NSLS II TECHNICAL NOTE BROOKHAVEN NATIONAL LABORATORY	NUMBER **259**
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04BM (XFM) Beamline Radiation Shielding Analysis	

1. Introduction

The radiation shielding of the 04-BM (XFM) beamline is analyzed for the gas bremsstrahlung (GB) and synchrotron radiation (SR) sources. The GB as a source originates from the long straight section of the storage ring during normal operation when the primary electrons interact with the residual gas molecules in the beam transport pipe giving rise to bremsstrahlung radiation. When the safety shutters are open, this can stream through the beampipe into the first optical enclosure (FOE) and beyond, and can result in a radiation environment that is present at a constant rate. In this analysis, scenarios are considered that can affect the radiation levels in and around the beamline during the operation of the beamline and the dose rates are estimated using the FLUKA Monte Carlo radiation transport code.

In the case of synchrotron radiation as the source, the STAC8 code is used to estimate the dose rates outside the FOE, beam transport pipe and the secondary optical enclosure (SOE), as well as inside Hutch C.

The Issue and Decision paper [1] dictates that the dose rates downstream of the FOE wall should not exceed 0.5 mrem/h on contact and 0.05 mrem/h at 30 cm away. For all other locations, the dose rates should be in accordance with the NSLS-II beamline radiation shielding policy [2].

2. Gas Bremsstrahlung Calculations

2.1. Layout of the FOE

Figure 1 (PD-XFM-RAYT-0001) shows the general layout of the FOE, beam transport pipe and SOE. Figure 2 shows the FOE and SOE layouts.

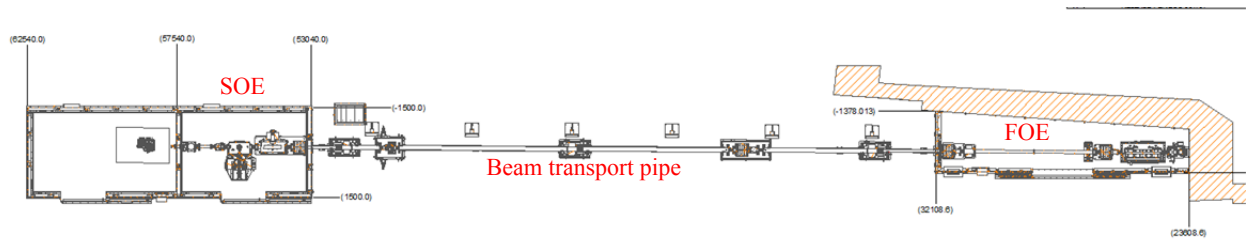

Figure 1: Layout of the FOE, Beam Transport Pipe and the SOE

The major components of interest in the FOE are the FOE slits, mirror M1, MSK1/LCO1 (fixed mask 1/lead collimator 1), secondary bremsstrahlung shield, MSK2/LCO2 and guillotine. The beam transport pipe has 5 mm of lead shield as the outer layer. The enclosures that house the collimator diagnostics (CODI) and the ion pumps in between the FOE and the SOE, are also shielded with lead. The MSK3/LCO3 is housed in the CODI. In the SOE, the important components are the MSK4/LCO4, mirror M2, double crystal monochromator (DCM), MSK5 /LCO5, the photon shutter and guillotine. Appendix A provides details of the components.

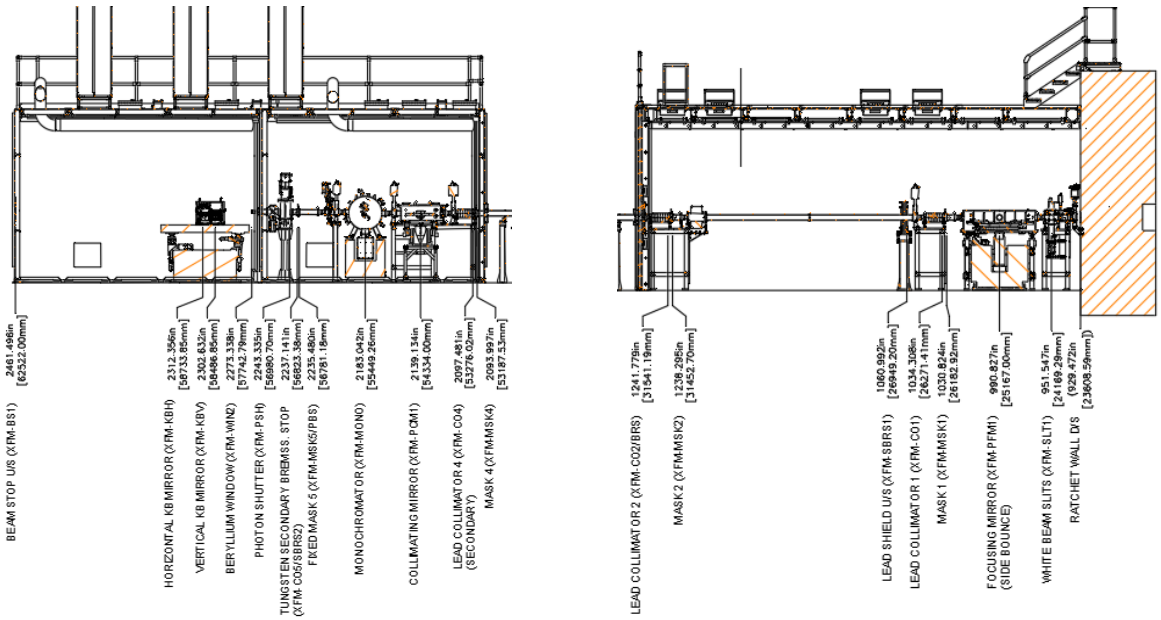

Figure 2: The various components in the FOE (right) and SOE. The beam travels from right to left.

2.2. FLUKA Simulations

The geometry of the beamline as modelled for FLUKA simulations is shown in Figures 3 through 6. The complete plan view of the geometry is shown in Figure 3. Figure 4 shows the details of the components of the FOE. Figure 5 shows the beam transport pipe in between the FOE and the SOE with the enclosures, while Figure 6 shows the SOE and the components inside it.

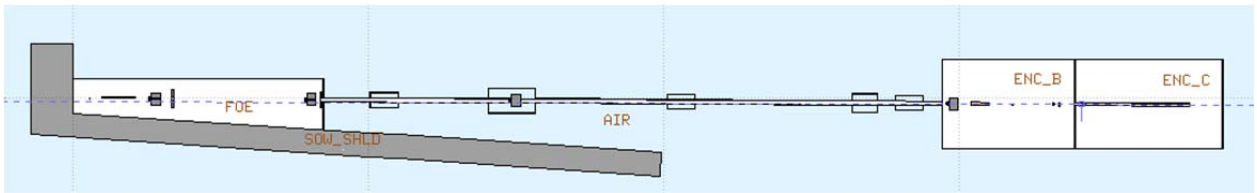

Figure 3: The plan view of the beamline complete with the FOE, beam transport pipe and the SOE. Beam travels from left to right.

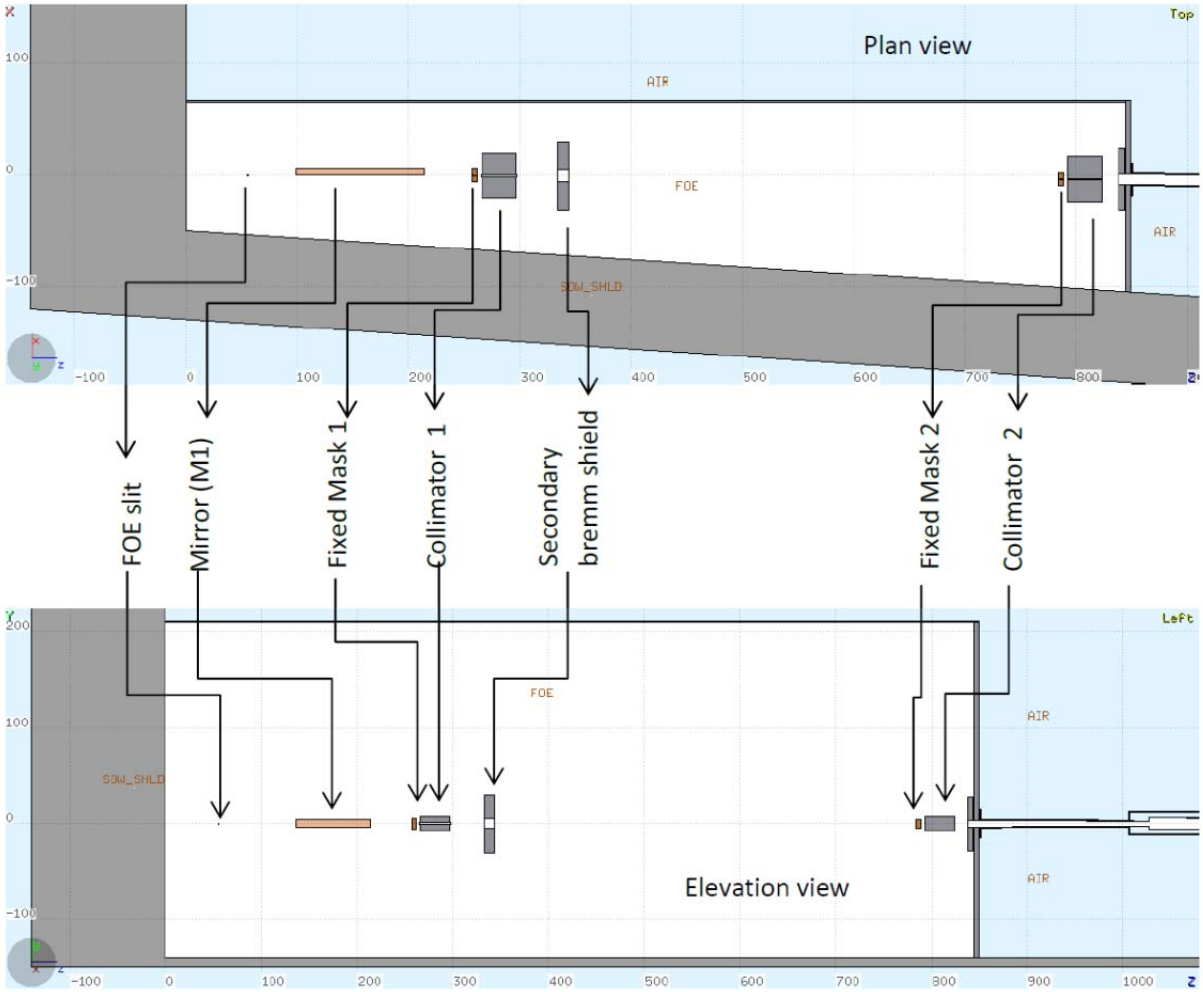

Figure 4: Plan and Elevation Views of the FOE

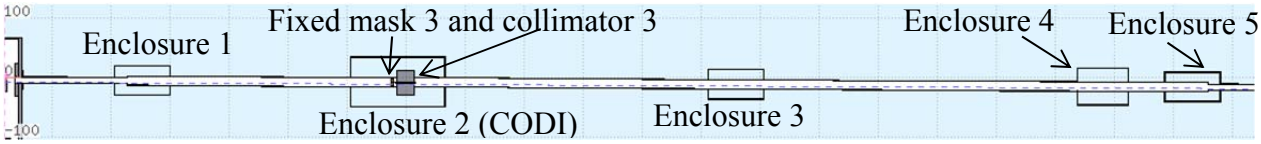

Figure 5: Beam Transport Pipe with the Enclosures between the FOE and SOE

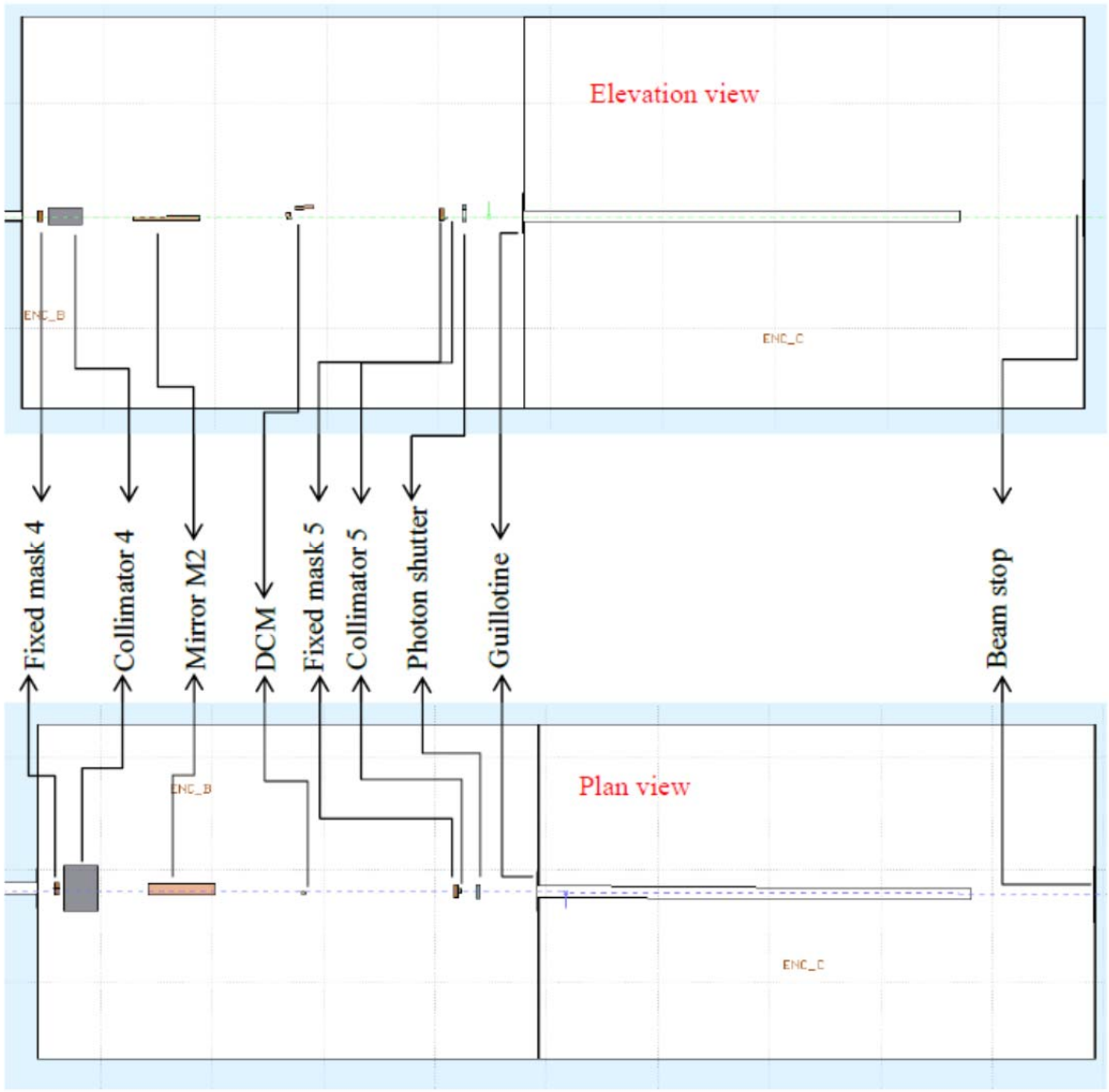

Figure 6: The SOE and the Components as Modelled for the FLUKA Monte Carlo Simulations

2.2.1. Simulations Details

The GB spectrum with end point energy of 3 GeV obtained from a separate FLUKA simulation, is used as the starting point of the simulations. A source routine samples the GB spectrum and transports the radiations across the geometry. The following points are considered as the starting points for the GB.

1. FOE slits. The slits are placed in the beamline for this simulation.
2. Upstream edge of the mirror M1
3. Center of the mirror M1

4. The top left corner of the fixed mask 1. This point will be closest to the outboard side and the roof when MSK1 is the target for the source.
5. A point close to the aperture of fixed mask 1. See point marked as “C” in Figure 7(b).
6. The top left corner of the fixed mask 2. This point will be closest to the outboard side and the roof when MSK2 is the target for the source. See point marked as “B” in Figure 7(b).
7. A point close to the aperture of fixed mask 2
8. Beam spread across the aperture on fixed mask 1

The source is considered to be a pencil beam impinging for all the cases except for the 8th case for which a rectangular beam is considered with dimensions equal to the footprint marked as “A” in Figure 7(a). The FOE slits are introduced in the geometry only for the scenario described in case 1.

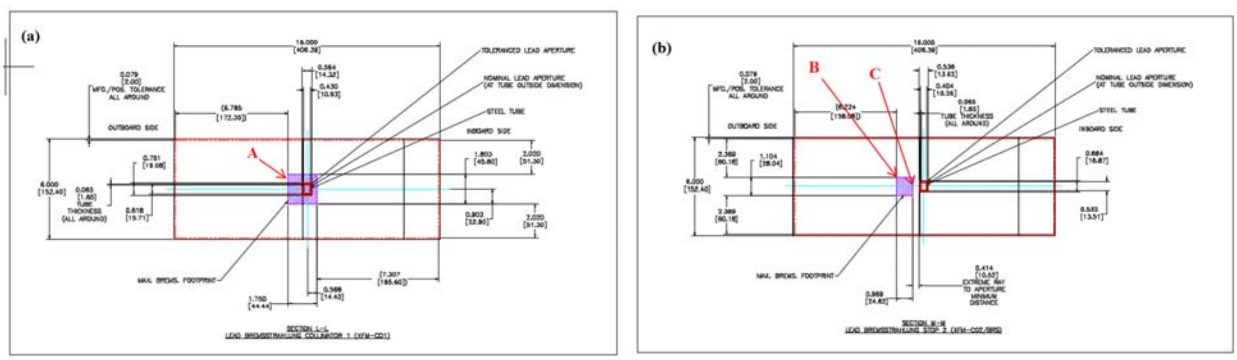

Figure 7: The bremsstrahlung foot print on the LCO1 (a) and LCO2 from which the coordinates of beam starting points are derived

Three dimensional mesh scoring (USRBIN) cards are used to estimate the fluence across the FOE and SOE for various particles, which are folded with the fluence to ambient dose equivalent conversion coefficients. The results are normalized to 8.67 μW of bremsstrahlung power and the results are given in mrem/h.

2.3. Results

2.3.1. Beam Hitting the FOE Slits

The GB strikes the FOE slits when they are inserted in the beam path. Figure 8 shows the plan and elevation views under this scenario. The shower develops from the slits, but continues to build up as it traverses the mirror. The lateral developments of the shower contributes to the dose rates outside the side wall and are estimated to be of the order of 0.04 mrem/h and well below 0.05 mrem/h outside the roof and the downstream wall. Neutrons are found to contribute marginally higher than photons outside the side wall.

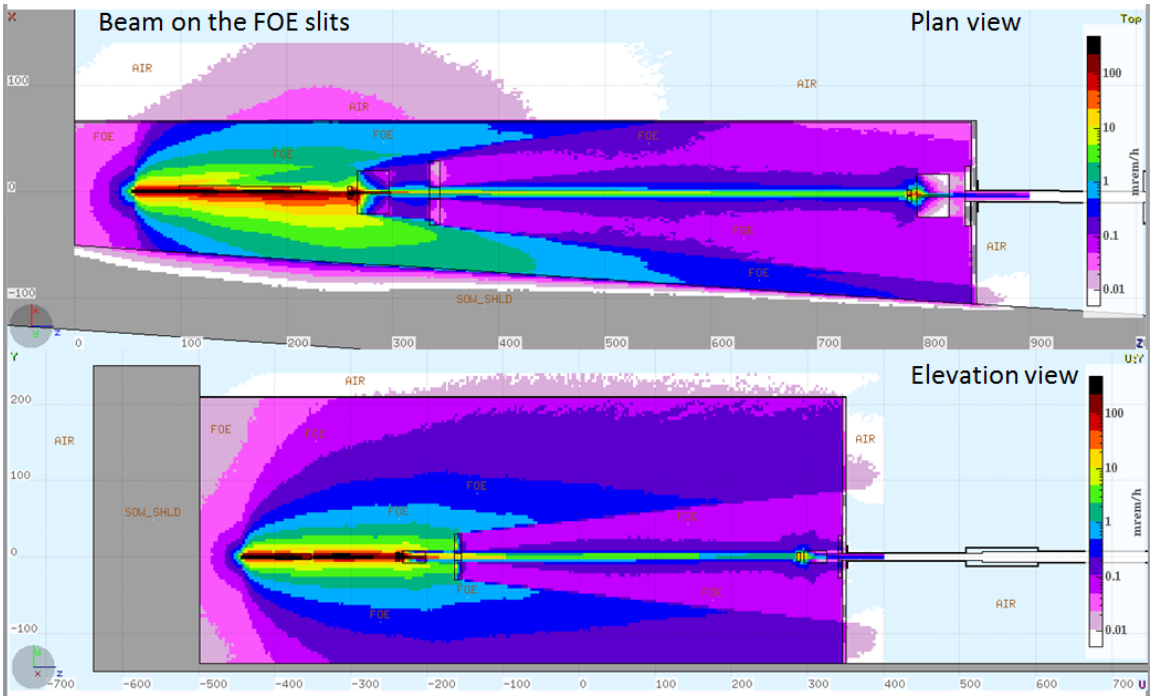

Figure 8: The plan (top) and the elevation view of the total ambient doe equivalent rates when the GB source strikes the slits in the FOE

2.3.2. Beam Hitting the Upstream Edge of M1

Figure 9 shows the plan and the elevation views of the total ambient dose equivalent rates expected to prevail when the beam hits the upstream edge of the mirror M1. The dose rates are similar to what is observed when the FOE slits are closed, with a dose rate of 0.03 mrem/h outside the side wall and well below 0.05 mrem/h outside the roof and the downstream wall.

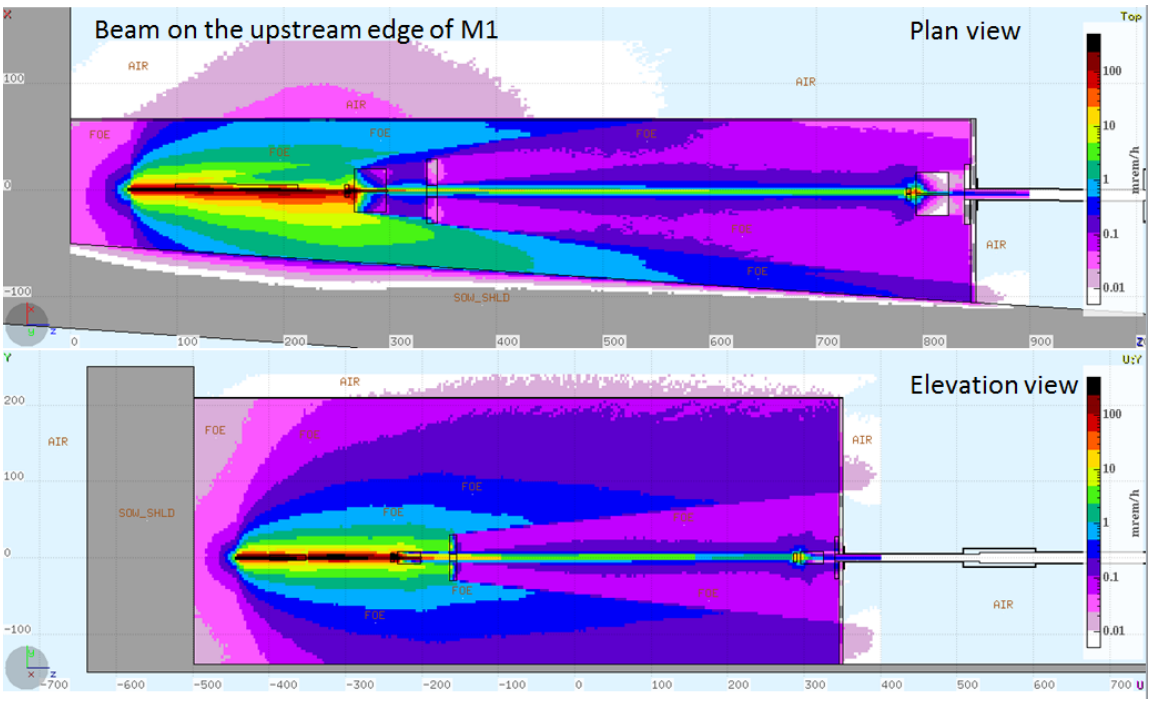

Figure 9: The plan (top) and the elevation views of the total ambient dose equivalent rates when the GB beam strikes the mirror M1

2.3.3. Beam Hitting the Center of the Mirror M1

In this case, the starting point of the beam is set at the center of the mirror M1. Figure 10 shows the plot of the total ambient dose equivalent rates prevailing under this condition. The dose rates are expected to be 0.04 mrem/h outside the side wall and less than 0.01 mrem/h outside the roof and the downstream walls.

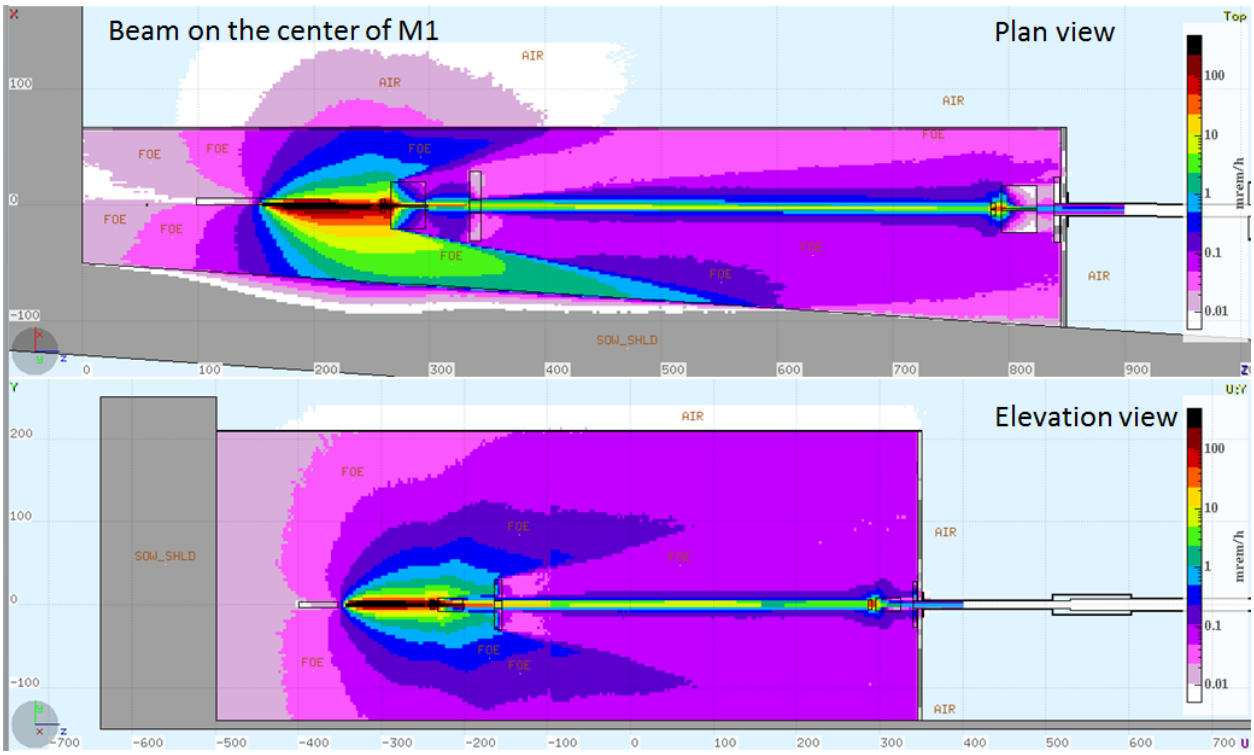

Figure 10: The plan (top) and the elevation views of the total ambient dose equivalent rates when the GB starting point is the center of the mirror

2.3.4. Beam Hitting the Upper Left Corner of the Fixed Mask 1

Here, the beam hits the fixed mask 1. From the bremsstrahlung foot print as provided in Figure 7 (a), the top left corner is chosen to be the location, as it is expected to the yield the maximum dose rates outside the side wall and the roof. Figure 11 provides the dose rate plots. The dose rate outside the side wall (on contact) is expected to be 0.06 mrem/h, which is marginally higher than the permitted level of 0.05 mrem/h. This falls to 0.03 mrem/h at 30 cm from the wall. The dose rates outside the roof and the downstream wall are below 0.05 mrem/h.

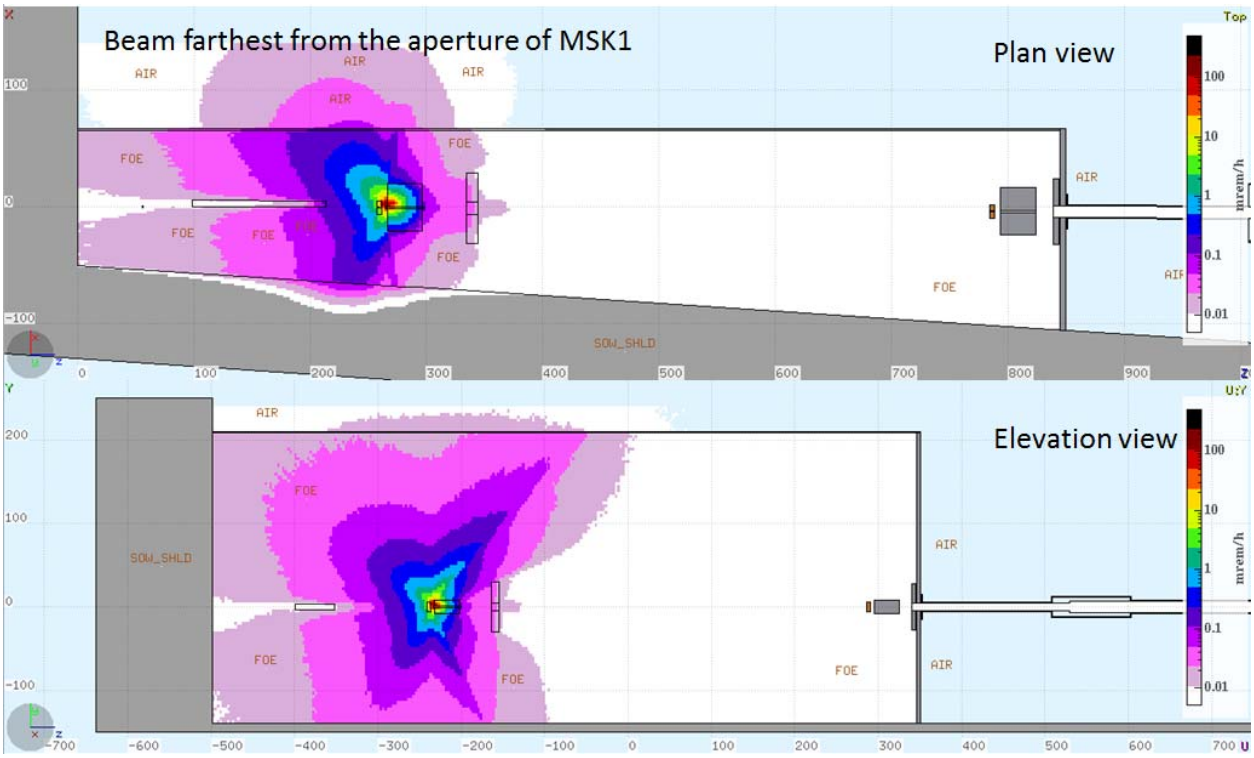

Figure 11: The plan (top) and the elevation views of the total ambient dose equivalent rates when the GB starting point is the top left corner of MSK1

2.3.5. Beam Hitting a Point Closet to the Aperture of Fixed Mask 1

The beam is incident at a point closest to the aperture of the fixed mask 1. Figure 12 shows the plan and the elevation views of the dose rates. In this case the dose rate on contact outside the downstream FOE wall is expected to be 0.3 mrem/h and 0.03 mrem/h at 30 cm away, which is acceptable as per the new ALARA policy [1]. The dose rate outside the side wall is expected to be 0.03 mrem/h and less than 0.01 mrem/h outside the roof.

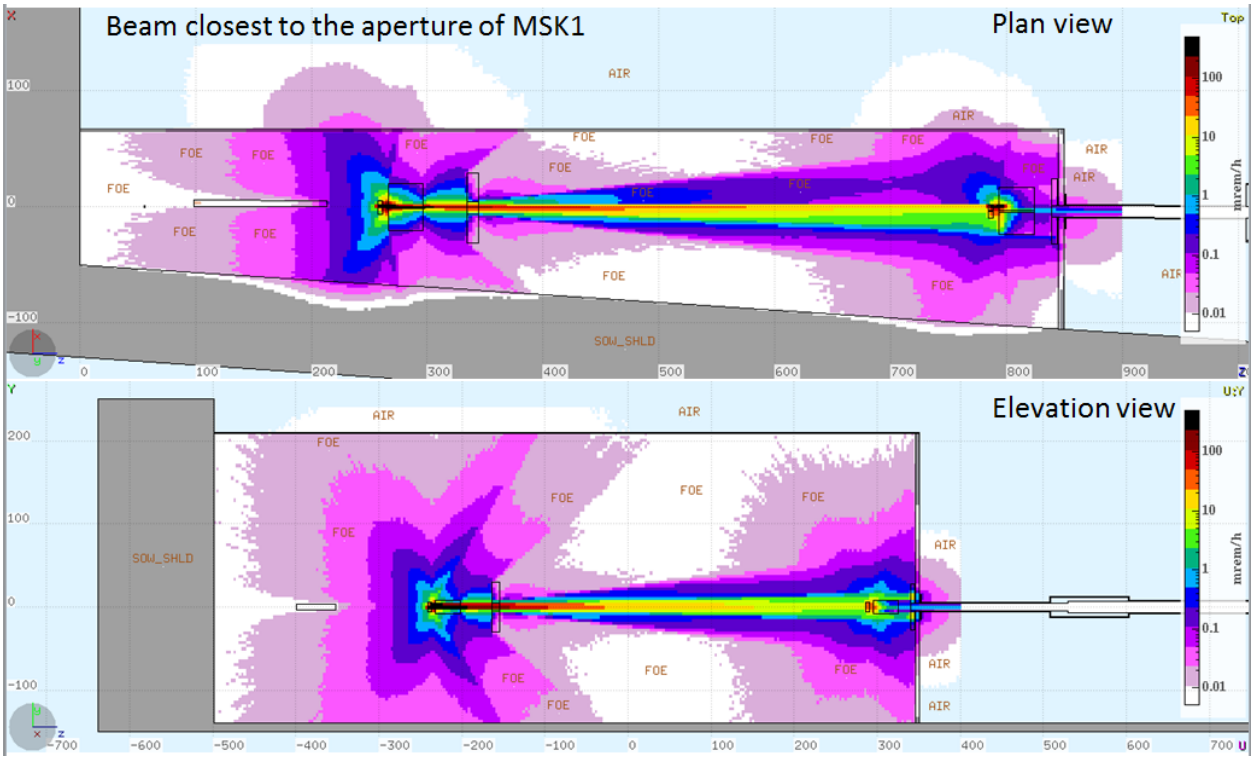

Figure 12: The dose rate plot showing the results when the GB hits a point close to the aperture of the fixed mask 1

2.3.6. Beam Hitting Top Left Corner of MSK2

The starting point of GB is taken to be the top left corner on the fixed mask 2, as shown in Figure 7(b). Figure 13, shows the expected dose rate outside the FOE to be 0.06 mrem/h on contact with the side wall, but is less than 0.05 mrem/h at 30 cm away. The dose rates at other locations are all expected to be lower than 0.05 mrem/h.

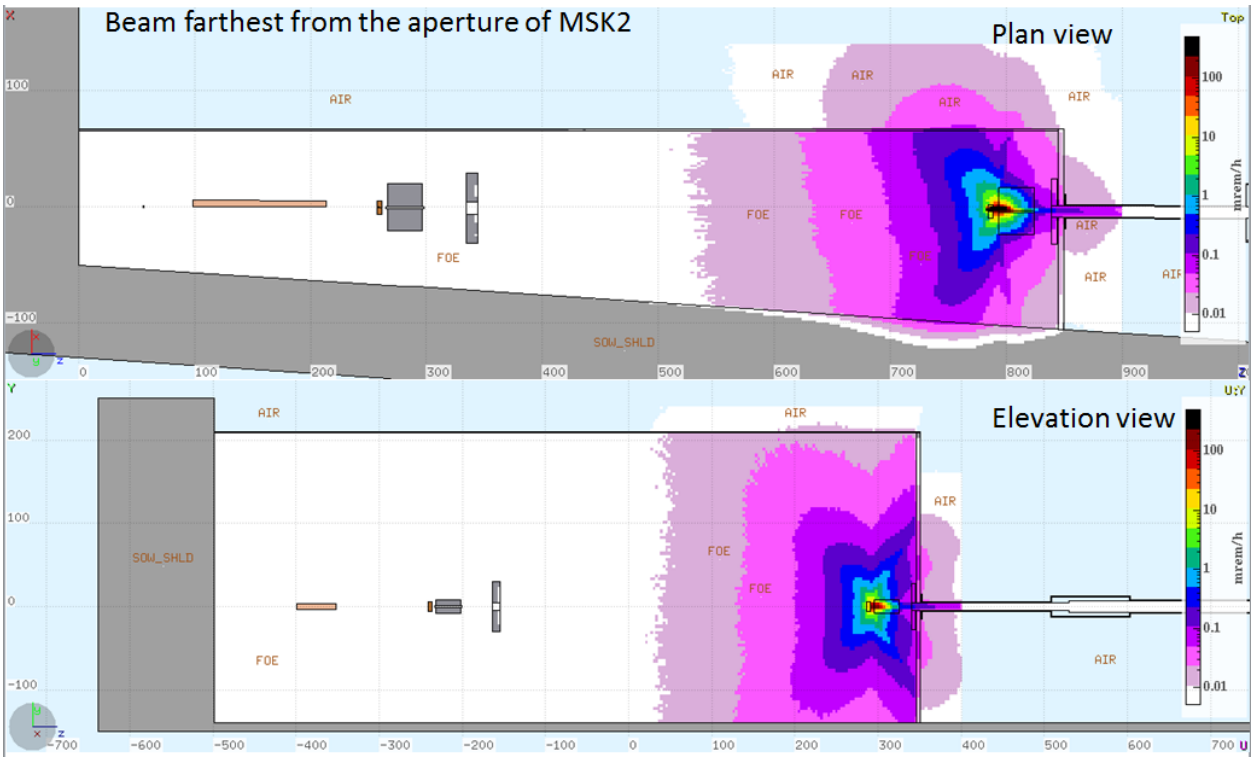

Figure 13: The dose rates outside the FOE when the GB beam strikes a point farthest from the aperture

2.3.7. Beam Hitting a Point Close to the Aperture of MSK2

Here, the beam is incident on a point that is close to the aperture of MSK2. Figure 14 shows the dose rates plots in this scenario. The maximum dose rate outside the downstream wall is estimated to be 0.04 mrem/h. It is well below 0.05 mrem/h outside the side wall and the roof.

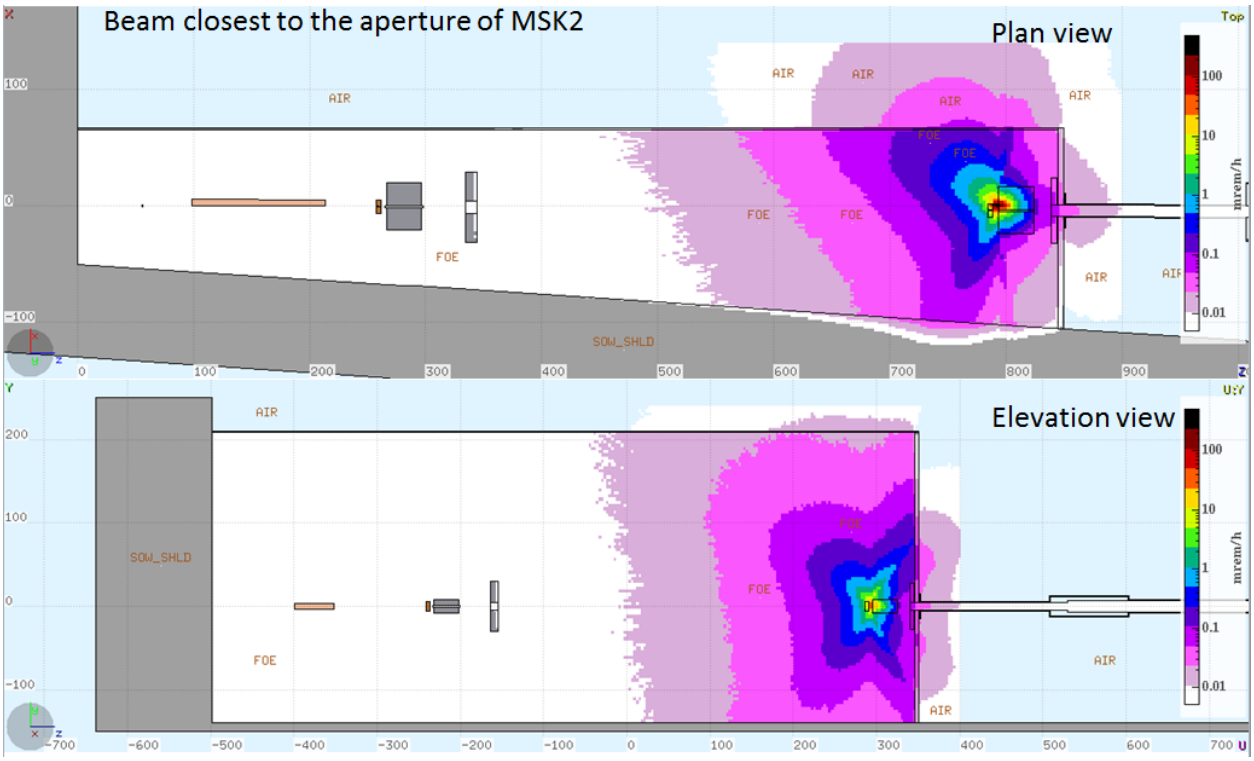

Figure 14: The dose rates outside the FOE when the GB strikes a point close to the aperture

2.3.8. Beam as a Rectangular Distribution on MSK1

Here, the bremsstrahlung starting point is sampled uniformly from a rectangle as obtained from the ray tracing and as shown in Figure 7 (a). The source sub routine is modified to sample not just the energy, but also the position of the starting point. The events whose starting points fall inside the aperture will interact with the downstream components, while the rest will interact with the fixed mask 1. Under this configuration, the dose rates are estimated to be lower than 0.05 mrem/h outside the FOE, as is seen in Figure 15.

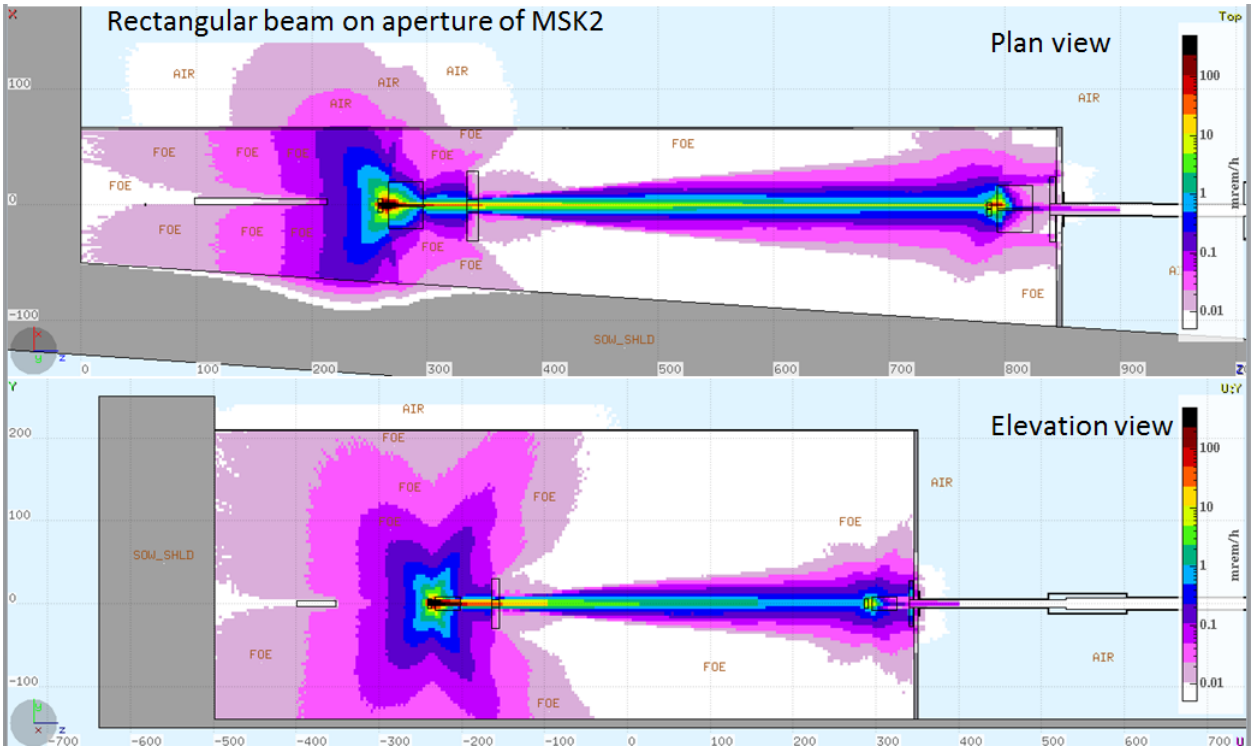

Figure 15: The dose rates outside the FOE when the GB is distributed uniformly in a rectangle with dimensions as given by the ray tracings

2.4. Photon and Neutron Contributions

The photon and neutron contributions outside the FOE side wall, for a few scenarios, are shown in Figure 16. The neutron contribution is seen to be comparable when the GB strikes the upstream edge of M1 while being higher for the other two cases.

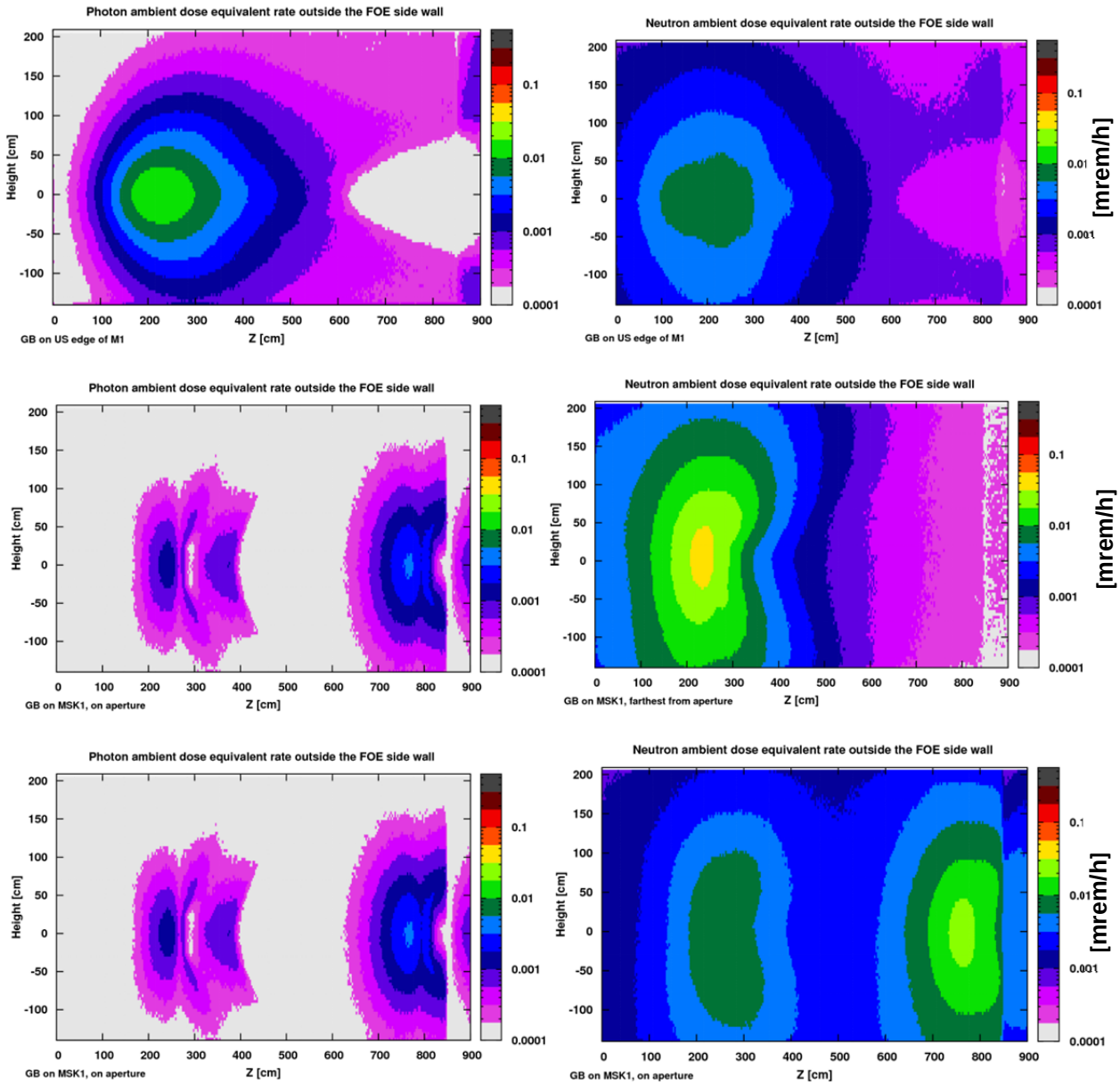

Figure 16: The photon and neutron dose rates outside the side wall of the FOE for a few scenarios. The figures, from top to bottom, show the results when GB is incident on the upstream edge of M1, on the farthest point from the aperture of MSK1 and on a point close to the aperture of MSK1.

2.5. Summary of Results

Table 1 provides a summary of the dose rates expected outside the FOE when gas bremsstrahlung strikes the various targets that are considered in the simulations. In 2 instances, the dose rates are estimated to be above 0.05 mrem/h (marked with asterisks in the table) on contact, but fall below 0.05 mrem/h at 30 cm distance.

Table 1: Ambient Dose Equivalent Rates outside the FOE with GB as Source

Beam incident on	**Ambient dose equivalent rate outside the FOE (mrem/h)**		
	Side wall	Roof	Downstream wall
FOE slits	< 0.05	< 0.05	< 0.05
US edge of M1	<0.05	< 0.05	< 0.05
Center of M1	<0.05	< 0.05	< 0.05
MSK1 upper edge	**0.06***	< 0.05	< 0.05
MSK1 on aperture	<0.05	<0.05	**0.3***
MSK2 upper edge	**0.06***	< 0.05	< 0.05
MSK2 closest to aperture	< 0.05	< 0.05	< 0.05
MSK1 on aperture (rectangular beam)	<0.05	< 0.05	< 0.05

* The dose rate falls below 0.05 mrem/h at 30 cm distance.

3. Synchrotron Radiation Calculations

The STAC8 analytical code is used to estimate the ambient dose equivalent rate outside the FOE, beam transport pipe and the SOE. The first mirror M1 of the XFM is in the FOE. The pink beam is transported to the SOE through the shielded beam transport pipe. In the SOE, it encounters the MSK4 and M2 before reaching the DCM. The following scenarios are identified from the ray tracings and are analyzed from the radiation shielding point of view.

1. White beam scattering off the mirror M1
2. Pink beam incident on an air column inside the transport pipe
3. Pink beam hitting the fixed mask 3 inside the CODI enclosure in the beam transport pipe
4. Pink beam hitting the fixed mask 4 inside the SOE
5. Pink beam hitting the mirror M2
6. Pink beam hitting the fixed mask 5
7. Reflected pink beam hitting the DCM
8. Reflected pink beam hitting the beam stop
9. Extreme reflected pink beam escaping the guillotine

Figure 17 shows a schematic of the various points listed above and Figure 18 shows the synchrotron radiation spectrum [3] from the three pole wiggler source used as the input for all the calculations here. The lower cut-off is kept at 1 keV to match the energy range considered by STAC8. The total synchrotron radiation power is 8.04 W. When the mirrors are considered as Si scatters, their reflective properties are neglected. When they are considered as mirrors for reflection, the loss of reflectivity due to the inherent roughness is not considered. The fixed masks are considered as copper blocks with thickness of 4.21 cm positioned normal to the incident beam.

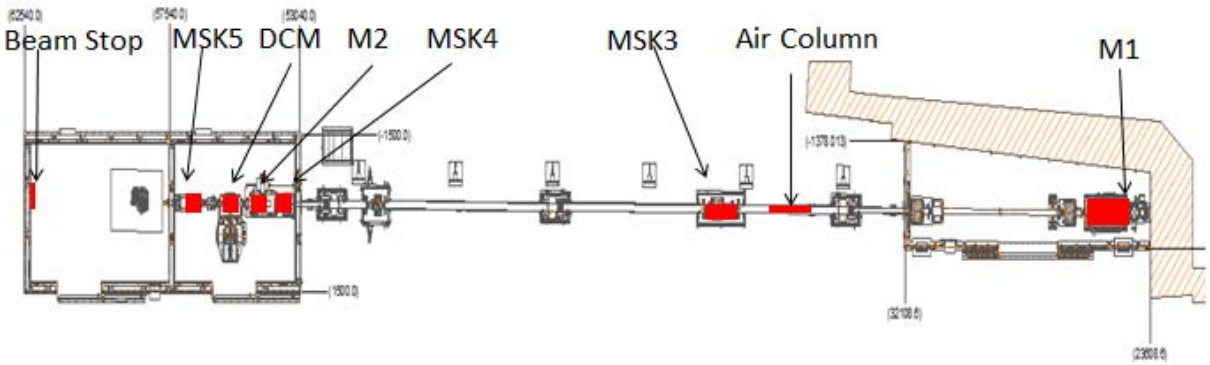

Figure 17: A sketch showing the various points of the interactions of the synchrotron radiation

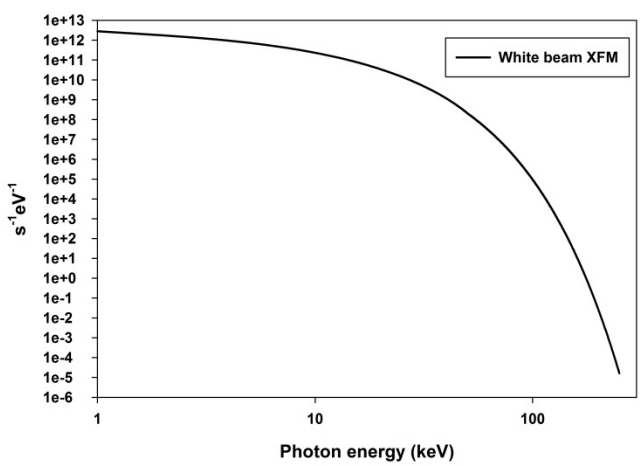

Figure 18: The white beam synchrotron radiation spectrum from the 3PW source of XFM

3.1. Scatter Targets in 04-BM-A

In the FOE, only mirror M1 is considered as the target. The white beam spectrum (Figure 18) is scattered off the mirror M1, and the dose rates are estimated outside the side wall, downstream wall and the roof. The mirror is considered as Si scatter with the reflective properties ignored.

Since the FOE is shielded with lead all around, the dose rates outside it are well below 0.01 mrem/h.

3.2. Scatter Targets in the Beam Transport Pipe

3.2.1. Pink Beam on an Air Column inside the Transport Pipe

A loss of vacuum condition would result in the pink beam from the FOE, scattering off the air in the beam transport pipe. The white beam is reflected from a Rh coated mirror (M1) and is made to scatter off from an air column. The shield is considered to be a cylindrical pipe with 2 mm Fe and 5 mm Pb at a distance of 5.08 cm (radius of the pipe). The resulting dose rates outside the pipe are found to be well below 0.01 mrem/h.

3.2.2. Pink Beam Hitting the Fixed Mask 3 inside the CODI Enclosure in the Beam Transport Pipe

The XFM beam line has a control and diagnostic enclosure (CODI) that has a fixed mask/lead collimator inside. The CODI itself is a shielded enclosure with lead/SS around it. The thickness of the lead is 9 mm on the upstream and top sides, 7 mm on the inboard and outboard sides and 14 mm on the downstream side. The bottom side has no lead but is covered by 25 mm thick SS as shield. In the analysis, the pink beam is assumed to scatter off the copper fixed mask and the dose rates outside the enclosures are estimated. The analysis shows that the lead shield thicknesses at all five directions and the SS thickness towards the floor are sufficient to keep the dose rates below 0.01 mrem/h outside the enclosures.

3.3. Scatter Targets in 04-BM-B

3.3.1. Pink Beam Hitting the Fixed Mask 4

Since the only mirror before the SOE (M1) is inside the FOE, the pink beam is transported into the SOE. The SOE is constructed with 3 mm SS as shield walls on all sides, except the downstream wall, which is 6 mm thick. The fixed mask 4 inside the SOE is 14.8 cm away from the inside face of the upstream wall. The dose scattered from the Cu mask in the lateral directions (145 cm from the interaction point) and the backward direction are calculated. In the backward direction, the guillotine (lead, 6 mm thick) shields the radiation scattered at angles greater than 130 degrees (with respect to the beam direction). At 130 degrees, the scattered radiation is shielded by the 3 mm SS wall. The dose rates outside the inboard and outboard walls (both at 145 cm) and the roof (210 cm) are found to be less than 0.01 mrem/h. The dose rate at the back wall, which is 14.8 cm away from the upstream face of the copper mask, is estimated to be 0.07 mrem/h on contact and 0.01 mrem/h at 30 cm away.

3.3.2. Pink Beam Hitting the Mirror M2

The next scatter target in the SOE is the mirror M2. In this analysis, M2 is assumed to be a scattering target while neglecting its reflective property. The dose rate is estimated to be 0.03 mrem/h outside the roof, while outside the lateral walls it is expected to be 0.05 mrem/h on contact. Outside the downstream wall and at angles that are outside the shadow of the guillotine, the dose rates are found to be 0.13 mrem/h on contact and 0.1 mrem/h at 30 cm distance, with 6 mm of SS as shielding.

In Figure 19(a), the white synchrotron radiation spectrum is shown as black solid line and the pink beam (reflection from M1) is shown as a red solid line. The pink beam undergoes scattering in M2 (silicon), the important one from the radiation shielding point of view is the Compton scattering. The total cross section for this process [4] is shown as a blue line (ordinate on right axis). Cleary, the photon spectrum from M1 is in the domain of Compton scattering. The photons so scattered in the direction of the shield will traverse it and get attenuated. A typical example of an emerging spectrum is given in Figure 19(b) for 6 mm steel. In this example, the spectrum shown is at 4° with respect to the beam direction and the ordinate is the ambient dose equivalent, which is obtained by folding the fluence with the ICRP fluence to dose conversion coefficient. In the plot shown, the total adds up to 0.12 mrem/h.

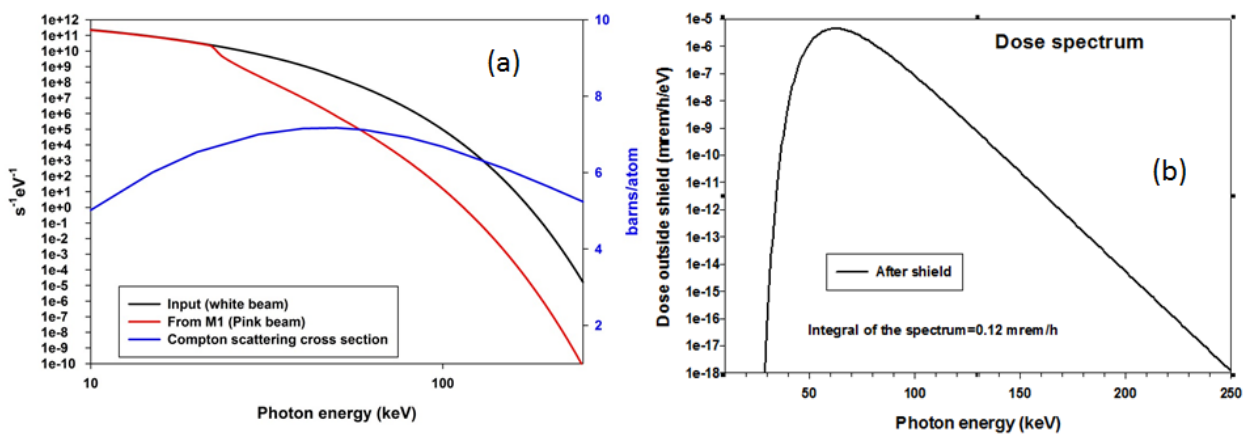

Figure 19(a) and (b): The while and pink beam spectra with the total Compton scattering cross section (left) and the dose spectrum after 6 mm shield when the pink beam scatters from M2.

To reduce the dose rates outside the downstream wall of the SOE below 0.05 mrem/h, it is estimated that an additional shield, thickness of 2 mm SS is required, which will cover the ±8° fan originating from M2. Figure 20 shows the dose rates estimated outside the downstream wall of the SOE, with 6 mm and 8 mm shield thicknesses.

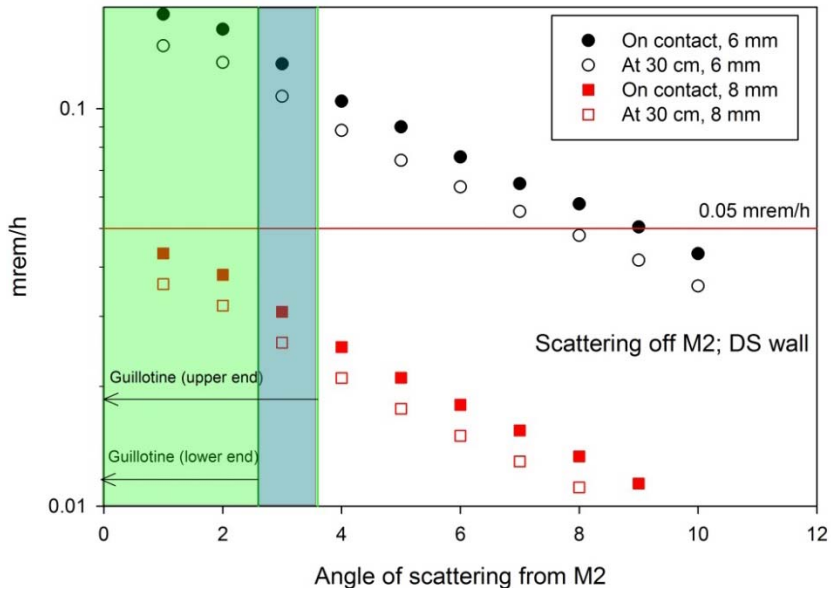

Figure 20: The dose rates outside the SOE wall with 6 mm (as built) and 8 mm SS as shield. The shaded regions are shadowed by the downstream guillotine.

The vertical offset of the guillotine effectively shields all angles below 2.6° (green shaded area) at the lower edge and 3.6° (blue shaded area) at the upper edge. It can be seen that the 6 mm downstream wall is insufficient to bring the dose rates to below 0.05 mrem/h (shown as a horizontal red line) between 2.6-8 degrees. With the introduction of an additional 2 mm of SS, the dose rates on contact with the wall at all angles are estimated to be lower than 0.05 mrem/h.

A new ray tracing was carried out to see if the DCM vessel can be used as a shield. The DCM vessel is at least 5 mm thick [PD-XFM-PCM-1000] and the effective thickness when the beam traverses it at an angle will be larger. Figure 21 shows the horizontal and vertical cuts of the synchrotron fan being intercepted by the DCM vessel. The ray trace confirms that the cylindrical part of the vessel interposes at least 2 mm of SS in the path of the beam [5]. When used as a shield, it helps reduce the dose rates below 0.05 mrem/h outside the hutch and should then be placed under configuration control.

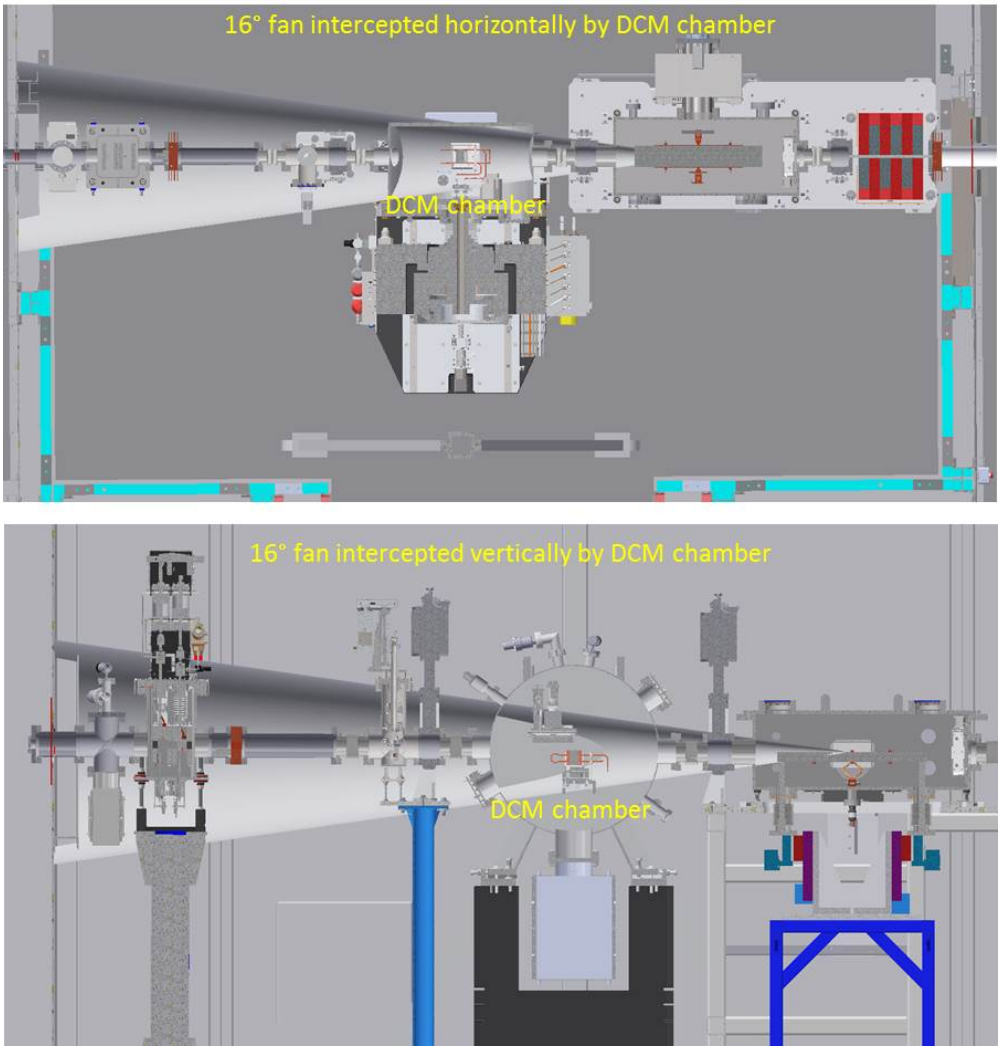

Figure 21: Ray tracing from the center of M2 with the DCM chamber intercepting the 8° half angle opening

3.3.3. Pink Beam Hitting the Fixed Mask 5

If the mirror M2 is retracted from the beam path, the pink beam will hit the fixed mask 5 normal to the incident beam. The dose rates in this scenario are estimated to be 0.03 mrem/h outside the lateral walls, 0.02 mrem/h at the roof and negligible outside the downstream wall.

3.3.4. Reflected Pink Beam Hitting the DCM

In this scenario, the beam reflected from M2 is incident on the DCM (assumed to be Si) and the dose rates are estimated outside the SOE walls. The 6 mm steel downstream and the 3 mm steel on the side walls reduce the dose rates to well below 0.05 mrem/h. This scenario is expected to be the worst case for the reflected beam scattering off any target, including in the 04-BM-C enclosure.

3.3.5. Extreme Reflected Pink Beam Escaping the Guillotine

When the reflected pink beam is not intercepted by the DCM, it is stopped by the lead beam stop. However an extreme misdirected beam (PD-XFM-RAYT-0001) at or above 62 mrad will miss the guillotine (dashed arrow in Figure 22) and will strike the steel wall. This scenario is considered with the reflected pink beam as a source, i.e., the beam missing the DCM. The dose rate outside 6 mm of the steel wall, with the mirror M2 at 62 mrad, with the reflected pink beam as source, is estimated to well below 0.01 mrem/h.

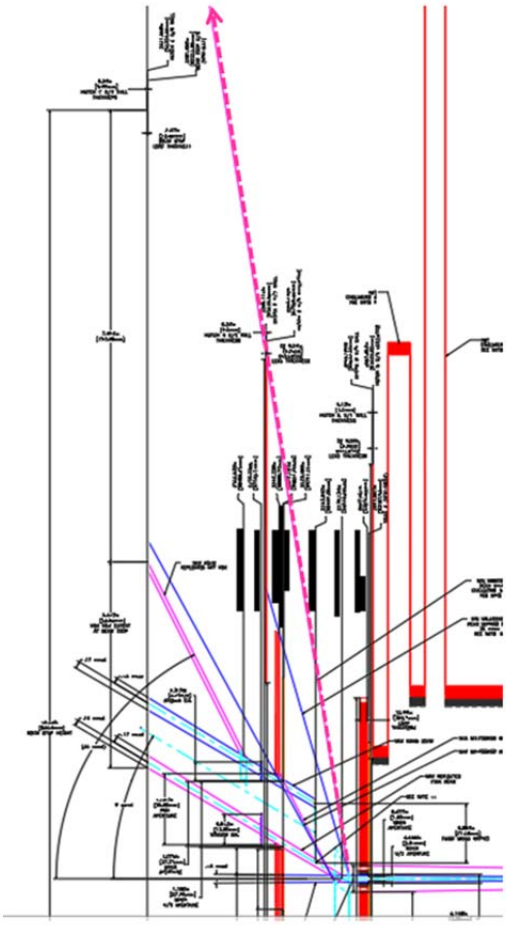

Figure 22: The extreme ray escaping the guillotine, marked as an arrow on a vertical synchrotron ray tracing drawing

3.4. Scatter Targets in 04-BM-B

3.4.1. Scattering of a Sample in 04-BM-C

The dimensions of the 04-BM-C are the same as that of 04-BM-B. In 04-BM-B, the reflected pink beam was scattered off a Si target and the dose rates outside the shield were estimated to be well below 0.05 mrem/h. From the shielding point of view, that is expected to be the worst case scenario and the dose rates outside the 04-BM-C are also expected to be well below 0.05 mrem/h.

3.4.2. Reflected Pink Beam Hitting the Beam Stop

The ray trace indicates that the reflected pink beam from M2 will hit the beam stop when the DCM is retracted and the photon shutter is opened. A section of the ray trace (Figure 23) shows this. The beam stop is 12 mm lead and the dose rates outside of it are estimated to be well below 0.01 mrem/h.

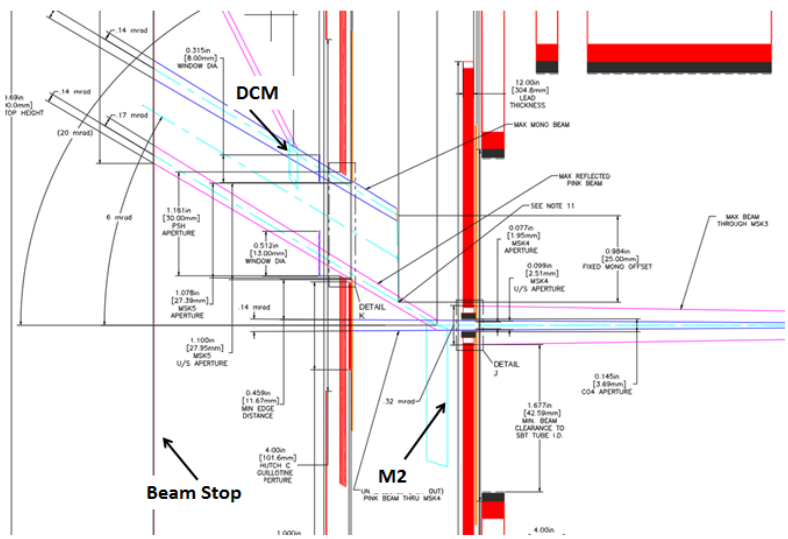

Figure 23: A section of the synchrotron radiation vertical ray trace showing the reflected pink beam being stopped by the beam stop

3.5. Summary of Results

Table 2 shows the dose rates for the various scenarios obtained from the STAC8 calculations.

Table 2: Ambient Dose Equivalent Rates with SR as Source

Beam/ Source	Ambient dose equivalent rates (mrem/h)		
	Outside the side wall	Outside roof	Outside DS wall
White beam on M1 in FOE	< 0.01	< 0.01	< 0.01
Pink beam on an air in transport pipe	< 0.01[(a)]	-	-
Pink beam on MSK3 in CODI	< 0.01	< 0.01	< 0.01
Pink beam on MSk4 in SOE	< 0.01	< 0.01	**0.07**[(b)]
Pink beam on M2 in SOE	0.05	0.03	**0.13**[(c)]
Pink beam on MSK5 in SOE	0.03	0.02	< 0.01
Reflected pink beam on DCM	< 0.01	< 0.01	< 0.01
Reflected pink beam on beam stop	-	-	< 0.01
Mis-steered and missing the guillotine	-	-	<0.01

[(a)] Outside the pipe.
[(b)] Outside the back wall of SOE. Dose rates fall below 0.05 mrem/h at 30 cm distance.
[(c)] The dose rate at 30 cm distance is above 0.05 mrem/h, but falls below 0.05 mrem/h when 2 mm additional SS is included.

4. Conclusions

An analysis of the dose rates outside the FOE, with GB as source show that the maximum dose rate is expected to be 0.3 mrem/h on contact outside the downstream wall of FOE. This happens when the GB interacts at a point close to the aperture of fixed mask 1. However, it is expected to be below 0.05 mreh/h at 30 cm distance and is thus acceptable as per the NSLS-II ALARA policy. In all other scenarios, the dose rates are expected to be lower than 0.05 mrem/h.

With SR as the source, the maximum synchrotron radiation dose rates outside the SOE downstream wall is expected to be 0.1 mrem/h at 30 cm distance from the downstream wall, when M2 is assumed as a Si scattering medium. The dose rate reduces to 0.05 mrem/h on contact with the wall when an additional 2 mm SS thickness is taken into account. The effective thickness of the DCM vessel is greater than 2 mm and can be used as a radiation shield by placing it under configuration control. In all other scenarios, the dose rates are estimated to be lower than 0.05 mrem/h.

References

1. R Lee, NSLS-II Issue and Decision Paper: ALARA Analysis for Installation of Secondary Bremsstrahlung Shields in the First Optics Enclosure, PS-C-ESH-STD-005.
2. R. Lee, Photon Sciences Shielding Policy, PS-C-ASD-POL-005.
3. Email from Tchoubar, Oleg dated Tue 7/11/2017 2:18 PM.
4. Email from Tappero, Ryan dated Tue 8/8/2017 7:28 PM.

5. Acronyms

ARM	Area Radiation Monitor
CODI	Control and Diagnostics
DCM	Double Crystal Monochromator
ESH	Environment, Safety and Health
ESM	Electron Spectrum Microscopy
FE	Front End
FOE	First Optical Enclosure
GB	Gas Bremsstrahlung
m	Meter
mrad	Millirad
mrem/hr	millirem per hour
LCO	Lead Collimator
MSK	Fixed Mask
NSLS-II	National Synchrotron Light Source II
PSD	Photon Science Division
RCT	Radiological Control Technician
SAF	Safety Approval Form
SBMS	Standards Based Management System
SBRS	Secondary bremsstrahlung shield
SR	Synchrotron radiation
XFM	X-ray Fluorescence Microprobe

APPENDIX A

4-BM / XFM Front End and Beamline Mask, Collimator and Shielding Data for FLUKA Calculations

First Optical Enclosure

Shielding Information (dimensions in mm) *	Distance/Position (m)	Thickness (mm)	Material
4-BM-A SR Ratchet Wall; US inside face of FE ratchet wall	Z = 22.153	See drawings	Concrete / Lead
DS face of ratchet wall (inside FOE)	Z = *23.601* (23.609)	indicated in table	Concrete / Lead
OB wall distance from 4-BM photon beam centerline	653 minimum	19.05 (reqmt = 18)	Lead
Minimum distance from beam centerline to roof Pb shielding	2.092	6.35 (reqmt = 4)	Lead
Min distance: white beam Z-axis to SR wall outer face	0.784		Concrete
Min distance: white beam Z-axis to hutch wall inside Pb face	0.647	19 (.75”)	Lead
Angle betw SR wall & white photon beam Z-axis: 4 degrees			
DS End of 4-BM FOE Back wall (inside face of lead)	Z ~ 32.053	50.8 (reqmt=50)	Lead

* dimensions indicated are from drawings or 3D models; measurements are in *italic* typeface.

Notes:

1- The X axis positive direction is outboard, the Y axis positive direction is upward, and the Z axis is collinear with the 4-BM nominal white beam centerline with the axis origin at the 4-BM 3PW Source Point.
2- Mirror M1 (centered at Z = 25.67 m and located inside the FOE) deflects the 4-BM white beam 6 milliradians inboard (i.e. the M1 Mirror optic is angled 3 mm inboard).
3- Mirror M2 (centered at Z = 51.33 m and located inside the SOE) deflects the XFM photon beam 6 milliradians upward (i.e. the M2 Mirror optic is angled 3 mm upward). The monochromator (located at Z = 55.45 m) deflects the photon beam 25 mm upward and parallel to the 6 milliradian pink beam centerline.
4- All vertical and horizontal masks have 1° included angle tapers on their upstream and downstream sides tapering to the BDA (located 0.385" upstream of the downstream/inside vacuum face). The O/A mask thickness is 1.658" inside the vacuum space.
5- A 50.8 mm thick Pb guillotine is attached to the inside/downstream FOE wall. The B hutch has guillotines with two sets of 6 mm thick Pb plates each (with 90° seams) straddling the US and DS walls. All guillotines overlap the holes in their attached walls.
6- The XFM beam transport line extends between the A and B butches. It uses stainless steel tubes wrapped with 5 mm Pb shielding (hutch interface SSt tubes are 4" O.D., intermediate tube sections are 6" O.D.). BL Mask3 & CO3 are located inside Pb-shielded enclosure #2 in the transport line. Shielding information for each enclosure is included in the table SBT table below.
7- The 4-BM front end configuration is specified in drawing SR-FE-3PW-6000, the front end ray tracing in drawing SR-FE-3PW-6001, the XFM beamline configuration in PD-XFM-BL-1000, and the beamline ray tracing in drawing PD-XFM-RAYT-0001.
8- Lead collimators use 3.36 mm total manufacturing and position tolerance. Ray trace drawings use worst-case apertures. The W collimator uses standard 0.80 mm manufacturing and position tolerance.

Front End and Beamline Components for FLUKA Calculations

Front End Component	Z location, m (Distance from Source Point) (U), (D) or center (C)	Dimensions		Offset (vertical or horizontal) w.r.t 4-BM white beam CL	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Lead CO or Mask Aperture, mm (W)x(H) or (Dia)			
Crotch Absorber (at beam CL)	3.0578 (US) 3.1025 (DS)	Irregular shape- See Dwg	21.47mm x 9.92 mm [13.92 mm including Mfg/Pos Tol]	-	AL-15 GlidCop	SR-VA-ABS-1098 SR-VA-ABS-1099 SR-VA-ABS-1092
Exit Absorber	4.63314 (US) 4.64985 (DS)	See Dwg [aperture not centered]	14.00 mm x 14.00 mm 18.00 mm x 18.00 mm [including Mfg/Pos Tol]	-	Cu-Cr-Zr	SR-FE-3PW-ABS-1011
FE Fixed Mask (MSK1)	8.276 (US) 8.321 (DS)	Ø115 mm x 42.1 mm	1.76 mm x 3.43 mm	-	Cu-Cr-Zr	SR-FE-3PW-MSK-1854
FE LCO1 (BC1)	8.366 (US) 8.671 (DS)	16” x 6”x 12”	17.80 mm x 19.12 mm including Mfg/Position /Clearance tolerance [14.80 x 14.12 mm Nom]	-	Lead	SR-FE-3PW-CO-0800

FE Flange Absorber1 (MSK2)	14.384 (US) 14.429 (DS)	Ø115 mm x 42.1 mm thick	6.06 mm x 8.94 mm [9.06 mm x 11.94 mm w/ Mfg/Pos Tol]	-	Cu-Cr-Zr	SR-FE-3PW-MSK-1855
FE Flange Absorber2 (MSK3)	20.125 (US) 20.170 (DS)	Ø115 mm x 42.1 mm thick	7.27 mm x 11.31 mm [10.27 mm x 14.31 mm w/ Mfg/Pos Tol]	-	Cu-Cr-Zr	SR-FE-3PW-MSK-1856
FE LCO2 (BC2)	20.215 (US) 20.520 (DS)	16” x 8” x 12”	23.02 x 29.24mm including Mfg/Pos Tol [20.02 x 24.24 mm Nom]	-	Lead	SR-FE-3PW-CO-0850
RCO	*22.161* (US SR wall face) *23.609* (DS SR wall face)	9.875/12t” Pb US + 28.8”t Concrete + 12”t Pb DS	67mm x 67mm US 58mm x 59mm DS [including tolerances]	- Note- See Dwg for shielding dimensions	Lead & Concrete	SR-FE-RCO-0700 SR-FE-RCO-3800

First Optical Enclosure Component	Z location, m (Distance from Source Point) (US), (DS) or center (C)	Dimensions		Offset (vertical or horizontal) w.r.t 4-BM white beam CL	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Lead CO or Mask Aperture, mm (W)x(H) or (Dia)			
White Beam Slits	24.169 (C)	10mm x 10mm x 6mm (total with all slits closed)	variable	-	Tungsten	PD-XFM-SLT-1000
M1 Side Bounce Mirror (toroidal; cylindrical with bender)	25.167 (C)	55mm × 80mm × 1150mm Si substrate (20x1000mm active area)	-	Mirror center: X = 0, Y = 0	Rh-coated /Cr base, single-crystal Si	PD-XFM-PFM-1000 FMB-O drawings AMM0434 (Assy), AMM0433 (Mirror Mount)
BL MSK1	26.183 (US)	Ø 115 mm x 42.1 mm t	3.67 x 10.38 nom BDA	X = -6 mm	Cu-Cr-Zr	PD-XFM-MSK-1101
BL CO1	26.271 (US)	16” x 6” x12”	10.94 x 15.72 nom 14.30 x 19.08 max	X = -7 mm	Lead	PD- XFM -CO-0100
SBRS1	26.949 (US)	24” x 24” x 4”	Ø 104 mm	X = -11 mm	Lead	PD-XFM-SBRS-0200

BL MSK2	31.453 (US)	Ø 115 mm x 42.1 mm	4.60 x 8.29 nom BDA	X = -38 mm	Cu-Cr-Zr	PD-XFM-MSK-1201
BL CO2	31.541 (US)	16” x 6” x 12”	10.26 x 13.53 nom 13.62 x 16.89 max	X = -39 mm	Lead	PD- XFM -CO-0200
Guillotine	31.994 (US)	22” x 22” x 2”t	4” I.D.	X = -40 mm	Lead	PD-XFM-HU-1100 (see note 5)

Shielded Beam Transport Component	Z location, m (Distance from Source Point) (US), (DS) or center (C)	Dimensions		Offset (vertical or horizontal) w.r.t 4-BM white beam CL	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Lead CO or Mask Aperture, mm (W)x(H) or (Dia)			
SBT Encl 1 (IP5)	33.674 (US Pb face)	502mm (X, ± 251mm), 227.5mm (Y, inner Pb face above beam), 949mm (Z)	[Pb wall thickness: 7mm US & DS, 9mm top, bottom, inboard & outboard]	X = -51 mm (at US face of US Pb)	Pb/Steel	PD-XFM-SBT-1000
SBT Encl 2 (CODI, MSK3 & CO3)-*Encl 3 for IP6 not included*	37.672 (US Pb face)	555 mm (X, ± 277.5), 805 mm (Y, inner Pb face above beam), 1605 mm (Z)	[Pb wall thickness: 9mm US & top, 7mm inboard & outboard, 14mm DS, steel: 25mm bottom]	X = -75 mm (at US face of US Pb)	Pb/Steel	PD-XFM-SBT-1000
BL MSK3	38.366 (US)	Ø 115 mm x 42.1 mm t	11.20 x 5.54 nom BDA	-79 mm	Cu-Cr-Zr	PD-XFM-MSK-1301
BL CO3	38.454 (US)	16” x 6” x12”	16.65 x 10.69 nom (See note 8)	-81 mm	Lead	PD- XFM -CO-0300

SBT Encl 4 (IP7)	43.733 (US)	502mm (X, ± 251mm), 227.5mm (Y, inner Pb face above beam), 949mm (Z)	[Pb wall thickness: 7mm US & DS, 9mm top, bottom, inboard & outboard]	X = -111 mm (at US face of US Pb)	Pb/Steel	PD-XFM-SBT-1000
SBT Encl 5 (SSA)	49.981 (US)	626mm (X, ± 313 mm), 430mm (Y, inner Pb face above beam), 871mm (Z)	[Pb wall thickness: 7mm US, top, inboard & outboard, 12mm DS, steel: 25mm bottom]	X = -149 mm (at US face of US Pb)	Pb/Steel	PD-XFM-SBT-1000
SBT Encl 6 (IP8)	51.462 (US)	502mm (X, ± 251mm), 227.5mm (Y, inner Pb face above beam), 949mm (Z)	[Pb wall thickness: 7mm US & DS, 9mm top, bottom, inboard & outboard]	X = -158 mm (at US face of US Pb)	Pb/Steel	PD-XFM-SBT-1000

Hutch B, C Component	Z location, m (Distance from Source Point) (US), (DS) or center (C)	Dimensions		Offset (vertical or horizontal) w.r.t 4-BM white beam CL	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Lead CO or Mask Aperture, mm (W)x(H) or (Dia)			
Guillotine	53.034 (US)	350mm x 350mm x 6mm	4” I.D.	X = -167 mm	Lead	PD-XFM-HU-1200 (see note 5)
Hutch B US Wall	53.040 (US)	3.00m x 3.50m x 3mm thick	7” ID hole (concentric with guillotine hole)	N/A	Steel	PD-XFM-HU-1200
BL MSK4	53.188 (US)	Ø 115 mm x 42.1 mm t	9.20 x 1.95 nom BDA	X = -168 mm	Cu-Cr-Zr	PD-XFM-MSK-1401
BL CO4	53.276 (US)	16” x 6” x12”	14.32 x 7.00 nom BDA (See note 8)	X= -170 mm	Lead	PD- XFM –CO-0400
M2 Mirror	54.334 (C) (US face: 54.034)	100mm x 40mm x 600mm	[flat mirror optic & bender below beam, angled upward 3 mrad]	X = -175 mm	single-crystal Si (half Rh-coated w/ Cr base)	PD-XFM-PCM-2000

DCM	55.449 (C) (beam center at 1st crystal, at 2nd crystal Z ≤ 55.614 m)	Crystal1: 15mm x 60mm x 35mm, Crystal2: 15mm x 24mm x 165mm	[crystal dimensions @ 0 degree theta angle; DCM energy determined by Bragg angle]	X = -176 mm Y = + 7 mm (Crystal1) -176 ≤ X ≤ -183 32 ≤ Y ≤ 33 (Crystal2)	Si	PD-XFM-PCM-1000, NSL-123-11-0001 (IDT drawing)
BL MSK5	56.781 (US)	Ø 115 mm x 42.1 mm t	7.00 x 27.39 nom BDA	X= -189.8 mm Y = +15 mm	Cu-Cr-Zr	PD-XFM-MSK-1501
BL CO5	56.823 (US)	32.25 mm x 25.40 mm	N/A – below mask aperture	X= -190.1 mm Y= -13 to +12 mm	W	PD-XFM-CO-1503
PSH	56.981 (US)	125mm x 150mm x (2x) 19mm	30 mm x 60 mm	X = -191 mm Y = + 28 mm	W	PD-COM-PSH-2000
Guillotine	57.528 (US)	350mm x 350mm x 6mm	4” I.D.	X = -194 mm Y = +31 mm	Lead	PD-XFM-HU-1200 (see note 5)
Hutch B	57.534 (US)	3.00m x 3.50m	N/A	X = -194 mm	Steel	PD-XFM-HU-1200

DS Wall		x 6mm thick		Y = +31 mm		
Double Be Window (Hutch C)	57.743 (C)	2.75”CF flange	8 mm ID Upper 12 mm ID Lower	X= -195 mm Y= 21 mm & 45 mm	SST flange	Moxtek MZ15039-02
Beam Stop	62.522 (US)	500 mm SQ x12 mm thick	N/A	X = -224 mm Y = +74 mm	Pb (steel-covered)	PD-XFM-HU-1300
Hutch C DS Wall	62.534 (US)	3.00m x 3.50m x 6mm thick	N/A	N/A	Steel	PD-XFM-HU-1300