Study on characteristics of neutron and γ-ray fields at compact neutron source RANS-II facility by simulation by the PHITS code

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Aiming at development of a compact neutron source for non-destructive inspection, RIKEN Accelerator-driven compact Neutron Source-II (RANS-II), based on the p-Li reaction with 2.49 MeV proton beam, has been under beam commissioning. As it is important to assess the validity of neutrons at the RANS-II facility, radiation fields in a rather narrow experimental room has been studied. The characteristics of neutron and γ-ray are calculated by simulation with Particle and Heavy Ion Transport code System (PHITS). As a result, except for a target station, neutrons and γ-rays distribute widely in the hall. The scattered radiation could be the major contributor to the background events in the future experiments. Thus, a collimator is designed to suppress the background radiation. In this article, we report the radiation fields in the RANS-II hall and the effectiveness of the collimator.

1 Introduction

RIKEN Accelerator-driven compact Neutron Source-II (RANS-II) has been under beam commissioning to demonstrate specific performance of the system[1]. At the RANS-II facility, neutrons are produced via ^{7}Li(p, n)^{7}Be reaction with 2.49 MeV proton beam. Through the studies of neutrons generated at RANS-II, RIKEN has a prospect of realizing novel non-destructive neutron inspection for infrastructures.

As prominent characteristics, RANS-II has the maximum neutron energy of 0.8 MeV, which is lower than that of 5 MeV at RANS based on the ^{9}Be(p, n)^{9}B reaction with 7 MeV proton injection[2]. Neutron at the RANS-II facility has extremely forward-favored angular distribution with respect to the proton beam direction. Also, it should be emphasized that the RANS-II system is installed in a relatively small space isolated by concrete shield with boron containment. Accordingly, there should be quite large differences in neutronic performances between RANS-II and RANS in terms of neutron spectrum and angular distributions. Prior to future experiments at RANS-II, the simulation of radiation fields for neutron and γ-ray in the RANS-II experimental hall plays a critical important role for designing experimental set-up in low background.

In this paper, we report characteristics of dose rate in the experimental hall. Major source of background and adequacy of shielding are discussed in viewing requirement from future experiment. Also we have preliminary designed collimators to provide neutron beam for the experiments. The effect of collimator is discussed from quality of neutron beam profile as well as reduction of radiation background in the hall.

2 Simulation

2.1 Cross section data and simulation code

We have performed simulations to characterize radiation fields of RANS-II with the use of Particle and Heavy Ion Transport code System (PHITS)[3]. To calculate neutron production via the ^{7}Li(p, n)^{7}Be reaction, Evaluated Nuclear Data File/B-VII.0 (ENDF/B-VII.0)[4] is employed. The cross section of ENDF/B-VII.0 is shown in Figure 1. Neutron energy spectra at six angles with respect to proton beam direction with ENDF/B-VII.0 is depicted in Figure 2. We use an angular width of $\pm 1.5°$ in the figure. According to Figure 2, characteristics of the maximum energy and the angler distributions of forward-favored are visible. Japanese Evaluated Nuclear Data Library-4.0 (JENDL-4.0)[5] and Livermore Evaluated Photon Data Library '97 (EPDL97)[6] is applied to calculate interactions of neutrons and γ-ray, respectively.

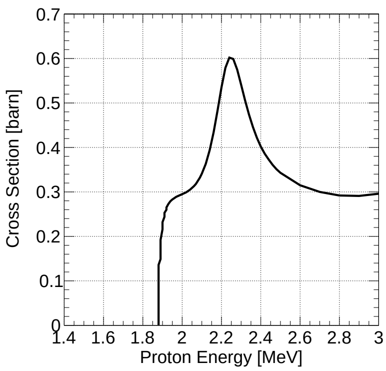

Figure 1: Cross section of ^{7}Li(p, n)^{7}Be reaction from ENDF/B-VII.0.

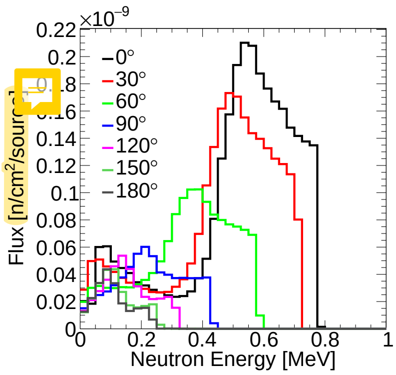

Figure 2: Neutron energy spectra from 0° to 180° at 30° intervals with respect to the proton beam direction.

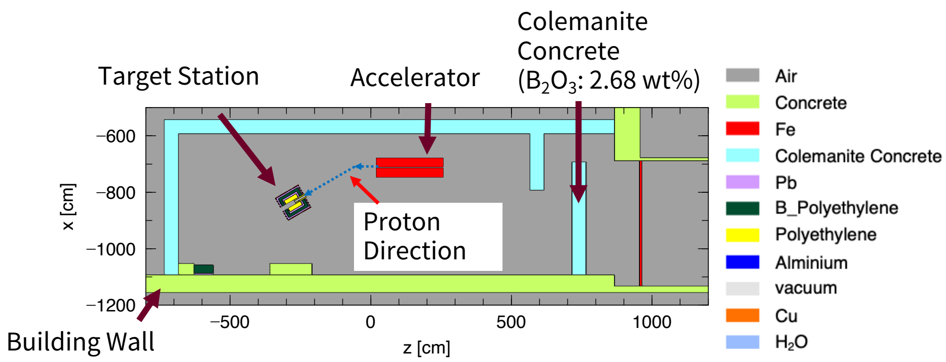

Figure 3: Plan view of the calculation model for the RANS-II experimental hall. Accelerator and target station of RANS-II are surrounded by concrete and partially colemanite concrete with boron.

2.2 Model for simulation

Simplified model of the RANS-II experimental hall, accelerator, target station in PHITS is illustrated in Figure 3. The size of the hall is about 14 × 5.5 × 3.0 m^3. An enlarged view of the target station is shown in Figure 4. The lithium(Li) target is made by depositing thin Li layer of about 100 μm on a 5 mm thick copper substrate cooled by water in the target station. The target station with all of the sides about 900 mm long has five layers, polyethylene(PE), lead(Pb), borated polyethylene with 10 % weight B_2O_3(BPE), lead and iron to reduce the radiation leakage. There is a hole with a 150 × 150 mm^2 cross section in the forward direction. Calculations introduced in the following chapters are performed with these systems.

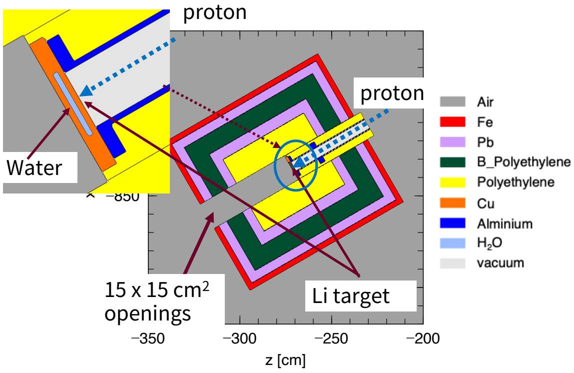

Figure 4: RANS-II target station.

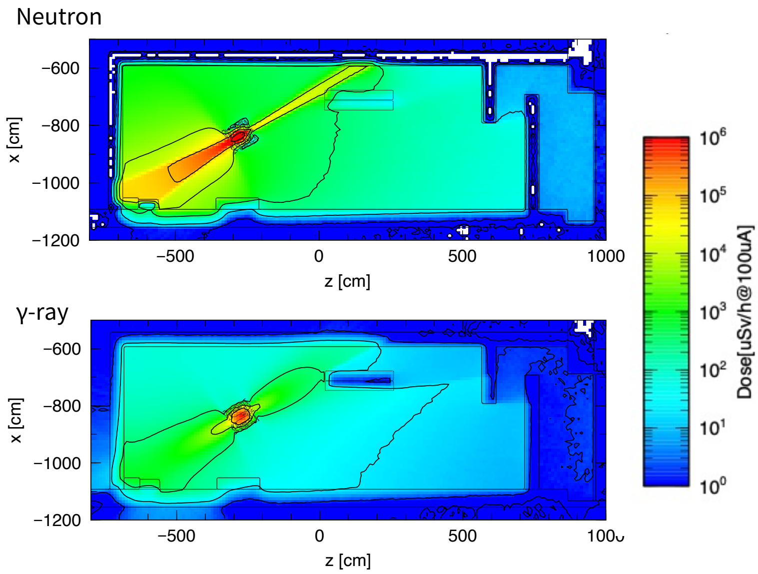

Figure 5: Dose rate distribution of neutrons and γ-rays at the RANS-II hall. The T-Track tally in PHITS is used. The mesh width for both x and z axis is 100 mm in the calculation.

3 Result and discussion

3.1 Dose rate distribution

We assume 100 μA for the proton beam current at the Li target. Dose rate distribution of neutrons and γ-rays at the RANS-II hall is depicted in Figure 5. The dose conversion coefficient[7] in PHITS is utilized in Figure 5. Along the downstream of the beam line, the highest dose rate of neutrons is shown. Except locations near the neutron production target and along the proton beam direction, dose rate distribute uniformly. Around the side of the target station, the dose rate is the order of 1.0 mSv/h and 0.1 mSv/h for neutron and γ-ray, respectively. For the neutrons, the dose rate is caused by the scattered neutrons with the down stream concrete walls. Dose rate of γ-ray is mainly attributed to γ-ray from the reactions between neutrons and elements in the concrete. The ratio of the component scattered from the concrete walls is about 90% for both neutrons and γ-ray at the region. The scattered neutrons and γ-rays become background events in the future experiments. Suppression of the background radiation is important. Therefore, we have a plan to install a collimator in the target station to reduce the excessive spread of the neutron beam introduced in the following chapter.

3.2 Collimator

To suppress the spread of neutrons, it is intended to insert a collimator in the downstream openings at the target station as shown in Figure 6. There is a cylindrical cavity at the center of the collimator. The length of the collimator is 530 mm. It is necessary to examine the influence of the collimator's material and hole diameter for neutron suppression capacity. The material of the collimator is assumed to be PE or BPE. The hole diameter is 10, 30 and 50 mm. At the downstream of the target station, detectors in simulation are aligned along a surface perpendicular to proton beam direction. Sizes of the detectors are $10 \times 10 \times 10$ mm^3 and $100 \times 100 \times 100$ mm^3 at the central region and outside region, respectively. x' axis is defined as the axis along the detectors. The number of neutrons is obtained by the T-Cross tally implemented in PHITS. The energy range for fast and thermal neutrons is set from 10^{-2} to 10^{2} MeV and from 10^{-9} to 10^{-7} MeV, respectively.

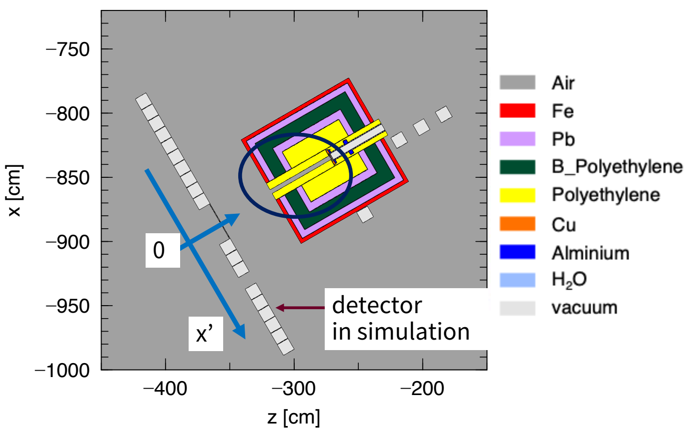

Figure 6: Target station with a PE collimator.

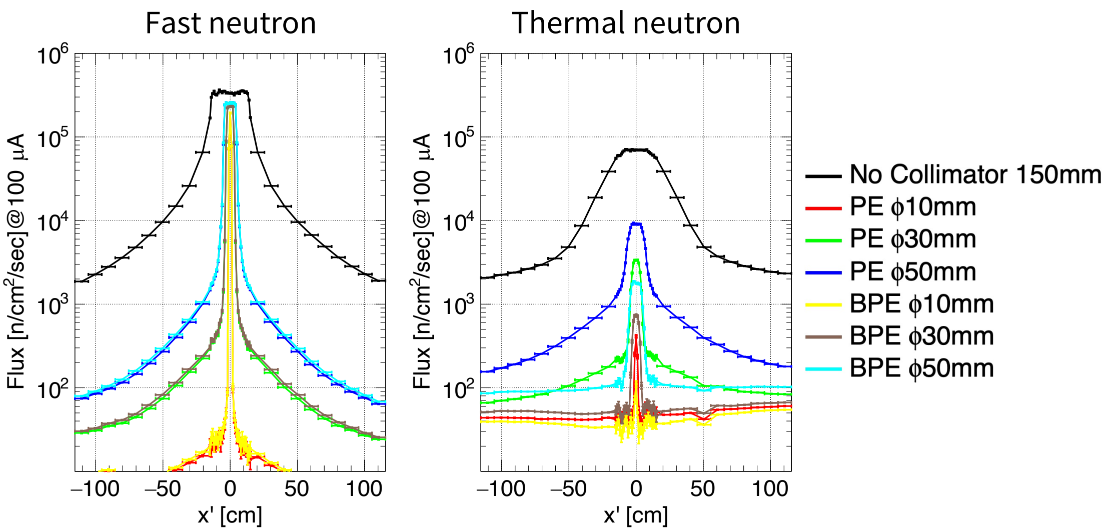

Figure 7: Fast and thermal neutron flux at the downstream. The horizontal axis means the value of x'. The vertical axis represents the flux of neutrons.

The results of neutron flux are shown in Figure 7. The black line stands for the result without the collimator. The red line means the outcome for the PE collimator with the 10 mm cylinder hole. The other colors' lines are similar to the red line. Because the PE or BPE collimator has elements with small mass number, it is effective for neutron suppression. According to the results of fast neutrons, the suppression ability for the PE collimator is a little greater than that for BPE collimator. This is attributed to the greater amount of hydrogen in the PE collimator than BPE one. For thermal neutrons, the BPE collimator has much stronger power than the PE collimator due to boron effect. The result suggests that the BPE collimator is appropriate to reduce the wide spreading of thermal neutrons. When the diameter of the collimator is 10 mm, the number of neutrons is too suppressed to utilize for future experiments. The collimator with 30 mm hole is enough to provide sharp neutron beam because the fast and thermal neutron flux are roughly to be less than 1/100 at the outer region from x' = 15 compared with the value at x' = 0. Accordingly, we conclude that BPE collimator with 30 mm hole is suitable for neutron suppression.

Because the γ-rays' attenuation in materials depends on the mass number, significant effect for γ-ray of the BPE collimator is not expected. To control γ-ray distribution, the material of the collimator is changed to BPE and Pb as shown in Figure 8. The length of the Pb collimator is 230 mm. The minimum and maximum energy in the tally is fixed to be from 10^{-9} to 10^{2} MeV for both neutrons and γ-rays. The other conditions for the calculation are the same as above calculation.

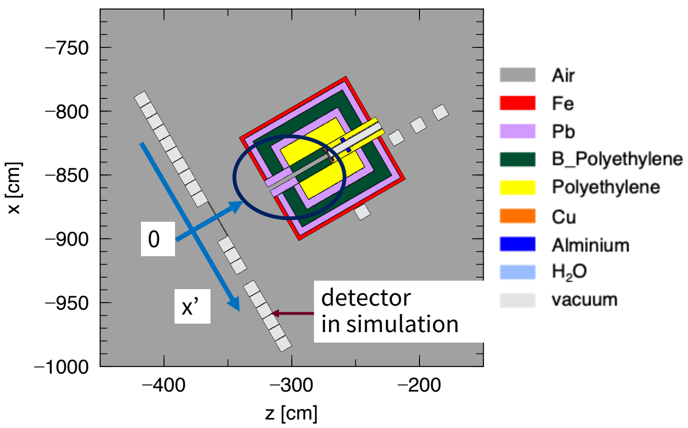

Figure 8: Target station with a BPE + Pb collimator.

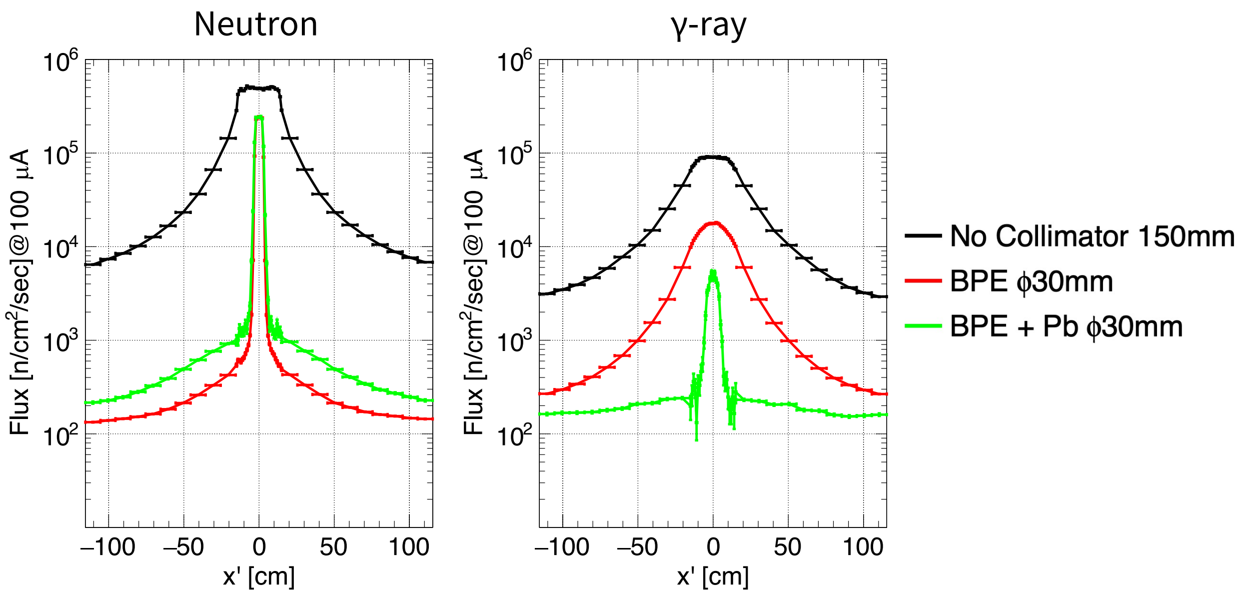

Figure 9: Neutron and γ-ray flux at the downstream.

The calculation results with BPE + Pb collimator are depicted in Figure 9. The black, red and green line stands for the result without the collimator, that with the BPE collimator and that with the BPE + Pb collimator, respectively. According to the neutron result, the neutron flux with the BPE and Pb collimator is a little greater than that of only BPE collimator due to the reduction of BPE area of the collimator. On the other hand, great contribution for γ-ray flux is observed. Compared with the value at the point of x' = 0, γ-ray flux drops by about 5% at the external area from x' = 15.

4 Conclusion

The distribution of neutrons and γ-rays in the RANS-II experimental hall are acquired with the use of PHITS. The interactions of neutrons and γ-rays are described by JENDL-4.0 and EPDL97, respectively. Due to the openings at the downstream of the target station and small experimental hall, Neutrons and γ-rays spread widely in the hall. When the BPE and Pb collimator is installed in the openings of the target station, The RANS-II facility can supply sharp neutron beam with low background condition.

References

[1] Kobayashi T, et al., Completion of a new accelerator-driven compact neutron source prototype RANS-II for on-site use, Nucl. Instr. Methods, Phys. Res., Sect. A, vol. 994, 2021, pp. 1-6, 165091.

[2] Otake Y, RIKEN Compact Neutron Systems with Fast and Slow Neutrons, Plasma Fusion Res., vol. 13, 2018, 2401017.

[3] Sato T, et al., Features of Particle and Heavy Ion Transport code System (PHITS) version 3.02, J. Nucl. Sci. Technol., vol. 55, 2018, pp. 684-690.

[4] Chadwick, M.B., et al., ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology, Nucl. Data Sheets, vol. 107, 2006, pp. 2931-3060.

[5] Shibata K, et al., JENDL-4.0: A New Library for Nuclear Science and Engineering, J. Nucl. Sci. Technol., vol. 48, 2011, pp. 1-30.

[6] Cullen, D.E., et al., "EPDL97: the Evaluated Photon Data Library, '97 Version", UCRL-50400, Vol. 6, Rev. 5, Lawrence Livermore National Laboratory (1997).

[7] Sakamoto Y et al., Dose conversion coefficients for high-energy photons, electrons, neutrons and protons, JAERI-1345, 2003 [in Japanese].

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