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17-BM XFP Beamline Radiation Shielding Analysis

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1. INTRODUCTION

The NSLS-II Radiation Shielding Standard [1] states: Radiation exposure to staff and users resulting from National Synchrotron Light Source II (NSLS-II) operations must comply with Brookhaven National Laboratory (BNL) and Department of Energy (DOE) radiation requirements and must be maintained as low as reasonably achievable (ALARA). Per the Photon Science Shielding Policy (PS-C-ASD-POL-005), in continuously occupied areas during normal operation, the dose rate is ALARA, and shall be < 0.5 mrem/h (based on occupancy of 2000 hours/year) or less than 1 rem in a year.

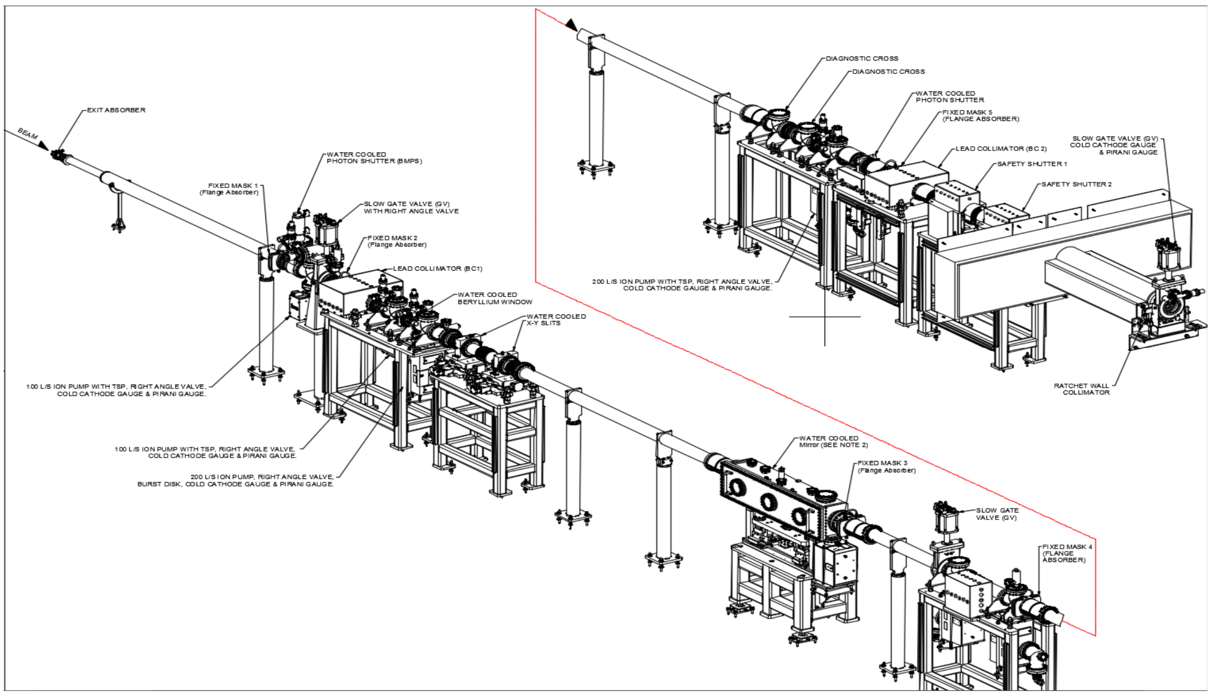
For a fault event, the dose shall be < 20 mrem in a non-radiation controlled area and < 100 mrem in a radiation controlled area. Although the experimental floor is initially designated as a radiation controlled area, it is hoped that in the future, it can be declared a non-radiation controlled area. As such, beamlines should be shielded so that in the event of a fault, the total dose integrated over the duration of the fault, is < 20 mrem.

Beamlines are required to shield against the two primary sources of radiation, the primary gas bremsstrahlung (GB) and the synchrotron beam, as well as the secondary radiation resulting from the scattering of these two primary beams by the beamline components. The shielding requirements for the FOE are dominated by the scattering of the primary bremsstrahlung and not the synchrotron radiation. 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 first optical enclosure (FOE) walls as well as dimensions of the supplementary shielding if required to reduce the dose on the downstream FOE walls. 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 X-ray Foot Printing (XFP) for In Vitro and In Vivo Structural Studies of Biological Macromolecules (17BM-XFP) 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 efficiency of the as-built FOE and the bremsstrahlung stop described in [2]. The layout of the 07BM-XFP beamline front end and FOE is presented in Figure 1. The FOE includes only a set of slits simulated as a copper target in this analysis.

The beamline component location and dimensions are described in detail in reference [2]. The ray trace drawings list the major components along the beamline and provide the position of each component. The positions, dimensions and materials of the main components are included in Appendix 1, including references to component drawings.

(a)



(b)

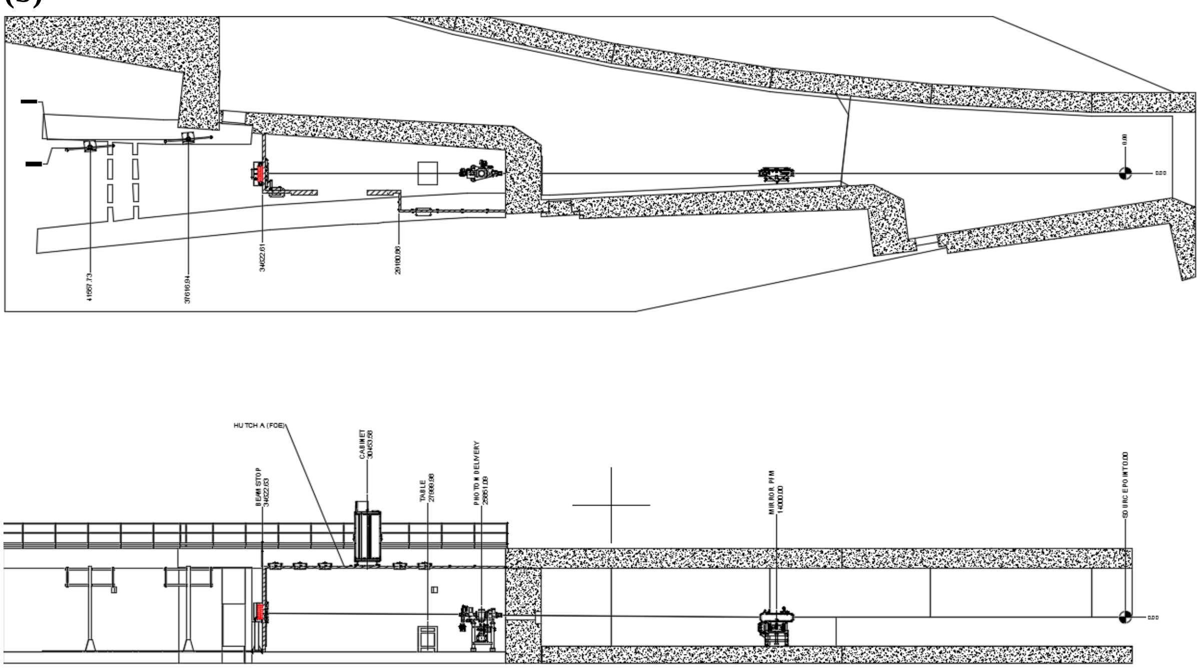


Figure 1: (a) Layout of 17BM-XFP Front End showing major components consisting of Masks, Mirror, Collimators, Safety Shutters, and Ratchet Wall Collimator **(b)** Plan and elevation view of the 17BM-XFP FOE

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 straight section	6.6 m
Pressure in straight section	1 ntorr

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

The FLUKA model is described in section 2 and the following simulations were performed to confirm the adequacy of the radiation safety components.

1. GB on White Beam Mirror (WBM)
2. GB on Fixed Mask 4 (FM4)
3. GB on upstream aperture of the ratchet wall collimator (RCO)

The results of the GB simulations are presented in section 3. The results of the synchrotron radiation analysis are presented in section 4. A summary of all simulation results is presented in section 5. The results of the GB simulations are summarized in Table 2. This table lists the maximum dose rate (in mrem/h) on the roof, sidewall and the downstream FOE wall for each simulation. All shielding simulations should be validated by comparisons with measurements of the dose rates on the roof and the walls of the FOE during commissioning.

2. DESCRIPTION OF THE FLUKA MODEL

At NSLS-II, the white beam or FOE shielding requirements are dominated by the scattering of the primary gas bremsstrahlung and not the synchrotron beam.

The white beam components disperse the primary bremsstrahlung without significant energy loss; thereby greatly increasing the angular range of very high-energy bremsstrahlung photons. It is necessary to intercept this secondary bremsstrahlung before it hits the downstream FOE wall. The design of the 17BM-XFP FOE includes a bremsstrahlung stop (BRS) in order to reduce the dose on the downstream wall.

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

The 17BM-XFP FLUKA model includes the relevant Front End components, surrounding storage ring shielding, and the FOE walls and roof. The FLUKA geometry for the storage ring shielding is based on the architectural drawing 42509a-fp01-RING.dwg. The FOE outboard lateral panel is made of 18 mm Pb, the roof is 4 mm Pb and the downstream FOE wall is 50 mm Pb (974.8 cm from the ratchet wall). A copper target is placed inside the FOE, approximately 100 cm from the downstream end of the ratchet wall and is inclined 15 degrees with respect to the beam.

The FLUKA model (Top and Elevation views) of the 17BM-XFP beamline is shown in Figure 2 with all components that were incorporated in the FLUKA model. All components are placed symmetrically with respect to the beam centerline in the transverse direction. For the FLUKA model, the Z axis represents the beam centerline, the X axis is the horizontal axis normal to the beam direction, the Y axis is the vertical axis and the beam travels from left to right.

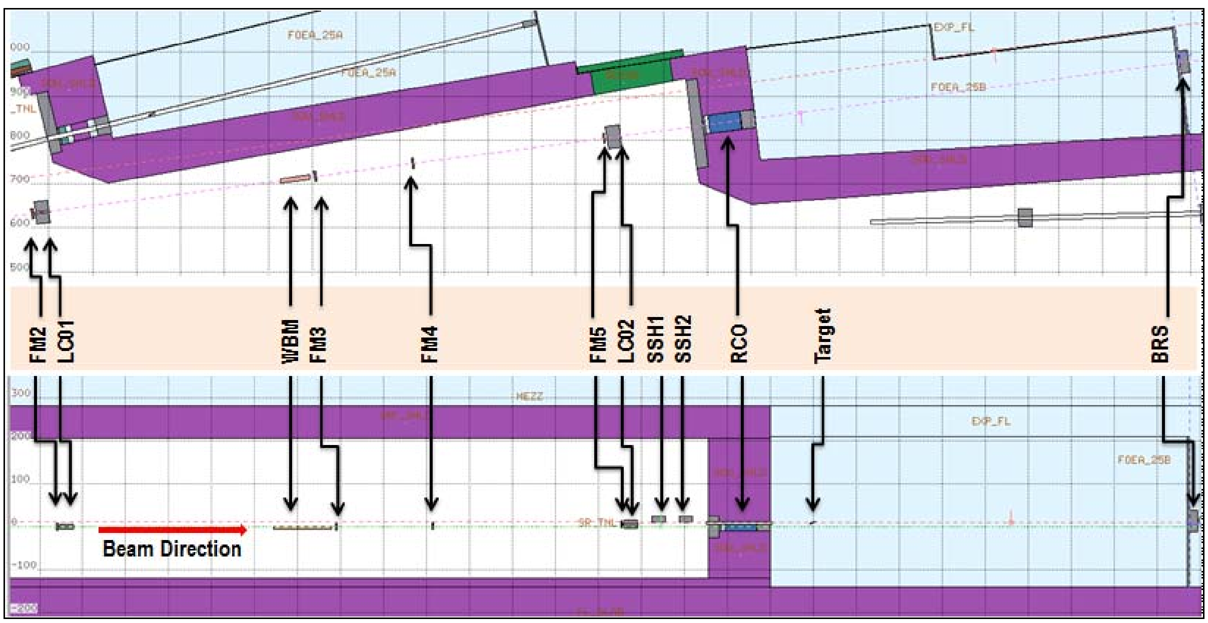


Figure 2: Plan and elevation view of the 17BM-XFP FLUKA geometry at the beam centerline

3. RESULTS FOR PRIMARY GB FLUKA SIMULATIONS

The main scattering targets considered for 17BM-XFP GB analysis are the white beam WBM, FM4, and the RCO (the worst ray shown in ray trace [2] is at 2.2 mm from the RCO upstream aperture).

3.1 GB on WBM

The WBM is a toroidal focusing silicon mirror, has a length of 1340 mm[1] and is centered at z =1400 cm from the center of the three pole wiggler (3PW). The mirror can be rotated from 0 mrad to 6 mrad with a working nominal angle of 4.2 mrad. In the FLUKA model, the mirror is rotated at 4.2 mrad with respect to the x-axis so, the reflected beam exits at 8.4 mrad to the original beam centerline.

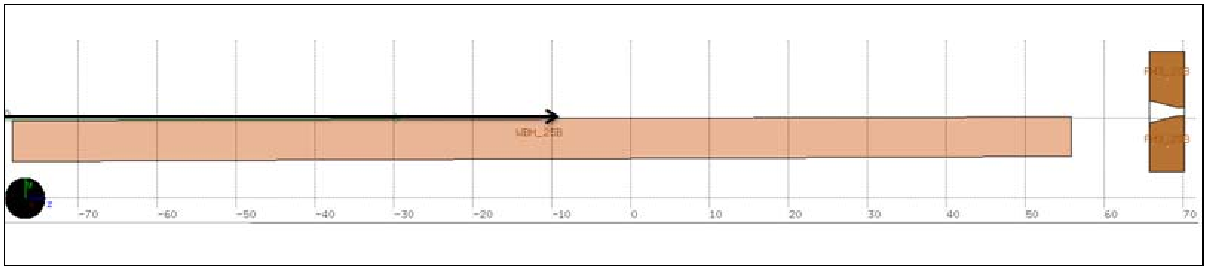


Figure 3: GB beam incident on the WBM

The GB is started just upstream of the WBM and strikes at its center so that the GB passes through half the mirror and is scattered largely upwards and in the forward direction. The forward GB is further scattered by FM4. The fraction that is transmitted through the apertures of the LCO2 and RCO impinges on the copper target located in the FOE, which becomes a scattering target. The dose distribution in the front end and FOE is shown in Figure 4, which clearly shows the impact of the lead collimator 2 (LCO2) and RCO in attenuating and collimating the secondary GB.

[1] Currently 17BM-XFP has a shorter mirror (110.0 cm) installed. There is a plan to install a longer mirror in the future for greater vertical acceptance. The use of a longer mirror in the simulation allows for more scattering and therefore, is more conservative.

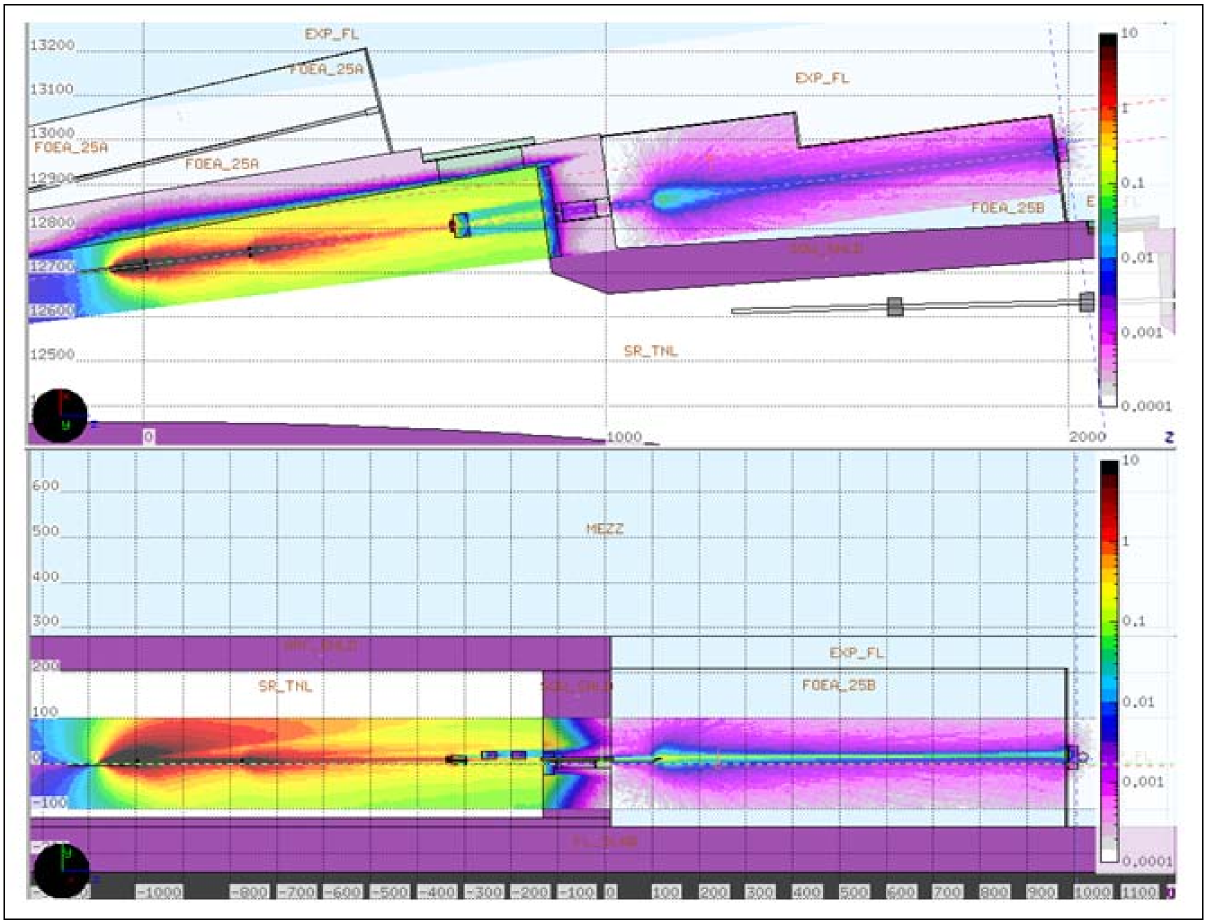


Figure 4: The total dose distributions (mrem/h) in the front end and FOE. The top figure shows a plan view and the bottom shows the elevation view at the beam centerline.

The total dose on the roof and lateral walls are less than 0.001 mrem/hr. The dose distribution on the downstream wall of the FOE is shown in Figure 5. The black square represents the BRS outline. The black spot [Figure 5(a)] on the FOE downstream wall is due to the dose coming through the wall at the small (5 mm) gap between the wall and the upstream face of the BRS. At the downstream face of the BRS and surrounding regions, [Figure 5(b)] the maximum dose is much smaller than 0.01 mrem/h. It clearly illustrates the impact of the BRS in attenuating the secondary GB on the FOE downstream wall.

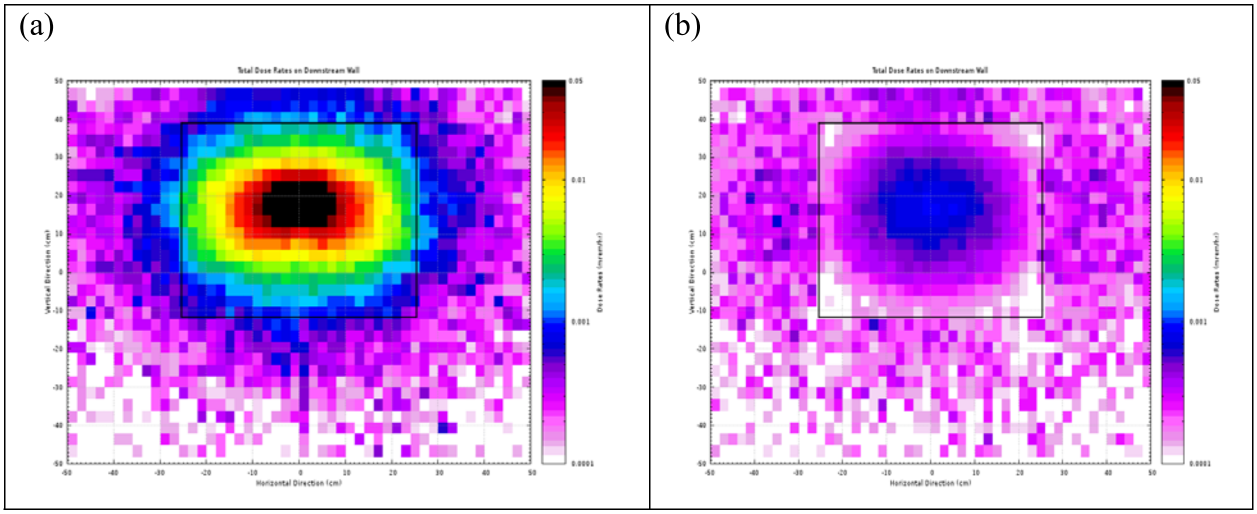


Figure 5: The total dose distributions in mrem/h **(a)** on contact on the downstream wall of the FOE and **(b)** on contact with the downstream face of the BRS at 20 cm from downstream wall.

3.2 GB Incident on the Aperture of FM4

The FLUKA model of the fixed mask is shown in Figure 7. The aperture is tapered in both the vertical and horizontal planes. In this simulation, the GB was started just upstream of the selected point of contact and impinges on the bottom tapered plane approximately 5 mm from the neck of the aperture.

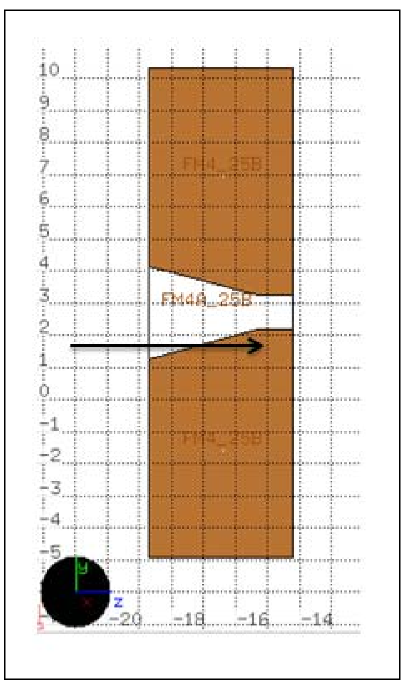


Figure 6: GB beam incident on the FM4

The elevation view (bottom) and plan view (top) of the dose distribution profiles in the front end and FOE are shown in Figure 7. The radiation transmitted through the aperture of the mask impinges on FM5 and LCO2 and it is scattered predominantly downwards. The RCO and ratchet wall shield stop most of the forward-directed radiation. The total dose on the roof and lateral walls are less than 0.001 mrem/hr. The dose distribution on the downstream FOE wall is depicted in Figure 8. Similar to the previous scenario, the total dose rates exceed 0.05 mrem/hr in a region between the downstream wall and upstream face of the BRS but it reduces to well below 0.01 mrem/hr at the downstream face of the BRS, and all regions outside the BRS area.

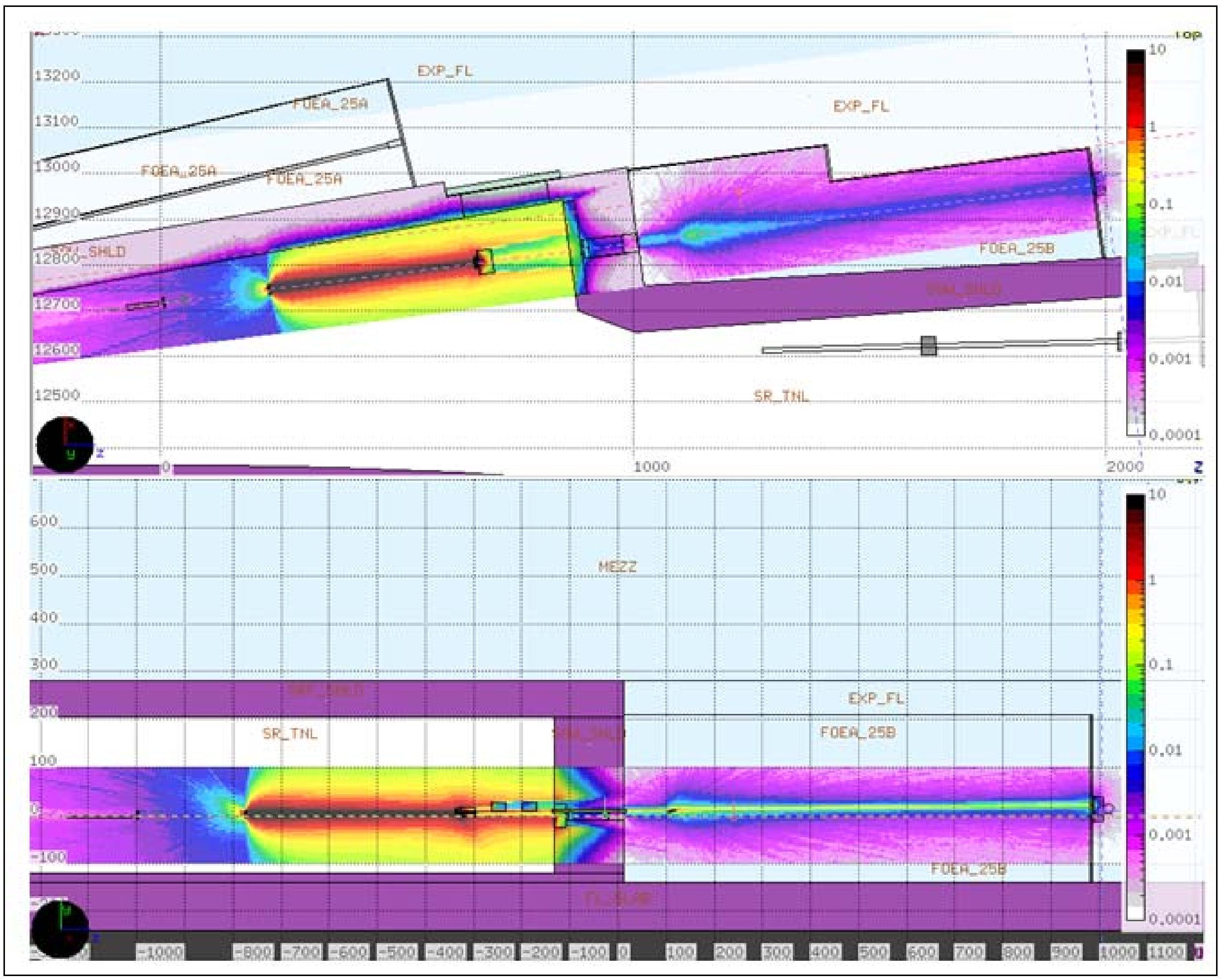


Figure 7: The total dose distributions (mrem/h) in the front end and FOE. The top figure shows a plan view and the bottom shows the elevation view at the beam centerline.

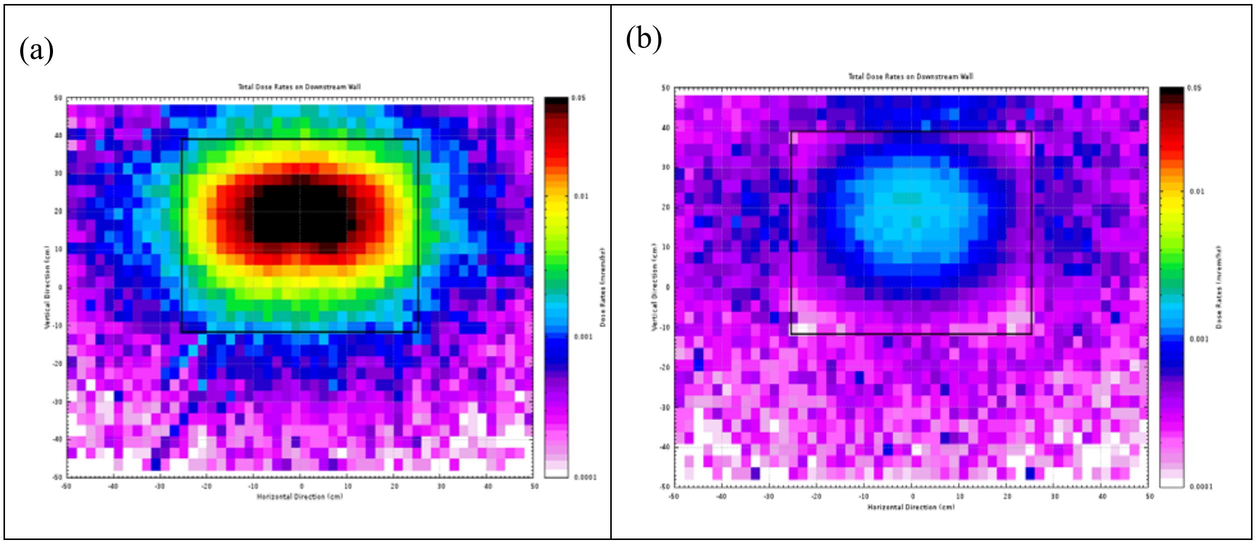


Figure 8: The total dose distributions in mrem/h (a) on contact on the downstream wall of the FOE and (b) on contact with the downstream face of the BRS at 20 cm from the downstream wall.

3.3 GB Near the Ratchet Wall Collimator Aperture

The worst ray is 2.2 mm below the RCO aperture, as shown in Figure 9. In FLUKA simulation, GB beam strikes 2.2 mm below the RCO upstream aperture.

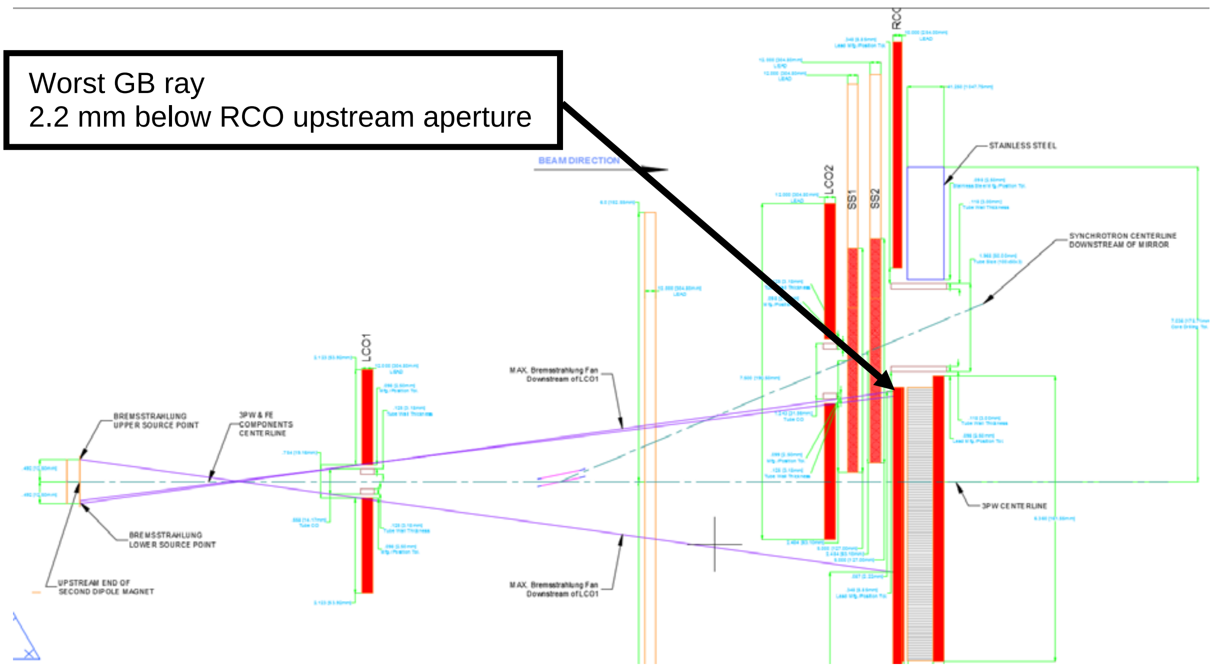


Figure 9: 17BM-XFP bremsstrahlung ray tracings vertical, showing the worst GB ray striking below the RCO upstream aperture

The elevation view (bottom) and plan view (top) of the dose distribution profiles in the front end and FOE are shown in Figure 10. The secondary GB is largely contained in the front end and FOE since the radiation has to go through significant material in the RCO before it undergoes another scattering at the copper target in the FOE. The total dose on the roof and lateral walls are less than 0.001 mrem/hr. The dose distribution on the downstream FOE wall is depicted in Figure 11. The total dose rates are approximately 0.01 mrem/hr on contact with the wall in a region above the BRS, but it reduces to well below 0.01 mrem/hr at approximately 20 cm (upstream face of the BRS) away from the downstream wall.

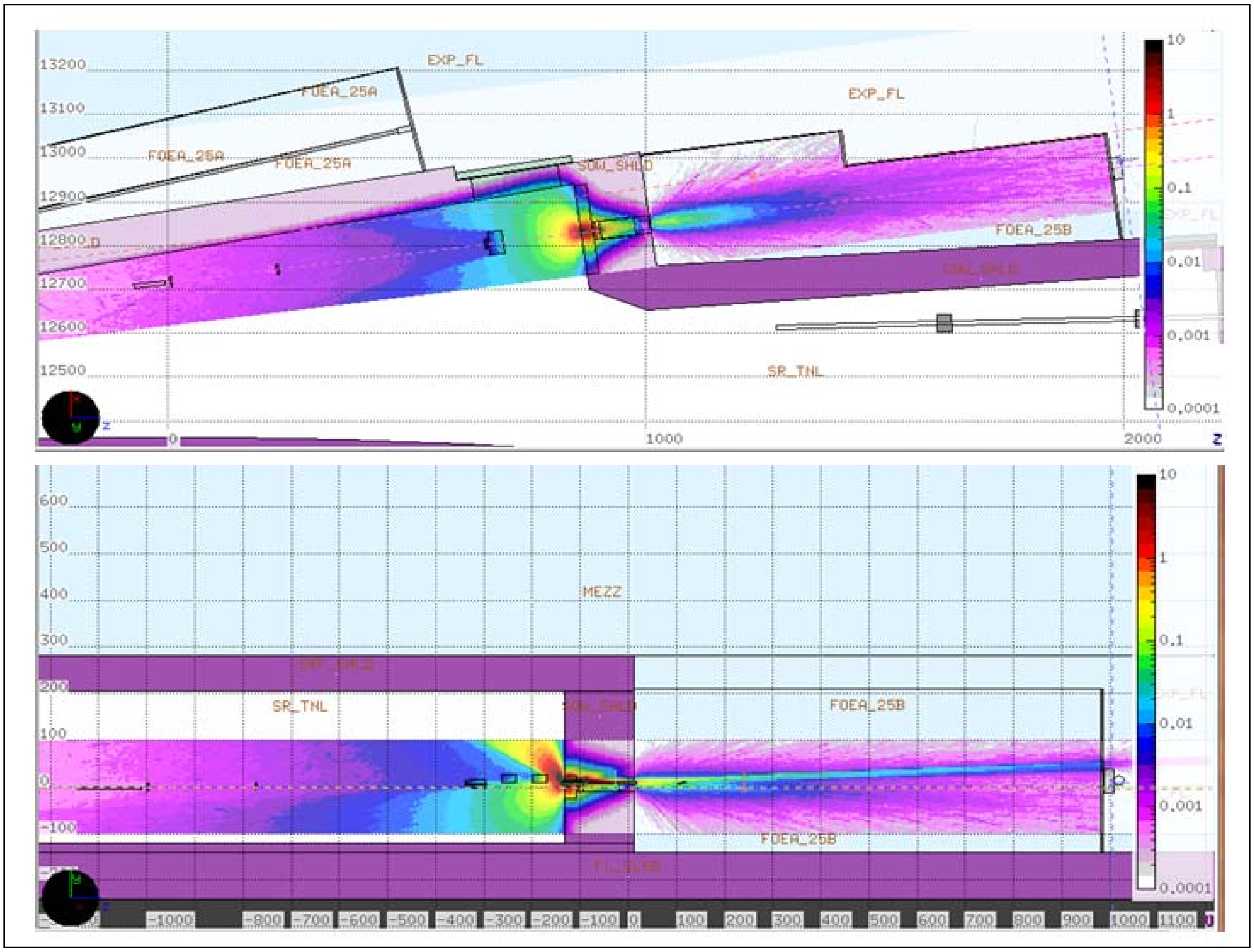


Figure 10: Same as Figure 9 but with injected striking the outboard side of the FM2

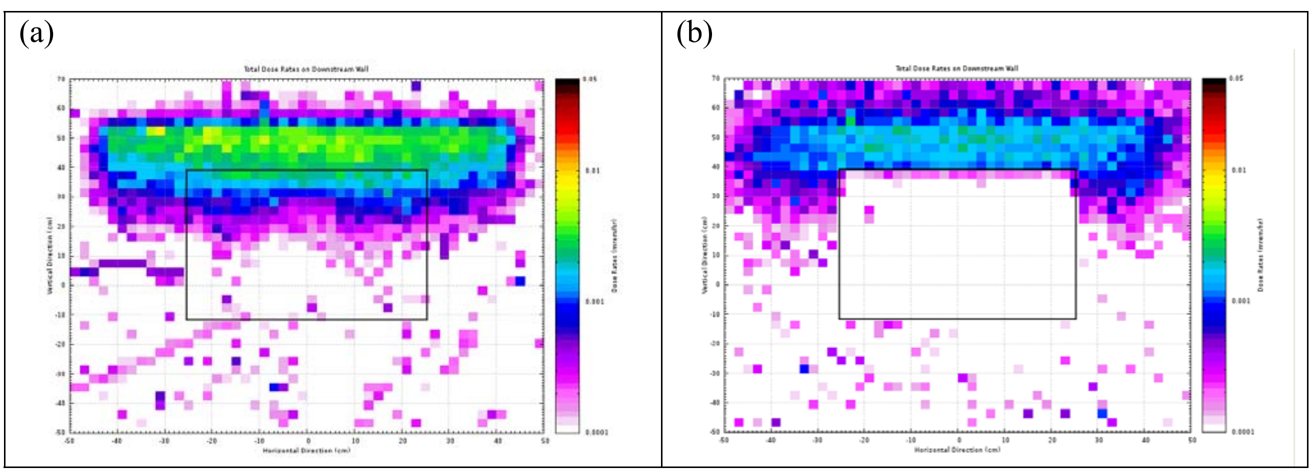


Figure 11: The total dose distributions in mrem/h (a) on contact on the downstream wall of the FOE and (b) on contact with the BRS at 20 cm from downstream wall.

4. SYNCHROTRON RADIATION CALCULATION

The 17BM-XFP beamline is a 3PW source with its parameters given in [1]. It has a toroidal focusing mirror in the front end, 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, but in this analysis a white beam is considered, which is very conservative. The horizontal opening angle for the 17BM source fan entering the FOE is provided in column 2. In addition, the stored beam parameters of 3 GeV and 500 mA (See Table 1) were used to calculate the critical energy (column 6) and total integrated power (column 7).

Table 2: Source Parameters Used for 17BM-XFP 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	1.12	0.25	6.7	0.28

The analytic code STAC8 [3] was used to calculate the ambient dose equivalent rates in the occupied areas outside the FOE. The build-up factor in shield was included in the calculation. However, the effect of SR polarization was not considered, leading to the same shielding requirements for the lateral wall and roof provided the distance from the scatter target to dose point is the same.

As a worse case scatter target, a silicon disk of 10 cm radius and 2 cm thick tilted at 0.155 degree with the respect to the incident beam is used [4]. The scatter target position is approximately in the middle of the FOE, 400 cm from the FOE downstream wall, 80 cm from the lateral wall and 200 cm from the roof. The minimum required shielding for the SR source (no credit to BRS) and the corresponding ambient dose rates are given in Table 3. The dose rate from SR is negligible on the downstream wall, lateral wall, and roof with existing FOE shielding. The existing shielding thicknesses of the FOE walls and roof as given in Appendix 1 are more than adequate to meet the shielding design goal of 0.05 mrem/h.

Table 3: SR Shielding Design Requirements for 17BM-XFP (FOE)

	Distance (cm)	Required Shielding	Ambient Dose rate (mrem/h)
Lateral wall	80	5 mm Pb	0.0159
Roof	200	4 mm Pb	0.0157
Downstream Wall (> 1^o)	400	7 mm Pb	0.0195

5. SUMMARY AND CONCLUSIONS

At NSLS-II, the 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 straight section is better than 10^{-9} Torr. Beamline components that intercept the primary GB beam were selected as scattering targets in the simulations.

A summary of the GB simulation results is presented in Table 4. For all cases studied, the dose rates on the roof, lateral wall and the downstream FOE wall were far below the shielding design goal of 0.05 mrem/h. Based on the STAC8 calculation, the dose rates outside the FOE are also less than the shielding design goal of 0.05 mrem/hr.

All shielding simulations should be validated by comparisons with measurements of the dose rates on the roof and the walls of the FOE during commissioning.

Table 4: Maximum Total Dose Rates (mrem/hr) on the Roof, Lateral and Downstream FOE walls

#	Simulation	**Maximum dose (mrem/hr)**		
		Roof	Sidewall	DS FOE wall and on contact with BRS
1	GB on WBM	< 0.001	< 0.001	<0.01
2	GB on FM4	< 0.001	< 0.001	<0.01
3	GB on RCO	< 0.001	< 0.001	<0.01

6. REFERENCES

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

[2] 17BM (XFP) Top-Off Radiation Safety Analysis, M. Benmerrouche, R. Fliller, and Y. Li, PS-C-ASD-TOS-RPT-004.

[3] Y. Asano, “A Study on Radiation Shielding and Safety Analysis for a Synchrotron Radiation Beamline,” JAERI-Research-2001-006, March 2001.

[4] Attenuation of Scattered Monochromatic Synchrotron Radiation in Iron and Lead”, Z. Xia and W.-K. Lee, NSLS-II TN145 (09/16/2014).

7. ACKNOWLEDGEMENTS

We would like to thank Mike Sullivan and John Tuozzolo for providing all the beamline geometry information listed in Appendix 1. We would like to thank Andrew Broadbent and Jen Bohon for multiple discussions.

Appendix 1

Table 1.1 17BM-XFP Beamline Enclosures

Wall	Position	Thickness	Material
D/S End of 17-BM-A Ratchet Wall	2489.2 cm		
D/S End of FOE (17-BM-A) Backwall	3464.0 cm	5.0 cm	Lead
D/S End of FOE Bump-out (17-BM-A) Backwall	2914.3 cm	5.0 cm	Lead
Distance of FOE Sidewall from SC	80.6 cm	1.8 cm	Lead
Distance of FOE Bump-out Sidewall from SC	159.9 cm	1.8 cm	Lead
Distance of FOE Roof from SC	210.6 cm	0.4 cm	Lead
Distance of FOE Floor from SC	140.0 cm		
Length of FOE	974.8 cm		

SC: Straight Centerline

Co-ordinate system

The z axis or beam centerline lies along the Front End centerline. The positions (z co-ordinates) of the various beamline components are defined with respect to the center of 3PW source. For 17BM-XFP the front end centerline was used as the z or beamline axis for the FLUKA models. Y is the vertical axis and x the horizontal axis orthogonal to the y and z axes.

Table 1.2 17BM-XFP Beamline Components

Components	Z = Distance from 3PW Center U,D or C	Dimensions (specify units)		Vertical (y)/ Horizontal (x) Offset & Rotation w.r.t CENTERLINE	Material used in FLUKA	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R)			
Fixed mask 2 (FM2)	827.7 cm (U)	22.86 cm (x) 15.24 cm (y) 4.45 cm (z)	US: 4.29cm (x) 2.14cm (y) DS: 2.50cm (x) 0.34cm (y)		Copper	SR-FE-3PW-MSK-1872
Lead Collimator 1 (LCO1)	836.6 cm (U)	50.80 cm (x) 12.70 cm (y) 30.48 cm (z)	4.04cm (x) 1.70cm(y)		Lead	SR-FE-3PW-CO-0700
White Beam Mirror (WBM)*	1400.0 cm (C)	10.16 cm (x) 5.08 cm (y) 134.00 cm (z)		4.2 mrad	Silicon	PD-XFP-PFM-1000

Components	Z = Distance from 3PW Center U,D or C	Dimensions (specify units)		Vertical (y)/ Horizontal (x) Offset & Rotation w.r.t CENTERLINE	Material used in FLUKA	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R)			
Fixed mask 3 (FM3)	1477.3 cm (U)	22.86 cm (x) 15.24 cm (y) 4.45 cm (z)	US: 5.38cm (x) 2.80cm (y) DS: 4.25cm (x) 1.10cm (y)	Y=+0.85cm	Copper	SR-FE-3PW-MSK-1873
Fixed mask 4 (FM4)	1702.2 cm (U)	22.86 cm (x) 15.24 cm (y) 4.45 cm (z)	US: 5.38cm (x)2.80cm (y) DS: 3.65cm (x)1.08cm (y)	Y=+2.71cm	Copper	SR-FE-3PW-MSK-1874
Fixed mask 5 (FM5)	2140.9 cm (U)	22.86 cm (x) 15.24 cm (y) 4.45 cm (z)	US: 3.78cm (x)2.77cm (y) DS: 2.05cm (x)1.05cm (y)	Y=+6.35cm	Copper	SR-FE-3PW-MSK-1875
Lead Collimator 2 (LCO2)	2149.9 cm (U)	51.82 cm (x) 19.05 cm (y) 30.48 cm (z)	3.64cm (x) 3.36cm (y)	Y=+6.24cm	Lead	SR-FE-3PW-CO-0600
Safety Shutter 1	2214.6 cm (U)	17.78 cm (x) 16.51 cm (y) 30.48 cm (z)		Y=+17.24cm (open)	Lead	SR-FE-3PW-SS-4000
Safety Shutter 2	2278.5 cm (U)	17.78 cm (x) 16.51 cm (y) 30.48 cm (z)		Y=+17.24cm (open)	Lead	SR-FE-3PW-SS-4001
Ratchet Wall Collimator (RCO)	2344.5 cm (U)	See FE Ray Tracing, SR-FE-3PW-7001	See FE Ray Tracing, SR-FE-3PW-7001	Aperture at Y=+8.73 cm See FE Ray Tracing, SR-FE-3PW-7001	Lead, Concrete Steel	SR-FE-3PW-RCO-7000
Bremsstrahlung Stop (BRS) Behind downstream wall of FOE (See Reference 2)	3464.5 cm (U)	Minimum Required 50.80 cm(x) 50.80 cm(y) 20.32 cm(z)		Y=+13.73 cm	Lead	PD-XFP-BRS-1000

*Currently 17BM-XFP has a shorter mirror (110.0 cm) installed. There is a plan to install in the future a longer mirror for greater vertical acceptance. The use of a longer mirror in the simulation allow for more scattering and therefore more conservative.