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Optimized concept design of the target station of Chinese spallation neutron source

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Abstract

CSNS (Chinese spallation neutron source) target station, with proton beam power of 100 kW, consists of Tungsten rectangular target surrounded by a beryllium/steel reflector, three wing-moderators and the shield having 18 beam tubes. The leakage neutron intensity from the target (with reflector) and heat deposition on the target, reflector and shield were calculated using Monte Carlo code NMTC/JAM respectively. It is reported that the target having rectangular section will produce more leakage neutron intensity than a square one for the same proton power. The temperature and thermal stress distribution in the target disks were calculated by the finite element method. The performances of moderators were calculated using MCNP-4A code.

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0. Introduction

The project of Chinese spallation neutron source, a multi purpose research scientific facility, was proposed by CAS (Chinese Academy of Sciences) since July 2000. In 2001, CAS and other organizations of scientific branches have sponsored three domestic meetings, which resulted in the submission of a proposal for a feasibility study of CSNS. The proposal was granted on the eve of 2002, hence began phase I of CSNS project, charging the Institute of Physics and Institute of High Energy Physics (both belonging to CAS), to complete a full design and feasibility study by 2003. Conceptually, the CSNS plan calls for a 70-MeV H^- Linac and a 1.6 GeV Synchrotron producing a proton current of 62 μA (100 kW) at a 25 Hz repetition rate, a heavy water-cooled tungsten target, a Beryllium/steel reflected–moderator system, a iron/concrete shield, and neutron-scattering instruments. The project requires the CSNS team to embark a detail design study, optimizing and integrating the influencing factors of the accelerator, target-moderator–reflector, and scattering-instrument components, for neutron production and scientific performance.

The first moderator-target planning meeting was organized by Institute of Physics, inviting an International Advisory Team (IAT) to comment on the preliminary plan of the CSNS. Although the focus of the meeting was on the target-moderator system, the CSNS presenters and the advisory team discussed related issues on the accelerators and scattering instrumentations. The IAT consisted of Gunter Bauer (Julich, Germany), Timothy Broome (Rutherford-Appleton Lab, UK, substituted by Stephen Bennington), John Carpenter (Argonne,

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USA), Gary Russell (Los Alamos, USA) and Noboru Watanabe (JAERI, Japan), Who represent most of the experience to date on spallation neutron sources. The meeting provided the first opportunity to examine the CSNS plan in the context of the present worldwide research and development of spallation neutron source technology.

1. Target

The conceptual design team was organized after the meeting, to start the work for accelerator, target station and instruments respectively. Target station team fortunately got the license from JAERI to use 'High energy particle transport code NMTC/JAM' August 2002 and start the Monte Carlo simulation for CSNS target station [1]. According to the comments of IAT, the stacking Tungsten target (similar to that of ISIS) was modeled, see Fig. 1. The calculations show that (it was supposed the size of the proton beam will be 80% of the height and width of target section, and the profile will be uniform):

(1) Target with rectangular section will produce higher intensity of leakage neutrons than square one if the area of section in constant (see Fig. 2).
(2) Target with smaller area of section will produce higher intensity of leakage neutron if the ratio of width to height is constant. Of course, the target with smaller area of section will have higher power density if the proton beam power is constant (100 kW for CSNS).
(3) Length of the target could take 40 cm, because it cannot produce larger total neutron flux with increasing length of target.
(4) The heat depositions in each disk were calculated and those of fifteen disks (upstream) were list in Table 1.

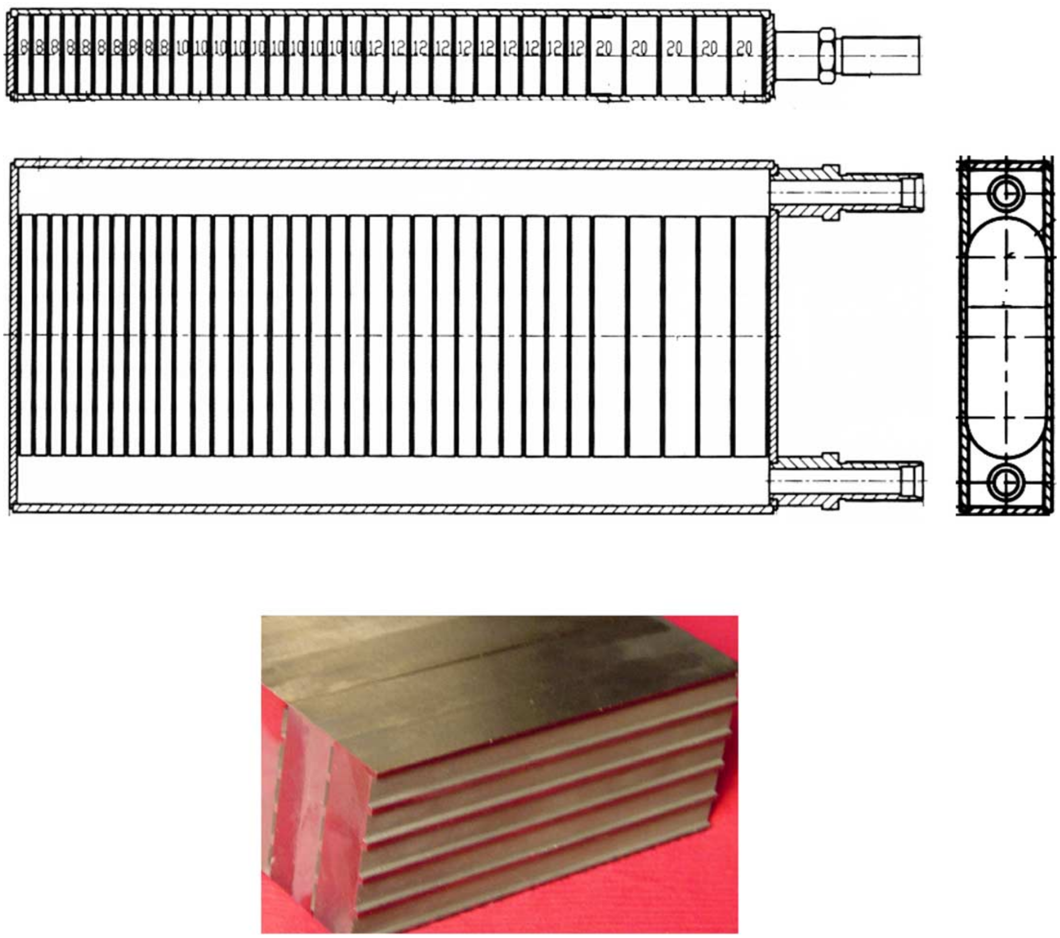

Fig. 1. Disks stacking tungsten target.

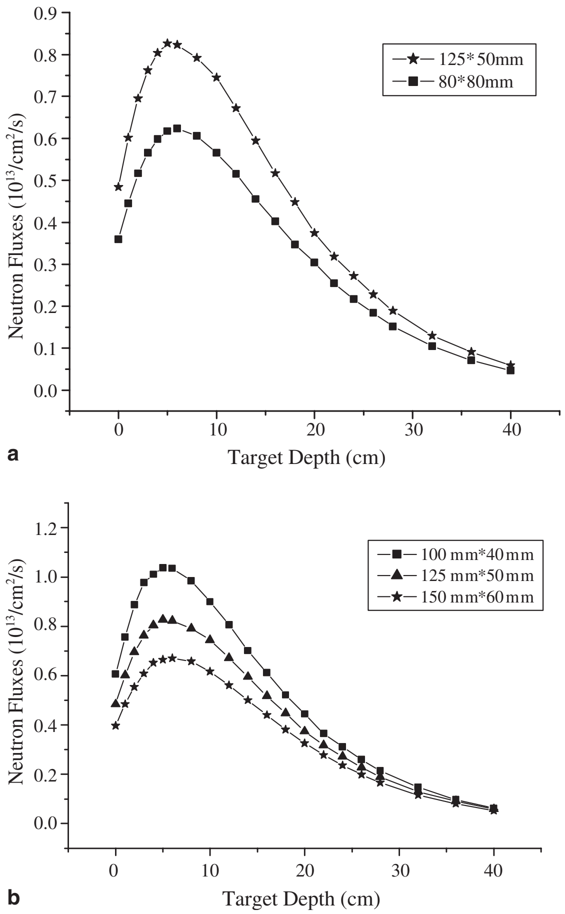

Fig. 2. Intensity of leakage neutron vs shape of target.

Table 1
Heat deposition of fifteen disks (upstream)

Disk number	Heat deposition (kJ/S)
1	3.36
2	3.54
3	3.39
4	3.25
5	3.10
6	2.92
7	2.71
8	2.46
9	2.26
10	2.08
11	1.89
12	1.74
13	1.58
14	1.43
15	1.30

(5) Optimum shape of CSNS target is plate: 40 mm height × 100 mm width × 40 disks. Intensity of leakage neutron from the CSNS (100 kW) target could compare with that of ISIS target (160 kW, with squire section).
(6) Heavy water will be used for cooling, it will reduce the absorption in the target and decouplers.

To analyze the distribution of temperature and thermal stress in the target, the following model was build for the calculating simulation. As mentioned before, the target consists of stacking rectangular Tungsten plates. Between each plate, there is a 1.5 mm gap that separated by the flange on one side of the Tungsten plate, as shown in Fig. 1. The temperature of input cooling water is 20 °C, and the velocity in the gaps is 2 m/s. The coolant passes through the gaps and takes away the heat from target plates, so the temperature of the target is reduced. With the IDEAS-TMG commercial thermal analyzing package and the above model, simulations are carried out to analyze the heat that generated on

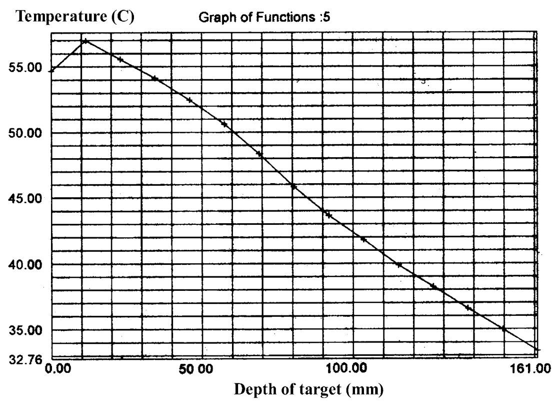

Fig. 3. The highest temperature in disks vs depth of target (*Z*-axis).

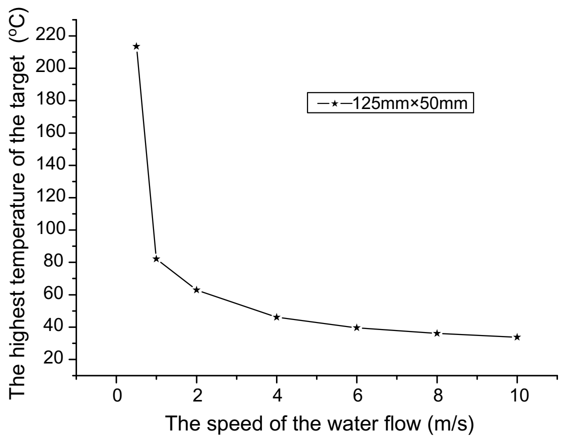

Fig. 4. The highest temperature in target vs speed of cooling water.

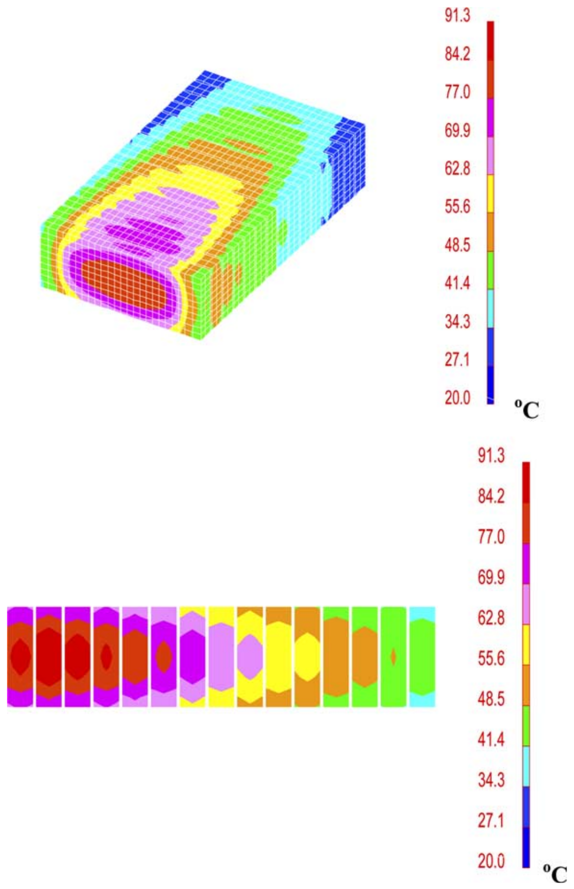

Fig. 5. 3D temperature distribution in target ($40 \times 100 \times 40$ disks, speed of water is 2 m/s).

each plate of the target. Fig. 3 shows the simulation results that depict the temperature variation of the target along the Z-axis, with the above coolant set-up.

The relation between the speeds of cooling water and highest temperature in the target is shown in Fig. 4. It is clear that the speed of 2 m/s is enough for cooling the target, because the highest temperature in the target is lower than 100 °C. 3-D temperature distribution in the target (40 mm height $\times$ 100 mm width $\times$ 40 disks) is given in Fig. 5 where speed of cooling water is 2 m/s.

The thermal stress distribution in the target was obtained and shown in Fig. 6. The highest thermal stress of the target is much lower than the design limit of Tungsten in case of CSNS, so thermal stress will not be an important effect on the lifetime of CSNS target.

2. Moderators

To optimize moderated thermal neutron pulse, the IAT suggested that the number of the moderator that deployed should be as few as possible to prevent interference especially for a coupled moderator, it is important to be located separately. Here we show the properties of the CSNS moderators.

Position	Type	Material	Working temperature	Lifetime
Upstream (top)	Decouple	H_2O	300 K	4 years
Downstream (top)	Decouple + poison	Liquid CH_4	100 K	Half a year
Bottom	Couple	Liquid H_2	20 K	2 years

The location of the moderators suits the requirement of all type of spectrometers for the neutron energy, peak value and width of neutron pulse, and neutron integration flux. At each moderator, the moderated thermal neutron would be released from both the front and back moderator surfaces (see Fig. 7).

The CSNS moderators have 2 cm water pre-moderator to increase the moderation efficiency. The water pre-moderator locates all interfaces between the target and the reflectors, and it lets the neutron quickly lose their energy without influence to the neutron pulse shape [2,3]. From the experience of other researchers, the optimal thickness of the water pre-moderator is 2 cm.

For the decoupler and the poison, there are many choices, such as B_4C, Cd, Gd and Ag–In–Cd alloy [4,5]. They can be used in different moderators for their different energy cut-off E_d. We have studied the moderator design of other spallation sources: ISIS uses 6mm B_4C for a decoupler of the room temperature water moderator and 0.05 mm Gd sheet for a poison of the 100 K methane moderator.... Also, a variety of Al–Mg alloy, whose mechanical property is good when it is working in lower temperature, are also good choices for moderator vessels. Fig. 8(a)–(c) shows the structure of the moderation system. The decision, what material will be used for decouples and poisons of the moderators, will depend on the design of neutron instruments.

The MCNP-4A software package was developed by the LOS ALAMOS national laboratory of the US, for neutron and gamma transport simulation using Monte Carlo method. The simulation was carried out with the CSNS tungsten target and its beryllium/iron reflector as the preliminary model. In the simulation, the wing geometry coupled water moderator was located at the peak value of leakage neutron flux plot, and it works at room temperature (300 K). The size of the moderator is $10 \times 10 \times 5$ cm^3, and the moderated thermal neutrons are released from the moderator surface. The distribution of the target leakage neutron flux, which mentioned on the moderator in Section 0, is also considered. The figure shows that water moderator efficiency decreases from 0.01 eV to almost 0, when moderator is working at room temperature. This result is identical to the Maxwell curve. Figs. 9 and 10 show the plot of the

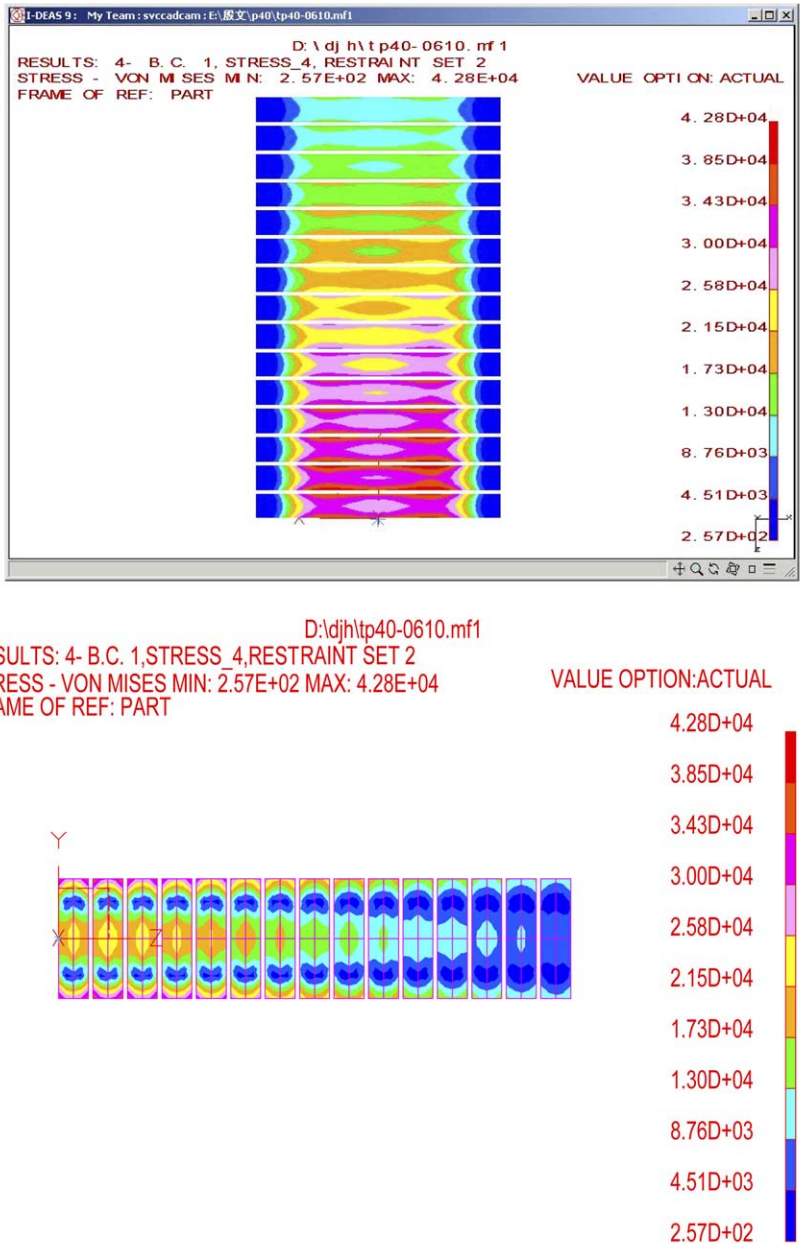

Fig. 6. Thermal stress distribution in target ($40 \times 100 \times 40$ disks, speed of water is 1 m/s).

moderated neutron flux along the depth (Z) direction and height (Y) direction.

Moderator	Heat deposition	
RT Water	255 W	
100 K liquid-methane	247 W	176 W (with 2 cm pre-moderator)
20 K liquid-hydrogen	148 W	105 W (with 2 cm pre-moderator)

3. Reflector

During the spallation reaction, many of the neutrons will be emitted in a direction away from the moderator. The reflector is located outside the moderator-target assembly to return these neutrons back to the moderator, hence to increase the efficiency of the moderator-target. For our design, the height of the reflector is 1 m, and consists of a 1.2 m diameter beryllium inner cylinder and a 2 m diameter steel outer cylinder. The

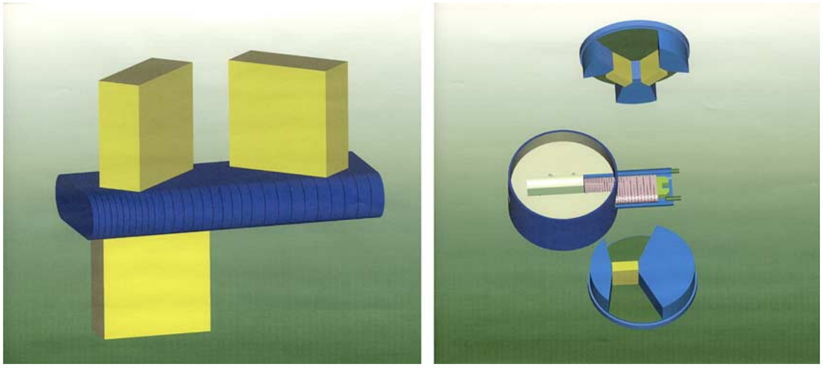

Fig. 7. Configuration of moderators for CSNS.

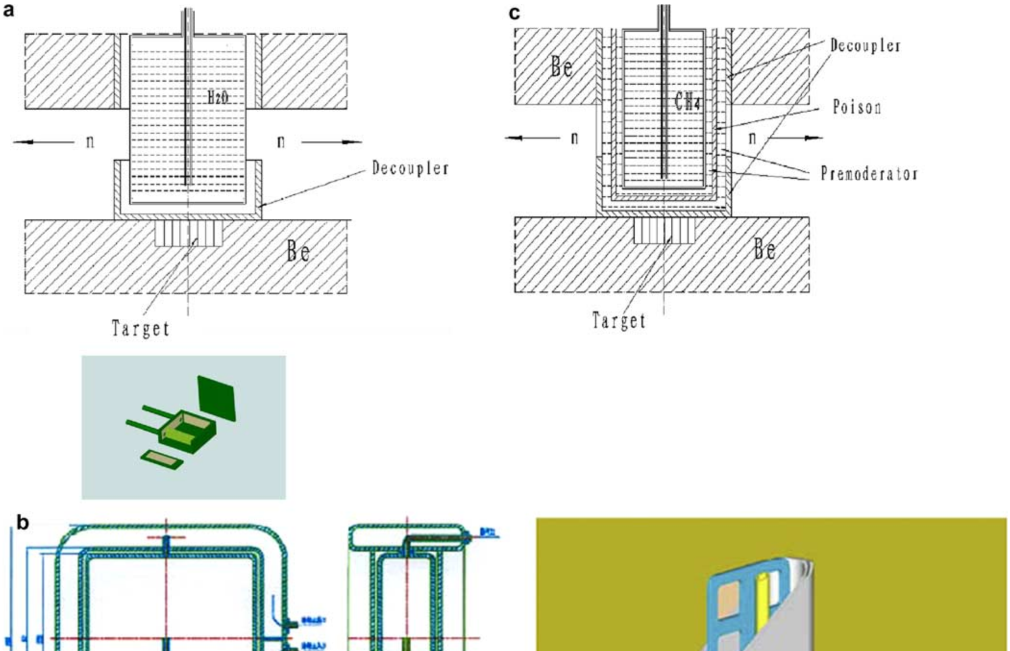

Fig. 8. Structure of moderators.

target container and the neutron beam lines are inserted at 0.5 m in height. Fig. 7 shows the section of the reflector and the moderator-target assembly. The steel outer cylinder is not shown in the figure. Neutrons that move away from the moderators, enter the beryllium/steel cylinder reflector. The neutrons collide elastically or non-elastically with the beryllium/iron atom. Therefore, the neutron direction is changed and the neutron energy is reduced, so the neutron is moderated. Also, from the (n, 2n) reaction, more low energy neutrons are produced. The scattered neutrons and new produced neutrons have high probability to be returned to the area near target with different energy levels. They would be moderated again at the moderators around the target. With the reflector the neutron flux increased by 18 °C.

IAT suggested that CSNS should use a Beryllium/steel reflector. The heat generation was also simulated. Using the NMTC/JAM package that JAERI developed,

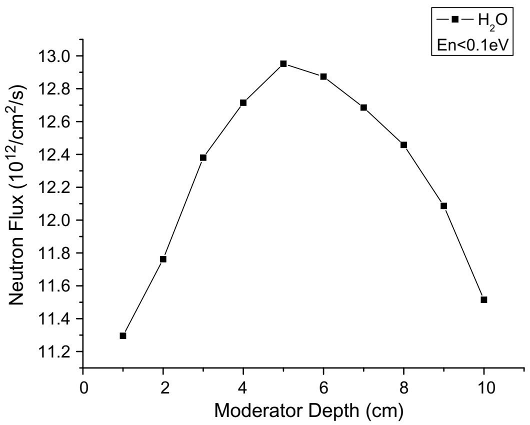

Fig. 9. Neutron flux vs moderator depth.

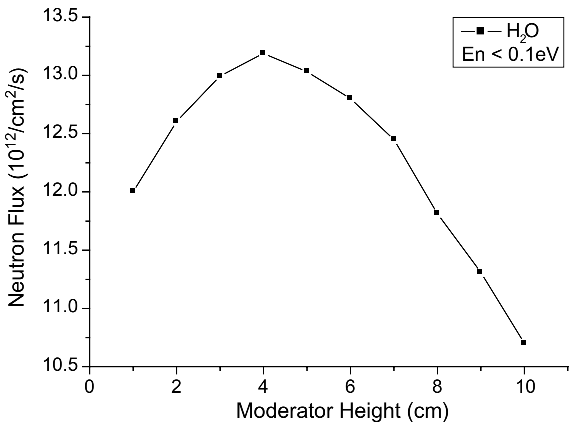

Fig. 10. Neutron flux vs moderator height (*Y*-axis).

the heat of 16 kJ/S was generated in the Beryllium/steel reflector. To reduce the neutron absorption of the reflector cooling system, the D_2O cooling system will be used (D_2O flow through the gap between the Be metal

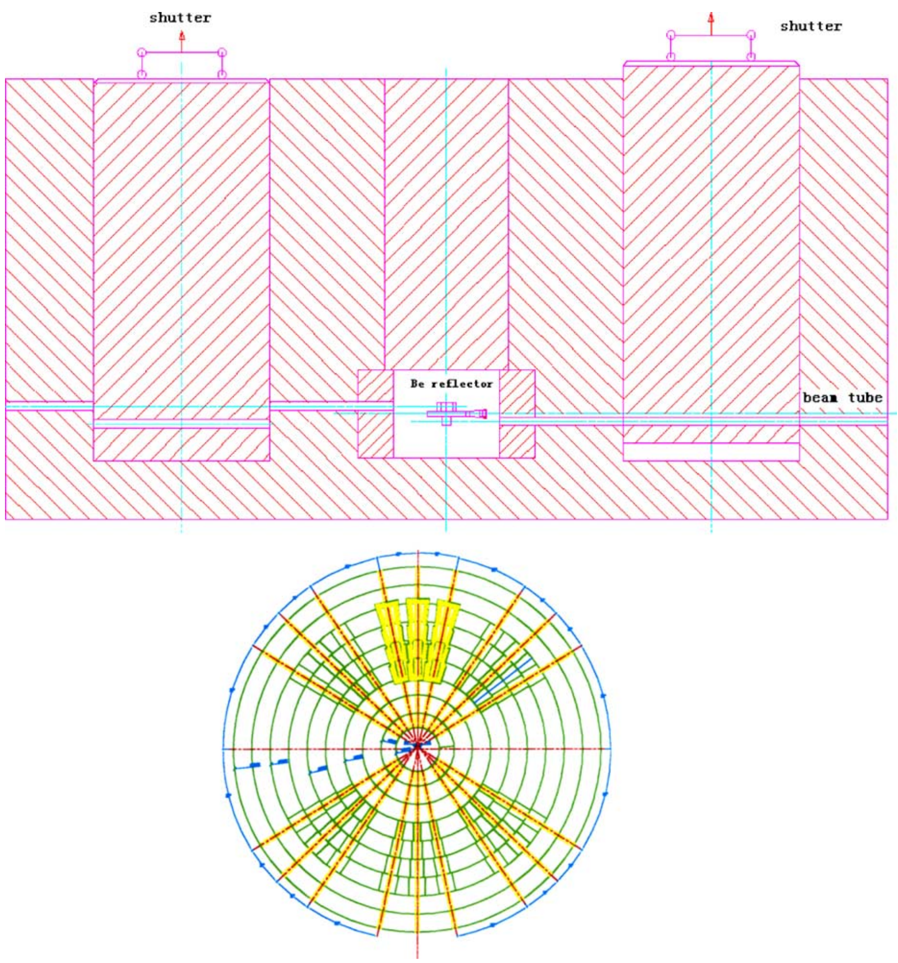

Fig. 11. Structure of shield.

sticks or balls). A cooling cover outside the steel reflector is efficient enough and simple, because the steel reflector generates less heat and has good heat conductivity. More heat is generated in the proton-beam forward direction than backward direction, so the coolant should enter the cylinder against the proton beam direction.

4. Shield

From the simulation estimated to be, the heat deposition of the CSNS biological shield is 11 kJ/S. For a 10 m diameter and 5 m high iron/high-density-iron-aggregate-concrete biological shield, the heat is small and dry air is enough for the cooling. Also, to prevent the radioactive gas to be released to the scattering spectrometers hall, air pressure inside the CSNS target station should be lower than the outside, and there is a (0.5–1 mm) nickel foil wrapping outside the biological shield.

For the convenience of maintenance, there is a railed carriage, electricity powered and with remote control, to carry the target body and its cooling system out from the side of the shielding tank.

There are 18 horizontal neutron beam lines in the iron/high-density-iron-aggregate-concrete shield. Each moderator faces 6 neutron-apertures, with 3 in front and 3 behind. At each side of the moderator, one of the neutron-apertures is in the normal direction of the moderator, and the other two are at the directions of angle of ±12°. An iron shutter, moving vertically in each neutron beam line is used to shut the flow of the neutron beam from the moderator. The shutters have 2 m horizontal thickness, which is sufficient to attenuate the neutron beam from the moderator, hence to protect the workers beside the spectrometer. As shown in Fig. 11, when the iron shutter is lifted, the neutron-aperture is open, and otherwise it is closed.

Fig. 11 shows the sectional drawing of the right side of the biologic shield. In the figure, there are 9 neutron-Apertures and their 2 m radial thickness iron shutters. To prevent the direct radial radiation, the sectional drawing of the shutter has a step-structure.

Acknowledgement

Design team of CSNS target station thanks again for the comments from IAT members in Beijing meeting. These comments are the base of the conceptual design of CSNS target station. The international resource helps us to push the design forward speedily.

Design team of CSNS target station would like to thank JAERI and KEK for granting the permission to use the Monte Carlo code NMTC/JAM and transfers HIP cladding techniques respectively.

Design team of CSNS target station thanks for the IAT support, since the anti-radiation-damage and corrosion experiments for all the materials that mentioned above will be carried out in PSI, Switzerland.

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