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AUTHOR: X. Yang and M. Benmerrouche	DATE **11/2/2016**
19-ID NYX Beamline Radiation Shielding Analysis	

1. Introduction

The NSLS-II Beamline Radiation Shielding Policy has been stated as follows in Reference 1: Radiation exposure to staff and users resulting from National Synchrotron Light Source II (NSLS-II) operations must comply with Brookhaven National Laboratory (BNL) and Department of Energy (DOE) radiation requirements and must be maintained as low as reasonably achievable (ALARA). In accordance with 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.

In this report, recommended shielding are based on calculations to achieve dose rates < 0.05 mrem/h in continuously occupied areas and < 0.5 mrem/h on contact with the downstream wall of the First Optical Enclosure (FOE) [2] during normal operations.

Beamlines are required to shield against 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 and/or air. The shielding requirements for the FOE are dominated by the scattering of the primary bremsstrahlung and not the synchrotron beam. Guidelines for the NSLS-II Beamline Radiation Shielding Design are also provided in Reference 1**.** These guidelines were used to determine the thickness of the FOE walls as well as dimensions of the supplementary shielding required to reduce the dose on the downstream FOE walls. The shielding recommended for the lateral wall 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 NYX Beamline (19-ID) is documented in this technical note. The goal of the simulations documented here was to estimate the radiation dose levels generated inside and outside the FOE during normal operations and some fault conditions, thus evaluating the efficiency of the as-designed SGB shielding.

The layout of the 19ID-NYX beamline is presented in Figure 1. These drawings were extracted from the Beamline Ray Trace Layout [NYSBC BEAMLINE RAYTRACE-AHB0560]. The ray trace drawings list the major components in the beamline and provide the position of each component. The positions, dimensions and materials of the main components are included in Appendix 1.The beam travels from right to left in the Ray Trace drawings.

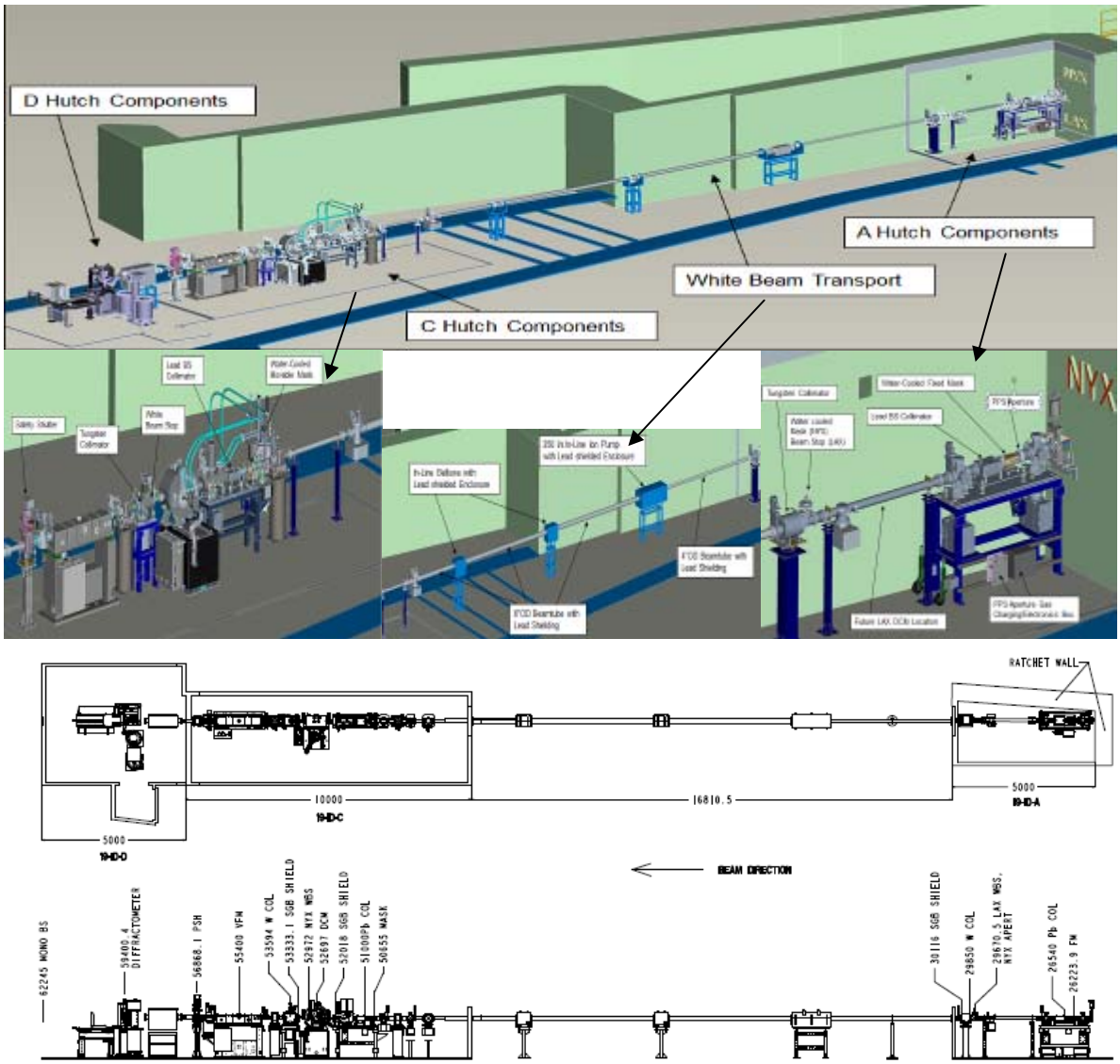


Figure 1: Layout of 19ID-NYX showing beamlines enclosures 19ID-A (FOE), white beam transport, 19ID-C, 19ID-D and major beamline components.

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 ID straight section	15.5 m
Pressure in straight section	1 ntorr

The beam is normalized at 17μW incident power, for the long (15.5 m) straight. This value corresponds to the estimated bremsstrahlung power generated by a 500 mA electron beam of 3GeV, assuming that the vacuum in the straight sections is better than 10^{-9} Torr. The bremsstrahlung source file is kept in the NSLS-II Radiation Physics Folder.

The FLUKA model is described in Section 2. The positions, dimensions and materials of the main components are included in Appendix 1. A prototype FLUKA input file is kept in the NSLS-II Radiation Physics folder.

Table 2: List of FLUKA simulations. FLUKA model longitudinally starts from the downstream end of the 19-ID-A ratchet wall.

#	Simulation	Position of GB source
1(a)	GB incident on the outboard aperture of the dual aperture fixed mask 1 (FM1)	x=0.5962, y=0, z=53.59
1(b)	GB incident on the inboard aperture of FM1	x=-4.1748, y=0, z=53.59
1(c)	GB incident on the top of the outboard aperture of FM1	x=0.0, y= 0.40, z=53.59
1(d)	GB incident on the outboard front face of FM1	x=2.7852, y=0, z=53.59
2(a)	GB incident on the outboard aperture of FM2	x=0.359, y=0, z=398.25
2(b)	GB incident on the inboard aperture of FM2	x=-5.881, y=0, z=398.25
2(c)	GB incident on the top of the outboard aperture of FM2	x=-0.221, y=0.23, z=398.25
2(d)	GB incident on the outboard front face of FM2	x=1.839, y=0, z=398.25
3(a)	GB incident on the inboard aperture of FM3	x=-0.507, y=0, z=2495.71
3(b)	GB incident on the middle point of the inboard front face of FM3	x=-4.045, y=0, z=2795.71
3(c)	GB incident on the edge of the inboard front face edge of FM3	x=-5.457, y=0, z=2495.71
4(a)	GB incident at the center of DCM1	x=0.0, y=0, z=2700.9
4(b)	GB incident on the upstream face of DCM1	x=0.0, y=-0.843, z=2697.9
5(a)	GB incident at the middle point of the inboard side front face of BC3	x=-6.157, y=0, z=2531.17
6(a)	GB incident on the inboard side of BC4	x=-1.212, y=0.0, z=2750.0.
6(b)	GB incident on the center close to the top of BC4	x=0, y=1.17, z=2750.
7(a)	GB incident along the extreme ray direction along the white beam transport	x=0, y=0, z=457.83
8(a)	GB incident on the scatter target (copper slit #1 in C-Hutch) with 1 slit in	x=0.0, y=0.0, z=2570
8(b)	GB incident on the scatter target (copper slit #1 in C-Hutch) with 2 slits in	x=0.0, y=0.0, z=2570
9(a)	GB normal incident to the WBS in C-Hutch	x=0.0, y=0.0, z=2720
10(a)	GB normal incident to the WBS in C-Hutch with the PS open	x=0.0, y=0.0, z=2720
10(b)	GB incident on copper slit #1 in the C-Hutch with 2 slits in and the PS open	x=0.0, y=0.0, z=2570

The results of the GB simulations and synchrotron radiation calculations are presented in Sections 3 and 4, respectively.

A summary of all simulation results is presented in section 5. The results of the GB simulations are summarized in Table 7. 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 near the walls of the FOE, the beam transport pipe and the end station enclosures 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 GB and not the synchrotron beam.

The white beam components disperse the primary GB without significant energy loss; therefore 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 19ID-NYX beamline includes additional shielding 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 analytical representation of the source's energy spectrum, which was scaled in intensity in accordance with the experimental estimate of total GB power. This custom source assumes a 1/E energy spectrum dependency, with a maximum energy of 3GeV, and generates internally the corresponding probability density function from analytical descriptions." The beam is normalized to 17μW incident power, for the long (15.5 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 19ID-NYX FLUKA model includes the FOE roof, sidewall, the downstream wall, as well as the ratchet wall and long wall of the storage ring. The FOE outboard lateral panel is made of 18 mm Pb (156.0 cm distance from NYX long straight centerline), the roof is 10 mm Pb (209.0 cm above long straight centerline) and the downstream FOE wall is 50 mm Pb (477.7 cm from the ratchet wall).

The FLUKA model [horizontal view (top) and vertical view (bottom)] of the 19ID-NYX Beamline is shown in Figure 2. All components, which are represented by acronyms with Z positions in brackets, are placed symmetrically with respect to the beam centerline in the transverse direction. For the FLUKA models, the Z axis represents the beam centerline, the X and Y axes are the horizontal axis normal to the beam direction and the vertical axis respectively. For the Ray Trace drawings, the zero of the co-ordinate system is the center of the long straight. However, for the FLUKA input files, the downstream end of the ratchet wall is set to zero in the Z axis. The beam travels from right to left in the Ray Trace drawings. For the FLUKA model the beam travels from left to right.

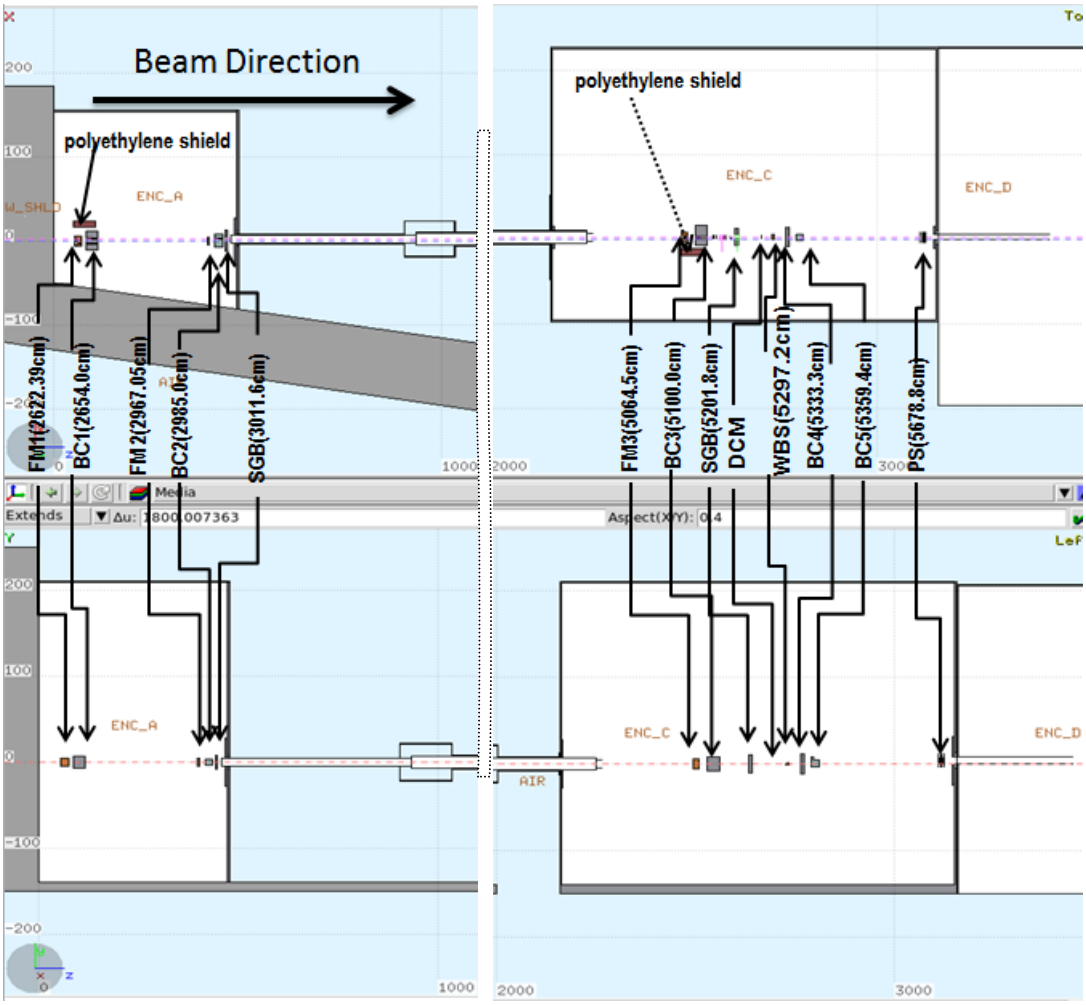


Figure 2: Plan view (y=0) and Elevation view (x=0) of the 19ID-NYX FLUKA geometry

ACRONYMS

FM Fixed Mask
BC Beam Collimator
SGB Secondary Gas Bremsstrahlung
PS Photon Shutter
DCM Double Crystal Monochromator

The positions, dimensions, materials and drawings of the main components are included in Appendix 1. The bremsstrahlung source file and FLUKA input files are kept in the NSLS-II Radiation Physics folder.

3. Results for Primary GB Simulations

The simulations performed to confirm the adequacy of the radiation safety components are presented in Table 2. In all of the simulations for C-Hutch, the photon shutter was closed, except cases 10(a) and (b), the photon shutter was open. Summary of the simulation results is presented in Section 5.

3.1 (a) GB Incident on the Outboard Aperture of FM1

The FLUKA model of the copper fixed mask and the impact location of the GB beam are shown in Figure 3(a). Both apertures are tapered in both the vertical and horizontal planes. In this simulation the GB was started just upstream of the selected point of contact at x=0.5962, y=0, z=53.59 and impinges on the outboard tapered plane close to the neck of the aperture.

The width and height of the downstream aperture is 4.3 mm × 2.2 mm. The total dose distributions in mrem/h at 30 cm away from the roof and the lateral wall, and on contact with the downstream wall of the FOE are shown in Figure 3(b), 3(c) and 3(d).

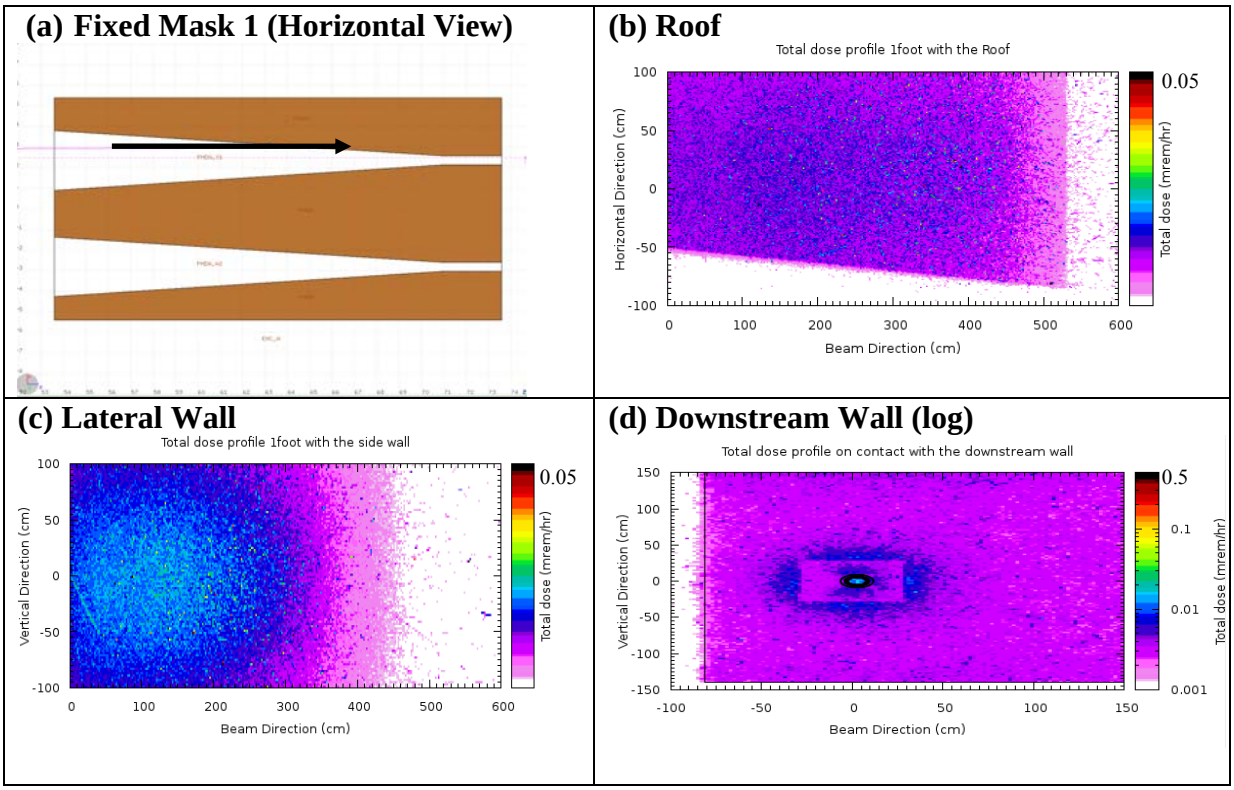


Figure 3: (a) GB incident on the outboard aperture of the dual aperture FM1. The total dose distributions in mrem/h **(b)** at 30 cm from the roof, **(c)** at 30 cm from the lateral wall, and **(d)** on contact with the downstream wall of FOE.

To understand the contribution of the various beamline components on the dose distribution it is useful to look at the vertical and horizontal profiles of the dose distribution in the FOE (Figure 4). When the GB hits the mask it is scattered largely in the forward direction. The radiation that passes through dual aperture fixed mask 1 (FM1) becomes attenuated and collimated by bremsstrahlung collimator 1 (BC1) before it impinges on fixed mask 2 (FM2) which becomes a scattering target. Figure 4 shows clearly the impact of BC1 in blocking the forward secondary GB. The total dose at 1 ft. away from roof and side wall are below 0.05 mrem/h while the maximum dose on contact with the downstream wall of FOE is 0.018 mrem/h.

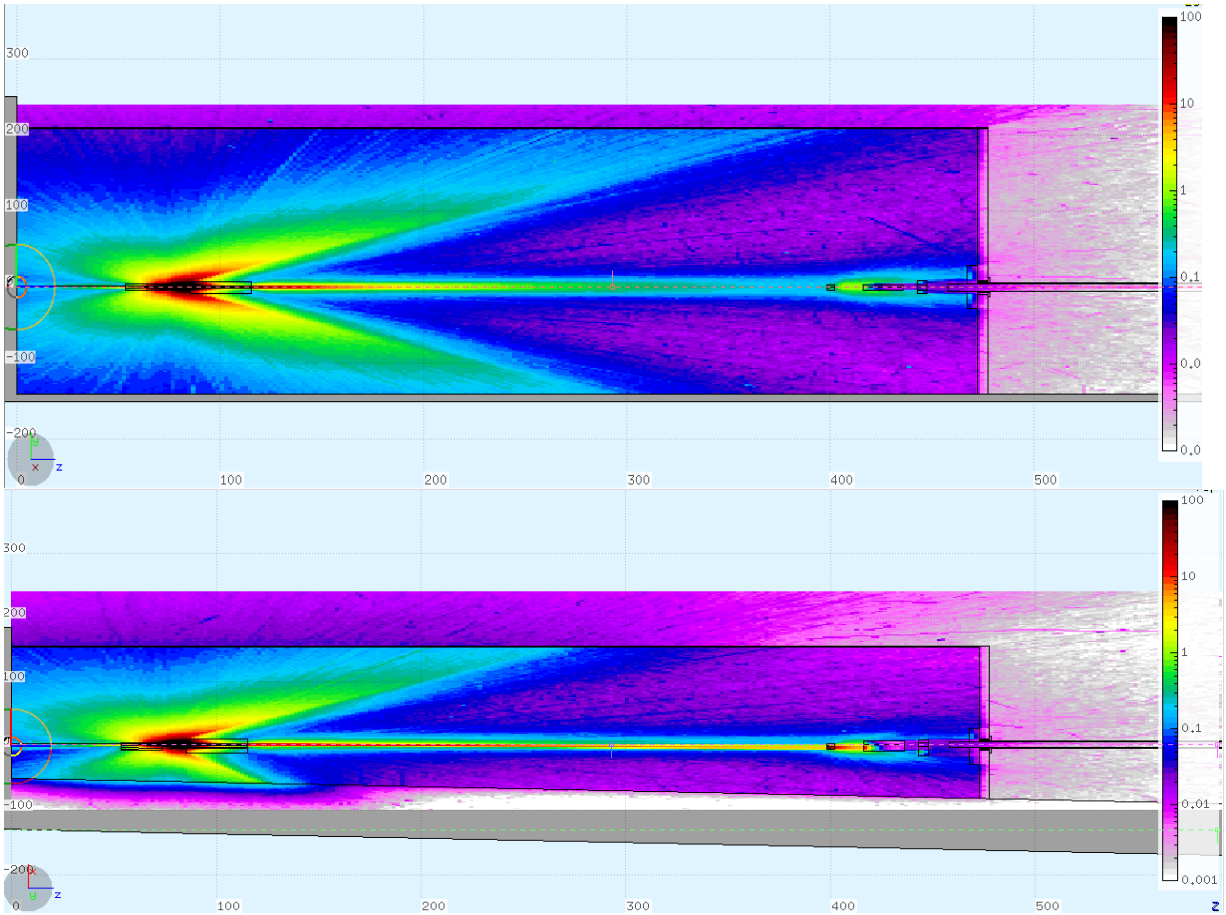


Figure 4: The total dose distributions (mrem/h) in the FOE. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.1 (b) GB Incident on the Inboard Aperture of FM1

In this simulation the GB was started at x=-4.1748, y=0, z=53.59 and impinges on the tapered plane close to the neck of the inboard aperture of the FM1 (see Figure 5a). The width and height of the downstream aperture is 4.3 mm × 2.2 mm. When the GB hits the mask the beam is scattered in all directions. The forward directed SGB that passes through the apertures of the FM1 is largely stopped at BC1. Most of the radiation leaks on the inboard side of BC1 before it impinges on FM2 which becomes a scattering target. BC1 attenuates most of the forward SGB. Total dose rate distributions on the FOE DS wall, the roof and the sidewall are shown in Figure 5. Similar to the previous case, dose rates on the roof and lateral wall are below 0.05 mrem/h at 1 ft. away. The total dose rate on contact with the downstream wall is 0.025 mrem/h. The total dose rate distribution in FOE is shown in Figure 6 which clearly demonstrates the effectiveness of BC1 in attenuating and stopping the forward secondary GB passing through the FM1 inboard aperture.

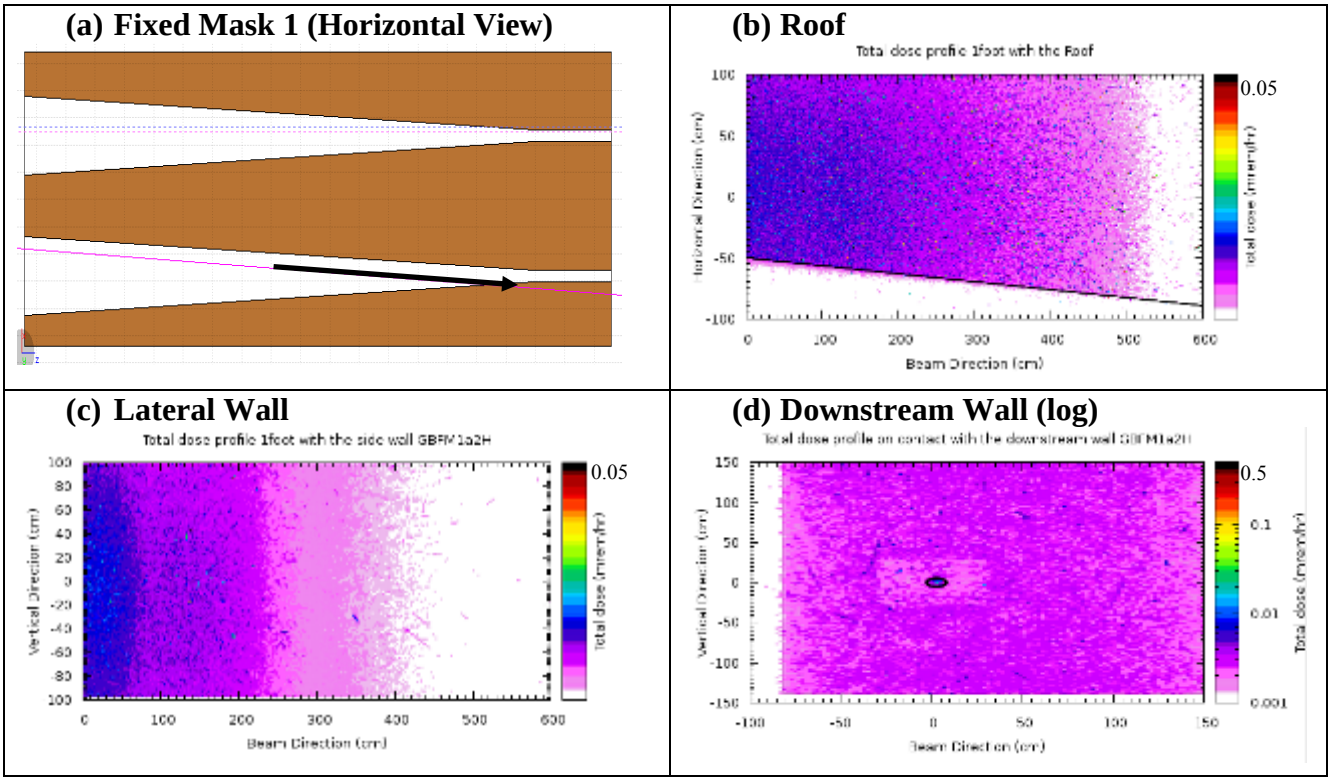


Figure 5: (a) GB incident on the outboard aperture of the dual aperture FM1. The total dose distributions in mrem/h **(b)** at 30 cm from the roof, **(c)** at 30 cm from the lateral wall, and **(d)** on contact with the downstream wall of FOE.

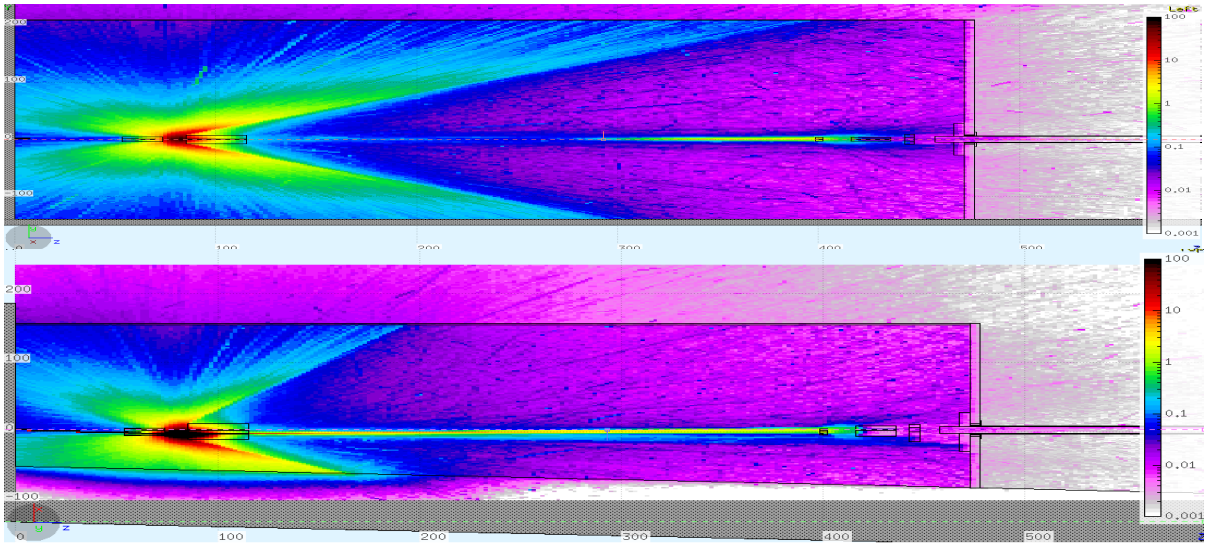


Figure 6: The total dose distributions (mrem/h) in the FOE. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.1 (c) GB Incident on the Top of the Outboard Aperture of FM1

In this simulation the GB was started at x=0.0, y=0.40, z=53.59 and impinges on the top tapered plane close to the neck of the aperture. The height of the aperture is 2.2 mm. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the FOE are shown in Figure 8. When the GB hits the mask the beam is scattered in all directions. The forward directed SGB passes through the apertures of BC1 and FM2 and impinges on the downstream components. However, BC1 effectively attenuates the radiation in the forward direction. Total dose rate distributions on FOE DS wall, the roof and the sidewall are shown

in Figure 7. Similar to the previous case, dose rates on the roof and lateral wall are below 0.05 mrem/h at 1 ft. away. The total dose rate on contact with the downstream wall reached 0.14 mrem/h but inside the beam pipe. The total dose rate distribution in the FOE is shown in Figure 8 which clearly demonstrates the effectiveness of BC1 and the guillotine in attenuating and stopping the forward secondary GB.

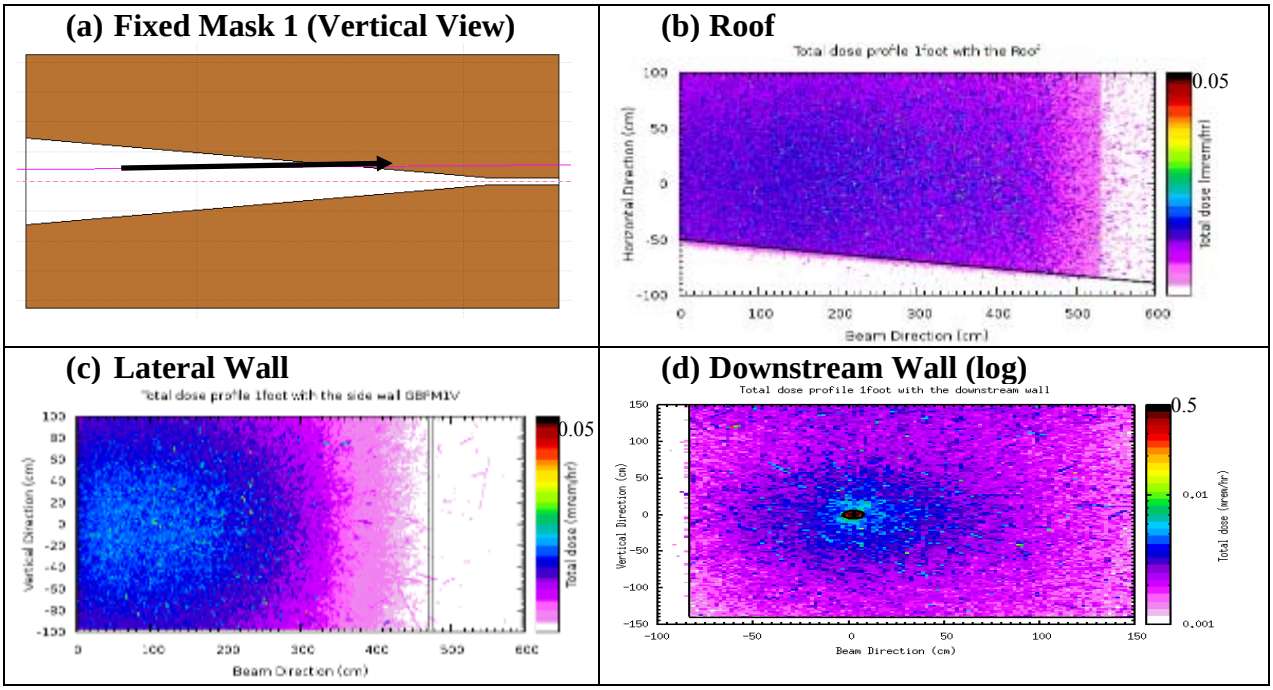


Figure 7: (a) GB incident on the top taper near the outboard aperture of FM1. The total dose distributions in mrem/h **(b)** at 30 cm from the roof, **(c)** at 30 cm from the lateral wall, and **(d)** on contact with the downstream wall of FOE.

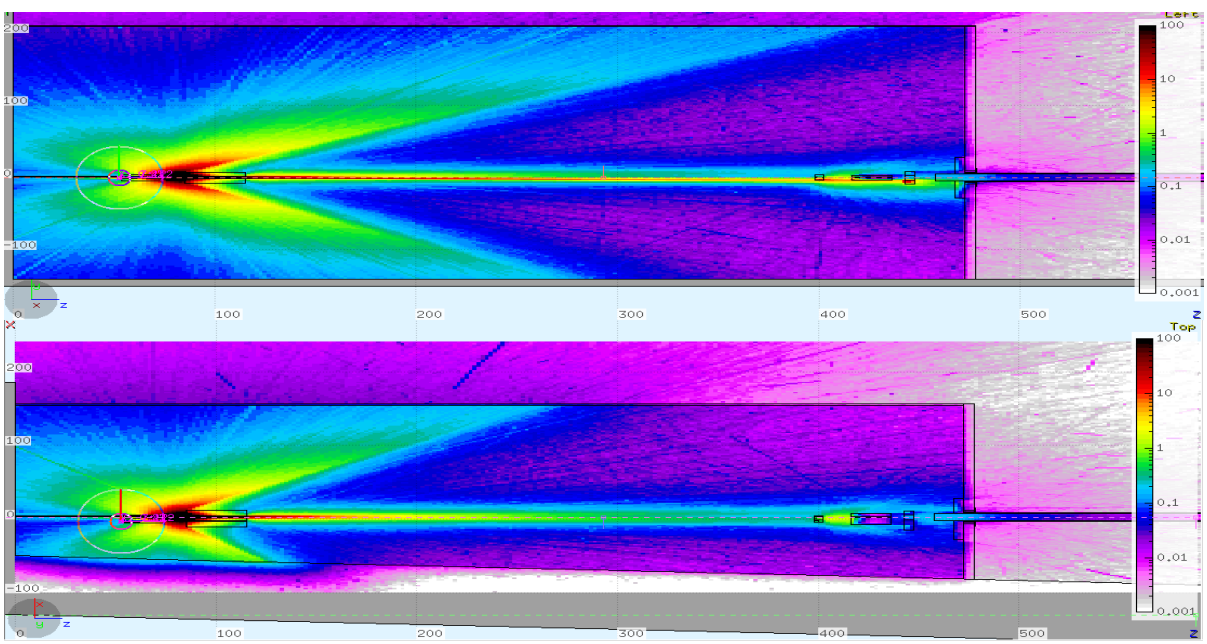


Figure 8: The total dose distributions (mrem/h) in the FOE. The top figure shows the vertical view and the bottom shows the horizontal view at the beam centerline.

3.1 (d) GB Incident on the Outboard Front Face of FM1

The GB source was placed just upstream of the front face of the dual aperture FM1. In this simulation the GB was started at x=2.7852, y=0, z=53.59 in the FLUKA model. The total dose rate distribution on the roof, 30 cm away from the lateral wall and on contact with downstream wall of the FOE are given in Figure 9. The BC1 is quite effective in stopping the GB in the forward direction resulting in a maximum dose rate of approximately 0.15 mrem/h on contact with the downstream wall of FOE. Besides, the polyethylene shielding is quite effective in stopping the SGB in the outboard direction keeping the maximum dose rate below 0.05 mrem/h at 1 ft. away from the lateral wall of FOE. The information on polyethylene is shown in Appendix. The total dose rate at 1 ft. away from the roof is also less than 0.05 mrem/h. The total dose rate distribution in the FOE is shown in Figure 10 which clearly demonstrates the effectiveness of BC1 in attenuating and stopping the forward secondary GB.

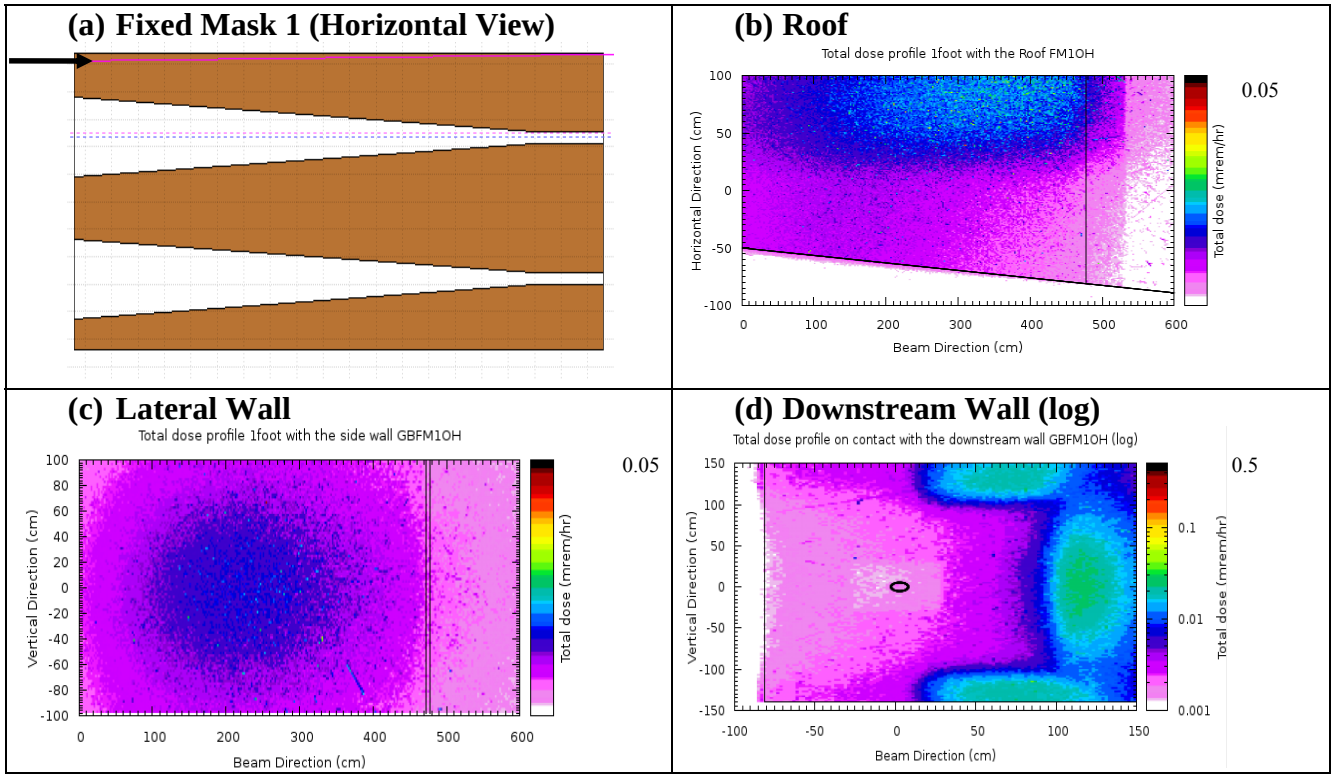


Figure 9: (a) GB incident on the outboard front face of the dual aperture FM1. The total dose distributions in mrem/h on **(b)** the roof**, (c)** at 30 cm from the lateral wall and **(d)** on contact with the downstream wall of FOE.

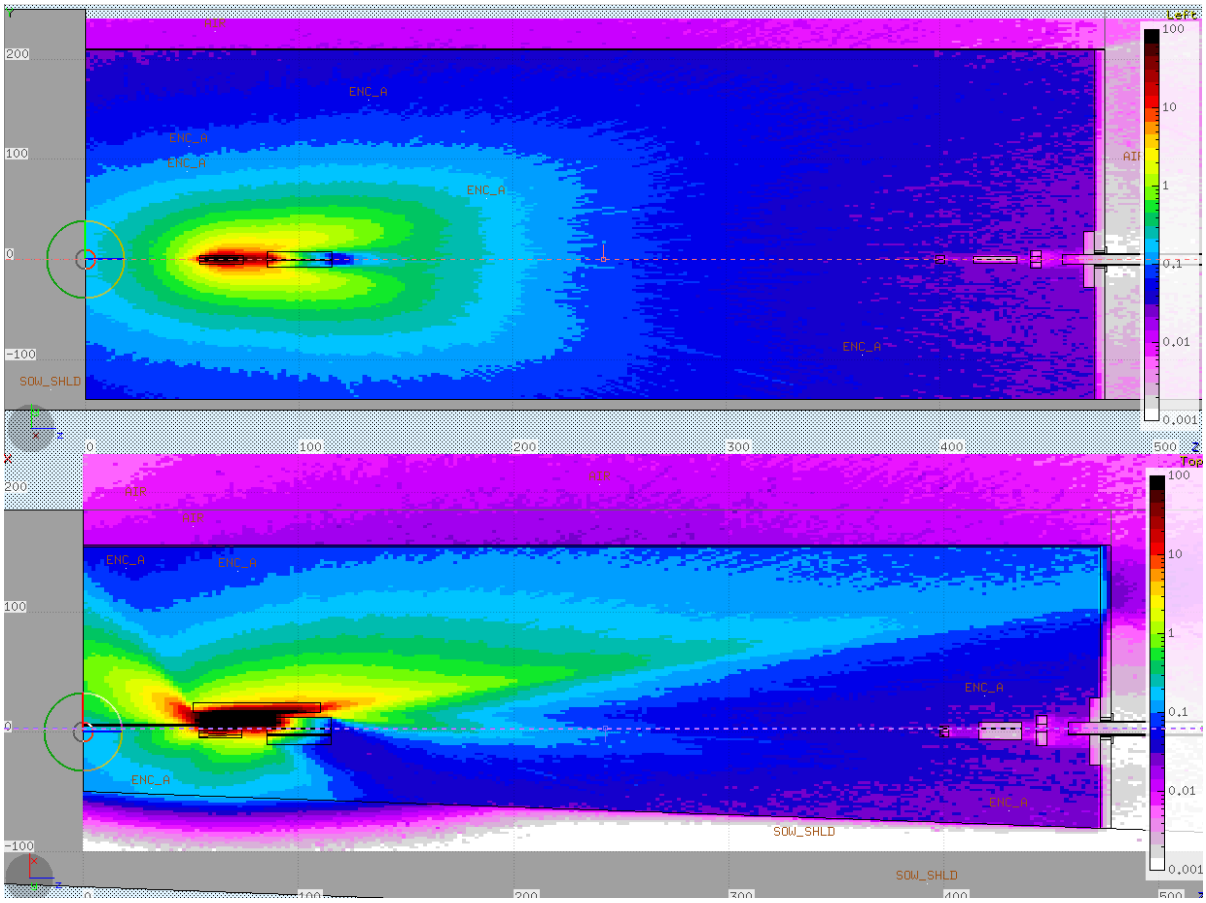
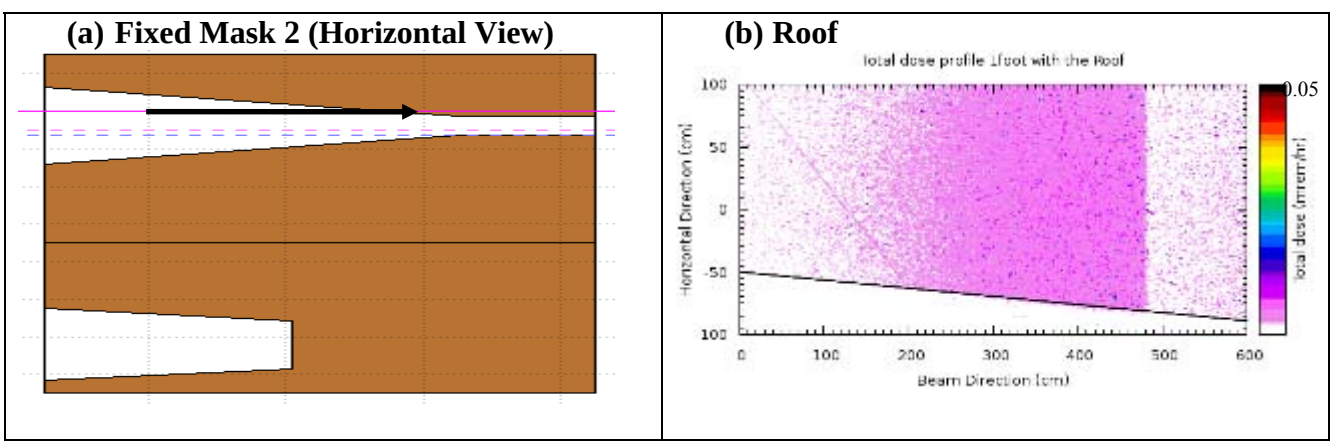


Figure 10: The total dose distributions (mrem/h) in the FOE. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.2 (a) GB Incident on the Outboard Aperture of FM2

In this simulation the GB was started at x=0.359, y=0, z=398.25 and impinges on the outboard tapered plane close to the neck of the aperture. The total dose rate distributions at 1 ft. away from the roof and the lateral wall and on contact with the downstream wall of the FOE are given in Figure 11. The total dose rates from the roof and the lateral wall at 1 ft. away are less than 0.05 mrem/h. The maximum dose rate outside the beam pipe on contact with the downstream wall of the FOE is 0.12 mrem/h.



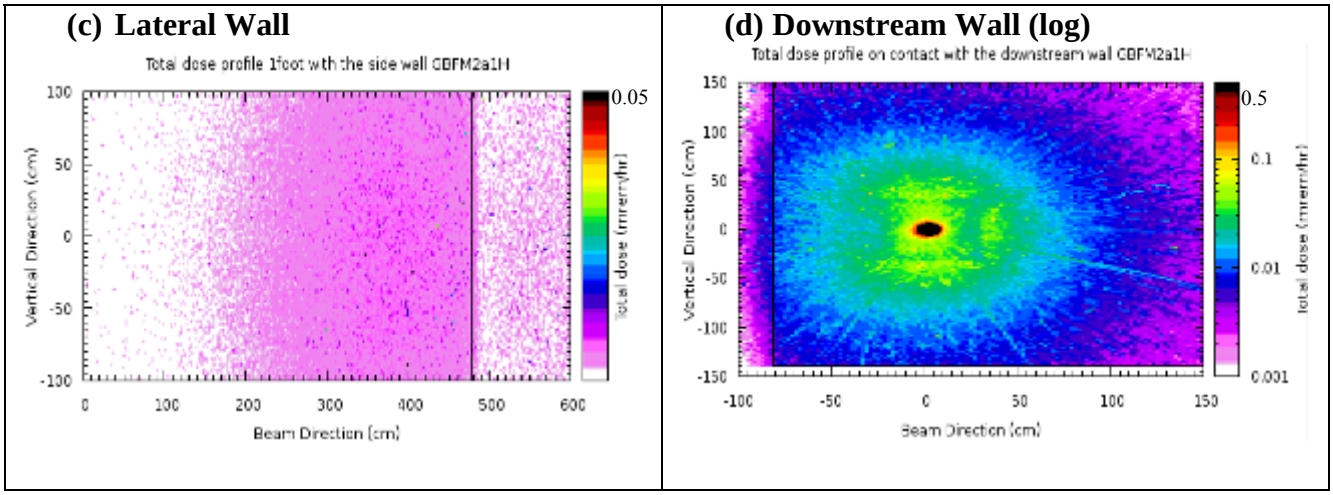


Figure 11: (a) GB incident on the outboard taper near the neck of the FM2 aperture. The total dose distributions in mrem/h **(b)** at 30 cm from the roof, **(c)** at 30 cm from the lateral wall and **(d)** on contact with the downstream wall of FOE

The radiation that is transmitted through the apertures of FM2, BC2 and SGB is contained inside the beam pipe. BC2 stops most of the forward directed radiation. The maximum dose rates have been checked at 1 ft. away from the outer surface of the white beam transport starting from 1 ft. downstream of FOE, and are below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in FOE are shown in Figure 12.

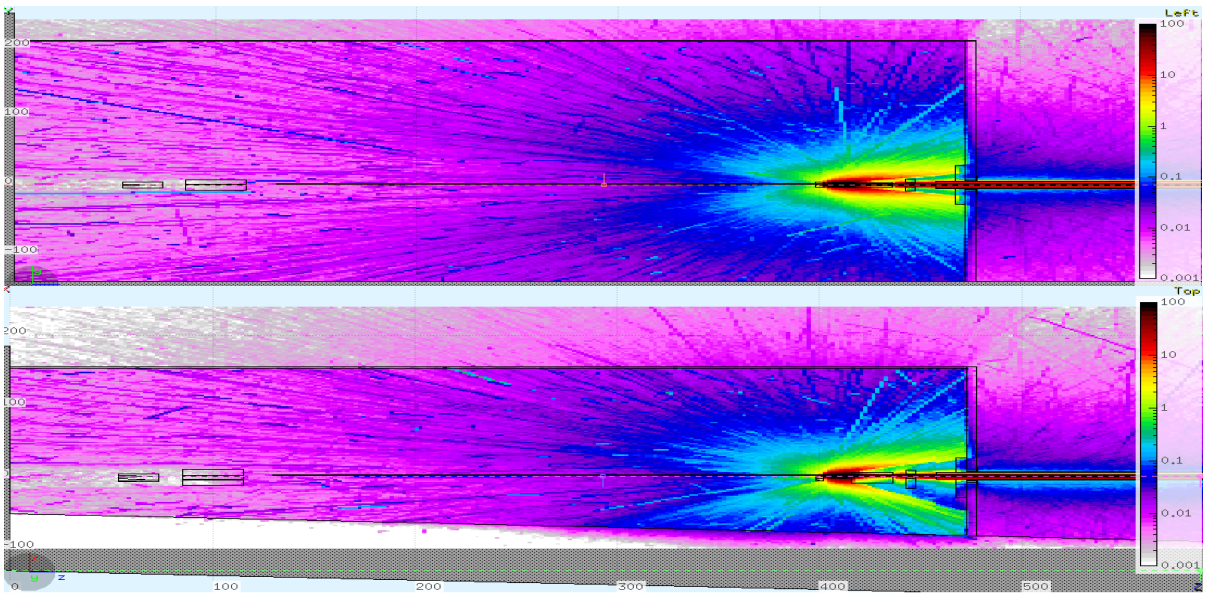


Figure 12: The total dose distributions (mrem/h) in the FOE. The top figure shows the vertical view and the bottom shows the horizontal view at the beam centerline.

3.2 (b) GB Incident on the Inboard Aperture of FM2

In this simulation the GB was started at x=-5.881, y= 0.0, z=398.25 and impinges on the inboard tapered aperture. The total dose rate distributions at 1 ft. away from the roof and the lateral wall and on contact with the downstream wall of the FOE are given in Figure 13. The total dose rates from the roof and the lateral wall at 1 ft. away are less than 0.05 mrem/h. The maximum dose rate on contact with the downstream wall of the FOE is 0.18 mrem/h.

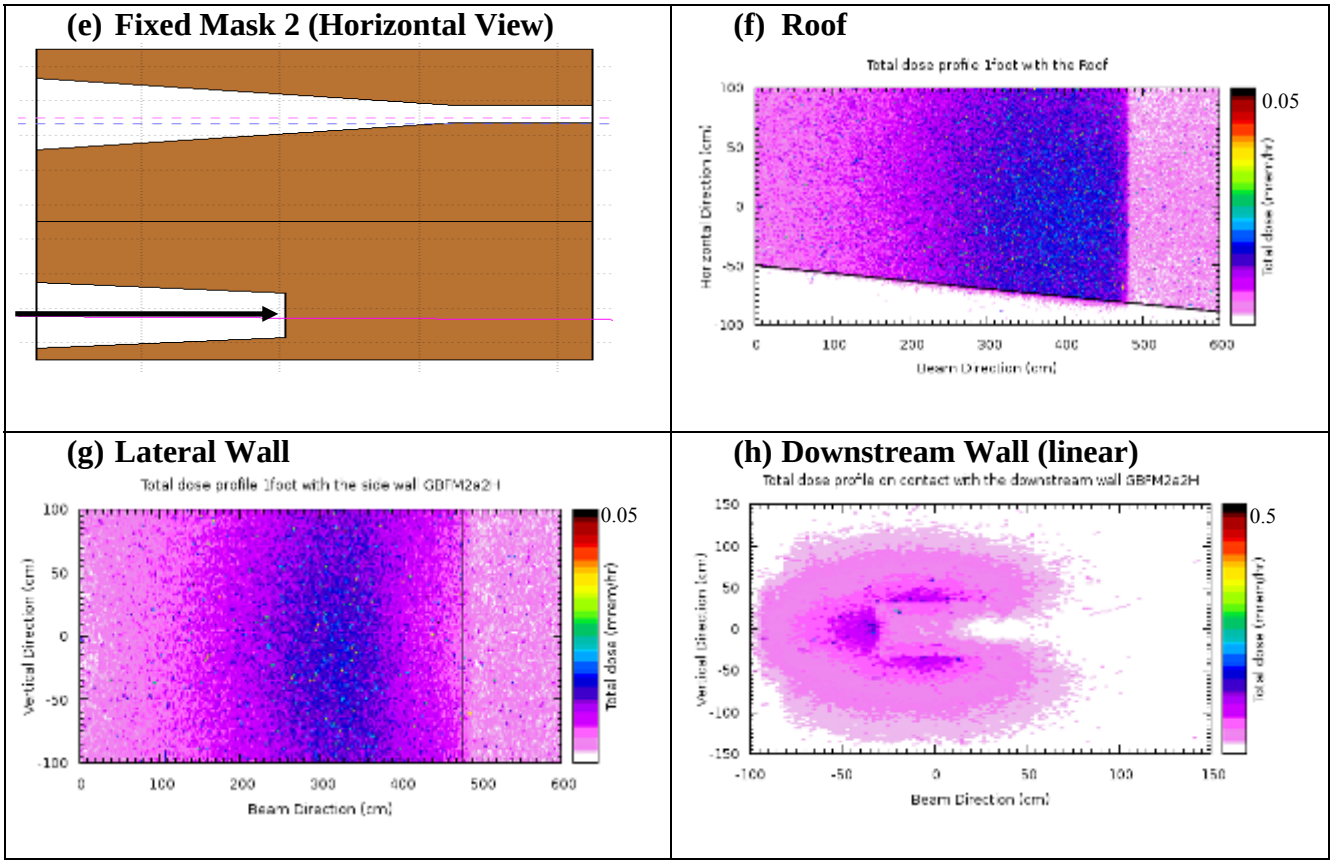


Figure 13: (a) GB incident on the outboard taper near the neck of the FM2 aperture. The total dose distributions in mrem/h **(b)** at 30 cm from the roof, **(c)** at 30 cm from the lateral wall and **(d)** on contact with the downstream wall of FOE

BC2 stops most of the forward directed radiation. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the FOE are shown in Figure 14.

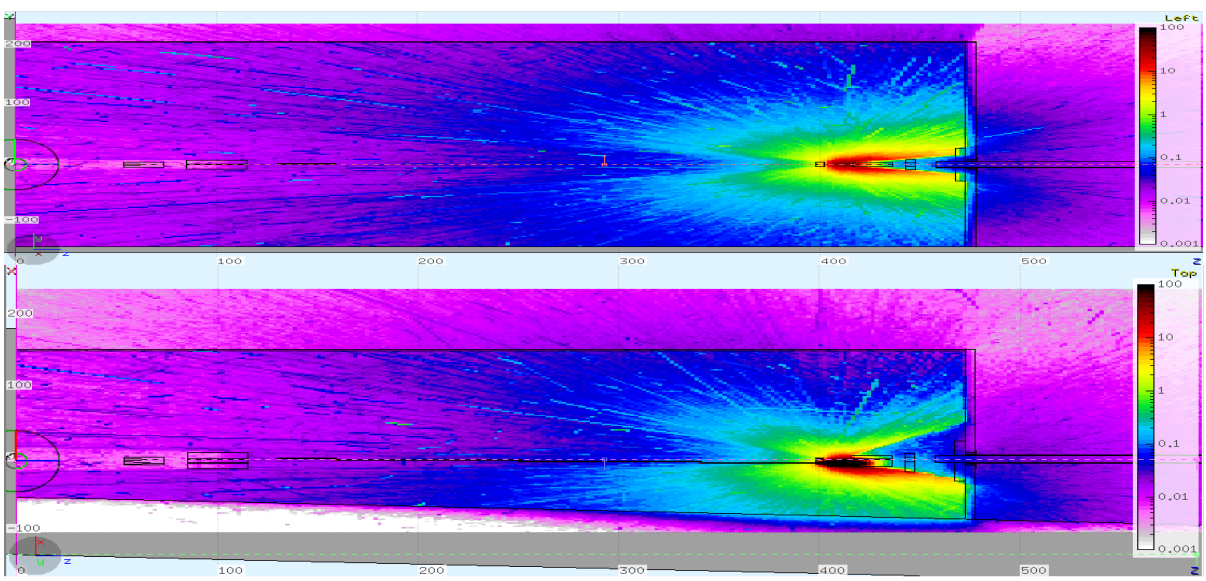


Figure 14: The total dose distributions (mrem/h) in the FOE. The top figure shows the vertical view and the bottom the horizontal view at the beam centerline.

3.2 (c) GB Incident on the Top of the Outboard Aperture of FM2

In this simulation the GB was started at x=-0.221, y=0.23, z=398.25 and impinges on the top tapered plane close to the neck of the aperture. The total dose rate distributions 30 cm away from the roof and lateral wall and on contact with the downstream wall of the FOE are given in Figure 15. The total dose rates at 30 cm away from the roof and the lateral wall are less than 0.05 mrem/h. The maximum dose rate outside the beam pipe on contact with the downstream wall of the FOE is 0.075 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the FOE are shown in Figure 16.

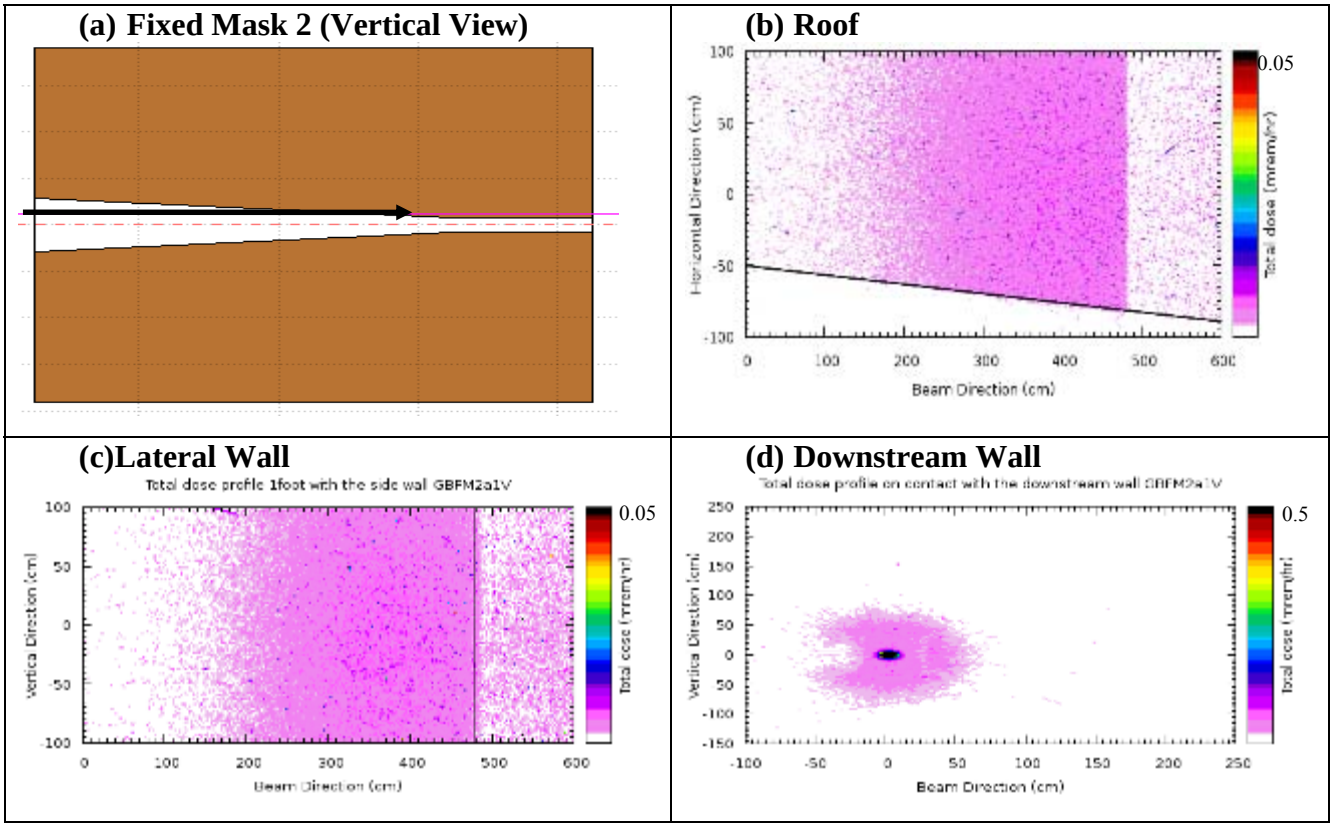


Figure 15. (a) GB incident on the top taper near the neck of the FM2 outboard aperture. The total dose distributions in mrem/h **(b)** at 30 cm from the roof, **(c)** at 30 cm from the lateral wall and **(d)** on contact with the downstream wall of FOE.

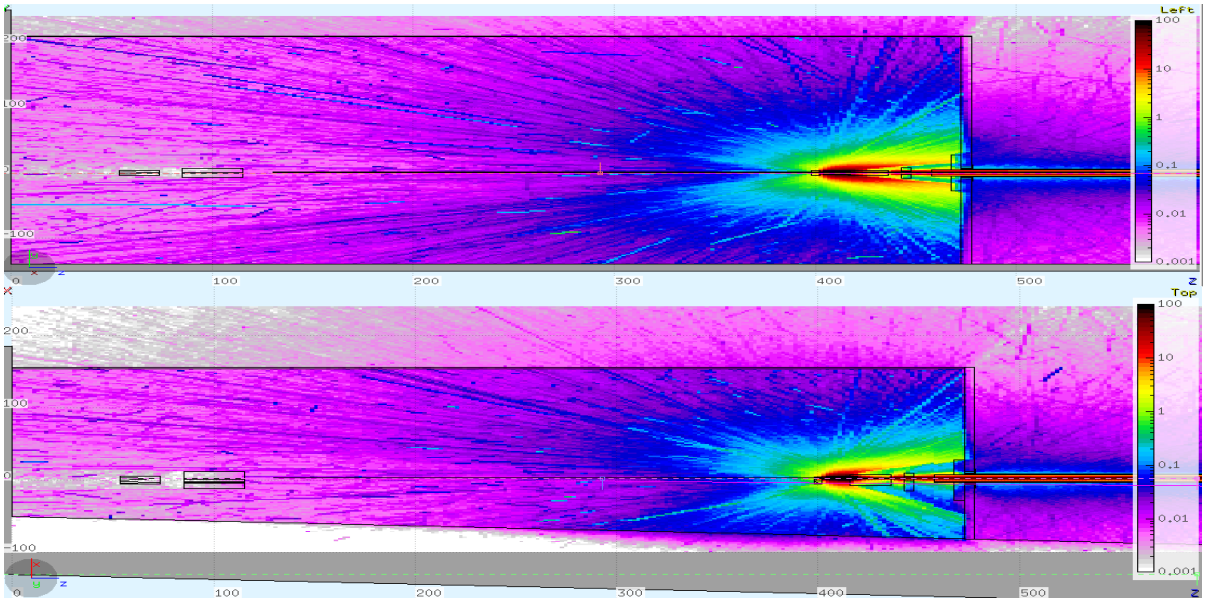


Figure 16. The total dose distributions (mrem/h) in the FOE. The top figure shows the vertical view and the bottom shows the horizontal view at the beam centerline.

3.2 (d) GB Incident on the Outboard Front Face of FM2

The GB source was placed just upstream of the front face of the dual aperture FM2. In this simulation the GB was started at x=1.839, y=0, z=398.25 in the FLUKA model. The total dose rate distribution 30 cm away from the roof and lateral wall and on contact with the downstream wall of the FOE are given in Figure 17. BC2 is quite effective in stopping the GB in the forward direction resulting in a maximum dose rate of approximately 0.146 mrem/h on contact with the downstream wall of the FOE. The total dose rates at 1 ft. away from the roof and lateral wall are less than 0.05 mrem/h. The total dose rate distribution in the FOE is shown in Figure 18 which clearly demonstrates the effectiveness of BC2 in attenuating and stopping the forward secondary GB.

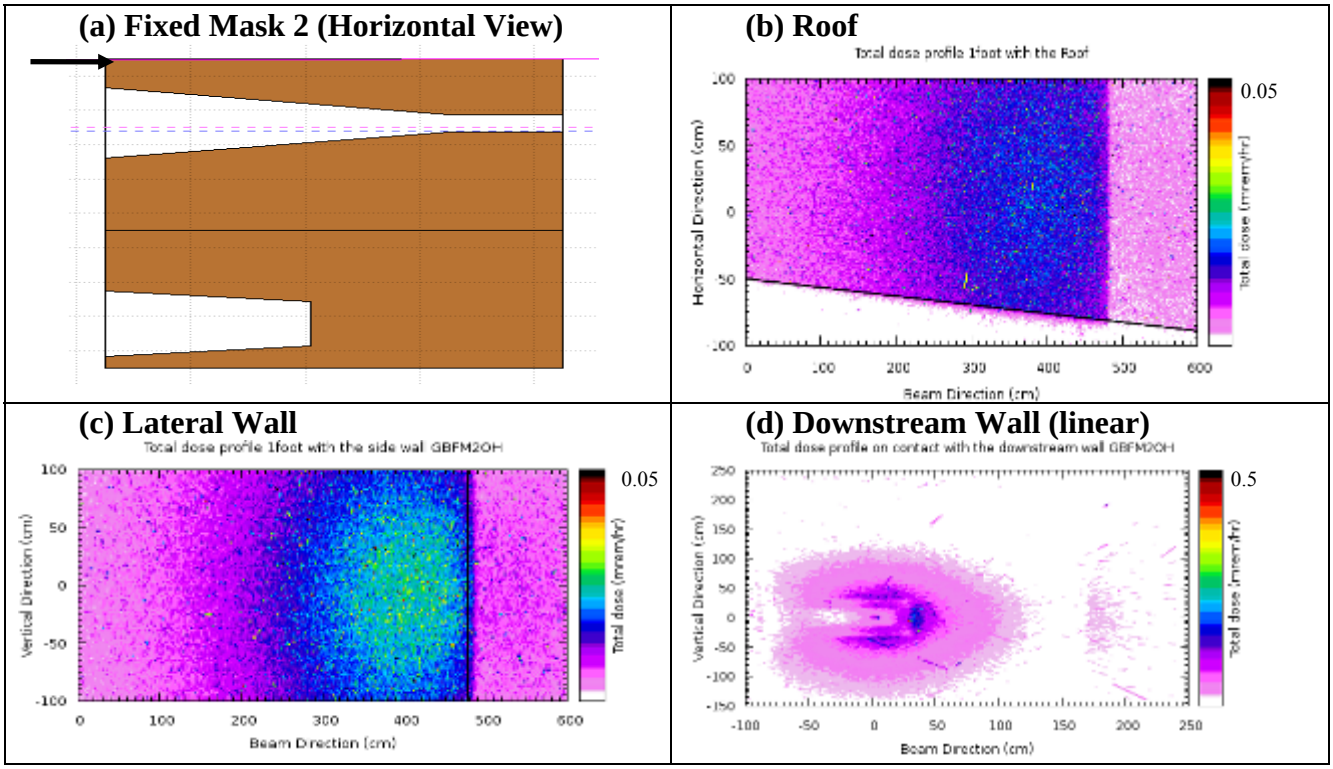


Figure 17: (a) GB incident on the outboard front face of the dual aperture FM2. The total dose distributions in mrem/h **(b)** at 30 cm from the roof, **(c)** at 30 cm from the lateral wall and **(d)** on contact with the downstream wall of FOE.

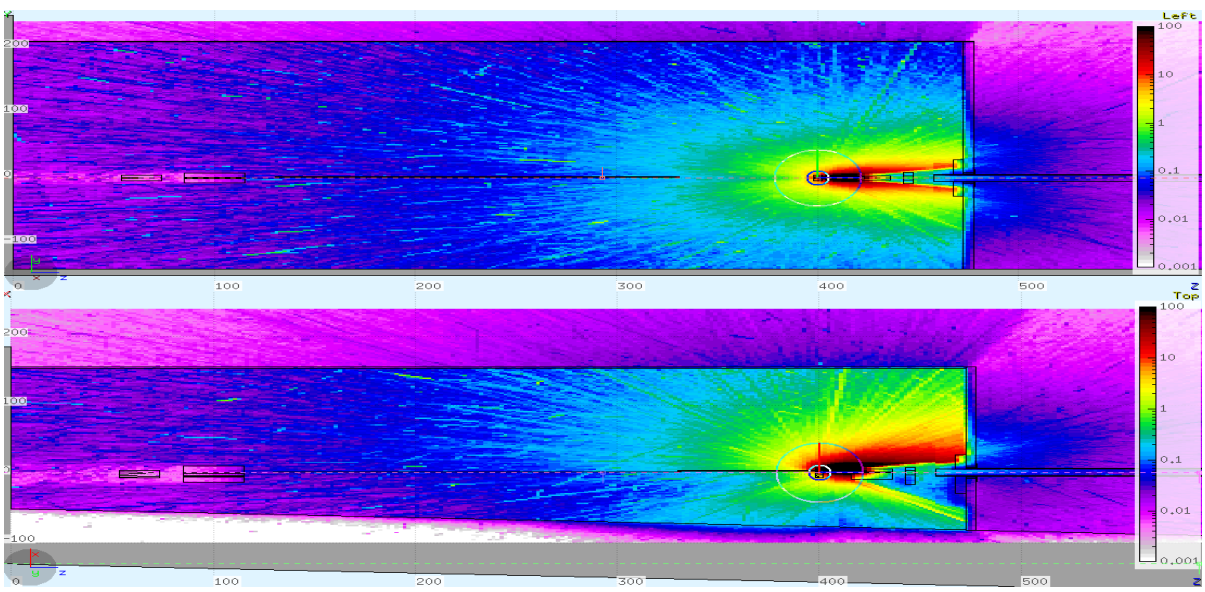


Figure 18: The total dose distributions (mrem/h) in the FOE. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.3 (a) GB Incident on the Inboard Aperture of FM3

The FLUKA model of the copper fixed mask and the impact location of the GB beam are shown in Figure 19(a). 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 at x=-0.507, y=0, z=2495.71 and impinges on the inboard tapered plane close to the neck of the aperture. The width and height of the downstream aperture is 8.0 mm × 4.0 mm. The total dose distributions in mrem/h at 30 cm away from the roof, inboard and outboard lateral walls, and

downstream and upstream walls of the C-Hutch are shown in Figure 19(b), (c), (d), (e), and (f), and are below 0.05 mrem/h.

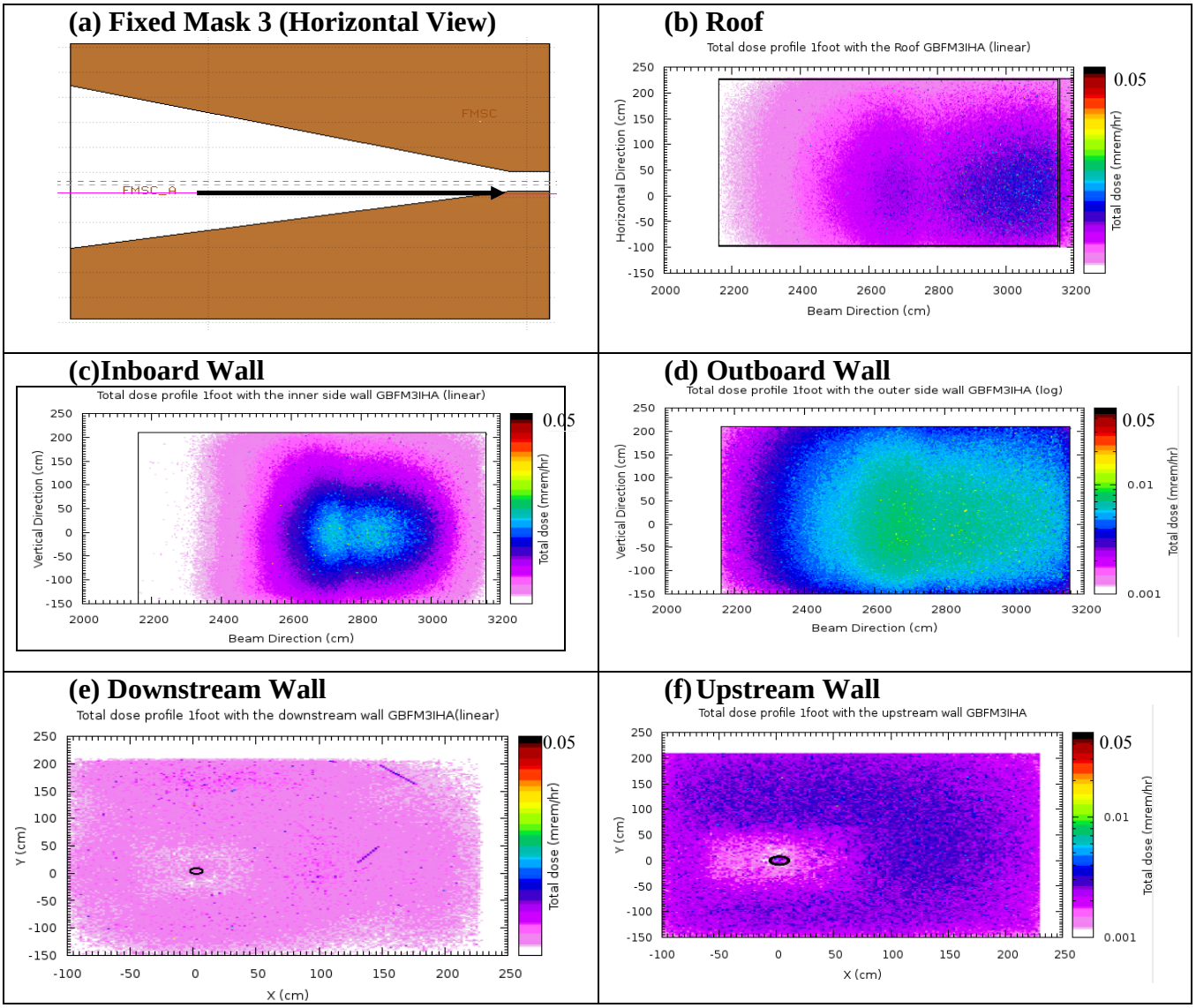


Figure 19: (a) GB incident on the inboard of the aperture of FM3. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

To understand the contribution of the various beamline components on the dose distribution it is useful to look at the vertical and horizontal profiles of the dose distribution in the C-Hutch (Figure 20). When the GB hits the mask it is scattered largely in the forward direction. The radiation that passes through the aperture of FM3 becomes attenuated and collimated by BC3 before it impinges on the white beam stop (WBS) which becomes a scattering target. Figure 20 shows clearly the impact of BC3 in blocking the forward secondary GB. The total doses at 1 ft. away from the roof, inboard and outboard side walls, and upstream and downstream walls are below 0.05 mrem/h in C-Hutch.

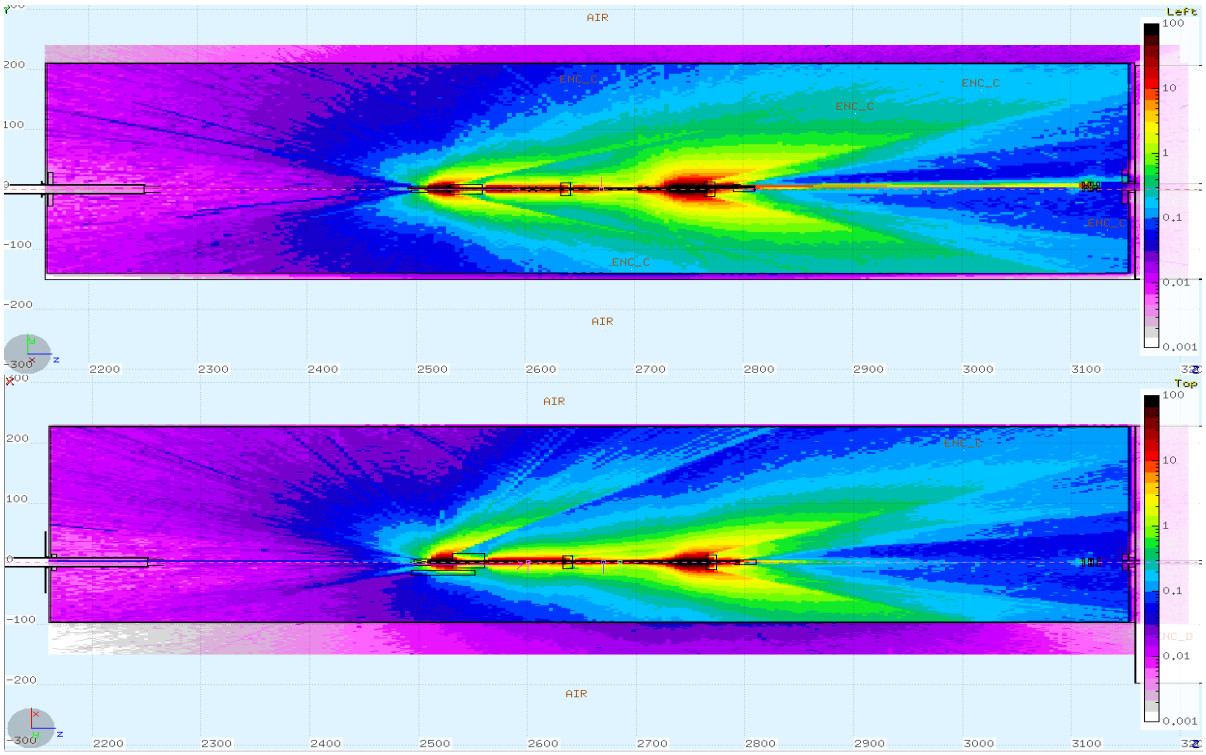
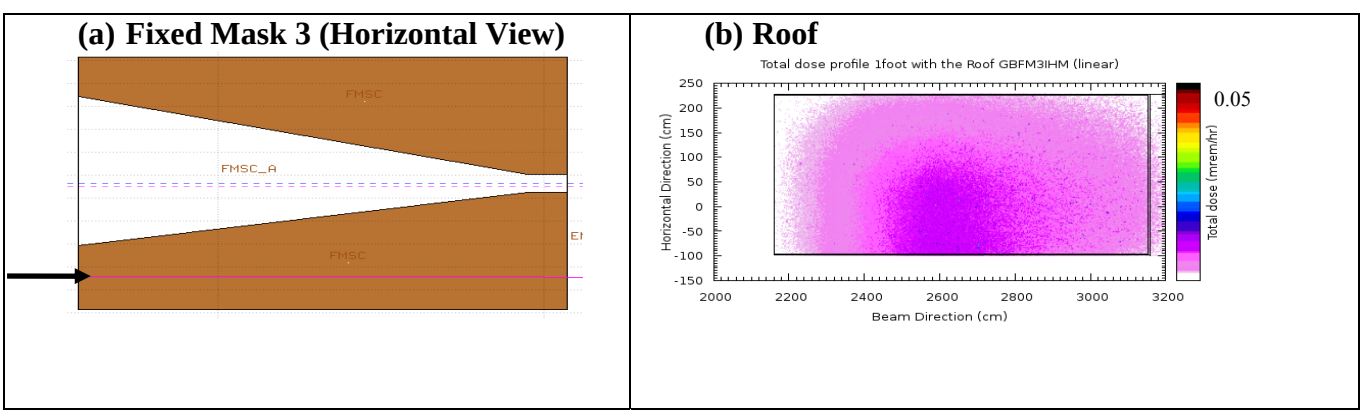


Figure 20: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.3 (b) GB Incident on the Middle Point of the Inboard Front Face of FM3

The GB source was placed at the middle point of the inboard front face of FM3. In this simulation the GB was started at x=-4.045, y=0, z=2795.71 in the FLUKA model. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 21. BC3 is quite effective in stopping the GB in the forward direction resulting in maximum dose rate below 0.05 mrem/h at 1 ft. away from the downstream wall in the C-Hutch. Besides, the polyethylene shielding, the same as the one in the FOE, is quite effective in stopping the SGB in the inboard direction keeping the maximum dose rate below 0.05 mrem/h at 1 ft. away from the inboard wall. The total dose rates at 1 ft. away from the roof, outboard side wall, and upstream wall are less than 0.05 mrem/h. The total dose rate distribution in the C-Hutch is shown in Figure 22, which clearly demonstrates the effectiveness of BC3 in attenuating and stopping the forward secondary GB.



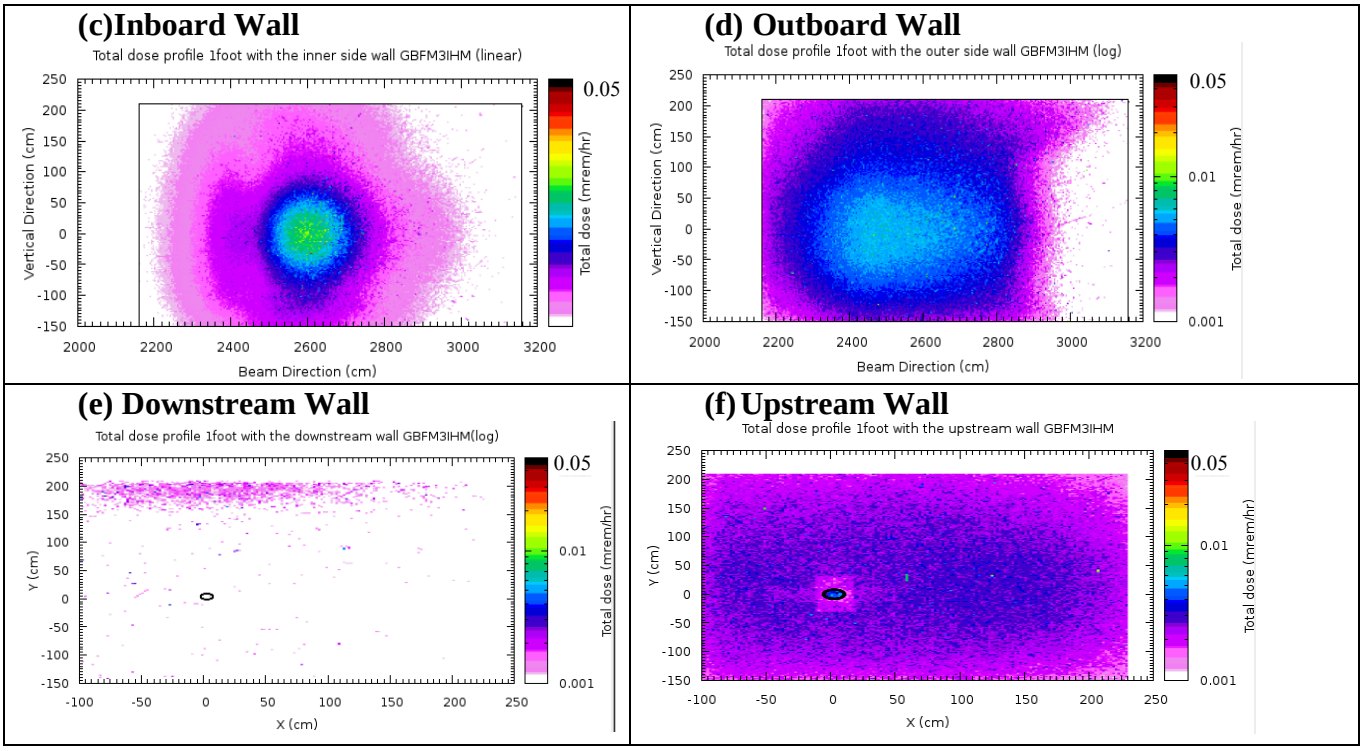


Figure 21: (a) GB incident on the middle point of the inboard front face of the FM3. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

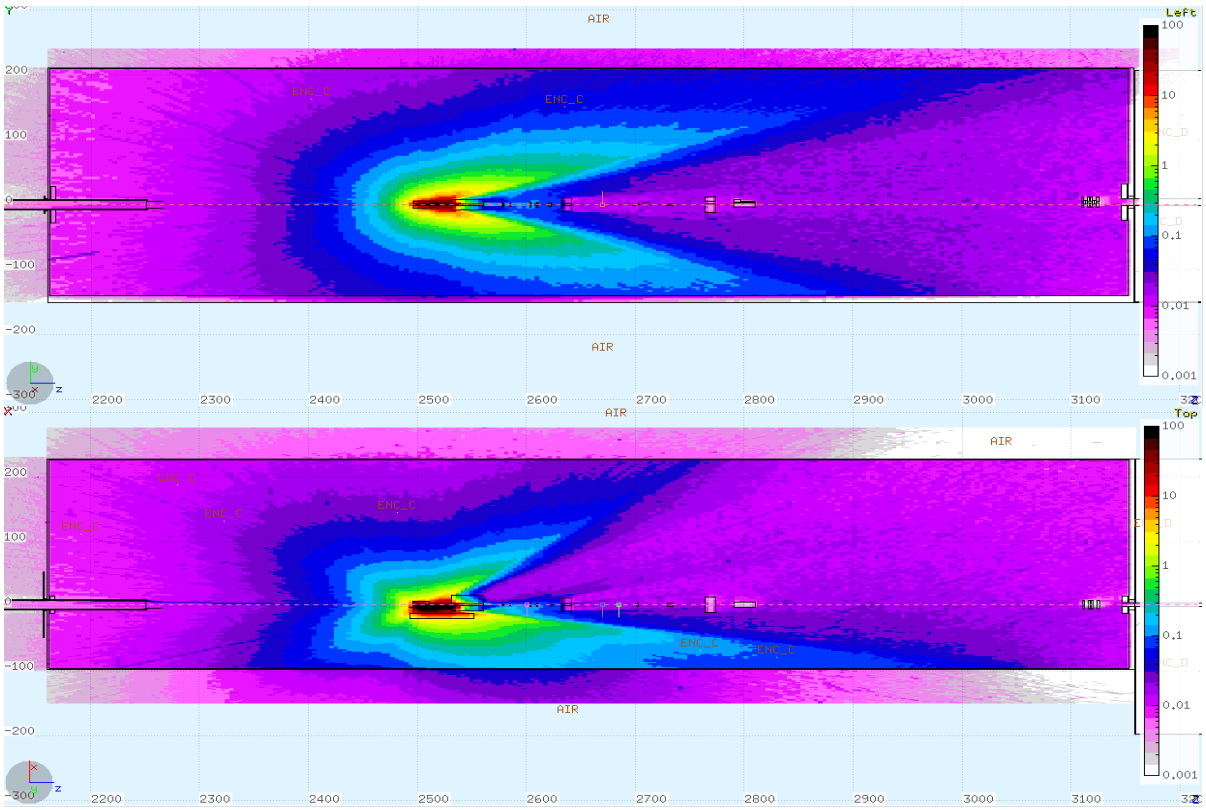


Figure 22: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.3 (c) GB Incident on the Edge of the Inboard Front Face of FM3

The GB source was placed just upstream on the edge of the inboard face of FM3. In this simulation the GB was started at x=-5.457, y=0, z=2495.71 in the FLUKA model. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 23. BC3 is quite effective in stopping the GB in the forward direction resulting in a maximum dose rate below 0.05 mrem/h at 1 ft. from the downstream wall of the C-Hutch. Besides, the polyethylene shielding which is placed at the inboard side of FM3 is quite effective in stopping the SGB transversely resulting in a maximum dose rate below 0.05 mrem/h at 1 ft. away from the inboard wall. The total dose rates at 1 ft. away from the roof, outboard wall, and upstream wall are less than 0.05 mrem/h. The total dose rate distribution in the C-Hutch is shown in Figure 24 which clearly demonstrates the effectiveness of the polyethylene shielding in attenuating and stopping the inboard directed secondary GB.

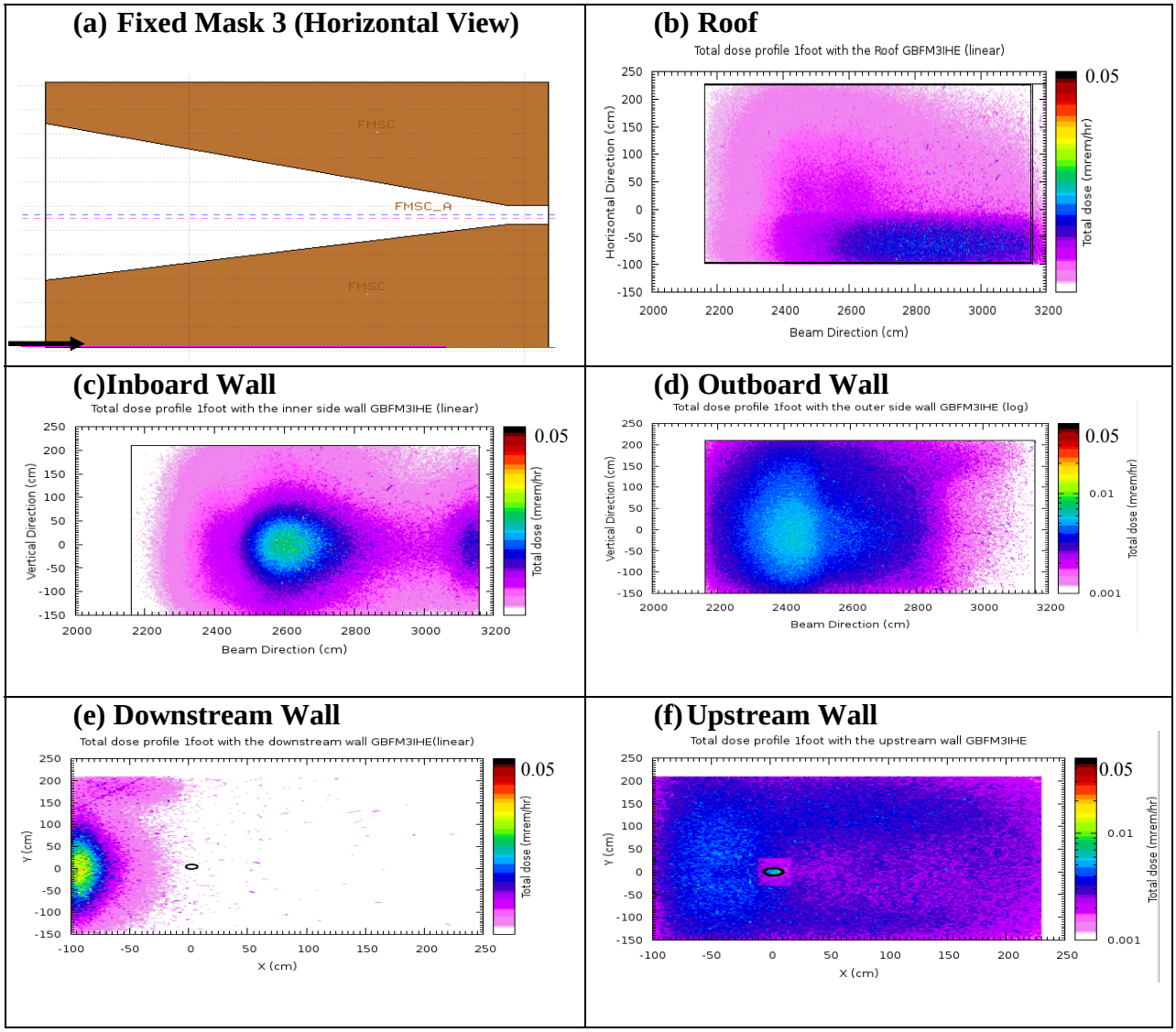


Figure 23: (a) GB incident on the edge of the inboard front face of FM3. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

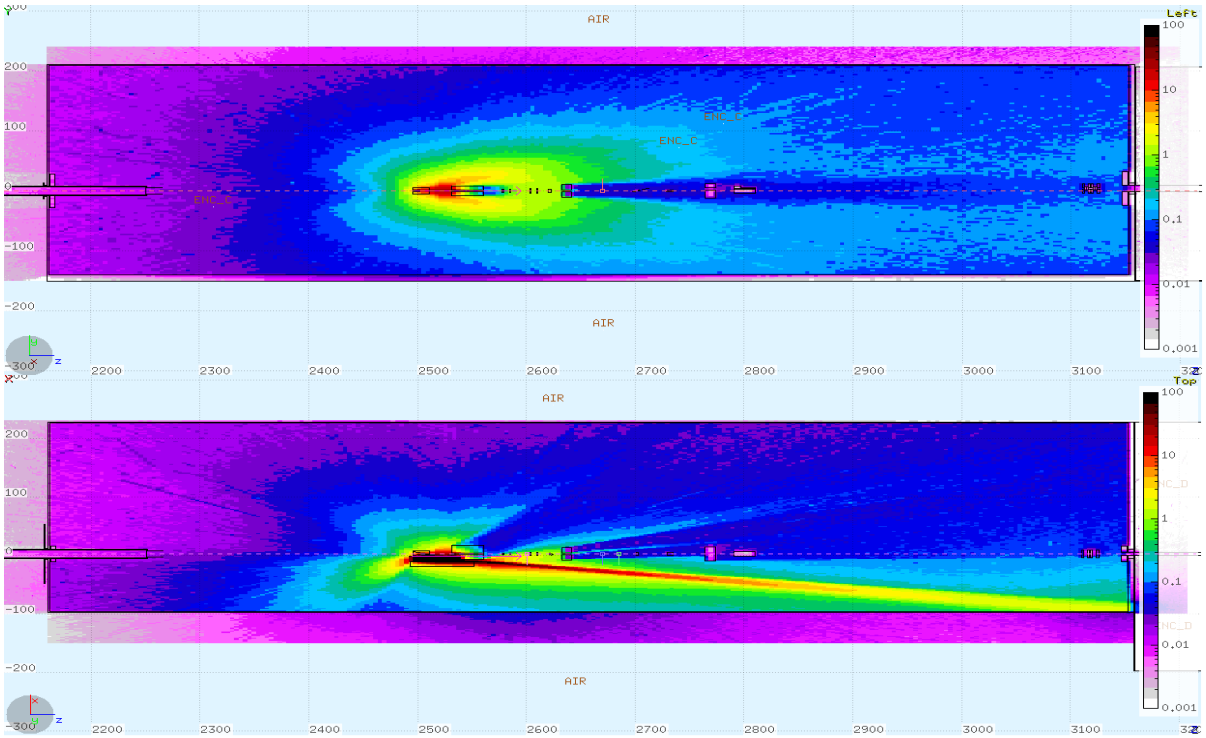
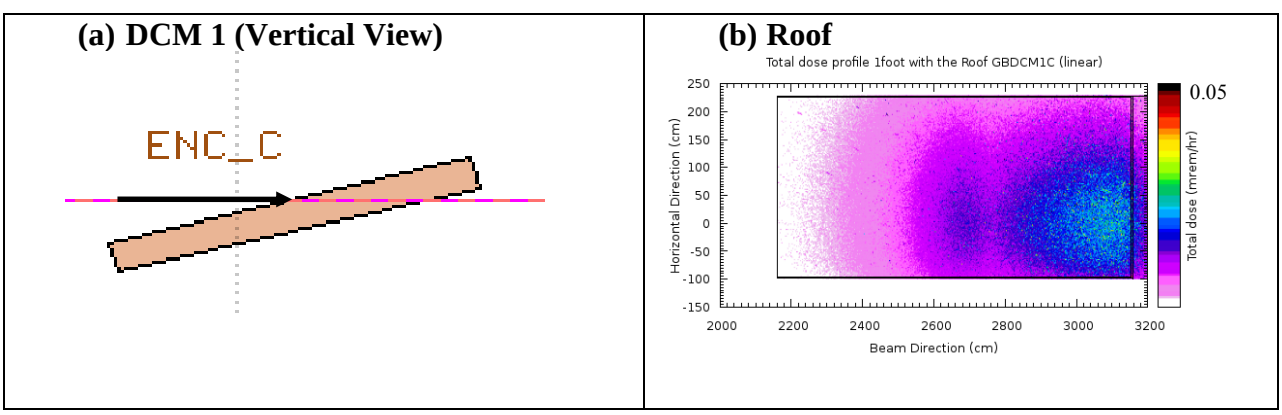


Figure 24: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.4 (a) GB Incident at the Center of DCM1

The silicon monochromator has two crystals. The bottom crystal (1) is centered at z=2700.9 and the top surface of the crystal is at y=0.0. The crystal is modeled as a rectangle block with 4 mm in x, 0.6 mm in y, and 6.5 mm in z. The crystal is rotated to select the energy of the mono-beam. The angle of the top crystal is adjusted to move the mono-beam to y=3.0 cm. In this simulation the GB impinges on the center of the crystal (1) from the top which has been rotated at 14.98º, x=0.0, y=0, z=2700.9. The crystal will reflect only the mono-beam and the GB will be transmitted to impinge on the WBS and the bremsstrahlung stop. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 25 and all are below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in C-Hutch are shown in Figure 26.



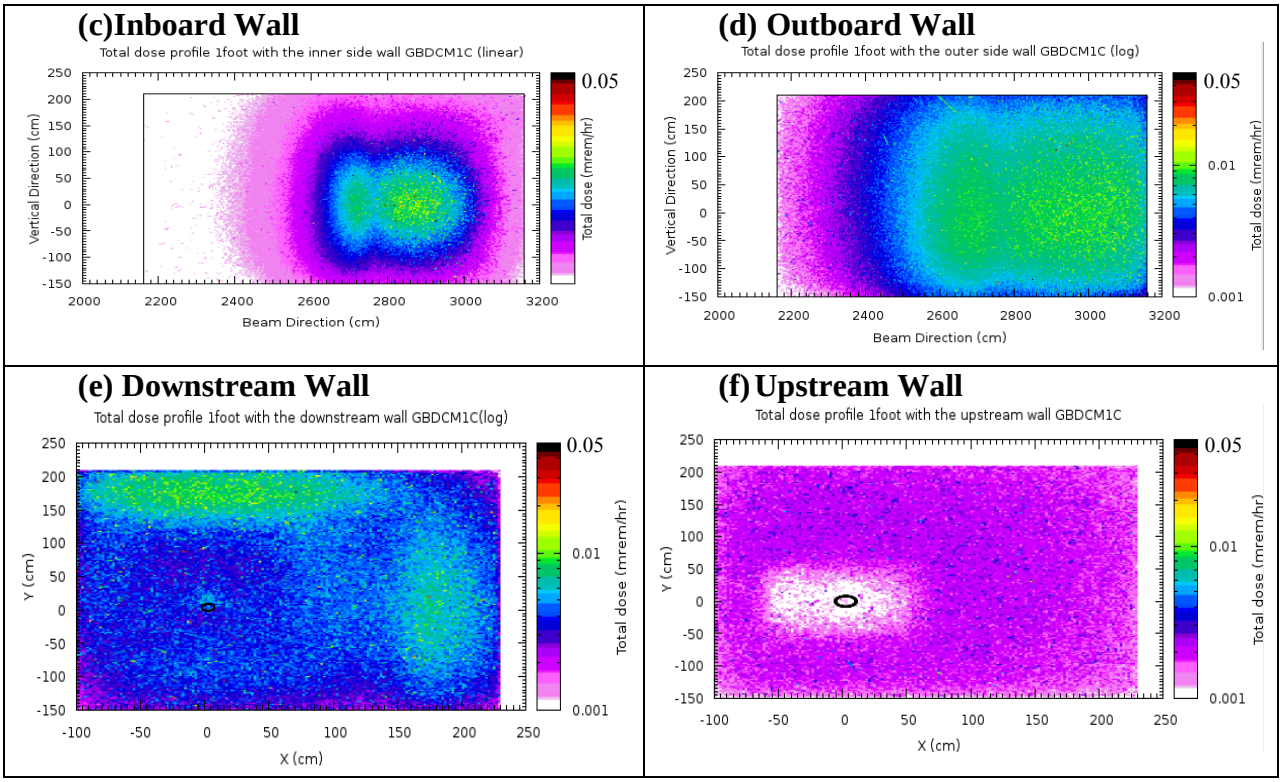


Figure 25: (a) GB incident on the center of DCM1. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

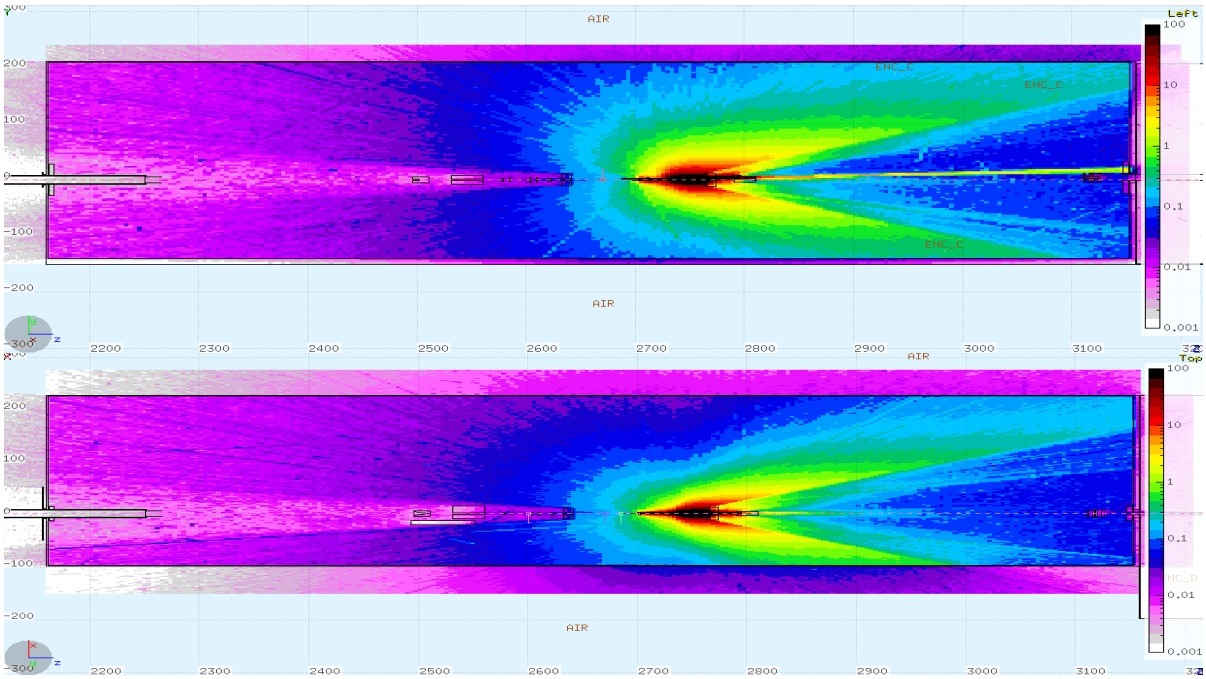


Figure 26: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.4 (b) GB Incident on the Upstream Face of DCM1

In this simulation, the GB impinges on the upstream of the crystal (1) from the top which has been rotated at 14.98º, x=0.0, y=-0.843, z=2697.9. The crystal will reflect only the mono-beam and the GB will be transmitted to impinge on the WBS and the bremsstrahlung stop. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard

lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 27 and are all below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the C-Hutch are shown in Figure 28.

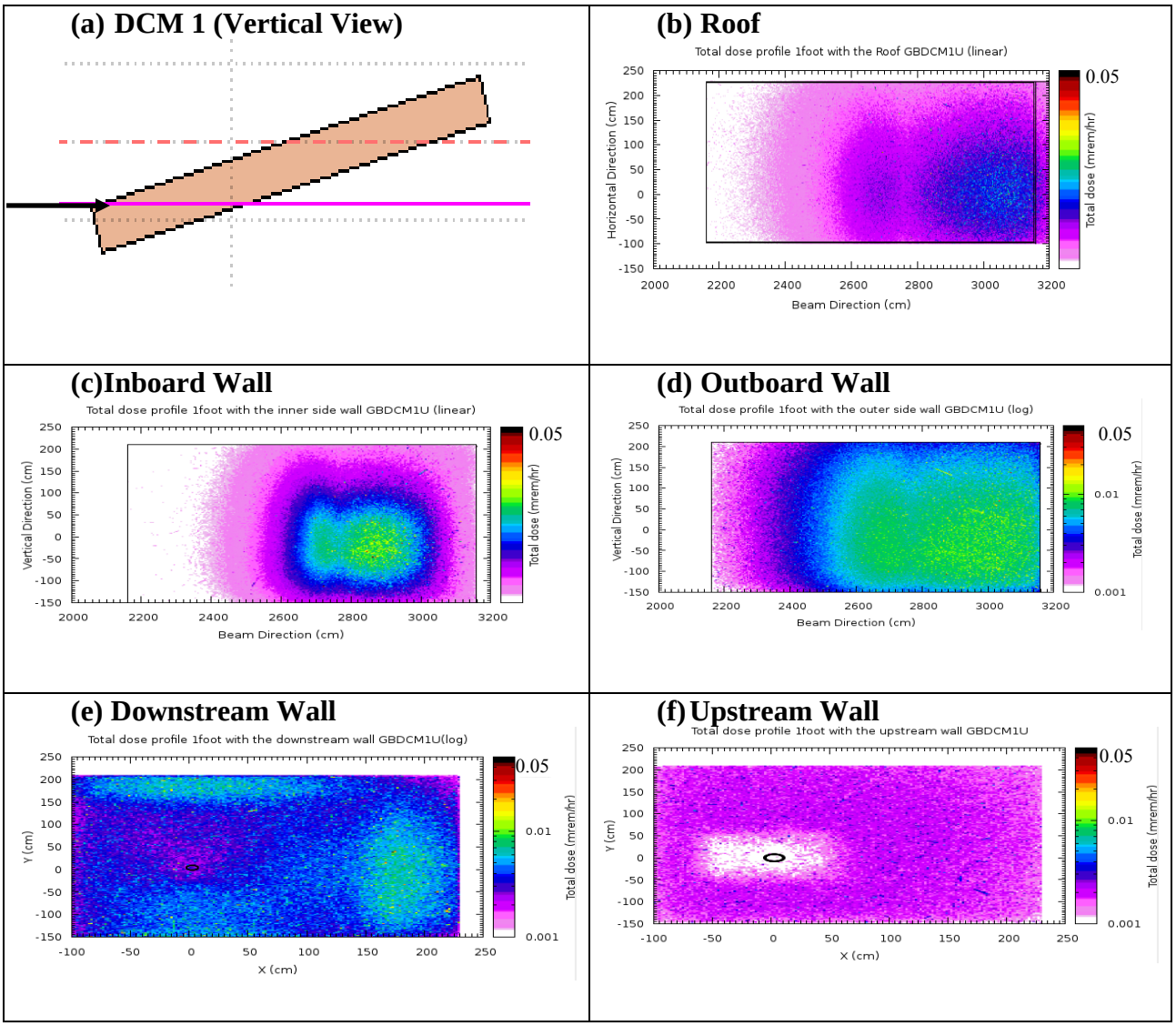


Figure 27: (a) GB incident on the upstream face of DCM1. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

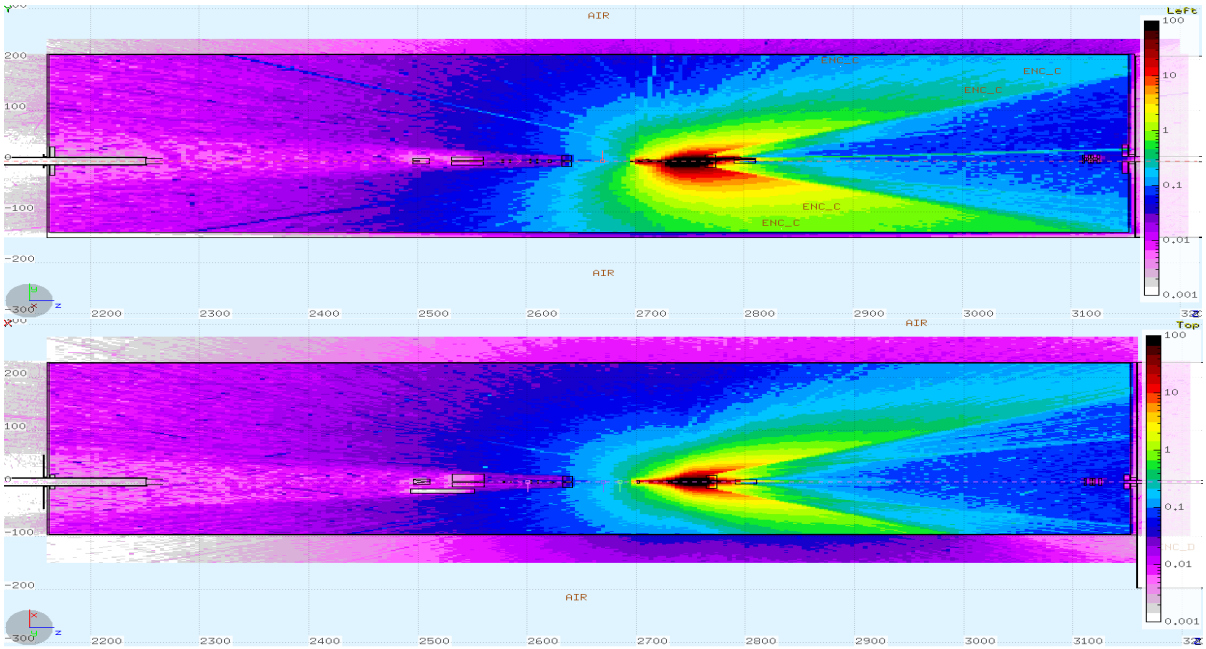
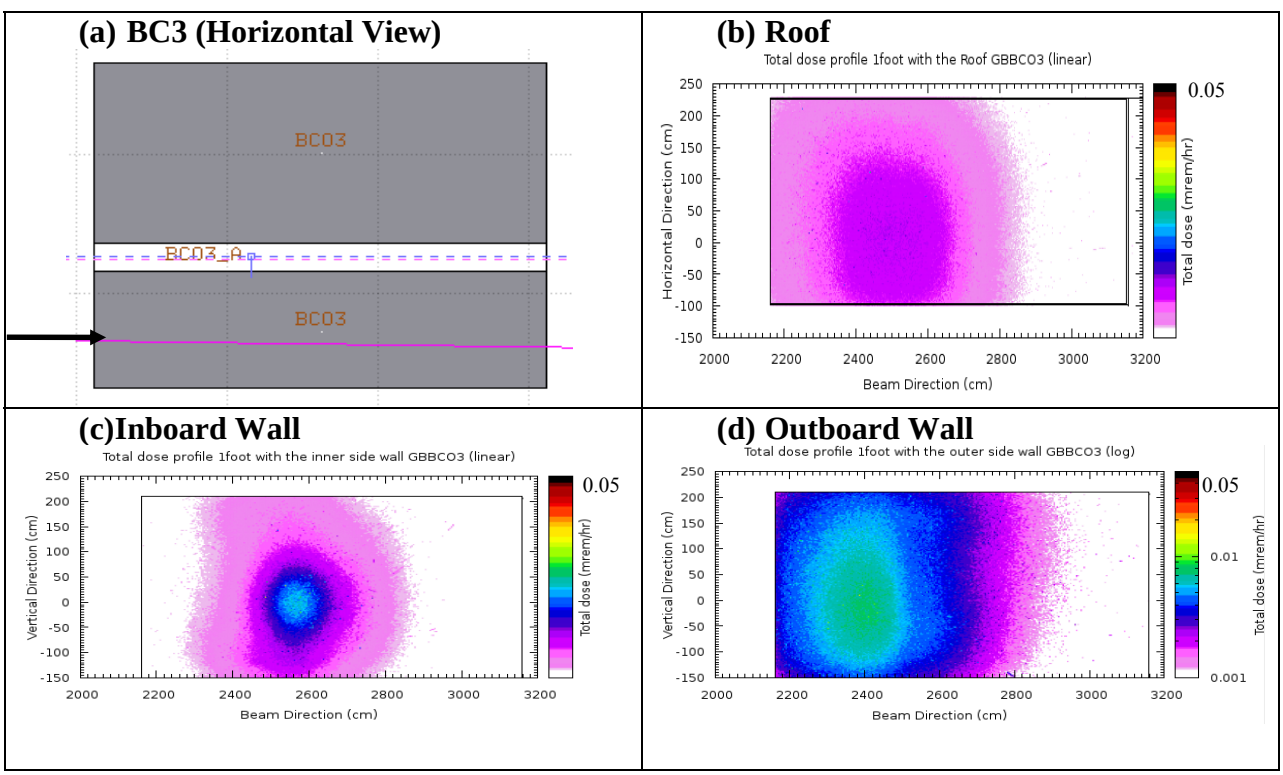


Figure 28: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.5 (a) GB Incident at the Middle Point of the Inboard Side Front Face of BC3

In this simulation it is assumed that the entire GB beam impinges on the front surface of the inboard side of BC3, x=-6.157, y=0, z=2531.17. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 29 and are all below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the C-Hutch are shown in Figure 30.



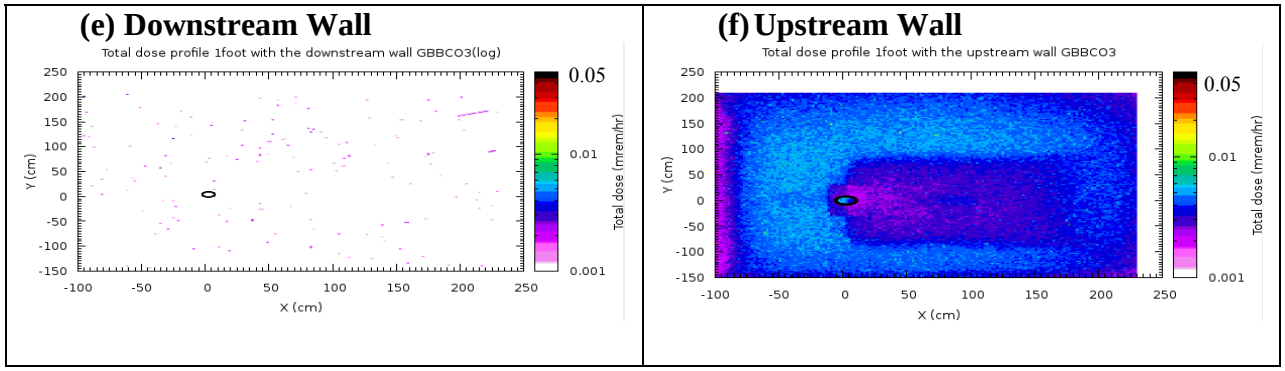


Figure 29: (a) GB incident at the middle point of the inboard side front face of BC3. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

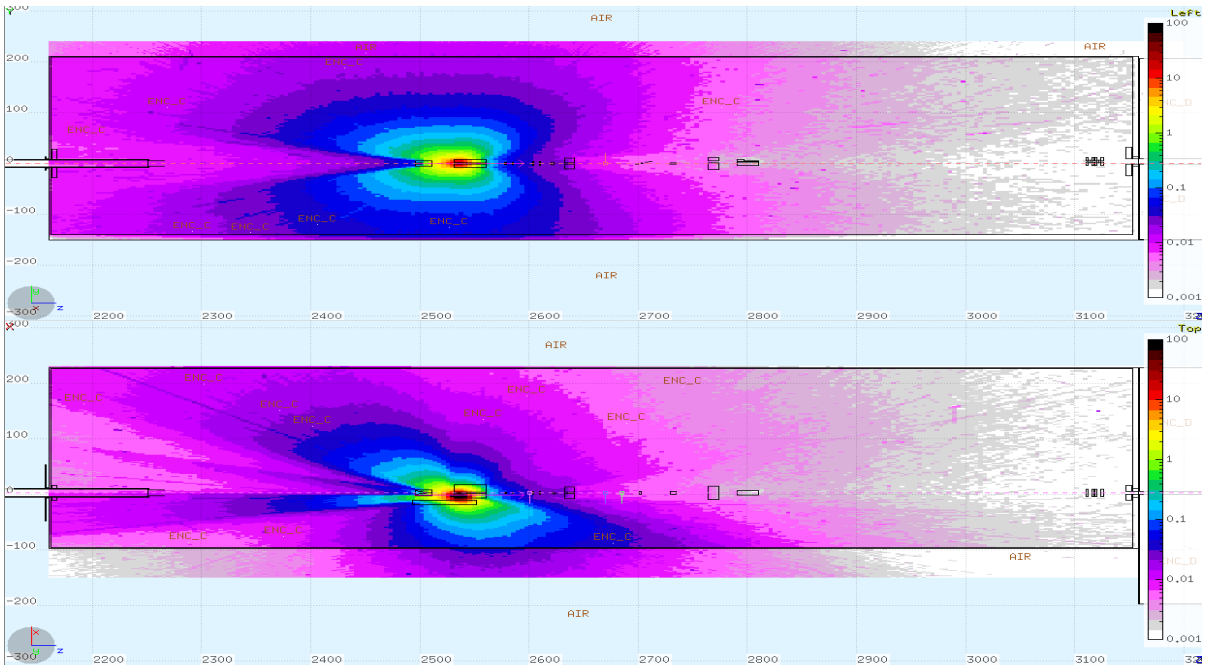


Figure 30: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.6 (a) GB Incident on the Inboard Side of BC4

In this simulation it is assumed that the entire GB beam impinges on the front surface of the inboard side of BC4, x=-1.212, y=0, z=2750.0. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 31 and all below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the C-Hutch are shown in Figure 32.

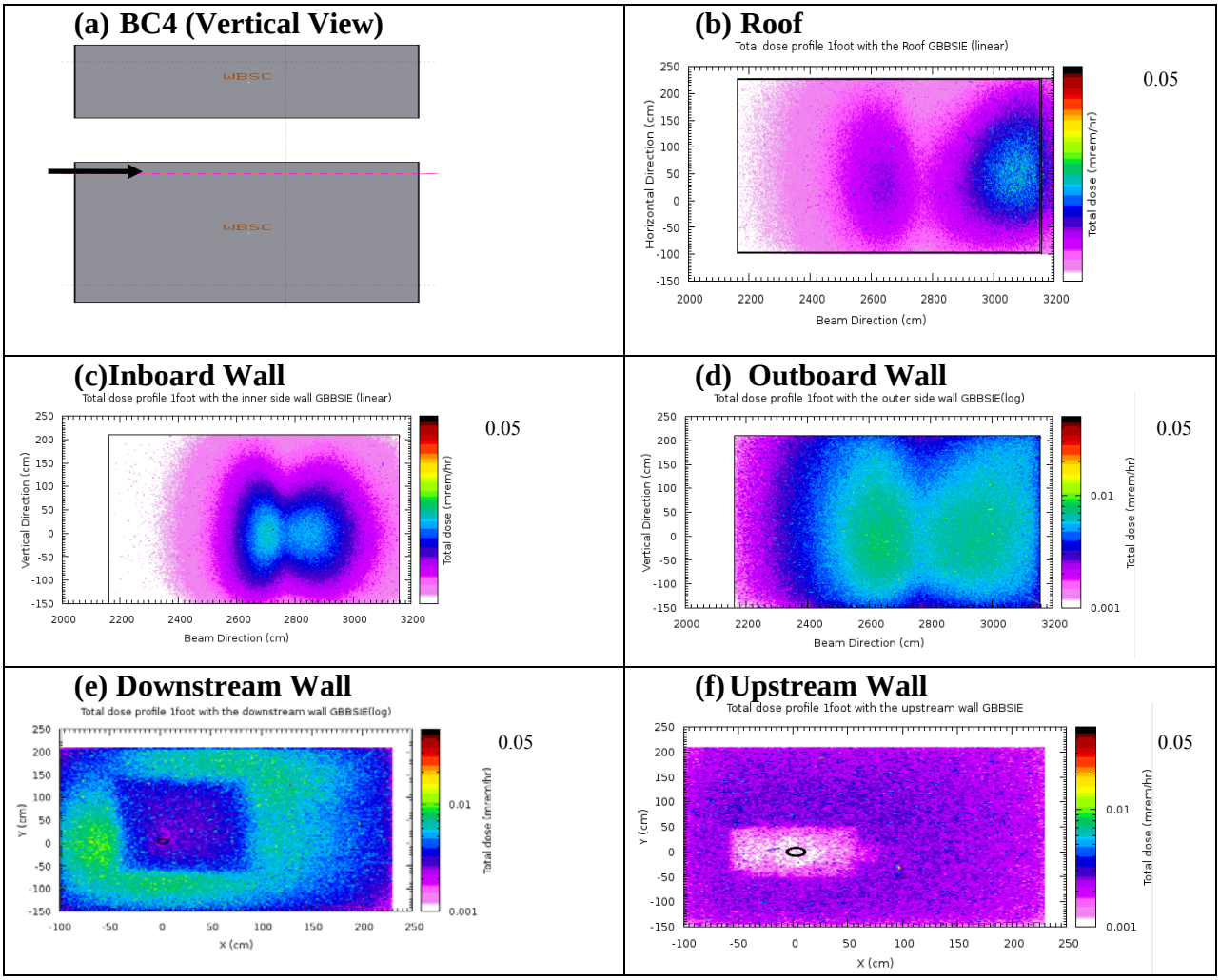


Figure 31: (a) GB incident on the inboard side of BC4. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

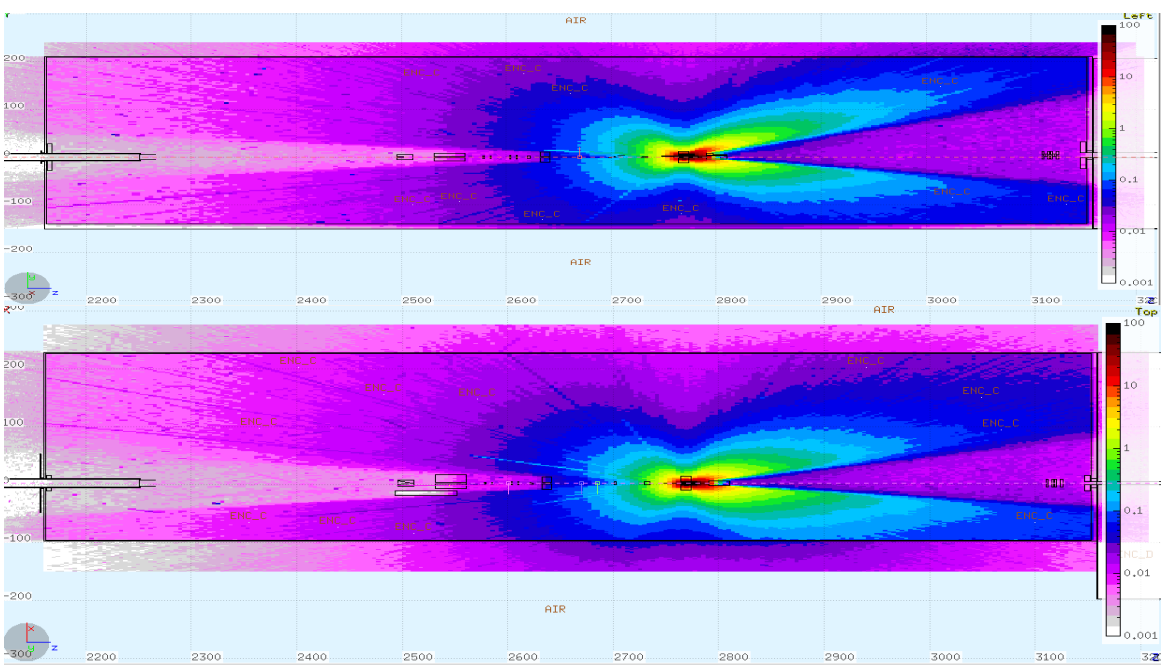


Figure 32: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom shows the horizontal view at the beam centerline.

3.6 (b) GB Incident on the Center Close to the Top of BC4

In this simulation it is assumed that the entire GB beam impinges on the front surface of the inboard side of BC4, x=0, y=1.17, z=2750. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 33 and are all below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the C-Hutch are shown in Figure 34.

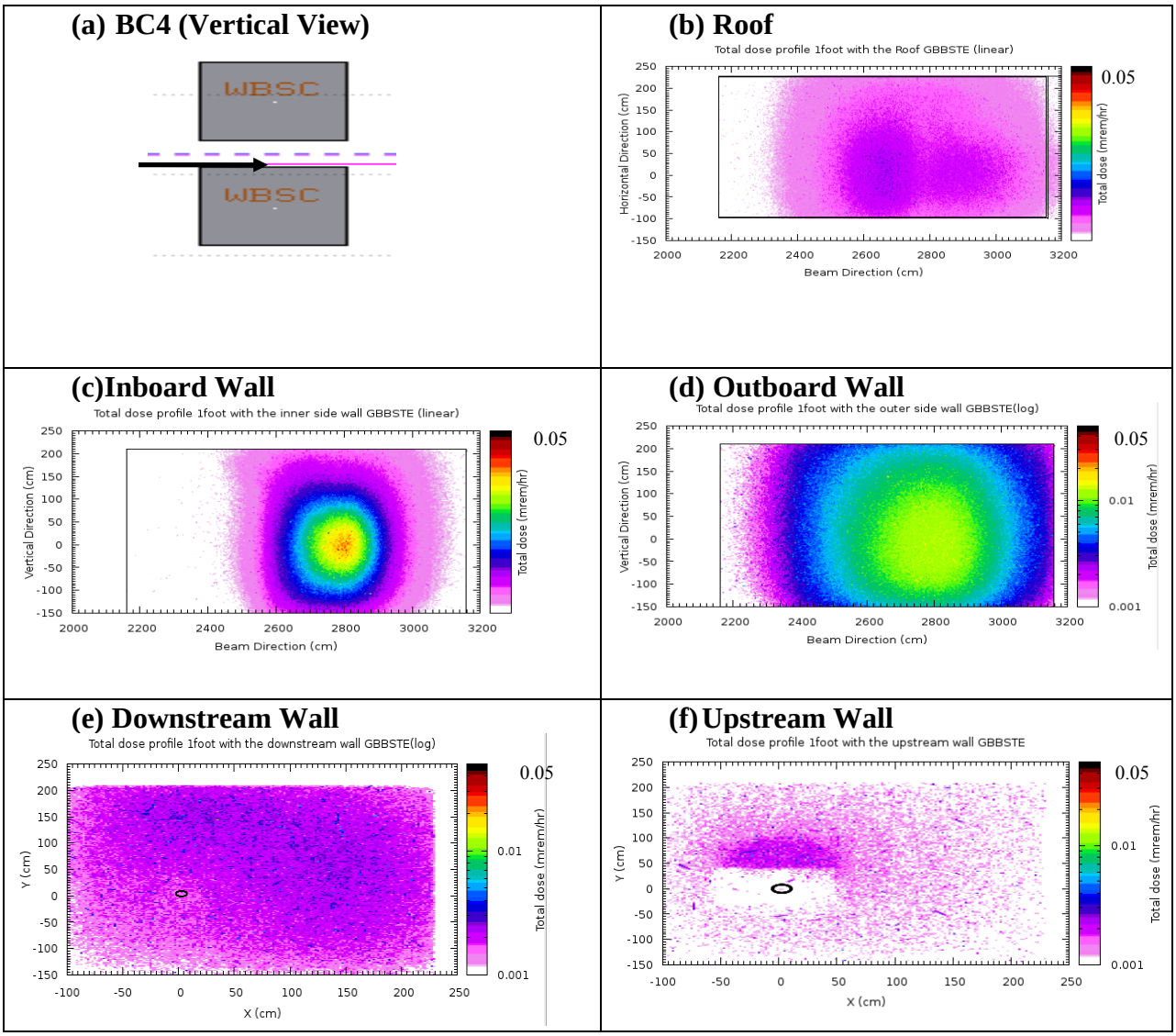


Figure 33: (a) GB incident on the center close to the top of BC4. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

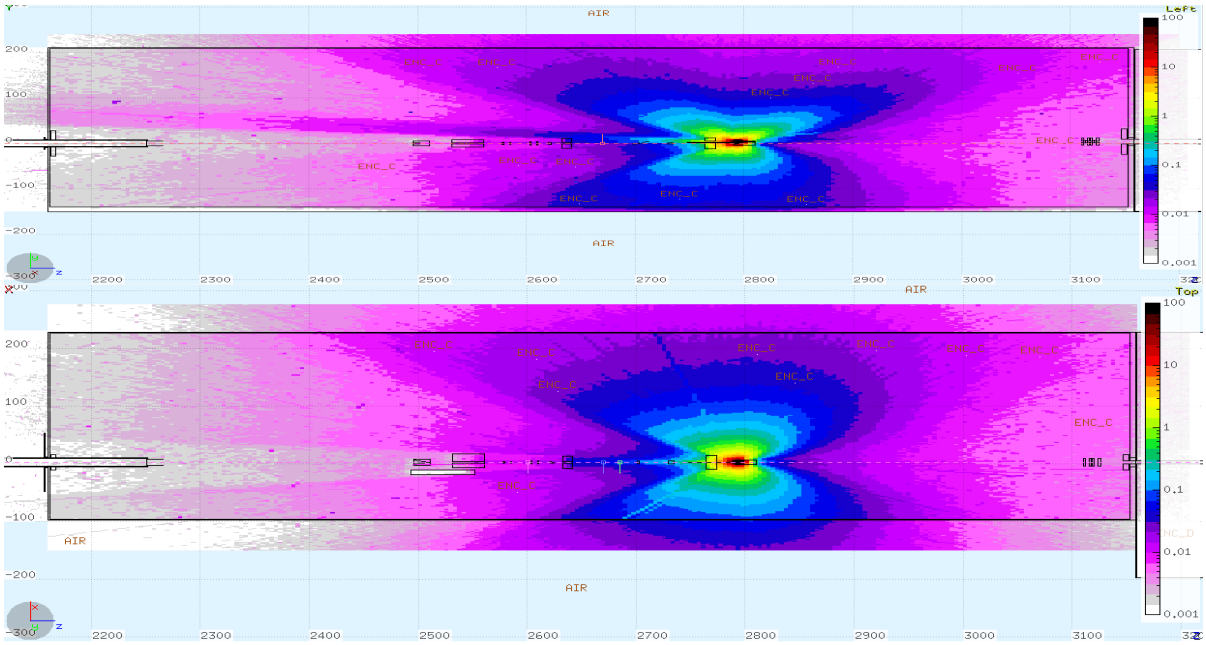


Figure 34: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom the horizontal view at the beam centerline.

3.7 (a) GB Incident along the Extreme Ray Direction along the White Beam Transport

The white beam transport line is defined as the beam pipe connecting the FOE and the C-Hutch. In this simulation it is assumed that the entire GB beam propagates along the extreme ray direction starting from x=0, y=0, z=457.83. The beam pipe is filled with air. The dose rates at 1 ft. away from the entire beam pipe are shown in Figure 36 and are below 0.05 mrem/h.

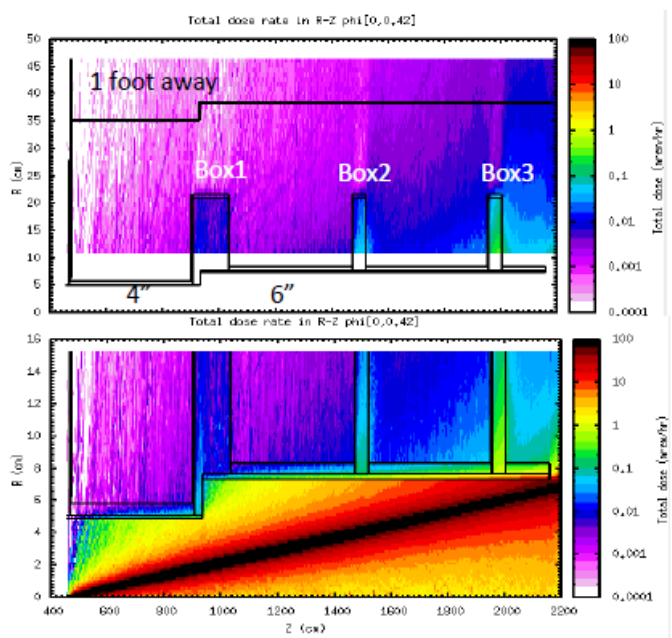


Figure 35: The total dose rate distributions in the white beam transport. The top shows the dose R-Z profile in the extreme ray plane at ~1 ft. away from the beam pipe. The bottom shows the dose R-Z profile in the extreme ray plane starting from the center of the beam pipe.

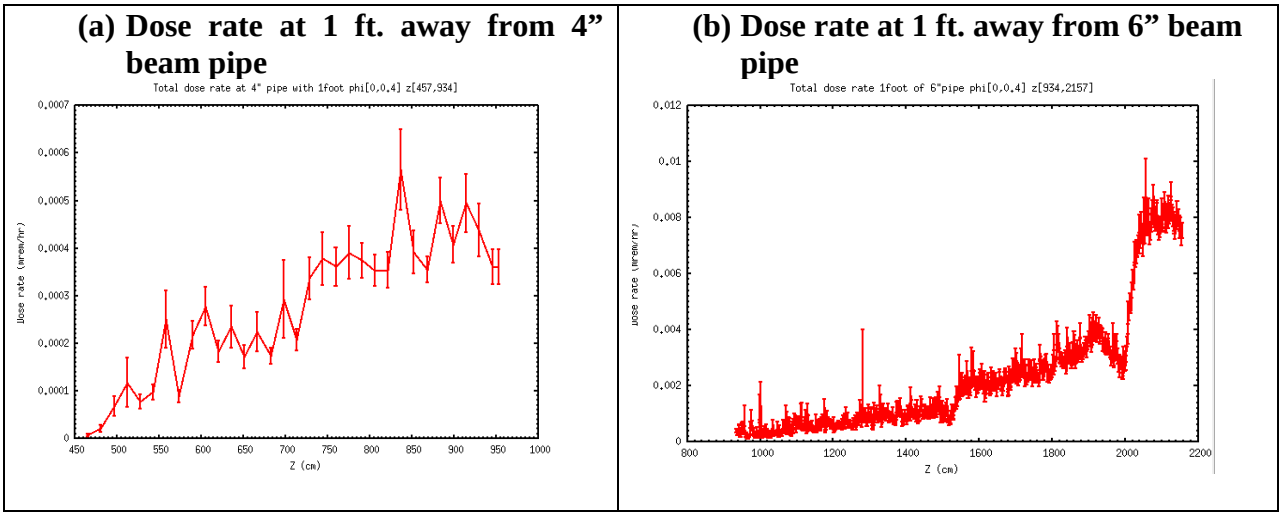
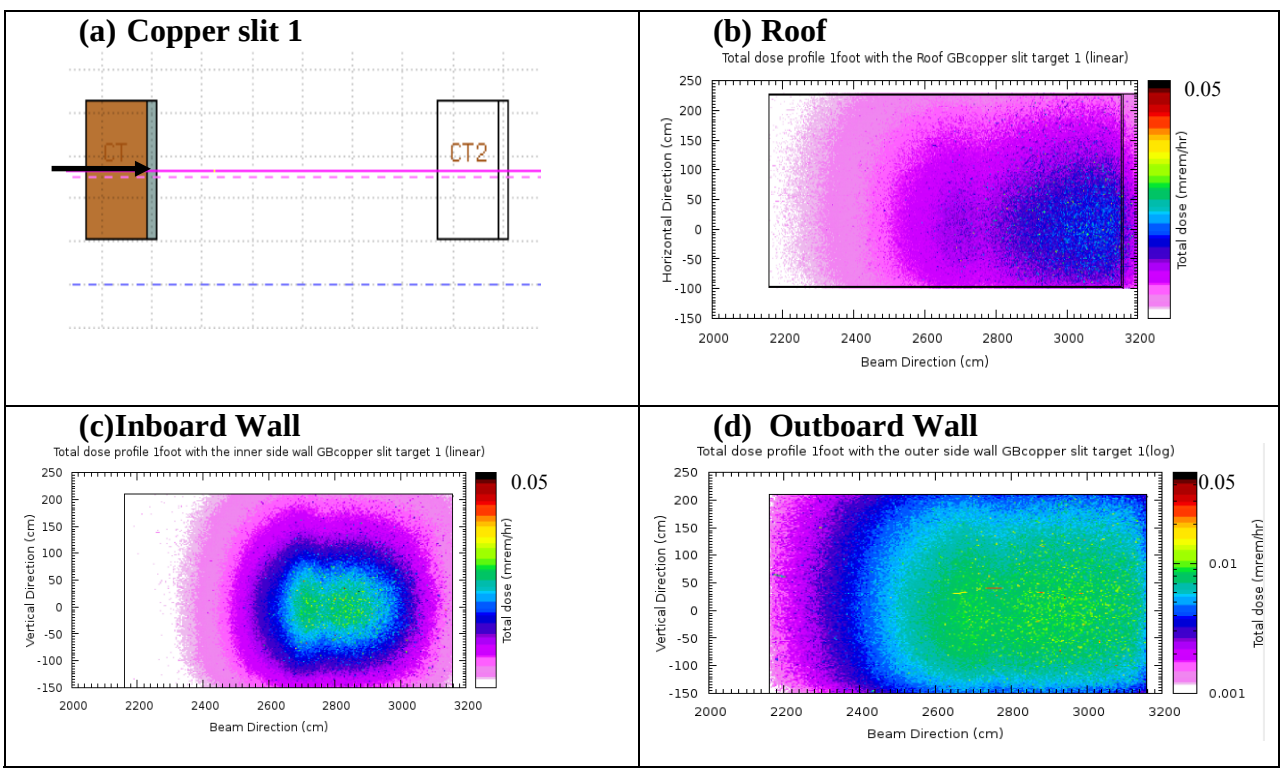


Figure 36: The total dose rates at 1 ft. away from the beam pipes of (a) 4 inch and (b) 6 inch in the extreme ray plane.

3.8 (a) GB Incident on the Scatter Target (copper slit #1 in C-Hutch) with 1 Slit In

In this simulation it is assumed that the entire GB beam impinges on the front surface of the 1st copper slit in the C-Hutch, x=0.0, y=0.0, z=2570 with only the 1st slit inserted. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 37 and are all below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the C-Hutch are shown in Figure 38.



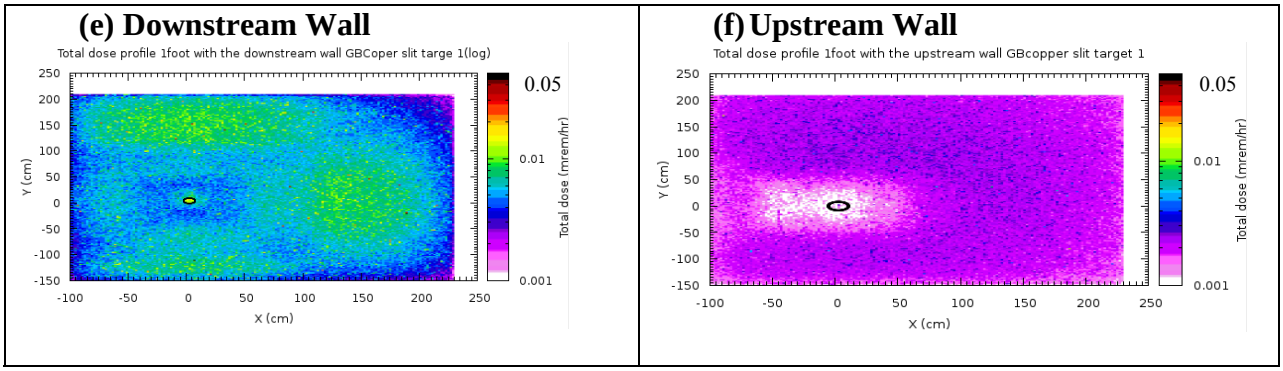


Figure 37: (a) GB incident on the copper slit #1 in the C-Hutch with only one slit inserted. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

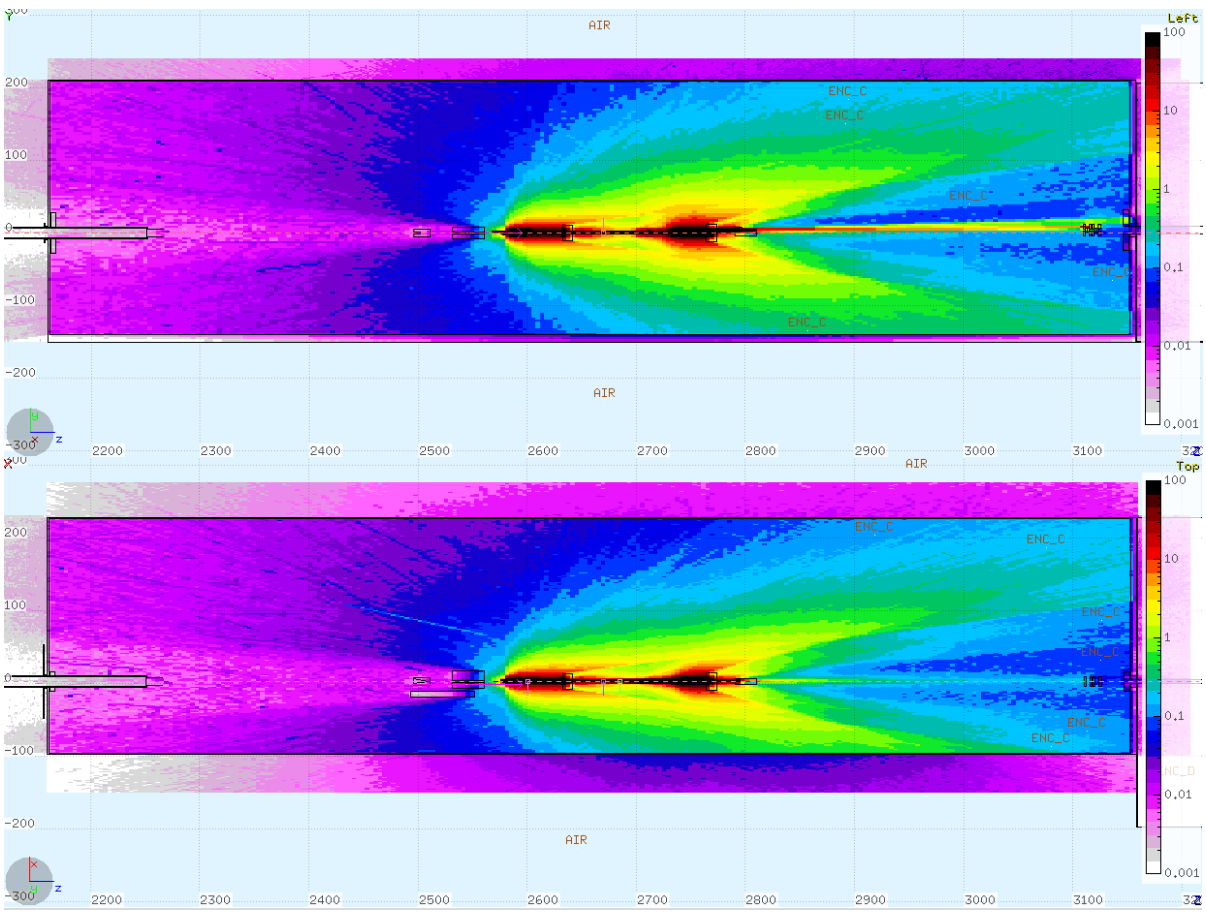


Figure 38: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom the horizontal view at the beam centerline.

3.8 (b) GB Incident on the Scatter Target (copper slit #1 in the C-Hutch) with 2 Slits In

In this simulation it is assumed that the entire GB beam impinges on the front surface of the 1st copper slit in the C-Hutch, x=0.0, y=0.0, z=2570 with both slits inserted. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 39 and are all below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the C-Hutch are shown in Figure 40.

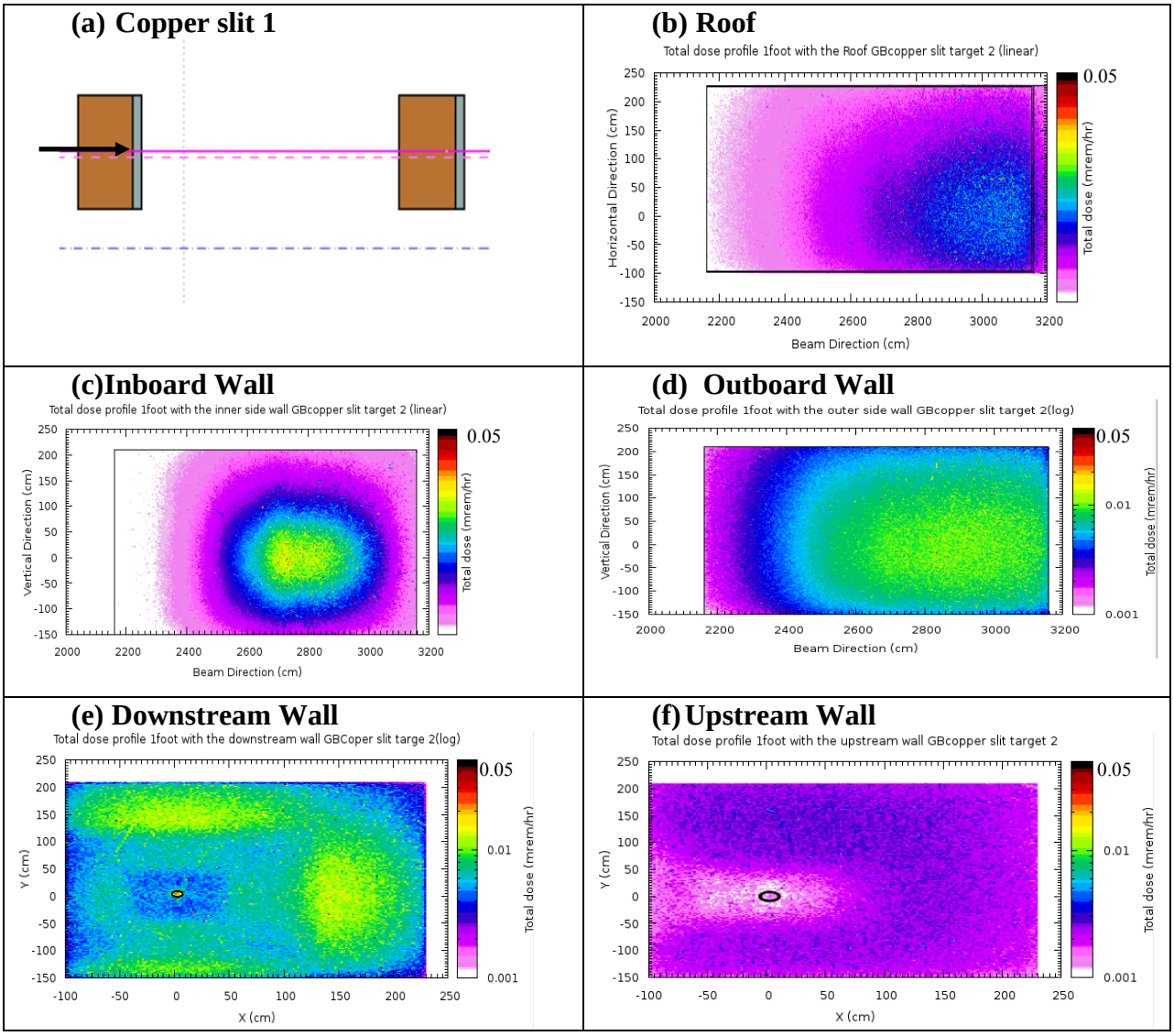


Figure 39: (a) GB incident on the copper slit #1 in the C-Hutch with two slits inserted. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

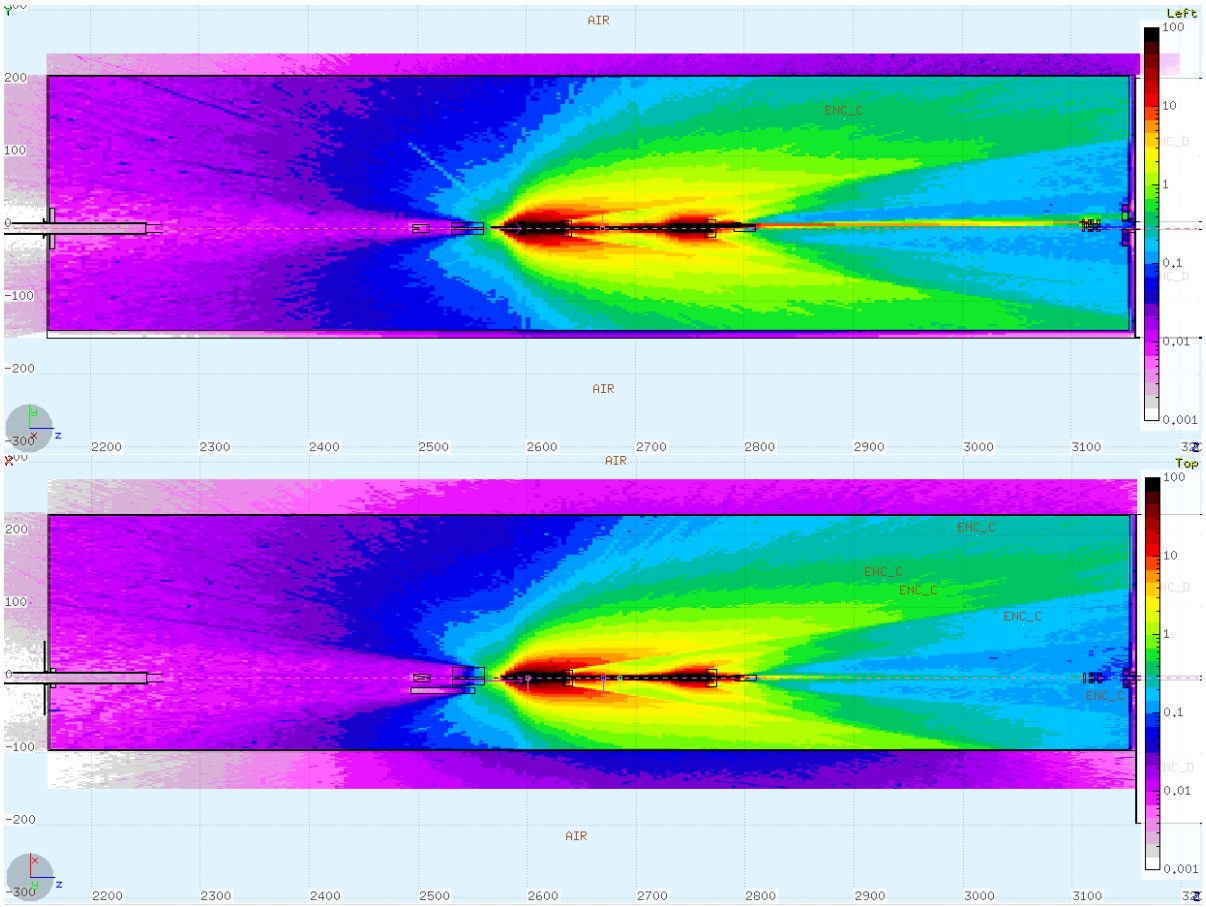
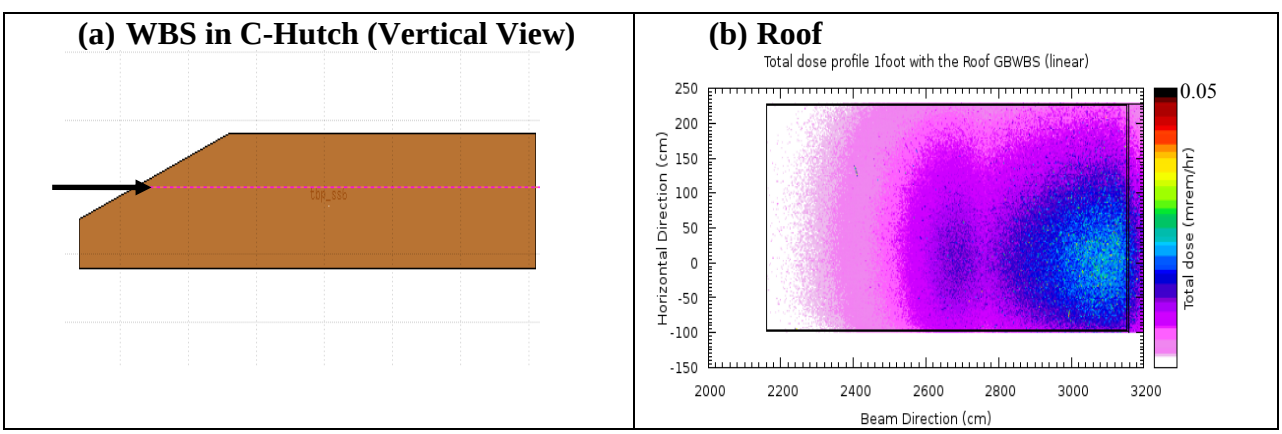


Figure 40: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom the horizontal view at the beam centerline.

3.9 (a) GB Normal Incident to WBS in C-Hutch

In this simulation it is assumed that the entire GB beam impinges on the front surface of the WBS in the C-Hutch, x=0.0, y=0.0, z=2720. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream and upstream walls of the C-Hutch are given in Figure 41 and are all below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the C-Hutch are shown in Figure 42.



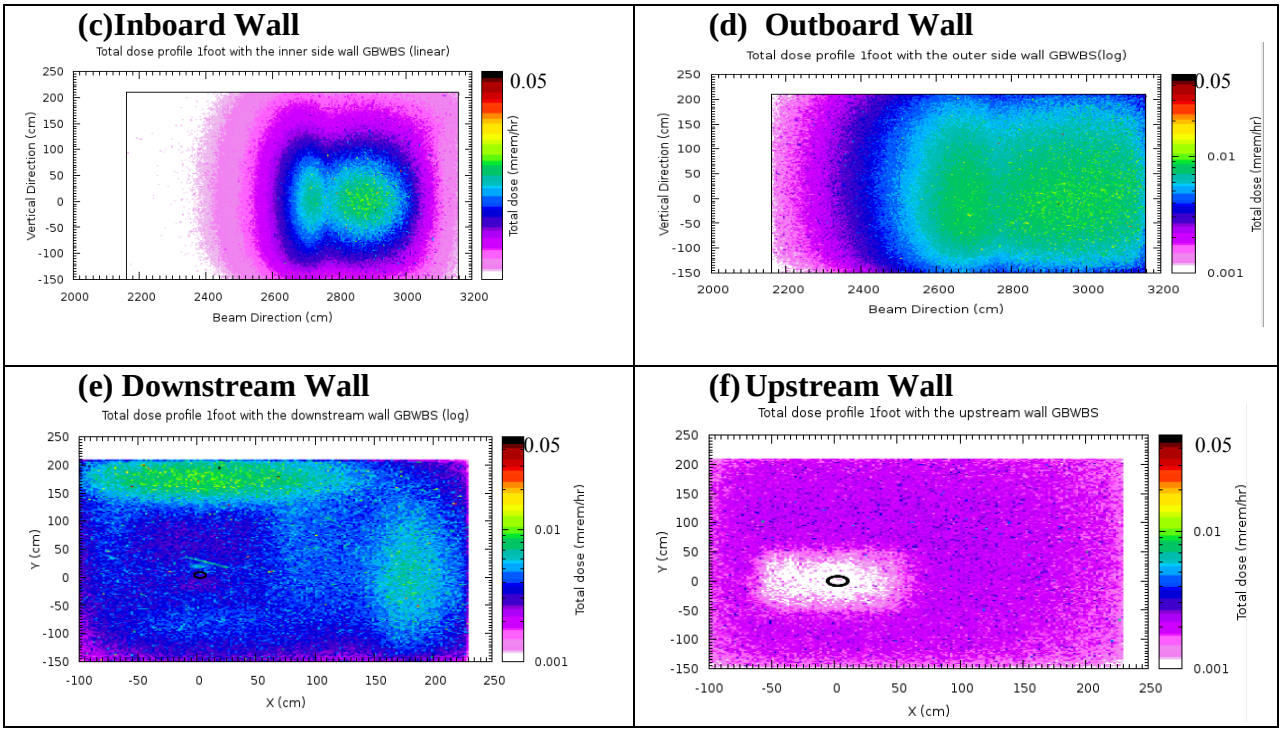


Figure 41: (a) GB incident on the WBS in the C-Hutch. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** the upstream wall of the C-Hutch.

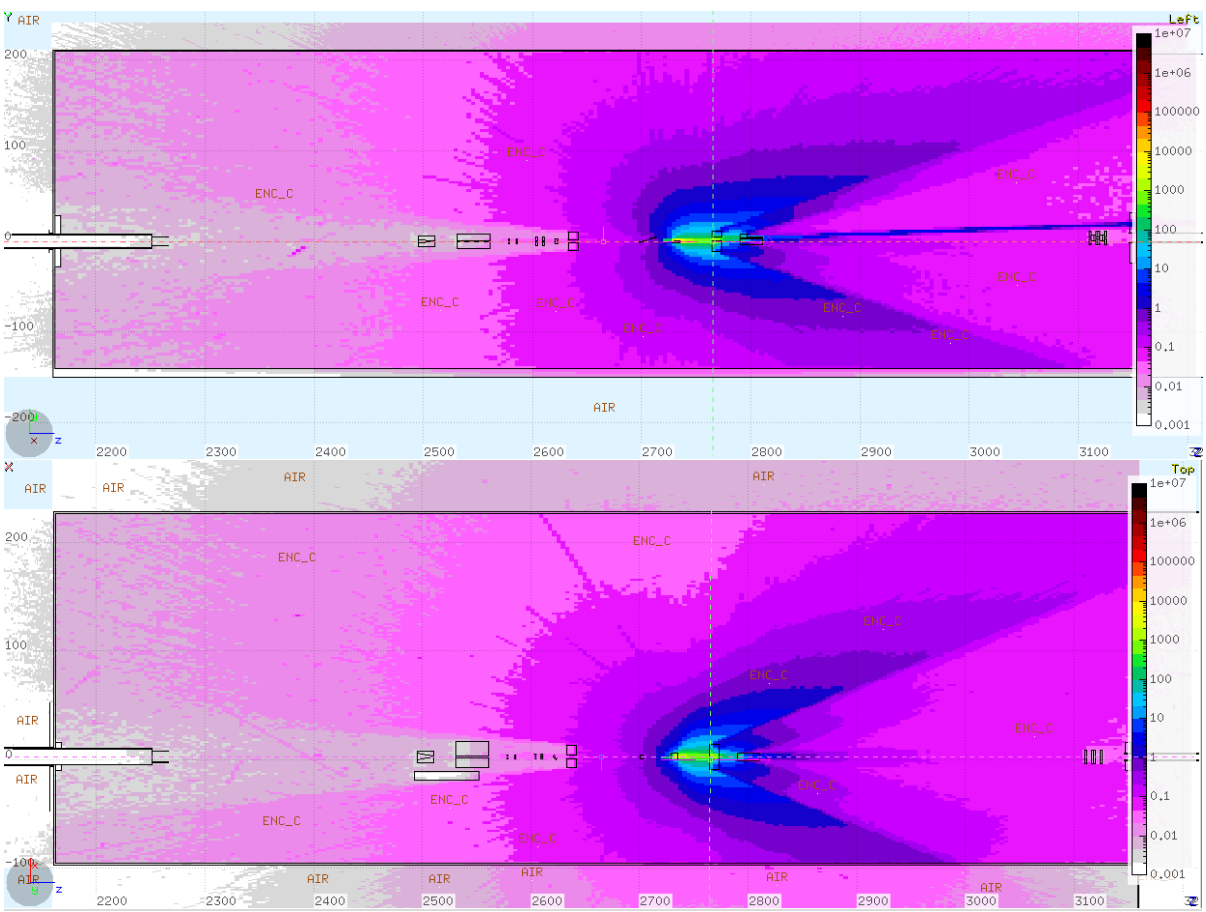


Figure 42: The total dose distributions (mrem/h) in the C-Hutch. The top figure shows a vertical view and the bottom the horizontal view at the beam centerline.

3.10 (a) GB Normal Incident to the WBS in the C-Hutch with the PS Open

In this simulation it is assumed that the entire GB beam impinges on the front surface of the WBS in the C-Hutch, x=0.0, y=0.0, z=2720 with the PS open. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream wall of the D-Hutch are given in Figure 43 and are all below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the D-Hutch are shown in Figure 44. In this case, it is safe to work in the D-Hutch when the PS opens.

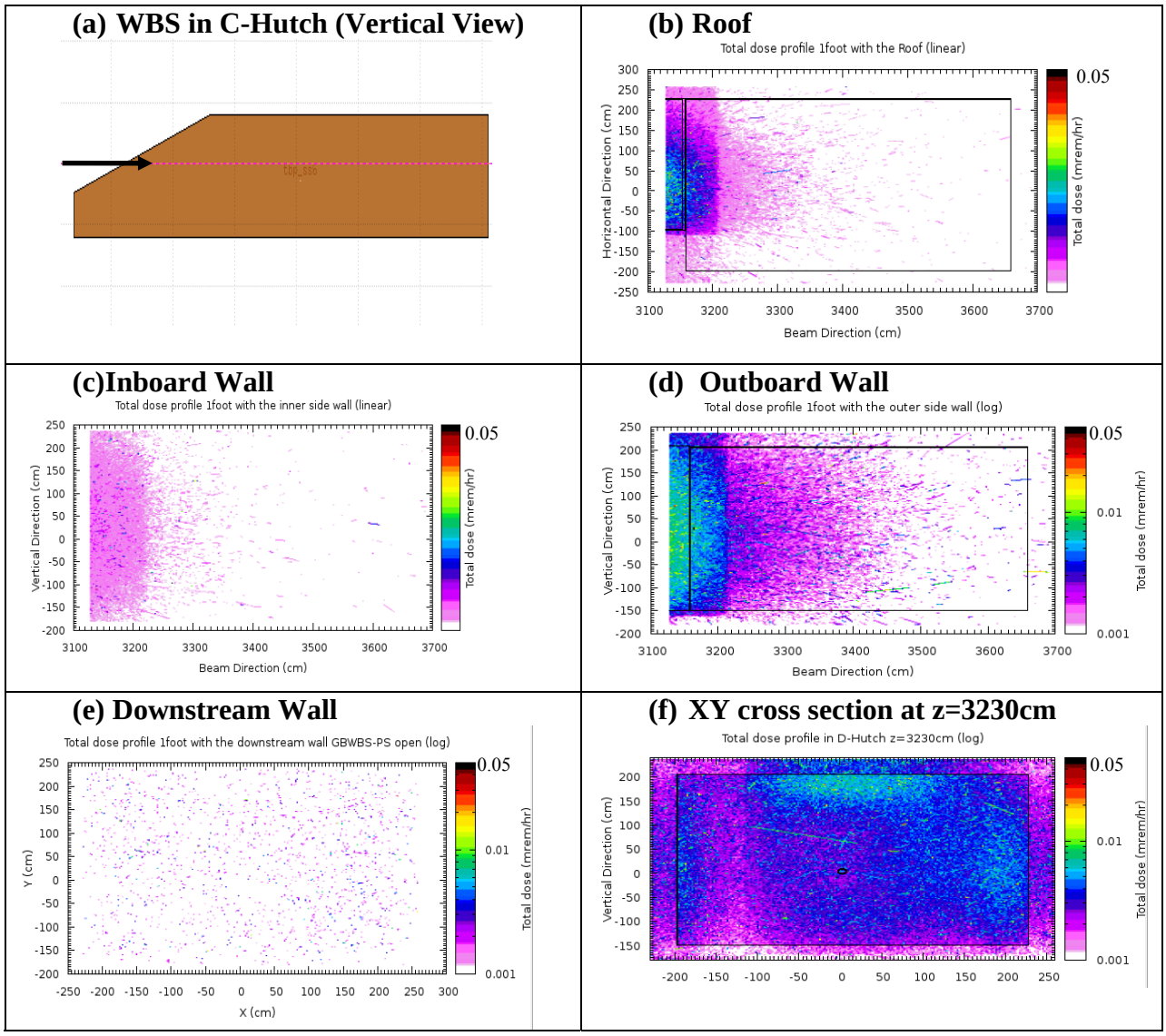


Figure 43: (a) GB incident on the WBS in the C-Hutch with the PS open. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** XY cross section at z = 3230 cm in D-Hutch.

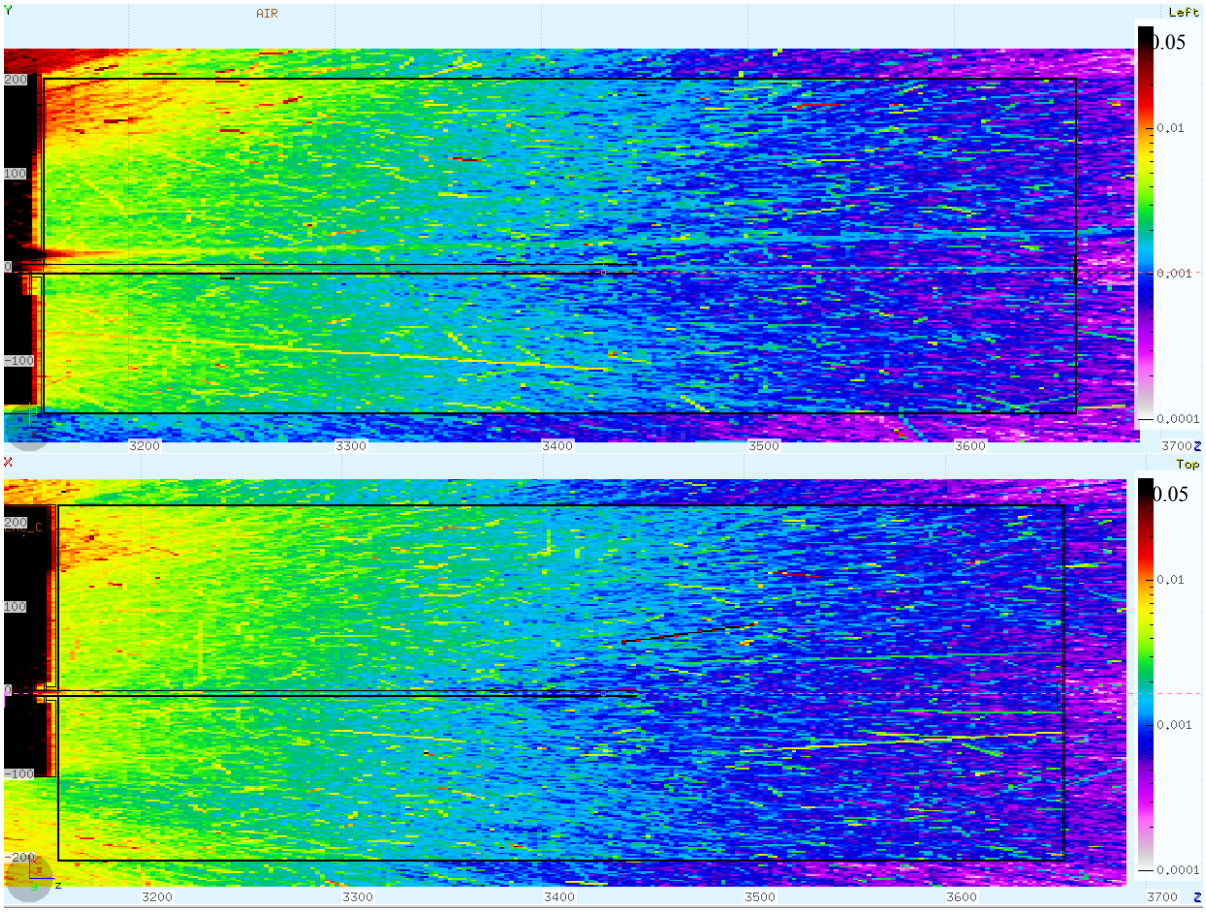


Figure 44: The total dose distributions (mrem/h) in the D-Hutch. The top figure shows a vertical view and the bottom the horizontal view at the beam centerline.

3.10 (b) GB Incident on the Copper Slit #1 In the C-Hutch with 2 Slits In and the PS Open

In this simulation it is assumed that the entire GB beam impinges on copper slit #1 in C-Hutch with 2 slits in, x=0.0, y=0.0, z=2570, and the PS open. The total dose rate distributions at 30 cm away from the roof, the inboard and outboard lateral walls, and the downstream wall of the D-Hutch are given in Figure 45 and are all below 0.05 mrem/h. The vertical (top) and horizontal (bottom) profiles of the dose distribution in the D-Hutch are shown in Figure 46. The leaked beam is well confined within the beam pipe.

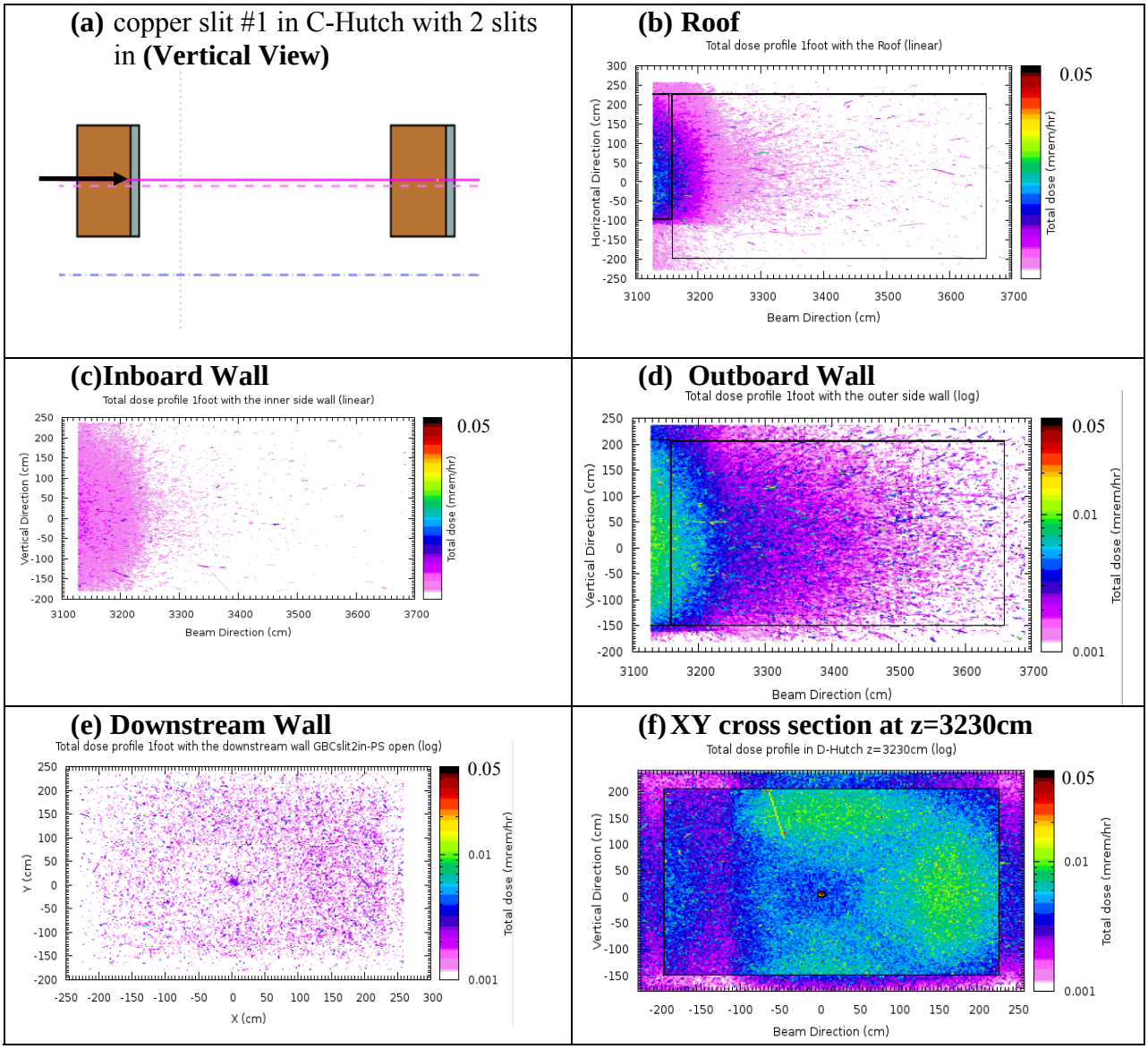


Figure 45: (a) GB incident on copper slit #1 in the C-Hutch with the 2 slits in and PS open. The total dose distributions in mrem/h at 30 cm from **(b)** the roof, **(c)** the inboard lateral wall, **(d)** the outboard lateral wall, **(e)** the downstream wall, and **(f)** XY cross section at z = 3230 cm in D-Hutch.

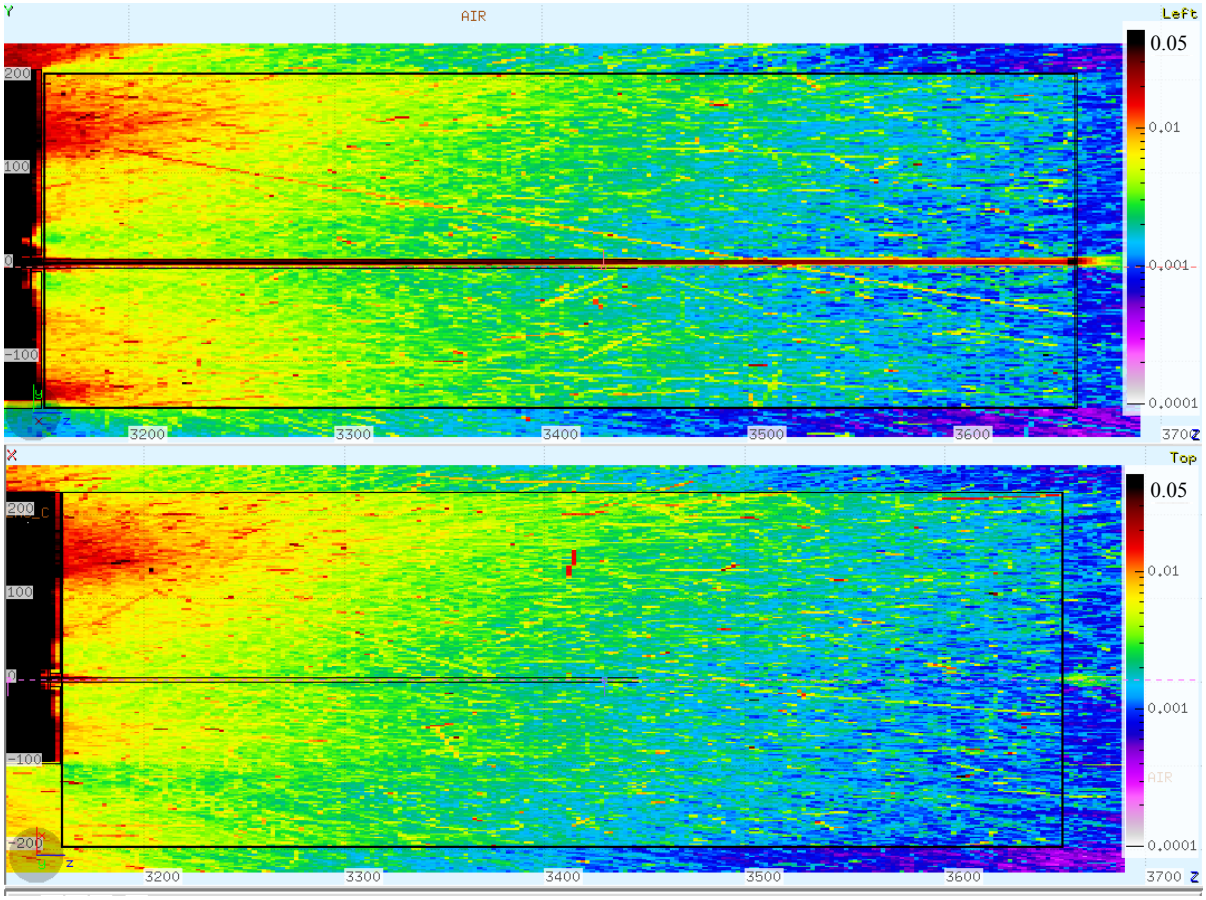


Figure 46: The total dose distributions (mrem/h) in the D-Hutch. The top figure shows a vertical view and the bottom the horizontal view at the beam centerline.

4. Synchrotron Radiation Calculation

In the analysis of the synchrotron radiation, we consider white beam from the in-vacuum undulator source up to the WBS located in the NYX beamline enclosure 19ID-C, and monochromatic beam from the DCM location in 19ID-C to the downstream enclosure 19ID-D.

19ID-NYX source parameters are given in the NSLS-II document PA-C-XFD-RSI-NYX-001 (Version 1, 24 Feb. 2015). There are two options that are considered for the NYX undulator: X25 IVU from NSLS (Total Power: 2.43 kW) and a Segmented Adaptive Gap Undulator (SAGU) (Total Power: ~7.6 kW). This analysis is based on the more powerful SAGU with the white beam flux provided by O. Tchoubar [3].

The analytic code STAC8 [4] was used to calculate the ambient dose equivalent rates in the occupied areas outside of the beamline enclosures and transport pipes. The build-up factor in shielding was included in the calculation. However, the effect of synchrotron radiation polarization was not considered leading to the same shielding requirements for the lateral wall and roof, provided the distance from the scatter target to the dose point is the same. The shielding calculations assume that the bremsstrahlung has been completely stopped in the 19ID-C enclosure. The scattering targets considered in the STAC8 calculations are labeled at their positions by numbers 1 through 4 in Figure 47. These cases are considered in Section 4.1(a) through 4.1(d) herein. The last case involving synchrotron monochromatic beam uses the monochromatic energies and bandwidths which are the same as considered in Reference 5 and are listed in Table 3 with the corresponding photon flux.

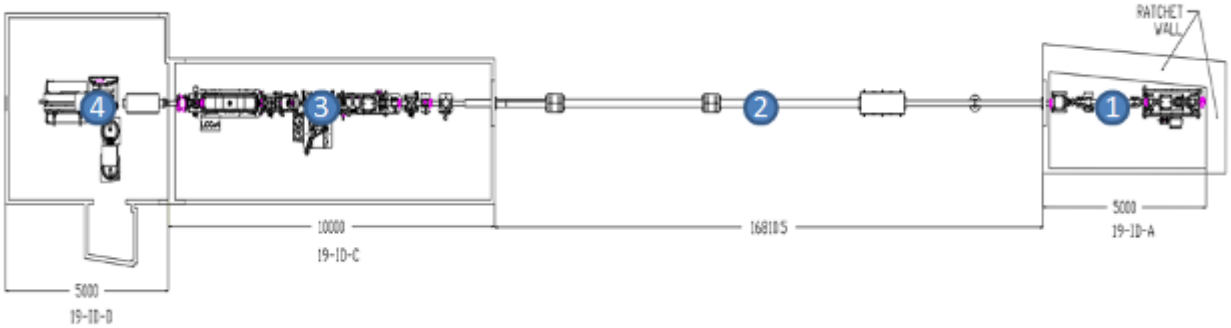


Figure 47: Graphical index of the list of operating cases. Numbered labels indicate the scattering target locations and are discussed in sections 4.a through 4.c

Table 3: Monochromatic beam energies, bandwidths and corresponding photon flux at 500 mA

Monochromatic Beam Energies (keV)	Bandwidths (keV)	Ph/s @ 500 mA
22.00	2.200E-03	1.106E+13
66.00	5.300E-04	4.889E+09
88.00	5.300E-04	3.038E+08
110.00	1.300E-04	4.037E+06
154.00	4.000E-05	4.981E+03

4.1 (a) White Beam at the WBS/Aperture in 19ID-A (Location 1)

The scattering target is assumed to be a copper disk of 40 cm radius and 2 cm thick at grazing incidence with respect to the white beam. The position of the scatter target is assumed to be located at the LAX WBS/NYX aperture approximately 74.4 cm from the FOE downstream wall, 154.2 cm from the lateral wall and 209.0 cm from the roof. The minimum required shielding for the synchrotron radiation source (no credit has been given to the SGB shielding or guillotine) and the corresponding ambient dose rates are given in Table 4. The results show that the shielding thicknesses required for the GB will largely shield the scattered synchrotron radiation. Therefore the existing shielding thicknesses of the 19ID-A hutch walls and roof as given in Appendix 1, are more than adequate to meet the shielding design goal of 0.05 mrem/h.

Table 4: SR shielding design requirements for 19ID-A (FOE)

	Distance (cm)	Required Shielding	Ambient Dose Rate (mrem/h)
Lateral Wall	154.2	6 mm Pb	1.16E-02
Roof	209.0	5 mm Pb	3.34E-02
Downstream Wall	74.4	11 mm Pb	2.68E-02

4.1 (b) White Beam Shielded Transport Pipe in Walkway (Location 2)

According to the beamline ray tracings the white beam will not hit the white beam transport pipes. The minimum shielding requirement is based on a vacuum loss accident and is described in Appendix G.1 of Reference 1. The lead thickness of the 19ID-NYX white beam transport pipe is 7 mm, which exceeds the minimum shielding requirement of 5 mm specified in Reference 1. GB usually dominates the white beam transport pipe thickness (see Section 3.7 (a) for GB FLUKA simulation).

4.1 (c) White Beam at the DCM in 19ID-C (Location 3)

The scattering target is assumed to be a silicon disk of 10 cm radius and 2 cm thick tilted at 0.155° with respect to the incident beam [6]. The position of the scatter target is assumed to be located at the NYX DCM, approximately 452 cm from the 19ID-C downstream wall, 95.5 cm from the lateral wall (inboard) and 209.0 cm from the roof. The minimum required shielding for the synchrotron radiation source (no credit has been given to the SGB shielding or guillotine) and the corresponding ambient dose rates are given in Table 5. The results show that the shielding thicknesses required for the GB will largely shield the scattered synchrotron radiation. Therefore, the existing shielding thicknesses of the 19ID-C hutch walls and roof as given in Appendix 1, are more than adequate to meet the shielding design goal of 0.05 mrem/h.

Table 5: Maximum dose rate on lateral wall, roof and downstream wall

	Distance (cm)	Required Shielding	Ambient Dose Rate (mrem/h)
Lateral Wall	95.5	6 mm Pb	6.19E-02
Roof	209.0	5 mm Pb	6.32E-02
Downstream Wall	452.0	8 mm Pb	4.22E-02

4.1 (d) Mono Beam at Sample in 19ID-D (Location 4)

The scattering target is assumed to be an aluminum disk of 5 cm diameter and 0.1 cm thickness oriented normal to the incident beam. Distances from the inboard lateral wall, roof, and downstream wall are tabulated below. The dose rates in the occupied areas on contact with the enclosure walls and roof are given in Table 6. Therefore, the shielding thicknesses of the 19ID-D hutch walls and roof as given in Table 6 are adequate to meet the shielding design goal of 0.05 mrem/h.

Table 6: Maximum dose rate on lateral wall, roof and downstream wall

	Distance (cm)	Existing Shielding	Ambient Dose Rate (mrem/h)
Lateral Wall	196.7	6 mm Fe	6.24E-04
Roof	206.0	6 mm Fe	5.69E-04
Downstream Wall	250.0	6 mm Fe	3.80E-02

5. Summary and Conclusions

At NSLS-II the white beam or FOE shielding requirements are dominated by the scattering of the primary bremsstrahlung and not the synchrotron beam. For the FLUKA simulations, the GB beam is normalized at 17μW 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 15.5 m long straight sections is better than 10^{-9} Torr. Beamline components that intercept the primary GB beam were selected as scattering targets in the simulations. A summary of the simulation results is presented in Table 7.

Table 7. Maximum total dose rates (mrem/h) on the roof, lateral wall and downstream wall of the FOE.

#	Simulation	**Maximum dose (mrem/h)**			
		Roof (at 1 ft.)	Lateral Wall (at 1 ft.)	DS FOE Wall (on contact)	US and DS C-Hutch wall (at 1 ft.)
1(a)	GB incident on the outboard aperture of FM1	< 0.05	< 0.05	< 0.5	
1(b)	GB incident on the inboard aperture of FM1	< 0.05	< 0.05	< 0.5	
1(c)	GB incident on the top of the outboard aperture of FM1	< 0.05	< 0.05	< 0.5	
1(d)	GB incident on the outboard front face of FM1	< 0.05	< 0.05	< 0.5	
2(a)	GB incident on the outboard aperture of the FM2	< 0.05	< 0.05	< 0.5	
2(b)	GB incident on the inboard aperture of FM2	< 0.05	< 0.05	< 0.5	
2(c)	GB incident on the top of the outboard aperture of FM2	< 0.05	< 0.05	< 0.5	
2(d)	GB incident on the outboard front face of FM2	< 0.05	< 0.05	< 0.5	
3(a)	GB incident on the inboard aperture of FM3	< 0.05	< 0.05		< 0.05
3(b)	GB incident on the middle point of the inboard front face of FM3	< 0.05	< 0.05		< 0.05
3(c)	GB incident on the inboard edge of the front face edge of FM3	< 0.05	< 0.05		< 0.05
4(a)	GB incident at the center of DCM1	< 0.05	< 0.05		< 0.05
4(b)	GB incident on the upstream face of DCM1	< 0.05	< 0.05		< 0.05
5(a)	GB incident at the middle point of the inboard side front face of the BC3	< 0.05	< 0.05		< 0.05
6(a)	GB incident on the inboard side of the BC4	< 0.05	< 0.05		< 0.05

6(b)	GB incident on the center close to the top of BC4	< 0.05	< 0.05		< 0.05
7(a)	GB incident along the extreme ray direction along the white beam transport	< 0.05	< 0.05		< 0.05
8(a)	GB incident on the scatter target (copper slit #1 in the C-Hutch) with 1 slit in	< 0.05	< 0.05		< 0.05
8(b)	GB incident on the scatter target (copper slit #1 in the C-Hutch) with 2 slits in	< 0.05	< 0.05		< 0.05
9(a)	GB normal incident to WBS in the C-Hutch	< 0.05	< 0.05		< 0.05
10(a)	GB normal incident to the WBS in C-Hutch with the PS open	< 0.05 D-Hutch	< 0.05 D-Hutch		< 0.05 D-Hutch
10(b)	GB incident on copper slit #1 in the C-Hutch with 2 slits in and the PS open	< 0.05 D-Hutch	< 0.05 D-Hutch		< 0.05 D-Hutch

For all cases, the total dose rates on the roof, side wall, and downstream and upstream walls of the C-Hutch were below 0.05 mrem/h at 1 ft. away. The total dose rates on the downstream wall of the FOE were below 0.5 mrem/h for all cases.

Based on the STAC8 calculations, the dose rates outside of the enclosures and beam transport pipe are consistent with the NSLS-II shielding policy for normal operating conditions.

All shielding simulations should be validated by comparisons with measurements of the dose rates near the walls of the FOE, the beam transport pipe and the end station enclosure during commissioning.

6. References

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

[2] PS-C-ESH-STD-005,NSLS-II Issue and Decision Paper: ALARA Analysis for Installations of Secondary Bremsstrahlung Shields in the First Optics Enclosure, R. Lee, (June 1, 2016).

[3] Email from O. Tchoubar to M. Benmerrouche (June 16, 2016).

[4] Y. Asano, "A study on radiation shielding and safety analysis for a synchrotron radiation beamline," JAERI-Research-2001-006, March 2001. Y. Asano and N. Sasamoto, "Development of shielding design code for synchrotron radiation beamline," Radia. Phys. Chem. 44 (1994) 133.

[5] NSLS-II Tech Note 147 "SMI 12-ID-B Hutch Design Shielding Review," Z. Xia (May, 13, 2014), Sec. 2.1.

[6] NSLS-II Tech Note 145 "Attenuation of Scattered Monochromatic Synchrotron Radiation in Iron and Lead," Z. Xia and W.-K. Lee, (September 16, 2014).

[7] Email from D. Holmes to X. Yang (April 15, 2016).

[8] PS-C-ASD-POL-005, Photon Science Shielding Policy, R. Lee (March 26, 2014)

[9] PA-C-XFD-RSI-NYX-001, RSI for the Insertion Devices and Front Ends for the NSLS-II 19-ID (NYX and LAX) Beamlines (February 24, 2015)

7. Acknowledgements

We would like to thank Douglas Holmes for providing all the beamline geometry information listed in Appendix 1. We would like to thank Andrew Broadbent, Joseph Lidestri and Howard Robinson for multiple discussions.

Appendix 1
19ID-NYX Beamline input provided by Douglas Holmes [7] – Last update on April 14, 2016

Co-ordinate system

The NYX beam centerline is used as the z or beamline axis for the following tabulated data, with positions from the center of straight. 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 19-ID-A Ratchet Wall	2568.8 cm		
D/S End of FOE (19-ID-A) Backwall (outside)	3046.5 cm	5.0 cm	Lead
Distance of FOE Outboard Sidewall (outside) from NYX CENTERLINE	156.0 cm	1.8 cm	Lead
Distance of FOE Inboard Sidewall from NYX CENTERLINE	Ratchet Wall		
Distance of FOE Roof (Inside) from NYX CENTERLINE	209.0 cm	1.0 cm	Lead
Distance of FOE Floor from NYX CENTERLINE	140.0 cm		
U/S End of C hutch (19-ID-C) Wall (outside)	4728.0 cm	1.8 cm	Lead
D/S End of C hutch (19-ID-C) Wall (outside)	5728.0 cm	5.0 cm	Lead
Distance of C hutch outboard Sidewall (outside)from NYX CENTERLINE	225.0 cm	1.8 cm	Lead
Distance of C hutch inboard Sidewall (outside)from NYX CENTERLINE	100.0 cm	1.8 cm	Lead
Distance of C hutch Roof (Inside) from NYX CENTERLINE	209.0 cm	1.0 cm	lead
U/S End of D hutch (19-ID-D) Wall (inside)	5728.0 cm	6mm	Steel
D/S End of D hutch (19-ID-D) Wall (outside)	6228.0 cm	6mm	Steel
Distance of D hutch outboard Sidewall (outside)from NYX CENTERLINE	225.0 cm	6mm	Steel
Distance of D hutch inboard Sidewall (outside)from NYX CENTERLINE	200.0 cm	6mm	Steel
Distance of D hutch Roof (Inside) from NYX CENTERLINE	206.0 cm	6mm	Steel

Table 1.2: Beamline Transport Pipes

Transport Pipe between FOE & C hutch (from Z Position 3046.5cm to 3505.7cm)	ID= 3.83 OD=4.00 inches Material: Stainless Steel	Shielding Thickness 7.0mm Shielding Material: Lead	Coincident with Z axis
Transport Pipes between FOE & C-Hutch (from Z Position 3505.7cm to 4728.0cm)	ID= 5.76 OD=6.00 inches Material: Stainless Steel	Shielding Thickness 7.0mm Shielding Material: Lead	Coincident with Z axis

Table 1.3: NYX A Hutch Beamline Components and SGB shield

The NYX Beam 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.

The NYX beam centerline is used as the z or beamline axis for the following tabulated data, with positions from the center of straight. Y is the vertical axis and x the horizontal axis orthogonal to the y and z axes.

Components	Z = Distance from center of straight	Dimensions (specify units)		Offset (vertical/ horizontal w.r.t NYX CENTERLINE & Rotation	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R)			
Poly Shield (SGB)	US: 2619.9 cm	7.62cm (x) (+16.16cm +23.78cm) (x) 28.48cm (y) (+16.0cm - 12.48cm) (Y) 58.96cm (z)	N/A	No aperture shield center: +19.97cm (X) 1.76cm (Y) wrt NYX Centerline	polyethylene	1453-00301
Dual Aperture NYX/LAX Fixed Mask DS of ratchet wall	US: 2622.39 cm	10.8cm (x) (-7.76cm +3.04cm)	Two tapered apertures US:3.0cm(x),3.0cm(y) DS:0.43cm(x)0.22cm(y)	NYX aperture 0.00 (X) 0.00 (Y)	Glidcop (Copper)	1453-00064

		(x) 8.50cm (y) 20.00cm (z)	Z=2639.9 Aperture Taper angle wrt NYX Centerline Horizontal: 4.05° Aperture Taper angle wrt NYX Centerline Vertical: 4.4°	wrt NYX Centerline LAX aperture -5.17 (X) 0.00 (Y) wrt NYX Centerline Glidcop block -2.36 (X) 0.00 (Y) wrt NYX Centerline		
Bremsstrahlung Collimator 1 (Dual aperture)	US: 2654.0 cm	23.0 cm (x) (-13.42cm +9.58cm) (x) 15.0 cm (y) 30.0 cm (z)	Double aperture 0.9 cm (round)(ss) 1.2 cm (round)(lead)	NYX Aperture Center: +0.028cm (X) 0.00cm (Y) wrt NYX Centerline LAX Aperture Center: -5.257cm (X) 0.00cm (Y) wrt NYX Centerline Lead Block Center: -1.92cm(X) 0.00cm (Y) wrt NYX Centerline	Lead	1453-00064
LAX White Beam stop and NYX aperture	US: 2967.05 cm	9.0cm diameter 4.0cm (z) centered at -2.62cm (x) 0.0cm (y)	One tapered aperture (NYX) US:2.05cm(x), 11.5cm(y) DS:0.50cm(x), 0.30cm(y) Z=2970.05 Aperture Taper angle wrt NYX Centerline Horizontal: 14.5°	NYX Aperture Center: +0.000cm (X) wrt NYX Centerline LAX Beamstop Center: US: -5.827cm (X) 0.00cm (Y) wrt NYX Centerline DS:	Copper	1453-00064

			Aperture Taper angle wrt NYX Centerline Vertical: 8.05^{o} One tapered Beamstop (LAX) US:1.90cm(x), 1.15cm(y) DS:0.50cm(x), 0.30cm(y) Z=2971.05 Beamstop sidewall Taper angle wrt NYX Centerline Horizontal: 10.0 Beamstop Bottom face Taper angle wrt NYX Centerline Vertical: 17.8^{o} Beamstop Top face Taper angle wrt NYX Centerline Vertical: 6.2^{o}	-5.827cm (X) +.859cm(Y) wrt NYX Centerline Copper cylinder Center: -2.62cm(X) 0.00cm (Y) wrt NYX Centerline		
Bremsstrahlung Collimator 2 (Single aperture)	US: 2985.0 cm	15.1 cm (x) (-9.65cm +5.45 cm) (x) 6.85 cm (y) 20.0 cm (z)	Single aperture 0.82 cm (x) 0.58 cm (y)	Aperture Center: +0.0085cm (X) 0.00cm (Y) wrt NYX Centerline Lead Block Center: -2.1cm(X) 0.00cm(Y) wrt NYX Centerline	Tungsten	1453-00064
SGB01 shield	US : 3011.6cm	25.2 cm (x) 17.0 cm (y)	6.4cm aperture (diameter)	Aperture Center: 0.00cm (X)	lead	1453-00064

		5 cm (z)		0.00cm (Y) wrt NYX Centerline Lead Block Center: -2.1cm (X) 0.00cm (Y) wrt NYX Centerline		

Table 1.4. NYX C Hutch Beamline Components and SGB shield.

The NYX Beam 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.

The NYX beam centerline is used as the z or beamline axis for the following tabulated data, with positions from the center of straight. Y is the vertical axis and x the horizontal axis orthogonal to the y and z axes.

Components	Z = Distance from center of straight	Dimensions (specify units)		Offset (vertical/ horizontal w.r.t NYX CENTERLINE & Rotation	Material	Associated Drawings
		Outer dimensions (W)x(H)x(L)	Aperture (W)x(H) or (R)			
Poly Shield (SGB)	US: 5063.2 cm	7.62cm (x) (-15.24cm - 22.86cm) (x) 28.16cm (y) (+16.3cm - 12.16cm) (Y) 58.96cm (z)		No aperture shield center: +19.05cm (X) 2.07cm (Y) wrt NYX Centerline	polyethylene	1453-00302
Single Aperture NYX Movable Mask	US: 5064.5 cm	11.0cm (x) 11.0cm (y) 15.00cm (z)	US:6.5cm(x) (-2.7cm +3.8cm)(x) ,3.47cm(y)	NYX aperture (US) +0.55 (X) 0.00 (Y)	Glidcop (Copper)	1453-00074

			DS:0.80cm(x), 0.40cm(y) Z=5078.3 Aperture Taper angle wrt NYX Centerline Horizontal: 13.84° INBD 9.46° OUTBD Aperture Taper angle wrt NYX Centerline Vertical: 6.37°	wrt NYX Centerline NYX aperture (DS) 0.00 (X) 0.00 (Y) wrt NYX Centerline Glidcop block 0.00 (X) 0.00 (Y) wrt NYX Centerline		
Bremsstrahlung Collimator 3 (Single aperture)	US: 5100.0 cm	23.5 cm (x) (-9.5cm +14.0cm) (x) 15.6 cm (y) 30.0 cm (z)	Single aperture 1.7 cm (round)(ss) 2.0 cm (round)(lead)	NYX Aperture Center: +0.00cm (X) 0.00cm (Y) wrt NYX Centerline Lead Block Center: +2.25cm(X) 0.00cm (Y) wrt NYX Centerline	Lead	1453-00074
Vertical Slit#1	US : 5146.5cm US : 5147.7cm	3.2 cm (x) 4.6 cm (y) 1.2 cm (z) 3.2 cm (x) 4.6 cm (y) 0.2 cm (z)	No aperture No aperture	0.00cm (X) 0.00cm (Y) wrt NYX Centerline 0.00cm (X) 0.00cm (Y) wrt NYX Centerline	Cu W	ASM0187
Vertical Slit#2	US : 5153.5cm	3.2 cm (x) 4.6 cm (y)	No aperture	0.00cm (X) 0.00cm (Y)	Cu	ASM0187

	US : 5154.7cm	1.2 cm (z) 3.2 cm (x) 4.6 cm (y) 0.2 cm (z)	No aperture	wrt NYX Centerline 0.00cm (X) 0.00cm (Y) wrt NYX Centerline	W	
Filter#1	US : 5171.5cm	4.5 cm (x) 8.9 cm (y) 1.1 cm (z)	0.8 cm (x) 0.4 cm (y)	0.00cm (X) 0.00cm (Y) wrt NYX Centerline	Cu	ASM0080
Filter#2	US : 5178.2cm	4.5 cm (x) 8.9 cm (y) 1.1 cm (z)	0.8 cm (x) 0.4 cm (y)	0.00cm (X) 0.00cm (Y) wrt NYX Centerline	Cu	ASM0080
Diamond Screen Aperture	US : 5191.9cm	5.0 cm (x) 4.0 cm (y) 1.7 cm (z)	1.47 cm (x) 0.5 cm (y)	0.00cm (X) 0.00cm (Y) wrt NYX Centerline	Cu	AQM0097
SGB02 shield	US : 5201.8cm	20.6 cm (x) 20.6 cm (y) 9 cm (z)	3.4cm aperture (diameter)	Aperture Center: 0.00cm (X) 0.00cm (Y) wrt NYX Centerline Lead Block Center: 0.0cm (X) 0.00cm (Y) wrt NYX Centerline	lead	1453-00074
Silicon DCM 1st Crystal (tangential)	Center: 5269.7cm	4.0 cm (x) 0.6 cm (y) 6.5 cm (z)	No Aperture	0.00cm (X) -0.3cm (Y) wrt NYX Centerline Bragg Angle Rotaion -14.98 degrees (about X axis)	Si	ADM0203
Silicon DCM 2nd Crystal (sagittal)	Center: 5279.0cm	4.0 cm (x) 0.6 cm (y) 6.5 cm (z)	No Aperture	0.00cm (X) +3.3cm (Y) wrt NYX Centerline	Si	AHD4515

				Bragg Angle Rotaion -14.98 degrees (about X axis)		
Bremsstrahlung Collimator 4 (Single aperture)	US: 5359.4 cm	7.5 cm (x) 6.5 cm (y) (-3.7cm to +4.8cm) (y) 20.0 cm (z)	Single aperture 1.2 cm (x) 1.2 cm (y) square	Aperture Center: 0.0cm (X) +3.0cm (Y) wrt NYX Centerline W Block Center: 0.00cm(X) +0.55cm(Y) wrt NYX Centerline	Tungsten	1453-00064
SGB04 shield	US : 5359.4cm	7.5 cm (x) 3.5 cm (y) (+4.8cm to +8.3cm) (y) 6 cm (z)	No Aperture	N/A	tungsten	1453-00064
Photon Shutter	5686.8cm to center	See shutter spec.	See shutter spec.	Aperture Center: 0.00 cm (X) +4.00cm (Y) wrt NYX Centerline	Cu and W	PD-COM-PSH-1000 S/N 14001-017

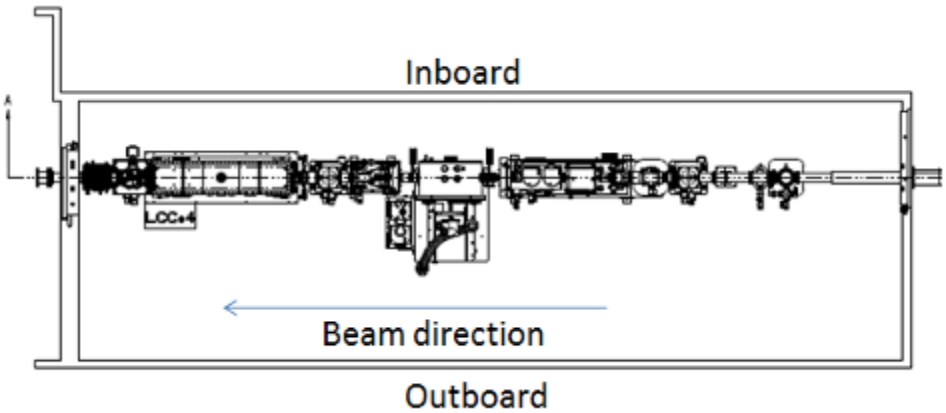


Figure 1.1: Horizontal View of Hutch C.

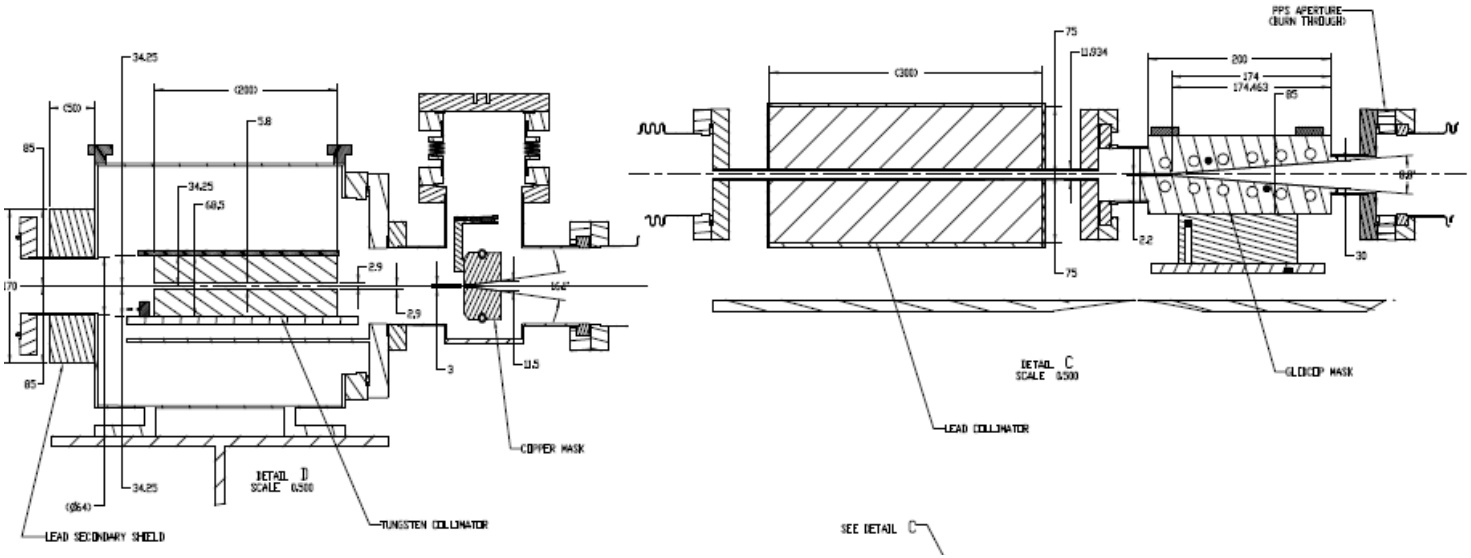


Figure 1.2: Detail View of FM1 and BC1.

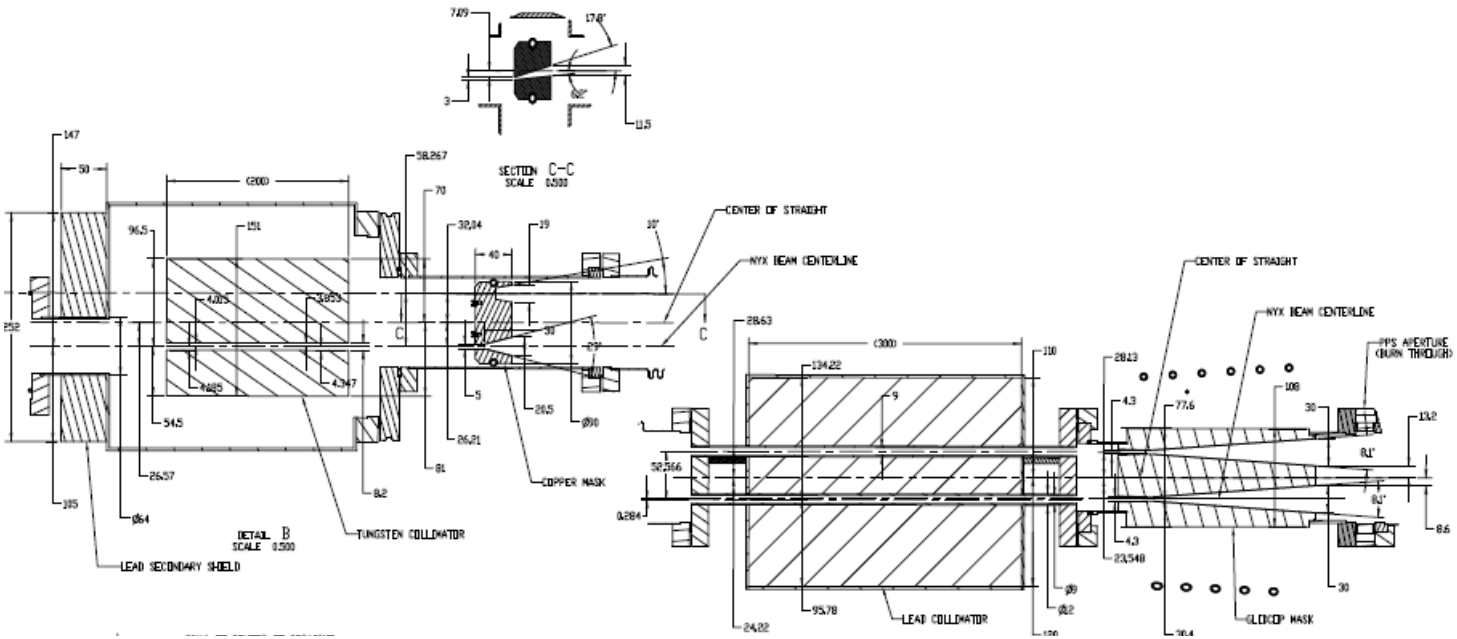


Figure 1.3: Detail View of FM2 and BC2.

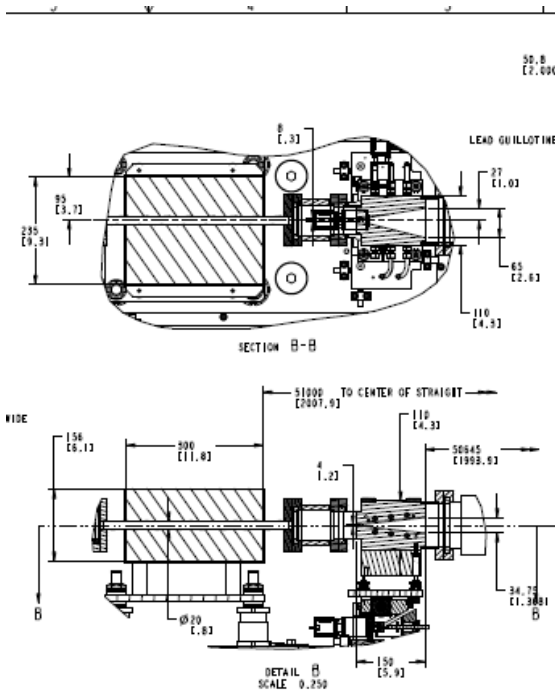


Figure 1.4: Detail View of F3 Aperture BC3

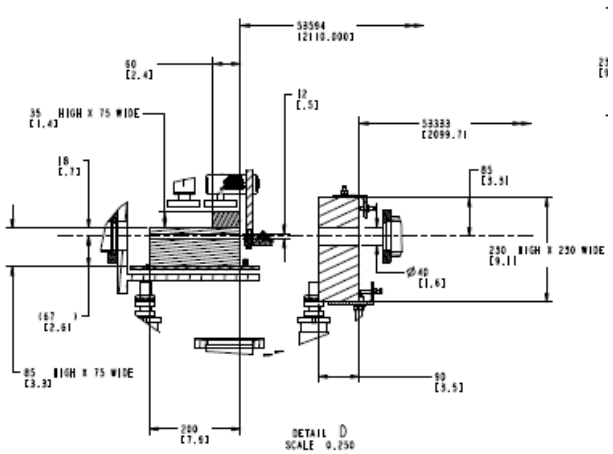


Figure 1.5: Detailed View of BC4 and BC5

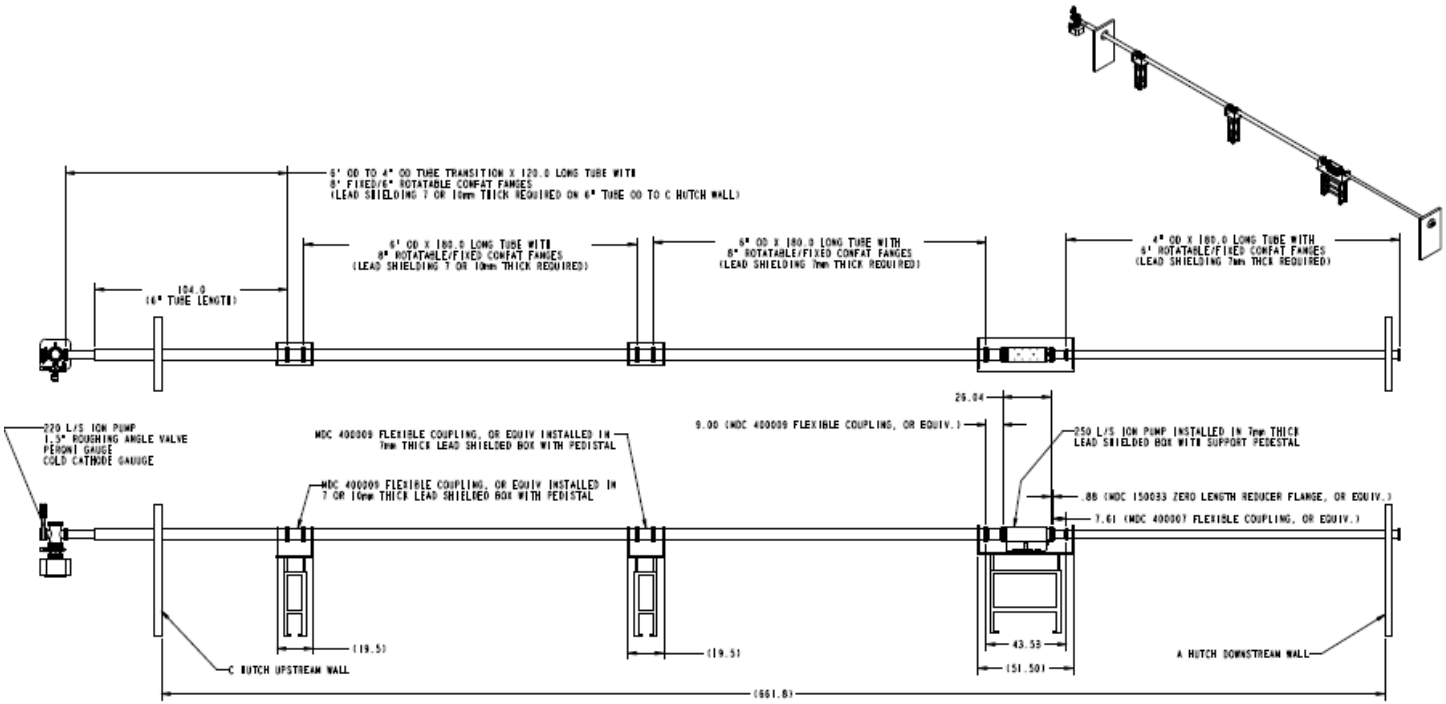


Figure 1.6: Detail of white beam transport