Study of shielding design for SANS at CSNS *

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Abstract: The small angle neutron scattering (SANS) instrument is presently being constructed at Chinese Spallation Neutron Source (CSNS) in China, and the biological shielding design is needed to prevent the instrument from causing excessive dose rates in accessible locations. In this paper, the study of shielding design for SANS that relies on Monte Carlo simulation is introduced. Beam line shielding calculations are performed considering both scenarios of closed versus open T0 chopper. The basic design scheme of the beam stop is discussed. The size of the T0 chopper rotor is also estimated.

Key words: neutron beam line, shielding design, Monte Carlo calculation

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1 Introduction

The China Spallation Neutron Source (CSNS), is under construction in Dongguan, Guangdong, China. The beam power of CSNS is 100 kW in its phase one and it can be upgraded to 500 kW in its phase two. The small angle neutron scattering (SANS) instrument is one of the three neutron science instruments that will be built during phase one in CSNS project [1]. The small angle neutron scattering experiment is an effective way to probe the structure features that occur on length scales between 1nm and 100 nm. The experiment measures the small-angle neutron scattering cross section of the sample, through which structure information (such as particle shape, size and density) can be obtained. It is applied in the field of sol-gelatin, surfactant, polymers, macromolecular system, membrane structures, delivering drugs, etc. SANS at CSNS faces to the coupled hydrogen moderator (CHM), the main components are collimators, T0 chopper, sample chamber, scattering chamber, and detectors. The sample position is 12 m away from the moderator (see Fig. 1).

The pulsed neutron beams emerging from the coupled hydrogen moderator are delivered to the SANS beam line, the radiation field produced from these neutrons have to be shielded by a heavy shielding structure to satisfy the radiation dose limitation of <2.5 μSv/h. In particular, the SANS at CSNS is a short straight (no curved guide) beam line, which places higher requirements on the shielding of deep penetrating high energy neutrons. The Monte Carlo (MC) method can treat radiation transport through complex shielding configuration. Therefore, MC simulation is generally used to give the best possible estimates for the design of the biological shielding.

The aim of this paper is to perform the preliminary shielding design for SANS using MC calculation method. The calculations will provide the basic data for determining the T0 chopper rotor size, beam line shielding configuration, and beam stop design.

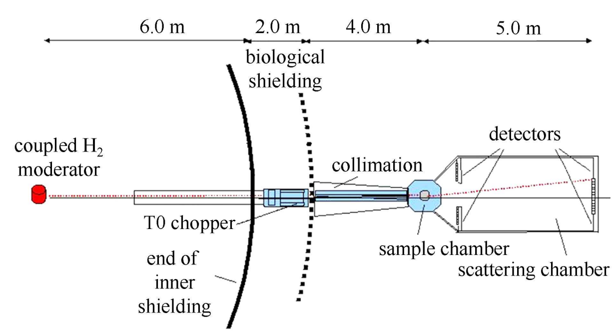

Fig. 1. Schematic of the SANS of CSNS.

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2 Calculation method

The neutron source term used in this study is generated from radiation transport calculation of CSNS target-moderator-reflector (TMR) model. It is built by scoring neutrons in the opening of the beam line duct, which is located 100 cm away from the target station center. It is a surface source with a cross sectional area of 12 cm×12 cm. Because neutrons with larger emission angles will be sent into regions that do not provide contribution to the results of the calculation, only neutrons within cones of 0–1 and 1–2 degree are considered. Fig. 2 shows the energy spectrum of the two angular groups. The photons are not considered as part of source term because of their very small contribution to the dose rate of the outer shield.

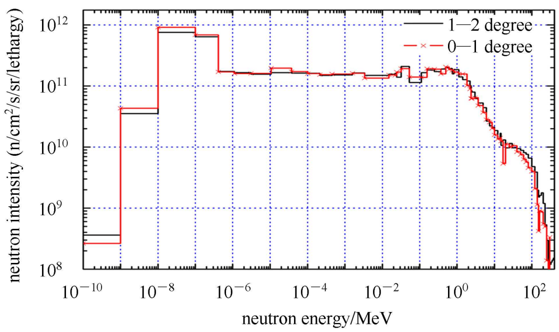

Fig. 2. Energy spectra of neutron source term used for SANS shielding calculation.

All geometric modeling and radiation transport calculations are performed by FLUKA2011.2.17–which is a multipurpose interaction and transport MC code [2, 3]. For the energy range involved in this work, the code handle all nuclear interactions by PEANUT (Pre-Equilibrium Approach to Nuclear Thermalization) model [4], except that neutron reactions below 20 MeV are treated by ENEA multi-group cross section library [5]. The radiation flux attenuation is over several orders of magnitude in this kind of bulk shielding calculation. So, it is imperative to use the variance reduction technique to make the calculation results statistically significant. The following methods are implemented to improve the calculation efficiency [6]:

1) The source angle biasing method is used to send more source particles to the far end of the beam line path.

2) The source energy biasing method is applied to increase the sampling probability of high energy neutrons that are more important to the shielding problem.

3) The particle number attenuation in shielding materials is compensated by assigning geometry importance.

4) For the calculation of T0 chopper rotor size and beam stop, geometry truncation is used to avoid tracking particle throughout the whole geometry model.

The shielding materials are mainly steel and concrete (Table 1). The ambient dose equivalent from all particles are scored using space mesh estimator “usrbin”. All of the calculation results are normalized to 500 kW beam power.

3 Results and discussion

3.1 Beam line shielding

Figure 3 shows the typical shielding calculation model of the SANS beam line. The vacuum ducts reserved for the main components of the instrument are described. The vacuum duct from 225 cm to 600 cm is a collimator, from 600 cm to 738 cm is the chopper cave. There is another collimator from 738 cm to 1100 cm, the sample chamber and scattering chamber are located at 1100 cm and beyond.

Figure 4 shows the total dose rate map for a case where the T0 chopper is closed. It can be seen that a high dose rate region appears around the chopper cave because of the strong scattering of high energy neutron with the rotor increase the radiation dose rate around the chopper cave. The dose rate decreases sharply in the region behind the chopper cave since the rotor effectively reduces the high energy neurons entering that region. Different shielding configurations were used around the chopper cave, and the radial total dose rate distributions are compared in Fig. 5. In pure concrete, the dose rate drops rapidly in the initial stage because the low energy neutrons can be effectively attenuated by the light elements in concrete. This process hardens the neutron spectrum and reaches equilibrium at a certain thickness. Then, the dose rate attenuation curve becomes relatively

Table 1. material.

material	density/(g/cm^3)	composition
carbon steel	7.85	Fe,98.60%; Mn,0.45%; Cu,0.15%; Si,0.25%; Cr,0.10%; Ni, 0.20%; C,0.20%; P,0.03%; S,0.02%
SS304	7.93	Fe,69.17%; Mn,1.80%; P,0.03%; Si,0.90%; Cr,18.00%; Ni,10.00%; C,0.07%; S,0.03%
regular concrete	2.35	O,49.80%; Ca,8.30%; Na,1.70%; H,0.60%; Mg,0.30%; Si, 31.50%; S,0.10%; Fe,1.20%; Al,4.60%; K,1.90%
high density concrete	3.93	O,32.40%; Ca,4.50%; Na,0.01%; H,0.24%; Mg,0.20%; Si,2.00%; S,0.10%; Fe,59.80%; Al,0.54%; K,0.02%; Mn,0.09%
inconel	8.28	Cr,15.00%; Al,0.70%; Nb,0.50%; Ta,0.50%; Ti,2.50%; Ni,73.80%; Fe,7.00%
boron carbide	2.52	B_4C

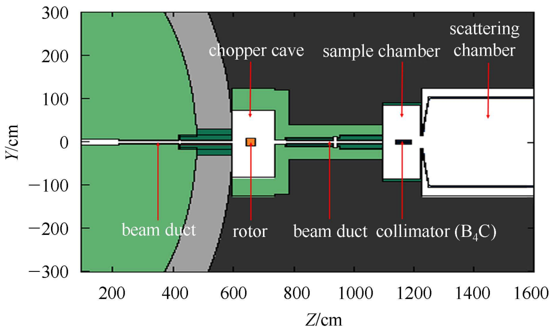

Fig. 3. (color online) The horizontal view of SANS beam line shielding geometry. The color marks: light green-low carbon steel, dark green-SS304, white-air, black-regular concrete, gray-high density concrete, yellow-Inconel.

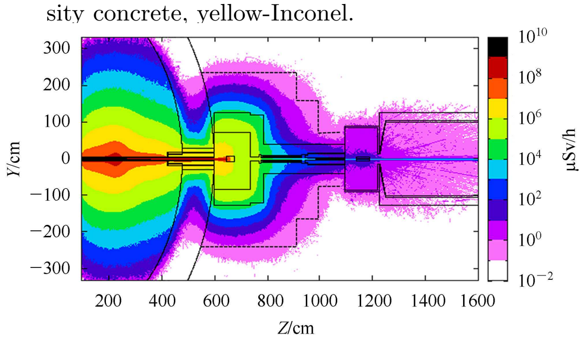

Fig. 4. Dose rate maps for the case that the T0 chopper is closed.

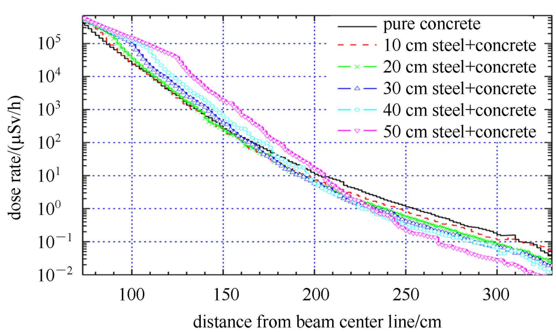

Fig. 5. The radial dose rate distributions as a function of distance from the beam center line, the scoring position is at 700 cm away from moderator (Z=700 cm).

flatter in the larger thickness because the high energy neutrons that have a longer attenuation length in concrete dominate the dose rate. Steel can efficiently decrease neutrons above 847 keV by inelastic scattering. However, neutrons below 847 keV can only decrease their energy in steel via elastic scattering, which is a very inefficient process [7]. So, a composite shield, including an inner layer of steel and an outer layer of concrete, is usually used to optimize the total shielding thickness. The comparison shows that using about 50 cm steel followed by concrete will be most appropriate because the radiation dose rate is decreased to 1 μSv/h in minimum shielding thickness.

Figure 6 shows total dose rate map for a case where the T0 chopper is open. When the T0 chopper is open, the high energy neutron of the incident beam will not be blocked by the rotor and so the dose rate in shields of downstream components is maximized. For example, the shielding requirement of the sample chamber and scattering chamber is mainly determined by the scattering of the collimator (in the sample chamber) with the incident beam, which includes a large fraction of high energy neutrons.

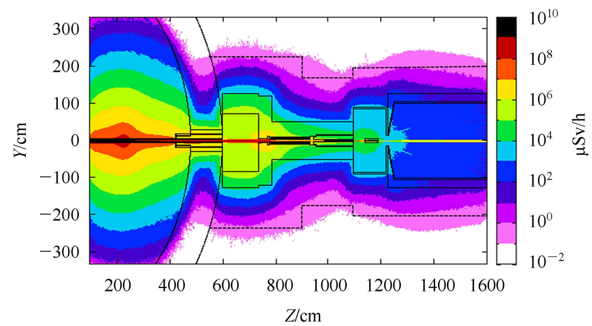

Fig. 6. Dose rate maps for the case that the T0 chopper is open.

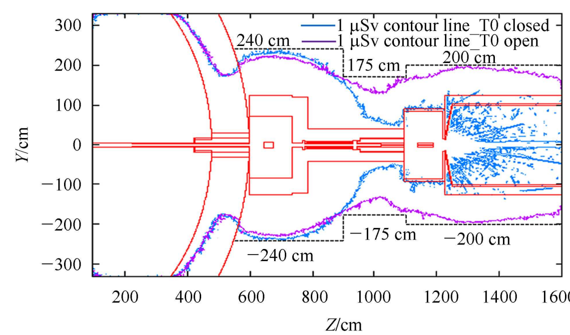

Fig. 7. Comparison of 1 μSv/h dose rate contour lines for the case of closed and open T0 chopper.

Table 2. Preliminary beam line shielding parameters of SANS.

position/cm	basic component	shielding configuration and material	calculation condition
start:600 finish:900	chopper cave	inner layer is a 50 cm thick steel, outer boundary of concrete layer is 240 cm from the beam center line	T0 chopper is closed
start:900 finish:1097	collimators	inner layer is a 50 cm thick steel, outer boundary of concrete layer is 175 cm from the beam center line	T0 chopper is open
start:1097 finish:1600	sample chamber and scattering chamber	pure concrete layer, and outer boundary is 200 cm from the beam center line	T0 chopper is open

The total dose rate contour line of 1 μSv/h for the case of closed and open T0 chopper are compared in Fig. 7. For safety, in determining shielding configuration around the chopper cave, it should be assumed that the T0 chopper is closed. For the region behind the chopper cave, the shielding requirement should be determined when the T0 chopper is open. Please see Table 2 for the detailed parameters.

3.2 Beam stop

The beam stop has to be designed to dissipate the beam energy at the end of the instrument. We proposed the basic design scheme of the beam stop taking into account the maximum beam intensity; that is, neutron beam un-chopped by T0 chopper.

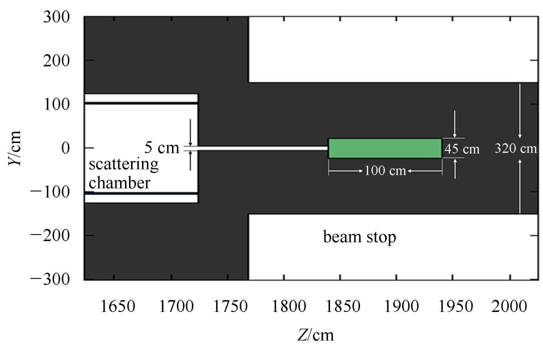

Fig. 8. The horizontal view of SANS beam stop geometry.

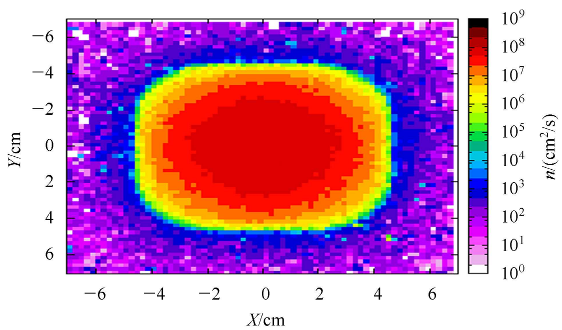

Fig. 9. Neutron flux distribution on the end section of the beam line.

The typical structure of beam stop can be a void cavity surrounded by different kinds of shielding materials (Fig. 8). Fig. 9 shows neutron flux distribution on the end section of the beam line, we find that the beam spot size is approximately 5 cm in diameter, so the cross section of the cavity is designed to accommodate the beam profile. The cavity should also has a certain length to reduce the backscattering neutrons entering the scattering room. Fig. 10 compares the incoming and outgoing neutron flux scored at the opening of the cavity. The backscattering neutrons are suppressed significantly by a 100 cm long cavity. The cavity is backed by a 100 cm thickness of steel, and the dimension of the surrounding concrete is 320 cm high, 320 cm wide and 300 cm long. Fig. 11 shows that the radiation fields are well contained by the beam stop. A further study on geometric configuration and material selection will be performed to optimize the beam stop design.

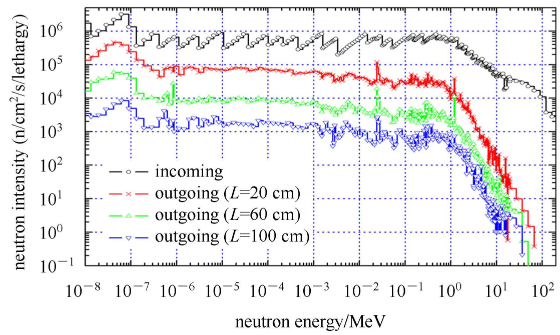

Fig. 10. Comparison of incoming and outgoing neutron spectrum scored at the opening of the cavity of beam stop, L is the length of the cavity.

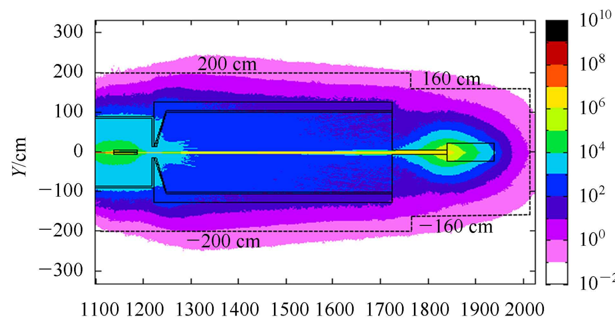

Fig. 11. The horizontal view of dose contour map of beam stop.

3.3 T0 chopper

The high energy component of the neutron beam will result in the background of the instrument, and the T0 chopper can suppress the background by shielding the incident high energy neutrons with its rotor. The rotor material is Inconel X-750, a non-cobalt material is very effective to reduce total activity [8]. For mechanical and structural consideration, the rotor is expected to realize a good shielding effect with less weight.

Figure 12 shows the geometry model for the T0 chopper rotor size calculations. The chopper cave is located 600 cm away from the moderator. A surface current estimator (boundary detector) is set in the beam duct, which is positioned 1m from the rotor end. Fig. 13 shows the neutron spectrum scored by the estimator. In this calculation the thickness of the rotor is held constant (30 cm) while the cross sectional area is varied. It can be seen that a rotor with cross sectional area of 8.6 cm×8.6 cm can well attenuate the high energy neutron: the intensity is decreased by more than one order of magnitude.

The fluctuations in the low energy range for the cases of small cross sectional area cases are due to the differences between the energy bin structure of source term and mandatory bin structure of FLUKA low energy neutron.

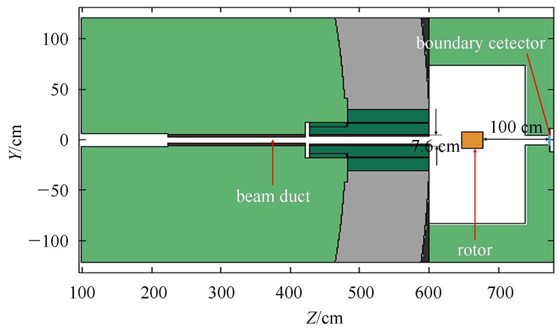

Fig. 12. Geometry model for the T0 chopper rotor size calculation.

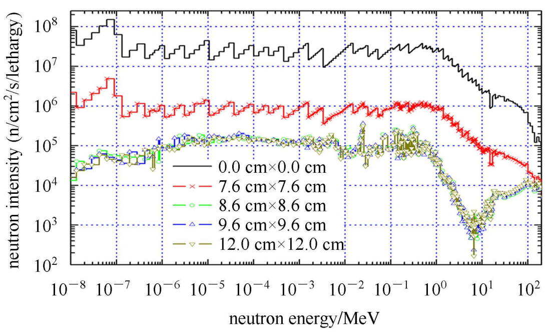

Fig. 13. Neutron spectrum as a function of cross sectional area of the rotor.

Figure 14 is the fast neutron (E_n>10 keV) intensity scored by the estimator. In this calculation, the cross sectional area of the rotor is held constant (8.6 cm×8.6 cm) while the thickness is varied. The result shows that a 30 cm thick rotor is sufficient to reduce the number of fast neutrons that pass directly through it; that is, when the rotor thickness is larger than 30 cm, the scored fast neutron will come mainly from those being scattered by the shield around the T0 chopper. According to the calculations above, the rotor size is determined as 8.6 cm×8.6 cm in cross sectional area and 30 cm in thickness.

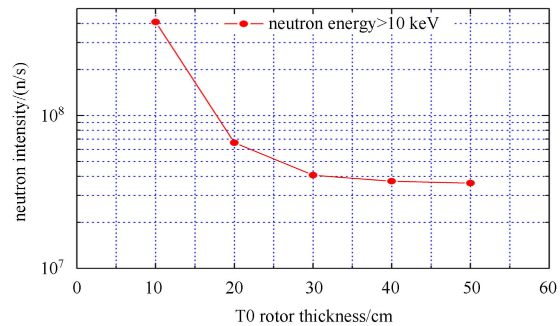

Fig. 14. Intensity of fast neutron (E_n>10 keV) as a function of the rotor thickness.

4 Conclusion

The preliminary shielding calculations have been performed for SANS of CSNS utilizing FLUKA MC code. The beam line shielding parameter at 600 cm to 900 cm from the moderator is proposed under the condition of closed T0 chopper. At distances larger than 900 cm, the shielding parameter is proposed under the condition of an open T0 chopper. The basic design scheme of the beam stop is presented. It is made of only steel and concrete, and the outer size is 320 cm in height, 320 cm in width and 300 in length. The proper size of the T0 chopper rotor is suggested as 8.6 cm×8.6 cm in cross sectional area and 30 cm in thickness. A dose rate limitation of 2.5 μSv/h is achieved by the current design. The results of the present study will provide an important basis for the optimization design of a SANS shielding structure.

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