11BM (CMS) TOP-OFF RADIATION SAFETY ANALYSIS

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11BM (CMS) Top-Off Radiation Safety Analysis	

1. Introduction

The primary radiological safety concern for Top-Off injection, with the front end (FE) safety shutters open, is the scenario where injected electrons could be transported down to the beamline through the FE due to an erroneous combination of lattice magnetic field settings and beam energy. These electrons will scatter off the First Optics Enclosure (FOE) components, thereby leading to potentially high dose rates on the FOE walls. The radiological consequences of this fault condition specifically for 11BM (CMS) are analyzed and discussed in this report. For this beamline, all FE comonents, the ratchet wall collimators and many FOE components lie along the short straight (SS) centerline. The goal of the simulations documented here was to estimate the radiation dose levels generated outside the FOE during this Top-Off fault condition, thus evaluating the efficacy of the FE radiation safety components and the FOE shielding. This beamline was not covered by the Top-Off design report issued in 2014 [1].

The layout of the 11BM (CMS) FE components is presented in Figure 1 and the layout of the FOE components is presented in Figure 2(a). One Area Radiation Monitor (ARM) is located on the sidewall of the FOE near the hutch door as shown in Figure 2(b).

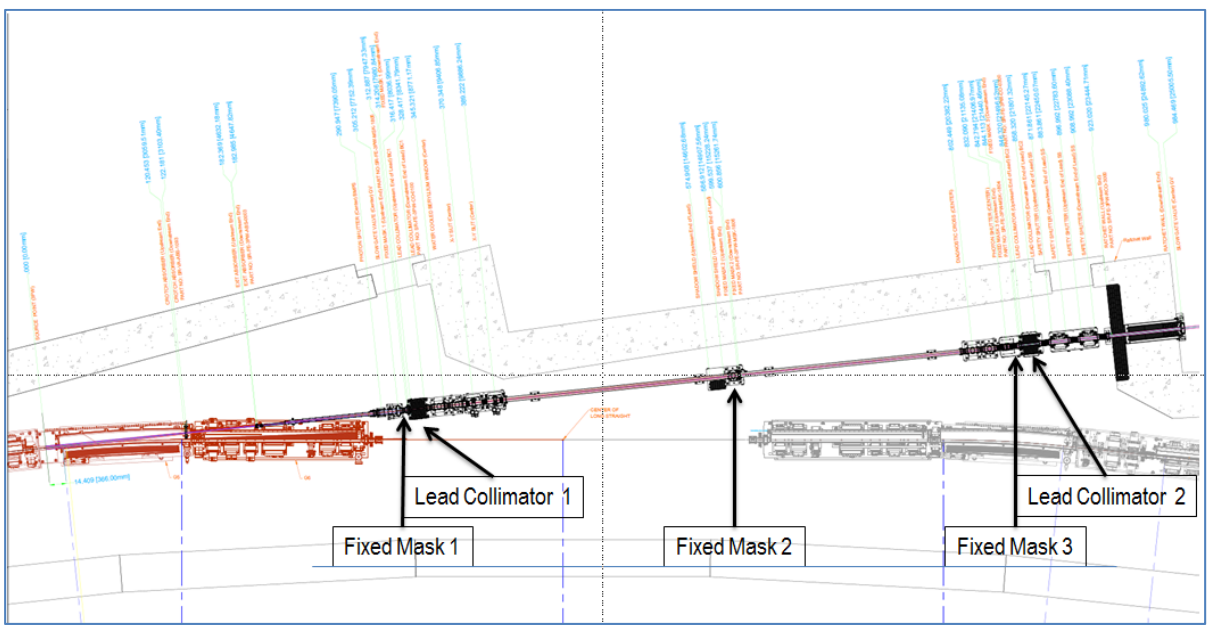

Figure 1: Layout of 11BM (CMS) FE showing major components consisting of Masks, Collimators, Safety Shutters, and Ratchet Wall Collimator.

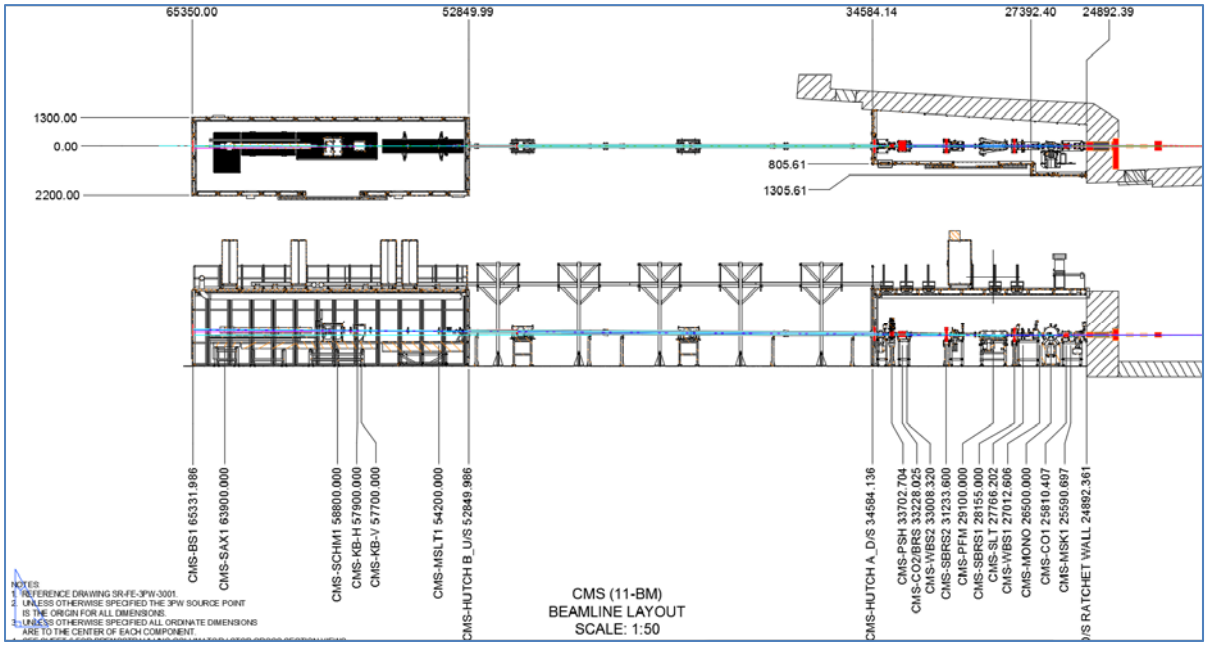

Figure 2(a): Layout of 11BM (CMS) Beamline

Figure 2(b): ARM detector installed on the side wall of the 11BM (CMS) FOE upstream of the sliding door

Backward particle tracking analysis was performed for 11BM (CMS) and has determined that the injected electrons will not travel beyond the lead collimator 2 (LCO2) in the FE. FLUKA simulations were performed with a pencil beam traveling from downstream aperture of fixed mask 1 (FM1) to the upstream face of LC02, both inboard and outboard at 5mm from the aperture edge.

The Top-Off backward particle tracking analysis for 11BM (CMS) is discussed in Section 2, the FLUKA model is described in Section 3 and the results of the simulations are discussed in Section 4. A summary and conclusions are presented in Section 5.

This report can be used as a basis to approve the Top-Off Operation of the 11BM (CMS) beamline, provided that the beamline and shielding configuration are not changed. The Top-Off Operation of new beamlines and the approval process shall be in accordance with procedure PS-C-ASD-PRC-183 [2].

2. Top-Off Particle Tracking Analysis

At NSLS-II, the Top-Off Safety System guarantees that the injected electron beam does not channel down the FE and into the beamline FOE. Particle tracking analysis for the 11BM (CMS) FE has shown that the safe endpoint for the injected electron beam is the LCO2. To ensure this safe point for 11BM (CMS), the apertures and tolerances are exactly the same as those called out in the TOSS interlock specification [1]:

- FM1, +/-2 mm horizontally
- LCO2, +/-2 mm horizontally
- Storage Ring Chamber S4, +/-5 mm horizontally
- Blank off flange on chamber S4 in place.

Figures 3(a), (b) and (c) show the particle tracking simulations for 11BM (CMS). The two apertures shown in the figures at positions ~13 m and ~27 m from the center of the straight represent the apertures through the FM1 and LCO2, respectively. In these simulations, the aperture of the FM1 was assumed to be 11.97 mm and the aperture of collimator LC02 was assumed to be 53.7 mm. Based on the backward particle tracking simulation [1], the electron beam will have a distance of at least 5 mm from the LC02 aperture edge.

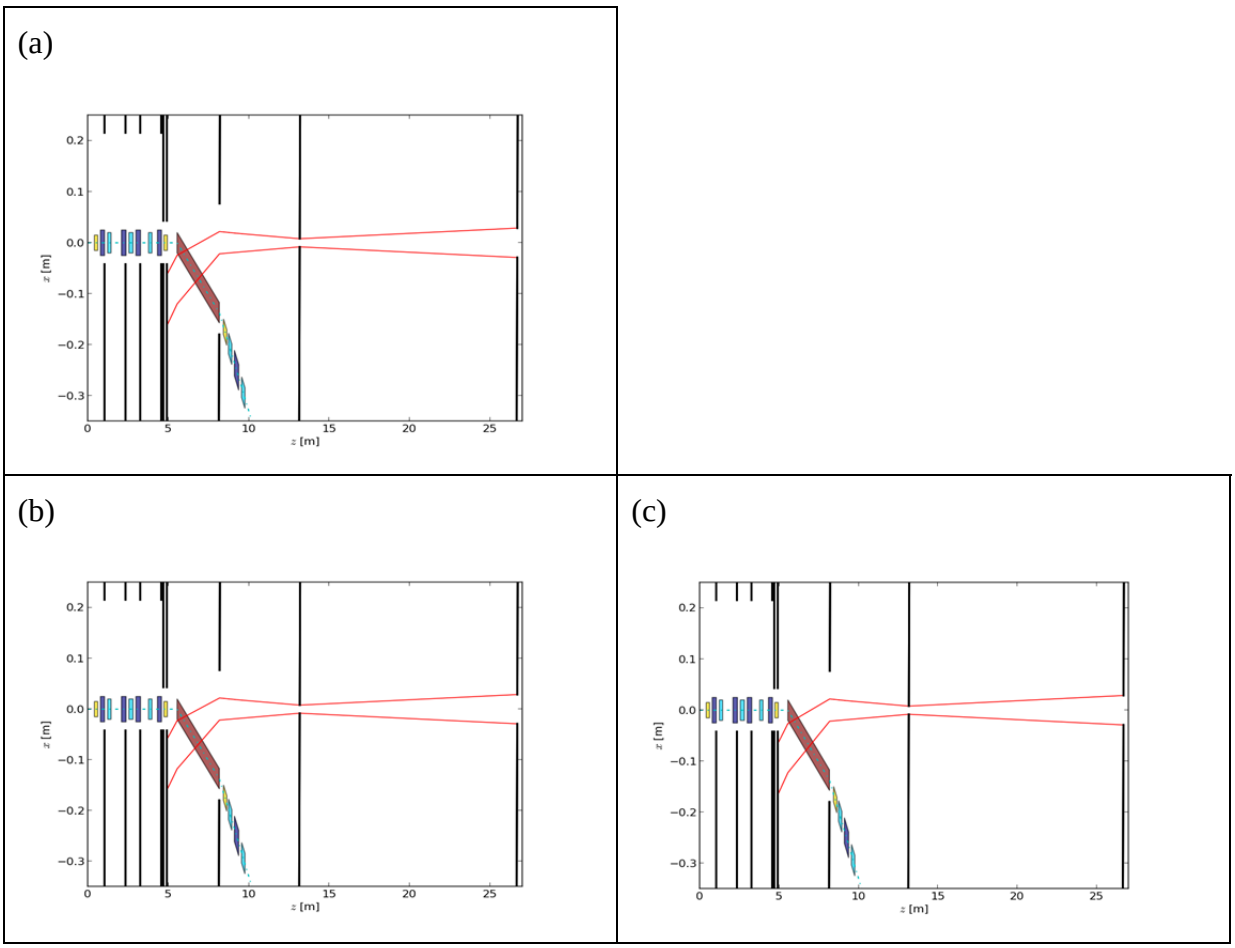

Figure 3. The envelopes of backward particle tracking trajectories for the 11BM (CMS) beamline assuming a distance of 5 mm from the aperture of LC02 with 2 mm tolerance included. 3(a): On momentum, 3(b): Off momentum (+3%) 3(c): Off momentum (-3%)

3. Description of the FLUKA Model

The plan and elevation views of the FLUKA geometry used for the Top-Off simulations of the 11BM (CMS) beamline are shown in Figures 4(a) and (b). The input used to generate the FLUKA model is listed in Appendix 1. The FLUKA input and output files are kept in the Radiation Physics Folder.

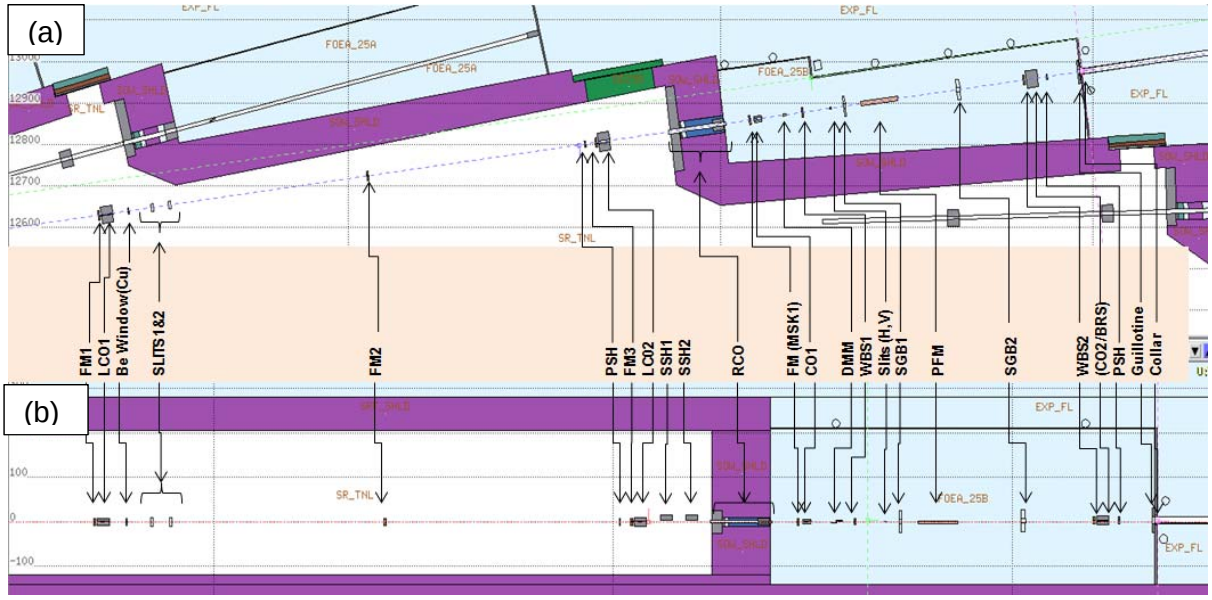

Figure 4: (a) P lan and **(b)** elvation views of the FLUKA geometry used in Top-Off simulation of the 11BM (CMS) Beamline**.**

4. Results for Top-Off FLUKA Simulations

In all FLUKA simulation, a pencil beam of 3 GeV electrons is assumed for the injected beam and all dose rates are normalized to a booster to storage ring injection charge rate of 45 nC/min. Based on the backward particle tracking analysis described in section 2, the beam is assumed to start at the downstream aperture of FM1 and travels down the front end toward the safe endpoint (5 mm from the upstream aperture edge of LC02).

The amount of radiation transmitted into the FOE is primarily determined by the aperture of the FE collimator LC02 and the ratchet wall collimator (RCO). The aperture dimensions for 11BM (CMS) are compared to those of other NSLS-II beamlines in Table 1. Table extracted from *Top-Off Safety Analysis for ISR, ISS and SMI Beamlines* (PS-C-ASD-TOS-RPT-003, August 17, 2015).

Table 1: CO2 and RCO aperture dimensions

	LCO2 Dimensions X (mm)	LCO2 Dimensions Y (mm)	RCO Dimensions X (mm)	RCO Dimensions Y (mm)
08-ID-ISS	**79.20**	**28.40**	**44.74**	**17.03**
04-ID-ISR	**79.33**	**28.22**	**88.16**	**30.56**
12-ID-SMI	**83.88**	**27.24**	**95.29**	**31.09**
05-ID-SRX	**79.20**	**28.40**	**78.44**	**21.80**
11BM-CMS	**49.20**	**21.06**	**95.70**	**57.70**

The dimensions of the 11BM (CMS) LC02 aperture is smaller than those for 04ID, 05ID, 08ID, 12ID, but the dimensions of the RCO aperture is somewhat larger. The 11BM-CMS simulations were undertaken to evaluate the implications of the larger apertures of RCO on the dose rates outside the FOE walls and roof.

The following four scenarios were considered in the FLUKA simulation analysis and the radiation dose results are reported in this note.

1. Injected beam starting at the inboard side of the downstream aperture of FM1 and directed toward the front face of LC02 at 5 mm from the inboard side of the aperture.
2. Injected beam starting at the inboard side of the downstream aperture of FM1 and directed toward the front face of LC02 at 5 mm from the outboard side of the aperture.
3. Injected beam starting at the outboard side of the downstream aperture of FM1 and directed toward the front face of LC02 at 5 mm from the inboard side of the aperture.
4. Injected beam starting at the outboard side of the downstream aperture of FM1 and directed toward the front face of LC02 at 5 mm from the outboard side of the aperture.

The dose rates on the downstream FOE wall were found to be much larger for cases 1 and 4 than for scenarios 2 and 3. In addition results for scenarios 3 and 4 are similar to results found for scenarios 2 and 1 respectively. The effect of the secondary GB shieldings (SGB1 & SGB2) are presented for scenario 1 but similar results are obtained for the other scenarios namely dose rates are reduced on the downstream wall of the FOE but no significant changes to the dose rates on the lateral walls and roof as expected.

4.1 Injected beam starting at the inboard side of the downstream aperture of FM1 and directed toward the front face of LC02 at 5 mm from the inboard side of the aperture

In this simulation, the injected electron beam was started downstream of the horizontal aperture on the inboard side of the FM1 and directed toward the front face of LCO2 at 5 mm from the inboard side of the horizontal aperture. The total dose distributions (mrem/h) in the FE and FOE are shown in Figure 5 and the corresponding neutron distributions are given in Figure 6.

When the electron hits fixed mask 2 (FM2), the beam is scattered largely in the forward direction until it intercepts fixed mask 3 and attenuated by LCO2 and RCO except the radiation that passes through the apertures of LCO2 and RCO which then strikes beamline components in the FOE in particular the collimator 1 (CO1), monochromator (DMM), white beam stop 1 (WBS1), and the primary focusing mirror (PFM).

Figure 5 shows that total dose rates are less than 2000 mrem/hr but exceeds 100 mrem/hr on the roof, lateral wall, and downstream wall. To obtain a more accurate estimates of the dose rates near the FOE walls and roof, a finer scoring bins were used in the regions outside the FOE.

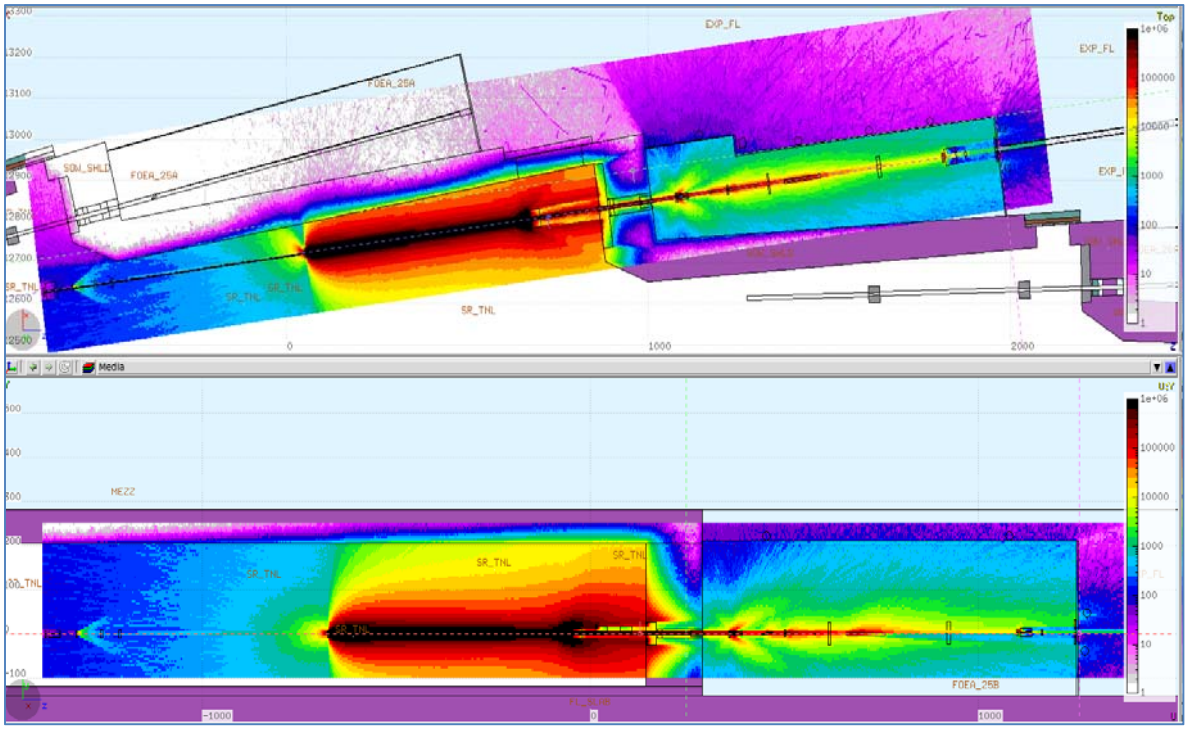

Figure 5: Total dose rate distributions (mrem/h). The Top view at y=0 is shown in the top figure and the elevation view in the bottom figure.

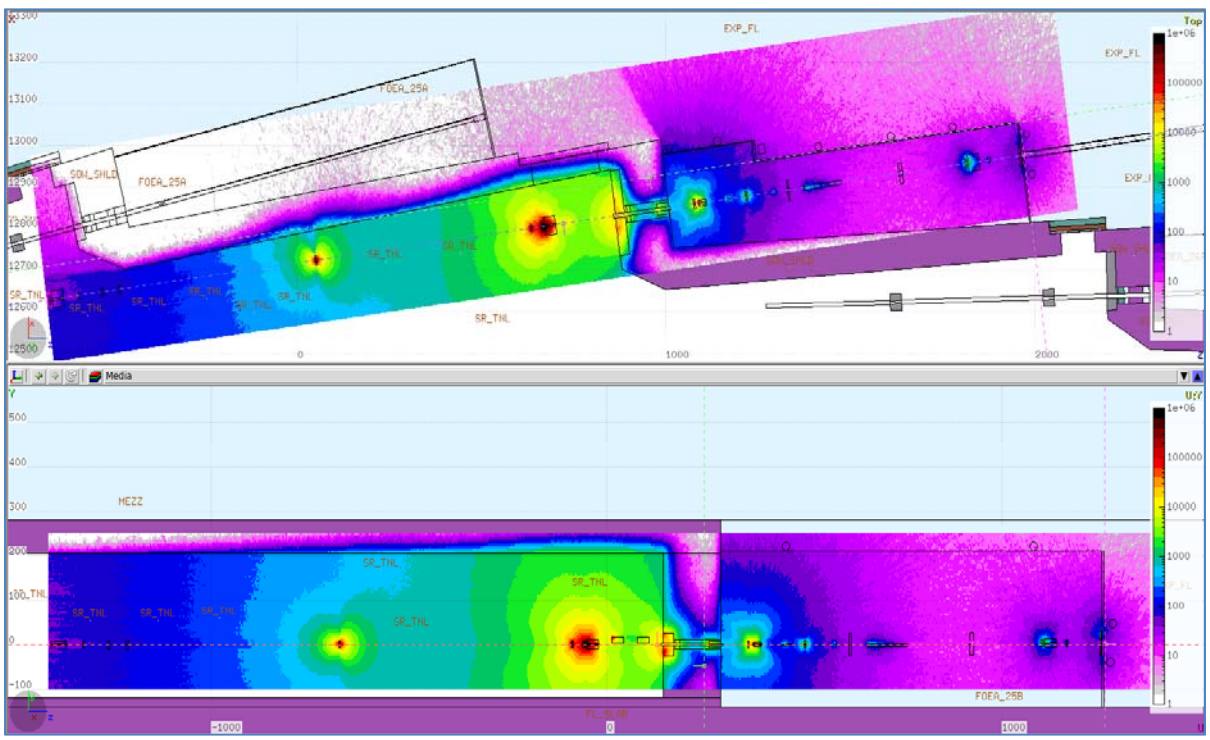

Figure 6: Neutron dose rate distributions (mrem/h). The Top view at y=0 is shown in the top figure and the elevation view in the bottom figure.

The dose rate on the roof [Figure 7(a)] and the lateral walls [Figure 7(c) and (d)] were below approximately 300 mrem/h. The maximum dose rate on contact with the downstream FOE wall is approximately 1400 mrem/hr but goes down to ~200 mrem/h when SGB1 and SGB2 shields were included in the simulation (see Figure 8). As expected the dose rates on the lateral wall and roof were not siginifanctly changed by the SGB shields.

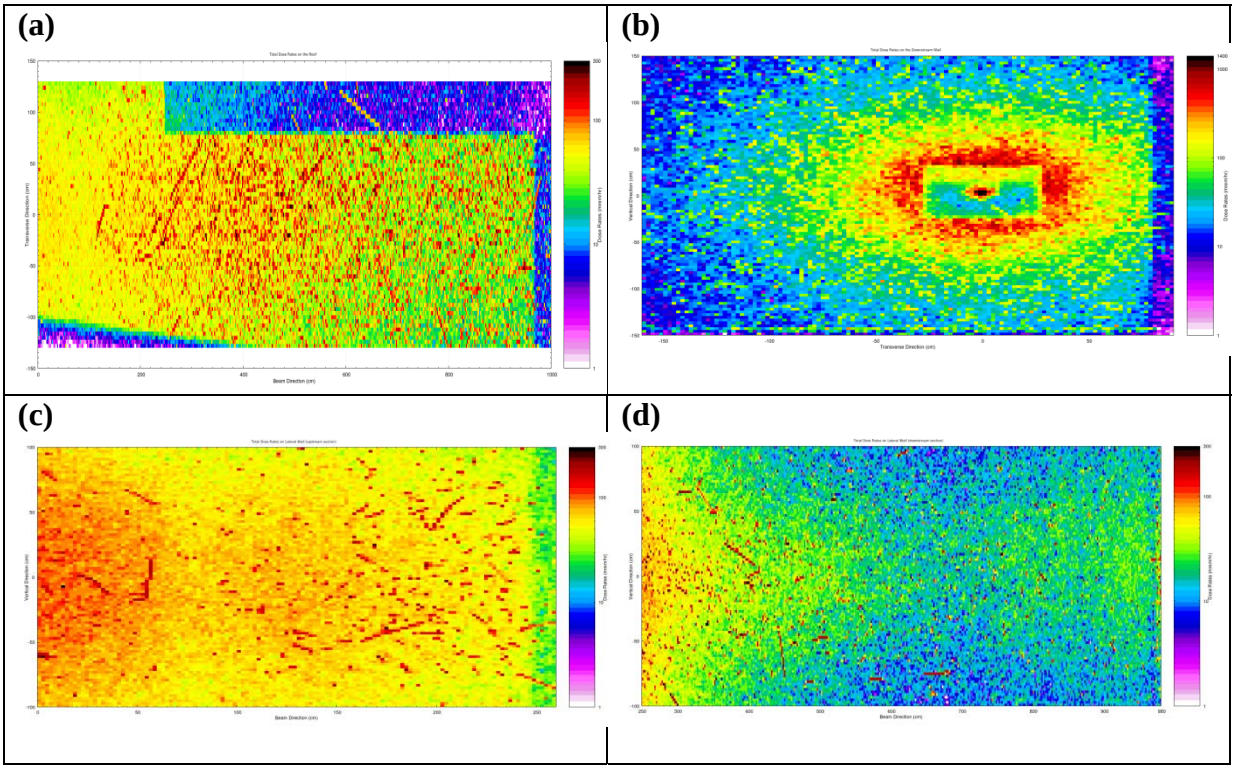

Figure 7: Total dose rate distributions (mrem/h) (a) on the roof, (b) on contact with the downstream FOE wall, (c) on the lateral wall (upstream section – bump-out wall), and (d) on the lateral wall (downstream section).

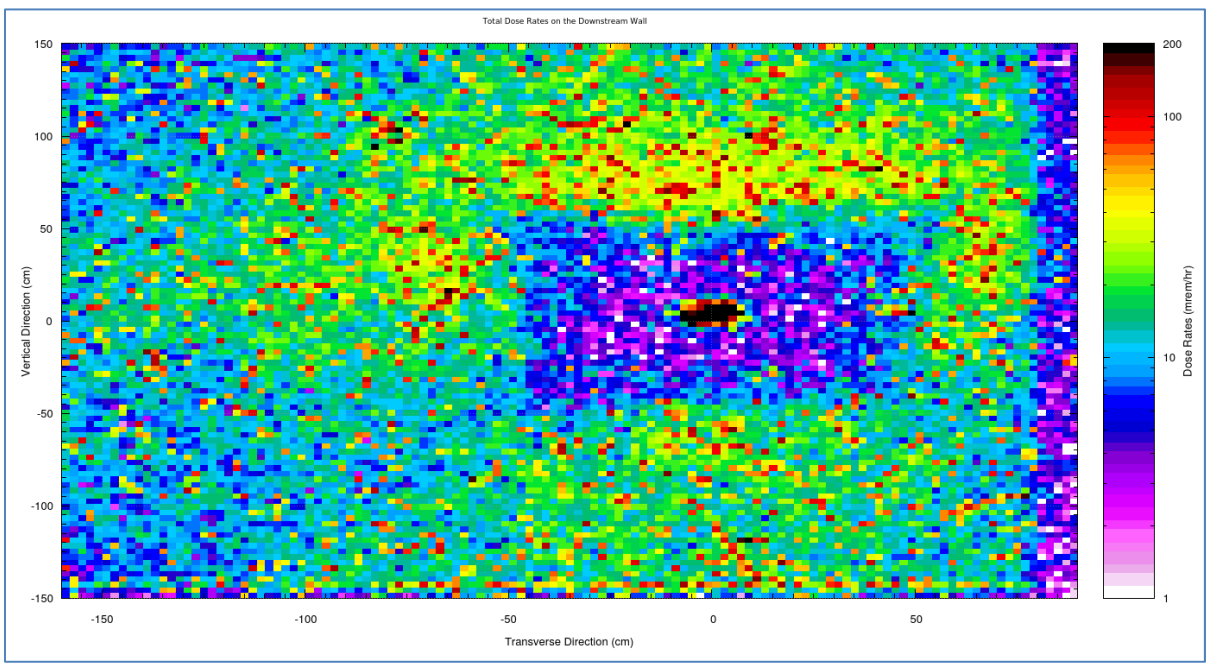

Figure 8: Total dose rate distributions (mrem/h) on contact with the downstream FOE wall with SGB1 and SGB2 shields included in the simulation.

4.2 Injected Injected beam starting at the inboard side of the downstream aperture of FM1 and directed toward the front face of LC02 at 5 mm from the outboard side of the aperture.

In this simulation, the injected electron beam was started downstream of the horizontal aperture on the inboard side of the FM1 and directed toward the front face of LCO2 at 5 mm

from the outboard side of the horizontal aperture. The total dose distributions (mrem/h) in the FE and FOE are shown in Figure 9.

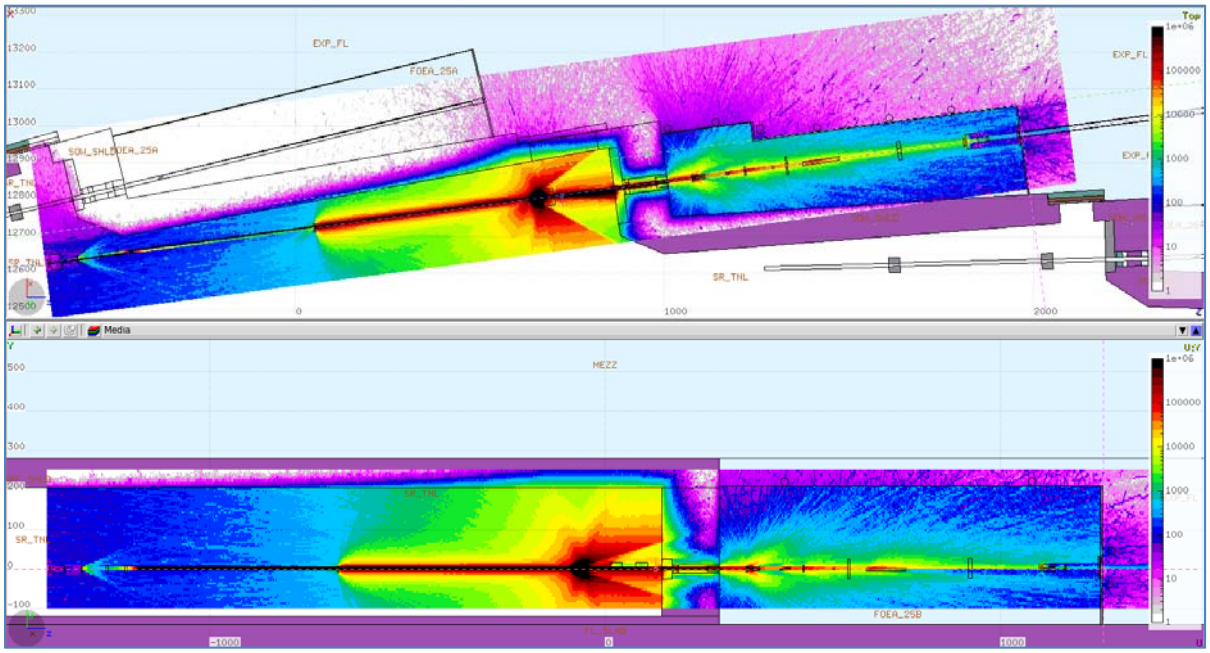

Figure 9: Total dose rate distributions (mrem/h). The Top view at y=0 is shown in the top figure and the elevation view in the bottom figure.

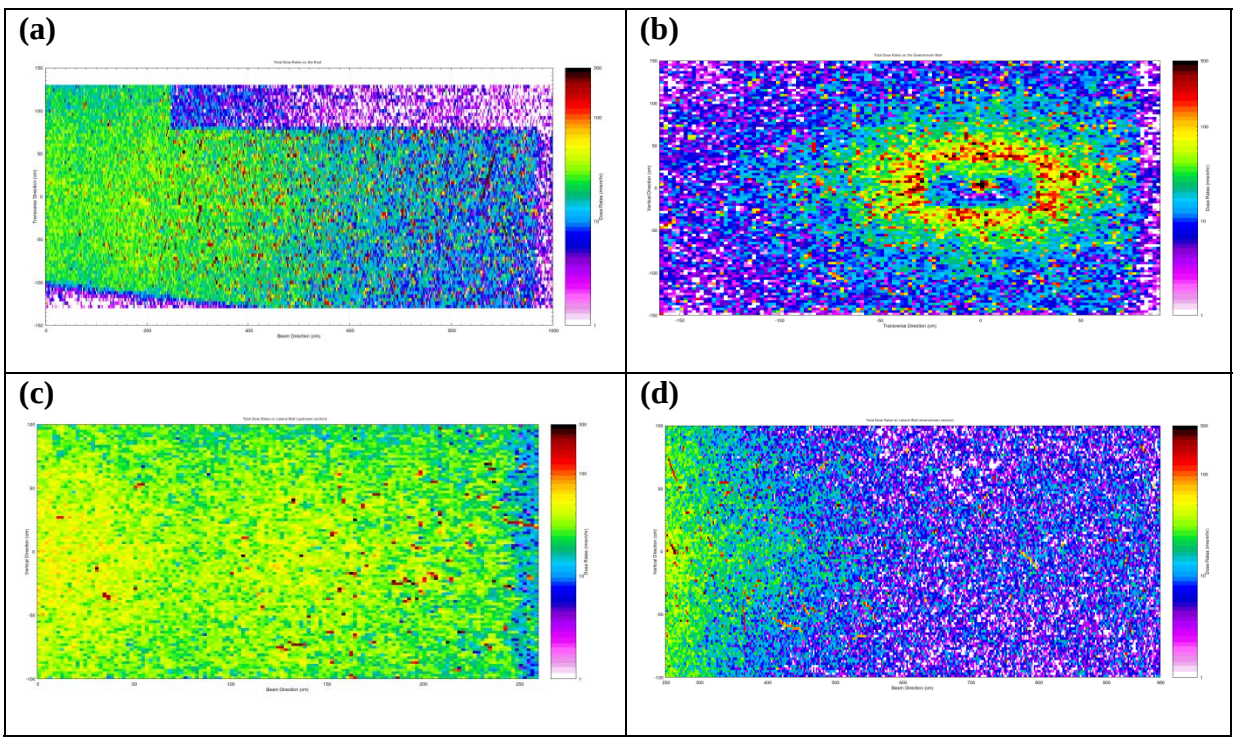

Figure 10: Total dose rate distributions (mrem/h) (a) on the roof, (b) on contact with the downstream FOE wall, (c) on the lateral wall (upstream section – bump-out wall), and (d) on the lateral wall (downstream section).

When the electron hits fixed mask 2 (FM2), the beam is scattered in the forward direction until it is further scattered by FM3 and attenuated by LCO2 and RCO except for the radiation that passes through the apertures of LCO2 and RCO which then strikes beamline components in the FOE in particular the collimator 1 (CO1).

The dose rate on the roof [Figure 10(a)] and the lateral walls [Figure 10(c) and (d)] were below approximately 100 mrem/h. The maximum dose rate on contact with the downstream FOE wall is approximately 500 mrem/hr but goes down to ~100 mrem/h when SGB1 and SGB2 shields were included in the simulation. The dose rates on the lateral wall and roof were not siginifanctly changed by the SGB shields.

4.3 Injected beam starting at the outboard side of the downstream aperture of FM1 and directed toward the front face of LC02 at 5 mm from the inboard side of the aperture

In this simulation, the injected electron beam was started downstream of the horizontal aperture on the outboard side of the FM1 and directed toward the front face of LCO2 at 5 mm from the inboard side of the horizontal aperture.

Figure 11 show the dose rates distributions (mrem/h) in the FE and the FOE. These dose rate distributions are very similar to those for scenario 2 and the maximum values of the dose rates are approximately the same.

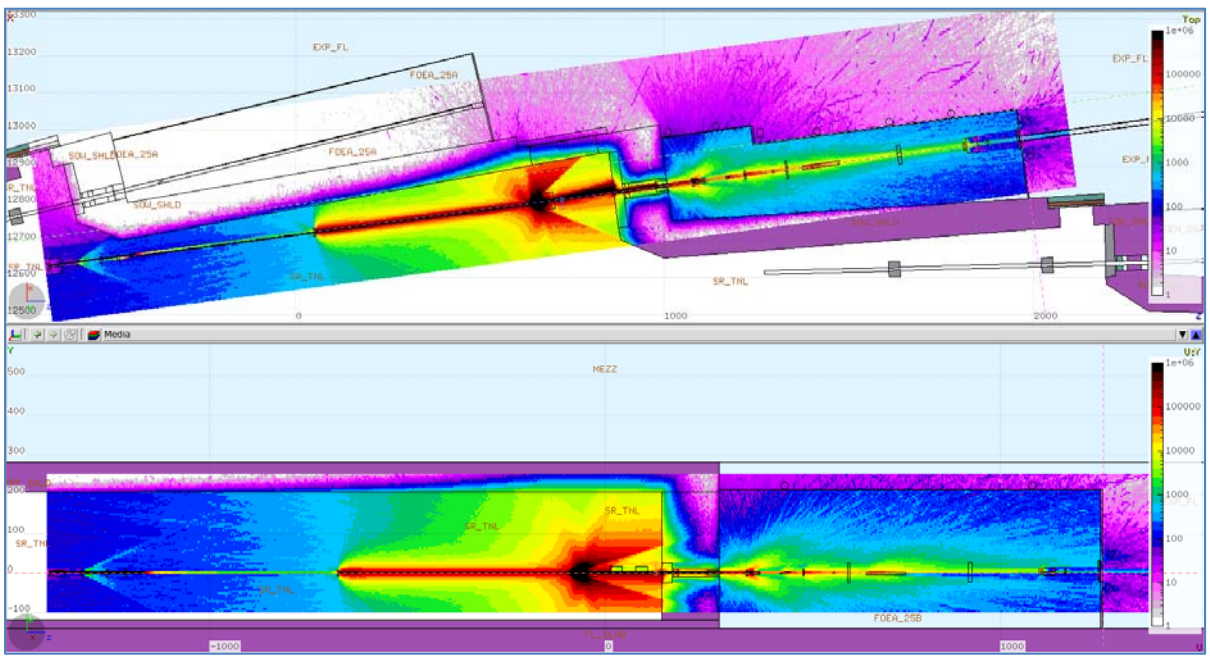

Figure 11: Total dose rate distributions (mrem/h). The elevation view at y=0 is shown in the top figure and the plane view in the bottom figure.

4.4 Injected beam starting at the outboard side of the downstream aperture of FM1 and directed toward the front face of LC02 at 5 mm from the outboard side of the aperture

In this simulation, the injected electron beam was started downstream of the horizontal aperture on the outboard side of the FM1 and directed toward the front face of LCO2 at 5

mm from the outboard side of the horizontal aperture.

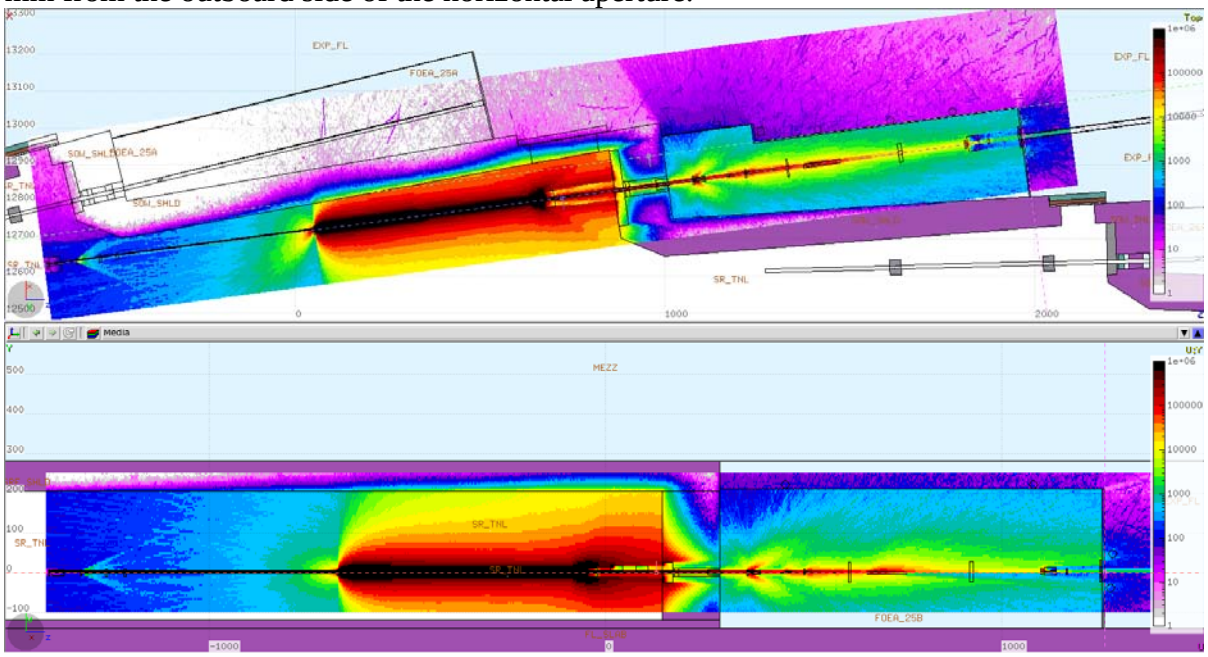

Figure 12: Total dose rate distributions (mrem/h). The elevation view at y=0 is shown in the top figure and the plane view in the bottom figure.

The dose rate distributions in this case (Figure 12) are very similar to the dose rate distributions in Figure 5 and the maximum values of the dose rates are approximately the same.

5. Summary and Conclusions

Based on the FLUKA simulations described in sections 4.1-4.4 of this note, assuming an injected beam starting at FM1 and directed toward the front face of LCO2 the ambient dose rates on the walls and roof of the 11BM (CMS) FOE are higher than 100 mrem/hr on contact but much less than 2000 mrem/hr.

According to the NSLS-II Shielding policy [3] "For normal operations, interlocking ARMs are planned for all radiologically Controlled Areas where the dose can exceed 100 mrem/hr." The interlocked ARM network will shut the beam (radiation source) "off" when a monitor detects radiation levels exceeding the high-alarm set point. For a radiologically Controlled Area, the high-alarm set point is currently set to 5 mrem/hr. In addition to the high-level alarm, the ARMs are equipped with a low-level alarm that is set to alert operators that dose rates are higher than expected and provide them an opportunity to take action and reduce the dose rate before the high-level set point is reached and an interlock action occurs.

The 11BM (CMS) FOE has an ARM installed on the bump-out wall just upstream of the sliding door [see Figure 2(b)]. If there is a Top-Off accident where injected electrons could be conveyed down the beamline to collimator LC2, the radiation plume produced in the FE will leak through the corner of the bump-out wall and be detected immediately by the ARM, thereby shutting off the injected beam via a PPS. This ARMs will ensure that the electron beam is turned off and that the beamline personel and users are not exposed to dose rate higher than those allowed by the NSLS-II shielding policy [3].

6. References

[1] Top-Off Safety Analysis and Requirement of Hazard Mitigation for NSLS-II Facility, PS-RASD-RPT-DRV-001, 2014.

[2] PS-C-ASD-PRC-183, Approval of New and Modified NSLS-II Beamline Front Ends for Top Off Safety, Jan 14, 2015.

[3] Photon Sciences Shielding Policy, PS-C-ASD-POL-005, March 26, 2014.

7. Acknowledgements:

We would like to thank Lucas Lienhard and John Tuozzolo for providing all the beamline geometry information listed in Appendix 1. We would like to thank Masa Fukuto and Lucas Lienhard for multiple discussions.

Appendix 1

Appendix 1
11BM (CMS) Beamline
Input provided by Lucas Lienhard

Co-ordinate system

For non-canted beamlines the z axis lies along the long or short straight centerline. The positions (z co-ordinates) of the various components are defined with respect to the center of the Three Pole Wiggler (3PW). The SS centerline was used as the z or beamline axis for the FLUKA models. Y is the vertical axis and x the horizontal axis orthogonal to the y and z axes.

Table 1.1 Beamline Enclosures

Wall	Position	Thickness	Material
D/S End of 11-BM-A Ratchet Wall	2489.24 cm		
D/S End of FOE (11-BM-A) Backwall	3458.25 cm	5.0 cm	Lead
Distance of Sidewall from straight CENTERLINE	80.56 cm	1.8 cm	Lead
Distance of Roof from straight CENTERLINE	210.00 cm	0.4 cm	Lead
D/S End of FOE bump-out Backwall	2739.27 cm	5.0 cm	Lead
Distance of bump-out Sidewall from straight CENTERLINE	131.01 cm	1.8 cm	Lead

Table 1.2 Beamline Transport Pipes

Transport Pipe between FOE & SOE (Both 4″ and 6″ OD pipe in transport, 6″ changes to 4″ @ 5066cm (z)	ID= 5.75 inches (min) OD=6.00 inches Material: Stainless Steel	Shielding Thickness = 5.0 mm Shielding Material: Lead

Endstation Enclosure

Wall	Position	Thickness	Material
U/S End of SOE (11-BM-B) Wall	5285.00 cm	0.3 cm	Steel
D/S End of 11-BM-B Backwall	6535.00 cm	0.6 cm	Steel
Distance of inboard Sidewall from straight CENTERLINE	130.00 cm	0.3 cm	Steel
Distance of outboard Sidewall from straight CENTERLINE	220.00 cm	0.3 cm	Steel

Distance of Roof from straight CENTERLINE	210.00 cm	0.2 cm	Steel
D/S Wall beam stop location (50cm x 50cm)	6533.2 cm (U/S)	1.2 cm	Lead

Table 1.3 11BM-CMS Beamline Components and SGB shields

Components	Z location (Distance from 3PW center) (U), (D) or center	Dimensions (specify units)		Offset (vertical or horizontal) w.r.t Straight CENTERLINE	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R) (MAX includes mfr & positional tolerance)			
Fixed Mask (MSK1)	2556.96 cm (U)	22.86cm (x) 15.24cm (y) 4.445cm(z)	US:5.91cm(x),2.20cm(y) DS:4.17cm(x),0.46cm(y) MAX		Cu-Cr-Zr	PD-CMS-MSK-1100
Bremsstrahlung Collimator (CO1)	2571.041 cm (U)	15.0 cm (x), 9.50 cm (y) 20.00 cm (z)	4.589 cm (x) MAX 0.799 cm (y) MAX	No offset	95% Tungsten alloy	PD-CMS-CO-0100
DMM 1st crystal (MONO)	2650 cm (C)	50mm × 25mm × 150mm (z) (rotated@ 31.4 mrad max)		Top surface at centerline	Silicon	PD-CMS-MONO-1000
DMM 2nd crystal (MONO)	2663 cm (C)	50mm × 25mm × 150mm (z) (rotated@ 31.4 mrad max)		Bottom surface offset 3mm +y, w.r.t. 1st crystal	Silicon	PD-CMS-MONO-1000
White Beam stop (WBS1)	2699.2 cm (U)	22.86cm (x) 15.24cm (y) 4.445cm(z)	US:5.80cm(x),2.22cm(y) DS:4.06cm(x),0.49cm(y) MAX	offset 6mm above GB centerline	Cu-Cr-Zr	PD-CMS-MSK-1200
Slits – Vertical (2 individual blades)	2775.3 cm (US-tungsten)	5.0cm (x) 1.7cm (y) 0.2cm (z) (Blade size)	5mm overlap – closed 25mm aperture – open	Center 6mm above GB centerline	Tungsten blade with copper plate for cooling	PD-CMS-SLT-1000
Slits – Horizontal (2 individual	2778.5cm (US-tungsten)	3.0cm (x) 3.0cm (y) 0.2cm (z)	5mm overlap – closed 50mm aperture - open	Center 6mm above GB centerline	Tungsten blade with copper	PD-CMS-SLT-1000

blades)		(Blade size)			plate for cooling	
Primary Focusing Mirror (PFM)	2910.0 cm (C)	1000mm (L) × 100mm (W) × 60 mm (H) (rotated@ 3.34 mrad max)	90mm radius of curvature	center and reflecting surface of crystal 6 mm above GB centerline	Silicon	PD-CMS-PFM-1000
White Beam stop (WBS2)	3298.7 cm (U/S)	22.86cm (x) 15.24cm (y) 4.445cm(z)	US:6.12cm(x),2.66cm(y) DS:4.39cm(x), 0.998cm(y)	3cm above GB centerline	Cu-Cr-Zr	PD-CMS-MSK-1300
Bremsstrahlung Stop (CO2/BRS)	3307.500 cm (U)	41.9 cm (x), 20.3 cm (y) 30.48 cm (z)	5.846 cm (x) MAX 1.986 cm (y) MAX	offset 3.151cm above GB centerline (angled at 6.18 mrad)	Lead	PD-CMS-CO-0200
Shutter (PSH)	3361.989 cm (U)	12.5 cm W × 15 cm H× 3.8 cm	40 mm × 25 mm	3.445 cm up	Tungsten	PD-COM-PSH-1000
Guillotine	3446.822 cm (U)	55.88 cm W × 55.88 cm H × 5.00 cm	152.4 mm (6″) diameter	guillotine and aperture 3.99 cm up	Lead	11-BM-A Guillotine
Hutch wall opening & collar square	3452.85cm (U)	Collar dimensions 30cm W x 30 cm H x 1cm Z	9″ diameter wall opening	33.99 cm (y) above centerline	Lead	Hutch wall and shielded pipe collar

**gap between lead wall and guillotine is 9.5mm*

Table 1.4 Beamline SGB Shielding

Shielding	Z location (Distance from S.S. center) (U), (D) or center	Dimensions (specify units)		Offset (vertical or horizontal) Straight CENTERLINE	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R)			
SGB shield SC01 (d/s of mono &	2812.96 cm (U)	50.0 cm (x) x 50.0 cm (y) x	10.8 cm MAX aperture (diameter)	Y=0.60 cm	Lead	PD-CMS-SBRS-1000

WBS)		5.0 cm (z) MINIMUM				
SGB shield SC02 (d/s of mirror)	3118.28 cm (U)	50.0 cm (x) x 50.0 cm (y) x 10.0 cm (z) MINIMUM	10.8 cm MAX aperture (diameter)	Y=1.89cm	Lead	PD-CMS-SBRS-2000

Table 1.5 Front End and Beamline Components for FLUKA Calculations

Shielding	Z location (Distance from S.S. center) (U), (D) or (C)	Dimensions (specify units)		Offset (vertical or horizontal) Straight CENTERLINE	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R) (MAX includes mfr & positional tolerance)			
FM1	794.7cm (US)	22.86cm (x) 15.24cm (y) 4.445cm(z)	1.212cm (x) MAX 0.135cm (y) MAX US: 2.935cm(x), 1.858cm(y)	0	Cu-Cr-Zr	SR-FE-3PW-MSK-1805
LCO1	803.7cm (US)	40.64cm (x) 15.23cm (y) 30.48cm (z)	2.889cm (x) MAX 1.698cm (y) MAX	0	Lead	SR-FE-3PW-CO-0100
Be Window	877.1cm (C)	15.24cm (x) 15.24cm (y) 2.54cm (z)	3.86cm (x) MAX 1.31cm (y) MAX	0	Glidcop with Beryllium foil in aperture	SR-FE-3PW-WIN-0250
X-Y Slit 1	940.7cm (C)	18.42cm (x) 19.37cm (y) 6.03cm (z)	Max opening (30mm H x 10 mm V) Minimum opening (-10mm overlap)	0	Cu-Cr-Zr	SR-FE-3PW-SLT-2000
X-Y Slit 2	988.6cm (C)	18.42cm (x) 19.37cm (y) 6.03cm (z)	Max opening (30mm H x 10 mm V) Minimum opening (-10mm overlap)	0	Cu-Cr-Zr	SR-FE-3PW-SLT-2000
Inboard Shadow Shield	1460.3cm (U)	17.78cm (x) 30.48cm (y) 30.48cm (z)		X = -7.92cm (outboard face)	Lead	SR-FE-3PW-1014

FM2	1522.8cm (US)	22.86cm (x) 15.24cm (y) 4.445cm(z)	2.758cm (x) MAX 0.698cm (y) MAX US: 4.19cm(x), 2.13cm(y)	0	Cu-Cr-Zr	SR-FE-3PW-MSK-1806
Photon Shutter	2113.5cm (C)	15.24cm (x) 15.88cm (y) 3.175cm (z)	5.334cm (x) 1.524cm (y)	Y=2.499cm (aperture offset from C/L)	Cu-Cr-Zr	SR-FE-3PW-PSH-0111
FM3	2140.7cm (US)	22.86cm (x) 15.24cm (y) 4.445cm(z)	3.693cm (x) MAX 0.798cm (y) MAX US: 5.13cm(x), 2.23cm(y)	0	Cu-Cr-Zr	SR-FE-3PW-MSK-1804
LCO2	2149.7cm (US)	43.18cm (x) 20.32cm (y) 30.48cm (z)	4.920cm (x) MAX 2.106cm (y) MAX	0	Lead	SR-FE-3PW-CO-0300
Safety Shutter1	2214.5cm (US)	16.5cm (x) 12.7cm (y) 30.48cm (z)		Y=+9.32cm when open	Lead	SR-FE-3PW-SS-4000
Safety Shutter2	2278.3cm (US)	16.5cm (x) 12.7cm (y) 30.48cm (z)		Y=+9.32cm when open	Lead	SR-FE-3PW-SS-4100
Ratchet Wall Collimator	2344.5cm (US)	See raytrace SR-FE-3PW-3001 revC	See raytrace SR-FE-3PW-3001 revC	0	Lead, concreate & HDPE	SR-FE-3PW-RCO-3000

U, D, C refer to upstream, downstream or center of the component.