ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2025, Vol. 22, No. 4, pp. 842–846. © Pleiades Publishing, Ltd., 2025.
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PHYSICS AND TECHNIQUE OF ACCELERATORS

Beam Shaping Assembly of the VITA Accelerator-Based Neutron Source

T. V. Shein[a, b, *], E. A. Berendeev[a, b], V. S. Degtyarev[a, b], A. M. Koshkarev[a, b], A. S. Kuznetsov[a, b], S. S. Savinov[a, b], and S. Yu. Taskaev[a, b, c]

[a] *Budker Institute of Nuclear Physics, Novosibirsk, 630090 Russia*
[b] *Novosibirsk State University, Novosibirsk, 630090 Russia*
[c] *Joint Institute for Nuclear Research, Dubna, 141980 Russia*
**e-mail: sychevatatyanav@gmail.com*

Received October 28, 2024; revised January 28, 2025; accepted January 31, 2025

Abstract—The VITA accelerator-based neutron source has been proposed and developed at the Budker Institute of Nuclear Physics (Novosibirsk, Russia) for boron neutron capture therapy (BNCT), which includes a vacuum-insulated tandem accelerator for proton beam production, a lithium target for neutron generation through the ^{7}Li(p, n)^{7}Be reaction, and a neutron beam shaping assembly (BSA) with MgF_2 moderator for therapeutic beam generation. This paper presents a comparison of the results of numerical simulations of boron dose and γ-ray dose spatial distributions in a water phantom for three different neutron beam shaping assemblies. The investigations are carried out at the VITA accelerator-based neutron source in the Budker Institute of Nuclear Physics, Siberian branch, Russian Academy of Sciences, using a small neutron detector to measure these components of ionizing radiation. An agreement between the measured and simulated results is obtained. For the VITA accelerator neutron source that was manufactured and is being supplied to the Blokhin National Medical Research Center of Oncology in Moscow with the purpose of conducting clinical trials of the BNCT technique in Russia and the subsequent treatment of patients, the BSA is optimized by numerical simulation with consideration for the equipment, the presence of structural materials, and the wall separating the installation room from the irradiation room. The description of materials that make it possible to form a neutron beam that meets the requirements of the BNCT and the design of manufactured BSA is presented.

DOI: 10.1134/S1547477125700700

INTRODUCTION

Boron neutron capture therapy (BNCT) is a promising method for treating oncological diseases. BNCT makes it possible to eliminate tumors by the selective accumulation of the stable isotope ^{10}B in the tumor cells and a subsequent irradiation of the patient by an epithermal neutron flux. As a result of absorption of a neutron by boron, the nuclear reaction ^{10}B(n,α)^{7}Li passes with a high energy release within one cell, which leads to its death [1].

The VITA accelerator-based neutron source is manufactured at the Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, to conduct BNCT in the National Medical Research Center of Oncology (Moscow), which is planned to be set in operation in 2025 with the purpose of using it for patient treatment. The accelerator is equipped with a beam shaping assembly (BSA) with a magnesium fluoride moderator for the generation of a therapeutic neutron beam. To put the BNCT into clinical practice and create an individual plan of treatment for each patient, a dosimetric planning system (DPS) of VITA is developed, which is the only one of its kind in the Russian Federation.

In this paper, a validation of the results of calculating the dose distribution of neutron and gamma radiation by the VITA DPS are described, the results of optimizing the BSA with a MgF_2 moderator performed by numerical simulation with consideration of the IAEA recommendations [1] are presented for a proton energy of 2.3 MeV and a current of 7 mA, and the structure of the neutron beam shaping system is presented.

1. VALIDATION OF THE CALCULATIONS OF THE VITA DPS

The experimental investigations were carried out at the VITA accelerator-based neutron source in the Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences [2, 3]. The neutron generation occurs in a lithium target in the ^{7}Li(p, n)^{7}Be reaction. The scheme of the experiment is shown in Fig. 1.

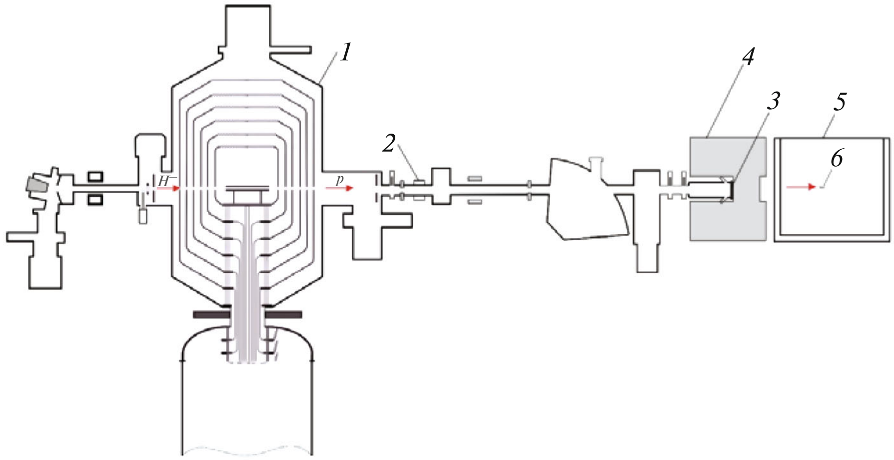

Fig. 1. Experimental setup: (*1*) vacuum-insulated tandem accelerator, (*2*) noncontact current sensor, (*3*) lithium target, (*4*) BSA, (*5*) water phantom, and (*6*) neutron and gamma-radiation detectors.

The BSA and a P3D01 water phantom are arranged in the horizontal tract of the beam.

The spatial distributions of the boron and gamma radiation doses in the water phantom were carried out with the help of two gamma and neutron detectors with lithium polystyrene scintillators, one of which is doped with boron [10, 11]. The detectors are installed on a platform that is relocatable over the entire inner volume of the phantom.

The total absorbed dose in the BNCT is the sum of four components [7]: boron, nitrogen, rapid neutron, and gamma-radiation doses.

In this work, 3D calculations of all four components of the total dose are performed at the voxel model of the water phantom with an edge of 8 mm with the help of the DPS of VITA with the use of the code of neutron and NMC gamma-radiation transfer by the Monte Carlo method [4].

The following procedure was chosen to carry out measurements: at first, the measurements were performed at a proton energy of 2.1 MeV and a current of 1 mA, since at such a proton energy, the neutrons generated in the $^7Li(p, n)^7Be$ reaction are characterized by an average energy of 100 keV [6] and they penetrate quite deep into the water in the absence of the moderator, forming the maximum of thermal neutron density at some depth, which makes it possible, by matching the maxima of the calculated and measured distributions, to accurately determine the sensor position with respect to the water phantom surface. Matching the calculated and measured distributions with respect to their amplitudes, one determines the coefficient of conversion of the detector count rate to the dose rate. For the gamma-radiation dose, the displacement associated with the accelerator radiation was also considered. These coefficients were applied to convert the detector count rate to the dose rate for other beam shaping assemblies: that with a moderator made of acrylic glass and for the earlier developed BSA with a moderator made of MgF_2 and a bismuth filter of gamma-radiation at the output of the BSA. After that, the calculated and experimental values were compared with each other.

Figure 2 shows the results of calculations and measurements with consideration for the conversion coefficient for the boron and gamma-radiation doses. The results of the measurements demonstrate a good agreement between the measured and calculated depth distributions of the boron and γ-radiation doses. The deviation of the calculated and experimental data for the boron and γ-radiation doses does not exceed 5%, which is comparable with the statistical error.

2. BSA OF THE ACCELERATOR-BASED NEUTRON SOURCE VITA

The results of the investigations have shown good agreements between the measured and calculated depth distributions of the boron and gamma-radiation doses. When using the manufactured BSA with a magnesium fluoride moderator in the VITA accelerator-based neutron source supplied to the Blokhin National Medical Research Center (Moscow), the neutron beam parameters at a proton energy of 2.3 MeV and a current of 7mA do not completely agree with the values recommended by the IAEA [1]; they are presented in Table 1 (the BSA column refers to the initial project). It is seen that, for the BSA parameters in air to correspond to the IAEA recommendations, it is necessary to reduce the ratio of the thermal flux to the epithermal flux, the fast neutron dose per unit of the epithermal flux, and the gamma-radiation dose per unit of the epithermal flux.

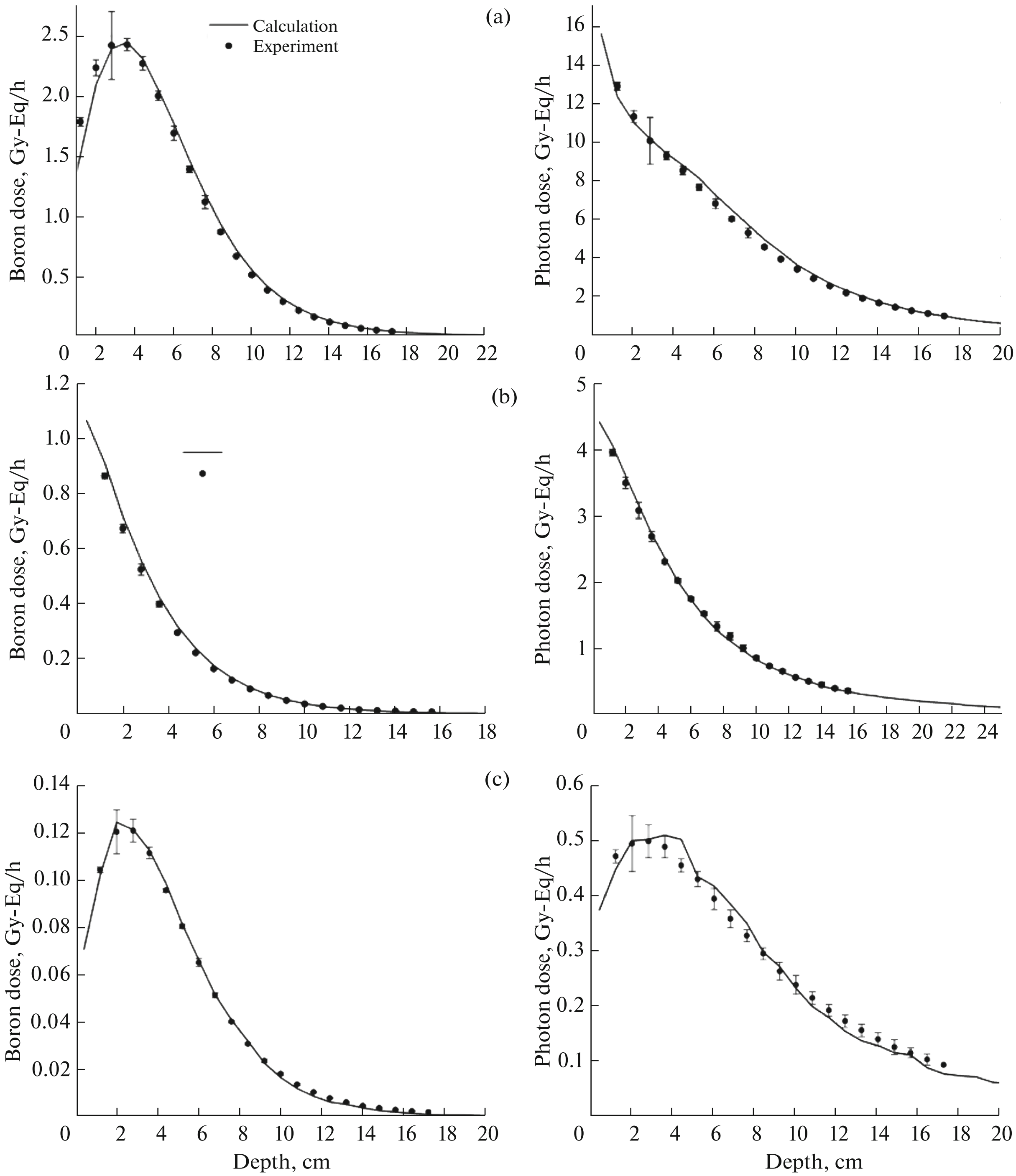

Fig. 2. Results of measurement and simulation of the boron and gamma-radiation dose distribution for three beam shaping assemblies. Current of 1 mA: (a) target assembly; proton energy is 2.1 MeV. (b) Target assembly with a moderator made of acrylic glass; proton energy is 2.1 MeV. (c) Target assembly and BSA with a MgF_2 moderator and a bismuth filter at the output.

In connection with this, the decision was taken about the necessity of structural changes in the BSA and the use of additional filters. To reduce the amount of thermal neutrons, it is decided to use cadmium foil with a thickness of 0.2 mm, to reduce amount of fast neutrons it is decided to use poliethylene with a lithium admixture with a thickness of 0.5 cm; to reduce the gamma radiation, it was decided to use the filter made of bismuth with a thickness of 0.2 cm. The increase in the part of epithermal neutrons and reduction of the gamma-radiation dose are due to the enlargement of the graphite reflector height in the forward semisphere of the beam by 5 cm and the removal of all structural elements made of titanium from the

Table 1. Parameters of the BSA in air at different stages of the project in comparison with the values recommended by the IAEA

Quality indicator	Epithermal neutron flux, ϕ_{epi}, cm^{-2} s^{-1}	Thermal to epithermal flux ratio, ϕ_{th}/ϕ_{epi}	Fast neutron dose per unit of the epithermal flux, $D_H/\int \phi_{epi}(t)\,dt$, Gy cm^2	γ-radiation dose per unit of the epithermal flux, $D_\gamma/\int \phi_{epi}(t)\,dt$, Gy cm^2
Values recommended by the IAEA	$\geq 5 \times 10^8$	≤ 0.05	$\leq 7 \times 10^{-13}$	$\leq 2 \times 10^{-13}$
Optimized BSA	7.26×10^8	0.028	5.9×10^{-13}	1.98×10^{-13}

model, except for the external case of the BSA, as well as the enlargement of the magnesium fluoride moderator. The further reduction of the gamma-radiation dose was obtained due to the replacement of polyethylene with lithium in the forward semisphere of the beam by lead and the increase in the bismuth filter thickness up to 0.5 cm. The models of the BSA at various stages of its designing are presented in Fig. 3. The neutron beam parameters of the final version of the BSA (Fig. 3c) completely meet the IAEA requirements (Table 1).

Based on the results of numerical simulation of the neutron and gamma-radiation transfer, the BSA was designed for the Blokhin National Medical Research Center of Oncology (Moscow); its three-dimensional image is shown in Fig. 3.

CONCLUSIONS

The BNCT technique is beginning to be part of clinical practices all over the world. The VITA accelerator-based neutron source is manufactured at the Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, to carry out boron neutron therapy in the Blokhin National Medical Research Center of Oncology in Moscow with the purpose of using it for patient treatment. The accelerator is equipped with BSA with a moderator made of magnesium fluoride to form the therapeutic neutron beam. To put the BNCT into clinical practice and elaborate an individual plan of treatment for each patient, the VITA DPS is developed. The validation of the calculation of the VITA DPS with the use of three beam shaping assemblies has shown that the deviation of the data from the experimental data does not exceed 5% for boron and γ-radiation doses for all the experiments. With the help of numerical simulation, the structure of the BSA was optimized for the Blokhin National Medical Research Center of Oncology with consideration for all recommendation of the IAEA. In this paper, we present a description of the means and materials used to shape a neutron beam that meets the IAEA requirements; the structure of the neutron BSA is presented.

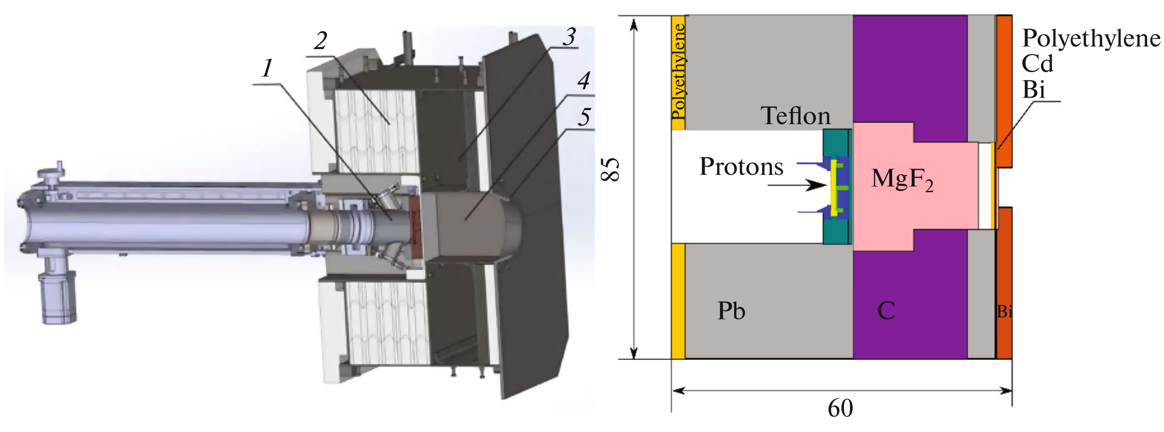

Fig. 3. (a) Neutron BSA designed for the Blokhin National Medical Research Center of Oncology: (*1*) target block with a lithium target, (*2*) lead reflector, (*3*) reactor graphite reflector, (*4*) moderator made of magnesium fluoride crystals, and (*5*) tungsten collimator. (b) Model of the optimized BSA. Sizes are in centimeters.

FUNDING

This work was supported by the Ministry of Science and Higher Education of the Russian Federation.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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Translated by E. Smirnova