VACUUM INSULATION TANDEM ACCELERATOR: PROGRESS AND PROSPECTS*

S. Taskaev#, T. Bykov, A. Ivanov, D. Kasatov, Ya. Kolesnikov, A. Koshkarev, A. Makarov, Yu. Ostreinov, I. Shchudlo, E. Sokolova, I. Sorokin, T. Sycheva,
BINP and Novosibirsk State University, Novosibirsk, Russia

Abstract

A promising method of treatment of many malignant tumors is the boron neutron capture therapy (BNCT). It provides a selective destruction of tumor cells by prior accumulation of a stable boron-10 isotope inside them and subsequent irradiation with epithermal neutrons. It is expected that accelerator based neutron sources will be created for the clinical practice. One such source could be an original source of epithermal neutrons, created in BINP. To obtain proton beam a new type of particle accelerator is used – tandem accelerator with vacuum insulation. Generation of neutrons is carried out as a result of the threshold reaction ^{7}Li(p,n)^{7}Be. Several changes were made in the construction of tandem accelerator with vacuum insulation during 2015-2016. This allowed us to suppress the unwanted flow of charged particles in the accelerator, to improve its high-voltage stability, and to increase the proton beam current from 1.6 to 5 mA. Such current value is sufficient for BNCT. The report describes in detail the modernization of the accelerator, presents and discusses the results of experiments on obtaining the proton beam and the formation of neutron flux using lithium target, and declares our prospective plans. The obtained neutron beam meets the requirements of BNCT: the irradiation of cell cultures provides the destruction of cells with boron and preservation of cells without boron. Irradiation of immunodeficient mice with grafted glioblastoma results in their recovery.

INTRODUCTION

Boron neutron capture therapy is currently considered as a promising technique for treatment of malignant tumors [1, 2]. For the widespread introduction of this technique in practice compact epithermal neutron sources based on charged particle accelerators are required. A new type of the accelerator – a tandem accelerator with vacuum insulation – was proposed [3] and constructed in BINP [4]. The accelerator is characterized by fast ion acceleration and a large distance between the ion beam and the insulator (on which electrodes are mounted). After the dark current was suppressed to an acceptable level [5], the injection of a negative hydrogen ion beam into the accelerator [6] and stripping in the gas target were optimized [7], the proton beam current was increased from the initial values of about 140 μA [8] to 1.6 mA [9], which was stable for more than one hour. In the elucidation of the reasons for the limitation of the current in the tube for accelerating negative hydrogen ions, a significant electron flow and a counter-flow of positive ions generated in the acceleration tube and in the stripping target were found and measured [10].

*Work supported by grant from the Russian Science Foundation (Project no. 14-32-00006), the Budker Institute of Nuclear Physics and the Novosibirsk State University
taskaev@inp.nsk.su

DESIGN OF THE ACCELERATOR

Figure 1 shows the accelerator. Coming from source *1* the low-energy negative hydrogen ion beam is defected in a magnetic dipole field by an angle of 15 degrees, focused by a pair of magnetic lenses *2*, injected into accelerator *3* and accelerated up to 1 MeV. In a gas (argon) stripper *7* which is installed inside a high-voltage electrode *6* negative hydrogen ions are converted into protons. Then protons are accelerated by the same 1 MV potential to an energy of 2 MeV. The potential for the high-voltage electrode *6* and five intermediate electrodes *5* of the accelerator is supplied by the sectioned rectifier *9* (most the source is not shown) through insulator *8*, wherein the resistive divider is set. Gas evacuation is performed by turbomolecular pumps *10* mounted on the ion source and at the accelerator exit and a cryogenic pump *4* via jalousies in the electrodes.

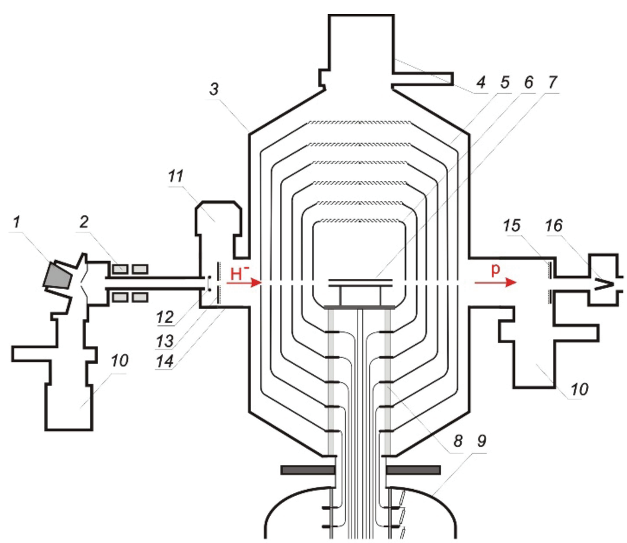

Figure 1: Modernized tandem accelerator with vacuum insulation: *1* – negative hydrogen ion source, *2* – magnetic lenses, *3* – accelerator, *4* – cryogenic pump, *5* –intermediate electrodes, *6* – high-voltage electrode, *7* – gas stripper, *8* – insulator, *9* – high-voltage sectioned rectifier, 10 – turbomolecular pumps, *11* – cryogenic pump, *12* – ring, *13* – cooled metallic diaphram and end detector with a grid, *14* – intake vacuum volume, *15* – detector with a grid, *16* – Faraday cup.

ISBN 978-3-95450-181-6

EXPERIMENTAL RESULTS

The accelerator entrance appears to be a critical point: here the injected ions still have a relatively low energy. As a consequence, there is a high probability of their interaction with atoms and molecules of the residual gas. The residual gas pressure at this point can be high because the gas flow from the stripper and the negative hydrogen ion source comes here. To prevent undesirable ion beam stripping we improved the vacuum conditions at the accelerator entrance by modernization of the accelerator. An intake vacuum volume (*14* in Fig. 1) was replaced by a new larger one. On the upper flange plate of the volume an additional cryogenic pump *11* was installed (*11* in Fig. 1). With the intent to improve the vacuum conditions within the entrance unit, diaphram *13* was mounted, which serves as vacuum resistance and limits the penetration of gas and ultraviolet radiation into the acceleration tube. The diaphram is cooled to prevent the secondary electron emission due to its heating by the peripheral part of the injected ion beam. Between the exit of the beam transport path and the diaphram, metal ring *12* is placed; a negative potential applied to this ring should suppress the flow of electrons accompanying the negative hydrogen ion beam. The entire surface of the diaphram from the accelerator side is covered by a tantalum wire grid to suppress secondary electrons, generated by positive ion irradiation, by supplying a negative potential to it. Between the diaphram and the grid, an insulated metal disk is mounted to measure the positive ion current. A similar disk with grid *15* is mounted within the exit unit of the accelerator.

The modernization resulted in drastic changes. Fig. 2 depicts the graphs of some measured parameters depending on the potential supplied to the grid in the entrance unit of the accelerator and to the ring. The measurements were carried out at an injected current of 800 μA, an accelerator voltage of 900 kV, and the gas supply to the stripping target providing 90 % beam stripping. As can be seen in Fig. 2a, the supply of the potential to the grid at the accelerator entrance significantly decreases the dose rate for bremsstrahlung, which is explained by a decrease in the current of electrons accelerated to the full voltage [11].

The current-voltage characteristic of the end detector (disk with a grid) at the accelerator entrance shown in Fig. 2c indicates that the secondary electron emission coefficient under the effect of positive ions formed is about 10. Such a high secondary electron emission coefficient is typical of many-electron ions and atoms with an energy above 100 keV [12].

The potential supply leads to an increase in the first electrode potential (Fig. 2b) given by a voltage divider and its approach to the equilibrium value of 150 kV obtained in the absence of currents in the gaps. The approach of the potential to the equilibrium value indicates a decrease in the current in the gap between the vacuum tank walls and the first electrode.

Fig. 2d clearly shows that the potential supply results in a noticeable decrease in the associated particle current.

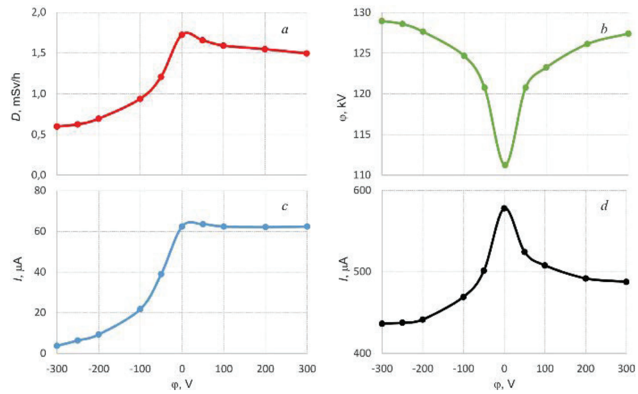

Figure 2: Dependence of the dose rate for bremsstrahlung *D* (*a*), the first electrode potential of the accelerator φ (*b*), the current supplied to the end detector *I* (*c*), and the associated particle current *I* (*d*) on the potential φ supplied to the ring and the grid mounted at the accelerator entrance.

The main result of the modernization is not so much a decrease in the unwanted charged particle flows [13], as a better high-voltage stability of vacuum acceleration gaps and almost complete disappearance of full-voltage breakdowns. This allowed us to raise the current of the injected negative hydrogen ion beam to the maximum and significantly increase the proton beam current, from 1.6 mA to 5 mA [14]. An accelerator with this current can be used in BNCT.

When the proton beam is dumped onto a lithium target [15], it allows us to obtain the epithermal neutron flux acceptabled for BNCT. *In vitro* and *in vivo* researches were carried out.

Human U251 and T98G glioma cells and Chinese hamster CHO-K1 and V-79 cells were incubated at various concentrations in the culture medium containing ^{10}B-enriched L-boronophenylalanine (BPA). The cells were irradiated with a neuron beam. A clonogenic assay was used to evaluate the viability of the irradiated cells. Irradiation of all four cell lines were cultured in the presence of ^{10}B was shown to reduce their colony-forming capacity compared with the control (Fig. 3) [16].

We irradiated immunodeficient mice at the 32nd day after U87MG tumor transplantation. Three of five mice became healthy.

We tested new boron delivery drugs – carbon nanohorn [17].

We have proposed a new method for measuring an absorbed dose in the BNCT [18] – delivery drug contain boron and gold. Neutron capture by boron leads to the absorbed dose, neutron capture by gold leads to activation. Measurement of activation by γ-spectrometer allows you to recover the absorbed dose. The idea was tested experimentally [19].

ISBN 978-3-95450-181-6

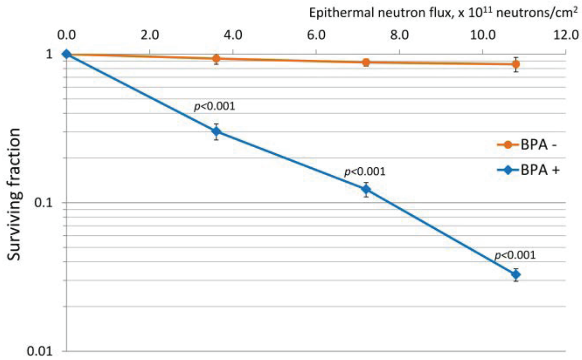

Figure 3: U251 MG cell survival ratio with and without BPA depending on neutron flux.

PROSPECTS

It is planned to replace the lithium target by the new one to set neutron beam shaping assembly [20] and to obtain therapeutic beam of neutrons that meets the requirements of BNCT to the greatest extent. New lithium neutron target [21] is a set of thin tantalum tubes with a thin lithium layer deposited. This target is characterized by maximum resistance to radiation blistering and a minimum level of γ-radiation at the absorption of protons in it.

The current understanding of the processes in tandem accelerator with vacuum insulation and the progress achieved allows us to consider the possibility of creating a specialized accelerator neutron source for the oncology clinic for the purpose of BNCT. The idea of reversing the high-voltage sectioned rectifier and insertion lower part of feedthrough insulator into it can be realized at the accelerator [22, 23]. This will reduce the facility height and make it really compact and attractive for placing in a clinic. This will significantly increase the stability of the accelerator because the potential for intermediate electrodes can be fed directly from the relevant sections of the rectifier.

CONCLUSION

The modernization significantly suppressed the unwanted charged particle flows in the tandem accelerator with vacuum insulation. This resulted in the improved high voltage stability of acceleration gaps and enabled an increase in the proton beam current from 1.6 to 5 mA that is sufficient for Boron Neutron Capture Therapy.

Prolonged stable generation of neutrons was implemented for *in vitro* and *in vivo* BNCT researches. The obtained neutron beam meets the requirements of BNCT: the irradiation of cell cultures provides the destruction of cells with boron and preservation of cells without boron. Irradiation of immunodeficient mice with grafted glioblastoma results in their recovery.

The planned modification of the facility will allow obtaining the therapeutic beam of neutrons that meets the requirements of BNCT to the greatest extent during the next year.

REFERENCES

[1] Neutron Capture Therapy. Principles and Applications. Eds.: W. Sauerwein *et al.* Springer (2012) 553 p.
[2] S. Taskaev, V. Kanygin, *Boron Neutron Capture Therapy*, (Novosibirsk: Publisher of SB RAS, 2016), 216.
[3] B. Bayanov et al., Nucl. Instrum. Meth. A 413 (1998) 397.
[4] S. Taskaev, Phys. Particles and Nuclei 46 (2015) 956.
[5] V. Aleinik et al., Instrum. Experim. Techn. 56 (2013) 497.
[6] A. Makarov et al., “Optimization of the negative hydrogen ion beam injection into the tandem accelerator with vacuum insulation”, RUPAC’2012, Saint-Petersburg, Russia, Sept. 2012, WEPPD038, p. 623 (2012).
[7] A. Kuznetsov et al., “Calibration testing of the stripping target of the vacuum insulated tandem accelerator”, RUPAC’2012, Saint-Petersburg, Russia, Sept. 2012, WEPPC057, p. 560 (2012).
[8] A. Kuznetsov et al., Techn. Phys. Lett. 35 (2009) 346.
[9] D. Kasatov et al, JINST 9 (2014) P12016.
[10] D. Kasatov et al., Techn. Phys. Lett. 41 (2015) 139.
[11] I. Shchudlo et al., “Measurement of the spatial distribution of gamma radiation at tandem accelerator with vacuum insulation”. RUPAC’2014, Obninsk, Russia, Oct. 2014, TUPSA37, p. 116 (2014).
[12] U. Arifov et al., Proc. of the Academy of Sciences of USSR, series: Physical 26 (1962) 1398.
[13] A. Ivanov et al., JINST 11 (2016) P04018.
[14] A. Ivanov et al., Techn. Phys. Lett. 42 (2016) 608.
[15] B. Bayanov, V. Belov, S. Taskaev, J. Phys.: Conf. Series 41 (2006) 460.
[16] O. Volkova et al., Russ. J. Radiology 97 (2016) 283.
[17] K. Nakai et al., “Application of carbon nanohorn containing boron to BNCT”. 17 Intern. Congress on Neutron Capture Therapy, Oct. 2016, Columbia, Missouri, USA, p. 111 (2016).
[18] A. Zaboronok, S. Taskaev, “The method of measurement of absorbed dose for boron neutron capture therapy”, *Patent application for the invention*, № 2015150701, 2015 (positive decision 16.09.2016).
[19] A. Zaboronok et al., “Accelerator-based neutron source for boron neutron capture therapy: in vitro efficacy evaluation with in-sample dosimetry using gold nanoparticles”, 17 Intern. Congress on Neutron Capture Therapy, October 2-7, 2016, Columbia, Missouri, USA, p. 42 (2016).
[20] L. Zaidi et al., Phys. Atom. Nuclei 80 (2017) 1.
[21] B. Bayanov, S. Taskaev, “Neutron producing target”, *Patent application for the invention*, № 2015150702, 2015.
[22] I. Sorokin, S. Taskaev, Appl. Radiat. Isot. 106 (2015) 101.
[23] E. Domarov et al., Instrum. Experim. Techn. 60 (2017) 1.

ISBN 978-3-95450-181-6