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PHYSICAL DEVICES FOR ECOLOGY, MEDICINE, BIOLOGY

Vacuum Insulated Tandem Accelerator VITA and Its Applications[1]

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Abstract—One of the charged-particle accelerators with relatively low energy and relatively high current is the vacuum insulated tandem accelerator. The work notes the originality of the accelerator design and presents the results of the research. It was shown that replacing ceramic insulators with a smooth side surface with insulators with a corrugated outer surface ensured the required voltage of 1.15 MV without breakdowns. The required current of 10 mA was obtained by upgrading the facility, which followed the experimental determination of the effect of space charge on the transport of ions and significant suppression of the flow of secondary charged particles. The measured phase portraits of a beam of negative hydrogen ions and a beam of protons injected into the accelerator are presented. It is noted that the facility is primarily used for the development of boron-neutron capture therapy techniques for malignant tumors, for radiation testing and modification of promising materials with a neutron flux, for measuring the cross section and yield of nuclear reactions, and for other applications.

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1. INTRODUCTION

To introduce into clinical practice a promising method for treating malignant tumors—boron neutron capture therapy (BNCT) [1]—accelerator sources of epithermal neutrons are required. One such source is the VITA accelerator neutron source [2], which consists of a tandem accelerator with vacuum insulation for producing a beam of protons or deuterons, a thin lithium target for generating neutrons, and a system for forming a therapeutic neutron beam. As the installation was improved, it began to be actively used for a number of other applications due to the possibility of obtaining a stationary monoenergetic beam of protons or deuterons with an energy of up to 2.3 MeV, a current of up to 10 mA, and the generation of a neutron flux in reactions ^{7}Li(p, n)^{7}Be and ^{7}Li(d, n), α-particles in reactions ^{7}Li(p, α)α and ^{11}B(p, α)αα, photons with energy of 478 keV in the reaction ^{7}Li(p, p'γ)^{7}Li, and positrons in the reaction ^{19}F(p, e$^+$e$^-$)^{16}O.

2. EXPERIMENTAL SETUP

The VITA accelerator neutron source is a modern physical installation that includes an electrostatic tandem accelerator of charged particles of an original design, later called a tandem accelerator with vacuum insulation, for obtaining a stationary beam of protons or deuterons, an original thin lithium target for generating neutrons, and a number of systems for forming a neutron beam with a moderator made of magnesium fluoride, organic glass, or heavy water. The installation was constantly upgraded as knowledge was gained and currently looks like the one shown in Fig. 1.

The setup is mainly housed in one radiation-protected bunker, with the adjacent bunker housing a lithium target with a neutron beam generation system suitable for patient therapy or a neutron or gamma spectrometer for scientific research. The installation is

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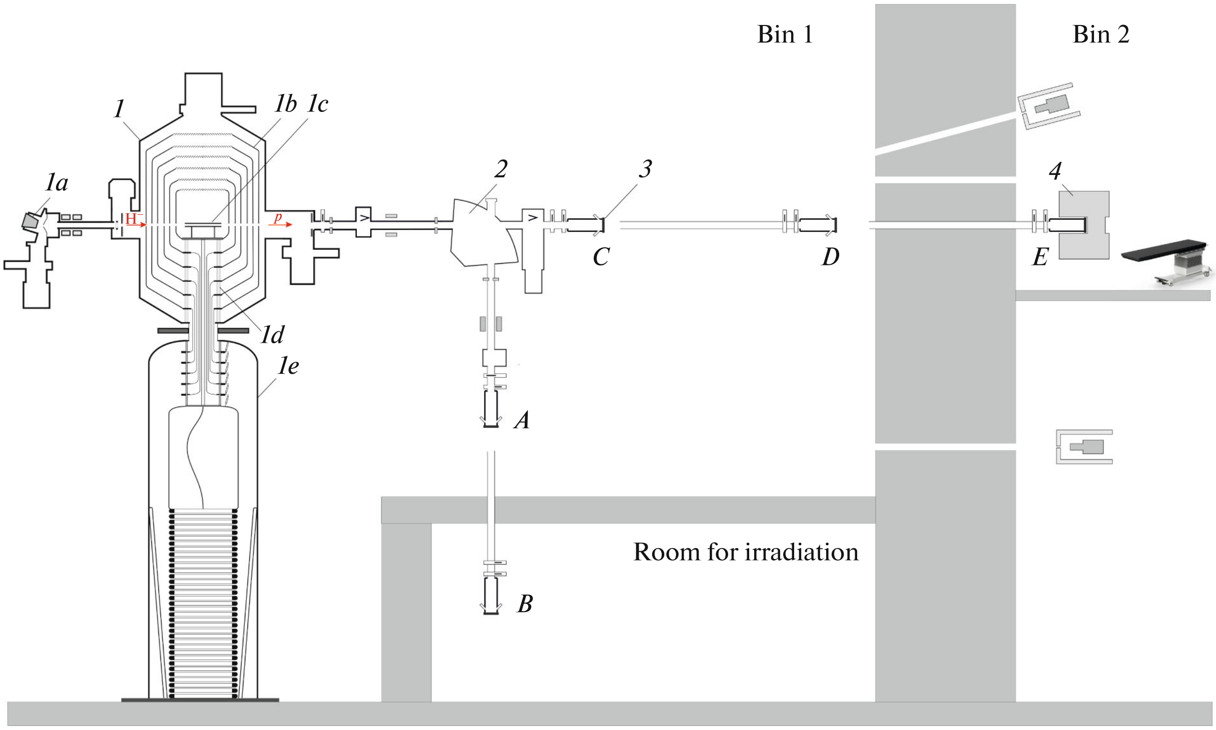

Fig. 1. Schematic diagram of the VITA accelerator neutron source: (*1*) tandem accelerator with vacuum insulation: (*1a*) source of negative ions, (*1b*) high-voltage and intermediate electrodes, (*1v*) gas stripping target, (*1g*) feedthrough insulator, (*1d*) high voltage power supply); (*2*) rotary magnet, (*3*) lithium target for neutron generation, (*4*) neutron beam formation system. The lithium target is placed in positions *A*, *B*, *B*, *G*, or *D*.

equipped with modern means of vacuum pumping, power supply, diagnostics, control, data collection, and storage.

The installation provides for the following:

1. Obtaining a powerful stationary beam of protons or deuterons with energy varying in the range from 0.3 to 2.3 MeV with a current from 0.5 to 10 mA. The ion beam is characterized by high monochromaticity and energy stability (0.1%) and high current stability (up to 0.4%). At the exit from the accelerator, the ion beam has a diameter of 10 ± 1 mm, an angular divergence of ±1.5 mrad, and a normalized geometric emittance of $\varepsilon_{\mathrm{norm}} = 0.2$ mm mrad.

2. Generation of a powerful neutron flux (up to 2×10^{12} s^{-1}) and the formation of a beam of neutrons of various energy ranges: cold, thermal, epithermal, exclusively epithermal, monoenergetic, supra-epithermal, or fast.

3. Generation of monoenergetic photons with energy of 478 keV, 511 keV, or 9.17 MeV,

4. Receiving α-particles and positrons.

The tandem accelerator with vacuum insulation is a linear electrostatic accelerator of charged particles of tandem type of original design. In the characterization of the accelerator, the term “linear” means that the ion beam passes through the accelerating intervals once. The term “electrostatic” means that the acceleration of charged particles occurs due to a constant electric field. The term “tandem” means that the high-voltage potential is used twice: first to accelerate negative ions and then, after reversing the polarity of their charge in the high-voltage terminal, to accelerate positive ions. The key advantage of the tandem acceleration concept is that the required acceleration voltage is reduced by half, which greatly simplifies electrostatic isolation and, therefore, reduces the size and cost of the accelerator. The originality of the design lies in the use of not traditional accelerating tubes but electrodes in the form of coaxial cylinders nested inside each other, which are attached to a single feedthrough insulator, as shown in Fig. 1. The main idea was to move the interelectrode insulators away from the charged particle beam to improve high-voltage strength and to ensure a high ion acceleration rate in the accelerating gap by placing the electrodes close together to increase the ion beam current.

The accelerator at the Budker Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences) consists of the following:

1. A cylindrical vacuum tank with a diameter of 1.4 m and a height of 2.3 m with openings for the input and output of an ion beam for vacuum pumping and for connection to a high-voltage power source.

2. A high-voltage electrode and five intermediate cylindrical electrodes, into which frames for fastening

diaphragms are welded on both sides and diaphragms are inserted, forming an acceleration channel.

3. A feedthrough insulator designed to supply potential to the high-voltage and intermediate electrodes from a high-voltage power source.

4. Gas stripping target.

5. A source of negative hydrogen or deuterium ions.

6. High-voltage power source: sectional rectifier of the industrial electron accelerator of the ELV series.

3. RESULTS AND DISCUSSION

Since the VITA vacuum-insulated tandem accelerator is a new type of charged particle accelerator, the achieved parameters were obtained as a result of upgrading all elements of the accelerator and conducting numerous scientific studies, which often changed the initial ideas.

A voltage of 1.15 MV was obtained after modifications to the vacuum section of the feedthrough insulator: replacing the indium seal with a rubber one; eliminating the resistive divider located inside by doubling the height of the insulator rings; replacing glass insulators with ceramic ones; replacing ceramic insulators with a smooth side surface with insulators with a corrugated outer surface [3]. It has been established that the high-voltage strength of the accelerator is limited by the strength of the accelerating gap and not by the effect of the total voltage.

The proton beam current of 10 mA was obtained after the following studies and modifications. When designing the accelerator, it was assumed that the space charge does not affect the transport of the negative ion beam due to the large gas inlet and affects the transport of the proton beam. In reality, everything turned out the opposite way.

The discovered influence of space charge on the transport of a beam of negative hydrogen ions [4] required the development and implementation of a number of diagnostic tools that ensure controlled input of an ion beam into the accelerator when the current and energy of the ions change. These are video cameras and a telescope that record the glow of an ion beam during its interaction with residual and stripping gas, a wire scanner, and an emittance meter.

The observed absence of influence of space charge on the transport of the proton beam [5] made it possible to replace two pairs of quadrupole lenses with cooled diaphragms with thermal resistances uniformly spaced along the azimuth, which ensured preventing the ion beam from burning through the vacuum chamber and controlling its position.

Significant progress in increasing the proton beam current has been achieved as a result of significant suppression of the flow of secondary charged particles by improving vacuum pumping and placing a cooled diaphragm at the entrance to the accelerator as well as partially covering the walls of the vacuum chamber with a metal mesh under a negative potential [6].

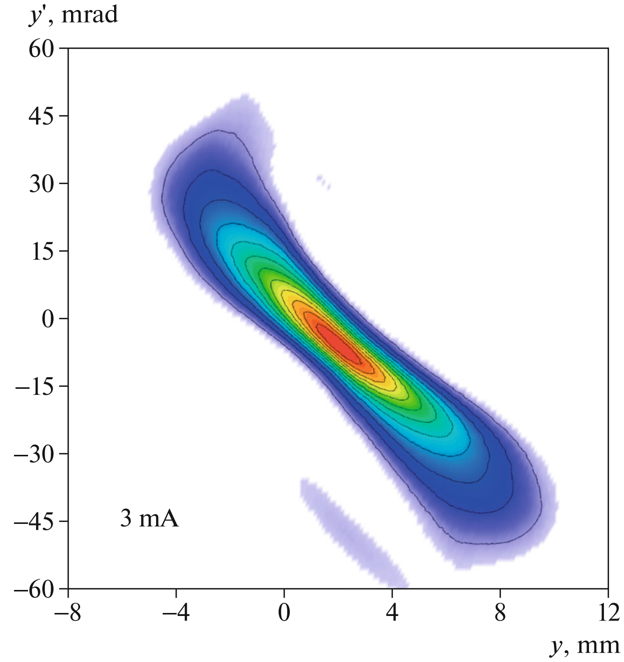

Fig. 2. Phase portrait of a beam of negative hydrogen ions injected into an accelerator.

The special design of the diaphragms of the high-voltage electrode of the accelerator radically suppresses the unwanted flow of argon ions from the gas stripping target into the accelerating channels [7].

The ion-optical system of the accelerator provides the possibility of implementing operational control of the efficiency of the gas stripping target [8].

Replacing hydrogen with deuterium in the ion source produces a deuteron beam [9].

The knowledge gained and the accelerator equipped with a large set of diagnostic tools make it possible to stably obtain a beam of protons or deuterons in a wide range of energies and currents over a long period of time. A typical phase portrait of a beam of negative hydrogen ions injected into an accelerator is shown in Fig. 2, and a phase portrait of a proton beam is shown in Fig. 3 [10].

4. APPLICATION

The main purpose of the proposed accelerator is to use it for boron neutron capture therapy of malignant tumors. The following important results were obtained at the facility at Budker Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences): (1) neutron irradiation of tumor cells preincubated in a boron-containing medium leads to a significant suppression of their viability; irradiation of mice with grafted tumors leads to their cure [11, 12]; (2) a posi-

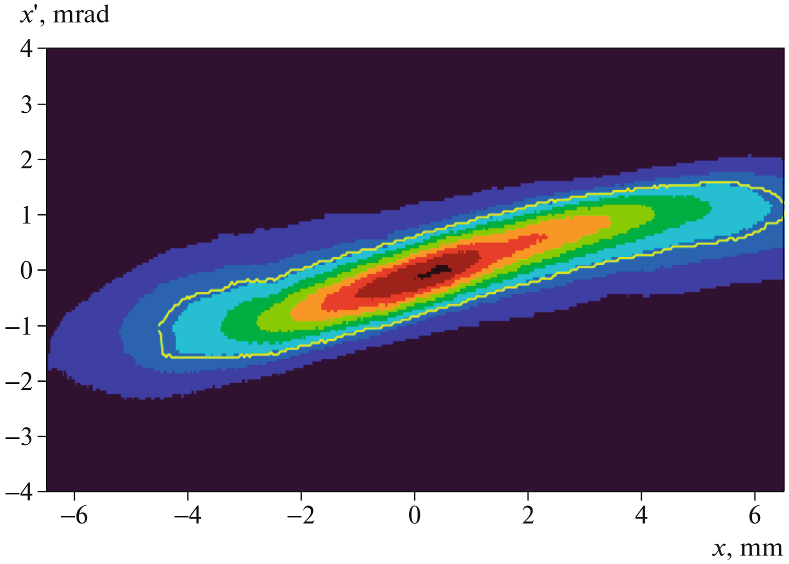

Fig. 3. Phase portrait of a proton beam.

tive effect has been achieved by irradiating large domestic animals with spontaneous tumors [13, 14]; (3) dosimetry tools and methods have been developed [15–18]; (4) new drugs for targeted boron delivery have been tested [19–25]; (5) the neutron yield in the reaction ^{7}Li(p, n)^{7}Be [26], yield of 478 keV photons in the reaction ^{7}Li(p, p'γ)^{7}Li [27], and reaction cross section ^{7}Li(p, p'γ)^{7}Li [27] and ^{7}Li(p, α)^{4}He [28] have been measured.

The developed accelerator neutron source VITA is used in a clinic in Xiamen (China) [29] for the treatment of cancer patients (second in the world) and is manufactured for the Center for Hadron Therapy in the field of oncology in Pavia (Italy) and for the Blokhin National Medical Research Center of Oncology in Moscow.

The process of blister formation on the surface of metals during proton implantation was studied in detail at the accelerator [30]. The effect of radiation blistering on the neutron yield from a target made in the form of a thin layer of lithium deposited on an effectively cooled copper substrate was studied [31].

A nondestructive in situ measurement method of the thickness of the lithium layer by measuring the intensity of radiation of photons with an energy of 478 keV in the reaction ^{7}Li(p, p'γ)^{7}Li has been proposed and implemented [32].

The facility is used for radiation testing of boron carbide and steel samples for the International Thermonuclear Experimental Reactor (ITER) [33], optical cables for the Large Hadron Collider (CERN), neodymium magnets for the high-power linac, titanyl phthalocyanine gas sensors [34], semiconductor photomultipliers, and electronic components and devices.

The facility is working on obtaining a cold neutron beam for neutronography and BNCT, and on implementing the instantaneous γ-spectroscopy method for measuring the boron dose during BNCT, for the implementation of lithium neutron capture therapy, providing 100% release of nuclear reaction energy in tumor cells [35], for the modification of promising materials, for the development of a method for sterilizing endoprostheses in situ, and on the development of a powerful compact source of fast neutrons and for other applications.

5. CONCLUSIONS

The VITA vacuum-insulated electrostatic tandem accelerator described in the paper is characterized by a wide range of changes in the energy and current of the proton or deuteron beam, which allows it to be used to generate flows of neutrons, photons, α-particles, and positrons, which are in demand for various applications.

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CONFLICT OF INTEREST

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

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