Vacuum Insulated Tandem Accelerator upgrade

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***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 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 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.**

Keywords—charged particle accelerator, phase portrait, boron neutron capture therapy

I. 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 neutron absorption by boron nuclei, a nuclear reaction occurs with a large release of energy in the tumor cell, which leads to its death.

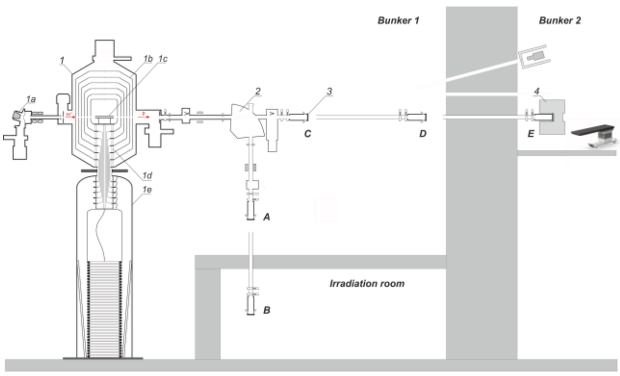

Fig. 1. Layout of the accelerator based neutron source VITA: *1* – vacuum insulated tandem accelerator (*1a* – negative ion source, *1b* – intermediate and high-voltage electrodes, *1c* – gas stripper, *1d* – feedthrough insulator, *1e* – high voltage power supply), *2* – bending magnet, *3* – lithium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

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

II. VACUUM INSULATED TANDEM ACCELERATOR (VITA)

The vacuum insulated tandem accelerator consists of a cylindrical vacuum tank and high-voltage and five intermediate cylindrical electrodes located coaxially with the body of the vacuum tank. Diaphragms 20-30 mm in diameter in electrods are located along the diameter coaxially with the input and output flange 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.

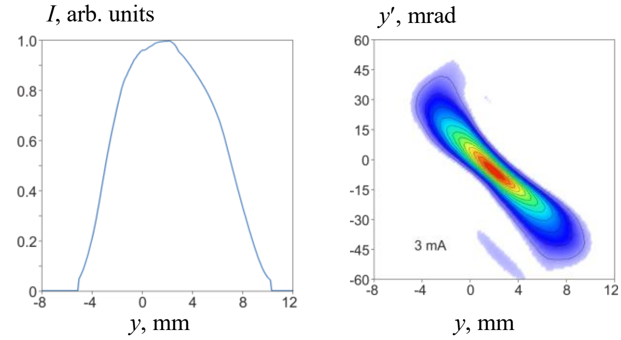

Fig. 2. Profile (left) and phase portrait (right) of a 3 mA beam of negative hydrogen ions.

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 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, 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 $\varepsilon_{norm} = \varepsilon_{rms}\beta\gamma$, where $\varepsilon_{rms} = (\det(\sigma_{xx'}))^{1/2}$, $\sigma_{xx'} = \begin{bmatrix} \langle x^2\rangle & \langle xx'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle \end{bmatrix}$; $\langle x^2\rangle = \frac{1}{N}\sum_1^N x_i^2$; $\langle x'^2\rangle = \frac{1}{N}\sum_1^N x'^2$; $\langle xx'\rangle = \frac{1}{N}\sum_1^N x_i\, x'_i$, $\beta = \sqrt{\frac{2E}{mc^2}}$, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$, 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 $n = 4$ $k = 86$ %. 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 converted into positive ions, which are then accelerated by the 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, the phase portrait of the proton beam was measured using a movable cooled diaphragm and a D-Pace OWS-30 Oscillating Wire Scanner. The proton beam has a transverse size 10 ± 1 mm, angular divergence from ± 0.5 mrad to ± 1.2 mrad, and normalized emittance 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 an undoubted advantage.

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 [9] 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 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.

Rationale for implementing the "hard" input of an ion beam into the accelerator is given in [8], the results of the study of the influence of the space charge on the transport of ion beam are given in [7], the results of measuring the phase portrait of ion beams are given in [9], the results of measuring the ion beam profile are given in [7-10], and all the results of the study are summarized in [11].

III. 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 in Moscow.

Firstly, the surface plasma source with the Penning geometry of the gas-discharge chamber developed by BINP was replaced by 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 with an energy of 30 keV generated by this source is characterized by a normalized emittance of 0.1 mm mrad at a current of 1 mA and 0.16 mm mrad at 15 mA.

Secondly, the negative hydrogen ion beam injected into the accelerator is additionally pre-accelerated by 100 keV.

The scheme of the accelerator based neutron source VITA-IIβ for the Blokhin National Medical Research Center of Oncology is shown in Fig. 3. The distance from the outlet of the negative hydrogen ion source to the center of the accelerator is 3.23 m, from the center of the accelerator to the lithium neutron-generating target is 6.66 m.

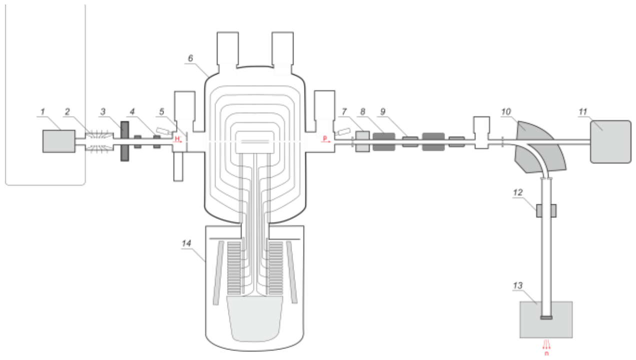

Fig. 3. Layout of the accelerator based neutron source VITA-IIβ: *1* – negative hydrogen ion source with Einzel electrostatic lens mounted on high-voltage platform, *2* – accelerator tube, *3* – solenoid, *4* – correctors, *5* – accelerator input diaphragm, *6* – vacuum insulated tandem accelerator, *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).

The beam of negative hydrogen ions leaving the source is divergent. An Einzel lens with a negative potential 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. 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. Typical phase portrait of a beam of negative hydrogen ions is shown in Fig. 4a.

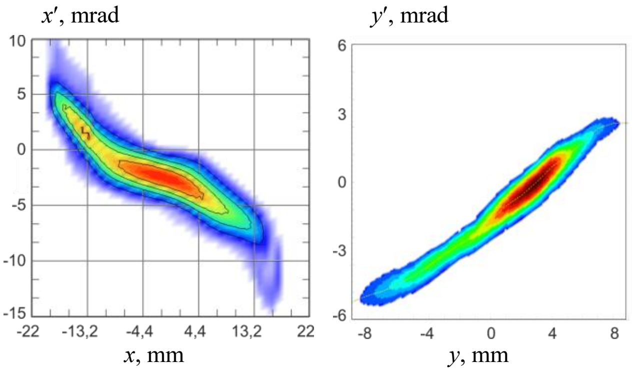

Fig. 4. Phase portrait of a negative hydrogen ion beam injected into the accelerator (left) and proton beam (right).

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 diaphragm and the D-Pace OWS-30 Oscillating Wire Scanner; a typical example is shown in Fig. 4b. 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 diaphragm horizontally or vertically (Fig. 5). 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 indicates the presence of spherical aberrations. This leads to the fact that different parts of the ion beam are focused at different distances and form a non-uniform proton beam. Transporting such a diverging proton beam to the lithium neutron-generating target requires the use of focusing means in this case a pair of quadrupole magnetic lenses.

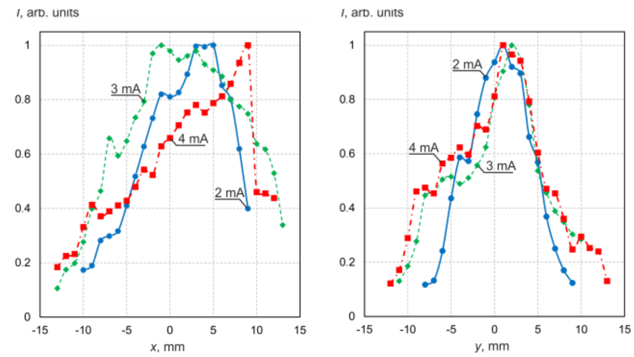

Fig. 5. Horizontal (left) and vertical (right) profile of proton beam at currents of 2, 3 and 4 mA.

Thus, the use of pre-acceleration 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. 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, use “soft” beam injection into the accelerator [14], 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 version of the vacuum insulated tandem accelerator is proposed to do away with pre-acceleration.

IV. 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. 3) and applying a positive potential to it.

Fig. 6 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.

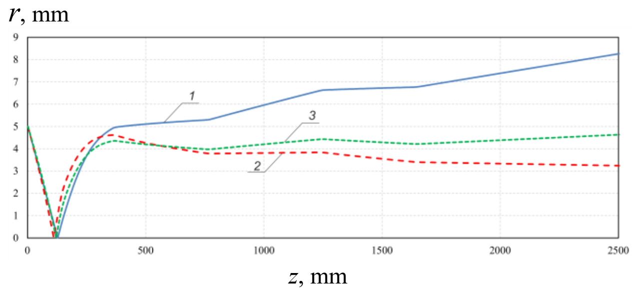

Fig. 6. Envelopes of ion beam: *1* – at diaphragm potential 0 V, *2* – at diaphragm potential –20 kV, *3* – at diaphragm potential –20 kV and focusing ion beam into the input diaphragm of the accelerator.

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. 6 shows the simulated envelope of the ion beam. Let us give an explanation. 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. 6 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 (Fig. 6), the ion beam envelope will change slightly: 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.

Of course, the space charge will change the real trajectories of the particles, but there is complete confidence that by changing the focusing strength of solenoid and the potential of the input diaphragm of the accelerator, it is possible to reduce the heating of the uncooled diaphragms of the accelerator and obtain a parallel proton beam, easily transported to the target.

V. 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 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.

Acknowledgment

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