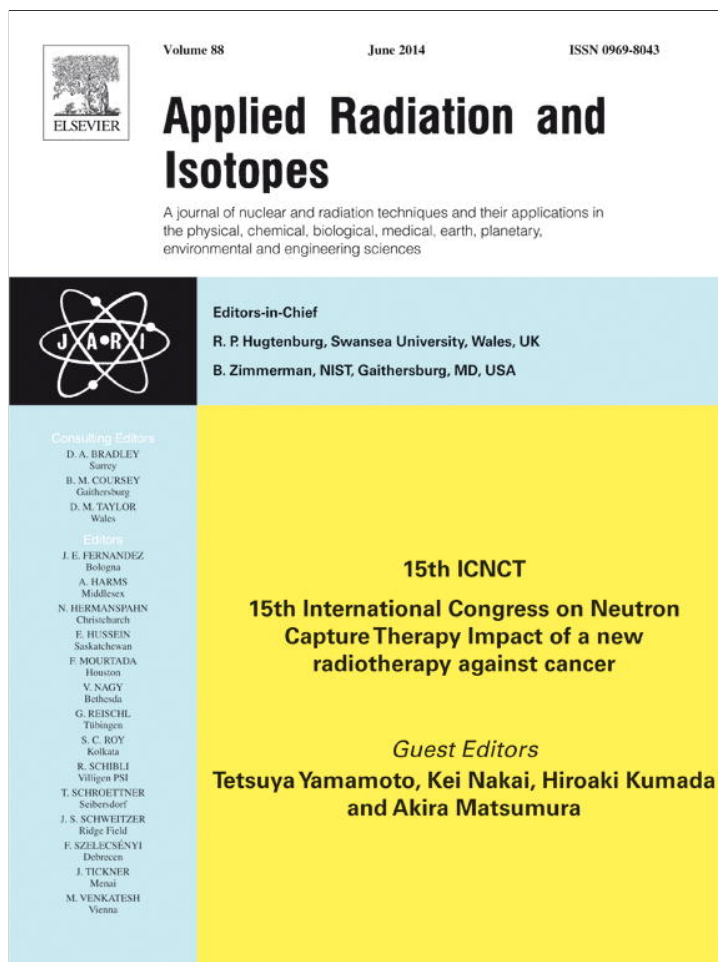


Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/authorsrights>



Contents lists available at ScienceDirect

Applied Radiation and Isotopes

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

Current progress and future prospects of the VITA based neutron source



V. Aleynik^a, A. Bashkirtsev^b, V. Kanygin^c, D. Kasatov^d, A. Kuznetsov^a, A. Makarov^a, I. Schudlo^b, I. Sorokin^a, S. Taskaev^{a,d,*}, M. Tiunov^a

^a Budker Institute of Nuclear Physics, 11 Lavrentiev ave., 630090 Novosibirsk, Russia

^b Novosibirsk State Technical University, 20 Karl Marx str., 630092 Novosibirsk, Russia

^c Neurosurgery Center, 2a Vladimirovskiy spusk, 630003 Novosibirsk, Russia

^d Novosibirsk State University, 2 Pirogov str., 630090 Novosibirsk, Russia

HIGHLIGHTS

- We have increased proton current up to 2 mA.
- VITA based neutron source is ready for *in vitro* investigations.
- We proposed to use a orthogonal neutron beam for BNCT with “à la gantry” possibility.

ARTICLE INFO

Article history:

Received 5 December 2012

Received in revised form

31 October 2013

Accepted 21 November 2013

Available online 11 December 2013

Keywords:

Boron neutron capture therapy

Epithermal neutron source

Accelerator

ABSTRACT

At the BINP, a pilot accelerator based epithermal neutron source is now in use. Most recent investigations on the facility are related with studying the dark current, X-ray radiation measuring, optimization of H⁻ beam injection and new gas stripping target calibrating. The results of these studies, ways of providing stability to the accelerator are presented and discussed, as well as the ways of creating the therapeutic beam and strategies of applying the facility for clinical use.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Presently, boron neutron capture therapy (BNCT) (Locher, 1936) is considered to be a promising method for the selective treatment of malignant tumours. The results of clinical trials, which were carried out using nuclear reactors as neutron sources, showed the possibility of treating brain glioblastoma and metastasizing melanoma incurable by other methods (Hatanaka, 1990; Hatanaka and Nakagawa, 1994). The broad implementation of the BNCT in clinics requires compact inexpensive sources of epithermal neutrons. At the BINP the source of epithermal neutrons based on 2 MeV Vacuum Insulation Tandem Accelerator (VITA) and neutron generation through ⁷Li(p,n)⁷Be reaction was proposed (Bayanov et al., 1998) and realized. Although the accelerator is designed to obtain a 5 mA proton beam, but in the experiments carried out in 2008–2010 we usually got the proton beam currents of hundreds of

microamperes, and occasionally for a short time—a few milliamps. Such a current was enough to demonstrate the generation of neutrons (Kuznetsov et al., 2009a) and monochromatic gamma-rays (Kuznetsov et al., 2009b), to carry out initial *in vitro* investigations (Mostovich et al., 2011), but it is clearly not sufficient for the thorough BNCT research and other applications. This paper presents the results of experiments carried out, aimed at increasing the current of the proton beam and improving the stability of the accelerator. We also discuss plans of works and strategies of applying the facility for clinical use.

General view of the accelerator is shown in Fig. 1. Negative hydrogen ions are injected and accelerated up to 1 MeV by potential applied to the electrodes, then H⁻ turn into protons in the stripping target and at last the protons are accelerated up to 2 MeV by the same potential. Pumping of the gaseous stripping target is carried out by cryogenic and turbomolecular pumps through the jalousies. The potential of the high-voltage and five intermediate electrodes is supplied by a high-voltage source through the insulator which has a resistive divider.

* Corresponding author.

E-mail address: taskaev@inp.nsk.su (S. Taskaev).

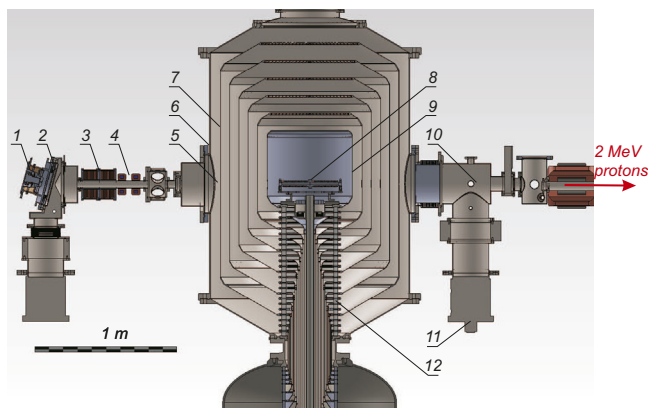


Fig. 1. High-current vacuum insulation tandem accelerator. 1— H^- ion source, 2—diaphragm, 3—magnetic lenses, 4—corrector, 5—a temporary location of the beam detector, 6—accelerator, 7—electrodes, 8—stripper, 9—high voltage electrode, 10—high energy beam transport, 11—turbo molecular pumps, 12—insulator.

2. Dark currents

The accelerator has a high electric field in the electrode gap – about 25 kV/cm, and a large total area of the electrodes – tens of square meters. In such a system in the electrode gap dark currents of different nature must inevitably occur, which may have a significant impact on the potential distribution along the accelerating channel.

When training the accelerator, at the time of voltage increasing, a dark current is recorded. It is associated with the appearance of micro-discharges, accompanied by desorption of adsorbed gases on the surface of the electrodes. Usually within an hour of training the value of the dark current decreases from the typical values of 100–300 μA to ten microamperes and then to few microamperes.

In a series of experiments in order to increase the H^- beam current the apertures of electrodes were increased from 20 to 58 mm, except for the high-voltage electrode, in which the diameter of the hole was still 20 mm. This change resulted in frequent registration of dark current of high intensity—up to 3–4 mA. Flowing of such a current compared to the standard training mode led to a nearly 100-times increase in radiation. The latter fact assumed high energy of electrons which is possible when the current flows not in the gap between adjacent electrodes but, for example, between the case of vacuum tank and the high-voltage electrode. This assumption was confirmed by measuring the X-ray spectrum by BGO-spectrometer: the maximum of the spectrum was shifted from 120 to 400 keV. It was found that when the aperture of the channel increases, the electric field on the sharp edge of the cathode part of diaphragm mountings increases by 20%—up to 51 kV/cm, which leads to increased emission of electrons directly into the acceleration channel. To prevent the occurrence of this phenomenon the aperture of the channel has been reduced and sharp edges of diaphragm mountings has been rounded. This study shows the danger of exceeding the electric field strength of 50 kV/cm. Earlier in (Dimov et al., 2003) we found that the 70 kV/cm electric field leads to dramatic increase of field emission current in the high-voltage gap.

3. Beam injection

Negative ion beam with energy of 21 keV and current of 5 mA is created by surface-plasma source with Penning discharge and hollow cathode. After turning at an angle of 15 degrees the peripheral part of the beam is cut off by 28 mm cone diaphragm and the rest center of the beam enters into the transport channel.

Then the divergent beam is focused by two magnetic lenses and can be shifted by corrector for subsequent precise input into the accelerator. VITA is characterized not only by a high rate of acceleration, but also by a strong entry electrostatic lens between the cover of the accelerator and the first accelerating electrode. To study the influence of the lens and to optimize H^- beam injection the 22-channel detector has been produced and installed at the entrance of the accelerator. Beam detector is mounted directly on the first electrode of the accelerator. Using the detector we have measured the dependence of the relative maximum beam current density on the focusing magnetic lenses current. It has been determined that the best agreement with the numerical calculation is achieved by assuming the full compensation of the space charge in the transport channel and setting the transverse ion temperature equal to 1 eV at the plasma boundary of the ion source. This study resulted in better focusing of the beam required for acceleration of the beam without significant losses.

4. Stripper

To increase the current a new stripping target has been made. It is designed as a cooled tube having length of 400 mm and internal diameter of 16 mm, with argon gas valve in the middle. Previously we used a tube with diameter of 10 mm.

Negative ion beam with energy of 21 keV was injected into the accelerator with the high-voltage electrode potential of 800 kV. When there was no gas supply in the stripping target the Faraday cylinder at the exit of the accelerator registered negative current. This current was the current of negative hydrogen ions, which were first accelerated and then decelerated. When the stripping target is filled with argon it exchanges negative hydrogen ions into protons. When the thickness of the target is $0.29 \times 10^{16} \text{ cm}^{-2}$ the number of appeared protons is comparable to the number of negative hydrogen ions and detected current becomes equal to zero. Registration of the moment of the current transition from negative to positive with changing argon pressure has become a useful direct diagnostics of stripping target thickness. Also the thickness of the target is indirectly characterized by the residual gas pressure, because the experimentally measured dependence of the residual pressure on the amount of supplied argon is linear in operating range of parameters. With a further target density increase there is a growth of output current and its saturation. When injected H^- current is around hundreds of microamps the dependence measured experimentally is in good agreement with the calculated one (Fig. 2). However, when the injected current is around few milliamps there is some reduction in the proton current in the saturation region with increasing gas supply. It is planned to investigate this effect in detail in the near future.

5. Orthogonal therapeutic neutron beam

Now the proton beam incidents on the neutron producing target vertically. We propose to change the configuration and use the horizontal proton beam for neutron generation. The vertical positioning of the target allows to reduce significantly the size of the facility and to locate the whole facility on the same floor. It is very important advantage when planning the practical use of the source in medical clinics.

To form the therapeutic beam of epithermal neutrons they use beam shaping assembly (BSA). The BSA involves moderator, reflector, absorber, and a filter in some cases. A BSA was accurately optimized for ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction at 2.3–3 MeV protons (Palamara et al., 2002; Kononov et al., 2004; Stichelbaut et al., 2006; Forton et al., 2009; Minsky et al., 2011). With the characteristic proton

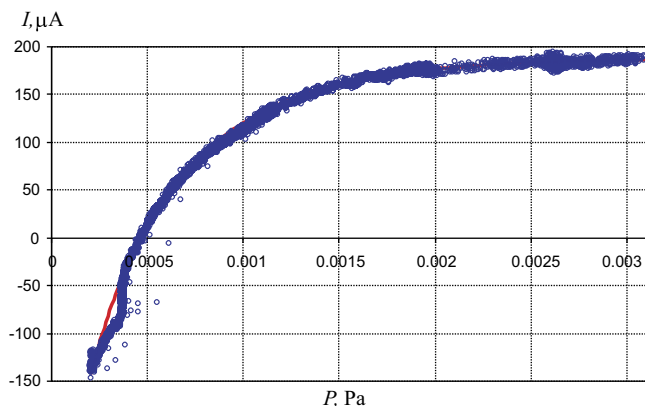


Fig. 2. Measured and calculated (solid line) dependence of the detected output current of the accelerator on the residual gas pressure.

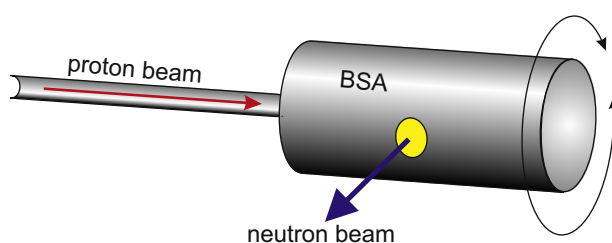


Fig. 3. Realization of rotating of therapeutic neutron beam.

beam current of 10 mA it provides a dose rate in tumor ~ 1 RBE Gy per minute, advantage depth of 9 cm, and therapeutic ratio up to 6. In all these cases therapeutic neutron beam is coaxial with a proton beam. The next suggestion is that for the therapy we should use the orthogonal neutron beam. According to calculations performed (Kashaeva et al., 2012) such a beam geometry can assure the similar quality as a beam of straight geometry. Moreover, as the energy of neutrons emitted to the side is smaller than the energy of neutrons emitted to the front it is more suitable for obtaining a better therapeutic beam. But the suggestion is not just to use the orthogonal beam. It is very important that such orthogonal beam can be used to easily direct the beam to the patient at any angle as it is shown in Fig. 3. This solution is “à la gantry” for proton therapy. The change of direction of therapeutic neutron beam is ensured by the rotation of the whole BSA or its part containing moderator about the axis of proton beam propagation.

6. Conclusions and prospects

The above-described investigations allowed us to move to a long stable operation with a much higher average current—1.5–2 mA instead of previously achieved 0.1–0.7 mA. This current provides the possibility of measuring neutron spectrum by the time-of-flight technique, carrying out *in vitro* and *in vivo* studies and developing other techniques for BNCT. In this work two suggestions were made about the concept of future development of BNCT medical facility based on VITA and ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction: to use horizontal beam for neutron generation and to use orthogonal neutron beam for therapy that can direct the beam to the patient at any angle by the rotation of BSA or its part.

References

- Bayanov, B., Belov, V., Bender, E., et al., 1998. Accelerator based neutron source for the neutron-capture and fast neutron therapy at hospital. Nucl. Instrum. Methods Phys. Res., Sect. A 413, 397–426.
- Dimov, G., Belchenko, Yu., Kraynov, G., et al., 2003. Vacuum insulation tandem accelerator for boron neutron capture therapy and for explosive detection by resonant absorption of monochromatic gamma radiation. At. Energy 94, 155–159.
- Forton, E., Stichelbaut, F., Cambriani, A., et al., 2009. Overview of the IBA accelerator-based BNCT system. Appl. Radiat. Isot. 67, S262–S265.
- Hatanaka, H., 1990. Clinical results of boron neutron capture therapy. Basic Life Sci. 54, 15–21.
- Hatanaka, H., Nakagawa, Y., 1994. Clinical results of long-surviving brain tumor patients who underwent boron neutron capture therapy. Int. J. Radiat. Oncol. Biol. Phys. 28, 1061–1066.
- Kashaeva, E., Malyshkin, G., Samarina, S., Taskaev, S., 2012. Regimes of therapeutic beam shaping from an accelerator neutron source. In: Abstracts of the 15th International Congress on Neutron Capture Therapy, 10–14 September 2012, Tsukuba, Japan, p. 138–139.
- Kononov, O., Kononov, V., Bokhovko, M., 2004. Optimization of an accelerator-based epithermal neutron source for neutron capture therapy. Appl. Radiat. Isot. 61, 1009–1013.
- Kuznetsov, A., Malyshkin, G., Makarov, A., Sorokin, I., Sulyaev, Yu., Taskaev, S., 2009a. First experiments on neutron registration at accelerator based source for boron neutron capture therapy. Tech. Phys. Lett. 35 (8), 1–6.
- Kuznetsov, A., Belchenko, Yu., Burdakov, A., et al., 2009b. The detection of nitrogen using nuclear resonance absorption of mono-energetic gamma rays. Nucl. Instrum. Methods Phys. Res., Sect. A 606, 238.
- Locher, G., 1936. Biological effects and therapeutic possibilities of neutrons. Am. J. Roentgenol. Radium Ther. 36, 1–13.
- Minsky, D., Kreyner, A., Valda, A., 2011. AB-BNCT beam shaping assembly based on ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction optimization. Appl. Radiat. Isot. 69, 1668–1671.
- Mostovich, L., Kutsenko, O., Grigor'eva, E., et al., 2011. Effect of epithermal neutrons on viability of glioblastoma tumor cells *in vitro*. Bull. Exp. Biol. Med. 151 (2), 264–267.
- Palamara, F., Mattioda, F., Varone, R., Giusti, V., 2002. Proton accelerator-based epithermal neutron beams for BNCT. In: Sauerwein, W., Moss, R., Wittig, A. (Eds.), Research and Development in Neutron Capture Therapy. Monduzzi Editore, pp. 283–288.
- Stichelbaut, F., Forton, E., Jongen, Y., 2006. Design of a beam shaping assembly for an accelerator-based BNCT system. Adv. Neutron Capture Ther. 2006, 308–311.