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07-ID (SST) Beamline Radiation Shielding Analysis	

1. Introduction

The 07-ID Spectroscopy Soft and Tender (SST) beamline is powered by two Undulators (U42 and EPU60) for the 2 beamlines; Soft (also known as the M branch) and Tender (L branch). The L branch is powered by the U42 out of vacuum undulator while the EPU60 (Elliptically Polarized Undulator) caters to the M branch. The beamline branches inside the FOE and the pink beams are transported up to the Double Crystal Monochromator (DCM) in the L branch and the Plane Grating Monochromator (PGM) in the M branch, both outside the FOE on the experimental floor. Downstream of the PGM the beam can be diverted to the M branch end stations or through 2 transfer lines to two different end stations in the L branch. Figure 1 shows the layout of the FOE and the components inside it while Figure 2 shows all the beamlines on the floor.

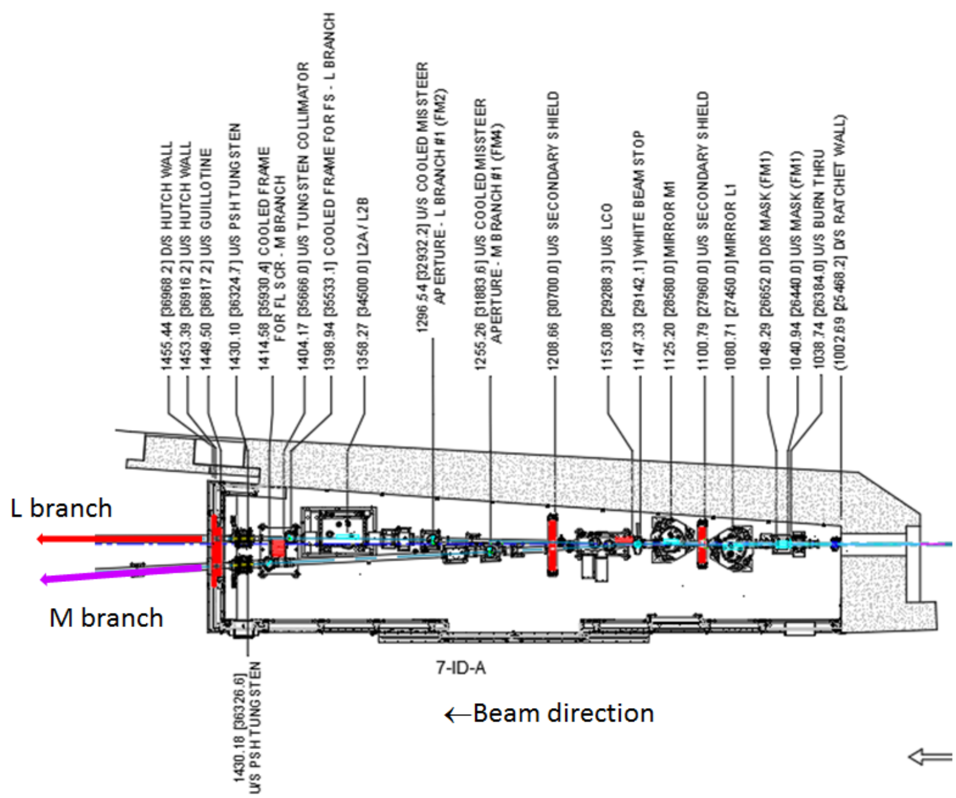


Figure 1: Layout of the FOE with the Beamline Components

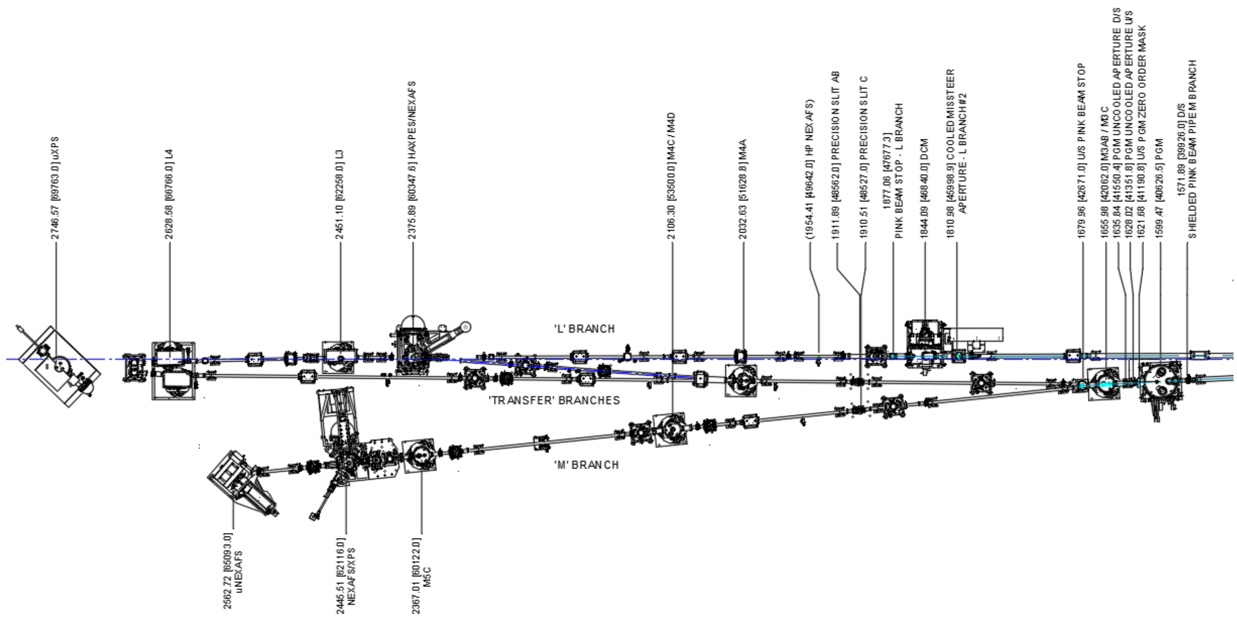


Figure 2: Layout of the beamlines outside the FOE. The M branch beam can also be delivered to the end stations in the L branch.

Outside the FOE, the 8 mm lead shielded beam pipe stops before the PGM and the DCM with 2 mm SS pipes, bellows and gate valves in between. The L branch has 2 experimental end stations: HAXPES and VPPEM. The M branch has 4 end stations LARIAT-1, µCal, NEXAFS and the LARIAT-2. The L branch (powered by U42) has a DCM that can provide X-rays up to 7.5 keV. The M branch (powered by the EPU60) has a PGM and can provide maximum 2.5 keV X-ray energy. By a combination of mirrors the end stations HAXPES and VPPEM in the L branch can receive beam from the L branch, M branch or from both branches simultaneously. The M branch however can use the beam only from the EPU60.

The radiation shielding analysis of the beamline is carried out for gas bremsstrahlung (GB) and synchrotron radiation (SR) as sources. Section 2 describes the GB related calculations while section 3 details the synchrotron radiation scatter analysis.

2. FLUKA Monte Carlo Analysis

This section is arranged in three sub sections. Section 2.1 describes the geometry along with the details of some of the components, section 2.2 describes the beam conditions as obtained from the ray traces and section 2.3 discusses the results.

2.1. FLUKA Geometry

Figure 3 shows the geometry of the FOE and the components inside it built using the information given in Appendix 1. The coordinate system is consistent with the one used in NSLS-II with the +Z axis as the beam direction, +Y axis as the vertical direction and +X pointing outboard.

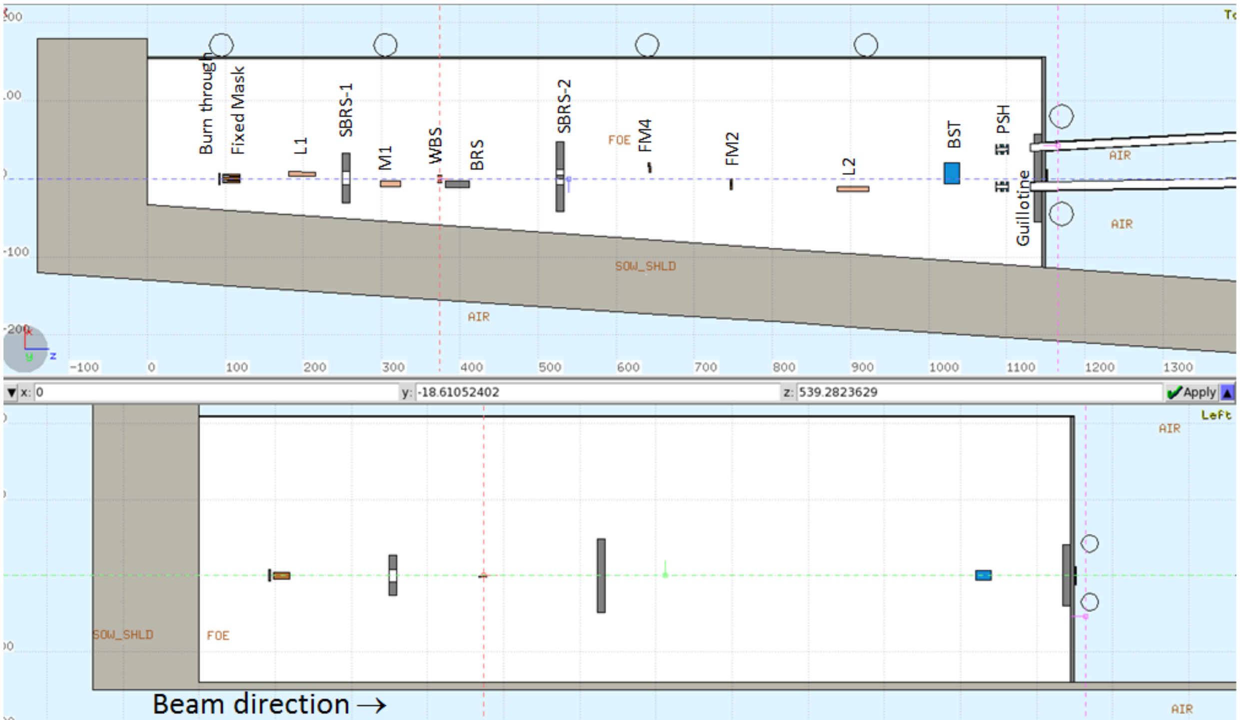


Figure 3: The horizontal (top) and vertical views of the FLUKA geometry of the FOE.

The major components inside the FOE include the burn through (BT) device and the fixed mask (FM) 1 (see Fig. 4); both are dual aperture devices to let the beams from the two undulators into the FOE. These are followed by L1 (first mirror in the L branch), a single aperture secondary bremsstrahlung lead shield (SBS-1), M1 (the first mirror in the M branch), a lead secondary bremsstrahlung shield (BRS), the white beam stop (see Fig. 5), a dual aperture lead secondary bremsstrahlung shield (SBS-2), FM4, FM2 (see Fig. 6), a tungsten bremsstrahlung stop (BST) and the photon shutters PSH1 and PSH4. The white beam stop has 2 inclined copper blocks that stops the white beams and the region intermediate is designed to allow the beams to pass through when reflected by the mirrors. Inside the FOE, the L branch has 2 mirrors (L1 and L2, both with 0.6° nominal angles) while the M branch has one (M1, 1.5° nominal). The FOE hutch has lead shields 18 mm on the side wall, 50 mm on the downstream wall and 10 mm on the roof. The lead guillotine is 10 cm thick and has dual apertures. The beam pipes exiting the FOE have lead shields up to 295.8 cm in the M branch and 509.3 cm in the L branch from the downstream end of the FOE wall and are also modelled here. The lead thickness is 8 mm and is wrapped around a 5 cm radius, 2 mm thick stainless steel pipe.

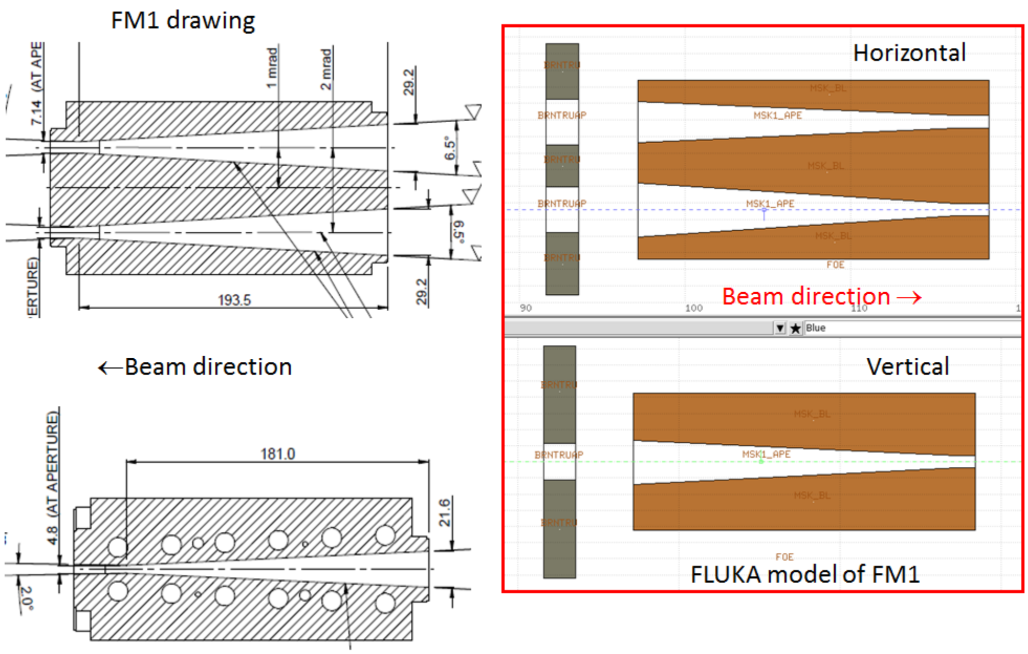


Figure 4: The drawing and the model in FLUKA of the FM1.

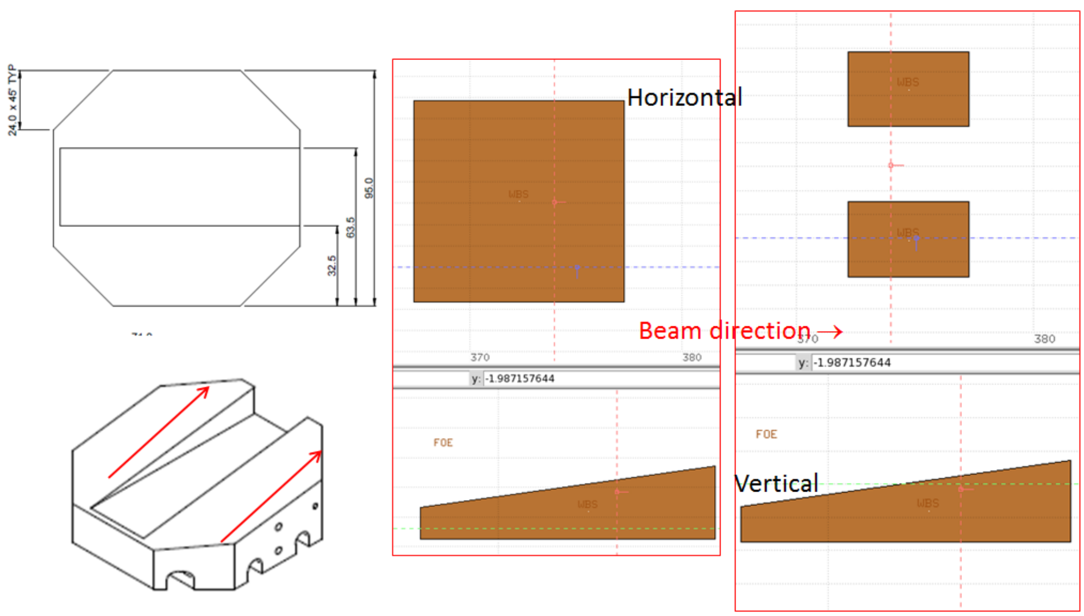


Figure 5: The white beam stop (WBS) in the drawings (left) and as modelled for the simulations. In the FLUKA model, the cutaway views are shown as horizontal views while the planes that are used to cut are shown as green lines on the vertical views (bottom figure).

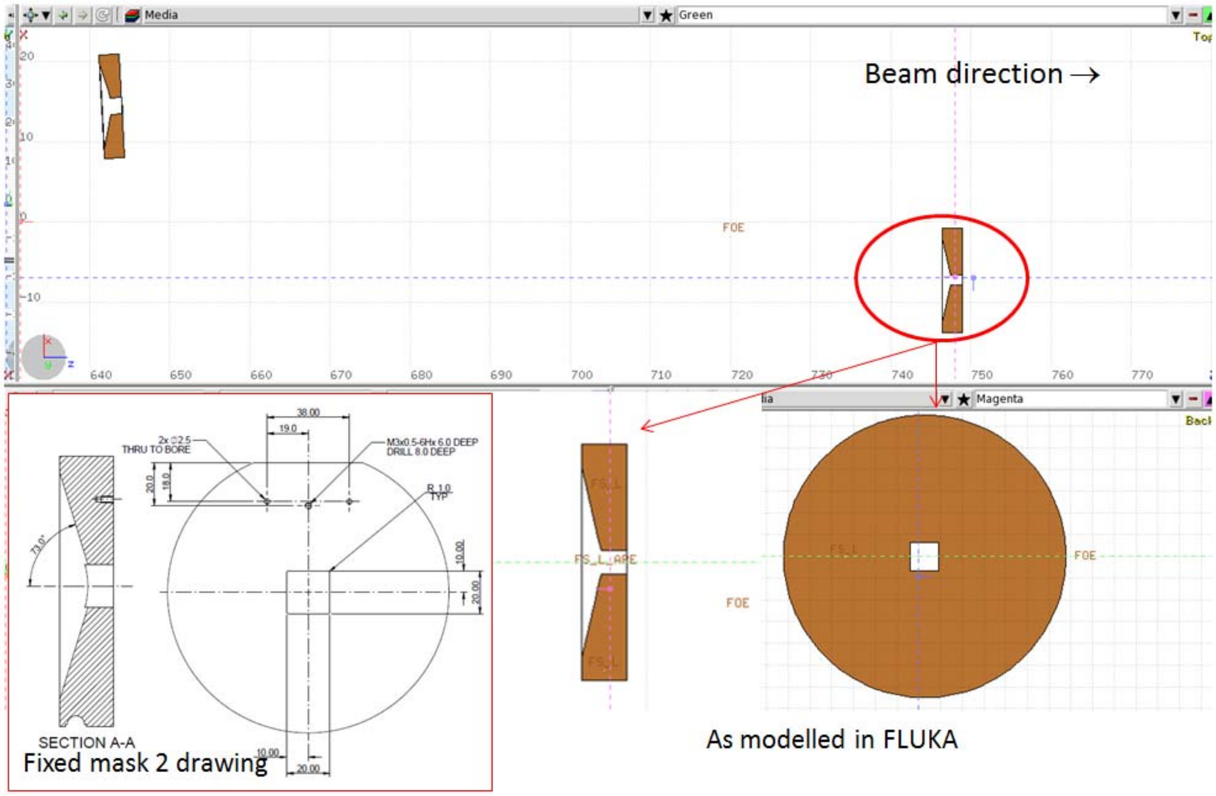
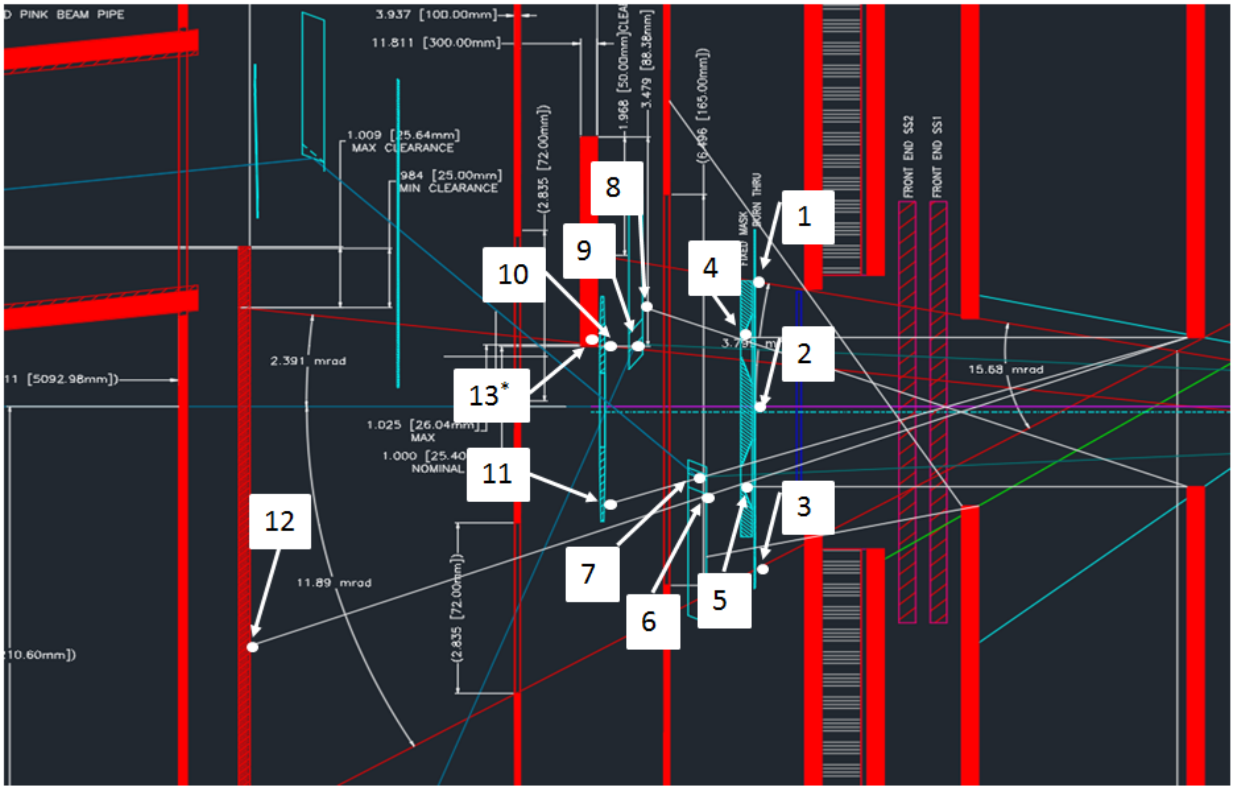


Figure 6: The fixed mask (2 and 4) in the drawings (left bottom) and as modelled for the simulations. The top figure shows the horizontal view while the bottom extreme right figure shows the vertical views.

2.2. Beam Conditions

The simulations were carried out for the gas bremsstrahlung spectrum obtained from an independent simulation of the long straight section. The normalized unit spectrum extending from 10 keV to 3 GeV is read as a source file and the resulting electromagnetic cascade and the photo neutrons are transported across the geometry and outside the shield. Figure 7 shows the horizontal bremsstrahlung ray trace identifying the beam loss points.



* Top outboard point. Ray missing the WBS.

Figure 7: The horizontal bremsstrahlung ray trace for the SST FOE. The beam loss points are identified as white dots.

The points along with the coordinates (x,y) are as follows. The directions of the beams are set according to the angles mentioned in the ray trace.

1. Inboard side of the burn through device (-5.273, 2)
2. Center of the burn through device (0,0)
3. Outboard side of the burn through device (6.9,0)
4. Inboard side of the aperture of the FM1 (-2.9,2)
5. Outboard side of the aperture of the FM1 (3.4,2)
6. Upstream edge of L1 mirror(3.77,0)
7. Center of the L1 mirror (2.975,0.525)
8. Upstream edge of M1 mirror (-4.2,2.3)
9. Centre of M1 mirror (-2.63,0)
10. Inboard side of WBS (-2.57,0)
11. Outboard side of WBS (4.17, 0)
12. Tungsten bremsstrahlung stop outboard side (10.1,0)
13. Top outboard point on the lead BRS (-2.57, 2.46)
14. As in scenario 13 but BRS is moved 3 mm inboard (-2.96, 2.46)
15. As in scenario 14 but beam is centered vertically (-2.96, 0)

Beam conditions 14 and 15 were separately simulated after the survey results indicated that the BRS position is moved inboard by 3 mm from its intended position. In these scenarios, the beam was started downstream of the BRS with the X coordinate moved accordingly. The Y coordinates were kept at the bremsstrahlung vertical foot print maximum in one scenario (numbered 14) and vertically centered in another scenario (numbered 15).

2.3. Results and Discussions

The GB power is taken as 17 µW, which is generated by 500 mA, 3 GeV electron beam in a 15.5 m long straight section with the vacuum better than 10^{-9} Torr. The results here are normalized to the length of the straight section of this beamline (14 m) and a vacuum of 10^{-9} Torr. The total ambient dose equivalent rates (mrem/h) for the 15 loss points described in section 2.2 are shown in the same order in Figures 8-22. In these figures, the upper plots show the horizontal view (at y=0) and the lower plots show the vertical views (at x=0). Table 1 shows the summary of the results from these figures.

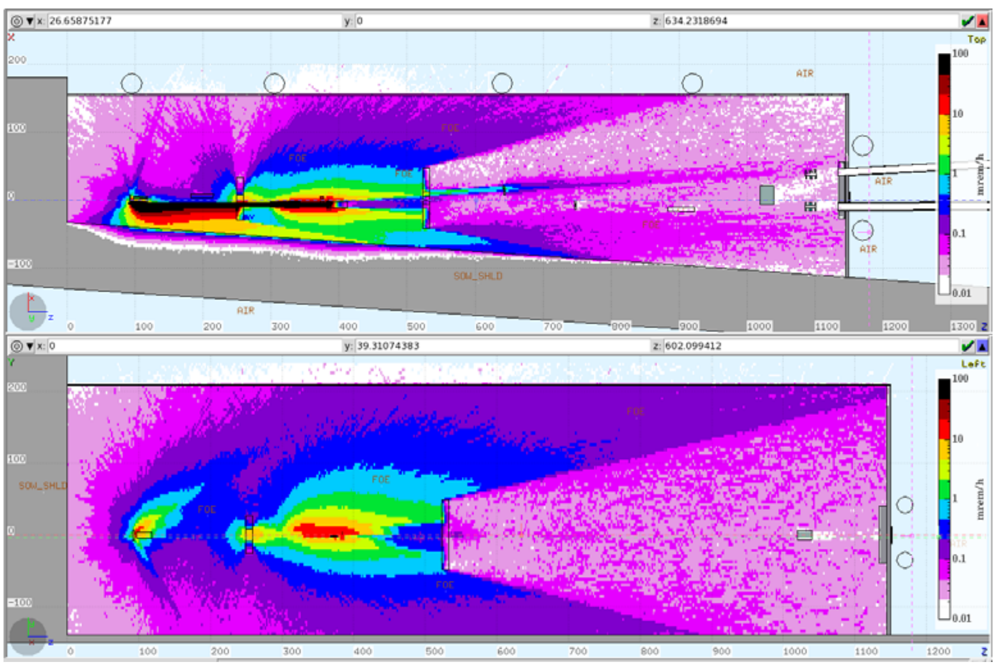


Figure 8: The total ambient dose equivalent rates when the beam is incident on the inboard side of the burn through device. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

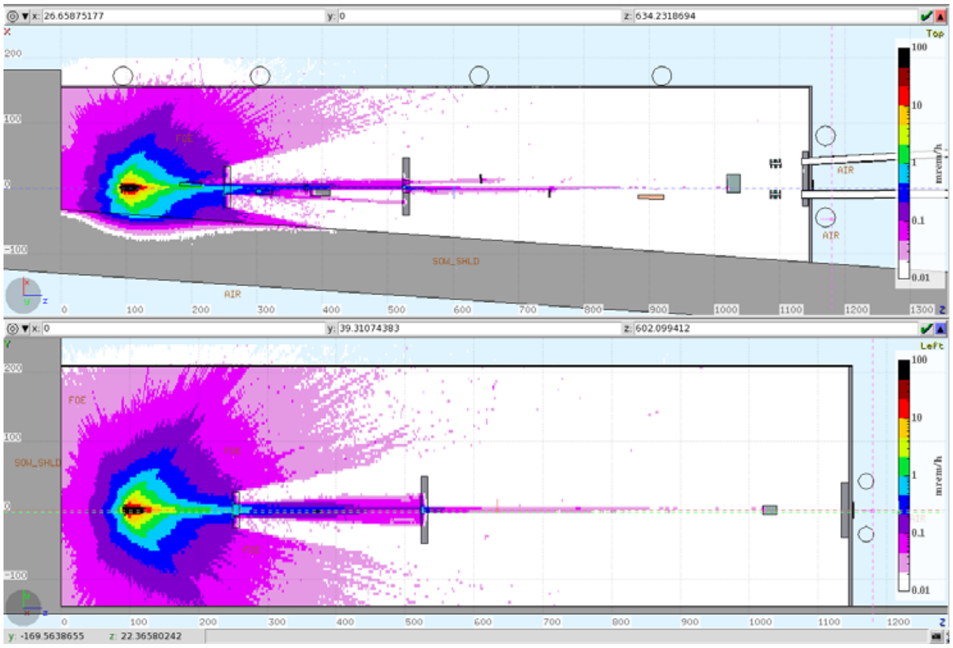


Figure 9: The total ambient dose equivalent rates when the beam is incident on the center of the burn through device. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

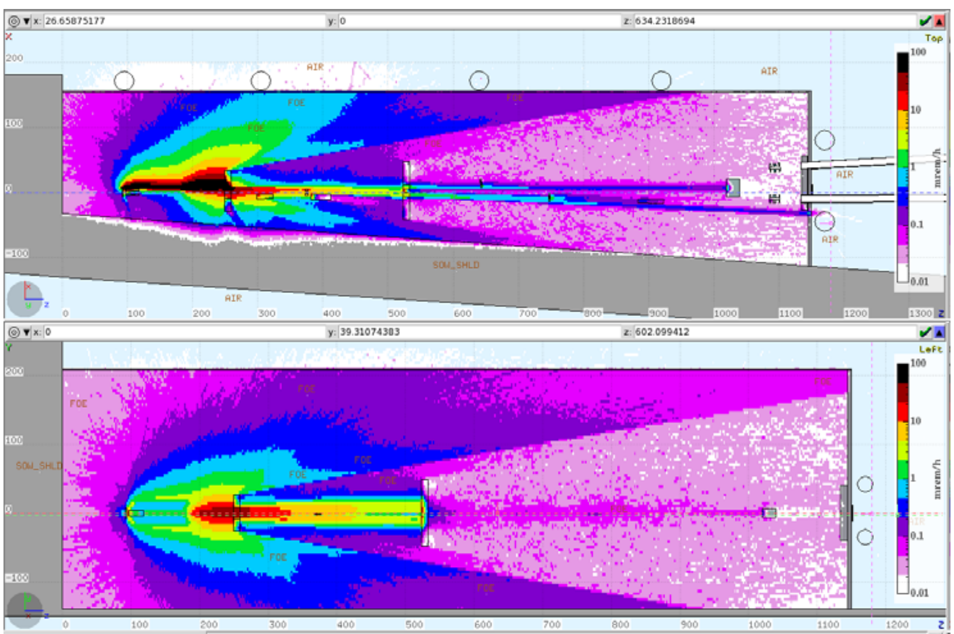


Figure 10: The total ambient dose equivalent rates when the beam is incident on the outboard side of the burn through device. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

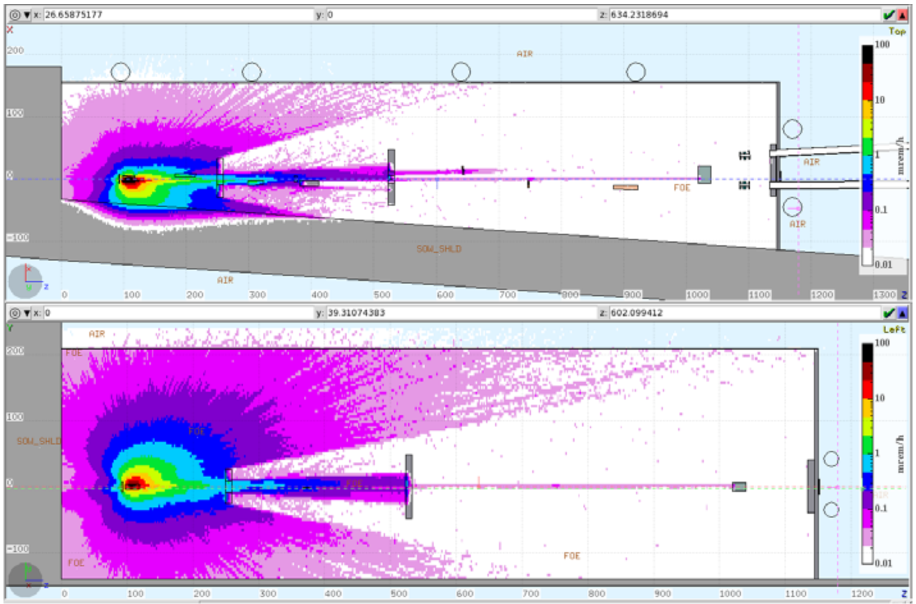


Figure 11: The total ambient dose equivalent rates when the beam is incident on the inboard side of the aperture of the FM1. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

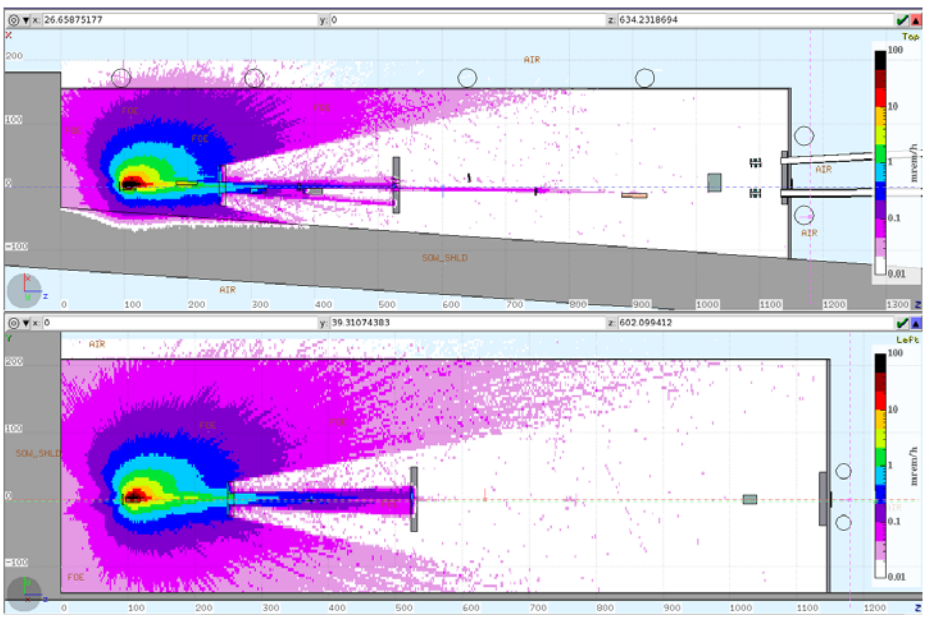


Figure 12: The total ambient dose equivalent rates when the beam is incident on the outboard side of the aperture of the FM1. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

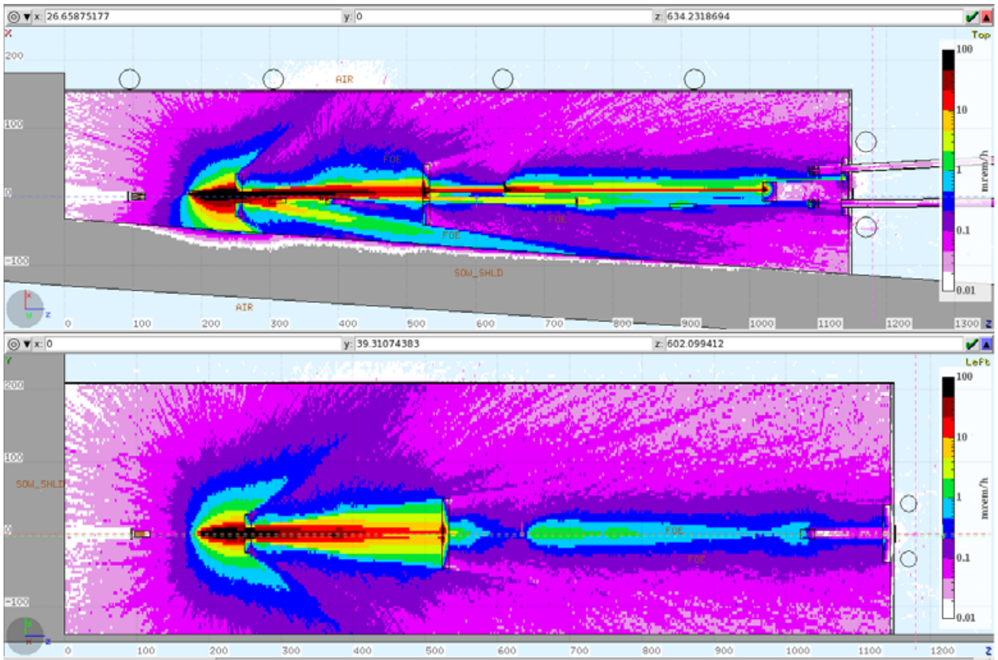


Figure 13: The total ambient dose equivalent rates when the beam is incident on the upstream edge of L1. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

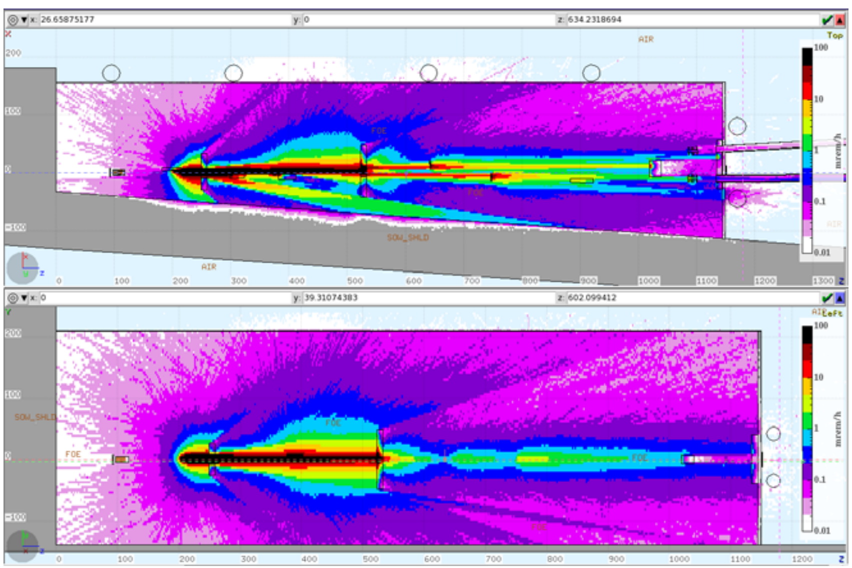


Figure 14: The total ambient dose equivalent rates when the beam is incident on the center of L1. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

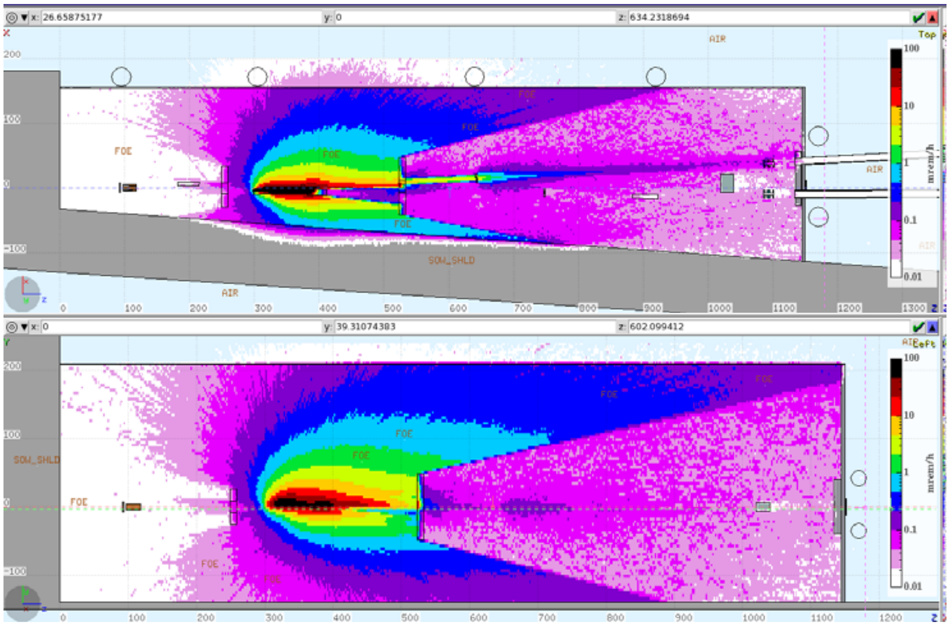


Figure 15: The total ambient dose equivalent rates when the beam is incident on the upstream edge of M1. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

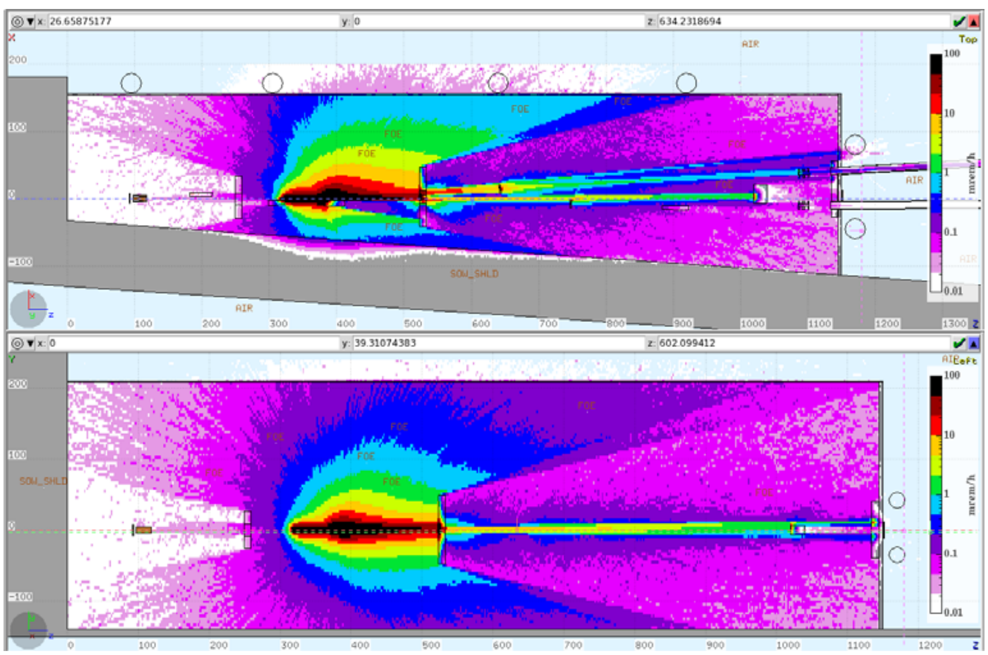


Figure 16: The total ambient dose equivalent rates when the beam is incident on the center of M1. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

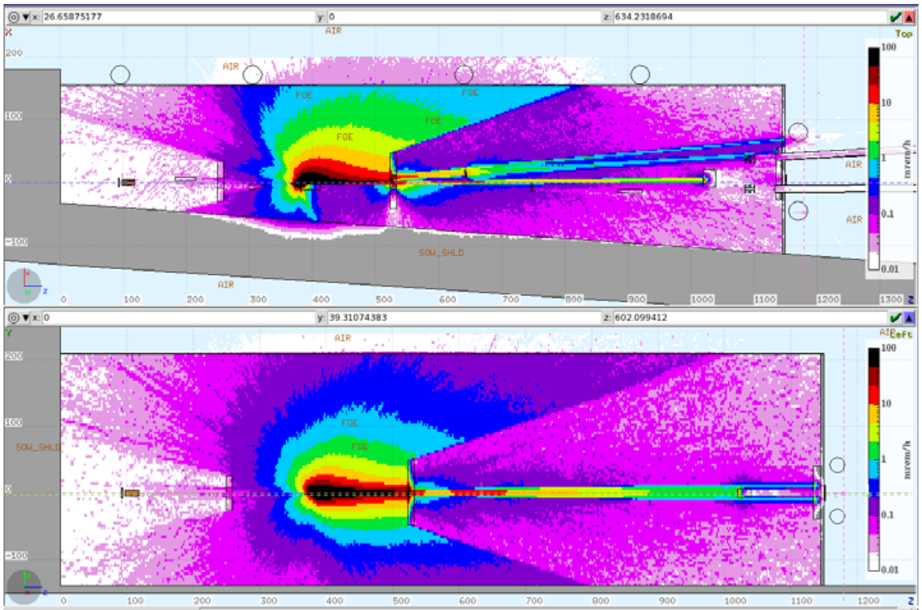


Figure 17: The total ambient dose equivalent rates when the beam is incident on the inboard side of the WBS. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

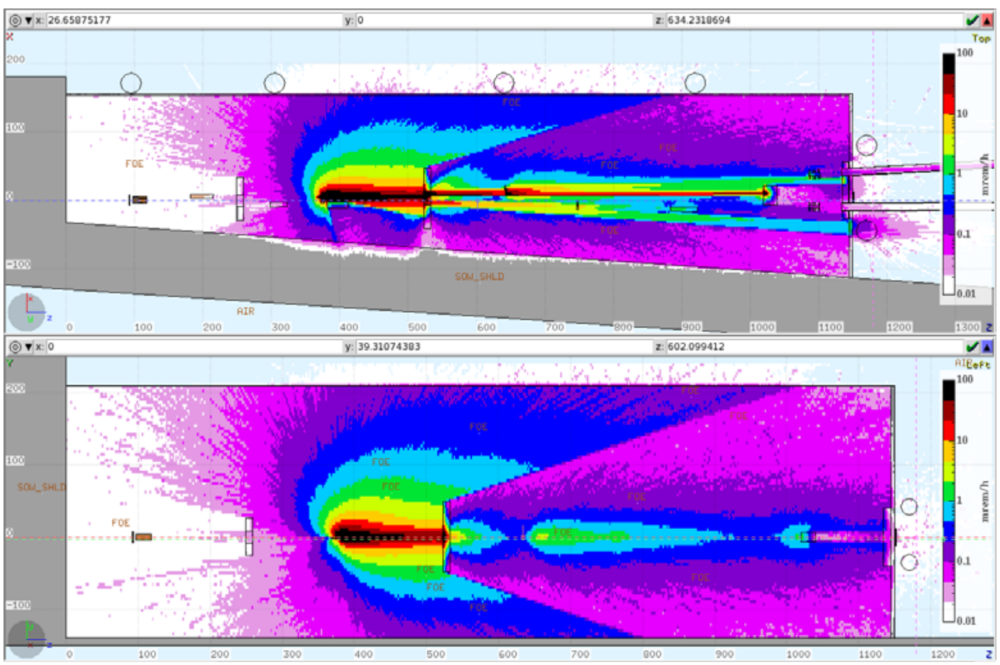


Figure 18: The total ambient dose equivalent rates when the beam is incident on the outboard side of the WBS. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

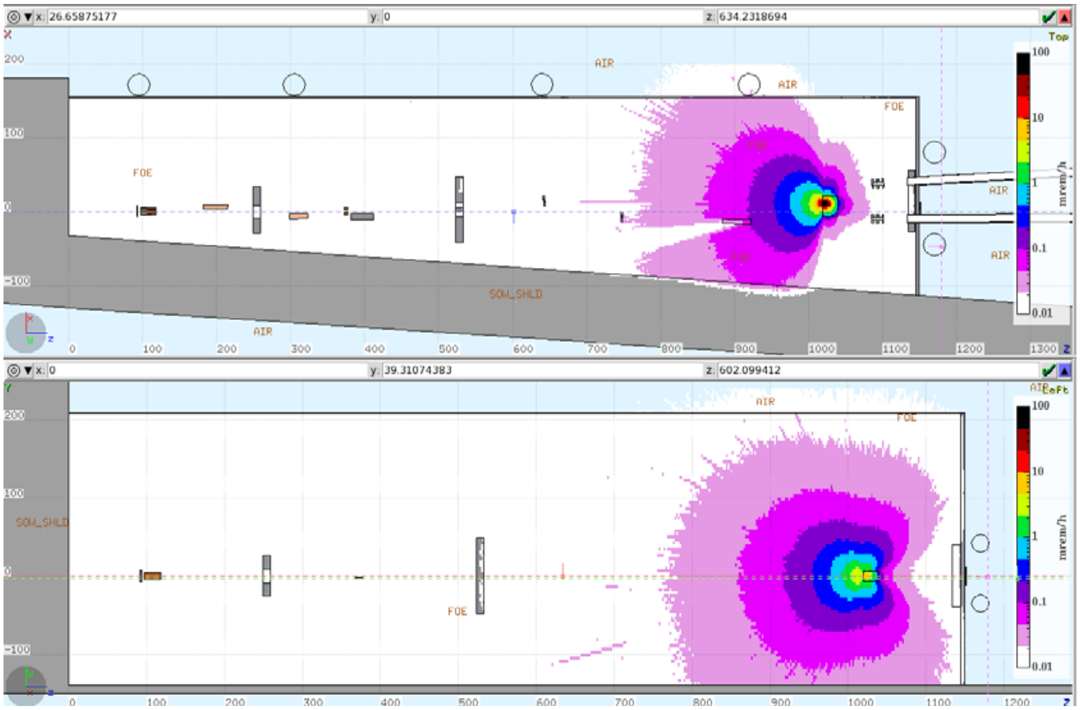


Figure 19: The total ambient dose equivalent rates when the beam is incident on the outboard side of the tungsten bremsstrahlung stop. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

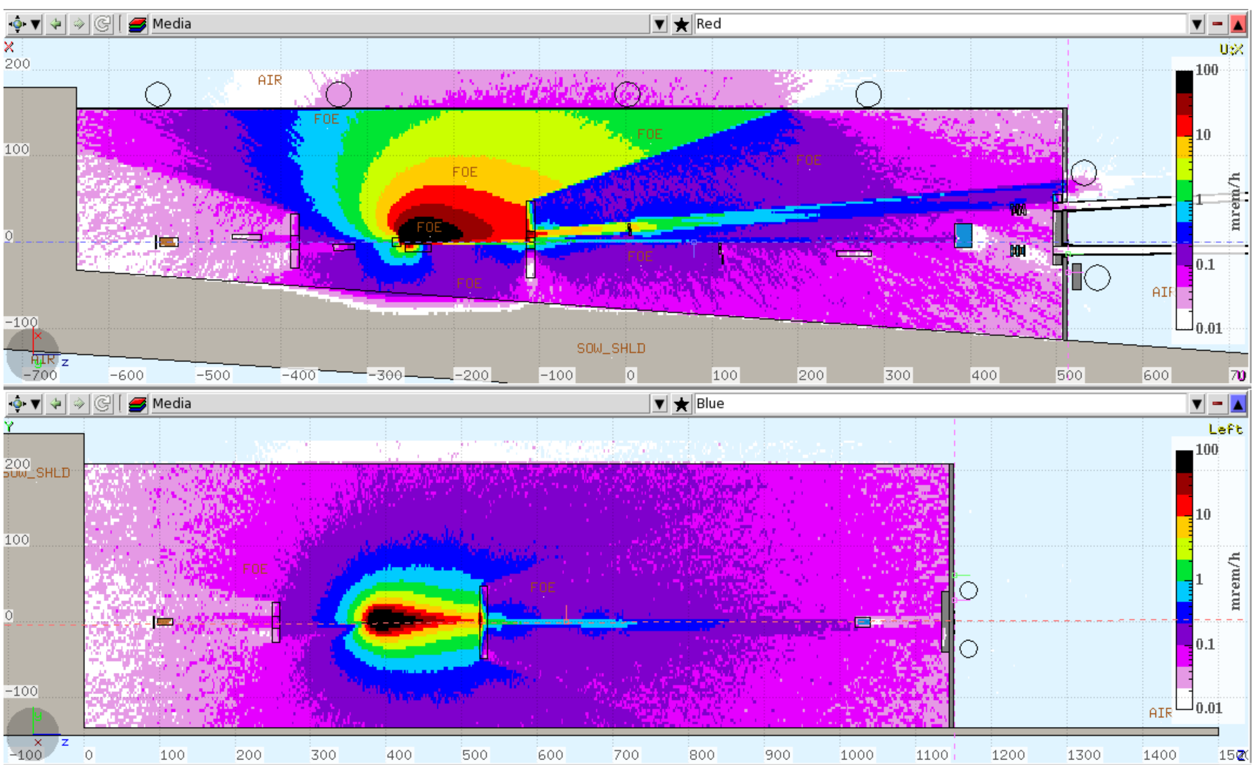


Figure 20: The total ambient dose equivalent rates when the beam is incident on the top outboard side of the lead bremsstrahlung shield. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

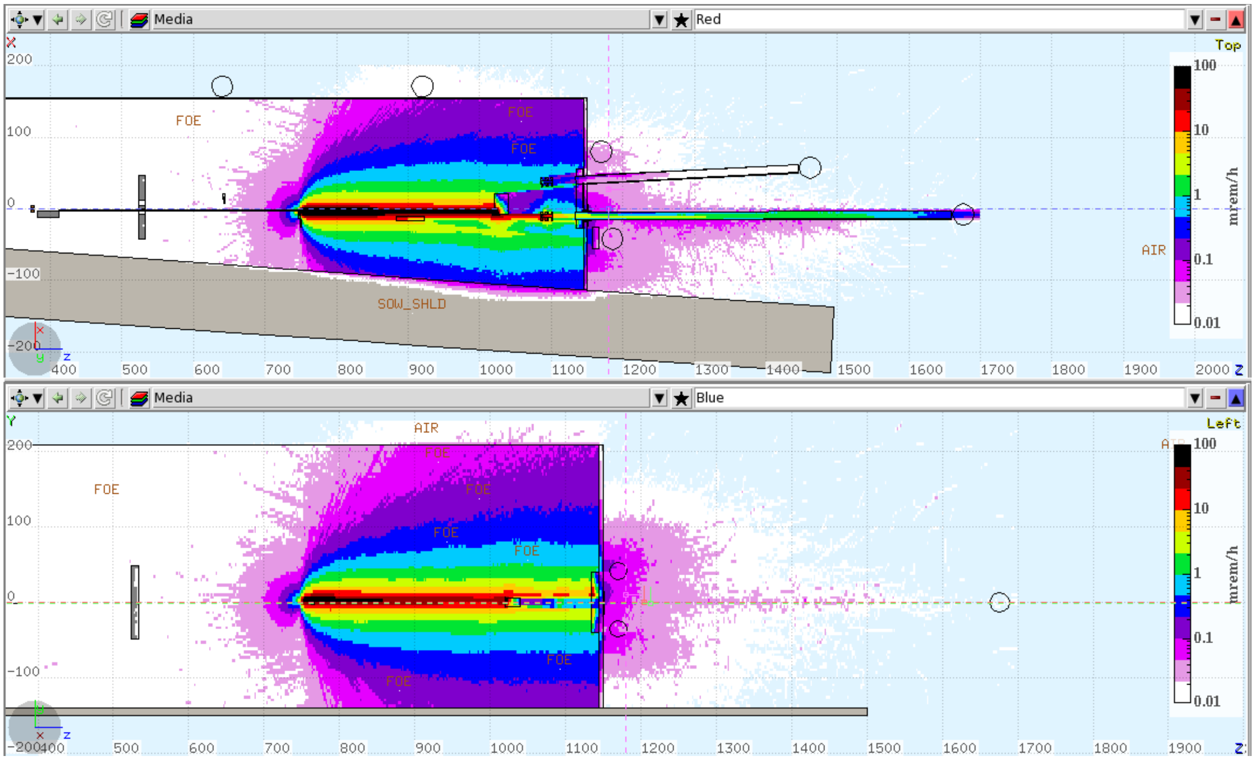


Figure 21: The total ambient dose equivalent rates when the beam misses the BRS due to its movement inboard and strikes the FM2. The beam has an upward vertical offset. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

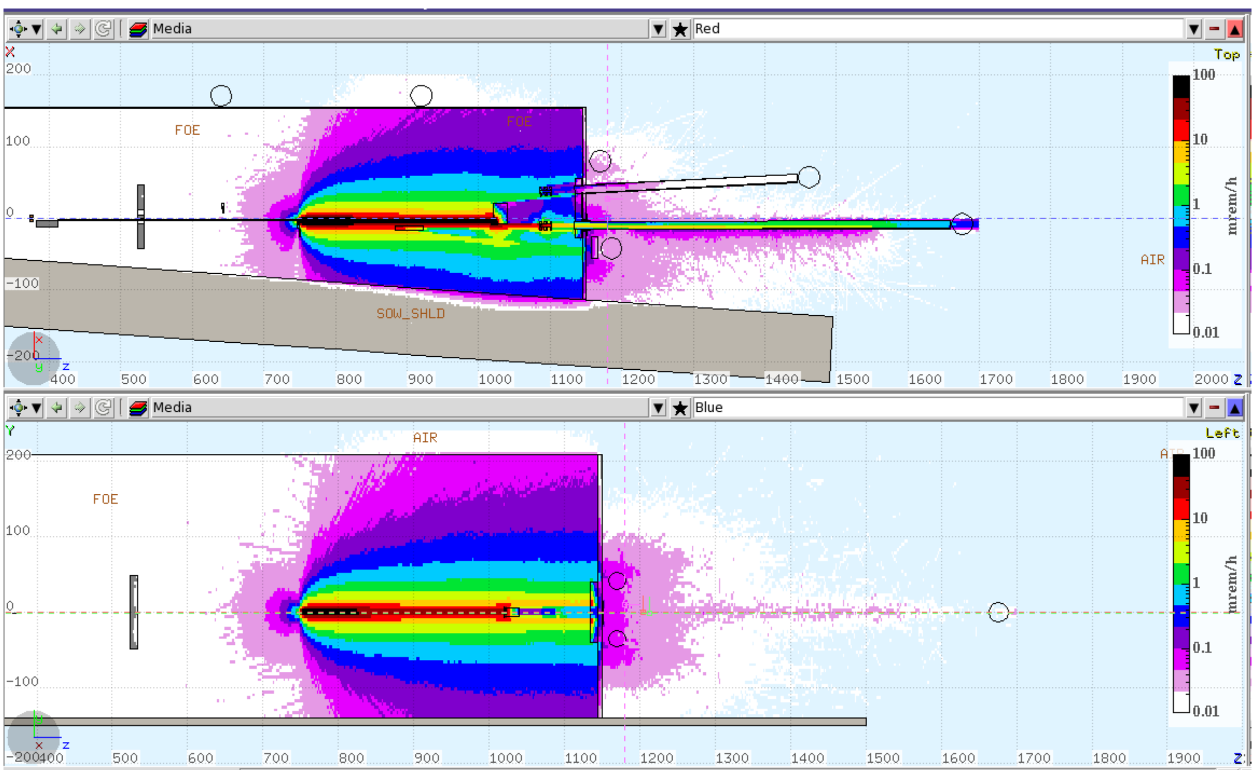


Figure 22: The total ambient dose equivalent rates when the beam misses the BRS due to its movement inboard and strikes the FM2. The beam is vertically centered. The top figure shows the horizontal view (y=0) and the bottom figure (x=0) shows the vertical view.

Table 1: Summary of the dose rates observed outside the FOE for the various beam conditions

Beam incident on	Ambient dose equivalent rates on contact (mrem/h)				
	Side wall	Roof	DS wall	Exit pipe L	Exit pipe M
1. Inboard of BT	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
2. Center of BT	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
3. Outboard of BT	< 0.05	< 0.05	0.07*	< 0.05	< 0.05
4. Inboard of FM aperture	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
5. Outboard of FM aperture	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
6. US edge of L1	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
7. Center of L1	< 0.05	< 0.05	0.15*	< 0.05	< 0.05
8. US edge of M1	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
9. Center of M1	< 0.05	< 0.05	< 0.05	< 0.05	0.07
10. Inboard of WBS	< 0.05	< 0.05	0.08*	< 0.05	< 0.05
11. Outboard of WBS	< 0.05	< 0.05	0.3#	< 0.05	< 0.05
12. Outboard of BST	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
13. Top outboard of BRS	0.07$^{\Phi}$	0.05	0.1*	< 0.05	< 0.05
14. As in 13, BRS moved	< 0.05	<0.05	0.45*	0.12$	<0.05
15. As in 14, beam centered	<0.05	<0.05	0.4*	0.1$	<0.05

$^{\Phi}$* Dose rates are less than 0.05 mrem/h at 30 cm distance.
Dose rate at 30 cm distance is more than 0.05 mrem/h.
$ Dose rate on contact with the pipe.

From the figures and the table, when the GB beam is incident on the top outboard point of the BRS, the dose rates outside the lateral wall of the FOE is 0.07 mrem/h on contact and is less than 0.05 mrem/h at 30 cm away. The ambient dose equivalent rates outside the downstream wall of FOE are less than 0.05 mrem/h, except for seven different beam conditions. They are when the beam is incident on the outboard side of the burn through device, center of the L1 mirror, on the inboard and outboard sides of the WBS, top outboard point on BRS and the rays that misses the BRS when it is moved inboard by 3mm, as per the survey data. These are marked with an asterisk in the table. As per the ALARA policy [1], the dose rates on contact with the downstream wall should not exceed 0.5 mrem/h and 0.05 mrem/h at a distance of 30 cm from the exterior surface. The dose rates in table 1 meet this requirement for all scenarios except when the beam is incident on the outboard side of WBS. Here, the contact dose rate is 0.3 mrem//h and is 0.08 mrem/h at 30 cm distance as shown in Figure 23. A set of simulations were carried out with an additional lead shield of dimensions 10 cm horizontally, 20 cm vertically and thickness between 1.5-3.5 cm placed inside the FOE to intercept the shower that is the cause of the higher dose rates. A dose rate plot for an additional shield thickness of 3.5 cm is given in Figure 24. The dose rates have now reduced to 0.2 mrem/h on contact and 0.03 mrem/h at 30 cm distance. It was recommended to add at least 3.5 cm thick lead inside the FOE that covers the shower streaming out of the FOE downstream wall. The location of the shield was however chosen to be outside the FOE on the downstream wall and it is recommended that the shield be 5 cm thick covering the stream that is marked as a black box in Figure 25. Vertically, it should be ±20 cm about the straight center line and horizontally it should extend from -25 to -55 cm (30 cm) with respect to the straight center line. The FLUKA geometry is built with the straight center line as the reference. It therefore coincides with the Z axis at (x=0, y=0) of the FLUKA geometry (upper plot in Figure 25) and is directed towards the reader at the origin in the bottom plots.

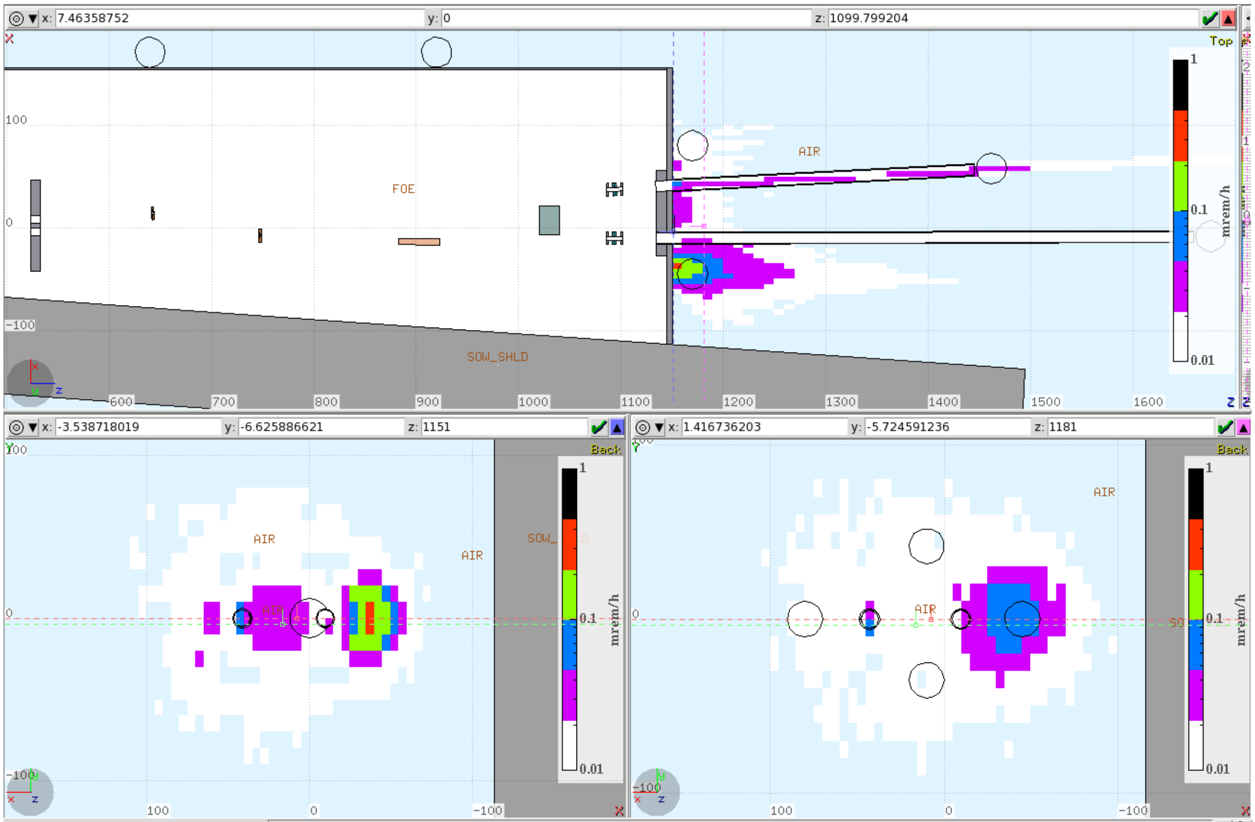


Figure 23: The dose rates on contact with the downstream wall and at 30 cm distance when the beam is incident on the outboard side of the WBS. The upper figure shows the horizontal view (y=0) and the bottom figures show the dose rates just outside the wall (bottom left corresponding the blue line on the top figure) and at 30 cm distance (bottom right corresponding to the magenta line on the top figure).

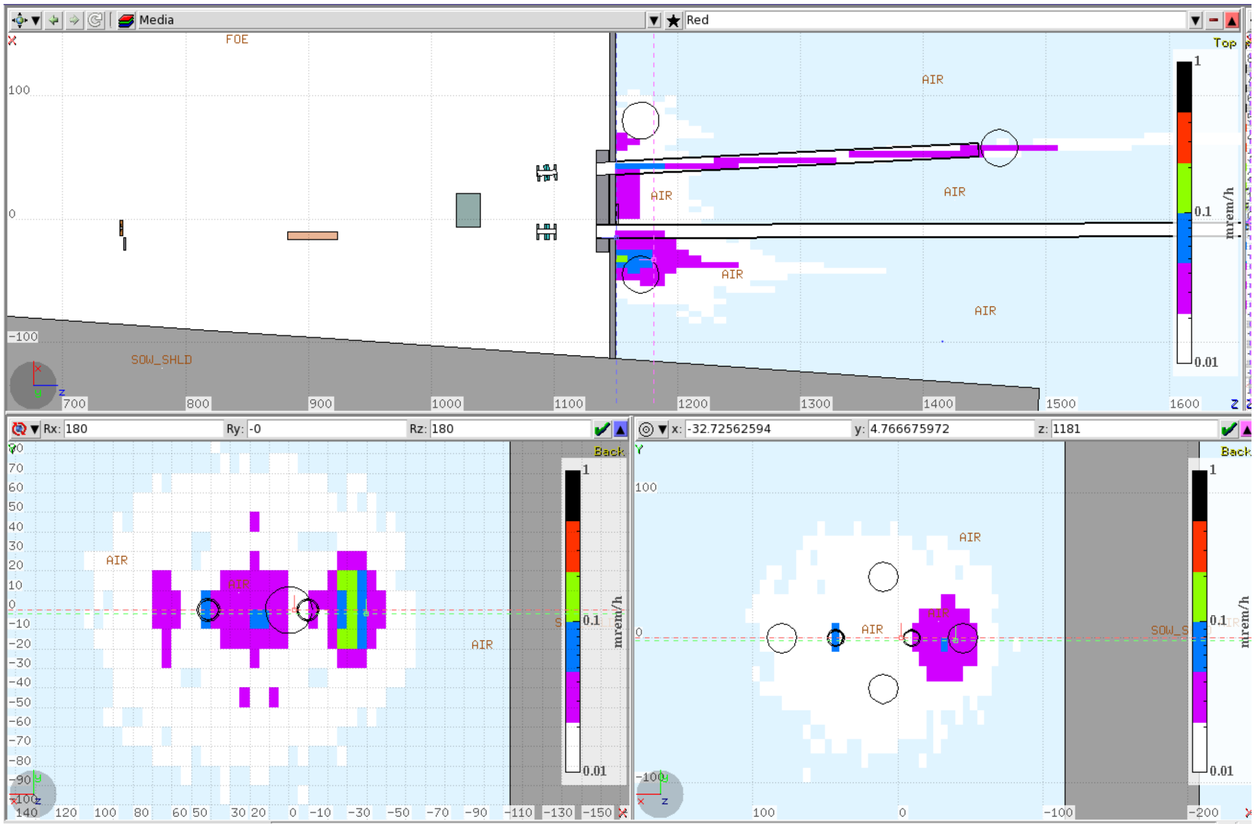


Figure 24: The dose rates on contact with the downstream wall and at 30 cm distance when the beam is incident on the outboard side of the WBS and an additional 3.5 cm lead shield is introduced. The upper figure shows the horizontal view (y=0) and the bottom figures show the dose rates just outside the wall (bottom left corresponding to the cut with the blue line on the top figure) and at 30 cm distance (bottom right corresponding to the cut with the magenta line on the top figure).

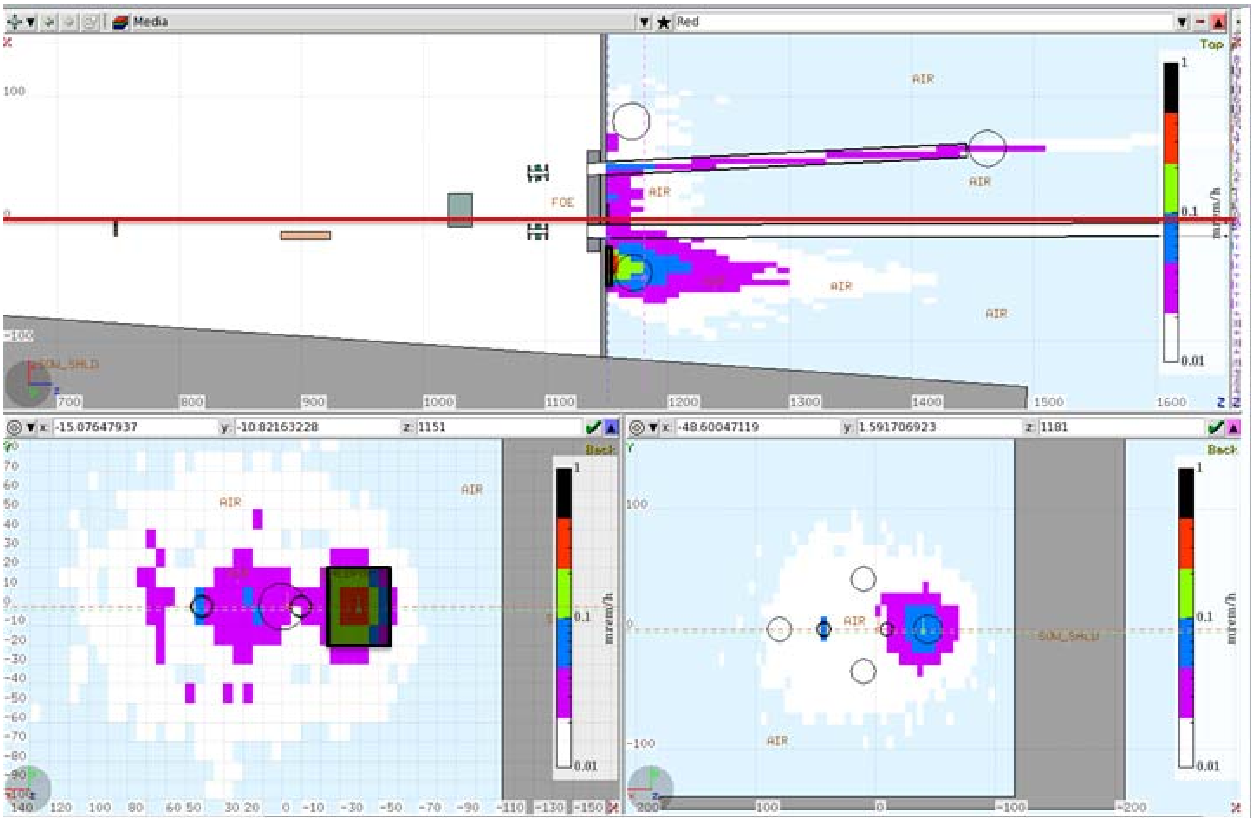


Figure 25: The dose rates outside the FOE downstream wall. The top plot shows the horizontal view. The bottom figure shows the cut view just outside the wall (bottom left) and at 30 cm distance (bottom right) when viewed in the downstream direction.

For the beam scenario number 13 when the beam is incident on the top outboard side of the BRS, the maximum dose rate outside the lateral wall is seen to be 0.06-0.07 mrem/h on contact but is less than 0.05 mrem/h at 30 cm distance. The dose rate outside the roof is estimated to be 0.05 mrem/h on contact. Outside the downstream wall, the dose rate on contact is estimated to be 0.1 mrem/h but is less than 0.05 mrem/h at 30 cm distance.

The mechanical survey data indicated that the SBS-1 and SBS-2 are smaller by 3-4.5 mm on the outboard side and 1.4-2.9 mm on the top while the dimensions and the coordinates of their apertures remain unchanged. From figure 20, the maximum dose rates outside the lateral wall and the roof occur when the beam hits the lead bremsstrahlung shield. This is situated in between SBS-1 and SBS-2. These dose rates are as a result of the lateral shower maximum, the development of which is not influenced by dimensions or the location of the SBS-1 or SBS-2. Further, the maximum dose rates observed outside the downstream wall are all due to the streaming of the electromagnetic shower through the apertures of SBS-2. Since there is no change in the dimensions or coordinates of the apertures of SBS-2, these results are also unaffected by the change in the dimensions as observed in the survey.

The survey also indicated that the lead BRS was moved inboard by 3 mm. An additional set of simulations were carried out with beam scenarios numbered as 14 and 15, where the BRS was moved as indicated by the survey. Further the additional shield (SBS-3) as discussed above was also included in the simulation. The installed thickness of the lead shield is 10 cm. The sum of photon and neutron dose rates at 30 cm distance from the downstream wall is shown in Figure 26. The maximum dose rates are 0.5 mrem/h on contact and 0.05 mrem/h at 30 cm distance.

The dose rates outside the L branch beam pipe are shown in Figure 27 for beam condition given number 14. The results are similar for beam condition mentioned in scenario 15. The dose rates occur as a result of a combination of photons and electrons from the electromagnetic shower entering the beam pipe through the open photon shutter and interacting with the SS and lead. An increase around the beam pipe can be seen at a distance that is beyond 30 cm up to 4.2 m from the downstream wall with the maximum occurring towards the inboard side (bottom right plot). When the photon shutter of the L branch inside the FOE is closed, the dose rates outside the beam pipe reduces to below 0.05 mrem/h as seen in figure 28.

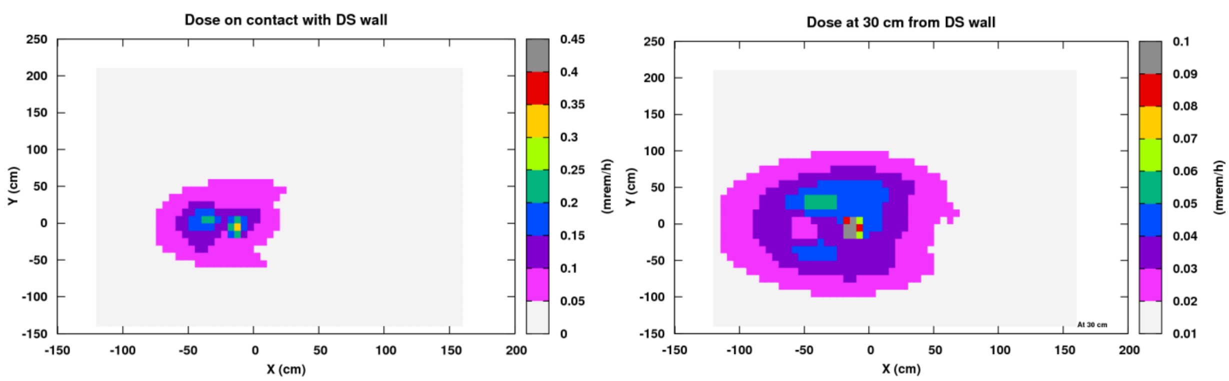


Figure 26: The dose rates on contact and at 30 cm distance outside the FOE downstream wall for the scenario numbered 14. The higher values are contained inside the lead pipe.

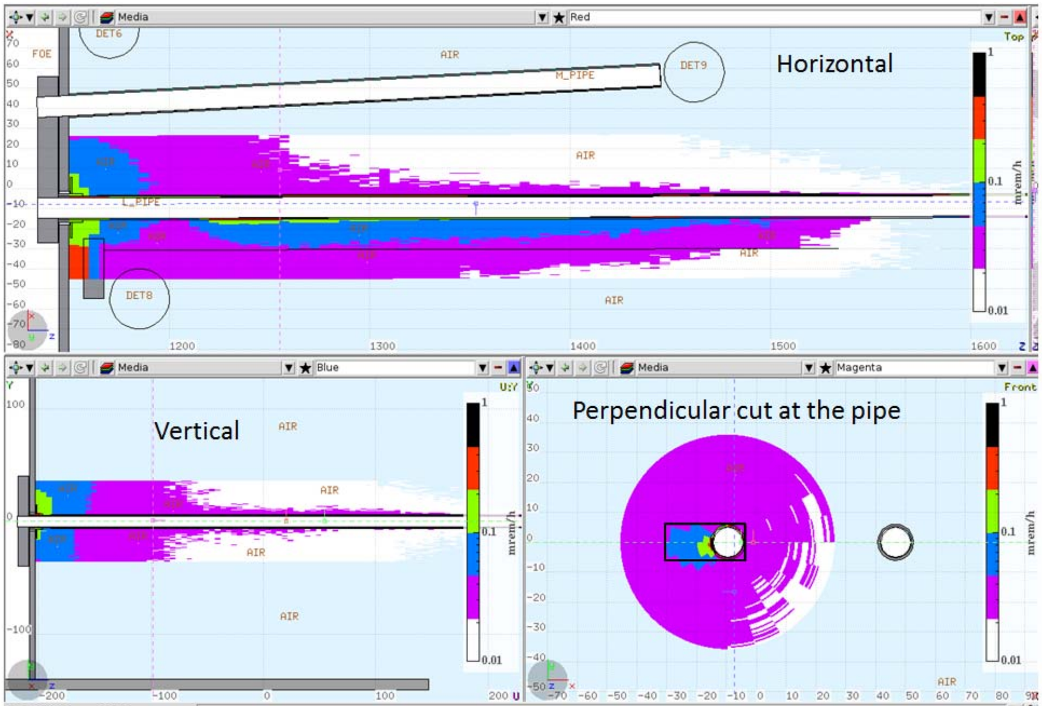


Figure 27: The dose rates outside the beam pipe with a beam condition described as scenario 14. The top figure shows the horizontal view (y=0) and the bottom left figure shows the vertical view at the beam pipe. The bottom right figure shows the radial distribution of the dose.

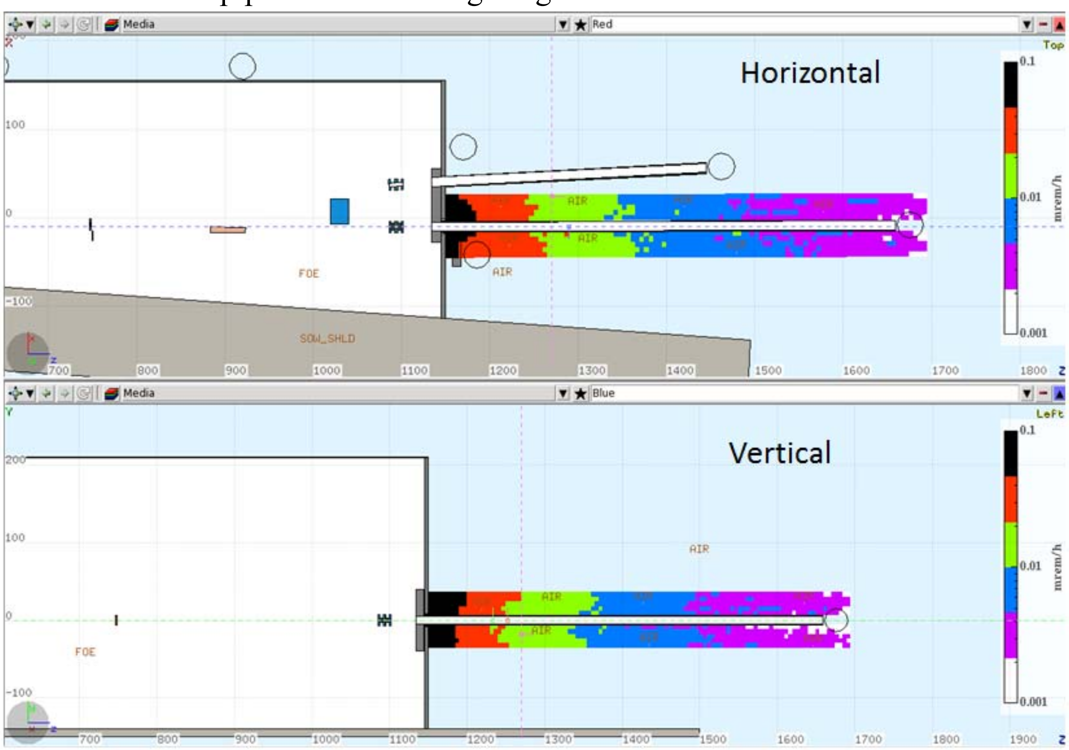


Figure 28: The dose rates outside the beam pipe with a beam condition described as scenario 14. The photon shutter inside the FOE is kept closed. The top figure shows the horizontal view (y=0) and the bottom left figure shows the vertical view at the beam pipe.

A separate set of simulations were carried out with 8 mm addition SS shields covering half the circumference of the pipe towards the inboard side, in addition the existing lead pipe. In figure 29 the results are shown with and without the additional SS shield for the angular bin (towards the inboard side) where the maximum dose occurs. The plot on the left shows that the dose rates reduce to 0.05 mrem/h at a radial distance of 20 cm from the surface of the lead pipe with no additional shield. The plot on the right shows that 8 mm of SS also reduces the contact dose rates to 0.05 mrem/h.

It is recommended that the L branch beam pipe be covered with 8 mm SS shield or with a shielded enclosure of at least 1mm thick SS extending 20 cm. They should be placed on the inboard side of the existing beam pipe covering half the circumference and should extend to 4.2 m along the beam direction when measured from the downstream wall. The enclosure can be box shaped as shown as an outline in figure 27 bottom right plot.

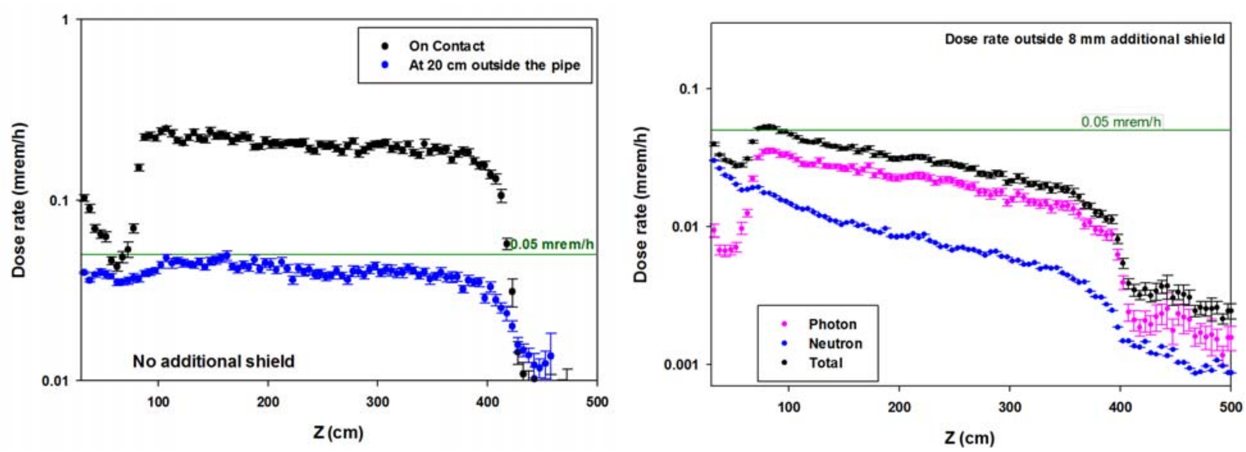


Figure 29: Maximum dose rates outside the L branch beam pipe without (left) and with additional SS shields, for beam scenario number 14.

2.4. Summary of GB Calculations

The FLUKA calculations for the GB radiation shows that the FOE downstream wall requires an additional lead shield of 40 cm (vertical) × 30 cm (horizontal) × 5 cm (thickness) on the inboard side of the guillotine centered vertically and 40 cm towards the inboard side with respect to the straight center line.

The inboard movement of the lead BRS is expected to give rise to dose rates that is greater than 0.05 mrem/h on contact with the beam pipe of the L branch. It is recommended that the pipe be provided a shield or shielded enclosure to reduce the dose rates on contact to 0.05 mrem/h.

3. Synchrotron Radiation Scatter Analysis

The source spectra that enter the FOE from the FE fixed mask are shown in Figure 30. These are used as the starting point for all calculations that are carried out with the STAC8 code. The various scattering targets in and out of the FOE are listed below along with the incident beam.

(a) Scattering targets inside the FOE

1. White beam from U42 on L1
2. White beam from EPU60 on M1
3. White beam from U42 and EPU 60 on WBS
4. Pink beam from M1 on FM4
5. Pink beam from L1 on FM2
6. Pink beams from L1 and M1 on photon shutters

(b) Scattering targets outside the FOE

7. Pink beam on an air column inside 8 mm lead (loss of vacuum)
8. Pink beam on an air column inside 2 mm SS pipe (loss of vacuum)
9. Pink beam on an air column inside bellows
10. Pink beams on silicon crystals inside the PGM and DCM
11. Pink beam on a Cu target inside 2 mm SS pipe
12. Pink and mono beams on SS flange (beam stop)
13. Monochromatic beams on generic scattering targets inside the end stations

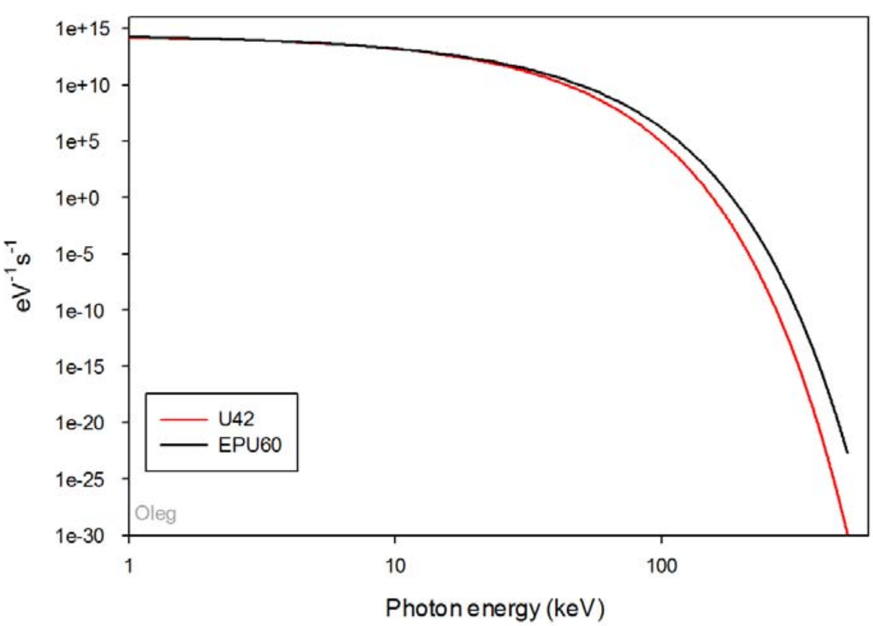


Figure 30: The SR spectra from U42 and EPU60 entering the FOE used as the starting point for the calculations.

3.1. Dose Rates Due to Scatter Targets inside the FOE

The white beam spectra shown in Figure 30 were used to estimate the dose rates outside the FOE. The distance to the wall was taken from the data sheet (Appendix 1). Table 2 summarizes the dose rates outside the FOE due to the various scatter targets. As can be seen from the table, the dose rates outside the FOE are well below 0.05 mrem/h.

Table 2: Dose rates on contact with the FOE walls when the SR scatters of targets inside FOE

Target	Beam	Ambient dose equivalent rates (μRem/h)		
		Side wall	Roof	DS wall
L1	White beam	< 1.0	< 1.0	< 1.0
WBS	Sum of white beams	< 1.0	< 1.0	< 1.0
M1	White beam	< 1.0	< 1.0	< 1.0
FM4	Pink beam	< 1.0	< 1.0	< 1.0
FM2	Pink beam	< 1.0	< 1.0	< 1.0
PSH-M	Pink beam	< 1.0	< 1.0	< 1.0
PSH-L	Pink beam	< 1.0	< 1.0	< 1.0

3.2. Dose Rates Due to Scatter Targets outside the FOE

In this section, the dose rates outside the beam pipe, bellows and end stations are discussed when the SR scatters off targets outside the FOE.

3.2.1. Pink and Mono Beams Stopped by SS Flange

The thickness required to stop the pink and monochromatic beams incident perpendicular on a stainless steel flange are investigated. Figure 31 shows the dose rates for different thicknesses of SS flange required to stop the pink beams, after 2 reflections for both L and M branches. To reduce the dose rates to 0.05 mrem/h, the flange thickness has to be at least 6 mm for the L branch and 2.6 mm for the M branch with all mirrors set to their minimum angles. For the mono beams, the corresponding thicknesses are estimated to be 2 mm (L branch) and 1 mm (M branch). The thickness of the flanges installed is expected to be 19 mm as beam stops.

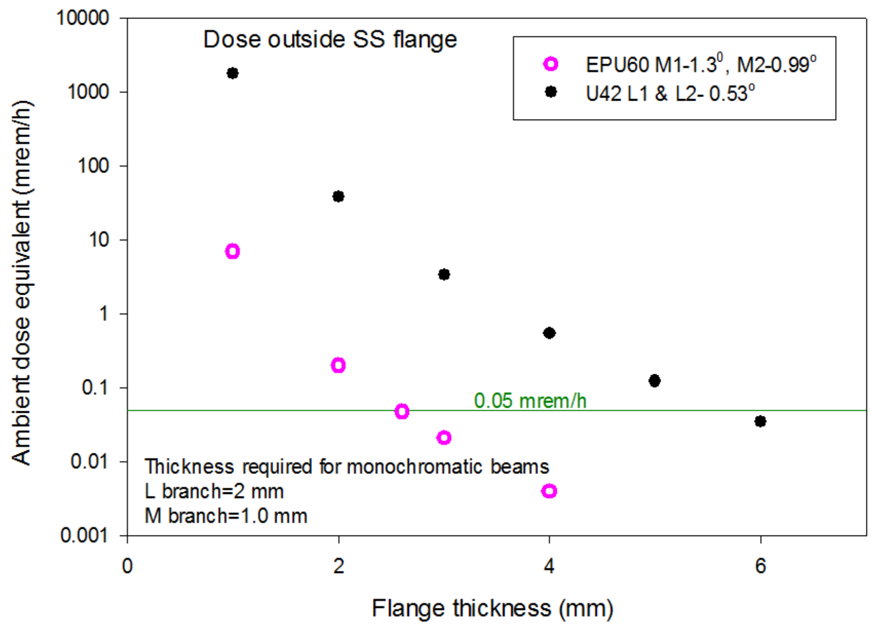


Figure 31: Dose rates outside an SS flange for pink beam from L and M branches.

3.2.2. Outside the Beam Pipe

The dose rates outside the beam pipe when the pink beams are scattered from an air column are discussed here. The lead thickness is assumed to be 8 mm wrapped around a 2 mm thick, 5 cm radius SS beam pipe. Where the beam pipe is not covered by Pb, only the SS pipe will contain the beam.

(a) M Branch

The minimum angle of mirror M1 is estimated to be 1.3°. The beam exiting the FOE can scatter off an air column in the event of a loss of vacuum condition. It can also hit the zero order mask and the first uncooled aperture when mirror M2 (inside the PGM chamber) is retracted. Figure 32 shows this configuration. The minimum angle of M2 is seen to be 0.99° from the same figure. The M2/PGM combination offsets the beam in the vertical direction and the mirror M3 downstream of the PGM deflects it outboard. When M3 is retracted, the beam from M2 will always be stopped by the pink beam stop.

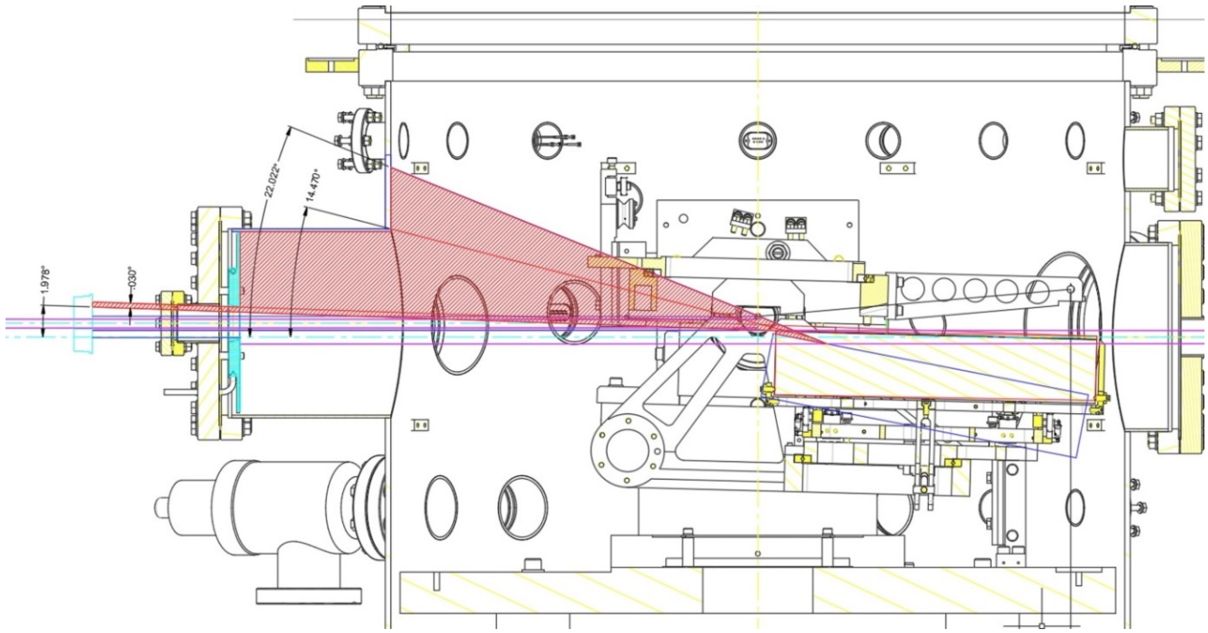


Figure 32: Vertical ray trace of the PGM showing the beam from M1 incident on the zero order mask and the first uncooled aperture.

With M1 at 1.3° the beam is scattered off an air column enclosed inside the lead and SS pipes and the dose rates are estimated outside. With the lead shield, the dose rates outside the pipe are well below 0.05 mrem/h. With 2 mm SS as the only shield, the ambient dose equivalent rates outside the pipe is estimated to be 1.3 mrem/h. The dose rates outside the bellows (considered as 0.2 mm thick SS) are higher. The minimum SS thickness required to reduce the ambient dose equivalent rates to 0.05 mrem/h is estimated to be 4 mm. The 2 mm SS pipe should have an additional 2 mm SS while the bellows should have the full 4 mm thickness as shield. These locations are marked as transparent red boxes in Figure 33.

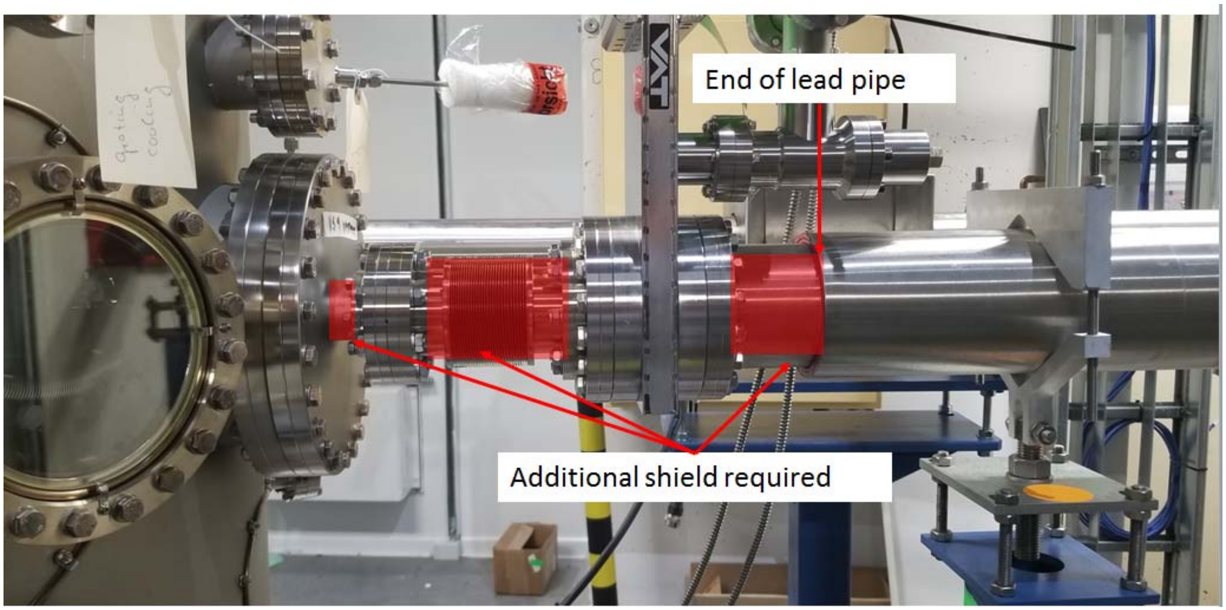


Figure 33: The beam pipe upstream of the PGM chamber that requires additional shielding.

The pink beam from M1 is also made to scatter from a Si target (simulating mirror M2) inside the PGM chamber. The inner radius of the PGM chamber is 40 cm and the vessel is made of 6 mm thick SS. The chamber also has 5 mm lead glass windows the composition of which is obtained from the NIST website. The weight fraction of lead in the glass is 0.752 and the density is 6.22 g cm^{-3}. The dose rates outside the PGM chamber for a beam emerging from M1 and scattering off a silicon target inside the chamber are shown in Figure 34. The 8 inch diameter beam pipe in the forward direction will cover about 14°. The dose rates outside the SS chamber and the lead glass windows are estimated to be less than 0.05 mrem/h.

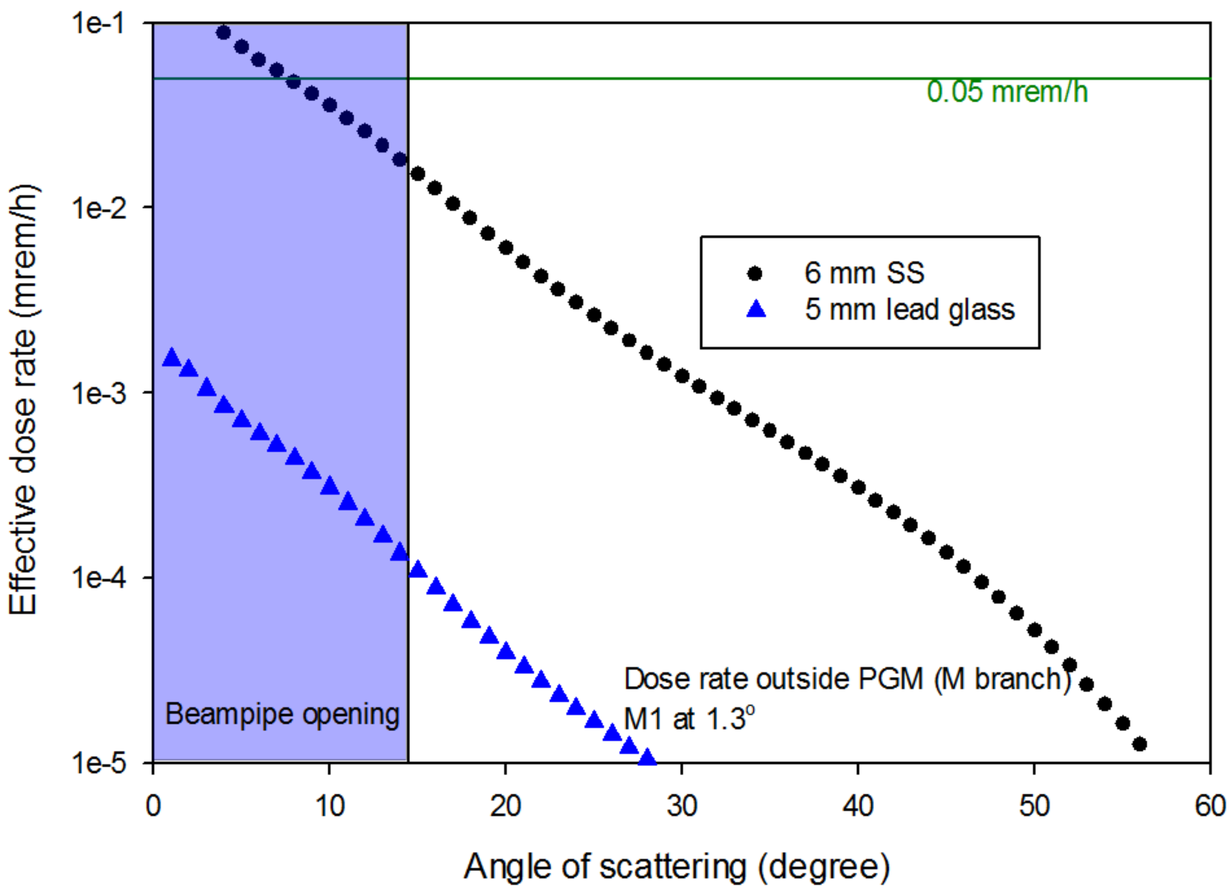


Figure 34: Dose rates outside the PGM for 6 mm SS and 5 mm lead glass. The beam pipe opening shown here is for the 8 inch pipe connected to the chamber.

The chamber has bellows on both the ends. The bellow immediately downstream is shadowed by the gate valve and the ray trace indicates that the miss-steered beam (Figure 35) will not hit the beam pipe or the bellows because of the presence of the zero order mask and the uncooled apertures. The zero order mask is 12 mm thick copper and is enclosed inside the 8 inch diameter SS pipe of the PGM chamber. For this target, the worst case scenario is the beam scattering in the backward direction and getting attenuated by the 3 mm thickness of the SS pipe (Figure 36).

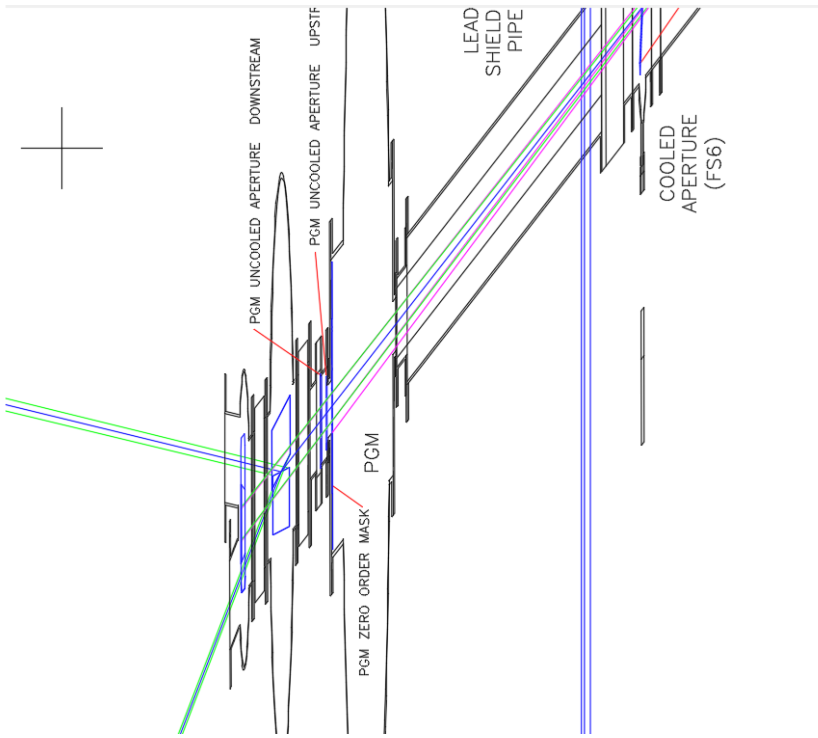


Figure 35: Mis-steered ray trace of the M branch showing the PGM and the apertures downstream of it.

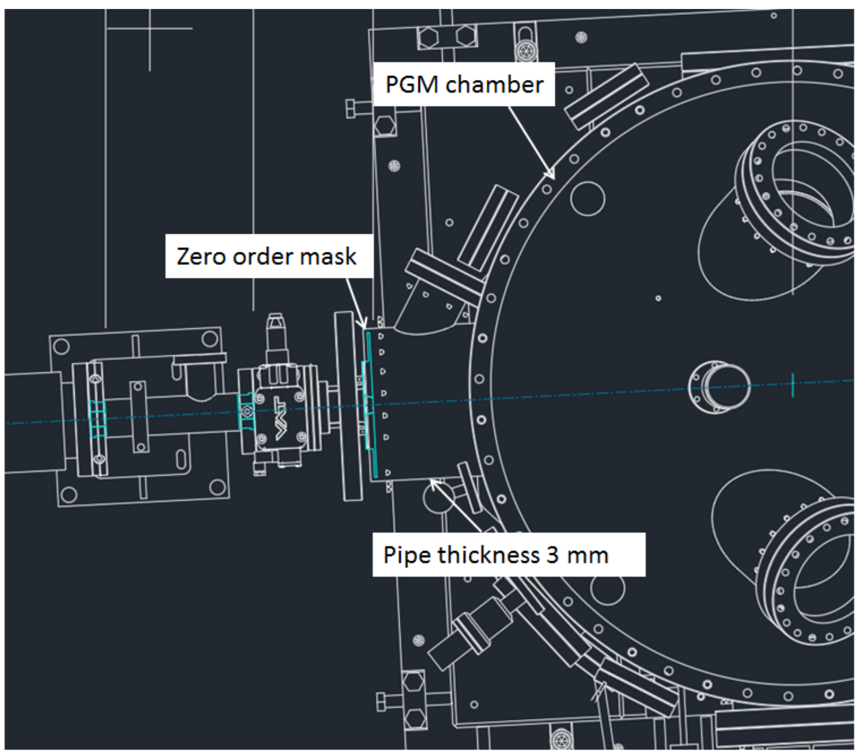


Figure 36: The zero order mask and the beam pipe outside which the dose rates are estimated.

The dose rates under this scenario are estimated to be less than 0.05 mrem/h. The uncooled aperture downstream of the zero order mask is 20 mm thick and in the backward direction it is shadowed by the gate valve. The minimum thickness of SS that intercepts the scattered beam from this aperture is expected to be 5 mm inside the gate valve assembly in the backward direction. This is larger than the 3 mm considered for the zero order mask. The dose rates when the beam scatters off this aperture will thus be lower than that obtained when the beam scatters off the zero order mask.

Downstream of the PGM and before the mirror M3, the beam pipes and the bellows have a thickness of at least 2 mm. For the bellows and the 5 cm dimeter 1.6 mm pipe, this is achieved by the installed additional SS covers. The dose rates outside 2 mm thick SS when the beam scatters from an air column is less than 0.05 mrem/h. Figure 32 indicates that the reflected beam from M2, when the grating is retracted can potentially hit the PGM chamber or the beam pipe downstream of it. The maximum dose rates outside a 2.6 mm SS plate when the beam from M2 is incident on it is found to be 0.04 mrem/h. The beam hitting the PGM chamber or the beam pipe downstream of it is not expected to result in dose higher than 0.05 mrem/h.

Downstream of M3 and up to the precision slits (in the M and transfer branches), the bellows have an additional 1 mm SS as shield. The dose rates outside a 1 mm SS shield is estimated to be less than 0.05 mrem/h. Beyond the precision slits, dose rates outside the bellows due to the mono beam scattering off an air column are estimated to be less than 0.05 mrem/h.

The M3 chamber is 4 mm thick on the side and 8 mm on top. The dose rates outside the chamber when beam from M2 scatters off a Si target (M3 mirror) is estimated to be less than 0.05 mrem/h.

The Cu pink beam stop is inclined at 45° with the vertical plane. It is housed in a 20 cm diameter, 2 mm thick SS chamber. The dose rates outside the chamber when the beam from M2 scatters off the stop is estimated to be less than 0.05 mrem/h. The upper flange is 20 mm thick and the lead glass on it is 5 mm thick. These are sufficient to reduce the dose rates below 0.05 mrem/h. Table 3 shows a summary of the additional shield requirement for the M branch.

Table 3: Additional Shield Requirement for the M Branch

Location	**Additional SS thickness recommended (mm)**
SS pipe upstream of PGM	2.0
Bellows upstream of PGM	4.0
2 inch diameter 1.6 mm SS pipe downstream of PGM	1.0
Bellows after PGM before PBS	2.0
Bellows after PBS before precision slits	1.0

(b) L Branch

In the L branch, the beam exits the FOE after 2 reflections (from L1 and L2). The dose rates outside the SS beam pipe and the bellows before the DCM is shown in Figure 37. The dose rates outside a 5 cm radius 2 mm thick SS beam pipe when this beam scatters off air is estimated to be less than 0.05 mrem/h. However outside the bellows, the dose rates are estimated to be higher and should be shielded by an additional 2 mm of SS. The bellow downstream of the DCM and before the pink beam stop should also be shielded by a 2 mm SS, as the first crystal of the DCM can be positioned flat letting the pink beam in this region. Downstream of the pink beam stop, the dose rates outside the bellows due to the mono beam scattering off an air column is estimated to be below 0.05 mrem/h.

The dose rates outside the 6 mm DCM chamber and the 1.5 mm lead glass on it, with both L1 and L2 at 0.53° and the beam scattering off a Si target (first crystal of the DCM) are estimated to be less than 0.05 mrem/h.

The dose rates outside a 2 mm SS beam pipe due to the beam scattering off a Cu target is estimated to be less than 0.05 mrem/h. This condition simulates the beam scattering from the cooled miss-steer aperture and the pink beam stop.

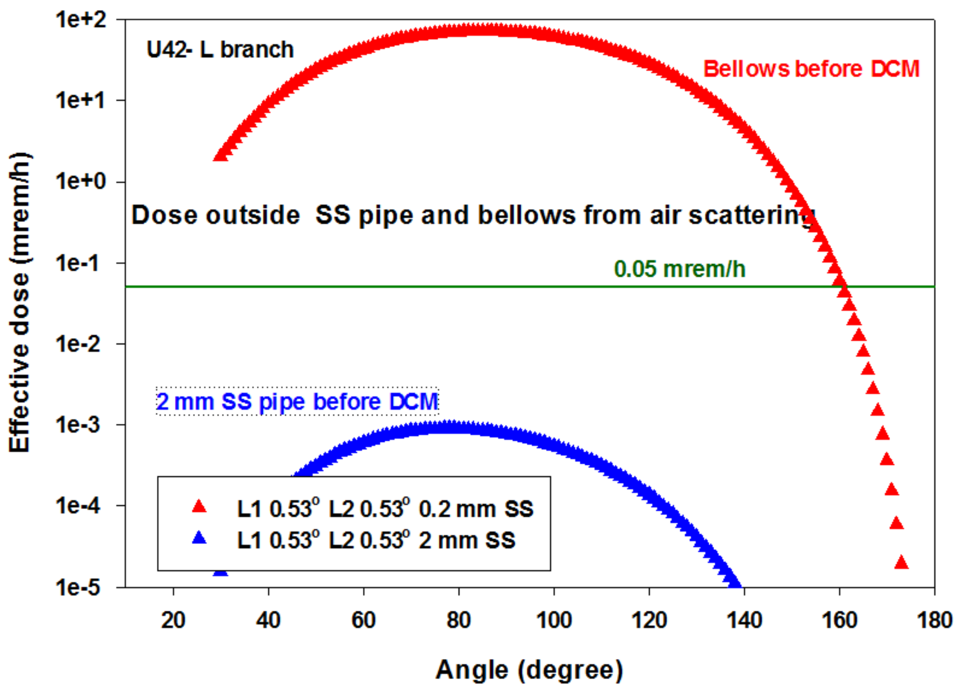


Figure 37: Dose rates outside the bellows before the DCM in the L branch from the beam scattering from an air column.

3.2.3. Dose outside the End Stations

Beyond the pink beam stop (L branch) and the precision slits (M and transfer branches) the beam is assumed to be mono energetic. The fundamental energy and the harmonics for these 2 beamlines are taken to maximize the flux at the K-edge of iron and are given in table 4. The mono beams are made to scatter off a generic sample (Al) inside an end station. The end station chambers are made of SS and have normal glass windows. The HAXPES end station on the L branch can receive beams from both the branches simultaneously and is considered for the analysis here as the worst case condition.

Table 4: Fundamental Energy Harmonics and the Bandwidths used for Calculations with Monochromatic Beams

Energy (keV)		Bandwidth
L Branch	M branch	
7.10*	2.37*	1.33E-04
14.20	7.10	8.06E-06
21.30	9.48	4.71E-06
28.40	11.85	1.39E-06
35.50	16.59	3.23E-07

*Fundamental energy

The end station is assumed to be an SS sphere of 17.9 cm radius and 4 mm thickness but it has also glass windows that are 2.8 mm thick. The borosilicate glass is assumed to have 2.23 g/cc density and has composition (with mass fraction in parentheses) approximated to O (0.607816), Al (0.011644) and Si (0.380541) to match the elements with cross sections available in STAC8. The dose rates outside the end station at all angles from both the beams (and their sum) are estimated to be less than 0.05 mrem/h for both glass and SS as shields. Figure 38 shows the angular distribution of the effective dose rates for the glass shields.

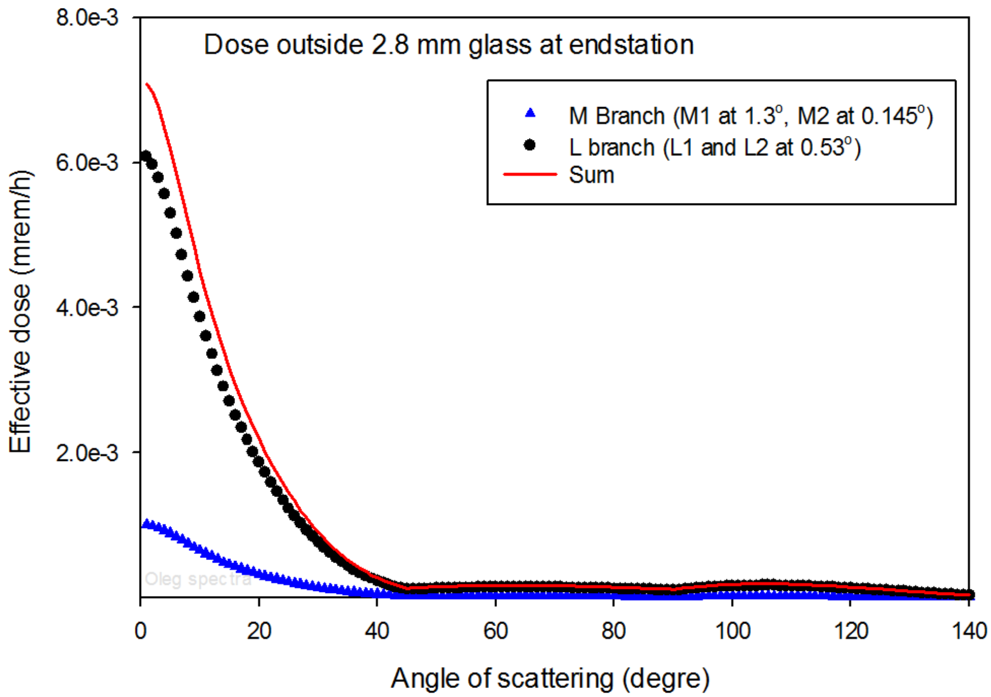


Figure 38: The angular distribution of the dose rates outside the glass windows of the HAXPES end station, as a function of angle of scattering.

3.3. Summary of SR Shielding Analyses

The analyses indicate that the dose rates outside the FOE due to the SR beams interacting with the components inside the FOE are all well below 0.05 mrem/h. Outside the FOE, under a loss of vacuum condition, the pink beam scattering from an air column is well shielded by the lead covered beam pipe but additional SS shields are recommended to keep potential dose rates below 0.05 mrem/h for the bellows and some sections of the SS pipes. These are, 2 mm for the SS beam pipe and 4 mm for bellows upstream of the PGM chamber (M branch), 1 mm for the 5 cm diameter 1.6 mm thick SS pipe downstream of the PGM, 2 mm for the bellow between the PGM chamber M3 chamber (M branch) and 1 mm shield for bellows downstream of M3 up to the precision slits (M and transfer branches). In the L branch an additional shield of 2 mm SS for all the bellows on the experimental floor up to the pink beam stop is recommended.

4. Summary and Conclusions

The radiation shielding analysis of the SST beamline has been carried out with FLUKA Monte Carlo radiation transport code and the analytical STAC8 code. The analysis indicates the need for additional shield for the FOE and some parts of the beamline to conform to the NSLS-II radiation shielding and ALARA policies.

For the FOE, an additional lead shield is recommended on the downstream wall of the FOE towards the inboard side of the guillotine to reduce the dose rates due to gas bremsstrahlung. Shielding or shielded enclosure for the L branch beam pipe is also recommended to keep dose rates acceptable.

For the beamlines on the experimental floor, additional SS shields are recommended for the 2 mm SS pipe before the PGM, 1.6 mm pipe after the PGM but before M3 chamber and the bellows up to the precision slits in the M and transfer branches. For the L branch, additional SS shields are recommended for all the bellows before the pink beam stop.

5. References

1. R. Lee, NSLS-II Issue and Decision Paper: ALARA Analysis for Installations of Secondary Bremsstrahlung Shields in the First Optics Enclosure, PS-C-ESH-STD-005, (06/01/2016).
2. Photon Sciences Shielding Policy, PS-C-ASD-POL-005, March 26, 2014.
3. Ray trace PD-SST-RAYT-001.
4. Composition of lead glass. NIST website

   https://physics.nist.gov/cgi-bin/Star/compos.pl?matno=170; last accessed January 25, 2018.
5. Composition of pyrex glass, NIST web iste

   https://physics.nist.gov/cgi-bin/Star/compos.pl?matno=169; last accessed January 25, 2018.

6. Acronyms

ALARA	As Low as Reasonably Achievable
ARM	Area Radiation Monitor
BRS	Bremsstrahlung Shielding
BST	Bremsstrahlung Stop
C	Center
DCM	Double Crystal Monochromator
DS	Downstream
EPU	Elliptically polarized Undulator
FE	Front End
FM	Fixed Mask
FOE	First Optical Enclosure
FS	Fluorescent Screen
GeV	Giga Electron Volts
H	Horizontal
HAXPES	Hard X-ray Photoelectron Spectroscopy
ID	Insertion Device
L*n*	n^{th} mirror on L Branch

LARIAT	Large Area Rapid Imaging Analysis Tool
LCO	Lead Collimator
M*n*	n^{th} mirror on M branch
NEXAFS	Near Edge X-ray Absorption Fine Structure
NSLS-II	National Synchrotron Light Source II
PBS	Pink Beam Stop
PGM	Plane Grating Monochromator
PSH	Photon Shutter
RCO	Ratchet Wall Collimator
SBS	Secondary Bremsstrahlung Shield
SLT	XY Slit
SS	Stainless Steel
SST	Spectroscopy Soft and Tender
U	Undulator
μCal	Micro Calorimeter
US	Upstream
V	Vertical
VPPEM	Vector Potential Photoelectron Microscopy
WBS	White Beam Stop

Appendix 1

7-ID-SST / Beamline Mask, Collimator and Shielding Data for FLUKA Calculations

First Optical Enclosure

Shielding Information (dimensions in mm) *	Distance/Position	Thickness (mm)	Material
	Z =		Concrete / Lead
DS face of ratchet wall (inside FOE)	Z = 25468.2mm	1447.8mm	Concrete / Lead
OB wall distance from 7-SST photon beam centerline	X= 1539.6	18.0	Lead
Minimum distance from beam centerline to roof Pb shielding	Y= 2085.8	10.0	Lead
Min distance: white beam (US) Z-axis to SR wall outer face	Z= -3673.9	-	Concrete / Lead
Min distance: white beam (US) Z-axis to hutch wall inside Pb face	Z= 7775.1	50.0	Lead
Angle betw SR wall & white photon beam Z-axis: 4 degrees	-	-	-
DS End of 7-SST FOE Back wall (inside face of lead)	36916.2	50.0	Lead

Z locations from the source point.
FOE dimensions, distances (to the lateral walls etc.)

Notes

Beamline Components for FLUKA Calculations
Dimensions in mm.
Aperture dimensions include all tolerances

Beamline Component	Z location, (Distance from Source Point) (US), (DS) or center (C)	Dimensions		Offset (vertical or horizontal) w.r.t SST white beam center line	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Lead CO or Mask Aperture, mm (W)x(H) or (Dia)			
FOE						
Burn through device	26384.0 (US)	&151.6 x 20.1 (offset X-0.136, measured from raytrace)	Inboard Aperture "M" Branch: 27.88 x 22.70 Outboard Aperture "L" Branch : 27.88 x 20.20	Offset: -0.136 (H) Inboard "M" Branch: -24.16 (C) (H) Outboard "L" Branch : 28.70 (C)	NIColoy E	PD-COM-APERT-0090
Fixed mask 1	26440.0 (US) 26652.0 (DS) Offset: -0.136	108 x85 x 212 (offset X=0.102, measured from raytrace)	Inboard "M" Branch: 29.82 x 24.7 (US) Inboard "M" Branch: 7.78 x 7.78 (DS) Outboard Aperture "L" Branch :29.82 x22.2 (US) Outboard Aperture "L" Branch : 7.78 x 5.4 (DS)	Offset: -0.136 (H) Inboard "M" Branch: -24.16 (H) Outboard "M" Branch:	Glidcop AL-15	FMB Dwg No: AAC0226 Rev 1

				28.70		
Mirror L1	27450.0 (C)	60 x 60 x 335	N/A	(H) Inboard "M" Branch: 29.72	Single Crystal Silicon	FMB Dwg No: AHM6101 Rev 4
Secondary shield #1 (Different dimensions reported in the survey)	27960.01 (US)	630 x 522 x 100 Offset X=15.0	& 165.0	7.0 (H) 0.0 (V)	Lead	FMB Dwg No: ABC0509 Rev 1/Innospec Drawing D424-01
Mirror M1	28580.0 (C)	70 x 60 x 250	N/A	-28.8 (H) 0.0 (V)	Single Crystal Silicon	FMB Dwg No: AHM6151 Rev 4
White beam stop	29142.1 (US)	See Fmb Dwg Offset X=1.03	31.64 x 11.9	1.03 (H) -12.09 (V)	OFHC Copper	FMB Dwg No: AQC0076 Rev 2, AQP0005 Rev 2 for reference
BRS (Different dimensions reported in the survey)	29288.3 (US)	88.39 x 149.22 x 300 Offset X=-6.9595	N/A	-25.4 (H) 0.0 (V)	Lead	FMB Dwg No: AAC0573 Rev 1
Secondary shield #2 (Different dimensions reported in the survey)	30699.99	890 x 968 x 100 Offset X=27.0	Inboard: &72.0 Outboard: &72.0	(H) Inboard: -36.0 (H) Outboard: 85.12	Lead	FMB Dwg No: ABC0510 Rev 1/Innospec drawing D424-02

FM2 L Branch	32932.2 (US)	&130.0	&105.36 (US) 13.05 x 13.05 (DS)	(H) -72.77	OFHC Copper	FMB Dwg No: AAC0674 Rev 1
Mirror L2A/L2B	34500 (C)	60x 60 x 400	N/A	(H) -104.75	Single Crystal Silicon	FMB Dwg No: AHM6201 Rev 3, AHM6202 Rev 2
Tungsten Collimator	35666.0 (US)	278 x 120 x 200 Offset X=71.6	N/A	(H) Inboard: -67.4 (Edge) (H) Outboard: 210.6 (Edge)	Tungsten	FMB Dwg No: ABC0415 Rev 1, AQM0178 for reference
Cooled Frame – FS- L Branch #1	35666.0 (US)	80 x 58 x 12	14.14 x 11.24 (US) 9.54 x 11.24 (DS)	(H) -102.01	OFHC Copper	FMB Dwg No: AFC0380 Rev 1
Cooled Frame – FS- M Branch	35930.4 (US)	100 x –x 12	17.58 x 11.24 (US) 13.55 x 11.24 (DS)	(H) 352.44	OFHC Copper	FMB Dwg No: AFC0465 Rev 1
FM4	31883.6 (US)	&130.0	&107.19 (US) 20.64 x 20.64 (DS)	(H) 143.51	OFHC Copper	FMB Dwg No: AAC0571 Rev 1. AAM0103 Rev 1 for reference.
Guillotine	36817.2 (US)	827 x 800 x 100	Inboard: &121.76 Outboard: &121.76	(H) Inboard: -99.31 (H) Outboard: 402.0(DS)	Lead	Dwg No: The Guillotine was not provided by FMB Oxford
L Branch						
Mis Steer aperture #2	45945.4 (US)	&130.0	&107.19 (US)	(H) Inboard: -78.13	OFHC Copper	FMB Dwg No: I call this FM3. AAC0673

			8.64 x 16.64 (DS			Rev 1
Pink beam stop	47677.3 (US)		--	(H) Inboard: -74.17	OFHC Copper	FMB Dwg No: AQC0495 Rev 1, APQ0044 Rev 1 for reference
M Branch						
PGM	40626.5 (C)	55 x 70 x 350	N/A	(H) Outboard: 592.94 (C)	Silicon	FMB Dwg No: FMB Berlin drawing 356-00-00 Rev B.
Mirror M3AB	42062.0 (C)	60 x 40 x 280	N/A	(H) Outboard: 666.73 (C)	Fused Silica	FMB Dwg No: AMC1571 Rev 2
Mirror M3C	42062.0 (C)	60 x 40 x 310	N/A	(H) Outboard: 666.73 (C)	Fused Silica	FMB Dwg No: AMC1572 Rev 2
Pink beam stop	42672.4 (US)	109.4 x 65 x 70	--	(H) Outboard: 702.54 (US)	OFHC Copper	FMB Dwg No: AFM0091 Rev 03 The stop drawing itself is AAC0507 Rev 1. AQC0834 Rev 1 is the clamped absorber that has been added to accommodate mis-steer off the PGM (M2)