Concept of Compact Fast Neutron Source VITAmin

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***Abstract*—Radiation testing of perspective materials by fast neutron flux is an important task for large physical facilities such as the Large Hadron Collider or the International Thermonuclear Experimental Reactor. Such a source of fast neutrons is the accelerator based neutron source VITA, proposed, developed and actively used at the Budker Institute of Nuclear Physics. In 2022, a long experiment on generation of fast neutrons was carried out. During the experiment, materials for the Large Hadron Collider, International Thermonuclear Experimental Reactor, Institute for Theoretical and Experimental Physics were irradiated. The maximum neutron flux density per sample unit reached 2.9×10^{14} cm^{-2}. However, the existing VITA facility was not originally designed for the deuteron beam, because it was initially created for research in the field of boron neutron capture therapy. Therefore, the power limit of the conducted deuteron beam is 10 times lower than that of a proton beam. The creation of a separate compact VITAmin facility for the generation of a powerful fast neutron flux will provide radiation testing of promising materials, as well as research in the field of fast neutron therapy of malignant tumors. The power supply for the VITAmin is proposed to be a symmetric cascaded Cockcroft-Walton voltage multiplier circuit. The high-voltage power supply will be located in the column to which the high-voltage electrodes of the accelerator-tandem are supplied. This paper presents the model, circuit, theoretical calculations, simulations and initial test results of the power supply.**

Keywords*—*perspective materials, radiation testing, fast neutrons, fast neutron therapy, Cockcroft-Walton generator

I. Introduction

The accelerator based neutron source VITA operating at the Budker Institute of Nuclear Physics (BINP), it consist of a vacuum-insulated tandem accelerator [1] to produce a stationary beam of protons or deuterons with an energy up to 2.3 MeV and a current up to 10 mA, a thin lithium target for neutron generation with total yield up to $2 \cdot 10^{12}$ s^{-1} and a number of neutron beam shaping assemblies for obtaining a required spectrum of neutrons. Scheme of the VITA is shown in Fig. 1. The accelerator source is used for biological research in the field of Boron neutron capture therapy (BNCT) [2], [3], measurement of cross sections of nuclear reactions (^{7}Li(p,p')^{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, ^{7}Li(d,α)αn) and other applications.

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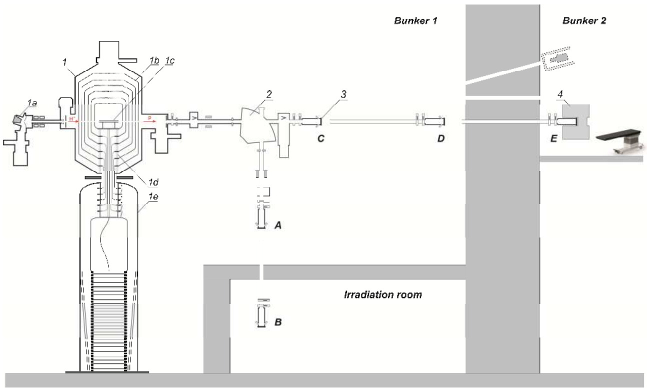

Fig. 1. Scheme of the VITA accelerator neutron source. 1 – vacuum-insulated tandem accelerator (1a – source of negative hydrogen ions, 1b – high-voltage and intermediate electrodes, 1c – gas stripping target, 1d – feedthrough insulator, 1e – high voltage supply), 2 – bending magnet, 3 – lithium neutron generating target, 4 –neutron beam formation system. The lithium target is placed on positions A–E.

II. Compact Fast Neutron Source

A. Testing of Perspective Materials

Neutron fluxes of different energy ranges can be generated on VITA, in particular, fast neutrons, which find wide practical application across various scientific groups for material science purposes. The radiation resistance tests of optical cables, semiconductor PMTs, and dc-dc converters for the Large Hadron Collider (LHC CERN) were conducted. Additionally, a diamond neutron detector was used to measure the content of undesirable impurities in boron carbide ceramic samples for the International Thermonuclear Experimental Reactor (ITER), neodymium magnets for a hybrid quadrupole lens of a powerful linac at the Institute for Theoretical and Experimental Physics (ITEP), and rice of various sorts were irradiated to increase its drought resistance for the Joint Institute for Nuclear Research (JINR), among other applications. A deuteron beam is produced on VITA, and a powerful fast neutron flux is generated on a lithium target as a result of the ^{7}Li(d,n) reaction. However, since this experimental neutron source was originally created for research in the BNCT, it must be adapted to generate fast neutrons. For example, due to the design of the source of negative hydrogen ions and the difference in the masses of negative hydrogen and deuterium ions, the maximum recoverable and accelerated deuteron beam current is 1.5 mA, and the energy is limited to 1.5 MeV due to the power limitation of the bending magnet.

B. Fast Neutron Therapy

One of the common directions in cancer therapy is fast neutron therapy. Currently, no specialized medical equipment has been developed for neutron therapy that would be used in clinics, which has led to a declining interest in the use of fast neutrons in oncology. The creation of a compact fast neutron source is a relevant issue and will aid the progress of fast neutron radiation therapy in oncology [4]. For the generation of epithermal range neutrons, the endothermic reaction ^{7}Li(*p, n*)^{7}Be with a neutron production threshold of 1.882 MeV is used. For the generation of fast neutrons from a lithium target, the exothermic (non-threshold) reaction ^{7}Li(*d, n*)^{8}Be is used. The Fig. 2 shows the dependencies of neutron yield on the energy of protons and deuterons for different targets [5], [6]. Thus, the total neutron yield in the reaction ^{7}Li(*p, n)*^{7}Be at a beam energy of 2 MeV is $1.09 \cdot 10^{11}$ mA^{-1}s^{-1}, and in the reaction ^{7}Li(*d, n*)^{8}Be at a beam energy of 1 MeV, it is approximately 10^{12} mA^{-1}s^{-1}.

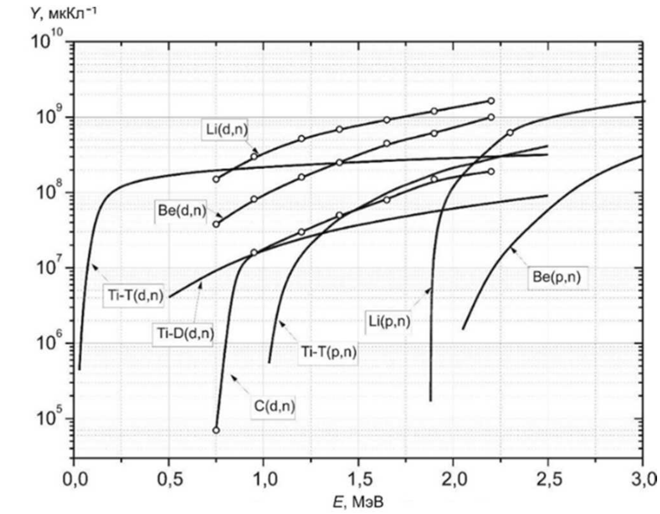

Fig. 2. Dependencies of neutron yield on the energy of protons and deuterons for different targets.

C. Concept of VITAmin

The idea is to create separate, more compact facility for generating of a fast neutron flux to provide radiation testing of perspective materials. The fast neutron accelerator source VITAmin being developed utilizes only the upper part of a feedthrough insulator, within which a high-voltage power source, specifically a symmetrical-type Cockcroft-Walton voltage multiplier [7], [8], is located. Thereby, the idea protected by a patent and described in the article [9], will be implemented. Fig. 3 shows the prototype of the VITAmin accelerator based fast neutron source.

There are several reasons for using a cascade multiplier for this purpose. First, it is relatively simple, compact and reliable. Second, the cascade multiplier is well suited for producing beams with relatively low energy (0.5-2 MeV) and a current of one to tens of mA. Thus, the Shanghai Institute of Applied Physics has developed a cascade multiplier for a beam with an energy of 1.2 MeV and a current of 50 mA [10], the Korea Institute of Radiological and Medical Sciences has developed a tandem accelerator based on a cascade multiplier to generate a proton beam with an energy of 2.4 MeV and a current of up to 20 mA for boron-neutron capture therapy [11], and the China Academy of Engineering Physics has developed a cascade multiplier for a beam with an energy of 300 keV and a current of 6 mA as the basis for a compact neutron generator [12]. Cockcroft-Walton cascade multipliers are also used at the Paul Sherrer Institute as an 870 keV pre-accelerator with subsequent acceleration to 590 MeV in the cyclotron ring at the High Intensity Proton Accelerator [13] or at the Los Alamos Neutron Science Center as part of a low energy beam line where the beam is accelerated to 750 keV [14].

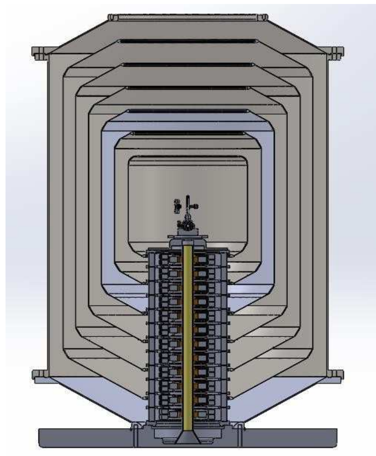

Fig. 3. Prototype of the VITAmin installation part.

III. High Voltage Power Supply

A. Theoretical Calculations and Simulations

The VITAmin uses a symmetrical cascade voltage multiplier with a capacitive coupling of stages in series as its power source. The scheme consists of 12 stages, with the intermediate high-voltage accelerator electrodes being connected directly to the power supply electrodes every other one. In each individual stage, diodes connected in series link two capacitor blocks with a constant voltage. The UHV-12A capacitors and 2CLG50KV-1A diodes in the scheme are designed for high voltages up to 50 kV, so the input to the cascade multiplier is an alternating voltage of no more than 25 kV. The components of each stage are placed in annular ceramic insulators, and KEV-1 resistors with a nominal value of R = 80 MΩ are added into the scheme for uniform distribution of electric potential between the electrodes. In the scheme, accelerator electrodes can be represented as capacitors connected parallel to every second stage. Such an idealized electrical schematic of the cascade generator with a 500 MΩ load (equivalent to 1 mA beam current) is shown in Fig. 4.

The secondary winding of the transformer will be inputted with an amplitude voltage of up to 24 kV and a frequency of 75 kHz to reduce voltage sag and ripple. The voltage sag of the cascade generator is calculated using the formula:

$$\Delta U = \frac{I}{fC}\frac{n}{3}\left(n^2 + \frac{3}{2}\right), \tag{1}$$

where a cascade of n = 12 stages, an input voltage to cascade generator is $U_0 = 20$ kV, a load current I ranging from 1 to 10 mA, a generator frequency is f = 75 kHz, and a capacitor

C of 1.7 nF in the UHV-12A. Voltage ripple is calculated using the formula:

$$\delta U = \frac{I}{fC}\frac{n}{2}. \quad (2)$$

Using the formula for the output voltage:

$$U = (2nU_0 - \Delta U \pm \delta U), \quad (3)$$

it was determined that the expected output voltage at a beam current of 10 mA is approximately 435 kV, with a voltage drop of 46 kV and a voltage ripple of 0.5 kV.

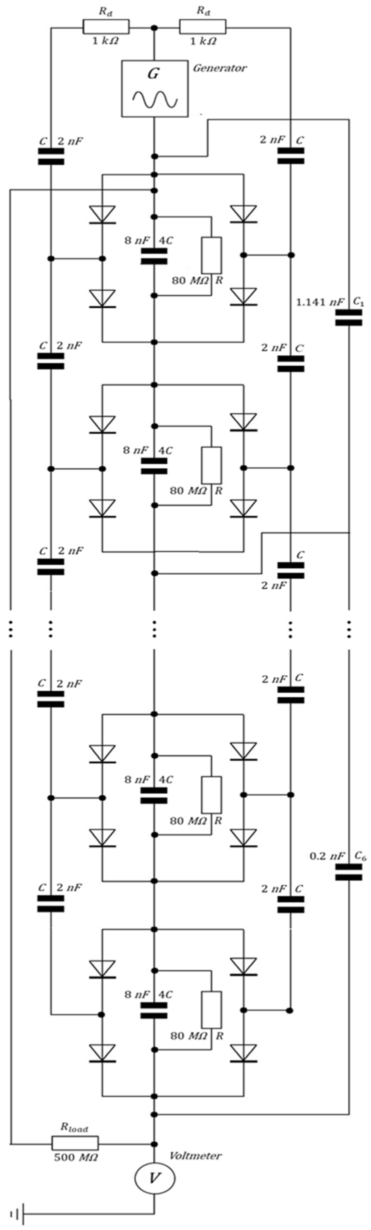

Fig. 4. Ideal scheme of the cascade multiplier with connected accelerator electrodes.

In calculating the output voltage of the generator, it is important to consider that the capacitors in the electrical circuit possess their own resistance and inductance. It has been measured and found that the insulation resistance of the capacitor is R_c = 320 MΩ, the equivalent series resistance is r = 4 Ω, and the equivalent series inductance is L = 0.28 μH, which can be neglected due to its minimal value. In the equivalent circuit of the cascade generator, resistances R_c were added in parallel with the capacitors and resistances r in series. Using the NL5 program [15] for simulating both the idealized and equivalent circuits with connected electrodes, it was shown that the impact of parasitic parameters on the circuit's output characteristics is not significant. The simulation revealed that the output voltage in the equivalent circuit is about 450 kV, the ripple voltage is 1 kV, and the voltage drop is about 1 kV. Additionally, simulations of the ideal and equivalent circuits at a frequency of 10 kHz were performed. The simulation results at different frequencies are presented in Fig. 5. The curve *1* corresponds to the output voltage of the ideal circuit at a frequency of 75 kHz, while the curve *2* represents the equivalent circuit. Similarly, the results at a frequency of 10 kHz are shown with the curves *3* and *4*, respectively.

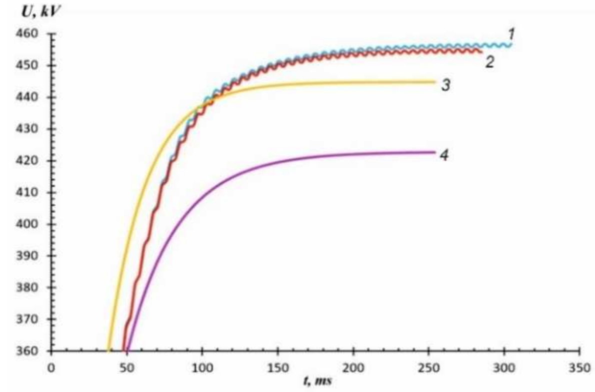

Fig. 5. Dependencies of output voltages versus time on a cascade multiplier at different input voltage frequencies.

The simulations show that frequency of the input voltage 75 kHz is more preferred, that 10 kHz. Moreover, modern electrotechnical devices, such as transistors, these frequencies can be achieved without many technical difficulties. Therefore, despite the initial decision to make the input supply at 10 kHz, it was decided to make the supply at 75 kHz.

B. Cascade Generator Power Supply

The power supply for the voltage multiplier will be provided by alternating current from the High Voltage AC Power Supply (HVPS) designed at the BINP, with an output amplitude voltage of 24 kV and a frequency of 75 kHz. Currently, it is planned to be supplying 24 kV of amplitude voltage at a frequency of 75 kHz to the input of the multiplier using this power supply. The block diagram of the source is shown in Fig. 6. The HVPS consists of a controller, a buffer power supply (BPS), an inverter, high-voltage transformers, and a voltage divider. Overall control is carried out by the controller, considering external control via the Ethernet interface of the local network within the VITAmin physical setup.

The constant power supply of the inverter at 380V from the external three-phase network with a voltage of 380 V and a frequency of 50 Hz is provided by the buffer power supply SHP-10K-380L manufactured by "Meanwell inc". This converter output voltage varying from 260 to 400 V with it's output power 10 kW, water cooling and remote controlling. The inverter converts the BPS voltage into alternating current with a frequency of 75 kHz and a maximum amplitude of 24 kV. The output of the power section of the inverter is based on a bridge scheme with silicon carbide field-effect transistors (SiC FETs). Inverter operation parameters such as amplitude voltage, conversion frequency, temperature, protection against maximum current, and output power are set by the controller. The high-voltage transformer with a U- shaped ferrite core increases the voltage and forms a resonant circuit with an additional capacity at the output, close to the inverter frequency. The high voltage resistive divider provides control of the output voltage after the high-voltage transformer. The high-voltage power from the transformer to the input of the cascade generator is transmitted via the coaxial cable RK 75-17-22. The voltage from the resistive divider of the cascade generator supplied to the HVPS controller, and together with other status information from the accelerator, determines the operating modes of the inverter.

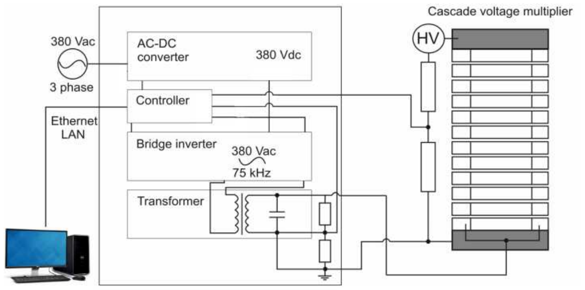

Fig. 6. Scheme of power supply.

IV. Initial Testing

To verify the multiplier construction, three of its sections were assembled with intermediate electrodes and insulators. The multiplier's construction and its elements are stable. Initial tests were conducted to check the compliance of the circuit's output parameters under different loads, with the maximum load being 80 W. For testing purposes, an existing pulse power supply with an output power of 100 W and a variable amplitude voltage of 160 V with 85 kHz frequency, isolated from the 220 V mains supply by a network transformer, was temporarily used as an AC and frequency generator. With such input parameters, the three-stage multiplier construction did not heat up. The assembled sections and the multiplier model are shown in Fig. 7.

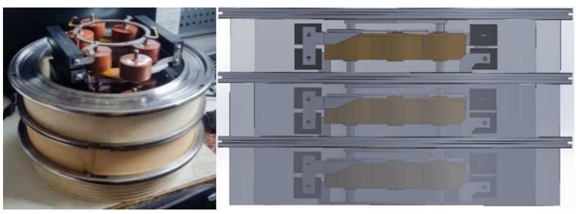

Fig. 7. Photograph of three assembled sections of a cascade multiplier (left), model of three sections of a cascade multiplier (right).

V. Future Plans

Since the initial tests of 3 sections of cascade multiplier were successful, the manufacturing of remaining sections started. Subsequently, it is planned to test 12-cascaded voltage multiplier by manufactured power supply with output voltage 24 kV with a frequency 75 kHz. Next step is to manufacture and test a gas-tight assembly internally filled with SF_6 with high voltage electrodes on it.

Final step of testing this system will be generation of fast neutrons on the lithium target, also manufactured in BINP.

VI. Conclusion

At the BINP, a compact source of fast neutrons with a 450 kV power supply is proposed and under construction. Since it is a tandem type of accelerator, simulations and calculations show that under beam loads of several milliamps, the energy of the deuteron beam varies from 870 to 900 keV. A deuteron beam with such energy, through the exothermic threshold reaction ^{7}Li(d,n) will generate a sufficient flux of fast neutrons with total yield up to $2 \cdot 10^{12}$ s^{-1} for conducting radiation testing of promising materials for large-scale physics facilities such as CERN and ITER and providing investigations in fast neutron therapy of malignant tumors.

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