TARGET OPTIMISATION STUDIES FOR THE EUROPEAN SPALLATION SOURCE*

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Abstract

The European Spallation Source (ESS) is one of Europe's biggest and most prestigious science projects. ESS will be the world's most powerful next generation neutron spallation source for research with neutrons, providing a unique tool for studies of the atomic structure and dynamics of matter. In this paper we use GEANT4 simulations to investigate the effects of spallation target material and incident proton energy on the total neutron yield integrated over the neutron energy and emission angle.

INTRODUCTION

Due to their unique properties neutrons are gentle probes that can penetrate deep into materials without causing damage, providing detailed information on crystallographic structure, atomic and molecular dynamics and magnetic properties. Over the past 60 years neutron scattering has become established as powerful tool in many research fields, including physics, chemistry, biology, materials science and engineering, and as a consequence the demand for more, and more intense, neutron beams continues to grow. At present neutrons are produced either by fission in research reactors optimised for thermal neutron flux, or by spallation in which high energy proton beams spall, or chip, neutrons from the nuclei in a heavy metal target. Third generation neutron sources are based on spallation rather than fission processes, as the former is far more efficient: for example the state-of-the-art Institut Laue Langevin in Grenoble utilises a 58 MW reactor, whilst the comparably intense ISIS pulsed spallation source at RAL in the UK operates at approximately 160 kW.

In the 1990s the OECD Megascience Forum strongly recommended that new MW-class high intensity spallation neutron sources should be constructed in each of the major regions of the globe. Both USA and Japan have now built their own MW spallation facilities, namely SNS at Oak Ridge and J-PARC at Tokai. However, although the 5 MW European Spallation Source (ESS) was the first and most powerful spallation source to be designed, and the EU FP7-funded ESS Preparatory Phase Project (ESS-PPP) was completed in March 2010, the decision to move forward to the construction phase of ESS, in Lund in Sweden, has yet to be taken.

The current ESS design [1], based upon an earlier double target station concept [2] is essentially a 5 MW long pulse (2 ms) linear accelerator which will deliver protons of the order of 1.3 GeV to a single liquid metal neutron spallation target. Initially liquid mercury (as employed at SNS and J-PARC) was suggested as target material. The advantages of such a liquid target is that no radiation damage occurs directly in the target material and there is a strongly reduced water contamination because cooling is outside the beam area [3]. Moreover, the mercury is circulated inside a closed process loop to allow the removal of both the heat deposited by the spallation processes and the radioactive spallation products.

The high energy neutrons generated by the spallation processes will be slowed down by moderators inserted horizontally above or below the target in so-called wing geometry. The thermalised low energy neutrons will then be extracted through 22 beam lines (11 on each side of the target) to the neutron scattering spectrometers where the experiments are performed [4].

ESS SPALLATION TARGET MATERIAL

Before construction begins, ESS will undergo a two year design optimisation phase. As part of ESS-PPP we have pre-empted aspects of the design optimisation by exploring aspects of the proton beam/spallation target interactions using, for the first time, GEANT4 [5]. In particular we have considered potential target materials as alternatives to mercury which, although initially the material choice for the target, is the subject of growing concerns regarding radiotoxicity and chemotoxicity. Indeed, since ESS was first designed, EU legislation has been put in place to limit the use of and exposure to mercury.

Whilst molten lead (melting point 327°C) is a potential material for a liquid spallation target, the eutectic alloy lead-bismuth, tested recently in the MEGAPIE spallation target at SINQ at the Paul Scherrer Institute, affords the advantage of lower melting temperatures (melting point 120°C). Unfortunately Pb-Bi is potentially corrosive, and produces polonium as biproduct of spallation. However, as part of the ESS Preparatory Phase Project, the University of Latvia has considered the possibility of using a Pb-17%Au eutectic (melting point 212°C) for the ESS target. In this study we have therefore explored spallation neutron yield from liquid mercury, lead and lead-gold eutectic. Additionally, we have compared the results with the yield from a solid spallation tungsten target, noting that it has been suggested, even at power levels as high as 5 MW, a solid target may remain an option for a long pulse ESS.

For the GEANT4 simulations we have used the existing

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ESS target geometry and dimensions for both liquid and solid target materials. The total length of the target is 653 mm and the outer width is 306 mm. The height is 153 mm at the rear edge and 106 mm at the front. The beam window has a rounded cross section with the outer radius of 53 mm at the center [6]. A schematic diagram of the current design of the ESS target can be seen in Fig. 1. Figure 2 shows the unmoderated energy spectra for the spallation neutrons produced by 1.3 GeV neutrons incident on liquid mercury, lead, and lead-gold eutectic, and on solid tungsten targets.

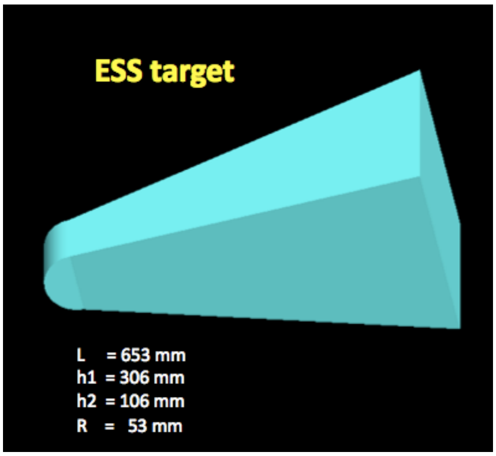

Figure 1: Geant4 modelling of the curent design of the ESS target.

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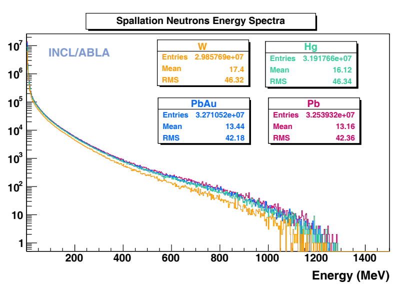

Figure 2: Energy spectrum of unmoderated spallation neutrons for liquid Hg, Pb, and Pb-Au and solid W target material. Incident proton energy is 1.3 GeV.

It is evident that the spallation neutron spectrum produced by all four target materials are closely similar. It is therefore evident that a liquid Pb-Au eutectic target could indeed replace the proposed mercury target without causing significant degradation in the the overall neutronic performance of ESS.

MODERATED NEUTRON SPECTRA

As an initial attempt to compare the thermal, moderated, spallation neutron spectra from a Pb, Pb-Bi and Pb-Au liquid targets and a solid tungsten we have adopted a very simple strongly coupled cylindical target/moderator assembly as shown in Fig. 3. The target is 300 mm long, 53 mm in radius and is surrounded by a water moderator having an inner radius of 53 mm and an outer radius of 103 mm and a length of 120 mm. Fig. 4 shows the thermal neutrons energy spectra produced by this using an 1.3 GeV incident proton beam. Interestingly it can be seen that the neutron productions rates of all three liquid target materials are similar but, for the thermal region, the performance of solid tungsten is noticeably better.

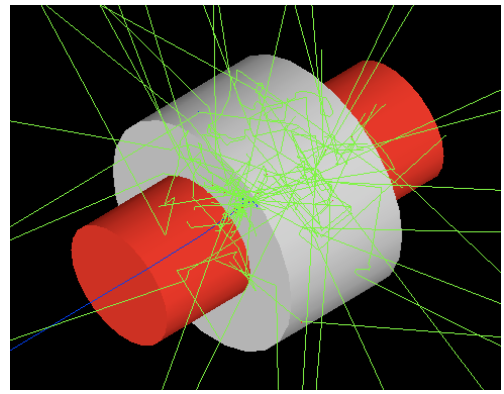

Figure 3: Geant4 modelling of a cylindrical target with moderator assembly.

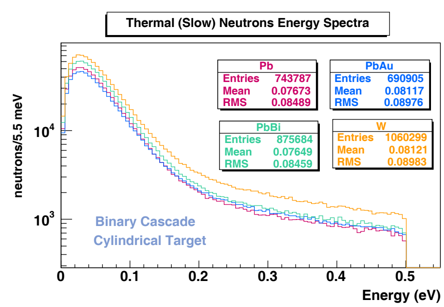

Figure 4: Thermal neutrons energy spectra using the cylindrical target geometry.

THE EFECTS OF PROTON ENERGY

GEANT4 also affords the potential of studying spallation neutron production as a function of incident proton energy. We have performed some preliminary simulations using a simple slab geometry for the target, with two (15x15x5) cm water moderators placed on each side of the slab. The neutrons leaving the outside face of the moderators were detected. The target material was Pb-Au. The neutron density within the target was also evaluated for proton beam energies of 1.3, 2 and 3GeV. The results indicate that most of the neutrons are produced in the first half of the target (Fig. 5). As the proton beam energy is increased to 2 and 3 GeV, the neutron density spot becomes longer and wider (Fig. 6) and (Fig. 7). Correspondingly

GEANT4 shows that the neutron yield decreases as the target length is reduced. This effect can be seen in (Fig. 8) where a decrease in the neutron yield at 3 GeV is apparent below the current target length of 600 mm, shown by a dotted line in the figure. These results indicate that a detailed re-optimisation of the target geometry, and moderator position and geometry must be performed if an increase in the ESS incident proton energy is envisaged. Finally it should be noted that whilst absolute neutron intensities are found to increase almost linearly with proton energy in the 1 GeV to 3 GeV range, it is likely that any increase in proton energy during the design optimisation phase of ESS will be balanced by a decrease in proton current, thereby maintaining ESS performance levels at 5 MW.

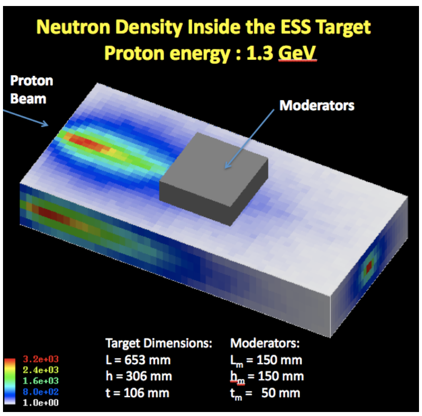

Figure 5: Geant4 modelling of neutron density inside the ESS target for 1.3 GeV protons.

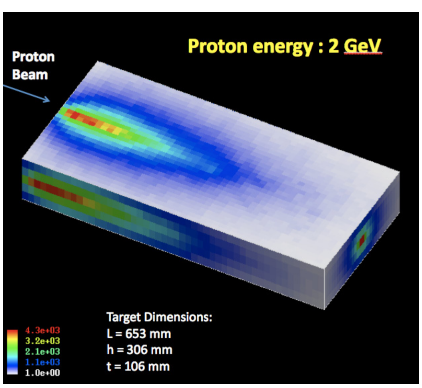

Figure 6: Geant4 modelling of neutron density inside the ESS target for 2 GeV protons.

CONCLUSIONS

The European Spallation Spallation Source is, hopefully, approaching the design optimisation and construction phase. In preparation for the design optimisation we have explored the effects of alternative target materials on spallation neutron production, and the effects of increasing proton energies on neutron production within the spallation target. GEANT4 simulations indicate that in general a molten Pb-Au eutectic alloy could successfully replace mercury within a liquid target, but that solid tungsten may provide a moderatly higher thermal neutron flux. The simulations have also shown, as expected, that increasing the ESS proton driver energy substantially changes the spallation neutron density distribution within the target, and that a substantial redesign of the target and moderator geometry is necessary if an increase of proton energy beyond 1.3GeV is introduced into the ESS functional design.

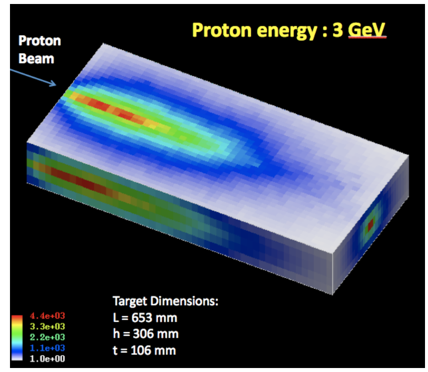

Figure 7: Geant4 modelling of neutron density inside the ESS target for 3 GeV protons.

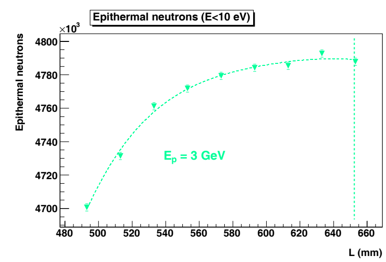

Figure 8: Epithermal neutron yield versus target length for 3 GeV protons.

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