Simulating BIFROST instrument to 35 meters from source. Dose rate in D03 due to fast neutrons from target.

Simulation software

For simulating BIFROST beamline FLUKA simulation package is used. The simulation model is prepared using CombLayer model builder. The materials (concrete, steel, etc.) are the defaults implemented in the CombLayer.

Simulation setup

Instrument model

The instrument was constructed using CombLayer and inserted into the simplified model of the ESS. The target was removed, however the beamport positions were kept at place (help from Konstantin Batkov).

The BIFROST instrument optics layout is as follows:

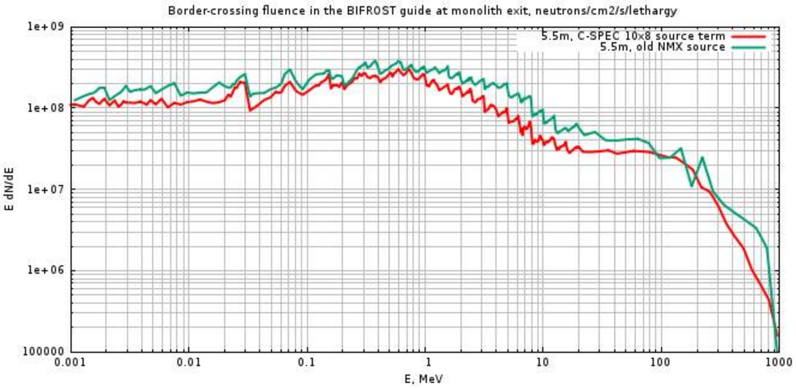
- Focusing part starts in the monolith at 2 meters from source and continues to the pulse shaping chopper at 6.45 m. The neutron beam is narrowed horizontally and expanded vertically. Copper substrates in the monolith and light shutter (to 6m), aluminium substrates later.
- Bender from 6.45m to 24.5 m with curvature of 1518.5 meters and internal dimensions of 3Hx5Vcm^2. Line of sight to the source is lost just before the bunker wall. Substrate – aluminium.
- Defocusing section starting in the bunker wall (24.5 m) and going to 34 m, borkron glass substrate outside the bunker. Copper substrate in the bunker wall (use of aluminium substrate there increases streaming of fast neutrons along the guide in the vacuum vessel).
- Straight section (5x7.5cm^2)
- Focusing section.

So far, the instrument was simulated just up to the start of defocusing section. The geometry and positioning of the optics was checked to match those in the CATIA model of the instrument. CATIA coordinates in the TCS were provided by Liam Whitelegg.

The bunker wall is MagnaDense concrete, the definition is of material is taken according to the defaults of the CombLayer. **All substrates in the bunker are 8mm thick including monolith insertion. No collimators assumed in the simulation.**

Neutron source

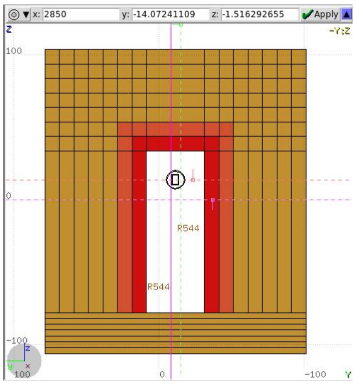
The results presented here are for the old NMX spectrum parameterization used as source at 2 meters. The reason for that is that most of the simulation work was done before the contemporary source terms were implemented. The report thus is a summary of results communicated informally to the BIFROST instrument team on several occasions. However, as the old NMX source has a minor difference with the contemporary C-SPEC source when the spectrum at 5.5m is considered (at least less than order of magnitude), the validity of the conclusions still holds. The picture below contains a comparison of the corresponding spectra. The zigzags are an artefact of step-like parameterization of the energy spectrum. The flat steps in the energy spectrum turn into linear growth when the it is multiplied by the energy to obtain lethargy spectrum.



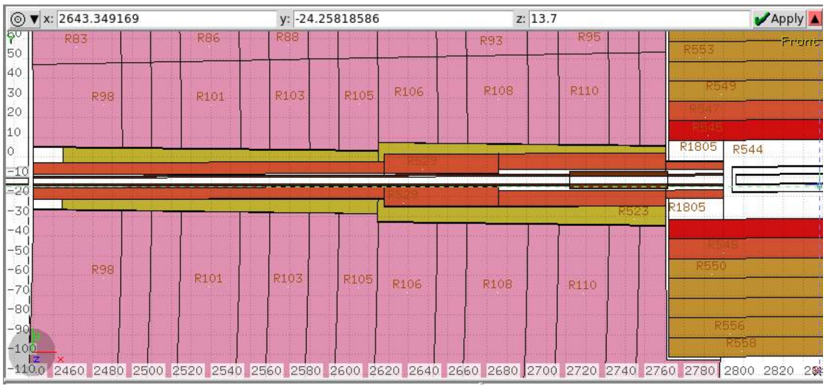
Biasing of the source in both direction and energy was implemented as it is described in the report on HEIMDAL beamline simulation. Neutrons were sampled on 9Wx6H cm^2 surface which covers the guide opening (6.87Wx3.46H), 2mm gap and approximately 1 mm of the monolith insertion steel around.

D03 shielding geometry

The simulations were done at the early stages of the ESS common shielding project. The lateral shielding layout is not completely up to date. In the simulation it consists of a layer of Carston concrete (10cm, PE+B4C 1.9g/cm^3) Mild steel (10 cm) and regular concrete (50 cm, 2.3 g/cm^3). The bunker wall insert and mild steel shimming around are modeled according to the actual CATIA model with the dimensions of thicknesses, angles and steps read off the STEP file received from the instrument lead engineer.



x: 2850 y: -14.07241109 z: -1.516292655



x: 2643.349169 y: -24.25818586 z: 13.7

Fluxes in the bunker

In the simulation only fast neutrons were sampled with energies above 1keV. Fluxes of neutrons in the bunker with 8mm thick substrates (Cu in monolith and Light Shutter, Al elsewhere).

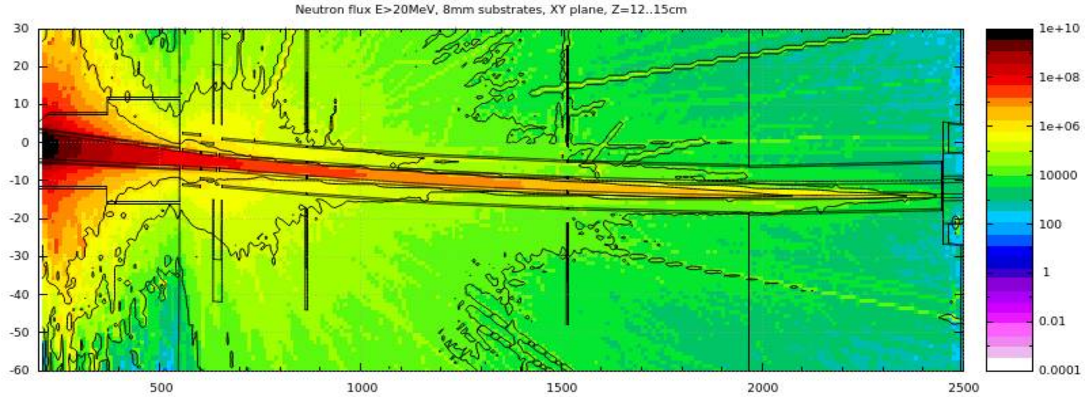

Neutron flux E>20MeV, 8mm substrates, XY plane, Z=12..15cm

FIGURE 1 NEUTRON FLUXES IN THE BUNKER. CUT BY HORIZONTAL PLANE. E>20MEV

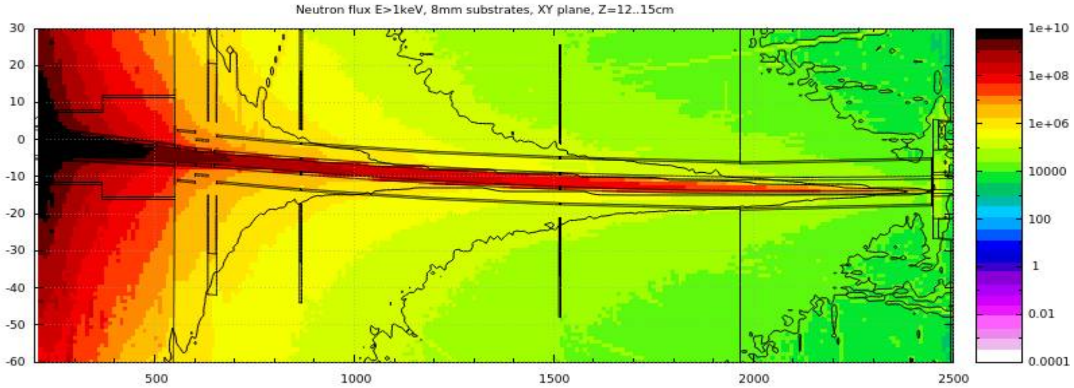

Neutron flux E>1keV, 8mm substrates, XY plane, Z=12..15cm

FIGURE 2 NEUTRON FLUXES IN THE BUNKER. CUT BY HORIZONTAL PLANE E>1KEV.

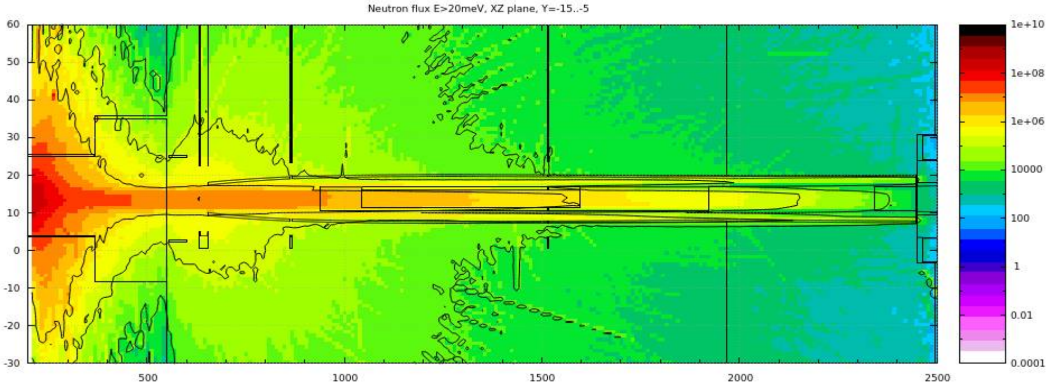

Neutron flux E>20meV, XZ plane, Y=-15..-5

FIGURE 3 NEUTRON FLUX IN THE BUNKER. CUT BY VERTICAL PLANE. E>20MEV

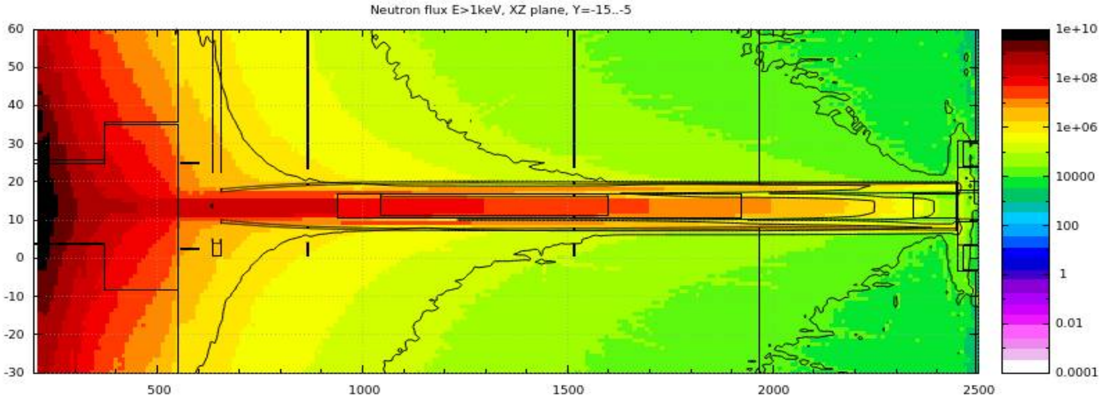
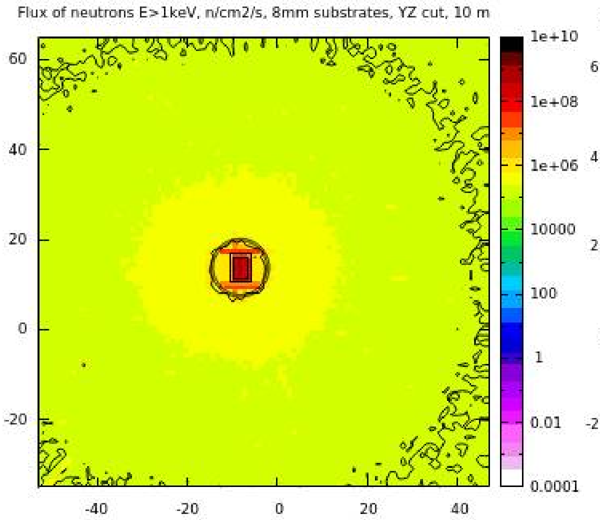
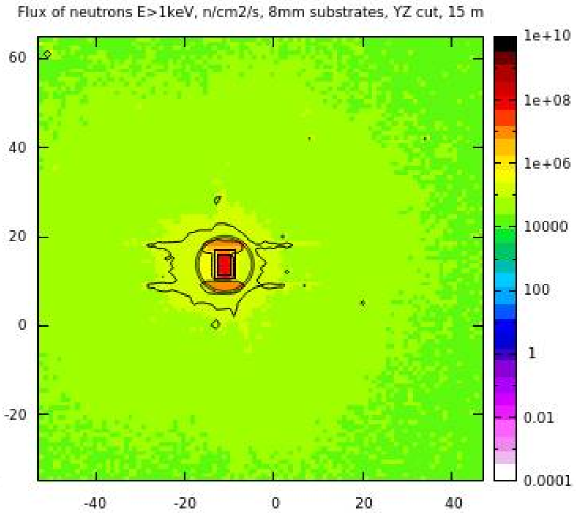

Neutron flux E>1keV, XZ plane, Y=-15..-5

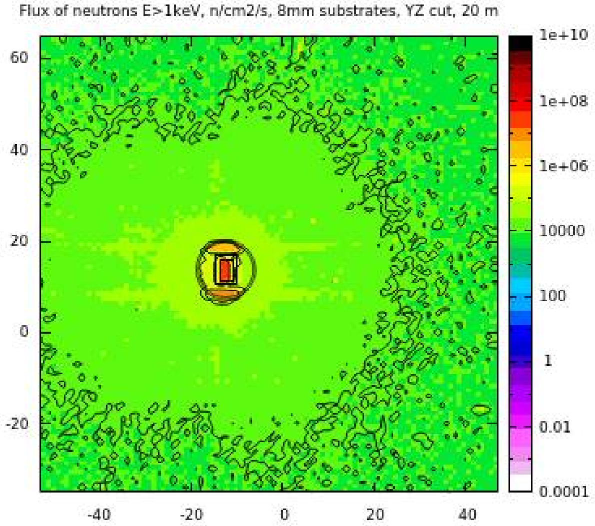
FIGURE 4 NEUTRON FLUX IN THE BUNKER. CUT BY VERTICAL PLANE. E> 1KEV

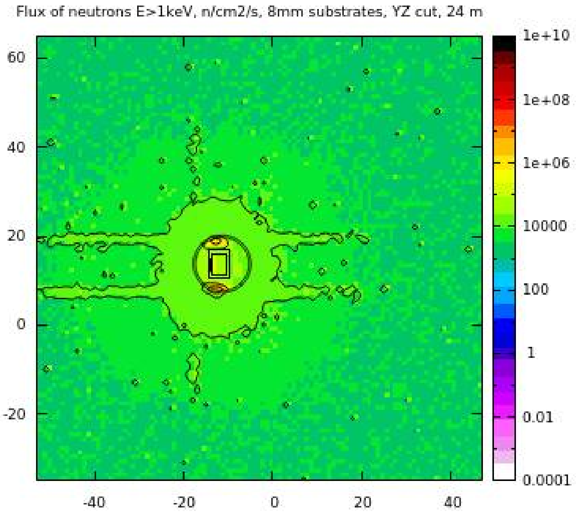
Streaming of neutrons in the vacuum tubing around the guide is apparent. Flux of neutrons (per cm^2 per second) above and below the neutron guide before the bunker wall, for both high-energy and fast neutrons overall, is even higher than in the guide opening itself. The origin of streaming in the vacuum tubing can be understood from looking at fluxes projection on the plane perpendicular to the guide direction.

Here are fluxes of fast neutrons (E>1keV) at 10, 15, 20 and 24.4 m from target center. Going out the line of sight to the moderator can be easily observed as disappearing of the red square in the guide opening with increasing distance, starting from y-positive side (y is horizontal coordinate). The horizontal stripes are apparently projections of gaps between the copper substrate in the monolith and steel of the monolith insertion. In the simulation the NBOA steps were not modeled, when present they will significantly reduce that contribution to the streaming.

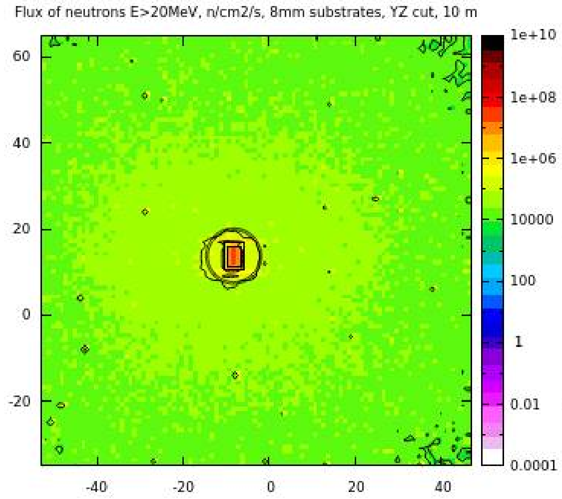

Flux of neutrons E>1keV, n/cm2/s, 8mm substrates, YZ cut, 10 m


Flux of neutrons E>1keV, n/cm2/s, 8mm substrates, YZ cut, 15 m

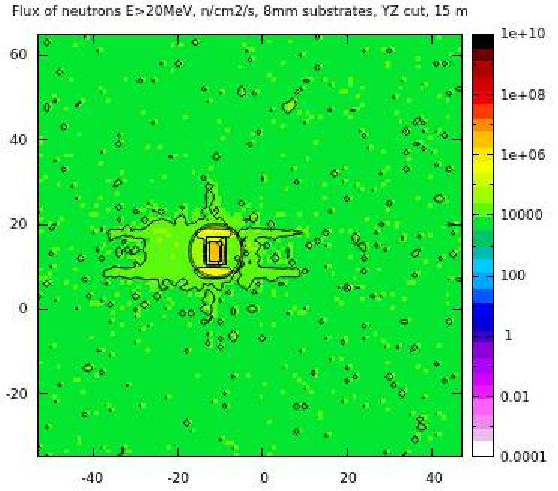

Flux of neutrons E>1keV, n/cm2/s, 8mm substrates, YZ cut, 20 m


Flux of neutrons E>1keV, n/cm2/s, 8mm substrates, YZ cut, 24 m

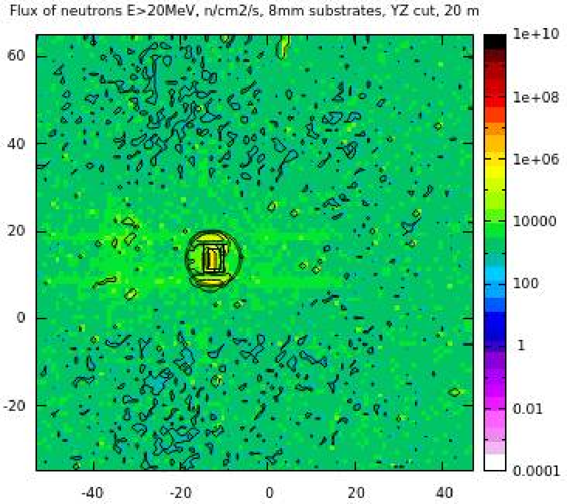
A similar picture is observed in high energy neutron flux. The vertical stripes are even more pronounced in this case. A bright spot at horizontal coordinate of -40 cm with flux between 10^3 and 10^4 n/cm^2/s corresponds to the projection of the NBOA axis on the bunker wall after passing through aluminium substrate and vacuum tubing at low angle. This spot is seen only in the high energy neutron flux due to lower attenuation at high energy.



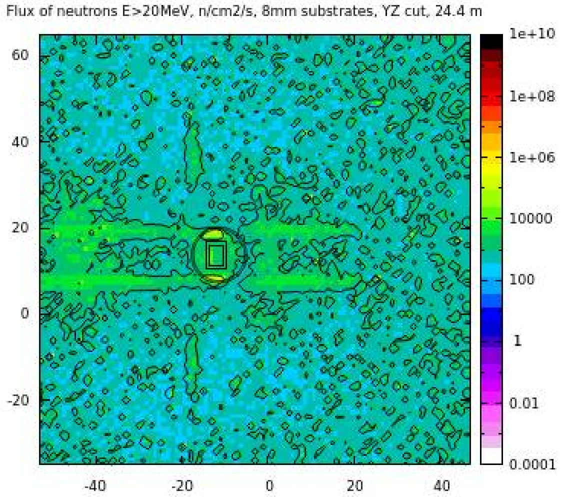
Flux of neutrons E>20MeV, n/cm2/s, 8mm substrates, YZ cut, 10 m



Flux of neutrons E>20MeV, n/cm2/s, 8mm substrates, YZ cut, 15 m

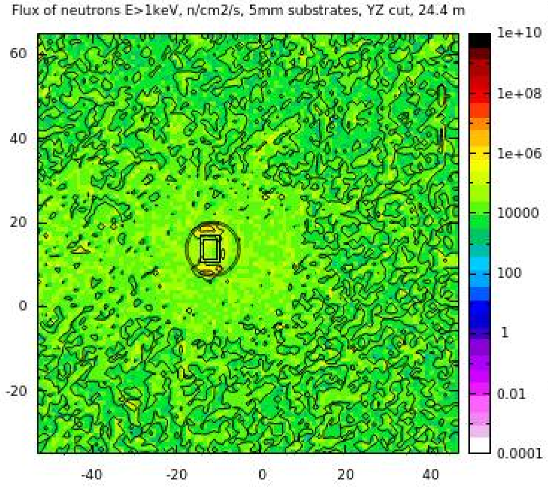


Flux of neutrons E>20MeV, n/cm2/s, 8mm substrates, YZ cut, 20 m

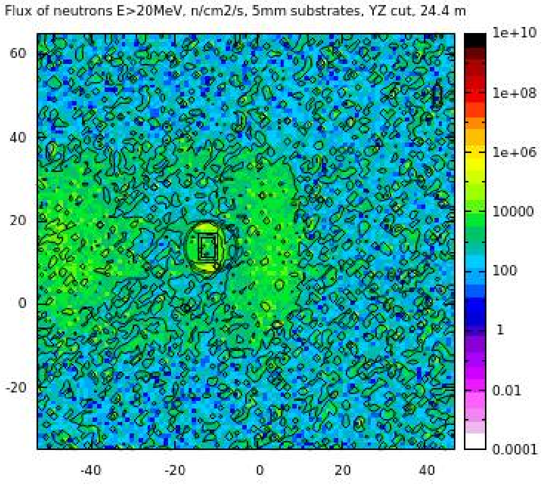


Flux of neutrons E>20MeV, n/cm2/s, 8mm substrates, YZ cut, 24.4 m

Neutron fluxes outside the vacuum tubing depends crucially on the substrate thickness. For 5mm aluminium substrates for example the bright spot at y=-40 cm can be also observed in the overall neutron flux at 24.4m. The amount of fast neutrons is also significantly larger. The run with 5mm substrate depicted below has lower statistics which explains larger intensity fluctuations.



Flux of neutrons E>1keV, n/cm2/s, 5mm substrates, YZ cut, 24.4 m



Flux of neutrons E>20MeV, n/cm2/s, 5mm substrates, YZ cut, 24.4 m

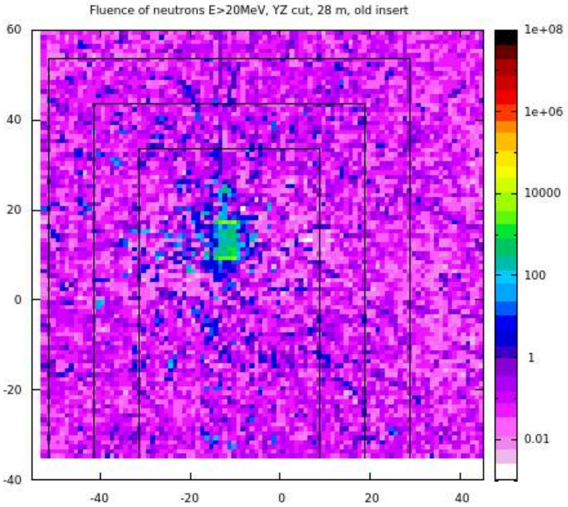
Streaming of neutrons in the vacuum tubing around the guide is of a similar magnitude compared to the guide opening itself. The two bright spots above and below the guide which have an order higher magnitude result from streaming in the 2mm gap in the monolith between substrate and insertion and will reduce once the NBOA steps will be modeled. **Except for those two bright spots, fast neutrons streaming in both vacuum tubing and guide opening is given by secondary neutrons coming from source neutron interaction in the substrate and the tubing.** This explain their similar magnitude. As streaming builds up along the guide starting from the monolith, the BIFROST team is currently considering having a collimator at 17m to reduce that contribution which potentially could cause higher activation levels of steel used for the vacuum vessel in the bunker wall feedthrough. Whether a collimator will have an effect or not depens on how much of fast neutron streaming inside the vacuum tubing build up before 17 m and should be explored upon updating the instrument model.

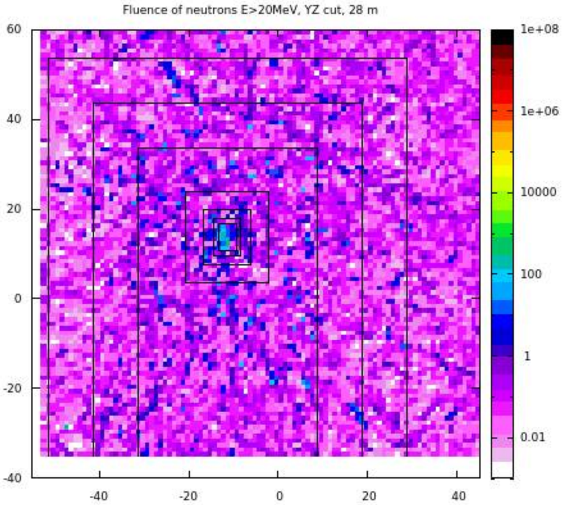
Bunker wall feedthrough

A decision on using copper substrate in the bunker wall and making a step in the substrate thickness was made upon comparing results of two simulations.

1. 5mm aluminium substrate in the bunker wall insert (also 5mm in the bunker). Vacuum vessel has a rectangular channel of constant cross section for the whole length. As the guide is defocusing, this implies large gaps between vessel walls and the substrate at the inner side of the bunker wall even when the gaps at the downstream part of the insertion are minimal. (Gaps are needed for the alignment purposes).
2. 8mm copper substrate with a step on the final part. Inner cross section of the vacuum vessel is changing at approximately 2/3 of its length (see snapshot in the beginning of the document). Besides incorporating a step in the substrate to avoid direct streaming from the bunker, this allows to reduce gaps in the upstream part which are now constrained at 2/3 of the insertion length. According to present concept steps in the substrate and vacuum vessel walls are achieved by bolting plates of appropriate thickness.

Results of the simulation in case 1 and case 2 are presented below, left and right respectively.



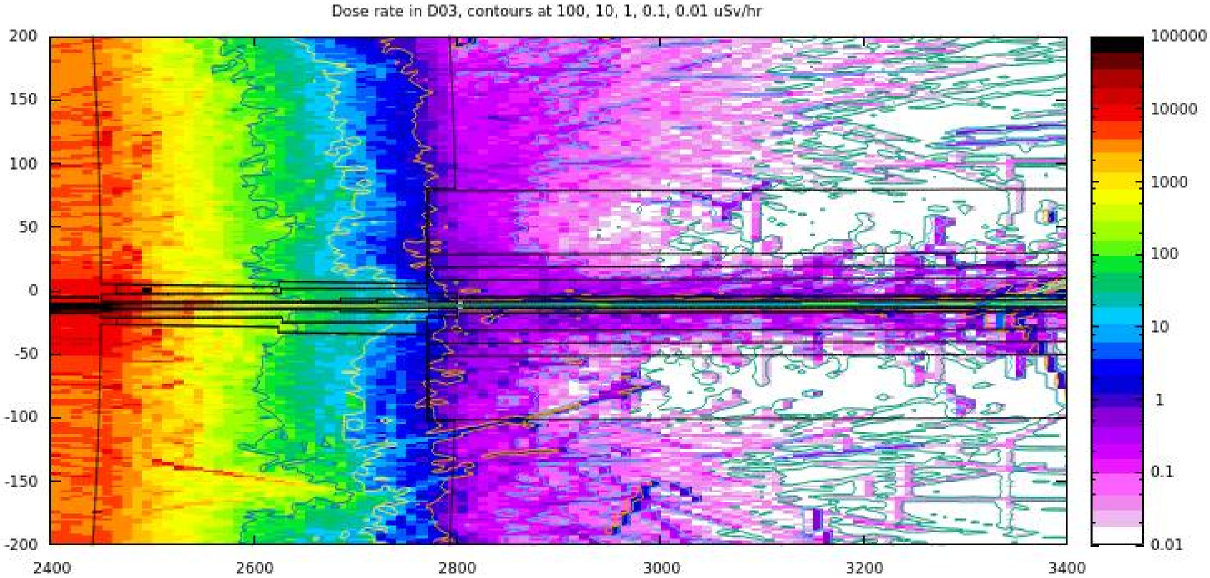


In case of aluminium substrate and constant cross section of the vacuum vessel (case 1, left figure), streaming of high neutrons to the left and to the right of the guide (in terms of flux, n/cm^2/s) has similar magnitude as streaming in the guide center. Above and below the guide the flux per cm^2 are even higher (partly because of the absence of NBOA steps in the simulation).

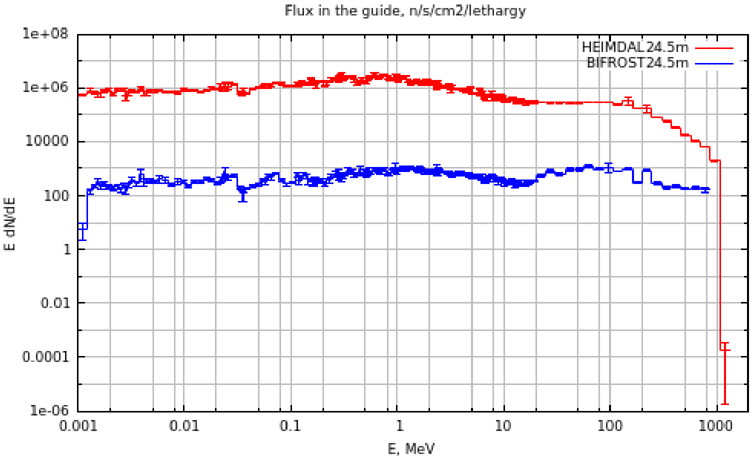
In case of copper substrate with a step (case 2, right figure), on the contrary, streaming in the gap around the guide is much lower than in the guide center, bright stripes above and below are absent. Also streaming in the center of the guide is reduced.

Dose rates in D03.

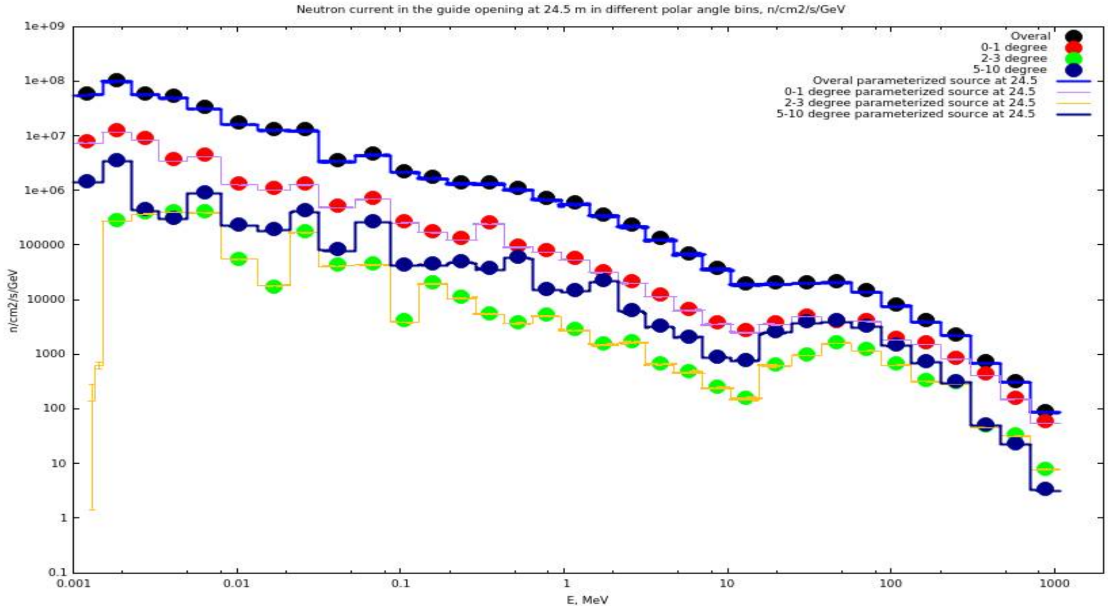
Here is a cut of the dose rate distribution in the horizontal plane. The simulation starts from using source term at 2 meters. This includes both neutrons and gamma radiation generated due to neutron inelastic scattering and capture in the shielding materials. Contribution of gamma radiation due to capture of transported thermal and cold neutrons in the guide coating is not included, its contribution is evaluated in a separate dedicated report ("Shielding prompt gamma at the ESS long instruments").



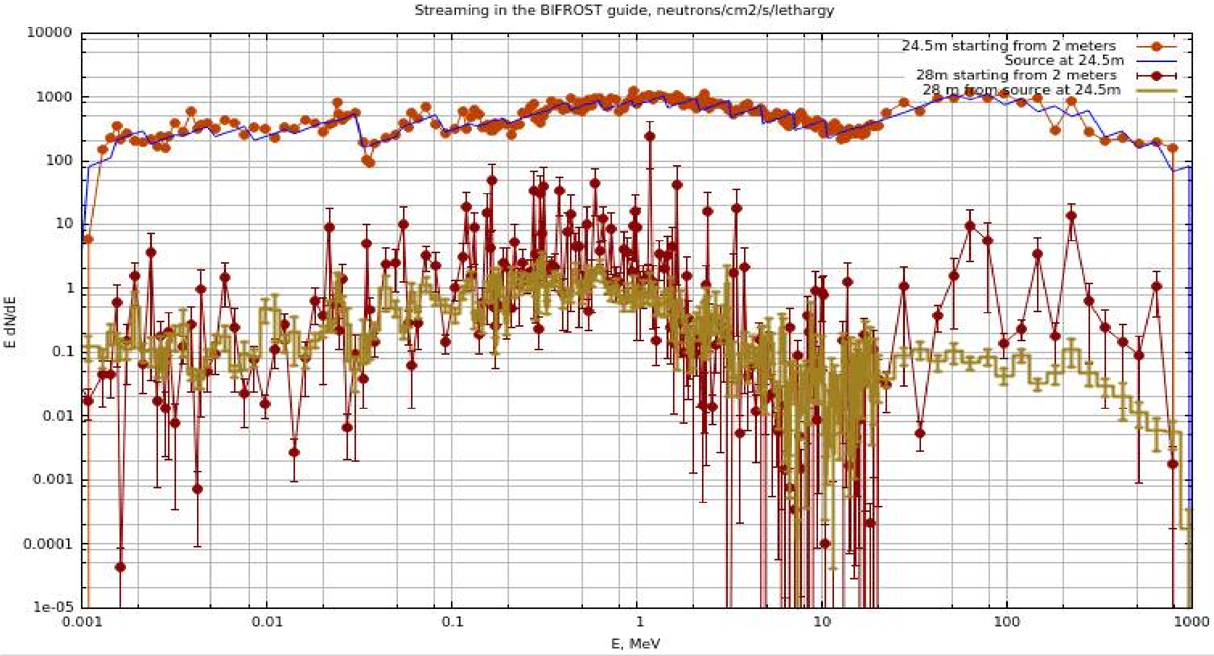
The dose rate reaches 1 uSv/hr level within the bunker wall. Beyond 1 m from the bunker wall the dose rate is of the order of 0.01 uSv/hr and is mainly due to shine of the bunker wall. Neutron streaming in the guide opening is not observed to have a significant contribution though the statistical error is large. This seems reasonable since compared to HEIMDAL, which for the same shielding layout would have 10-15uSv/h outside lateral shielding, BIFROST has 2 orders magnitude lower neutron flux in the guide opening at 24.5 meters.



To minimize the statistical error of the calculation, a separate 2-stage simulation was performed. At the first step of simulation the neutron transport in the wall was not modelled. Instead, a neutron current in the guide opening at 24.5 m was calculated as a function of energy in several polar angle θ bins: 0-1 degree, 1-2, 2-3, 3-4, 4-5, 5-10, 10-25 25-36 and further up to 90 degrees keeping uniform cos θ binning of 0.1 units. The parameterized spectrum was sampled in the guide opening at 24.5 m. For a consistency check, the spectra in the guide opening were compared in the same angular bins to the simulation starting from 2 meters. Below is neutron current in several energy bins as calculated in the run starting from 2m (dots) and neutron flux as calculated using spectra obtained at 24.5 m as input in same angular bins (histogram). The fluxes are nicely reproduced.

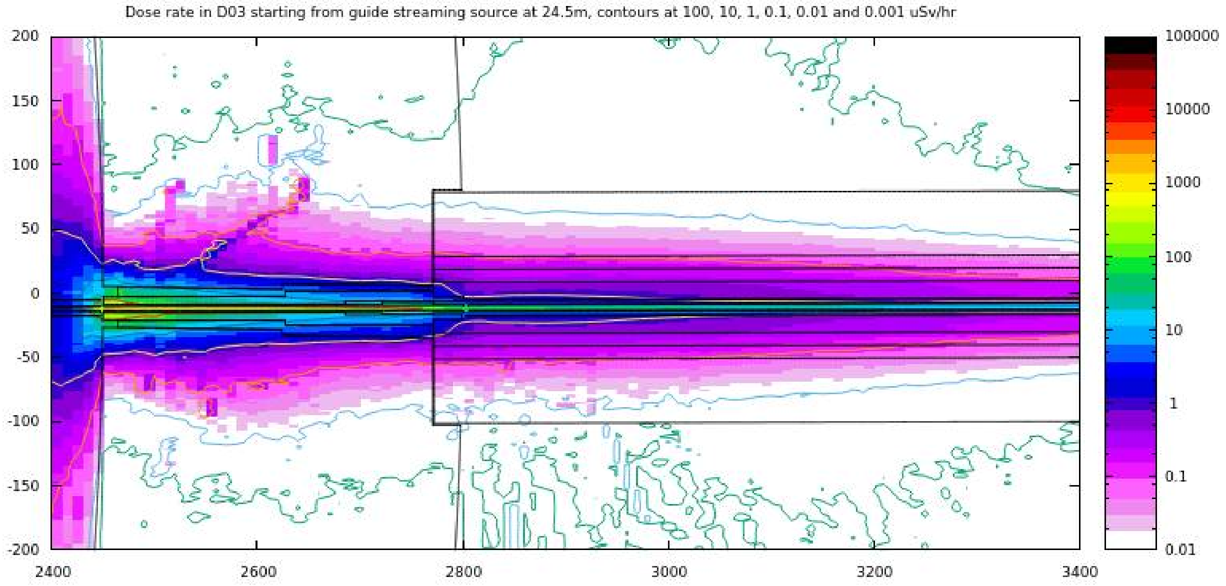


When comparison is made beyond the bunker wall (28 m) some difference is observed in the neutron flux between the two runs (though error for the run starting from 2m are high).



Fluxes of neutrons with energies above ~50MeV at 28m are higher in the run starting at 2 meters. The difference is supposedly due to a higher collimation of high energy neutrons in this case. The simulation starting at 24 meters assumes uniform neutron distribution within 0-1 degrees of the polar angle which may not be the case. On the other hand, a higher divergence results in higher dose rates close to the bunker wall. Another reason for the difference between the two runs at 28 m might be some non-uniformity in a distribution of neutrons in the guide opening plane at 24 meters.

Below is the figure giving the dose rates outside the lateral shielding resulting from fast neutron streaming in the guide opening (horizontal plate cut at guide height). The dose rates inside the lateral shielding are slightly higher that in the simulation starting from 2 meters. Forgetting about statistical error of the run starting at 2 meters this can in principle be explained both by increased divergence of high energy neutrons for the source starting at 24 m. The order of magnitude of the simulated dose rate in both cases is the same: between 0.001 and 0.01 uSv/hr.



The conclusion valid for the instruments which loose line of sight within the bunker. Fast neutrons from the source don’t give a sizeable contribution to the dose rate outside the bunker wall compared to prompt gamma radiation due to capture of transported cold and thermal neutrons in the guide coating.