 87.90.+y, 07.05.Tp , 78.70.−g

INTRODUCTION

According to World Health Organization (WHO) statistics from the pre-Covid period, oncology ranks second among non-communicable diseases in mortality after cardiovascular diseases [1]. However, the rate of increase in cancer deaths between 2007 and 2017 is second only to deaths from neurological disorders and diabetes and may take the lead in the coming years.

Radiation therapy methods are used quite successfully in the fight against these diseases, but there is a need to find optimal ways of obtaining ionising radiation sources and approaches that could increase the effectiveness of their use in treatment.

In the world clinical practice such direction of radiation therapy as neutron-capture therapy is successfully applied, which is based on the use of elements with high cross-section of slow neutrons capture by nuclei, such as ^{10}B [2, 9]. Preparations containing ^{10}B are injected into the affected area of the patient's tissue prior to irradiation. The interaction of the delayed neutrons with ^{10}B results in a nuclear reaction with an energy release of 2.3 MeV inside the cancer cell and the production of ^{7}Li and alpha particles, which are absorbed within the cell, resulting in its death.

PROBLEM FORMULATION

The purpose of this paper is to report on the search and identification of opportunities for the creation of new technologies for the production of beams of therapeutic neutrons for use in neutron-capture therapy. Since the problems with cancer are a problem for the entire population of the planet Earth, therefore, the search and development of the most effective methods for the treatment of cancer today is an urgent task for the world community of physicists, engineers and physicians [3–5], to which the scientists of NSC KIPT belong [6–8].

Currently, the achievements of modern physics are widely used in medical technology. The high-tech medical equipment pipeline includes small-sized, high-current electron accelerators that can be used to generate high-density neutron fluxes in clinical sources. The accelerator is the most expensive component of this equipment.

Joint efforts of physicists, engineers and medical professionals have introduced combined models of PET+CT, MRI+CT and other tomographs in many centres. Super-modern technologies of gamma ray therapy, such as gamma knife and cyber knife, have appeared, which are quite widely involved in practical use and can be further modernised to create concentrated beams of therapeutic neutrons.

At the same time, the number of new technologies related to nuclear medicine is rapidly increasing.

The emergence of high-quality therapeutic neutron beams with minimal accompanying background, which are generated using non-standard methods of obtaining high flux densities, can become, accordingly, a major breakthrough in the use for specialised forms of radiation therapy and will expand the standard areas of its application.

Treatment of oncological diseases by boron-neutron-capture therapy (BNCT) in clinical conditions requires, at least, the availability of appropriate neutron sources for this purpose, of which there are still a small number in the world [2]. At present, Japan is the leader in this field.

We are convinced that the establishment of international nuclear medicine centres on the basis of partnership cooperation of scientific world associations aimed at fighting cancer will make a significant contribution to the successful development of methods for overcoming this disease worldwide.

OBJECTS OF RESEARCH

In the present study we intend to research for the potential of NSC KIPT capabilities to create on its basis a clinical neutron source for nuclear medicine. Obviously, the existing equipment for nuclear research and the infrastructure supporting its functioning can be used for this purpose.

Our study considers the possibility of locating a putative neutron source for nuclear medicine in the experimental hall of the direct output of the LUE-2 GeV accelerator, which is currently decommissioned. We have

developed a schematic diagram of such a source and presented it in Fig. 1.

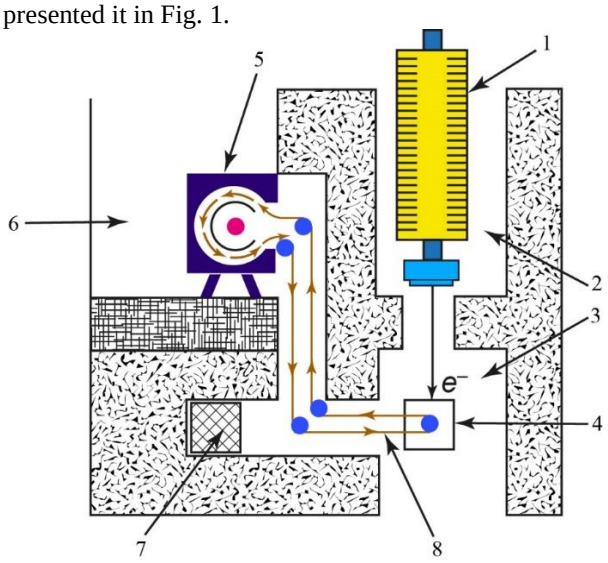

Fig. 1. Schematic diagram of a clinical-based neutron source:
1 – electron accelerator, 2-accelerator bunker;
3 – activation zone bunker; 4 – combined target (core);
5 – therapeutic slow neutron beam shaper;
6 – room isolated from the accelerator and core, designed to place the shaper and service personnel;
7 – background absorber;
8 – system for transporting activated targets

Let us consider the functional purpose of each of the units that make up the neutron source:

– high-current electron accelerator with energy of 35 MeV and a beam power of 35 kW is designed to produce photo neutrons in the primary tungsten target located in the active zone;

– the accelerator bunker and activation zones fulfil the role of biological environmental protection;

– core is designed for neutron multiplication.

Fig. 2 shows that the beam of accelerated electrons (7) from the vacuum chamber (6) of the accelerator through the separating foil (5) is led to the primary target (8) made of a set of tungsten plates stacked together. There is a gap between the plates to allow cooling air to pass through.

An electron beam with an energy of 35 MeV and a power of 35 kW interacts with a primary target and produces photoneutrons in it. At this energy, it can be assumed that there are about 10^{12} n/s per kW of electron beam power. Then the intensity of the produced neutrons will be $3.5 \cdot 10^{13}$ n/s.

Note that the primary target is surrounded by a multiplying target (4), made of natural uranium in the form of a cylinder with an internal diameter of 10 cm and a height of 10 cm, and the thickness of the cylinder wall is 1 cm. The surface area of the cylinder is 31.4 cm^2, and the volume of natural uranium is 314 cm^3. In this case, the number of ^{238}U nuclei in the target will be $1.51 \cdot 10^{25}$ cm^{-3}. Since the multiplying target has a cylindrical surface and not a spherical one, only about half the intensity of the neutrons that were produced in the primary target can interact with ^{238}U nuclei. Then, during the interaction of photoneutrons from the primary target with the multiplying target, the process of fission of ^{238}U nuclei occurs, as a result of which prompt and delayed fission neutrons are formed, the total intensity of which will be $4.9 \cdot 10^{14}$ n/s.

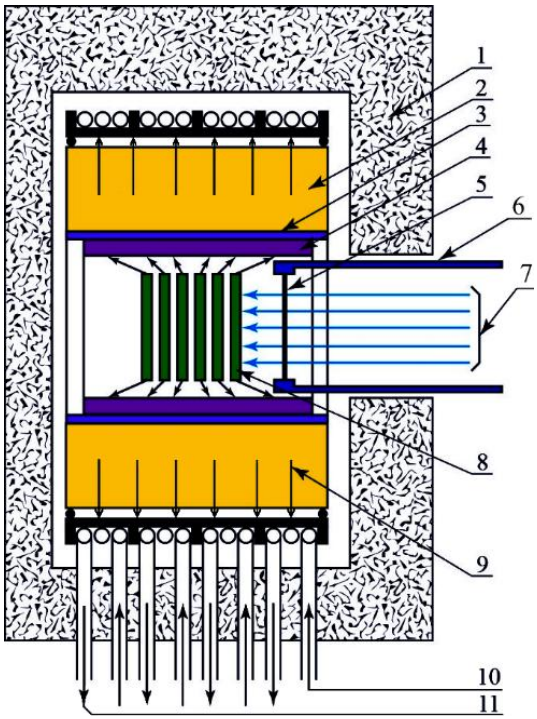

Fig. 2. Schematic of the active zone located at the output of the electron accelerator:
1 – active area wall; 2 – polyethylene moderator;
3 – target for production of radioactive medical drugs;
4 – n-multiplication target; 5 – e-beam output foil;
6 – vacuum accelerator chamber; 7 – electron beam;
8 – primary target; 9 – neutron streams;
10 – feeding of activated uranium dioxide targets;
11 – return of activated uranium dioxide targets

Further, from Fig. 2 we see that on the surface of the multiplying target there is a target made of material for the production of medical preparations (3), and behind it there is a polyethylene moderator designed to slow down neutrons from the breeding target. This entire structure, together with the primary target, is placed in a cylindrical body with a diameter of 20 cm and a length of 20 cm, on which special guide grooves are made for moving activated uranium dioxide targets into them.

The activated targets are standard uranium dioxide pellets for WWER-1000 fuel rods. These tablets are enriched up to 5% in ^{235}U. Let us determine the intensity of neutrons after moderation in a polyethylene moderator (2). Let's assume that the number of uranium dioxide pellets that will pass through the core will be $4.8 \cdot 10^3$ s^{-1}. Each pellet contains $6 \cdot 10^{20}$ nuclei of ^{235}U. Then $2.8 \cdot 10^{24}$ n/s will pass through the active zone, and the intensity of thermal neutrons incident on the tablets located on a cylindrical surface will be $2.5 \cdot 10^{14}$ n/s. In this case, the cross section for fission of ^{235}U by thermal neutrons will be $5.8 \cdot 10^{-22}$ and the number of fission events will be $4 \cdot 10^{17}$ divisions/s. Since there are 2.5 neutrons for each fission event, the total intensity of prompt and delayed fission neutrons will be 10^{18} n/s. In this case, the number of delayed neutrons is 1% of the total and equal to 10^{16} n/s. Considering the fact that the

total number of neutrons in the core is 10^{18} n/s, the possibility of using them to produce radioactive medical isotopes can be considered. In this case, delayed neutrons with an intensity of 10^{16} n/s after they leave the core can be delivered by two separate transport channels through a closed loop to the formers, which are located at a remote distance from the core in different rooms and are intended for different purposes, for example, one for creating a concentrated neutron flux, and the other for conducting a session of boron neutron capture therapy, as shown in Figs. 3 and 4.

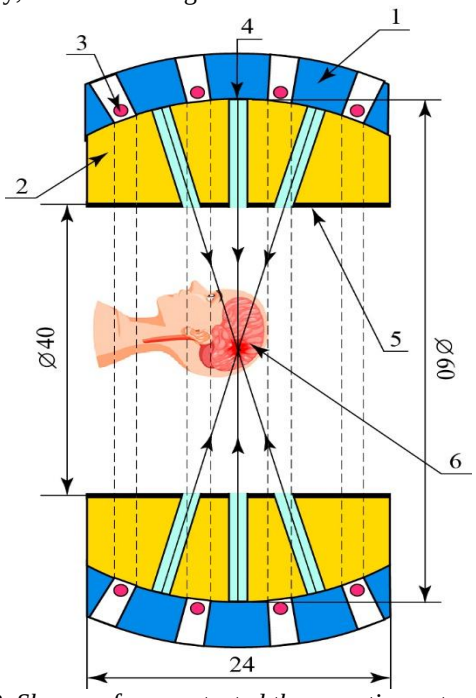

Fig. 3. Shaper of concentrated therapeutic neutron flux: 1 – polyethylene moderator; 2 – neutron collimator; 3 – activated targets; 4 – therapeutic neutron flux; 5 – gamma radiation absorber; 6 – irradiated object

Four chains of activated targets of equal length pass through each shaper, emitting delayed neutrons, from which the total intensity in each shaper will be $5 \cdot 10^{15}$ n/s. One chain contains 600 pieces of activated targets emitting delayed neutrons with an intensity of $1.2 \cdot 10^{15}$ n/s, which pass through the moderator. After their moderation, the intensity of the moderated neutrons in the shaper is approximately $3.6 \cdot 10^{14}$ n/s, and their angular distribution is isotropic. Since the distance from the moderator to the irradiated object is 50 cm, the flux density of moderated neutrons on it after passing through one collimator will be $1.44 \cdot 10^{11}$ n/(cm^2·s).

Figs. 3 and 4 show diagrams of shapers of different designs. The shaper in Fig. 3 contains about 300 collimators directed from its spherical surface to the center of the ball to one point, at which a concentrated flow of therapeutic neutrons is created on the irradiated object. The density of this flow can be approximately $4.4 \cdot 10^{13}$ n/(cm^2·s). This flow can be used for radiosurgery on the brain. At the same time, the flux density of therapeutic neutrons in the shaper in Fig. 4 remains at the level of $1.44 \cdot 10^{11}$ n/(cm^2·s), however, the spot size of these neutrons can vary from minimum to maximum, commensurate with the size of a cancer tumor, which can well be used for carrying out boron neutrons grip therapy.

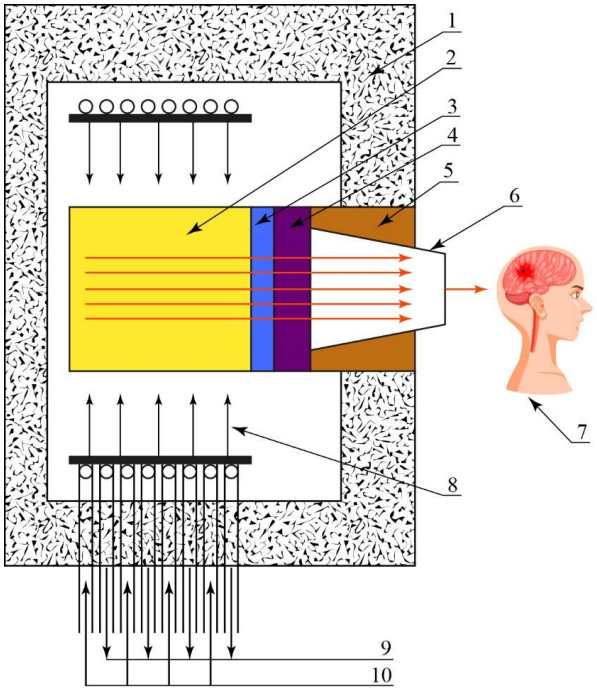

Fig. 4. Formator of therapeutic delayed neutron for boron neutron capture therapy: 1 – graphite reflector; 2 – polyethylene moderator; 3 – thermolyzed neutron absorber; 4 – gamma radiation absorber; 5 – delayed neutron collimator; 6 – beam aperture; 7 – irradiated object; 8 – delayed neutrons from an activated target; 9 – returning activated targets; 10 – feeding activated targets

CONCLUSIONS

Thus, as a result of previous and present studies, it has been shown that:

1. The use of delayed fission neutrons to generate therapeutic beams of delayed neutrons is currently the most promising way to obtain high neutron flux densities for BNCT and nuclear medicine in general.

2. The presented estimated therapeutic neutron flux densities indicate that they significantly exceed existing world analogues.

3. In this work, we conducted a study of the capabilities of NSC KIPT as a potential participant in the global community of physicists, engineers and physicians who can contribute to the creation of a clinical-based neutron source and, on its basis, create an international center for nuclear medicine to fight cancer diseases, which are today are a global problem for all humanity. It is obvious that the equipment for nuclear research created over many years by a whole generation of employees of NSC KIPT, the infrastructure that ensures its operation and scientific developments in nuclear medicine can be used for this purpose as its share contribution from the world community.

REFERENCES

1. G.A. Roth et al. Global, regional, and national age-sex-specific mortality for 282 causes of death in

195 countries and territories, 1980–2017: a systematic analysis for the Global Burden of Disease Study 2017 // *The Lancet*. 2018, N 10159, v. 392, p.1736-1788.

2. Advances in Boron Neutron Capture Therapy. Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2023. [Online]. Available: https://www.iaea.org/publications/15339/advances-in-boron-neutron-capture-therapy

3. M. Tatari and A.H. Ranjbar, Design of a photoneutron source based on 10 MeV electrons of radiotherapy linac // *Annals of Nuclear Energy*. 2014, v. 63, p. 69-74.

4. C.K.C. Wang, T.E. Blue, and R. Gahbauer. Neutronic study of an accelerator-based neutron irradiation facility for boron neutron capture therapy // *Nuclear Technology*. 1989, v. 84, N 1, p. 93-107.

5. H. Tanaka et al. Experimental Demonstration of Beam Characteristics for Cyclotron-Based Epithermal Neutron Source (C-BENS) // *New Challenges in NEUTRON CAPTURE THERAPY 2010 Proceedings of 14th International Congress on Neutron Capture Therapy*. 2010, p. 447-450.

6. E.L. Kuplennikov, A.N. Dovbnya, V.A. Tsymbal, S.S. Kandybei, and A.F. Stoyanov. Estimation of ^{99}Mo and ^{99m}Tc production on KIPT ^{9}Be(d,n) generator // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations*". 2012, N 4(80), p. 155-159.

7. A.N. Dovbnya et al. An increase of ^{99}Mo yield under mixed γ, n-irradiation of target from natural molybdenum // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations*". 2008, N 4(80), p. 151-154.

8. V.O. Voronko, R.N. Dronov, B.I. Shramenko, I.V. Beloziorov, and I.O. Girka. Proposal for creation of positron-emission tomography center on the basis of school of medicine and school of physics and technology of Kharkiv National University // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations*". 2020, N 3(127), p. 168-171.

9. V.V. Tsyats'ko, S.P. Gokov, Yu.G. Kazarinov // *Problems of Atomic Science and Technology*. 2023, N 3(145), p. 168;
https://doi.org/10.46813/2023-145-168

Article received 30.04.2024

ДЖЕРЕЛО НЕЙТРОНІВ КЛІНІЧНОГО БАЗУВАННЯ ДЛЯ ЗАСТОСУВАННЯ В ЯДЕРНІЙ МЕДИЦИНІ ТА НЕЙТРОН-ЗАХОПЛЮВАЛЬНІЙ ТЕРАПІЇ

В.Й. Касілов*, В.В. Цяцько, Ю.Г. Казарінов, В.О. Григоренко, С.Г. Карпусь, Г.Д. Коваленко, С.С. Кочетов, Є.В. Цяцько

Запропоновано найбільш перспективний спосіб генерації потоків нейтронів великих щільностей для БНЗТ і ядерної медицини з використанням нейтронів поділу, що запізнюються. Представлено оціночні щільності потоків терапевтичних нейтронів порядку $4.4\cdot10^{13}$ нейтр./(см^2·с) для радіохірургічних операцій та $1.44\cdot10^{11}$ нейтр./(см^2·с) для БНЗТ, що суттєво перевищує існуючі світові аналоги. Подано пропозиції конструктивного рішення пристрою джерела нейтронів клінічного базування. Проведено дослідження можливостей ННЦ ХФТІ як потенційного учасника міжнародного центру ядерної медицини.