

## INNOVATIVE ACCELERATOR BASED NEUTRON SOURCE

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Pilot innovative accelerator-based facility had just started its operation at Budker Institute of Nuclear Physics, Novosibirsk, Russia. This facility is based on compact vacuum insulation tandem accelerator with proton current up to 10 mA. Epithermal neutrons for boron neutron capture therapy are proposed to be generated by protons of 1.915 MeV bombarding a lithium target using  ${}^7\text{Li}(p, n){}^7\text{Be}$  threshold reaction. Monochromatic 9.17 MeV  $\gamma$ -quantum for detection of explosives by nuclear resonance absorption technique is proposed to be produced by 1.75 MeV protons bombarding a carbon-13 target. The 2 mA 2 MeV proton beam had just been obtained. In the report, the pilot facility design is given, results of first experiments on proton beam transport, on monochromatic  $\gamma$ -rays generation and neutron generation are presented.

### 1. Introduction

The concept of neutron capture therapy (NCT) was introduced in 1936 [1], four years after the discovery of neutrons. The idea of the boron neutron capture therapy (BNCT) is simple and elegant. A tumor-seeking compound containing stable isotope  ${}^{10}\text{B}$  is introduced into blood and allowed time to be accumulated in the tumor. The tumor is then irradiated with epithermal neutrons that are captured by  ${}^{10}\text{B}$  isotope. Capturing neutrons causes the boron nuclei to break apart, resulting in the emission of  $\alpha$ -radiation and recoiling  ${}^7\text{Li}$  nuclei. Both  $\alpha$ -particles and lithium are high in energy (2.8 MeV in 94 %, 2.3 MeV in 6 %) but short in range (5 - 9  $\mu\text{m}$ ) for and high relative biological effectiveness, which means that they destroy the malignant cells where boron is embedded without hurting the adjacent healthy cells. Therefore, BNCT will make it possible to destroy tumor cells selectively at higher  ${}^{10}\text{B}$  concentration than in normal ones. Over 350 patients with glioblastoma multiforme and melanoma have been treated successfully in a number of different reactors world-wide [2, 3]. The development of BNCT into a routine therapeutic modality will then depend, in part, on the availability of suitable neutron sources that are compactible with installation in a hospital environment. A low-energy accelerator-based neutron source has the potential for meeting the requirements of a clinical facility. Ten years ago we proposed an innovative accelerator-based neutron source [4]. Neutron generation is proposed to be carried out by protons bombarding a lithium target using  ${}^7\text{Li}(p, n){}^7\text{Be}$  threshold reaction. A 10 mA 2 - 2.5 MeV proton beam is formed by electrostatic vacuum insulation tandem accelerator (VITA). Creation of an accelerator with proton beam intensity of 10 mA will decrease exposure time for necessary therapeutic dose to tens of minutes.

Other application for vacuum insulation tandem accelerator is explosive detection by nuclear resonance absorption technique [5]. Most of available explosives contain a higher concentration of nitrogen compared to common domestic materials, which makes it possible to use gamma resonance absorption in nitrogen to detect explosives. In this method, a load is scanned by  $\gamma$ -rays with the energy of 9.17 MeV (monochromatic  $\gamma$ -rays is produced by 1.75 MeV protons bombarding a carbon-13 target). This radiation is absorbed in nitrogen and dissipated by other elements. A comparison between resonance and non-resonance spectra allows us to determine whether an explosive material exists in the load.

In this paper, the pilot facility design is presented and discussed. Current status of project realization and results of experiments on neutron generation and  $\gamma$ -ray generation are presented.

### 2. Epithermal neutron source

Pilot variant of accelerator based epithermal neutron source for neutron capture therapy has been created at the Budker Institute of Nuclear Physics. Design of the facility is shown in Fig. 1. Negative hydrogen ion beam [6] is injected into electrostatic vacuum insulation tandem accelerator (VITA). After charge-exchange of negative hydrogen ion into proton inside the charge-exchange tube in the center of high-voltage electrode, a proton beam is formed at the outlet of the tandem. It is accelerated up to double voltage of high-voltage electrode. Neutron generation is proposed to be carried out by protons bombarding a lithium target using  ${}^7\text{Li}(p, n){}^7\text{Be}$  threshold reaction.

In the accelerator, the beam is accelerated in the electric field of 33 kV  $\text{cm}^{-1}$ . Five intermediate electrodes and a high-voltage one 600 mm in diameter are placed inside a vacuum tank with diameter of 1400 mm. Inside the high-voltage electrode, stripping gas target is placed, made as a tube of 400 mm length and 10 mm in diameter. To decrease gas flow in accelerating channel, gas recirculation with turbo-molecular pump inside the high-voltage electrode is provided. Vacuum volume is to be pumped out through the profiled covers of intermediate electrodes with a cryogenic pump placed on top. Potential is fed to the high-voltage electrode through insulator from a 40 kW 1.25 MV sectioned rectifier of ELV-type industrial electron accelerator.

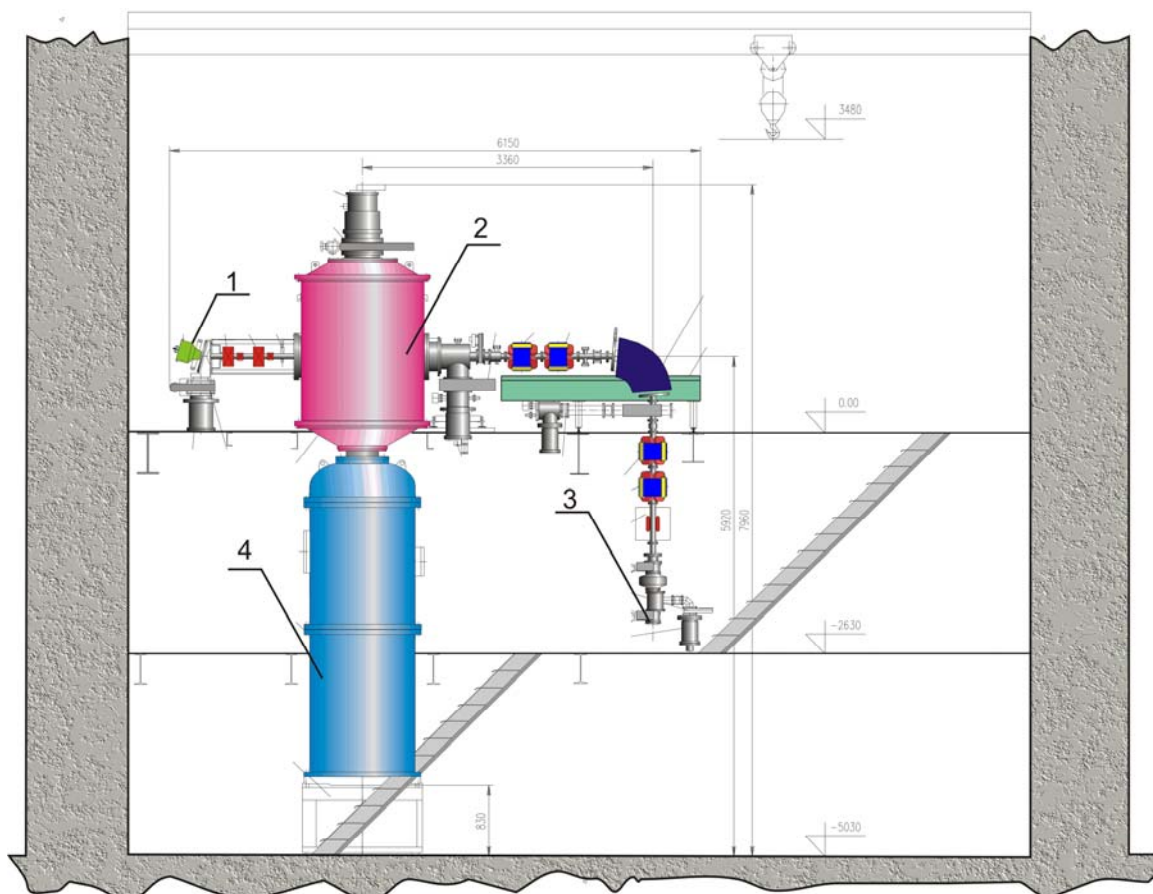


Fig. 1. Pilot variant of facility for NCT: 1 – negative hydrogen ions source; 2 – vacuum insulation tandem accelerator (VITA); 3 – neutron producing target; 4 – high voltage power supply.

Using vacuum insulation tandem accelerator instead of the conventional scheme with ceramic columns allows hoping for the obtaining of high currents. However, the working capacity of VITA was not clear because of the great energy content between electrodes (up to 30 J). It is known [7] that breakdown of millimeter vacuum gaps with 10 J energy released results in drop of voltage durability of vacuum gap. A set of experiments on study of high voltage durability of 45 mm vacuum gap with large square electrodes was carried out on the available 0.6 MeV tandem-accelerator. The results of these experiments showed that 50 J stored energy released in breakdown did not result in detrainning of 45 mm vacuum gap [8]. Then after the cycle of gaps training on accelerator the required voltage of 1 MV was obtained. After the checkout of charge-exchange gas target the proton beam with energy of 2 MeV and current of 2 mA was obtained.

After accelerating, the beam is focused by quadrupole lens doublet, and then it is deviated 90° in vertical plane with use of bend magnet, focused again by quadrupole lens doublet, passed through magnetic sweep system, and finally falls onto the neutron producing target. Minimal size of the proton beam on the target is 2.5 cm.

Additionally, using vacuum insulation tandem accelerator instead of the radiofrequency quadrupole accelerator allows hoping for the obtaining of highly monochromatic and stable proton beam energy. Highly monochromatic and stable proton beam energy is needed for the most efficient innovative operating mode of the neutron generation at proton energy of 1.915 MeV that is 33 keV higher than the threshold of the  ${}^7\text{Li}(p, n){}^7\text{Be}$  reaction. In this case, kinematically collimated forward beam of neutrons with the mean energy of 40 keV may be used for BNCT after a slight moderation. In ordinary mode, at proton energy of 2.5 MeV, the neutron source produces neutron beam with maximum energy of 790 keV appropriate for neutron capture therapy after moderation.

During the spring of 2008, the experiments on neutron generation were carried out. Neutrons were registered by various techniques. The results of these experiments are described in detail in the article presented on this Conference [10].

### 3. Monochromatic $\gamma$ -ray source

The recently created powerful electrostatic tandem accelerator VITA has been used to generate monochromatic gamma-quanta. While dumping a proton beam with energy 1.747 MeV on the graphite target enriched with an isotope of carbon-13, the excited nucleus of nitrogen with the energy of excitation 9.172 MeV is formed as a result of resonant reaction  ${}^{13}\text{C}(p){}^{14}\text{N}^*$ . This nucleus is moving with kinetic energy 125 keV in the direction of movement of the absorbed proton. Excitation is removed by emission of gamma-quantum, which energy depends on the angle between the direction of radiation and the momentum of the excited nucleus of nitrogen because of the Doppler Effect. Irradiating

under angle of  $80.7^\circ \pm 0.35^\circ$ , gamma-quanta have energy  $9.172 \text{ MeV} \pm 122 \text{ eV}$  and can be subjected to resonance absorption in nitrogen. Energy homogeneous beam of protons with high energy stability is required to create a source of resonance gammas with high brightness, which the designed accelerator provides.

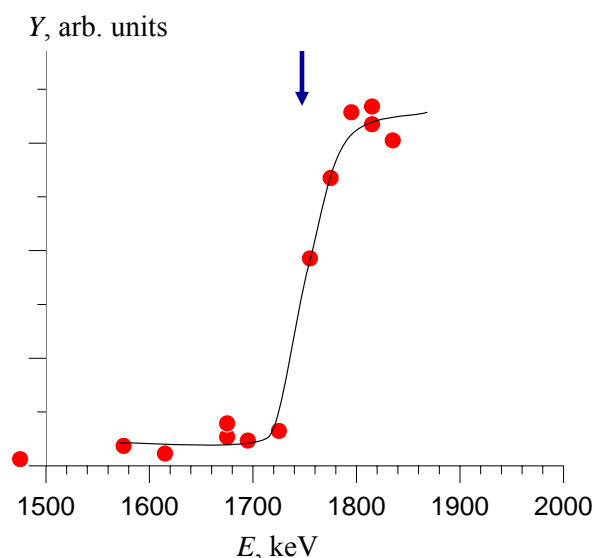


Fig. 2. Dependence of resonant gamma-ray yield  $Y$  from proton beam energy  $E$ .

energy drift during the experiment. The half-width on the half-height of proton beam energy instability found from the diagram is equal to 20 keV. Such stability is acceptable for generation of neutrons in near-threshold regime and for monochromatic  $\gamma$ -rays.

#### 4. Other applications of the VITA

Accelerators similar to the created one can be used for production of radioactive isotopes or for generation of neutrons for research purposes. Specific uses of the accelerator for the named purposes require further development work and improvements.

#### 5. Conclusion

Pilot innovative vacuum insulation tandem accelerator has started its operation at BINP, Novosibirsk, Russia. Proton beam with energy of 2 MeV and current of 2 mA has been obtained. At the present time, the work on optimization of beam transport to obtain 10 mA is underway. First experiments on generation of epithermal neutrons and 9.17 MeV  $\gamma$ -rays were carried out. Attenuation of monochromatic  $\gamma$ -rays in nitrogen has been detected. If the next proof-of-principle experiments planned for 2008 - 2009 are successful, the accelerator-based sources will provide a compact and low cost solution for neutron capture therapy and for detection of explosives.

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