Analysis of Shielding Requirements for the Freia Instrument

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Revision	Revision Date	Summary of changes
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Approvals

This document has the following approvals:

Name	Title
Jim Nightingale	Lead Engineer

Contents

1 Introduction

The radiological shielding for a scattering instrument at ESS needs to comply with Swedish radiological safety requirements and specifically with the implementation of those at ESS.

The instrument shielding will be designed to be in accordance to the *"NOSG phase 2 guidelines for designing instrument shielding for radiation Safety"* [1] and following revisions:

"The instrument shielding needs to ensure that the emitted radiation levels are low enough to allow a) the instrument halls to be operated as supervised areas, as defined in [2] and b) that the overall ESS dose limits for the public, as defined in [3] are not exceeded." [1]

and

"In accordance to [2], normal operation (H1) and likely accidents (H2) need to be assessed to verify the radiological zoning of a workspace. In order to do this, different H1 (normal operations and maintenance) and H2 (anticipated during the lifetime of the facility) events have to be investigated. The frequencies of these types of events are defined in [3]. The instrument teams have to demonstrate that their proposed shield design complies with requirements." [1]

Accident scenarios that shall be considered are:
For H1:

- Full beam, with instrument components like a shutter, chopper, or slits being closed.
- Full beam hitting the beam-stop/downstream end of the instrument cave.
- Full beam scattering of worst case sample environment equipment.
- Full beam scattering of a worst-case sample

For H2:

- Sheet of cadmium at end of guide
- Sheet of cadmium in the sample location
- Misaligned sample environment equipment

In addition to these, "potential H1 and H2 scenarios, which are relevant for the specific instrument, have to be identified and investigated" [1]

2 Hazard Scenarios

A full analysis of hazard scenarios has yet to be performed. The calculations herein are based on conversion of all neutrons to 2MeV photons emitted into 4π steradians as carried out by the Loki instrument [4].

3 Shielding Concept

The bunker shielding is calculated and designed by ESS. All shielding out of the bunker will be unique to Freia. The area directly after the bunker wall, called the 'bunker-to-cave' shielding contains a chopper pit. This section of shielding can be used to help shield high energy neutrons that will stream through the bunker wall and reduce quantity entering the cave. The shielding will comprise of 400mm steel and 500mm standard concrete, as shown in **Figure 1**. There is space to increase shielding in the direction of the beam but limited space to increase height, owing to the position of the bunker service routes. Localised borated moderating material and streaming shielding will also be employed in this area.

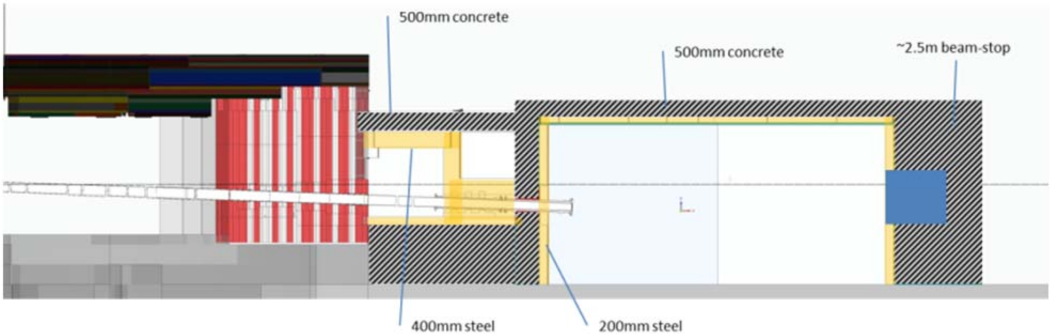

Figure 1 – Section side view of Freia cave showing shielding concept

The cave is designed with 200mm steel and 500mm concrete. A ~2.5m beam-stop is shown, which can be increased following further investigation.

4 Shielding Calculations

4.1 In-bunker

No shielding calculations for the guide within the bunker have yet been performed. The Freia team intend to follow general ESS guidelines on avoiding air activation by lining the guide vacuum vessels with borated material.

4.2 Bunker-to-Cave

The current concept is for 400 mm steel and 600 mm concrete shielding. This should be more than satisfactory to shield gammas but its main purpose is to reduce high-energy neutrons entering the cave. Neutronics will be required to determine suitability.

4.3 Cave

4.3.1 Cave layout

The Freia focussing supermirror guide ends at 20m from the target, show as point a in **Figure 2**. The beam continues to focus towards the sample position at ~22.7m, shown as point b.

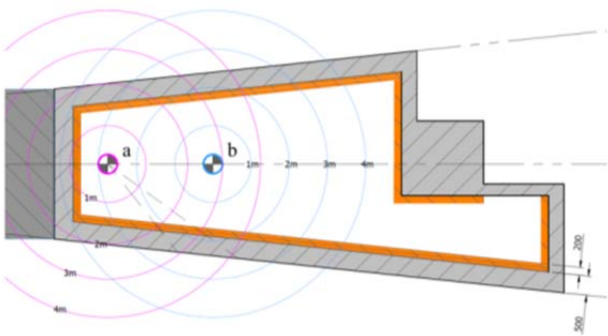

Figure 2 – Schematic plan view of Freia cave showing a) end of guide, and b) sample position

The precise neutron flux entering the instrument cave under “Full Beam” conditions will be highly dependent on the details of the design of the flight tube, the out-of-bunker shielding and the design of the front cave wall, which have not yet been assessed. Under normal collimation conditions, the expected maximum flux for different scenarios is as follows:

Scenario	Description	Moderator Design	Area (cm^2)	Neutron flux (n/cm^2/s)	Neutrons (n/s)	Photons (photons/s/sr)
1	Guide exit @20m = 160x40mm	Future moderator@5MW	64	6.25E+09	4.00E+11	3.2E+10
2	sample position - Large sample - 100x40mm sample	Future moderator@5MW	40	1.00E+09	4.00E+10	3.2E+09
3	sample position - Normal op's - 10x40mm sample	Future moderator@5MW	4	1.00E+09	4.00E+09	3.2E+08

Table 1: Operational scenarios with neutron flux and photon point source

4.3.2 Gamma Shielding Hand Calculations

4.3.2.1 Scenario 1 - Conversion of all neutrons at guide exit to 2MeV photons

Using the photon flux stated in **Table 1** we can then calculate the dose rate on the inside of the wall as a function of distance using the conversion factor of 2.69×10^{-2} µSv/h per gamma/(cm^2/s), as defined in 'ESS procedure for designing shielding for safety' [5]

Distance from conversion point (m)	Photon flux on shielding (photons/cm^2/s)	Dose rate on shielding (µSv/hr)
0.5	1.27E+07	342501.44
0.75	5.66E+06	152222.86
1	3.18E+06	85625.36
1.25	2.04E+06	54800.23
1.5	1.41E+06	38055.72
1.75	1.04E+06	27959.30
2	7.96E+05	21406.34
2.25	6.29E+05	16913.65
2.5	5.09E+05	13700.06
2.75	4.21E+05	11322.36
3	3.54E+05	9513.93
3.25	3.01E+05	8106.54

Table 2: Flux to dose for full beam at guide exit to 2MeV photon scenario

The required thickness of material can be calculated then using tabulated attenuation factors via:

$$\frac{D}{D_0} = e^{-\left(\frac{\mu}{\rho}\right)\rho x}$$

where D is the required dose rate on the exterior of the shielding, D_0 is the dose rate on the interior of the shielding, ρ is the material density, μ/ρ is the photo mass attenuation coefficient from [ref!!], and *x* is the physical thickness.

Calculating from the dose rates in Table 1, we can obtain the required thicknesses of shielding to reduce the dose rate to 1 μSv/hr on the outside of the shielding:

	Material Thickness (mm) required to reduce dose rate to 1 μSv/hr outside the shielding.		
Distance from conversion point (m)	Lead	Steel	Concrete
0.5	244	380	1216
0.75	228	356	1139
1	217	339	1084
1.25	209	325	1041
1.5	202	314	1006
1.75	196	305	977
2	191	297	951
2.25	186	290	929
2.5	182	284	909
2.75	179	278	891
3	175	273	874
3.25	172	268	859
3.5	169	264	845
3.75	167	260	831
4	164	256	819

Table 3: Single layer shield thickness to reduce dose rate to 1μSv/hr (narrow beam)

The effectiveness of multiple layers of shielding can be calculated using:

$$D = D_0 e^{-\left(\left(\frac{\mu}{\rho_1}\right).\rho_1.x_1+\left(\frac{\mu}{\rho_2}\right).\rho_2.x_2\right)}$$

Using multi-layer shielding of 200mm of steel followed by 500mm concrete we calculate the following dose rates:

	Dose rates outside shielding in μSv/hr		
Distance from conversion point (m)	200mm Steel	500mm concrete	200mm steel + 500mm concrete
0.5	417.96	1814.35	2.21
0.75	185.76	806.38	0.98
1	104.49	453.59	0.55
1.25	66.87	290.30	0.35
1.5	46.44	201.59	0.25
1.75	34.12	148.11	0.18
2	26.12	113.40	0.14
2.25	20.64	89.60	0.11
2.5	16.72	72.57	0.09
2.75	13.82	59.98	0.07
3	11.61	50.40	0.06
3.25	9.89	42.94	0.05
3.5	8.53	37.03	0.05
3.75	7.43	32.26	0.04
4	6.53	28.35	0.03

Table 4: Dose rates for full beam at guide exit to 2MeV photon scenario (narrow beam)

The above calculations assume collimated narrow beam geometry. However, the point source will behave as broad beam and be subject to scattering. Therefore, build-up factors must be considered [7].

$$D = B.D_0 e^{-\left(\left(\frac{\mu}{\rho_1}\right).\rho_1.x_1\right)}$$

The build-up factor, B, has been derived from experimentation and depends upon shield material, photon energy levels, and shield thickness.

For the example of 200mm of steel followed by 500mm concrete the following build-up factors have been used:

	Physical thickness	Build-up factor, B, for 2MeV photons
Iron (Fe)	200mm	7.02
Concrete	500mm	6.205

Table 5: Shielding build-up factors for selected material thickness with 2MeV photons

Which gives the following broad beam dose rates:

	Dose rates outside shielding in μSv/hr		
Distance from conversion point (m)	200mm Steel	500mm concrete	200mm steel + 500mm concrete
0.5	2934.07	11258.03	96.44
0.75	1304.03	5003.57	42.86
1	733.52	2814.51	24.11
1.25	469.45	1801.28	15.43
1.5	326.01	1250.89	10.72
1.75	239.52	919.02	7.87
2	183.38	703.63	6.03
2.25	144.89	555.95	4.76
2.5	117.36	450.32	3.86
2.75	96.99	372.17	3.19
3	81.50	312.72	2.68
3.25	69.45	266.46	2.28
3.5	59.88	229.76	1.97
3.75	52.16	200.14	1.71
4	45.84	175.91	1.51

Table 6: Dose rates for full beam at guide exit to 2MeV photon scenario (broad beam)

The multi-layer shielding effectiveness has been calculated using the following equation:

$$D = (B_1 . B_2) D_0 e^{-\left(\left(\frac{\mu}{\rho_1}\right).\rho_1.x_1+\left(\frac{\mu}{\rho_2}\right).\rho_2.x_2\right)}$$

It should be noted that this is an approximation. Build-up factors change depending on multiple layers and layer order and this data is not available.

4.3.2.2 Scenario 2 - Conversion of all neutrons on large sample to 2MeV photons

Using the photon flux stated in **Table 1** we can then calculate the dose rate on the inside of the wall as a function of distance using the conversion factor of 2.69×10^{-2} μSv/h per gamma/(cm^2/s), as defined in 'ESS procedure for designing shielding for safety' [5]

Distance from conversion point (m)	Photon flux on shielding (photons/cm^2/s)	Dose rate on shielding (uSv/hr)
0.5	1.27E+06	34250.14
0.75	5.66E+05	15222.29
1	3.18E+05	8562.54
1.25	2.04E+05	5480.02
1.5	1.41E+05	3805.57
1.75	1.04E+05	2795.93

2	7.96E+04	2140.63
2.25	6.29E+04	1691.37
2.5	5.09E+04	1370.01
2.75	4.21E+04	1132.24
3	3.54E+04	951.39
3.25	3.01E+04	810.65
3.5	2.60E+04	698.98
3.75	2.26E+04	608.89
4	1.99E+04	535.16

Table 7: Flux to dose for full beam on large sample to 2MeV photon scenario

Using the build-up factors listing in **Table 5** we obtain the following dose rates:

	Dose rates outside shielding in μSv/hr		
Distance from conversion point (m)	200mm Steel	500mm concrete	200mm steel + 500mm concrete
0.5	293.41	1125.80	9.64
0.75	130.40	500.36	4.29
1	73.35	281.45	2.41
1.25	46.95	180.13	1.54
1.5	32.60	125.09	1.07
1.75	23.95	91.90	0.79
2	18.34	70.36	0.60
2.25	14.49	55.60	0.48
2.5	11.74	45.03	0.39
2.75	9.70	37.22	0.32
3	8.15	31.27	0.27
3.25	6.94	26.65	0.23
3.5	5.99	22.98	0.20
3.75	5.22	20.01	0.17
4	4.58	17.59	0.15

Table 8: Dose rates for full beam on large sample to 2MeV photon scenario (broad beam)

4.3.2.3 Scenario 3 - Conversion of all neutrons on normal sample to 2MeV photons

Using the photon flux stated in **Table 1** we can then calculate the dose rate on the inside of the wall as a function of distance using the conversion factor of 2.69×10^{-2} μSv/h per gamma/(cm^2/s), as defined in the 'ESS procedure for designing shielding for safety' [5]

Distance from conversion point (m)	Photon flux on shielding (photons/cm^2/s)	Dose rate on shielding (uSv/hr)
0.5	1.27E+05	3425.01
0.75	5.66E+04	1522.23
1	3.18E+04	856.25
1.25	2.04E+04	548.00
1.5	1.41E+04	380.56
1.75	1.04E+04	279.59
2	7.96E+03	214.06
2.25	6.29E+03	169.14
2.5	5.09E+03	137.00
2.75	4.21E+03	113.22
3	3.54E+03	95.14
3.25	3.01E+03	81.07
3.5	2.60E+03	69.90
3.75	2.26E+03	60.89
4	1.99E+03	53.52

Table 9: Flux to dose for full beam on normal sample to 2MeV photon scenario

Using the build-up factors listed in **Table 5**, we obtain the following dose rates:

	Dose rates outside shielding in µSv/hr		
Distance from conversion point (m)	200mm Steel	500mm concrete	200mm steel + 500mm concrete
0.5	29.34	112.58	0.96
0.75	13.04	50.04	0.43
1	7.34	28.15	0.24
1.25	4.69	18.01	0.15
1.5	3.26	12.51	0.11
1.75	2.40	9.19	0.08
2	1.83	7.04	0.06
2.25	1.45	5.56	0.05
2.5	1.17	4.50	0.04
2.75	0.97	3.72	0.03
3	0.82	3.13	0.03
3.25	0.69	2.66	0.02
3.5	0.60	2.30	0.02
3.75	0.52	2.00	0.02
4	0.46	1.76	0.02

Table 10: Dose rates for full beam on normal sample to 2MeV photon scenario (broad beam)

5 Conclusions

5.1 Gamma Shielding

Calculations using a realistic broad beam point source with build-up factors result in significantly higher dose rate estimations. The concept shielding of 200mm of steel followed by 500mm of concrete may not be fully adequate for H2 event and additional shielding may be required near the end of the guide or a safety device employed that limits the size of beam.

Conversely, the calculations suggest that it may be possible to reduce the shielding requirements for sample position scattering events (H1).

Multi-layer calculations are approximations as only build-up factors for individual materials are available. The high dose rates found using broad beam is greatly influenced by the approach of converting all neutrons to 2MeV photons. A cautious approach to shielding is highly advisable. Experience shows that fitting additional shielding after commissioning is expensive and if it is not accommodated for during the original design it can compromise instrument operation. However, the reality of all neutrons to 2MeV should be examined as it could result in over specification of shielding, reduction in experiment floor-space and increased floor loadings.

Sufficient space for additional shielding is considered in the Freia concept and the shielding will be optimized based on neutronic calculations.

6 References

[1] (ESS-0052625) NOSG phase 2 guidelines for designing instrument shielding for radiation Safety
[2] (ESS-0001786) Definition of Supervised and Controlled Radiation Areas
[3] (ESS-0000004) General Safety Objectives for ESS
[4] (ESS-0114072) Analysis of Shielding Requirements for the LoKI Instrument
[5] (ESS-0019931) ESS Procedure for designing shielding for safety
[6] NISTIR 5632 - X-Ray Mass Attenuation Coefficients
[7] “American National Standard for Gamma-Ray Attenuation Coefficients and Buildup Factors for Engineering Materials”, ANSI/ANS-6.4.3-1991 (1991)