Project Title:

Simulation and design of a transportable and compact neutron source based radiography system for industrial applications

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Description of the project

1. Background

Investigation of inside structure as well as outside profile is important for many industrial applications. Concerning X-ray imaging systems, they have been applying not only to measure the outside profile but to investigate the inside defects such as welding part, cast components and so on. However, X-ray imaging system has limit on penetration depth so that it is hard to measure large industrial components or structures.

Neutron beam has advantages on penetration depth over X-ray. Furthermore, material information like strain or temperature that may be obtained by using pulsed neutron source will be quite useful in production engineering. Thus, neutron radiography is expected to be widely utilized in the production processes compared to X-ray CT systems, which are recently becoming popular method for product inspection on-site. Neutron radiography has a number of advantages over X-ray system. However, it requires very large accelerator systems.

Primary applications of compact accelerator based neutron source are radiography of industrial components. By utilizing deep penetration depth of neutron beam, investigation of pores inside cast iron parts or other heavy materials are preferable application. Inspection of junction between composite material (carbon fiber structure and steel or aluminium) could be another good application taking advantage of neutron radiography. If transportable neutron source is possible, it can be applied to investigation of large industrial product like aircraft or ship or large scale structures like bridges and buildings.

Furthermore, neutron scattering research is performed primarily at large-scale facilities. However, history has shown that smaller scale neutron scattering facilities can play a useful role in education and innovation while performing valuable materials research.

For industrial radiography applications, we have designed and constructed a compact neutron source using a small proton accelerator (proton energy about 7.0MeV and 0.7kW beam power) combined with a beryllium target during last year based on Monte Carlo calculation by using RICC. It was named as RIKEN Accelerator-driven compact Neutron Source (RANS). It is located in RIBF Building inside RIKEN Wako campus as shown in Fig. 1. The facility is surrounded by the concrete with thickness of 1.5 meters. In front of the neutron beam, a Hazama concrete wall with thickness of 0.5 meter is put to shield both of neutron and photon.

The detailed design is displayed in Fig. 2. The target/moderator/reflector/shielding design for the 7.0 MeV small neutron source is displayed in Fig. 2. To make a compact size, a multi-layer shielding design is adopted to shield both of photon and neutron. Boracic acid resin is used to shield the neutron and lead to shield photon. A beryllium plate which has 5 cm diameter and 300 μm thickness was used for target. For reflection of neutron, graphite was adopted.

Monte Carlo calculation is the basic and the most important tool for the compact neutron source design, as well as for the whole radiography system design.

As known to all, Monte Carlo calculation is very time-consuming. The calculation cost almost has linear relationship with the particle number. At the same time, Monte Carlo code always has a perfect parallel efficiency. So running the parallel Monte Carlo calculation by using RIKEN Cluster (RICC) is very necessary for the success of this project. The necessary parts that should be decided via the Monte Carlo simulation are the sizes of moderator and reflector as shown in Fig. 3, as well as the shielding design.

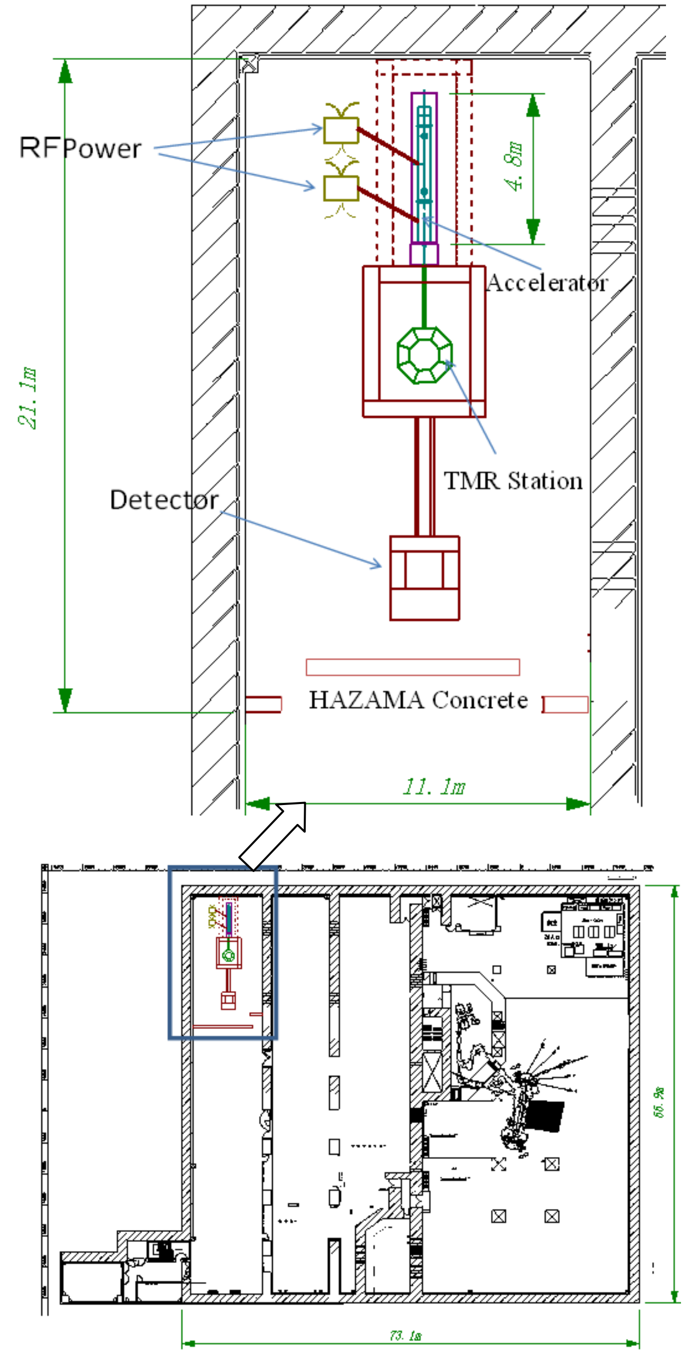

Fig.1. Layout of small-scale neutron source facility in RIBF Building on RIKEN Wako Campus

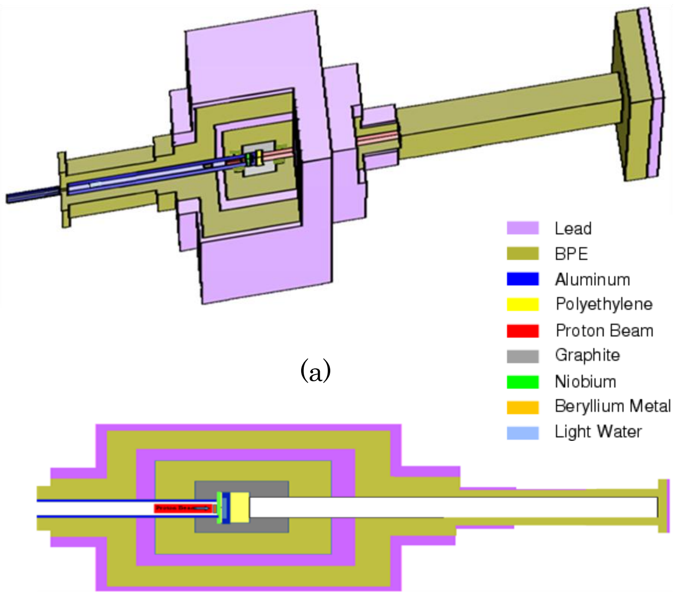

Fig. 2 The design of RANS: (a) Three-dimensional (b) Two-dimensional

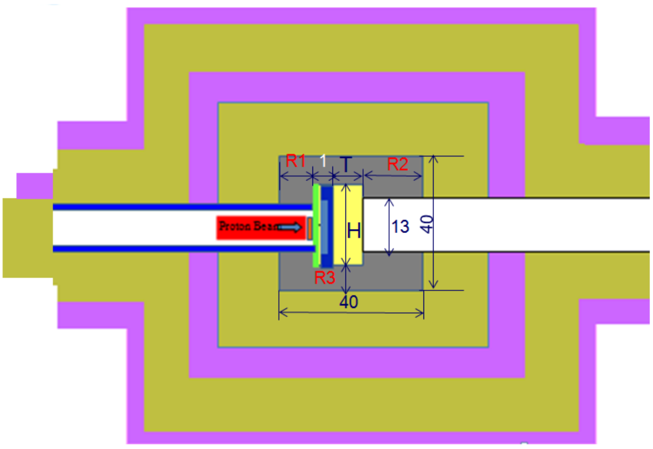

Fig. 3 Sizes to be optimized via Monte Carlo calculation

2. Simulation results

To get the thermal neutron as much as possible, the optimized design for moderator is the most important thing. There are two parameters that we should decide for the moderator. One is its thickness, and another one is the height. From Fig. 4, you may find that with the thickness of 4cm, the moderator has the best moderation effect. As indicated in Fig. 5, the moderator with the height of 20cm has the highest thermal neutron flux. Therefore, the moderator with 4cm thickness and 20cm height has best performance, and has been adopted in the RANS.

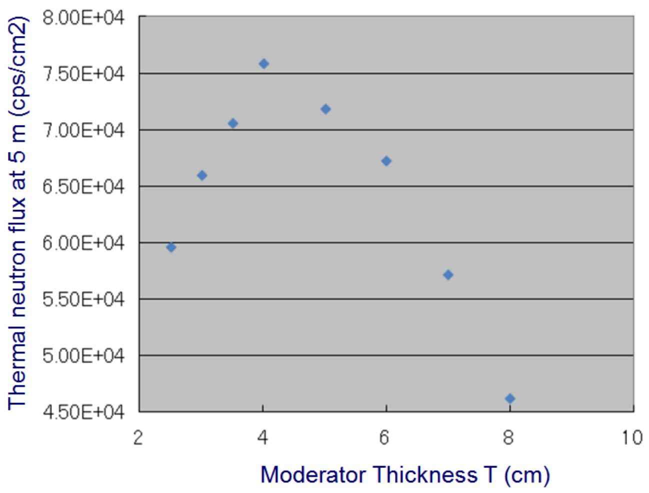

Fig. 4 Thermal neutron flux vs moderator thickness

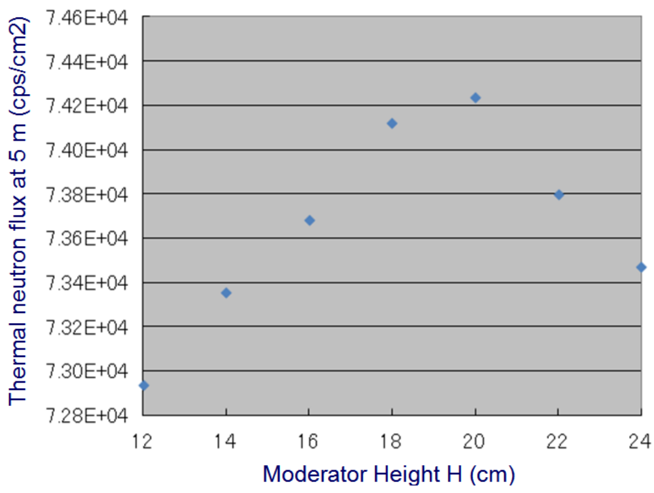

Fig. 5 Thermal neutron flux vs moderator height

About the reflector, the sizes that should be determined based on Monte Carlo calculation using RICC are R1, R2 and R3 as shown in Fig. 3.

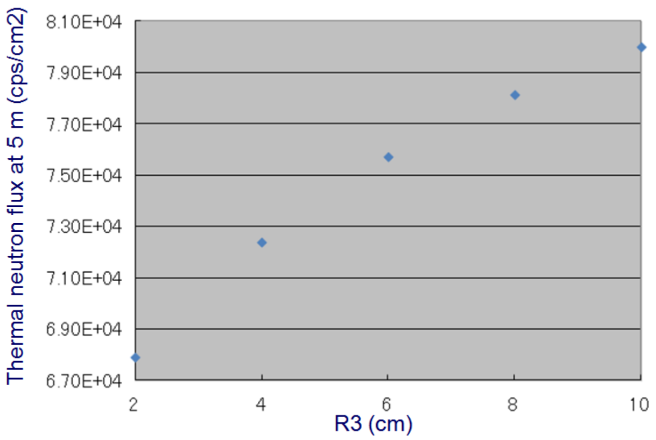

Fig. 6 Thermal neutron flux vs reflector size R3

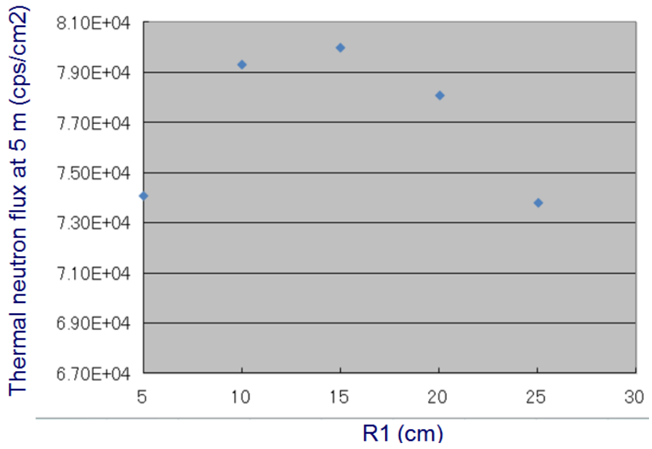

Fig. 7 Thermal neutron flux vs reflector size R1

Based on the calculation results shown in Fig. 6 and Fig. 7, the reflector with R1=15cm, R2=20cm, R3=10cm has the highest thermal neutron flux.

With the optimized moderator and reflector, the neutron energy spectrum distributions on the detector which is placed at 3m and 5m away from the target are shown in Fig. 8 and Fig. 9 respectively. From the two figures, you may find there are two peak values. One happens within the thermal neutron range and another one happens in the fast neutron range. The fast neutron flux is high and we will try to make use of it for the development of fast neutron imaging system.

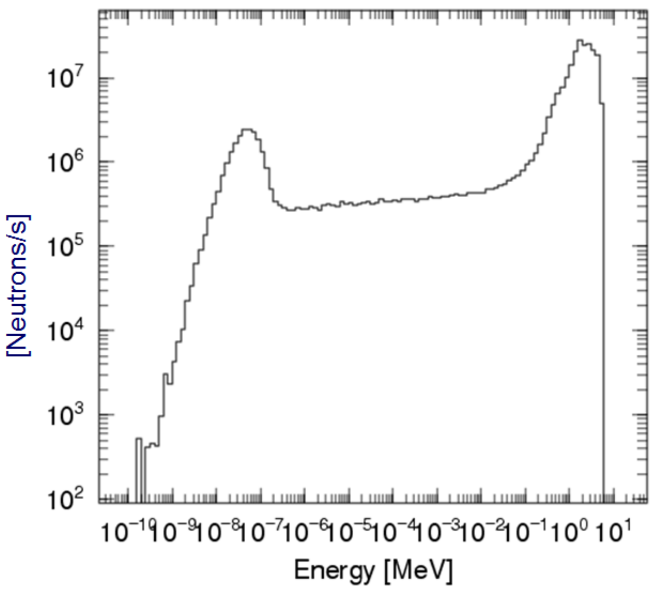

Fig. 8 Neutron energy spectrum at detector 3m away from target

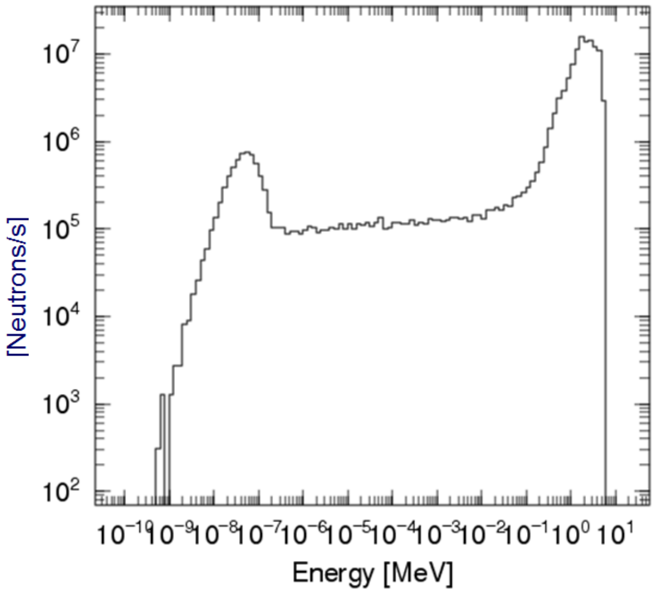

Fig. 9 Neutron energy spectrum at detector 5m away from target

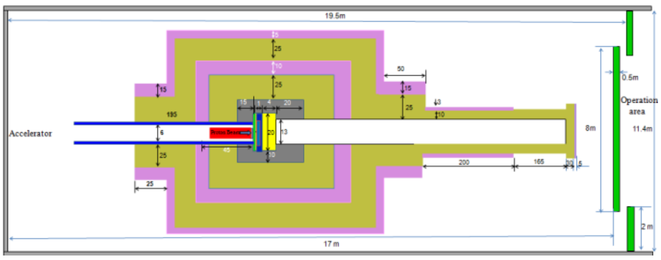

Fig. 10 Trial case of shielding design

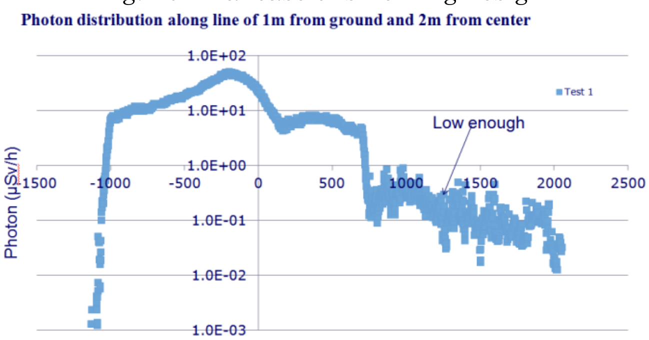

Fig. 11 Photon distribution with trial case

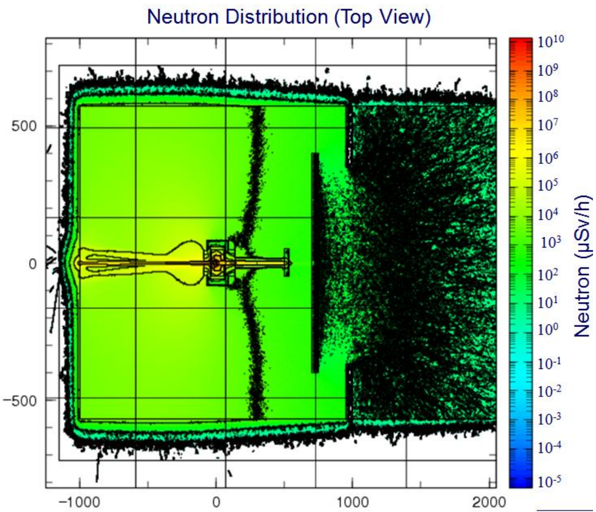

Fig. 12 Neutron distribution (2D) with trial case

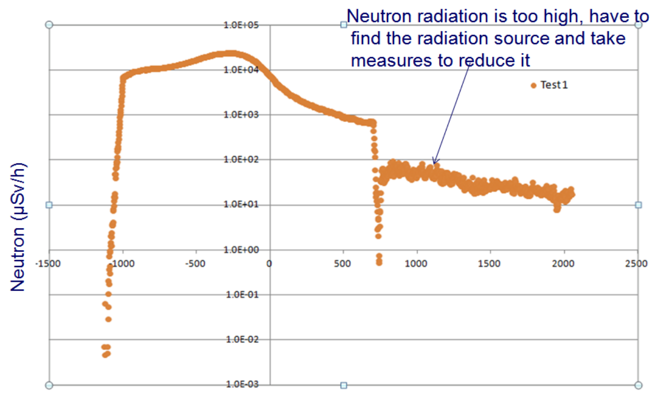

Fig. 13 Neutron distribution (1D) with trial case

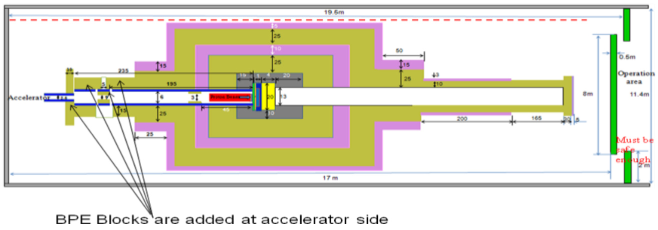

Fig. 14 Shielding design after adding BPE blocks in accelerator side

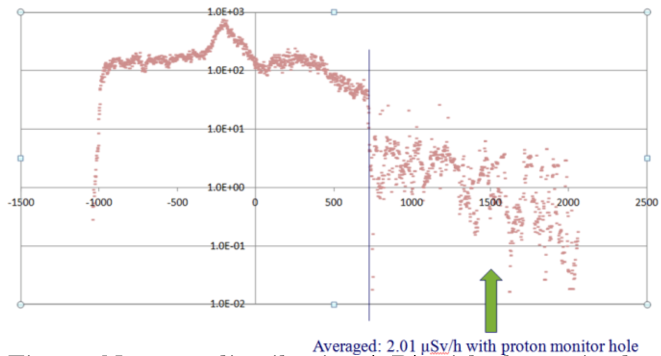

Fig. 15 Neutron distribution (1D) with the revised shielding design

To evaluate the multi-layer shielding design, the Monte Carlo calculation for the photon and neutron dose distribution was carried out for the whole domain. Figure 10 shows a trial case of shielding design. With this design, you may find from Fig. 11 that the radiation level of photon is low enough, however the radiation level of neutron is too high to be accepted as indicated in Figs. 12 and 13. Therefore we put additional BPE blocks for neutron shielding in accelerator side. With the addition BPE blocks the shielding effect is very evident and the neutron radiation level around the operational area is decreased to 2.01 μSv/h as shown in Fig. 15. This radiation level is quite acceptable and the shielding design is a final scheme for RANS.

3. Current status of RANS

At present, RANS has been constructed as shown in the following figure and thermal neutron beam with our expected flux has been detected. RANS has passed the radiation inspection by Japanese government and the safety certificate has been obtained.

Fig. 16 Current status of RANS

4. Conclusion

The optimized design for moderator and reflector and shielding design have been carried out by Monte Carlo calculation via RICC. Based on the calculations, RANS with thermal neutron beam line has been constructed and passed the radiation inspection. RICC has given us big helps. Without RICC, it is impossible for us to achieve our objective. We really appreciate RICC very much!

5. Schedule and prospect for the future

Within the fiscal year of 2013, the following three objectives have to be achieved with Monte Carlo simulation running on RICC. (1) Apr. 1, 2013-May 31, 2013: Complete the design for cold neutron beam line design based on the RANS; (2) June 1, 2013-Oct. 31, 2013: Complete the shielding designs for two compact neutron source facilities (3.9 MeV+7.0 MeV) and for the building where to put them; (3) Nov. 1, 2013-Mar. 31, 2014: Start an optimized design for fast neutron imaging system.

6. If you wish to extend your account, provide usage situation (how far you have achieved, what calculation you have completed and what is yet to be done) and what you will do specifically in the next usage term.

Up to now, we have reached to a new stage, i.e., RANS with thermal neutron beam line has been constructed and passed the radiation inspection based on the Monte Carlo calculations using RICC. In the next usage term, a new cold neutron beam line will be designed on the RANS. After that, a new building for two compact neutron source facilities (3.9 MeV and 7.0 MeV) will be built in RIKEN Wako campus. Since the researcher and technical staff's office will be also in the same building, the radiation level must be very low and must be safe enough. Therefore, the shielding design for the two neutron source facilities and the building is very important and must be carried out carefully with Monte Carlo calculation by using RICC. Our final objective is to develop a transportable fast neutron imaging system. So after finishing the design for the two neutron source facilities and the building, optimized design for fast neutron imaging system will be started.

Fiscal Year 2012 List of Publications Resulting from the Use of RICC

[Publication]

1. Sheng Wang, Yutaka Yamagata, Jungmyoung Ju, Shin-ya Morita, Yoshie Otake and Katsuya Hirota, Simulation and design of a simple and easy-to-use small-scale neutron source at Kyoto University, The Third Meeting of The Union for Compact Accelerator-Driven Neutron Sources, Bilbao, Spain, July 29-Aug. 3, 2012.

2. Sheng Wang, Yutaka Yamagata, Jungmyoung Ju, Shin-ya Morita, Yoshie Otake and Katsuya Hirota, Simulation and design of moderator/reflector/shielding assembly for compact neutron source at RIKEN, The Third Meeting of The Union for Compact Accelerator-Driven Neutron Sources, Bilbao, Spain, July 29-Aug. 3, 2012.

3. Jungmyoung Ju, Sheng Wang, Shin-ya Morita, Yoshie Ohtake, Katsuya Hirota, Yutaka Yamagata, Simulation and design of beryllium target combined with hydrogen diffusible metal for compact neutron source, The Third Meeting of The Union for Compact Accelerator-Driven Neutron Sources, Bilbao, Spain, July 29-Aug. 3, 2012.