Slab geometry type cold neutron moderator development based on neutronic study for Riken Accelerator-driven compact Neutron Source (RANS)

Baolong Ma[1,2,*], *Yujiro* Ikeda[2,3], *Yoshie* Otake[2,1], *Makoto* Teshigawara[3], *Yasuo* Wakabayashi[2], *Masahide* Harada[3], *Motoki* Ooi[3], *Takao* Hashiguchi[2], *Yutaka* Yamagata[2], and *Shin* Takeda[2]

[1]School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, China
[2]RIKEN center for advanced photonics, RIKEN, Wako, Saitama, Japan
[3]J-PARC Centre, Japan Atomic Energy Agency, Naka-gun, Ibaraki, Japan

Abstract. Cold neutrons with energy less than several meV are good probes for material research, and they have been available on large neutron facilities, whereas it is not commonly available on compact accelerator-driven neutron source. RIKEN Accelerator-driven Neutron Source (RANS) is a pulsed neutron facility which provides thermal neutrons and high energy neutrons at several MeV. We started a project to implement a cold neutron moderator for RANS to broaden cold neutrons applications. A cold neutron moderator system with a mesitylene moderator at 20K and a polyethylene pre-moderator at room temperature in the slab geometry was designed for RANS. So far, the thickness of the pre-moderator and mesitylene have been optimized to get the highest cold neutron flux by using a Monte Carlo simulation code, PHITS. Graphite reflector dimensions were also proven to have significant effect to increase the cold neutron intensity.

1 Introduction

Cold neutrons are important in neutron scattering investigation for material science because they have suitable energies for materials structure analysis. However, cold neutron sources are usually available at spallation neutron sources like J-PARC (Japan Proton Accelerator Research Complex) [1], ESS (European Spallation Source) [2], and SINQ (The Swiss Spallation Neutron Source at PSI) [3] and reactor neutron sources like ILL (Institut Laue–Langevin) [4], HFIR (High Flux Isotope Reactor) [5], and JRR-3 (Japan Research Reactor No.3) [6]. Recent advanced accelerator technology dramatically increases the availability of neutrons, especially with compact accelerator-driven neutron sources. RANS is an accelerator-based pulsed neutron facility using the ^{9}Be(p,n)^{9}B reaction [7] in a beryllium target with 7 MeV proton injection.

The slab geometry was taken for RANS cold neutron moderator to couple the neutron production target and the moderator. Polyethylene (PE) was adopted as a pre-moderator and mesitylene as a moderator. To maximize the cold neutron intensity as much as possible, pre-moderator thickness and mesitylene thickness were optimized by a Monte Carlo simulation, Particle and Heavy Ion Transport code System (PHITS) [8]. The graphite reflector effect on cold neutron intensity was investigated.

2. Overview of RANS

At RANS, pulsed neutrons are produced via the ^{9}Be(p,n)^{9}B reaction with 7 MeV proton injection. RANS has a beryllium target which is brazed to a vanadium backing material to let hydrogen diffuse and to mitigate hydrogen embrittlement. RANS target is cooled by water which flows through a titanium cavity. Currently, RANS uses 40 mm-thick polyethylene moderator for thermal neutrons. The core area of RANS target is surrounded by a graphite reflector to enhance the neutron beam intensity. RANS target station adopts a multi-layer shielding structure of BPE, Pb, BPE, and Pb with the thickness of 25 cm, 10 cm, 25 cm, and 5 cm, respectively. A schematic diagram of RANS target station is shown in Fig.1.

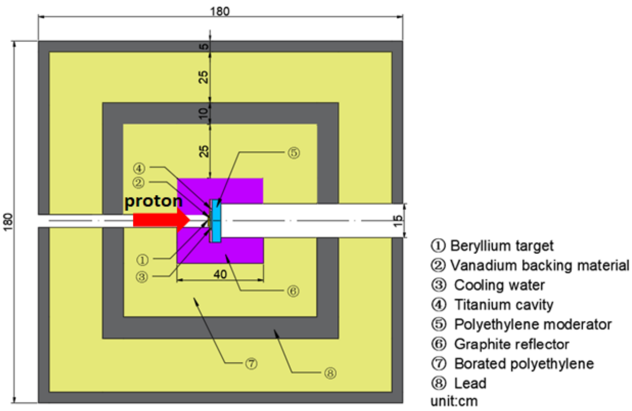

Fig. 1. RANS target station.

* Corresponding author: baolong.ma@riken.jp

With current RANS target assembly, the calculated neutron spectrum by PHITS at 3 m away from the target along the neutron extraction direction is shown in Fig.2. It shows that both thermal neutron flux and high energy neutron flux can be obtained.

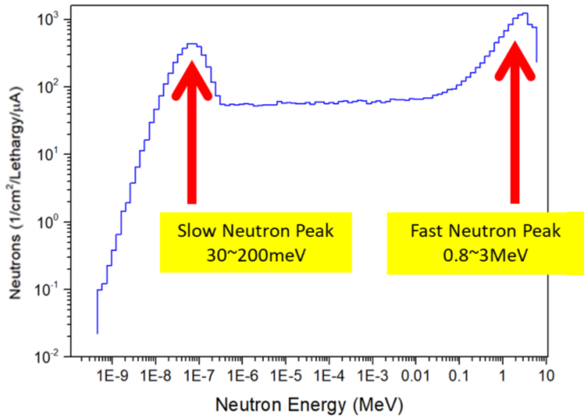

Fig. 2. RANS neutron spectrum at 3 m away from the target by PHITS simulation.

3. Simulation calculation

3.1 RANS cold moderator design

RANS cold moderator configuration uses a mesitylene cold moderator at 20K with a polyethylene pre-moderator at room temperature in a slab geometry. Mesitylene has good characteristics of non-explosive, easy to handle, good irradiation tolerance, and good neutronic performance [9]. In this study, we considered a realistic configuration of moderator with a 0.3 cm aluminium vessel wall and vacuum layer. The lateral size of the cold moderator is about 10 x 10 cm^2, and the size of the neutron beam extraction hole is 7.5 x 7.5 cm^2. Mesitylene is installed in an aluminium vessel which is surrounded by polyethylene pre-moderator (See Fig. 3(a)). Fig.3 (b) shows the RANS target assembly with the cold moderator using a slab geometry. The cold neutron performance at 2 m in the extraction direction from the target was characterized. So far, we have optimized the thickness of the pre-moderator and the mesitylene to get the highest cold neutron flux.

3.2 Thickness optimization

The PE pre-moderator thickness T_1 and the mesitylene moderator thickness T_2 were free parameters of the optimization. In the calculation for the cold neutron intensity, neutron scattering kernels of mesitylene (20K), polyethylene (296K), water (296K), and graphite (293.6K) were used. The scattering kernel data of polyethylene, water, and graphite are from JENDL-4.0 [10] and scattering kernel data of mesitylene was provided by F. Cantargi, et al. [11]. In the calculation, the detector was placed at 2 m away from the RANS target. [T-Track] tally was used to calculate the neutron intensity within an energy range of 0.1meV to 10meV. The dimension of the surrounding polyethylene was kept as shown in Fig.3 (a).

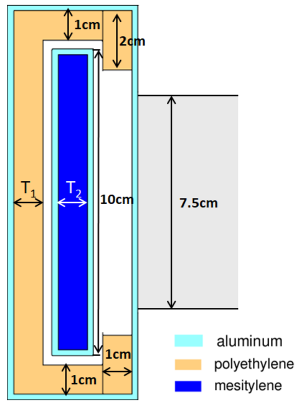

Fig.3 (a). RANS cold moderator with slab geometry.

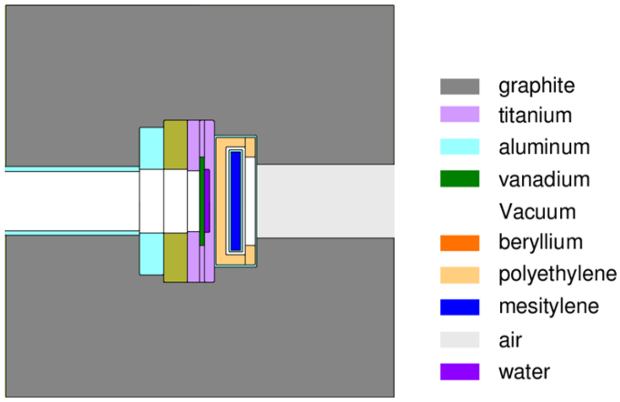

Fig.3 (b). RANS cold neutron moderator geometry.

Cold neutron intensity was calculated by varying pre-moderator thickness from 0 to 5 cm and moderator thickness from 1 cm to 6 cm. Optimization results are shown in Fig. 4.

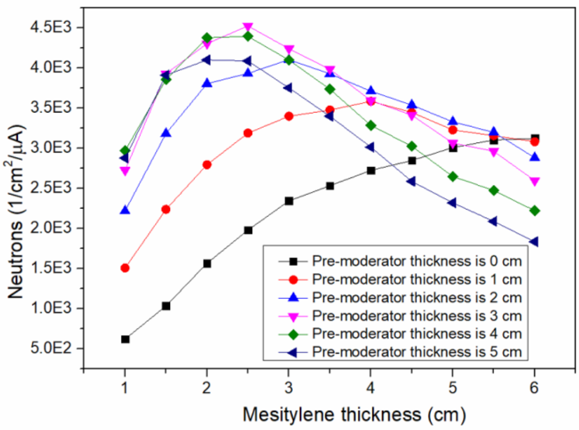

Fig. 4. Cold neutron intensity as a function of pre-moderator and moderator thickness

The pre-moderator is a key to maximize the cold neutron flux. When the pre-moderator thickness increase beyond 4 cm, the efficiency becomes smaller. For a fixed pre-moderator thickness, the cold neutron intensity increases up to a mesitylene thickness of 2.5 cm. The highest cold neutron intensity was found to be 4.5×10^3 neutron/cm^2/μA with a pre-moderator thickness of 3 cm and a moderator thickness of 2.5 cm.

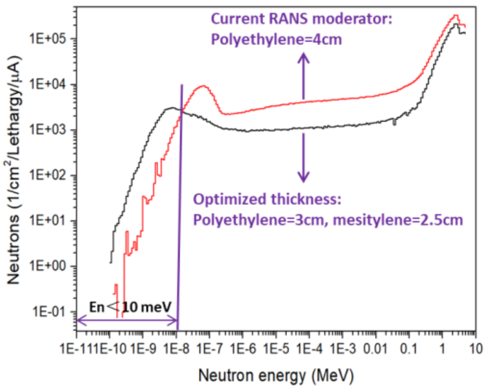

Fig. 5. Neutron spectrum of the RANS current moderator and for an optimized cold moderator

Compared with the RANS current moderator of 4 cm polyethylene and the optimized cold moderator with pre-moderator and mesitylene moderator thicknesses are 3 cm and 2.5 cm, respectively. The optimized moderator gives neutron intensity below 10 meV higher by a 5.6 compared to the current RANS moderator.

3.2 Evaluation of reflector dimension

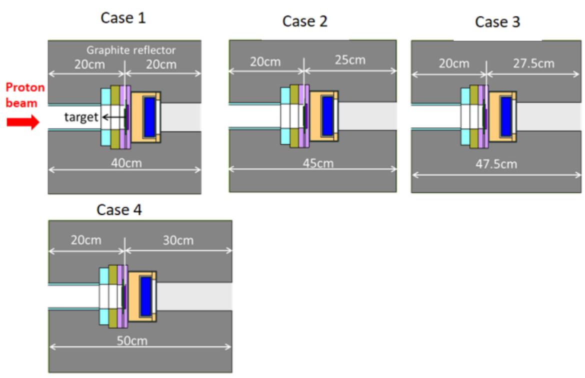

Fig. 6. Four cases of graphite reflector dimension

The cold neutron intensity was evaluated with respect to the reflector dimensions. Case 1 is the current RANS graphite dimension with 20 cm-thick in both forward and backward direction from the neutron production target. For case 2, case 3, and case 4, the graphite thickness in forward direction was increased by 5 cm, 7.5 cm, and 10 cm, respectively while the graphite thickness in backward direction is kept as 20 cm. All the calculation conditions were kept the same as previously in terms of kernel nuclear data, cold neutron energy, and tally. The statistical errors of the calculation are below 2%. The results are shown in Fig. 7.

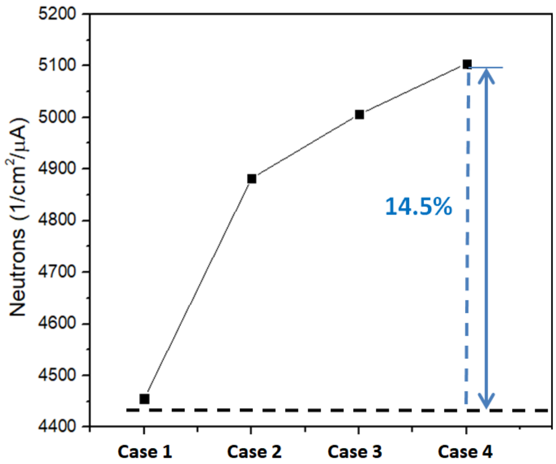

Fig. 7. Cold neutron intensity as a function of the graphite reflector dimension

It shows that by adding thickness in the forward direction, i.e., neutron extraction direction, the cold neutron intensity can be increased accordingly. By adding 10 cm of graphite at neutron emission side, cold neutron intensity could be increased by 14.5% .

4. Conclusions

Currently, we focused on the neutron intensity enhancement. The main conclusions are as follows:
1. By optimizing the thickness of polyethylene and mesitylene, at 2 m away from the target, the cold neutron intensity can be increased by a factor of 5.6 compared with the current moderator model;
2. Increasing the graphite thickness in the neutron emission direction has considerable effects to increase the cold neutron intensity. For RANS case, graphite is going to be remoulded to get higher cold neutron intensity;
3. High energy neutrons whose energy is higher than 1 MeV exist in the spectrum with respect to the slab geometry. So the neutron extraction at other angles will be considered for RANS to decrease the fast neutron background.
4. The estimations of neutron pulse and neutron brightness are under study.

Reference

[1] Takada, Hiroshi, et al. "Materials and life science experimental facility at the Japan proton accelerator research complex I: pulsed spallation neutron source." Quantum Beam Science 1.2 (2017): 8. < https://j-parc.jp/c/en/ >.
[2] Bauer, Günter S. "The European Spallation Neutron Source Project (ESS)." Utilisation and Reliability of High Power Proton Accelerators (1998): 59. <https://europeanspallationsource.se/>.
[3] Fischer, W. E. "SINQ—the spallation neutron source, a new research facility at PSI." Physica B: Condensed Matter 234 (1997): 1202-1208. <https://www.psi.ch/en/media/the-sinq-neutron-source>.

[4] Ageron, Paul. "Cold neutron sources at ILL." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 284.1 (1989): 197-199. < https://www.ill.eu/>.
[5] Mason, T. E., et al. "The Spallation Neutron Source in Oak Ridge: A powerful tool for materials research." Physica B: Condensed Matter 385 (2006): 955-960. < https://neutrons.ornl.gov/hfir>.
[6] Kawabata, Yuji, et al. "Characteristics of neutron guide tubes in upgraded JRR-3." Journal of Nuclear Science and Technology 30.10 (1993): 1050-1058. < https://jrr3.jaea.go.jp/>.
[7] Yamagata, Yutaka, et al. "Development of a neutron generating target for compact neutron sources using low energy proton beams." Journal of Radioanalytical and Nuclear Chemistry 305.3 (2015): 787-794.
[8] Niita, Koji, et al. "PHITS—a particle and heavy ion transport code system." Radiation measurements 41.9-10 (2006): 1080-1090.
[9] Natkaniec, Ireneusz, Krystyna Holderna-Natkaniec, and Jurgen Kalus. "Neutron scattering studies of methyl derivatives of benzene selected as potential materials for cold neutron moderators." Physica B: Condensed Matter 350.1-3 (2004): E651-E653.
[10] Shibata, Keiichi, et al. "JENDL-4.0: a new library for nuclear science and engineering." Journal of Nuclear Science and Technology 48.1 (2011): 1-30.
[11] Cantargi, F., et al. "New scattering kernels for some materials of interest as advanced cold neutron moderators." Physica B: Condensed Matter 385 (2006): 1312-1314.