NSLS II TECHNICAL NOTE BROOKHAVEN NATIONAL LABORATORY	NUMBER **224**
AUTHORS: M. Benmerrouche	DATE 8/3/2016
11-BM CMS Beamline Radiation Shielding Analysis	

1. Introduction

Beamlines are required to shield against two primary sources of radiation, the primary gas bremsstrahlung (GB) and the synchrotron beam, as well as the secondary radiation resulting from the scattering of these two primary beams by the beamline components and/or air. The shielding requirements for the First Optical Enclosure (FOE) are dominated by the scattering of the primary bremsstrahlung and not the synchrotron beam. Guidelines for the NSLS-II Beamline Radiation Shielding Design are also provided in reference 1**.** These guidelines were used to determine the thickness of the FOE walls as well as dimensions of the supplementary shielding required to reduce the dose on the downstream FOE wall. The shielding recommended for the lateral and roof panels is generally sufficient for most white beam component configurations. However, the recommended as-built shielding for the downstream FOE wall may not be sufficient to protect against secondary gas bremsstrahlung (SGB).

The NSLS-II BEAMLINE RADIATION SHIELDING POLICY has been stated as follows in reference 1: Radiation exposure to staff and users resulting from National Synchrotron Light Source II (NSLS-II) operations must comply with Brookhaven National Laboratory (BNL) and Department of Energy (DOE) radiation requirements and must be maintained as low as reasonably achievable (ALARA). Per the Photon Science Shielding Policy (PS-C-ASD-POL-005), in continuously occupied areas during normal operation the dose rate is ALARA, and shall be < 0.5 mrem/h (based on occupancy of 2000 hours/year) or less than 1 rem in a year. For a fault event, the dose shall be < 20 mrem in a non-radiation controlled area and < 100 mrem in a radiation controlled area. Although the experimental floor is initially designated as a radiation controlled area, it is hoped that in the future, it can be declared a non-radiation controlled area. As such, beamlines should be shielded such that in the event of a fault, the total dose, integrated over the duration of the fault, is < 20 mrem.

The radiation shielding analysis for the Complex Materials Scattering (CMS) beamline (11BM-CMS) is documented in this technical note. The goal of the simulations described here was to estimate the radiation dose levels generated inside and outside the FOE during normal operations and some fault conditions, thus evaluating the efficiency of the as-designed SGB shielding.

The layout of the 11BM-CMS beamlines is presented in figure 1. These drawings were extracted from the Beamline Ray Trace Layout [PD-CMS-RAYT-0001]. The beam travels from right to left in the Ray Trace drawings.

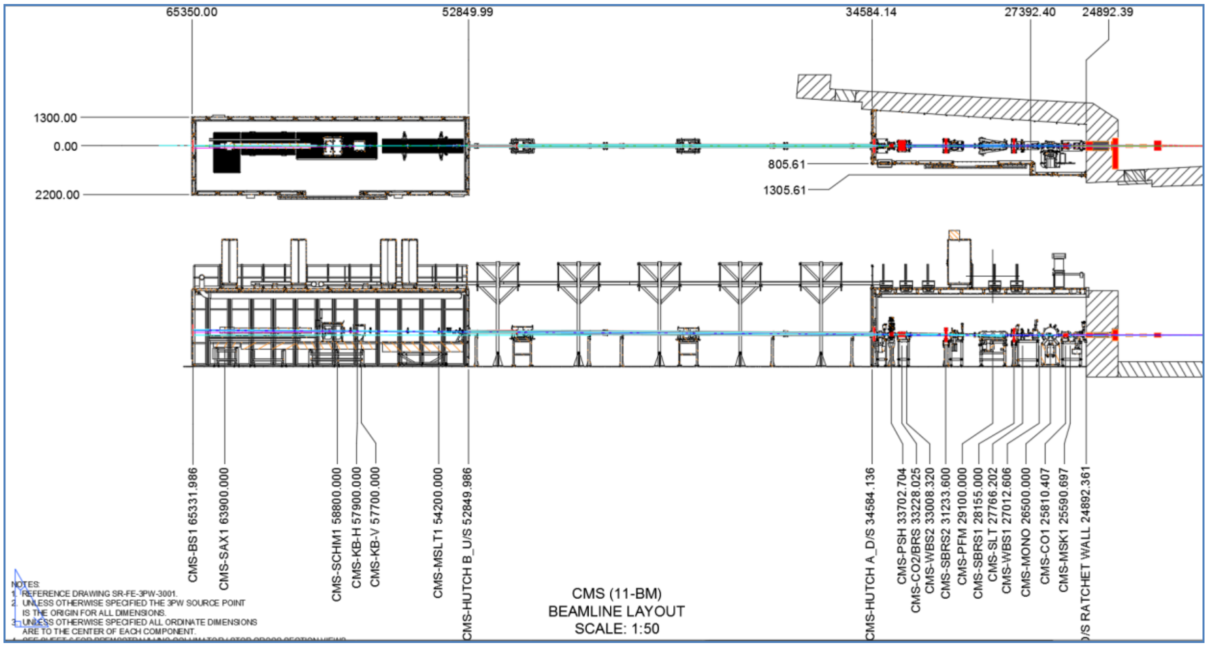

Figure 1: Layout of 11BM-CMS showing the major beamline components, the FOE (11-BM-A) and End Station Enclosure (11-BM-B)

The NSLS-II primary gas bremsstrahlung (GB) source parameters are listed in Table 1.

Table 1. NSLS-II primary bremsstrahlung source parameters

Electron energy	3 GeV
Stored current	500 mA
Length of short straight section	6.6 m
Pressure in straight section	1 ntorr

The beam is normalized at 7.2μW incident power, for the short (6.6m) straight. This value corresponds to the estimated bremsstrahlung power generated by a 500mA electron beam of 3GeV, assuming that the vacuum in the straight sections is better than 10^{-9}Torr. The bremsstrahlung source file is kept in the NSLS-II Radiation Physics folder.

The FLUKA model is described in section 2. The positions, dimensions and materials of the main components are included in Appendix 1. A prototype FLUKA input and output files are kept in the NSLS-II Radiation Physics folder.

The simulations performed to confirm the adequacy of the radiation safety components are presented in Table 2. The position of the GB source is given with respect to the short straight centerline. The results of the GB simulations are presented in section 3.

Table 2. List of FLUKA simulations

#	Simulation	Position of GB source
1(a)	GB incident near the neck of the fixed mask (FM) on the outboard tapered side	x=2.185, y=0.0, z=66.702
1(b)	GB incident near the neck of the FM on the top tapered side	x=0.0, y=0.33, z=66.702
1(c)	GB incident on the front face of the FM near the	x=3.677, y=0.0, z=66.702

	outboard edge	
1(d)	GB incident on the front face of the FM near the top edge	x=0.0, y=1.497, z=66.702
2(a)	GB incident near the center of crystal 1 of Double Multilayer Monochromator (DMM)	x=0.0, y=0.0, z=144.738
2(b)	GB incident near the front face of crystal 1 of DMM	x=0.0, y=-0.446, z=144.738
2(c)	GB incident near the front face of crystal 2 of DMM	x=0.0, y=0.454, z=144.738
3(a)	GB incident near the neck of white beam stop 1 (WBS1) on the bottom tapered side	x=2.13, y=0.6, z=208.893
3(b)	GB incident near the neck of the WBS1 on the outboard tapered side	x=0.0, y=0.255, z=208.893
3(c)	GB incident on the front face of WBS1 near the outboard edge	x=2.573, y=-0.483, z=208.893
4(a)	GB incident near the center of the primary focusing mirror (PFM)	x=0.0, y=0.6, z=369.738
4(b)	GB incident near the downstream edge of PFM	x=0.0, y=0.622, z=369.738
4(c)	GB incident near the upstream edge of PFM	x=0.0, y=-0.588, z=369.738
5(a)	GB horizontal extreme ray incident on WBS2	x=3.861, y=0.853, z=808.438
5(b)	GB vertical extreme ray incident on WBS2	x=0.0, y=0.853, z=808.438

The results of the synchrotron radiation simulations are presented in section 4.

A summary of all simulation results is presented in Section 5. The results of the GB simulations are summarized in table 5. This table lists the maximum dose rate (in mrem/h) on the roof, sidewall and the downstream wall of the FOE for each simulation.

All shielding simulations should be validated by comparisons with measurements of the dose rates near the walls and roof of the FOE, the end station enclosure (ESE) and the beam transport pipe during commissioning.

2. Description of the FLUKA model

At NSLS-II the First Optical Enclosure (FOE) shielding requirements are dominated by the scattering of the primary gas bremsstrahlung and not the synchrotron beam.
The white beam components disperse the primary bremsstrahlung without significant energy loss; thereby greatly increasing the angular range of very high-energy bremsstrahlung photons. It is necessary to intercept this secondary bremsstrahlung before it hits the downstream FOE wall. The design of the 11BM-CMS beamline includes additional shielding in order to reduce the dose on the downstream wall.

As recommended by reference 1 Appendix A we use the “custom GB generator based on an analytic representation of the source’s energy spectrum which was scaled in intensity in accordance with the experimental estimates of total GB power. This custom source assumes a 1/E energy spectrum dependency, with a maximum energy of 3GeV, and generates internally the corresponding probability density function from analytical descriptions”. The beam is normalized at 7.2μW incident power, for the short straight (6.6m). This value corresponds to the estimated bremsstrahlung power generated by a 500mA electron beam of 3GeV, assuming that the vacuum in the straight sections is better than 10^{-9}Torr.

The 11BM-CMS FLUKA model includes the FOE roof, sidewall, the downstream wall as well as the ratchet wall and long wall of the storage ring (SR). The FOE outboard lateral panel is made of 18 mm Pb (80.56 cm from short straight centerline and becomes 131 cm for the bump-out wall), roof 4 mm Pb (210 cm above short straight centerline) and downstream FOE wall 50 mm Pb (~969 cm from the ratchet wall).

The FLUKA model (vertical view) of the 11BM-CMS beamline is shown in figure 2. All components are placed symmetrically with respect to the beam centerline in the transverse direction. For the FLUKA models the Z axis represents the beam centerline, the X axis the horizontal axis normal to the beam direction and the Y axis is the vertical axis. For the Ray Trace drawings the zero of the co-ordinate system is the center of the long straight. However, for the FLUKA input files the downstream end of the ratchet wall is set as the zero of the Z axis. The beam travels from right to left in the Ray Trace drawings. For the FLUKA model the beam travels from left to right.

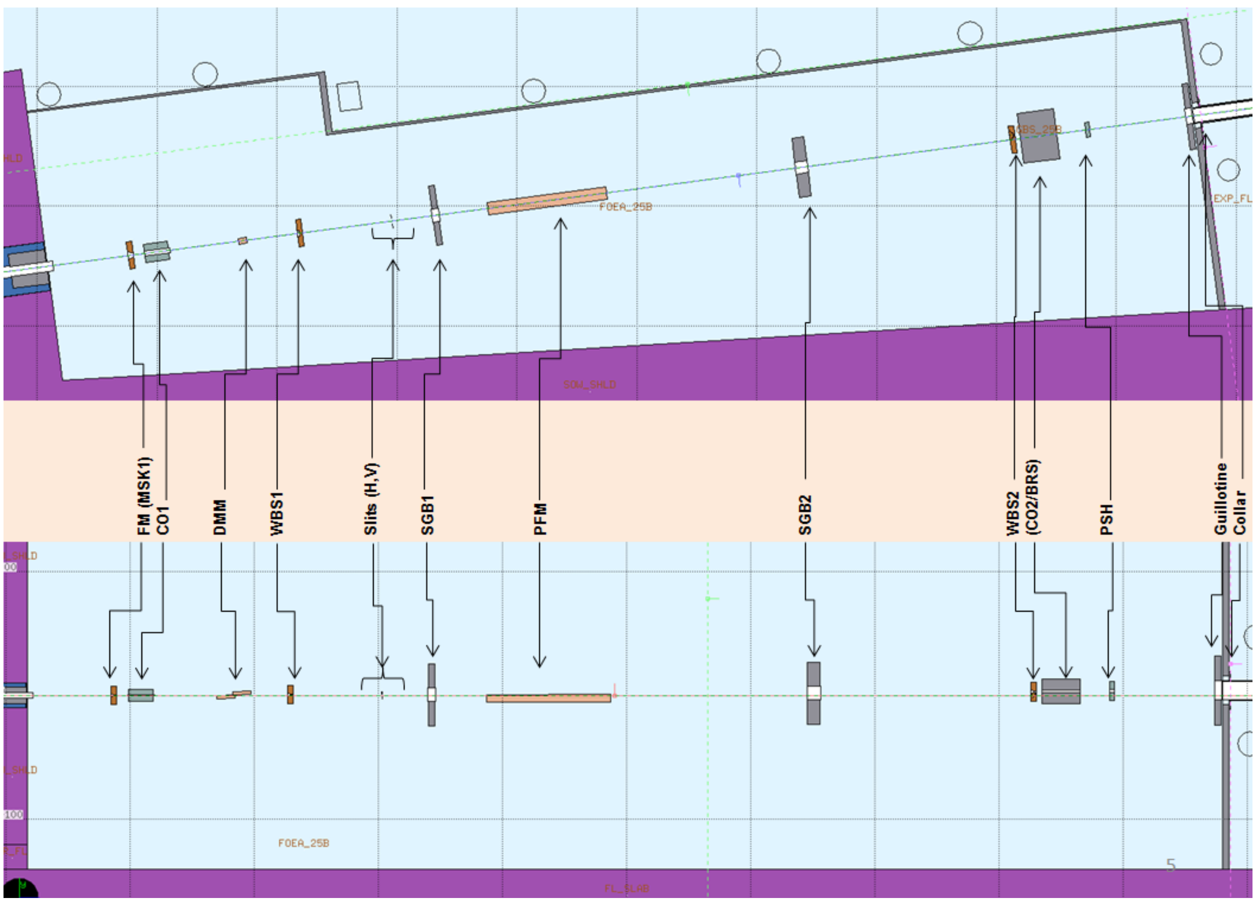

Figure 2: Plan view (y=0) and elevation view of the 11BM-CMS FLUKA geometry

The positions, dimensions, materials and drawings of the main components are included in Appendix 1. The bremsstrahlung source file is attached as Appendix 2. A sample FLUKA input

3. Results for primary gas Bremsstrahlung (GB) simulations

The simulations performed to confirm the adequacy of the radiation safety components are presented in Table 2. In all of the simulations, the SGB1 and SGB2 shields were included. A summary of the simulation results is presented in Section 5.

3.1(a) GB incident near the neck of the FM on the outboard tapered side

In this simulation the GB was started just upstream of the selected point of contact at x=2.185, y=0.0, z=66.702 and impinges on the outboard tapered plane close to the neck of the downstream aperture of FM. The width and height of the downstream aperture is 41.7 mm × 4.6 mm. The total dose distributions (mrem/h) in the FOE are shown in Figure 3 and the corresponding neutron distributions are given in Figure 4.

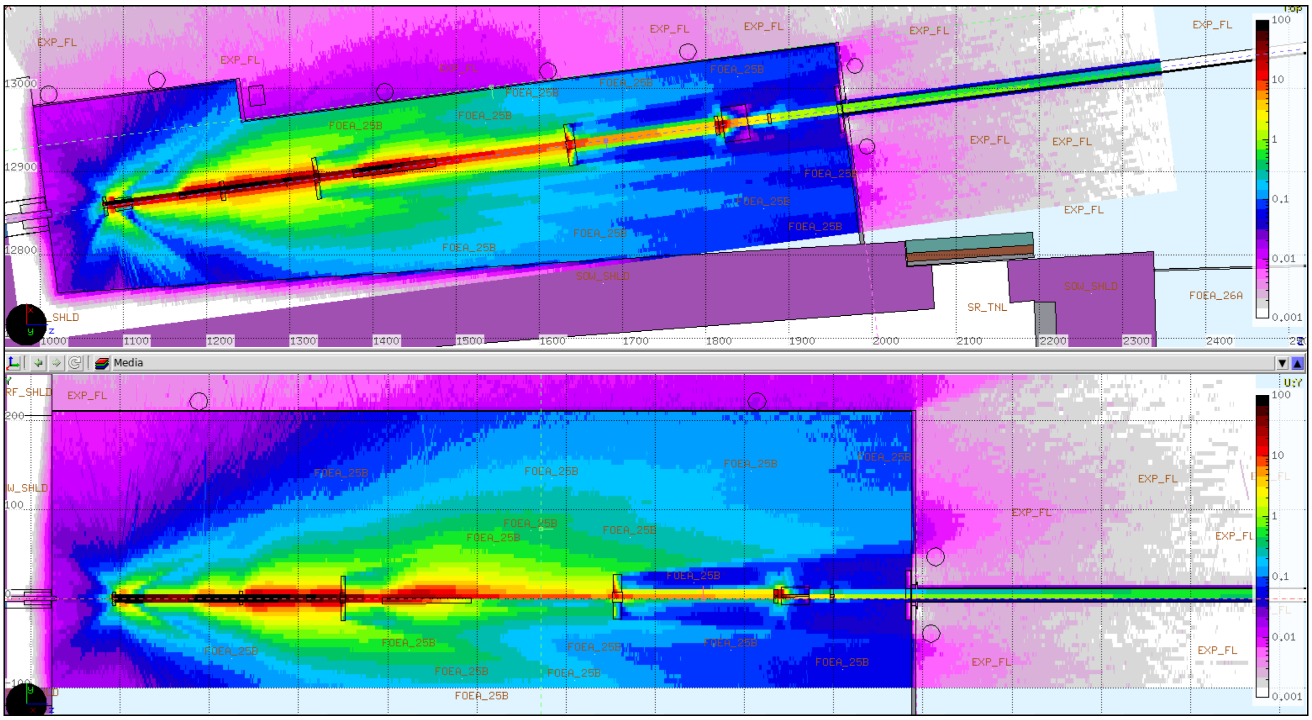

Figure 3: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

The total dose distributions in mrem/h on the lateral wall [Figure 5(a) and (b)], on the roof [Figure 5(c)] and on contact with the downstream wall [Figure 5(d)] of the FOE are below 0.05 mrem/hr. As shown in Figure 3 and 5(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport they decrease to less than 0.01mrem/hr due to the lead shielding around the transport pipe.

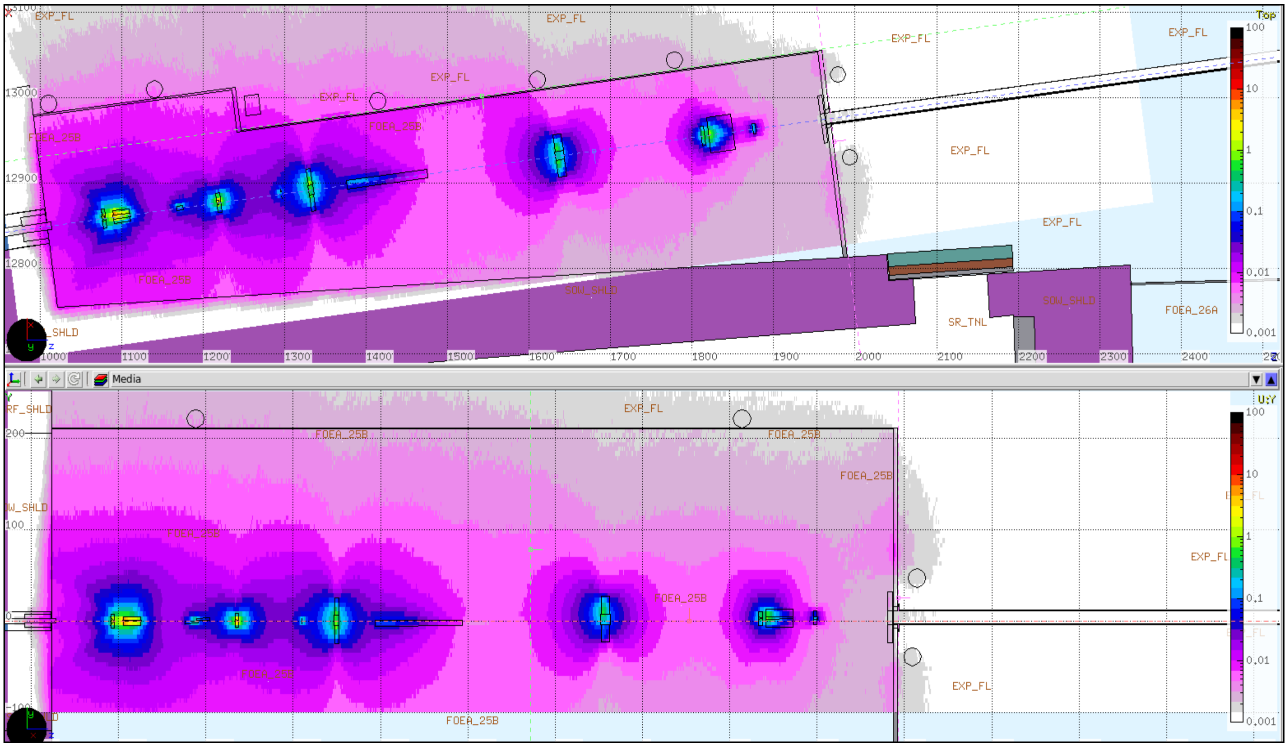

Figure 4: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

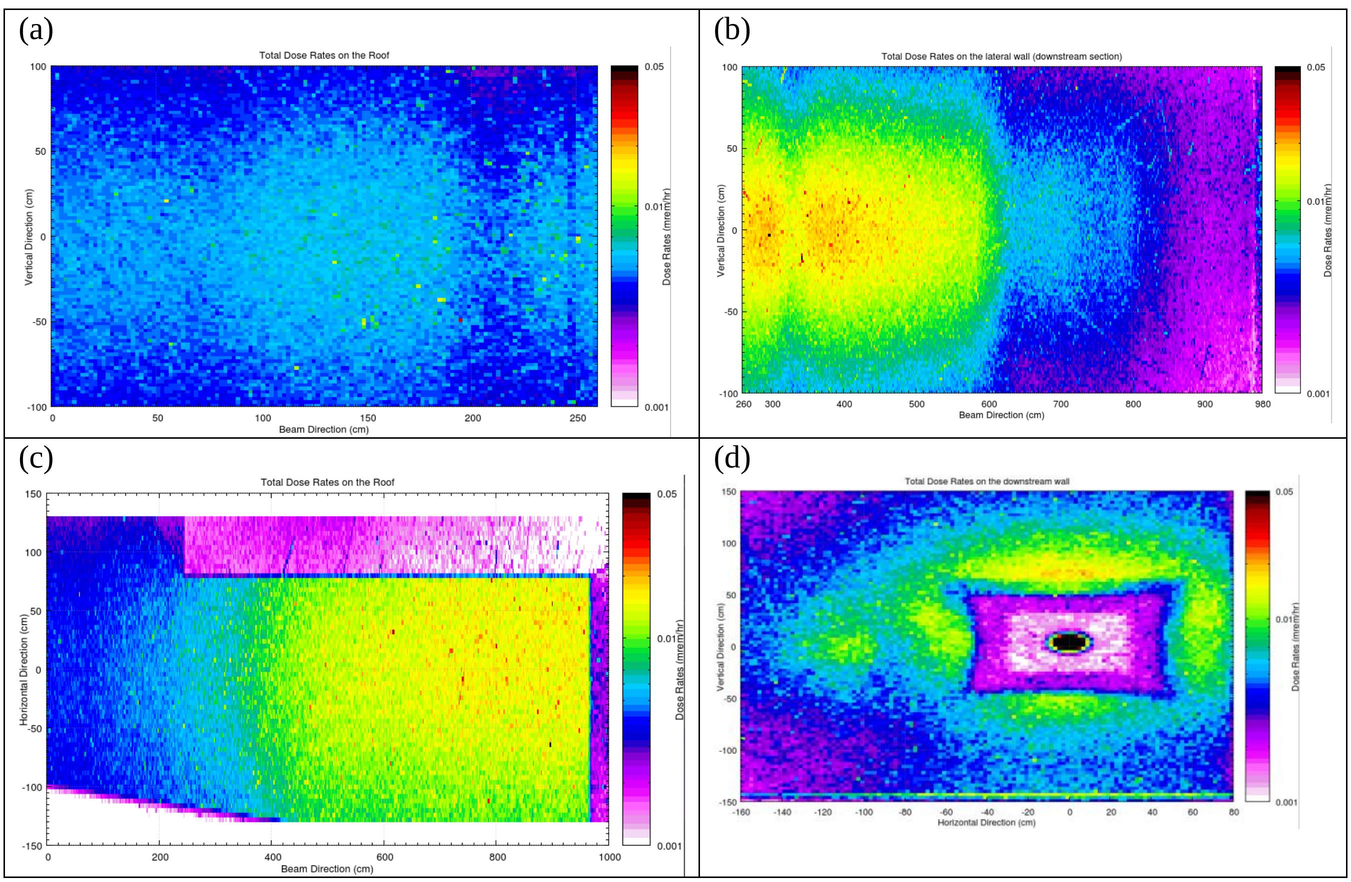

Figure 5: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.1(b) GB incident near the neck of the FM on the top tapered side

In this simulation the GB was started just upstream of the selected point of contact at x=0.0, y=0.33, z=66.702 and impinges on the top tapered plane close to the neck of the downstream aperture of FM. The total dose distributions (mrem/h) in the FOE are shown in Figure 6 and the corresponding neutron distributions are given in Figure 7.

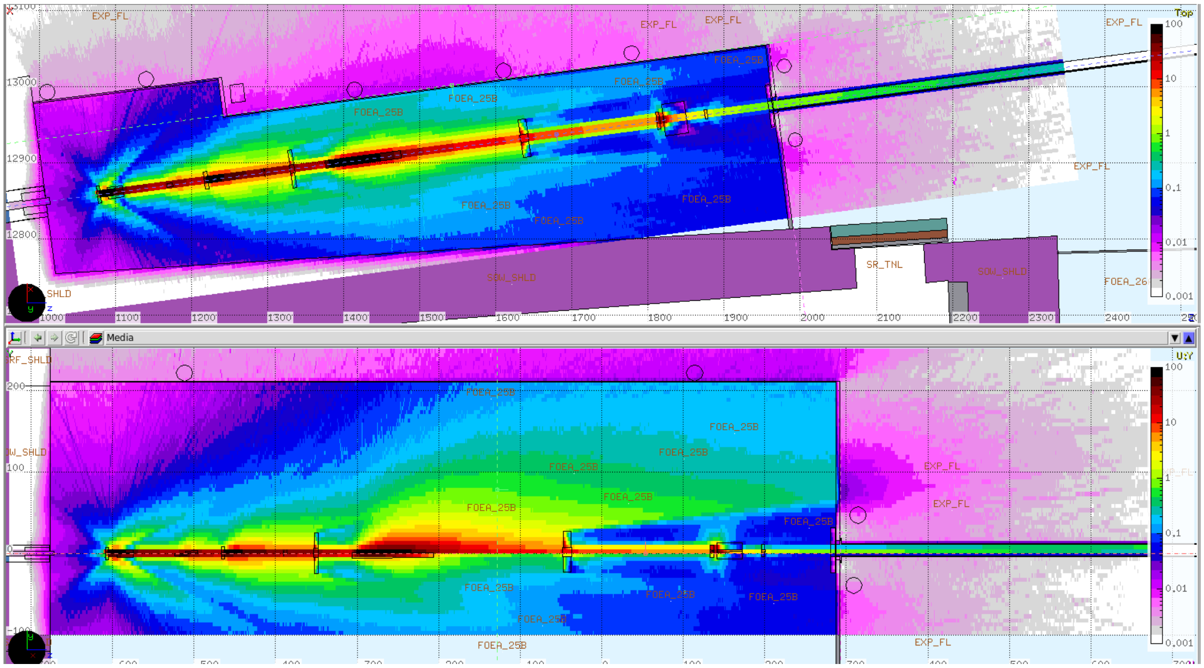

Figure 6: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

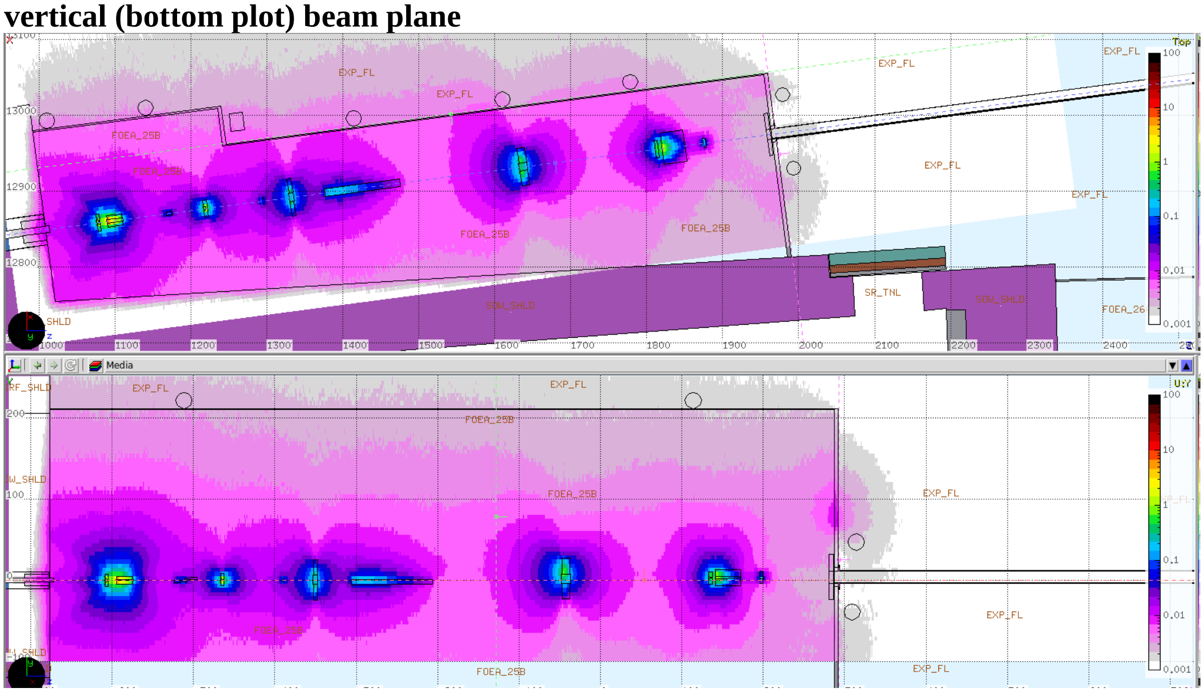

Figure 7: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

The total dose distributions in mrem/h on the lateral wall [Figure 8(a) and (b)], on the roof [Figure 8(c)] and on contact with the downstream wall [Figure 8(d)] of the FOE are below 0.05 mrem/hr. As shown in Figure 6 and 8(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport they decrease to less than 0.01mrem/hr due to the lead shielding around the transport pipe.

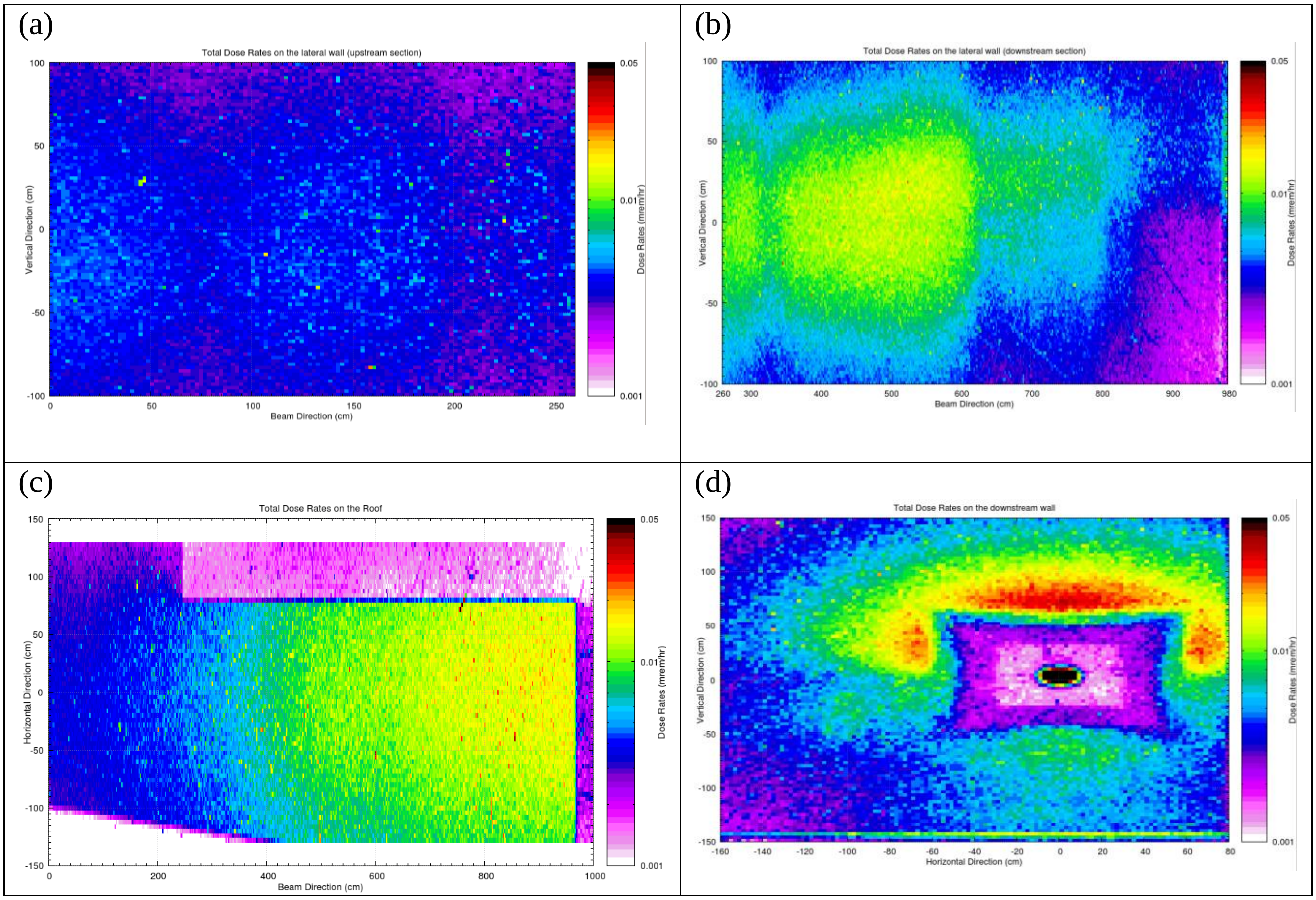

Figure 8: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.1(c) GB incident on the front face of the FM near the outboard edge

In this simulation the GB was started just upstream of the selected point of contact at x=3.677, y=0.0, z=66.702 and impinges on the front face of FM near the outboard edge. The total dose distributions (mrem/h) in the FOE are shown in Figure 9 and the corresponding neutron distributions are given in Figure 10.

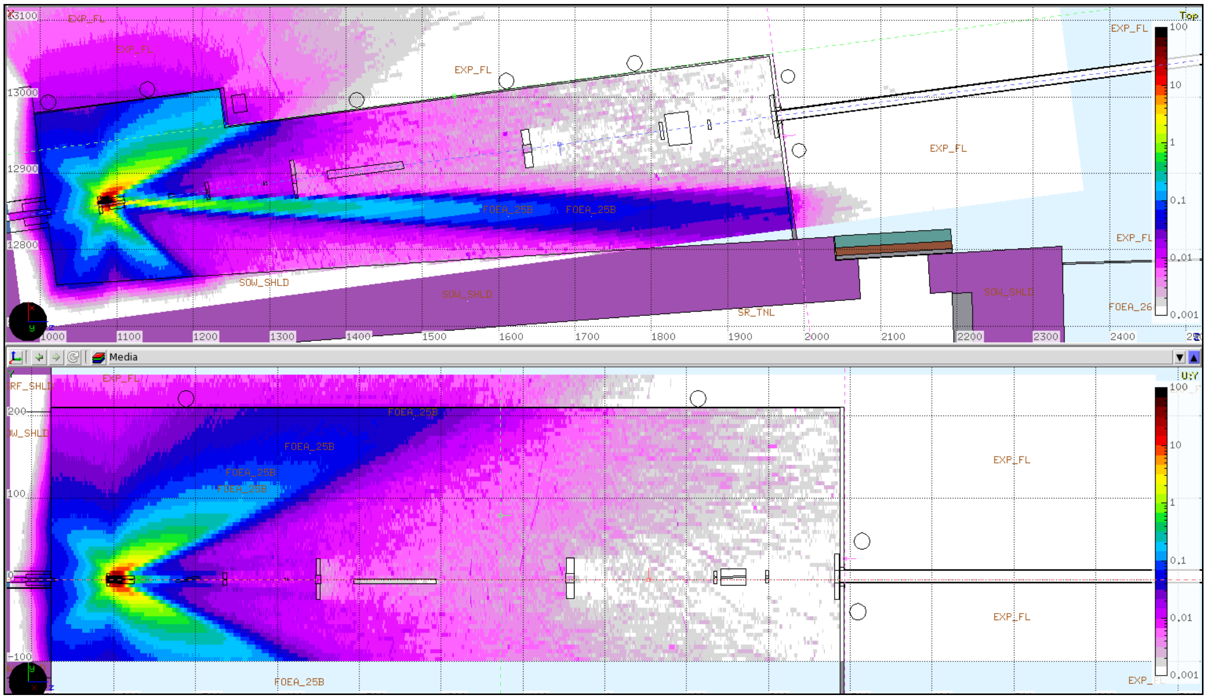

Figure 9: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

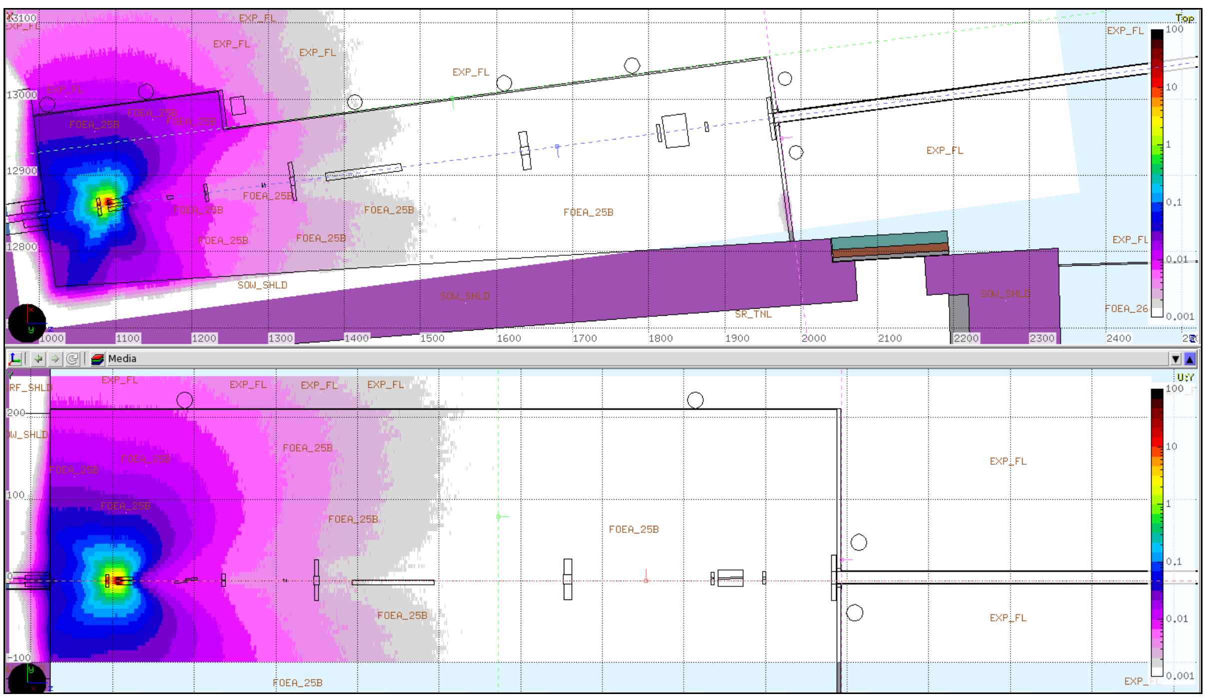

Figure 10: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

The total dose distributions in mrem/h on the lateral wall [Figure 11(a) and (b)], on the roof [Figure 11(c)] and on contact with the downstream wall [Figure 11(d)] of the FOE are below 0.05 mrem/hr. The highest dose rates are found on the upstream side of the lateral wall but remain below 0.05 mrem/hr.

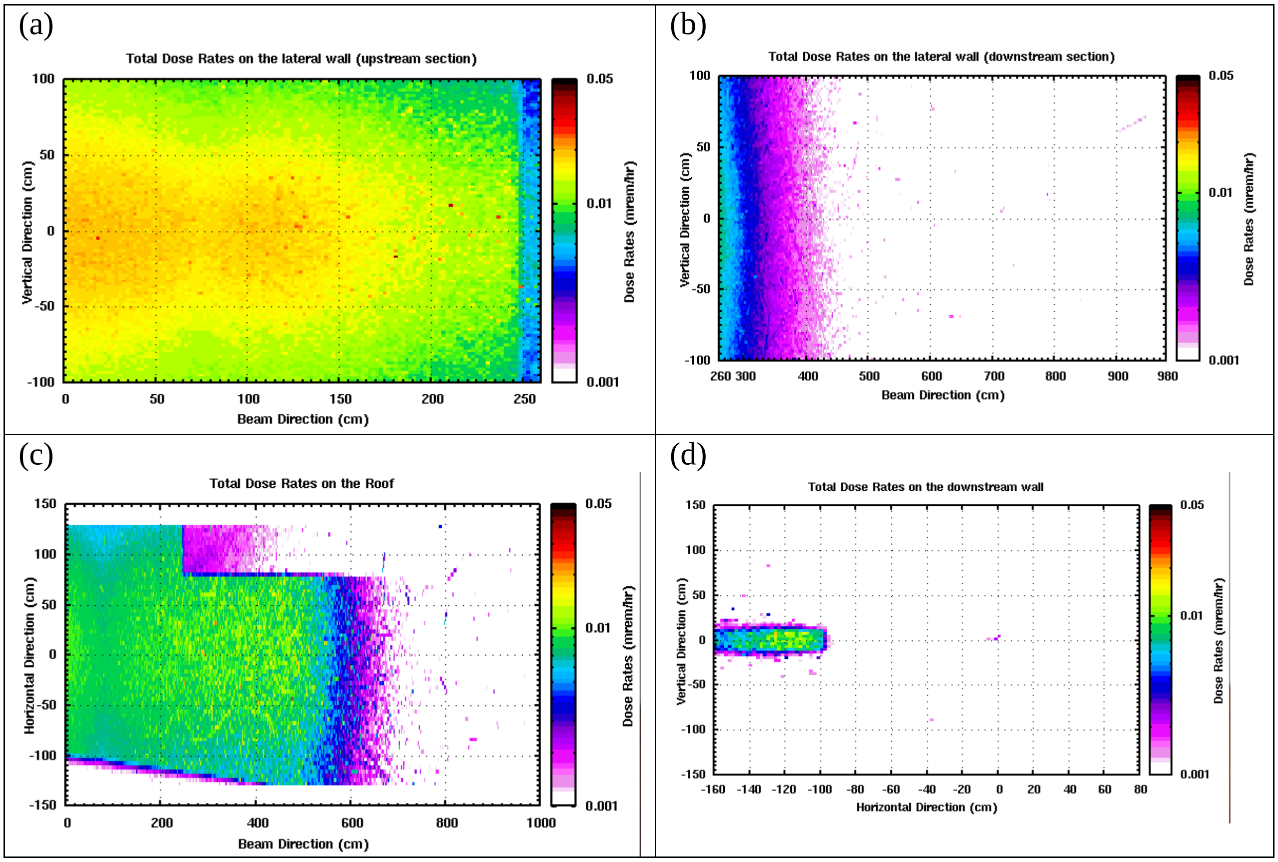

Figure 11: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.1(d) GB incident on the front face of the FM near the top edge

In this simulation the GB was started just upstream of the selected point of contact at x=0.0, y=1.497, z=66.702 and impinges on the front face of FM near the top edge. The total dose distributions (mrem/h) in the FOE are shown in Figure 12 and the corresponding neutron distributions are given in Figure 13.

The total dose distributions in mrem/h on the lateral wall [Figure 13(a) and (b)], on the roof [Figure 13(c)] and on contact with the downstream wall [Figure 13(d)] of the FOE are below 0.05 mrem/hr. The highest dose rates are found on the upstream side of the lateral wall and then roof but remain below 0.05 mrem/hr. Dose rates on the downstream wall and inside/outside the transport pipe are background levels.

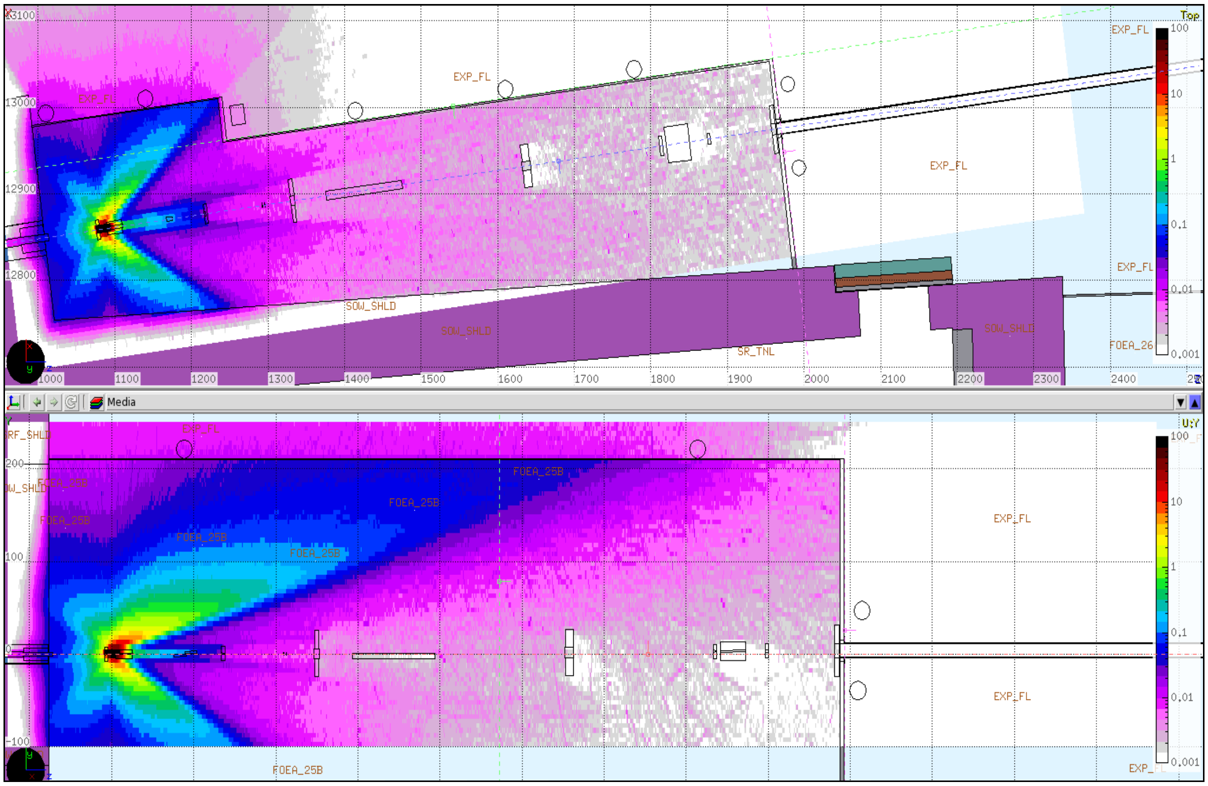

Figure 12: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

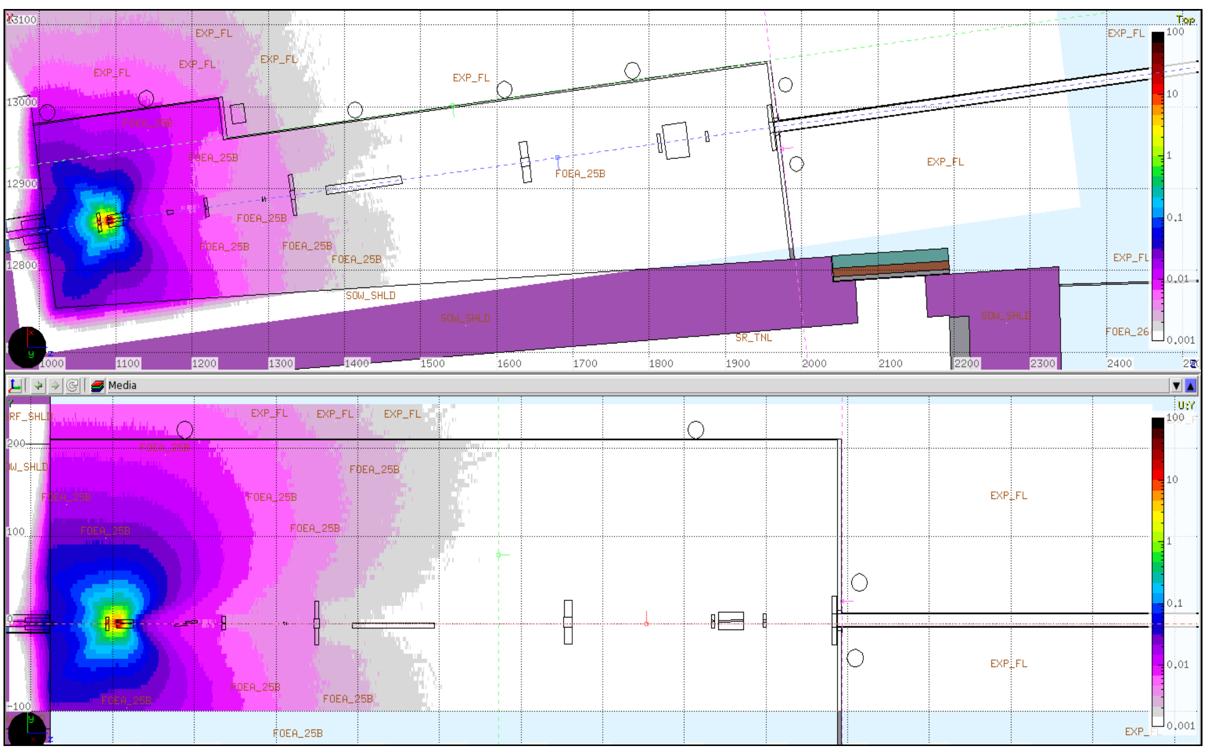

Figure 13: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

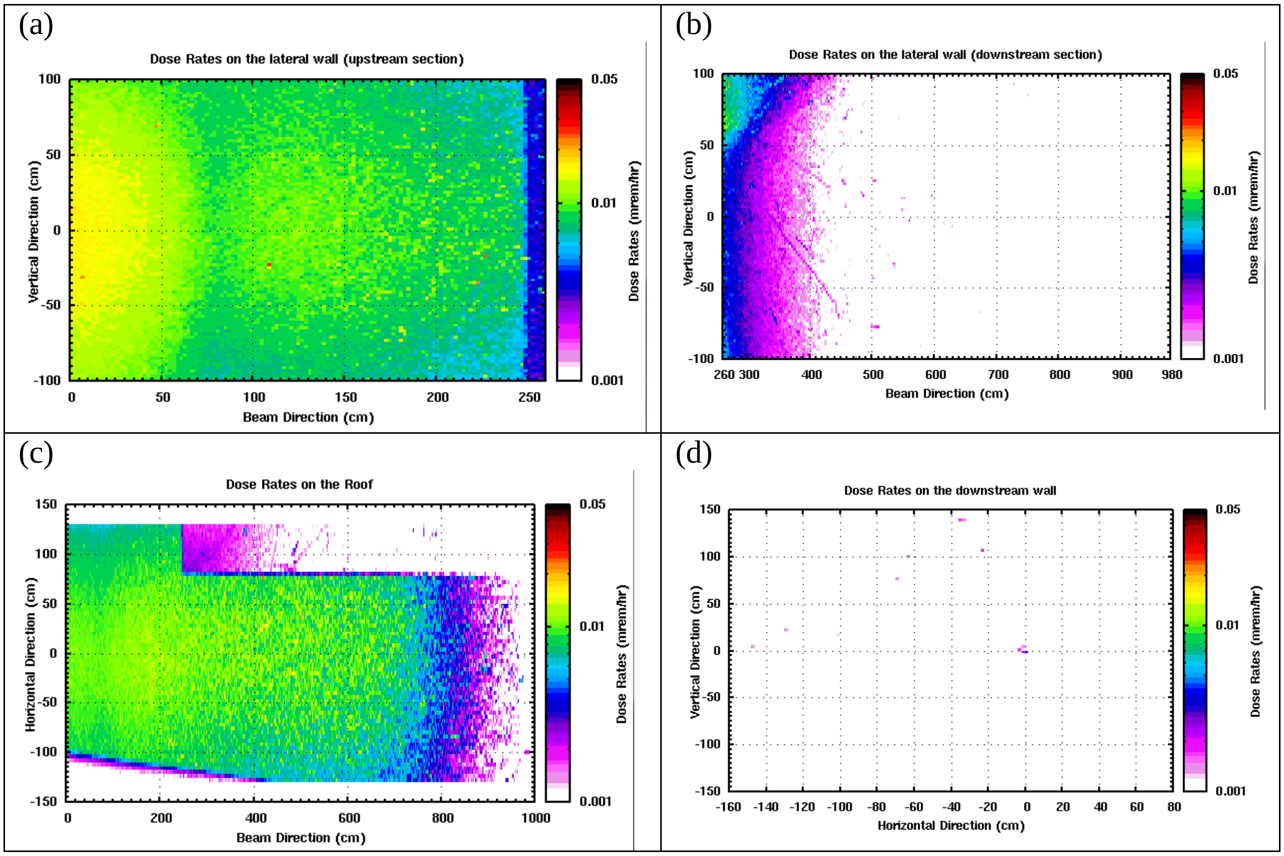

Figure 14: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.2(a) GB incident near the center of the first crystal of DMM

In this simulation the GB was started just upstream of the selected point of contact at x=0.0, y=0.0, z=144.738 and impinges near the center of the first crystal of the DMM. Both crystals of the DMM were assumed to be in their nominal orientation of 31.4 mrad. The separation between the 2 crystals is 3 mm.

The total dose distributions (mrem/h) in the FOE are shown in Figure 15 and the corresponding neutron distributions are given in Figure 16. The total dose distributions in mrem/h on the lateral wall [Figure 17(a) and (b)], on the roof [Figure 17(c)] and on contact with the downstream wall [Figure 17(d)] of the FOE are below 0.05 mrem/hr.

The highest dose rates are found on the downstream wall of the FOE but remain below 0.05 mrem/hr. As shown in Figure 15 and 17(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport they decrease to less than 0.01mrem/hr due to the lead shielding around the transport pipe.

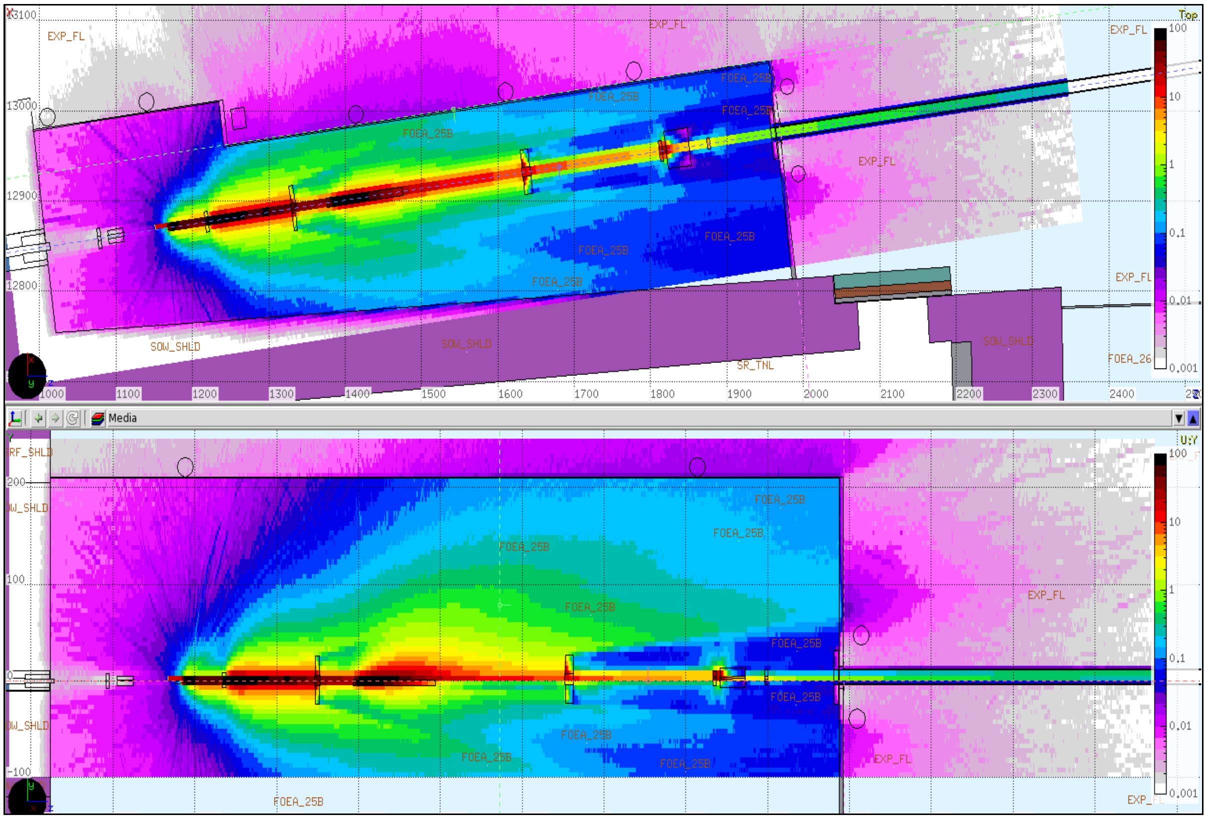

Figure 15: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

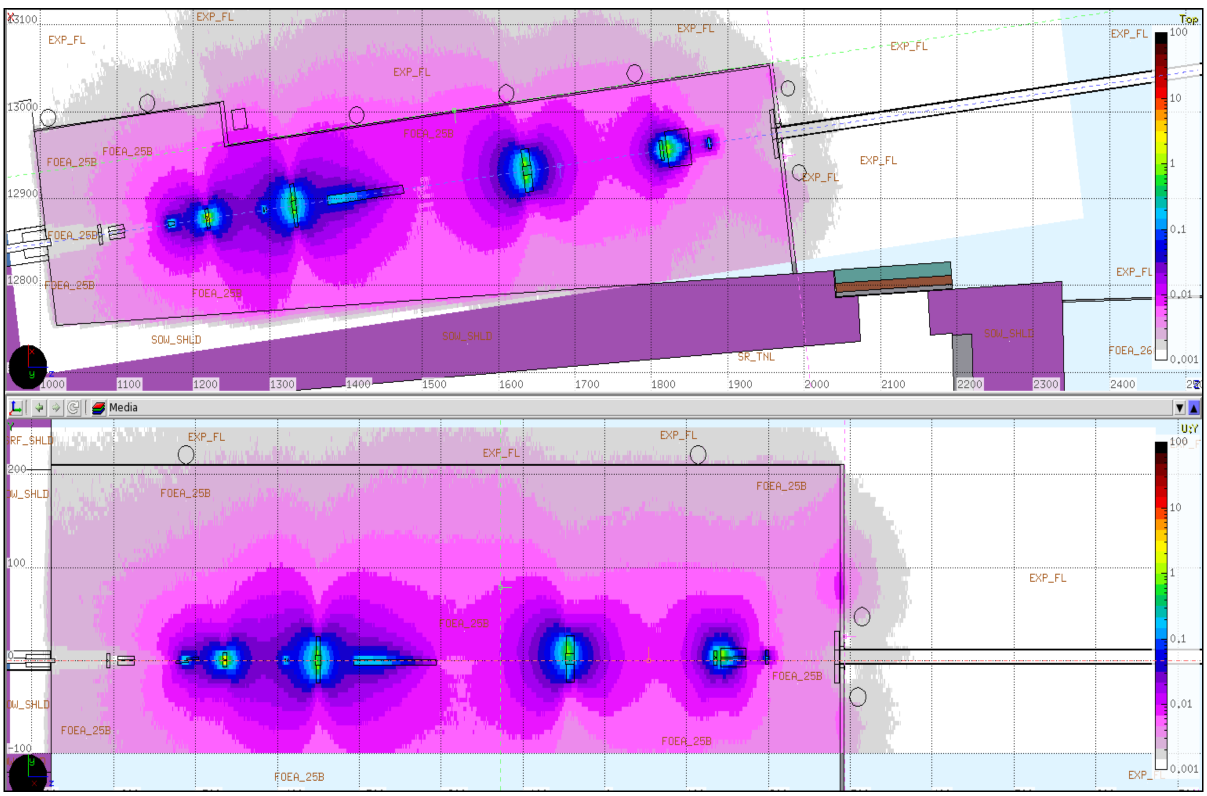

Figure 16: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

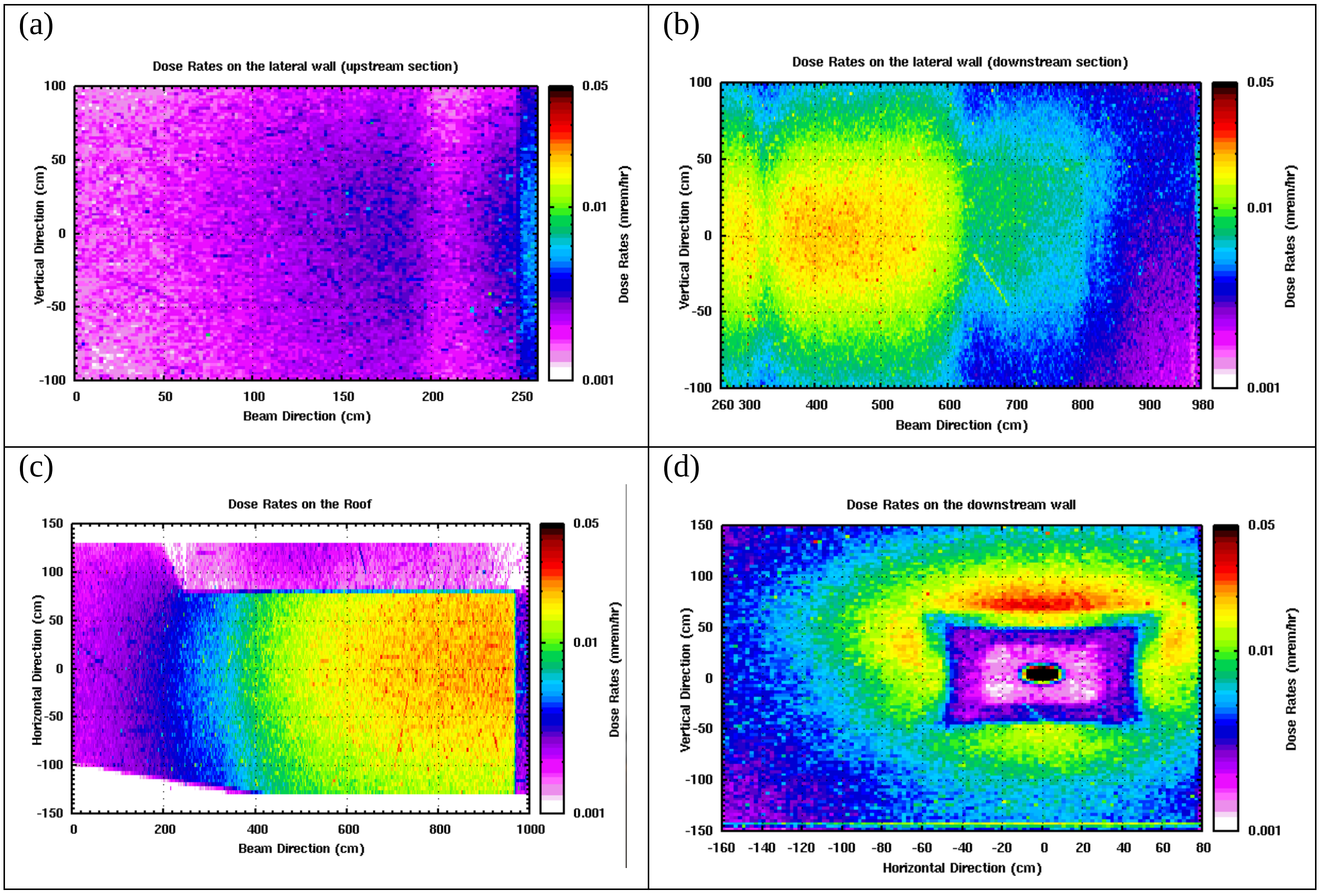

Figure 17: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.2(b) incident near the front face of the first crystal of DMM

In this simulation the GB was started just upstream of the selected point of contact at x=0.0, y=-0.446, z=144.738 and impinges near the front face of the first crystal.

The total dose distributions (mrem/h) in the FOE are shown in Figure 18 and the corresponding neutron distributions are given in Figure 19. The total dose distributions in mrem/h on the lateral wall [Figure 20(a) and (b)], on the roof [Figure 20(c)] and on contact with the downstream wall [Figure 20(d)] of the FOE are below 0.05 mrem/hr.

The highest dose rates are found on the downstream side of the lateral wall of the FOE but remain below 0.05 mrem/hr. As shown in Figure 18 and 20(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport they decrease to less than 0.01mrem/hr due to the lead shielding around the transport pipe.

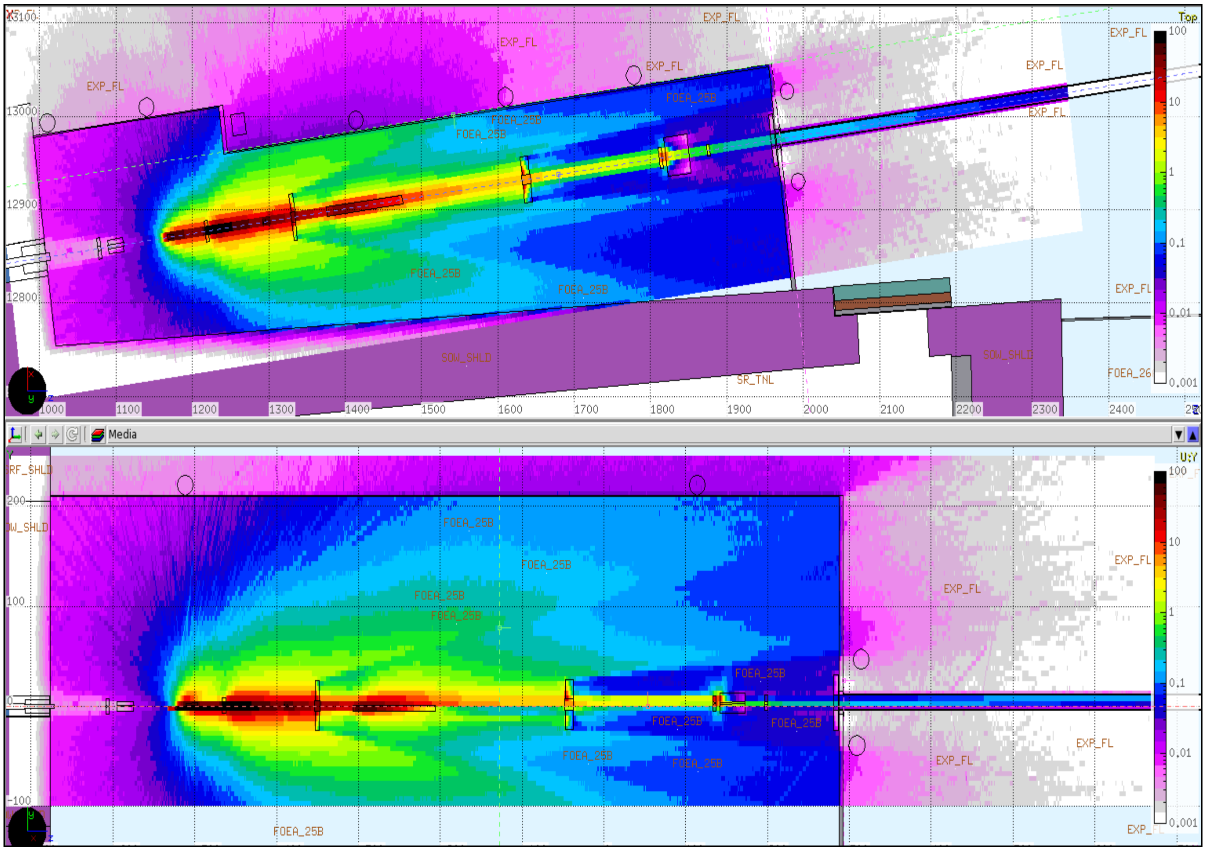

Figure 18: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

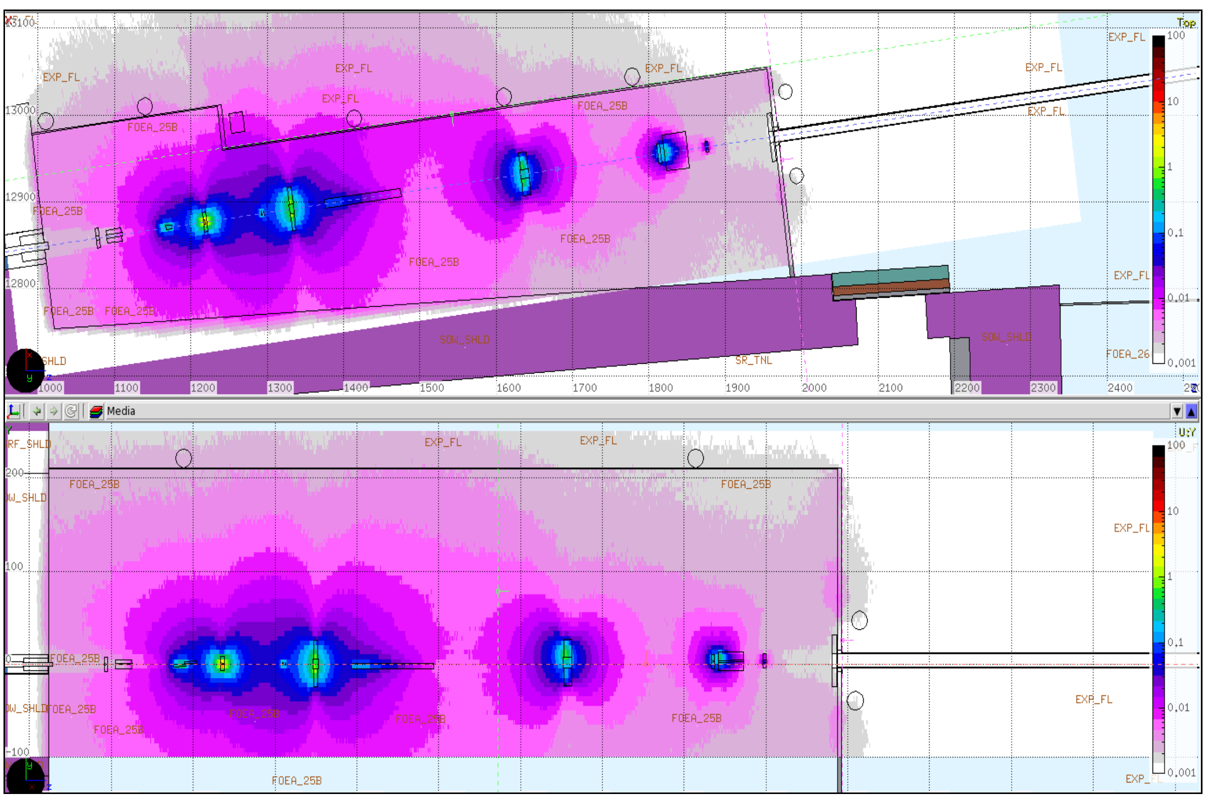

Figure 19: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

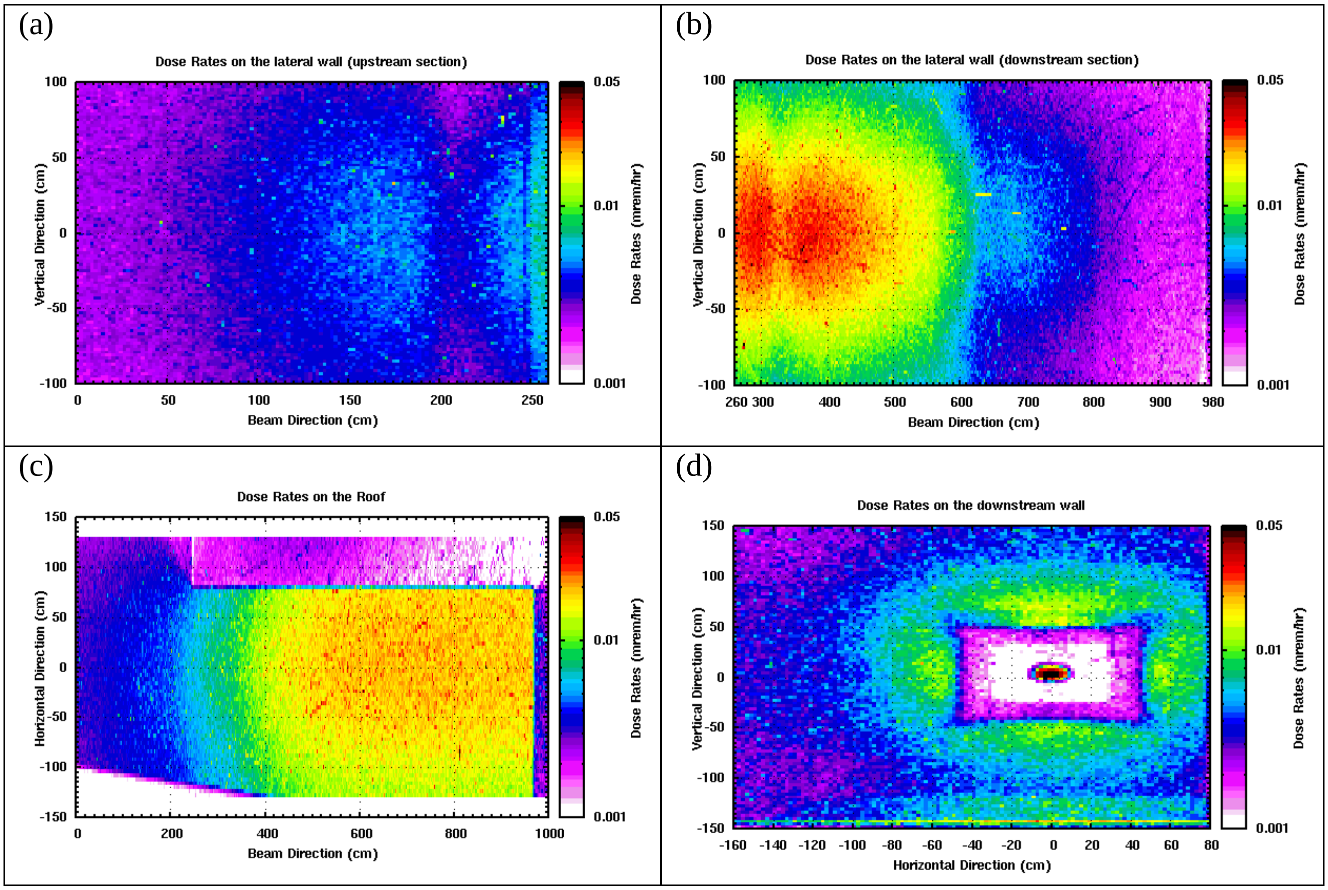

Figure 20: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.2(c) GB incident near the front face of the second crystal of DMM

In this simulation the GB was started just upstream of the selected point of contact at x=0.0, y=0.454, z=144.738 and impinges near the front face of the second crystal.

The total dose distributions (mrem/h) in the FOE are shown in Figure 21 and the corresponding neutron distributions are given in Figure 22. The total dose distributions in mrem/h on the lateral wall [Figure 23(a) and (b)], on the roof [Figure 23(c)] and on contact with the downstream wall [Figure 23(d)] of the FOE are below 0.05 mrem/hr.

The highest dose rates are found on the downstream side of the lateral wall and the downstream wall of the FOE but remain below 0.05 mrem/hr. As shown in Figure 21 and 23(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport they decrease to less than 0.01mrem/hr due to the lead shielding around the transport pipe.

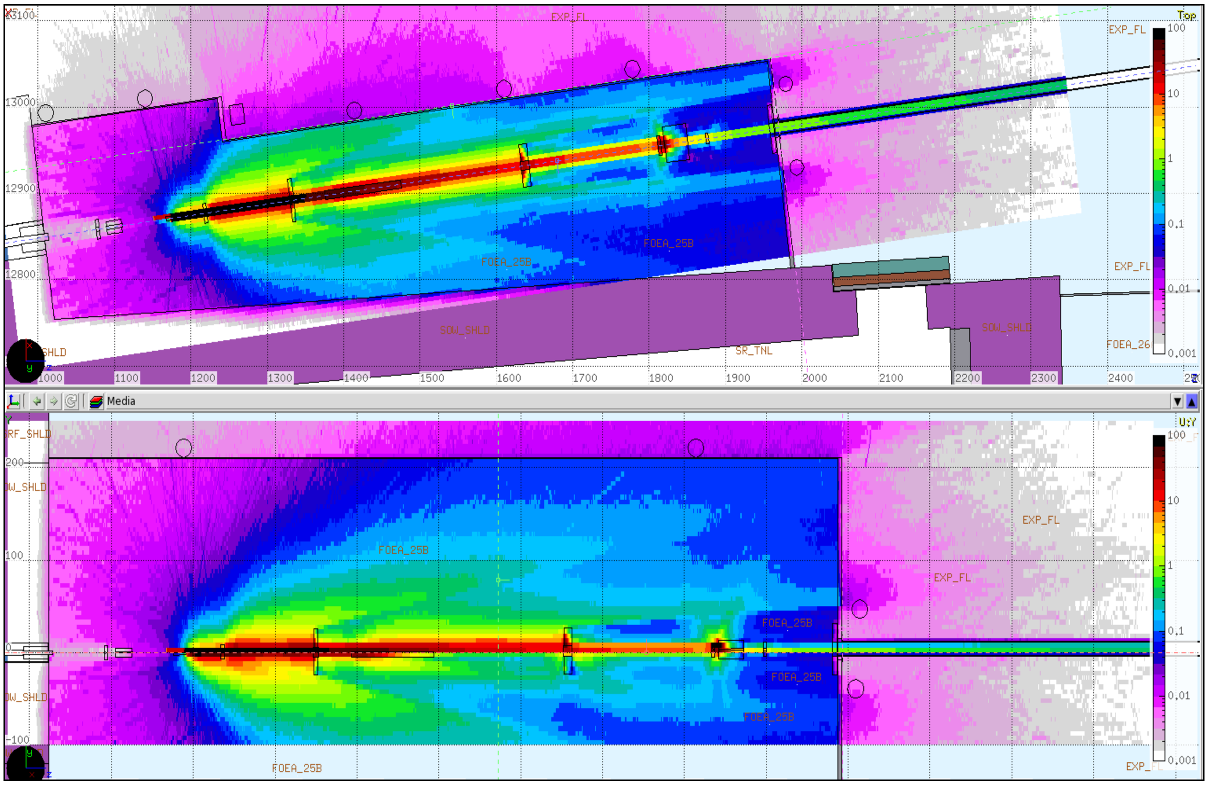

Figure 21: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

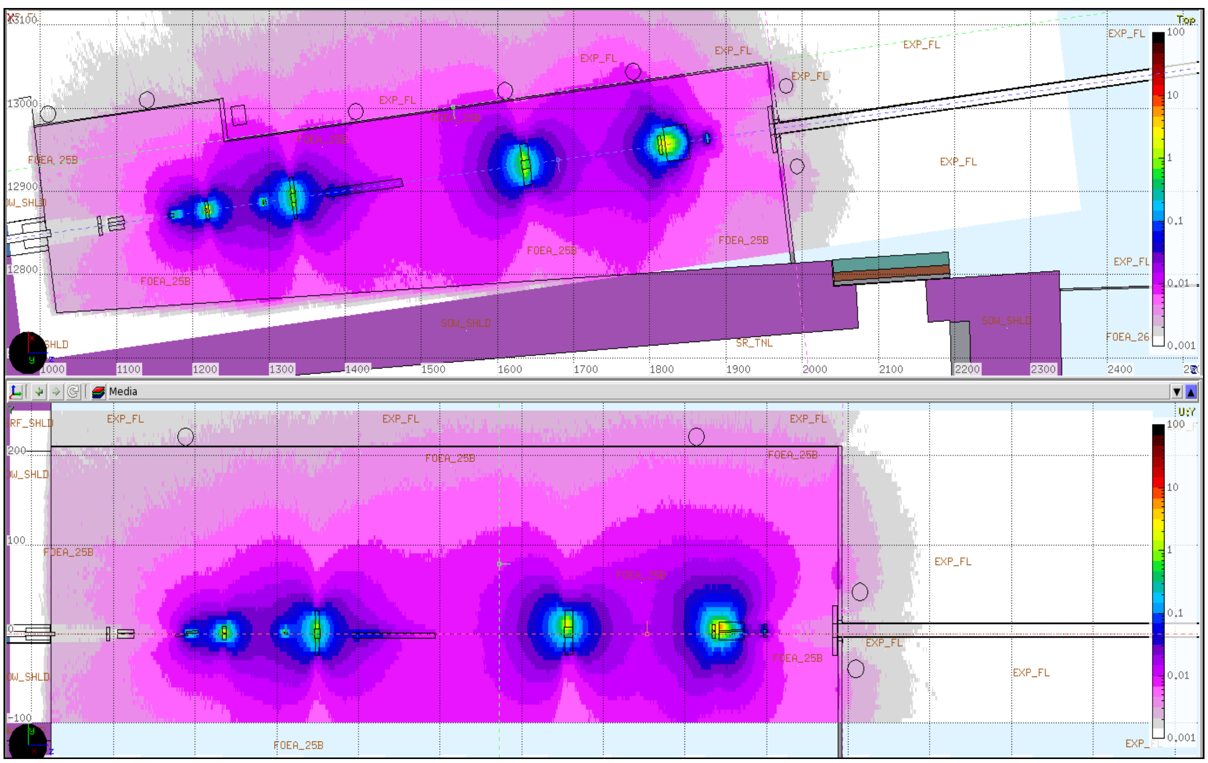

Figure 22: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

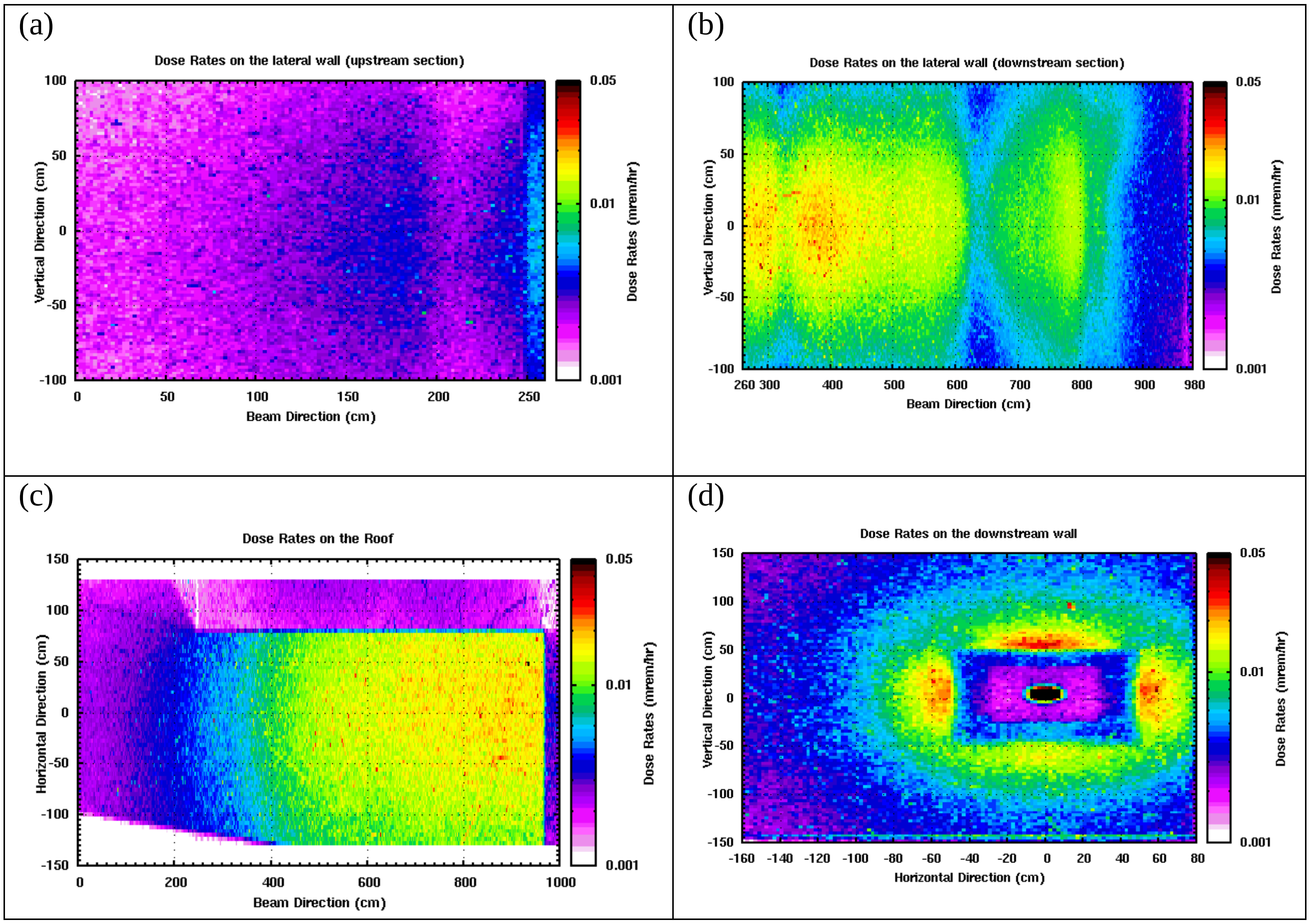

Figure 23: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.3(a) GB incident near the neck of WBS1 on the bottom tapered side

In this simulation the GB was started just upstream of the selected point of contact at x=0.0, y=0.255, z=208.893 and impinges near the bottom tapered side of WBS1. .

The total dose distributions (mrem/h) in the FOE are shown in Figure 24 and the corresponding neutron distributions are given in Figure 25. The total dose distributions in mrem/h on the lateral wall [Figure 26(a) and (b)] and on the roof [Figure 26(c)] of the FOE are below 0.05 mrem/hr. Even though the total dose rates on contact with the downstream wall of the FOE [Figure 26(d) and Figure 27(a)] are more than 0.05 mrem/hr the dose rates at 30 cm away from the exterior of downstream wall [Figure 27(b)] are less than 0.05 mrem/hr.

From all scenarios simulated this scenario gives the highest dose rates on contact with the downstream wall of the FOE and is approximately 0.15 mrem/hr. As shown in Figure 24 and 26(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport pipe they decrease to less than 0.01mrem/hr due to the lead shielding around the transport pipe.

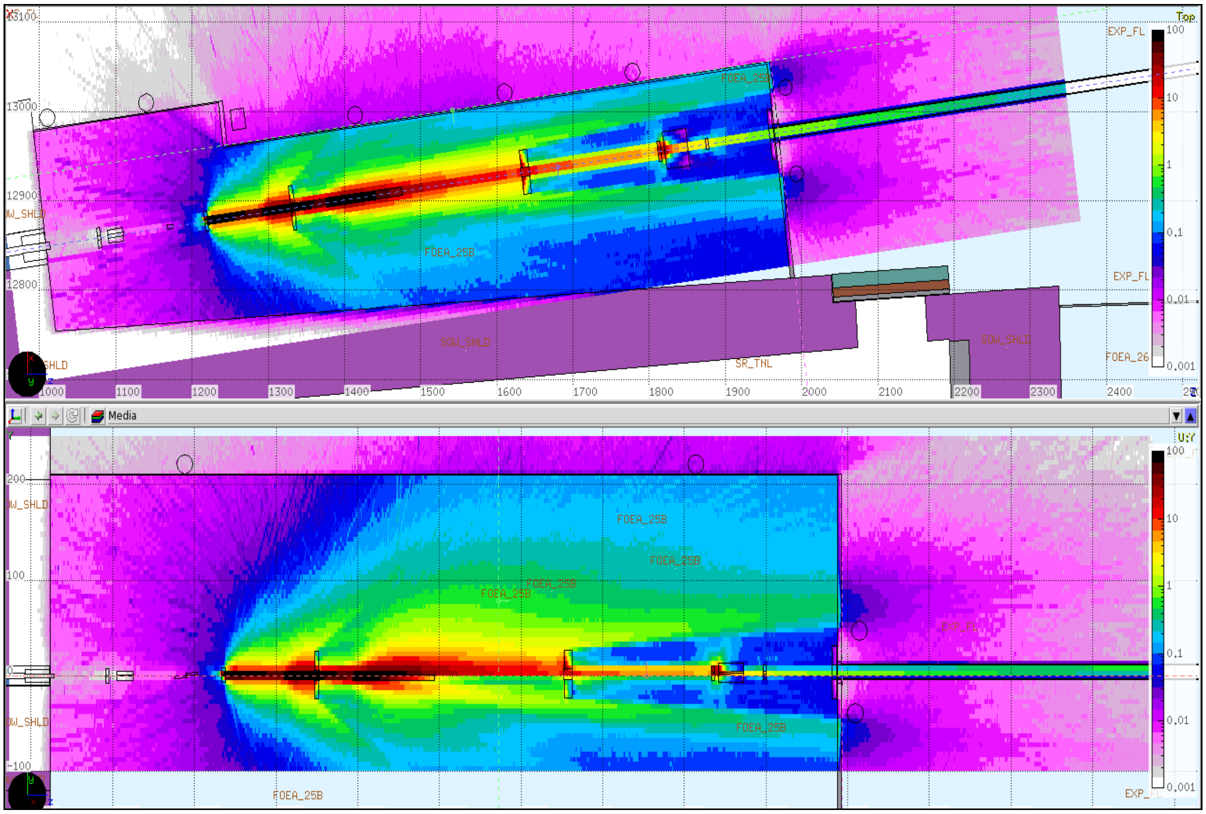

Figure 24: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

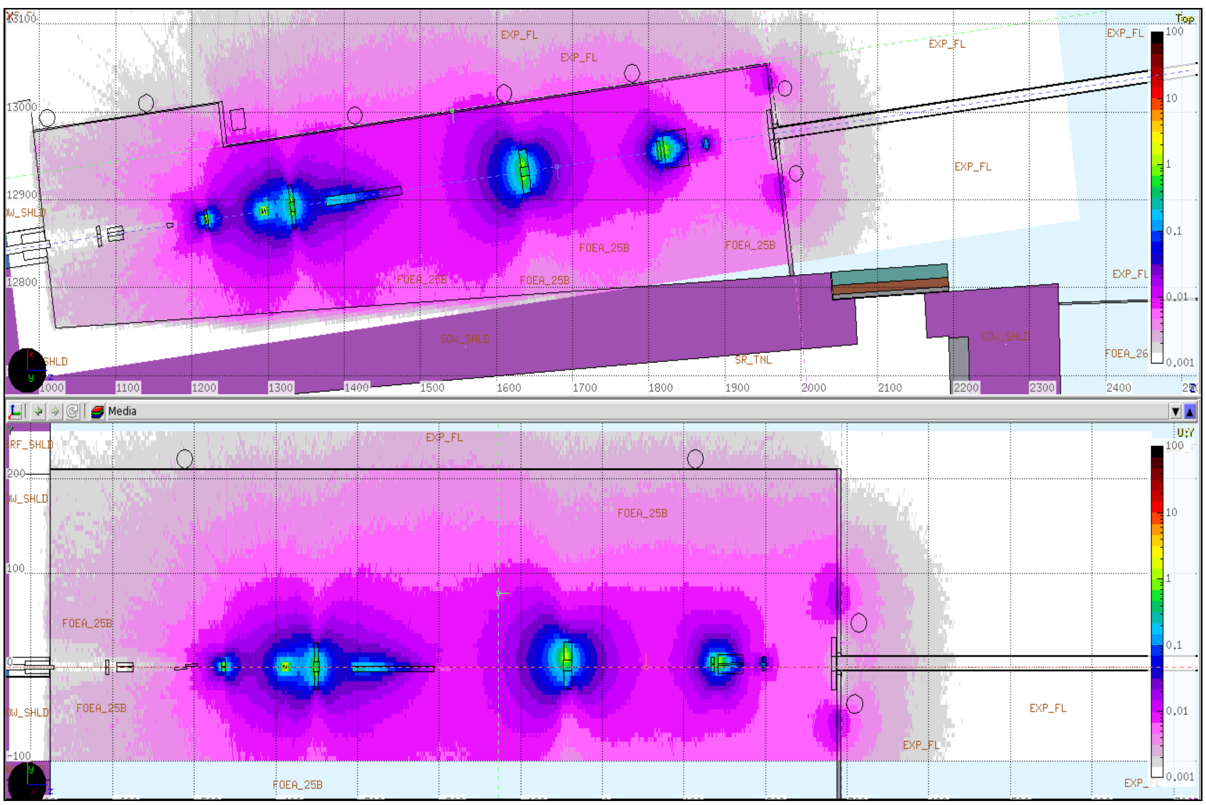

Figure 25: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

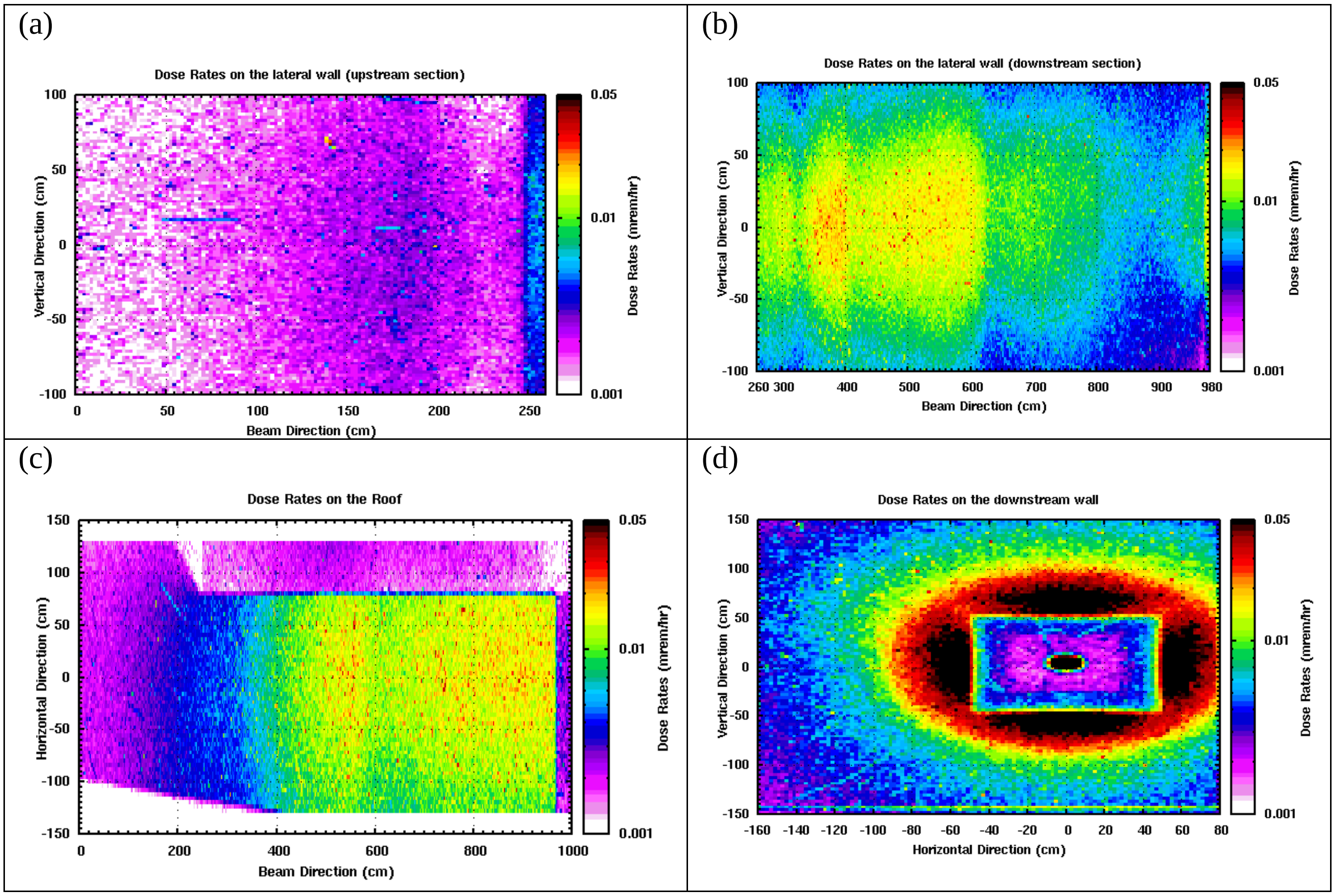

Figure 26: The total dose rate distribution in (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

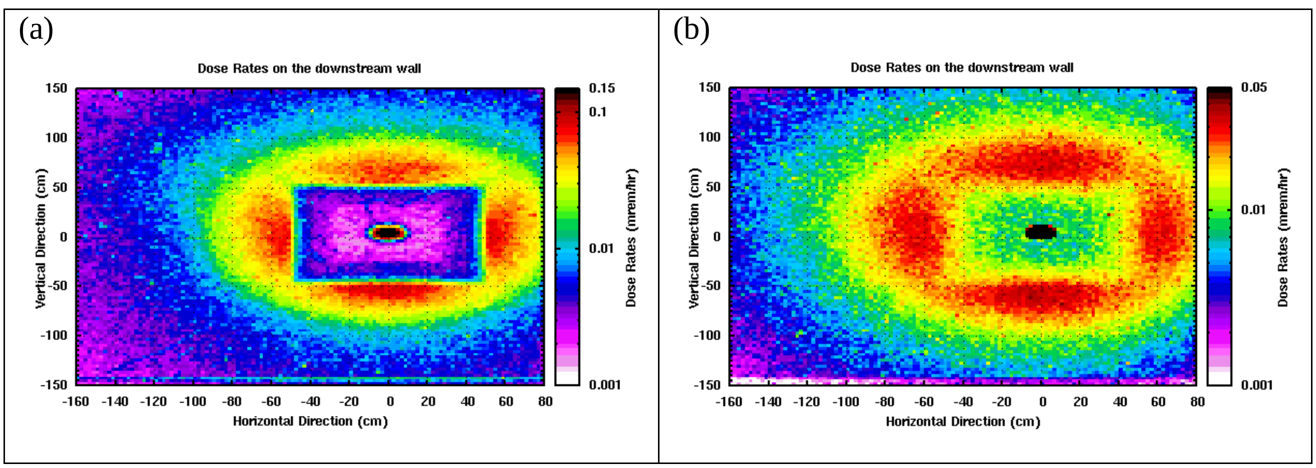

Figure 27: The total dose rate distribution (a) on contact with the downstream wall of the FOE and (b) at 30 cm from the FOE downstream wall

3.3(b) GB incident near the neck of the WBS1 on the outboard tapered side

In this simulation the GB was started just upstream of the selected point of contact at x=2.13, y=0.6, z=208.893 and impinges near the neck of the WBS1 on then outboard tapered side. The total dose distributions (mrem/h) in the FOE are shown in Figure 28 and the corresponding neutron distributions are given in Figure 29.

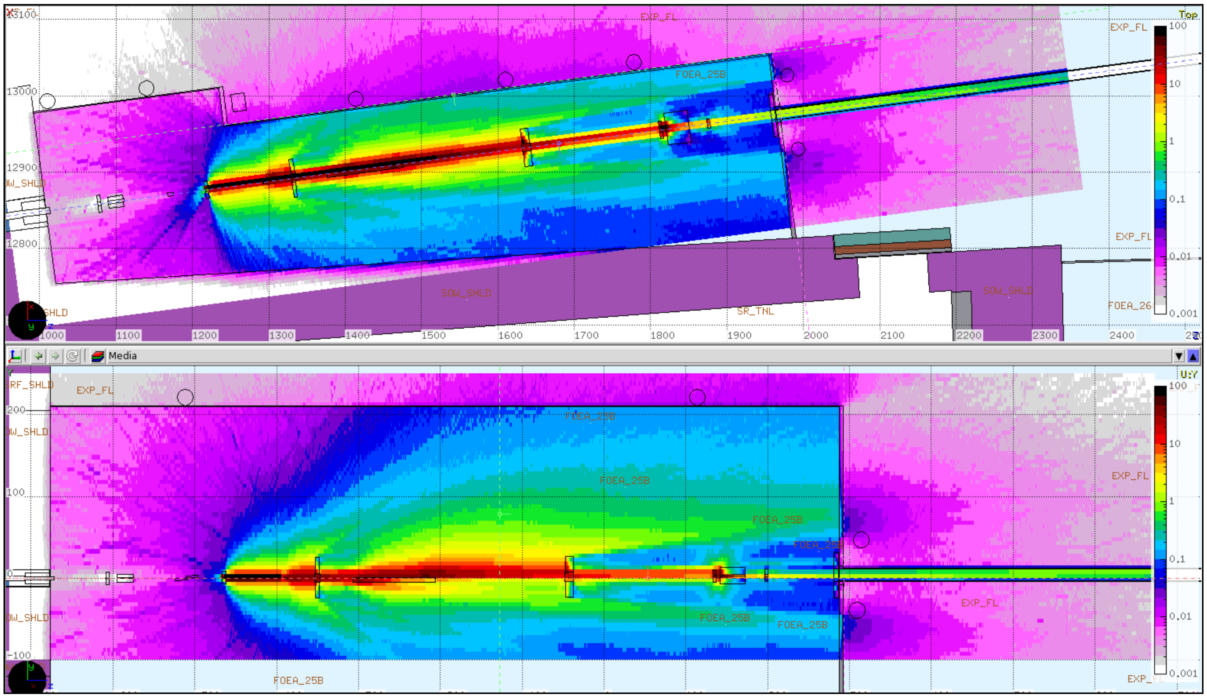

Figure 28: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

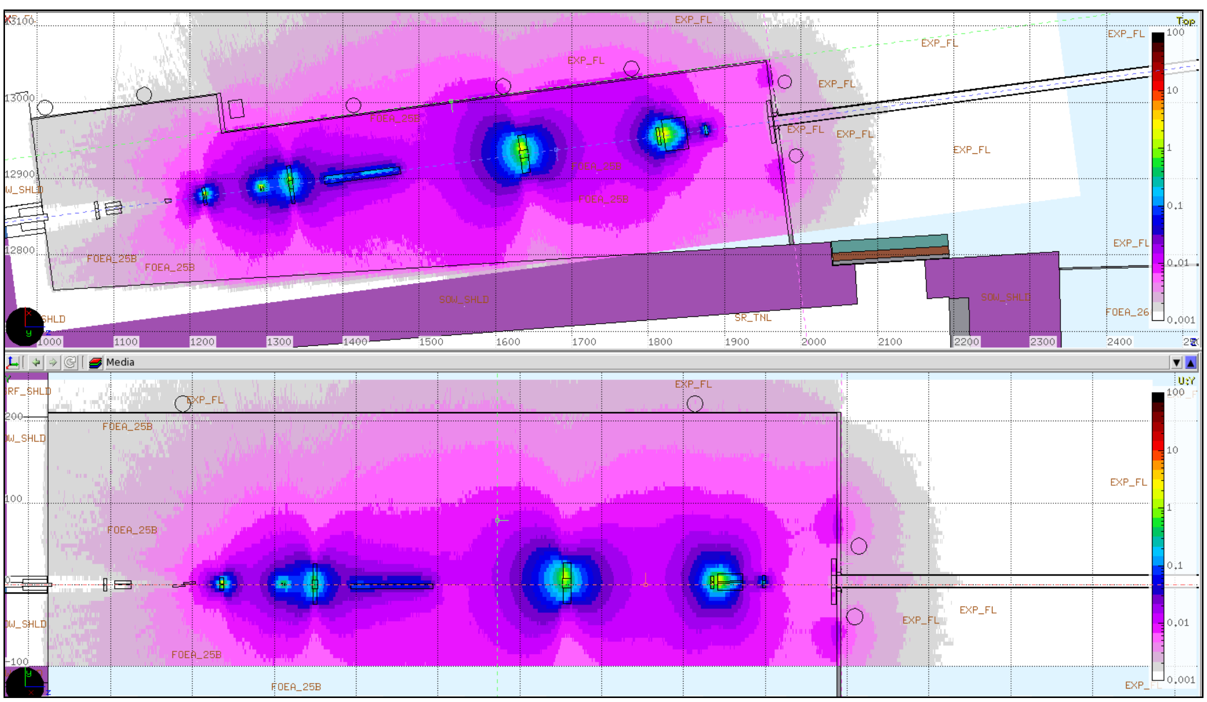

Figure 29: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

The total dose distributions in mrem/h on the lateral wall [Figure 30(a) and (b)] and on the roof [Figure 30(c)] of the FOE are below 0.05 mrem/hr. Even though the total dose rates on contact with the downstream wall of the FOE [Figure 30(d) and Figure 31(a)] are more than 0.05 mrem/hr the dose rates at 30 cm away from the exterior of downstream wall [Figure 31(b)] are less than 0.05 mrem/hr. From all scenarios simulated this scenario gives the next highest dose rates on contact with the downstream wall of the FOE and is approximately 0.08 mrem/hr. As shown in Figure 28 and 30(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport pipe they decrease to less than 0.01mrem/hr due to the lead shielding around the transport pipe.

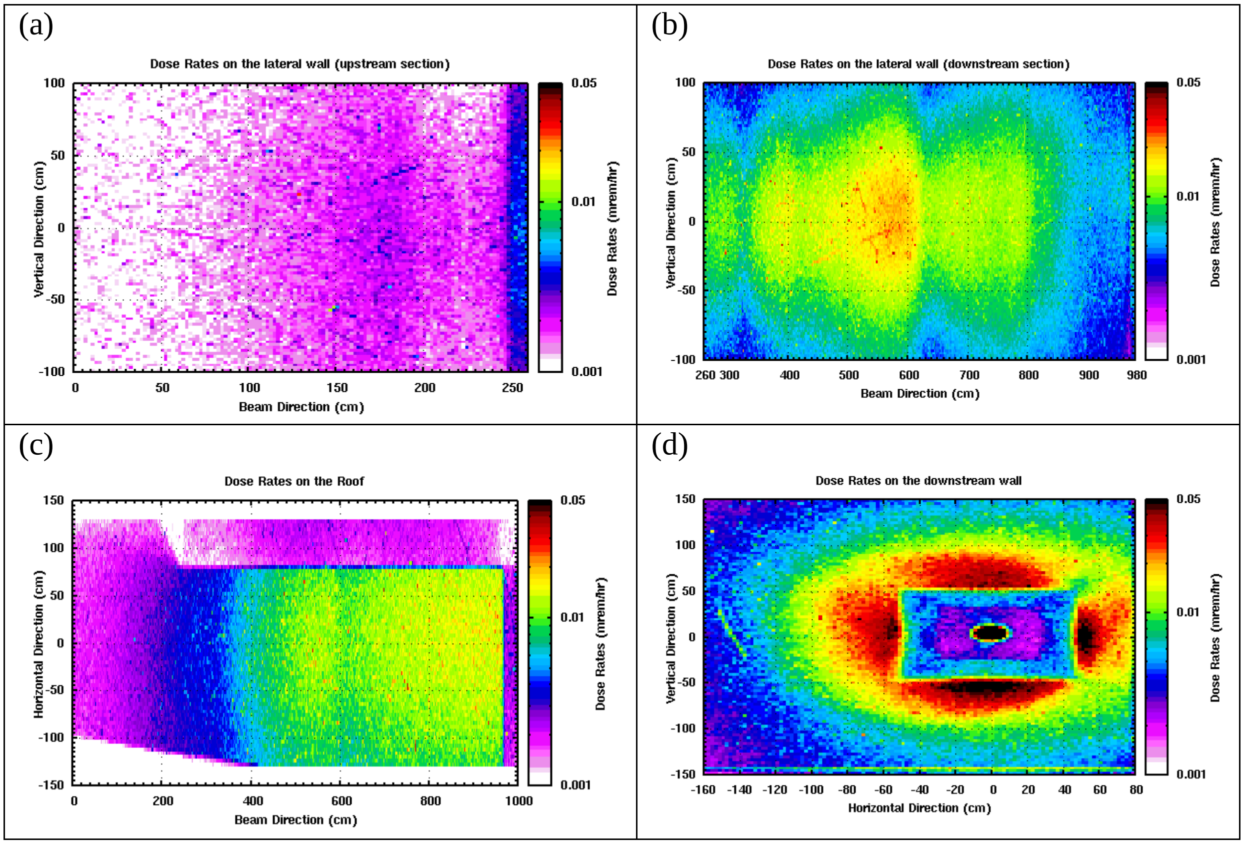

Figure 30: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

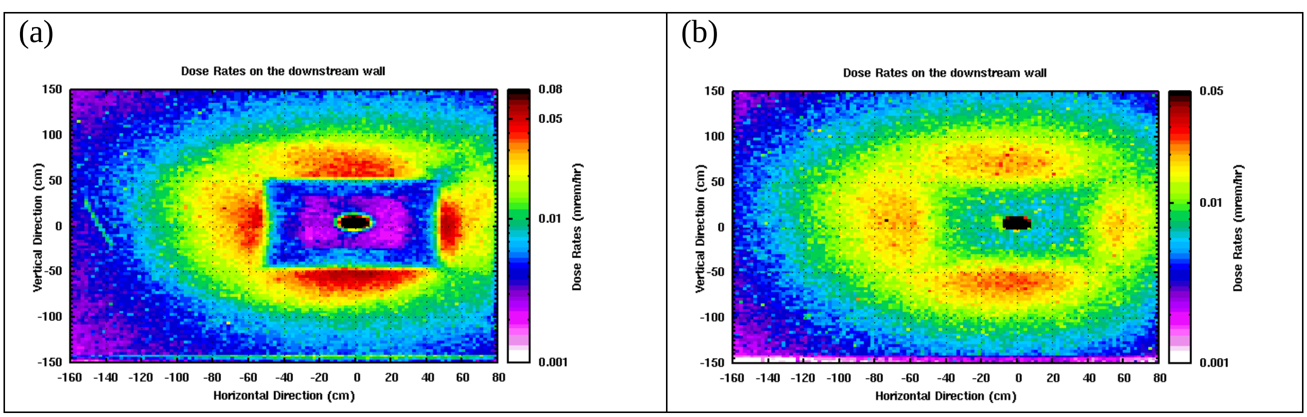

Figure 31: The total dose rate distribution (a) on contact with the downstream wall of the FOE and (b) at 30 cm from the FOE downstream wall

3.3(c) GB incident on the front face of WBS1 near the outboard edge

In this simulation the GB was started just upstream of the selected point of contact at x=2.573, y=-0.483, z=208.893 and impinges on the front face of the WBS1 near the outboard edge. The total dose distributions (mrem/h) in the FOE are shown in Figure 32 and the corresponding neutron distributions are given in Figure 33.

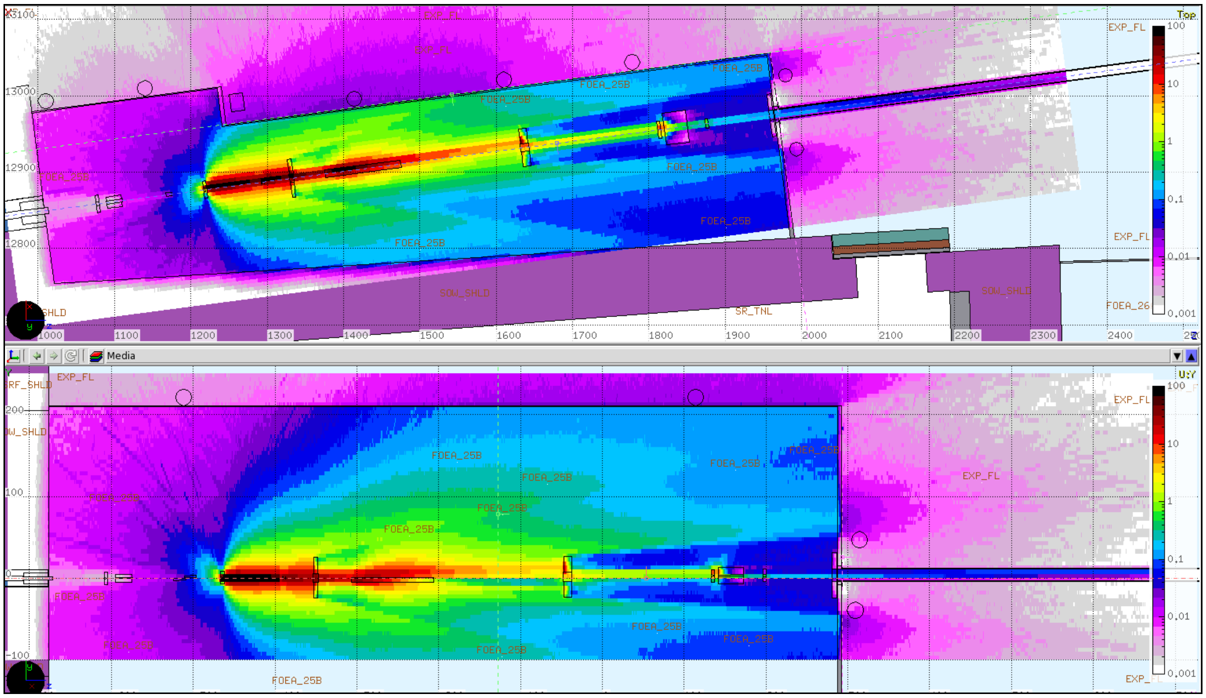

Figure 32: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

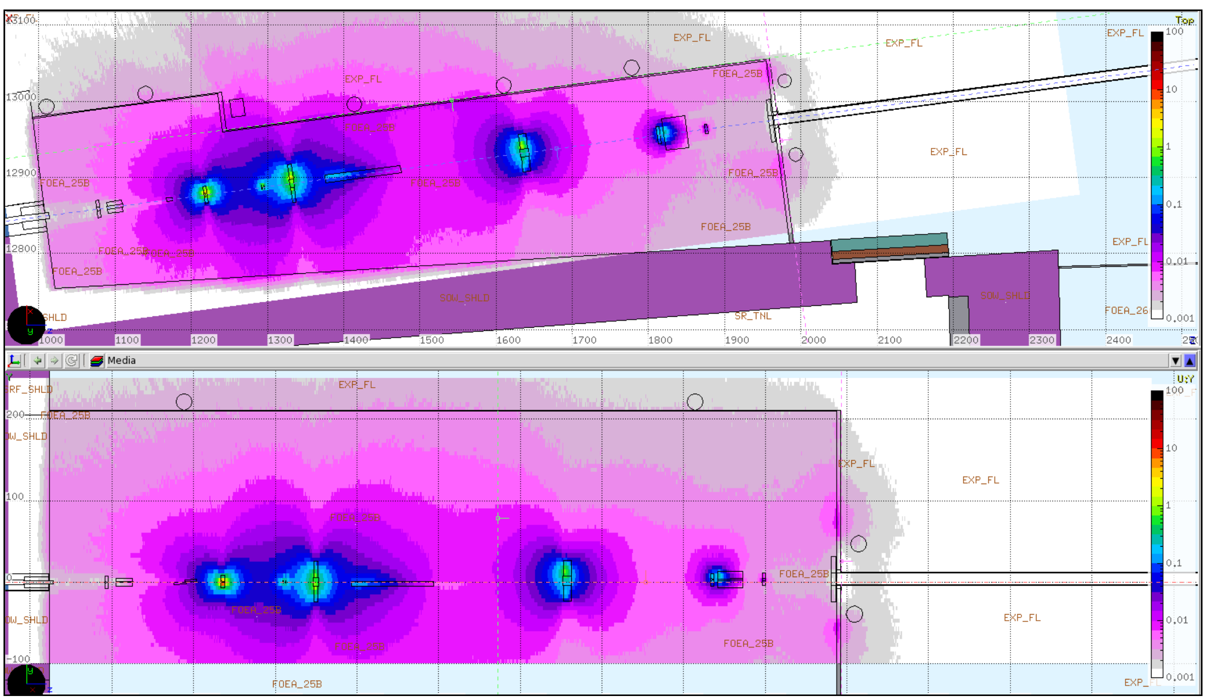

Figure 33: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

The total dose distributions in mrem/h on the lateral wall [Figure 34(a) and (b)], on the roof [Figure 34(c)] and on contact with the downstream wall [Figure 34(d)] of the FOE are below 0.05 mrem/hr.

The highest dose rates are found on the downstream side of the lateral wall and the downstream wall of the FOE but remain below 0.05 mrem/hr. As shown in Figure 32 and 34(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport they decrease to less than 0.01mrem/hr due to the lead shielding around the transport pipe.

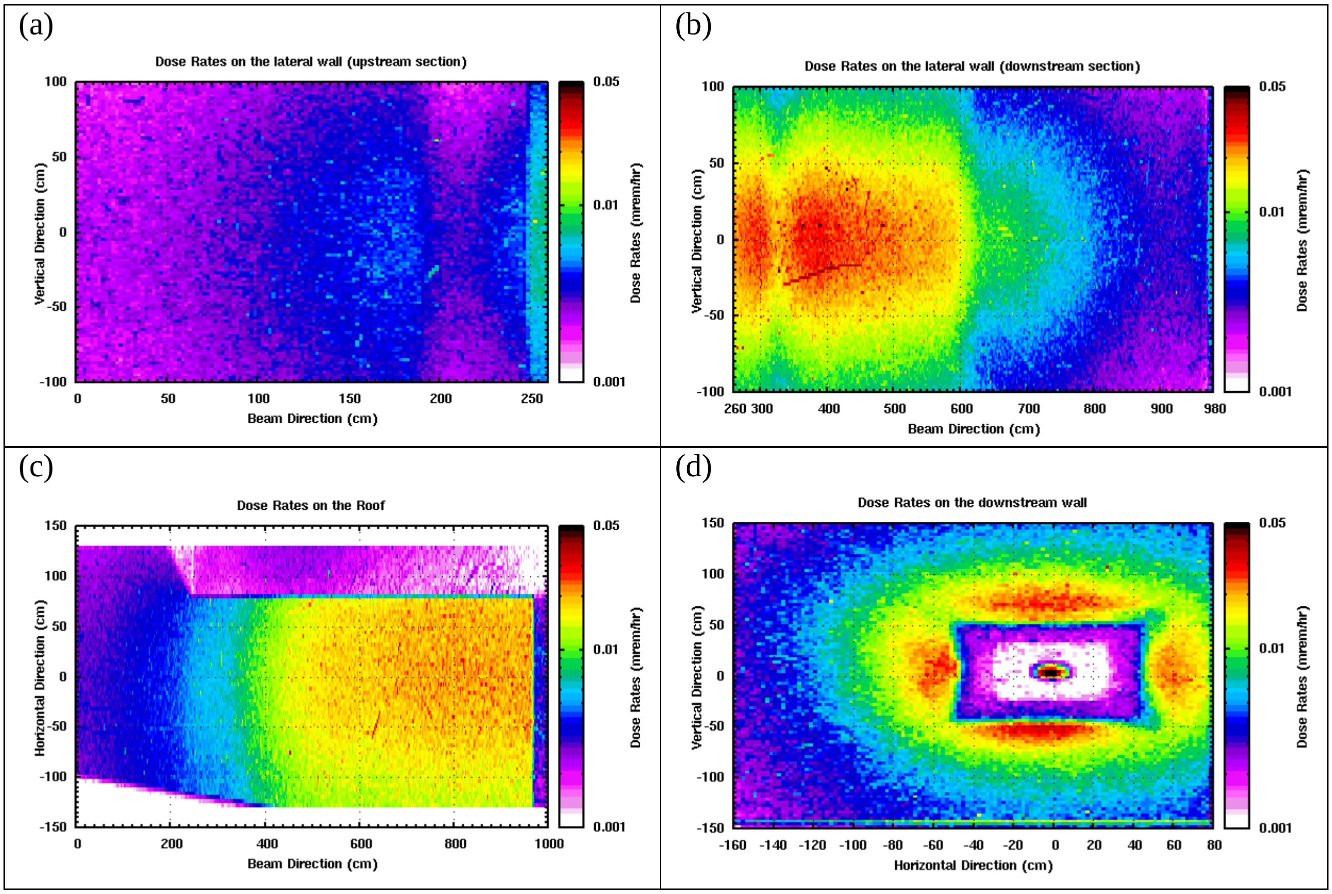

Figure 34: The total dose rate distribution (mrem/hr) (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.4(a) GB incident near the center of the PFM

In this simulation the GB was started just upstream of the selected point of contact at x=0.0, y=0.6, z=369.738 and impinges near the center on the PFM. The crystal of the PFM is assumed to be in its nominal orientation of 3.34 mrad. The total dose distributions (mrem/h) in the FOE are shown in Figure 35 and the corresponding neutron distributions are given in Figure 36.

The total dose distributions in mrem/h on the lateral wall [Figure 37(a) and (b)], on the roof [Figure 37(c)] and on contact with the downstream wall [Figure 37(d)] of the FOE are below 0.05 mrem/hr.

The highest dose rates are found on the downstream side of the lateral wall and the downstream wall of the FOE but remain below 0.05 mrem/hr. As shown in Figure 35 and 37(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport they decrease to less than 0.05 mrem/hr due to the lead shielding around the transport pipe.

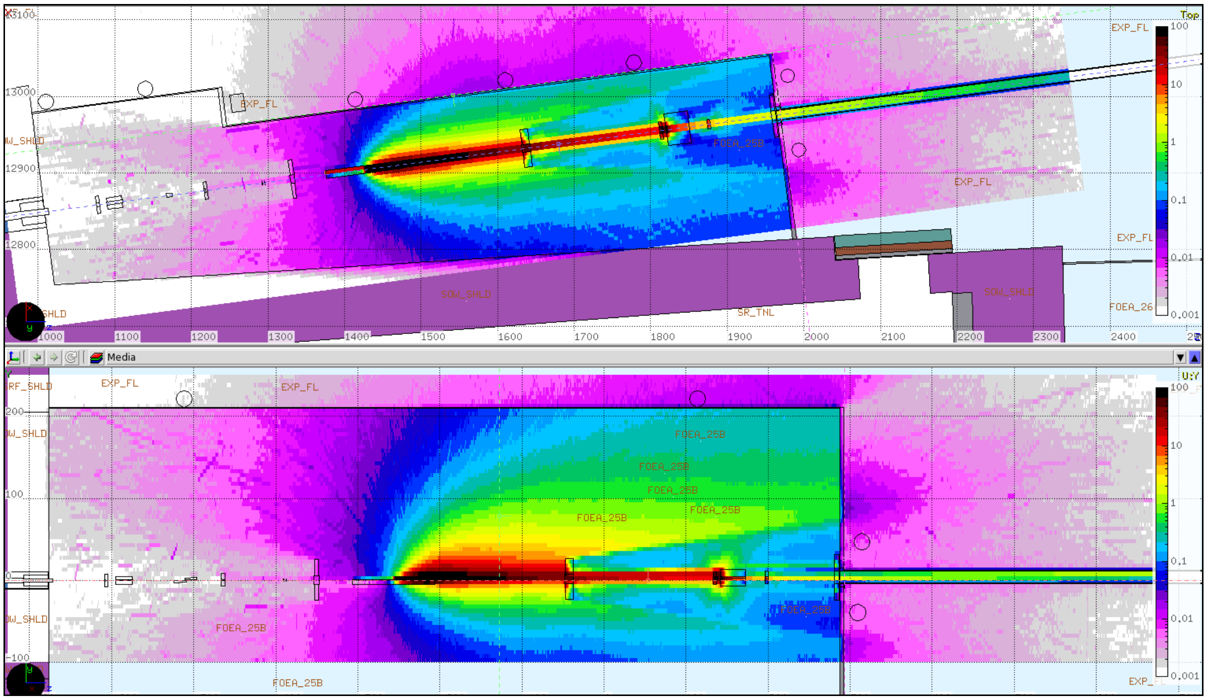

Figure 35: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

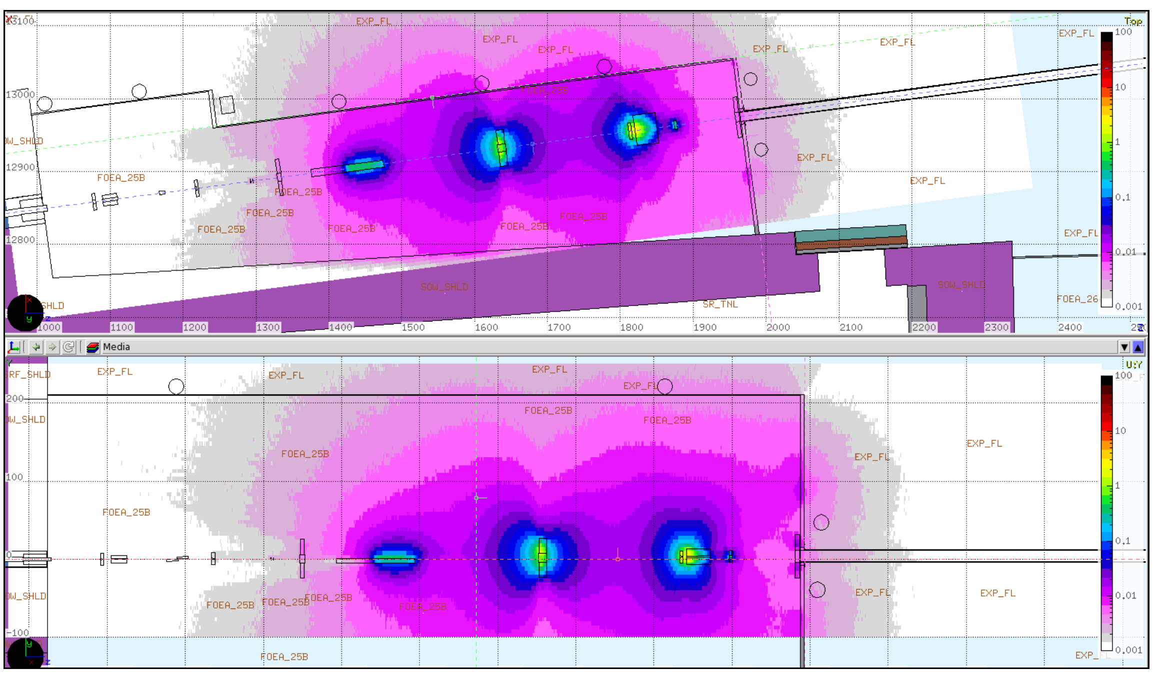

Figure 36: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

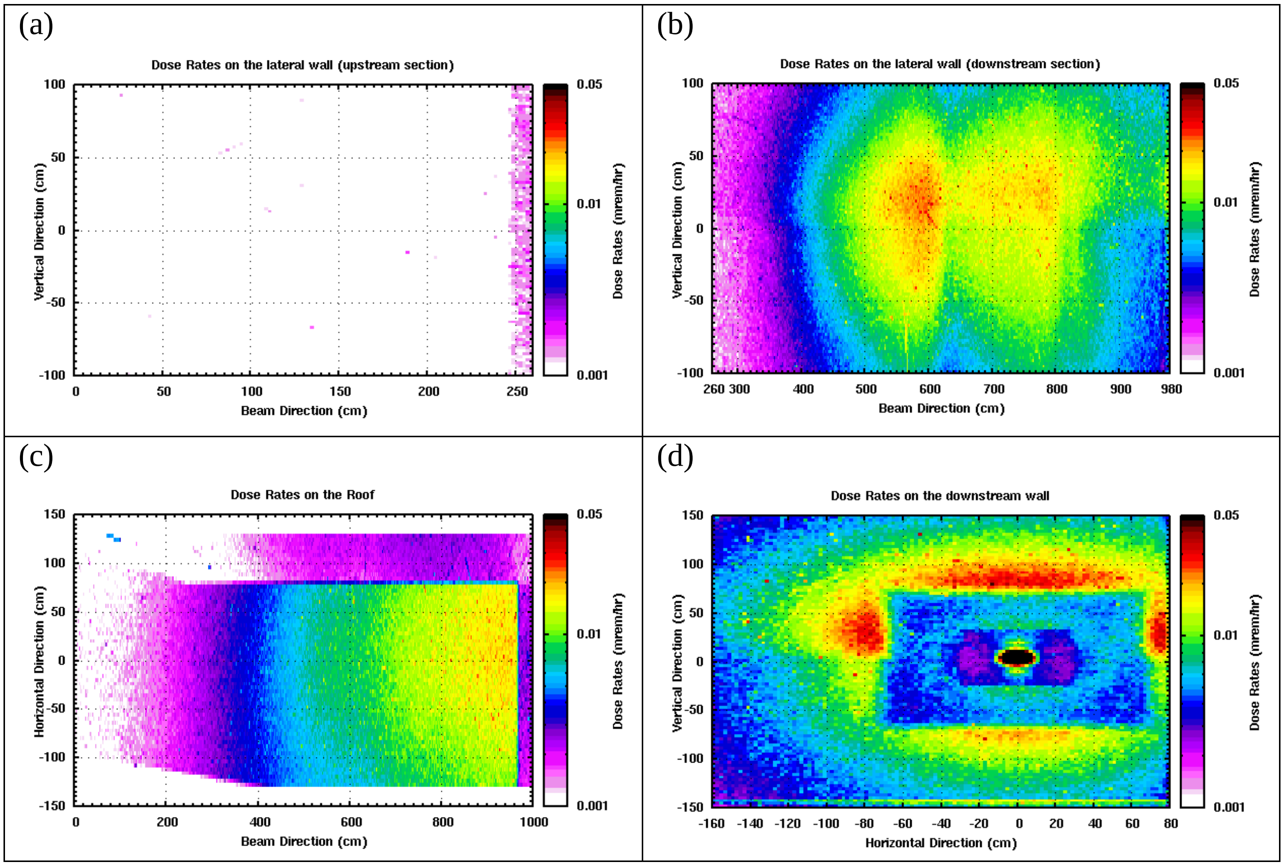

Figure 37: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.4(b) GB incident near the downstream edge of PFM

In this simulation the GB was started just upstream of the selected point of contact at x=0.0, y=0.622, z=369.738 and impinges near the downstream edge of the PFM. The total dose distributions (mrem/h) in the FOE are shown in Figure 38 and the corresponding neutron distributions are given in Figure 39.

The total dose distributions in mrem/h on the lateral wall [Figure 40(a) and (b)], on the roof [Figure 40(c)] and on contact with the downstream wall [Figure 40(d)] of the FOE are below 0.05 mrem/hr.

The highest dose rates are found on the downstream side of the lateral wall and the downstream wall of the FOE but remain below 0.05 mrem/hr. As shown in Figure 38 and 40(d) dose rates inside the transport pipe exceed 0.05 mrem/hr. However just outside the transport they decrease to less than 0.05 mrem/hr due to the lead shielding around the transport pipe

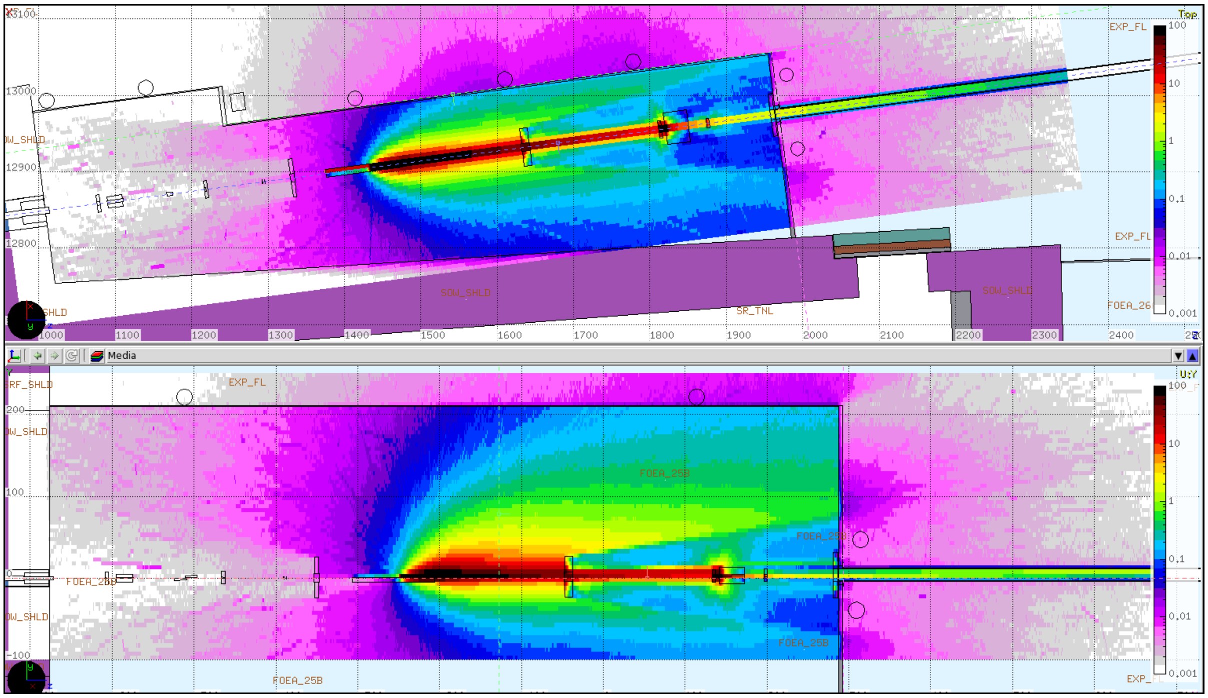

Figure 38: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

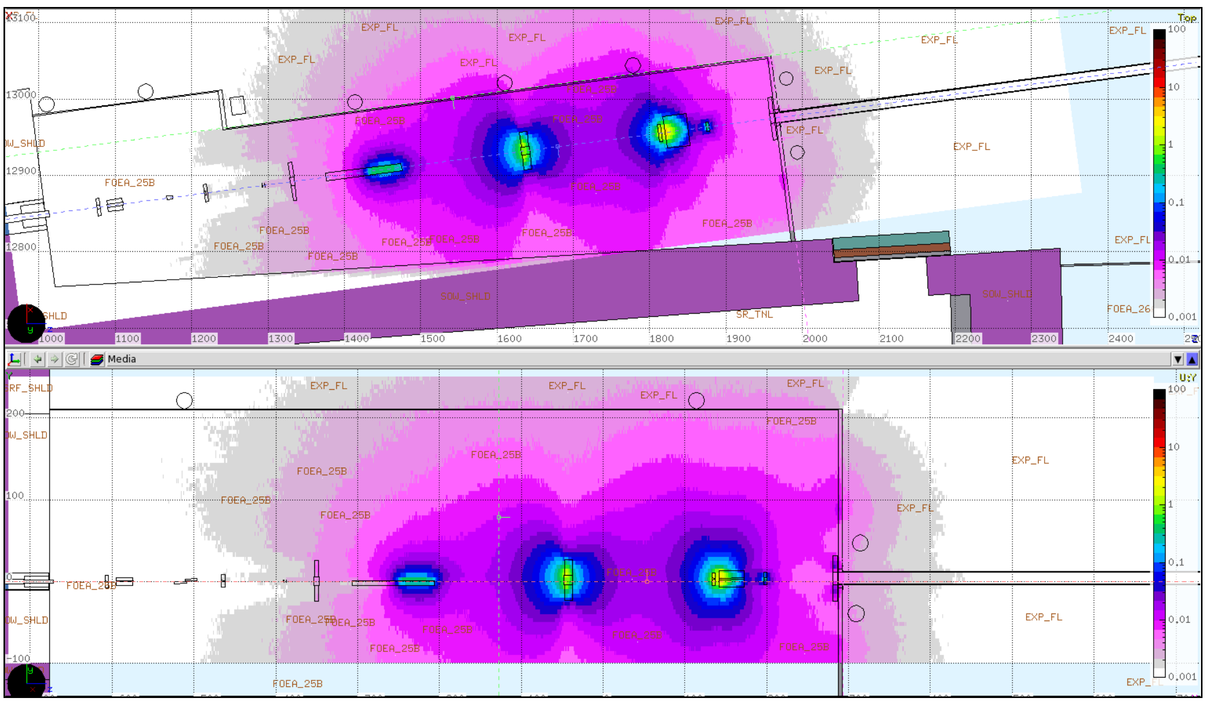

Figure 39: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

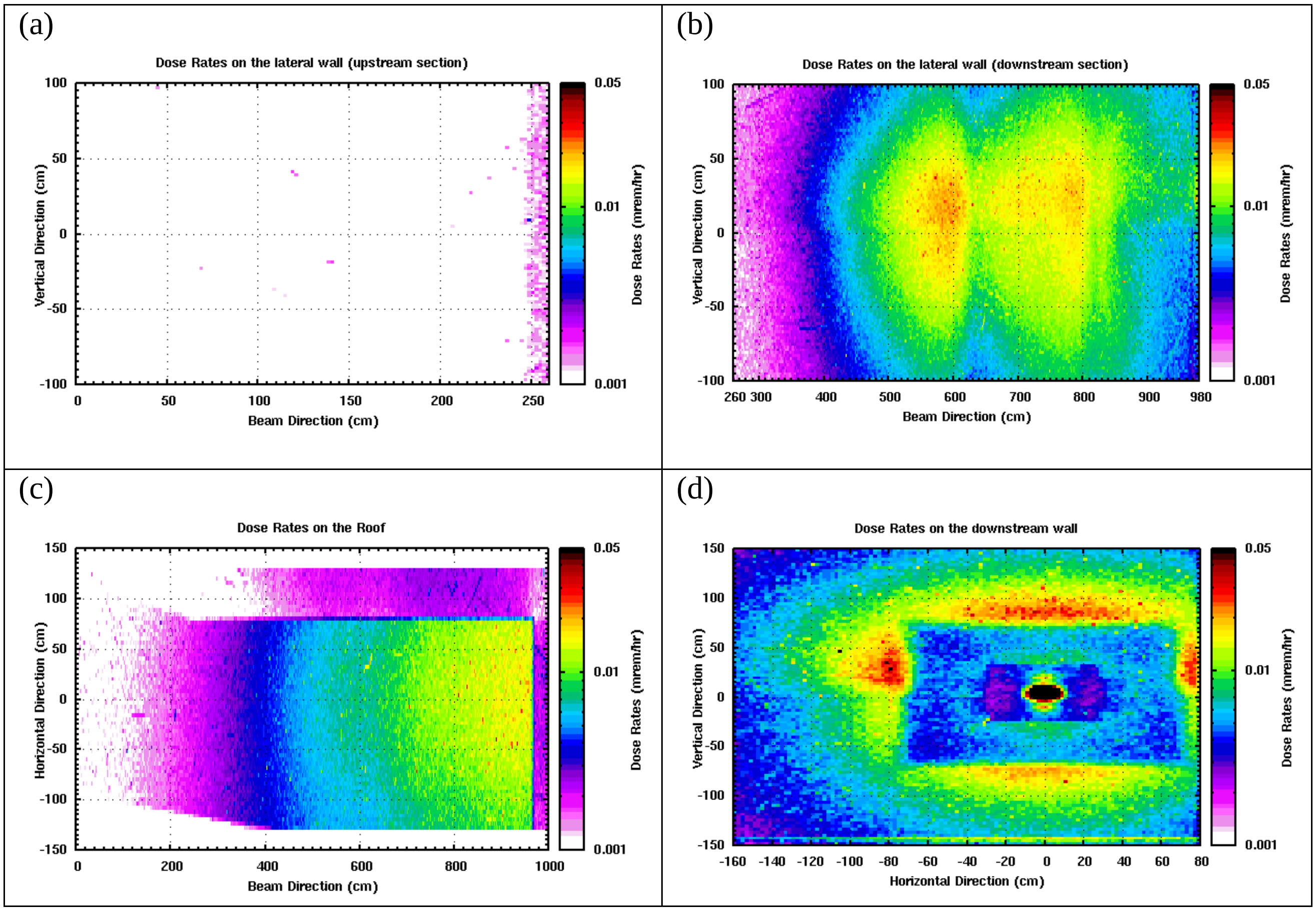

Figure 40: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.4(c) GB incident near the font face of PFM

In this simulation the GB was started just upstream of the selected point of contact at x=0.0, y=-0.588, z=369.738 and impinges near the front face of the PFM. The total dose distributions (mrem/h) in the FOE are shown in Figure 41 and the corresponding neutron distributions are given in Figure 42.

The total dose distributions in mrem/h on the lateral wall [Figure 43(a) and (b)] and on the roof [Figure 43(c)] of the FOE are below 0.05 mrem/hr. Even though the total dose rates on contact with the downstream wall of the FOE [Figure 43(d) and Figure 44(a)] are more than 0.05 mrem/hr the dose rates at 30 cm away from the exterior of downstream wall [Figure 44(b)] are less than 0.05 mrem/hr. The maximum total dose rates on contact with the downstream wall of the FOE is approximately 0.08 mrem/hr. As shown in Figure 41 and 43(d) dose rates inside the transport pipe are less than 0.05 mrem/hr and much less than 0.01 outside the transport pipe.

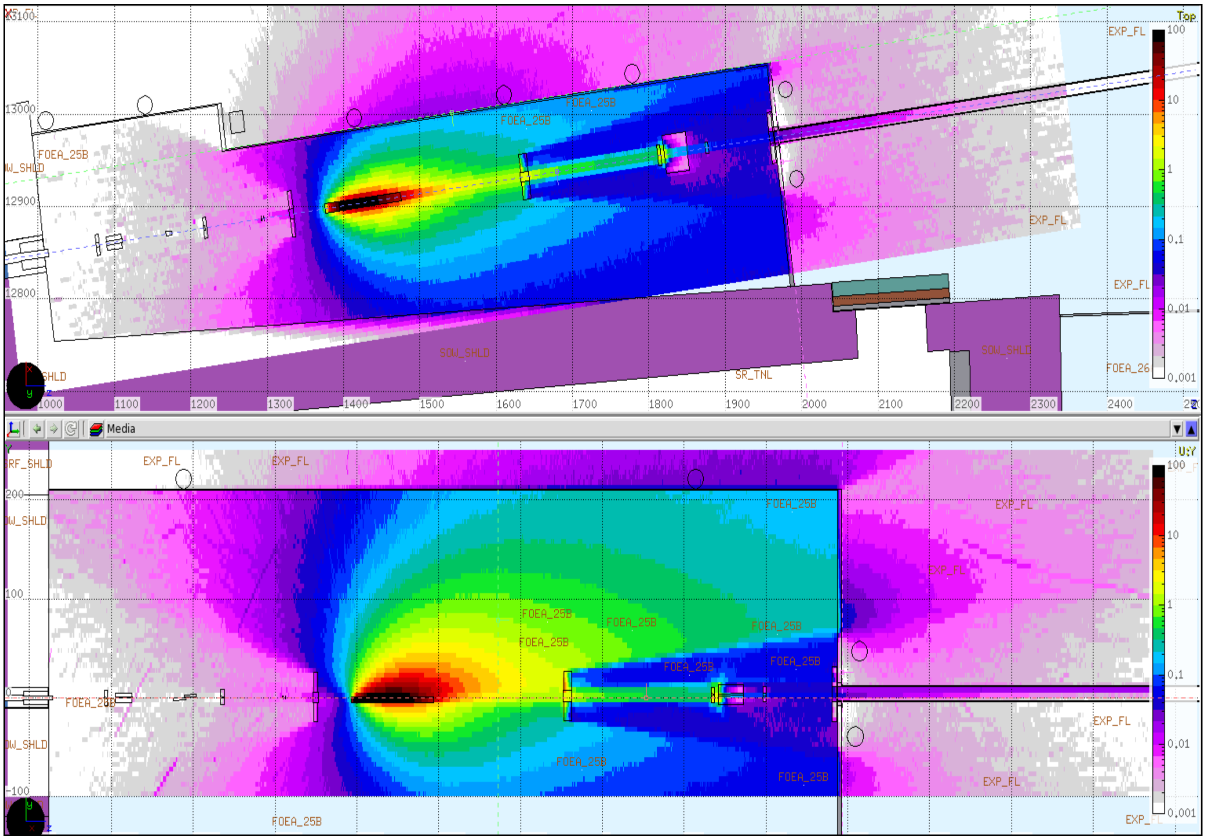

Figure 41: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

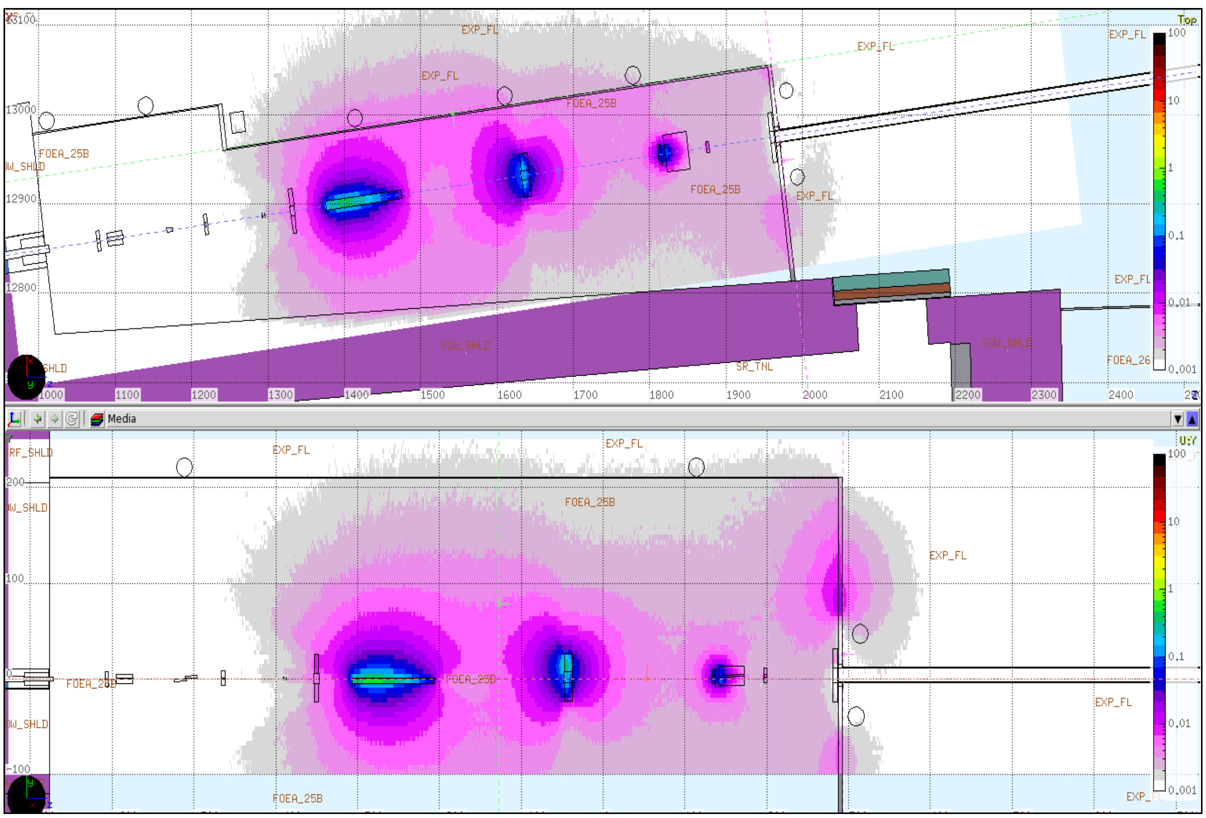

Figure 42: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

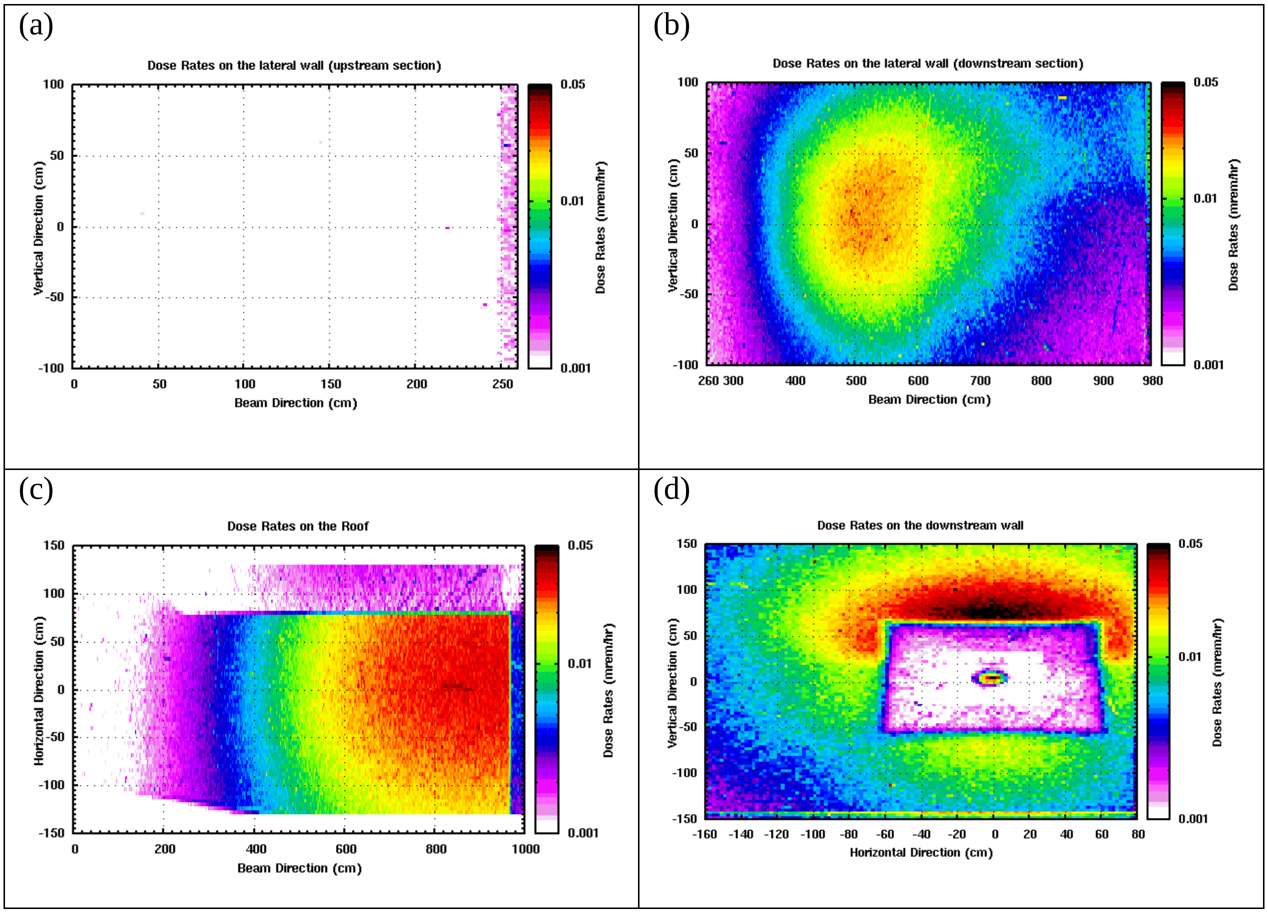

Figure 43: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

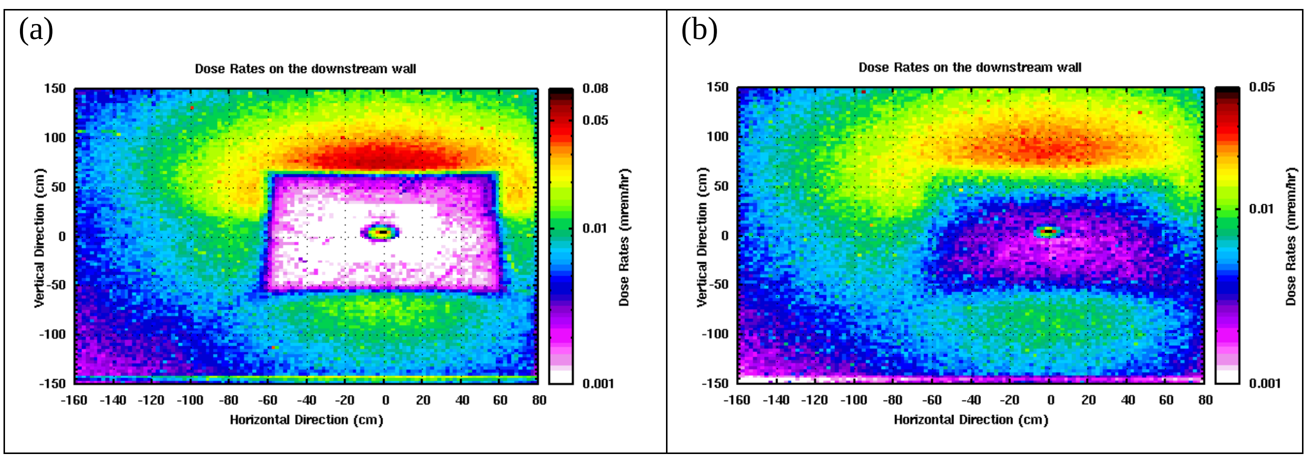

Figure 44: The total dose rate distribution (a) on contact with the downstream wall of the FOE and (b) at 30 cm from the FOE downstream wall

3.5(a) GB horizontal extreme ray incident on WBS2

In this simulation the GB was placed just upstream of the front face of the WBS2. According to ray tracing drawings the extreme GB ray will impinge 2.147 cm below the center of the aperture of WBS2 and 3.861 cm outboard from the center of the aperture of WBS2. The impact point coordinate is x=3.861, y=0.853, z=808.438. The total dose distributions (mrem/h) in the FOE are shown in Figure 45 and the corresponding neutron distributions are given in Figure 46.

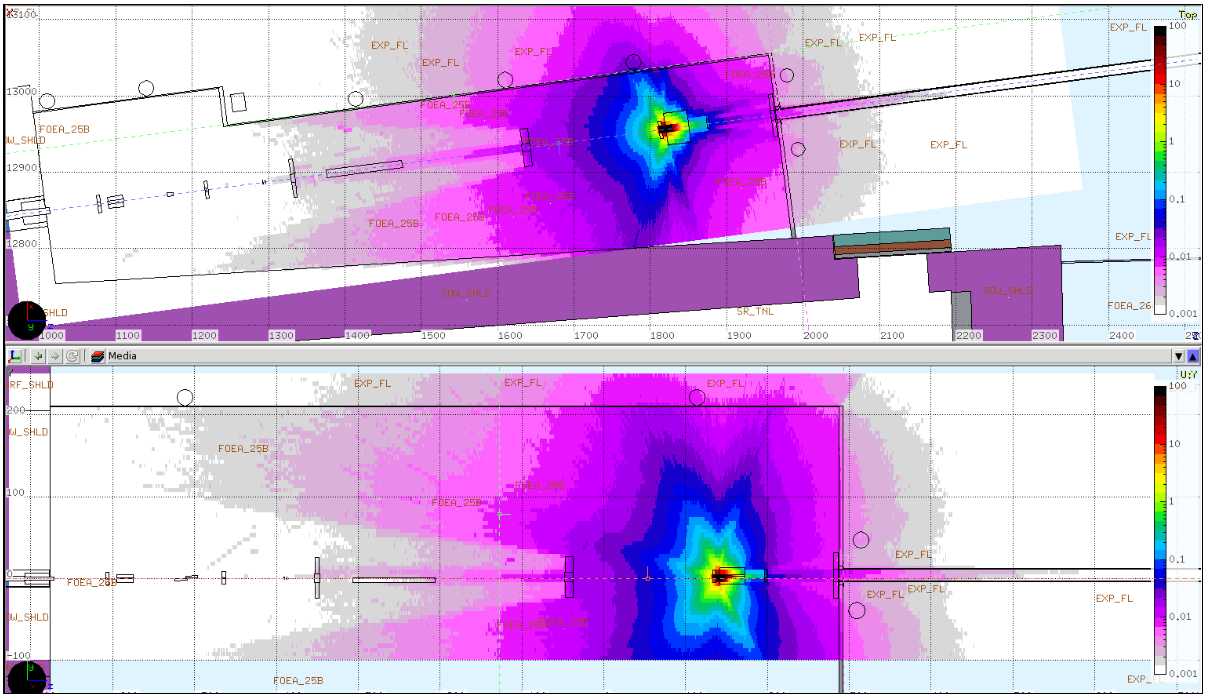

Figure 45: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

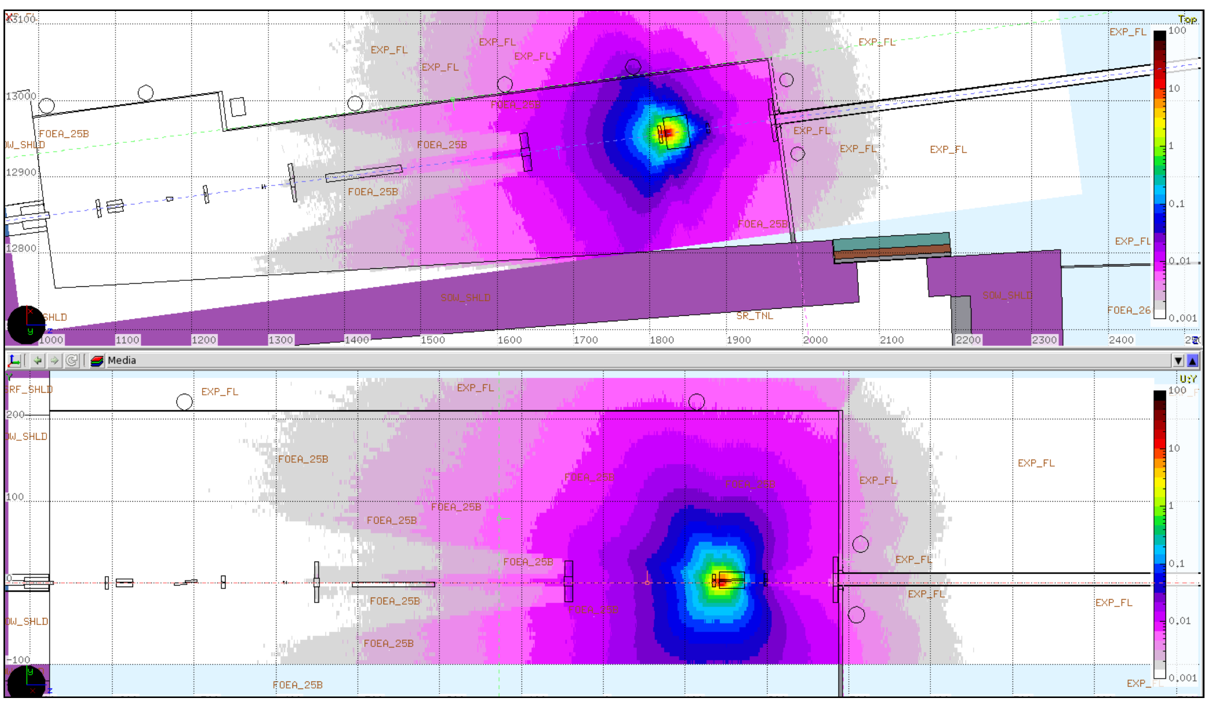

Figure 46: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

The total dose distributions in mrem/h on the lateral wall [Figure 47(a) and (b)], on the roof [Figure 47(c)] and on contact with the downstream wall [Figure 47(d)] of the FOE are below 0.05 mrem/hr.

The highest dose rates are found on the downstream side of the lateral wall of the FOE but remain below 0.05 mrem/hr. The GB collimator/stop just downstream from WBS2 is very effective in containing the electromagnetic shower in the forward direction. As shown in Figure 45 and 47(d) dose rates inside and outside the transport are much less than 0.05 mrem/hr.

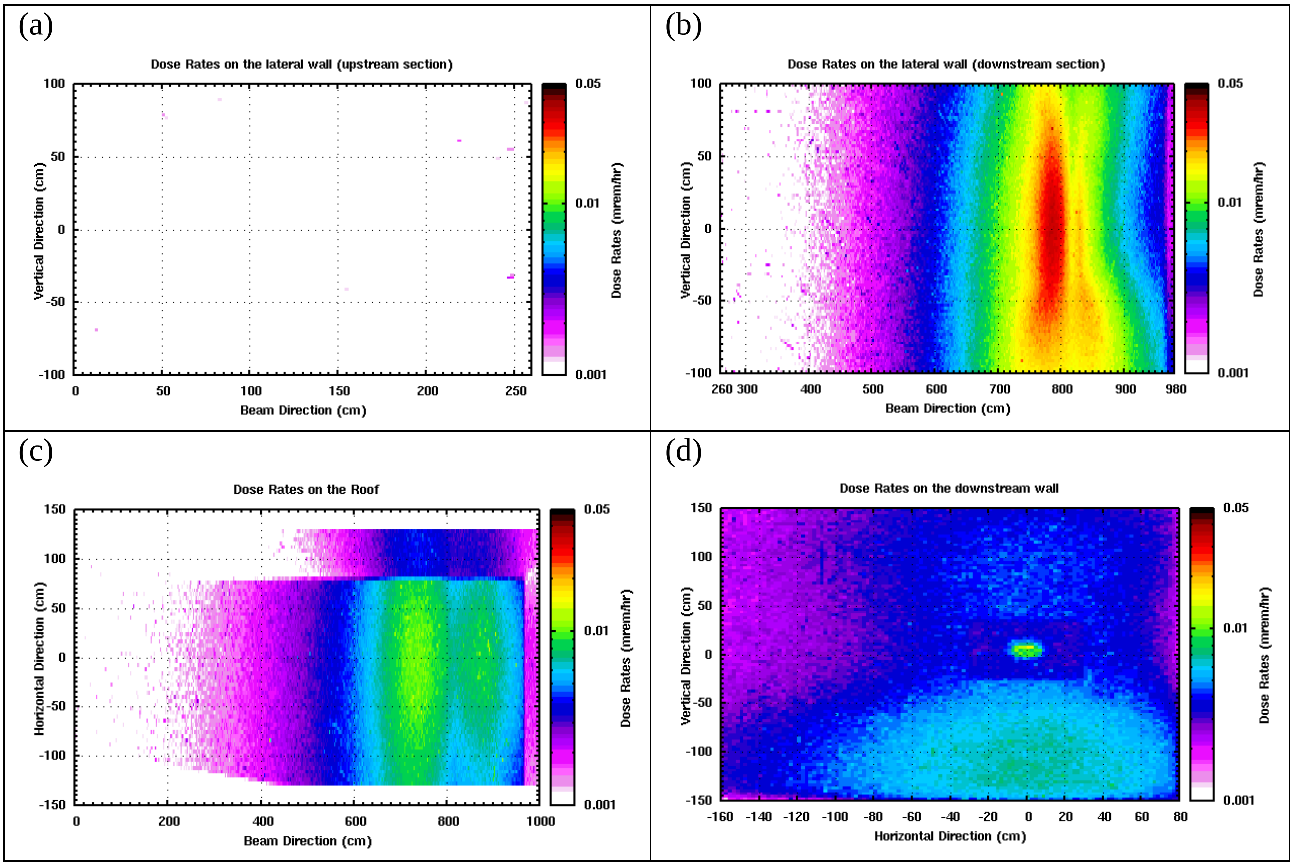

Figure 47: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

3.5(b) GB vertical extreme ray incident on WBS2

In this simulation the GB was placed just upstream of the front face of the WBS2. According to ray tracing drawings the extreme GB ray will impinge 2.147 cm below the center of the aperture of WBS2. The impact point coordinate is x=0.0, y=0.853, z=808.438. The total dose distributions (mrem/h) in the FOE are shown in Figure 48 and the corresponding neutron distributions are given in Figure 49.

The total dose distributions in mrem/h on the lateral wall [Figure 50(a) and (b)], on the roof [Figure 50(c)] and on contact with the downstream wall [Figure 50(d)] of the FOE are below 0.05 mrem/hr. The dose rates distributions are similar to scenario 3.5(a).

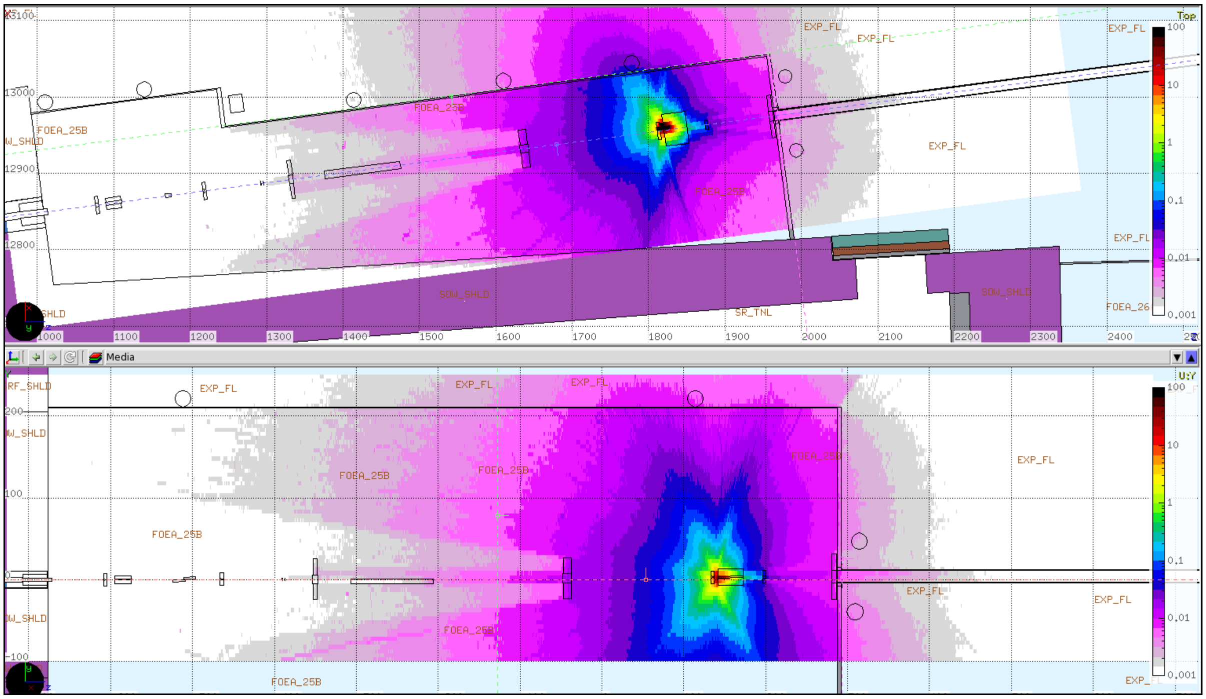

Figure 48: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

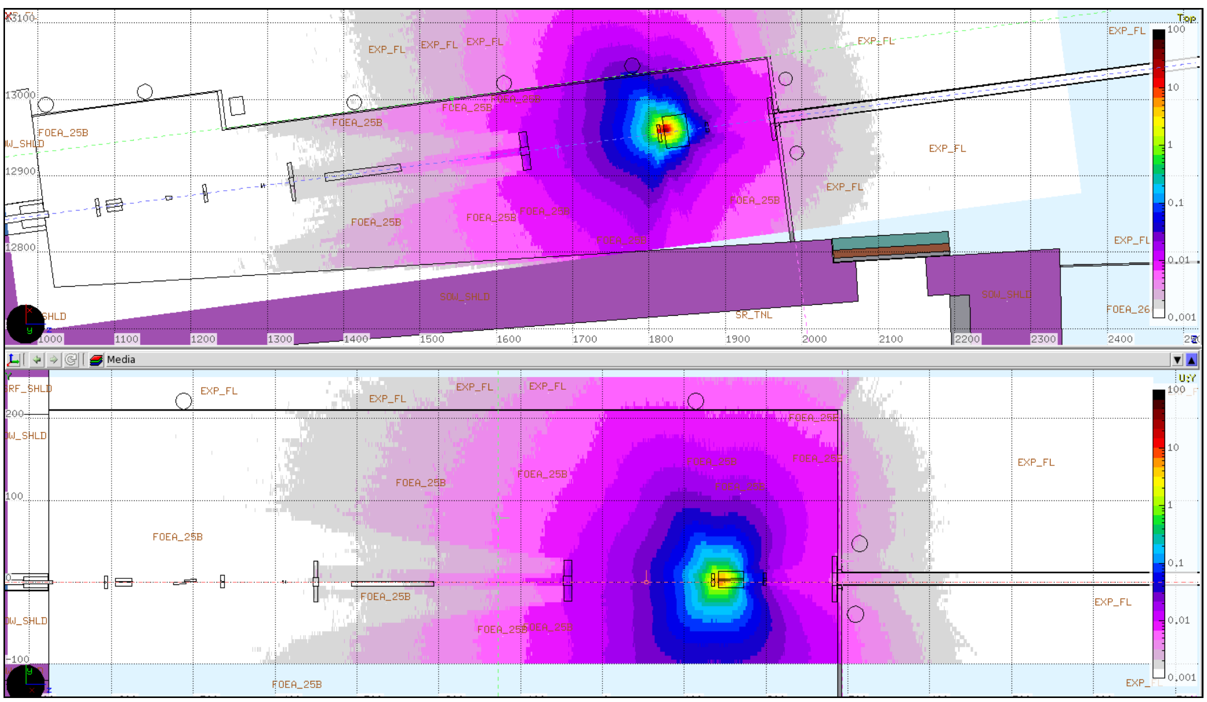

Figure 49: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

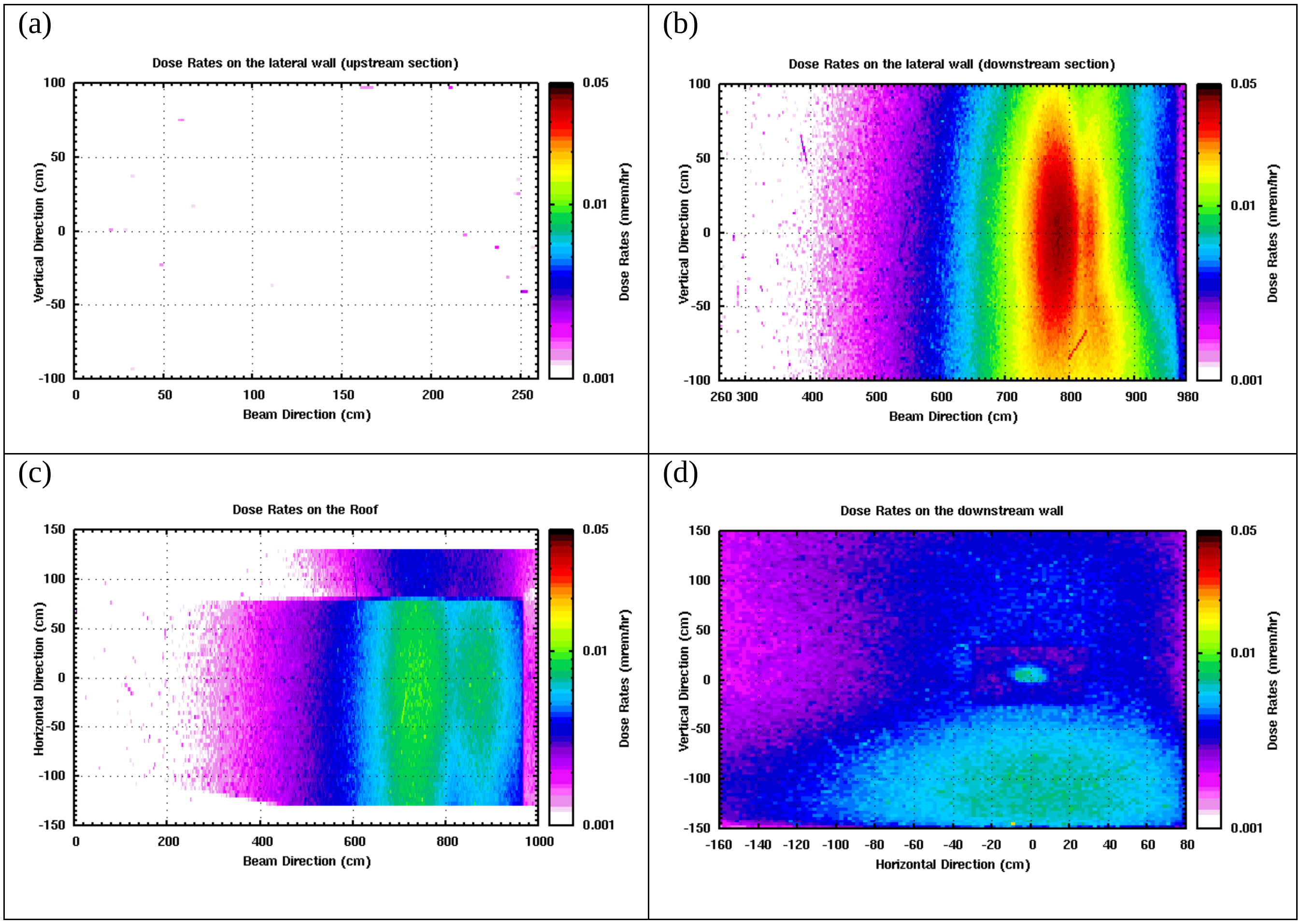

Figure 50: The total dose rate distribution (a) on the lateral wall (upstream section), (b) lateral wall (downstream section), (c) on the roof, and (d) on the downstream FOE wall

4. Synchrotron Radiation Calculation

The 11BM-CMS beamline is a 3 pole wiggler source and its parameters are extracted from reference 1 and reproduced in Table 3. The NSLS-II stored electron beam parameters of 3 GeV and 500 mA (See Table 1) have been used to calculate the critical energy (column 6) and the total integrated power (column 7).

Table 3: Source parameters used for 11BM (CMS) synchrotron radiation calculations

Source	Max. source opening	No. Of periods	Max. B_{eff} (T)	Period (mm)	E_c (keV)	STAC8 Total power (kW) @500 mA
3PW	4.0 mrad-H	1	1.12	--	6.7	0.37

The analytic code STAC8 [3] was used to calculate the ambient dose equivalent rates in the occupied areas outside beamline enclosures and transport pipes. The build-up factor in shield was included in the calculation. However, the effect of SR polarization was not considered leading to the same shielding requirements for the lateral wall and roof provided the distance from the scatter target to dose point is the same. The shielding calculations for the transport beam pipe and ESE assume that bremsstrahlung has been completely stopped in the FOE.

4.1 First Optics Enclosure (FOE)

For maximum scattered radiation the scattering target is assumed to be a silicon disk of 10 cm radius and 2 cm thick tilted at 0.155 degree with the respect to the incident beam [4]. The position of the scatter target is assumed to be located at 11BM-CMS DMM approximately 808 cm from the FOE downstream wall, 131 cm from the lateral wall and 210 cm from the roof. The minimum required shielding for the SR source (no credit has been given to the SGB shielding or Guillotine) and the corresponding ambient dose rates are given in Table 4. The results show that the shielding thicknesses required for the gas-bremsstrahlung will largely shield for the scattered synchrotron radiation. Therefore the existing shielding thicknesses of the FOE walls and roof as given in Appendix 1 are more than adequate to meet the shielding design goal of 0.05 mrem/h.

Table 4: SR shielding design requirements for FOE (11-BM-A enclosure)

	Distance (cm)	Minimum Required Shielding	Ambient Dose rate (mrem/h)
Lateral wall	131	4 mm Pb	0.040
Roof	210	4 mm Pb	0.016
Downstream Wall (> 1^o)	808	6 mm Pb	0.032

4.2 Transport pipe and ESE (11-BM-B)

The lead thickness of the 11BM-CMS monochromatic beam transport pipe is 5 mm which exceed the minimum shielding requirement of 2 mm specified in reference [1]. Figure 51 shows the synchrotron ray tracings for vertical beam mis-steer. The reflected beam off the PFM shown in purple in the bottom drawing could potentially strike the lead shielded junction box (used to transition from the 6’’ pipe to the 4’’pipe). The synchrotron fan shown in blue is completely stopped by the 12 mm (50 cm x 50 cm) beam stop on the downstream wall of the ESE. We assumed a pink beam from Rh coated PFM with a lowest incident angle of 1.95 mrad needed for the reflected beam to strike the junction box consisting of 12 mm of

Lead. The dose rate calculated using STAC8 by the "NICK" card directly downstream of the junction box is 2.43E-04 mrem/hr which is below the design criteria of 0.05 mrem/hr.

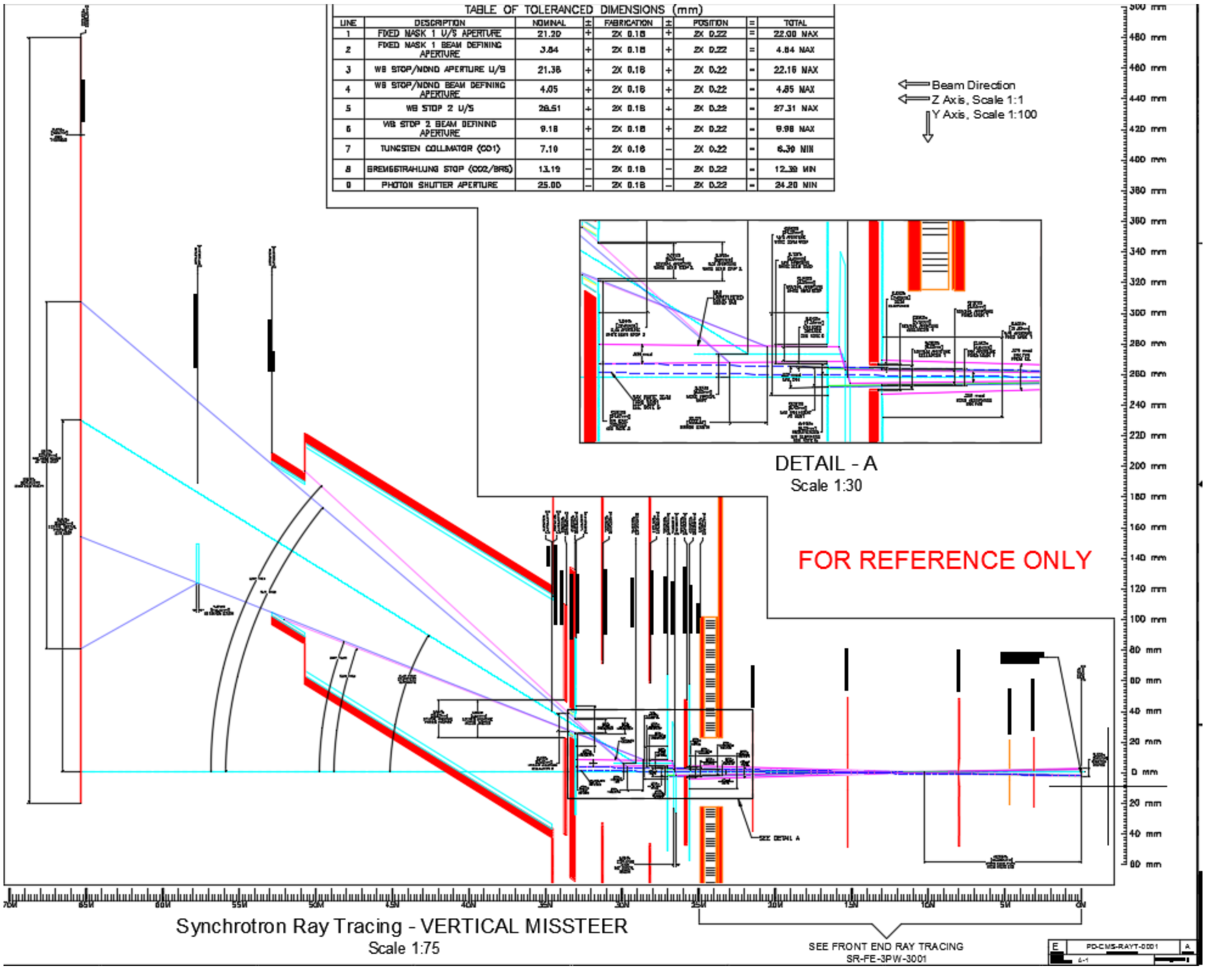

Figure 51: Synchrotron ray tracings – vertical mis-steer.

The ESE dimensions are given in appendix 1 (Table 1.3). The STAC8 calculation was carried out with the same optimum silicon scatter target used for the FOE analysis. The location of target is assumed to be at the position of the Double Harmonic Rejection Mirror. For the beam to enter the beam transport pipe the DMM and PFM inside the FOE must be inserted to direct the beam into the beam transport pipe and toward the ESE. Rh coated mirror at 3.34 mrad to the incident beam is used for the PFM and the DMM crystals assumed at nominal angle of 23.2 mrad [2]. The dose rates on the walls and roof are given in Table 4 and are negligible.

Table 5: SR shielding design requirements for ESE (11-BM-B enclosure)

	Distance (cm)	Minimum Required Shielding	Ambient Dose rate (mrem/h)
Lateral wall	130	3 mm Fe	8.1E-08
Roof	210	2 mm Fe	2.8E-07
Downstream Wall (> 1^{o})	625	6 mm Fe	1.7E-08

5. Summary and Conclusions

At NSLS-II the white beam or First Optical Enclosure (FOE) shielding requirements are dominated by the scattering of the primary bremsstrahlung and not the synchrotron beam. For the simulations the GB beam is normalized at 7.2µW incident power. This value corresponds to the estimated bremsstrahlung power generated by a 500mA electron beam of 3GeV, assuming that the vacuum in the 6.6 m short straight sections is better than 10^{-9}Torr.

Beamline components that intercept the primary GB beam were selected as scattering targets in the simulations based on the Ray Trace Drawings. All simulations were performed with the two secondary bremsstrahlung shields included. A summary of the simulation results is presented in table 6.

Table 6. Maximum total dose rates (mrem/hr) on the roof, lateral wall, and the downstream wall of 11BM-CMS FOE. The numbers in parentheses are the dose rates at 30 cm downstream of the FOE wall.

#	Simulation	Maximum dose (mrem/hr)		
		Roof	Lateral Wall	Downstream wall
1(a)	GB incident near the neck of the FM on the outboard tapered side	< 0.05	< 0.05	< 0.05
1(b)	GB incident near the neck of the FM on the top tapered side	< 0.05	< 0.05	< 0.05
1(c)	GB incident on the front face of the FM near the outboard edge	< 0.05	< 0.05	< 0.05
1(d)	GB incident on the front face of the FM near the top edge	< 0.05	< 0.05	< 0.05
2(a)	GB incident near the center of crystal 1 of the DMM	< 0.05	< 0.05	< 0.05
2(b)	GB incident near the front face of crystal 1 of DMM	< 0.05	< 0.05	< 0.05
2(c)	GB incident near the front face of crystal 2 of DMM	< 0.05	< 0.05	< 0.05
3(a)	GB incident near the neck of WBS1 on the bottom tapered side	< 0.05	< 0.05	< 0.15 (< 0.05)
3(b)	GB incident near the neck of the WBS1 on the outboard tapered side	< 0.05	< 0.05	< 0.08 (< 0.05)
3(c)	GB incident on the front face of WBS1 near the outboard edge	< 0.05	< 0.05	< 0.05
4(a)	GB incident near the center of the PFM	< 0.05	< 0.05	< 0.05
4(b)	GB incident near the downstream edge of PFM	< 0.05	< 0.05	< 0.05
4(c)	GB incident near the upstream edge of PFM	< 0.05	< 0.05	< 0.08 (< 0.05)
5(a)	GB horizontal extreme ray incident on WBS2	< 0.05	< 0.05	< 0.05
5(b)	GB vertical extreme ray incident on WBS2	< 0.05	< 0.05	< 0.05

Simulations 3.3(a), 3.3(b) and 3.4(c) show that the total dose rates on contact with the downstream wall of the FOE will be higher than 0.05 mrem/h but reduces to less than 0.05 mrem/hr at 30 cm away for the exterior of the wall.

Based on the STAC8 calculation, the dose rates outside the FOE, ESE, and beam transport pipe are below 0.05 mrem/hr and consistent with the NSLS-II shielding policy for normal operating conditions as well as fault events.

All shielding simulations should be validated by comparisons with measurements of the dose rates near the walls and roof of the FOE, the ESE, and the beam transport pipe during commissioning.

6. References:

[1] LT-C-ESH-STD-001, Guidelines for the NSLS-II Beamline Radiation Shielding Design, November 7, 2014.
[2] Email from M. Fukuto to M. Benmerrouche (July 13, 2016) and private communication.
[3] Y. Asano, "A study on radiation shielding and safety analysis for a synchrotron radiation beamline," JAERI-Research-2001-006, March 2001.
[4] Attenuation of Scattered Monochromatic Synchrotron Radiation in Iron and Lead", Z. Xia and W.-K. Lee, NSLS-II TN145 (09/16/2014).

7. Acknowledgements:

We would like to thank Lucas Lienhard for providing all the beamline geometry information listed in Appendix 1. We would like to thank Masa Fukuto and Lucas Lienhard for multiple discussions.

Appendix 1
11BM-CMS Beamline - input provided by beamline design engineer Lucas Lienhard

Co-ordinate system

For non-canted beamlines the z axis lies along the long or short straight centerline. The positions (z co-ordinates) of the various components are defined with respect to the center of the Three Pole Wiggler (3PW). The SS centerline was used as the z or beamline axis for the FLUKA models. Y is the vertical axis and x the horizontal axis orthogonal to the y and z axes. *U, D, C refer to upstream, downstream or center of the component.*

Table 1.1 Beamline Enclosures

Wall	Position	Thickness	Material
D/S End of 11-BM-A Ratchet Wall	2489.24 cm		
D/S End of FOE (11-BM-A) Backwall	3458.25 cm	5.0 cm	Lead
Distance of Sidewall from straight CENTERLINE	80.56 cm	1.8 cm	Lead
Distance of Roof from straight CENTERLINE	210.00 cm	0.4 cm	Lead
D/S End of FOE bump-out Backwall	2739.27 cm	5.0 cm	Lead
Distance of bump-out Sidewall from straight CENTERLINE	131.01 cm	1.8 cm	Lead

Table 1.2 Beamline Transport Pipe

Transport Pipe between FOE & SOE (Both 4” and 6” OD pipe in transport, 6” changes to 4” @ 5066cm (z)	ID= 5.75 inches (min) OD=6.00 inches Material: Stainless Steel	Shielding Thickness = 5.0 mm Shielding Material: Lead

Table 1.3 End Station Enclosure

Wall	Position	Thickness	Material
U/S End of 11-BM-B Wall	5285.00 cm	0.3 cm	Steel
D/S End of 11-BM-B Backwall	6535.00 cm	0.6 cm	Steel
Distance of inboard Sidewall from straight CENTERLINE	130.00 cm	0.3 cm	Steel
Distance of outboard Sidewall from straight CENTERLINE	220.00 cm	0.3 cm	Steel
Distance of Roof from straight CENTERLINE	210.00 cm	0.2 cm	Steel
D/S Wall beam stop location (50cm x 50cm)	6533.2 cm (U/S)	1.2 cm	Lead

Table 1.4 Beamline Components

Components	Z location (Distance from 3PW center) (U), (D) or center	Dimensions (specify units)		Offset (vertical or horizontal) w.r.t Straight CENTERLINE	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R) (MAX includes mfr & positional tolerance)			
Fixed Mask (MSK1)	2556.96 cm (U)	22.86cm (x) 15.24cm (y) 4.445cm(z)	US:5.91cm(x),2.20cm(y) DS:4.17cm(x),0.46cm(y) MAX		Cu-Cr-Zr	PD-CMS-MSK-1100
Bremsstrahlung Collimator (CO1)	2571.041 cm (U)	15.0 cm (x), 9.50 cm (y) 20.00 cm (z)	4.589 cm (x) MAX 0.799 cm (y) MAX	No offset	95% Tungsten alloy	PD-CMS-CO-0100
DMM 1st crystal (MONO)	2650 cm (C)	50mm × 25mm × 150mm (z) (rotated@ 31.4 mrad max)		Top surface at centerline	Silicon	PD-CMS-MONO-1000
DMM 2nd crystal (MONO)	2663 cm (C)	50mm × 25mm × 150mm (z) (rotated@ 31.4 mrad max)		Bottom surface offset 3mm +y, w.r.t. 1st crystal	Silicon	PD-CMS-MONO-1000
White Beam stop (WBS1)	2699.2 cm (U)	22.86cm (x) 15.24cm (y) 4.445cm(z)	US:5.80cm(x),2.22cm(y) DS:4.06cm(x),0.49cm(y) MAX	offset 6mm above GB centerline	Cu-Cr-Zr	PD-CMS-MSK-1200
Slits – Vertical (2 individual blades)	2775.3 cm (US-tungsten)	5.0cm (x) 1.7cm (y) 0.2cm (z) (Blade size)	5mm overlap – closed 25mm aperture – open	Center 6mm above GB centerline	Tungsten blade with copper plate for cooling	PD-CMS-SLT-1000
Slits – Horizontal (2 individual blades)	2778.5cm (US-tungsten)	3.0cm (x) 3.0cm (y) 0.2cm (z) (Blade size)	5mm overlap – closed 50mm aperture – open	Center 6mm above GB centerline	Tungsten blade with copper plate for cooling	PD-CMS-SLT-1000
Primary Focusing Mirror (PFM)	2910.0 cm (C)	1000mm (L) × 100mm (W) × 60 mm (H)	90mm radius of curvature	center and reflecting surface of	Silicon	PD-CMS-PFM-1000

		(rotated@ 3.34 mrad max)		crystal 6 mm above GB centerline		
White Beam stop (WBS2)	3298.7 cm (U/S)	22.86cm (x) 15.24cm (y) 4.445cm(z)	US:6.12cm(x),2.66cm(y) DS:4.39cm(x), 0.998cm(y)	3cm above GB centerline	Cu-Cr-Zr	PD-CMS-MSK-1300
Bremsstrahlung Stop (CO2/BRS)	3307.500 cm (U)	41.9 cm (x), 20.3 cm (y) 30.48 cm (z)	5.846 cm (x) MAX 1.986 cm (y) MAX	offset 3.151cm above GB centerline (angled at 6.18 mrad)	Lead	PD-CMS-CO-0200
Shutter (PSH)	3361.989 cm (U)	12.5 cm W × 15 cm H× 3.8 cm	40 mm × 25 mm	3.445 cm up	Tungsten	PD-COM-PSH-1000
Guillotine	3446.822 cm (U)	55.88 cm W × 55.88 cm H × 5.00 cm	152.4 mm (6") diameter	guillotine and aperture 3.99 cm up	Lead	11-BM-A Guillotine
Hutch wall opening & collar square	3452.85cm (U)	Collar dimensions 30cm W x 30 cm H x 1cm Z	9" diameter wall opening	33.99 cm (y) above centerline	Lead	Hutch wall and shielded pipe collar

**gap between lead wall and guillotine is 9.5mm*

Table 1.5 Beamline SGB Shielding

Shielding	Z location (Distance from S.S. center) (U), (D) or center	Dimensions (specify units)		Offset (vertical or horizontal) Straight CENTERLINE	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R)			
SGB shield SC01 (d/s of mono & WBS)	2812.96 cm (U)	50.0 cm (x) x 50.0 cm (y) x 5.0 cm (z) MINIMUM	10.8 cm MAX aperture (diameter)	Y=0.60 cm	Lead	PD-CMS-SBRS-1000
SGB shield SC02 (d/s of mirror)	3118.28 cm (U)	50.0 cm (x) x 50.0 cm (y) x 10.0 cm (z) MINIMUM	10.8 cm MAX aperture (diameter)	Y=1.89cm	Lead	PD-CMS-SBRS-2000

Table 1.6 Front End Components

Shielding	Z location (Distance from S.S. center) (U), (D) or (C)	Dimensions (specify units)		Offset (vertical or horizontal) Straight CENTERLINE	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R) (MAX includes mfr & positional tolerance)			
FM1	794.7cm (US)	22.86cm (x) 15.24cm (y) 4.445cm(z)	1.212cm (x) MAX 0.135cm (y) MAX US: 2.935cm(x), 1.858cm(y)	0	Cu-Cr-Zr	SR-FE-3PW-MSK-1805
LCO1	803.7cm (US)	40.64cm (x) 15.23cm (y) 30.48cm (z)	2.889cm (x) MAX 1.698cm (y) MAX	0	Lead	SR-FE-3PW-CO-0100
Be Window	877.1cm (C)	15.24cm (x) 15.24cm (y) 2.54cm (z)	3.86cm (x) MAX 1.31cm (y) MAX	0	Glidcop with Beryllium foil in aperture	SR-FE-3PW-WIN-0250
X-Y Slit 1	940.7cm (C)	18.42cm (x) 19.37cm (y) 6.03cm (z)	Max opening (30mm H x 10 mm V) Minimum opening (-10mm overlap)	0	Cu-Cr-Zr	SR-FE-3PW-SLT-2000
X-Y Slit 2	988.6cm (C)	18.42cm (x) 19.37cm (y) 6.03cm (z)	Max opening (30mm H x 10 mm V) Minimum opening (-10mm overlap)	0	Cu-Cr-Zr	SR-FE-3PW-SLT-2000
Inboard Shadow Shield	1460.3cm (U)	17.78cm (x) 30.48cm (y) 30.48cm (z)		X = -7.92cm (outboard face)	Lead	SR-FE-3PW-1014
FM2	1522.8cm (US)	22.86cm (x) 15.24cm (y) 4.445cm(z)	2.758cm (x) MAX 0.698cm (y) MAX US: 4.19cm(x), 2.13cm(y)	0	Cu-Cr-Zr	SR-FE-3PW-MSK-1806
Photon Shutter	2113.5cm (C)	15.24cm (x) 15.88cm (y)	5.334cm (x) 1.524cm (y)	Y=2.499cm (aperture	Cu-Cr-Zr	SR-FE-3PW-PSH-0111

		3.175cm (z)		offset from C/L)		
FM3	2140.7cm (US)	22.86cm (x) 15.24cm (y) 4.445cm(z)	3.693cm (x) MAX 0.798cm (y) MAX US: 5.13cm(x), 2.23cm(y)	0	Cu-Cr-Zr	SR-FE-3PW-MSK-1804
LCO2	2149.7cm (US)	43.18cm (x) 20.32cm (y) 30.48cm (z)	4.920cm (x) MAX 2.106cm (y) MAX	0	Lead	SR-FE-3PW-CO-0300
Safety Shutter1	2214.5cm (US)	16.5cm (x) 12.7cm (y) 30.48cm (z)		Y=+9.32cm when open	Lead	SR-FE-3PW-SS-4000
Safety Shutter2	2278.3cm (US)	16.5cm (x) 12.7cm (y) 30.48cm (z)		Y=+9.32cm when open	Lead	SR-FE-3PW-SS-4100
Ratchet Wall Collimator	2344.5cm (US)	See raytrace SR-FE-3PW-3001 revC	See raytrace SR-FE-3PW-3001 revC	0	Lead, concreate & HDPE	SR-FE-3PW-RCO-3000