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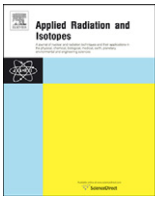

# Optimization of the target of an accelerator-driven neutron source through Monte Carlo numerical simulation of neutron and gamma transport by the PRIZMA code

Ya. Kandiev[a], E. Kashaeva[a], G. Malyshkin[a], B. Bayanov[b], S. Taskaev[b,*]

[a] All-Russian Scientific Research Institute of Technical Physics, 13 Vasil'ev str., 456770 Snezhinsk, Chelyabinsk Region, Russia
[b] Budker Institute of Nuclear Physics, 11 Lavrentiev ave., 630090 Novosibirsk, Russia

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ABSTRACT

At Budker Institute of Nuclear Physics, epithermal neutron source for neutron-capture therapy was built and neutron generation was realized. Source is based on tandem accelerator and uses near-threshold neutron generation from the reaction $^7$Li($p$,$n$)$^7$Be. The paper describes target optimization through the numerical simulation of proton, neutron and gamma transport by Monte Carlo method (PRIZMA code). It is shown that the near-threshold mode attractive due low activation provides high efficiency of the dose and acceptable therapeutic ratio and advantage depth.

## 1. Introduction

In 1998 at the Budker Institute of Nuclear Physics (Novosibirsk, Russia) an original source of epithermal neutrons has been conceived based on the 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 10 mA 1.9–2.5 MeV proton beam.

The generated neutron energy exceeds the necessity of NCT, therefore to form the therapeutic beam of epithermal neutrons they use moderators made of heavy water, magnesium fluoride, polytetrafluoroethylene and Fluental®. A moderator was accurately optimized for proton beams of 2.3–3 MeV: it appeared that the best material for moderator is $MgF_2$. With the characteristic size of 20 cm it provides a dose rate in tumor ~0.5 RBE Gy/min, advantage depth of 9 cm and therapeutic ratio up to 6 (Kononov et al., 2004, 2006; Stichelbaut et al., 2006).

In the present work, the possibility of formation of a therapeutic neutron beam in the near-threshold mode has been studied, with the proton beam energy exceeding 30–120 keV the threshold of the $^7$Li($p$,$n$)$^7$Be reaction (1.882 MeV).

## 2. Neutron spectra simulations

During the first experiments on neutron generation (Kuznetsov et al., 2009), a target with good thermal removal characteristic was used (Bayanov et al., 2006). Target unit up to 6 cm thick was made of stainless steel. It had a cave inside. In the cave, water was rotated for smooth inflow into cooling channels of the beam absorber. At near-threshold mode neutrons generated have an average energy of 40 keV and are collimated kinematically. As a result of scattering in the constructional materials of the target and in the coolant, the neutron spectrum became softer. An average neutron energy at the outlet of the target unit decreased to 13 keV for 1.915 MeV proton beam (Bayanov et al., 2009), and such neutrons could already be suitable for neutron-capture therapy. At the same time, a considerable flux of neutrons with energies around 60 keV is present due to small scattering cross-section of neutrons on iron nuclear in this energy range.

To form a better neutron flux, a new thin target was proposed and manufactured. Behind it, a more adequate moderator should be placed. Stainless steel was not used for the new target. Presence of manganese in stainless steel resulted in substantial activation of the material by neutrons. Besides, the protons falling on the steel walls of the vacuum chamber caused neutron generation. Though the flux of such neutrons was small, it was an obstacle in applying the time-of-flight technique for measuring the neutron spectrum (Aleynik et al., 2011). The thin target (122 mm diameter, 9 mm thick) was made from copper (2/3) and cooling water (1/3). A 10 μm lithium layer was evaporated on the target. Immediately behind target, a moderator of 46 mm thickness was placed, made of the $^6$Li (1 mm), $MgF_2$ (6 mm), Al (18 mm), $C_2H_4$ (16 mm) and Ti layers. At the moderator, the moderating agent is $C_2H_4$ layer. $MgF_2$, Al and Ti layers are just filters scattering the neutrons with energies higher than 10 keV. The target, moderator and vacuum chamber are surrounded by

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[*] Corresponding author. Fax: +7 383 330 71 63.
*E-mail addresses:* taskaev@inp.nsk.su, taskaev.sergey@gmail.com (S. Taskaev).

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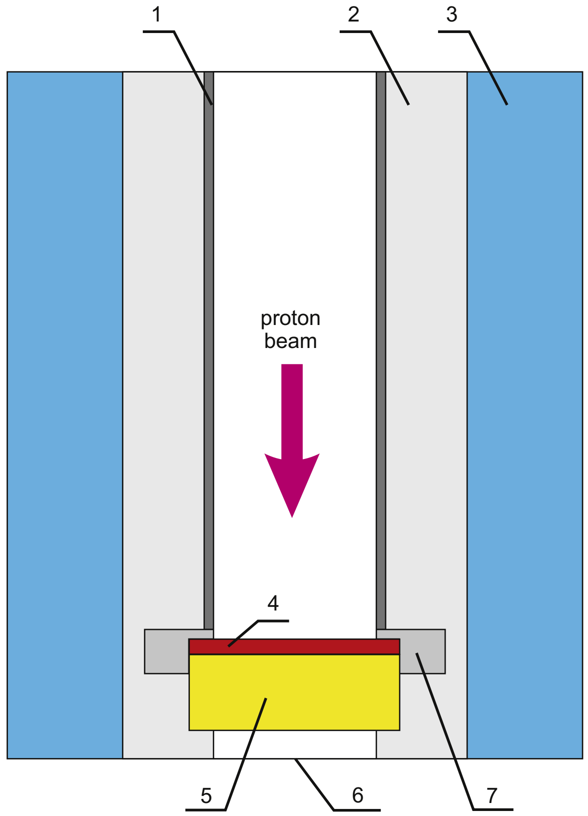

**Fig. 1.** Calculation model: 1—titanium vacuum chamber, 2—graphite reflector, 3—absorber, 4—target, 5—filter-moderator, 6—surface of neutron spectra calculation, 7—target holder from aluminum.

a 50 mm thick graphite reflector, and a 50 mm thick borated polyethylene absorber with 10 mm thick lead cylinders.

The numerical simulation of protons, neutrons and γ-quanta transport in the new neutron-generating target and its environment (Fig. 1) was made with PRIZMA program (Arnautova et al., 1993) with ENDF/B-VI cross-section library and handbook by Abramovich et al. (1989). The neutron spectra calculated for a distance of 2 cm from moderator on the surface of phantom are shown in Fig. 2.

With a proton beam energy of 1.915 MeV the epithermal neutron flux is 3.4 $10^8$ $cm^{-2}$ $s^{-1}$, which is 1.5 times greater than with the use of previous target (Bayanov et al., 2009). The epithermal neutron fraction (from 0.5 eV to 10 keV) in this case increases from 60% to 70%. Mean neutron energy decreased from 13 keV to 10 keV.

## 3. Dose simulations

For the new target, the dose along the axis was calculated for modified Snyder head phantom (Goorley et al., 2002), placed 2 cm behind the moderator. In Fig. 3 the contributions of the main processes into the dose are shown at 1.915 MeV 10 mA proton beam. The calculations were made with even distribution of $^{10}B$ over the phantom with 1 ppm concentration.

In Fig. 4, the equivalent dose depth profile is shown for a tumor tissue and a healthy one. For consistency of the paper by Harling and Riley (2003) we have assumed that for brain the RBE for photons is 1.0, the RBE for neutrons is 3.2, and that the compound biological effectiveness (CBE), the product of the compound factor and the RBE, is 1.35. The RBEs for the tumor are assumed to be the same as those that are listed above. The CBE for

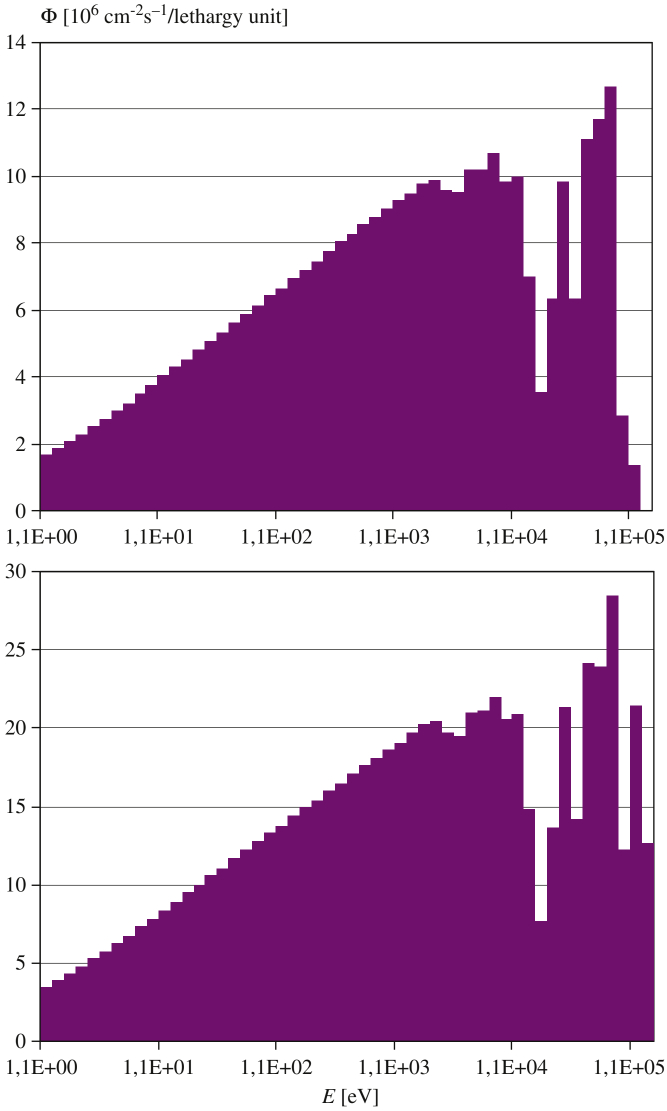

**Fig. 2.** Neutron energy spectrum for 1.915 (above) and 1.95 MeV (below) at 10 mA.

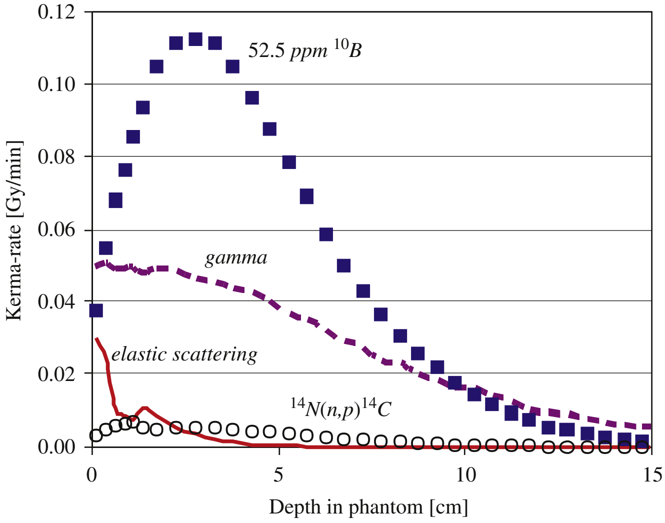

**Fig. 3.** Depth-kerma rate profile.

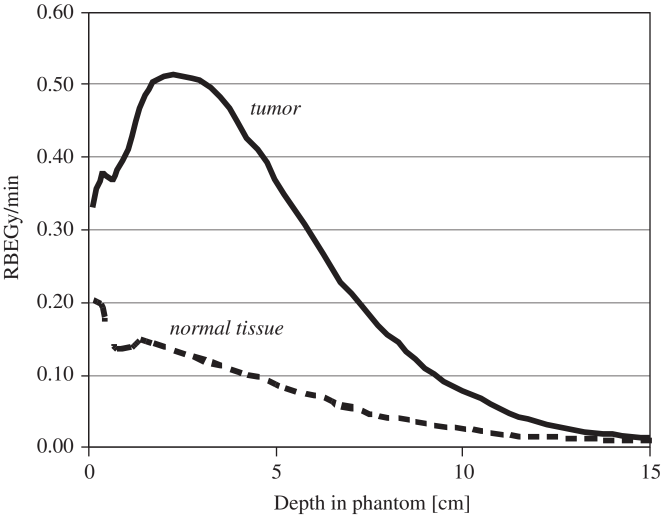

**Fig. 4.** Absorbed dose profile in tumor and normal tissue.

**Table 1**

| Proton energy, MeV | $C_2H_4$ thickness, mm | Pb thickness, mm | Dose rate in tumor, RBE Gy/min | Therapeutic ratio | Advantage depth, cm |
|---|---|---|---|---|---|
| 1.915 | 16 | – | 0.51 | 2.56 | 7.25 |
| | 22 | – | 0.43 | 2.82 | 7.3 |
| 1.95 | 16 | – | 1.15 | 2.14 | 6.6 |
| | 22 | – | 0.96 | 2.42 | 6.75 |
| | 16 | 5 | 1.06 | 2.19 | 6.75 |
| | 16 | 10 | 1.02 | 2.27 | 6.75 |

tumor is assumed to be 3.8. We have used 15 ppm for normal tissue and 52.5 ppm for tumor of boron concentrations in our calculations.

The calculations were also made for the different proton beam energies, for $C_2H_4$ thickness increase in the moderator from 16 to 22 mm, and for extra lead disk 5 and 10 mm thick placed between the moderator and phantom, respectively. In Table 1, the main parameters are shown: the dose rate, the therapeutic ratio and the depth of therapy for some modes.

It is seen that the near-threshold generation mode provides high efficiency of the dose and acceptable therapeutic ratio and advantage depth. Proton beam energy increase from 1.915 to 1.95 MeV allows to provide dose rate more than 1 RBE Gy/min with 10 mA at some decrease of therapeutic ratio and the depth of therapy. They can be improved using the thicker layer of $C_2H_4$ and extra lead disk, but due to decrease of the dose rate. In case of shallow tumor, the therapeutic ratio may be improved by placing BDE (boron dose enhancer) (Bengua et al., 2004) in front of the phantom. The simplicity of the moderating filter allows to modify the neutron spectrum easily, in order to increase the quality of specific tumor therapy, which is the advantage of the near-threshold neutron generation mode, together with the low activation of the target and facility. The further calculations are planned at the aim specification (increasing the therapeutic ratio, dose efficiency, optimization at the tumor localization, etc.).

Thus, the near-threshold generation mode was shown to be successfully used for neutron-capture therapy. Though it yields to the mode of generation at 2.3–3 MeV in the proton beam in a number of parameters, it has also a number of advantages.

## 4. Conclusions

At the Budker Institute of Nuclear Physics, a pilot epithermal neutron source has been built and started up. It is based on a compact vacuum insulation tandem accelerator and uses neutron generation from the reaction $^7$Li($p$,$n$)$^7$Be. In this paper the numerical simulation of protons, neutrons and $\gamma$-rays transport was made with Monte Carlo method (PRIZMA code) for near-threshold mode of neutron generation attractive due to low activation. Kerma rate in a modified Snyder head phantom was calculated for the thin target with several variants of the moderator. It was found out that the near-threshold mode provides a high dose rate in tumor and acceptable therapeutic ratio and advantage depth.

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