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Faculty of Science
Division of Particle and Nuclear Physics

Neutron backgrounds in neutrino-nucleus scattering at the European Spallation Source

Bachelor´s Thesis

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Abstract

Being, when built, the most powerful neutron accelerator in the world, there will be a large number of potential discoveries at the European Spallation Source (ESS) in Lund. One of the most exciting of these, from a particle physics point of view, is the Coherent Elastic Neutrino-Nucleus Scattering (CEνNS). The goal of the thesis project is to calculate the neutron background in a room that could potentially be used for such an experiment. To achieve this, the Monte Carlo simulator program, called Particle and Heavy Ion Transport code System (PHITS), was used to simulate the neutron transport in a model of the ESS, starting from the proton collisions within the tungsten target. To achieve this, the weight window method will be used, so that more particles get through the shielding. With this, the goal is to eventually characterise completely the background and sources, so that future experiments can obtain the best results. Part of this goal was achieved by obtaining a neutron spectrum in the room. Nevertheless, further investigations are needed and a number of improvements have been identified which can be implemented in future work.

Contents

Abbreviations

CEνNS - Coherent Elastic Neutrino-Neutron Scattering
DTL - Drift Tube Linac
ESS - European Spallation Source
HEBT - High Energy Beam Transport
JAEA - Japan Atomic Energy Agency
LEBT - Low Energy Beam Transport
MEBT - Medium Energy Beam Transport
PHITS - Particle and Heavy Ion Transport code System
RFQ - Radio Frequency Quadrupole
SNS - Spallation Neutron Source
WWG - Weight Window Generator

1 Introduction

Even if initially theorised in 1930, neutrinos have been a big question mark throughout most of the 20^{th} century [1]. In its latter stages, we started developing technology to detect them, eventually controlling them enough to experiment with them. One of the most significant studies to surge out of this expanding field was the Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) [2]. This process involves low-energy neutrinos colliding elastically with the nucleus, which has produced outputs that have indicated several potential discoveries in different areas of nuclear and particle physics. Currently, a project called COHERENT [3] running at the Spallation Neutron Source (SNS) in the USA [4], is at the forefront of the CEνNS meansurements, but scientists have been looking to improve the overall setup so that new findings can come faster and dig deeper into this new rabbit hole.

Around 2010, the plans for a new infrastructure, the European Spallation Source (ESS) [5], took shape. Because of its extremely high energy levels, the collisions cause a great number of neutrinos to dissipate, both of low and high energies, making it a suitable contender for CEνNS experiments. The ESS being a vast facility, the question then is where to locate the study. A room was identified after some study, but it is now up to the physicists leading the operations in the field to analyse if it is an appropriate locale. The study of the background radiation is of the utmost importance here, and one of the biggest threats to the integrity of the measurements is the neutron, given the amount of these particles created by the proton collisions in the target area of the accelerator.

The tracking of the neutron background radiation in this room is the focus of this project. For this purpose, we'll be using a program called Particle and Heavy Ion Transport code System (PHITS) [6]. PHITS allows the user to build a 3D model, run particles with various conditions, and track several chosen parameters. Using this tool, we designed a geometry of parts of the ESS facility that are relevant to our study in order to obtain the most real image of what the background in the appointed CEνNS room looks like.

2 Theory

2.1 CEνNS

The neutrino is a subatomic particle with no electrical charge and a very small mass. In fact, the particle is very elusive to detect, since it only interacts weakly. These interactions have an extremely low probability of happening, meaning that detecting them is quite hard, both because it is difficult to get enough repetition for a viable statistical value, and due to the fact that the background tends to be spotted more than the neutrinos themselves. In the past, it has been possible to detect high-energy neutrinos with the charged current interaction. In this process, the neutrino transforms itself into its charged lepton counterpart, either an electron, muon, or tau, depending on which one it is associated with. More recently, detection of their interaction with the nucleus via the neutral current was carried out in the CEvNS experiment [3].

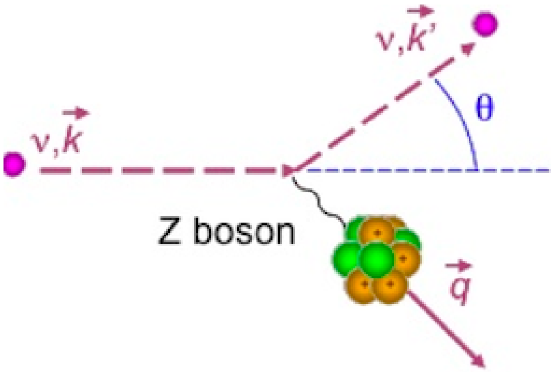

Figure 1: Illustration of the CEνNS. The neutrino interacts with the nucleus via the Z boson, changing momentum by $|\vec{k}' - \vec{k}|$ and direction with angle θ. The nucleus' momentum is also affected by $\vec{q}$. Figure provided by [3].

This scattering is, as the name indicates, coherent throughout the whole nucleus, meaning the neutrino interacts equally with the whole, instead of each proton or neutron individually. For neutrinos to interact coherently with the nucleus, they need to be at energies smaller than 10 MeV [3]. This energy level is considered to be very low for these particles, meaning that only dedicated detectors designed for high resolution at low energy can trace the impact the interaction has. For this reason, even if theorised for a long time, the scattering was only detected experimentally over 40 years later. After overcoming this difficulty, it was observed that the cross-section for this interaction increases by approximately the square of the number of nucleons present in the target.

Already there have been glimpses of the discoveries that result from the development of the CEνNS experiments. A more complete comprehension of the nuclear structure, the study of the neutrino's electromagnetic properties and its mixing angle, as well as developments on non-standard neutrino interactions, would be several examples of these. There have also been signs of potential steps forward in new physics, such as sterile neutrinos (particles like their namesakes but that do not interact with others via the weak force), and the understanding of the background in dark matter experiments, which could shine a light over a concept there is presently very little knowledge of [2] [3] [7].

To study the CEνNS, we need a high flux of low-energy neutrinos. Uncommon in many places, this can be found at spallation sources. The neutron production process starts by colliding high-energy protons with a nucleus, which emits, among neutrons of course, a π^+ meson. Losing quickly its energy, it then decays according to the following:

$$\begin{aligned} &\pi^+ \rightarrow \mu^+ + \nu_\mu \\ &\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu \end{aligned} \tag{1}$$

With this decay, one can observe how in every single collision three neutrinos and antineutrinos are produced [8]. The SNS, being a very powerful neutron accelerator, has been the main host for CEνNS experiments. Now, with the construction of an even brighter source, the opportunity is there to develop even further and achieve results that could potentially lead to groundbreaking discoveries in the scientific world.

2.2 The ESS

For the continued development of our knowledge of physics, more powerful and precise facilities need to be built and improved using state-of-the-art technology. With this in mind, 13 different European countries came together to plan and build the ESS, locating it in Lund. With its 2 GeV proton accelerator, energy which then is transferred to the neutrons themselves, it will be the most powerful source in the world for a great many years to come.

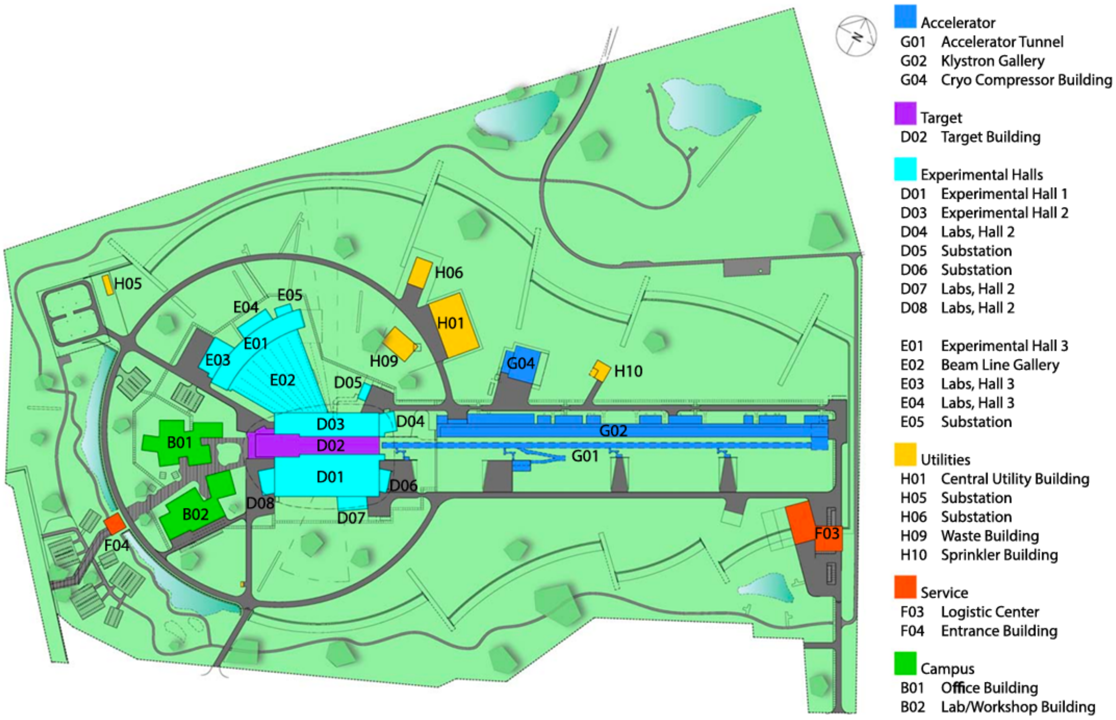

Figure 2: Plan of the ESS facility. Figure provided by [5].

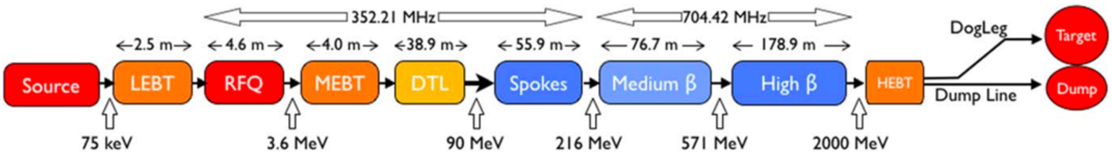

Figure 3: Detailed layout of the ESS accelerator. Figure provided by [5].

In Figures 2 and 3 above one can see in more detail the layout of the facility and the accelerator itself. Here, the initial proton source has only 75 keV of energy when it goes through the Low Energy Beam Transport (LEBT) to the Radio Frequency Quadrupole

(RFQ), where the particles get accelerated to 3.6 MeV. Here reaching a higher energy level, it is then transported through the 4 meters of Medium Energy Beam Transport (MEBT) to the Drift Tube Linac (DTL), section in which the beam is accelerated again, this time up to 90 MeV. At this point, the protons enter three consecutive superconductor areas: the spoke, which increases the energy to 216 MeV; the Medium β, where the beam reaches an energy of 571 MeV; and the High β, where the particles are accelerated to its peak of 2 GeV. [8]

Finally, the protons go through the High Energy Beam Transport to hit the tungsten target, which will be rotating at 23.3 $revolutions/minute$. This collision extracts a large number of fast neutrons, within the energy level of $(1-20)$ MeV, by which point they get moderated to slow neutrons in the range of the meV. These particles will then fulfill the main purpose of the ESS - they will be channeled through one of the neutron beamlines, each one colliding with a different target, which then provides essential information about the target's nuclear composition.

As shown before, out of the proton-tungsten interaction come not only neutrons but a great number of neutrinos too. Whilst the effectiveness and efficiency of the neutron experiments are key, running studies on neutrinos in parallel does not influence it. As a consequence, scientists are given the opportunity to take advantage of the abundant neutrino source at their disposal in such a facility. There are two main projects on this topic: one is using the high-energy neutrinos that come out of the initial collision and building a so-called Super Beam [2]. The CEνNS is the other, and only possible with low-energy neutrinos, a great amount of which also originates from the initial scattering.

For such studies, one naturally needs an appropriate room with low background radiation. After some analysis, a room was identified as a potential host. This needs to be carefully investigated since it is of the utmost importance that its properties align with the goal of the experiment. Figure 4 shows the floor level plan for the ESS facility.

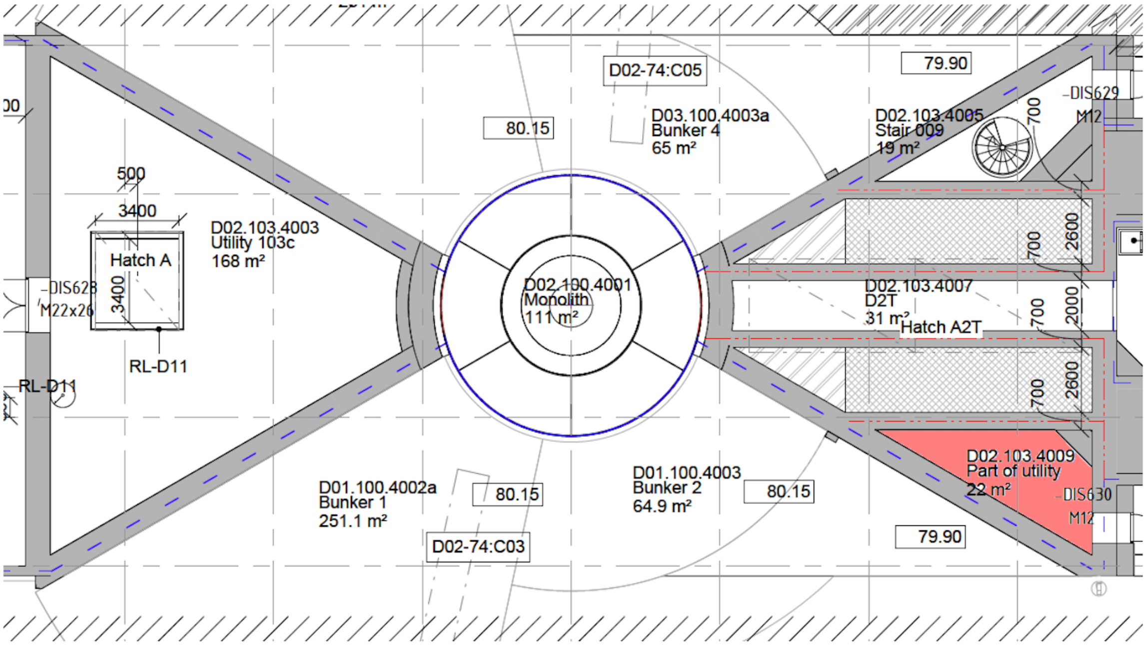

Figure 4: Blueprint at the ground level of the ESS facility. Marked in orange is the room designated for the CEνNS experiments. Figure provided by ESS.

3 Method

3.1 PHITS

The first step in this project was to design a simplified model of the ESS, where it would be possible to run the particle collisions using the Monte Carlo method. Because it is impossible to predict how each individual particle reacts but there generally is a statistical pattern, the Monte Carlo method takes this into account every time the code is run in order to obtain a realistic statistical result. For this purpose, PHITS was the program chosen. This simulator, developed by the Japan Atomic Energy Agency (JAEA) [9], is frequently used in nuclear and particle physics studies due to the rigorous development of the code as well as the large variety of tallies that can be applied to different purposes within the field [6]. Other programs can also be used, like GEANT4 [10] and MCNP6 [11], the latter being used to investigate the background radiation in a previous study [12].

All three programs mentioned above are Monte Carlo simulators. This entails that when the code is run, it includes one or several variables which are based on an estimated range of values as opposed to a fixed set, meaning they have implied randomness in individual results. Because the simulations are associated with probability distributions, the results get increasingly accurate as the program runs, obtaining a different result every time. Variables like these are called stochastic. For instance, a certain particle of set energy has a specific probability of crossing a barrier of a particular width and density. The simulators mentioned above each take these variables into consideration, making the results of the simulations closer to those obtained experimentally [8] [13].

The above-mentioned software is made of different codes. This means that the particle interactions with surfaces will be distinct, as is the process to generate the Monte Carlo method. Since they take different routes but are all accurate in the end, it adds value if projects take different approaches and then compare results. In general, studies with different Monte Carlo codes can provide a more robust estimate of the background in the room.

Some of the events we are working with are extremely rare, which makes them way too improbable to happen in the simulation, even though they are observed experimentally. We would observe them by running the program over a long enough period of time but it is a very ineffective process. However, methods, such as weight windows, have been developed in order to make such simulations possible. Figure 5 below shows how the weight-window method works. The weight window parameters are generated with a weight window generator (WWG).

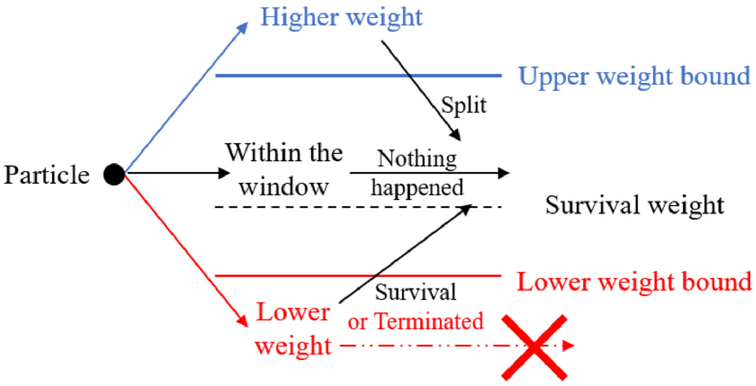

Figure 5: Illustration of how weight windows function. Reprinted from "Development and benchmarking of the Weight Window Mesh function for OpenMC", Vol 170, Yuan Hu, Yuefeng Qiu, Ulrich Fischer, "Illustration of the Weight Window function.", Page 2, Copyright (2021), with permission from Elsevier [14].

As a particle approaches a surface between two geometrical objects, it is attributed a weight, and a window is set and only if the particle's weight lies within the upper and lower limits will it go through. If it is above the window the particle splits, goes down in weight and through. If its weight is below, a "lottery" is played so that there is a probability of the particle "winning" and rising above the lower limit of the window to get across the obstacle. On the other hand, particles that lose this game don't go through [14][15].

Since a particle is more likely to get through a thin wall than a thick one, splitting a block into smaller pieces and using the WWG will result in more particles making it to the other side of the entire obstacle. For PHITS's weight windows specifically, if a particle's weight (wgt) is lower than the product of the upper boundary (w_{max}) with the ratio of the importance (R), the probability of the particle surviving is $p_s = wgt/(w_{min} * R)$, with w_{min} being the window's lower boundary. If it survives, its weight is then updated to $wgt = w_{min} * R$. When using the WWG, a constant, $c = 0.01$ for instance, is applied to the density of each of the subdivided sections, and the program run. If all the areas are populated by the tracked particle, the constant is increased, perhaps up to $c = 0.1$. This process repeats itself until c goes back to 1 and the density back to its previous value. The weight window generator in PHITS is a global weight window generator, meaning it aims to populate all regions of a model. The downside of it being so is that we are only interested in the population of the significant pathways from the target to the room, meaning that running time is spent in areas of no particular importance to our study. One approach to help compensate for this is to limit the geometry to only the areas of interest.

3.2 The Model

In PHITS, one starts building the 3D geometry by composing cells, inserting their shape and Cartesian coordinates in the source code editor. These can be used individually or in combination with others to make surfaces. Besides the cell numbers, to build a surface one needs to add the material and its density, since it plays a big part in the outcome of the simulations. Surface by surface, a model of the ESS was built, including the proton beamline, the tungsten target, the monolith surrounding it, and the shielding all the way until the room where the CEνNS experiments were planned to run.

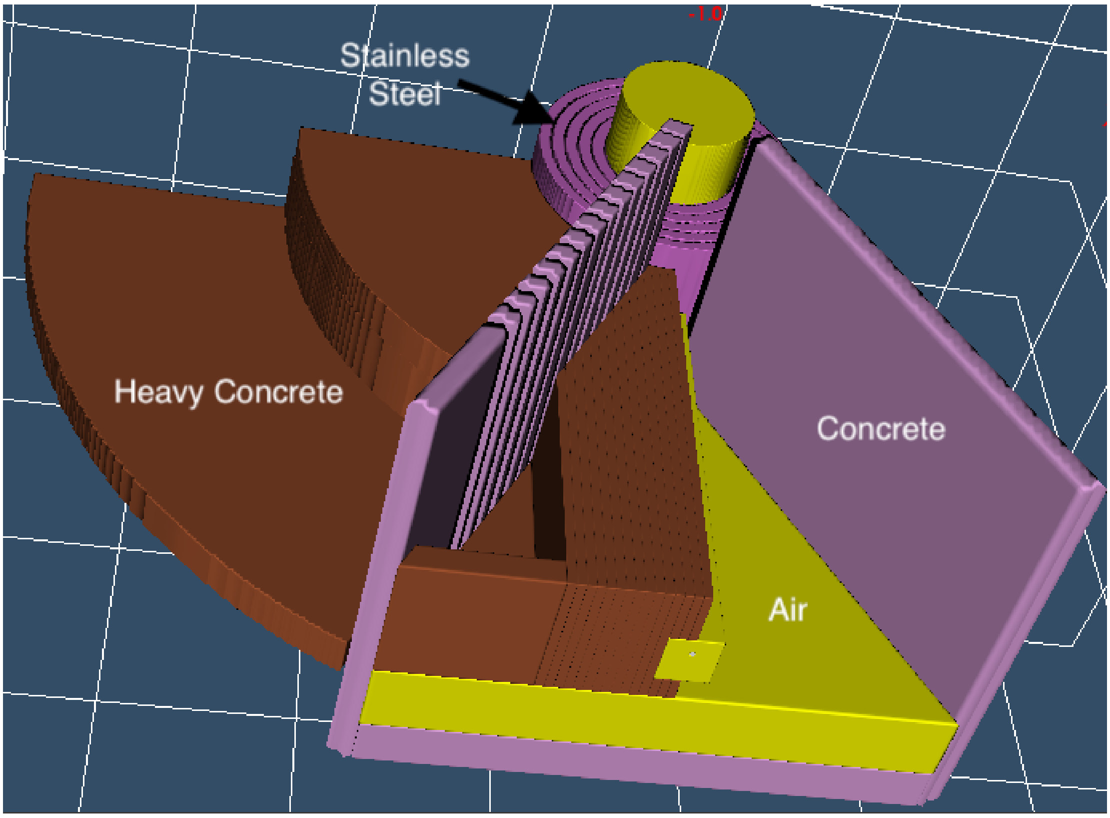

Figure 6: 3D view of the final model. To each colour corresponds a material: yellow is air, brown is heavy concrete, the brighter lilac cylinders are stainless steel and water and the more opaque lilac walls in the triangular area are concrete.

Figure 6 has been obtained via a 3D viewer included in the PHITS package called PHIG3D [6]. The model has been designed with several subdivisions of bigger areas in order to apply the weight windows, as can be seen in the monolith, the left wall of the triangular section, and the concrete shielding at the centre left of it. Other shielding components have been omitted from the picture in order to show more clearly the interior of the geometry.

The starting point of this project was designing the target area. This was a section where the previous Bachelor's thesis ([8]) had a lot of details and subdivisions, making it one where we attempted to simplify the most. From here, the assembly of the monolith followed, with a special focus on using the right materials and not leaving any gaps or double-defined areas between it and the target. Then the triangular area was built, where the room in question is located, as well as the layers above and below ground level. Finally, the bunker area was modeled, which is an area that will be open from shielding and host numerous neutron scattering instrument components and could be a source of background to the experiment room.

When the PHITS model was concluded, the geometry was tested. This was done by running a $2GeV$ proton source along the beamline to the target, like the one planned when ESS is built. At first, there were no neutrons crossing beyond the monolith. Since this is not realistic, further subdivisions in this area were designed, in order to apply more detailed weight windows and obtain better results. The same had to be done to the triangular area to the left of the beamline so that some neutrons made their way through to the room.

4 Results

The model above was then run in PHITS and Figure 7 was obtained. The source normalisation was $1.56 * 10^{16}$ protons/s.

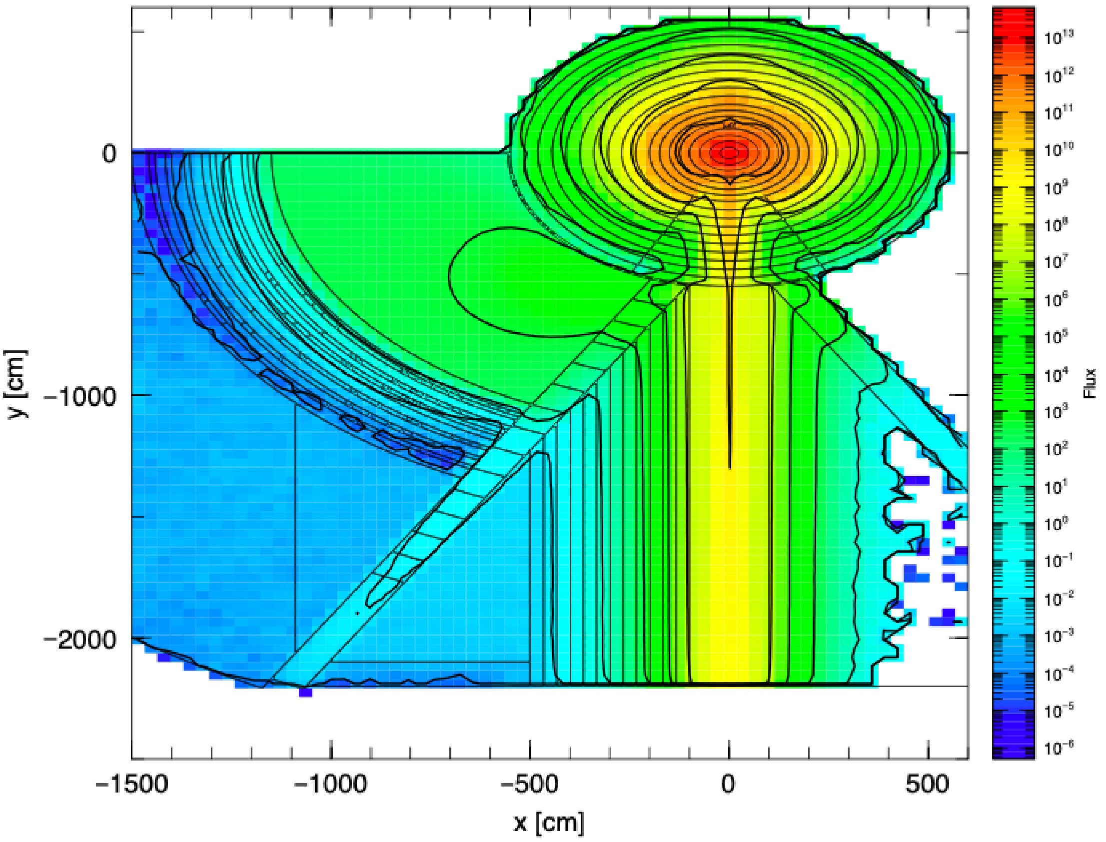

Figure 7: Neutron flux map at $z = 0$, in a coordinate system where the origin is at the centre of the target.

Expectedly, the highest flux of neutrons is naturally surrounding the target, where they are created after the proton collision with the tungsten. A fraction of them can be seen being directed back along the proton beamline. Otherwise, the flux gradually diminishes as the number of barriers increases, given that not all of the particles will get through. It is worth noticing that the population of statistics on the left side of the beamline is higher than on the right, showing that the WWG affects the statistics positively. In the room where the CEνNS experiments are planned on being held, there is a flux of approximately 10^{-2} $neutrons/(cm^2 * s)$.

Analysing this room in particular, we then obtained more details about the energy of the neutrons present in it, as shown in Figure 8 below. This is the energy-dependent flux integrated over the whole volume of the room.

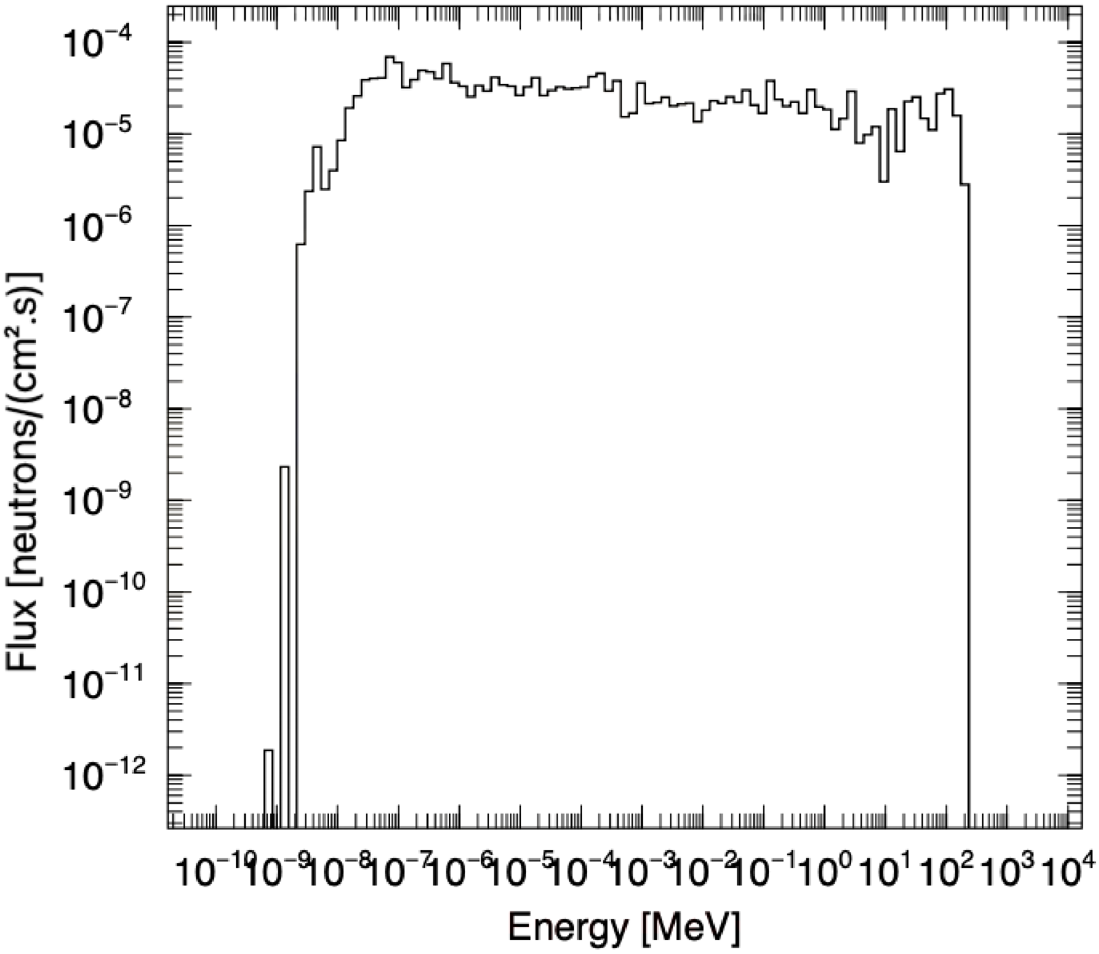

Figure 8: Graph showing the flux and energy on neutrons present in the designated room.

As seen in Figure 8, the neutron flux is relatively flat between 10^{-8} and 10^{2} MeV and reaches a maximum at 100 MeV. The flux between $1-10$ MeV is on the order of 10^{-4} $neutrons/(cm^{2}*s)$.

5 Discussion

As previously mentioned, this project took over from where another Bachelor's student left off with his thesis [8]. The main goal to achieve this time was to make the neutrons reach the designated room, which was accomplished. Nonetheless, there are several plans for improvement of the research and results that would be put in place if given more time. For instance, a bigger timeframe would allow us to correlate a developed version of our results with both the work done at the ESS with MCNP6, and the measurements at the SNS. However, continued investigation with the current approach should be carried out in order to understand the background in more detail.

The first step could be, for example, to improve the directional dependance of the variance reduction. This can be seen by looking at figure 7 where a significant amount of statistics are in the forward direction of the tungsten target. These neutrons have very little chance of reaching the room, meaning that they are somewhat irrelevant to our study. By adjusting the geometry, we make the program spend less time in these areas, resulting in a higher efficiency overall.

The above being completed, a future project could then investigate the impact of neutron beamlines in the bunker. These were not included in this model, but are part of the planned ESS design [5]. The beamlines result in some of the steel of the monolith being removed, allowing for more high-energy neutrons to enter the bunker, which could lead to additional contributions to the background in the room. Furthermore, some of the detailed geometry should be revisited, in particular in important regions of the model that were greatly simplified in this work. Specifically, some of the steel in the monolith should be removed to include the reflector geometry, and no earthquake gap was included between the monolith and the bunker. The consequences of the former could be more neutrons being redirected toward the room, increasing the background radiation, whilst the latter should mean that some particles escape the facility through that breach.

Another study that could prove interesting and change the interpretation of results would be to examine the neutron flux as a function of the height in the room. Perhaps it is not uniform, which could make the location sustainable as a host for the CEνNS at certain elevations. A realistic detector geometry of the room would also be of immense value. Having the flux integrated over the entire room leaves a lot of information gaps. Perhaps the neutron radiation is focused on a segment of the room, making the rest of it appropriate for the experiments.

It would then be curious to investigate the neutrino signal in the room as well. Since this is the particle of focus in the CEνNS experiments, it would definitely affect the measurements. Obtaining the neutrino flux in the room and comparing it to the neutron background is essential to evaluate the room's characteristics as a potential host for the study.

6 Conclusion and Outlook

All things considered, the project had a positive outcome. The main goal of simulating neutrons in the planned room was achieved, proving that the method to model the neutron background was a valid one. Having taken a significantly different approach to the previous Bachelor's thesis on this topic [8], we found ourselves with a considerable amount of new information that, with time, we could have assimilated and adapted to the geometry. The project being a short one, those improvements will be potentially passed on to a future study.

There is a fair amount of room for the PHITS model to be improved. As mentioned, in the process of simplifying it to make the process of running the simulation and adjusting the geometry faster, there were areas that have been substantially simplified.

This was a risk with this approach and should be investigated as discussed in the previous section. For example, oversimplifications may have occurred in the important pathways that lead the neutrons to the room, but these would need to be evaluated by a potential future project. During this process, comparisons with the previous studies can and should be made, in order to achieve more accurate results. Eventually, it would be worthwhile to compare the simulated results against measurements collected physically in the room when the ESS is operative. The research on this matter is still in its early days, so many directions can be taken that would add value and information to then extract the best out of such extraordinary facilities.

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Appendix

Below is the input file of the geometry of the ESS model on PHITS.

```
 [Title]
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icntl       =              8 $ --  8 geometry, 11 3dshow
itall       =              1
maxcas      =          1
maxbch      =           1
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file(6)     = phits.out
rseed       =       432432
ipnint = 1

emin(2)  = 1.0E-10
dmax(2)  = 20.0

emin(14) = 0.001
dmax(14) = 3000
icells=0

maxbnk = 10000*15000

$ ++++++++++++++++++++++ END ++++++++++++++++++++++++++++
 $ parameters
set: c91[1] $gshow $1
set: c92[3] $resol  $3
set: c93[1] $epsout $1
set: c94[1.0]

[cell]
1 -1 1
2 60 0.00120463 -1 (-813 : 839 : 155) (794 : -840 : -155 : -805 : -189 :
-214 : -236 : 237) (-157 : 3 : 237 : -842 : 165 : -200 : 853 : -212 : 2)
(-157 : 3 : 237 : -236 : 214 : -165 : 801 : -212) #162 #860 #3010 $ (big
target cylinder) (triangular section) (bunker) (right triangular wall)
33 0 -35 -2 805 #860
92 0 136 -137 123 -16 125 -152
93 0 142 -143 123 -16 125 -152
109 0 136 -137 140 -141 125 -152 #1075
110 0 142 -143 140 -141 125 -152 #1075
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#860 #1075 #1076
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123 1034 c94*0.085465 846 −847 278 −284
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134 1034 c94*0.085465 849 −850 284 −725 #780 #781
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160 60 c94*4.988e−05  157 −3 −168 167 −165 200 −187 212 −2
161 1040 c94*0.0478094 157 −3 −237 236 −214 165 −801 212 −870
162 1040 c94*0.0478094 157 3 −237 236 −189 186 −801 185
163 1044 c94*0.0896464 841 −811 856 −3 155 805 189 214 #33 #3001
164 1044 c94*0.0896464 841 −811 857 −856 155 805 189 214 #3001
165 1044 c94*0.0896464 841 −811 858 −857 155 805 189 214 #3001
166 1044 c94*0.0896464 841 −811 859 −858 155 805 189 214 #3001
167 1044 c94*0.0896464 841 −811 860 −859 155 805 189 214
168 1044 c94*0.0896464 841 −811 861 −860 155 805 189 214
169 1044 c94*0.0896464 841 −811 862 −861 155 805 189 214
170 1044 c94*0.0896464 841 −811 863 −862 155 805 189 214
171 1044 c94*0.0896464 841 −811 864 −863 155 805 189 214
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172 1044 c94*0.0896464 841 -811 865 -864 155 805 189 214
173 1044 c94*0.0896464 841 -811 866 -865 155 805 189 214
174 1044 c94*0.0896464 841 -811 867 -866 155 805 189 214
175 1044 c94*0.0896464 841 -811 868 -867 155 805 189 214
176 1044 c94*0.0896464 841 -811 869 -868 155 805 189 214
177 1044 c94*0.0896464 841 -811 809 -869 155 805 189 214
178 1044 c94*0.0896464 841 -811 -809 855 155 805 189 214 #2096
179 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 870 -871
180 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 871 -872
181 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 872 -873
182 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 873 -874
183 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 874 -875
184 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 875 -876
185 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 876 -877
186 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 877 -878
187 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 878 -879
188 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 879 -880
189 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 880 -881
190 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 881 -882
191 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 882 -883
192 1040 c94*0.0478094 -3 -237 236 -214 165 -801 212 883
377 0 -423 265 239 -240
780 1014 c94*0.0847901  -154 239 -264
781 1018 c94*0.042395  -154 239 -265 264
860 1029 c94*0.0501185  -240 239 423 -854
1075 0 -125 140 -141
1076 0 123 -16 -125
1985 1044 c94*0.0896464 -3 -168 167 -165 200 187 -763 212 -2
1986 1044 c94*0.0896464 -3 -168 167 -165 200 763 -764 212 -2
1987 1044 c94*0.0896464 -3 -168 167 -165 200 764 -765 212 -2
1988 1044 c94*0.0896464 -3 -168 167 -165 200 765 -766 212 -2
1989 1044 c94*0.0896464 -3 -168 167 -165 200 766 -767 212 -2
1990 1044 c94*0.0896464 -3 -168 167 -165 200 767 -768 212 -2
1991 1044 c94*0.0896464 -3 -168 167 -165 200 768 -769 212 -2
1992 1044 c94*0.0896464 -3 -168 167 -165 200 769 -770 212 -2
1993 1044 c94*0.0896464 -3 -168 167 -165 200 770 -771 212 -2
1994 1044 c94*0.0896464 -3 -168 167 -165 200 771 -772 212 -2
1995 1044 c94*0.0896464 -3 -168 167 -165 200 772 -773 212 -2
1996 1044 c94*0.0896464 -3 -168 167 -165 200 773 -774 212 -2
1997 1044 c94*0.0896464 -3 -168 167 -165 200 774 -775 212 -2
1998 1044 c94*0.0896464 -3 -168 167 -165 200 775 -776 212 -2
1999 1044 c94*0.0896464 -3 -168 167 -165 200 776 -190 212 -2
$2095 1044 c94*0.0896464 -806 805 214 -803 841 -811 #2096
2096 60 c94*4.988e-05 214 -809 808 836 -811
3001 60 c94*4.988e-05 -833 834 -835 836 805 -837 155 #33 #5019
3002 1044 c94*0.0896464 157 -3 168 -173 -165 200 -190 212 -2
3003 60 c94*4.988e-05 154 -838 -827 #780 #781
3004 1044 c94*0.0896464 154 -839 -155 #3003
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3005 1040 c94*0.0478094 -794 840 155 805 189 214 811 -154
3006 60 c94*4.988e-05 -794 840 155 805 189 214 154 -839
3007 1040 c94*0.0478094 -794 840 155 805 189 214 839 -237
3008 60 c94*4.988e-05 -794 840 155 805 189 214 813 -841
3009 1040 c94*0.0478094 -794 840 155 805 189 214 236 -813
3010 1044 c94*0.0896464 157 -3 -167 842 -165 200 -853 212 -2
3012 60 c94*4.988e-05 157 -3 -237 167 -165 200 -853 212 -2 (3 : -842 :
173 : 165 : -200 : -157 : 190 : -212 : 2) #3010 #4000
4000 60 c94*4.988e-05 190 234 -165 167 -173 200
5000 1034 c94*0.085465 724 -725 152 -814 #33 #860 #6000
5001 1034 c94*0.085465 724 -725 814 -815 #33 #860 #6001
5002 1034 c94*0.085465 724 -725 815 -816 #33 #6002
5003 1034 c94*0.085465 724 -725 816 -817 #33 #6003
5004 1034 c94*0.085465 724 -725 817 -818 #33 #6004
5005 1034 c94*0.085465 724 -725 818 -819 #33 #6005
5006 1034 c94*0.085465 724 -725 819 -820 #33 #6006
5007 1034 c94*0.085465 724 -725 820 -821 #33 #6007
5008 1034 c94*0.085465 724 -725 821 -822 #33 #6008
5009 1034 c94*0.085465 724 -725 822 -155 #33 #6009
5010 1034 c94*0.085465 725 -154 -823
5011 1034 c94*0.085465 725 -154 823 -824 #780 #781
5012 1034 c94*0.085465 725 -154 824 -825 #780 #781
5013 1034 c94*0.085465 725 -154 825 -826
5014 1034 c94*0.085465 725 -154 826 -827
5015 1034 c94*0.085465 725 -154 827 -828
5016 1034 c94*0.085465 725 -154 828 -829
5017 1034 c94*0.085465 725 -154 829 -830
5018 1034 c94*0.085465 725 -154 830 -831
5019 1034 c94*0.085465 725 -154 831 -155
5020 1034 c94*0.085465 -724 812 -823
5021 1034 c94*0.085465 -724 812 823 -824
5022 1034 c94*0.085465 -724 812 824 -825
5023 1034 c94*0.085465 -724 812 825 -826
5024 1034 c94*0.085465 -724 812 826 -827
5025 1034 c94*0.085465 -724 812 827 -828
5026 1034 c94*0.085465 -724 812 828 -829
5027 1034 c94*0.085465 -724 812 829 -830
5028 1034 c94*0.085465 -724 812 830 -831
5029 1034 c94*0.085465 -724 812 831 -155
5030 1032 c94*0.0620709 -812 813 -823
5031 1032 c94*0.0620709 -812 813 823 -824
5032 1032 c94*0.0620709 -812 813 824 -825
5033 1032 c94*0.0620709 -812 813 825 -826
5034 1032 c94*0.0620709 -812 813 826 -827
5035 1032 c94*0.0620709 -812 813 827 -828
5036 1032 c94*0.0620709 -812 813 828 -829
5037 1032 c94*0.0620709 -812 813 829 -830
5038 1032 c94*0.0620709 -812 813 830 -831
```

```
5039 1032 c94*0.0620709 -812 813 831 -155
6000 1034 c94*0.085465 724 -725 152 -814 212 185 #33 #860
6001 1034 c94*0.085465 724 -725 814 -815 212 185 #33 #860
6002 1034 c94*0.085465 724 -725 815 -816 212 185 #33
6003 1034 c94*0.085465 724 -725 816 -817 212 185 #33
6004 1034 c94*0.085465 724 -725 817 -818 212 185 #33
6005 1034 c94*0.085465 724 -725 818 -819 212 185 #33
6006 1034 c94*0.085465 724 -725 819 -820 212 185 #33
6007 1034 c94*0.085465 724 -725 820 -821 212 185 #33
6008 1034 c94*0.085465 724 -725 821 -822 212 185 #33
6009 1034 c94*0.085465 724 -725 822 -155 212 185 #33

[surface]
1 so 3500
2 py 0.0
3 px 0.0
16 pz -10.8
35 cy 10.5
123 pz -36
125 cz 35.3
136 p 0.866025404 -0.5 0.0 -2.675
137 p -0.866025404 -0.5 0.0 2.675
140 pz 12.4
141 pz 15.3
142 p -0.866025404 0.5 0.0 -2.675
143 p 0.866025404 0.5 0.0 2.675
151 pz 200
152 cz 200
154 pz 400
155 cz 550
157 cz 556
165 p 0.38 -0.22 0.0 40
166 p 0.207911691 -0.978147601 0.0 1.42108547e-14
167 pz -120
168 pz 150
173 pz 300
175 pz 170
185 p 0.894934362 -0.446197813 0.0 0.0
186 p -0.38 -0.22 0.0 40
187 cz 1150
189 p -0.38 -0.22 0.0 80
190 cz 1500
200 p -0.207911691 -0.978147601 0.0 1.42108547e-14
212 p -0.894934362 -0.446197813 0.0 0.0
214 p 0.38 -0.22 0.0 80
232 py -2600
234 px -1090
235 px 1090
```

```
236 pz −750
237 pz 1000
239 pz −4
240 pz 4
254 c/z 0 112.2 71.8
263 pz 435
264 c/z 0 112.2 5
265 c/z 0 112.2 13.5
278 pz 30
284 pz 40
423 c/z 0 112.2 83.8
724 pz −50
725 pz 50
763 cz 1195
764 cz 1210
765 cz 1225
766 cz 1255
767 cz 1270
768 cz 1290
769 cz 1305
770 cz 1325
771 cz 1355
772 cz 1370
773 cz 1401
774 cz 1416.5
775 cz 1442
776 cz 1457.5
794 px 1200
801 cz 2455.6
803 px −420
805 py −2200
806 py −1100
808 py −2100
809 px −500
810 pz −155
811 pz 295
812 pz −300
813 pz −550
814 cz 235
815 cz 270
816 cz 305
817 cz 340
818 cz 375
819 cz 410
820 cz 445
821 cz 480
822 cz 515
823 cz 55
```

```
824  cz  110
825  cz  165
826  cz  220
827  cz  275
828  cz  330
829  cz  385
830  cz  440
831  cz  495
832  py  29
833  px  100
834  px  −100
835  pz  70
836  pz  −150
837  py  −500
838  pz  700
839  pz  800
840  px  −1200
841  pz  −250
842  pz  −270
843  pz  20
844  pz  −40
845  pz  −45
846  cz  25
847  cz  50
848  cz  75
849  cz  100
850  cz  125
851  cz  150
852  cz  175
853  cz  2500
854  c/z  0  112.2  125
855  px  −1200
856  px  −33
857  px  −66
858  px  −99
859  px  −133
860  px  −166
861  px  −199
862  px  −233
863  px  −266
864  px  −299
865  px  −333
866  px  −366
867  px  −399
868  px  −433
869  px  −466
870  cz  650
871  cz  750
```

```
872  cz  850
873  cz  950
874  cz  1050
875  cz  1150
876  cz  1250
877  cz  1350
878  cz  1450
879  cz  1550
880  cz  1650
881  cz  1750
882  cz  1850
883  cz  1950

[ Material ]
$ Material : Air rho=0.00120463 g/cc
mat[60]
    C         7e-09
  14N         3.9128e-05
  16O         1.0512e-05
  40Ar          2.3207e-07
$ Material : SS316L rho=7.85 g/cc
mat[1014]
    C         0.0001180788816
  28Si          0.0006209229816
  29Si          3.154334099e-05
  30Si          2.081790808e-05
  31P         3.052509725e-05
  32S         1.400460341e-05
  33S         1.105662286e-07
  34S         6.265984886e-07
  36S         1.441430894e-09
  50Cr          0.000671565282
  52Cr          0.01295046837
  53Cr          0.001468479175
  54Cr          0.0003655355128
  55Mn          0.001548887617
  54Fe          0.003251255828
  56Fe          0.05103776402
  57Fe          0.001178684581
  58Fe          0.0001568612581
  59Co          2.406477356e-05
  58Ni          0.006853958453
  60Ni          0.002640132541
  61Ni          0.0001147646928
  62Ni          0.0003659202053
  64Ni          9.318910082e-05
  92Mo          0.0001819501259
  94Mo          0.0001137034605
```

```
  95Mo          0.000195870448
  96Mo          0.000205479196
  97Mo          0.0001177686348
  98Mo          0.0002979941311
  100Mo          0.0001191237494
$ Material : SS316L3925 rho=3.925 g/cc
mat[1018]
    C          5.90394408e-05
  28Si          0.0003104614908
  29Si          1.57716705e-05
  30Si          1.040895404e-05
  31P          1.526254863e-05
  32S          7.002301703e-06
  33S          5.528311428e-08
  34S          3.132992443e-07
  36S          7.20715447e-10
  50Cr          0.000335782641
  52Cr          0.006475234187
  53Cr          0.0007342395875
  54Cr          0.0001827677564
  55Mn          0.0007744438084
  54Fe          0.001625627914
  56Fe          0.02551888201
  57Fe          0.0005893422906
  58Fe          7.843062906e-05
  59Co          1.203238678e-05
  58Ni          0.003426979227
  60Ni          0.001320066271
  61Ni          5.738234641e-05
  62Ni          0.0001829601026
  64Ni          4.659455041e-05
  92Mo          9.097506297e-05
  94Mo          5.685173026e-05
  95Mo          9.793522402e-05
  96Mo          0.000102739598
  97Mo          5.88843174e-05
  98Mo          0.0001489970655
  100Mo          5.956187471e-05
$ Material : Tungsten_15.3g rho=15.3 g/cc
mat[1029]
  180W          6.014221328e-05
  182W          0.01328140543
  183W          0.007171958933
  184W          0.01535631179
  186W          0.0142486927
$ Material : SS316L_10H2O rho=7.084 g/cc
mat[1034]
  1H          0.006685763977
```

```
   C          0.0001050529551
  16O         0.003342881988
  28Si         0.0005524255753
  29Si         2.806362272e-05
  30Si         1.852137091e-05
  31P         2.715770701e-05
  32S         1.245967909e-05
  33S         9.836906385e-08
  34S         5.574749861e-07
  36S         1.282418777e-09
  50Cr         0.0005974812468
  52Cr         0.01152183146
  53Cr         0.001306483215
  54Cr         0.0003252112934
  55Mn         0.001378021362
  54Fe         0.002892592035
  56Fe         0.04540750945
  57Fe         0.001048657446
  58Fe         0.0001395570358
  59Co         2.141005692e-05
  58Ni         0.006097860852
  60Ni         0.002348885097
  61Ni         0.0001021043726
  62Ni         0.0003255535484
  64Ni         8.2908902e-05
  92Mo         0.0001618782135
  94Mo         0.0001011602106
  95Mo         0.0001742629088
  96Mo         0.0001828116633
  97Mo         0.0001047769333
  98Mo         0.0002651207705
  100Mo         0.0001059825578
$ Material : SkanskaConcrete rho=2.35 g/cc
mat[1040]
  1H         0.000160505669
  16O         0.01827956151
  24Mg         9.083776936e-05
  27Al         0.0009179395641
  28Si         0.005980949972
  32S         0.0003872557536
  39K         0.0007553877663
  40Ca         0.01877473265
  48Ti         0.0001816755387
  55Mn         0.0001003996398
  56Fe         0.002122735242
  58Ni         5.737122275e-05
$ Material : MagnadenseHC rho=3.8 g/cc
mat[1044]
```

```
   1H          0.01204081554
   2H          1.384818771e-06
   16O          0.04747856916
   23Na           0.0004582335099
   27Al           0.0005432223875
   28Si           0.00352692974
   29Si           0.0001791722042
   30Si           0.000118245395
   31P          0.0003253269901
   32S          2.035277124e-05
   33S          1.607289656e-07
   34S          9.106199589e-07
   36S          2.153848564e-09
   39K          8.19371031e-05
   40K          1.032038852e-08
   41K          5.913139199e-06
   40Ca           0.001096812983
   42Ca           7.320237663e-06
   43Ca           1.527408806e-06
   44Ca           2.360125916e-05
   46Ca           4.522995039e-08
   48Ca           2.115810063e-06
   54Fe           0.001386122948
   56Fe           0.02176019575
   57Fe           0.0005025320604
   58Fe           6.687711745e-05
$ -----------------------------------------------------------
$ ------------------- TALLY CARDS ----------------------------
$ -----------------------------------------------------------
[Source]
   s-type =   2           # mono-energetic axial source
     proj =   proton      # kind of incident nucleus
       e0 =   2000.000      # energy of beam [MeV/u]
      factor = 1.56e16
      x0  = -7.0
      x1  =  7.0
      y0  = -30.0
      y1  = -30.0
      z0  = -1.6
      z1  = 1.6
      dir =   0.0000      # z-direction of beam [cosine]
      phi = 90.0

[end]
```