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NUCLEAR EXPERIMENTAL TECHNIQUE

Study of an Ion Beam in Vacuum Insulated Tandem Accelerators

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Abstract—Boron neutron capture therapy, a promising method for treating malignant tumors, requires accelerator sources of neutrons in the epithermal energy range. One of the popular charged particle accelerators is a tandem electrostatic accelerator of an original design, later called the vacuum insulated tandem accelerator VITA. The paper presents the results of measuring the phase portrait of an ion beam obtained at an experimental facility at Budker Institute of Nuclear Physics and at oncology clinic facilities that feature preacceleration. The advantages and disadvantages of using preacceleration are shown. Proposals are made to improve the vacuum insulated tandem accelerator, which require experimental verification.

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1. INTRODUCTION

Boron neutron capture therapy (BNCT) [1–3] is considered a promising method for treating malignant tumors; it ensures selective destruction of tumor cells by accumulating boron in them and subsequent irradiation with neutrons. As a result of the absorption of a neutron by boron, a nuclear reaction occurs with a large release of energy in the tumor cell, which leads to its death.

The Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences) proposed, created, and effectively uses the VITA accelerator neutron source, which includes an electrostatic tandem accelerator of charged particles of an original design, later called the VITA tandem accelerator with vacuum insulation, to obtain a stationary monoenergetic beam of protons or deuterons with an energy of up to 2.3 MeV, a current of up to 10 mA, an original thin lithium target for generating neutrons with an output of up to 2×10^{12} s^{-1}, and a number of neutron beam shaping systems for producing a beam of cold, thermal, epithermal, or fast neutrons [3–5]. The setup currently appears as in Fig. 1.

2. VITA VACUUM INSULATION TANDEM ACCELERATOR

The tandem accelerator with vacuum consists of 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 (on the side) for vacuum pumping (on top) and for connection to a high-voltage power source (on the bottom) and high-voltage and five intermediate cylindrical electrodes located coaxially with the body of the vacuum tank (the diameter of the high-voltage electrode is 600 mm, the diameters of the intermediate electrodes are 740, 870, 1000, 1130, 1260 mm). Frames for fastening diaphragms are welded into the electrodes on both sides, and diaphragms with a hole usually 20 mm in diameter in the negative ion acceleration path and in the high-voltage electrode and 30 mm in the positive ion acceleration path are inserted. The diaphragms are located along the diameter coaxially with the input and output flange of the ion beam and form an acceleration channel. The potential to the high-voltage and intermediate electrodes is supplied from a high-voltage power source through a feedthrough insulator. A gas-stripping target is installed inside the high-voltage electrode coaxially with the accelerating channel, designed to convert negative ions into positive ones.

A beam of negative hydrogen or deuterium ions from the surface plasma source with the Penning geometry of the gas discharge chamber is focused by a solenoid onto the inlet of the accelerator, creating a diverging ion beam at the entrance to the accelerator. The characteristic profile and phase portrait of a beam of negative hydrogen ions at a distance of 57 mm in front of the input hole are shown in Fig. 2; an ES-4 emittance meter (D-Pace, Canada) was used. It can be seen that the beam is close to ideal, and there are

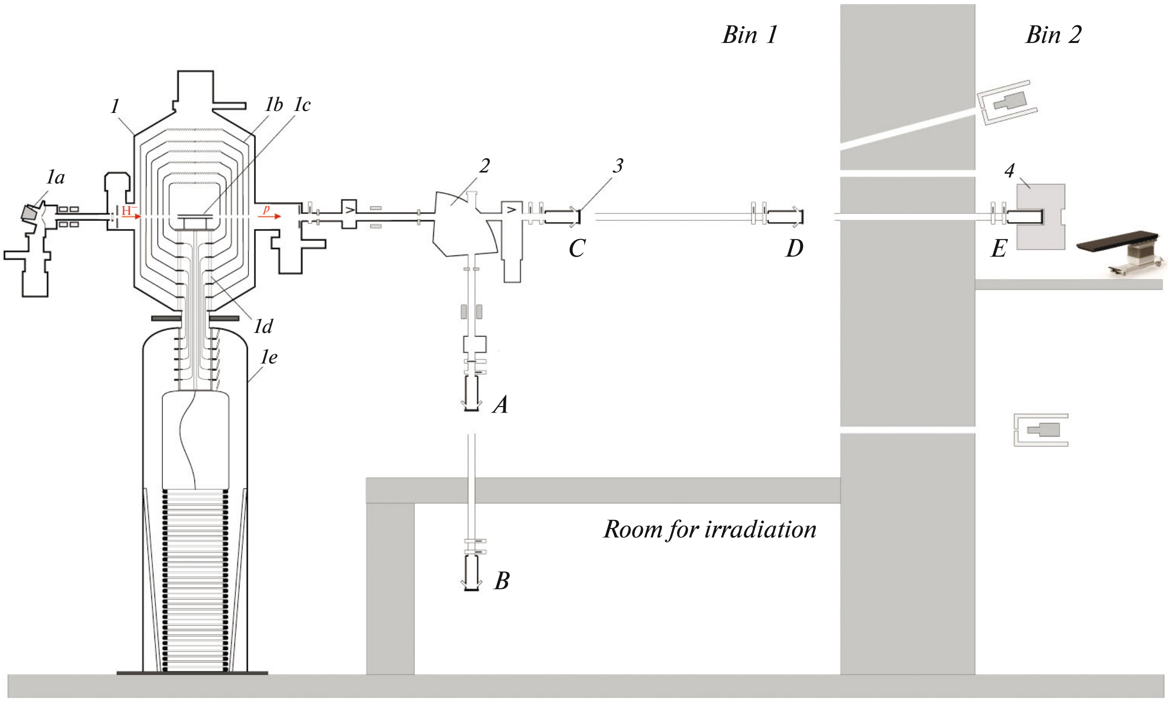

Fig. 1. Schematic diagram of the VITA accelerator neutron source: (*1*) tandem accelerator with vacuum insulation, (*1a*) source of negative ions, (*1b*) high-voltage and intermediate electrodes, (*1c*) gas-stripping target, (*1d*) feedthrough insulator, (*1e*) high-voltage power supply); (*2*) rotary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

hardly any spherical aberrations. Its transverse profile deviates from Gaussian towards more uniform in the center due to the action of space charge during its transport. The characteristic transverse size of the ion beam at this location is 8–9 mm, the convergence is ±30 mrad, and the normalized emittance is from 0.13 mm mrad at a current of 0.5 mA to 0.2 mm mrad at a current of 3 mA. Here is the normalized emittance $\varepsilon_{\text{norm}} = \varepsilon_{\text{rms}}\beta\gamma$, where

$$\varepsilon_{\text{rms}} = (\det(\sigma_{xx'}))^{1/2}, \quad \sigma_{xx'} = \begin{bmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{bmatrix},$$

$$\langle x^2 \rangle = \frac{1}{N}\sum_1^N x_i^2, \quad \langle x'^2 \rangle = \frac{1}{N}\sum_1^N x'^2,$$

$$\langle xx' \rangle = \frac{1}{N}\sum_1^N x_i x_i', \quad \beta = \sqrt{\frac{2E}{mc^2}}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}},$$

E is the energy of a charged weakly relativistic particle, and m is its mass. The area of the phase portrait ellipse is defined as $S = \pi\varepsilon_{xx'}$. For a Gaussian beam distribution, the portion of the beam included in the ellipse $n\varepsilon$ is determined by the expression k [%] = $100\%(1 - e^{-n/2})$. Thus, for $n = 1$ we get $k = 39\%$; for $n = 2$, we have $k = 63\%$; for $n = 4$, magnitude $k = 86\%$. For real (non-Gaussian) beams these values depend on the beam shape. Please note that the emittance values given below are for $n = 1$.

This focusing of the ion beam onto the accelerator input hole ensures a "rigid" beam input: a highly divergent ion beam enters the accelerator, which is focused by the accelerator's strong input electrostatic lens into a practically parallel beam with a diameter of 4–5 mm. In the gas-stripping target of the tandem accelerator, negative ions are converted into positive ones, which are then accelerated by an electric field and, leaving the accelerator, are slightly defocused by the accelerator's output electrostatic lens. At a distance of 1.86 m from the accelerator center, using a movable cooled diaphragm and an OWS-30 wire scanner (D-Pace, Canada), the phase portrait of the proton beam was measured; a typical example is shown in Fig. 3.

At this point, the proton beam has a transverse size of 10 ± 1 mm, angular divergence from ±0.5 mrad up to ±1.2 mrad, and normalized emittance is 0.2 mm mrad. The transverse profile of the proton beam at this location and at a number of other locations where it was measured using several independent techniques is well described by a Gaussian distribution. Such a weakly diverging beam of protons allows it to be transported to the lithium target without the use of focusing lenses, which is an undoubted advantage (the maximum transport distance is 10 m, see Fig. 1).

The only significant drawback of this injection mode is the heating of the uncooled diaphragm of the first accelerating electrode, which is highly dependent

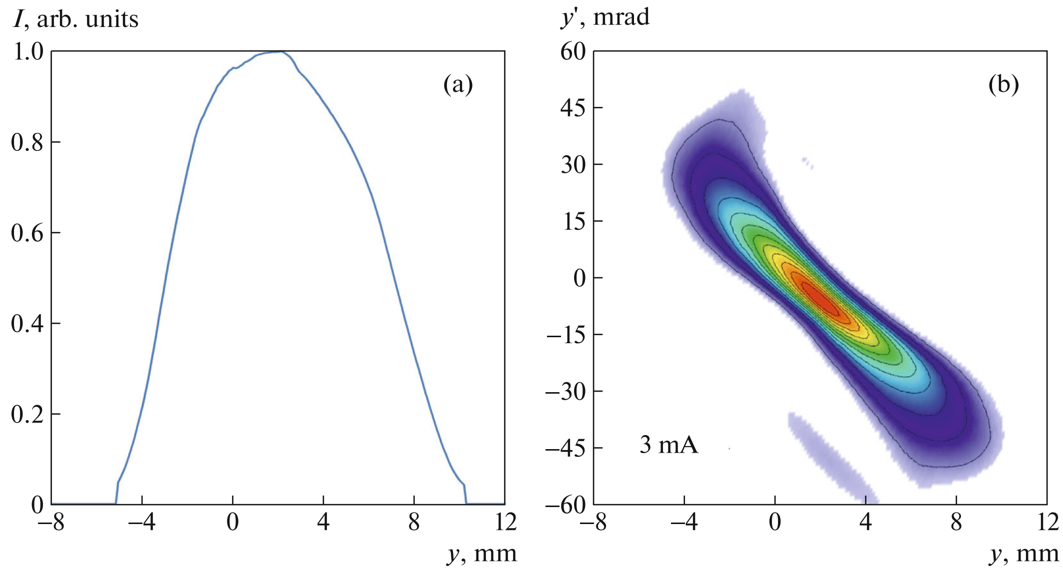

Fig. 2. (a) Profile and (b) phase portrait beam of negative hydrogen ions at current value of 3 mA.

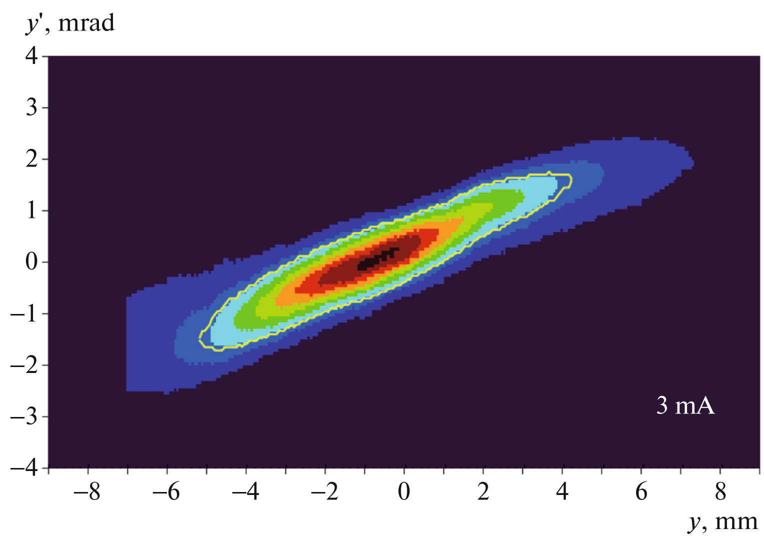

Fig. 3. Phase portrait of a proton beam at a current of 3 mA.

on the focusing of the ion beam at the accelerator input and on the potential of the high-voltage electrode. Thus, it is shown in work [6] that, if the current strength of the magnetic focusing lens (solenoid) is increased by 1.6% relative to the optimal mode, then the proton beam will be even less divergent, practically parallel, but the diaphragm will heat up significantly more; if the current strength of the lens is reduced by 1.6%, then the beam divergence will increase by 1.5 times. Even more strongly, the heating of the diaphragm and the divergence of the proton beam depend on the potential of the high-voltage electrode of the accelerator, i.e., on the energy of the protons. The reason is that, while the accelerator was initially designed for boron neutron capture therapy with a fixed proton energy, it later began to be used for a whole range of other applications requiring a beam of protons or deuterons with energies from 0.1 to 2.3 MeV.

The implementation of such a “hard” beam input mode into the accelerator, resulting in the production of a weakly diverging proton beam, is effectively ensured by the following set of diagnostic tools: (1) two pairs of video cameras directed at the uncooled input and output diaphragms of the first accelerating electrode, the images from which provide control of the position and size of the ion beam, as well as the heating of the diaphragms, and (2) thermocouples inserted into cooled copper diaphragms in the highenergy ion transport path, the readings of which provide control of the position, size, and divergence of the proton or deuteron beam.

We will add that the rationale for implementing a "hard" input of an ion beam into the accelerator is given in the preprint [7], the results of the study of the influence of the space charge on the transport of a beam of negative hydrogen ions are given in the article [6], the results of measuring the phase portrait of a beam of negative hydrogen ions, a beam of protons and the transverse size of the ion beam in the gas-stripping target of the accelerator are given in the article [8], the results of measuring the profile of the ion beam are given in the articles [6–9], and all the results of the study are summarized in the dissertation [10].

3. VITA-II VACUUM INSULATION TANDEM ACCELERATOR

In the next two accelerator neutron sources, delivered to the BNCT Clinic in Xiamen (China) [11] and to the Blokhin National Medical Research Center of Oncology in Moscow, two significant changes were made.

First, the surface plasma source with Penning geometry of the gas discharge chamber developed by the Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences) was replaced by a source from D-Pace (Canada) with volumetric formation of negative ions [12]. To generate plasma in the ion source, an arc discharge is used between heated tantalum cathodes and the wall of the source chamber, which serves as the anode. On the wall of the gas discharge chamber, there is a multipole magnetic field created by permanent magnets installed on the outside and serving for magnetic confinement of the plasma. The 30 keV negative hydrogen ion beam generated by this source has a normalized emittance of 0.1 mm mrad at 1 mA, 0.13 mm mrad at 10 mA, and 0.16 mm mrad at 15 mA (equipment manufacturer's data). The measurements we carried out confirmed these data.

Second, the beam of negative hydrogen ions injected into the accelerator is additionally preaccelerated to an energy of 100 keV. Initially, preacceleration of the injected ion beam was proposed to reduce the flow of secondary charged particles and an accelerating tube was made for this purpose, but the problem was solved in another way: by improving vacuum pumping, suppressing secondary emission of electrons from the walls of the vacuum chamber irradiated by the flow of secondary positive ions, and suppressing the penetration of electrons from the transport channel into the accelerator [13]. The accelerator tube was used in a neutron source for a Chinese clinic to increase the energy of protons; a similar accelerator tube is used in a neutron source for a Moscow clinic. Thus, preacceleration has been implemented in both accelerator neutron sources for oncology clinics.

A schematic diagram of the VITA-IIβ accelerator neutron source for the Blokhin National Medical Research Center of Oncology is shown in Fig. 4. The diameter of the accelerator vacuum tank is 1.56 m and its height is 2.4 m. The distance from the outlet of the negative hydrogen ion source to the center of the accelerator is 3.23 m and that from the center of the accelerator to the lithium neutron-generating target is 6.66 m.

The beam of negative hydrogen ions emerging from the source is diverging. An Einzel lens with a braking potential (included in the source kit) is placed near the source outlet, which focuses the diverging ion beam and makes it close to parallel. Next, this ion beam is accelerated in an accelerator tube and then focused by a magnetic lens (solenoid) onto the entrance to the accelerator. An emittance meter ES-4 (D-Pace, Canada) is placed in front of the accelerator input diaphragm, with the help of which the phase portrait of the injected ion beam was determined in different focusing and preacceleration modes. It was found that focusing with an Einzel lens and a magnetic lens does not change the value of the ion beam emittance, while preacceleration increases the normalized emittance by 1.5 times. With increasing current, the size of the ion beam increases due to the action of the space charge, mainly in the zone of action of the Einzel lens, where ion deceleration occurs. Characteristic phase portraits of a beam of negative hydrogen ions are shown in Fig. 5.

The transverse size of the ion beam at this location is 17–24 mm, the convergence is ±5–7 mrad, and the normalized emittance is from 0.15 to 0.2 mm mrad. The size and convergence indicate that the ion beam is focused to a distance of 1.3–3 m, i.e., a weakly converging beam is injected into the accelerator. A strong input electrostatic lens further focuses the ion beam, causing it to be refocused inside the accelerator. At the exit from the accelerator, the output electrostatic lens makes the beam even more divergent.

At a distance of 2.17 m from the center of the accelerator, using a movable cooled diaphragm and an OWS-30 wire scanner, the phase portrait of the proton beam was measured; a typical example is shown in Fig. 6. At this point, the proton beam has a transverse size of 15–20 mm, a divergence of ±3–4 mrad, and the normalized emittance is 0.15–0.2 mm mrad.

By shifting the diaphragm horizontally or vertically, the proton beam profile was measured (Fig. 7). It can be seen that the proton beam profile differs from the shape of a Gaussian distribution. The form phase portrait of a beam of negative hydrogen ions shown in Fig. 5 indicates the presence sof pherical aberrations in the ion-optical path. This results in different parts of the ion beam being focused at different distances, forming a nonuniform proton beam. Transporting such a diverging proton beam to a lithium neutron-generating target requires the use of focusing means,

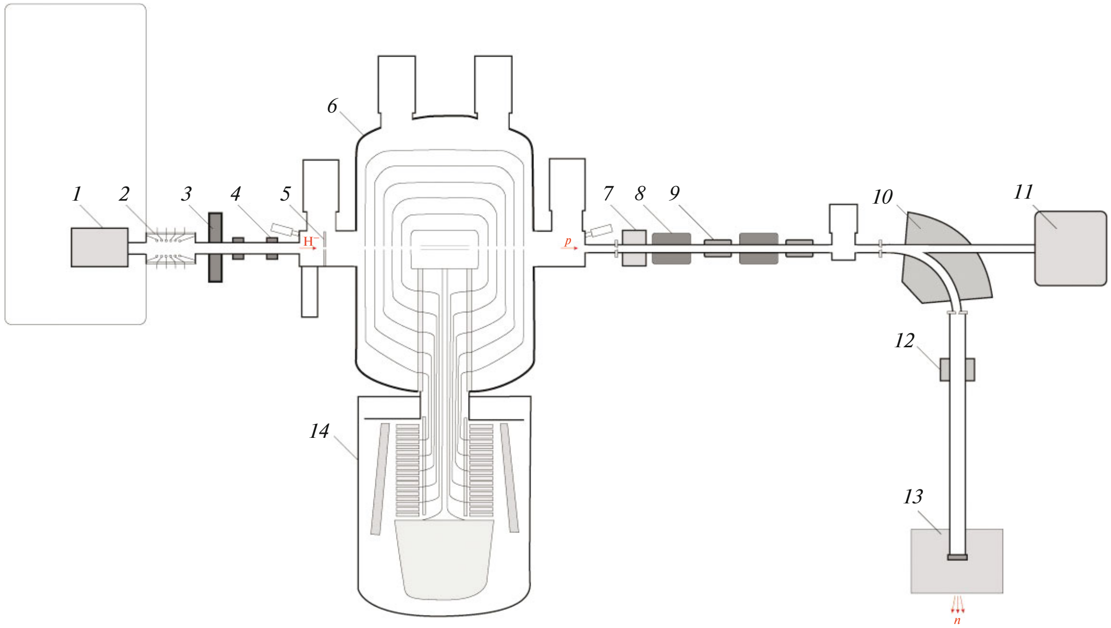

Fig. 4. Schematic diagram of the VITA-II accelerator neutron sourceβ: (*1*) source of negative hydrogen ions with an electrostatic Einzel lens mounted on a high-voltage platform, (*2*) acceleration tube, (*3*) solenoid, (*4*) correctors, (*5*) accelerator input diaphragm, (*6*) tandem accelerator with vacuum insulation, (*7*) noncontact current sensor, (*8*) quadrupole lenses, (*9*) correctors, (*10*) rotating magnet (the proton beam is rotated in a horizontal plane), (*11*) beam receiver, (*12*) magnetic scan, (*13*) lithium target for neutron generation and neutron beam formation system, (*14*) high-voltage power supply for the accelerator. The arrows show the propagation of negative hydrogen ions (H^-), protons (p), and neutrons (n).

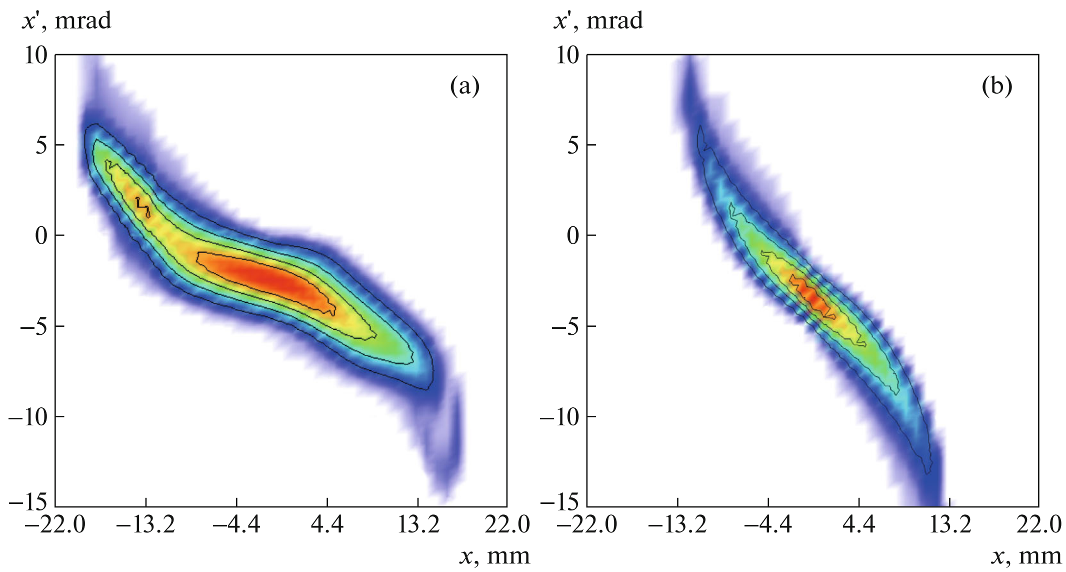

Fig. 5. Phase portrait of a beam of negative hydrogen ions injected into the accelerator with a current of (a) 5 and (b) 9 mA.

which is a pair of quadrupole magnetic lenses in this case.

Thus, using preacceleration has both positive and negative effects. The positive effect is that the proton energy is increased by 100 kV and there is no heating of the uncooled diaphragms of the accelerator due to the smaller size of the ion beam in the accelerator, especially at the beginning. The negative effect is that the quality of the resulting proton beam has deteriorated: it has become larger in size, its divergence has become greater, and it has become nonuniform. Obtaining such a beam complicates the installation since focusing means are required for its transportation. The use of preacceleration itself also complicates the installa-

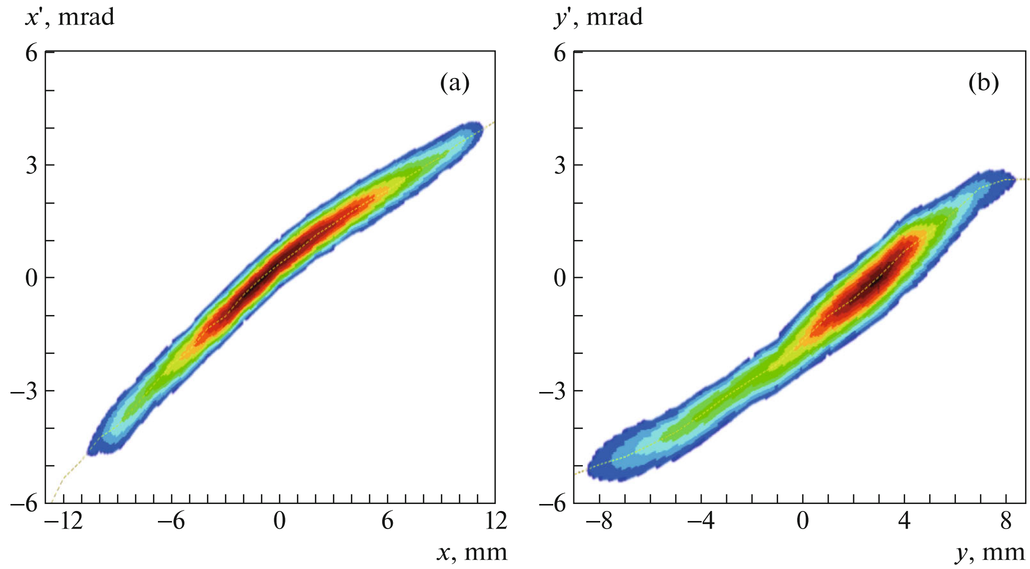

Fig. 6. Phase portrait of a proton beam (a) horizontally and (b) vertically at a current value of 3 mA.

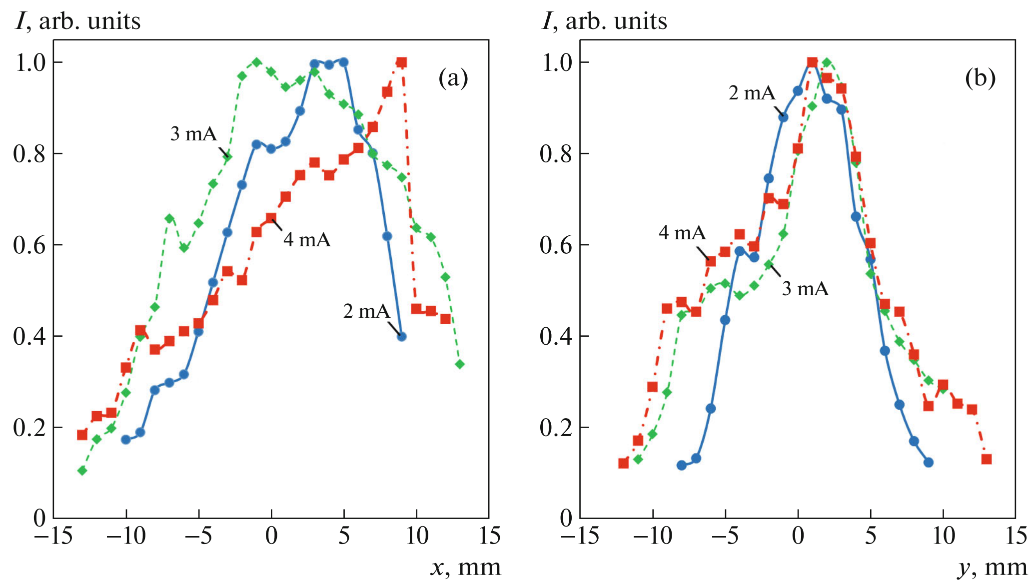

Fig. 7. Profile of proton beam (a) horizontally and (b) vertically at current values of 2, 3, and 4 mA.

tion: it requires a high-voltage platform and an isolation transformer.

It is clear that it is possible to improve the accelerating tube and reduce spherical aberrations, but it is hardly worthwhile to use preacceleration in the future, which crosses out the main advantage of tandem accelerators: the placement of the injector and target under the ground potential. In the next version of the tandem accelerator with vacuum insulation without preacceleration, it is proposed to optimize the injection, for example by using a Q-snout lens [14], optimize the acceleration channel, make the input lens of the first accelerating electrode cooled, etc. Since autumn 2024, cooling of the high-voltage electrode diaphragms has been implemented in the accelerator at the Budker Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences) site, which has improved its performance.

4. CONCLUSIONS

The original design of the tandem electrostatic accelerator, later called the VITA vacuum-insulated tandem accelerator, is widely used for the development of boron neutron capture therapy, for radiation testing of advanced materials, for measuring the cross-section of nuclear reactions, and for other applications. Unlike the accelerator at the Budker Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences), the accelerators delivered to oncology clinics use preacceleration. Measuring the phase portrait of the ion beam of these installations and comparing them made it possible to establish the advantages and disadvantages of using preacceleration. Proposals have been made to improve the vacuum-insulated tandem accelerator that require experimental verification.

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CONFLICT OF INTEREST

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

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