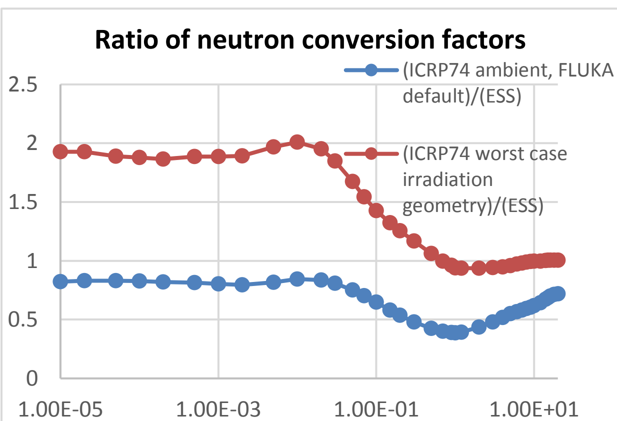
Simulating HEIMDAL beamline (thermal guide) at the ESS. Dose rates in D03.

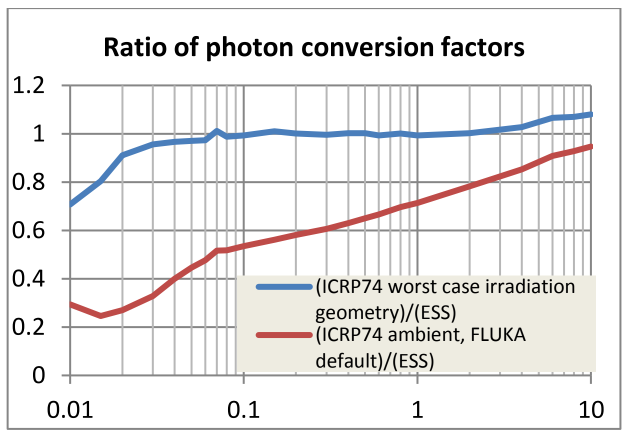
Simulation software

For simulating HEIMDAL 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.

Flux to dose conversion factors in FLUKA

FLUKA uses a built-in flux to dose conversion factors providing several options. The default is conversion factors according to ICRP publication 74 for ambient irradiation. This however can be changed to the ICRP74 conversion factors for the worst-case irradiation geometry (usually frontal irradiation). The comparison of the two options versus ESS 19931 is in the figure below.



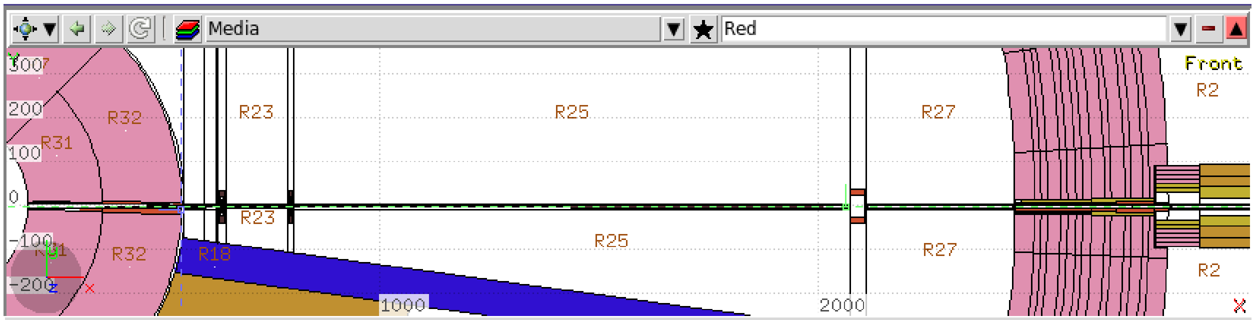


Thus making FLUKA simulations of the dose rate using flux to dose factors for the worst-case irradiation geometry is compliant with the ESS requirements (and even has a certain reserve for thermal neutrons).

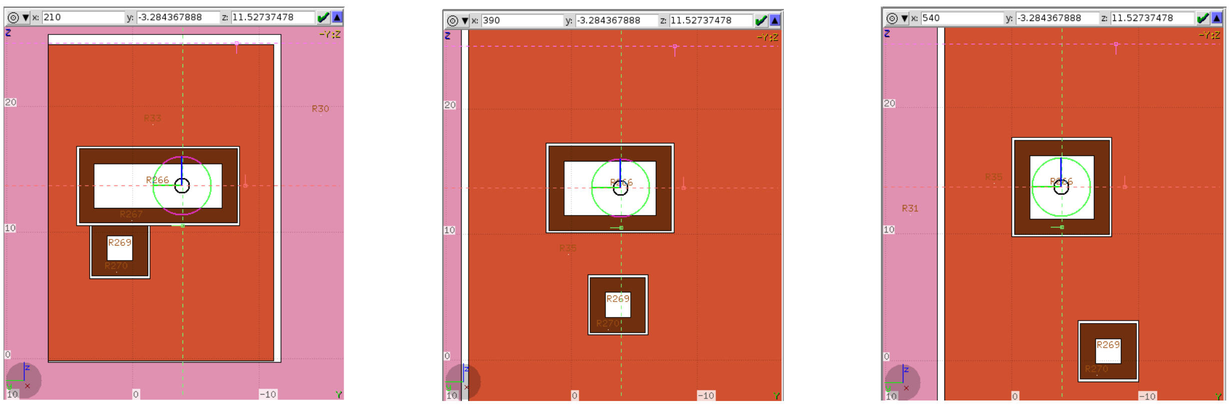
Simulation setup

Instrument model

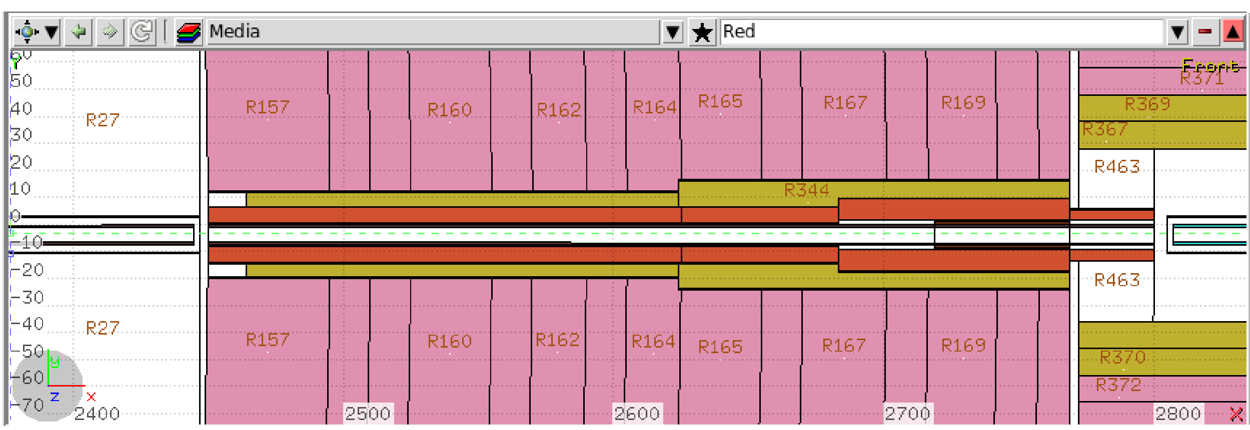
The instrument was constructed using CombLayer and inserted into the simplified model of the ESS. The target was removed, however the beamport positions were kept at place (help from Konstantin Batkov). Only a part of the instrument (up to 10 meters from the bunker wall) was simulated. Shielding thicknesses outside the bunker were taken close to the anticipated in common shielding project. 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 (including light shutter) is 8mm Aluminium. No collimators assumed in the simulation.**



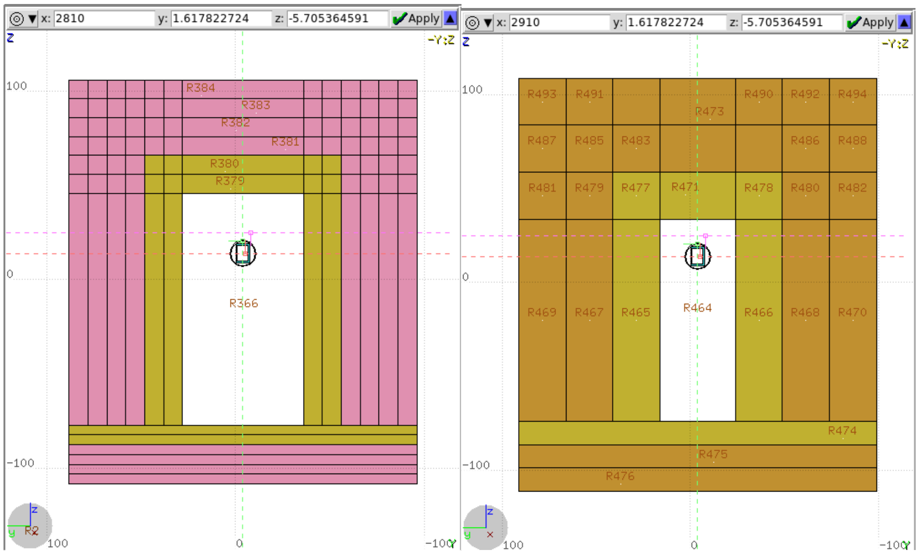
The NBOA has a tapered shape with entrance and exit windows according to the engineering drawings. No steps in thickness of the NBOA substrates are simulated. The cut of insertion with the NBOA at 210, 300 and 540 cm from target center are on the figure below.



In the bunker wall insertion a vacuum vessel was modelled (steel type 304, CombLayer default) with a step, the shimming material is ChipIRsteel (combLayer default), all similar to BIFROST simulation. The exact dimensions of the vacuum vessel and the shimming are still to be implemented. Same "ChipIRsteel" material is used for lining the lateral guide shielding beyond bunker wall from inside. Cold guide is not modeled in the bunker.



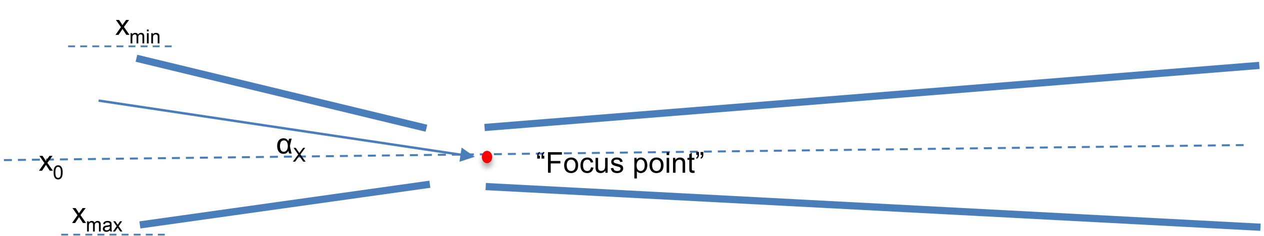
The ChipIRsteel/MagnaDenseHC (20 cm/40cm)shielding is modeled from bunker wall to 28.7 meters from target (1 m long block with 30 cm deepening in the bunker wall), from 28.7 meters the MagnaDenseHC is replaced by regular concrete (CombLayer default).



Source spectra

In the simulation a spectrum parameterization at 2 meters is used prepared by Valentina Santoro. Report on spectra contains several parameterizations for various size of the opening in the monolith insertions. Benchmarking of the spectra parameterizations with the runs from proton are shown for a 8Wx10H cm^2 straight opening aligned with the beamport axis.

A source routine for generating primaries with both energy and angular biasing was written for the FLUKA simulation which contains this parameterization. The key idea behind the biasing is to sample more neutrons which are propagating further, so the source is biased to imitate the “duct source” option for PHITS however keeping track of the actual angular distribution.



The following biasing is implemented:

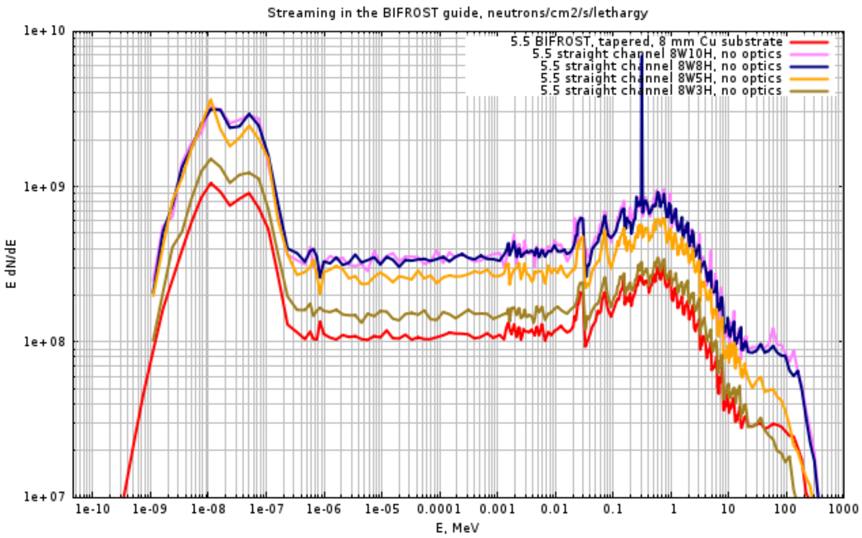
- Horisontal position biasing in front of thermal guide opening:

$$p_{bias}(x|x < x_0) = \frac{4\,(x - x_{min})^3}{(x_{max} - x_{min})(x_0 - x_{min})^3} \quad p_{bias}(x|x > x_0) = \frac{4\,(x_{max} - x)^3}{(x_{max} - x_{min})(x_{max} - x_0)^3}$$

- Focusing biased angular distribution to the direction dependent on position:
  $p_{bias}(t_X, t_Y) = \frac{1-s}{\pi[(d^2+1)^{1-s} - d^{2(1-s)}]} \cdot \frac{1}{[d^2+t_X^2+t_Y^2]^s}$
  - Centered towards the "focus point" (different for cold and thermal guides)
  - $d = d_0 + \sin^2\alpha_X + \sin^2\alpha_Y$ $\quad$ $s = 1.1 + 120 \cdot (\sin^2\alpha_Y + \sin^2\alpha_X)$
  - $s = 1$ & $d = 0$: uniform illumination of the tube from inside - duct source equivalent
- Bias energy distribution: $p_{bias}(E) = \frac{1-\alpha}{[E_{max}^{1-\alpha} - E_{min}^{1-\alpha}]} \cdot \frac{1}{E^\alpha}$

The source is tested by doing simulations for the straight rectangular openings in the monolith. A spherical detector of radius of 1.2 cm is placed in front of the opening center at 551.5 cm from moderator. The flux is calculated according to a standard fluence definition: total number of neutrons entering the sphere from outside divided by the sphere cross section area (4.52 cm^2). Fluxes per unit lethargy are plotted below. FLUKA calculation for 8x10 cm with the corresponding source spectrum (TALLY241) reproduces the figure from Valentina's report on the source term, which indicates correct implementation of the spectra together with angular and energy distribution biasing[1]. A large difference is seen between results for 8x10 and 8x3 opening: the calculation for 8x3 opening (using corresponding source TALLY271) is a factor 2 below. Valentina's report on source term doesn't contain the corresponding picture, so it would be important to figure out whether change in the height of the opening has a so large effect on neutron flux per cm^2 outside the monolith.

[1] The zig-zag structure on the spectra per lethargy is an artefact of step-wise energy spectrum and fine FLUKA energy binning for neutrons below 20 MeV which can't be changed. When calculating spectrum with binning finer than initial one, a step in the spectrum transforms to linear growth when multiplied by energy (lethargy spectrum).



Spectra in front of the BIFROST guide opening were simulated in the same manner. A tapered shape with 8mm thick substrate and 2mm gap around was taken. The BIFROST opening at 2m is 6.87Wx3.46H cm^2 and at 5.5m 5.114Wx4.88H cm^2. A source spectrum corresponding to 8Wx10Hcm2 opening was sampled on 9Wx6H cm2 area and the normalization factor of $6.72*10^{13}$ n/s was correspondingly rescaled by 54/80. The BIFROST flux at 5.5 m is below the result for 8x3 opening by a factor around 1.4 and below the result for 8x10 opening by factor 3. Besides different geometry (tapered instead of rectangular) the guide is also tilted by 1.5 degree with respect to the beamport axis.

Total fluxes (all energies) of neutrons for the different options at 5.5 m:

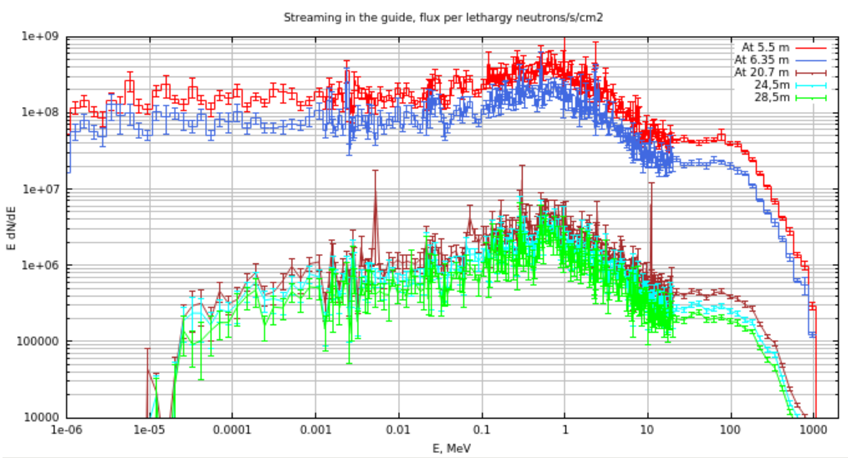
- 8Wx10H channel: $1.78*10^{10}$ n/cm^2/s
- 8Wx8H channel: $1.86*10^{10}$ n/cm^2/s
- 8Wx5H channel: $1.45*10^{10}$ n/cm^2/s
- 8Wx3H channel: $1.0*10^{10}$ n/cm^2/s
- BIFROST NBOA: $5.94*10^{9}$ n/cm^2/s

To compare, the flux for ODIN instrument at 5.5m calculated by Florian Grünauer is $5.89*10^{9}$ n/cm^2/s. Opening of the NBOA is 4.4Wx3.4H cm^2. When the opening is replaced by a 6x6 cm^2 straight channel the flux becomes $8.52*10^{9}$ n/cm^2/s. At the same time the flux communicated by Douglas Di Julio to Florian, seemingly for a straight 6x7 cm opening, is $1.8*10^{10}$ n/cm^2/s which coincides with Valentina's result for a 8x10 cm opening. To be clarified with Douglas. **Throughout the simulation for HEIMDAL a spectrum parameterization for 8W10H C-SPEC opening was used (TALLY241) rescaled for a sampling are of 125.9 cm^2 covering opening of both guides of the instrument in the monolith insertion at 2 meters.**

Simulation results

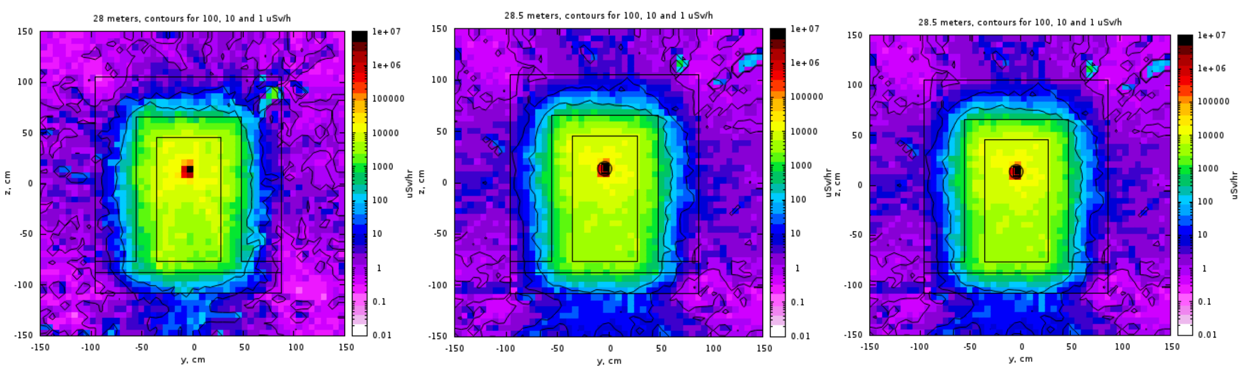
At the bunker wall the shielding is kept at 20 cm steel and 40 cm heavy concrete. Inner space is 64 cm wide (as in Senad's drawings). Beyond 28.7 meters two different options has been studied so far, inner space there is 40 cm wide. The neutron guide beyond the bunker wall is 8mm borosilicate glass, the vacuum tubing is 5mm aluminium. In the simulations neutrons are sampled starting from 1eV.

Streaming spectra of fast and epithermal neutrons are shown below. The spectrum shape beyond 20 m is apparently unchanged, increase of the distance affects only the overall magnitude.

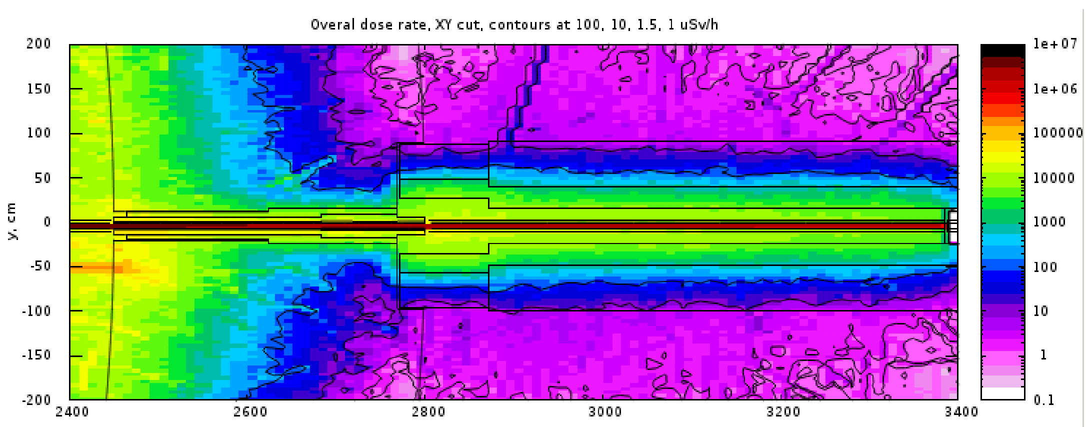


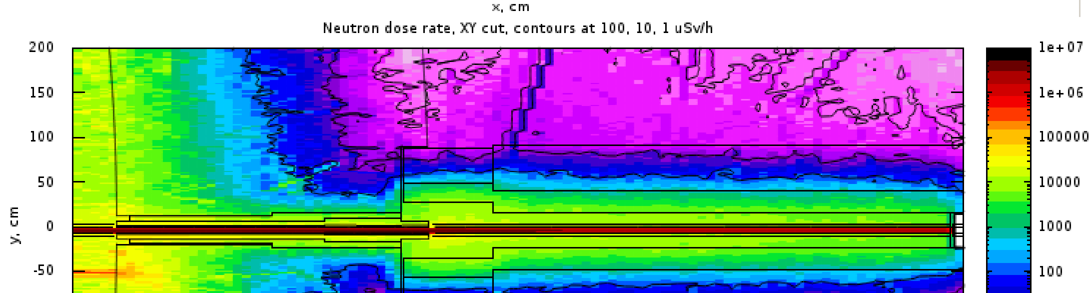
25cm steel 50cm concrete in D03; 8mm Al substrates in the light shutter and before the pinhole at 6.35 m

Here is vertical cross section of the dose rate distribution at 28, 28.5 and 29 m

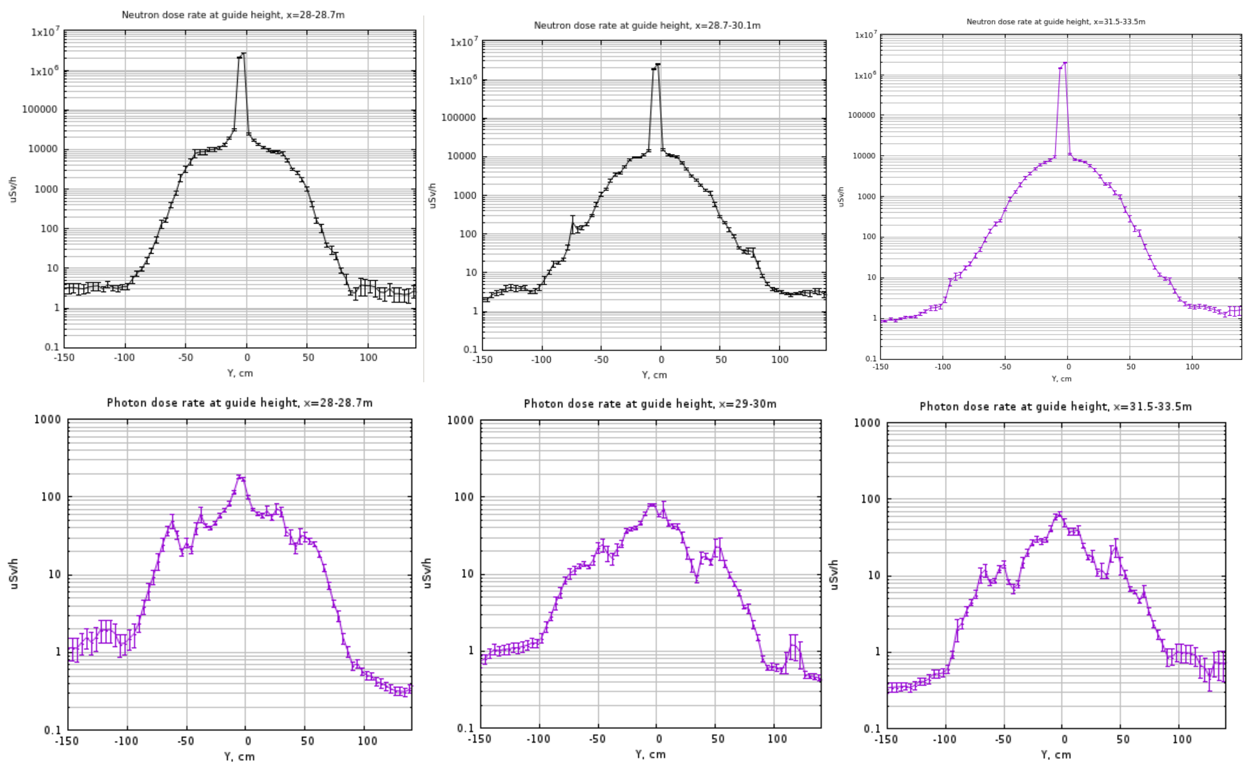


A horizontal cut for overall dose rate, neutron dose rate and photon dose rate:





One-dimensional plots illustrating the neutron and photon dose as a function of distance from the guide (at y=-3.5 cm) close to bunker wall, next to the HC/NC connection point and beyond 31m (see captions).

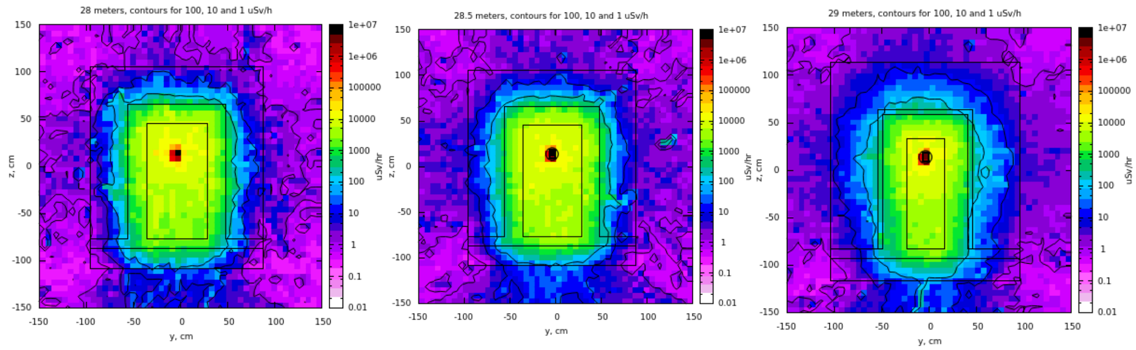


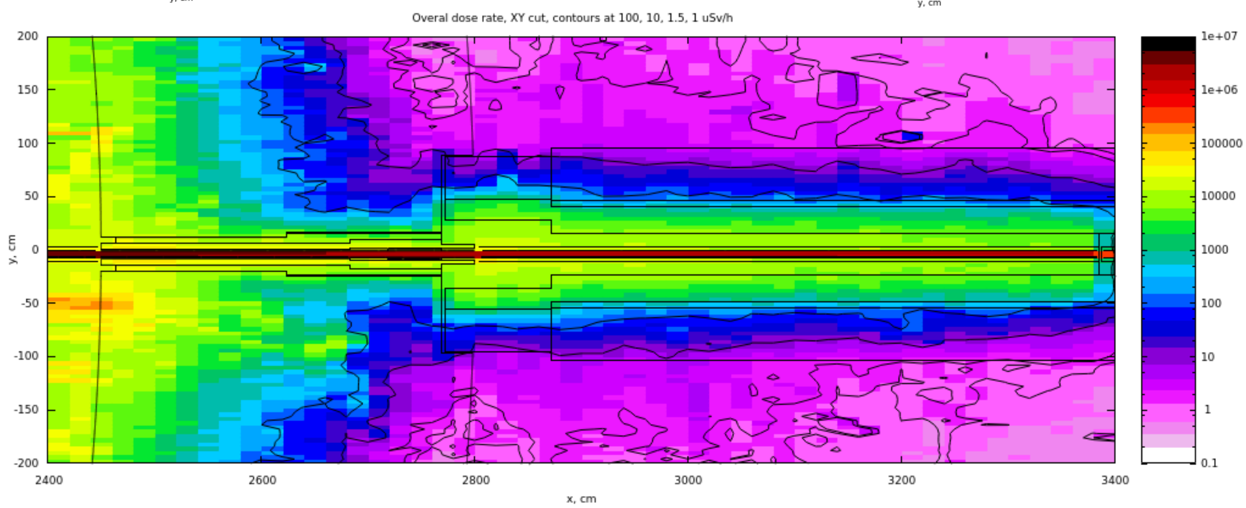
When steel/HC changes to steel/NC composition the overall dose rate at the surface remains approximately the same due to slower attenuation of neutron radiation in the regular concrete. A week place is the transition point between the two types of shielding. Due to larger inner dimensions of the heavy concrete shielding, fast neutrons can arrive at the beginning of the regular concrete shielding too close to its surface for a sufficient attenuation.

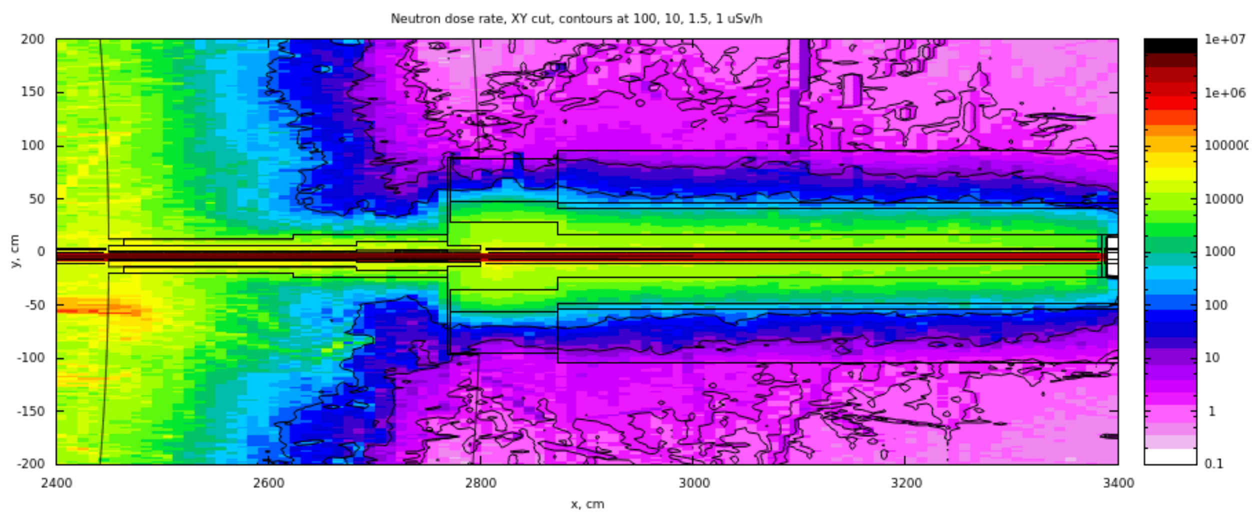
The neutron dose rate and photon dose rate are of the same order at the shielding surface in this layout: the neutron dose rate is between 3 and 4uSv/hr while the photon dose rate is around 1 uSv/hr. This means that by reducing gamma radiation from to neutron capture in shielding materials it is possible to significantly reduce the dose rates at the shielding surface. The plots for gamma dose rate as a function of distance from the neutron beam indicate two peaks (plots on the right for normal concrete) at y=-50 and y=47 cm. These two peaks correspond to the interface between the steel and concrete. Besides capture in the concrete itself, the neutrons after thermalization in the concrete can be captured by steel with emission of high energy photons (up to 10MeV). To avoid this, a layer of borated concrete could be helpful.

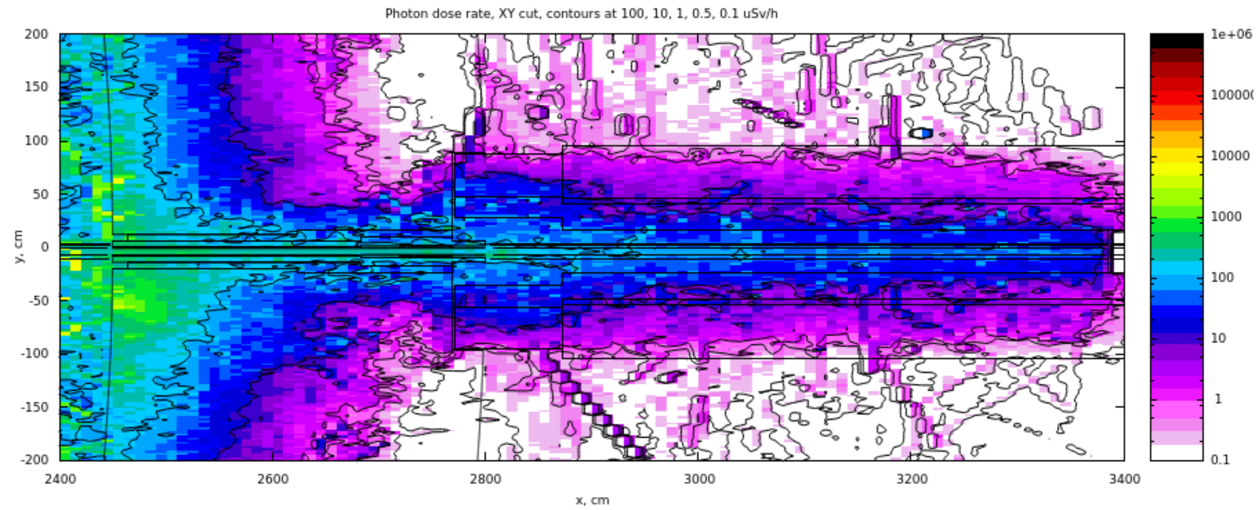
25 cm steel + 5cm Carston concrete (B4C+PE, 1.9g/cm^3) + 50 cm regular concrete in D03; 8mm Al substrates in the light shutter and before the pinhole at 6.35 m

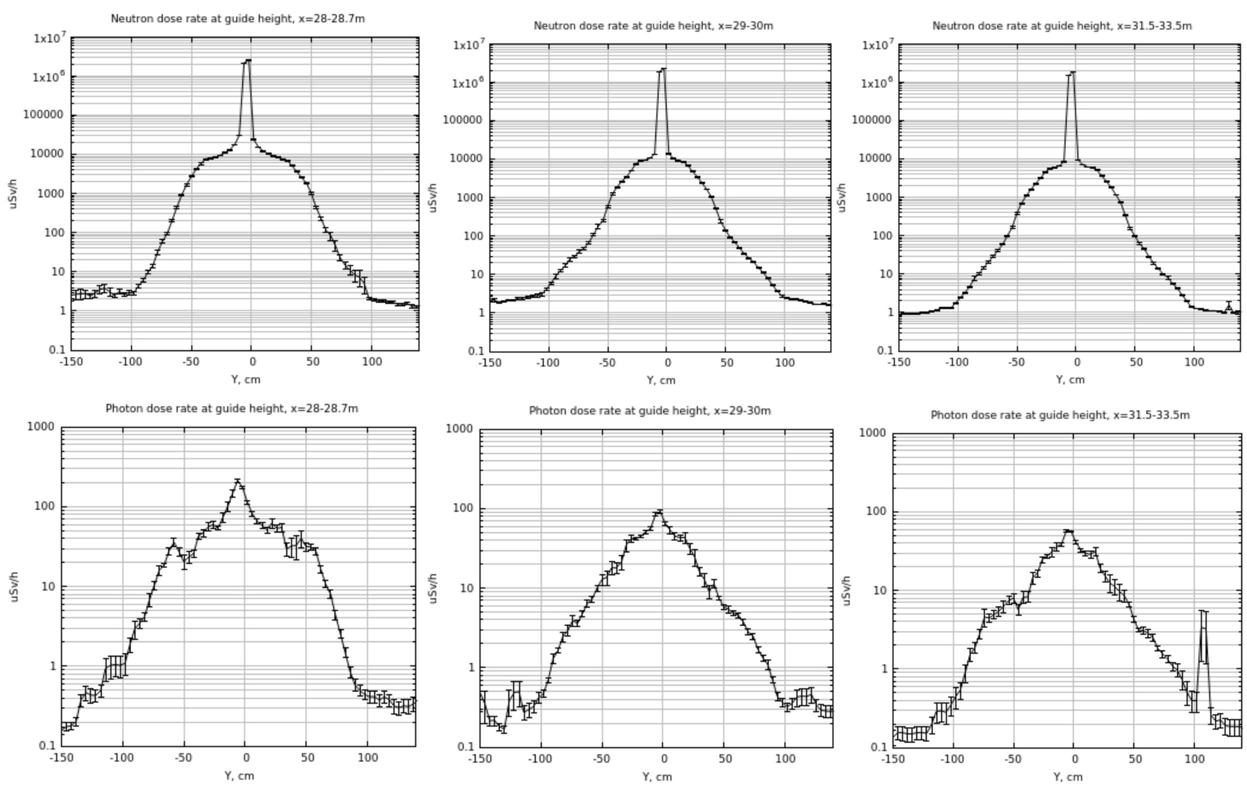
Lateral shielding in D03 beyond the steel/HC interface has been changed and a layer of Carston concrete (CombLayer default material) of 5 cm was added between steel and concrete layers.


28 meters, contours for 100, 10 and 1 uSv/h
28.5 meters, contours for 100, 10 and 1 uSv/h
29 meters, contours for 100, 10 and 1 uSv/h
z, cm
y, cm
uSv/hr


Overal dose rate, XY cut, contours at 100, 10, 1.5, 1 uSv/h
y, cm
x, cm


Neutron dose rate, XY cut, contours at 100, 10, 1.5, 1 uSv/h
y, cm
x, cm





With 5 cm layer of borated concrete beyond steel the photon dose rate becomes insignificant compared to the neutron dose rate beyond 29m. The dose rate at the surface of the shielding is around 1.5 uSv/hr.

Increasing total concrete thickness to 60 cm (5 cm borated +55 regular) can seemingly reduce the total dose to 1 uSv/hr.

The week point at the connection of HC and NC shielding is still there due to transition of sub-MeV neutrons to the regular concrete layer beyond the borated layer. The problem can be solved either introducing borated layer also between steel and heavy concrete or by casting the first block at the position where narrow inner shielding starts from heavy concrete.

Connection between the bunker wall and the lateral shielding is problematic. In present setup with no collimators and Al substrates in the bunker (including light shutter) a beam impact at the bunker wall produces a sizeable contribution to the dose at +/- 100 cm from the beam position. The contribution may be itself of the order of 1 uSv/hr.

Results of previous simulations (discussed at the Common Shielding Project meeting in August 2018, shown below) indicate that it is result of streaming of fast neutrons is mainly through the guide substrates in the light shutter (which is Al). It can be reduced (almost by order of magnitude) by replacing substrates before the pinhole at the Pulse Shaping Chopper position by copper. Increasing thickness of the of the copper substrate might also be explored.

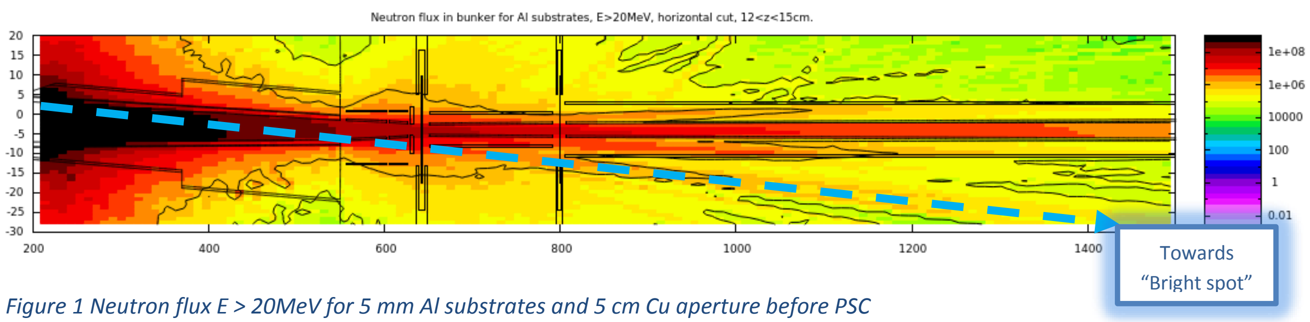


Figure 1 Neutron flux E > 20MeV for 5 mm Al substrates and 5 cm Cu aperture before PSC

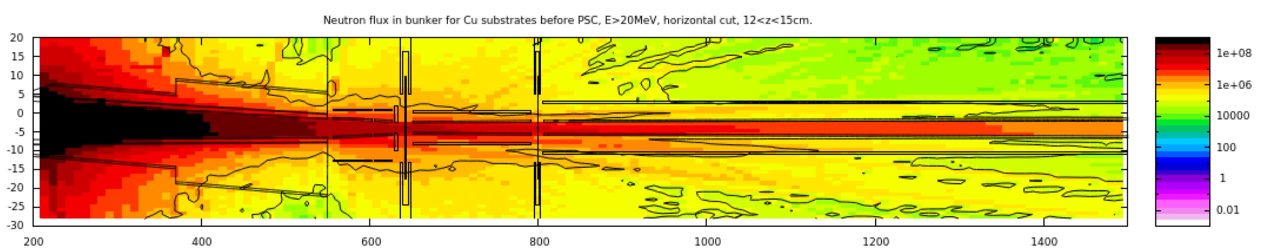
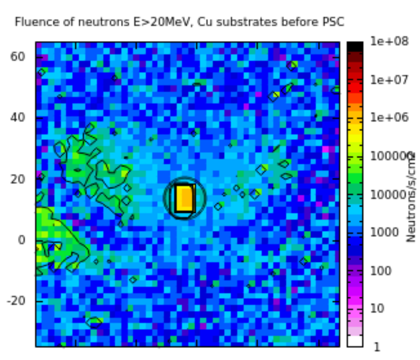
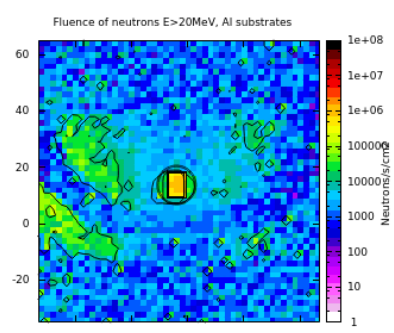


Figure 2 Neutron flux E>20MeV for 5mm Cu substrates and 5 cm Cu apperture before PSC.



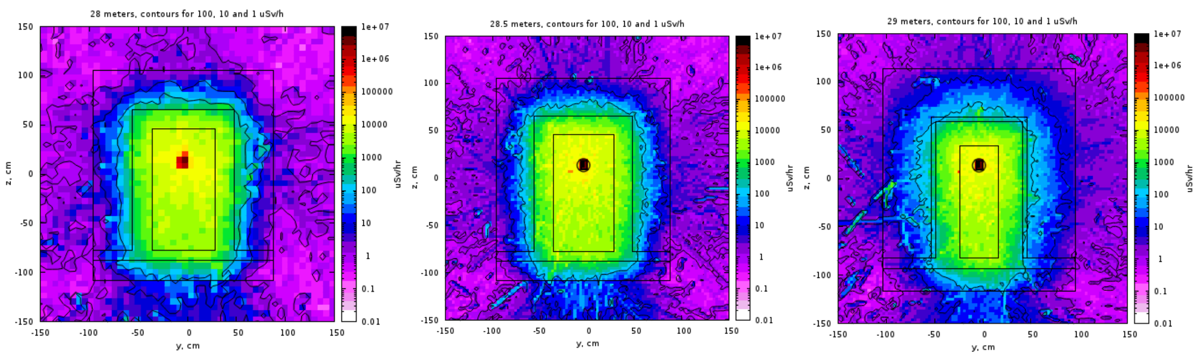
4Neutron fluxes E>20MeV at the bunker wall, Cu substrate before PSC



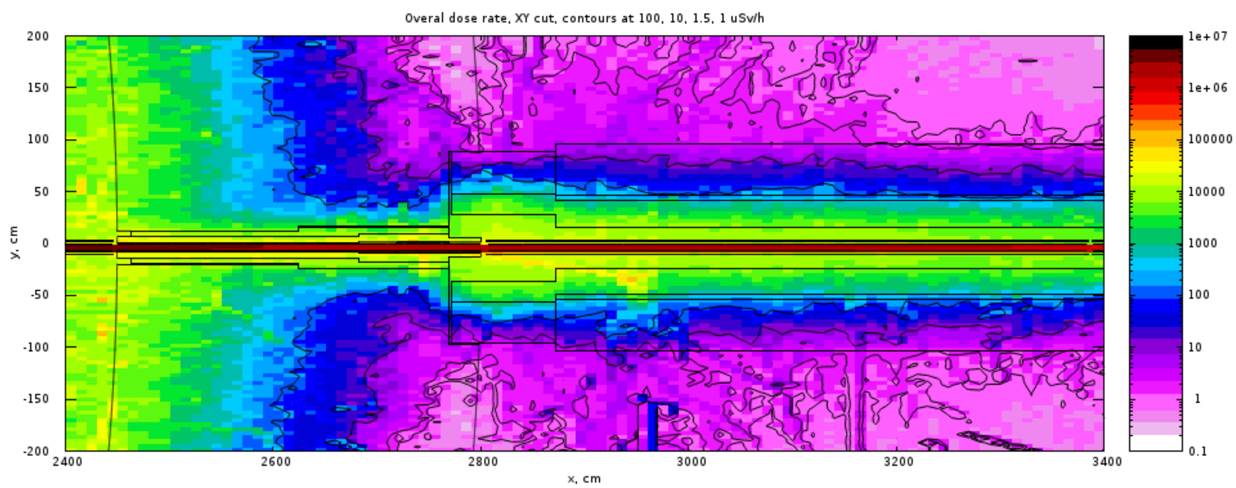
3Neutron fluxes E>20MeV at the bunker wall, Al substrate before PSC

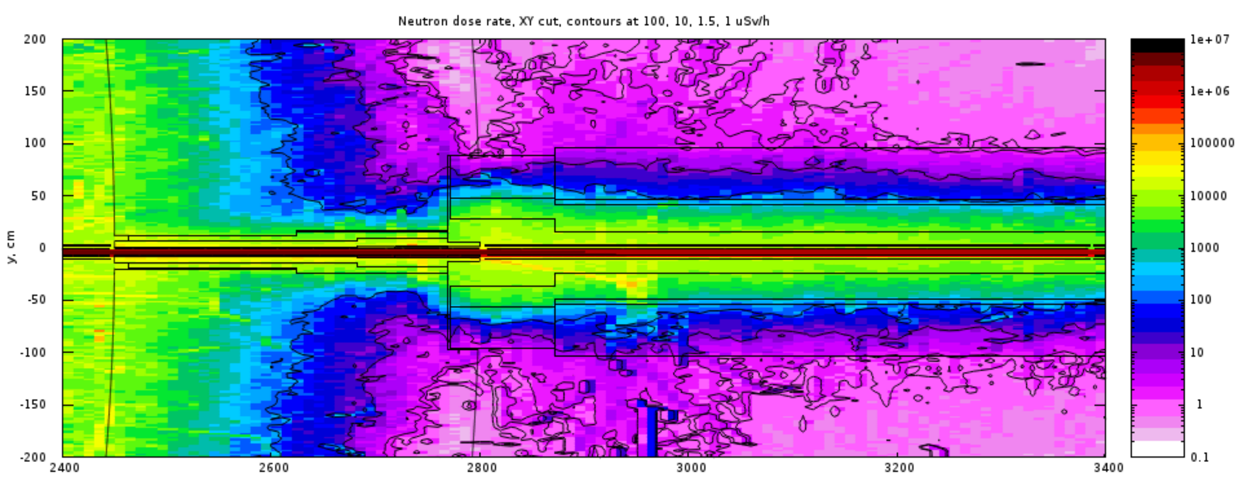
25 cm steel + 5cm Carston concrete (B4C+PE, 1.9g/cm^3) + 50 cm regular concrete in D03 + 12 mm Cu substrate in light shutter and before pinhole at 6.35 m.

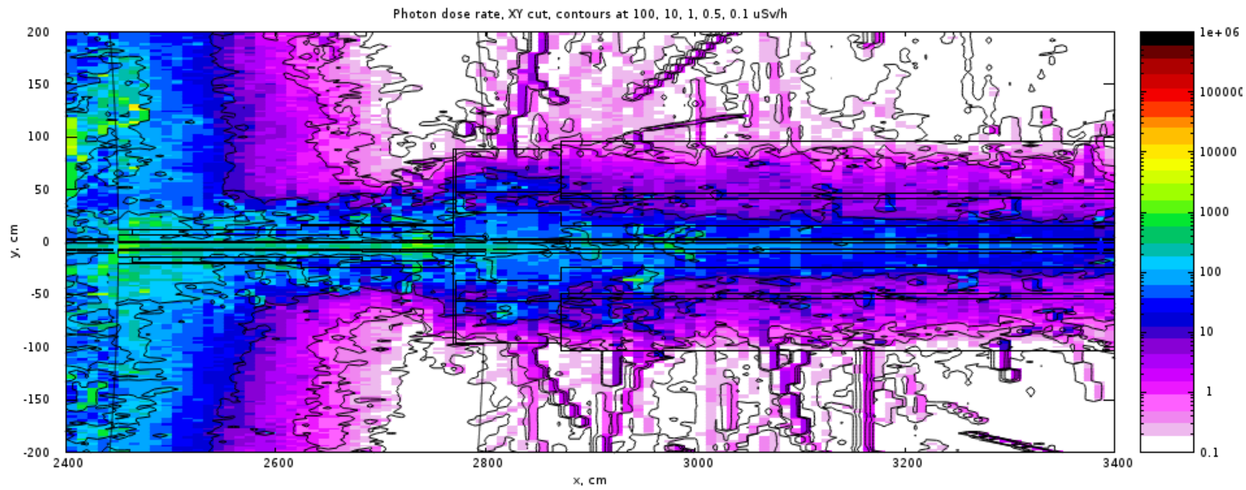
Vertical cut of the dose rate map at 28, 28.5 and 29 meters.

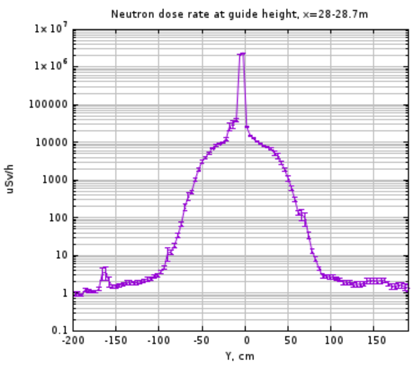


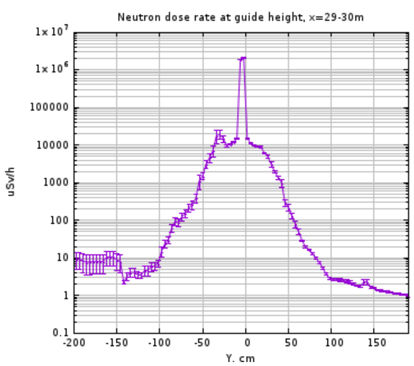
Horizontal cut of the dose rate map in the bunker wall. Overall, neutrons and photons.

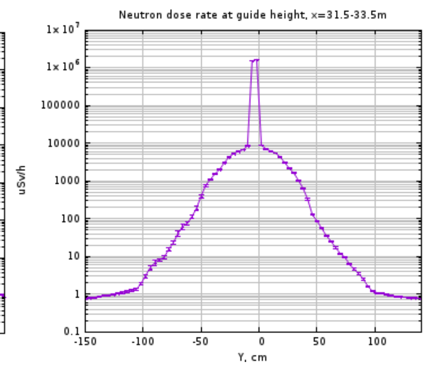


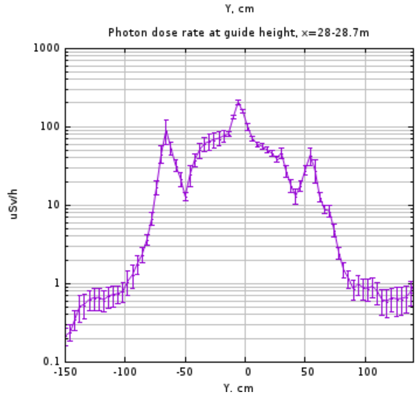


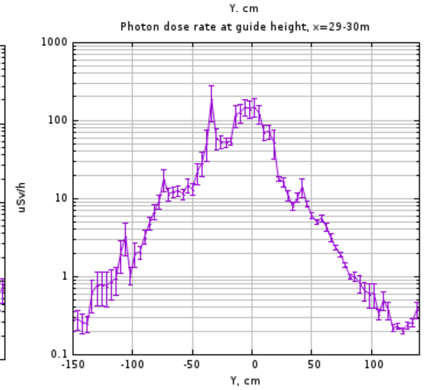


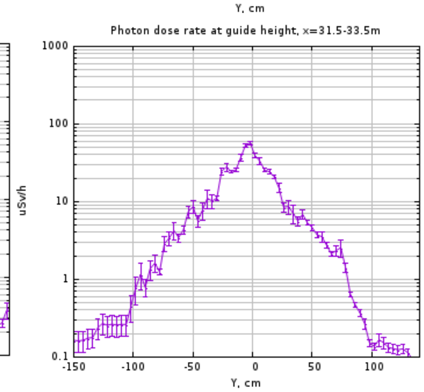












A significant reduction of both neutron and photon dose rate at the surface of the bunker wall is observed compared to previous option. The heavy concrete next to the bunker wall however is still leaking, and a lot of photons is generated in it resulting in 1uSv/hr contribution to the dose next to the bunker wall only from gamma radiation. The next option to explore will be adding borated-polyethylene layer between steel and heavy concrete next to the bunker wall and replacing Carston concrete with borated polyethylene downstream.