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PHYSICS AND TECHNIQUE OF ACCELERATORS

Evolution of Accelerator Based Neutron Source VITA

M. I. Bikchurina[a, b], T. A. Bykov[a, b], G. D. Verkhovod[a, b], V. S. Degtyarev[a], D. A. Kasatov[a, b], A. A. Kashcheev[a], Ya. A. Kolesnikov[a, b], V. D. Konovalova[a, b], A. M. Koshkarev[a, b], A. S. Kuznetsov[a, b], G. M. Ostreinov[a, b], S. S. Savinov[a, b], N. Sh. Singatulina[a, b], E. A. Sokolova[a, b], A. E. Soldatov[a], I. N. Sorokin[a, b], T. V. Shein[a, b], A. A. Shuklina[a], I. M. Shchudlo[a, b], and S. Yu. Taskaev[a, b, c, *]

[a] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[b] *Novosibirsk State University, Novosibirsk, Russia*
[c] *Joint Institute for Nuclear Research, Dubna, Russia*
**e-mail: taskaev@inp.nsk.su*

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Abstract—Budker Institute of Nuclear Physics has proposed, developed, and is operating accelerator based neutron source VITA, which includes an electrostatic tandem accelerator of charged particles of an original design (vacuum insulated tandem accelerator), a lithium neutron-generating target, and set of neutron beam shaping assemblies. The facility generates the stationary beam of protons or deuterons with the energy of up to 2.3 MeV and the current of up to 10 mA, the generation of a powerful neutron flux, and the formation of a beam of neutrons of various energy ranges, from cold to fast. The facility is actively used for the development of boron neutron capture therapy of malignant tumors (BNCT), radiation testing of promising materials, measuring the cross-section of nuclear reactions and some other applications. The second version of the accelerator based neutron source VITA-II features the presence of pre-acceleration to increase the proton energy, the use of a volumetric source of negative hydrogen ions instead of a surface plasma source to increase the proton beam current, and a decreased height of the installation due to the modernization of the high-voltage power supply and its connection to the accelerator. The accelerator based neutron source VITA-IIα was provided to the BNCT clinic in Xiamen (China) for the treatment of patients with the BNCT method. The second accelerator neutron source, VITA-IIβ, was manufactured to equip Blokhin National Medical Research Center of Oncology in Moscow to conduct clinical trials of the BNCT technique in the Russian Federation starting in 2025. Based on the experience gained, the third version of the accelerator based neutron source VITA-III and the compact accelerator based neutron source VITAmin are under development. The design of neutron sources, their features, parameters and applicability are presented and discussed.

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INTRODUCTION

Boron neutron capture therapy (BNCT) [1] is considered a promising method for treating malignant tumors. It ensures selective destruction of tumor cells by accumulating non-radioactive boron-10 nuclei in tumors and subsequent irradiation with neutrons. As a result of the absorption of a neutron by a boron nucleus, a nuclear reaction ^{10}B(n, α)^{7}Li occurs with a large release of energy in the cell, which leads to its death. BNCT requires an intense beam of epithermal neutrons, optimally in the energy range of 1 to 10 keV. The best solution is considered the reaction ^{7}Li(p, n)^{7}Be at a proton energy of around 2.5 MeV—near the reaction threshold. In this case, the emitted neutrons have minimal energy (~100–400 keV) and the moderator can be used to form a therapeutic neutron beam with a minimal contribution of fast and thermal neutrons. Such a neutron source, which includes a set of new solutions, was proposed and implemented at the Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences and is effectively used for conducting scientific research and clinical trials of the method. The article provides a description of the manufactured accelerator based neutron sources VITA and proposals for its improvement.

1. ACCELERATOR BASED NEUTRON SOURCE VITA

The accelerator based neutron source VITA [2, 3] includes a vacuum insulated tandem accelerator for producing a stationary beam of protons or deuterons with an energy of up to 2.3 MeV and a current of up to 10 mA, a lithium target for generating neutrons, and a set of beam shaping assemblies for producing a beam of neutrons in various energy ranges from cold to fast neutrons. The schematic diagram of the installation deployed at the Budker Institute of Nuclear Physics is shown in Fig. 1. The facility is equipped with modern

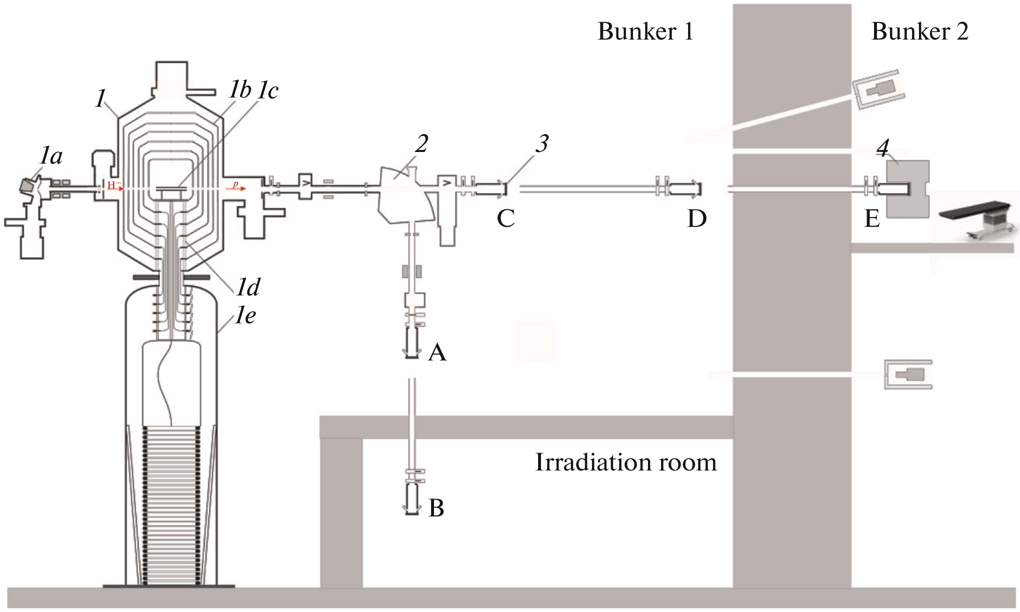

Fig. 1. Schematic diagram of the accelerator based neutron source VITA: (*1*) vacuum insulated tandem accelerator ((*1a*) source of negative ions, (*1b*) high-voltage and intermediate electrodes, (*1c*) gas stripping target, (*1d*) feedthrough insulator, (*1e*) high voltage power supply), (*2*) bending magnet, (*3*) lithium neutron-generating target, (*4*) neutron beam shaping assembly. The lithium target is placed in positions A, B, C, D or E.

diagnostic equipment, including γ-, α-, and neutron spectrometers and dosimeters, which enables conducting scientific research in various fields of knowledge.

The accelerator based neutron source is a linear electrostatic accelerator of charged particles of tandem type of original design. The term "linear" in the description of the accelerator implies that the ion beam passes through the accelerating intervals once. The term "electrostatic" implies that a constant electric field acts on a particle, i.e., increases its energy. The term "tandem" implies that the applied DC acceleration voltage is used twice. Negative ions are accelerated by a positive potential applied to the central high voltage electrode. Inside it, negative ions are converted into positive ones, which are again accelerated by the same potential. The key advantage of the tandem acceleration concept is that the required acceleration voltage is reduced by half, which greatly simplifies electrostatic isolation and reduces its size. The vacuum-insulated tandem accelerator features a unique design that does not involve accelerator tubes, unlike conventional tandem accelerators. Instead, embedded intermediate cylindrical electrodes (*1b* in Fig. 1), are used, fixed to a single feedthrough insulator (*1g* in Fig. 1). The advantage of this arrangement is that the ceramic parts of the feedthrough insulator are removal from the ion beam to increase the high-voltage strength of the accelerating gaps and obtain a high ion beam current.

Lithium target (*3* in Fig. 1) is a copper disk, one side of which is thermally coated in a vacuum with a thin layer of pure lithium of crystalline density. On the reverse side of the copper disk, there are spiral channels for water cooling. A flat aluminum disk with holes for the feed and drain of cooling water is pressed against the reverse side of the copper disk. The lithium target is a part of the target assembly, which includes an aluminum pipe, a gate valve, and pipes with windows for diagnostic equipment or for monitoring the surface condition of the lithium layer of the target. The lithium target provides long-term stable generation of neutrons without degradation of the yield.

To obtain a beam of neutrons of various energy ranges, neutron beam formation systems are used (*4* in Fig. 1) with a moderator made of heavy water at cryogenic temperature, plexiglass or magnesium fluoride crystals. Also, to obtain a beam of neutrons exclusively in the epithermal energy range or a monoenergetic beam of neutrons, kinematic collimation is used.

The following scientific results were obtained in developing the boron neutron capture therapy technique at the facility: (i) the effect of neutron radiation on the survival of cell cultures and laboratory animals was studied, (ii) treatment of domestic cats and dogs with spontaneous tumors was carried out, (iii) a small-sized detector with a cast polystyrene scintillator was developed for measuring the boron dose and γ-ray dose in air and in a water phantom, (iv) a method for measuring the total the dose of fast neutrons and the nitrogen dose, called a "cellular dosimeter" was proposed and implemented, (v) a method for prompt γ-ray spectrometry for in situ measurements of boron dose has been developed, (vi) a detector of epithermal neutron flux has been developed using the reaction $^{71}Ga(n, \gamma)^{72}Ga$, and (vii) for the first time it was shown that lithium-neutron capture therapy is feasible, providing 100% release of nuclear reaction energy in tumor cells.

The facility also provided the following important scientific results in other fields of knowledge: (i) the process of blister formation on the metal surface during proton implantation and its effect on neutron release from a thin lithium layer deposited on the metal surface were studied, (ii) thermal neutron flux was used to determine the activation of boron carbide ceramic samples manufactured by four manufacturers for an International Thermonuclear Experimental Reactor ITER, (iii) the density and strength of boron carbide ceramic and steel samples were altered using fast neutron flux, (iv) the dependence of optical fiber transparency on the fluence of fast neutrons was studied to be used in the planned operation of the CERN Large Hadron Collider in the high-luminosity mode, (v) a method for measuring the thickness of lithium by measuring the intensity of photons emitted during inelastic scattering of a proton on a lithium atomic nucleus has been proposed and implemented, (vi) the yield of particles in two nuclear reactions and the cross-section of 20 nuclear reactions were measured. The latter allows (i) reliable determination of the dose of ionizing radiation during BNCT, (ii) determine of the dependence of the neutron energy spectrum on the deuteron energy in the most productive Li(d,n) reaction, which has seven channels for generating fast neutrons, and (iii) assessment of the prospects for implementing neutron-free thermonuclear energy in the $^{11}B(p, \alpha)\alpha\alpha$ reaction.

2. ACCELERATOR BASED NEUTRON SOURCE VITA-II

Neuboron Medtech Ltd. (China) ordered development and manufacture of the second version of the accelerator based neutron source VITA. It is distinguished by the presence of pre-acceleration to increase the energy of the proton beam, the use of a source of negative hydrogen ions distributed by D-Pace (Canada) with volumetric ion generation instead of BINP's surface-plasma source for stable ion generation over a long period of time, and a more compact arrangement of the high-voltage power source [4]. This facility (Fig. 2), called VITA-IIα, was delivered to the newly created BNCT Center at the clinic based in Xiamen (China). After the facility attained design parameters and studies were conducted with cell cultures and laboratory animals at the BNCT center, 28 patients with large tumors of the neck and head and with glioblastoma were treated from October 9, 2022, as part of clinical trials initiated by the developer. Then, after

Fig. 2. Image of the VITA-IIα accelerator neutron source at the Institute of Nuclear Physics before transportation to China.

registering the boron delivery drug developed and receiving a certificate confirming the facility's compliance with safety and efficacy standards, treatment of patients began on May 22, 2024, as part of state-initiated Phase I clinical trials. China is the world's second country after Japan to introduce the BNCT technique into clinical practice.

The second similar facility, named VITA-IIβ, was manufactured for the Blokhin NMIC of Oncology of the Russian Ministry of Health to conduct clinical trials in Russia and subsequent treatment of patients. Russia can become the world's fourth country to introduce the BNCT technique into clinical practice.

3. ACCELERATOR BASED NEUTRON SOURCE VITA-III

Currently, the third version of the accelerator based neutron source VITA is under development to equip the Burnazyan Federal Medical and Biological Agency of of Russia and other oncological clinics. Experience gained from operating previous facilities requires making two changes. First, it is necessary to abandon pre-acceleration, which not only complicates the installation and increases its size, but also deteriorates the phase portrait of the ion beam. Second, a negative hydrogen ion source with volumetric ion generation should be used: it is easier in operation, and to obtain the required ion beam current it is sufficient to set several parameters in the control rack. Such a VITA injector has been manufactured and will be tested in the near future. Also, in the accelerator based neutron source VITA, the gas stripping target was replaced with a similar one with a hole of a smaller diameter and shorter length, and if it turns out to be suitable, it will be possible to reduce the size of the high-voltage electrode and the entire accelerator.

4. ACCELERATOR BASED NEUTRON SOURCE VITAmin

The height of the accelerator based neutron source VITA can be significantly reduced by accommodating the high-voltage power supply inside the upper vacuum part of the feedthrough insulator and eliminating the lower gas part of the feedthrough insulator [5]. This solution with a symmetrical Cockcroft—Walton cascade generator as a high-voltage power source is currently under implementation. Even if the voltage required for BNCT is not achieved, such a deuterium beam setup can be used as a powerful source of fast neutrons for various applications.

CONCLUSIONS

The Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences has proposed and developed the accelerator based neutron source VITA. The first version of the neutron source has been actively used for a decade to develop methods of boron neutron capture therapy for malignant tumors, for radiation testing of promising materials, for measuring the cross-section of nuclear reactions, and for a number of other applications. The second version of the neutron source is operated in China to conduct clinical trials of the BNCT technique and is expected to be used for clinical trials in the Russian Federation from 2025. The third version of the neutron source is under development for subsequent equipping of oncological clinics with the aim of active introduction of the method into clinical practice. An alternative version of the neutron source is currently under development as a powerful compact source of fast neutrons.

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CONFLICT OF INTEREST

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

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