Nuclear Instruments and Methods in Physics Research A 1077 (2025) 170587

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Comparison of vacuum insulated tandem accelerators and suggestion for its improvement

Timofey Bykov [a,b], Yaroslav Kolesnikov [a,b], Alexey Koshkarev [a,b], Georgii Ostreinov [a,b], Sergey Savinov [a,b], Ivan Shchudlo [a,b], Sergey Taskaev [a,b,*]

[a] Budker Institute of Nuclear Physics, 11 Lavrentiev ave., 630090, Novosibirsk, Russia
[b] Novosibirsk State University, 2 Pirogov str., 630090, Novosibirsk, Russia

ARTICLE INFO

Keywords:
Charged particle accelerator
Phase portrait
Boron neutron capture therapy

ABSTRACT

Boron neutron capture therapy, a promising method for treating malignant tumors, requires accelerator based sources of neutrons in the epithermal energy range. One of the popular charged particle accelerators is an electrostatic tandem accelerator of an original design called Vacuum Insulated Tandem Accelerator (VITA). The paper presents the results of phase portrait measurements of an ion beam conducted at the Budker Institute of Nuclear Physics experimental facility and at oncology clinics equipped with pre-acceleration. The advantages and disadvantages of using pre-acceleration are shown. A proposal is made to improve VITA, confirmed by the results of numerical simulation of ion beam transportation and acceleration.

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 then irradiating them with neutrons. As a result of the absorption of neutrons by boron nuclei in the tumor cell, a nuclear reaction of the decay of the boron nucleus in an excited state occurs with a large release of energy, which leads to its death.

The Budker Institute of Nuclear Physics (Novosibirsk, Russia) proposed, created and effectively uses an accelerator based neutron source [3–5]. The facility includes an electrostatic tandem accelerator of an original design (Vacuum Insulated Tandem Accelerator, VITA), an original thin lithium target, and number of neutron beam shaping assemblies. The accelerator is used to obtain a dc monoenergetic beam of protons or deuterons with an energy up to 2.3 MeV, a current up to 10 mA. Lithium target is used for generating neutrons in ^{7}Li(p,n)^{7}Be reaction with yield of up to 2 10^{12} s^{-1}. Beam shaping assemblies is used to obtain a flux of cold, thermal, epithermal or fast neutrons. At present, the facility looks as shown in Fig. 1.

2. Vacuum Insulated Tandem Accelerator (VITA)

The vacuum insulated tandem accelerator consists of a cylindrical vacuum tank with a diameter of 1.4 m, and a height of 2.3 m, with holes for the input and output of the ion beam (on the side), for vacuum pumping (on top), and for connection to the high-voltage power supply (on the bottom). High-voltage and five intermediate cylindrical electrodes are located coaxially within 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 an aperture of 20 mm in diameter are inserted in the negative ion acceleration path and in the high-voltage electrode and 30 mm in the positive ion acceleration path. The diaphragms are located along the diameter coaxially with the input and output flanges of the ion beam input and output, and form an accelerating channel. The potential on the high-voltage and intermediate electrodes is supplied from the high-voltage power supply through a feedthrough insulator. A gas stripper 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 is obtained from a surface-plasma source with a Penning geometry of the gas-discharge chamber and is focused by a solenoid onto the accelerator input, creating a diverging ion beam at the accelerator input. The typical profile and phase portrait of a beam of negative hydrogen ions, measured by the D-Pace ES-4 Emittance Scanner [6] at a distance of 57

* Corresponding author. 11 Lavrentiev ave., 630090, Novosibirsk, Russia.
E-mail address: taskaev@inp.nsk.su (S. Taskaev).

https://doi.org/10.1016/j.nima.2025.170587
Received 10 March 2025; Received in revised form 29 April 2025; Accepted 29 April 2025
Available online 29 April 2025
0168-9002/

mm in front of the input, is shown in Fig. 2. It is evident that the beam is close to ideal and there are practically no spherical aberrations. Its transverse profile differs from Gaussian in the direction of more uniformity in the center due to the action of the space charge during its transportation. The typical transverse size of the ion beam at this location is 8–9 mm, the convergence is ±30 mrad, while 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. Normalized emittance is $\varepsilon_{\text{norm}} = \varepsilon_{\text{rms}}\beta\gamma$, where $\varepsilon_{\text{rms}} = (\det(\sigma_{xx'}))^{1/2}$, $\sigma_{xx'} = \begin{bmatrix} \langle x^2\rangle & \langle xx'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle \end{bmatrix}$; $\langle x^2\rangle = \frac{1}{N}\sum_1^N x_i^2$; $\langle x'^2\rangle = \frac{1}{N}\sum_1^N x'^2$; $\langle xx'\rangle = \frac{1}{N}\sum_1^N x_i x'_i$, $\beta = \sqrt{\frac{2E}{mc^2}}$, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$, E – energy of a charged weakly relativistic particle, m – 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 $n\varepsilon$ ellipse is given by:

k [%] = 100 % · (1 – $e^{-n/2}$). So, for $n = 1$ we get $k = 39$ %, for $n = 2$ $k = 63$ %, for $n = 4$ $k = 86$ %. For real (non-Gaussian) beams, these values depend on the beam shape. Note that the emittance values given below are for $n = 1$.

Such focusing of the ion beam on the accelerator input aperture provides a “hard” beam input: a strongly diverging ion beam enters the accelerator, which is focused by the accelerator’s strong input electrostatic lens into a beam of 4–5 mm diameter close to parallel. In the gas striper of the tandem accelerator, negative ions are transformed into positive ions, which are subsequently accelerated by the electric field. Upon exiting the accelerator, these ions experience slight defocusing due to the output electrostatic lens. At a distance of 1.86 m from the accelerator center, the phase portrait of the proton beam was measured using a movable cooled collimator and a D-Pace OWS-30 Oscillating Wire Scanner; a typical example is shown in Fig. 3.

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

The only significant disadvantage of this injection mode is the heating of the uncooled diaphragm of the first accelerating electrode, which strongly depends on the focusing of the ion beam at the accelerator input and on the potential of the high-voltage electrode. Thus, in Ref. [7] it is shown that if the current of the magnetic focusing lens (solenoid) is increased by 1.6 % relative to the optimal mode, the proton beam will be even less divergent, practically parallel, but the diaphragm will heat up significantly more; if the current of the lens is reduced by 1.6 %, the beam divergence will increase by 1.5 times. The heating of the diaphragm and the divergence of the proton beam depend even more 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 was later used for a whole range of other applications requiring a beam of protons or deuterons with an energy of 0.1 MeV–2.3 MeV.

The implementation of such a “hard” mode of beam input into the accelerator, resulting in the production of a weakly divergent proton beam, is effectively ensured by the following set of diagnostic means: i) 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 and control of the heating of the diaphragms, ii) thermocouples inserted into cooled copper diaphragms in the high-energy ion transport path, the readings of which provide control of the position, size and divergence of the proton or deuteron beam.

We add that the rationale for implementing the “hard” input of an ion beam into the accelerator is given in Ref. [9], 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 Ref. [8], 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 stripper of the accelerator are given in Ref. [7], the results of measuring the ion beam profile are given in Refs. [7–10], and all the results of the study are summarized in the thesis [11].

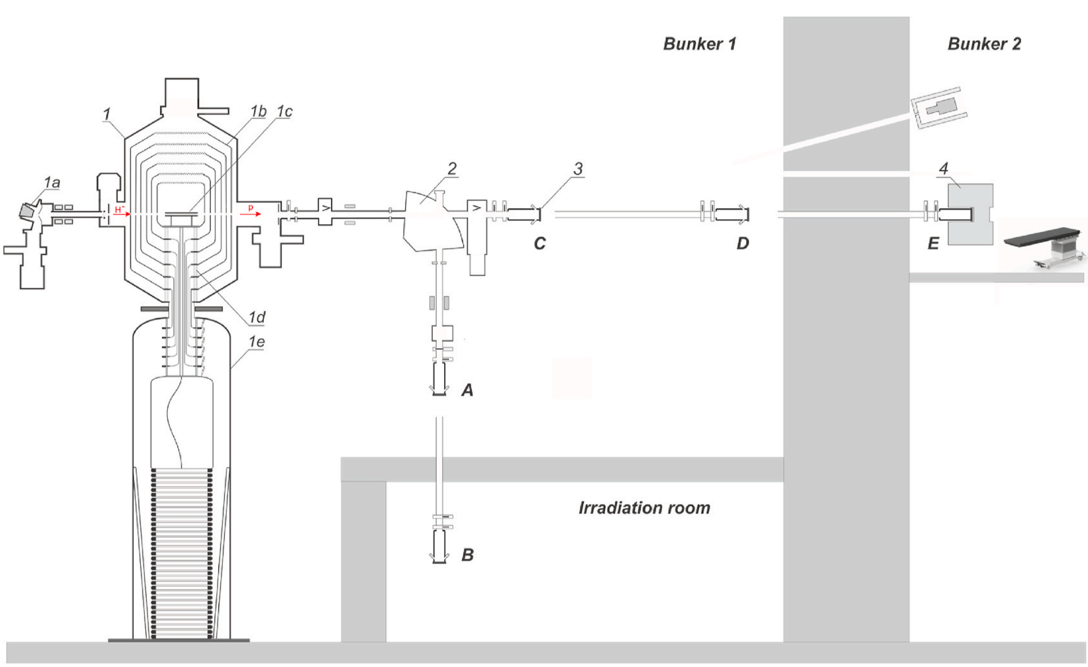

Fig. 1. Layout of the accelerator based neutron source: *1* – vacuum insulated tandem accelerator (*1a* – negative ion source, *1b* – intermediate and high-voltage electrodes, *1c* – gas stripper, *1d* – feedthrough insulator, *1e* – high voltage power supply), *2* – bending magnet, *3* – lithium target (can be placed in positions *A*, *B*, *C*, *D*, *E*), *4* – beam shaping assembly.

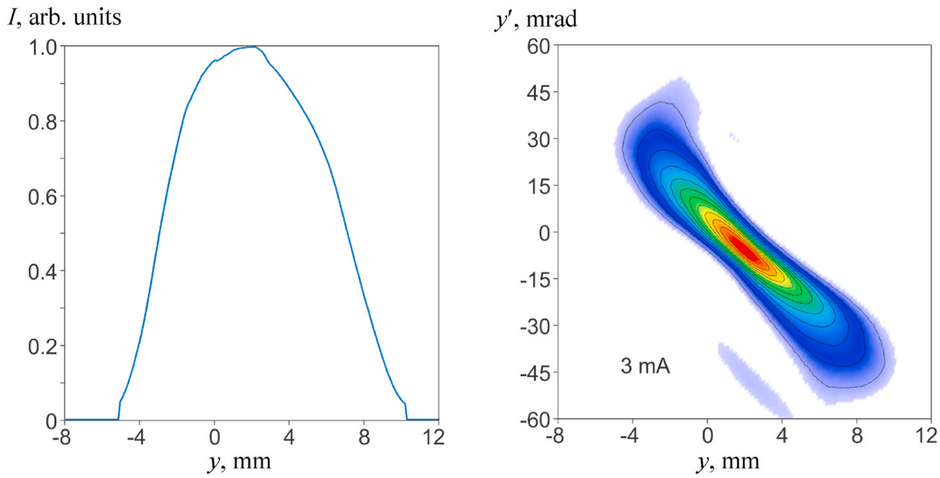

Fig. 2. Profile (left) and phase portrait (right) of a 3 mA beam of negative hydrogen ions.

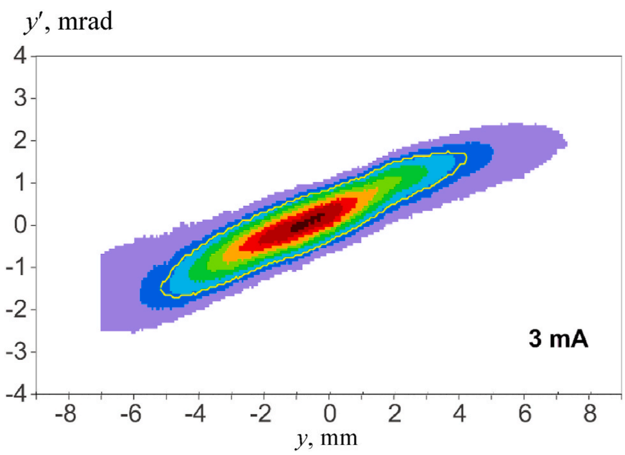

Fig. 3. Phase portrait of 3 mA proton beam (y, y').

3. Vacuum Insulated Tandem Accelerator VITA-II

Two significant changes were made in the next two accelerator based neutron sources, delivered to the BNCT clinic in Xiamen (China) [12] and to the Blokhin National Medical Research Center of Oncology of the Ministry of Health of the Russian Federation in Moscow.

Firstly, the surface plasma source with the Penning geometry of the gas-discharge chamber developed by BINP was replaced by a D-Pace Filament Volume-Cusp Source [13]. 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 outside and used for magnetic confinement of the plasma. The beam of negative hydrogen ions generated by this source, with an energy of 30 keV, is characterized by a normalized emittance of 0.1 mm mrad at a current of 1 mA, 0.13 mm mrad at 10 mA and 0.16 mm mrad at 15 mA (data from the equipment manufacturer). Our measurements confirmed these data.

Secondly, the negative hydrogen ion beam injected into the accelerator is additionally pre-accelerated by 100 keV. Initially, it was proposed to pre-accelerate the injected ion beam to reduce the flux of secondary charged particles and an accelerating tube was made, but the problem was solved in a different way: by improving vacuum pumping, suppressing secondary electron emission from the walls of the vacuum chamber irradiated by the flux of secondary positive ions, and suppressing the penetration of electrons from the transport channel into the accelerator [14]. Then this accelerating tube was used in a neutron source for a Chinese clinic to increase the proton energy; a similar accelerating tube is used in a neutron source for a Moscow clinic. Thus, pre-acceleration is implemented in both of the accelerating neutron sources for oncology clinics.

The scheme of the accelerator based neutron source VITA-IIβ for the Blokhin National Medical Research Center of Oncology of the Ministry of Health of the Russian Federation is shown in Fig. 4. The diameter of the accelerator vacuum tank is 1.56 m while 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 from the center of the accelerator to the lithium neutron-generating target is 6.66 m.

The beam of negative hydrogen ions leaving the source is divergent. An Einzel lens with a negative potential (included in the source kit) is placed near the source output, which focuses the divergent ion beam and makes it close to parallel. Then, this ion beam is accelerated in the accelerating tube and then focused by a magnetic lens (solenoid) onto the accelerator input. The D-Pace ES-4 Emittance Scanner is placed in front of the accelerator input diaphragm, which measures the phase portrait of the injected ion beam in different focusing and pre-acceleration modes. It was found that focusing by an Einzel lens and a magnetic lens does not change the ion beam emittance value, while pre-acceleration increases the normalized emittance by 1.5 times. It has been determined that the size of the ion beam increases with increasing current due to the action of the space charge, mainly in the zone of action of the Einzel lens, where ion deceleration occurs. Typical phase portraits of a beam of negative hydrogen ions are shown in Fig. 5.

The transverse size of the ion beam at this point 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 at a distance of 1.3–3 m, i.e. a weakly converging beam is injected into the accelerator. A strong input electrostatic lens focuses the ion beam even more, causing it to refocus 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, the phase portrait of the proton beam was measured using a movable cooled collimator and the D-Pace OWS-30 Oscillating Wire Scanner; 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 a normalized emittance of 0.15–0.2 mm mrad.

The proton beam profile was measured by shifting the collimator horizontally or vertically (Fig. 7). It is evident that the proton beam profile differs from the Gaussian distribution. The shape of the phase portrait of the negative hydrogen ion beam shown in Fig. 5 indicates the presence of spherical aberrations in the ion-optical path. This leads to

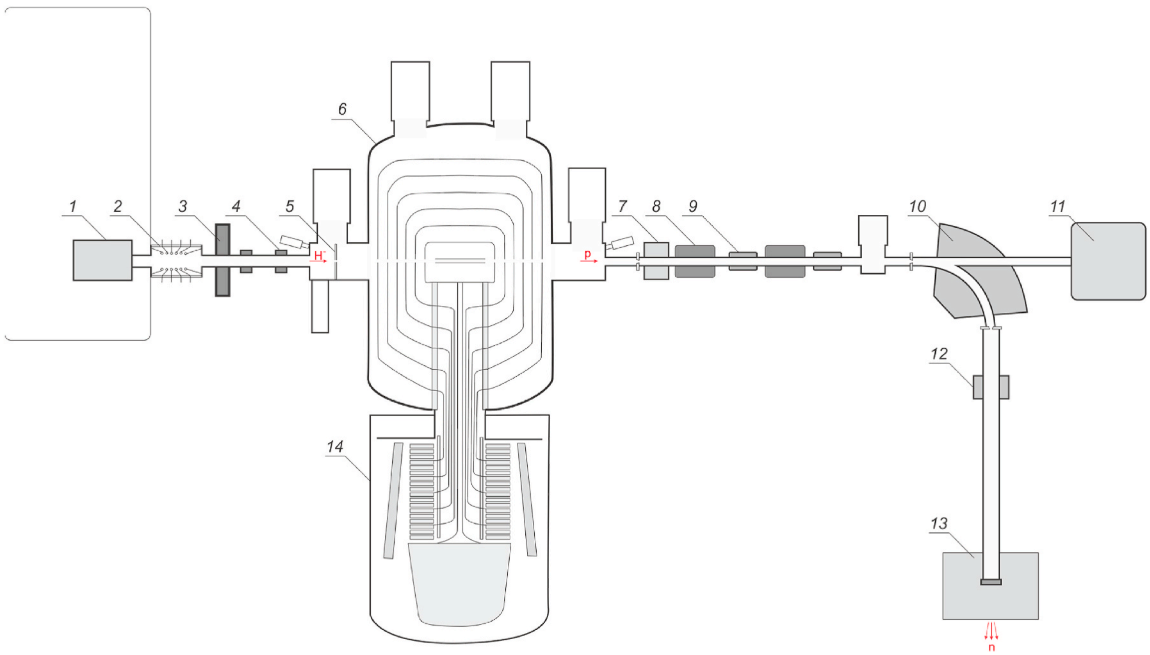

Fig. 4. Layout of the accelerator based neutron source: *1* – negative hydrogen ion source with Einzel electrostatic lens mounted on high-voltage platform, *2* – accelerator tube, *3* – solenoid, *4* – correctors, *5* – accelerator input diaphragm, *6* – vacuum insulated tandem accelerator, *7* – contactless current sensor, *8* – quadrupole lenses, *9* – correctors, *10* – bending magnet (proton beam is rotated in horizontal plane), *11* – beam absorber, *12* – magnetic sweep, *13* – lithium target for neutron generation and neutron beam shaping assembly, *14* – high-voltage power supply. Arrows show propagation of negative hydrogen ions (H^-), protons (p) and neutrons (n).

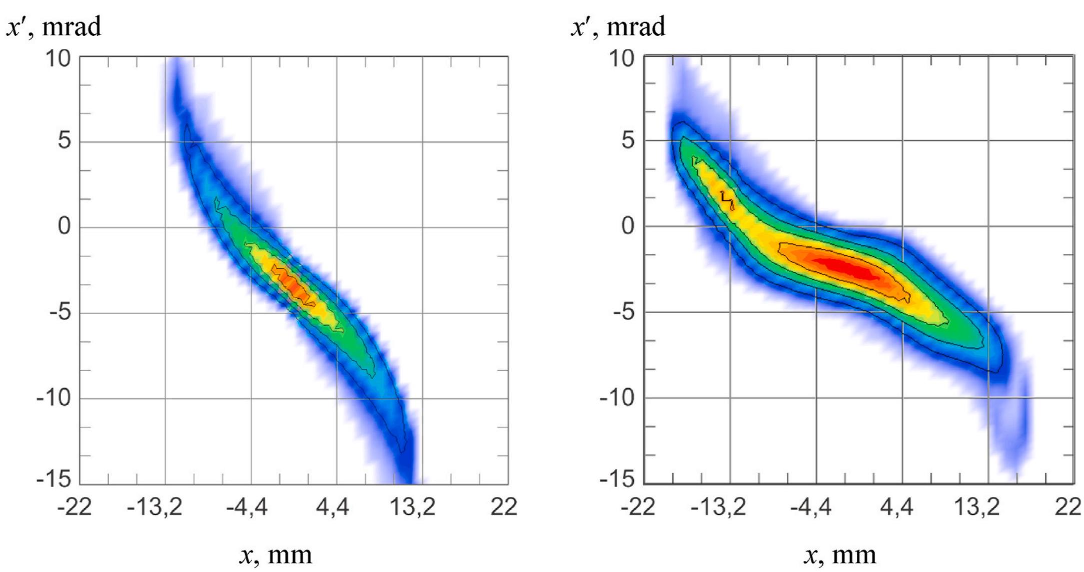

Fig. 5. Phase portrait of a negative hydrogen ion beam injected into the accelerator with a current of 5 mA (left) and 9 mA (right).

the fact that different parts of the ion beam are focused at different distances and form a non-uniform proton beam. To ensure efficient transport of the diverging proton beam to the lithium-based neutron-generating target, focusing elements are required. In this setup, a pair of quadrupole magnetic lenses is employed to collimate and direct the beam toward the target with the necessary focusing.

Thus, the use of pre-acceleration has both positive and negative effects. The positive effect is that the proton energy is increased by 100 keV 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, non-uniform, and its divergence has become greater. Obtaining such a beam complicates the facility since focusing means are required for its transportation. The use of pre-acceleration itself also complicates the facility – a high-voltage platform and an isolating transformer are required.

It is clear that it is possible to improve the accelerating tube, reduce spherical aberrations, and use "soft" beam injection into the accelerator [15], but it is hardly worthwhile to use pre-acceleration in the future, which negates the main advantage of tandem accelerators – the placement of the injector and target under the ground potential. The next-generation design of the vacuum insulated tandem accelerator proposes eliminating the need for a pre-acceleration stage, aiming to

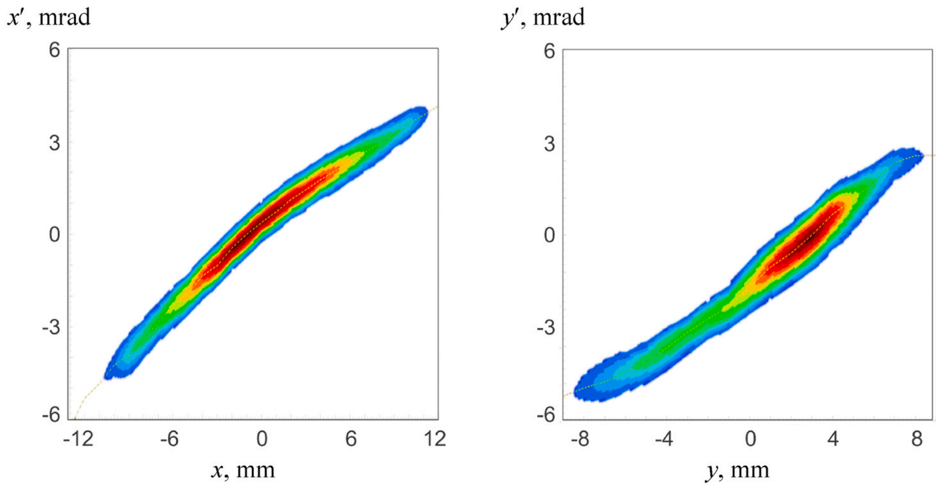

Fig. 6. Phase portrait of a 3 mA proton beam horizontally (left) and vertically (right).

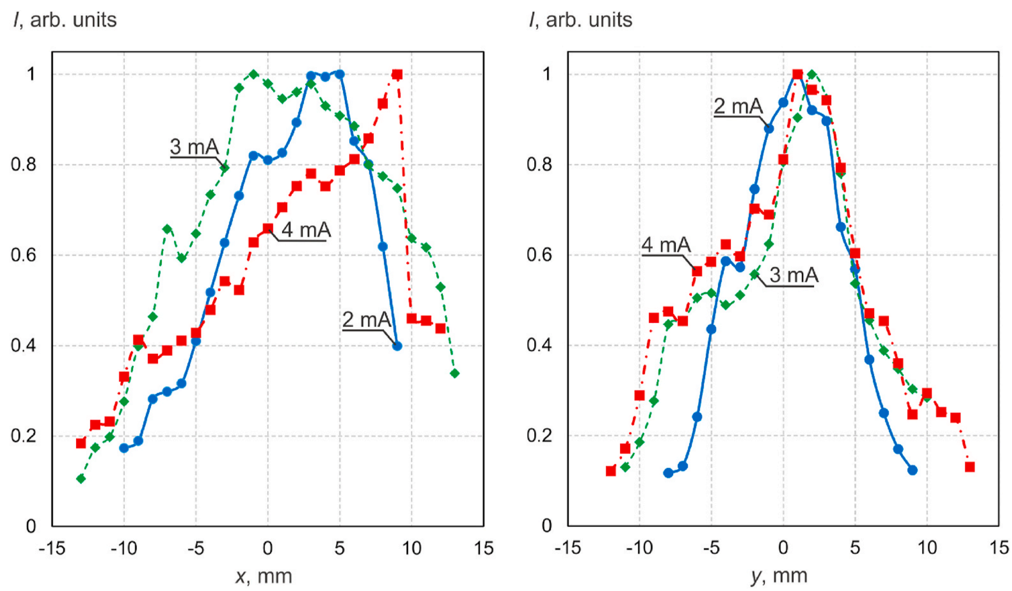

Fig. 7. Horizontal (left) and vertical (right) profile of proton beam at currents of 2, 3 and 4 mA.

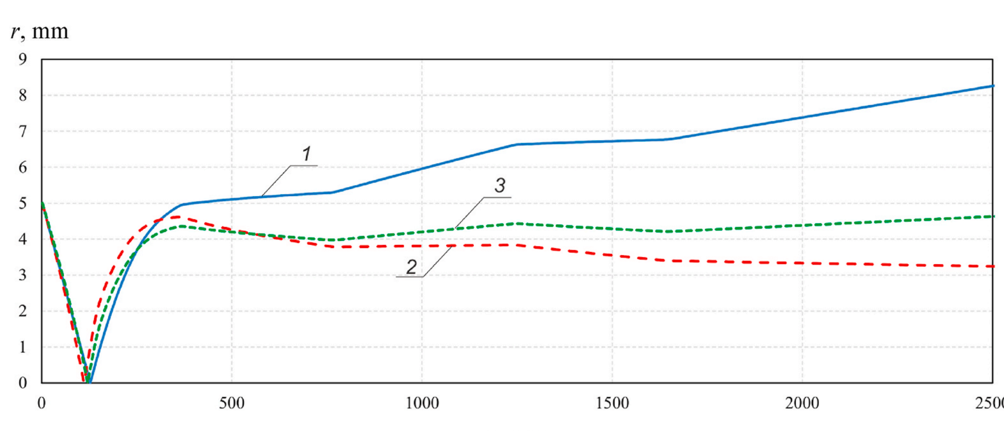

Fig. 8. Envelopes of ion beam: *1* – at diaphragm potential 0 V, *2* – at diaphragm potential −20 kV, *3* – at diaphragm potential −20 kV and focusing the ion beam into the input diaphragm of the accelerator.

simplify the system while maintaining or improving beam quality and performance.

4. VITA-III

A fundamental proposal for improving the accelerator is to slow down the ion beam injected into the accelerator. This can be achieved by insulating the input diaphragm of the accelerator (*5* in Fig. 4) and applying a positive potential to it. Since the supplied voltage is tens of kilovolts, it seems that there will be no great difficulties in implementing such a proposal.

Fig. 8 shows the envelopes of an ion beam during its transportation and acceleration, obtained using numerical simulation without taking into account the effect of space charge. The finite element simulation was performed in COMSOL Multiphysics 5.2a in two stages. First, the three-dimensional Poisson equation was numerically solved for the given setup geometry in the Electrostatics module. The boundary conditions are specified as electrode potentials. The grid element size in the beam motion region and axial diaphragms was set manually and was 0.05 mm. Then, the dynamic equation for the beam in the pre-calculated fields was solved in the Charged particle tracing module. In the Particle beam submodule, a focused H^- beam with a Gaussian distribution on the phase plane was specified at the accelerator input. The built-in post-processing tools were used to calculate the envelope containing 95.4 % of the beam. The initial beam energy was 30 keV, the transverse size was 5 mm. The initial normalized emittance $\varepsilon = 0.14$ mm mrad. The number of particles is 25,000, the time step is 1 ns, the total simulation time is 0.5 μs.

In the coordinate $z = 0$, an ion beam with a radius of 5 mm and an angle that ensures its focusing into the input diaphragm of the accelerator ($z = 127$ mm) is specified. The diaphragm potential is 0. Curve 1 in Fig. 8 shows the simulated envelope of the ion beam at accelerator potential 1 MV. It can be seen that the diverging ion beam is focused by a strong input electrostatic lens of the accelerator to the uncooled diaphragm of the first intermediate electrode ($z = 367$ mm). The beam is then accelerated to the high-voltage electrode, at the entrance to which it is defocused due to the electric field penetrating into the high-voltage electrode ($z = 767$ mm). Negative hydrogen ions are converted into protons in the gas stripper placed inside the high-voltage electrode. The proton beam outgoing from the high-voltage electrode is focused by an electrostatic lens in the area of the high-voltage electrode diaphragm ($z = 1247$ mm), then accelerated and defocused at the exit by the accelerator's output electrostatic lens ($z = 1647$ mm).

Curve 2 in Fig. 8 shows the simulated ion beam envelope when −20 kV is applied to the accelerator input diaphragm. It is evident that not only has the ion beam size decreased in the region of the uncooled diaphragm of the first accelerating electrode, but the proton beam has also become smaller in size and even slightly converging.

It can be noted that, when applying the negative potential, the focal point shifts toward the source. If we weaken the focusing to such an extent that we focus again into the center of the accelerator's cooled input diaphragm, the ion beam envelope will change slightly (curve 3 in Fig. 8): the beam size in the region of the uncooled diaphragm will decrease, and the proton beam will become parallel. Such a proton beam can be transported without the use of focusing elements which makes the facility simpler and more reliable.

The obtained result can be qualitatively explained as follows: the effect of the isolated diaphragm under potential is analogous to that of an Einzel lens, which focuses the ion beam. The deceleration and focusing of the ion beam into the diaphragm hole by the negative potential reduce its transverse momentum, thereby aiding the subsequent focusing by the input electrostatic lens of the accelerator.

The obtained result is important for BNCT and other applications. When generating neutrons for BNCT, the proton beam is scanned over the surface of the lithium target in order to reduce the thermal load to an acceptable level. Obtaining a smaller proton beam allows for more uniform heating of the target surface, which eliminates the possibility of unwanted local overheating leading to damage to the target. Producing a smaller proton beam using a rotating target allows for high-density neutron production for a planned repeat of the famous Stern-Gerlach experiment and the creation of a neutron-electron collider [16].

5. Conclusion

The electrostatic tandem accelerator of the original design called Vacuum Insulated Tandem Accelerator (VITA) is widely used for the development of boron neutron capture therapy, for radiation testing of promising materials, for measuring the cross-section of nuclear reactions, and for other applications. Unlike the accelerator at the Budker Institute of Nuclear Physics, the accelerators delivered to oncology clinics use pre-acceleration. Measuring the phase portrait of the ion beam of these facilities and comparing them establishes the advantages and disadvantages of using pre-acceleration. The positive effect of using pre-acceleration is that the energy of the protons increases and does not cause heating of the uncooled diaphragms of the accelerator. The negative effect is that the quality of the resulting proton beam has deteriorated: it has become larger in size, non-uniform and its divergence has become greater. To improve the vacuum insulated tandem accelerator, it is proposed to decelerate the beam injected into the accelerator. The results of numerical simulations show that it allows to reduce the heating of the uncooled diaphragms of the accelerator and obtain a parallel proton beam at the output that is easy to transport.

CRediT authorship contribution statement

Timofey Bykov: Visualization, Data curation. **Yaroslav Kolesnikov:** Methodology, Investigation. **Alexey Koshkarev:** Software. **Georgii Ostreinov:** Software, Formal analysis. **Sergey Savinov:** Writing – original draft, Validation. **Ivan Shchudlo:** Writing – original draft, Investigation. **Sergey Taskaev:** Writing – review & editing, Supervision, Conceptualization.

Data availability

The theoretical and experimental data presented in this work are available from the corresponding authors on reasonable request.

Funding

This work was supported by the Russian Science Foundation [grant number 19-72-30005].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] W. Sauerwein, A. Wittig, R. Moss, Y. Nakagawa (Eds.), Neutron Capture Therapy. Principles and Applications, Springer, 2012, https://doi.org/10.1007/978-3-642-31334-9.

[2] M. Dymova, S. Taskaev, V. Richter, E. Kuligina E, Boron neutron capture therapy: current status and future perspectives, Cancer Commun. 40 (2020) 406–442, https://doi.org/10.1002/cac2.12089.

[3] Advances in Boron Neutron Capture Therapy, International Atomic Energy Agency, Vienna, Austria, 2023. ISBN: 978-92-0-132723-9.

[4] S. Taskaev, E. Berendeev, M. Bikchurina, T. Bykov, D. Kasatov, I. Kolesnikov, A. Koshkarev, A. Makarov, G. Ostreinov, V. Porosev, S. Savinov, I. Shchudlo, E. Sokolova, I. Sorokin, T. Sycheva, G. Verkhovod, Neutron source based on vacuum insulated tandem accelerator and lithium target, Biology 10 (2021) 350, https://doi.org/10.3390/biology10050350.

[5] S. Taskaev, Accelerator Based Neutron Source VITA, FizMatLit, Moscow, 2024. ISBN 978-5-9221-1979-5.

[6] D-Pace ES-4 Emittance Scanner, https://www.d-pace.com/?e=2.
[7] M. Bikchurina, T. Bykov, Ia Kolesnikov, A. Makarov, G. Ostreinov, S. Savinov, S. Taskaev, I. Shchudlo, Measuring the phase portrait of an ion beam in a tandem accelerator with vacuum insulation, Instrum. Exp. Tech. 65 (4) (2022) 551–561, https://doi.org/10.1134/S0020441222040169.
[8] T. Bykov, D. Kasatov, Ia Kolesnikov, A. Koshkarev, A. Makarov, Yu Ostreinov, E. Sokolova, I. Sorokin, S. Taskaev, I. Shchudlo, Use of a Wire scanner for measuring a negative hydrogen ion beam injected in a tandem accelerator with vacuum insulation, Instrum. Exp. Tech. 61 (5) (2018) 713–718, https://doi.org/10.1134/S0020441218050159.
[9] G. Derevyankin, G. Kraynov, A. Kryuchkov, G. Silvestrov, S. Taskaev, M. Tiunov, The Ion-Optical Channel of 2.5 MeV 10 mA Tandem Accelerator, 2002. Preprint Budker INP 2002-24, Novosibirsk.
[10] Ya Kolesnikov, G. Ostreinov, P. Ponomarev, S. Savinov, S. Taskaev, I. Shchudlo, Measuring the current of a beam of argon ions accompanying a beam of protons in a tandem accelerator with vacuum insulation, Instrum. Exp. Tech. 64 (4) (2021) 503–507, https://doi.org/10.1134/S0020441221040199.
[11] Ya Kolesnikov, Study and optimization of ion beam transportation and acceleration in a vacuum insulated tandem accelerator. Dissertation for the Degree of Candidate of Physical and Mathematical Sciences, Novosibirsk, 2022, p. 149.
[12] Going down in History: China Reaches a New Milestone to Develop an Advanced In-Hospital BNCT Solution for Clinical Use. https://isnct.net/blog/2023/03/08/newsletter-19/.
[13] 10 kW Filament Volume-Cusp, https://www.d-pace.com/?e=304.
[14] A. Ivanov, D. Kasatov, A. Koshkarev, A. Makarov, Yu Ostreinov, I. Shchudlo, I. Sorokin, S. Taskaev, Suppression of an unwanted flow of charged particles in a tandem accelerator with vacuum insulation, J. Inst. Met. 11 (2016) P04018, https://doi.org/10.1088/1748-0221/11/04/P04018.
[15] G. Ostreinov, S. Savinov, I. Shchudlo, S. Taskaev, Modernization of the ion-optical system of the VITA accelerator, Instrum. Exp. Tech. 67 (Suppl.1) (2024) S33–S38, https://doi.org/10.1134/S0020441224701306.
[16] A. Bogomyagkov, V. Druzhinin, E. Levichev, A. Milstein, I. Okunev, S. Taskaev, Quantum and classical dynamics of neutron in a magnetic field, Nuclear Physics, Section B 1012 (2025) 116833, https://doi.org/10.1016/j.nuclphysb.2025.116833.