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Simulation and design of a simple and easy-to-use small-scale neutron source at Kyoto University

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Abstract

A simple and easy-to-use compact neutron source based on a low power level proton accelerator (proton energy 3.5 MeV and 0.35 kW beam power) at Kyoto University was designed with the conception of low cost, compact size, high safety and intensive thermal neutron flux via Monte Carlo method with PHITS code. By utilizing (p, n) reactions in a beryllium target coupled to a polyethylene moderator and graphite reflector with a wing configuration, this facility is expected to produce time-averaged thermal neutron fluxes suitable for neutron scattering and development of instrumentation, and play a role in educating students in neutron science and performing research with neutrons. Borated polyethylene (BPE) and ordinary concrete were combined to shield the neutron and photon. By using niobium as target backing and water as cooler, it is promising to cope with the problem of thermal damage and hydrogen embrittlement damage. The sizes of moderator and reflector are optimized to have thermal neutron flux as high as possible, while keeping the low ratio of fast neutron flux to thermal neutron flux. The neutron and gamma dose equivalent rates were evaluated and the current shielding configuration is acceptable.

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Keywords: KUANS; Compact accelerator-driven neutron source; Monte Carlo simulation; PHITS.

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1. Introduction

In order to generate high neutron fluxes to accommodate more scientific applications, high-power spallation sources, such as the ISIS, J-PARC, and SNS facilities have been realized [1]. An even more powerful source, the European Spallation Source (ESS), is currently under study [2]. However, since the primary mission of the high-power neutron sources is to serve a large number of users for materials characterization, it is not cost-effective to use such expensive facilities for education and training or for evaluation of instrumentation ideas [3]. Employing low-energy (~10 to 100 MeV) protons on low-Z targets (e.g., Li, Be) permits the use of compact accelerator-driven neutron sources (CANS). The CANS, due to their modesty in scale and capital/operation costs, and flexibility in instrumental configuration, are ideal to play a complementary role with respect to high-power neutron source. Therefore, the world community has increasingly recognized the value of CANS. In Japan, several CANS projects have been proposed or constructed. One of them is Kyoto University Accelerator-driven Neutron Source (KUANS) with 3.5 MeV proton Linac and 0.35 kW beam power. It has following two missions: (1) producing time-averaged thermal neutron fluxes suitable for neutron scattering and development of instrumentation; (2) playing a role in educating students in neutron science and performing research with neutrons. In this study, based on the conception of low cost, compact size, high safety and intensive thermal neutron flux, the target/moderator/reflector/shielding of KUANS was designed and simulated with Monte Carlo code PHITS [4] by running massively parallel calculations on RIKEN Integrated Cluster of Clusters (RICC).

2. Design and simulation of KUANS

2.1. Configuration of KUANS target station

According to the mission of KUANS, the thermal neutron is what we need, and the fast neutron flux should be as small as possible to reduce the noise. Therefore the target station of KUANS was designed as a wing moderator configuration shown in Fig. 1.

Long life and reliable target design is a key factor for stable operation and performance of CANS. Thanks to the high neutron yield, high melting point, mechanical strength and stable performance, beryllium was used as KUANS's target. However, due to the problem of thermal damage and hydrogen embrittlement damage (blistering) on the beryllium target [5,6], the target has to be maintained and replaced frequently. Recovery from any target failure takes many days: waiting for radiation decay, unstacking shielding, removing the highly radioactive target, cleaning the vacuum system, reassembling the system and waiting for vacuum recovery [6]. Hydrogen diffusible metal niobium was selected as target backing [7] and water as cooler for KUANS, as shown in Fig. 1. The combination of hydrogen diffusible metal and water cooling system provide a promising method to cope with the target damage problems for compact accelerator-driven neutron source.

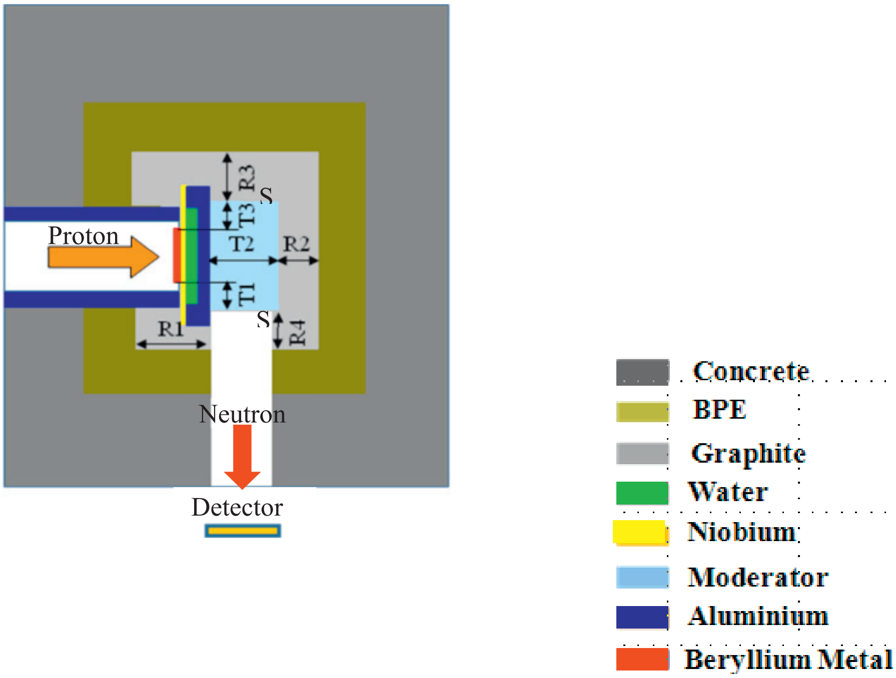

Fig. 1. Configuration of KUANS target station.

2.2. Neutron and gamma source data for target

In this study, the neutron energy spectral distributions from the beryllium target for the incident proton energy of 3.5 MeV for θ = 0-180° (0°, 10°, 20°, 40°, 60°, 80°, 110°, 115°, 120°, 125°, 130°, 135°, 140°, 145°, 148°) were obtained by extrapolating the results of W. B. Howard et al measured at bombarding energies of 3.7 and 4.0 MeV [8]. The neutron energy spectrums of 0°, i.e., proton beam direction, for 3.5 MeV, 3.7 MeV and 4.0 MeV are shown in Fig. 2. According to M.R. Hawkesworth [9], the total neutron yield of proton with 3.5 MeV incident energy bombarding beryllium is 9.0×10^8 n/μC.

The measured ratio of gamma-ray to neutron yield for protons on beryllium at laboratory angle of 55° with less than 10% error is shown in Fig. 3 [10]. In the case of 3.5 MeV, the ratio is about 0.065. W. B. Howard et al [8] also measured the neutron yield for different solid angles in the case of 3.5 MeV proton energy. For 55°, it is about 5.9×10^7 neutrons/(sr·μC). So for proton it is about 3.8×10^6 photons/(sr·μC). Under the assumption of isotropic angular distributions, the total photon yield can be obtained.

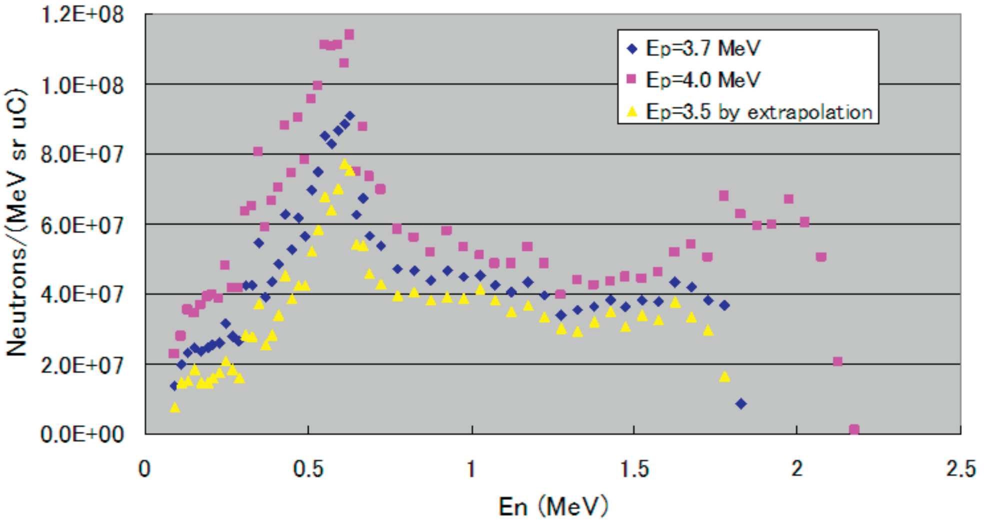

Fig. 2. Neutron energy spectrum at 0º for proton energy of 3.5 MeV, 3.7 MeV and 4.0 MeV.

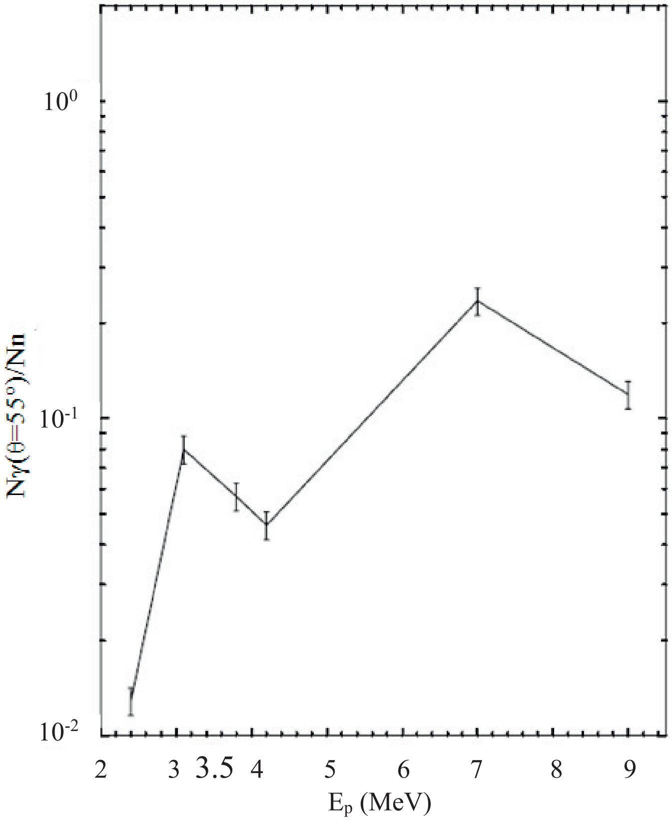

Fig. 3. Ratio of photon to neutron yield at laboratory angle of 55° under different proton energies.

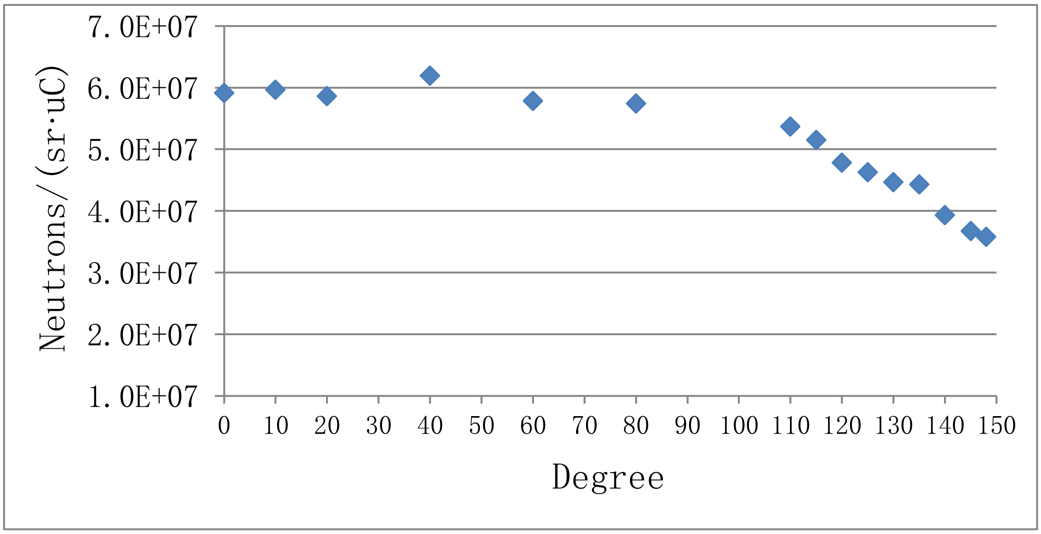

Fig. 4. Neutron yield under different laboratory angles for 3.5 MeV proton energy.

According to A. Z. Kiss, et al [11], photon is only generated from ^{9}Be(p,α,γ)^{6}Li when ^{9}Be bombarded by proton with energy of 3.5 MeV, and the photon energy is 3.562 MeV.

2.3. Moderator simulation

Polyethylene was selected as moderator material for KUANS due to its excellent moderation effect. It has three parameters T1, T2 and T3 that have to be optimized as shown in Fig. 1 to get the thermal neutron flux as high as possible, while keeping the low ratio of fast neutron flux to thermal neutron flux. T1 is the distance from neutron emission surface S1 on the moderator to the nearest edge of the target, T2 is the thickness of moderator in proton beam direction, and T3 is the distance from the moderator surface S2 to the nearest edge of the target. The moderator surfaces S1 and S2 are displayed in Fig. 1. The thickness of moderator in neutron beam direction is the sum of T1, T3 and the target diameter. The thickness of moderator in the direction being perpendicular to the paper is kept the same as T2.

In this study, the thermal neutron is defined as the neutron with the energy from 1.0 meV to 0.5 eV, and its flux is checked at the detector which is put at 2 m away from the target center. Furthermore, the collimator diameter is kept at 10 cm. Fig. 5 shows the thermal neutron flux with the variation of T1 and T2 under the condition of T3 = 2.5 cm. From the figure, it is indicated that under the condition of same T1, with the increase of T2 thermal neutron flux increases at first, then decreases. The maximum value is obtained when T2 has same size with the collimator diameter, i.e., 10 cm. From the figure, we also can see that the thermal neutron flux is sensitive to T1. For example, thermal neutron flux increases about 14% when T1 was changed from 2 cm to -1.5 cm under the condition of T2 = 12 cm. Based on Fig. 5, the maximum thermal neutron flux for each T1 is extracted and displayed in Fig. 6. You can find that the maximum thermal neutron flux can be obtained in the case of T1 = -1.5 cm and T2 = 12 cm (point with black circle in Figs. 5 and 6). According to the mission of KUANS, small ration of fast neutron flux to thermal neutron flux is necessary. The ratios at two surfaces, i.e. neutron emission surface of moderator and detector surface at 2m away for the target center, were checked, and the results are displayed in Fig. 7 and Fig. 8, respectively. To have low fast neutron to thermal neutron ratio, while keeping high thermal neutron flux, T1 = -0.5 cm and T2 = 12 cm (point with red circle in Fig. 6) may be a good choice based on the two figures.

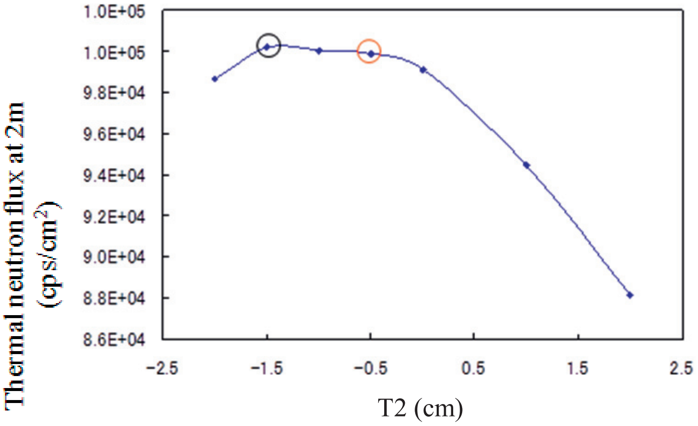

Fig. 5. Thermal neutron flux at 2m vs T2 under different T1.

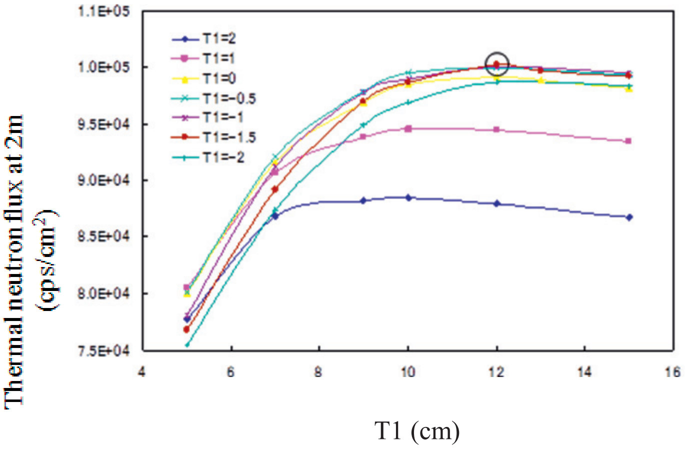

Fig. 6. Max. thermal neutron flux at 2m for each T1.

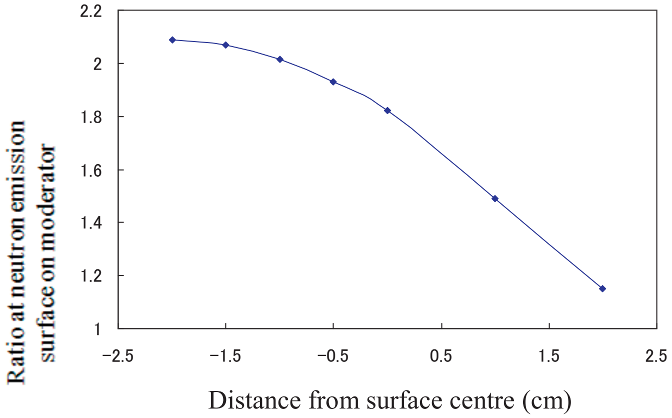

Fig. 7. Fast neutron to thermal neutron ratio on neutron emission surface of moderator.

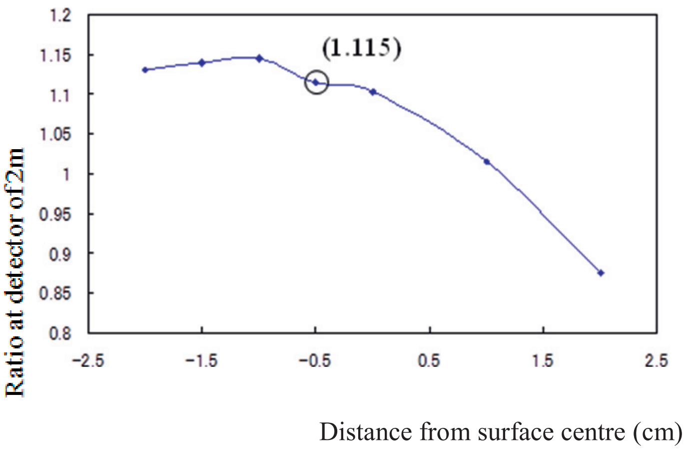

Fig. 8. Fast neutron to thermal neutron ratio on detector at 2m away from target centre.

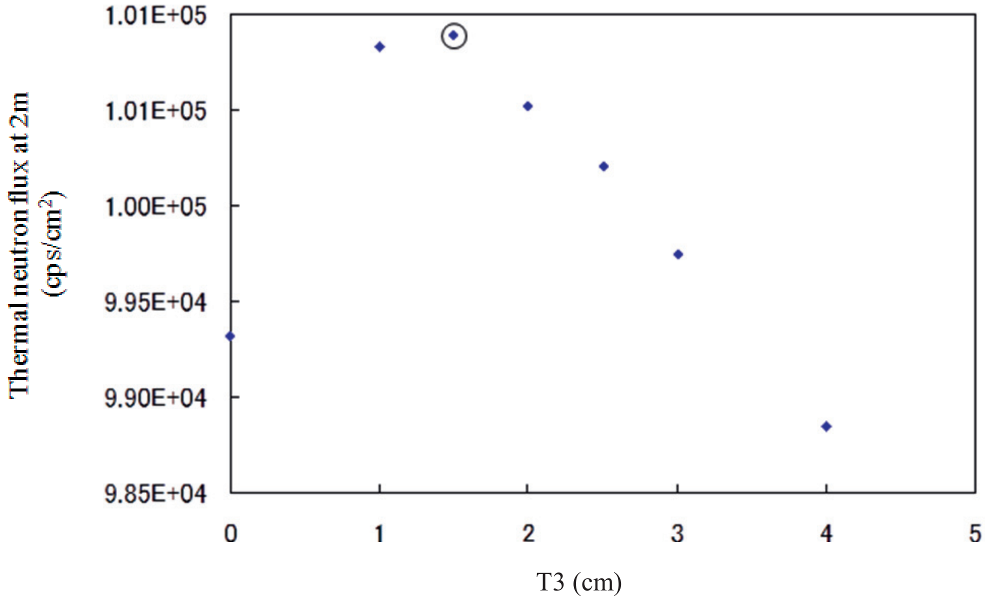

Fig. 9. Thermal neutron flux on detector at 2m away from target centre vs T3.

By fixing T1 and T2, T3 was varied from 1 cm to 4 cm. The thermal neutron flux is not sensitive to T3 as shown in Fig. 9. For example, when T3 increases from 1.5 cm to 4 cm, the thermal neutron flux only decreases about 2%.

Finally, the optimized moderator sizes may be: T1 = -0.5 cm, T2 = 12 cm and T3 = 1.5 cm.

2.4. Reflector optimization

For reflector, there are five parameters, i.e. R1, R2, R3, R4 and R5 should be optimized. R1, R2, R3 and R4 are indicated in Fig. 1, and R5 is the reflector thickness in the direction being perpendicular to the paper. As shown in Fig. 10, with the increase of reflector thickness, thermal neutron flux on the detector increases. But thermal neutron flux is only very sensitive to R4, for example, when R4 increases from 3 cm to 30 cm, the thermal neutron flux increases about 27.4%. Considering the situation on-the-spot and effect of each side thickness of reflector to thermal neutron flux, an appropriate reflector parameter sizes may be: R1 = 13 cm, R2 = 5 cm, R3 = 5 cm, R4 = 20 cm and R5 = 9 cm.

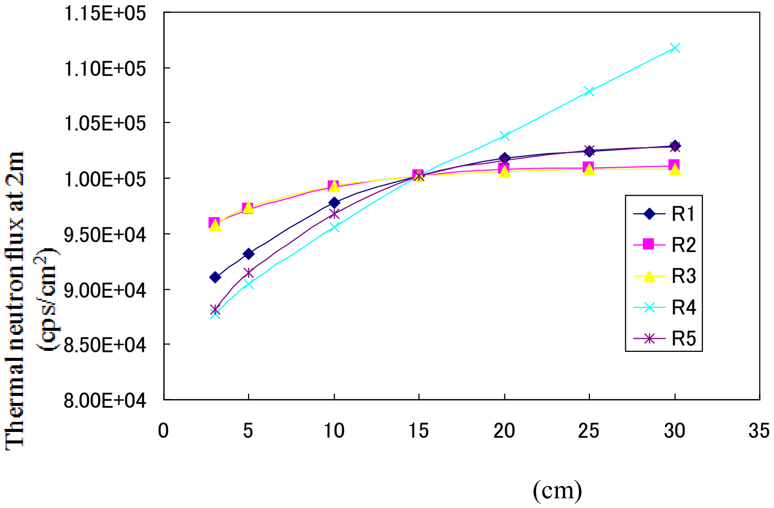

Fig. 10. Thermal neutron flux vs reflector thickness.

2.5. Shielding design

To make the shielding design compact, effective and low cost, borated polyethylene (BPE) with thickness of 50 cm was put along the proton beam and neutron beam. Outside of BPE block, normal concrete was put as shown in Fig. 11. According to the shielding simulation results in Figs. 12 and 13, along the neutron beam direction, both of neutron and gamma radiations are low, but in other directions, the neutron radiation is at the order of 10^3μSv/100μA/h, and the gamma radiation is about 10^2 to 10^3μSv/100μA/h. But since the accelerator-target complex of KUANS is in the shielded experimental hall and no one can have access to the room while beam is on, this radiation level can still be acceptable.

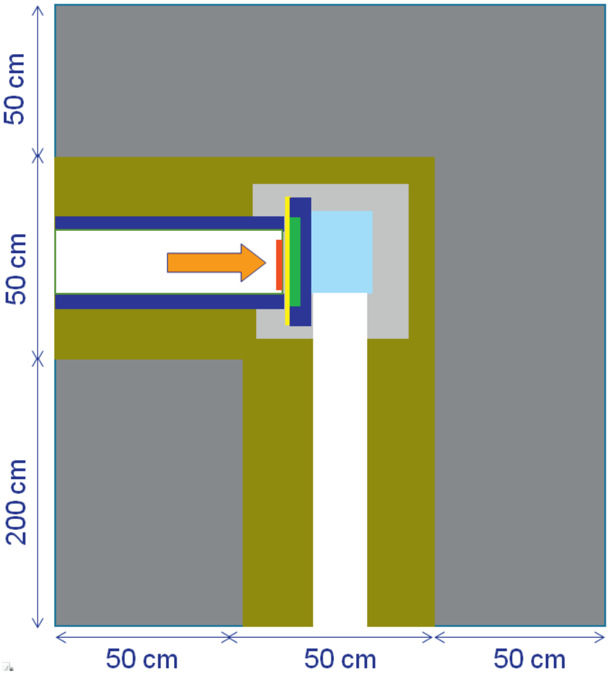

Fig. 11. Shielding design of KUANS.

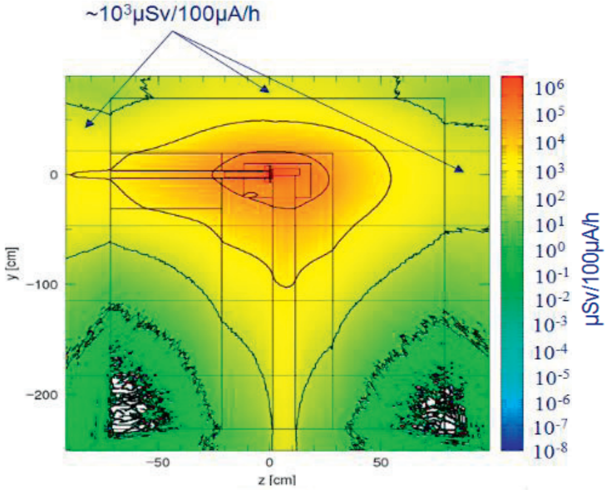

Fig. 12. Gamma radiation distribution.

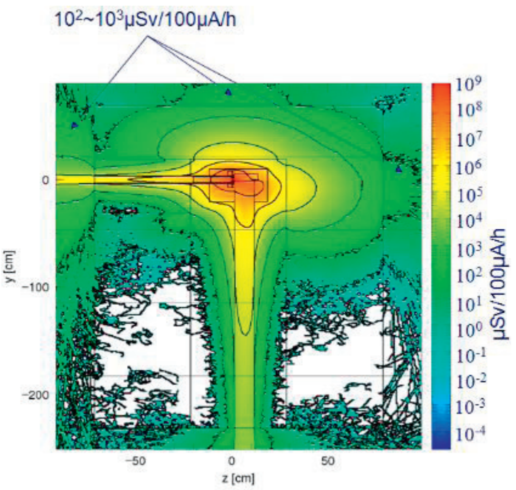

Fig. 13. Neutron radiation distribution.

Conclusions

In this paper, the design of target/moderator/reflector/shielding assembly of KUANS is introduced. The sizes of moderator and reflector were optimized with Monte Carlo code PHITS to have a high thermal neutron flux on the detector and keep the low ratio of fast neutron flux to thermal neutron flux. The optimized moderator sizes are: T1 = -0.5 cm, T2 = 12 cm and T3 = 1.5cm. The reflector can be designed as R1 = 13 cm, R2 = 5 cm, R3 = 5 cm, R4 = 20 cm and R5 = 9 cm. The BPE and normal concrete are combined to shield neutron and gamma radiations. Although the radiations are high in the direction of backward direction of neutron beam, the current shielding design can still be acceptable since the operation room is different with the room where KUANS accelerator-target complex is put.

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