NSLS II TECHNICAL NOTE BROOKHAVEN NATIONAL LABORATORY	NUMBER **235**
AUTHOR: M. Benmerrouche	DATE **02/01/2017**
02ID SIX Beamline Radiation Shielding Analysis - Revised	

1. Introduction

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 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 to an individual 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 Controlled Area – TLD Required, it is hoped that in the future, it can be declared a Controlled Area – No TLD Required. As such, beamlines should be shielded so that in the event of a fault, the total dose to an individual, integrated over the duration of the fault, is < 20 mrem.

In this report the recommended shielding is based on calculations to achieve dose rates less than 0.05 mrem/h in continuously occupied areas and less than 0.5 mrem/h on contact with the downstream wall of the First Optical Enclosure (FOE) [2] during normal operations

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 sources by the beamline components and/or air. The shielding requirements for the 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) and additional shielding is usually necessary.

The radiation shielding analysis for the Soft Inelastic X-Ray (SIX) scattering beamline is documented in this Technical Note. The goal of the simulations documented here was to estimate the radiation dose levels generated inside and outside of the FOE during normal operations and some fault conditions, thus evaluating the effectiveness of the as-designed shielding.

The layout of the 02ID-SIX beamline is presented in Figure 1. These drawings were extracted from the Beamline Ray Trace Layout [PD-SIX-RAYT-0001]. The ray trace drawings list the major components in the beamline and provide their positions. Beam is shown traveling from right to left. For shielding analysis, this information in addition to the geometries and materials of the components and shielding are collected into an input document, included herein as Appendix 1.

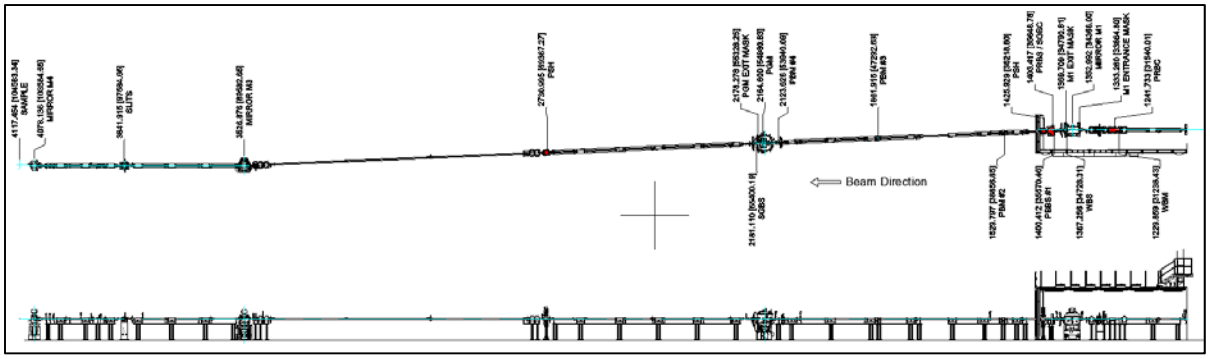

Figure 1: Layout of 02ID-SIX showing the major beamline components, FOE, PGM, and beam transport pipes

The remainder of this document is organized as follows:

- Section 2 describes the model generated for FLUKA analysis of primary GB and SGB in 02ID-SIX FOE, using NSLS-II source parameters, and all 02ID-SIX shielding and optical components as described in the rays tracings and component construction drawings.
- Section 3 presents the FLUKA simulation results. The analysis finds that bremsstrahlung radiation is mostly stopped by shielding at or before the 02ID-SIX FOE downstream wall, but some amount of radiation leaks through the pink beam transport pipe (PBT), making GB/SGB analysis of the PBT necessary.
- Section 4 describes analysis of the synchrotron radiation, considering white beam from the EPU source up to the white beam stop (WBS) located in the FOE, and pink beam through the transport pipe and downstream plane grating monochromator (PGM), and zero-order beam downstream from the PGM.
- Section 5: Summary and Conclusions.
- Section 6: References.
- Section 7: Acknowledgments.

2. Description of the FLUKA Model

At NSLS-II the FOE shielding requirements are dominated by the scattering of the primary GB 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 02ID-SIX beamline includes additional shielding in order to reduce the dose on the downstream wall and around the transport pipe.

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 NSLS-II primary 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 ID straight section	15.5 m
Pressure in straight section	1 ntorr

The beam is normalized at 17 μW incident power for the long straight (15.5 m). The 17 μW value corresponds to the estimated bremsstrahlung power generated by a 500 mA, 3 GeV electron beam, 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.

Based on 02ID-SIX ray tracings primary GB will interact with some of the components per the descriptions in Appendix 1. The areas of the components irradiated by the primary GB are shown in each subsection of Section 3, which describes the results of the primary GB striking each component. Only areas illuminated by the primary GB, per the ray tracing, were sampled for analysis. The simulations performed to confirm the adequacy of the FOE shielding, transport pipe, PGM, and radiation safety components are presented in Table 2. Components referenced in Table 2 are described in more detail below and in Appendix 1.

The 02ID-SIX FLUKA model includes the FOE roof, lateral wall, 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 (164.53 cm distance from beam), the roof is 10 mm Pb (211.2 cm above beam) and the downstream FOE wall is 50 mm Pb (999.42 cm from the ratchet wall). See Appendix 1 for more details. A prototype FLUKA input file is kept in the NSLS-II Radiation Physics Folder.

The FLUKA model (plan view) of the 02ID-SIX beamline is shown in Figure 2. In addition to the FOE, PBT, and PGM, a section of the monochromatic beam transport pipe just downstream of the PGM was also included in the FLUKA model. The FLUKA models use the Z axis along the straight centerline. In Appendix 1, component X, Z coordinates are referenced from the center of the straight. In the FLUKA models, the Z coordinate has an offset of 2672.274 cm setting the origin at the ratchet wall. In the Appendix 1 input tables and in the FLUKA model, the X axis is horizontal with positive sense outboard, and the Y axis is vertical with positive up, Y=0 at the beam orbit height. The positions, dimensions, materials and drawings of the main components are included in Appendix 1. The beamline components in the FOE are shown in Figure 3 and the PGM components are shown in Figure 4.

Table 2: List of FLUKA Simulations

Case # / Report Section	Simulation	GB Beam Position (x, y, z) in cm
1(a) / 3.1 (a)	**WBMEH**: GB extreme horizontal ray on the front face of the White Beam Mask	(2.765 , 0.0 , 449.0)
1(b) / 3.1 (b)	**WBMEV**: GB extreme vertical ray on the front face of the White Beam Mask	(0.0 , 2.152 , 449.0)
1(c) / 3.1 (c)	**WBMAH**: GB near the neck of the White Beam Mask (outboard)	(0.5 , 0.0 , 449.0)
1(d) / 3.1 (d)	**WBMAV**: GB near the neck of the White Beam Mask (top)	(0.0 , 0.5 , 449.0)
2 / 3.2	**BCOEH**: GB on the front face of the Bremsstrahlung collimator	(4.036, 0.0 , 474.0)
3(a) / 3.3 (a)	**ETMSKEH**: GB upstream of the neck of the M1 entrance mask on the outboard side	(1.313 , 0.0 , 709.0)
3(b) / 3.3 (b)	**ETMSKEV**: GB upstream of the neck of the M1 entrance mask on the top side	(0.0 , 1.085 , 709.0)
4(a) / 3.4 (a)	**WBMRCH**: GB incident at the center of the M1 mirror	(0.0 , 0.0 , 738.0)
4(b) / 3.4 (b)	**WBMREH**: GB extreme horizontal ray incident on the front face of M1 mirror	(-1.329 , 0.0 , 738.0)
5 (a) / 3.5 (a)	**WBSTCH**: GB incident at the center of the white beam stop	(0.0 , 0.0 , 790.0)
5 (b) / 3.5 (b)	**WBSTEH**: GB extreme horizontal ray incident on the white beam stop near its aperture	(0.511 , 0.0 , 790.0)

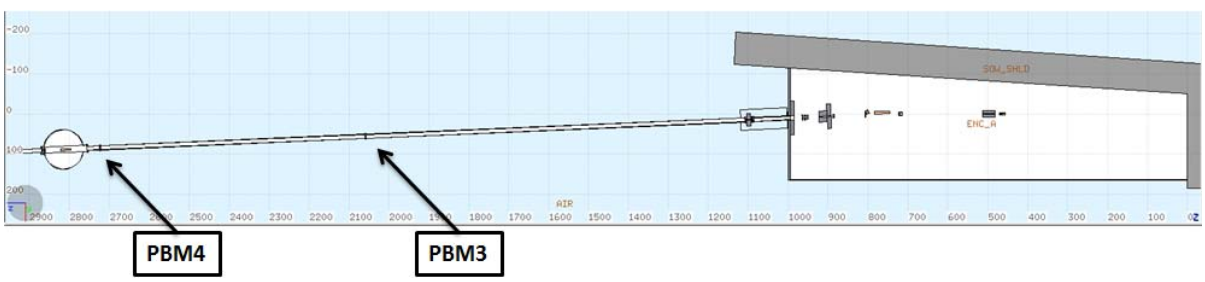

Figure 2: Plan view of the 02ID-SIX FLUKA geometry at the beam centerline (y=0)

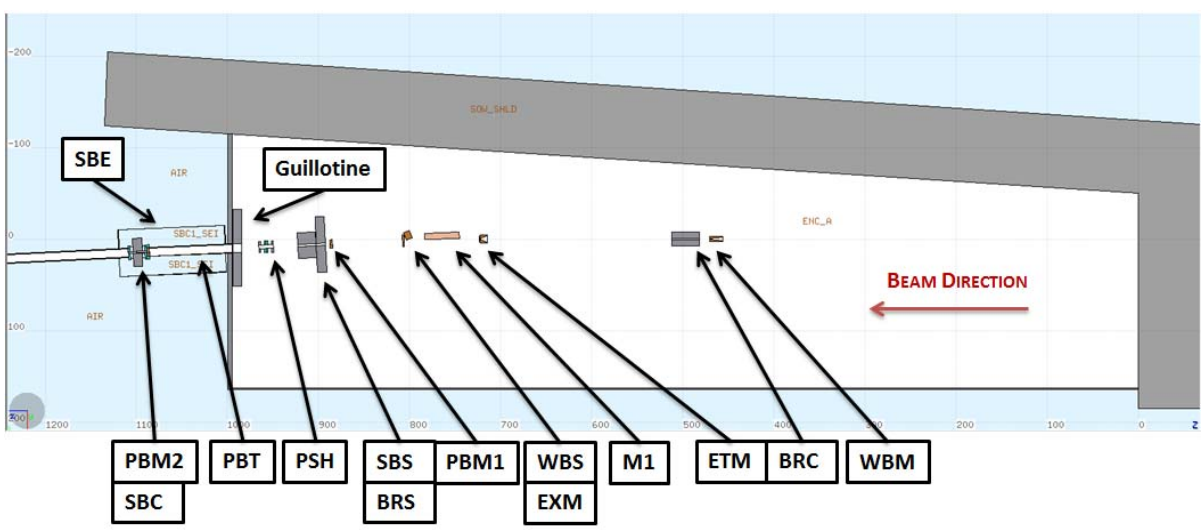

Figure 3: Plan view of the 02ID-SIX beamline components inside the FOE and near the downstream wall of the FOE

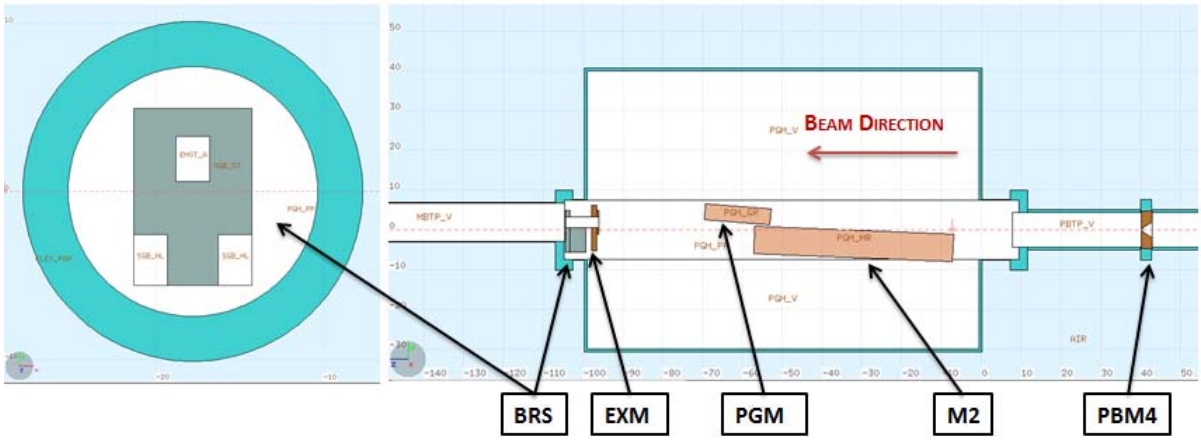

Figure 4: Elevation view of the PGM housing and vertical cut through the bremsstrahlung stop (BRS).

ACRONYMS:

BRC Bremsstrahlung Collimator
BRS Bremsstrahlung Stop
EPU Elliptical Polarized Undulator
ETM Entrance Mask
EXM Exit Mask
FOE First Optical Enclosure
GB Gas Bremsstrahlung
M1 Mirror M1
M2 Mirror M2
PBM Pink Beam Mask
PBS Pink Beam Stop
PBT Pink Beam Transport pipe
PGM Plane Grating Monochromator
PSH Photon Shutter
SBC Secondary Bremsstrahlung Collimator
SBS Secondary Bremsstrahlung Shield
SBE Secondary Bremsstrahlung Enclosure
SR Storage Ring
WBM White Beam Mask
WBS White beam Stop

3. Results for Primary GB Simulations

The simulations performed to confirm the adequacy of the radiation safety components are presented in Table 2. A summary of the simulation results is presented in Section 5.

3.1 (a) WBMEH

The FLUKA model of the copper fixed white beam mask (WBM) and the impact location of the GB beam are shown in Figure 5(a). The WBM aperture is tapered and circular with a diameter of 6.5 mm for the downstream aperture. In this simulation the GB was started just upstream of the selected point of contact at x=2.765 cm, y=0 cm, z=449 cm and impinges on the front face of the WBM on the outboard side. The total dose rate distributions in mrem/h on contact with the roof and at 30 cm away from the lateral wall and downstream wall are shown in Figure 5(b), 5(c) and 5(d). The Bremsstrahlung collimator (BRC) downstream from the WBM is quite effective in stopping the scattered GB in the forward direction resulting in total dose rates not exceeding 0.03 mrem/h one foot away from the downstream wall of FOE. The total dose rates on the roof and the lateral wall are below 0.04 mrem/h. The total dose rate distribution in the FOE is shown in Figure 6, which clearly demonstrates the effectiveness of the collimator in attenuating and stopping the forward secondary GB. The total dose rate distribution in and around the PBT and the PGM is well below 0.01 mrem/h.

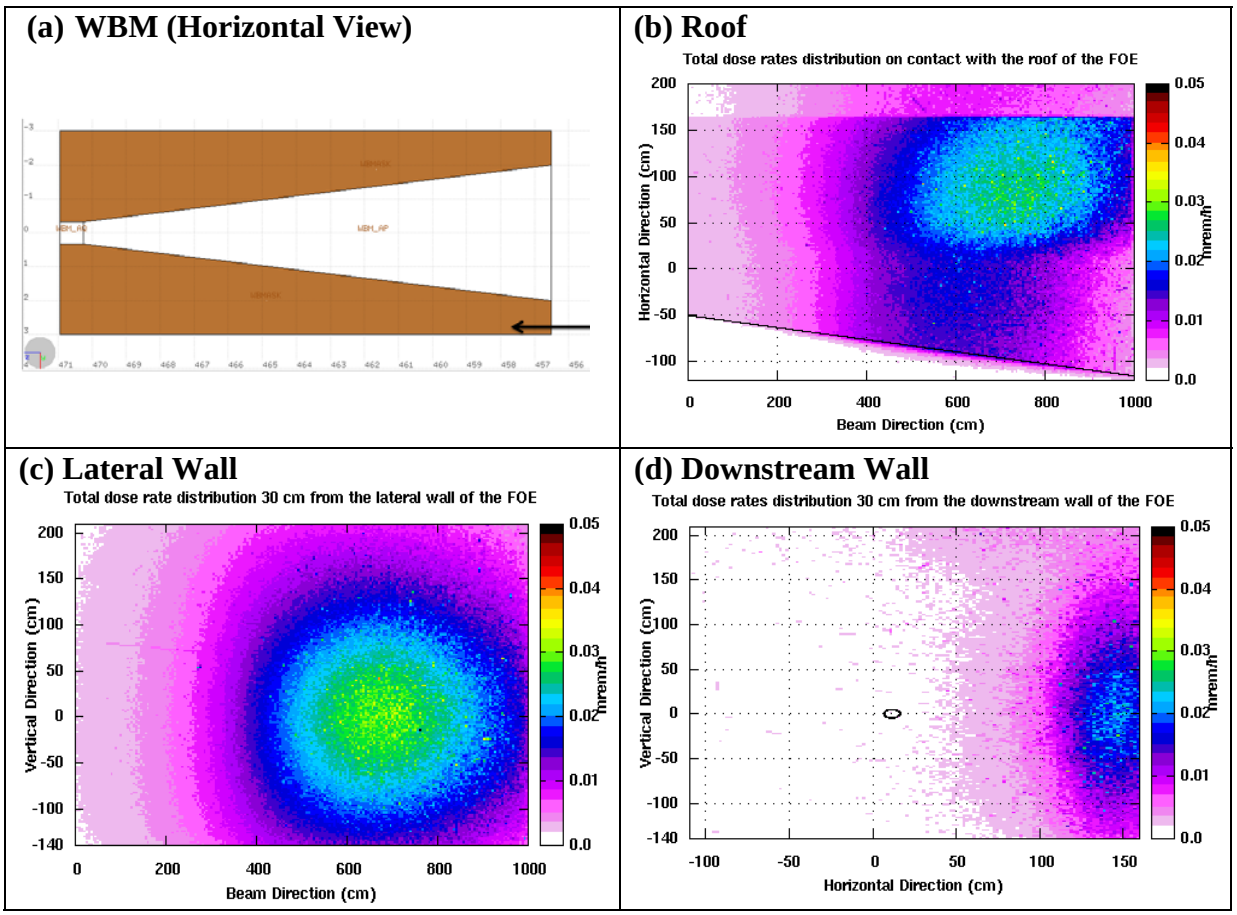

Figure 5: (a) GB position on the WBM. The total dose distributions in mrem/h on **(b)** the roof, **(c)** at 30 cm from the lateral wall and **(d)** 30 cm from the downstream wall of FOE

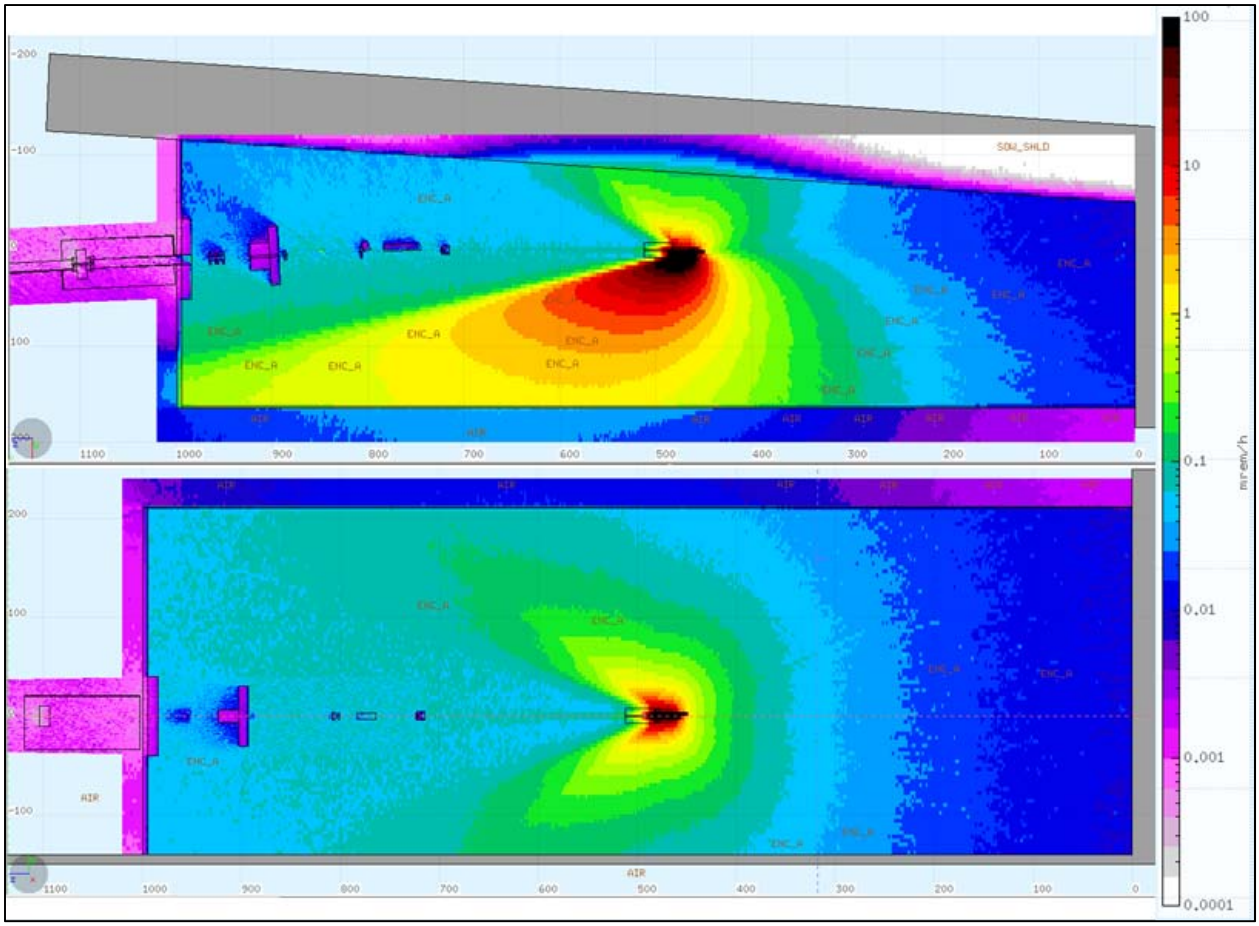

Figure 6: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

3.1 (b) WBMEV

In this simulation the GB was started just upstream of the selected point of contact at x=0 cm, y=2.152 cm, z=449 cm and impinges on the front face of the WBM near the top as illustrated in Figure 7(a). The vertical view of the WBM as modeled in FLUKA is depicted in Figure 7(a) showing eight cooling pipes that run horizontally through the copper block above and below the aperture.

The total dose rate distributions in mrem/h on contact with the roof and at 30 cm away from the lateral wall and downstream wall are shown in Figures 7(b), 7(c) and 7(d). As in the case of WBMEH, the BRC downstream from the WBM is quite effective in stopping the scattered GB in the forward direction resulting in total dose rates not exceeding 0.02 mrem/h one foot away from the downstream wall of FOE. The total dose rates on the lateral wall is below 0.02 mrem/h. The highest dose rates are found on the roof, but they still are below 0.05 mrem/h.

The total dose rate distribution in the FOE is shown in Figure 8, which clearly demonstrates the effectiveness of the BRC in attenuating and stopping the forward secondary GB. The total dose rate distribution in and around the PBT and the PGM is well below 0.01 mrem/h.

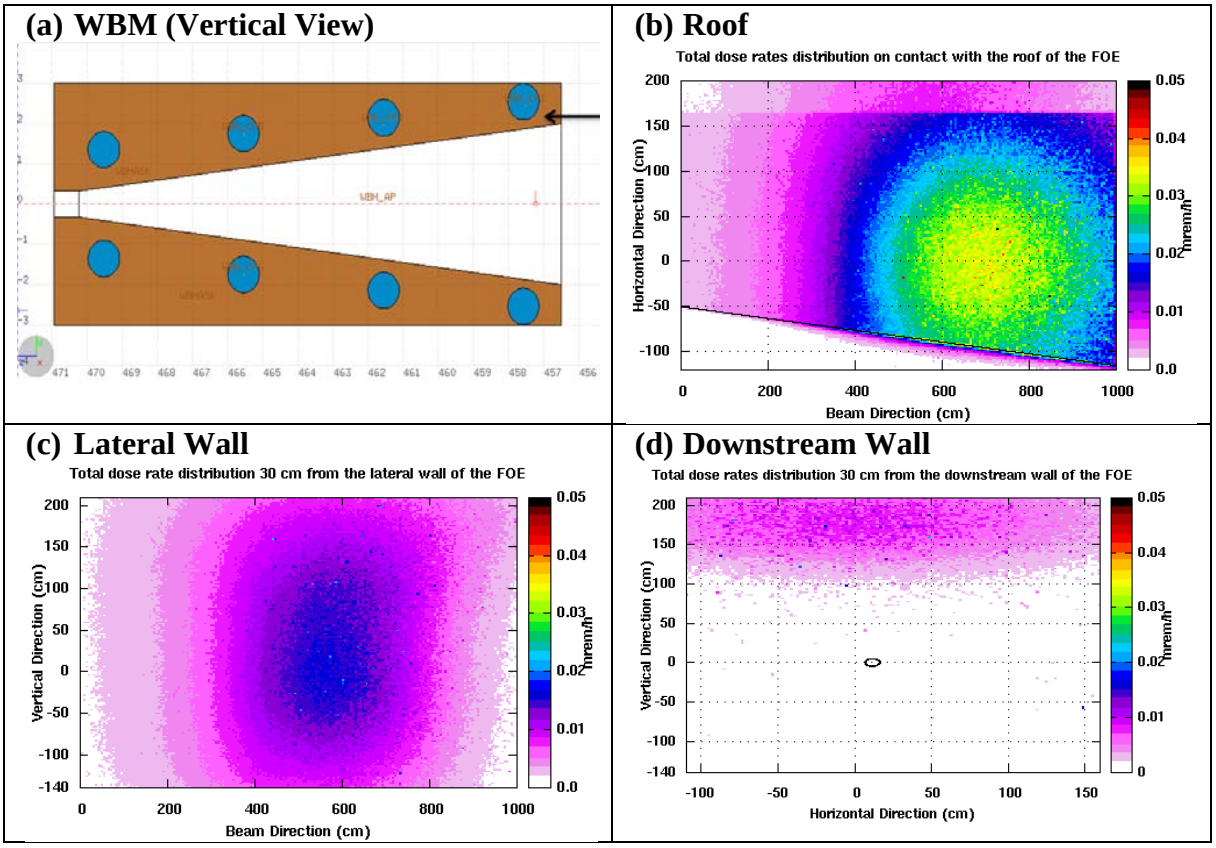

Figure 7: (a) GB position on the WBM. The total dose distributions in mrem/h on **(b)** the roof, **(c)** at 30 cm from the lateral wall and **(d)** 30 cm from the downstream wall of FOE

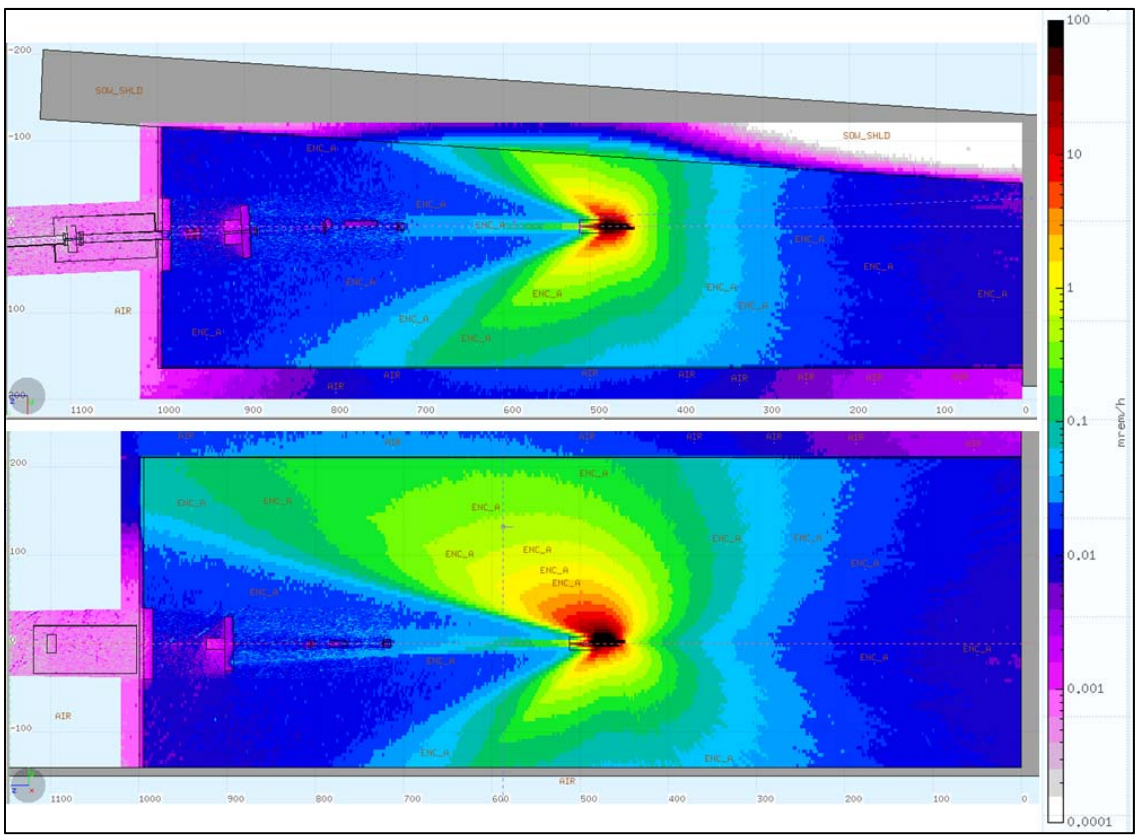

Figure 8: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

3.1 (c) WBMAH

In this simulation the GB was started just upstream of the selected point of contact at x=0.5 cm, y=0.0 cm, z=449 cm and incident near the neck of the WBM aperture on the outboard side as illustrated in Figure 9(a).

The total dose rate distributions in mrem/h on contact with the roof, at 30 cm away from the lateral wall and on contact with the downstream wall are shown in Figures 9(b), 9(c) and 9(d). The total dose rates on the roof are below 0.03 mrem/h, while on the lateral wall they are below 0.02 mrem/h. The total dose rates 30 cm away from the downstream wall reached approximately 0.06 mrem/h, but they are well below 0.5 mrem/h on contact.

The total dose rate distribution in the FOE is shown in Figure 10. It demonstrates that the WBM becomes a source of SGB, which propagates down the aperture of the BRC and scatters by entrance mask, mirror M1 and the WBS. The scattered radiation travels through the apertures of the SGB shield/ BRS, photon shutter, guillotine, and down the PBT as shown in Figure 11. The secondary bremsstrahlung collimator (SBC) downstream from pink mask 2 is quite effective in attenuating and stopping the forward secondary GB. Total dose rate distribution on contact with the PBT and the PGM is less than 0.05 mrem/h, except for a small region between the Pink Beam Mask 2 (PBM2) and SBC, as depicted in Figure 11 (c). In this small region, the maximum total dose rates are approximately 3 mrem/h and the secondary bremsstrahlung enclosure should prevent people from getting close to that region.

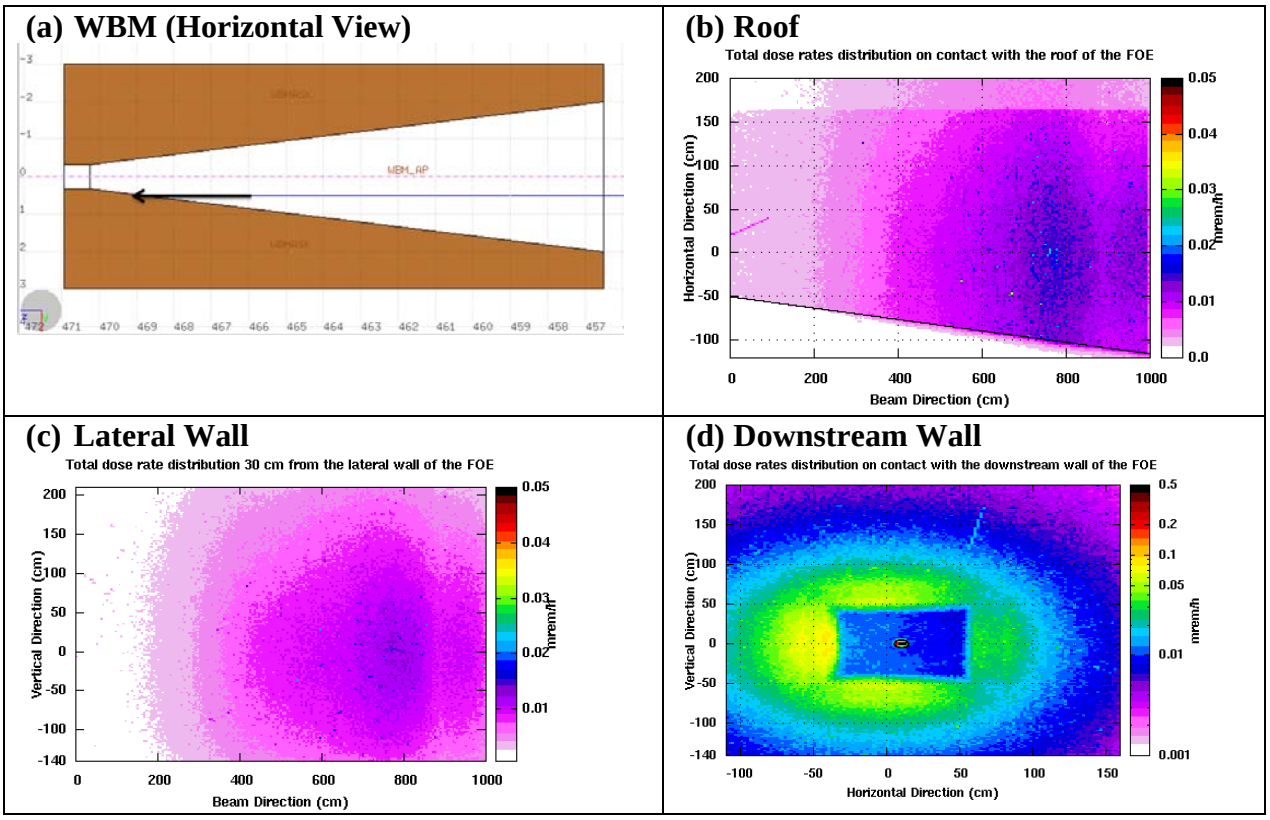

Figure 9: (a) GB position on the WBM. The total dose distributions in mrem/h on **(b)** the roof, **(c)** at 30 cm from the lateral wall and **(d)** on contact with the downstream wall of FOE

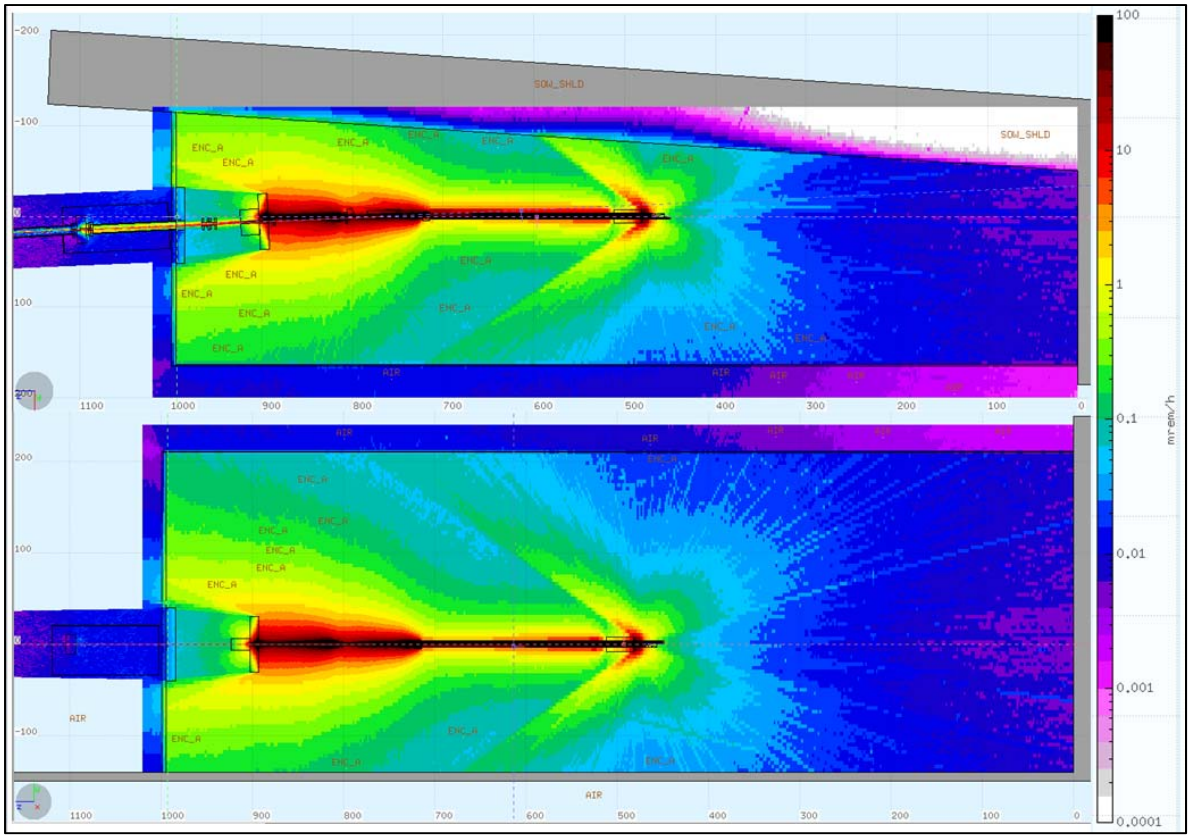

Figure 10: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

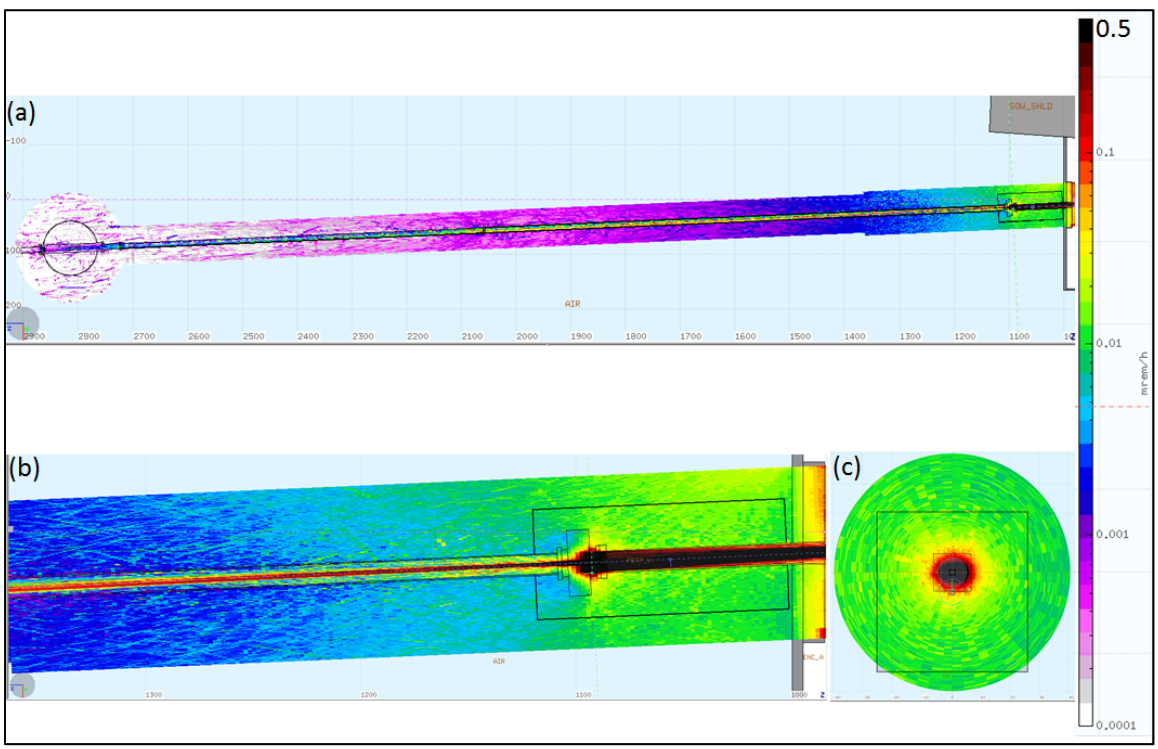

Figure 11: Total dose rate distribution (mrem/h) **(a)** in and around the PBT and the PGM (plan view); **(b)** in the vicinity if a section of the pipe downstream of the FOE and **(c)** at a vertical cut between the PBM 2 and SBC.

3.1 (d) WBMAV

In this simulation the GB was started just upstream of the selected point of contact at x=0.0 cm, y=0.5 cm, z=449 cm and incident near the neck of the WBM aperture on the top side as illustrated in Figure 12(a).

The total dose rate distributions in mrem/h on contact with the roof, at 30 cm away from the lateral wall and on contact with the downstream wall are shown in Figures 12(b), 12(c) and 12(d). The total dose rate distribution in the FOE and in the vicinity of the PBT and the PGM are given in Figures 13 and 14. These dose rate distributions are very similar to those for case WBMAH.

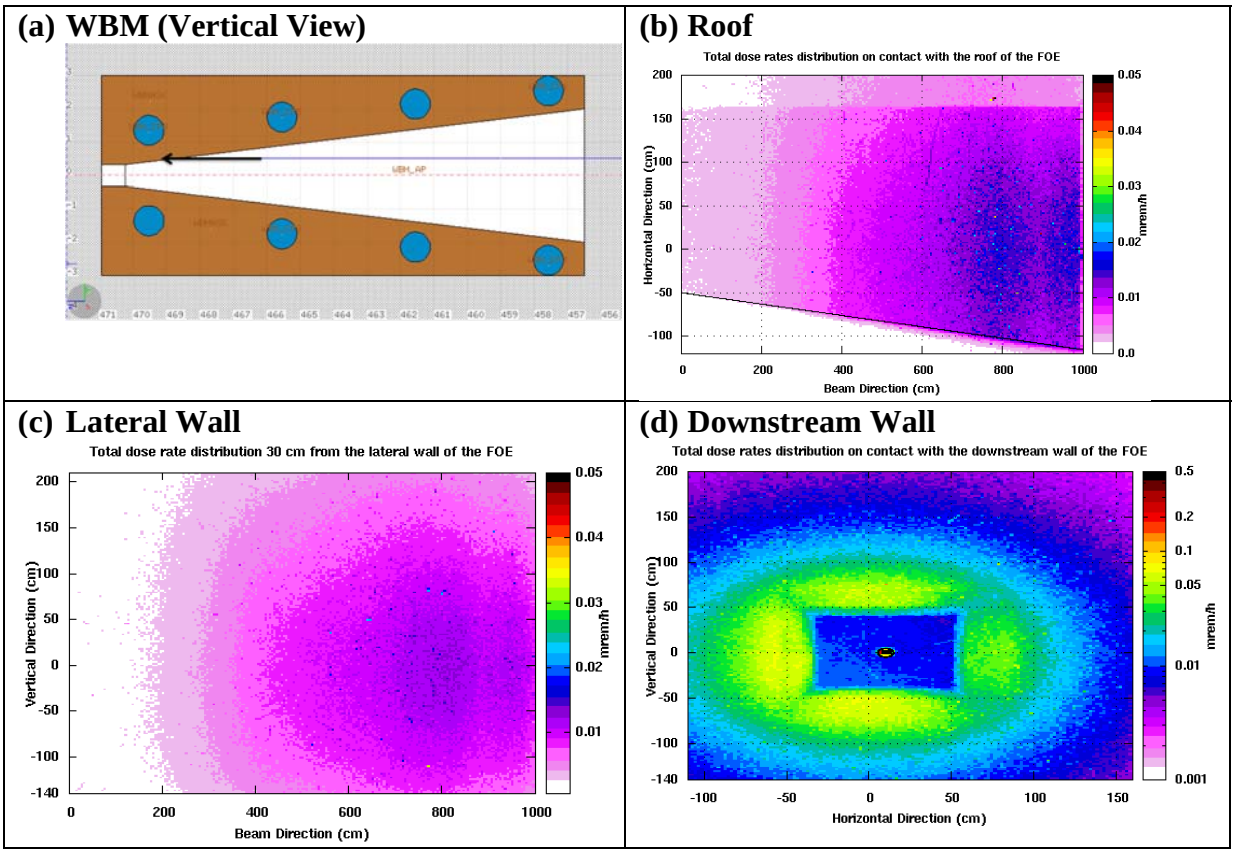

Figure 12: (a) GB incident on the WBM. The total dose distributions in mrem/h on **(b)** the roof, **(c)** at 30 cm from the lateral wall and **(d)** on contact with the downstream wall of FOE

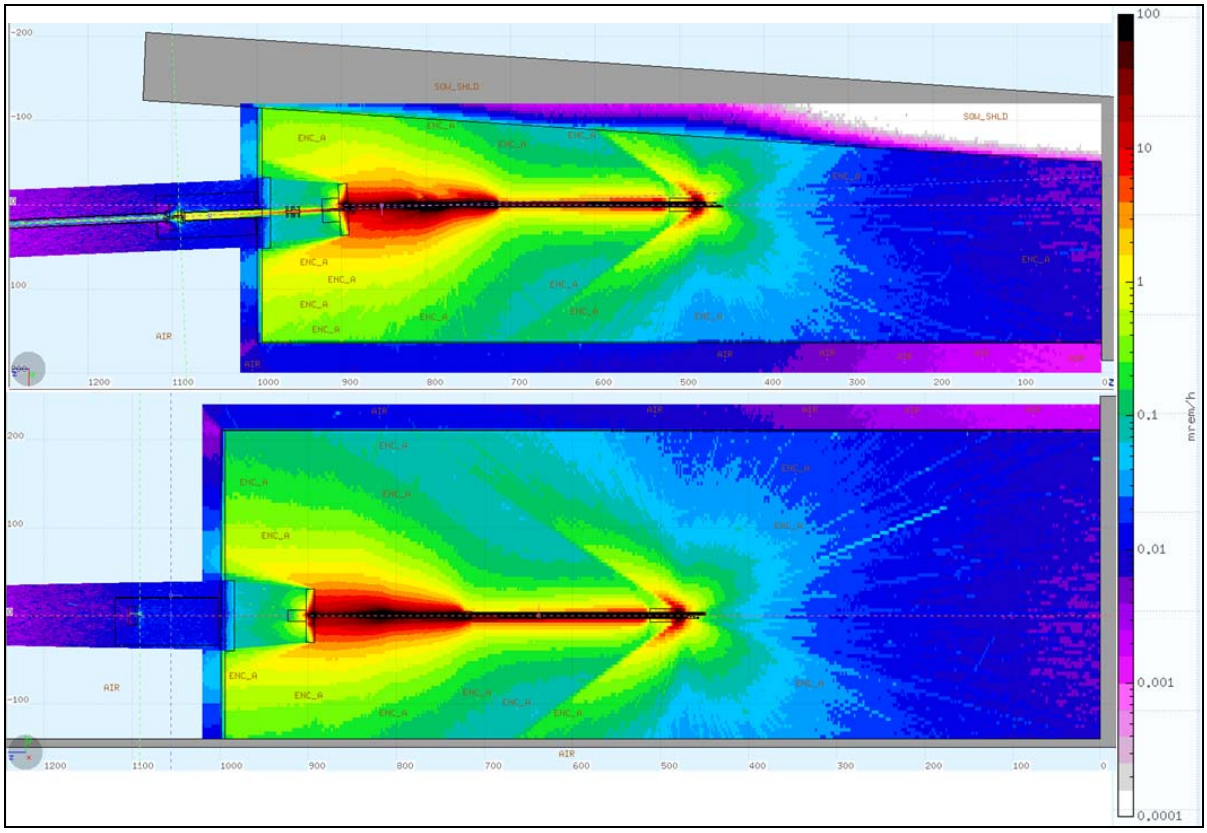

Figure 13: Total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

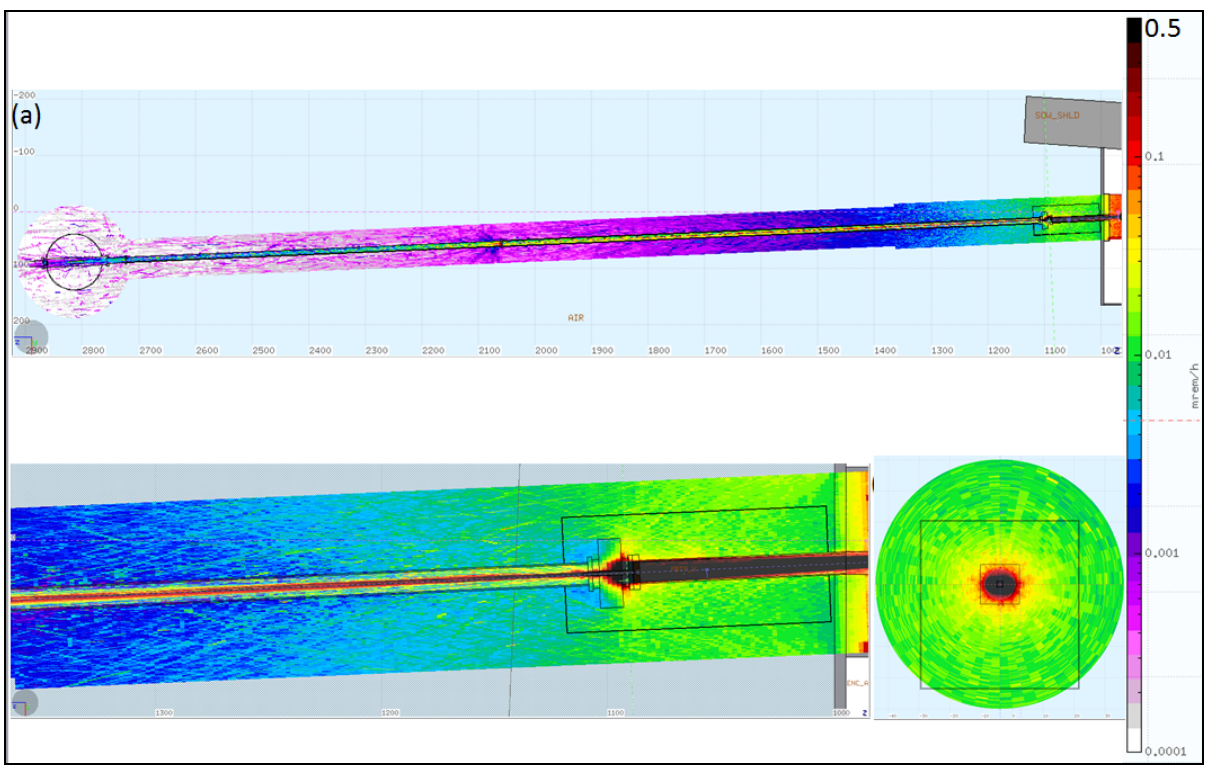

Figure 14: Total dose rate distribution (mrem/h) **(a)** in and around the PBT and the PGM (plan view); **(b)** at a section of the pipe downstream of the FOE and **(c)** at a vertical cut between the PBM2 and SBC

3.2 BCOEH

The GB source was placed just upstream of the front face of the BRC. According to the ray trace drawings, the extreme GB ray will impinge on the collimator 3.08 cm from the outer edge at x=4.036cm, y=0.0 cm, and z=474.0 cm as illustrated in Figure 15(a).

The total dose rate distributions in mrem/h on contact with the roof, at 30 cm away from the lateral wall and on contact with the downstream wall are shown in Figures 15(b), 15(c) and 15(d).

The total dose rate distribution in the FOE and in the vicinity of the PBT and the PGM are given in Figures 16 and 17. The BRC is quite effective in stopping the GB. However, it becomes a source of neutrons that are emitted isotropically. This results in high neutron contributions to the total dose rate on the transverse walls of the FOE as illustrated in Figures 16 and 17.

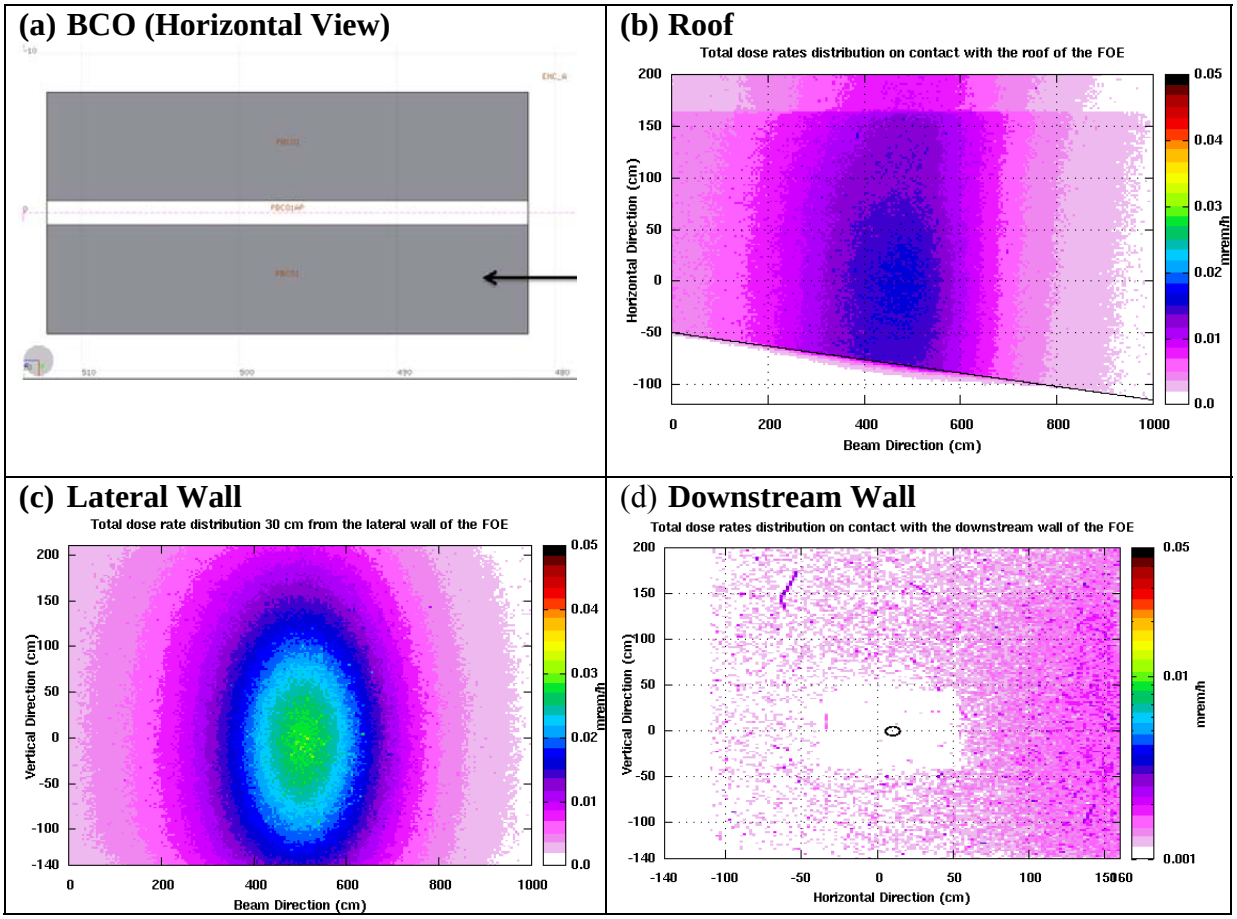

Figure 15: (a) GB position on the Bremsstrahlung collimator BCO. The total dose distributions in mrem/h on **(b)** the roof, **(c)** at 30 cm from the lateral wall and **(d)** on contact with the downstream wall of FOE

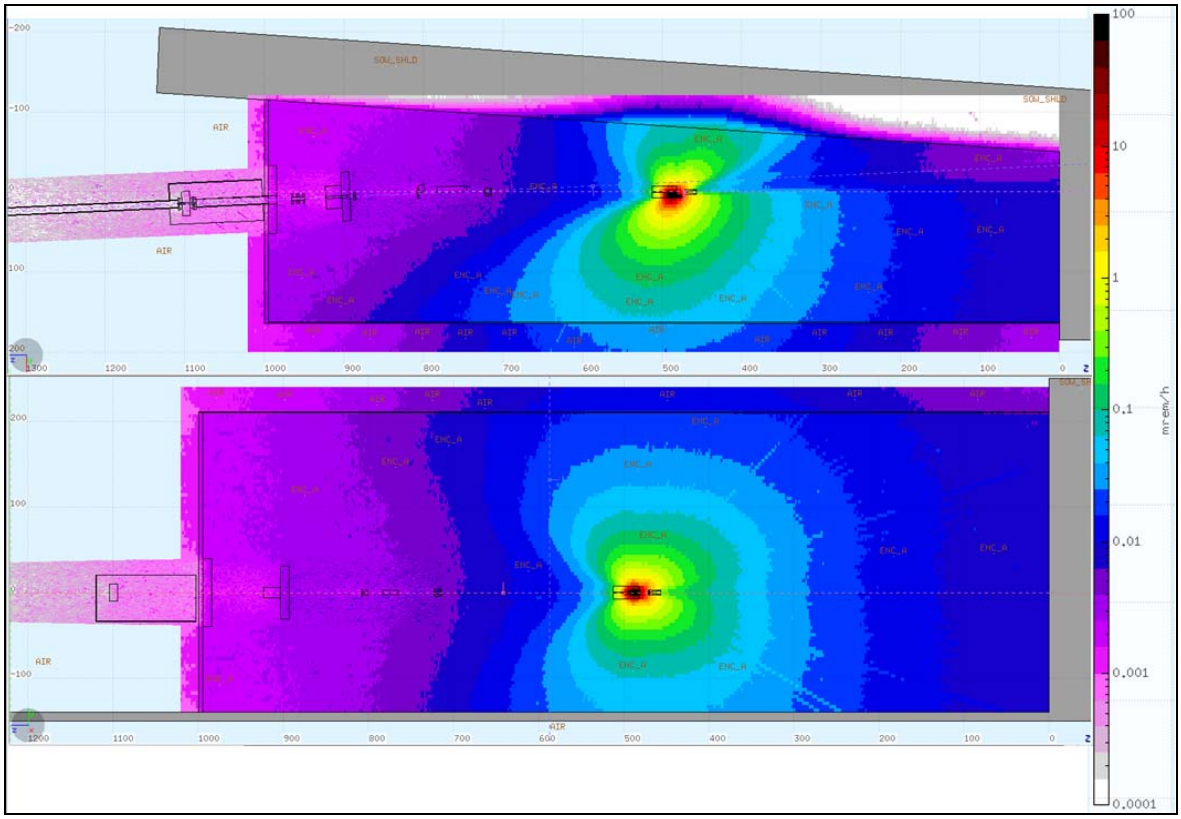

Figure 16: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

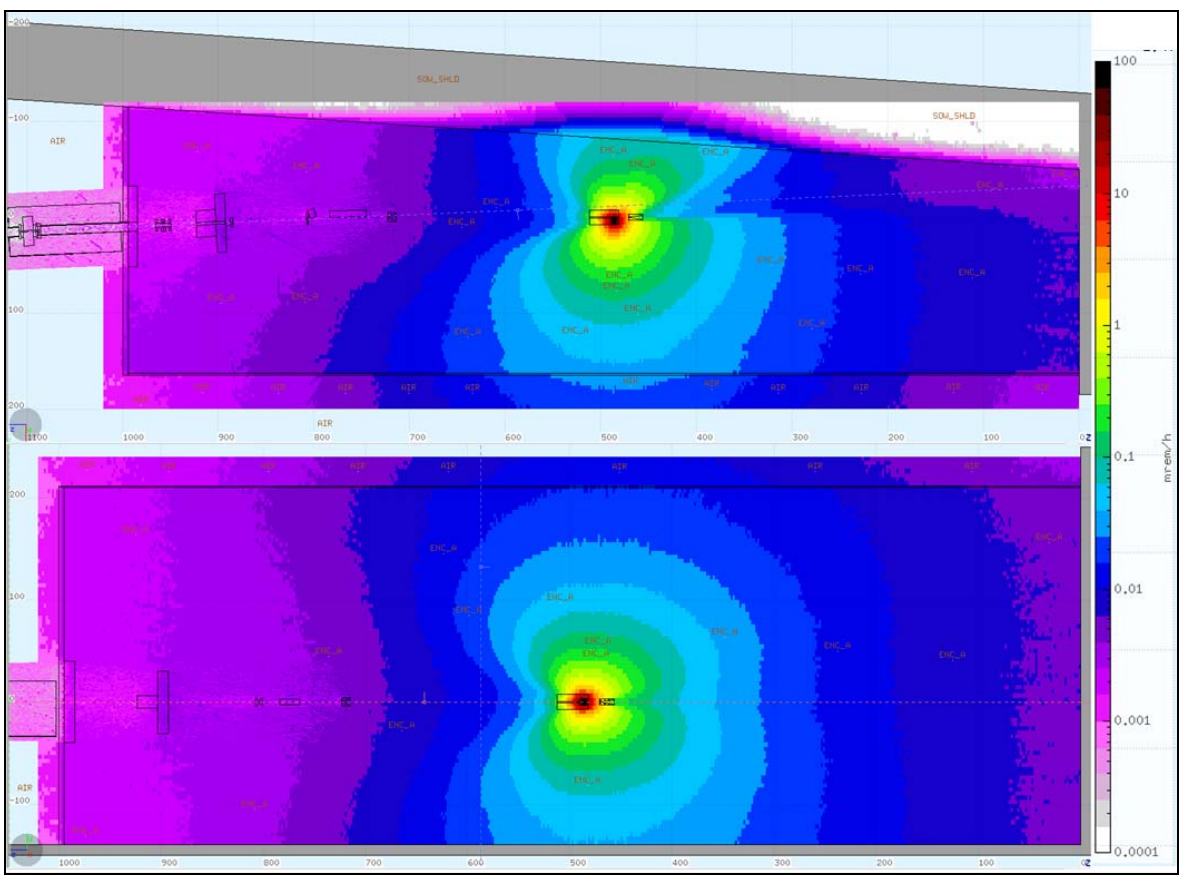

Figure 17: The neutron dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

3.3(a) ETMSKEH

In this simulation the GB was started just upstream of the selected point of contact at x=1.313 cm, y=0 cm, z=709 cm and incident just upstream of the neck of the M1 entrance mask as illustrated in Figure 18(a).

The total dose rate distributions in mrem/h on contact with the roof, at 30 cm away from the lateral wall and on contact with the downstream wall are shown in Figures 18(b), 18(c) and 18(d). The total dose rates on the roof are below 0.02 mrem/h ,while on lateral wall they are below 0.03 mrem/h. The total dose rates 30 cm away from the downstream wall reached approximately 0.07 mrem/h, but are well below 0.5 mrem/h on contact with downstream wall.

The total dose rate distribution in the FOE is shown in Figure 19.When the GB beam impinges on the neck of the entrance mask ,the mask becomes a source of SGB. This SGB is scattered by mirror M1 through the apertures of the SGB shield, BRS, PBM1, photon shutter and guillotine, down the PBT to the PBM2 and SBC. Most of the radiation is stopped by SBC except for a small amount of radiation that propagate through the SBC aperture down the transport pipe. Dose rates in the vicinity of the transport pipe and PGM are shown in Figure 20. Dose rates around the transport pipe and the PGM were found to be less than 0.05 mrem/h, except for a small region in the vicinity of PBM2 as depicted in Figures 20 (b) and (c). The secondary bremsstrahlung enclosure shown in the rectangular box in Figures 20(b) and 20(c) should prevent people from getting close to that region.

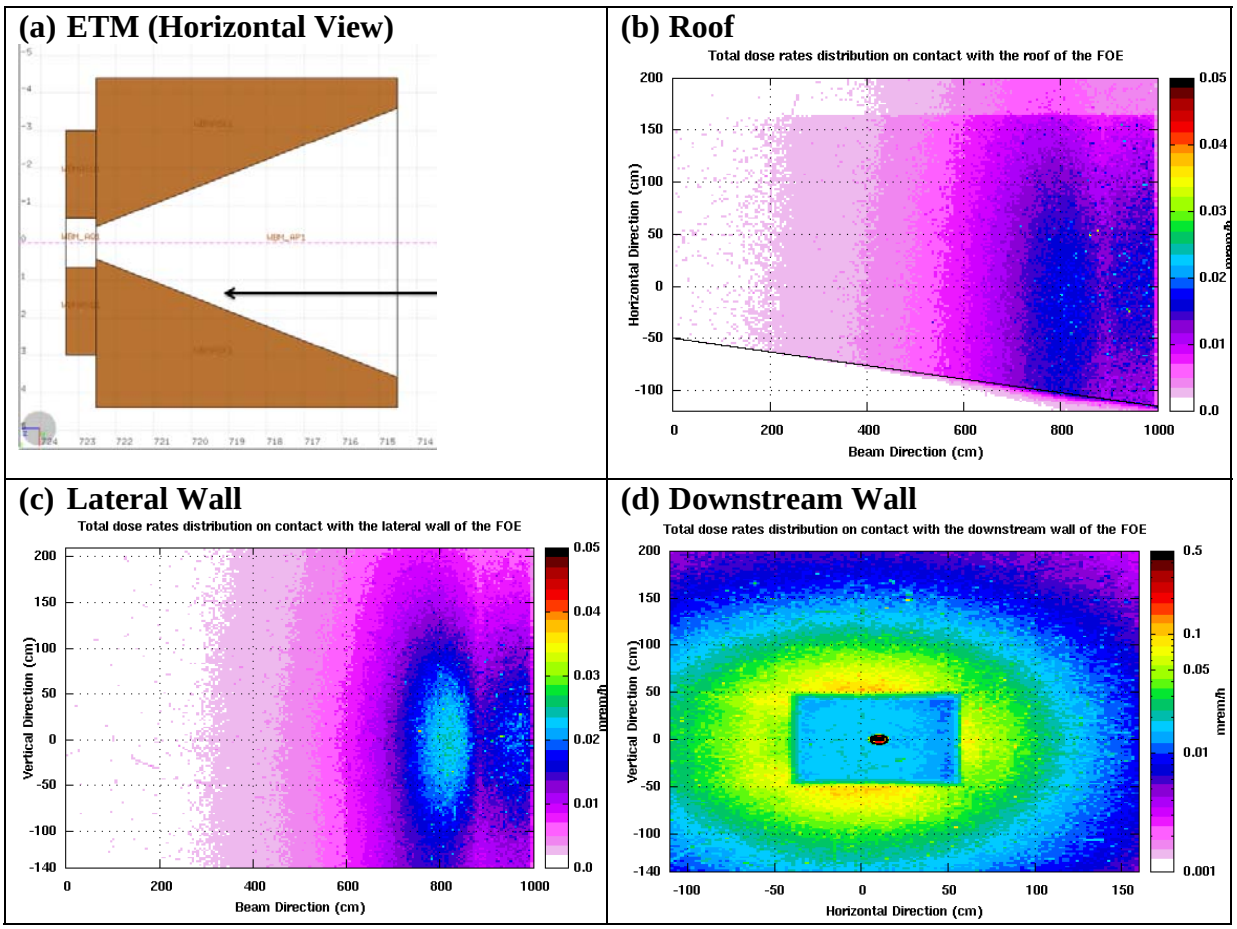

Figure 18: (a) GB position on the M1 entrance mask ETM. The total dose distributions in mrem/h on **(b)** the roof, **(c)** on contact with the lateral wall and **(d)** on contact with the downstream wall of FOE

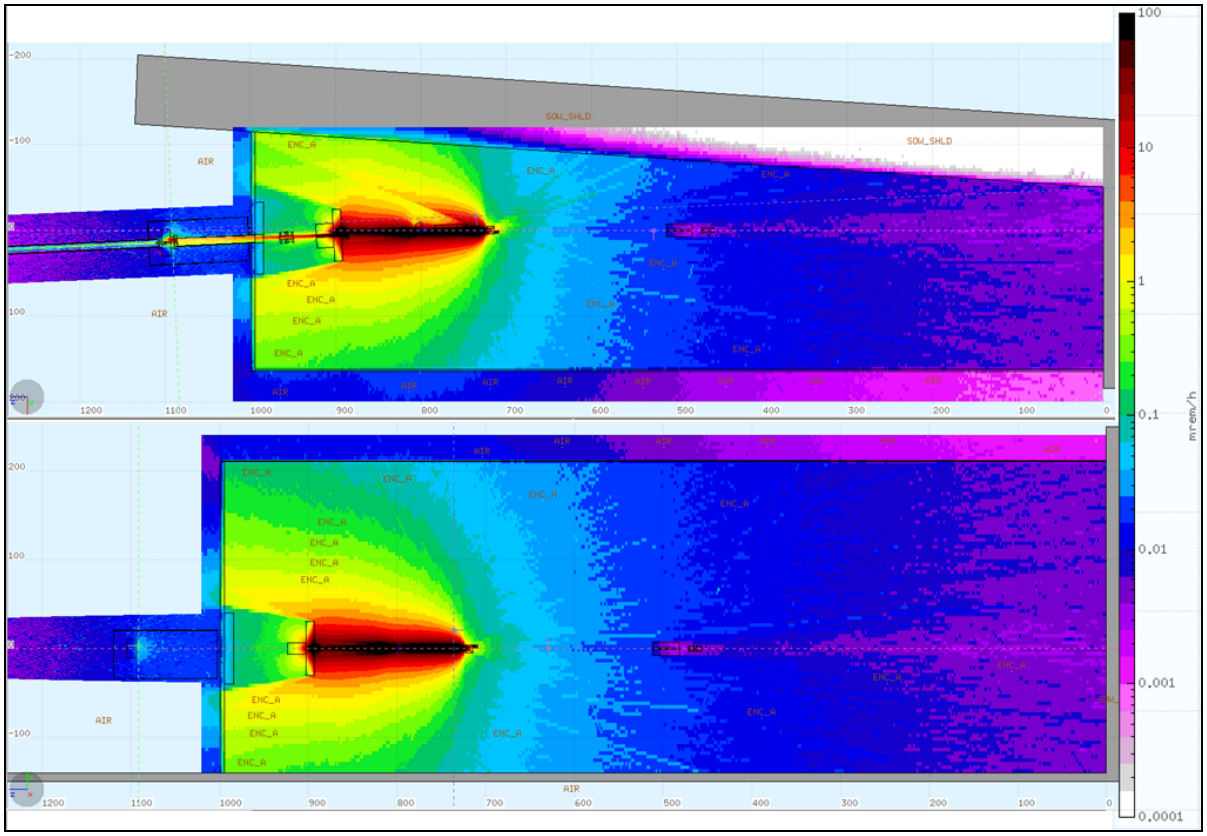

Figure 19: Total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

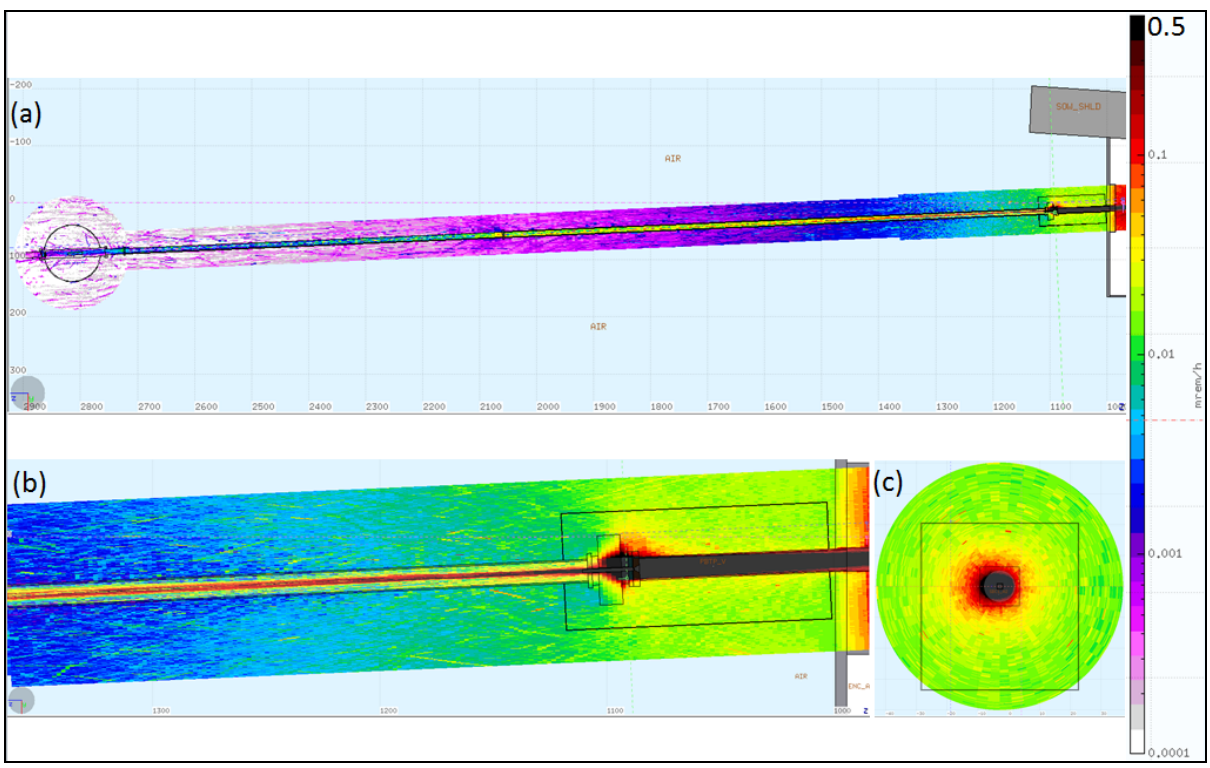

Figure 20: Total dose rate distribution (mrem/h) **(a)** in and around the PBT and the PGM (plan view); **(b)** at a section of the pipe downstream of the FOE and **(c)** at a vertical cut between the PBM2 and SBC.

3.3(b) ETMSKEV

In this simulation the GB was started at x=0 cm, y=1.085 cm, z=709 cm and impinges on the top tapered plane close to the neck of the aperture of the M1 entrance mask, as illustrated in Figure 21(a).

This case is similar to previous case ETMSKEH except the secondary radiation transmitted down the PBT is reduced. The total dose rate distributions in mrem/h on contact with the roof, the lateral wall and downstream wall are shown in Figures 21(b), 21(c) and 21(d). The total dose rate distribution in the FOE is shown in Figure 22. Dose rates in the vicinity of the PBT and PGM are shown in Figure 23. Dose rates on contact with the roof, lateral wall, outside the SBC enclosure, around the PBT and the PGM were found to be less than 0.05 mrem/h. The maximum total dose rate on contact with the downstream wall is ~0.2 mrem/h, while 30cm away it is ~0.07 mrem/h.

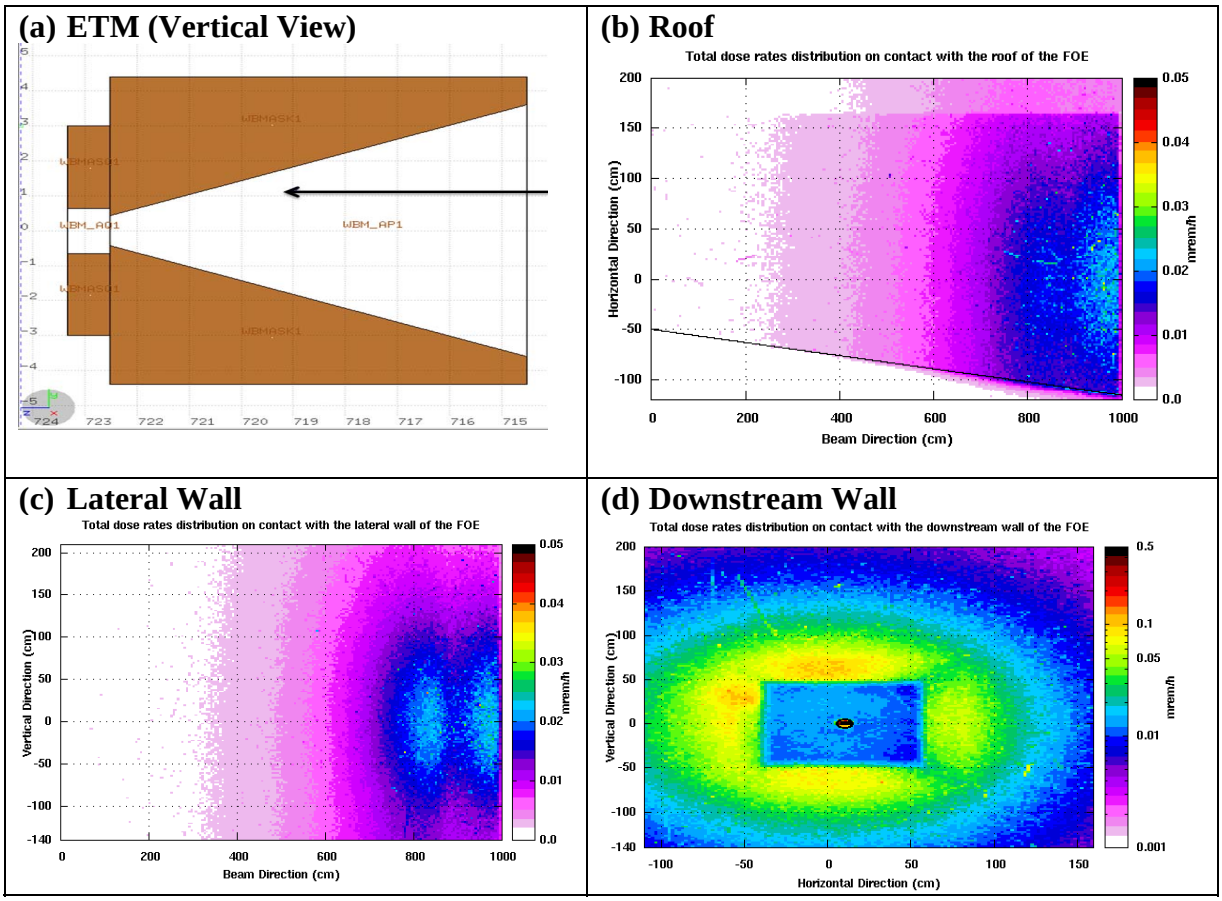

Figure 21: (a) GB position on the M1 entrance mask ETM. The total dose distributions in mrem/h **(b)** on the roof, **(c)** on contact with the lateral wall and **(d)** on contact with the downstream wall of FOE

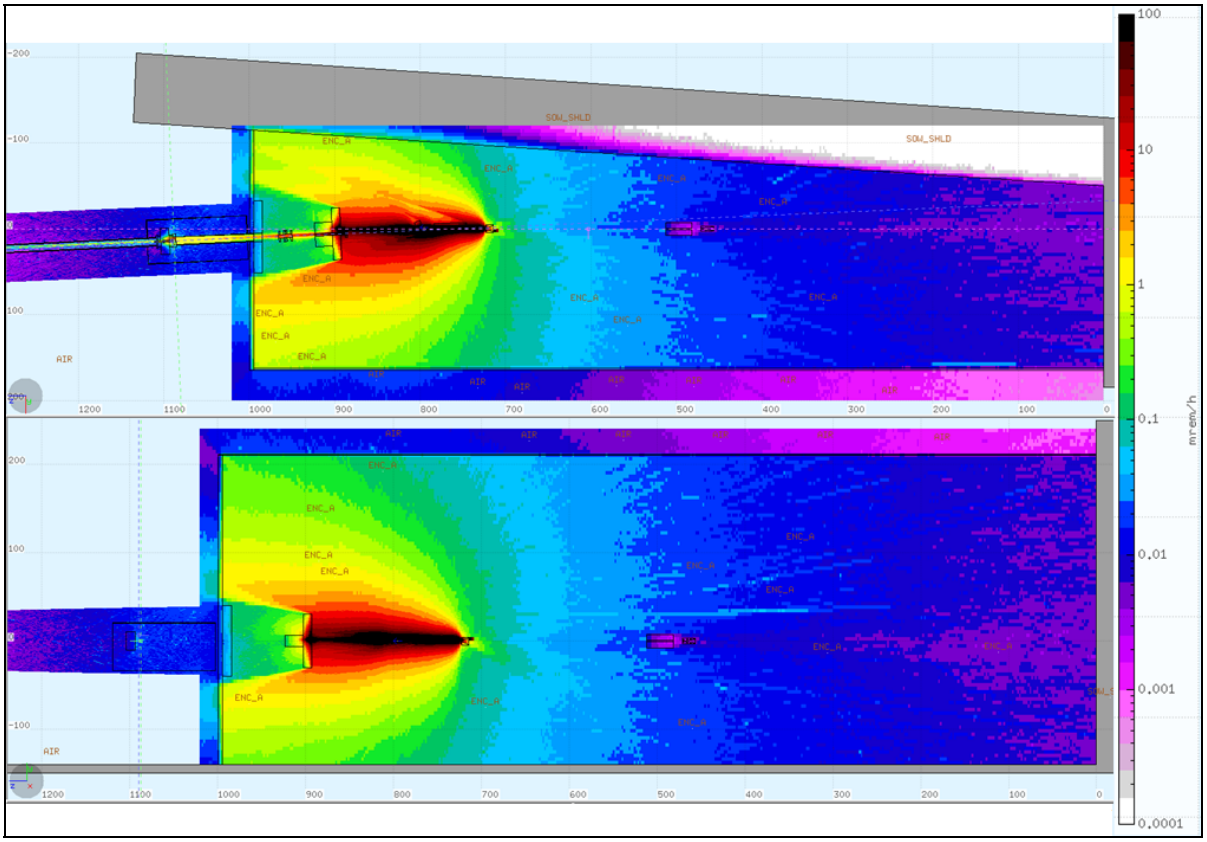

Figure 22: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

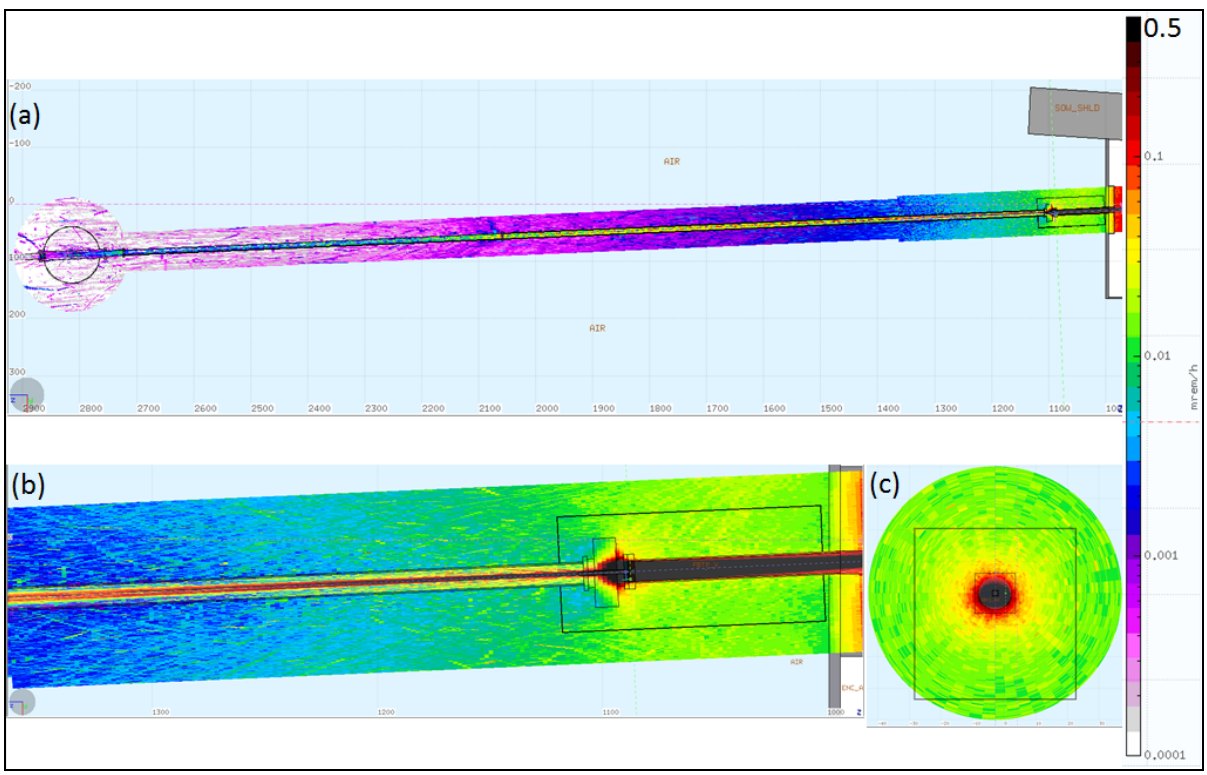

Figure 23: Total dose rate distribution (mrem/h) **(a)** in and around the PBT and the PGM (plan view); **(b)** at a section of the pipe downstream of the FOE and **(c)** at a vertical cut between the PBM2 and SBC

3.4(a) WBMRCH

The GB starts at the nominal position x=0 cm, y=0 cm, z=738 cm and is incident on the center of the mirror M1. The beam is scattered by half the mirror and part of the SGB directed at ~2.47 degrees (the path of the reflected synchrotron beam), passes through the M1 exit mask, PBM1, and SGB shield and BRS, down the transport pipe into the PBM2, with the SBC being very effective in stopping the SGB. The amount of radiation that leaks through the collimator aperture undergoes a scatter at the PBM3, but is too weak to produce any substantial dose.

The total dose rate distributions in mrem/h on contact with the roof, the lateral wall and downstream wall are shown in Figures 24(b), 24(c) and 24(d). The total dose rate distribution in the FOE is shown in Figure 25. Dose rates in the vicinity of the PBT and PGM are shown in Figure 26. The vertical cut through the transport pipe between PBM2 and SBC shows that even though some radiation leaks through the PBT, the total dose rate elsewhere on contact with pipe is less than 0.05 mrem/h. The SBC enclosure will prevent people from getting close to the high dose region. Dose rates on contact with the roof, lateral wall, outside the SBC enclosure, around the PBT and the PGM were found to be less than 0.05 mrem/h. The maximum total dose rate on contact with the downstream wall is ~0.2 mrem/h, while 30cm away it is ~0.06 mrem/h.

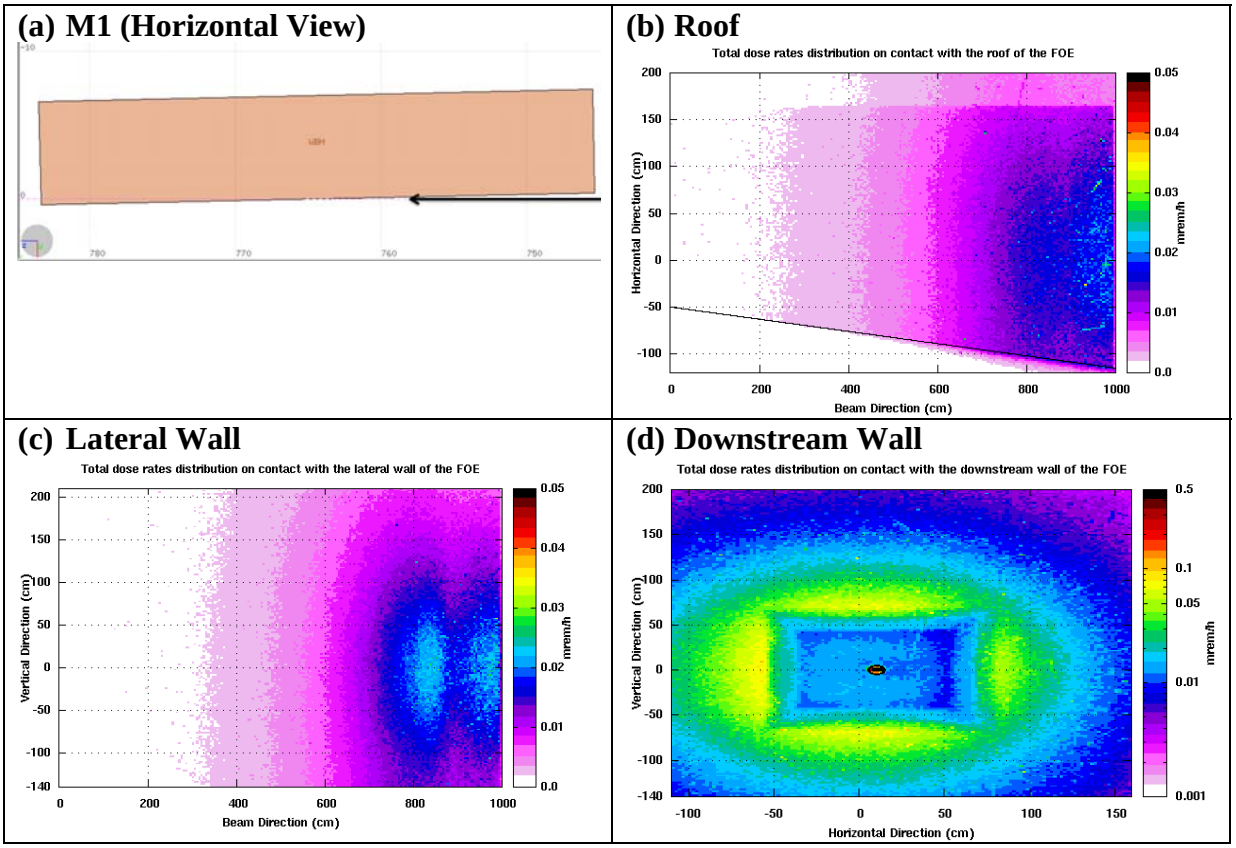

Figure 24: (a) GB position on the M1 mirror. Total dose distributions in mrem/h **(b)** on the roof, **(c)** on contact with the lateral wall and **(d)** on contact with the downstream wall of FOE

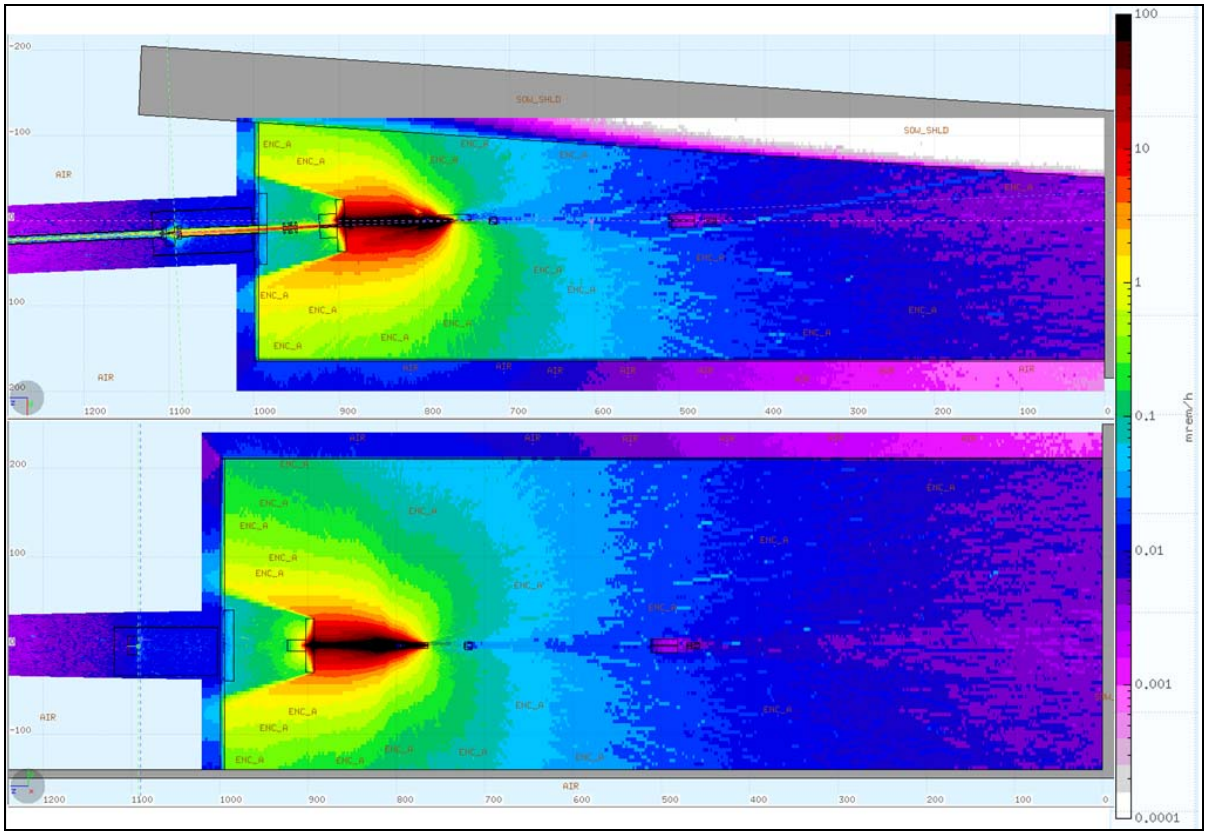

Figure 25: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

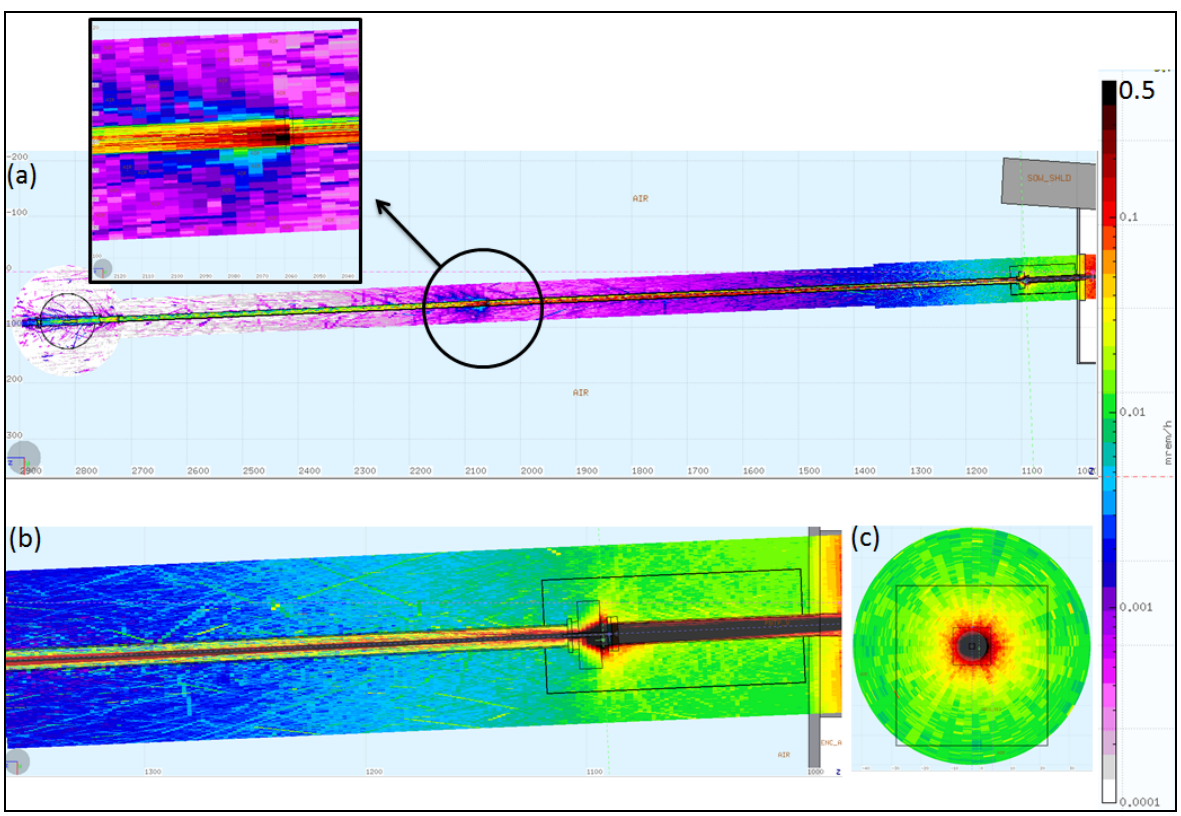

Figure 26: Total dose rate distribution (mrem/h) **(a)** in and around the PBT and the PGM (plan view); **(b)** at a section of the pipe downstream of the FOE and **(c)** at a vertical cut between the PBM2 and SBC

3.4(b) WBMREH

The inboard extreme ray starts at x=-1.329 cm, y= 0 cm, and z= 738.0 and hits the upstream edge of M1 mirror as shown in Figure 27(a). Unlike to the previous case WBMRCH, the amount of the SGB exiting the FOE and propagating down the PBT is reduced because the full length of the M1 mirror intercepts and attenuates the primary GB.

The total dose rate distributions in mrem/h on contact with the roof, the lateral wall and downstream wall are shown in Figures 27(b), 27(c) and 27(d). The total dose rate distribution in the FOE is shown in Figure 28. Dose rates in the vicinity of the PBT and PGM are shown in Figure 29. Dose rates on contact with the roof, lateral wall, outside the SBCr enclosure, around the PBT and the PGM were found to be less than 0.05 mrem/h. The maximum total dose rate on contact with the downstream wall is ~0.1 mrem/h, while 30cm away it is ~0.06 mrem/h.

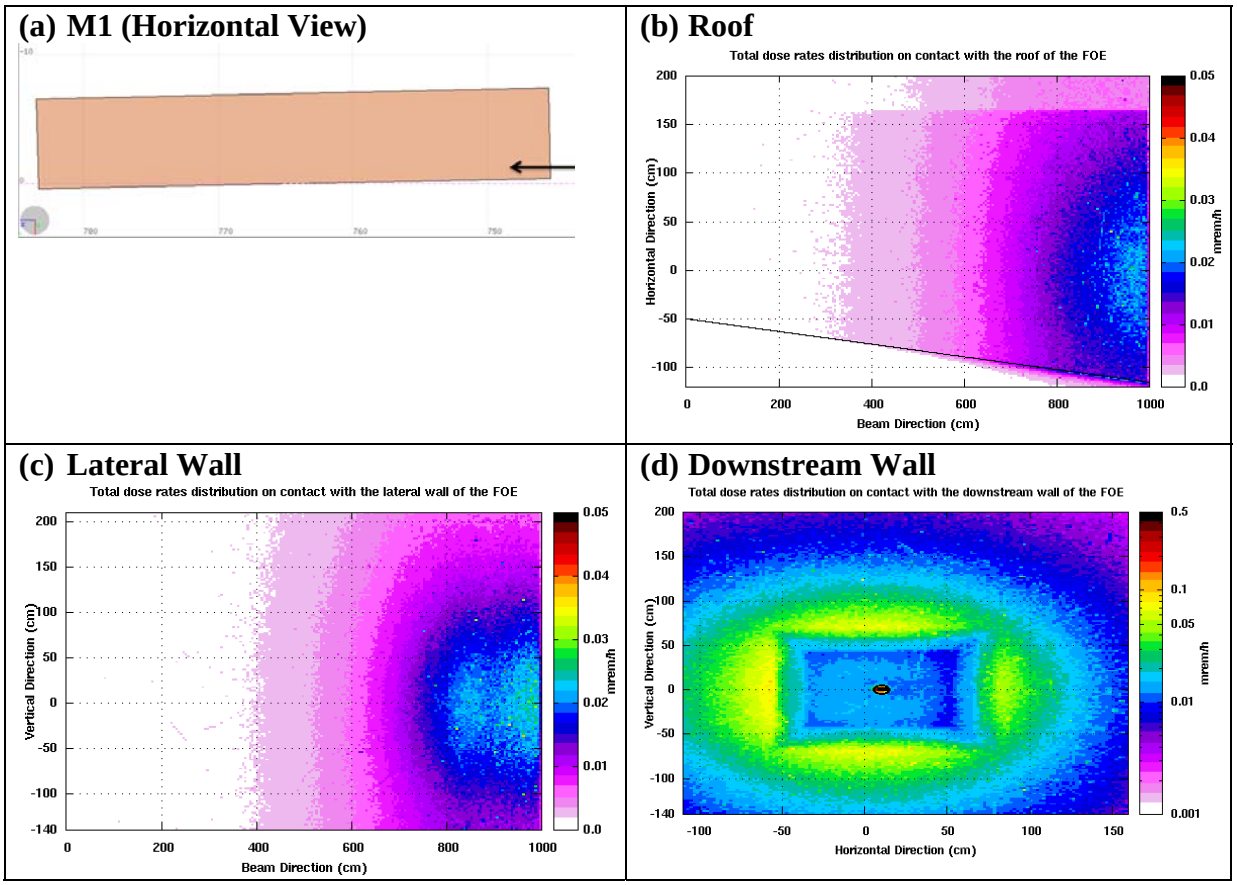

Figure 27: (a) GB position on the M1 mirror. Total dose distributions in mrem/h **(b)** on the roof, **(c)** on contact with the lateral wall and **(d)** on contact with the downstream wall of FOE

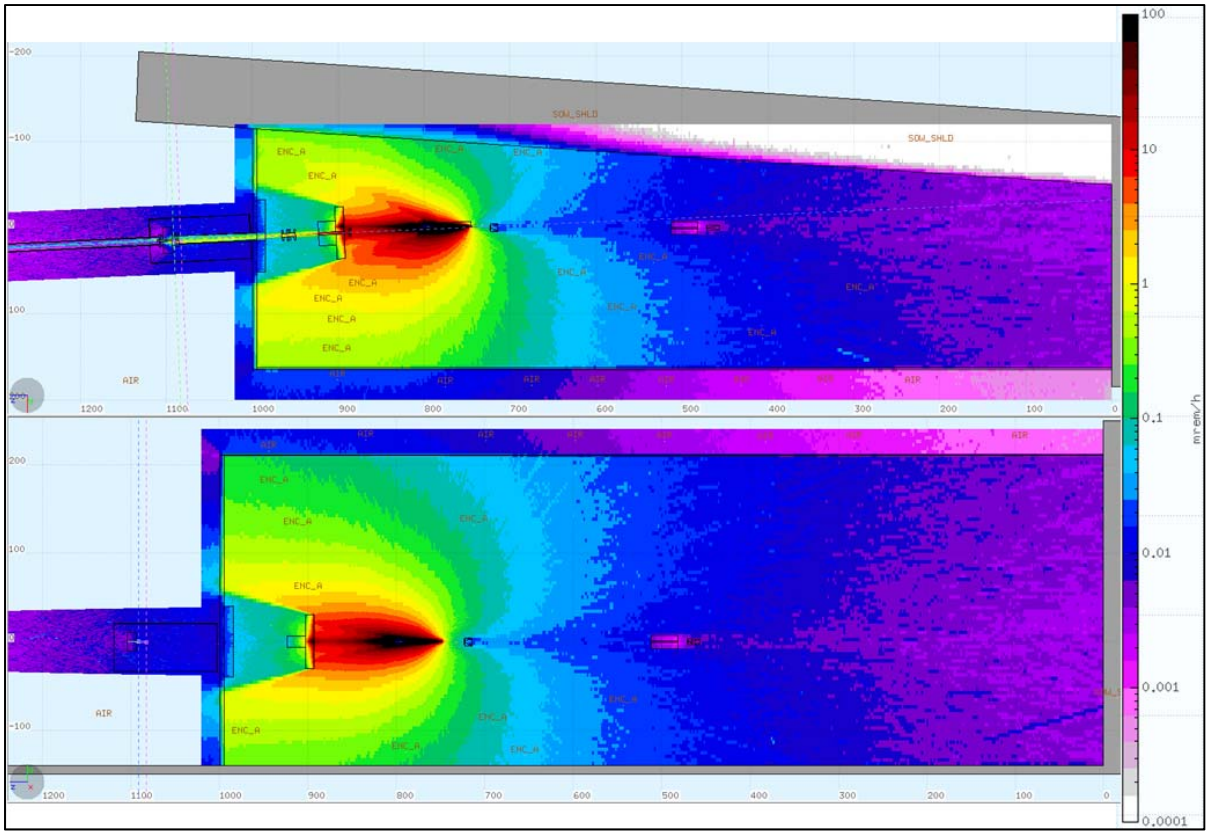

Figure 28: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

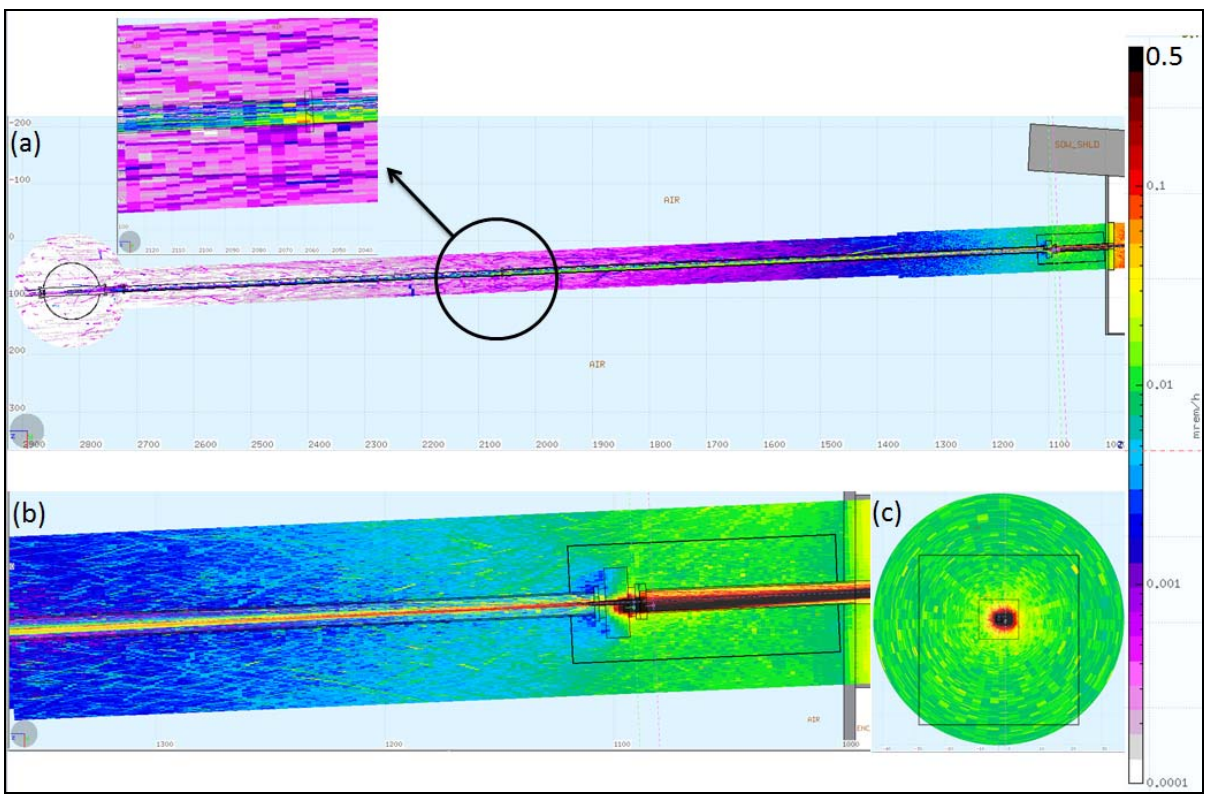

Figure 29: Total dose rate distribution (mrem/h) **(a)** in and around the PBT and the PGM (plan view); **(b)** at a section of the pipe downstream of the FOE and **(c)** at a vertical cut between the PBM2 and SBC

3.5 (a) WBSTCH

In this simulation the GB was started just upstream of the selected point of contact at x=0 cm, y=0 cm, z=790.0 cm and incident on the WBS, as illustrated in Figure 30(a). This will be the nominal GB beam position if the M1 mirror is temporarily moved out of the beam.

The total dose rate distributions in mrem/h on contact with the roof, the lateral wall and downstream wall are shown in Figures 30(b), 30(c) and 30(d). The total dose rate distribution in FOE is shown in Figure 31. Dose rates in the vicinity of the PBT and PGM are shown in Figure 32. Dose rates on contact with the roof, lateral wall, outside the SBC enclosure, around the PBT and the PGM were found to be less than 0.05 mrem/h. The maximum total dose rate on contact with the downstream wall is ~0.1 mrem/h, while 30cm away it is ~0.06 mrem/h.

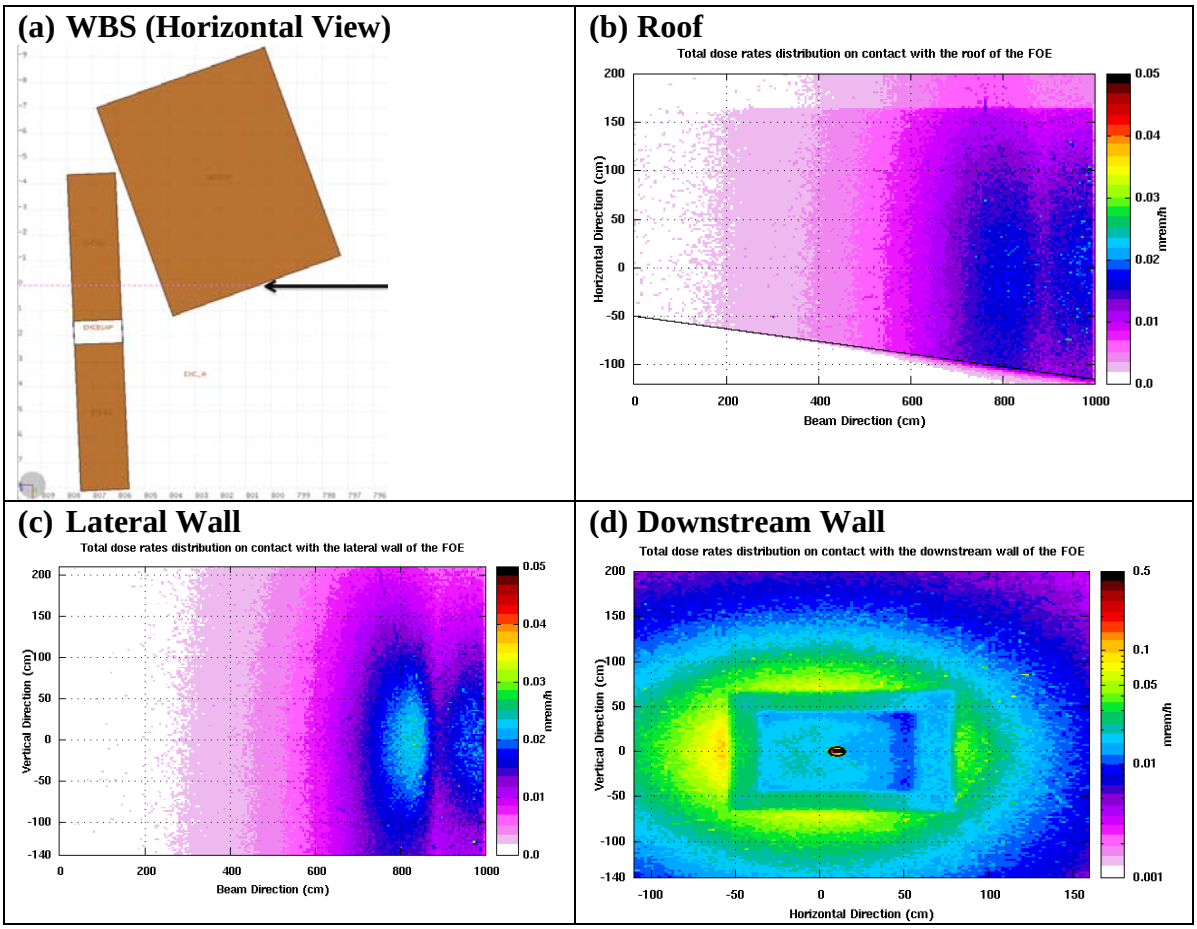

Figure 30: (a) GB position on the WBS. Total dose distributions in mrem/h **(b)** on the roof, **(c)** on contact with the lateral wall and **(d)** on contact with the downstream wall of FOE

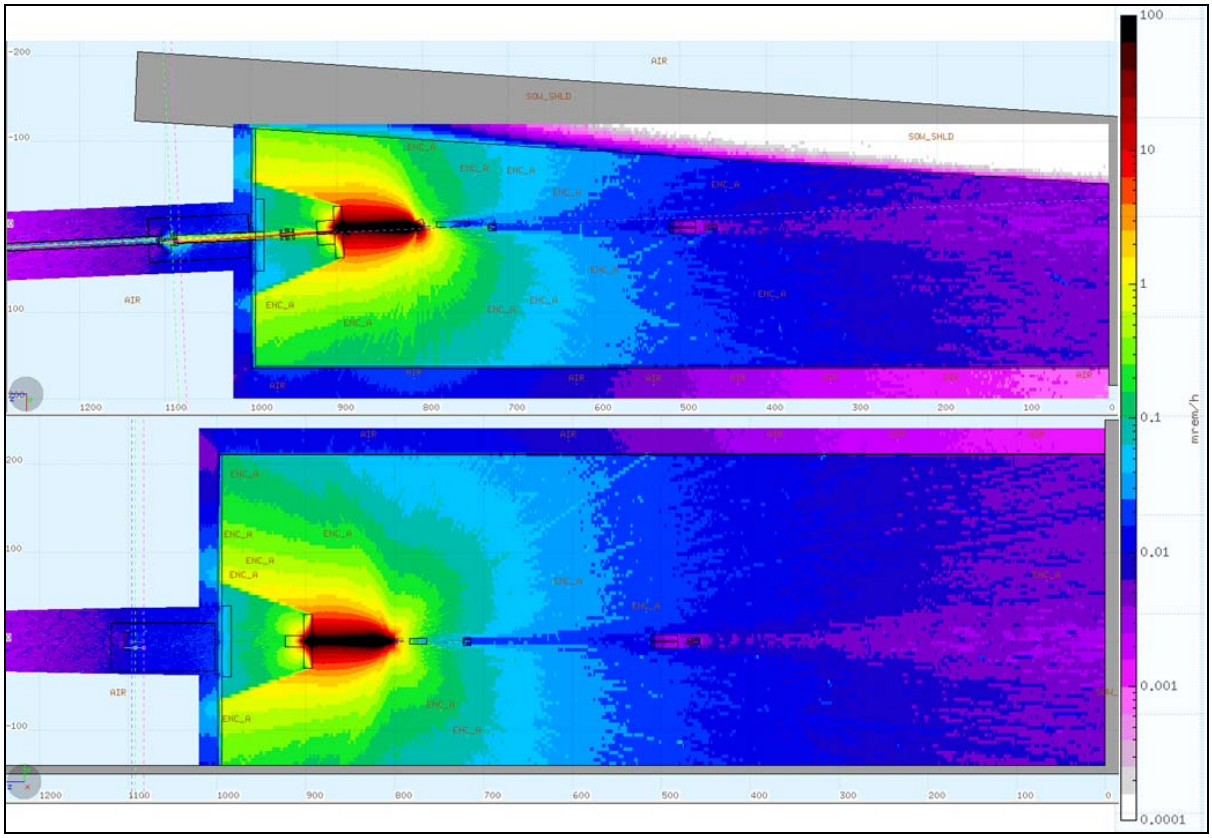

Figure 31: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

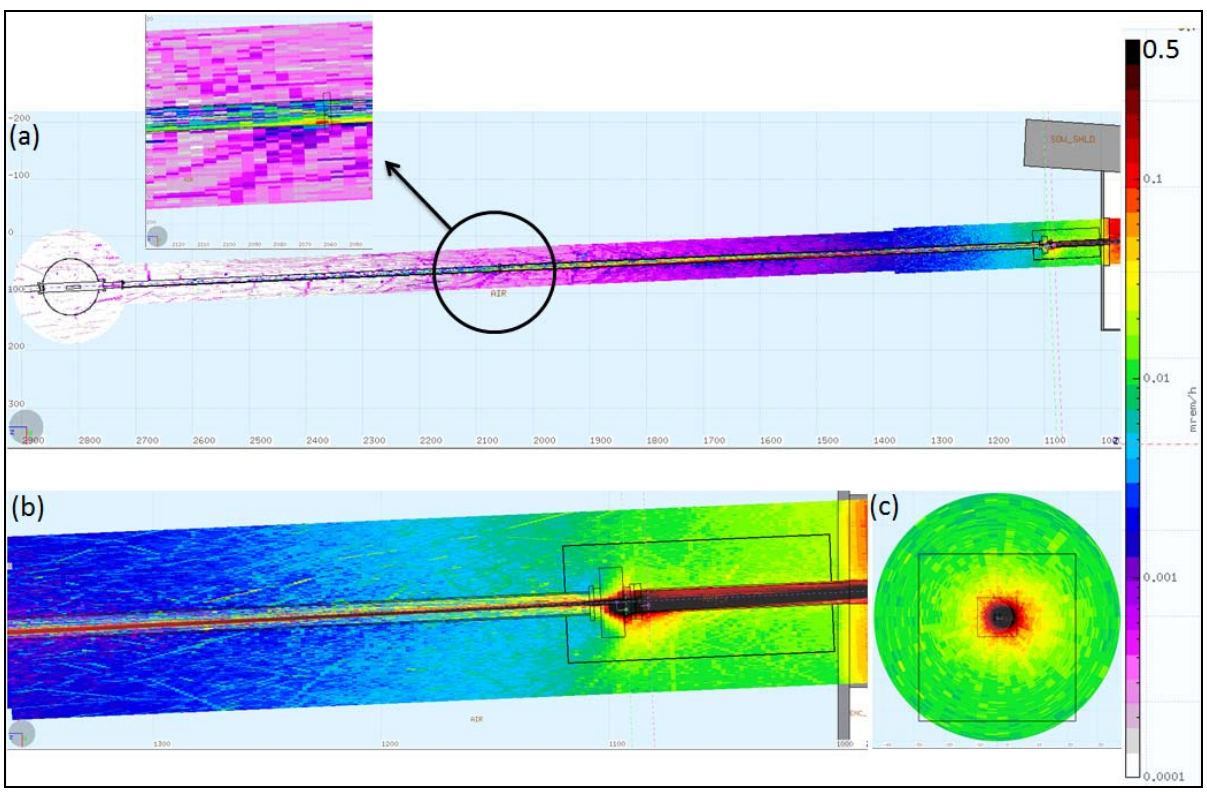

Figure 32: Total dose rate distribution (mrem/h) **(a)** in and around the PBT and the PGM (plan view); **(b)** at a section of the pipe downstream of the FOE and **(c)** at a vertical cut between the PBM2 and SBC

3.5 (b) WBSTEH

In this simulation the GB was started just upstream of the selected point of contact at x=0.511 cm, y=0 cm, z=790.0 cm and incident on the WBS as illustrated in Figure 33(a). This beam position corresponds to an outboard extreme ray closest to the M1 exit mask aperture.

The total dose rate distributions in mrem/h on contact with the roof, the lateral wall and downstream wall are shown in Figures 33(b), 33(c) and 33(d). The total dose rate distribution in the FOE is shown in Figure 34. Dose rates in the vicinity of the PBT and PGM are shown in Figure 35. Dose rates on contact with the roof, lateral wall, outside the SBC enclosure, around the PBT and the PGM were found to be less than 0.05 mrem/h. The maximum total dose rate on contact with the downstream wall is ~0.07 mrem/h, while 30cm away it is ~0.05 mrem/h.

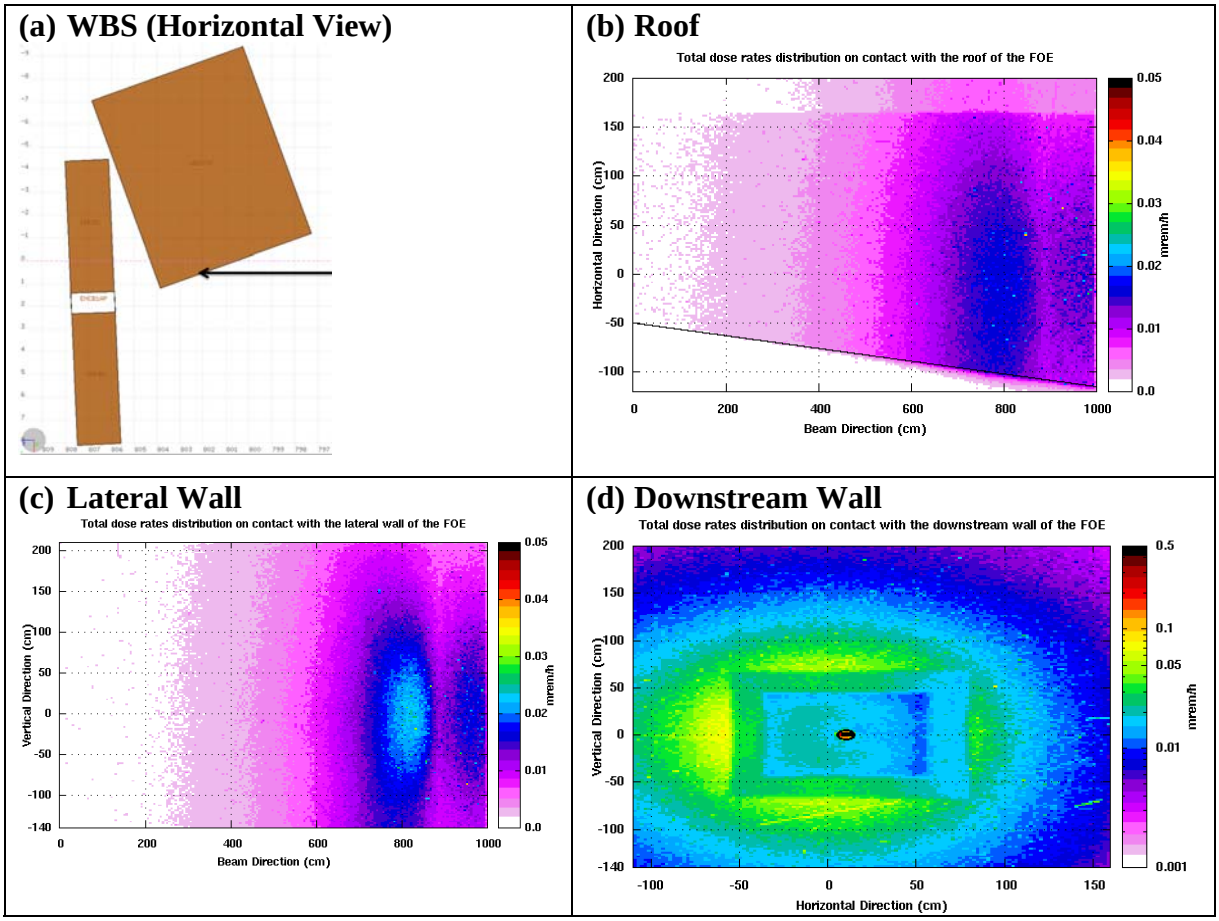

Figure 33: (a) GB position on the WBS. Total dose distributions in mrem/h **(b)** on the roof, **(c)** on contact with the lateral wall and **(d)** on contact with the downstream wall of FOE

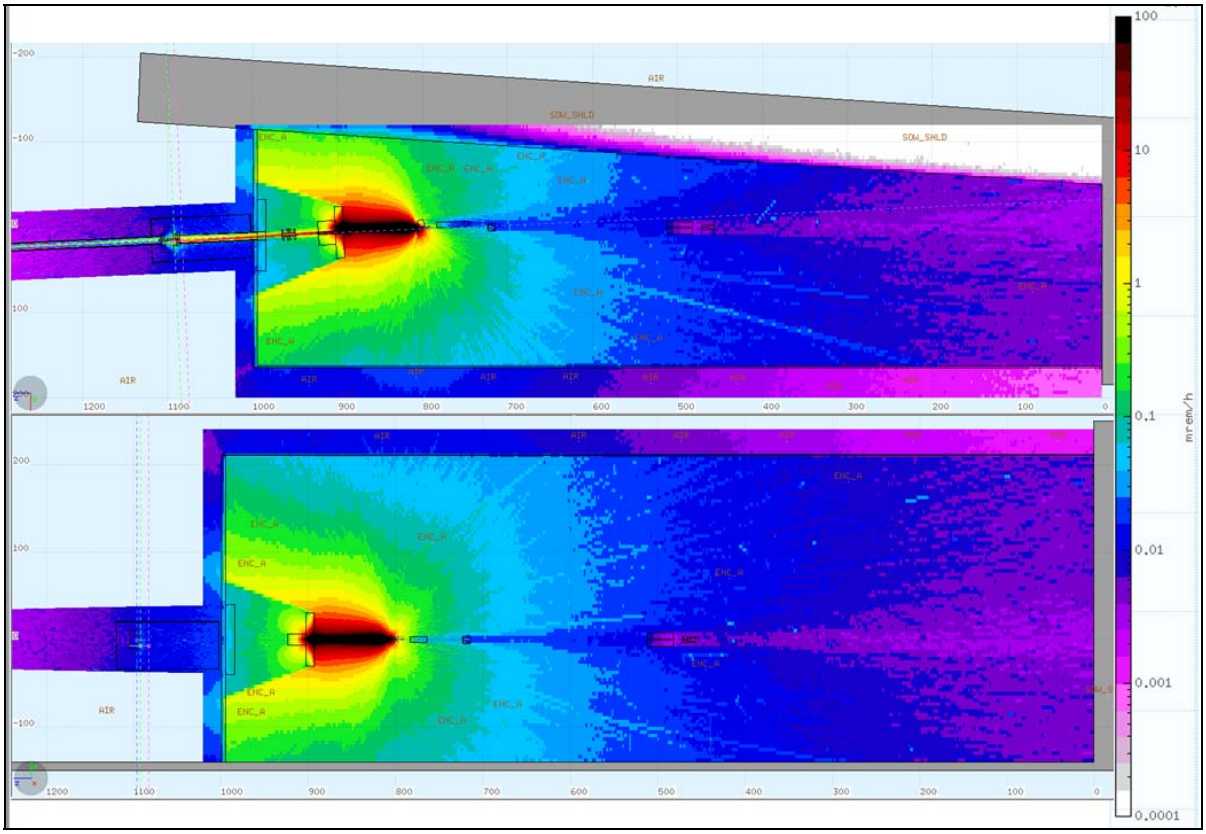

Figure 34: The total dose rate distribution (mrem/h) in the horizontal (top plot) and vertical (bottom plot) beam plane

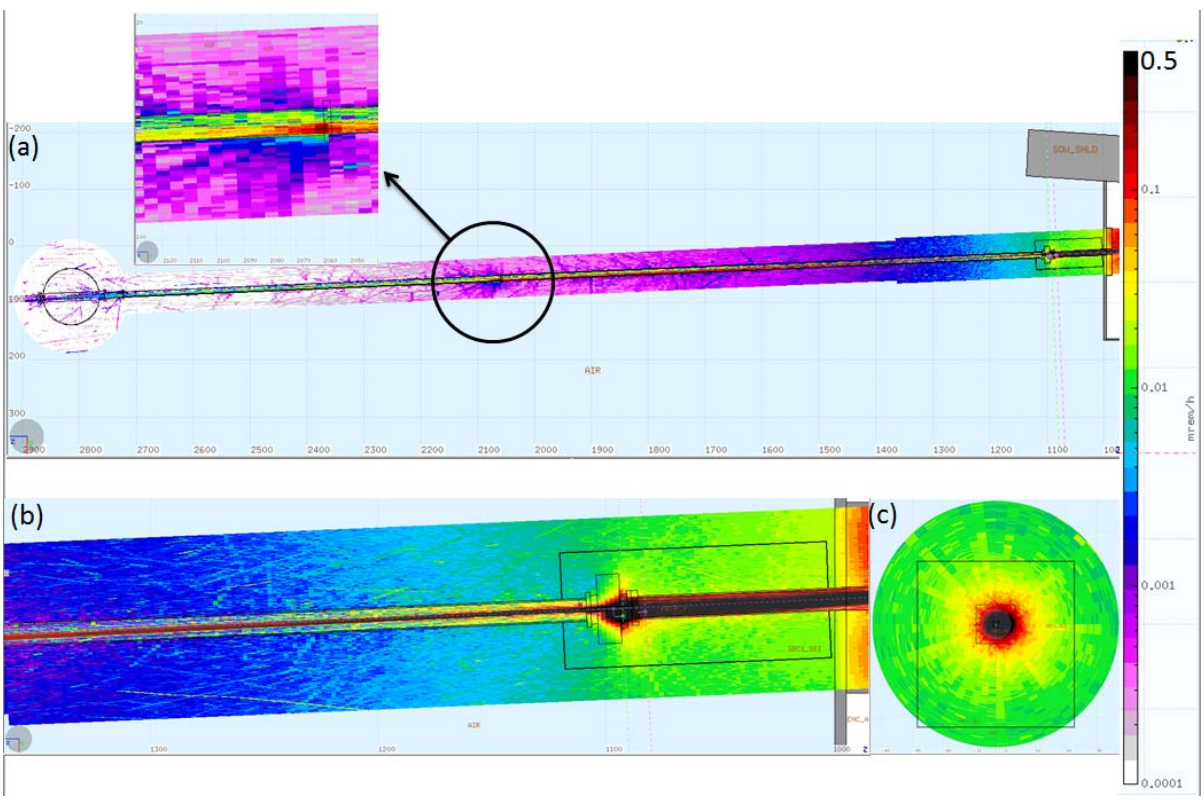

Figure 35: Total dose rate distribution (mrem/h) **(a)** in and around the PBT and the PGM (plan view); **(b)** at a section of the pipe downstream of the FOE and **(c)** at a vertical cut between the PBM2 and SBC

4. Synchrotron Radiation Calculation

In the analysis of the synchrotron radiation, we consider white beam from the EPU source up to the WBS located in the FOE, pink beam from mirror M1 through the transport pipe to the PGM housing, then monochromatic beam from the PGM to experiment end station.

02ID-SIX source parameters are given in reference [3] which identifies the source and period length (EPU with 57mm period), and the maximum field strength. This beamline is designed for two EPUs, but only one will be installed for the first few years of operations. However, this analysis is based on 2 EPUs at 500 mA stored beam current. The spectral photon flux is given in Figure 36 for the pink beam reflected off M1 (yellow trace), pink beam reflected off mirror M1 then M2 at 0.4 degrees (blue trace) and pink beam reflected off mirror M1 then M2 at 3.5 degrees (red trace) as calculated by J. Dvorak [4].

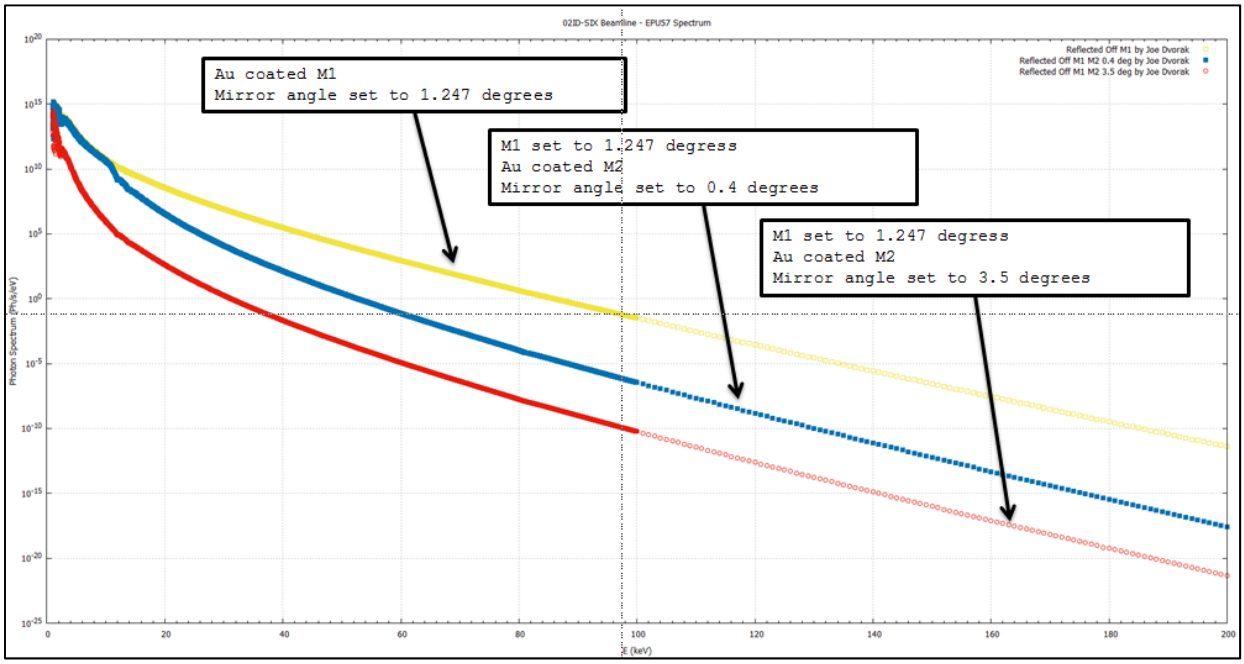

Figure 36: Spectral flux used as input into the STAC8 calculations

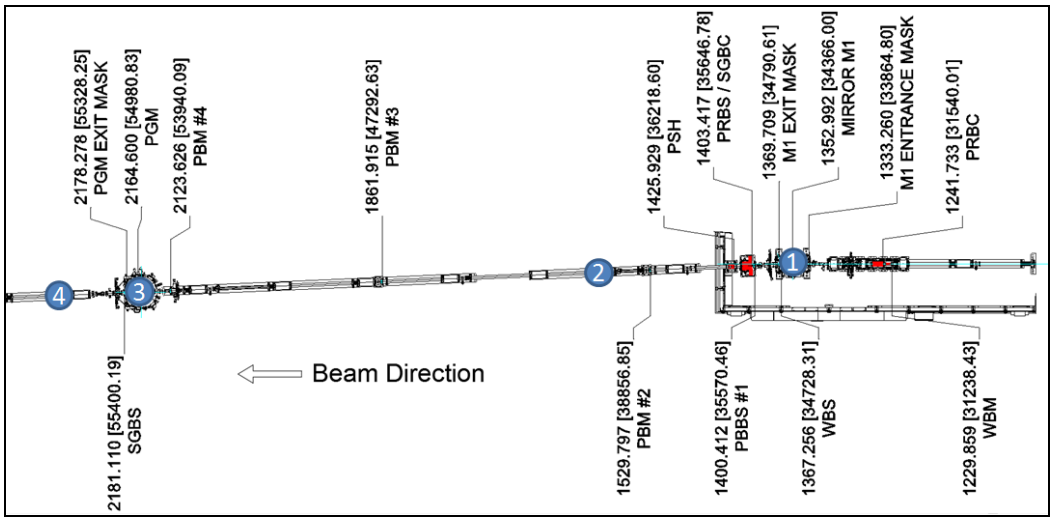

Figure 37: Graphical index of the target locations used in STAC8 calculations. Numbered labels indicate the scattering target locations and are discussed in sections 4.1 through 4.4

The analytic code STAC8 [5] was used to calculate the ambient dose equivalent rates in the occupied areas outside the FOE, PBT and PGM housing. The build-up factor in shielding 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 assume that the primary bremsstrahlung has been completely stopped in the FOE. The scattering targets considered in STAC8 calculations are labeled at their positions by numbers 1 through 4 in Figure 37. These cases are considered in Section 4.1 through 4.4 herein. The last case involving zero-order beam uses both Mirror M2 and grating in the parallel configuration for maximum reflected power exiting the PGM.

4.1 White Beam at the WBM in the FOE (Location 1)

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 [6]. The position of the scatter target is assumed to be located at the 02ID-SIX WBM approximately 235 cm from the FOE downstream wall, 163 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 3. The results show that the shielding thicknesses required for the GB 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 3: SR Shielding Design Requirements for 02ID-SIX FOE

	Distance (cm)	Minimum Required Shielding	Max Ambient Dose Rate (mrem/h)
Lateral wall	163	5 mm Pb	0.008
Roof	210	4 mm Pb	0.034
Downstream Wall (> 1°)	235	8 mm Pb	0.039

4.2 Pink Beam Transport Pipe (Location 2)

The SR shielding requirements for the beam transport pipe connecting the FOE to the PGM housing and around the PGM housing is determined by the pink beam scattering off masks, flanges, and air inside the transport pipe. Based on the ray tracings, pink beam will not strike the transport pipe. For the pink beam to leave the FOE a reflecting white beam mirror inside the FOE must be inserted to direct the beam into the PBT and toward the PGM. A gold coated mirror at 1.247 degrees to the incident white beam is used for the pink beam. The PBT is 6.35 mm thick stainless steel pipe and 4” in diameter (see Appendix 1, Table 1.2). Bellows, short nipples, and the SGB collimator tube are covered with 6.35 mm stainless steel thick collars. The STAC8 calculation was carried for 2 solid targets (pink beam mask and gate valve) that can potentially intercept the pink beam and an air target for a vacuum loss accident using approximately 18 m of air column at one atmosphere. The maximum dose rates on contact with the pipe are given in Table 4 and are well below the beamline shielding design criteria of 0.05 mrem/h [1].

Table 4: Dose Rates on Contact with the PBT for 6 mm Thick Pipe

Scatter Target	Maximum Ambient Dose Rate On Contact with pipe (mrem/h)
Copper Mask @ 30 degrees incidence	9.4E-03
Gate Valve @ normal incidence	1.5E-03
Vacuum Loss (18 m air target, fault condition)	3.2E-03

4.3 PGM Housing (Location 3)

The PGM housing is cylindrical with a 110 cm OD and a height of 70 cm (see Table 1.4). The SR shielding requirements for the PGM housing is determined by the pink beam scattering off mirror M2 inside the PGM and the direct beam reflected off mirror M2 and striking the PGM housing normal

incidence as illustrated in the top ray tracings of Figure 38. In the latter case the effective dose rate is negligible (4.1E-09 mrem/h). For the scattering case the calculation was carried out with the same optimum silicon scatter target used for the FOE analysis. The maximum contact dose rates on contact with the lateral walls of the 8 mm stainless steel vessel is 9.7E-05 mrem/h and 5.4E-04 mrem/h on contact with 1 mm Pb equivalent lead glass viewport. On the downstream wall of the PGM housing, 50 mm of tungsten secondary BRS inside the PGM housing will be largely sufficient to reduce the dose rates on axis below the 0.05 mrem/h. The maximum dose rates on the downstream wall of the PGM are 8.7E-03 mrem/h for scattering angles greater than 1 degree.

4.4 Monochromatic Beam Transport Pipe (Location 4)

The 02ID-SIX monochromatic beam transport pipe is 2.0 mm thick stainless steel pipe and 4" in diameter. The shielding requirements for the monochromatic transport beam pipe downstream of the PGM housing is determined by scattered radiation off mirror M2 and zero-order beam. The radiation resulting from the scatter of pink beam off the mirror M2, which then leaks through the (20 mm×27 mm) aperture of monochromatic beam (see Figure 4, left panel). This scatter radiation will travel inside the monochromatic transport pipe until it scatters off the fixed mask downstream from the PGM chamber (see bottom ray tracings of Figure 38) resulting in dose rates on contact with the pipe not exceeding 5.1E-06 mrem/h. For the reflected beam off M2, we assume the same optimum silicon target used in section 4.1 placed inside the pipe to obtain maximum scattered radiation. The maximum dose rate on contact with the monochromatic beam transport pipe is 2.4E-03 mrem/h.

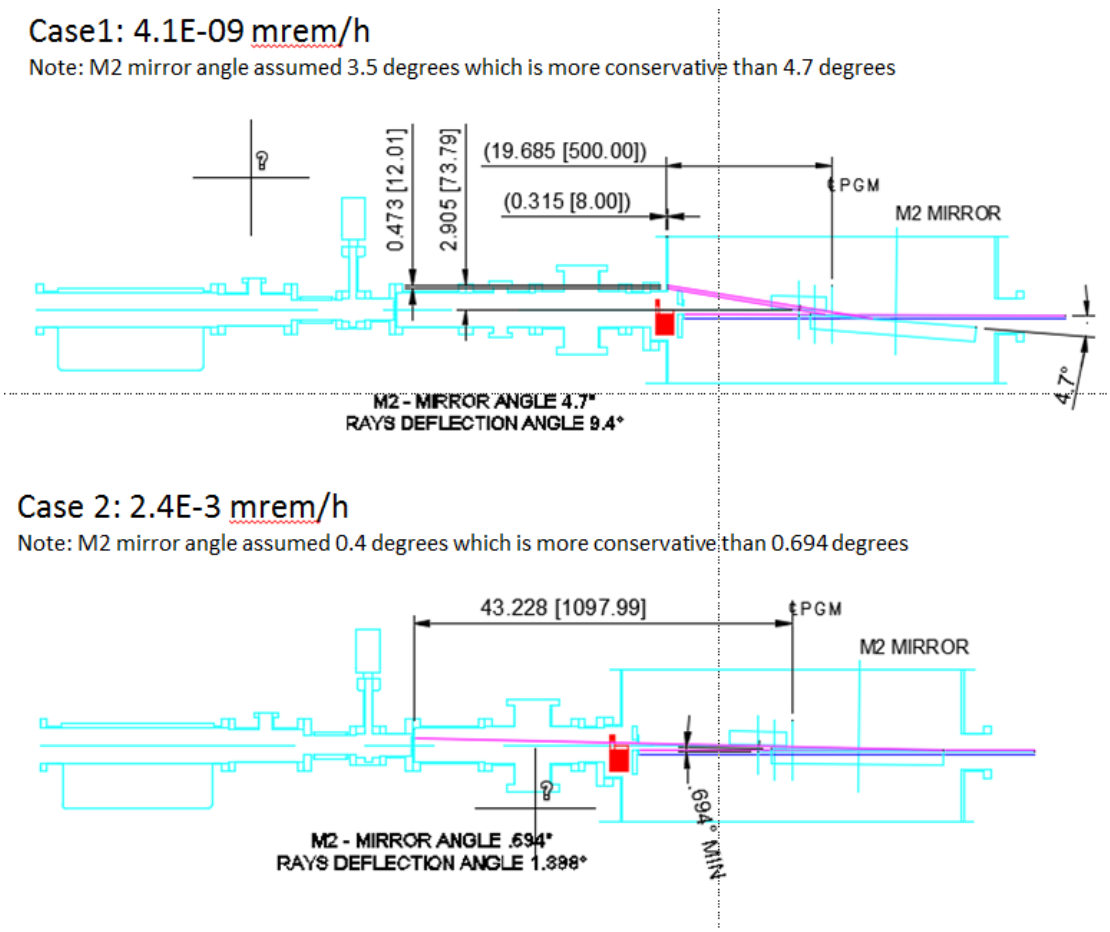

Figure 38: Beam mis-steering for the 2 cases of direct beam striking the PGM chamber (top ray tracings) and beam scattering off the fixed mask downstream of PGM chamber (bottom ray tracings).

5. Summary and Conclusions

At NSLS-II, the white beam or 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 17 μW incident power. This value corresponds to the estimated bremsstrahlung power generated by a 500 mA electron beam of 3 GeV, assuming that the vacuum in the 15.5 m long 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. A summary of the simulation results is presented in Table 5.

Table 5: Maximum total dose rates (mrem/hr) on the roof, lateral wall, the downstream wall of the FOE and the PGM exit plane. The numbers in parentheses are the dose rates on contact with downstream wall of the FOE

Case # / Report Section	Simulation	**Maximum dose (mrem/h)**					
		Roof	Lateral Wall	D/S Wall	SB Collimator Enclosure	Pink Beam Transport Pipe	PGM
1(a)/ 3.1(a)	**WBMEH**	< 0.05	< 0.05	< 0.05 (< 0.05)	< 0.05	< 0.05	< 0.05
1(b)/ 3.1(b)	**WBMEV**	< 0.05	< 0.05	< 0.05 (<0.05)	< 0.05	< 0.05	< 0.05
1(c)/ 3.1(c)	**WBMAH**	< 0.05	< 0.05	< 0.06 (<0.09)	< 0.05	< 0.05	< 0.05
1(d)/ 3.1(d)	**WBMAV**	< 0.05	< 0.05	< 0.06 (0.08)	< 0.05	< 0.05	< 0.05
2/ 3.2	**BCOEH**	< 0.05	< 0.05	< 0.05 (<0.05)	< 0.05	< 0.05	< 0.05
3(a)/ 3.3(a)	**ETMSKEH**	< 0.05	< 0.05	< 0.07 (0.2)	< 0.05	< 0.05	< 0.05
3(b)/ 3.3(b)	**ETMSKEV**	< 0.05	< 0.05	< 0.07 (0.2)	< 0.05	< 0.05	< 0.05
4(a)/ 3.4(a)	**WBMRCH**	< 0.05	< 0.05	< 0.06 (0.2)	< 0.05	< 0.05	< 0.05
4(b)/ 3.4(b)	**WBMREH**	< 0.05	< 0.05	<0.06 (0.1)	< 0.05	< 0.05	< 0.05
5(a)/ 3.5(a)	**WBSTCH**	< 0.05	< 0.05	<0.06 (0.1)	< 0.05	< 0.05	< 0.05
5(b)/ 3.5(b)	**WBSTEH**	< 0.05	< 0.05	< 0.05 (0.07)	< 0.05	< 0.05	< 0.05

Based on the STAC8 calculation, the dose rates outside of the beam transport pipe and PGM housing are 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 of the FOE, the beam transport pipe and the end station enclosure during commissioning.

6. References

[1] *Guidelines for the NSLS-II Beamline Radiation Shielding Design* LT-C-ESH-STD-001, November 7, 2014.

[2] *NSLS-II Issue and Decision Paper: ALARA Analysis for Installations of Secondary Bremsstrahlung Shields in the First Optics Enclosure*, R. Lee, PS-C-ESH-STD-005, (06/01/2016).

[3] NSLS-II document NX-C-XFD-RSI-001 (Version 5, 25 Nov. 2013).

[4] Emails from J. Dvorak to M. Benmerrouche (January 28, 30, and 31, 2017).

[5] Y. Asano, "*A study on radiation shielding and safety analysis for a synchrotron radiation beamline*," JAERI-Research-2001-006, March 2001. Y. Asano and N. Sasamoto, "*Development of Shielding Design Code for Synchrotron Radiation Beamline*," Radia. Phys. Chem. 44 (1994) 133.

[6] *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 Y. Zhu for providing all the front end and beamline component information listed in Appendix 1. We would like to thank J. Dvorak, S. Hulbert, I. Jarrige and Y. Zhu for multiple discussions.

Appendix 1

02ID-SIX Beamline
Input provided by Yi Zhu (updated on November 16, 2016)

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 straight. 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. The following convention is used to specify distance of the component from the straight section (SS) centerline: U: upstream, D: downstream, and C: center of component.

Table 1.1 Beamline Enclosures

Wall	Position	Thickness	Material
D/S End of 02ID-A Ratchet Wall Collimator	26722.74 mm		
D/S End of FOE (02ID-A) Backwall	36716.96 mm	50 mm	Lead
Distance of FOE Sidewall from SS CENTERLINE	1627.3 mm	18 mm	Lead
Distance of FOE Roof from SS CENTERLINE	2102 mm	10 mm	Lead
Distance of FOE Floor from SS CENTERLINE	1400 mm	-	

Table 1.2 Beamline Transport Pipe

Transport Pipes extending beyond FOE Backwall	ID= OD= inches	Shielding Material: Stainless Steel (SS)	Point of exit Angle wrt Z axis
	ID = 3.5″ OD = 4.0″	SS thickness=0.25″=6.35 mm	2.47° (outboard)

Table 1.3: 02ID-SIX Beamline Components and SGB shields

Components	Z = Distance from SS centerline U,D or C	Dimensions (specify units)		Offset/ Rotation wrt Straight Centerline	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R)			
White Beam Mask	31287.8 mm(U)	Radius 30 mm 144.4 mm(L) $R_{effective}$ = 20.0 mm	20 mm(Radius)(U) 3.25 mm(Radius)(D) Z1=137.4 mm Z2=144.4 mm	-	Glidcop AL-15	PD-SIX—BL-MSK-1000
Brem collimator	31540.0 mm(U)	165.1 mm(W)X 152.4 mm(H)X 304.8 mm(L)	15.04 mm(W) 15.04 mm(H)	-	Lead	PD-SIX-BRS-1000
M1 Entrance mask	33864.80 mm(U)	See drawings (a)L=80.0 mm $R_{effective}$ = 44 mm (b)L=8.0 mm $R_{effective}$ = 30 mm	(a)36 mm(Radius)(U) 4.25 mm(Radius)(D) (b) 6.5 mm (Radius)	-	Glidcop	PD-SIX-BL-MIR-1020
White beam Mirror	34366.0 mm(C)	70 mm(W) 60 mm(H) 380 mm(L)	Rotates beam 2.47 degree wrt Z axis	Rotate 1.235 degree wrt Y axis	Silicon	PD-SIX-BL-MIR-0010
White beam stop	34728.3 mm surface center	Length 87.5 mm OD: 81 mm $R_{effective}$ = 35 mm	-	X: 0 mm Rotated -70 deg	copper	PD-SIX-BL-MIR-1015
M1 Exit mask	34790.6 mm(U)	125 mm(W) 80 mm(H) 19 mm(L)	9.0 mm(W) 9.0 mm(H)	Rotated 2.47 deg X:+18.32 mm(U)	OFHC	PD-SIX-BL-MIR-1008
Pink Beam mask PBM #1 PBMs identical	35570.5 mm(U)	See drawings 47.1 mm (Radius) 27 mm(L)	35.346 mm(Diameter)(U) 4.625 mm(Radius)(D) Z2=27.0-4.4=22.6 mm	X:+51.96 mm(U)	Glidcop AL-15	PD-SIX-BL-MSK-2000
Shielding wall SGB1	35646.8 mm(U)	609.6 mm(W)X 609.6 mm(H)X 101.6 mm(L)	26.42 mm(W) 17.07 mm(H)	X:+55.25 mm(U)	Lead	PD-SIX-BRS-1050
Brem Stop	35748.3 mm(U)	279.4 mm(W) 127 mm(H) 203.2 mm(L)	26.42 mm(W) 17.07 mm(H)	X:+59.63(U)	Lead	PD-SIX-BRS-1050
Photon Shutter	36218.60 mm (C)	12.5 cm (W)	40 mm × 25 mm	X:+79.91(U)	Tungsten	PD-COM-PSH-1000

Simplified model		15.0 cm (H) 3.8 cm (L)	Centered wrt block			
Guillotine	36565.96 mm(U)	84 cm W 80 cm H 10 cm (L)	External diameter of pipe = 4 inch	X:+94.9 mm	Lead	-

Table 1.4: Beamline Components outside the FOE

Pink Beam Mask #2	37579.7 mm(U)	See drawings 47.1 mm (Radius) 27 mm(L)	35.596 mm(Diameter)(U) 4.75 mm(Radius)(D) Z2=27.0-4.4=22.6 mm	X:+ 138.51 mm	Glidcop AL-15	PD-SIX-BL-MSK-3000
Secondary brem. Collimator	37657.9 mm(U)	304.8 mm (W) 203.2 mm (H) 101.6 mm (L)	20 mm(W) 20 mm(H)	X:+ 142.00 mm	Lead	PD-SIX-BRS-3000
Pink beam Mask #3	47292.6 mm(U)	See drawings 47.1 mm (Radius) 27 mm(L)	38.096 mm(Diameter)(U) 6 mm(Radius)(D) Z2=27.0-4.4=22.6 mm	X:+ 557.61 mm	Glidcop AL-15	PD-SIX-BL-MSK-4000
Pink beam mask #4	53940.1 mm(U)	See drawings 47.1 mm (Radius) 27 mm(L)	39.096 mm(Diameter)(U) 6.5 mm(Radius)(D) Z2=27.0-4.4=22.6 mm	X:+ 844.36 mm	Glidcop AL-15	PD-SIX-BL-MSK-5000
Plane grating monochromator (PGM) housing	54865.4 mm(C)	OD=1000.0 mm ID=984.0 mm Height 700.0 mm		SS Cylinder -30 <Y< 40 cm X:+884.27mm	SS	PD-SIX-PGM-1000
PGM Exit mask 2 blocks	55328.3 mm(U)	(a) 95mm(W) 102mm(H) 12mm (L) (b) 60mm(W) 60mm(H) 5mm (L)	20 mm (W)X27 mm(H)	X:+904.2 mm Y: +19.25 mm	OFHC	PD-SIX-PGM-1010
Secondary Brem stop #1	55360.2 mm(U)	See drawings 40 mm(L)	See drawings	X:+905.6 mm Y:+19.25 mm	Tungsten	PD-SIX-PGM-1010
Secondary Brem stop #2	-	See drawings 10 mm(L)	See drawings	Y: +19.25 mm	Tungsten	PD-SIX-PGM-1010

PGM mirror (not in center of the tank)	-320 mm(C) Along reflected beam from M1	50mm(W) 70mm(H) 500 mm(L)	-	Top surface at y=0 in rotated 3.1 d wrt x axis	Silicon	PD-SIX-BL-MIR-0020
Monochromator Grating	+115.5mm(C) Along reflected beam from M1	40 mm(W) 40 mm(H) 165 mm(L)	-	Y: +40 mm	Silicon	PD-SIX-BL-GRTG-0001