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PHYSICS AND TECHNIQUE OF ACCELERATORS

Compact Accelerator-Based Fast Neutron Source for the Radiation Testing of Promising Materials

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Abstract—The VITA accelerator neutron source based on a vacuum-insulated tandem accelerator operates at the Budker Institute of Nuclear Physics. At the accelerator source, when transporting a powerful (up to 10 kW/cm^2) beam of protons or deuterons to the target, neutrons with a wide range of energies—cold, thermal, epithermal, and fast—are generated. The transported beam or neutron flux is used for conducting research in the field of boron neutron capture therapy (BNCT); measuring the cross section of nuclear reactions (^{7}Li(p, $p'\gamma$)^{7}Li, ^{7}Li(p, α)^{4}He, ^{6}Li(d, α)α, ^{7}Li(d, α)^{5}He, ^{6}Li(d, p)^{7}Li, and ^{7}Li(d, α)αn); conducting materials science research together with INP, CERN, and ITER; and for other applications. The creation of a separate compact installation for the generation of fast neutrons is an urgent task; it will allow the treatment of malignant tumors by fast neutrons and the radiation testing of promising materials. The generation of fast neutrons at the existing accelerator neutron source is complicated, because the source of negative hydrogen ions and the bending magnet were designed and produced for the generation and transportation of a proton beam. The installation being created will be designed to generate and conduct a deuteron beam, while the high-voltage and intermediate electrodes of the accelerator will be connected directly to the corresponding sections of the high-voltage power source located inside the gas part of the feedthrough insulator. This paper presents the concept of a compact accelerator source of fast neutrons under development; the results of numerical calculations, modeling, and preliminary testing of the accelerator power supply in air are presented and summarized and further steps of manufacturing and testing of the proposed power supply are formulated.

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INTRODUCTION

The VITA accelerator source of epithermal neutrons [1] operates at the Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, to develop boron neutron capture therapy (BNCT) for malignant tumors [2, 3]. VITA consists of a tandem accelerator with vacuum insulation to produce a proton beam with an energy of 2.3 MeV and a current of up to 10 mA; a lithium target for generating neutrons as a result of the threshold reaction ^{7}Li(p, n)^{7}Be; and a set of beam-forming systems to generate a flux of epithermal, fast, and cold neutrons [4]. The layout of the VITA accelerating neutron source is shown in Fig. 1.

The accelerator source is used to carry out biological research in the field of BNCT [5, 6] and the generation of fast neutrons [7, 8] to measure the content of undesired impurities in the samples of boron carbide ceramic developed for the International Thermonuclear Experimental Reactor and the radiation testing of optical fibers of the system of laser calibration of the CMS calorimeter to provide the operation of the Large Hadron Collider (CERN) in the high luminosity mode, as well as to determine with a higher accuracy the inelastic scattering cross sections of various nuclear reactions [9, 10] and other applications.

The task of creating the accelerator neutron source for carrying out BNCT has been successfully completed; this is confirmed by clinical trials at the VITA accelerating neutron source in Xiamen (China) [11] and the creation of VITA for carrying out BNCT at the Blokhin National Medical Research Center of Oncology (Moscow, Russia). The current tasks are the development of a domestic boron-delivery agent, dosimetry methods for BNCT, and a wide range of investigations of promising materials under the radiation load from a flux of epithermal and fast neutrons. Despite the successful generation of fast neutrons [7] as a result of the Li(d, n) reaction, VITA is not optimized for the generation of fast neutrons—the design of the source of negative hydrogen ions does not allow

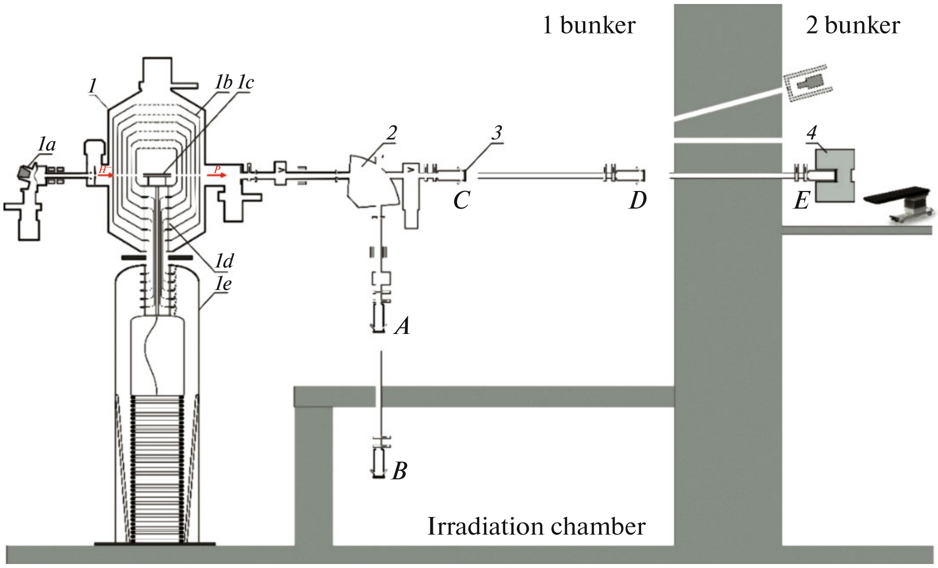

Fig. 1. Layout of the VITA accelerator neutron source: (*1*) tandem accelerator with vacuum insulation ((*1a*) source of negative ions of hydrogen, (*1b*) high-voltage and intermediate electrodes, (*1c*) gas stripping target, (*1d*) bushing, and (*1e*) high-voltage power supply source), (*2*) bending magnet, (*3*) lithium neutron-generating target, and (*4*) neutron-beam formation system; (*A*–*E*) points of arrangement of the targets.

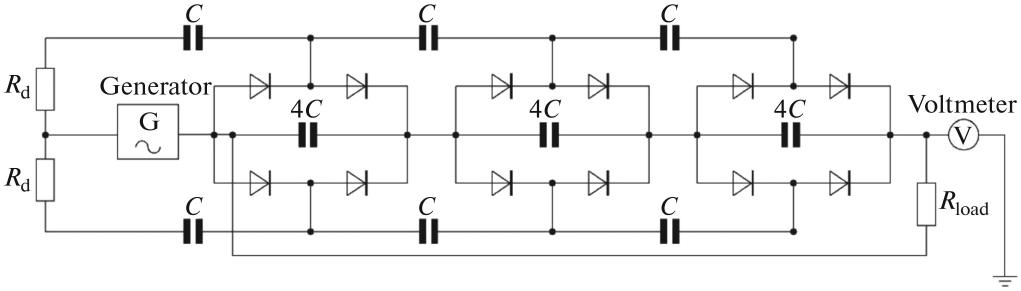

Fig. 2. Circuit of the three-section symmetric cascade multiplier with load.

injecting a beam of negative deuterium ions with a current exceeding 1 mA; in addition, the bending magnet and its power supply designed and produced for a proton beam are not designed to rotate a beam of deuterons with an energy higher than 1.5 MeV. In addition, the setup with an accelerator and a power supply has a considerable height and does not seem to be promising for replication; therefore, one should strive to reduce the height of the accelerator and its power supply system.

For these reasons, it becomes relevant to develop and manufacture a separate compact accelerator source of fast neutrons. The compactness of the manufactured source of fast neutrons lies in the fact that, in this case, the power supply of the accelerator electrodes is achieved directly through the sections of the symmetrical cascade voltage multiplier without using a bushing, thereby realizing the idea described in this paper and patented [12, 13].

1. SCHEME OF INSTALLATION

The accelerator power supply in this compact source of fast neutrons is a symmetrical cascade multiplier with series of capacitive coupling of cascades [14–16]. The classical scheme of such a multiplier is shown in Fig. 2.

The manufactured installation uses a circuit of 12 cascades of generator. The accelerator electrodes are connected to every second cascade; in the scheme, they can be shown as capacitors connected in parallel. Series-connected diodes link two modules of high-voltage capacitors with alternating voltage, which provide the power supply of the central module of constant-voltage capacitors. The circuit elements are designed for voltages of up to 50 kV, which imposes a limit on the voltage at the input to the cascade multiplier, which must not exceed 25 kV. To uniformly distribute the electrical potential, KEV-1 resistors with a nominal $R = 80$ MΩ and a power of 1 W are intro-

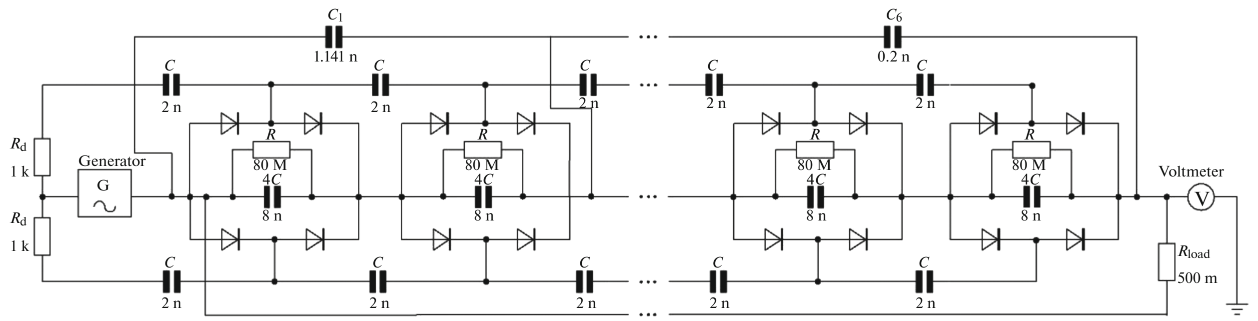

Fig. 3. Ideal circuit of the produced cascade multiplier with connected accelerator electrodes.

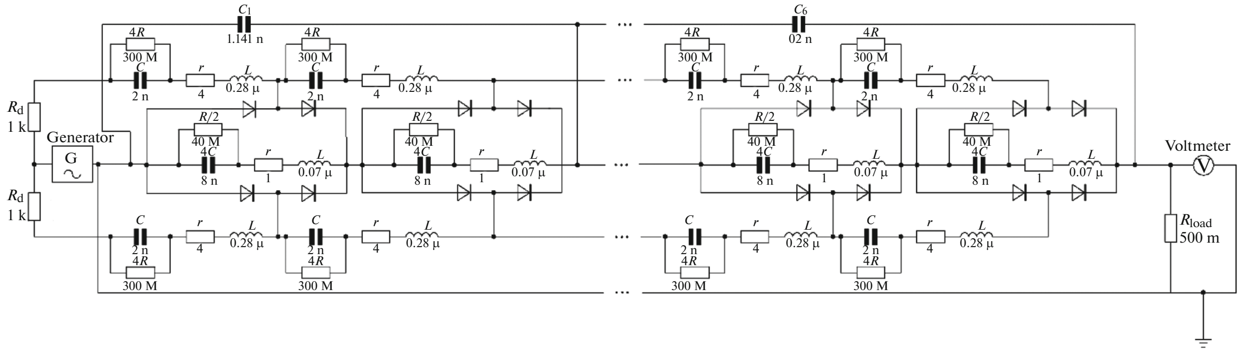

Fig. 4. Equivalent circuit of the produced cascade multiplier with connected accelerator electrodes.

duced between the cascade sections parallel to the capacitors of the rectifier column; this is shown in Fig. 3. The secondary winding of the transformer with a voltage of up to 25 kV and a frequency of 75 kHz will be at the input. Thus, the maximum constant output voltage will be 480 kV. The output voltage is reduced because of the effect of parasitic parameters of the system and the generator load. The capacitors in the electrical circuit have their own resistance and inductance: $R_C = 320$ MΩ is the resistance of the capacitor insulation (indicated as 4R in the diagram), $r = 4$ Ω is the equivalent series resistance, and $L = 0.28$ μH is the equivalent series inductance.

Figure 4 shows the equivalent electrical circuit of the cascade multiplier being manufactured with consideration for the parasitic parameters of individual elements.

The multiplier will be arranged in the upper part of the accelerator bushing (Fig. 1d) and consists of 12 cascade sections; each circuit section is inside the ring insulator. Between the insulators, there are electrodes to which the high-voltage electrodes of the tandem accelerator will be supplied through every second section. The three assembled sections of the cascade multiplier and the model are shown in Fig. 5. The multiplier structure will be tested on the compliance with the performed calculations. First and foremost, we will investigate the effects associated with the presence of parasitic parameters of the multiplier in the system and the determination of its impedance.

With this purpose, the existing switch-mode power supply (PS) with an output power of 100 W and an alternating-voltage amplitude of 160 V insulated from the 220-V input circuit by means of the circuit transformer will be temporarily used as a generator of alternating current and frequency. The PS block diagram is shown in Fig. 6. The power supply consists of a high pass filter, a diode bridge rectifier, a power factor corrector (PFC), an invertor, and a blocking capacitor C to cut off the constant component of the output voltage.

The next step is to test the cascade generator "in air" on the design parameters by using an alternating voltage generator manufactured at the Budker Institute of Nuclear Physics.

2. RESULTS AND DISCUSSION

Before the direct testing of the cascade multiplier, the ongoing processes were simulated. To simulate the charging processes of cascade multiplier sections, the NL5 program was used [17]. Figure 7 shows the curves of charging the sections of the cascade generator in the two considered circuits at a load equivalent to the 10-mA beam, in this case, for the sake of illustration, at a supply frequency of 10 kHz.

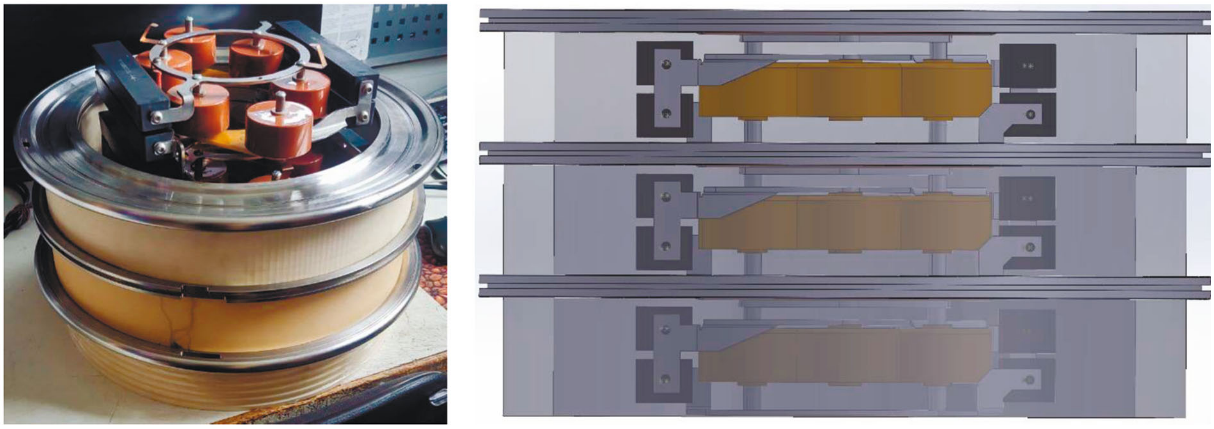

Fig. 5. Image of three assembled sections of the cascade multiplier (on the left); model of three sections of the cascade multiplier (on the right).

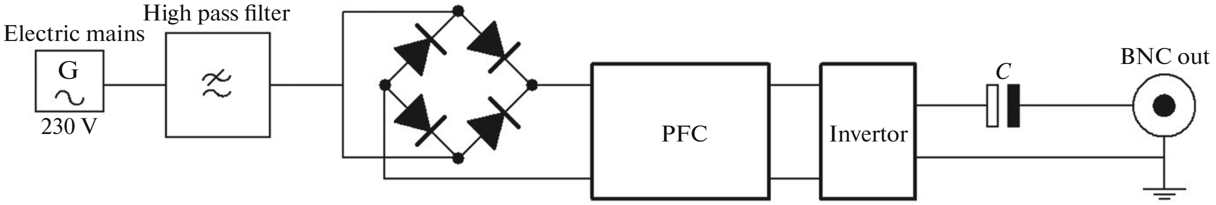

Fig. 6. Circuit of the power supply source with an output voltage of 160 V, power of 100 W, and frequency of 85 kHz.

It is seen from the graph that the output voltage in the ideal circuit is higher. This is explained by the fact that the output voltage in the cascade voltage multiplier is $U = (2NU_0 - \Delta U \pm \delta U)F$ [18, 19], where

$\Delta U = \sqrt[k]{\Delta U_C^k + \Delta U_R^k + \Delta U_{L_s}^k}$ is the total slump of the output voltage;

$\Delta U_C \approx \frac{I}{fC}\frac{N^3}{3}$ is the slump related to generator loading;

$\Delta U_R = (3\pi)^{\frac{2}{3}} NU_0 \left(\frac{R_t + R}{U_0} I\right)^{2/3}$ is the slump related to the direct resistance of the rectifier;

$\Delta U_{L_s} = 2.32NU_0 \left(\frac{\omega L_s}{U_0} NI\right)^{1/2}$ is the slump related to the leakage inductance of the transformer;

$\delta U = \frac{I}{fC}\frac{N}{2}$ is the output voltage ripple under load;

$F = \frac{\tanh\left(2N\sqrt{C_s/C}\right)}{2N\sqrt{C_s/C}}$ is the efficiency of the circuits, where

$U_0 = 20$ kV is the input voltage applied to the cascade generator (voltage of the secondary winding of the transformer), k is an integer number (usually ≥3), $N = 12$ is the number of sections of the cascade generator, $I = 1–10$ mA is the load current, $f = 10$ kHz is the generator frequency, $C = 1.7$ nF is the capacitor capacitance (UHV-12A) in the sections, R_t is the equivalent resistance of the secondary winding of the transformer, R is the direct resistance of the diode (2CLG50KV-1A), L_s is the leakage inductance of the transformer, and C_s is the equivalent parasitic capacitance of a section.

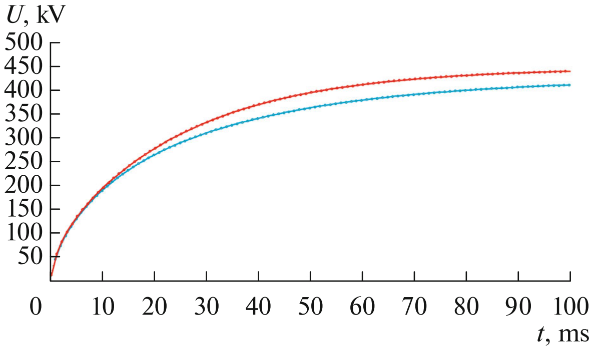

Fig. 7. Modeled curves of charging the sections of the cascade generator with a power-supply frequency of 10 kHz. The red curve indicates the ideal circuit; the blue curve indicates the equivalent circuit.

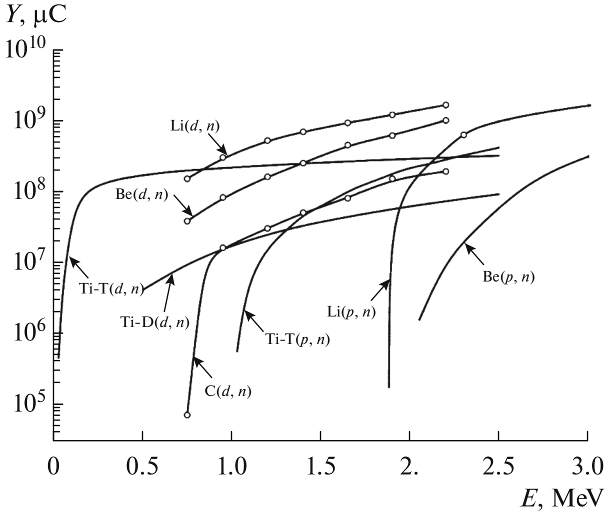

Fig. 8. Neutron yield of some reactions from thick targets.

With such system parameters, $\Delta U_R \approx 1.5$ kV, $\Delta U_{L_s} \approx$ 2.5 kV, and $\Delta U_C = (dU/dI)I = \alpha I$, where α is the slope of the load characteristic (14 kV/mA for the ideal circuit and 15 kV/mA for the equivalent circuit); thus, we assume that $\Delta U \approx \Delta U_C$ and $F = 0.95$ for the ideal circuit and 0.9 for the equivalent circuit.

The output voltage ripple δU in the ideal circuit agrees with the presented expression $\delta U = (I/fC)(N/2)$, and its value is ±0.55 kV/mA; in the equivalent circuit, the voltage ripple increases to a value of ±0.7 kV/mA.

The same procedure performed for a supply frequency of 75 kHz leads to the following results: $F = 0.97$ for the ideal circuit and 0.95 for the equivalent circuit; α are 1.33 and 1.5 kV/mA, respectively. When the cascade multiplier is loaded with a beam with a current of 10 mA, the output voltage ripple is $\delta U \approx 1$ kV. Obviously, it is more reasonable to use the power supply with a frequency of 75 kHz; the increase in the voltage drop due to the increase in the leakage inductance of the transformer is insignificant.

Thus, the value obtained theoretically at the cascade generator is $U\,[\text{kV}] = (2NU_0 - kI)F = 465 - 1.4I$ [mA], with the voltage ripple $\delta U\,[\text{kV}] = \pm 0.1\, I$ [mA]. Since the cascade generator is designed to be used as a power source for a tandem accelerator, the energy obtained of the deuteron beam at it is $E = E_0 + 2 \times (465 - 1.4I) = E_0 + 900\text{–}930$ keV, where E_0 is the injected beam energy.

Let us evaluate the theoretical yield of fast neutrons based on the proposed cascade voltage multiplier as a power source for the tandem accelerator. Figure 8 shows the dependences of the neutron yield from different targets. Thus, during a long run to irradiate promising materials for CERN, fast neutrons were generated as a result of the nuclear reaction ^{7}Li(d, n) at a deuteron beam energy of 1.5 MeV and a beam current of about 1 mA, which corresponded to a total neutron yield of up to 2×10^{12} s^{-1}. Since little is known about the cross section of the Li(d, n) reaction at energies lower than 0.75 MeV, the total neutron yield can only be estimated approximately and its value is estimated to be 10^{11}–3×10^{11} mA s^{-1}. Such a neutron yield is acceptable for research on radiation testing of promising materials and other applications, in particular, the possible use of the accelerator for research on fast neutron therapy.

CONCLUSIONS

A compact accelerator source of fast neutrons was proposed at the Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, for the radiation testing of promising materials. As a power supply of the tandem accelerator in it, a symmetric cascade voltage multiplier with a capacitive coupling consisting of 12 sections is used.

In this work, the cascade generator is investigated; its output parameters are estimated with consideration for the parasitic elements of the system; the output energy of the deuteron beam and the total yield of fast neutrons as a result of the ^{7}Li(d, n) reaction corresponding to it and to the beam current were also estimated.

It is estimated that the output energy of deuterons in this accelerator varies from 900 to 930 keV, with an accuracy of up to the energy of the injected beam of negative deuterium ions, which corresponds to a total yield of fast neutrons of 10^{11}–3×10^{11} mA s^{-1}. Such a neutron yield is acceptable for the use of the proposed fast neutron source in the radiation testing of promising materials and other applications; there is also a possibility to achieve a relatively simple setup to carry out investigations on fast neutron therapy.

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CONFLICT OF INTEREST

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

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