ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2025, Vol. 22, No. 4, pp. 794–797. © Pleiades Publishing, Ltd., 2025.
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PHYSICS AND TECHNIQUE OF ACCELERATORS

Cockroft–Walton Generator as a Power Supply for the Vacuum Insulated Tandem Accelerator

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

Abstract—The accelerator-based neutron source, VITA, operated at the Budker Institute of Nuclear Physics is actively used for both the generation of epithermal neutron fluxes for the development of boron–neutron capture therapy and the generation of fast neutron fluxes for radiation testing of advanced materials. The demand for such neutron sources intended for a wide range of applications, including the testing of new boron-targeted drugs and irradiation of cell cultures and laboratory animals for the development of boron neutron capture therapy, was driving the development of a less powerful but compact neutron source that can be used research groups to carry out such research on a continuous basis. The basic idea is to use a Cockcroft–Walton generator rather than a sectioned rectifier connected to a vacuum-insulated tandem accelerator through a feedthrough insulator and to place it in the upper vacuum part of the feedthrough insulator, removing the lower gas part of the feedthrough insulator, which significantly reduces the size and cost of the installation. The Cockcroft-Walton symmetric cascade multiplier is described, its characteristics are presented, and the results of computer modeling of the ideal and equivalent circuits, test results of the cascade voltage multiplier, and plans for further research are reported and discussed.

DOI: 10.1134/S1547477125700591

INTRODUCTION

Neutrons are generated in linear accelerators of charged particles when beam ions interact with target atoms. Various neutron-generating nuclear reactions are available. Figure 1 shows the total neutron yield per 1 μC of the incident beam. The reactions that are most promising among those displayed in Fig. 1 are Li(*d*, *n*) and Li(*d*, *n*).

Reaction Li(*d*, *n*) has a neutron generation threshold of 1.882 MeV. At an incident proton energy of 2 MeV, the reaction generates ~1.1×10^{11} neutrons per 1 mA of proton current. This reaction is used to generate epithermal neutrons employed for research in boron neutron capture therapy of malignant tumors [1, 2], such as testing drugs for targeted delivery of boron and conducting tests on cell cultures, laboratory and domestic animals.

The Li(*d*, *n*) has no threshold, and at an incident deuteron energy of 1 MeV, ~10^{12} fast neutrons are produced per 1 mA of beam current. This reaction is used to conduct radiation testing of advanced materials. For example, in 2022, a long-term run generating fast neutrons for a number of scientific groups [4] was carried out at the accelerator based neutron source VITA [3], and some materials were irradiated [5–9]. Throughout the entire experimental run, fast neutrons were generated with a stability of 10%. Depending on their location, the materials were irradiated with a fast neutron

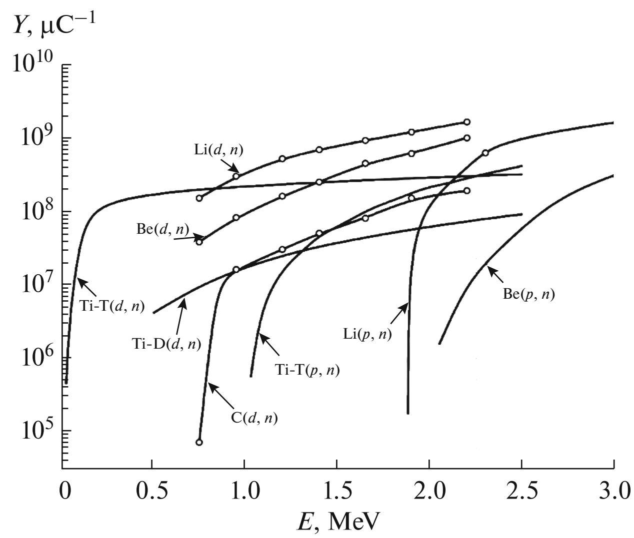

Fig. 1. Energy dependence of the total neutron yield from the main neutron-generating nuclear reactions per 1 μC of the incident beam.

fluence of 3×10^{13} to 3×10^{14} cm^{-2}. First and foremost, this study confirmation that the accelerator based neutron source VITA is indeed a reliable facility. This study also showed that the generation of a powerful flux of fast neutrons is an urgent task, as is the creation of compact and powerful fast neutron generators designed for this purpose.

1. FEATURES OF USING VITA AS A FAST NEUTRON GENERATOR

The accelerator based neutron source VITA, which was a fast neutron generator, still features some disadvantages in what regards such a task.

First, VITA was designed and developed to conduct research in boron neutron capture therapy. This task was accomplished, and indeed, the proton beam obtained at VITA meets the requirements for boron neutron capture therapy: the beam energy can be varied from 0.3 to 2.3 MeV, and the beam current, from 1 nA to 10 mA. However, VITA is not optimized for deuteron beam delivery. Thus, the beam current is limited to 1.5 mA due to the ion source optics, which was originally designed to generate an H^- beam, and the beam energy is limited to 1.5 MeV due to the bending magnet, also designed and built to conduct the beam of negative hydrogen ions.

Second, the accelerator neutron source, although a relatively compact facility, occupies three floors of building. Initially, vacuum insulated tandem accelerator consisted of three parts: a high-voltage power source of the ELV series, a feedthrough insulator through which the high-voltage potential from the ELV is transmitted to the central accelerating electrode, and, using a resistive divider, to the intermediate accelerating electrodes.

Third, many studies are conducted at the accelerator neutron source: studies related to boron neutron capture therapy, measurements of total and differential cross-sections of nuclear reactions (20 have been measured so far), studies on blistering on the surface of metals during proton implantation, etc.

For these reasons, the implementation of the idea presented in [10] and protected by a patent [11] is now an urgent task. The concept of a vacuum-insulated tandem accelerator remains the same: the electrodes and insulators are spaced apart to reduce the distance over which the beam is accelerated. However, now the power will be supplied to the accelerating electrodes directly at the location of the upper part of the feedthrough insulator. The tandem accelerator will be powered by a symmetrical Cockcroft–Walton cascade multiplier [12, 13]. The installation designed to generate fast neutrons based on such an accelerator was named VITAmin.

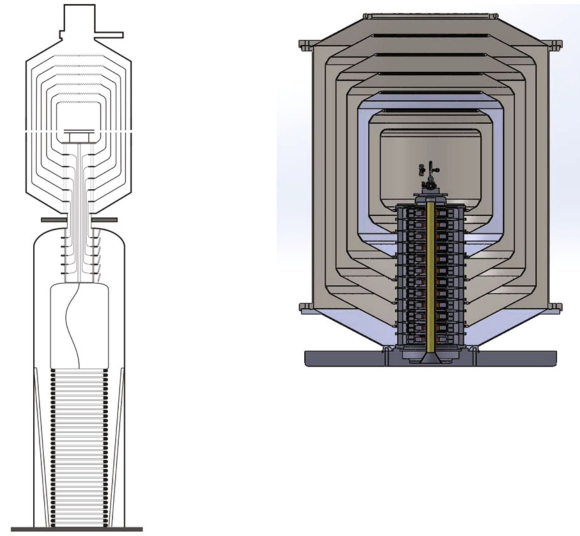

Fig. 2. Schematic of the VITA tandem accelerator with an ELV power supply (left), and a model of the VITAmin tandem accelerator with a Cockcroft–Walton generator as a power source (right)

2. COCKCROFT–WALTON GENERATOR AS A POWER SOURCE FOR VITAmin

The cascade voltage multiplier, which will be located on the top of the accelerator feedthrough insulator, will include 12 cascade stages, each stage of the circuit being inside the insulator. Located between the insulators are electrodes to which high-voltage electrodes of the tandem accelerator will be connected through one section as is shown in Fig. 2.

In the electrical circuit of the generator, the connected electrodes of the accelerator are shown as connected in parallel to the capacitor. diodes connected in series connect two banks of high-voltage AC capacitors that feed a central bank of DC capacitors. To evenly distribute the electrical potential, resistors are introduced into the design between the cascade stages, parallel to the capacitors of the rectifier column. Such an electrical circuit of a cascade generator is displayed in Fig. 3 with a 500 MΩ load, which is equivalent to a conducted beam current of 1 mA. The output voltage on the cascade generator with an input voltage of 20 kV amplitude and a beam current of 10 mA is expected to be approximately 435 kV, with a voltage drop of 46 kV and a ripple of 0.5 kV, according to calculations. If we assume that the output voltage from the high-voltage transformer will not exceed 24 kV, the output voltage of the generator will be up to 530 kV.

The output voltage is reduced due to the influence of parasitic system parameters and generator load. Capacitors in an electrical circuit have their own resistance and inductance. An equivalent electrical circuit of the manufactured cascade multiplier was modeled, taking into account the effects associated with the

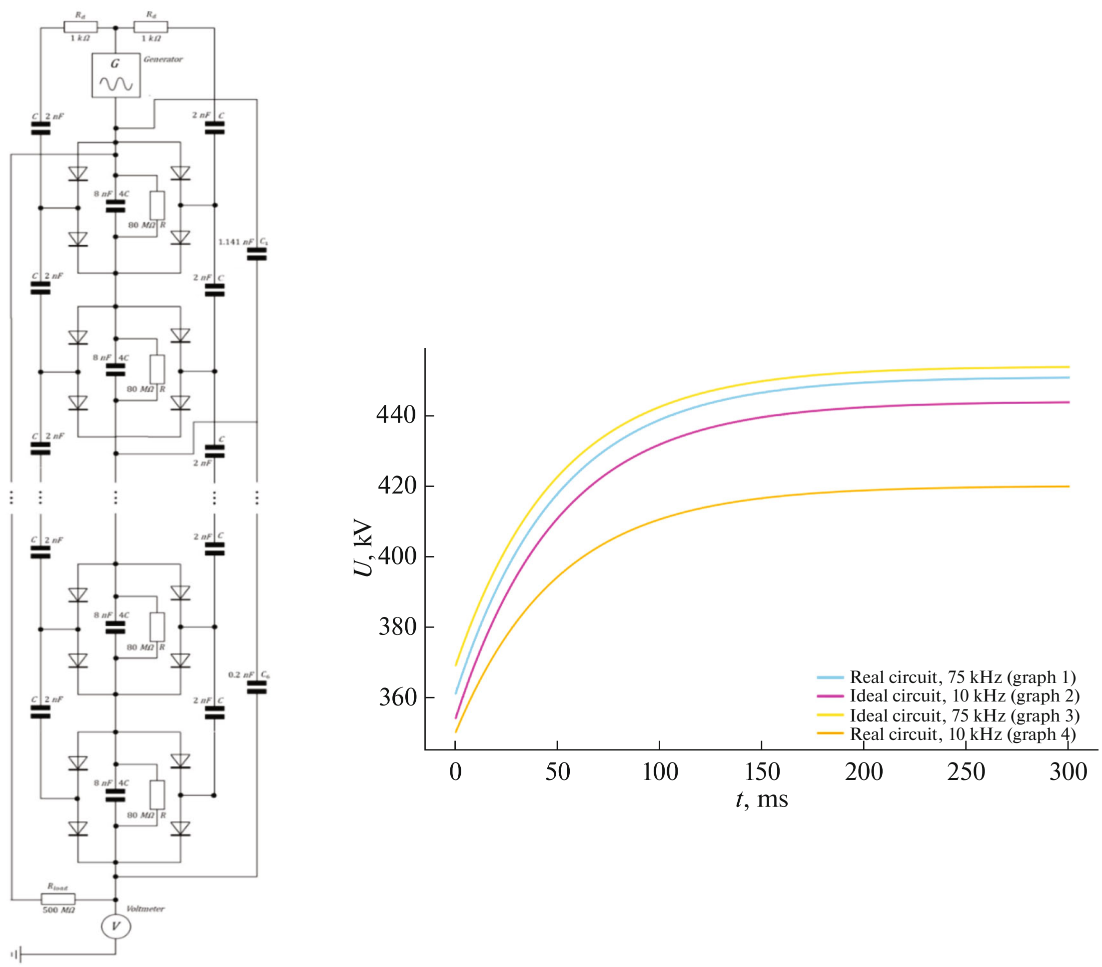

Fig. 3. Schematic of the manufactured cascade multiplier with connected accelerator electrodes (left), and the plot of output voltages on the cascade multiplier at various input voltage frequencies (right).

presence of parasitic parameters of individual elements in the system. To do this, the processes occurring during charging of the generator at frequencies of 75 and 10 kHz were simulated, since it was necessary to determine the parameters of the power source for the high-voltage transformer. Figure 3 shows plotted charge curves of a cascade multiplier. Curve *1* corresponds to the voltage at the output of a real circuit with accelerator electrodes connected at a frequency of 75 kHz, while curve *3* corresponds to an ideal circuit also with electrodes. Simulation results at 10 kHz are also shown—in plots 4 and 2, respectively. It is apparent that using a power source with a frequency of 75 kHz is more appropriate, and the increase in voltage drop due to the increase in the leakage inductance of the transformer is insignificant.

The Cockcroft–Walton multiplier design contains a suitable resistance in its circuit to provide short-circuit current protection that prevents serious damage to the electrical components. Research shows that the diodes of the upper and lower stages of the multiplier are most susceptible to this type of damage [14]. The 2CLG50KV-1A diode used in the multiplier design begins to conduct current at a voltage of 27 V, the maximum allowed current being 1 A. To calculate the protective resistance R_0, the maximum working current of the diode is selected to be I_m = 1 A, according to the formula $R_0 = 2\frac{U_0}{I_m}\sqrt{\frac{\tau}{T_m}}$, where τ is the short-circuit transient time, which typically ranges from 10 to 1000 μs; the time period $T_m = 1/f$, where f is the generator frequency. The R_0 value is calculated at τ = 1000 μs. With the same parameters of input voltage and frequency, R_0 = 347 kΩ was obtained. During high-voltage testing of a cascade multiplier, suitable resistors are selected to provide current protection for the circuit elements.

On a cascade generator, the theoretically obtained value of the output voltage is U [kV] = $(2nU_0 - kI)F$ = 465 – 1.4I [mA], where F is utilization rate and k is an integer, typically ≥3 for the number of cascades n = 12, with voltage pulsation δU [kV] = ±0.1I [mA]. Since the cascade generator is intended to operate as a power source for the tandem accelerator, the energy of the deuteron beam obtained on it is doubled. $E = E_0 + 2 \times (465 - 1.4I) = E_0 + 900–930$ [keV], where E_0 is the injected beam energy. This beam energy with a beam current of up to 10 mA is sufficient for conducting research on radiation testing of advanced materials and other applications, in particular, the possible use of the accelerator for conducting research on fast neutron therapy.

CONCLUSIONS

At the Budker Institute of Nuclear Physics, a new accelerator, VITAmin, based on the existing vacuum insulated tandem accelerator was proposed. It is distinguished by its compactness and placement of the power supply inside the upper part of the feedthrough insulator. A twelve-stage symmetrical Cockcroft–Walton cascade multiplier was chosen as the power source for the accelerator. The accelerator based neutron source VITA as a fast neutron generator is discussed and results of a long-term experimental run are briefly present. The design parameters of VITAmin are analyzed, and it is shown that these parameters are sufficient to generate a large flux of fast neutrons required for radiation testing of advanced materials.

FUNDING

The study was supported by the Russian Science Foundation. (project no. 24-62-00018, https://rscf.ru/project/24-62-00018/).

CONFLICT OF INTEREST

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

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