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A neutron producing target for BINP accelerator-based neutron source

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ABSTRACT

An innovative accelerator-based neutron source for BNCT has just started operation at the Budker Institute of Nuclear Physics, Novosibirsk. One of the main elements of the facility is a lithium target producing neutrons via the threshold ^{7}Li(p,n)^{7}Be reaction at 25 kW proton beam with energies of 1.915 MeV or 2.5 MeV. The design of an optimal target and results of the investigation of radiation blistering of the lithium layer were presented at previous NCT Congresses. During the last two years the neutron target has been manufactured, assembled and placed in the facility. Optimization of the target is carried out with the Monte Carlo simulation code MCNP. In this article, the design of the target is discussed, results of all previous investigations are summarized, results of target testing and neutron generation are described, and results of simulation of neutron spectra are presented.

1. Introduction

In 1998 at the Budker Institute of Nuclear Physics (BINP) an original source of epithermal neutrons was conceived based on a tandem accelerator with vacuum insulation, suitable for widespread use of BNCT in clinical practice (Bayanov et al., 1998). It is intended to generate neutrons with the threshold reaction ^{7}Li(p,n)^{7}Be bombarding a lithium target with a 1.915 MeV 10 mA proton beam. At the present moment the accelerator has been constructed (Kudryavtsev et al., 2008), and the first experiments on generating neutrons have been carried out (Bayanov et al., 2009). In this work the results of these experiments are presented.

2. Summary of previous investigations

Four neutron-producing charged particle reactions have been proposed for use in accelerator-based BNCT: ^{7}Li(p,n), ^{9}Be(p,n), ^{9}Be(d,n) and ^{13}C(d,n) (Blue and Yanch, 2003). The best reaction for epithermal neutron generation is ^{7}Li(p,n): neutron production from this reaction is high and the relatively soft spectrum requires less moderation than those generated in other reactions. This reaction is going to be used by us in spite of the poor mechanical, chemical, and thermal properties of lithium metal.

Pure lithium is more effective for neutron generation as compared with lithium hydride, oxide, nitride or fluoride (Lee and Zhou, 1999). However it requires efficient heat removal to avoid melting (lithium melting temperature is 182 °C) so as to prevent the undesirable release of ^{7}Be. A liquid metal coolant is preferable to water at a high power density. However during thermal tests with gallium as a coolant, target damage occurred due to the high chemical activity of gallium (Belov et al., 2002). Then it was found that the target size for near-threshold generating mode could be increased up to 10 cm without any negative consequence on the neutron beam characteristics (Bayanov et al., 2005). It was experimentally demonstrated in (Bayanov et al., 2004) that water cooling is the best one for a target of 10 cm diameter, and that the lithium target could run up to 10 mA proton beam before melting.

As a result of proton bombardment of lithium an undesirable flux of 478 keV γ-rays appears (Savidou et al., 1999). To decrease it appreciably, the production via evaporation of a thin lithium layer is needed — from 5 to 100 μm thickness for protons with energies from 1.915 to 2.5 MeV. This thickness of lithium layer slows down the protons to 1.882 MeV — the threshold energy for neutron generation. Then the protons can be absorbed without γ-radiation in any metal heavier than aluminum.

New techniques have been proposed and developed to evaporate thin lithium layers (Bayanov et al., 2006), to facilitate the evaporation process (Bayanov and Taskaev, 2007) and to measure the radial distribution of the evaporated lithium layer thickness (Bayanov et al., 2008a). It was determined that evaporated lithium density corresponds to the metal lithium density.

A 10% decrease in the neutron yield per unit current has been observed within 3 h after firing a proton beam on a lithium target in the experiment at the Birmingham accelerator, UK (Brown

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et al., 2002). This decrease may be caused by a change in the lithium layer composition as a result of its interaction with residual gas since the neutron yield, e.g., in lithium nitride is a factor 1.66 lower than in pure lithium. We investigated the dependence of the secondary negative ion yield on the layer depth for lithium layers exposed under different vacuum conditions using the secondary-ion mass spectrometry method (Bayanov et al., 2008b). It was found that changes in the lithium layer composition as a result of its interaction with the residual gas could not be the cause for the 10% observed decrease in neutron yield. During these experiments the evaporated layer was ascertained to consist of pure lithium.

Monoenergetic proton absorption in a metal results in radiation damage. The appearance of blistering on different metals was experimentally examined. It was found that the beam with the design parameters blistered copper in less than one hour. For metals that have a good level of hydrogen solubility, this time increases by more than a factor of 100 times.

3. Simulations

During the first experiments on neutron generation, a target with good thermal removal characteristic was used. Fig. 1 illustrates the target general view.

In 2007 T. Kobayashi and G. Bengua made MCNP calculations on the acceptability of this target for BNCT by method that are described in (Bengua et al., 2006). They have proved that it is useful to replace a stainless steel backing by a tungsten one, to use heavy instead of light water and to use a polyethylene boron dose enhancer.

Then the numerical simulation of protons, neutrons and γ-quanta transporting in the neutron-generating target and its environment was made. The simulation was performed with the PRIZMA program (Arnautova et al., 1993). To understand better the physical nature of this process, all calculations were made for two different geometrical models: a full target geometry (Fig. 2) and a simplified one where a part of the target below the backing 1 was absent. The water phantom 20 cm in diameter and 20 cm height has been placed 2 cm below the target. All obtained results were averaged over 5 cm diameter and over a depth of 5–10 cm.

Figs. 3 and 4 illustrate the results of neutron flux calculations on the surface of the phantom for the simplified and full target geometries in the case of near-threshold neutron generation (proton energy: 1.915 MeV, current: 10 mA, lithium thickness: 10 μm). As a result of scattering in the constructional materials of the target and in the coolant, the neutron spectrum became softer and more appropriate for neutron-capture therapy without losses in flux density. Still a considerable flux of neutrons with energies around 60 keV is present. Obviously, the use of iron backing is

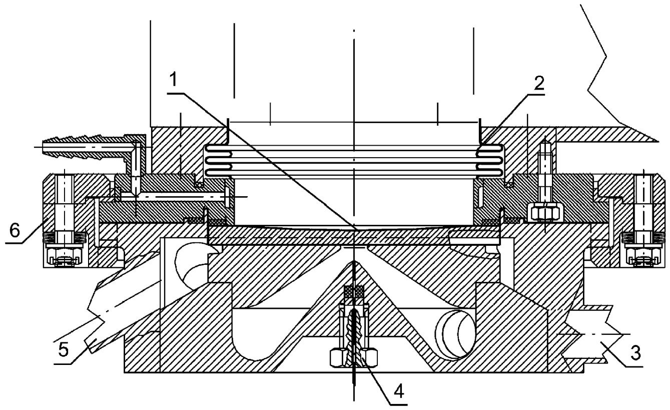

Fig. 1. Target for BINP accelerator neutron source: 1—backing with lithium layer, 2—bellow, 3—water input, 4—thermocouple, 5—water output, 6—bayonet.

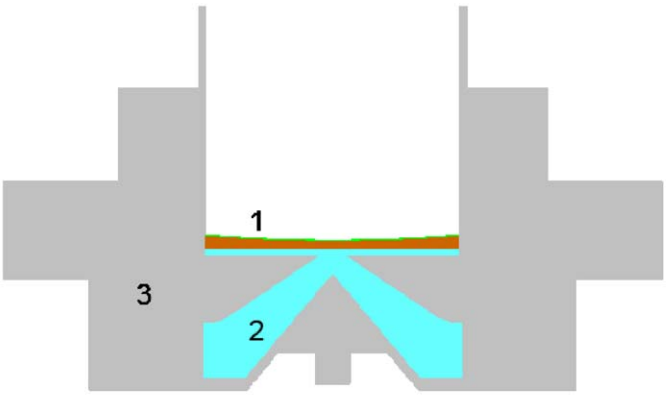

Fig. 2. Calculation model of the target: 1—copper backing 10 cm in diameter with thin lithium layer, 2–water, 3—stainless steel.

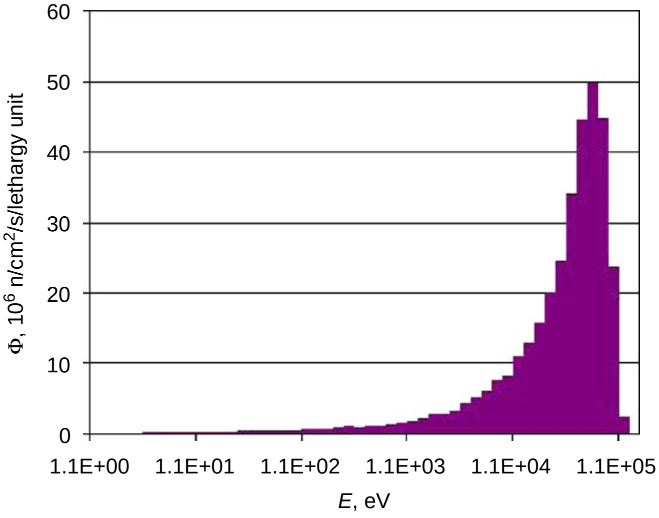

Fig. 3. Neutron energy spectrum for simplified target geometry.

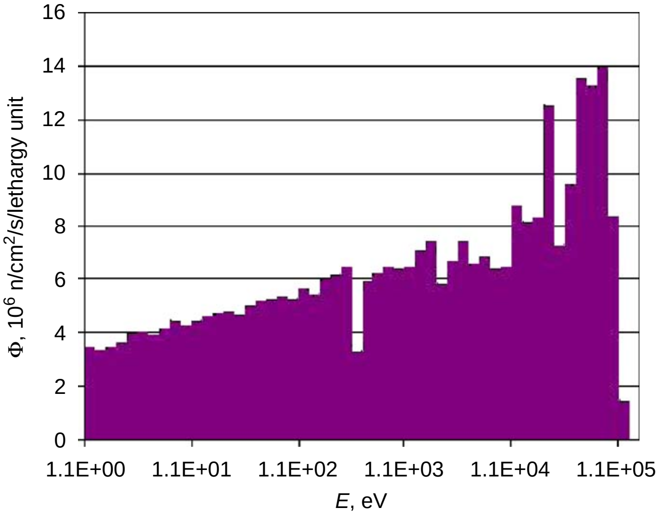

Fig. 4. Neutron energy spectrum for full target geometry.

Fig. 5. Target substrate with lithium after neutron generation. The mark left by the beam can be seen on the left.

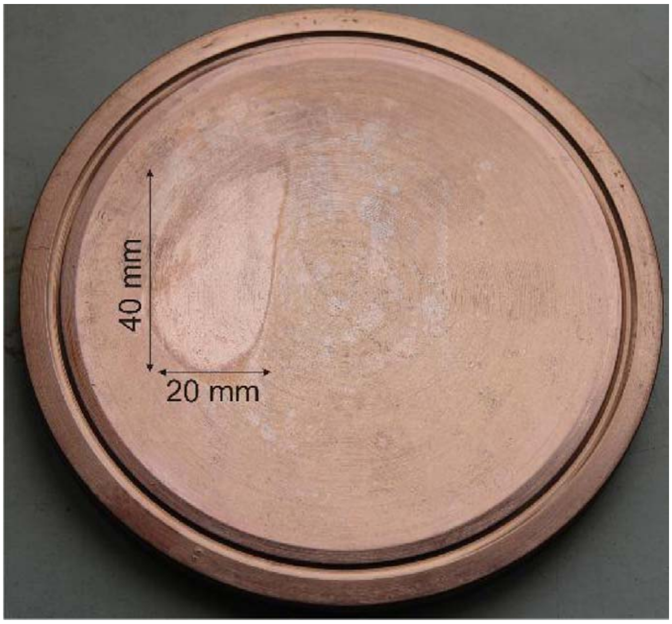

Fig. 6. Target substrate without lithium after neutron generation. The mark left by the beam can be seen on the left.

inadmissible for optimal target geometry due to the presence of windows in the scattering cross-section.

4. Neutron generation

Recently neutron generation at the facility was first achieved (Bayanov et al., 2009). The target used in the conducted experiments is shown in Fig. 1. To ensure radiation protection, the beam current was limited to 140 μA. At the same time the beam was fixed (not sweeping) and Figs. 5 and 6 show the marks left by the beam. The beam is 2 cm in diameter, in good agreement with calculations. At this beam size the power density on the target is about half the design value. The critical changes in the lithium layer were not observed thus indicating an adequate heat removal.

4. Conclusions

In this work the authors have summarized the results of all previous investigations that concern the choice of the neutron generation reaction, the design of the heat-removal system, the determination of the lithium layer thickness, the employment of new evaporation techniques to produce the lithium layer, the study of the lithium layer characteristics and the analysis of the blistering.

During first experiments on neutron generation it has been demonstrated that the target is acceptable as far as providing the necessary level of heat removal. Calculations of the neutron flux and spectrum are in agreement with the measurements. Studies are ongoing to find possible drawbacks in the target design and to discover ways to improve it.

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