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07-BM QAS Beamline Radiation Shielding Analysis

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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 Beamline for Quick x-ray Absorption and Scattering (QAS) 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 07-BM (QAS) beamline is presented in Figure 1. These drawings were extracted from the Beamline Ray Trace Layout [PD-QAS-RAYT-0001]. The ray trace drawings include 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.

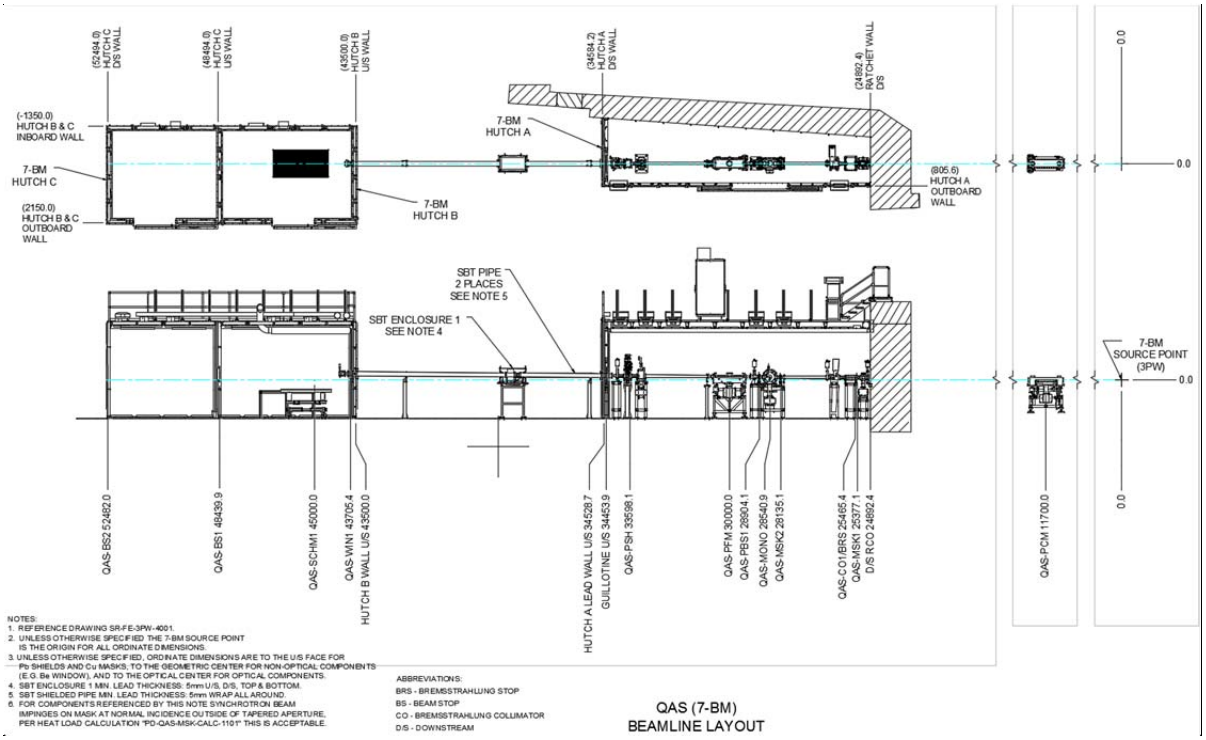


Figure 1: Layout of 07BM-QAS showing the location of the 3PW source, mirror PCM in the FE, major beamline components, the FOE (07BM-A) and End Station Enclosures (07BM-B and 07BM-C).

The remainder of this document is organized as follows:

- Section 2: Describes the model generated for FLUKA analysis of primary GB and SGB in the 07-BM (QAS) FE and FOE, using NSLS-II source parameters, and all 07-BM (QAS) shielding and beamline components as described in the rays tracings and component design drawings.
- Section 3: Presents the FLUKA simulation results. The analysis finds that bremsstrahlung radiation is mostly stopped by shielding at or before the 07-BM (QAS) FOE downstream wall.
- Section 4: Describes analysis of the synchrotron radiation, considering pink beam from the M1 mirror up to the pink beam stop (PBS) located in the FOE, and monochromatic beam through the transport pipe to the end station enclosure 07-BM-B.
- 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 07-BM (QAS) beamline includes additional shielding in order to reduce the dose on the downstream wall and around the transport pipe.

As described in Appendix A of Reference 1 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 3 GeV, 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 BM straight section	6.6 m
Pressure in straight section	1 ntorr

The beam is normalized at 7.2 μW incident power for the short straight (6.6 m). This 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 07BM-QAS ray tracings primary GB will interact with some of the components as described in Appendix 1. The areas of the components intercepted 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 intercepted by the primary GB including nominal and extreme rays downstream of LCO1 as per the FE ray tracing SR-FE-3PW-4001 were sampled for analysis. The simulations performed to confirm the adequacy of the FOE shielding and radiation safety components are presented in Table 2. For extreme rays, we considered top and bottom extreme rays downstream from LCO1 as shown in sheet 7 of ray tracing drawing SR-FE-3PW-4001. Components referenced in Table 2 are described in Appendix1.

Table 2: List of FLUKA Simulations

Case # / Report Section	Simulation	GB Beam Position (x, y, z) in cm
1 / 3.1	**PCM**: GB incident near center of Mirror PCM	(0.0 , 0.0 , -1209.47)
2 / 3.2	**FM2**: GB incident on Fixed Mask 2	(0.0 , 0.0 , -1044.72)
3 / 3.3	**FM3**: GB (top extreme ray) incident on FM3 in the FE	(0.0 , 3.00 , -771.02)
4 / 3.4	**FM4**: GB (top/bottom extreme rays) incident on FM4 in the FE.	(0.0 , 4.53 , -204.12) (0.0 , 3.62 , -204.12)
5 / 3.5	**MSK1**: GB (top/bottom extreme rays) incident on MSK1 in the FOE.	(0.0 , 5.60 , 192.73) (0.0 , 4.42 , 192.73)

The 07-BM (QAS) 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 (80.56 cm from short straight centerline), roof 4 mm Pb (210 cm above short straight centerline) and downstream FOE wall 50 mm Pb (~969 cm from the ratchet wall). See Appendix 1 for more details.

The FLUKA model of the 07-BM (QAS) beamline components in the FE and the FOE are shown in Figure 2. 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 short straight. However, for the FLUKA input files the downstream end of the ratchet wall is set as the zero of the Z axis. In FLUKA model the beam travels from left to right. The positions, dimensions, materials and reference to drawings of the main components are given in Appendix 1.

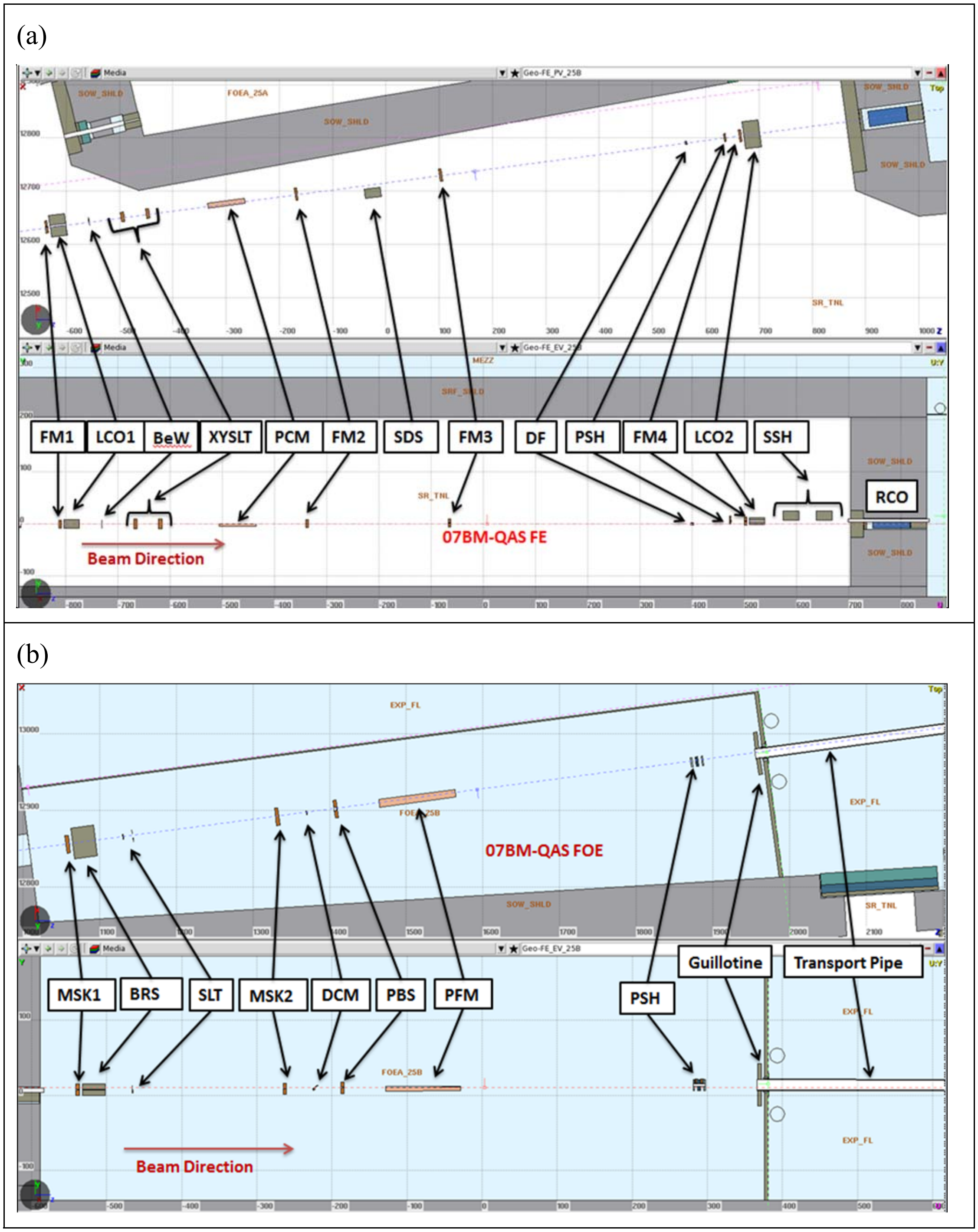


Figure 2: FLUKA Model used in Top-Off simulation of the 07BM-QAS Beamline (a) Front End and (b) Beamline

ACRONYMS:

3PW	Three Pole Wiggler
ALARA	As Low As Reasonably Achievable
BeW	Beryllium Window
BM	Bend Magnet
BRS	Bremsstrahlung Stop
DCM	Double Crystal Monochromator
DOE	Department of Energy
ESE	End Station Enclosure
DF	Diagnostic Flag
FE	Front End
FM	Fixed Mask
FOE	First Optical Enclosure
GB	Gas Bremsstrahlung
GeV	Giga Electron Volts
keV	Kilo Electron Volts
LCO	Lead Collimator
MSK	Mask
NSLS-II	National Synchrotron Light Source II
PBS	Pink Beam Stop
PCM	Photon Collimating Mirror
PFM	Photon Focusing Mirror
PSH	Photon Shutter
QAS	Quick x-ray Absorption and Scattering
RCO	Ratchet Wall Collimator
SDS	Shadow Shield
SLT	Slits
SSH	Safety Shutter
SGB	Secondary Gas Bremsstrahlung
SR	Synchrotron Radiation
TLD	Thermoluminescent Dosimeter

3. Results for Primary GB Simulations

The shielding requirement for the FOE is dominated by the scattering of the primary Gas Bremsstrahlung radiation, originating from the storage ring's electron beam interacting with residual gas in the storage ring. The paths of this radiation are determined by ray tracing of the GB through and around the FE and beamline components. The analysis approach was to place the GB beam at various locations within the area of the component intercepted by the primary. The simulations performed to confirm the adequacy of the radiation safety components are presented in Table 2. Section 5 includes a summary of the simulations results.

3.1 PCM

In this simulation the GB was started just upstream of the selected point of contact at x=0.0 cm, y=0 cm, z=-1209.47 cm and impinges near the center of PCM. The total dose distributions (mrem/h) in the FE and FOE are shown in Figure 3 and the corresponding neutron distributions are given in Figure 4. The amount of radiation that leaks through the RCO is negligible because FE components downstream from the PCM are effective in attenuating the forward directed electromagnetic shower. The total dose rates on the roof, lateral wall and downstream wall of the FOE are below 0.001 mrem/h.

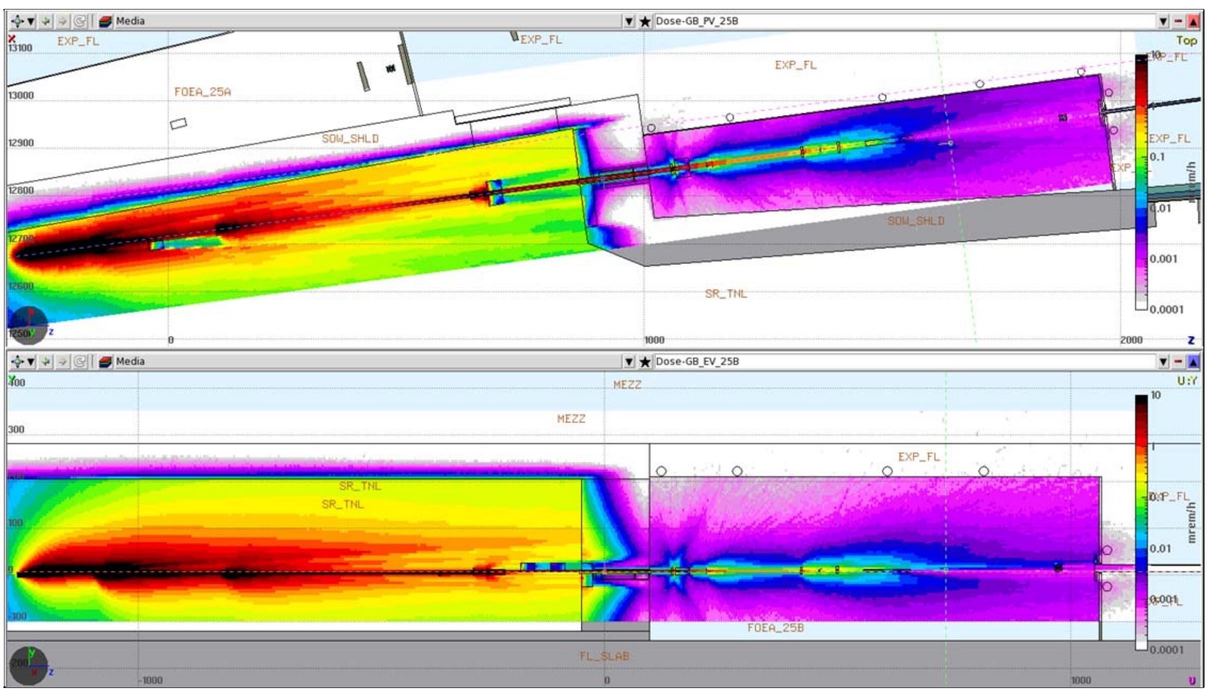


Figure 3: The total dose rate distribution (mrem/h) in the horizontal at y = 6.47 cm (top plot) and vertical (bottom plot) beam plane

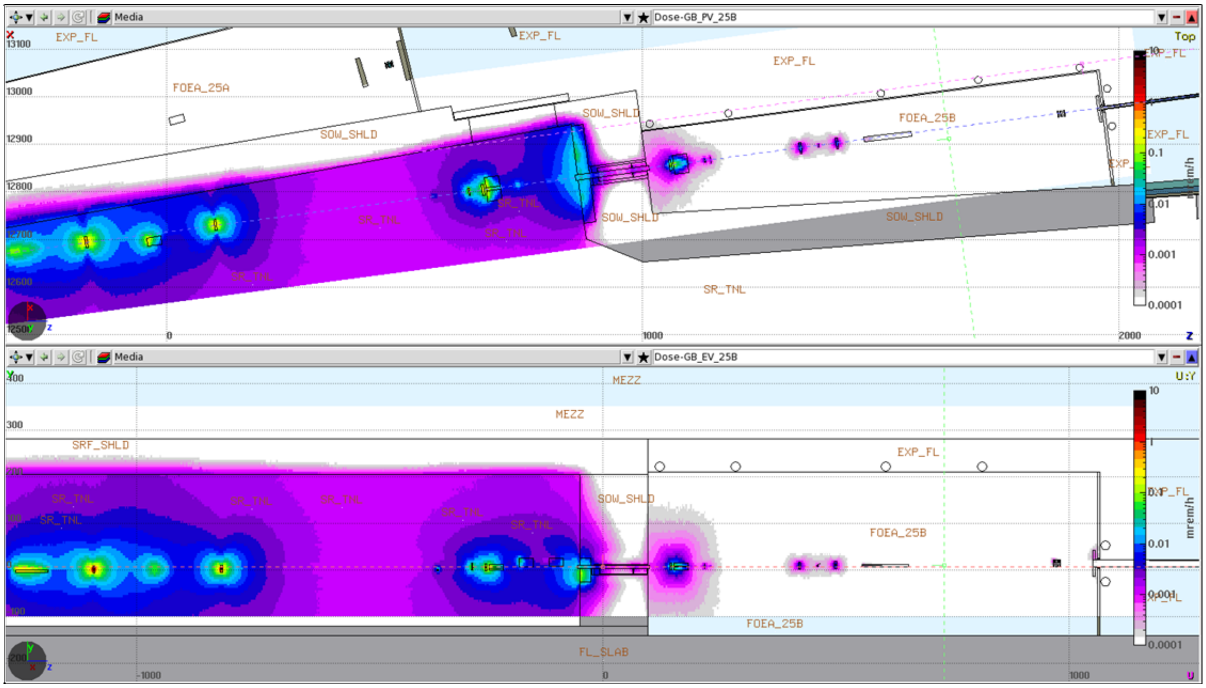


Figure 4: The neutron dose rate distribution (mrem/h) in the horizontal at y = 6.47 cm (top plot) and vertical (bottom plot) beam plane

3.2 FM2

In this simulation the GB was started just upstream of the selected point of contact at x=0 cm, y=0.0 cm, z=-1044.72 cm and impinges at the position of the nominal GB ray on the front face of FM2. The total dose distributions (mrem/h) in the FOE are shown in Figure 5 and the corresponding neutron distributions are given in Figure 6. The amount of radiation that leaks through the aperture of the RCO is significantly attenuated by the FE components downstream from FM2 including LCO2. The total dose rates on the roof, lateral wall and downstream wall of the FOE are below 0.001 mrem/h.

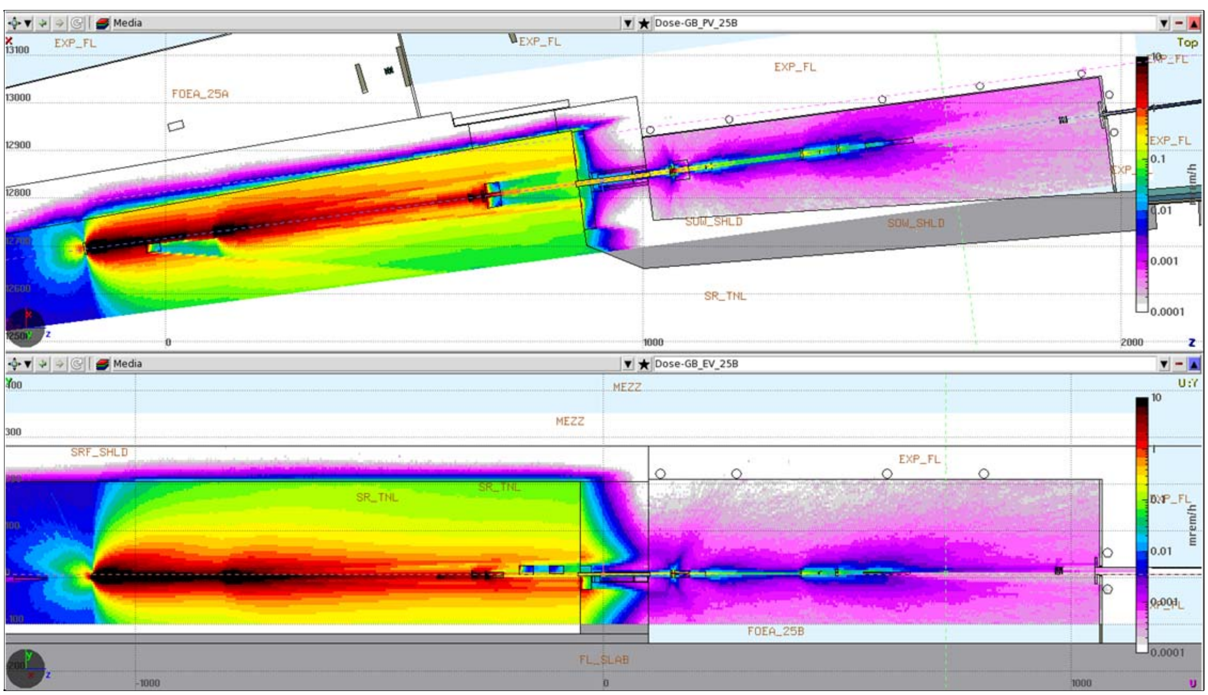


Figure 5: Total dose rate distributions (mrem/h). The Top view at y=6.47 cm (centerline of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

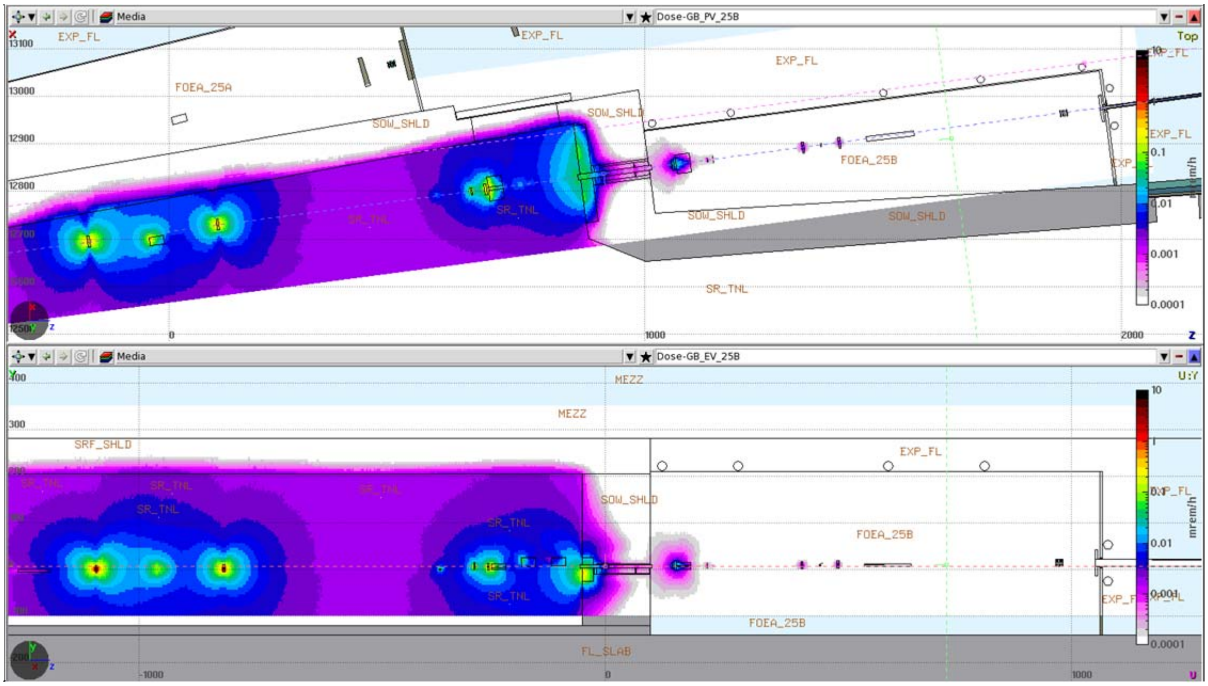


Figure 6: The neutron dose rate distribution (mrem/h) in the horizontal at y = 6.47 cm (top plot) and vertical (bottom plot) beam plane

3.3 FM3

In this case GB was started just upstream of the selected point of contact at x=0 cm, y=3.00 cm, z=-771.02 cm and impinges at the position of the top extreme ray on the front face of FM3. The total dose distributions (mrem/h) in the FOE are shown in Figure 7 and the corresponding neutron distributions are given in Figure 8, which clearly shows that LCO2 is very effective in attenuating the forward electromagnetic shower and the amount of radiation that leaks through its aperture is further attenuated by beamline components in the FOE.

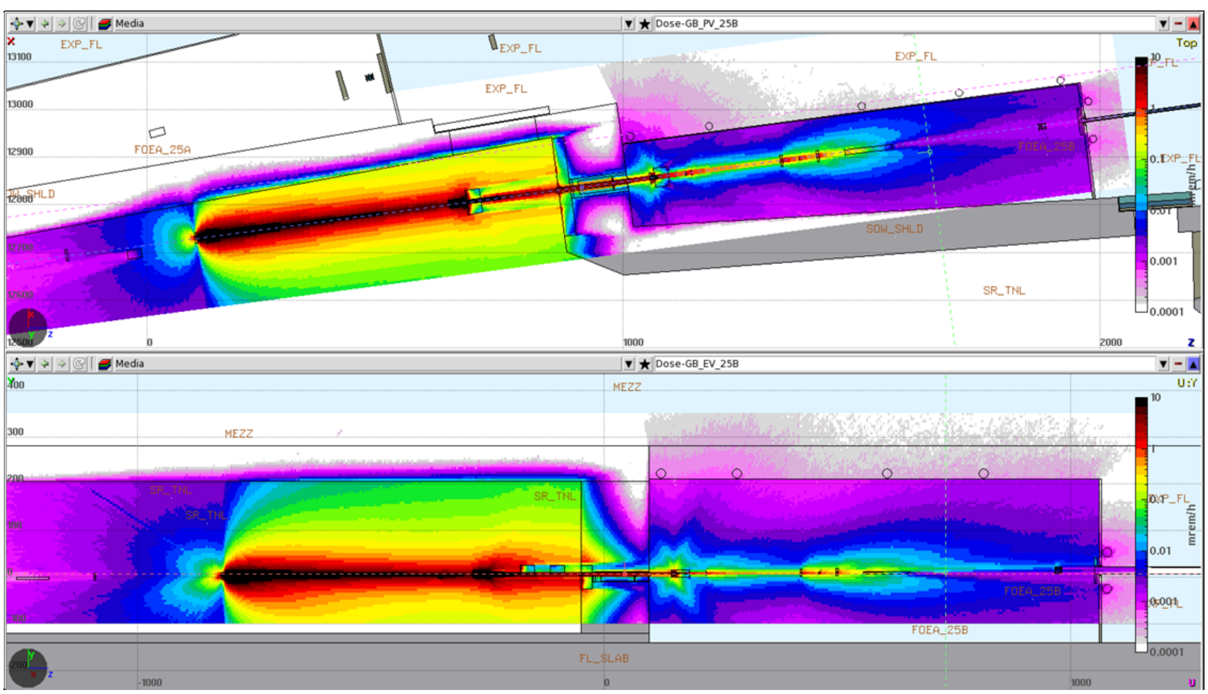


Figure 7: Total dose rate distributions (mrem/h). The Top view at y=6.47 cm (centerline of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

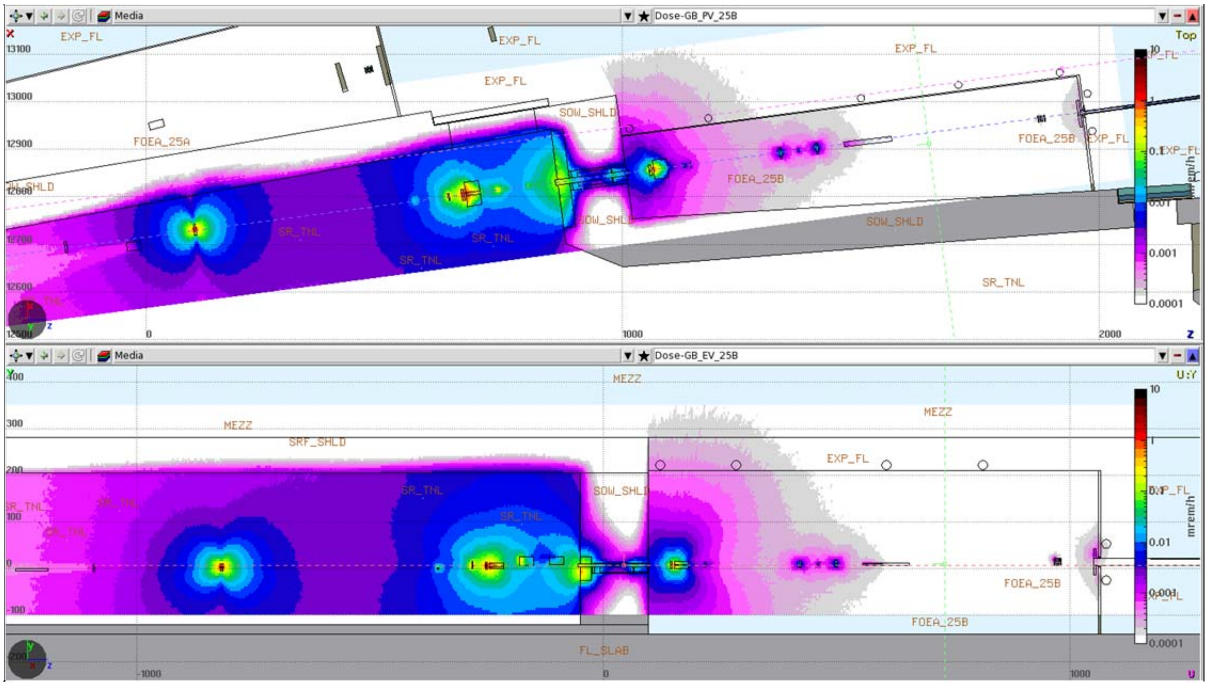


Figure 8: Neutron dose rate distributions (mrem/h). The Top view at y=6.47 cm (center of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

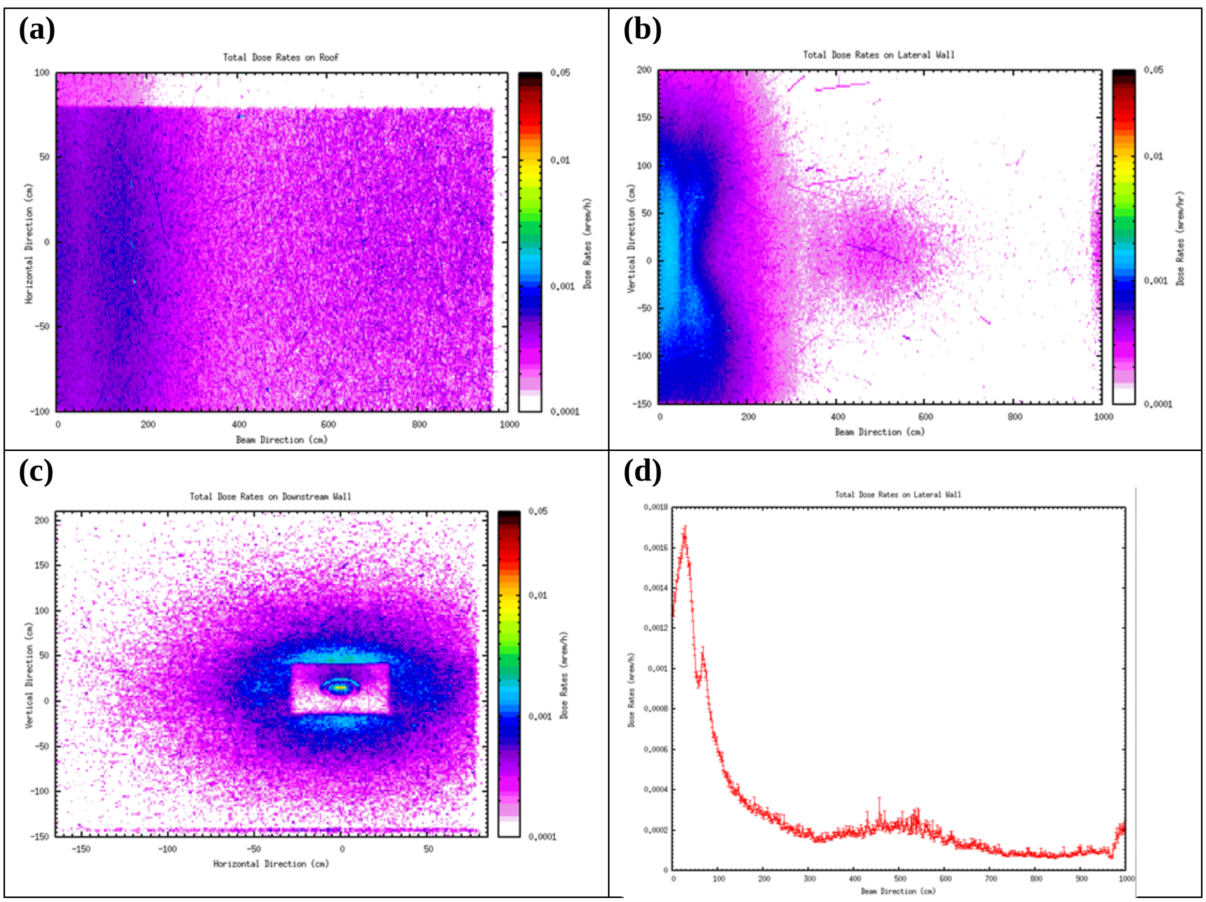


Figure 9: Total dose rate distributions (mrem/h) (a) on the roof, (b) on the lateral wall, (c) on contact with the downstream FOE wall and (d) total dose rates along the lateral wall averaged over an elevation of y = ± 4cm.

Unlike the previous 2 cases, total dose rates are slightly above 0.001 mrem/h on the roof [Figure 9(a)], the downstream wall [Figure 9(c)] and the lateral wall [Figure 9(b) and (d)], but below 0.01 mrem/h.

3.5 FM4

In this simulation, the GB was started just upstream of the selected point of contact at x=0 cm, y=4.53 cm, z=-204.12 cm and impinges at the position of the top extreme ray on the front face of the FM4. The total dose distributions (mrem/h) in the FOE are shown in Figure 10 and the corresponding neutron distributions are given in Figure 11.

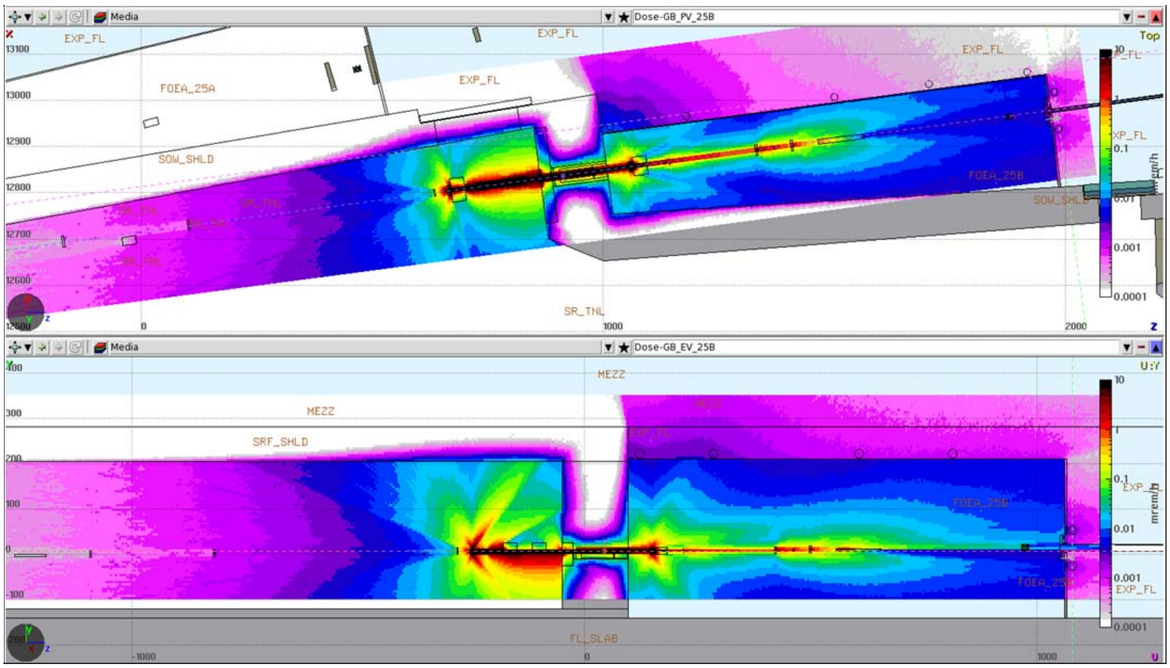


Figure 10: Total dose rate distributions (mrem/h). The Top view at y=6.47 cm (centerline of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

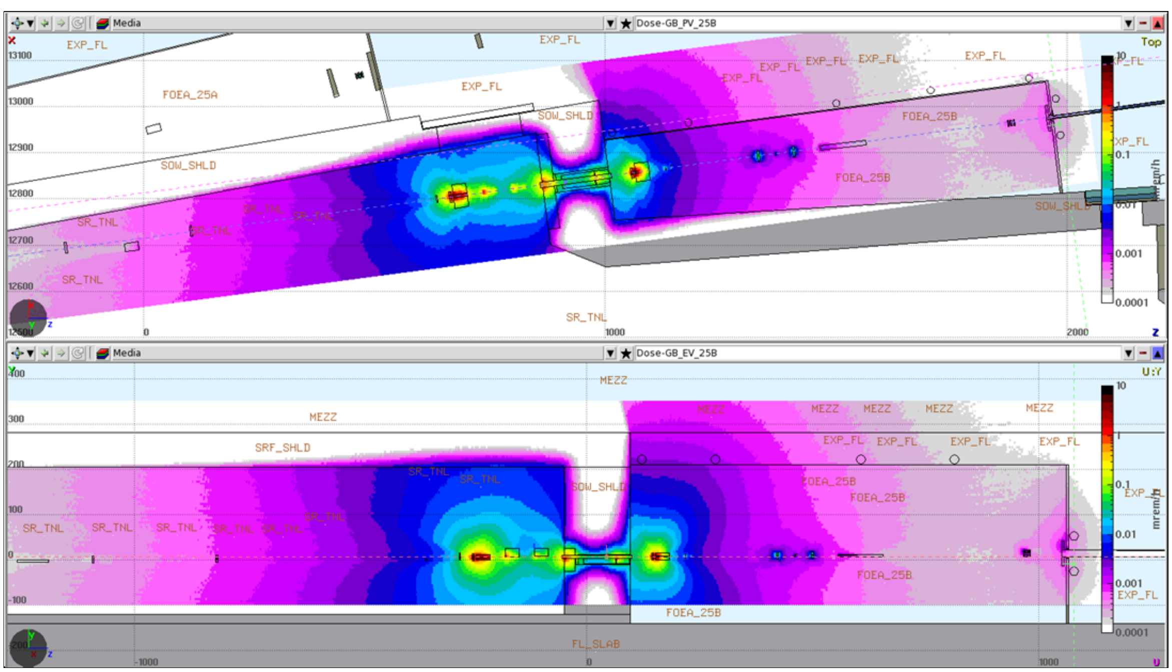


Figure 11: Neutron dose rate distributions (mrem/h). The Top view at y=6.47 cm (center of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

The total dose rates are highest on the lateral wall in proximity of the MSK1 and BRS, as illustrated in Figure 12(b) and Figure 12(d) shows that the total dose rates on the lateral do not exceed 0.01 mrem/h. The dose rates on contact with the roof [Figure 12(a)] and the downstream wall [Figure 12(c)] are also below 0.01 mrem/h. The BRS is very effective in attenuating the forward electromagnetic shower generated in the FE, which is further shadowed by the guillotine, as can be seen in Figure 12(c). The amount of radiation that leaks through the apertures of BRS is attenuated by the beamline components downstream from the BRS.

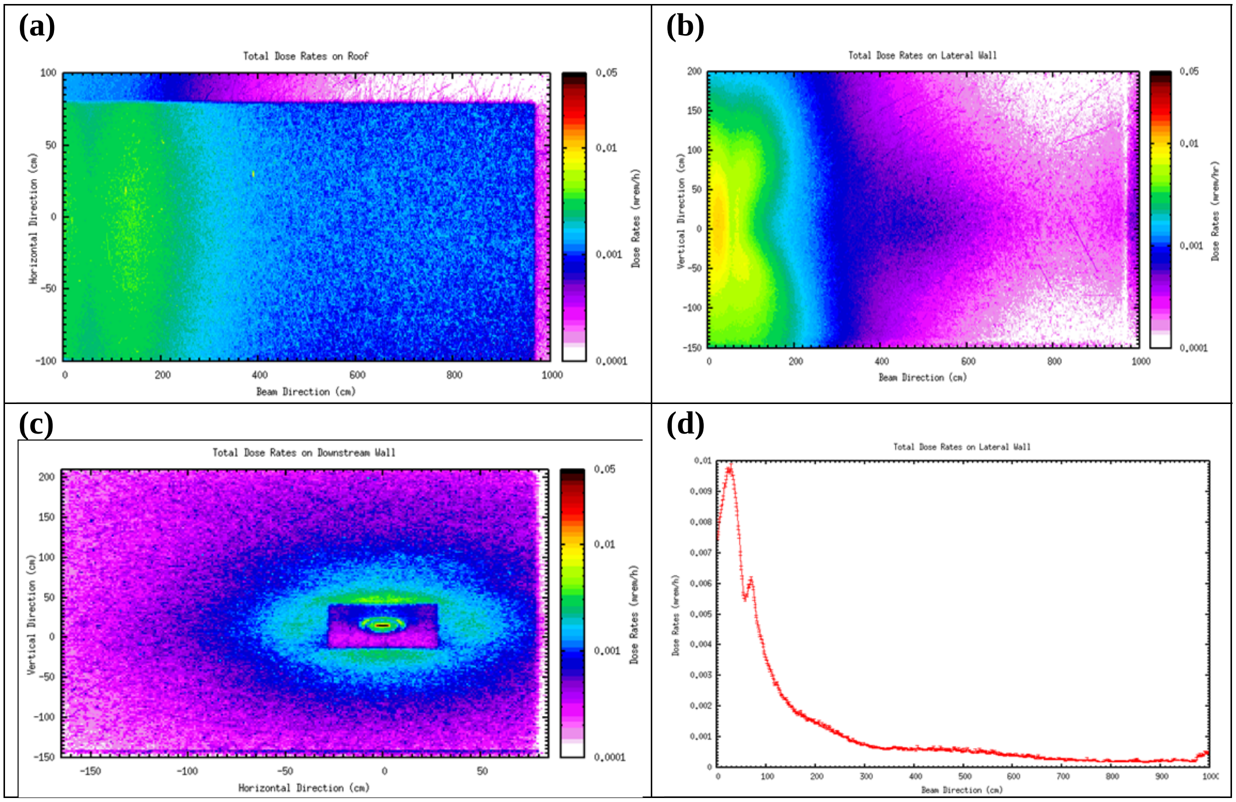


Figure 12: Total dose rate distributions (mrem/h) (a) on the roof, (b) on the lateral wall, (c) on contact with the downstream FOE wall and (d) total dose rates along the lateral wall averaged over an elevation of y = ± 4cm.

In this simulation, the GB was started just upstream of the selected point of contact at x=0 cm, y=3.62 cm, z=-204.12 cm and impinges at the position of the bottom extreme ray on the front face of the FM4. The total dose distributions (mrem/h) in the FOE are shown in Figure 13 and the corresponding neutron distributions are given in Figure 14.

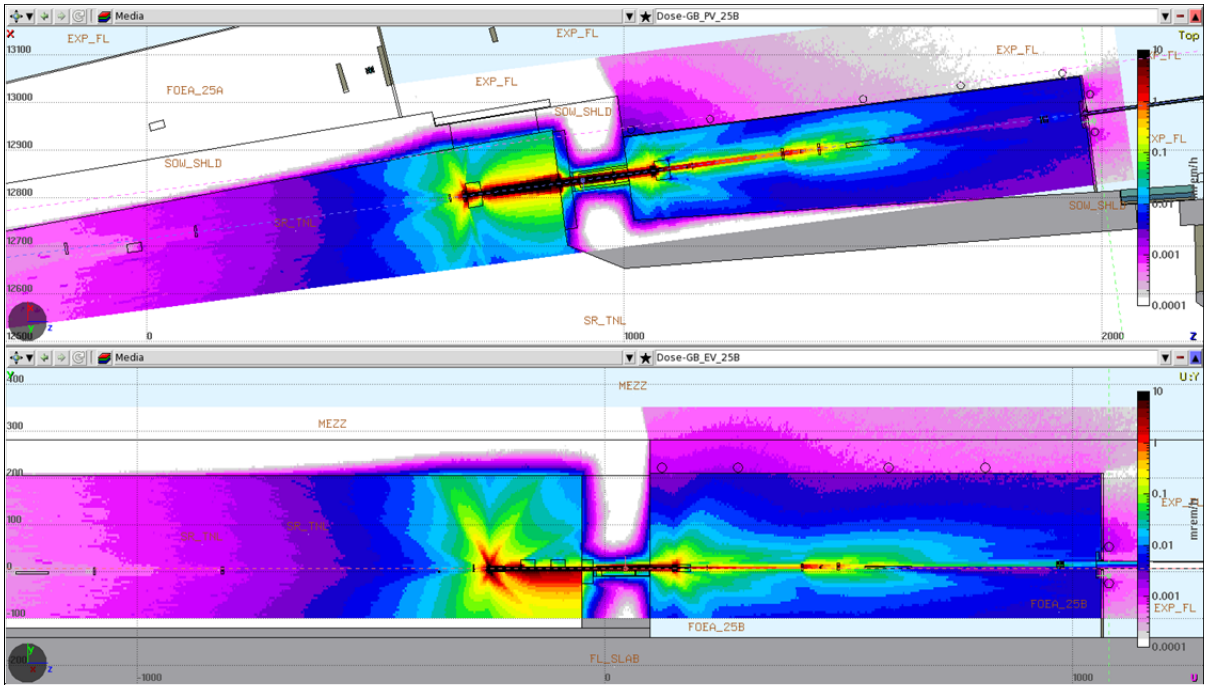


Figure 13: Total dose rate distributions (mrem/h). The Top view at y=6.47 cm (centerline of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

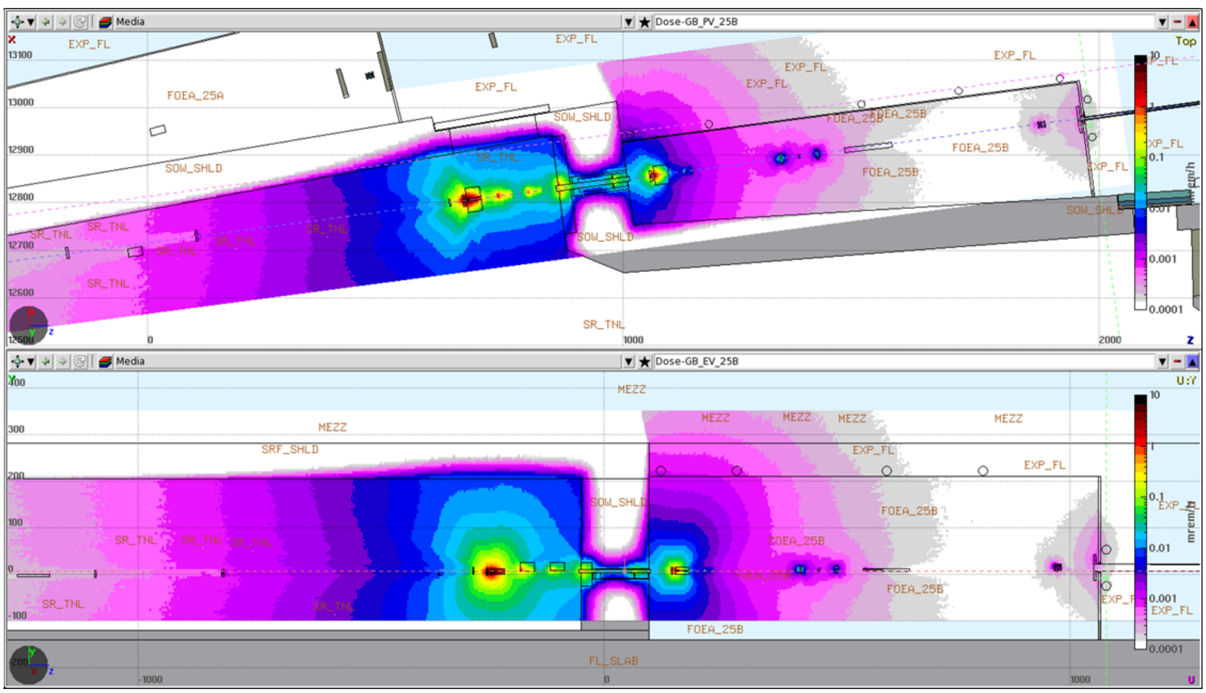


Figure 14: Neutron dose rate distributions (mrem/h). The Top view at y=6.47 cm (center of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

The total dose rates are similar to previous case and are highest on the lateral wall in proximity of the MSK1 and BRS, as illustrated in Figure 15(b) and Figure 15(d). These figures show that the total dose rates on the lateral do not exceed 0.0045 mrem/h. The dose rates on contact with the roof [Figure 12(a)] and the downstream wall [Figure 12(c)] are well below 0.01 mrem/h.

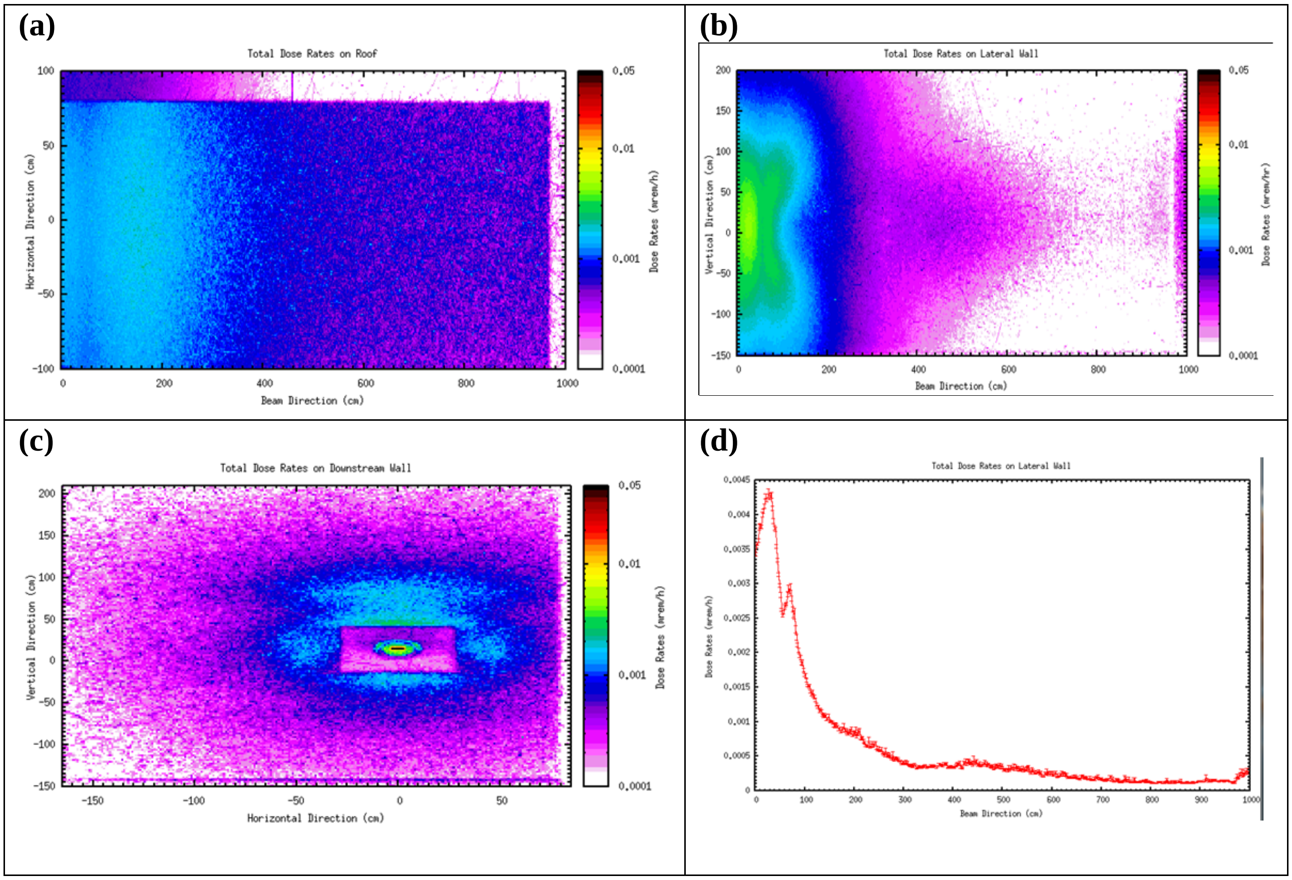


Figure 15: Total dose rate distributions (mrem/h) (a) on the roof, (b) on the lateral wall, (c) on contact with the downstream FOE wall and (d) total dose rates along the lateral wall averaged over an elevation of y = ± 4cm.

3.5 MSK1

In this simulation, the GB was started just upstream of the selected point of contact at x=0 cm, y=5.60 cm, z=192.73 cm and impinges at the position of the top extreme ray on the front face of the MSK1. The total dose distributions (mrem/h) in the FOE are shown in Figure 16 and the corresponding neutron distributions are given in Figure 17. It clearly shows that neutrons dominate the dose rate on the lateral wall and roof. BRS is very effective in attenuating the forward electromagnetic shower, resulting in negligible total dose rates on the downstream as it can be seen from Figure 18(c). The total dose rates are highest on the lateral wall, but below 0.04 mrem/h as shown in Figure 18(d). The dose rates on contact with the roof [Figure 18(a)] are below 0.02 mrem/h while on contact with the downstream wall [Figure 18(c)] they are below 0.001 mrem/h.

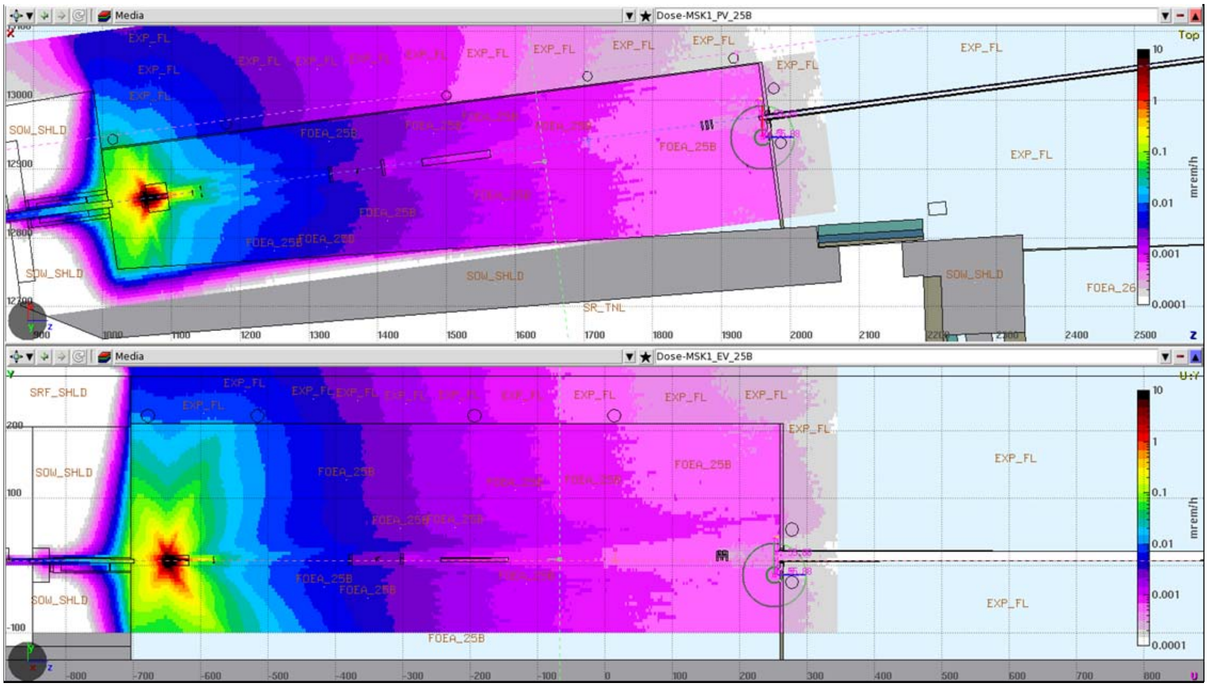


Figure 16: Total dose rate distributions (mrem/h). The Top view at y=6.47 cm (centerline of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

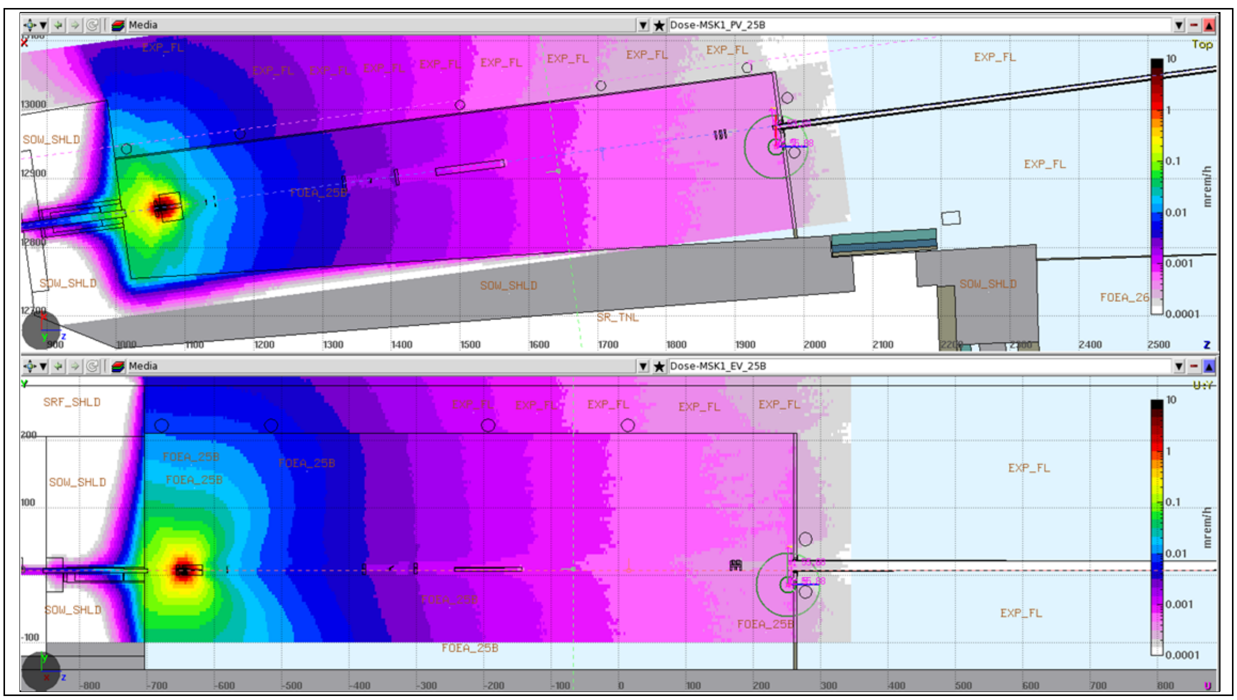


Figure 17: Neutron dose rate distributions (mrem/h). The Top view at y=6.47 cm (center of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

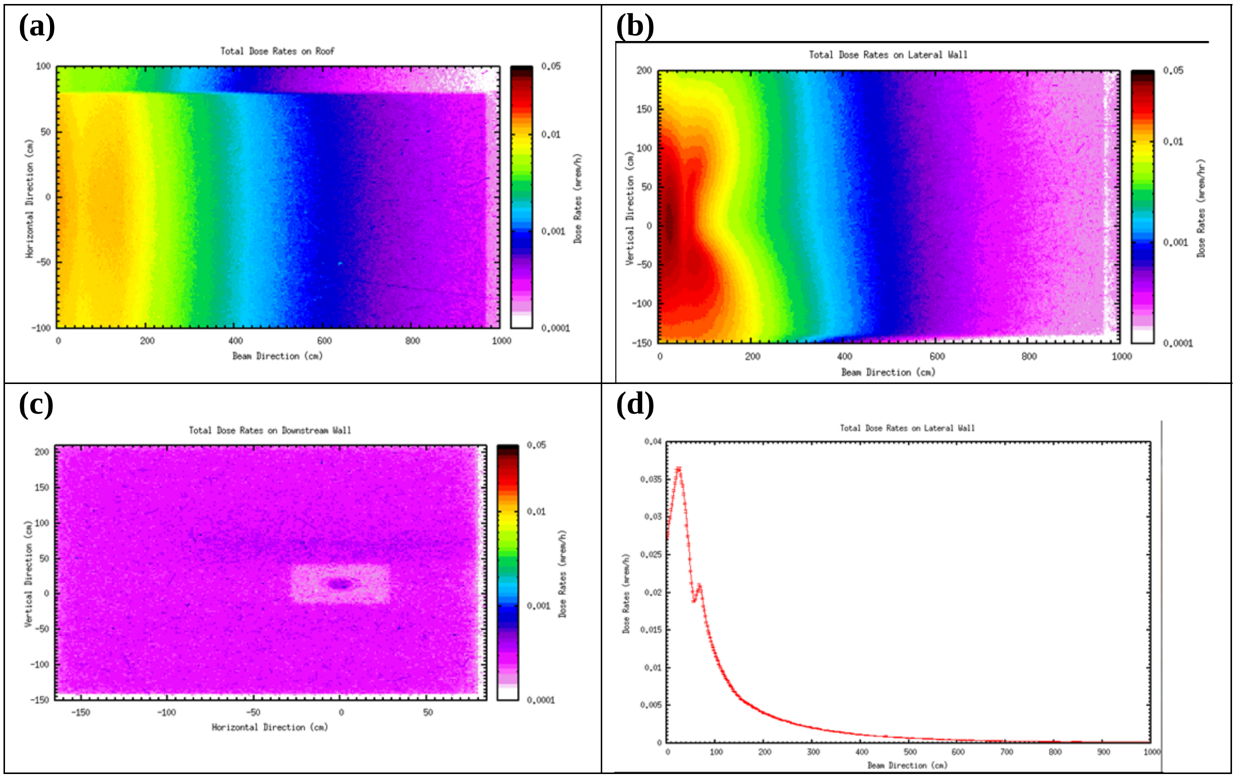


Figure 18: Total dose rate distributions (mrem/h) (a) on the roof, (b) on contact with the downstream FOE wall, (c) on the upstream lateral wall (bump-out wall), and (d) on the downstream on lateral wall.

In this simulation, the GB was started just upstream of the selected point of contact at x=0 cm, y=4.42 cm, z=192.73 cm and impinges at the position of the bottom extreme ray on the front face of the MSK1. The total dose distributions (mrem/h) in the FOE are shown in Figure 19 and the corresponding neutron distributions are given in Figure 20. The dose rates distributions are similar to the previous case where the top extreme ray strikes MSK1.

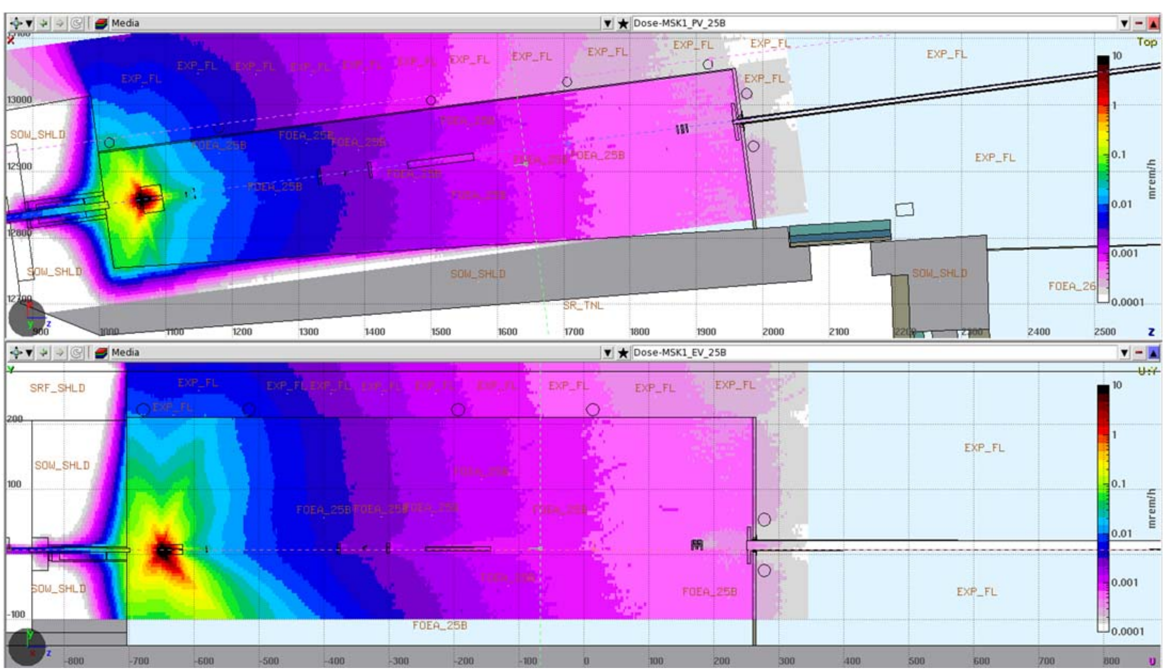


Figure 19: Total dose rate distributions (mrem/h). The Top view at y=6.47 cm (centerline of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

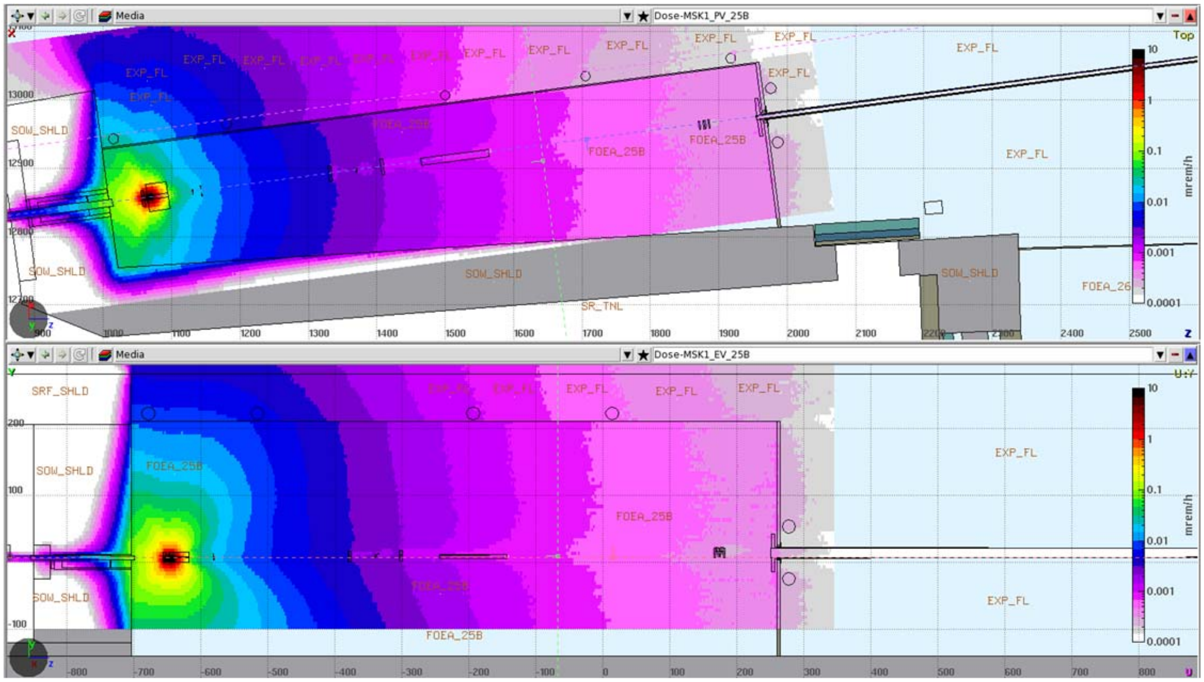


Figure 20: Neutron dose rate distributions (mrem/h). The Top view at y=6.47 cm (center of the RCO) is shown in the top figure and the elevation view shown in the bottom figure.

4. Synchrotron Radiation Calculation

The 07-BM (QAS) beamline is a three pole wiggler (3PW) source and its parameters are extracted from references [1] and reproduced in Table 3. It has a collimating mirror in the FE, which will deflect the synchrotron beam vertically and pass through the vertically offset RCO aperture. Therefore, the synchrotron beam entering the FOE is a mirror reflected pink beam. For simplicity, the FOE analysis below is based on a white beam, which is very conservative. The horizontal opening angle for the 07-BM (QAS) source fan entering the FOE is provided in column 2. 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 STAC8 total integrated power (column 7).

Table 3: Source Parameters Used for 07-BM (QAS) Synchrotron Calculations

Source	Max. source opening	No. Of periods	Max. B_{eff} (T)	Length (m)	E_c (keV)	STAC 8 Total Power (kW) @ 500mA
3PW	3.0 mrad-H	1	1.2	0.25	6.7	0.28

The analytic code STAC8 [4] was used to calculate the ambient dose equivalent rates in the occupied areas outside the FOE, monochromatic beam transport pipe and end-station enclosure 07-BM-B. 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 for the transport pipe and the ESEs assume that the primary bremsstrahlung has been completely stopped in the FOE. Targets for maximum scattered radiation were considered in the STAC8 calculations. These cases considered are described in Section 4.1and 4.2.

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 grazing angle of 0.155 degree with the respect to the incident beam [4]. The position of the scatter target is assumed to be located at the DCM approximately 604 cm from the FOE downstream wall, 80 cm from the lateral wall and 210 cm from the roof. The minimum required shielding for the SR (white beam) source (no credit has been given to the secondary bremsstrahlung shielding or guillotine) and the corresponding ambient dose rates are given in Table 4. 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 4: SR Shielding Design Requirements for 07BM-QAS FOE

	Distance (cm)	Minimum Required Shielding	Max Ambient Dose Rate (mrem/h)
Lateral wall	80	5 mm Pb	0.015
Roof	210	4 mm Pb	0.014
Downstream Wall (> 1^{o})	604	6 mm Pb	0.041

4.2 Transport Pipe and ESE (07-BM-B/C)

The lead thickness of the 07-BM (QAS) monochromatic beam transport pipe is 5 mm, which exceeds the minimum shielding requirement of 2 mm; specified in Reference [1]. Figure 21 shows the vertical synchrotron ray tracings, which illustrate that under certain Mirror PFM configuration, the monochromatic beam shown in section D-D could potentially strike the lead shielded transport pipe.

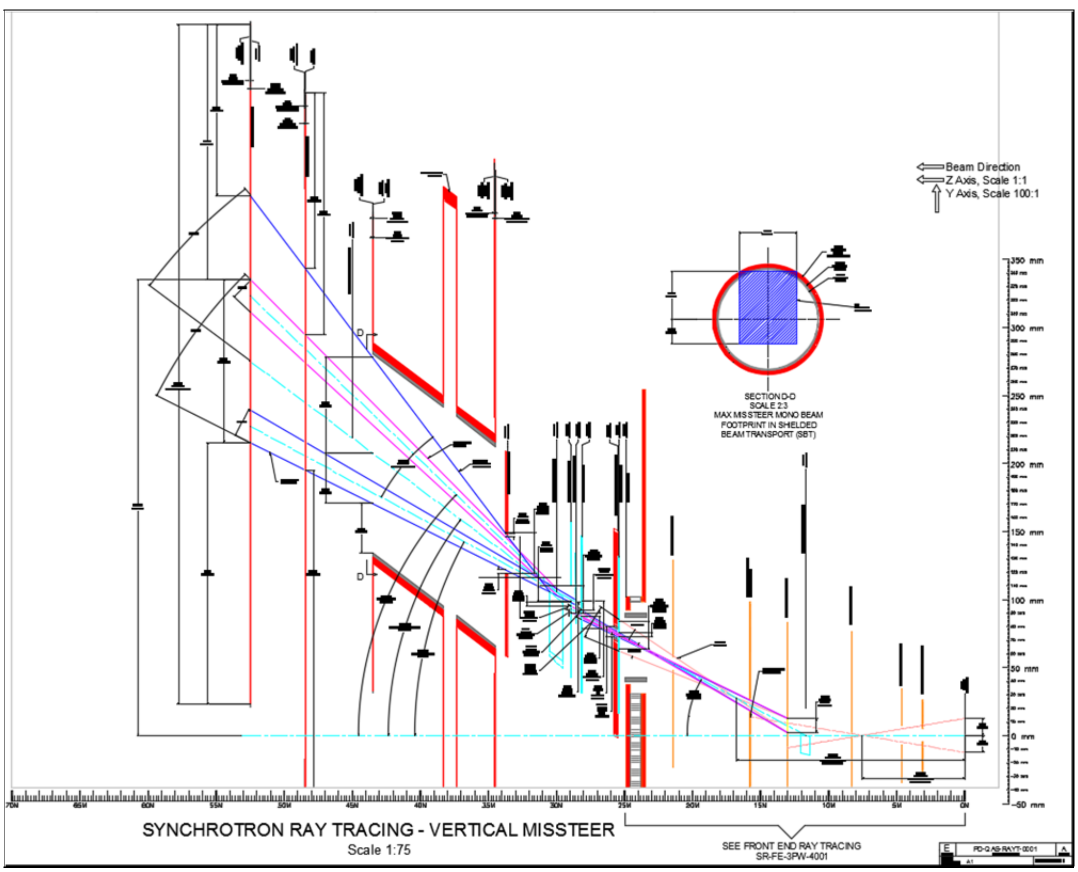


Figure 21: Synchrotron vertical ray tracings showing mis-steered monochromatic beam striking the shielded transport pipe (section D-D).

We assumed a pink beam from Rh coated M1 mirror with a lowest incident angle of 2.7 mrad needed for the reflected beam to enter the FOE and incident on the first crystal of the DCM. Assuming five higher harmonic reflections (111, 333, 444, 555, and 777) of the fundamental mode of 22 keV with corresponding bandwidths [5], the dose rate is calculated directly on contact with the lead shielded transport pipe by the "NICK" card in STAC8. The calculated ambient dose rate is 2.7E-04 mrem/h for this abnormal mis-steering event and is well below the design criteria of 0.05 mrem/h.

The ESE dimensions are given in Appendix 1 (Table 1.3). The STAC8 calculation was carried out with the same silicon scatter target used for the FOE analysis. The location of target is assumed to be along the monochromatic beam centerline at 200 cm from the downstream wall. For the beam to enter ESE, the DCM and PFM inside the FOE must be inserted to direct a focused beam into the beam transport pipe and toward the ESE. For this calculation, we ignore the reflections from PFM, which is very conservative. The dose rates on the walls and roof are given in Table 5. For the downstream wall the dose rates correspond to a target located approximately 50 cm downstream from the center of the 07-BM-B enclosure, and for the 07-BM-C enclosure it is located at its center and no credit was given to the beam stop. In all cases the ambient dose rates are well below the design criteria of 0.05 mrem/h.

Table 5: SR Shielding Design Requirements for ESE (07BM-B/C Enclosures)

	Distance (cm)	Installed Shielding	Ambient Dose rate (mrem/h)
Lateral wall	135	3 mm Fe	5.4E-05
Roof	210	2 mm Fe	5.2E-05
Downstream Wall (> 1^{o})	200	6 mm Fe	7.1E-04

In the absence of any targets in the ESE, the maximum synchrotron fan through the shielded transport pipe should be completely stopped by the 12 mm lead beam stop on the downstream wall of the 07-BM-B and 07-BM-C enclosures (see Ray Tracings PD-QAS-RAYT-0001 Sheet 2 and 3).

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 7.2 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 6.6 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 6.

Table 6: Maximum Total Dose Rates (mrem/h) on the Roof, Lateral Wall, and the Downstream Wall of the FOE

Case # / Report Section	Simulation	Roof (mrem/h)	Lateral Wall (mrem/h)	D/S Wall (mrem/h)
1 / 3.1	**PCM**	< 0.05	< 0.05	< 0.05
2 / 3.2	**FM2**	< 0.05	< 0.05	< 0.05
3 / 3.3	**FM3**	< 0.05	< 0.05	< 0.05
4 / 3.4	**FM4**	< 0.05	< 0.05	< 0.05
5 / 3.5	**MSK1**	< 0.05	< 0.05	< 0.05

Based on the STAC8 calculation, the dose rates outside of the FOE, beam transport pipe and the ESEs are much less than 0.05 mrem/h and 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 ESE 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] 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.

[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 thank M. Breitfeller, L. Lienhard, and S. Ehrlich for providing all the beamline information required for FLUKA simulations and STAC8 calculations and for multiple discussions.

Appendix 1

07-BM (QAS) Input provided by Mark Breitfeller and Lukas Lienhard: updated on Jul 24, 2017.

The source point is the origin of the co-ordinate system. The FE centerline was used as the z or beam axis for the FLUKA models. Y is the vertical axis and x the horizontal axis orthogonal to the y and z axes.

Table 1.1 Beamline Enclosure: First Optical Enclosure

Wall	Position	Thickness	Material
D/S End of 7-BM Ratchet Wall	24892.4 mm		
D/S End of FOE (7-BM-A) Backwall	34584.2 mm	50 mm	Lead
Distance of Sidewall from straight CENTERLINE	805.6 mm	18 mm	Lead
Distance of Roof from straight CENTERLINE	2100.0 mm	4 mm	Lead

Table 1.2 Beamline Transport Pipe

Transport Pipe between FOE & SOE	ID = 5.75 inches (min) OD = 6.00 inches Material: Stainless Steel	Shielding Thickness = 5.0 mm Shielding Material: Lead Beampipe is 13.9 cm (y) above center line

Table 1.3 Endstation Enclosures (B&C share walls)

Wall	Position	Thickness	Material
U/S End of 7-BM-B Wall	43500 mm (z)	3 mm	Steel
D/S End of 7-BM-B Backwall	48500 mm (z)	6 mm	Steel
D/S end of 7-BM-C Backwall	52500 mm (z)	6 mm	Steel
Distance of inboard Sidewall from straight CENTERLINE (B&C)	1350 mm (x)	3 mm	Steel
Distance of outboard Sidewall from straight CENTERLINE (B&C)	2150 mm (x)	3 mm	Steel
Distance of Roof from straight CENTERLINE	2100 mm (y)	2 mm	Steel
D/S Wall beam stop location B hutch (395mm H x 560mmV)	48439.9 mm (U/S) Center +193mm (y)	12 mm	Lead
D/S Wall beam stop location C hutch (50cm x 50cm)	52482.0 mm (U/S) Center +273mm (y)	12 mm	Lead

Table 1.4 FE Components (SR-FE-3PW-4001, Ray Trace)

Shielding	Z location (Distance from S.S. center) (US), (DS) 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) (MAX includes mfr & positional tolerance)			
Crotch Absorber	306.2cm (US)	26.44cm (x) 4.24body/1.40tip cm (y),4.445cm (z)	2.547cm (x) 1.392cm (y)	-0.319 (x)	Glidcop AL-15	SR-VA-ABS-1098
Exit Absorber	463.2cm (US)	6.93cm (x) 6.93cm (y) 1.91cm (z)	1.80cm (x) MAX 1.80cm (y) MAX Aperture .85 cm (x) offset from body ctr	0	Cu-Cr-Zr	SR-FE-3PW-ABS-0011
FM1	832.1cm (DS)	22.86cm (x) 15.24cm (y) 4.445cm(z)	DS & US (No Taper) 1.674cm (x) MAX 0.260cm (y) MAX	0	Cu-Cr-Zr	SR-FE-3PW-MSK-1824
LCO1	836.6cm (US)	41.25cm (x) MIN 12.5cm (y) MIN 30.0cm (z) MIN	Lead Aperture 3.348cm (x) MAX 1.824cm (y) MAX	0	Lead	SR-FE-3PW-CO-0400
Be Window	910.1cm (C)	15.24cm (x) 15.24cm (y) 0.254mm (z)	3.86cm (x) MAX 1.00cm (y) MAX	0	Glidcop with Beryllium foil in aperture	SR-FE-3PW-WIN-0250
X-Y Slit 1	973.6cm (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-2011
X-Y Slit 2	1021.5cm (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-2021
Collimating Mirror (Flat)	1170.0cm (Center)	10cm (x) 5cm (y) 70cm (z)	2.7 mrad pitch about center	0 (top surface centered on	Silicon	PD-QAS-PCM-1000

				beam)		
FM2	1304.7cm (DS)	22.86cm (x) 15.24cm (y) 4.445cm(z)	DS: 3.225cm (x)MAX DS: 1.002cm (y)MAX Vert angle = 1 deg US: 1.075cm (y)MAX	+.73cm (y)	Cu-Cr-Zr	SR-FE-3PW-MSK-1825
Inboard Shadow Shield	1511.4cm (US)	17.5cm (x) MIN 30.0cm (y) MIN 30.0cm (z) MIN	No aperture	X = -7.62cm (outboard face)	Lead	SR-FE-3PW-4015
FM3	1578.4cm (DS)	22.86cm (x) 15.24cm (y) 4.445cm(z)	DS: 3.776cm (x)MAX DS: 1.086cm (y)MAX Vert angle = 1 deg US: 1.159cm (y)MAX	+2.21cm (y)	Cu-Cr-Zr	SR-FE-3PW-MSK-1826
Diagnostic flag (sketch)	2038.4cm (C)	6cm (x) 4cm (y) 4cm (z)	No aperture	Centered on beam when in	Cu	PD-COM-DG-0100
Photon Shutter	2113.7cm (C)	15.24cm (x) 15.88cm (y) 3.175cm (z)	DS & US (No Taper) 5.334cm (x) 1.524cm (y) (aperture offset to part C/L, y = -2.50 cm)	Y=5.10cm to SR Beam Ht when open	Cu-Cr-Zr	SR-FE-3PW-PSH-0111
FM4	2145.3cm (DS)	22.86cm (x) 15.24cm (y) 4.445cm(z)	DS: 4.916cm (x)MAX DS: 1.261cm (y)MAX Vert angle = 1 deg US: 1.334cm (y)MAX	+5.27cm (y)	Cu-Cr-Zr	SR-FE-3PW-MSK-1827
LCO2	2149.9cm (US)	51.25cm (x) MIN 12.5cm (y) MIN 30.0cm (z) MIN	Lead Aperture 6.349cm (x) MAX 3.252cm (y) MAX	+5.27cm (y)	Lead	SR-FE-3PW-CO-0450
Safety Shutter1	2214.6cm (US)	17.5cm (x) MIN 17.5cm (y) MIN 30.0cm (z) MIN	Tube Aperture 9.4 cm (x) 3.4 cm (y)	Y=+5.62cm when open	Lead	SR-FE-3PW-SS-4000
Safety Shutter2	2278.6cm (US)	17.5cm (x) MIN 17.5cm (y) MIN 30.0cm (z) MIN	Tube Aperture 9.4 cm (x) 3.4 cm (y)	Y=+5.96cm when open	Lead	SR-FE-3PW-SS-4100
Lead in Ratchet wall RC0 (sketch)	2344.5cm (US)	205.0 cm (x) MIN 50.0 cm (y) MIN 25.0 cm (z) MIN	Lead Aperture 11.6 cm (x) MAX 6.8 cm (y) MAX	+6.47cm (y) Tube centerline	Lead	SR-FE-3PW-RCO-4000
Lead block RC1 (sketch)	2369.9cm (US)	40.0 cm (x) MIN 20.0 cm (y) MIN	Lead Aperture 11.6 cm (x) MAX	+6.47cm (y) Tube	Lead	SR-FE-3PW-RCO-4000

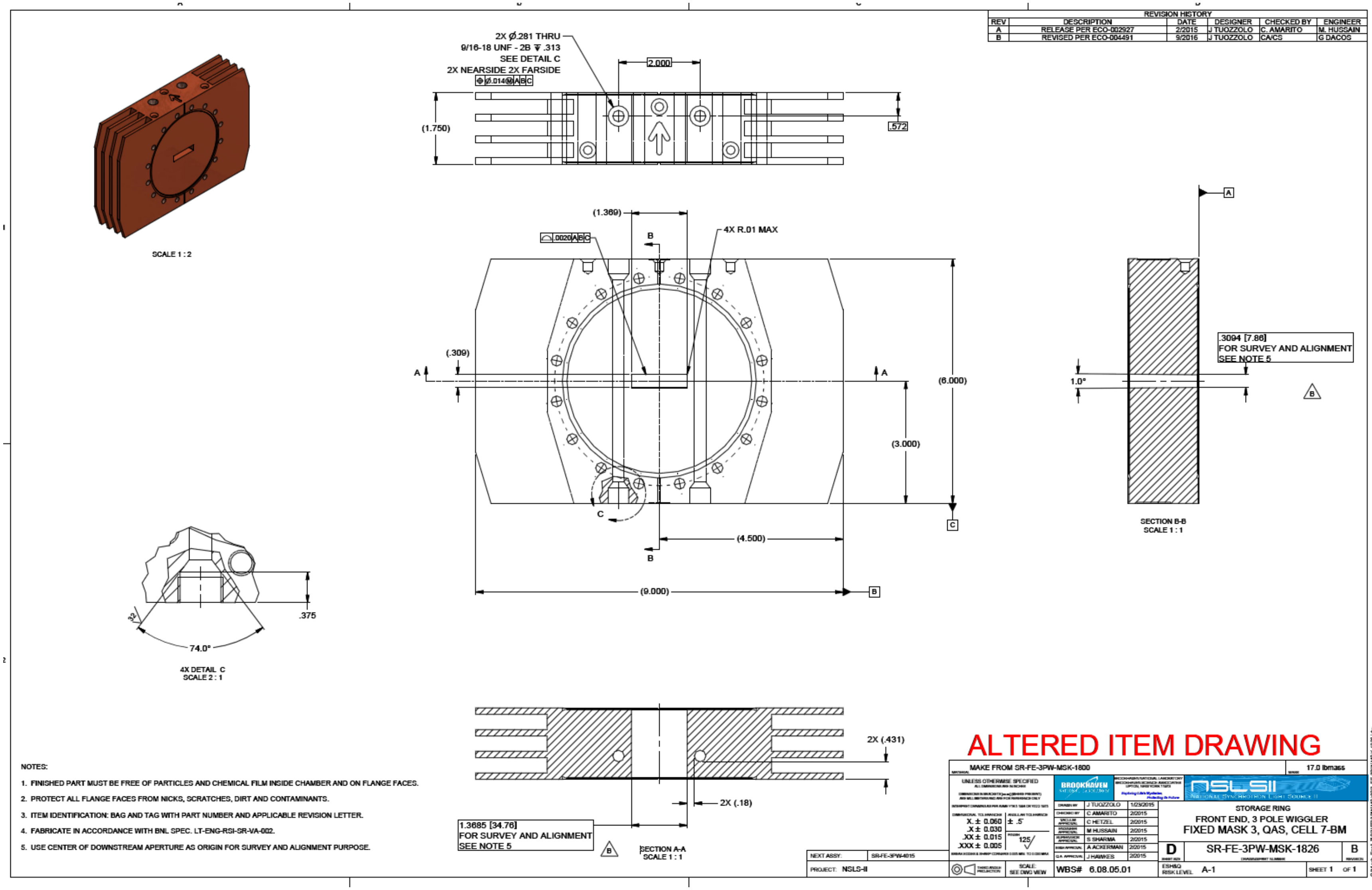
		5.0 cm (z) MIN	6.8 cm (y) MAX	centerline		
RCO Concrete Block (sketch)	2457.5cm (DS)	28.9 cm (x) MIN 12.5 cm (y) MIN 72.0 cm (z) MIN	Concrete Aperture 11.6 cm (x) MAX 6.8 cm (y) MAX	+6.47cm (y) Tube centerline	Lead, concreate & HDPE	SR-FE-3PW-RCO-8180
RCO Lead Brick (sketch)	2489.2cm (DS)	28.9 cm (x) MIN 12.5 cm (y) MIN 30.0 cm (z) MIN	Lead Aperture 10.4 cm (x) MAX 5.5 cm (y) MAX	+6.47cm (y) Tube centerline	Lead, concrete & HDPE	SR-FE-3PW-RCO-8180

Table 1.5 Beamline FOE Components

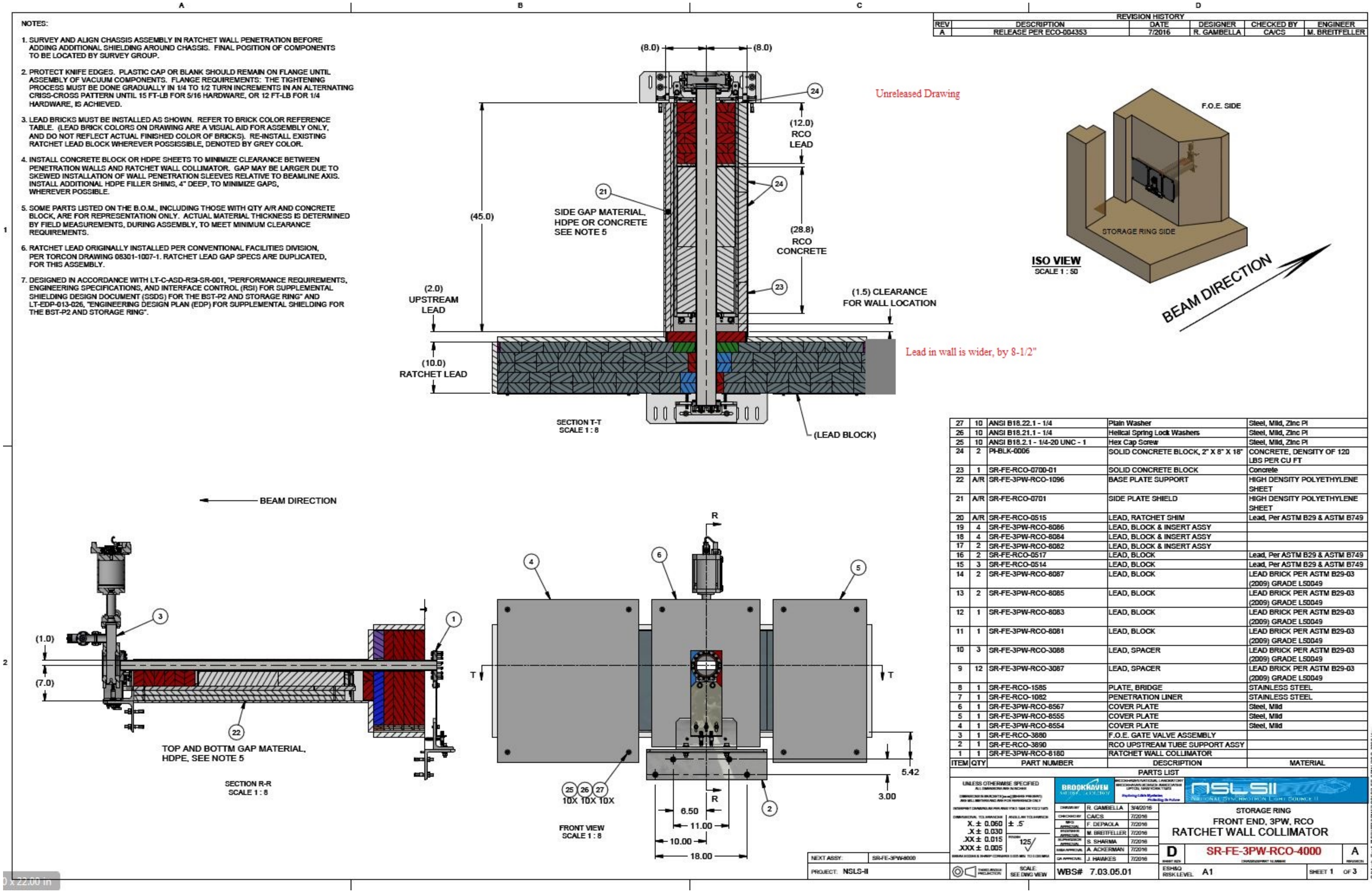
Components	Z location (Distance from 3PW center) (U), (D) or center	Dimensions (specify units)		Offset (vertical or horizontal) w.r.t Straight CENTERLINE	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R) (MAX includes mfr & positional tolerance)			
Fixed Mask (MSK1) See Sketch 3	2537.7 cm (U)	22.86cm (x) 15.24cm (y) 4.445cm(z)	US:6.35cm(x),2.15cm(y) DS:4.62cm(x),0.41cm(y) MAX	+7.385cm (y) At center	Cu-Cr-Zr	PD-QAS-MSK-1101
Bremsstrahlung Stop (CO1/BRS)	2546.5 cm (U)	40.2 cm (x) 14.84 cm (y) 30.0 cm (z)	5.782 cm (x) MAX 1.474 cm (y) MAX	5.4 mrad pitch +7.516cm (y) at center	Lead	PD-QAS-CO-0100
Slits – Vertical (2 individual blades)	2612.6 cm (US-tungsten)	6.5cm (x) 4.5cm (y) 0.4cm (z) (Blade size)	10mm overlap – closed 10mm aperture – open	Center 7.8cm above GB centerline	Tungsten blade with copper plate for cooling	PD-QAS-SLT-1000
Slits – Horizontal (2 individual blades)	2625.0cm (US-tungsten)	4.5cm (x) 6.5cm (y) 0.4cm (z) (Blade size)	10mm overlap – closed 60mm aperture - open	Center 7.8cm above GB centerline	Tungsten blade with copper plate for cooling	PD-QAS-SLT-1000
Fixed Mask (MSK2) See Sketch 3	28135 mm (U)	22.86cm (x) 15.24cm (y) 4.445cm(z)	US:6.01cm(x),2.06cm(y) DS:4.28cm(x),0.32cm(y) MAX	+8.86cm (y) at center	Cu-Cr-Zr	PD-QAS-MSK-1201
DCM 1st crystal (MONO) See sketch 5	2854.1 cm (C)	50mm × 5mm × 16mm (z) (rotated@ 30	No aperture	Top surface at +9.09cm (y)	Silicon	PD-QAS-MONO-1000

		deg max)				
DCM 2nd crystal (MONO) See sketch 5	2857.9 cm (C)	50mm × 3mm × 71mm (z) (rotated@ 30 deg max)	No aperture	Bottom surface offset 3.75mm +y, w.r.t. 1st crystal	Silicon	PD-QAS-MONO-1000
Mono diagnostic screen	2864.67 cm (U)	8.89cm (x) 2.54cm (y) 1.90cm (z)	No aperture	+9 cm	Cu	
Pink Beam stop (PBS1) See sketch 4	2890.4 cm (U)	22.86cm (x) 15.24cm (y) 4.445cm(z)	US:6.01cm(x),1.055cm(-y) DS:4.28cm(x), 1.87mm(-y),10.4mm(+y) MAX	+10.0cm (y)	Cu-Cr-Zr	PD-CMS-MSK-1301
Mono beam Mirror (PFM) See sketch 6	3000.0 cm (C)	1000mm (z) × 100mm (x) × 60 mm (y) (rotated@ 2.135 mrad max)	42.7mm radius of curvature (60mm curvature width)	center of reflecting surface +105.8mm (y)	ULE Glass	PD-QAS-PFM-1000
Diagnostic screen	3318.766 cm (U)	6.0 cm (x), 3.0 cm (y) 0.5 cm (z)	No aperture	+13.0cm (y)	Cu	
Shutter (PSH)	3359.8 cm (U)	12.5 cm W × 15 cm H× 3.8 cm	60 mm × 30 mm	+13.3cm (y)	Tungsten	PD-COM-PSH-2100
Guillotine	3445.390 cm (U)	55.88 cm W × 55.88 cm H × 5.00 cm	152.4 mm (6”) diameter	guillotine and aperture +13.9 cm up	Lead	7-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	+13.9 cm (y) above centerline	Lead	Hutch wall and shielded pipe collar

Front end fixed masks



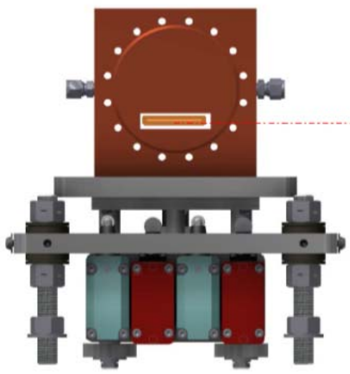
Ratchet wall collimator



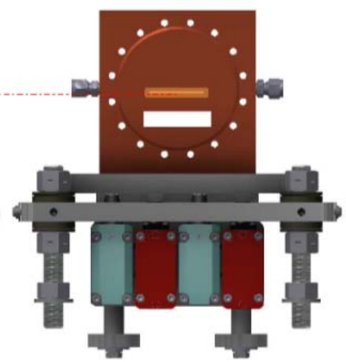
PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION	MATERIAL
27	10	ANSI B18.22.1 - 1/4	Plain Washer	Steel, Mild, Zinc Pl
26	10	ANSI B18.21.1 - 1/4	Helical Spring Lock Washers	Steel, Mild, Zinc Pl
25	10	ANSI B18.2.1 - 1/4-20 UNC - 1	Hex Cap Screw	Steel, Mild, Zinc Pl
24	2	PI-BLK-0006	SOLID CONCRETE BLOCK, 2" X 8" X 18"	CONCRETE, DENSITY OF 120 LBS PER CU FT
23	1	SR-FE-RCO-0700-01	SOLID CONCRETE BLOCK	Concrete
22	A/R	SR-FE-3PW-RCO-1096	BASE PLATE SUPPORT	HIGH DENSITY POLYETHYLENE SHEET
21	A/R	SR-FE-RCO-0701	SIDE PLATE SHIELD	HIGH DENSITY POLYETHYLENE SHEET
20	A/R	SR-FE-RCO-0515	LEAD, RATCHET SHIM	Lead, Per ASTM B29 & ASTM B749
19	4	SR-FE-3PW-RCO-8086	LEAD, BLOCK & INSERT ASSY	
18	4	SR-FE-3PW-RCO-8084	LEAD, BLOCK & INSERT ASSY	
17	2	SR-FE-3PW-RCO-8082	LEAD, BLOCK & INSERT ASSY	
16	2	SR-FE-RCO-0517	LEAD, BLOCK	Lead, Per ASTM B29 & ASTM B749
15	3	SR-FE-RCO-0514	LEAD, BLOCK	Lead, Per ASTM B29 & ASTM B749
14	2	SR-FE-3PW-RCO-8087	LEAD, BLOCK	LEAD BRICK PER ASTM B29-03 (2009) GRADE L50049
13	2	SR-FE-3PW-RCO-8085	LEAD, BLOCK	LEAD BRICK PER ASTM B29-03 (2009) GRADE L50049
12	1	SR-FE-3PW-RCO-8083	LEAD, BLOCK	LEAD BRICK PER ASTM B29-03 (2009) GRADE L50049
11	1	SR-FE-3PW-RCO-8081	LEAD, BLOCK	LEAD BRICK PER ASTM B29-03 (2009) GRADE L50049
10	3	SR-FE-3PW-RCO-3088	LEAD, SPACER	LEAD BRICK PER ASTM B29-03 (2009) GRADE L50049
9	12	SR-FE-3PW-RCO-3087	LEAD, SPACER	LEAD BRICK PER ASTM B29-03 (2009) GRADE L50049
8	1	SR-FE-RCO-1585	PLATE, BRIDGE	STAINLESS STEEL
7	1	SR-FE-RCO-1082	PENETRATION LINER	STAINLESS STEEL
6	1	SR-FE-3PW-RCO-8567	COVER PLATE	Steel, Mild
5	1	SR-FE-3PW-RCO-8555	COVER PLATE	Steel, Mild
4	1	SR-FE-3PW-RCO-8554	COVER PLATE	Steel, Mild
3	1	SR-FE-RCO-3880	F.O.E. GATE VALVE ASSEMBLY	
2	1	SR-FE-RCO-3890	RCO UPSTREAM TUBE SUPPORT ASSY	
1	1	SR-FE-3PW-RCO-8180	RATCHET WALL COLLIMATOR	

Front end photon shutter design

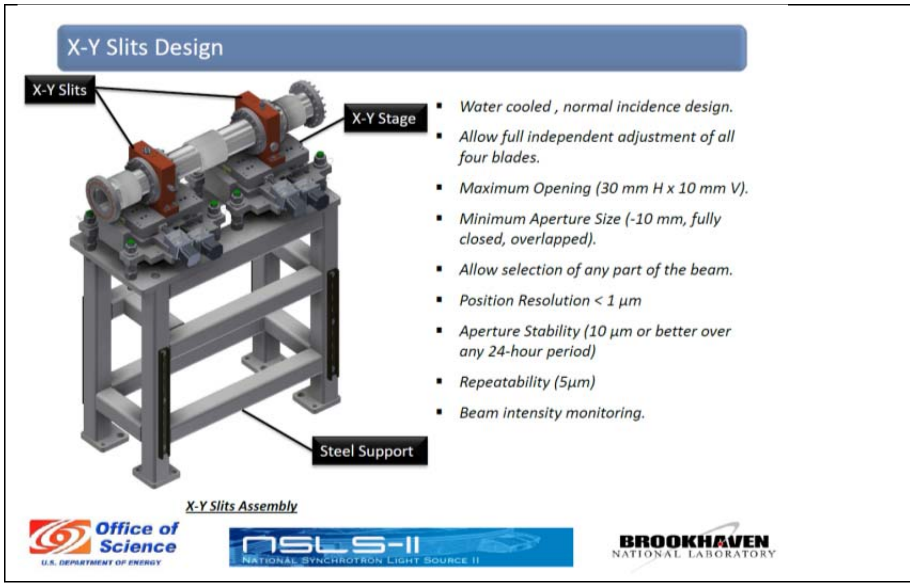


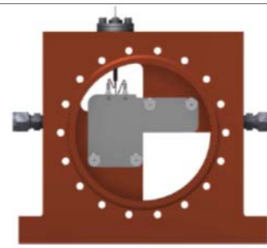
Photon Shutter Open Position



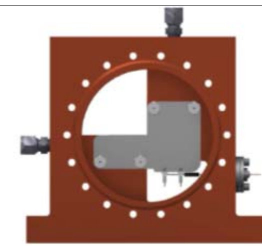
Photon Shutter Closed Position

Front end slits

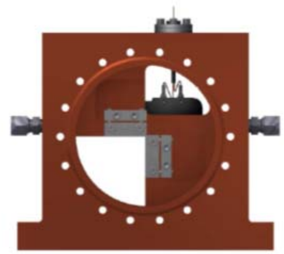




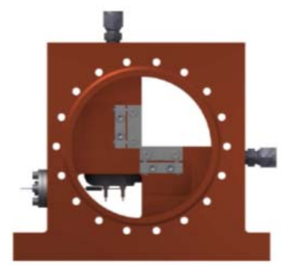
Front View (Upstream Slit)



Front View (Downstream Slit)

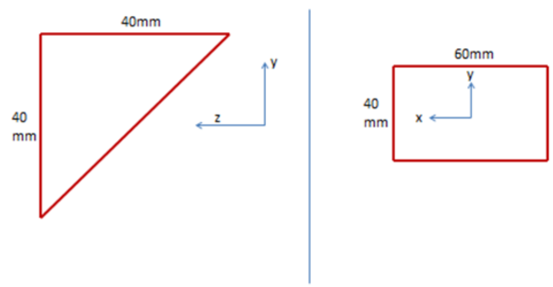


Back View (Upstream Slit)

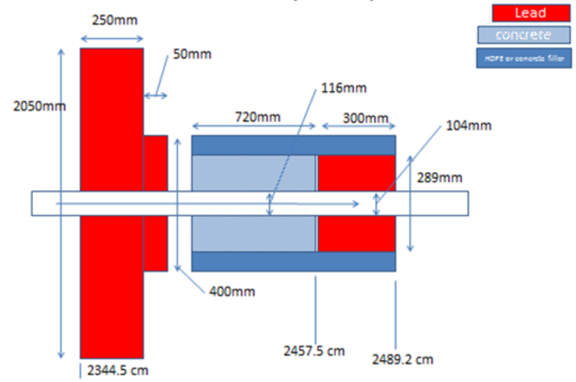


Back View (Downstream Slit)

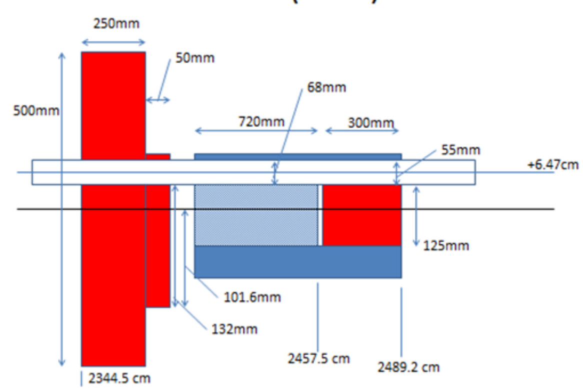
Sketch 1 (FE diagnostic flag)



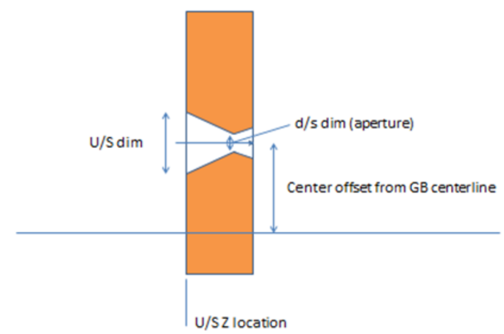
Sketch 2 (RWC) hor



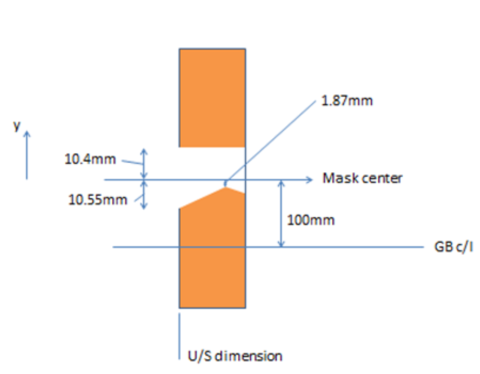
Sketch 2 (RWC) vert



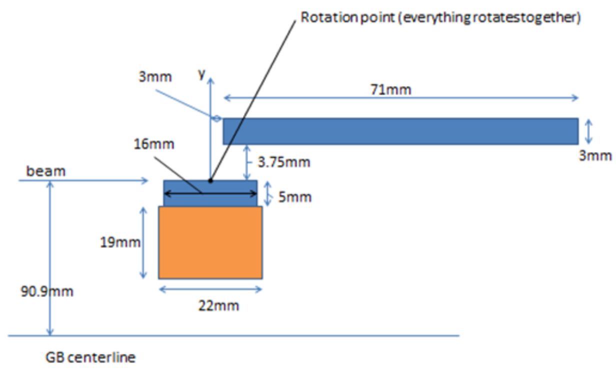
Sketch 3: Beamline MSK1 & 2



Sketch 4: Beamline PBS1 vert



Sketch 5: Mono crystal



Sketch 6: Focusing mirror