Neutron Beam Extraction and tailoring useful neutrons to instruments at ESS

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Abstract. The ESS has a characteristic design of the target and moderator system. The 2.5m-diameter target wheel needs a large horizontal vacant space around the moderator, and a thin moderator produces more high energy neutrons (HEN) in comparison with other facilities. Therefore, it is quite important to avoid HEN as much as possible before ejecting them into the beam line, although a curved guide or T₀ chopper can get rid of them. In this report we show the present situation of these issues and discuss the measures to be taken.

1. Introduction
The European Spallation Source (ESS) is the first long pulsed source under construction, at the outskirts of Lund, Sweden. The characteristic parameters of the accelerator are 5MW, 14Hz, 2GeV and long pulse of 2.7msec. This will be the most powerful accelerator-based neutron source in the world. Since it is a long pulsed source, therefore, it will be very suitable for production of cold neutrons. Moderators and instruments will be designed to extract the best performance of the source and would have a different character and unexpected issues compared with fairly well established short pulse sources such as ISIS, SNS and J-PARC. One possible choice of moderator system would be a thin moderator (3cm), which benefits from the low cross-section of para-hydrogen below 30meV [1], and will enhance the brightness of the source. However, as we will discuss in this report, there will be a drawback which needs to be carefully dealt with.

The spallation process naturally produces high energy neutrons. Dose mal-effect drastically increases and shielding performance of any material decreases more than one order of magnitude in the 1MeV range compared with thermal neutrons. It is, therefore, quite important to get rid of high energy neutrons (HEN) within the target monolith shield as much as possible. Beam extraction ports to the instruments accepts both useful neutrons and unwanted HEN. However, by knowing the neutron distribution at the source, we can reduce HEN to the beam port by well designed optical components outside the monolith.

In this report, we briefly describe the character of the neutron distribution at the moderator, the structure of the beam course in the monolith and possible measures to get a clean beam at the sample in comparison with an example of J-PARC instruments.
2. Mechanical Structure around the Target

The shield/collimator design around the moderator is depicted in Fig. 1. Since ESS will take a 2.5m-diam Tungsten target wheel, there is horizontally a large void space around the moderators, and the beam port shield/collimator can only start at 2m out from the moderator due to the target structure, narrow beam separation and heat load on the guide system. We can contrast this situation with the beam port collimation in ISIS, SNS and J-PARC, where individual beam ports are separated horizontally and vertically. Therefore, it is not difficult to have a suitable collimation to avoid HEN to the beam port.

Fig. 1 (a) Horizontal cut-section of the target monolith shield for neutronics calculations. A tally was set at 2.0m at the entrance of the beam extraction system or at the beam port outside the monolith at 5.5m. (b) vertical cuts of the W1 and W9 beam axes, showing the steel plate shield above the target wheel highlighted in yellow [2].

Figure 1 (a) is the horizontal cut-section of the geometrical model and (b) is the vertical cut-section of the engineering model in the monolith, which shows how much shielding material, coloured in yellow, exists through a ray trajectory from the hot spot in the target (red) to the beam guide entrances of 5 cm in height at W1(30º), W9(78º) [2]. The W1 port (forward direction) seems not to have good enough shielding material, so that the high energy neutron flux is drastically enhanced as we will see in Fig. 2. However, neutrons from the hot spot can be shielded by the Tungsten target itself at W9.

3. Neutron Spectrum

Figure 2 shows the energy spectrum at the guide entrance at 2m from the moderator as shown in Fig.1(a). Here, we took two tally (measurement points in the simulation) methods of MCNPX, F4 and F5. F4 is the first principle calculation taking any nuclear reactions in the process and the tally counts particles which pass through it. F5 is an approximation method which assumes isotropic scattering processes in the physics model region above 150 MeV. Therefore the F4 tally gives a more accurate neutron flux above 150 MeV. Calculation was done for three different beam ports at the forward direction (30º), the perpendicular direction (90º), and the backward direction (150º). It is clearly seen that the high energy neutron intensity is very much enhanced in the forward direction at 30º. It is about one order of magnitude higher than the backward direction at 150º above 150MeV. We could not see a clear difference between F4 and F5 within the statistics, however,
4. Neutron Distribution at the moderator

The neutron distribution around the moderator was estimated by tracing back the neutron trajectory from the 6 cm sphere tally at 2.0 m at 90° in Fig.1.

Figure 3 shows the neutron distribution along the moderator height for 1.5, 3.0 and 10.0 cm thick moderators. Fig. 3 (a) shows the slow neutron distribution integrated between 0 and 5 meV, where a brightness enhancement for the thinner moderator is clearly observed. Fig. 3 (b) shows the distribution of high energy neutrons integrated above 100 keV. Fig. 4 (c) shows over-plot of 0-5 meV and >100 keV for 3 cm thickness. There is a very sharp peak structure at the edge of moderators in Fig. 3 (b), which comes from the 3 mm thick Al container. The intensity at the 13 cm position, which corresponds to the lower Al edge of the moderator, has a similar intensity for the different moderator thicknesses. But intensity at the other side of edge has a systematic decrease with thickness, and it seems to be almost proportional to 1/R² (R is the distance from target). We should note that this edge effect can become more significant above 100 MeV, where the cross section of Al largely exceeds that of H₂ but is just a half that of steel.

Figure 4 shows energy spectrum above 1 MeV to show the contribution from the Al container. Here, the moderator thickness is 3 cm and the aperture of the tally was changed from 11(w) x 3(h), 11(w) x 9(h) to 4.5(w) x 3(h) cm, with a different collimation condition, i.e. Here, “Art Coll” means the steel shield behaving as a perfect collimator, “no Al” means no Al moderator casing, “nothing” is the geometrical model shown in Fig. 1. The figure clearly shows a larger enhancement for the larger aperture of tally above 100 MeV. Probably the larger tally views a wider area around the moderator. The contribution from the Al container observed in no-Al is comparable nevertheless to the tally size. It is about factor 2.0. However, this contains the contribution from the front surface of the moderator, which cannot be avoided in any case, and the contribution for the Al edge can be 30% as seen from Fig. 3 (c). A message from Fig. 4 is that good collimation is very important for beam extraction.
5. Beam Extraction
J-PARC/MLF is a sharp pulse source, where a sharp neutron pulse is produced by the decoupling concept. A decoupled moderator has an intensity maximum at the center of moderator, Fig.5 [4]. Therefore, the moderator was designed to avoid high energy neutrons by having an off-set Al container from the beam course with a viewed surface of 10x10 cm². Also we chose to constrain the viewing area on the moderator surface with typically a 1cm-margin from the edge of the viewing surface. The good collimation system helped with rejection of high energy neutrons too. Therefore, essentially, the instrument does not directly see the Al casing of the moderator from the beam port except for viewing front surface.

6. General remark for high energy neutrons.
There are mainly two remarks to keep in mind for high energy neutrons. One is the reduction of the cross-section of shielding materials in the high energy region. Roughly speaking the cross section decreases one order of magnitude for 1MeV range than that for thermal energies. Another factor is the biological dose effect of neutrons. The Dose Conversion Coefficient of neutrons is 100 times larger at 1MeV in comparison with that at thermal energies [5]. From the two factors, the amount of biological shielding material should be drastically increased to keep the required dose rate in the high energy range.

As we saw in Fig. 3 and 4 large HEN contribution to a beam port comes from the Al casing and surroundings around moderator. We cannot avoid to view the front surface of the moderator; however, better collimation can avoid HEN from the surroundings.

As we showed in Ref. [6] adoption of either a curved guide or T₀ chopper is quite effective to get rid of HENs to the sample. However, even after a line-of-sight of curved guide, HENs are transported because of elastic scattering by the guide substrate. The intensity difference between thermal neutron transported by the guide and HENs can be less than 1/million. This N/S ratio is good enough for most of instrument and can be improved further for long flight-path instruments at the ESS. Therefore, it is not unrealistic to achieve the world’s best background performance at the ESS. Good collimation in the neutron beam extraction system (NBEX) can help the this aim; therefore, careful design of NBEX is highly required.

7. Conclusion and suggestion
We have reviewed the current neutronics calculations on the high energy neutron contribution to the instrument beam port at the ESS and compared with the performance at J-PARC. We found HEN produced from the Al edge and surroundings. Although we cannot avoid HEN from the front surface of the moderator, a good collimation system in NBEX and the downstream optical system can reject HEN from the Al collimator edge and surroundings, and may realize the best N/S ratio at the ESS.

References
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