

Experiments to Increase the Parameters of the Vacuum Insulation Tandem Accelerator for Boron Neutron Capture Therapy

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Abstract—An epithermal neutron source that is based on a vacuum insulation tandem accelerator (VITA) and lithium target was created in the Budker Institute of Nuclear Physics for the development of boron neutron capture therapy (BNCT). A stationary proton beam with 2 MeV energy and 1.6 mA current has been obtained. To carry out BNCT, it is necessary to increase the beam parameters up to 2.3 MeV and 3 mA. Ways to increase the parameters of the proton beam have been proposed and discussed in this paper. The results of the experiments are presented.

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INTRODUCTION

An experimental model of an epithermal neutron source that is based on a vacuum insulation tandem accelerator (VITA) for boron neutron capture therapy (BNCT) [1] was suggested [2] and made in the Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences (see Fig. 1).

A beam of negative hydrogen ions that flows from an ion source 1 and has 23 keV energy and 5 mA current is rotated through an angle of 15° in a magnetic field, then focused by a pair of magnetic lenses 2, injected into an accelerator, and accelerated there up to 1 MV. In a gas (argon) stripping target 7 that is inside a high voltage electrode 5, negative hydrogen ions are transformed into protons, which then are accelerated by the same potential of 1 MV up to 2 MeV energy. The potential is applied to the high voltage electrode 5 and five intermediate electrodes of the accelerator 6 by a high voltage power supply 10 through a bushing insulator 9, where a resistive divider is established. Gas is pumped by turbomolecular pumps 8 that are set near the ion sources and at the accelerator output and by a cryogenic pump 4 through the electrode shutters. A stationary proton beam that has 2 MeV energy and 1.6 mA current with high energy monochromatism of 0.1% and current stability of 0.5% was obtained using the accelerator [3]. At the beam dump in a lithium target, neutrons were generated [4] and the effect of the neutron radiation on cell cultures was studied [5]. To carry out the therapy, it is necessary to increase the voltage up to 1.15 MV and the current of the proton beam at least up to 3 mA.

1. EXPERIMENTAL RESULTS

For a necessary increase in the energy of the proton beam, the voltage at the accelerator was increased up

to 1.15 MV (Fig. 2), which was accompanied by breakdowns. Upon a decrease in the residual pressure (P), dark current (I_{dark}), and X-ray dose rate (D), it can be seen that a training process develops which requires time for starting operations without breakdowns.

An increase in the voltage up to 1.15 MV leads to an increase in the electric intensity at the high voltage elements of the bushing insulator by 15%, which promotes breakdowns on the surface of individual insulators and a loss of the high voltage strength of the accelerator. A way to solve this problem is to change the geometry of the surface of the insulators.

An investigation of insulators (Fig. 3) with a different geometry of the outside surface [6] has demon-

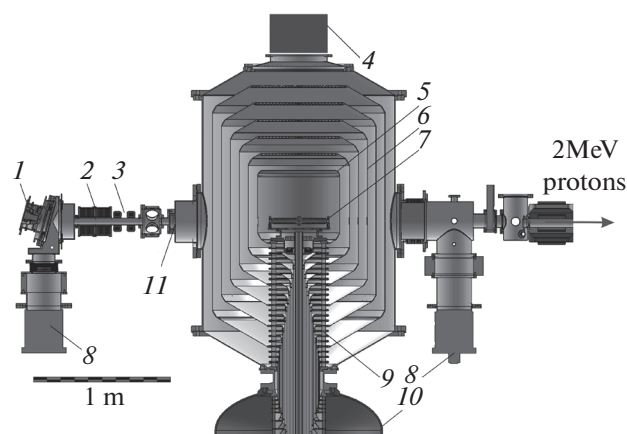


Fig. 1. Vacuum insulation tandem accelerator: 1 source of negative hydrogen ions, 2 magnetic lenses, 3 corrector, 4 cryogenic pump, 5 high voltage electrode, 6 intermediate electrodes, 7 gas stripping target, 8 turbomolecular pump, 9 bushing insulator, 10 high-voltage power supply, and 11 location of a diaphragm or detector.

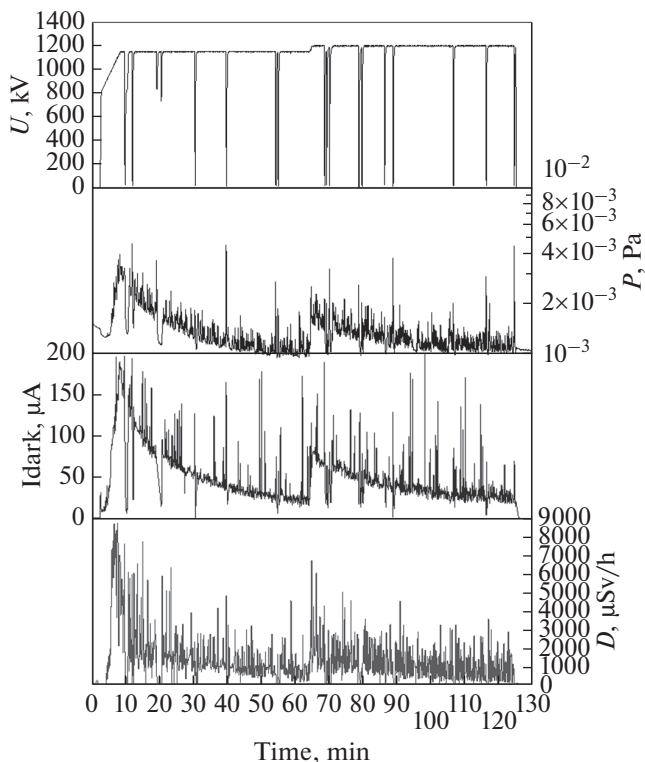


Fig. 2. Increase in the voltage in a tandem accelerator.

stated that the ribbed surface with the radii of the ribs and dips from 0.5 to 1 mm increases the electric strength up to 100% when compared to the smooth surface (3 in Fig. 3). The technology for processing inorganic insulators that has been developed makes it possible to implement the ribbed geometry of the surface.

To find the reasons for the breakdowns, experiments have been performed by obtaining the maximal current of the proton beam in the accelerator at different voltages with a gradual increase in the injected current of negative hydrogen ions up to the occurrence of the breakdowns (Fig. 4). It can be seen that, at a voltage of 1 MV, the maximal proton current is 1.5 mA and, at 625 kV, it is 1.67 mA. Since the maximal proton current almost does not depend on the energy, it is unlikely that the reason for the breakdowns is connected with the high voltage strength of the vacuum accelerating gaps.

In the next experiment, at the constant injection current of negative hydrogen ions, the dependence of the current of the proton beam and the current of accompanying charged particles [7] on the voltage that is applied to the high voltage electrode have been measured (Fig. 5).

It can be seen that, upon an increase in the voltage from 400 kV to 1 MV, the current of the proton beam increases from 500 to 850 μA , whereas the current of the accompanying particles decreases from 750 to 500 μA . At a voltage of 600 kV, the vacuum conditions were worsened by cutting off the pumping by the cryogenic pump (the volume continued being pumped by

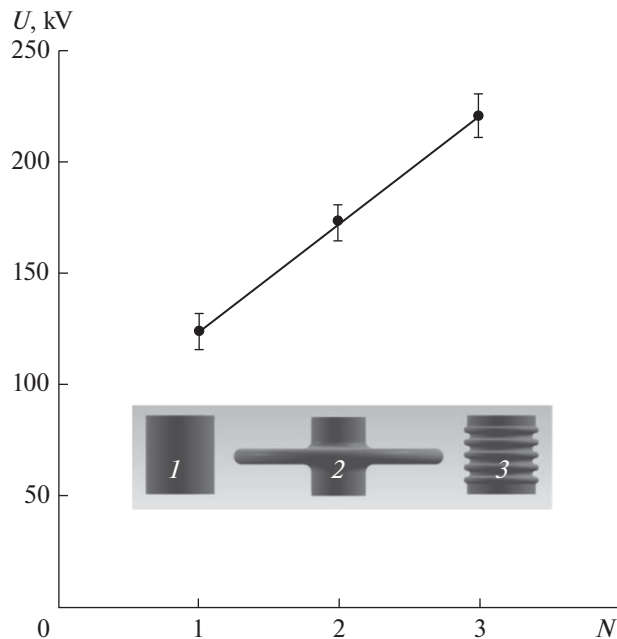


Fig. 3. Dependence of the breakdown voltage on the surface of an insulator: 1 smooth, 2 with one rib, and 3 ribbed.

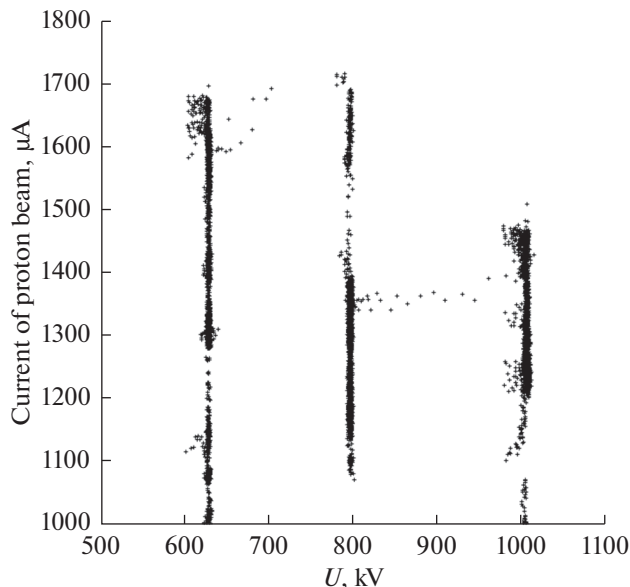


Fig. 4. Dependence of the proton beam on the voltage upon changing the injection current of negative hydrogen ions.

the turbomolecular pump), and the current of the proton beam decreased by one-third, while the current of the accompanying particles increased by a factor of 2. All these results indicate insufficiently good vacuum conditions, especially in the beginning of the acceleration of the injected ion beam. To improve the vacuum conditions and suppress the flow of accompanying charged particles, the input node of the accelerator has been upgraded: a cooled diaphragm that functions as

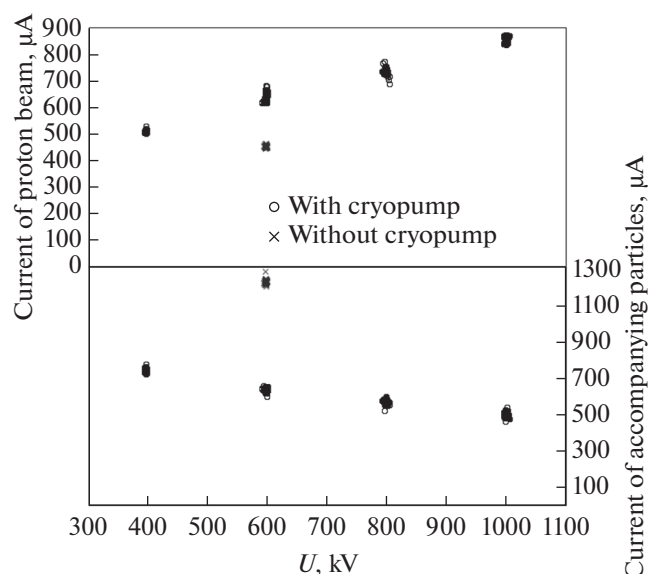


Fig. 5. Voltage dependence of the current of the proton beam and that of accompanying particles in a tandem accelerator.

vacuum resistance has been established and an additional cryogenic pump and a grid to suppress the secondary emission from the walls of the vacuum chamber have been established.

To improve the quality of the therapeutic neutron beam, the neutron-generating target and systems that form the neutron beam have been upgraded. When compared to the target that was developed earlier [8], the new target is made as thin as possible to make it possible to form a neutron beam with higher quality and the target substrate, on which a thin layer of lithium is deposited, is made of tantalum, which has the maximal resistance to blistering and provides the minimal power of gamma irradiation upon proton absorption in it [9]. The system for the formation of a neutron beam has a composite moderator applied for the first time, magnesium fluoride near the target and aluminum fluoride at the output, and a composite reflector is applied for the first time as well, graphite in the front hemisphere and lead in the back hemisphere, which has made it possible to increase both the absorbed dose rate in a tumor and the therapeutic ratio.

CONCLUSIONS

The epithermal neutron source that is based on the VITA and lithium neutron-generating target was made for the development of BNCT in the Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences. As a result of the experiments that have been carried out, a voltage of 1.15 MV has been achieved and the ways to increase the high voltage strength of the accelerator have been found. The reasons for the limitation of the current of the proton beam have been determined and the upgrade of the input node of

the accelerator to increase the current of the proton beam from 1.6 to 3 mA has been suggested. A neutron-generating target with the deposition of the lithium layer on the cooled thin tantalum substrate and a system for the formation of the neutron beam have been developed. The implementation of the accelerator upgrade with the purpose of increasing the current of the proton beam and the use of the new neutron-generating target with the system for beam formation would make it possible to form a beam of epithermal neutrons that meets the BNCT requirements the most.

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REFERENCES

1. *Neutron and Capture Therapy: Principles and Applications*, Ed. by W. Sauerwein, A. Wittig, R. Moss, and Y. Nakagawa (Springer, 2012).
2. B. Bayanov, V. Belov, E. Bender, M. Bokhovko, G. Dimov, V. Kononov, O. Kononov, N. Kuksanov, V. Palchikov, V. Pivovarov, R. Salimov, G. Silvestrov, A. Skrinsky, and S. Taskaev, "Accelerator based neutron source for the neutron-capture and fast neutron therapy at hospital," *Nucl. Instrum. Methods Phys. Res. A* **413**, 397–426 (1998).
3. D. Kasatov, A. Kuznetsov, A. Makarov, I. Shchudlo, I. Sorokin, and S. Taskaev, "Proton beam of 2 MeV 1.6 mA on a tandem accelerator with vacuum insulation," *J. Instrum.* **9**, 12016 (2014).
4. A. S. Kuznetsov, G. N. Malyshkin, A. N. Makarov, I. N. Sorokin, Yu. S. Sulyaev, and S. Yu. Taskaev, "First experiments on neutron detection on the accelerator-based source for boron neutron capture therapy," *Tech. Phys. Lett.* **35**, 346 (2009).
5. L. A. Mostovich, N. V. Gubanova, O. S. Kutsenko, V. I. Aleinik, A. S. Kuznetsov, A. N. Makarov, I. N. Sorokin, S. Yu. Taskaev, G. I. Nepomnyashchikh, and E. V. Grigor'eva, "Effect of epithermal neutrons on viability of glioblastoma tumor cells in vitro," *Bull. Exp. Biol. Med.* **151**, 264–267 (2011).
6. A. M. Kryuchkov, I. N. Sorokin, and V. V. Shirokov, "Research and development of accelerating tubes for charge particle high voltage accelerators," Preprint BINP 94-54 (Budker Inst. Nucl. Phys., Novosibirsk, 1994).
7. D. A. Kasatov, A. N. Makarov, S. Yu. Taskaev, and I. M. Shchudlo, "Recording of current accompanying an ion beam in a tandem accelerator with vacuum insulation," *Tech. Phys. Lett.* **41**, 139 (2015).
8. B. Bayanov, V. Belov, and S. Taskaev, "Neutron producing target for accelerator based neutron capture therapy," *J. Phys.* **41**, 460–465 (2006).
9. D. A. Kasatov, A. N. Makarov, S. Yu. Taskaev, and I. M. Shchudlo, "Radiation accompanying the absorption of 2-MeV protons in various materials," *Phys. At. Nucl.* **78**, 905 (2015).

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