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Alternative target design for power upgrade of the TS1 target at the ISIS Neutron Facility

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Abstract. ISIS is one of the world's most powerful spallation neutron sources for the study of material structures and dynamics. Currently ISIS has two spallation targets, TS1 operating at proton beam powers of up to 200 kW, and TS2 operating to 45 kW. This paper focuses upon an upgrade study of TS1 with the goal of increasing the ultimate operating power to 0.5 MW and beyond. During this study we have taken into consideration the necessity of maintaining the spallation neutron pulse width at current values. The increased heat deposition was monitored and the target plates dimensions were modified to take this into account. Preliminary studies of an alternative molten metal target capable to cope with a higher power are also included.

1. Introduction

ISIS [1] is currently the world's most productive spallation neutron source hosting two target stations TS1 and TS2. The first target station has been operating since 1984 and over the past thirty years high quality research has been carried out at the ISIS facility at the Rutherford Appleton Laboratory in a large range of topics from physical and biological sciences to chemistry and archeology. The high demand for neutron yield and beam time for the experiments carried out at RAL led not only to the construction of a second target station TS2 but also to an upgrade of the previous target TS1, which will lead to an increased neutron flux at the instruments enabling a larger number of experiments to be carried out in a much shorter time. The TS1 target station operates at proton beam powers of up to 200 kW and the goal is to increase the operating power to 1 MW and beyond. There are many factors that could limit the performance of a high power target therefore the design of such a target presents a major technical challenge in terms of the engineering constraints of heat removal and structural radiation damage while optimising the neutron yield. Considerable efforts have been done so far for the target design and a recent study to increase the neutronic output at the TS1 target was done at ISIS [2]. This paper focuses on a target capable to cope with an increased heat deposition at 1 MW power and beyond while maintaining the spallation neutron pulse width at current values.

The ISIS accelerator has been upgraded to achieve the increased beam intensity necessary to provide a 10 pulses per second (pps) proton beam to TS2 at the same time as maintaining present intensity to TS1 where the repetition rate is reduced from 50 pps to 40 pps. The ISIS TS1 target is driven by an 800 MeV, 200 μA proton beam equivalent to almost 0.2 MW beam power.

2. The TS1 target

A schematic diagram of the ISIS target is shown in Fig. 1. It consists of a stack of 12 solid tungsten plates (105 × 80 mm) of different thicknesses (from 15 to 50 mm) enclosed in a stainless steel pressure vessel which contains heavy water for cooling the plates. The thicknesses of the tungsten target plates are shown in Table 1.

Past experiences at other neutron facilities identified water corrosion of bare tungsten as a shortcoming for neutron spallation targets. Studies of tungsten performance under flowing water at even modest temperatures have shown significant corrosion rates that are dramatically enhanced by the presence of radiolysis products induced by irradiation [3]. The slow loss of W as it is corroded will result in a drop of the delivered neutron flux to the instruments and will also facilitate the presence of radioactive tungsten isotopes in the coolant water. Irradiation embrittlement in conjunction with large scale material losses may produce drastic failures in the targets and introduce geometry variations or cracking in a manner that perturbs target temperature distributions or coolant flow beyond those anticipated in either standard operation or transient analyses [4]. All these issues degrades the operational reliability and creates safety concerns therefore the best approach to remedy these shortcomings was to clad the tungsten target with a material that is both resistant to corrosion and which also maximises the neutron yield. These two requirements suggested that heavy atomic nuclei materials like Tantalum were the solution. This approach was taken by the KYK Neutron Scirnce Laboratory (KENS) over a decade ago to overcome the limitations of bare tungsten targets [5]. At ISIS each tungsten plate is cladded in a 2 mm thick tantalum layer. The Ta/W interface must remain in close contact as developing gaps would restrict the coolant flow and create resistance to the heat evacuation generated by the target. The gaps between the plates is 2 mm and is used for cooling the plates with heavy water. The flow of heavy water is redistributed using stainless steel manifolds.

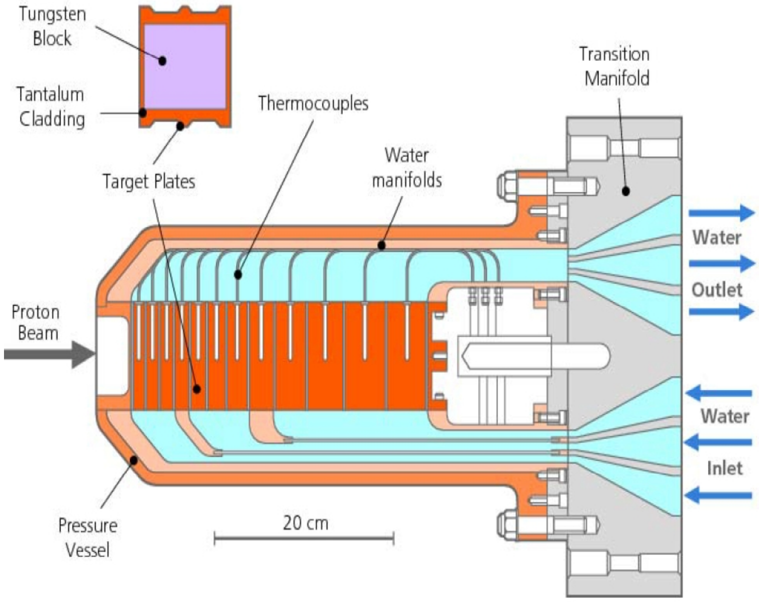

Figure 1: Layout of the ISIS-TS1 spallation target.

Four moderators are used to slow down fast neutrons escaping from the target to the lower speeds required for neutron scattering experiments. Two use water at room temperature, one uses liquid methane at 100 K and the fourth consists of liquid hydrogen at 20 K. The different temperatures result in different energy neutron beams. The moderators are small, about 0.5

Table 1: Thicknesses of the tungsten target plates.

plate no.	1	2	3	4	5	6	7	8	9	10	11	12
thickness (mm)	15	15	16	17.5	19	22	25	30	38	44	50	50

l, and are surrounded by a water-cooled beryllium reflector which scatters neutrons back into the moderators and doubles the useful flux of neutrons. Surrounding radially the reflector are the neutron channels which conduct the neutrons to the instruments for neutron scattering applications.

Based on a set of engineering drawings, the ISIS TS1 target geometry was implemented into the Geant4 Monte Carlo code [6], and Fig. 2 shows the modelling of the target and the surrounding components. In this figure, the four neutron moderators that are used to thermalize the neutrons are shown in different colours: the two water moderators (blue), the liquid methane moderator (green) and the liquid hydrogen (yellow). The two water moderators are at ambient room temperature 300 K, the liquid methane moderator operates at 100 K and the liquid hydrogen moderator at 20 K. The liquid methane moderator has curved surfaces unlike the others. The target and the moderators are embedded in a beryllium reflector shown here in grey. Also the neutron beamlines are shown (lower right) which lead the neutrons to the experimental stations.

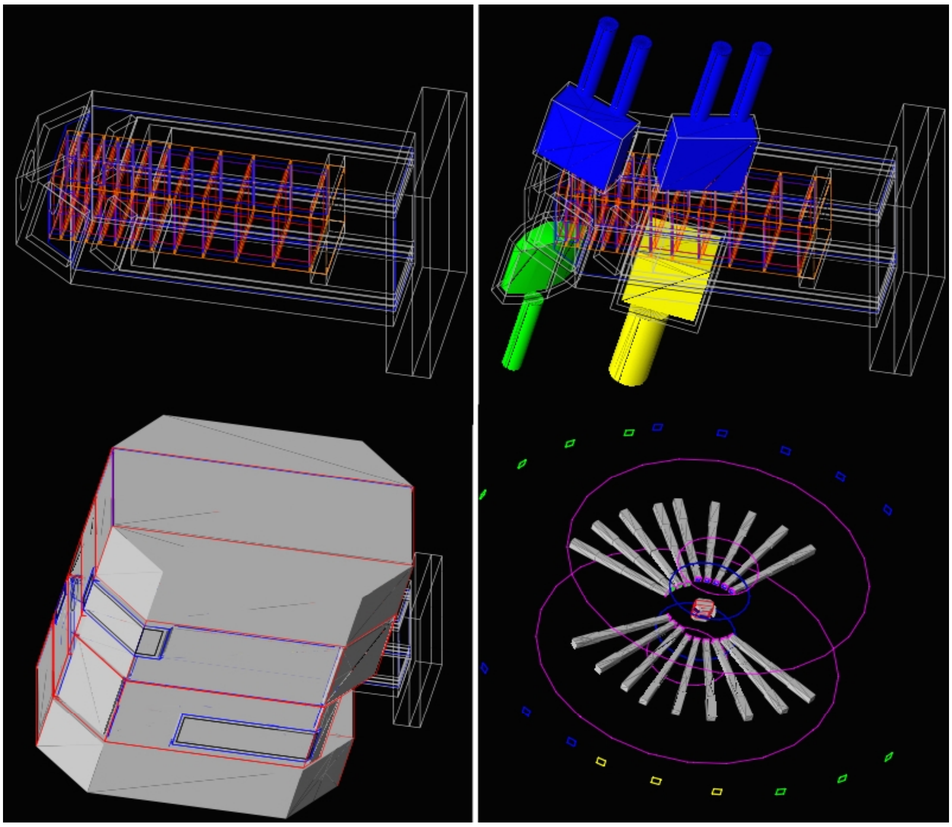

Figure 2: GEANT4 modelling of the ISIS TS1 target (upper left) , neutron moderators (upper right), reflector (lower left), shielding and instruments channels (lower right).

2.1. Heat Deposition Inside the Target

In a spallation process, as a result of the interaction of protons with target nuclei, high energy particles are produced leaving the nuclei in an excited state. They deexcite by evaporation producing more energetic particles. All these particles interact further with other nuclei in processes called nuclear cascades. The heat deposited in the target comes from the energy loss of the protons and of the nuclear recoils due to ionisation processes and is proportional to the beam current. Considering a beam current of 200 μA, the total heat rate deposition in the target plates is shown in Fig. 3 and it can be seen that it decreases gradually along the series of plates. For this reason the first plates are made thinner than the last plates. However, the heat is deposited differently in the inner tungsten material and tantalum cladding as Fig. 4 and Fig. 5 show.

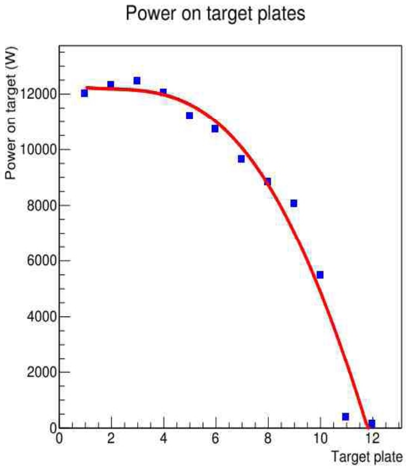

Figure 3: Energy deposition inside the target plates.

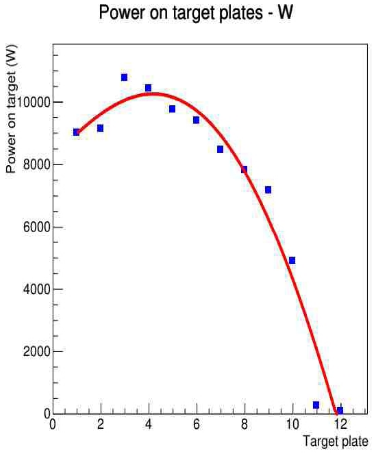

Figure 4: Energy deposition inside the inner tungsten material.

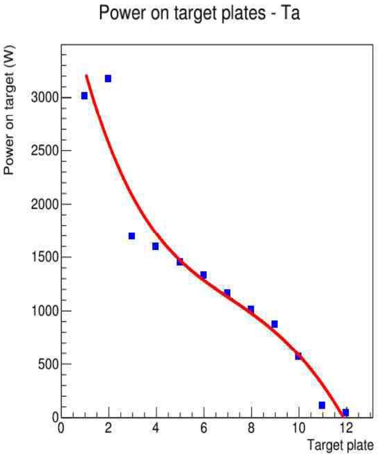

Figure 5: Energy deposition inside the tantalum cladding.

The spatial distributions of the volumetric heat deposition rates on the various target plates were calculated and the results are shown in Fig. 6. The heat deposition rates have peaks around the centre of the target plates with the maximum value being about 0.5 W/mm^3 (the bin size is 60 mm^3). These values will be used as reference values for this power upgrade study. In order to keep the fixed solid target design, more thinner plates are required to cope with the increased heat deposition due to the additional power on target. The thickness of the tungsten plate can be reduced all the way down to 5 mm, however the existing 2 mm tantalum cladding thickness can only be reduced to 1 mm due to limitations imposed by manufacturing conditions.

The neutron yields energy spectra measured at various instruments pointing to the neutron moderators are shown in Fig. 7. Because the neutron moderators operate at different temperatures the neutron spectra show a strong dependence on the moderator temperature, resulting in an increase in the number of thermal neutrons for lower operating temperatures.

3. Power upgrade to 0.5 MW and beyond

There are a number of things to consider when redesigning the target plates in order to cope with the increased proton beam power. The peak values in power on each plate should not exceed the current values. Also the maximum temperature inside the target plates should be much

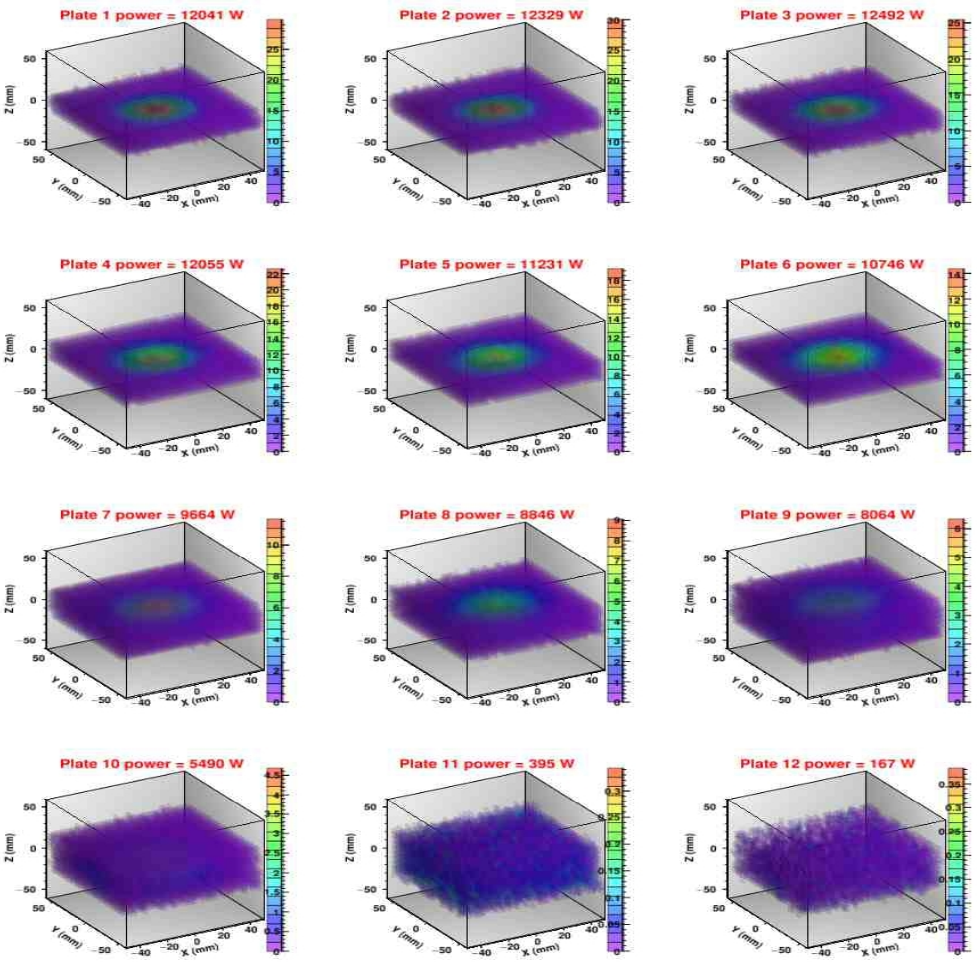

Figure 6: Spatial distribution of the volumetric heat deposition rates inside the target plates.

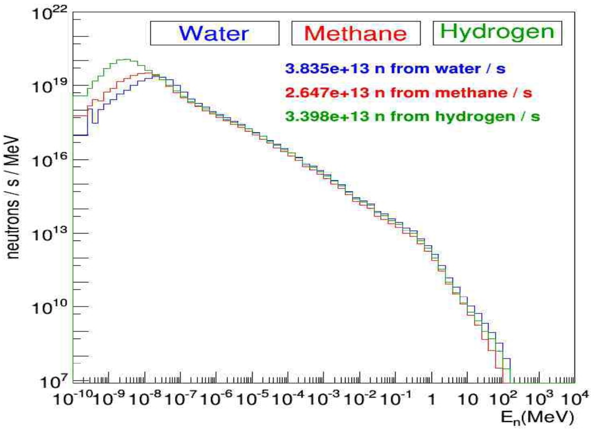

Figure 7: ISIS TS1 neutron yields for the current target plates design and a proton beam intensity of 200 μA.

lower than the melting point of the target material. There is also a limitation on the stress due to fatigue failure. Finally the water volume inside the target should not be increased too much in order to avoid slowing down the neutrons and altering the neutron pulse time distribution at the instruments. Various target plates configurations have been simulated, ending up with a new design consisting of 31 plates (instead of the current 12 plates), each plate having 1 mm Ta outer cladding on all sides.

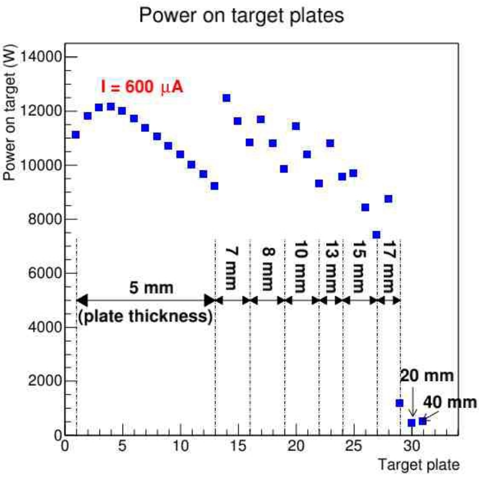

Figure 8: Total heat rate deposition inside both materials W plates and Ta cladding for a proton beam intensity of 600 μA.

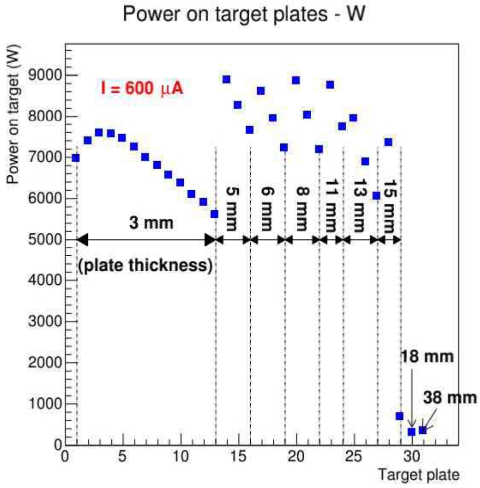

Figure 9: Total heat rate deposition inside the W plates for a proton beam intensity of 600 μA.

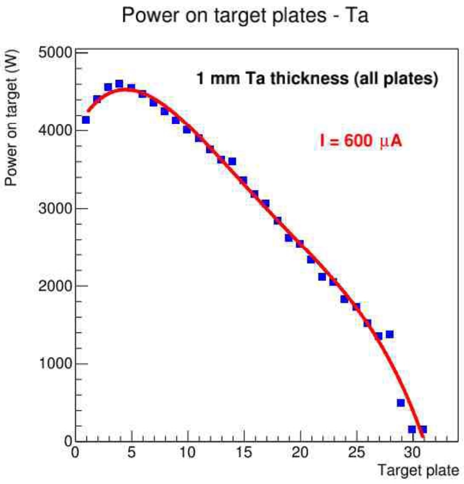

Figure 10: Total heat rate deposition inside the target plates Ta cladding for a proton beam intensity of 600 μA.

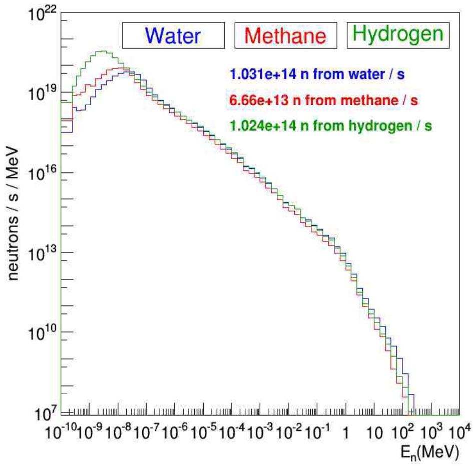

Figure 11: ISIS-TS1 neutron yields for the new thinner target plates design and a proton beam intensity of 600 μA.

The tungsten plates cladded with tantalum have an increased thickness starting from 5 mm for the first 13 plates all the way up to 40 mm for the last plate. The total power deposition on target plates is shown in Fig. 8 for all 31 target plates of different thicknesses. It can be seen that although we increased the power on target from less than 0.2 MW to 0.5 MW, by making the plates thinner the new power on them is kept at similar values as in the current design. To avoid having a large number of thin plates, each time the power drops to a safe value, the thickness of the next plate is increased. The power deposition on plates drops to zero after the 31st plate. The power deposition inside the inner tungsten material can be seen in Fig. 9 and as expected one can see the same pattern. Although the tantalum cladding thickness was reduced by half, this being the minimum achievable thickness, the power deposition has exceeded the values in the current design. This means the new power on target of 0.5 MW is the maximum value the solid target plates can sustain. Further power increase can be achieved only by a complete redesign of the target either by having a rotating solid target or a molten metal target. The speed of rotation must be chosen such that an element of the target is fully cooled during one revolution. The design of the rotating seals and of the remote handling required are both demanding from the engineering perspective.

The neutron spectra measured at the instruments corresponding to the neutron moderators are shown in Fig. 11 for this new target design. The liquid hydrogen moderator is the most efficient in thermalizing the spallation neutrons produced inside the new target. It can be seen that there is a gain in neutron yield for the 31 target plates design. The neutron yield coming from the water and hydrogen moderator is one order magnitude higher than in the current design and for the methane moderator the neutron yield is more than twice the current value.

For a direct comparison between the new target design and the current one, the neutron yields were plotted for each moderator in the energy range of interest for the neutron instruments. The direct comparison is shown in Fig. 12 and shows that with the new target plates design the neutron yield is approximately three times higher than with the current target design.

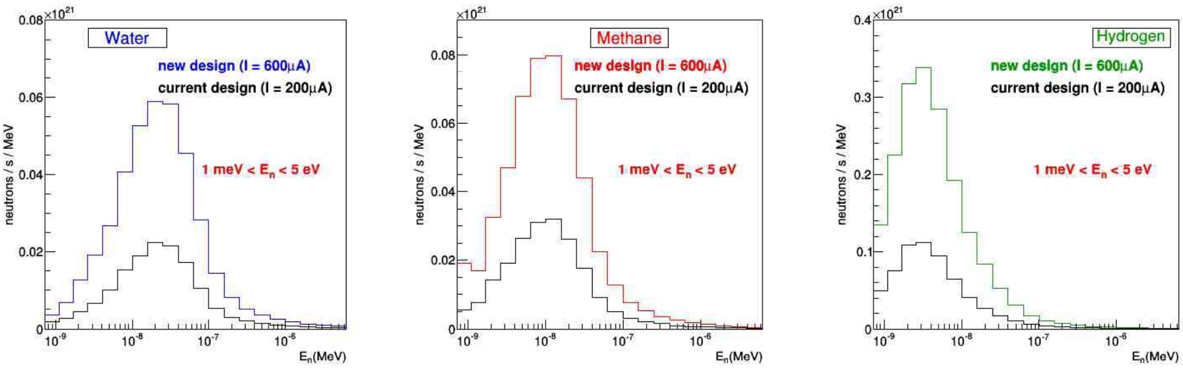

Figure 12: ISIS-TS1 neutron yields comparison between the current design and the new thinner target plates design for the neutron energy range of interest.

4. Molten target

There are a couple of advantages for having a liquid metal target. As the irradiation damage is small, the target should last long minimizing the waste disposal problem. Additionally the mean density of the liquid metal target is not diluted by a coolant because the target itself acts as the coolant with the heat being removed by convective flow. Any hazardous volatiles could be continuously extracted to reduce the potential hazard. By using an eutectic PbBi alloy containing 17% Bi the neutron production is increased twice the current ISIS values (Fig. 7) at the water and hydrogen moderators and slightly higher at the methane moderator as Fig. 13 shows. Other eutectic alloys are also being studied and show similar increase.

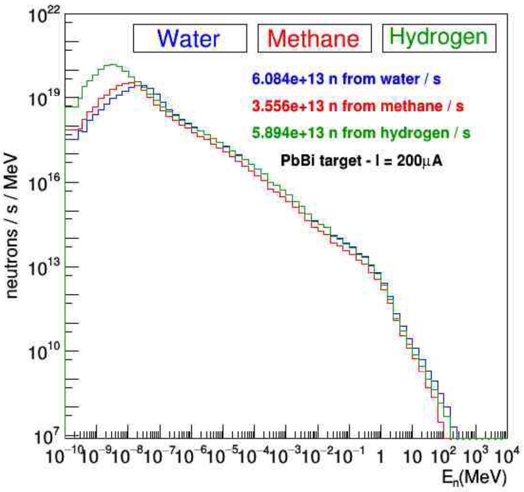

Figure 13: The neutron yield for a PbBi alloy target.

5. Conclusion

Several suggestions with varying degrees of practicality have been described above for upgrades of the TS1 target. Increasing the proton beam current from the current value of 200 μA to 600 μA requires the use of much thinner target plates, which allows the target to cope with the additional proton beam power. The goal is to increase the power on target from 0.2 MW to 0.5 MW and beyond. Several target plates configurations have been simulated and an optimum design was proposed. This consists of a set of 31 tungsten plates of increasing thickness each having a 1 mm tantalum cladding on all sides. It was found that this design copes with the additional power on target. The neutron yield increased by a factor of three compared to the current target design. Any further increase in the beam power will result in a much higher thermal stress in the Ta cladding of the target plates. A completely new design involving either a rotating solid target or a molten metal target will be required for a proton beam power above 0.5 MW.

6. Bibliography

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