# ACCELERATOR-BASED NEUTRON SOURCE FOR BORON NEUTRON CAPTURE THERAPY AND OTHER APPLICATIONS

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## Abstract

An accelerator-based neutron source has been proposed and created at the Budker Institute of Nuclear Physics in Novosibirsk, Russia. The source comprises an original design tandem accelerator, solid lithium target, and a neutron beam shaping assembly. The neutron source is capable to produce the high neutron flux in various energy ranges, from thermal to fast, for boron neutron capture therapy, as well as for other applications. The paper describes the facility, its features and the results obtained with its use.

## 1. INTRODUCTION

The main objective for the accelerator based BNCT system is to design a compact neutron source that best satisfies the BNCT requirements [1], namely, a source of beam of epithermal neutrons with minimized fraction of fast and thermal neutrons. In order to form the narrowest neutron spectrum within the epithermal energy range, it was proposed to use the $^7$Li(p,n)$^7$Be reaction with a high-current low-energy proton beam for BNCT [2]. Experimental implementation of the proposal required two decades of research, culminating in the creation of a compact reliable neutron source demanded by BNCT and other applications. In the paper, we give a description of the constituent parts of the neutron source, its features and the results obtained with its use.

## 2. EXPERIMENTAL FACILITY

The layout of the facility is shown in Fig. 1. The neutron source comprises an original design tandem accelerator, solid lithium target, a neutron beam shaping assembly, and is placed in two bunkers as shown in Fig. 1. Each bunker is 10.8 m × 9.1 m and 10 m height, the wall thickness of the bunker is from 1.2 m to 1.3 m, the wall thickness between the bunkers is 1.47 m. The facility has the ability to place a lithium target in 5 positions; in Fig. 1 they are marked as positions A, B, C, D, E.

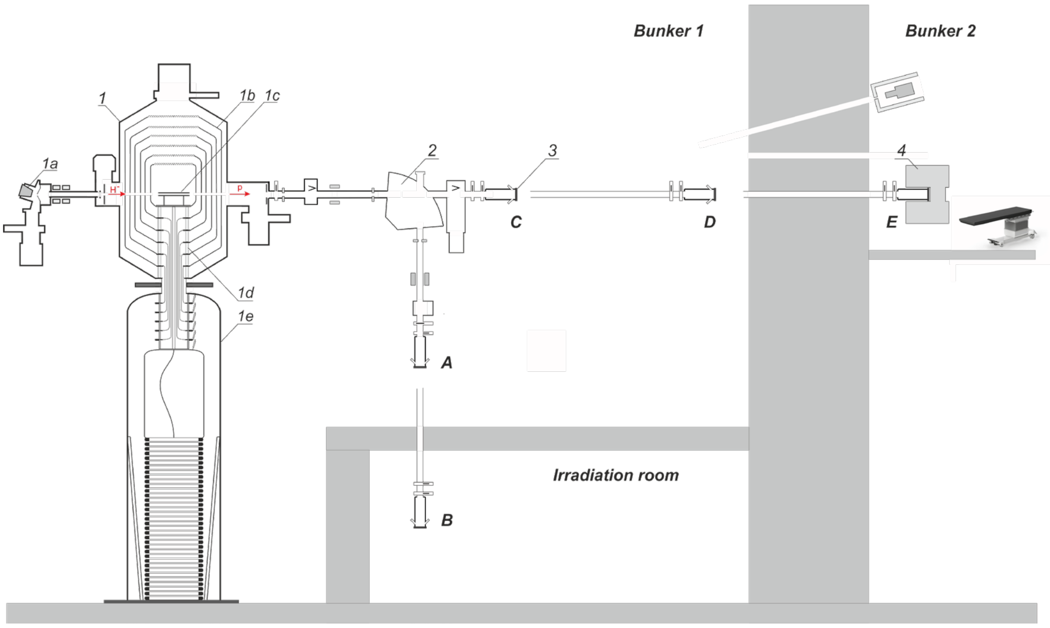

*FIG. 1. Layout of the experimental facility: 1 – vacuum insulated tandem accelerator (1a – negative ion source, 1b - intermediate and high-voltage electrodes, 1c – gas stripper, 1d – feedthrough insulator, 1e – high voltage power supply), 2 – bending magnet, 3 – lithium target, 4 – beam shaping assembly.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

In order to generate a high-current low-energy proton beam, a DC tandem accelerator is used. The term "tandem" means that the applied DC accelerating voltage is used twice. Negative hydrogen ions are injected to the input of the tandem accelerator, accelerated by a positive potential applied to the central electrode, then stripped to the positive ions, and accelerated again by the same potential. A key advantage of the tandem acceleration concept is to reduce the necessary accelerating voltage by half, which tremendously simplifies electrostatic insulation and consequently reduces the size and cost of the accelerator.

The BINP tandem accelerator, which was named as Vacuum Insulated Tandem Accelerator (VITA), has a specific design that does not involve accelerating tubes, unlike conventional tandem accelerators. Instead of those, the nested intermediate electrodes (*1b*) fixed at a feedthrough insulator (*1d*) is used, as shown in Fig. 1. The advantage of such an arrangement is moving ceramic parts of the feedthrough insulator far enough from the ion beam, thus increasing the high-voltage strength of the accelerating gaps given high ion beam current. A consequence of this design was also a fast rate of ion acceleration – up to 25 keV/cm.

The proton beam energy can be varied within a range of 0.6 MeV – 2.3 MeV keeping a high-energy stability 0.1 %. The beam current can also be varied in a wide range (from 0.1 mA to 10 mA) with high current stability (0.4 %) [3]. The tandem accelerator is also capable of generating a deuteron beam with similar characteristics [4].

In the design of the neutron target, the following factors were considered:

1) The lithium layer must be thick enough to slow down protons in it only to the neutron generation threshold of 1.882 MeV. This can decrease the accompanying 0.478 MeV $\gamma$-ray flux and the temperature on the lithium surface.
2) The lithium layer must consist of pure lithium to maximize the neutron yield. The neutron yield from the lithium hydride, oxide, and fluoride is 1.43, 2, and 3.3 times lower than that from pure lithium, respectively.
3) The lithium layer must remain solid to prevent backstreaming of the lithium vapor and $^{7}$Be in the beam duct.
4) The substrate must be intensively cooled to maintain the lithium layer in the solid state during its heating by the powerful proton beam.
5) The substrate on which the lithium layer is deposited must be thin. This enables optimization of the moderator and placing the moderator close to the neutron generation surface.
6) The substrate must be resistant to radiation damage.
7) The target plate must be easily removable at the end of the target life.
8) All materials of the target assembly should have minimal activation by neutrons.

Lithium target 10 cm in diameter has three layers: a thin layer of pure lithium to generate neutrons in $^{7}$Li(p,n)$^{7}$Be reactions; a thin layer of material totally resistant to radiation blistering [5]; and a thin copper substrate for efficient heat removal. Thermal evaporating of lithium in a vacuum on copper substrate is carried out on a specially designed stand. The practical application of our proposed non-destructive in situ method for measuring the thickness of lithium [6] made it possible to optimize the deposition of a layer of lithium uniform in thickness. This target provides a stable neutron yield for a long time (at least the treatment time for 340 patients, as was measured) with an acceptably low level of contamination of the beam transport path by the inevitably formed radioactive isotope beryllium-7 [7].

A Beam Shaping Assembly (BSA) is applied to convert neutron flux into a beam of epithermal neutrons with characteristics suitable for clinical applications. We use two BSA. The first BSA consists of a magnesium fluoride moderator, a composite reflector (graphite in the front hemisphere and lead in the back), an absorber, and a filter [8]. Second BSA is a plexiglas moderator 72 mm thick.

## 3. FACULTY APPLICATIONS

In Boron Neutron Capture Therapy, the total absorbed dose is the sum of four dose components with different RBE: boron dose; high-LET dose from the $^{14}$N(n,p)$^{14}$C reaction ("nitrogen" dose); fast neutron dose; $\gamma$-ray dose. We developed a new approach for measuring boron dose, nitrogen dose and fast neutron dose. A small-sized neutron detector (1 mm × 1 mm in diameter) with two cast polystyrene scintillators one of which is enriched in boron has been developed and is being used for dosimetry of boron dose and $\gamma$-ray dose [9]. For measuring nitrogen dose and fast neutron dose we proposed a new approach: the cell lines are irradiated by γ-radiation and mixed radiation (neutron and γ-radiation) for the same time measuring γ-ray dose. After that by comparing the doses of γ-radiation causing the same effect, for example, survival, determine the doses due to high-LET particles dose [10]. We have developed a boron delivery drug loaded with gold, which allows *in situ* absorbed dose evaluation in BNCT [11].

As a result of studies carried out at the facility, it has been established that the neutron irradiation of U251 and T98G human glioma cells, pre-incubated in the medium with boron, leads to a significant suppression of their vitality [12]. Irradiation of immunodeficient mice with grafted human glioblastoma with pre-injection of $^{10}$B-enriched drugs results in their reduce or suspend or their complete recovery [13]. The experience gained allows us to successfully treat pets with spontaneous tumors [14].

Since BNCT is a binary technique, another important aspect is the boron delivery drug. A large number of new drugs have been tested at the facility [11, 13, 15-19], and more are expected.

The developed neutron source became a prototype of the commercial neutron beam system for hospital-based BNCT. This neutron source is installed at the new BNCT Center at Xiamen Humanity Hospital in Xiamen, P.R. China. The next two such sources are made for National Oncological Hadron Therapy Center (CNAO) in Pavia (Italy), and for National Medical Research Center of Oncology in Moscow (Russia).

Using the accelerator blistering of metal surface under proton implantation [20] and its effect on the neutron yield [7] have been studied in detail. The $^7$Li(p,p'γ)$^7$Li reaction cross section [21], the $^7$Li(p,α)α reaction cross section [22], the 478 keV photon yield from a thick lithium target [21], and the neutron yield from lithium target in $^7$Li(p,n)$^7$Be reaction[23] have been measured.

The source was used to measure the content of hazardous impurities in boron carbide samples developed for thermonuclear fusion reactor ITER [24, 25].

The source was used for radiation tests of perspective materials by fast neutrons [4] with a fluency of $10^{14}$ to $10^{15}$ neutrons/cm$^2$. These prospective materials were: i) fibers of the laser calorimeter calibration system of the CMS electromagnetic detector developed for the High-Luminosity Large Hadron Collider in CERN, ii) photomultipliers and DC-DC converters for ATLAS detector in CERN, iii) diamond neutron detector and boron carbide ceramics for ITER, iv) neodymium magnets for high power linac of the Kurchatov Institute. Users were given the opportunity to measure the parameters of the studied samples in real time and see the parameters of the facility.

## 4. CONCLUSION

A compact neutron source has been proposed and created at the Budker Institute of Nuclear Physics in Novosibirsk, Russia. The source comprises an original design tandem accelerator, solid lithium target, and a neutron beam shaping assembly. The neutron source produces the high neutron flux for boron neutron capture therapy, as well as for other applications. The neutron source has been used and is planned to be used for a variety of different scientific studies including clinical trials.

## ACKNOWLEDGEMENTS

This research was funded by Russian Science Foundation, grant number 19-72-30005.

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