Generic Document	
Document Number	ESS-0052649
Date:	April 18, 2016
Revision	3
State	General Document
Page	1 (30)

Neutronic Design of the Bunker

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Contents

1 Introduction

The ESS is a long-pulse spallation neutron source which is significantly different from both reactor and short-pulse spallation concepts that have been built as major facilities before. New problems will be encountered by the ESS and these will differ from those at reactor sources which have issues with low brilliance and those at short-pulse sources which are limited by total neutron flux. An expected problem for long-pulse sources is background. This arises from the requirements to ”chop” the neutron beam while a fast background component is being produced and the need to place choppers as close to the source as possible, which leads to shielding compromises. Thus, for the ESS, effort must be made to reduce the backgrounds not just for radiological protection but also to reduce the noise at the instrumental detectors. In this report, we propose a shielding bunker concept which meets both the radiation safety requirements outside of the bunker area and at the same time aims to reduce instrument background levels, which allows ESS beamlines to achieve their operational targets.

2 About this document

The primary purpose of this report is to present a working model of a bunker design which meets its neutronic requirements. This will serve as the starting point for the engineering design, which allow a detailed costing, manufacture and installation. It will also serve as the basis for a more detailed report which will be needed for the SSM licensing application. The document is organised in the following way: first we give an overview of the radiation sources coming from the target and the moderator (section 3), then we discuss the requirements that the bunker must fulfil (section 5). In section 6 we describe the design that meets the requirements. Finally, in section 6.5 we show several features of such a design, with a focus on instrument performance. It should be noted that the proposed bunker design will be subject to optimisation during the engineering design phase. The engineering design has to be validated by further simulations.

3 Background and Radiation Sources

Spallation neutron sources have very different backgrounds compared to reactor sources since they are affected by high-energetic particles produced during the spallation process. These particles have enough energy to produce a phenomenon known as particle showers where a cascade of secondary particles is produced (for more details see [1]). The primary and secondary particles create a background and a radiation issue that must be confined first in the monolith and then in the bunker. The neutron energy spectrum at the beam port entrances that are located 2 m after the moderator are shown in figure 1 and give an overview of the background component.

This neutron energy spectrum has a large energy range that goes from the signal neutrons (cold and thermal $E_{\text{neutrons}} < 0.5$ eV) up to a high energy component that ends with a tail almost up to the incident proton beam energy. The dashed vertical line in figure 1 divides the signal component from the background one. The neutrons with energies greater than 100 keV are called fast neutrons and represent one of the most critical sources of background and radiation safety issues since they can travel large distances, lose energy in the instrument shielding, and can generate more secondaries in the process. This background component can enter directly into the beamline openings along with the cold and thermal neutrons. In addition, these fast neutrons can lead to the creation of secondary neutrons further down the instrument. Other engineering realities, such as clear-

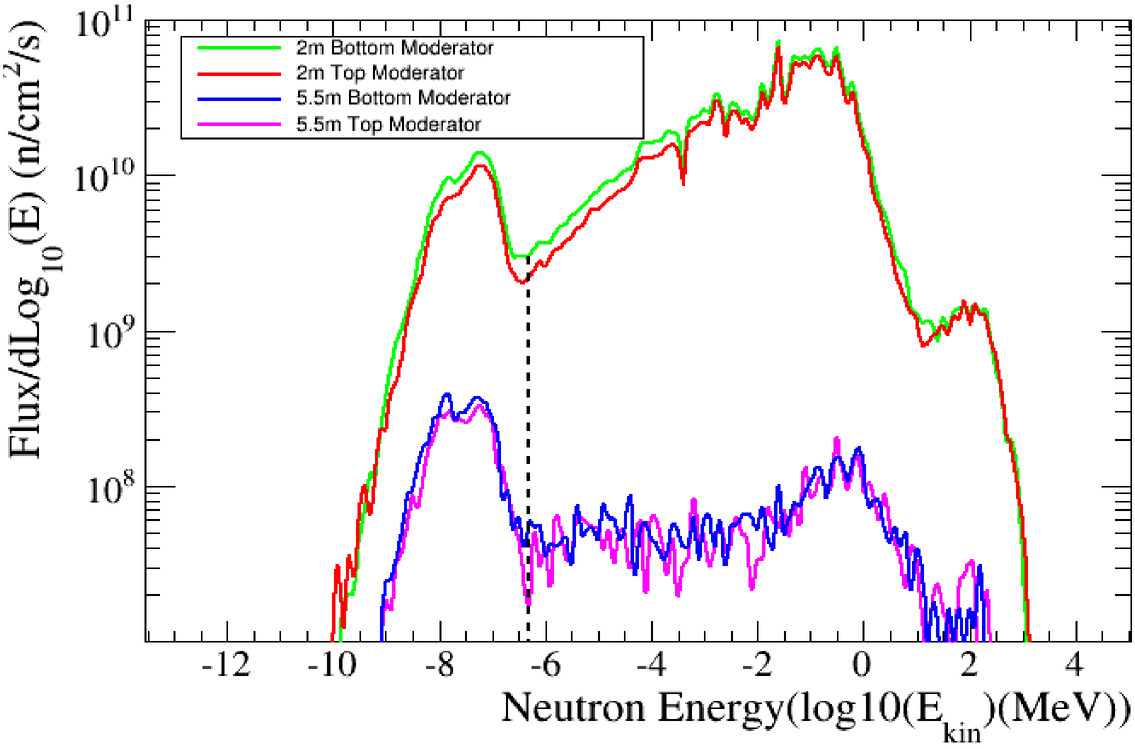
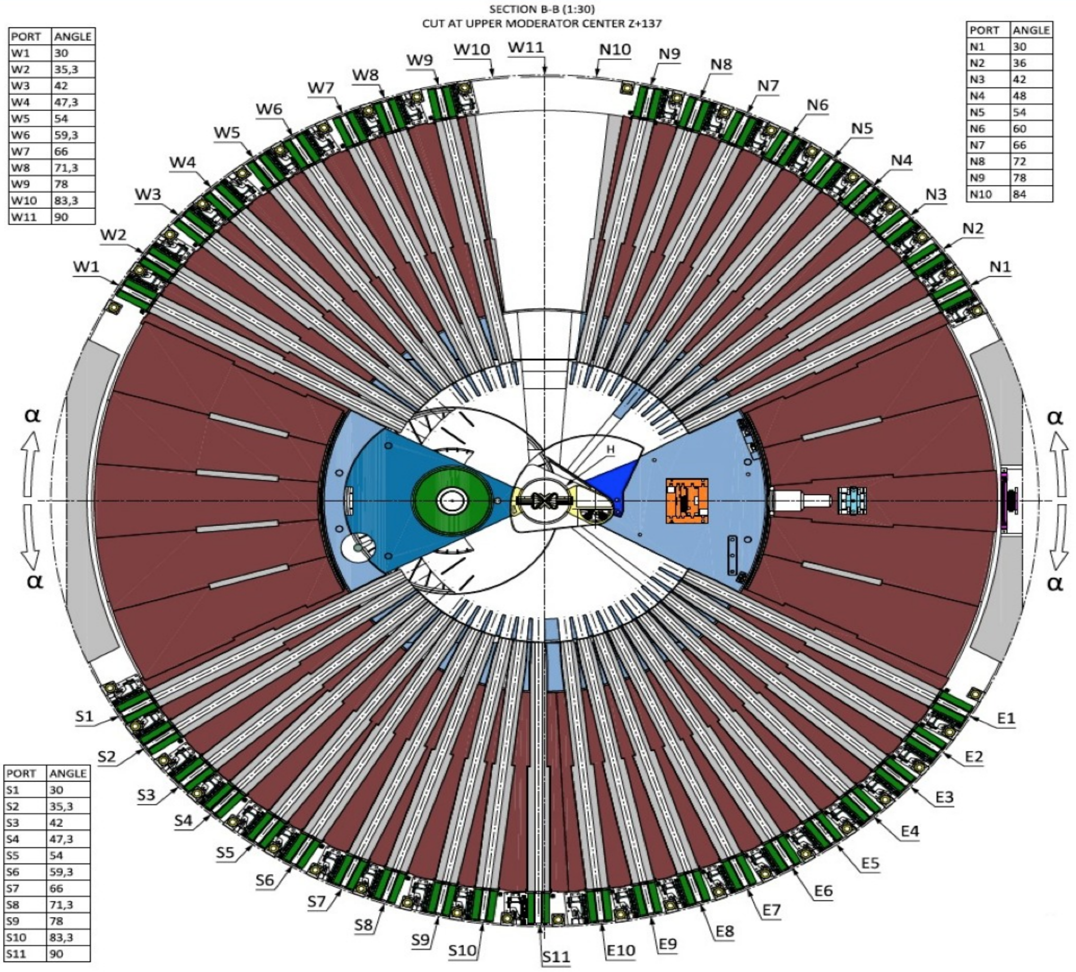


Figure 1: Spectrum at the guide entrance at 2 m, for a downstream beam line (corresponding to the W2 port in the west sector see figure 2) for the top and bottom moderator [2] (red and green line) and at the monolith exit (magenta and blue line) 5.5 m after the moderator. The dashed vertical line divides the signal neutrons (cold and thermal $E_{neutrons}$ <0.5 eV) from the background neutrons ($E_{neutrons}$ >0.5 eV)). Calculations were performed with MCNPX2.7.0 using f4 tallies. Note that in these calculations the beam inserts have openings of 7 × 14 cm^2 and guide substrates or additional shielding were not modelled.



PORT	ANGLE
W1	30
W2	35,3
W3	42
W4	47,3
W5	54
W6	59,3
W7	66
W8	71,3
W9	78
W10	83,3
W11	90

PORT	ANGLE
N1	30
N2	36
N3	42
N4	48
N5	54
N6	60
N7	66
N8	72
N9	78
N10	84

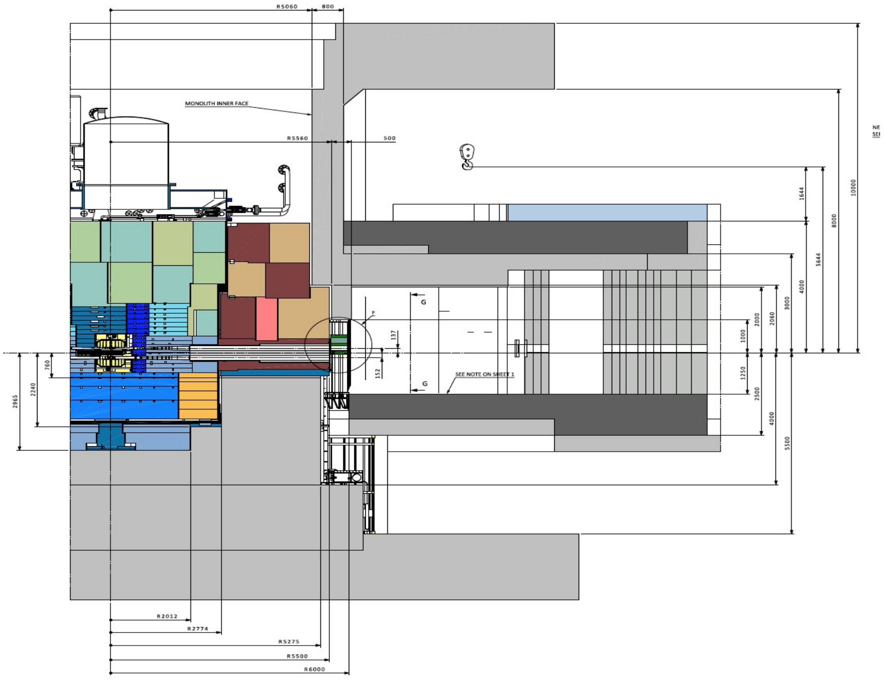
PORT	ANGLE
S1	30
S2	35,3
S3	42
S4	47,3
S5	54
S6	59,3
S7	66
S8	71,3
S9	78
S10	83,3
S11	90

Figure 2: Overview of the beam ports for the top moderator.

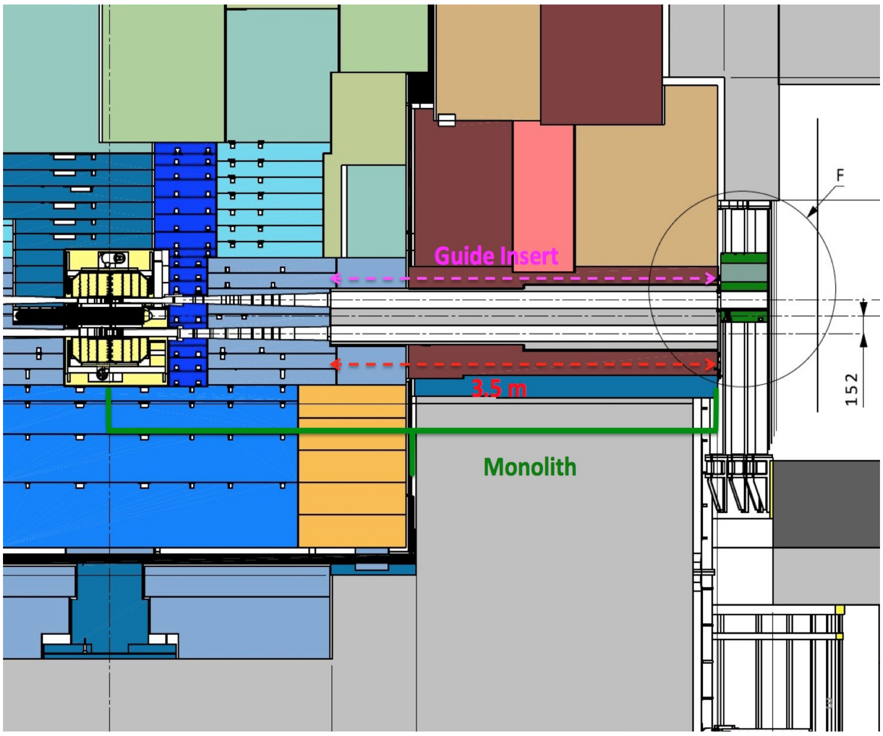
ance gaps needed in all directions for the beam port inserts (see figure 3(b)) and between the guide support and the guide itself to allow for the guide alignment, can contribute to propagation of the fast neutron background.

4 Monolith shield wall

The ESS target monolith will be shielded by a steel layer (the monolith shield wall) which extends to a radius of 5.5 m (the design of the monolith shield wall is not part of this report). Within this monolith shield wall there will be beam extraction ports for each instrument, as can be seen in the picture in figure 2. The monolith wall will shield the target and reduce the radiation escaping from it. The effect of the 5.5 m shielding wall in reducing the background neutrons can be seen in figure 1. The neutron background component, even though it has been reduced by about two orders of magnitude, is still substantial and must be shielded and contained in the bunker. A schematic overview of the target, including the monolith and the bunker is shown in figure 3a. Figure 3b shows a zoomed in picture inside the monolith, where it is shown that the guide insert starts at a distance of 2 m from the moderator and extends to 5.5 m at the end of the monolith shield wall. This means that in the horizontal direction the total shielding thickness is 3.5 m at the beam port level.



(a) Schematic view of the target and the bunker.



(b) Zoom of the beamline insert

Figure 3: Target and the bunker (a). Beamline insert inside the monolith(b).

5 Bunker requirements

The primary bunker purpose is to confine the radiation (neutrons and photons) coming from the monolith and from the first sections of the beamlines in order to provide a safe working environment immediately outside of the bunker area. In addition to its primary purpose, the bunker must fulfil several different mechanical constraints. A full list of the bunker requirements can be found in reference [3].

Below is a list of radiation safety and operational requirements which are considered of primary interest for the design of the bunker that will be discussed below.

- The bunker shall ensure that the calculated radiation at the bunker external surfaces is less than 1.5 μSv/h [1]
- The bunker must be designed in such a way that it allows access to all instruments components within an instrument corridor.
- The bunker shall be designed in such a way to allow access to, removal and exchange of all guide inserts or plugs.
- The amount of shielding blocks to be handled to access instruments components should be minimised in order to minimise the time needed for accessing the components.

In addition, there are also mechanical constraints that have been placed on the bunker design, which are listed below in order of importance.

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[1] The area outside the bunker is considered supervised ESS area. For this kind of zone the swedish law ESS implementation requires that the long-term whole body dose for normal operation shall be less that 3 μSv/h [4], but a safety factor of 2 shall be applied to all particle transport code calculations [5].

Floor loading	CF floor - max peak load. 30 tonne/m^2
Access Requirement	The complexity must be reduced to the point that the access time to the instrument components in the bunker is within 2 days with the available cranes.
Surface Activation	Surface activation dose must be within a level to allow removal of the walls or roof of the bunker safely, e.g. outshine from any cavity must be below 100 μSv/hour [6] .
Instruments Requirement	The bunker must be able to accomodate all the instruments components and installation tools.
Costs	Costs for the bunker must be within reasonable bounds. (The budget for the bunker is 14.6M€)

6 The Bunker

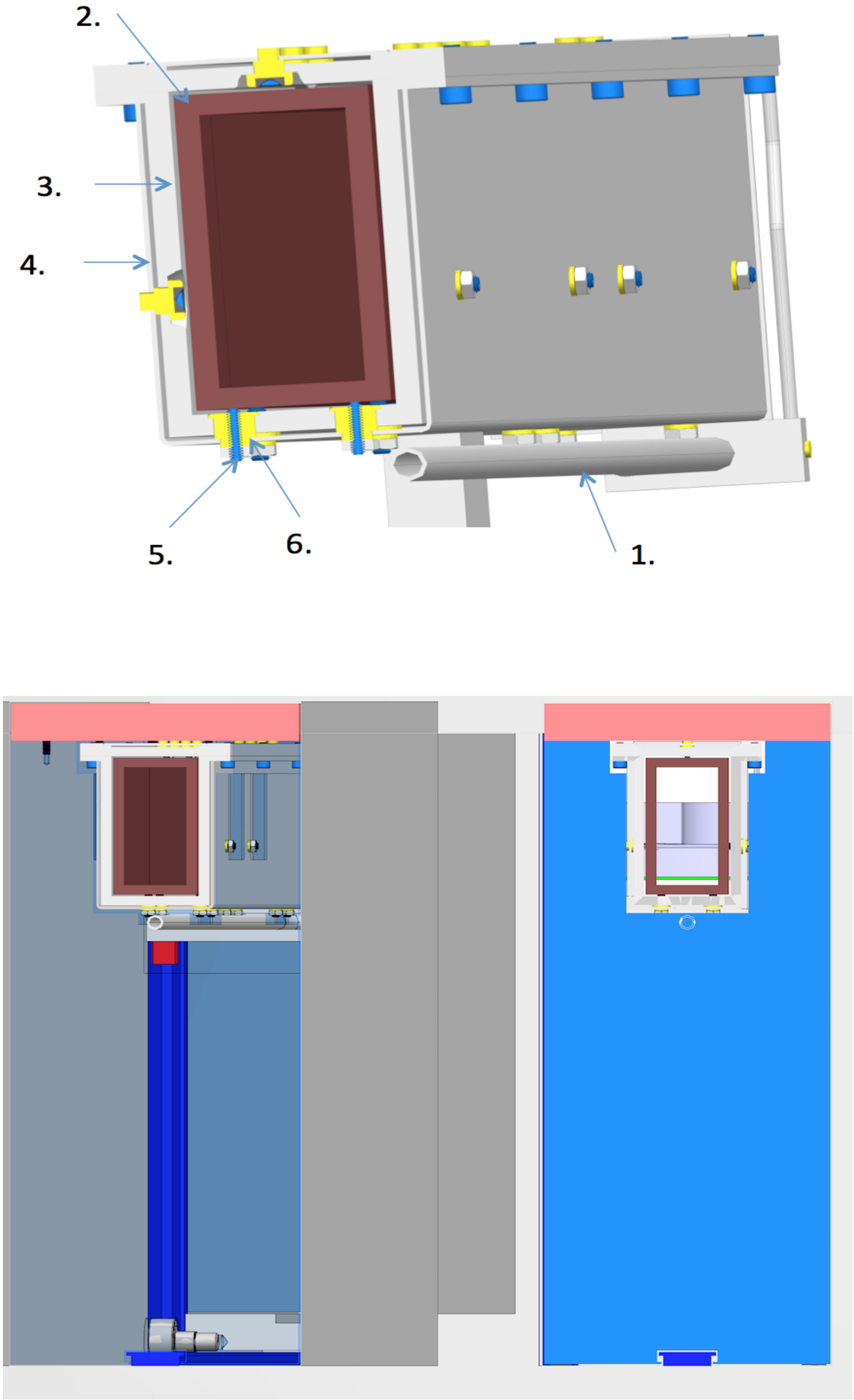
6.1 The radiation source in the bunker

Primary radiation in the bunker and hitting the bunker wall comes via the guide-insert within the monolith. This has two main components (a) the direct beamline guide volume and (b) the different clearance gaps that surrounds the guide-insert in the monolith. In figure 4 is shown the front view of the guide insert with all the details. There are different sets of clearance gaps: the alignment gap (figure 4 (a)), the cooling gap (figure 4 (a)) and the large clearance gap that surround the insert itself and the port block inside the monolith (figure 4 (b)). The size of this clearance gap is not yet fixed but the planned goal is 2mm each side . All these gaps provide a substantial fast neutron flux compared to that exiting the guide.

The radiation exiting the monolith via these routes has a number of paths through which it can be scattered rather than directly striking the bunker wall:

- **The metal substrates of neutron guides.**

  Guides are required to transport low energy neutrons of the desired wavelength out to the distance of the bunker external shielding wall. Many existing facilities use glass guides. Evacuating the guide itself has resulted in numerous reported guide failures, particularly with borated glasses, as the glass degrades in the high neutron fluxes close to neutron sources. The current best practice is to use a radiation-hard substrate within the source shielding, and outside the source shielding a non-borofloat glass guide with an externally supported vacuum system. The latter is frequently a metal housing made from plated mild steel with reinforcement ribs.



(a)

(b)

Figure 4: (a) Details of the guide insert with all its component. 1. is the cooling of the monolith insert. 2. Guide substrate (10mm of copper). 3. Alignment gap 2mm. 4. Cooling gap 2mm. 5. Set screw copper -cooling point. 6. Sleeve. (b) Overview of the insert and port block in the monolith.

To further mitigate the risks associated with fast neutron albedo transport, radiation damage, activation and handling, the ESS has standardised [7] on aluminium guides as the radiation-hard substrate, and extends its use throughout the bunker. There, the aluminium guides will be surrounded by a thermal neutron absorber, e.g. B_4C/Gd or Li, to reduce the activation footprint. The density of aluminium is approximately the same as glass, and just under 30% of the density of steel, but aluminium can be welded and is not as fragile as glass. This means that the expected fast neutron albedo transport through ESS aluminium guides is the same as, or lower than, glass guides with vacuum housings, depending on whether the aluminium guides have separate vacuum housings or are welded[2]. On the other hand, the gamma emmission from aluminium guides, associated with thermal/cold neutron capture, is of a higher energy than that of borated glasses.

Bearing in mind that detailed engineering design is not yet complete on any instrument project, and taking all of these possibilities into consideration, in our models we have assumed steel channels to provide a realistic upper envelope of the radiation issues for the bunker.

Finally, it should be noted that the radiation field in the bunker is dominated by higher energy processes associated with spallation, and cold/thermal beam transport through the guides is not included in the simulations to improve calculation speed.

- **The choppers and the collimators.**

  The ESS is a long pulse neutron source and that requires the shaping of the pulse via multiple choppers, which need to be as close to the source as possible. Secondly, the main pulse is very long, so significant T0 choppers are envisaged by many instruments. Choppers and collimators within the bunker area give rise to a significant scattering neutron component for two reasons: (i) they create ”prompt” scattering centres within the bunker and (ii) most choppers are large and there is a considerable void volume in the surrounding chopper housing where shielding cannot be placed. This leads to additional streaming channels, mainly directed to the roof of the bunker.

6.2 The bunker design

The neutron beams exiting from the monolith, depending on the instruments, correspond to radiation doses ranging from several tens of Sv/h to hundreds of Sv/h and the bunker wall must be able to reduce such dose levels to below 1.5 μSv/hour. If we assume that about 1% of the beam is composed of neutrons above 120 MeV, to reduce a 200 Sv/hr beam to 1 μSv/hour, we need at least 2.5 m of steel (6 *tenth-lengths*) since the tenth value of steel is 41 cm [8]. Based on the above considerations, the following bunker design is proposed to fulfil the radiation safety requirements, the operational requirements and

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[2] This issue should be resolved during 2016 when the NMX project finalises detailed engineering design

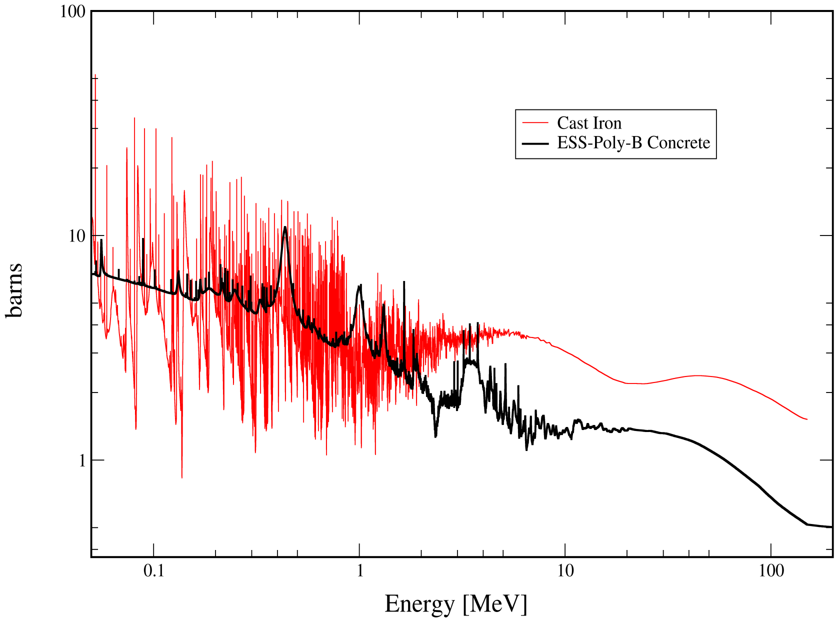

Figure 5: Total cross sections for cast iron and ESS-BP concrete.

the mechanical constraints. The bunker will consist of an external multi-layer wall of 3.5 m thickness for the instrument sectors (in the short and long sectors) and a multi-layer roof of 2 m thickness. Suppression of the dose requires that the fast neutron flux is first *moderated* and then absorbed followed by absorption of the resultant gamma rays. At high energy ($>$10MeV), the cross section for neutron interaction is approximately $A^{\frac{2}{3}}$ [8]. This leads to the requirement of using steel in the design and starting the shielding wall with steel. Also due to the resonant nature of the intermediate [1 keV-10 MeV] energy cross section of most materials, an effect called *streaming* takes place in which neutrons that come to a gap in the cross section between resonances are able to travel a long way (metres) without scattering. The proposed solution is to add a second different material to make a composite structure. In the bunker wall, the proposed design is made of steel and ESS-Poly-Boron Concrete (ESS-PBC) [9]. This is made from a mixture of limestone (CaO), polyethylene and B_4C with a medium density of around 2 g/cc [3]. Standard concrete is typically based on silicon oxide (sand) and is a medium density concrete of 2.34 g/cc. ESS-PBC has a higher hydrogen and boron content which greatly reduces the population density of neutrons. Figure 5 shows the resonant region of cast iron and ESS-PBC. Within the region below 1MeV, the two materials are complementary to each other and layers of each are used to supress the streaming from the other.

The addition of boron and polyethylene to the concrete decreases the gamma dose from the absorption of the neutrons. The boron only produces 0.511 MeV photons on absorption of neutrons while the polyethylene prevents a significant number of sub-eV neutrons from escaping the concrete and being absorbed in the steel, which would otherwise give

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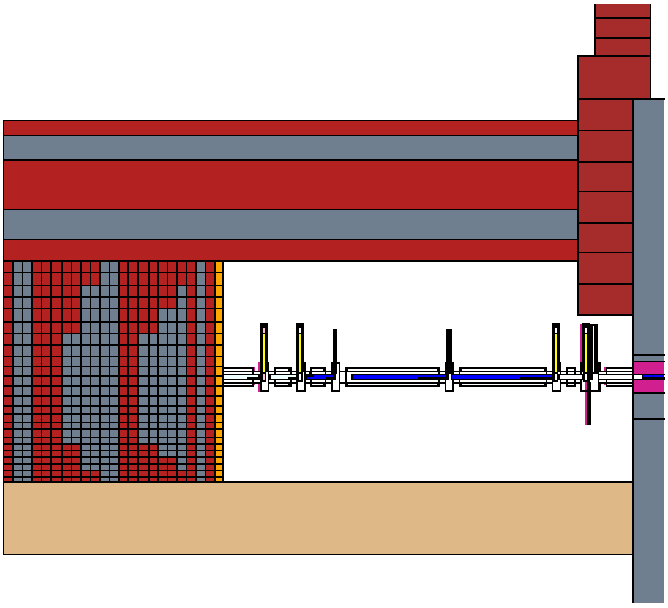
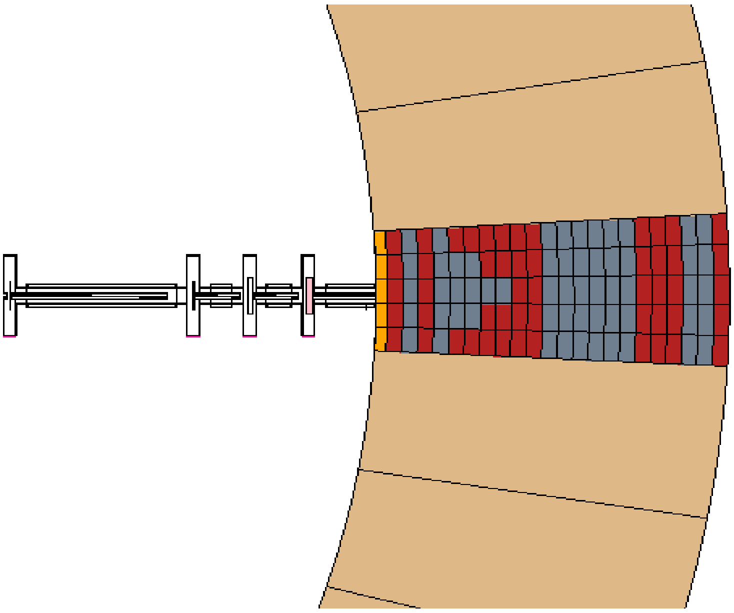
[3] previously called *Carsten concrete* (CC)



(a) Overview of the bunker wall for the DREAM beamLine



(b) Overview of the bunker wall and roof for the DREAM beamline.

Figure 6: Sketch of the bunker wall and bunker roof for DREAM beamLine. The yellow layer represents lead, which is covered with B_4C, the red one is ESS-PBC concrete and the grey one is steel.

rise to higher-energy-photons. Despite this, it was still found to be necessary to have a final layer of steel for gamma absorption in the design. This leaves a basic design layout of steel-concrete-steel-concrete-steel-concrete. Building such a configuration is not simple because of the weight limitation. In order to achieve sufficient shielding density, the centre biased spatial distribution (the neutrons predominantly arrive in the center of the wall) of the neutron flux into the bunker wall needs to be exploited. The beam that exits the monolith is relatively directional for the higher (>MeV) energies. Neutrons need to be involved in multiple collisions to produce an isotropic spatial distribution on the wall and neutrons predominately lose energy in collisions, therefore the incoming flux on the wall at higher energies must remain centrally biased. The lower energy neutrons also have a tendency to be directional because scattering is more probable within the channel directly going forward. This leads to the triangle like design seen in figure 6. The triangles reduce the total material in the wall while still providing sufficient shielding for the centre directed beam. In addition to the basic shielding concept, three initial layers have been added: (i) a thin 0.5 cm B_4C layer, (ii) a 10 cm lead layer and (iii) a layer of ESS-PBS concrete.

Layer #	Material	Thickness (mm)
1	B_4C	5
2	Lead	100
3	ESS-PBC	155
4	Steel	155
5	ESS-PBC	155
6-10	Steel	755
11-12	ESS-PBC	310
13-18	Steel	930
19-21	ESS-PBC	465
22-23	Steel	310
24	ESS-PBC	155

Table 1: Structure of the bunker wall from the inner part to the outer part.

Layer #	Material	Thickness (mm)
1	B_4C	5
2	ESS-PBC	291
3	Steel	389
4	ESS-PBC	778
6	Steel	291
7	ESS-PBC	195

Table 2: Structure of the bunker roof the inner part to the outer part.

The proposed design includes a layer of B_4C that reduces the thermal neutron flux and consequently the activation. The layer of antimony-free Pb reduces the gamma from the

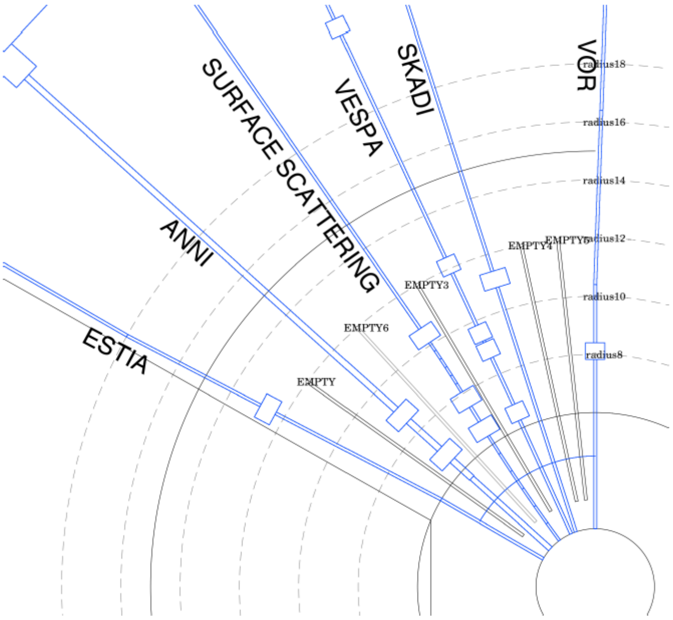


Figure 7: Layout for the instruments in the East sector. The picture shows clearly that the bunker will be crowded with choppers.

steel [and Pb gets significantly less active than steel] and finally, a layer of ESS-BPC to thermalize those neutrons involved in the inelastic Pb channels. A detailed description of the composition layer by layer of the wall and the roof can be found in table 1 and table 2. In addition, the outside wall has to provide sufficient attenuation to prevent cross talk of the hadronic shower between neighbouring beamlines. In the short sectors, the wall is placed at 11.5 m. This position is constrained by the floor loading but also aims for a general shielding solution for all beamlines, in order to minimise cost by avoiding custom shielding designs for each beamline. In particular for the short sectors, the area inside the bunker will also be densely packed with choppers (see figure 7). The open bunker concept minimises the amount of shielding within the bunker that needs to be un-stacked and stacked when replacing choppers. This concept is planned to be used also at the SNS in the design of the second target station [10]. Furthermore, the bunker area should also allow for enough space for the beamline insert tool. For the long sectors, the bunker wall is placed at 24.5 m due to floor loading constraints. In addition to that this ensures that the long instruments can lose line of sight within the bunker in order to reduce the amount of shielding in the experimental hall. A schematic overview how the bunker will look like for the short and long sector is shown in figure 8.

An overview of the structure of the main wall and the roof is shown in figure 6. The beamline shown in this figures is the DREAM [11] beamline which has been used in our study as a reference, since it has a reasonable number of choppers and a metallic guide substrate that is quite common for many beamlines. The gray layer in figure 6 represents steel and it is assumed to be standard low quality cast steel. This kind of steel typically has a high level of impurities and a high level of carbon (4.5%).

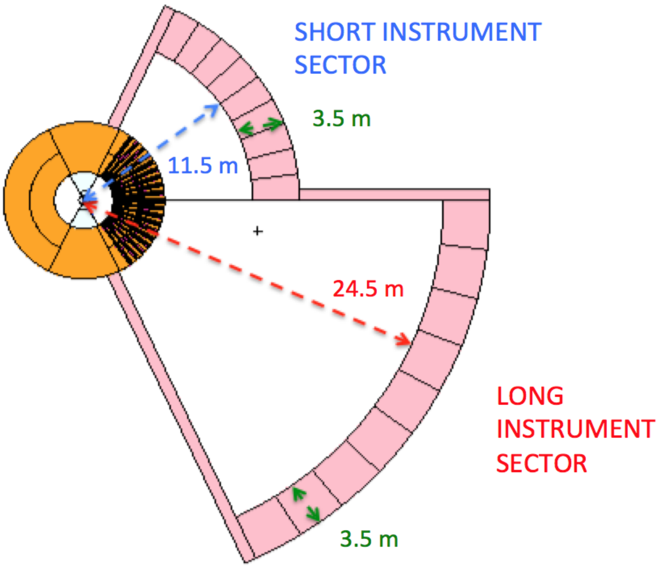


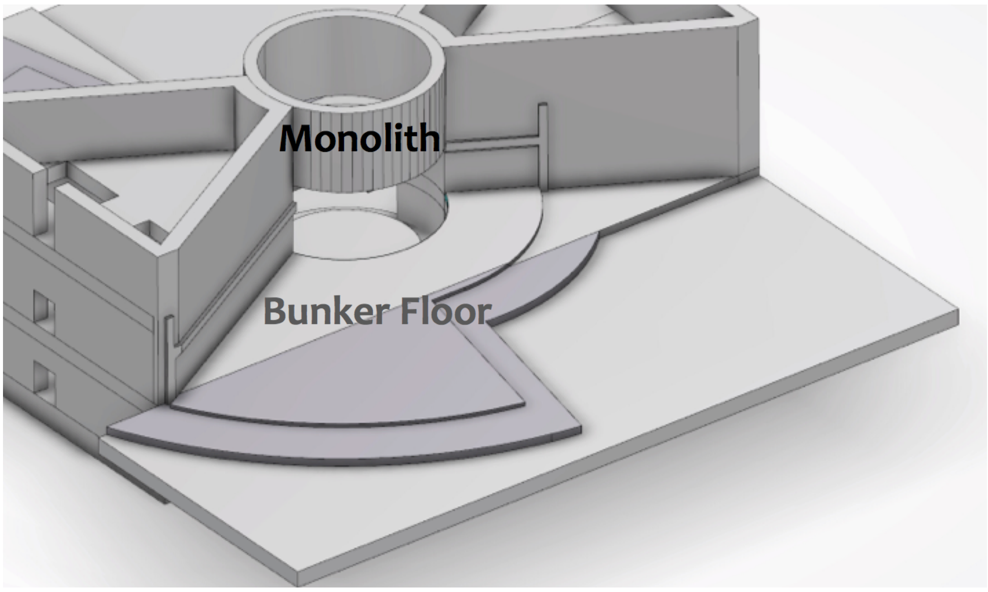
Figure 8: Schematic view of the bunker wall.

6.3 Impact on the other area of the current bunker design

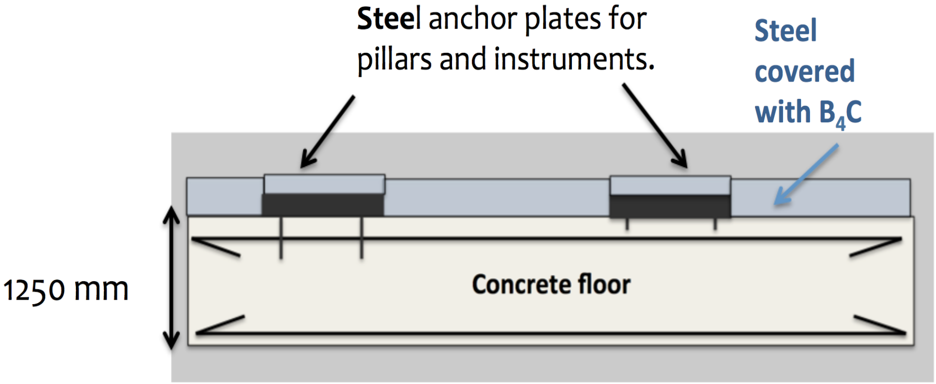
- **bunker floor**. The bunker floor will be made out of normal steel-reinforced concrete. It is stepped down from the inner side of the the bunker wall to prevent a shine path under the bunker wall. Since the majority of the floor will be covered by steel anchor plates for choppers and guide supports, a layer of boron containing tiles will be placed (without fixation) on this steel. A schematic view of the bunker floor and its composition is shown in figure 9.

  Bunker Pillars There are sets of pillars that support the bunker roof. Henceforth as the pillars-R6 since they are located at 6 m from the origin of target coordinate system. These pillars are made by regular steel and they will be covered by a layer of B_4C. A view of the pillars R6 is shown in figure 10.

  - There is an additional set of pillars throughout the bunker area and the exact numbers and locations are still to be determined. These are referred to as the pillars-Rx, where x designates their radial distance from the monolith center. These pillars will also be covered by B_4C. They are shown in Figure 10.
  - For the purpose of the simulation, these pillars have been put at 9,12,15,18 and 21 m at 6 degree separation. There were modelled as simple cylinders of steel with a radius of 8 cm.



(a) Overview of the bunker floor.



(b) Composition of the bunker floor.

Figure 9: The bunker floor and its composition.

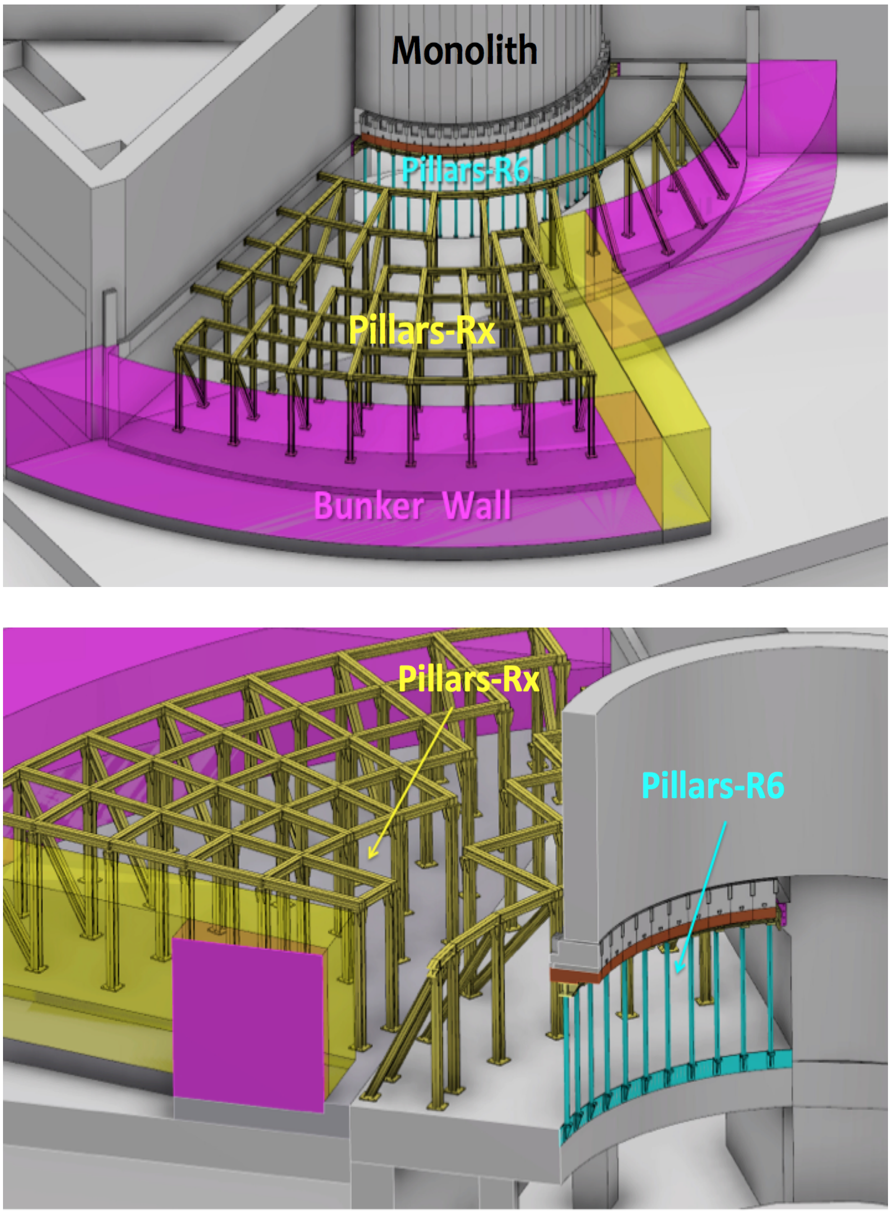


Figure 10: Overview of the bunker pillars. The pillars-R6 (light blue) are located at the beginning of the bunker while the pillars-Rx (yellow) extend throughout the bunker areas.

Instrument	Beam Port	Width (mm) at 2m	Height (mm) at 2m	Width (mm) at 5.5m	Height (mm) at 5.5m	Shape in the Monolith
NMX	W1	30	45	30	45	Hor. Bender (r=1.2km)
DREAM	S4	80	35	20	45	Vert. elliptically tapered
LOKI	N7	30	30	30	30	Hor. S-Bender, (r= 66 m)
ESTIA	E1	100	48	100	52	Straight tapered
ODIN	S2	76	76	76	76	No Guide
VOR	S11	21	31	59	39	Elliptic taper

Table 3: Instrument details of beam port opening in the monolith in the Comblayer simulation.

6.4 Neutronic calculations

Simulation of the design was carried out using MCNP6 [12] with CombLayer [13] providing the tools to build the model of the ESS from the proton beam to the bunker wall and construct the variance reduction parameters used in the simulation.

The CombLayer target and moderator model, used for all simulations presented here, has also been used by the target group in their work. Certain additions, like the aluminium flow channels within the pre-moderators and the cooling channels in the reflector were not modelled. The bunker inserts are constructed going from 2 m (18 x 18 cm^2) to (22 x 22 cm^2) at 3.75 m with an 8 mm clearance and the 4 cm dog-leg. The guide system is placed as a tight fitting cut within this space. The beam port opening in the monolith are modelled as described in table 3 while in table 4 is shown the actual instrument configuration.

Engineering configuration models of the instruments have been included in the study to give a semi-realistic neutron distribution that hits the wall and roof of the bunker. These models include the choppers with blades (some open and closed) and motors. The full choppers are modelled with disks, vacuum housing, spindle and motors. For example, DREAM [11] uses three T0 choppers, each with two discs of radius 75 cm, which are 20 cm apart and composed of 5 cm of W blades and 0.5 cm of B_4C on front/back.

The guides have all been modelled as 1.0 cm thick metal substrates [the coherent scattering from the guide surface has not been modelled], and vacuum housing has been added to many beamlines. Windows between vacuum sections have not been added.

In the simulations every alternate beam port was used in the short sectors, while for the long sector every port has been filled by an instrument. Models of ODIN [14], LOKI[15], VOR [16], ESTIA [17] and DREAM [11] have been included to fill the short instrument section while DREAM, ESTIA, and NMX [18] were repeated around the long section. Symmetry is assumed and no differentiation has been implemented between the north and south sectors.

The MCNP simulation methodology is detailed in appendix A.

Instrument	Beam Port	Width (mm) at 2m	Height (mm) at 2m	Width (mm) at 5.5m	Height (mm) at 5.5m	Guide Coating	Shape in the Monolith
NMX	W1	30	45	30	45	m=1	Hor. straight. Vert. linearly tapered
BEER	W2	120	36	20	80	m= 2 –5	Hor. linearly tapered Vert. Elliptical
CSPEC	W3	90	40	40	90	m= 3	Hor. tapered Vert. straight
BIFROST	W4	100	140	100	140	m= 2 – 5	Parabolic
MIRACLES	W5	100	100	100	100	m=1.5 – 4	Parabolic
MAGIC	W6	<80	<80	<80	<80		Single mirror bispectral
TREX	W7	107	70	107	70	m=1.5 –3	Single mirror bispectral
HEIMDAL thermal guide	W8	30	60	15	40	m=2–5	Double ellipse
HEIMDAL cold guide	W8	30	30	30	30	m=2	Vert. bender
FREIA	N5	40	140	50	250	m=6	Hor. S-bender Vert. Single ellipse
LOKI	N7	30	30	30	30	m=6	Hor. single bender Vert. Straight
ESTIA	E1	60	127	60	60	m=3.5 – 4	Elliptic guide
VESPA	E7	60	30				Elliptic guide
SKADI	E8	30	30	30	30	m=4	S-bender
ODIN	S2	50	50	50	50	m=5	Straight
DREAM	S4	95	25	20	45	m=3	Single mirror bispectral

Table 4: Instrument details of beam port opening in the monolith.

6.4.1 Radiation dose in the bunker

Figure 11 and 12 show a simulated dose map for >1 keV neutrons and >5 MeV photons, respectively for at the beam height and a cut above the main axis (at 25 cm above the target centre) of the short bunker layout in which a number of beamlines are separated by 12^o. Starting from the lower point in figure 11 and 12 at the long/short divide, the beamlines simulated are (i) *short*-DREAM, (ii) LOKI, (iii) ODIN (iv) *short*-DREAM and (v) VOR. At the top of the picture, the concrete wall that separates the target service area (TSA) from the bunker space is simulated.

short-DREAM is the DREAM concept with the final in-bunker guide section shortened to keep the beamline within the short bunker section. It is not proposed to be built like this, but the complexity of the DREAM choppers and guide configuration can be rapidly configured to either significantly broaden the dose on the bunker wall, or to provide large peak doses to the bunker roof. Although this configuration is not as foreseen, it gives a reasonable indication of the dose spread due to the beamline components. Figure 11 and 12 show that the radiation inside the bunker will not be isotropic with typical maximum doses up to 100 Sv/h. Instruments will interact heavily with each other up to about 9 m. ODIN, which is 20 cm below of the majority of beamlines because it is on the lower moderator, still produces a significant dose at this level. However, this is due in part to the fact that the ODIN model was the first beamline implemented and lacks the local shielding and vacuum components that the other beam lines have. Further simulations will be performed and will include the long sector.

6.4.2 Radiation dose on the bunker wall

The bunker roof and the bunker wall have different worst case radiation dose scenarios. There are two main worst-case scenarios for the wall and one for the roof. The two scenarios for the wall are (i) a highly scattered beam in which the incident flux is lower but it is much more uniform over the inner wall area giving the neutrons easier pathways around the central steel section of the wall (ii) a direct beam without a beamline. Figure 13 (a) shows the dose due to the neutrons propagating through the bunker wall from the DREAM beamline with all the T0 choppers open except the one at 9.5 m which is partly clipping. This maximises the uniformity of the beam hitting the wall. The figure shows the dose being attenuated by the different layers of the composite wall. In the space outside the bunker wall the neutron dose is drastically reduced by 8 orders of magnitude resulting in a radiation dose below 1.5 μSv/h. The prompt photon dose is shown in figure 13 (b), the dose is completely attenuated and absorbed by the wall (within the level of statistics of the simulation). In this plot photons produced by neutrons below 1eV were not considered in order to make the variance reduction viable.

Figure 14 represents the second worst case scenario where the main beam hits the bunker wall without attenuation. In this case the wall is also able to shield completely the radiation. In figure 14 (a) is shown the radiation dose throughout the bunker wall.

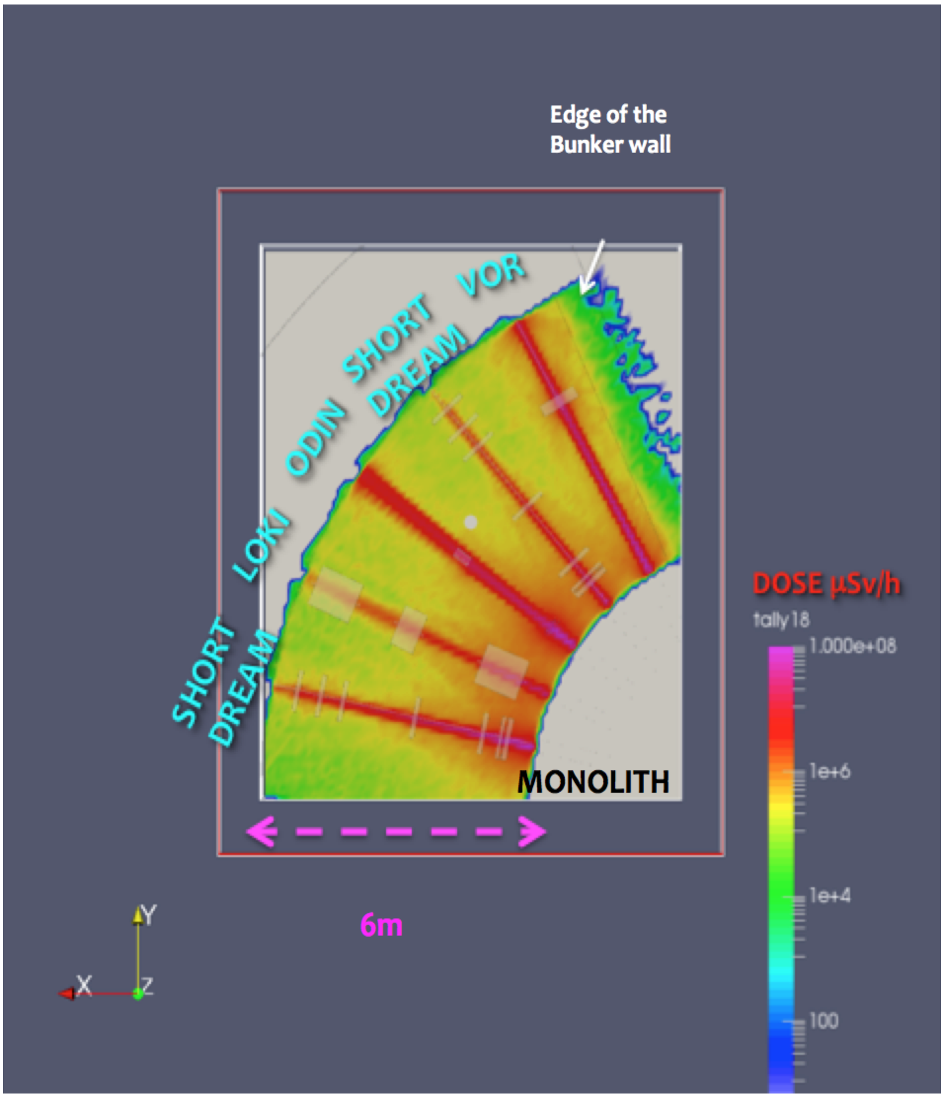


Figure 11: Radiation dose in the bunker at the beam line level. Starting form the left the plot shows the radiation dose map for the *short*-DREAM[11] (see the text for definition of *short*-DREAM), LOKI [15], ODIN [14], *short*-DREAM, VOR [16]. ODIN lies on the bottom moderator so is 20 cm below the other beam lines but is less well shielded in this model and looks at a bigger viewport to the moderator. The plots are for neutrons with energy greater than 1 keV and prompt gammas with energy greater than 5 MeV.

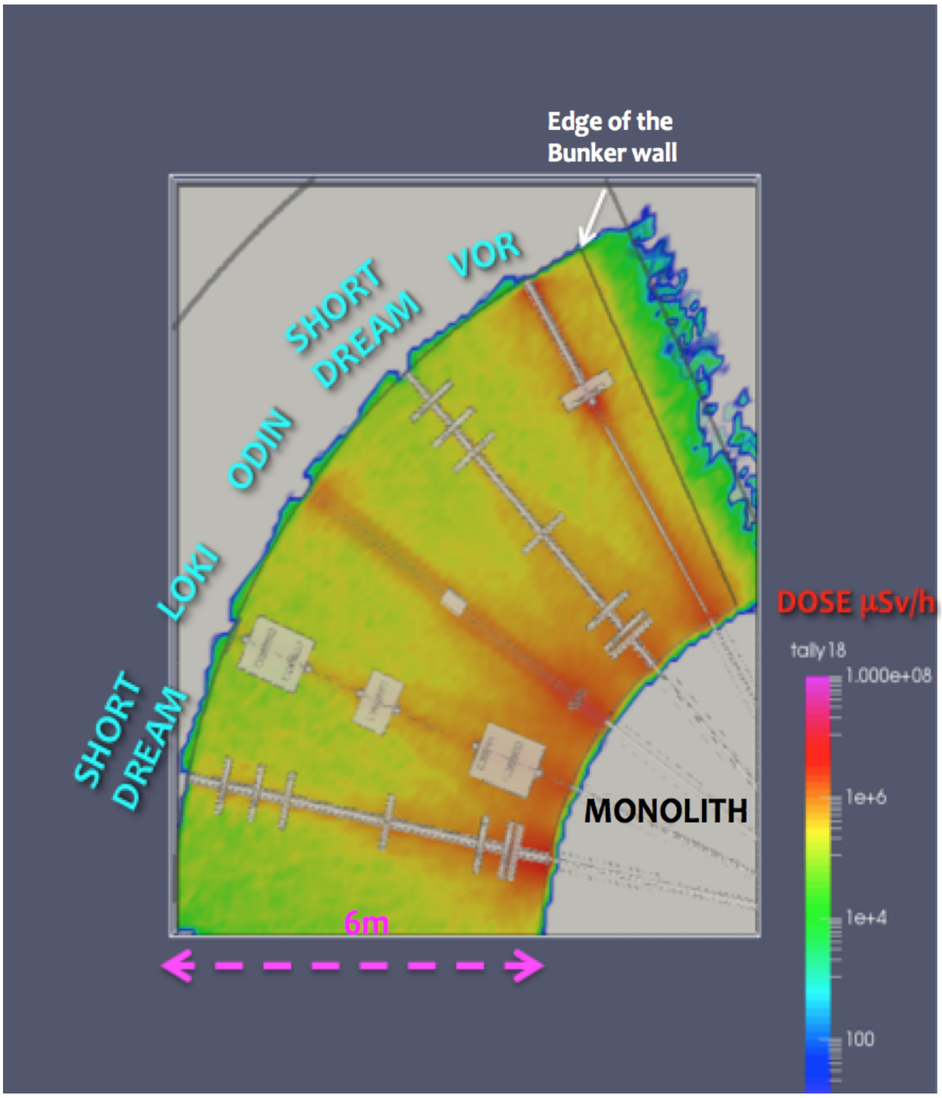


Figure 12: Radiation dose in the bunker 25 cm above target centre. The plots are for neutrons with energy greater than 1 keV and prompt gammas with energy greater than 5 MeV.

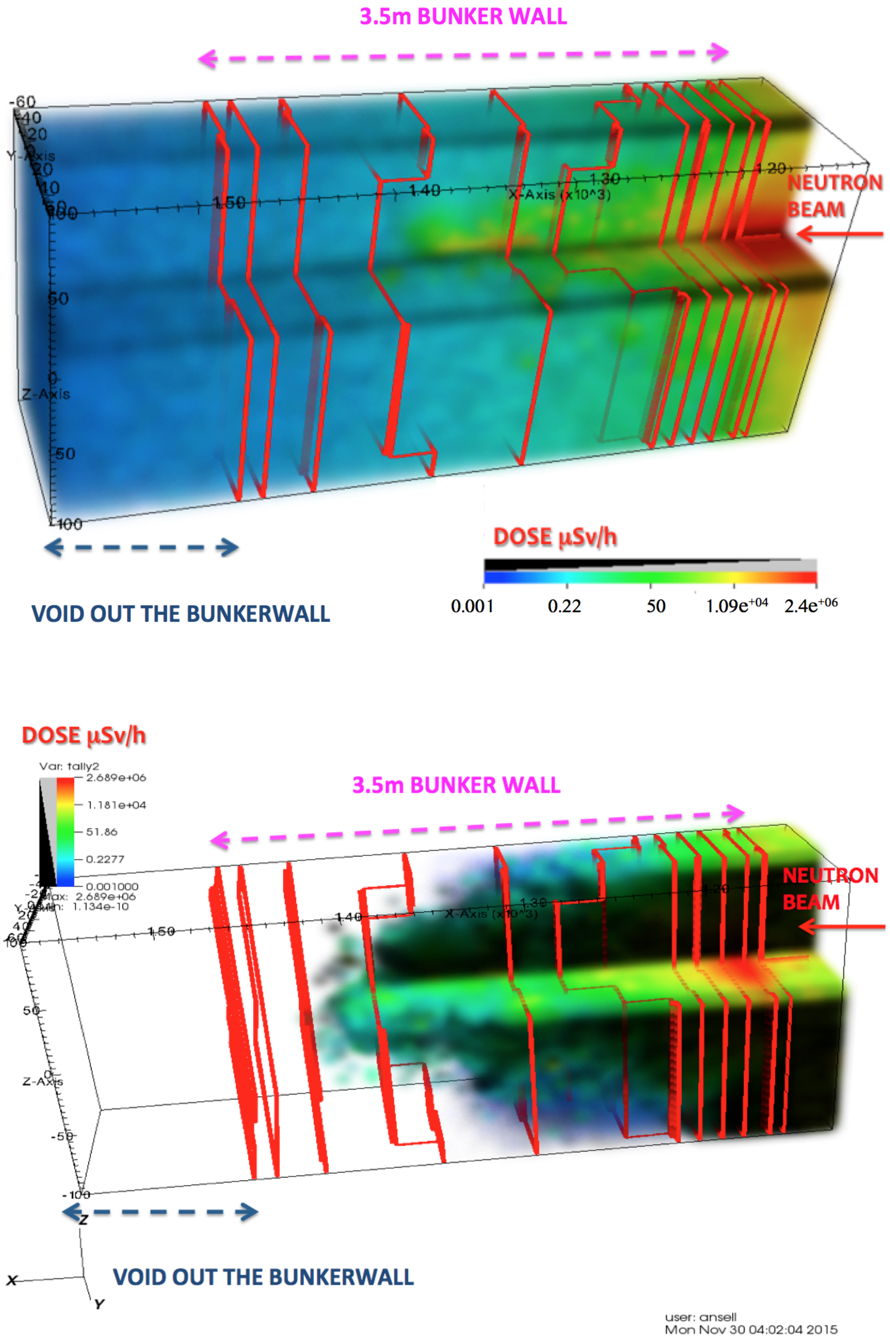


Figure 13: Radiation dose for the neutrons throughout the bunker wall for DREAM beamLine for the case of the 9.5 m chopper clipping 1/4 of the beamline (a) and radiation dose for the photons (prompt-only) (see text) (b).

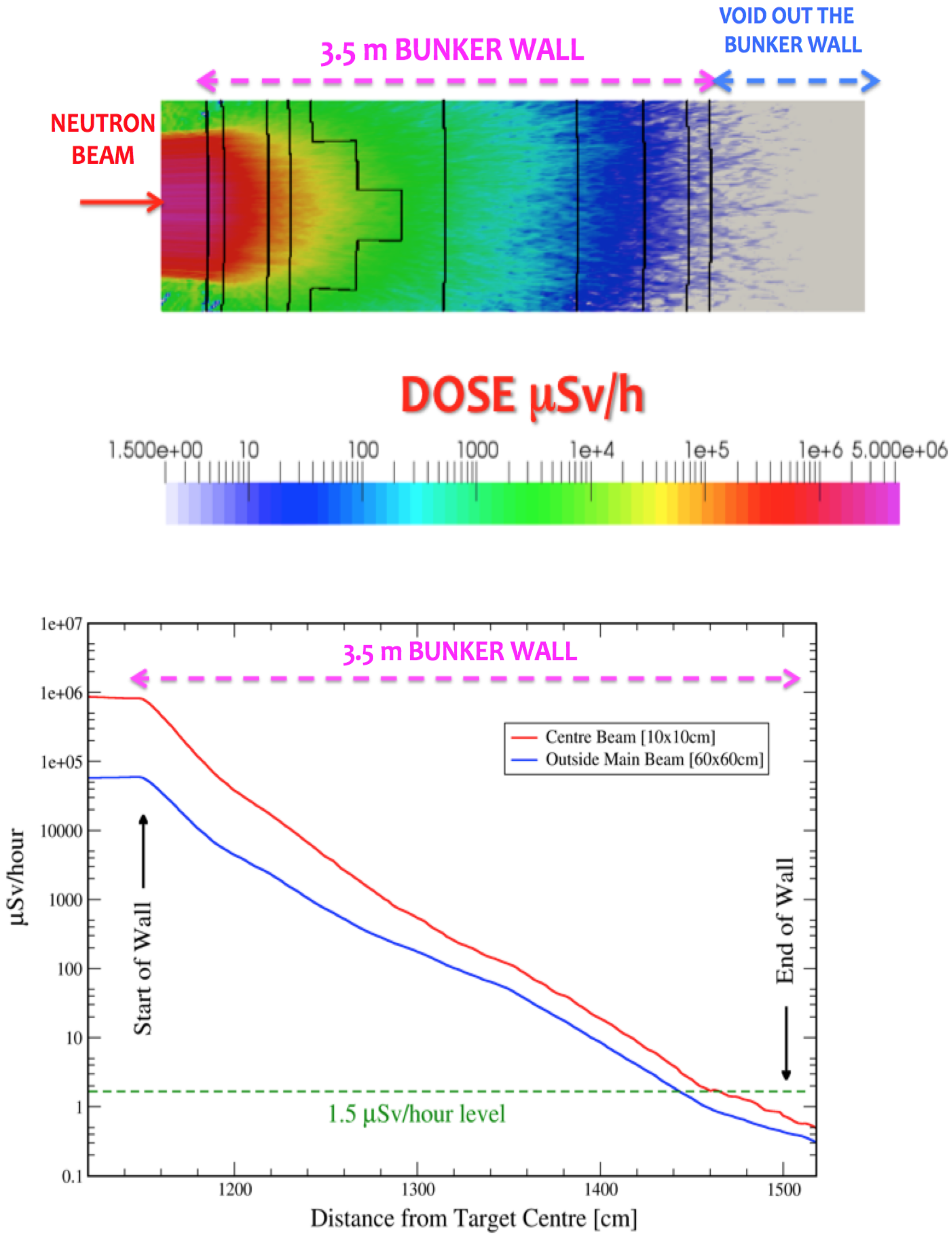


Figure 14: Neutron radiation dose for the main beam hitting the bunker wall. (a) Dose throughout the wall (note that the gray area represents where the dose drop below the 1.5 μSv/hour level) .(b) Integrated dose outside the bunker wall at the guide level (red one) and around the guide (blue line).

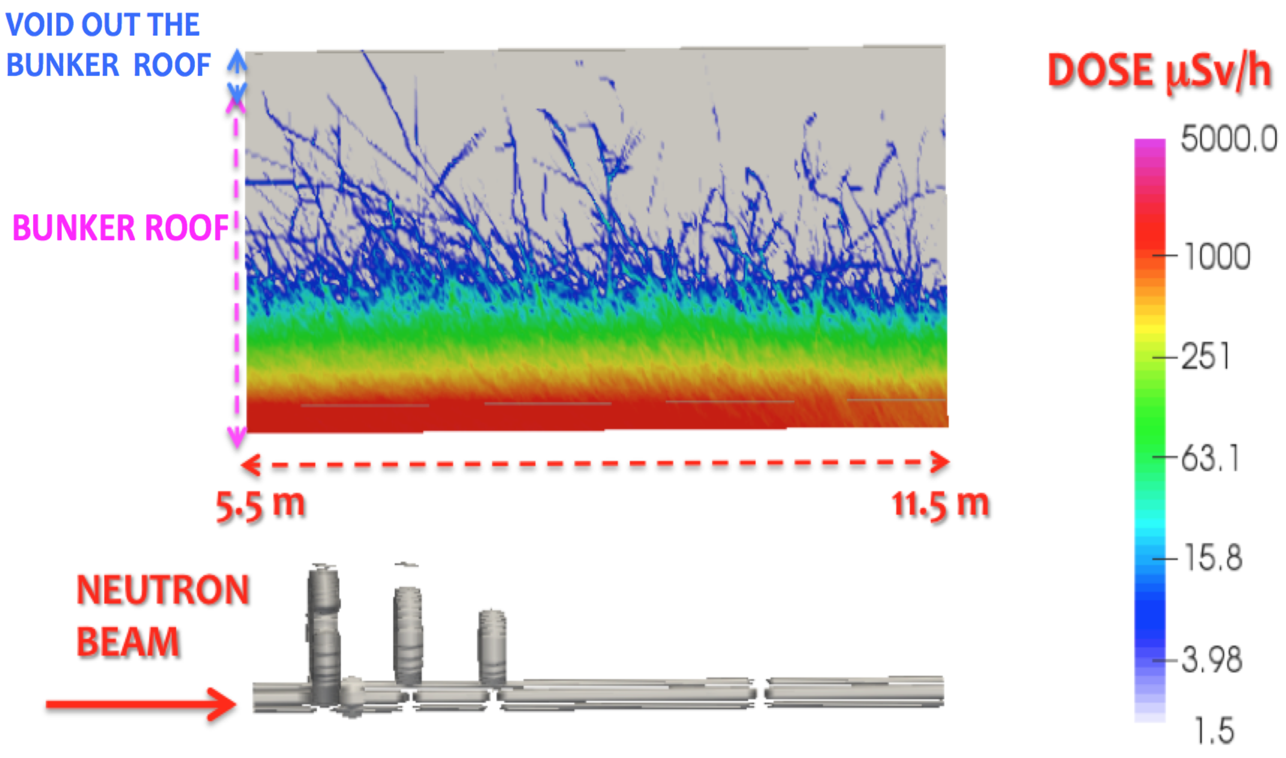
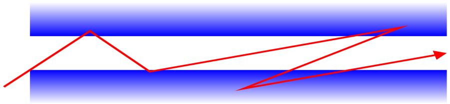


Figure 15: Neutron radiation dose on the roof for a beamline which is composed by three choppers and a guide with a pin-hole collimator.

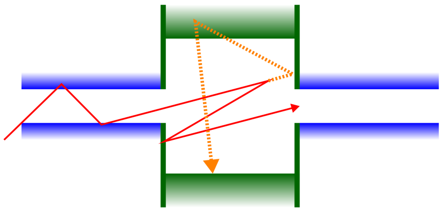
The gray area represents where the dose drop below the 1.5 μSv/hour level, there is some statistical tracking though the wall at the 10 μSv/hour level but the integral dose is below 1.5 μSv/hour as shown in figure 14 (b).

6.4.3 Bunker roof

The roof design is a multi-layered composite structure. It is modelled as uniform layers in the radial and cross-radial direction because (i) the roof needs to be lifted and replaced quickly and easily to facilitate maintenance, (ii) the exact beamport in use and exact chopper configuration of the beamlines is not fixed for the lifetime of the facility and (iii) if there is no significant weight/neutronic benefit for the roof being multidimensional, then the places of slight over shielding make optimal points for feed thoughs. One of the worst case roof scenarios occurs when a highly focussing beamline with a metal substrate guide scatters the direct beam in many directions. To represent this case we have used a beamline which is composed of a guide focussing to a pin-hole collimator at 9.7m. In addition, there are three choppers: two band pass choppers at 6.5m, and 7.2 m with B_4C blades, and at 8.5 there is a 1/4 closed W-T0 chopper. This beamline configuration creates a scattering and spray of particles that hits the bunker roof because the non-reflected neutrons that are



Simple Shielding



Cavity Shielding

Figure 16: Cavity shielding concept : Neutrons scatter multiple times down a beamline (top) . In the case of an open cavity along the direction of travel, the neutron has a lower chance to scatter down the beamline direction due to simple geometric considerations (bottom).

travelling down the straight beam direction have a long path length in the guide substrate. This produces a highly uniform illumination as well as one of the highest radiation dose scenarios for the bunker roof. Figure 15 shows the radiation dose map for the roof. The roof is able to deal with both the main scattering from the guide transports system and the bright points provided by the chopper system. Further simulations will be performed as the engineering design progresses.

6.5 Background suppression

The proposed bunker design is a *cavity bunker concept*, in that the walls and roof provide the main radiation shielding while the inner space is as material free as possible. In addition to providing a safe working environment for workers outside of the bunker area, the design implements the idea of cavity-based shielding to reduce neutron instrument backgrounds [19].

The principle of cavity-based shielding has minimal benefit for directional beams and maximal benefit for completely isotropic distributions. The concept is illustrated in figure 16. This can be very effective with beamlines that go out of line of sight within the bunker. The neutrons that are going straight then hit the bunker wall, while those neutrons that scatter off the guide/choppers have the least probability to scatter into the exit port of the beamline in the bunker wall. This effect is illustrated in figure 17 whereby the neutron flux at 15m for an open bunker concept and a completely filled bunker are compared. However it should be mentioned that the filled bunker design cannot be built for mechanical

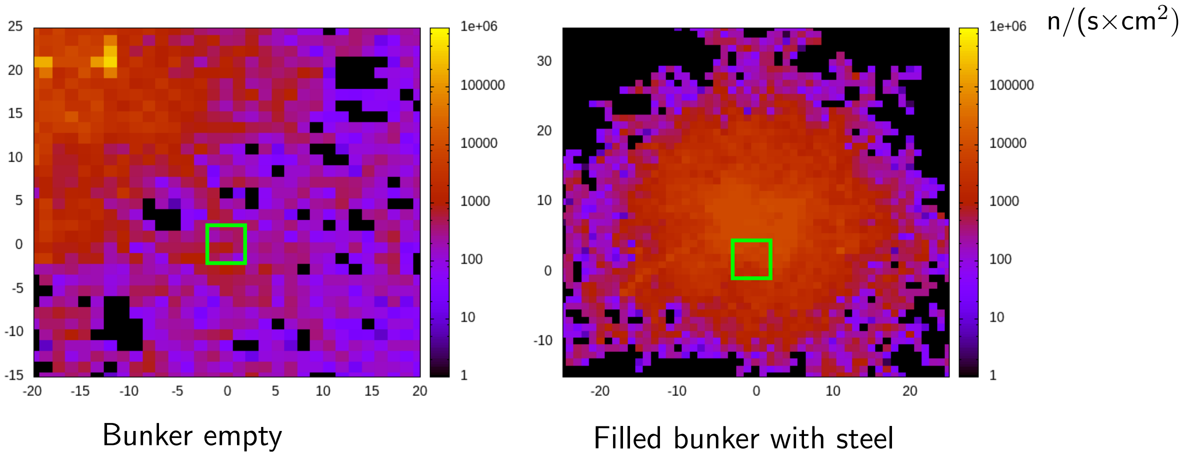


Figure 17: Image of neutrons ($E_{neut} > 1$keV) at 15 m going down a generic curved guide. The results highlight the principle behind the background suppression mechanism. Comparison between adding the steel into the bunker and leaving the bunker void. The model was run with a beamline on every other port. The green square represents the position of the guide.

reasons, such as the need to fit the amount of choppers within the bunker area and also to meet the floor loading requirements (of 30 tonnes/m^2). In the filled bunker design, all space was completely filled with steel and for comparison we selected a generic beam line which is curved twice out of line of sight by 30 m. The simulations were run with (a) no additional shielding in the bunker (but with every port open) and (b) with all unfilled space filled with steel. The neutron flux for neutrons with energy greater than 1 keV was tallied on the inner surface of the bunker wall. Figure 17 (right panel) shows that a considerable flux hits the bunker wall when it's filled with steel. In particular, the void of the guide causes neutrons to be directed into the exit port of the beamline. In the case of the open bunker (left panel), considerably more neutrons hit the bunker wall, however these are displaced from the beamline exit port. This shows how the open bunker design is better from a background point of view for the ESS target/moderator concept. In addition, the filled bunker design still requires a shielding wall to attenuate the dose to 1.5μSv/h.

7 Conclusions

We propose a bunker design with a 3.5 m wall for the short and the long sectors with a composite roof. This bunker design fulfils the radiation requirement of 1.5 μSv/h and meets the mechanical constraints and requirements described in this report. The current design represents a common shielding structure which minimises custom shielding designs for individual beamlines, reduced cost and facilitate integration and later operations. Lastly, it was shown that the cavity style bunker design can also lead to reduced neutron instrument background levels.

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A Process

Modifications have been carried out to MCNP6 and to the method of variance reduction. Firstly, a number of arrays in MCNP needed to be increased to deal with a model that exceeds 30,000 non-repeating cells. Secondly, very standard modifications were carried out to improve run-time performance:

1. dxtran spheres [4] and point tallies were modified so that a particle was determined if it was within the energy range of the dxtran/point tally before the particle was tracked to the point tally. Additionally, if point/dxtran weight biasing was used, this random number call was only done if the energy was within range.
2. Modifications to tally, to calculate the energy bin first rather than the other components to shorten the summation path if the energy was out of range.
3. Directional biasing used on surface crossing to void and the extent of biasing was relative to the distance to the bunker wall.
4. Electron physics cut at 1.5 MeV.

All weights are calculated from protons on target.

The following definition of energies is applied: Low energy : n $<$ 1 keV Mid energy : 1 keV $<$ n $<$ 1 MeV High energy : n $>$ 1 MeV

It should be recalled that all $>$ 1 eV neutrons can albedo transport and that all neutrons including those below 1eV can produce thermal capture gamma. However, inorder to preserve simulation speed neutrons below 250 eV were culled inside 2 m and low energy neutrons rouletted very strongly in the monolith region.

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[4] forward attractor with on-going particle transport.