ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2025, Vol. 22, No. 4, pp. 713–716. © Pleiades Publishing, Ltd., 2025.
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PHYSICS AND TECHNIQUE OF ACCELERATORS

Vacuum-Insulated Tandem Accelerator as a Powerful Fast Neutron Generator

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

Abstract—High flux neutron sources are required for many scientific research and technological applications. The accelerator based neutron source VITA operated by the Budker Institute of Nuclear Physics is used both to generate epithermal neutron fluxes for the development of boron-neutron capture therapy and to generate fast neutron fluxes for radiation testing of advanced materials. For example, some materials developed for the Large Hadron Collider (LHC), the International Thermonuclear Experimental Reactor (ITER), the Institute of Theoretical and Experimental Physics, and other research institutions were irradiated with a fast neutron flux up to a fluence of 3×10^{14} cm^{-2}, and a new knowledge was obtained. The accelerator based neutron source VITA as a powerful fast neutron generator is described and the results of a long experimental run on fast neutron generation are presented. The features and limitations of using the accelerator based neutron source VITA to generate a powerful fast neutron flux are noted and suggestions for increasing the neutron flux for its further use for both radiation testing of materials and equipment are discussed.

DOI: 10.1134/S154747712570044X

INTRODUCTION

Neutrons are used for a variety of purposes. In case of radiation testing of materials, at least 10^{13}–10^{14} neutrons per cm^2 must be accumulated on the test material, for which the neutron flux density must be at least 10^8–10^9 cm^{-2} s^{-1}. Neutrons are also used for nuclear doping of silicon, for which 10^{14}–10^{18} neutrons per 1 cm^2 of material should be accumulated [1]; nuclear reactors are used to this end. Neutrons are also used for small-angle scattering, diffractometry, spectrometry, reflectometry, and studies of mechanical stress, magnetic and crystal structure of materials. The neutron flux density required for these studies is 10^5–10^6 cm^{-2} s^{-1} [2].

Neutrons are generated in linear stationary accelerators of charged particles with an energy of the order of units to tens of MeV and a current of the order of units to tens of mA using a number of nuclear reactions. The most common neutron-generating reactions [3] are presented in Fig. 1. Distinguished among them in terms of neutron yield is the reaction a lithium nucleus with a deuterium nucleus, Li(d, n), when the energy of the incident deuterium nucleus exceeds 0.8 MeV. The yield of neutrons in this reaction at a deuteron energy of 1 MeV is comparable to that in the Li(p, n) nuclear reaction. The Li(d, n) nuclear reaction is promising for generating a neutron flux in studying radiation resistance and other properties of neutron-irradiated materials.

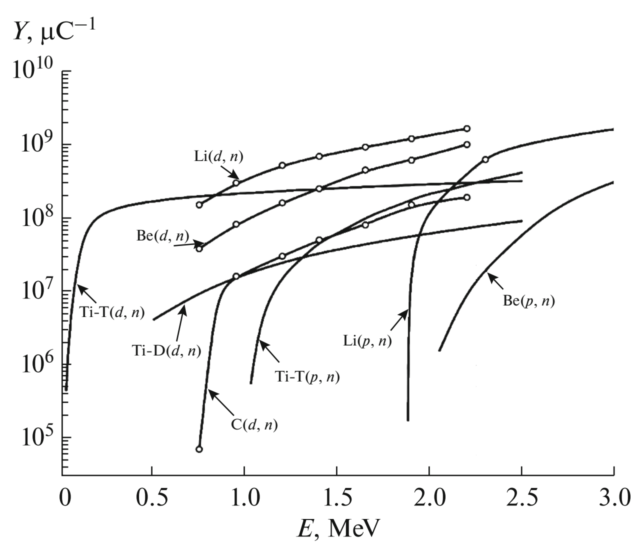

Fig. 1. Neutron yield in neutron-generating reactions in thick targets.

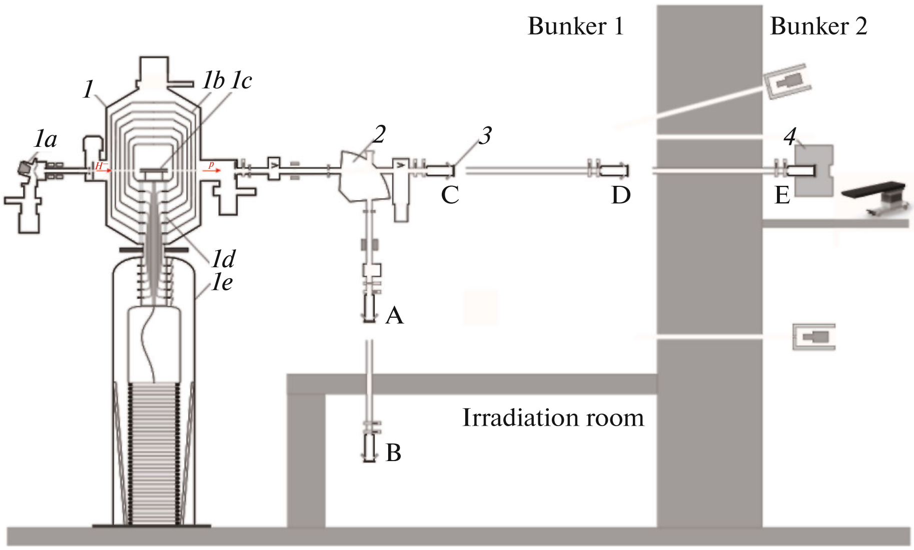

Fig. 2. Schematic diagram of the accelerator based neutron source VITA: (*1*) accelerator based neutron source ((*1a*) negative ion source, (*1b*) high-voltage and intermediate electrodes, (*1c*) gas stripping target, (*1d*) feedthrough insulator, (*1d*) high-voltage power source), (*2*) bending magnet,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

We now formulate the requirements for an optimal setup for conducting research on the radiation resistance of materials. First and foremost, the neutron yield at the facility as a value inverse to the required irradiation time of the materials is of importance. This refers not only to the maximum neutron yield, but also the ability to control this value, i.e., to control the current and/or beam energy at the facility. The facility should preferably be reliable, easy to repair, compact and at the same time simple to implement, and inexpensive. These are the main criteria; additionally, worth indicating are the convenience of placement/rearrangement of samples and the use of structural materials in the facility that are weakly activated or not activated by neutron flux.

1. VACUUM INSULATED TANDEM ACCELERATOR

We now consider a tandem accelerator with vacuum insulation—a linear electrostatic accelerator of charged particles of a tandem type of original design [4]. Without going into technical details, we outline the parameters of this facility. The vacuum insulated tandem accelerator is designed to produce a stationary beam of protons or deuterons with an energy of up to 2.3 MeV and a current of up to 10 mA. An original feature of suchlike accelerator is that instead of the conventional accelerating tube-insulator arrangement, all the insulators are located outside the accelerating electrodes and together form a feedthrough insulator, from which high-voltage potentials are transmitted to the corresponding accelerating electrodes. This design allows the accelerating electrodes to be placed as close to each other as possible, alleviating the problems of obtaining the required vacuum level and compensating for the beam space charge effect. The accelerator is distinguished by its relatively simple design, easy maintenance of the ion source, and flexible regulation of the beam energy and current: the energy can be varied from 0.3 to 2.3 MeV, and the current, from nA to 10 mA.

2. ACCELERATOR BASED NEUTRON SOURCE VITA

In this section, we consider the accelerator based neutron source VITA displayed in Fig. 2. It was initially proposed at the Budker Institute of Nuclear Physics SB RAS to implement the boron neutron capture therapy of malignant tumors. Originally it was designed as a vacuum insulated tandem accelerator *1* located on three floors: the accelerating electrodes *1b* and a stripping target *1c* are located on the top floor; a feedthrough insulator *1d,* on middle one, and a high-voltage power source was located on the bottom floor.

Initially, the accelerator based neutron source VITA was used to conduct research in the field of boron neutron capture therapy; to obtain the required neutron yield from a thin lithium target by increasing the maximum energy and current of the proton beam; to conduct testing on cell cultures, laboratory, and domestic animals, and to test drugs for targeted delivery of boron. The facility is currently used for a variety of applications where neutron generation with a total yield of up to 10^{12} s^{-1} or a beam of protons/deuterons with a power density of 1 μW/cm^2 up to 20 kW/cm^2 is required.

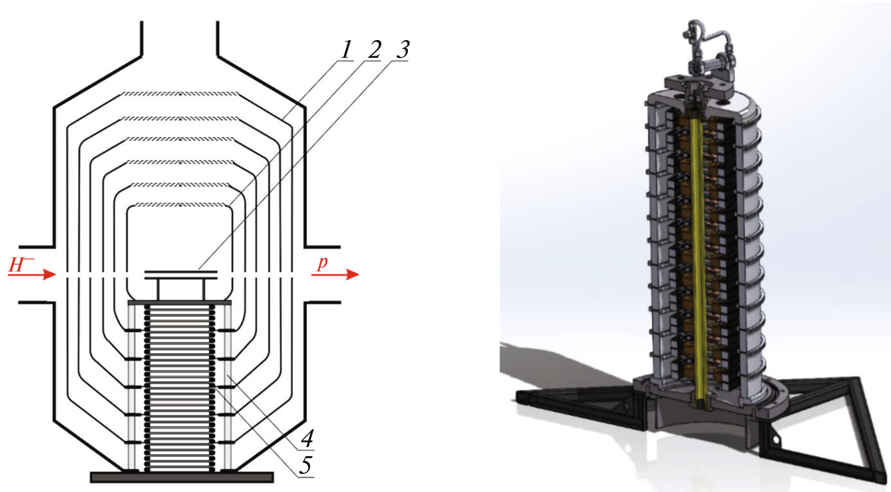

Fig. 3. Schematic diagram (left) and model (right) of the compact vacuum-insulated tandem accelerator under development for the VITAmin facility.

One such application is the generation of fast neutrons for radiation testing of advanced materials for ITER, CERN, and other research institutions. In 2022, a long-term experimental run for the generation of fast neutrons was carried out. During 18 working days, fast neutrons were generated within 8 h. The neutron yield was constant throughout the entire experimental run with an accuracy of 10% [5]. Groups from various scientific institutions took part in the experimental run, and the following materials were irradiated:

— coils of optical cable developed at the Saclay Nuclear Research Centre (France) for the operation of the Large Hadron Collider (CERN) in high-luminosity mode;

— semiconductor PMTs and DC-DC converters for the ATLAS detector of the Large Hadron Collider at CERN;

— diamond neutron detector for the International Thermonuclear Experimental Reactor ITER (Cadarache, France);

— boron carbide plates for ITER (Cadarache, France) [6];

— neodymium magnets for the hybrid quadrupole lens of the powerful linac of the Institute of Theoretical and Experimental Physics (Moscow) [7];

— natural Popigai (an impact crater in northern Siberia, Russia) and synthetic diamonds for the Institute of Inorganic Chemistry of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk);

— gas sensors based on titanyl phthalocyanines for the Laboratory of methods for studying the composition and structure of functional materials at Novosibirsk State University [8].

The samples accumulated from 3×10^{13} up to 3×10^{14} cm^{-2} neutrons depending on their placement.

However, despite the successful experimental run, VITA is not optimized for providing high-power deuteron beam. The deuteron beam current is limited to 1.5 mA, the limitation being due to the fact that the ion source optics are optimized to generate a beam of negative hydrogen ions. The deuteron beam energy is limited to 1.5 MeV, the limitation being due to the fact that the power source of the bending magnet is designed to bend a proton beam with an energy of 2.3 MeV.

For these and other reasons, the implementation of the proposal published in [9] and protected by a patent [10] has become an urgent task. The idea is to place the high-voltage power supply inside the upper section of the tandem accelerator feedthrough and to eliminate the bottom part of the feedthrough. This facility, VITAmin, which will be located on one floor, will also be based on a tandem accelerator with vacuum insulation.

3. VITAmin ACCELERATOR NEUTRON SOURCE

The accelerator based neutron source VITA$_{\mathrm{min}}$ under development uses a symmetrical Cockcroft–Walton cascade multiplier to supply high-voltage power to the accelerating electrodes of a vacuum-insulated tandem accelerator. The diagram from [9] and the model of the compact vacuum insulated tandem accelerator currently under development for the VITAmin facility are displayed in Fig. 3.

Here, *1*, *2,* and *3* are intermediate electrodes, high-voltage electrode and gas stripping target being the same as the corresponding elements on the accelerator based neutron source VITA. The difference is in feedthrough insulator *4*—VITAmin has only the upper part, in which all ceramic insulators are identical in composition and height. *5* is the Cockcroft–Walton cascade multiplier; in [4] it was proposed to use four sections per accelerating electrode.

Currently, twelve 73 mm high ceramic insulators are used for the six accelerating electrodes of the vacuum-insulated tandem accelerator; electrodes are located between the insulators, to which sections of the Cockcroft–Walton symmetric cascade multiplier are connected. Thus, there are twelve sections; the UHV-12A capacitors and 2CLG50KV-1A diodes in them are rated for a maximum voltage of 50 kV. A voltage of 24 kV with a frequency of 75 kHz will be supplied to the input of the cascade multiplier; for this purpose, an AC-DC converter Meanwell SHP-10K-380L and an inverter and high-voltage transformer developed at the Budker Institute of Nuclear Physics are used. For example, for a load current in mA units, the theoretical output voltage will be $U\,[\mathrm{kV}] = \; 2NU_0 - (V)/(3fC) \; = 2\times 12\times 2, \;\; 4\times 10^4 - \left(I\times 10^{-3}\times 12^3\right)/\left(3\times 7.5\times 10^4\times 1.7\times 10^{-9}\right) \;\; 4.8 \;\; \times 10^5 - 4.5\times 10^3 I$ [mA]. Thus, for a current of 10 mA, the voltage drop will be 45 kV, and the maximum voltage will be 435 kV. Given the tandem design of the accelerator and the beam injection energy, the beam energy will be ~900 keV. The beam with this energy and a current of 10 mA is sufficient to generate fast neutrons with a total yield of 3×10^{12} s^{-1}.

Preliminary experiments were carried out on the cascade voltage multiplier, which showed the operability of the proposed design. Debugging and commissioning of the half-bridge inverter and high-voltage transformer is currently underway.

CONCLUSIONS

The Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences has proposed and developed a vacuum insulated tandem accelerator. The accelerator based neutron source VITA was created on its basis; it has been actively used for a decade to develop the boron neutron capture therapy for malignant tumors, for radiation testing of promising materials, for measuring the cross-section of nuclear reactions, and for many other applications. A long-term experimental run on the generation of fast neutrons was carried out at the VITA to study the radiation resistance of promising materials. This approach demonstrated the high reliability of the VITA, but also revealed some of its shortcomings in generating a powerful flux of fast neutrons. Based on the gained experience, a new powerful compact accelerator based neutron source, VITAmin, is currently under development: on the one hand, it is based on a tandem accelerator with vacuum insulation as before, and, on the other hand, the feedthrough insulator and the power source for acceleration have undergone significant changes. It has been shown that the accelerator neutron source under development can achieve a total neutron yield of up to 3×10^{12} s^{-1}.

FUNDING

The study was supported by the Russian Science Foundation (project no. 19-72-30005).

CONFLICT OF INTEREST

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

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