1 Introduction:

This report, an addendum to the BNL report number 217 [1], describes the shielding analysis carried out with the pink beam baffle slits (PBBS) in the geometry model using gas bremsstrahlung (GB) and synchrotron radiation (SR) as sources of radiation.

The NSLS-II beamline radiation shielding policy [2]**,** dictates the areas that are continuously occupied be shielded to have exposure levels less than 0.5 mrem/h, based on an occupancy of 2000 hours per year, or less than 1 rem in a year. In the event of a fault scenario, the total exposure over the entire event shall be less than 20 mrem in a non-radiation controlled area and less than 100 mrem in a radiation controlled area.

Two separate calculations are carried out to estimate the dose rate outside the FOE and in the proximity of the beam lines.

In the first simulation, carried out by the FLUKA [3] Monte Carlo code, the GB spectrum from the long straight section is taken as the primary source hitting the white beam mirror. The resulting electromagnetic shower is tracked along the geometry and the dose rates are estimated in three dimensional meshes in and around the FOE and the beam pipe.

The second set of calculations are carried out by the STAC8 [4] analytical code, with the synchrotron radiation produced from the EPU105 and EPU57 undulators as sources. The ambient dose equivalent rates are calculated for three different scenarios.

a) The pink beam is scattered off the PBBS and is transmitted laterally through PBBS chamber, through the joint of the chamber and beam pipe (at 41 degree), and through the upstream and downstream bellows. For the lateral dose calculation, the chamber is taken as 24.5 mm thick steel at a distance of 61 mm. For the transmission through the joint, just the beam pipe (2 mm SS) is assumed as shield at 50.8 mm distance. The bellows are considered to be 24.1 cm away from the slits.
b) The pink beam reflected off the mirror M2 is transmitted through the PGM chamber of 8 mm thick SS. The ambient dose equivalent is estimated with the angle of mirror M2 varied from 2-10°.
c) The M2 is replaced with a Si scatterer and the resulting beam is propagated trough the opening of the exit mask and gamma stop at 2-8° and transmitted through the 2 mm exit beam pipe.

The details of the FLUKA simulations are described in section 2 and the results from the STAC8 calculations are shown in section 3.

2 FLUKA Simulations

In figure 1, the layout of the 21ID-ESM beamlines as extracted from the Beamline Ray Trace Layout [PD-ESM-RAYT-0001] is given. The beam travels from right to left in the Ray Trace drawings while in the FLUKA model it is in the opposite direction. The changes to the FLUKA model are described in section 2.2. The NSLS-II parameters used to estimate the gas bremsstrahlung (GB) source are listed in Table 1. The radiation dose is estimated in a three dimensional mesh by scoring the fluence and folding them with the fluence to ambient dose equivalent conversion coefficients. The results are normalized to 17μW bremsstrahlung power, estimated for the long (15.5m) straight section. This is the GB power generated by a 500 mA electron beam of 3 GeV striking the residual air when the vacuum is 10^{-9} Torr.

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

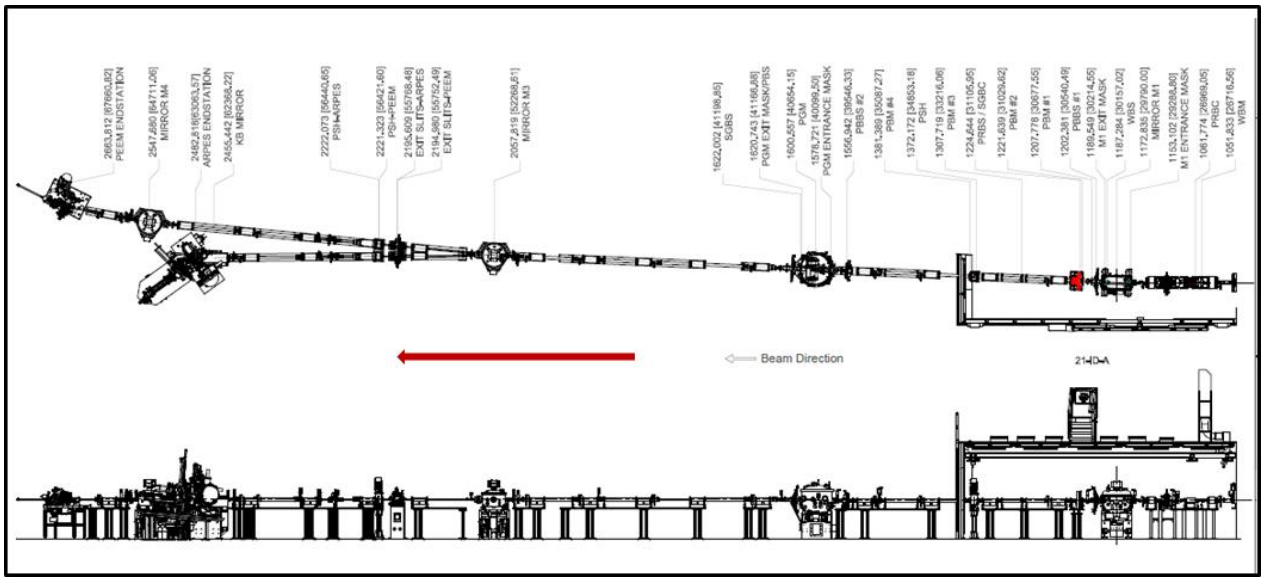

Figure 1. Layout of 21ID-ESM showing the major beamline components and the FOE

2.1 Description of the Fluka model

The FLUKA model has been described in detail in the previous report [1]. It includes the FOE outboard lateral panel made of 18 mm Pb (162.73 cm away from beam), roof of 10 mm Pb (210.2 cm above beam) and the downstream FOE wall with 50 mm Pb (~1300 cm from the ratchet wall). Figures 2-4 shows the FLUKA model of the FOE and beamline.

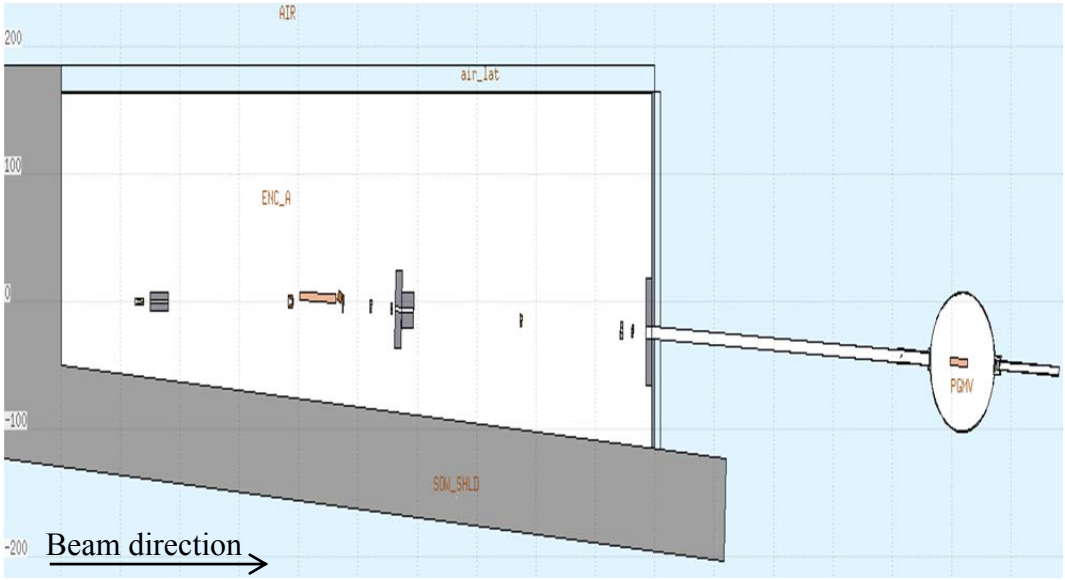

Figure 2. The plan view of the full FLUKA model. The beam travels from left to right.

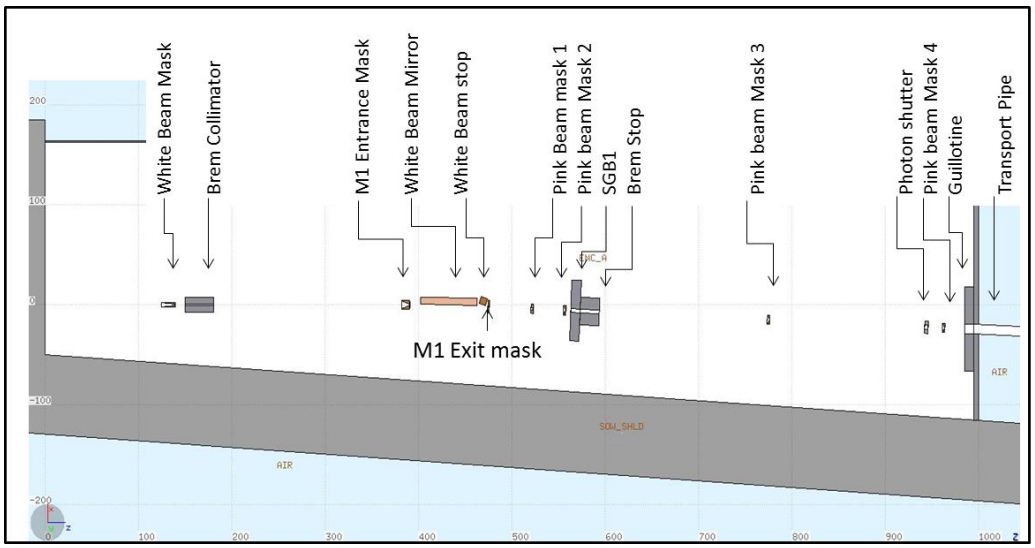

Figure 3. Plan view of the ESM beamline components in the FOE.

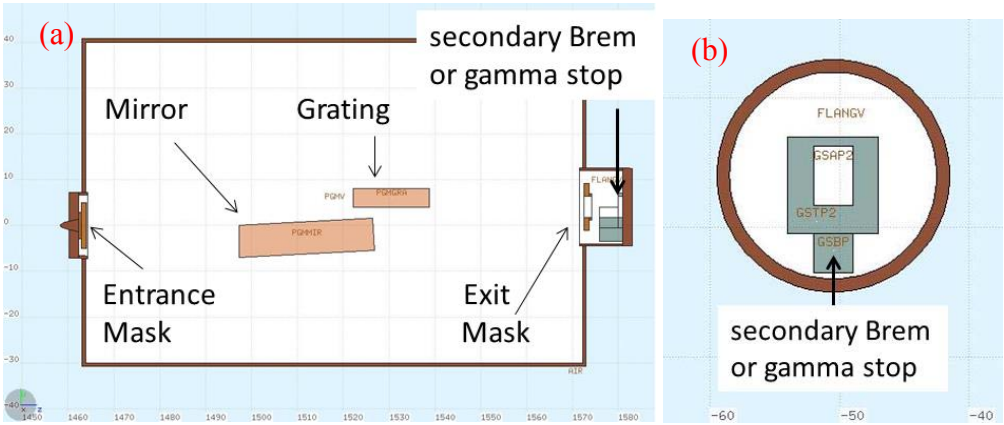

Figure 4(a) Elevation view of the PGM components and (b) vertical cut through the gamma stop.

2.2 Changes in the geometry and simulation parameters

The results here are obtained with the following changes made in the geometry and the simulation approach.

In the geometry, the PBBS and an additional thickness of the beam pipe corresponding to the chamber housing it are introduced. The slit is modelled as a piece of copper 6.45 mm thick (Z axis) and 71.6 mm high (Y axis) and 30 mm (X axis) broad, placed at 45° angle with respect to the beam direction. The outer radius of the chamber is kept 22.5 mm more than the beam pipe thickness (2 mm) giving a net thickness of 24.5 mm. While the components downstream of the plane grating monochromator (PGM) are not included, the beam pipe after the PGM chamber is extended by 1 meter instead of blanking it off. This is expected to remove any artefact in the dose plot at that point, as a result of the photons hitting the blank off. Figure 5 shows the PBBS, the chamber and the extension of the pipe.

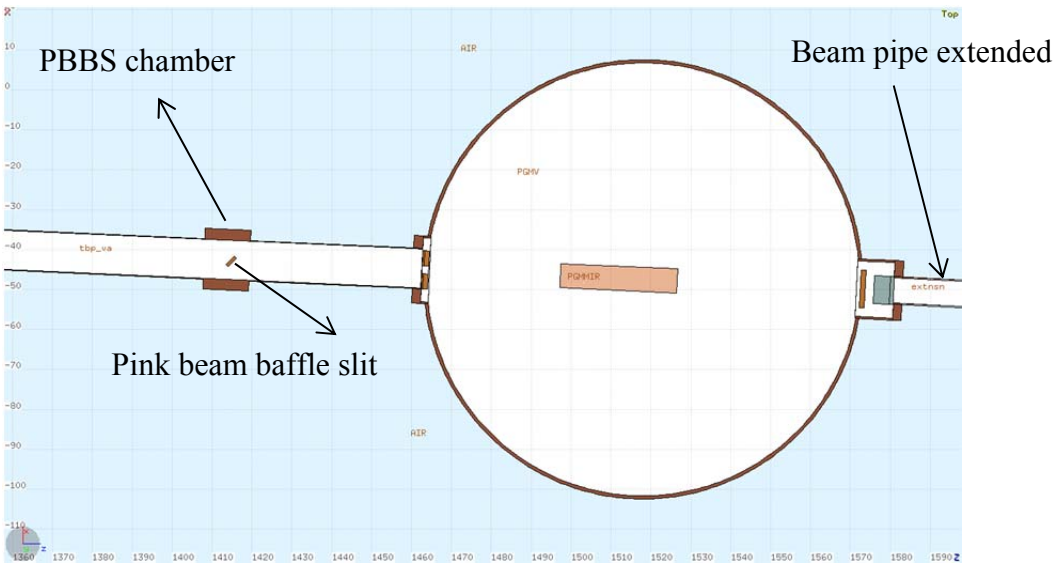

Figure 5. The pink beam baffle slits and its chamber approximated as an additional thickness of the beam pipe are shown. Also, the extension of the beam pipe beyond the PGM chamber can be seen.

A separate FLUKA calculation is carried out to estimate the bremsstrahlung spectrum. This is in turn used to calculate the fluence weighted average energy and also as the source for the GB simulations with the geometry shown in figure 1. The fluence weighted average energy is estimated to be 200 MeV and is used to convert the bremsstrahlung power of 17μW to the number of photons. A cumulative distribution from the differential energy spectrum is used to sample the source particles for the GB simulation.

2.3 Results

In the simulation, the GB photons are incident on the white beam mirror at FLUKA coordinates of (0,0,400). Figure 6 shows the total ambient dose equivalent rate in the plan view. Figure 7 shows the same results in a vertical view. The dose rates outside the front and lateral walls of the FOE are shown in figure 8 while a similar plot for the roof is shown in

figure 9. These results include the contribution from photons and neutrons. It can be seen from these figures that the maximum dose rates do not exceed 0.02 mrem/h.

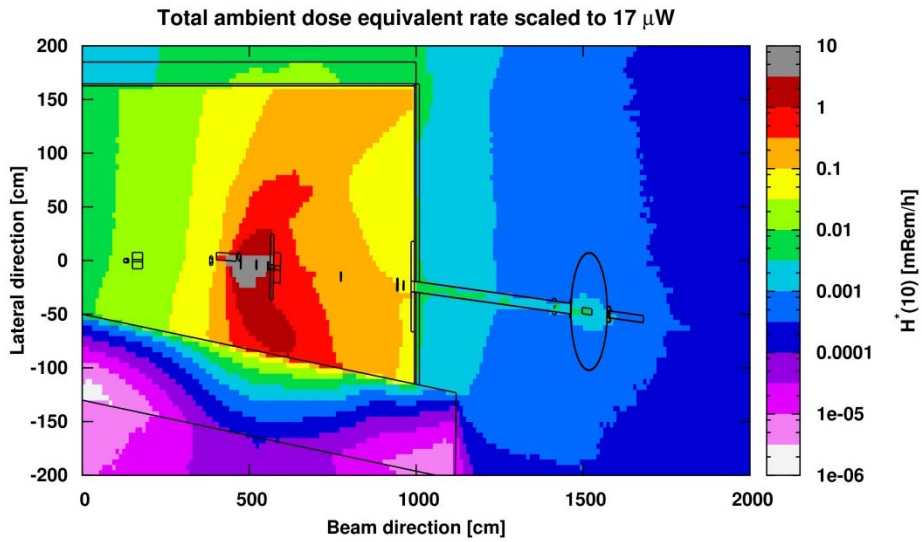

Figure 6. The total ambient dose equivalent when GB strikes the white beam mirror, shown as a plan view (geometry cross section at Y=0)

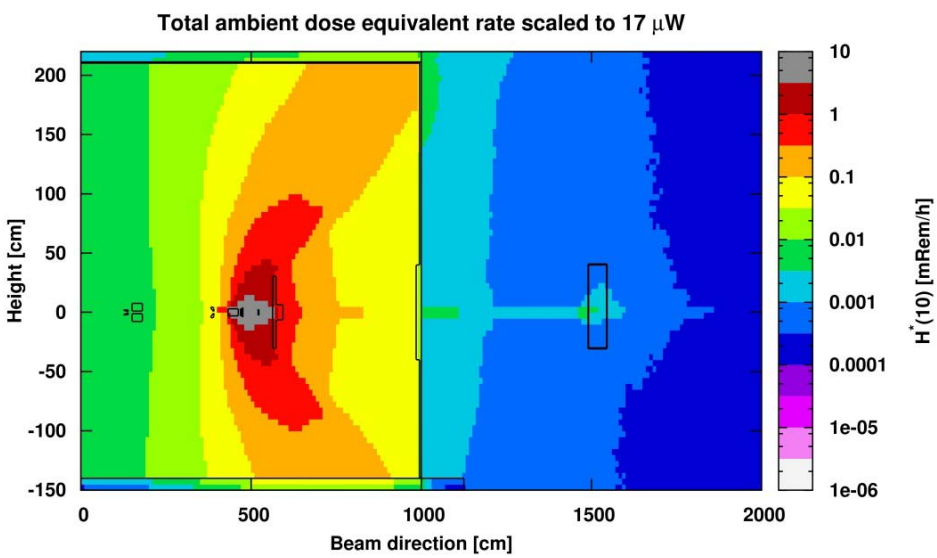

Figure 7. The total ambient dose equivalent when GB strikes the white beam mirror, shown as a vertical view. (Geometry cross section at X=0)

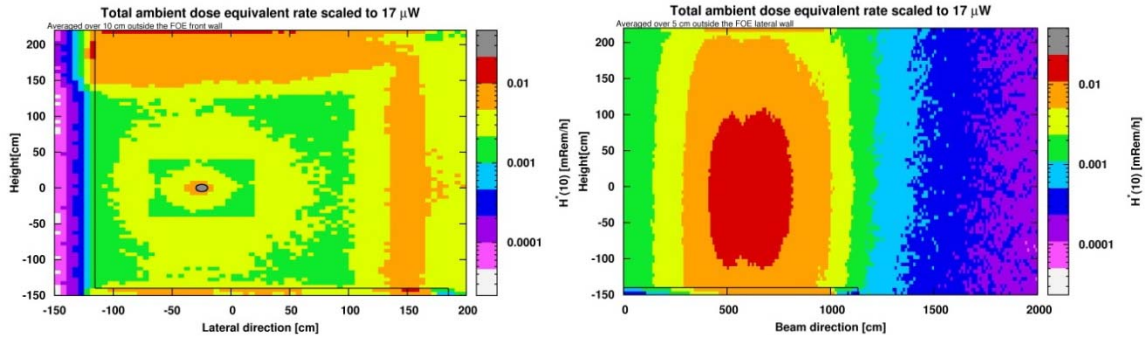

Figure 8. The dose rates outside the front (left) and lateral (right) FOE walls.

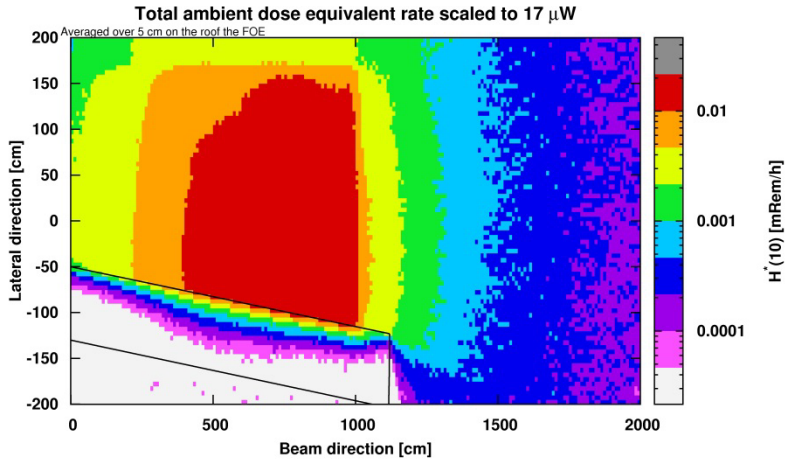

Figure 9. The dose rates outside the roof of the FOE.

Figure 10 shows the bremsstrahlung dose rates in and around the beam pipe with the slit in place. Some amount of showering can be seen caused by the slit but this is contained inside the pipe and the dose rates outside it are within acceptable values. In figure 11, vertical plots shows the dose outside the PBBS chamber (left) and the PGM chamber (right). Here the beam is directed towards the reader from the plot plane. Outside the beam pipe, the dose rates can be seen to lower than 0.01 mrem/h.

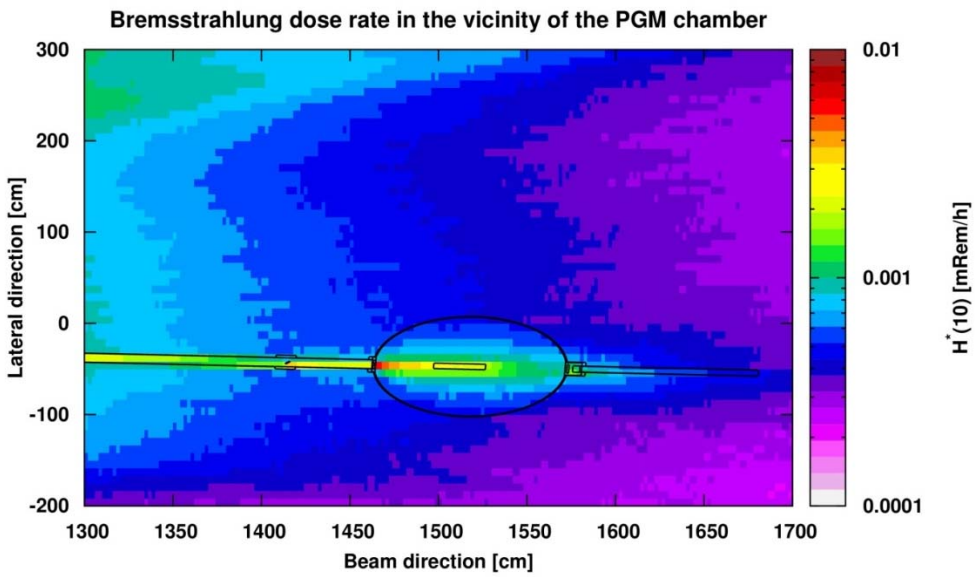

Figure 10. The ambient dose equivalent rates around the PBBS and PGM chambers.

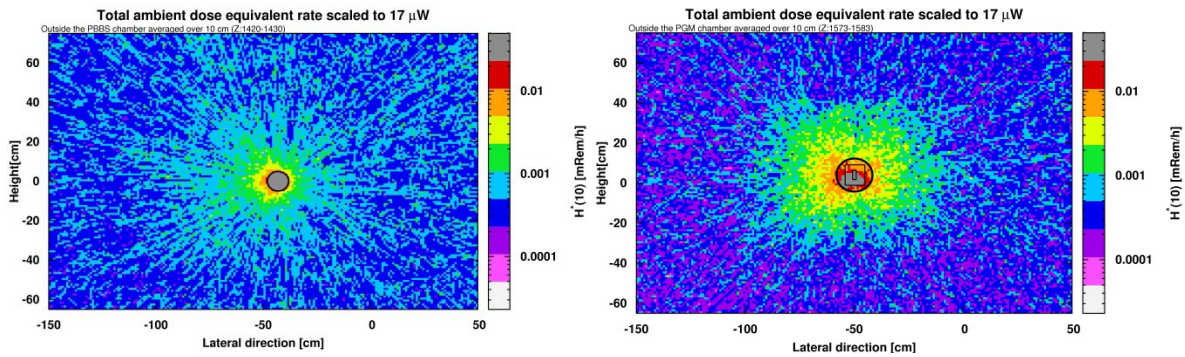

Figure 11. The dose outside the PBBS chamber (plot on the left) and PGM chamber (plot on the right) shows the dose rates on averaged over 10 cm distance on Z axis. The beam direction is perpendicular to the plot plane and is traveling towards the reader.

3 Synchrotron Radiation Calculation

The 21ID-ESM beamline is served by two EPU sources. Their source parameters are listed in Table 2. STAC8 code is used to calculate the ambient dose equivalent rates due to SR, in the occupied areas outside the beam pipe. The synchrotron spectra given by the beamline group [5] are used as the inputs for STAC8 calculations and are shown in figure 12. The build-up effect in the shield is included in the calculation. The calculations are carried out with unpolarized beam.

Table 2: Source parameters used for 21ID (ESM) in STAC8 calculations.

Source	Max. source opening	No. Of periods	Max. B_{eff} (T)	Period (mm)	E_c (keV)
EPU 105	1.0 mrad-H	27	1.14	105	6.82
EPU 57	1.0 mrad-H	25	0.83	57	4.97

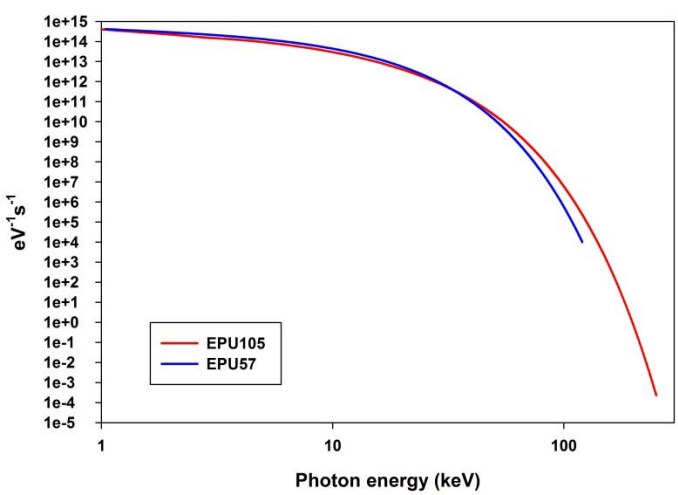

Figure 12. The source spectrum obtained from the beamline group and used as the input for STAC8 calculations.

3.1 Results

3.1.1 Outside the PBBS chamber

The beam from the undulator is reflected off a gold coated mirror (M1) of 400 mm radius, placed at 1.25° glancing angle. Scattering off the mirror and the effect due to its roughness are neglected. The resulting beam is then incident on a Cu target (the pink beam baffle slit), 6.45 mm thick and kept at 45°. The ambient dose equivalent rates are calculated on contact, outside the PBBS chamber and at the joint of the beam pipe and the chamber. The total distance at which the dose is estimated also includes the inner radius of the chamber, which is 61 mm for the chamber and 50.8 mm for the pipe.

The ambient dose equivalent rates from these calculations are given in table 3 for EPU105 and EPU57 sources. The doses rates are not expected to exceed the exposure levels permitted for full occupancy.

Table 3. Ambient dose equivalent rates on contact outside the pink beam baffle slit chamber.

	Ambient dose equivalent rate (mrem/h) on contact	
	Lateral to the chamber	Joint of chamber and pipe
EPU105	8e-7	0.05
EPU57	1e-7	0.03

3.1.2 Outside the bellow upstream of the PBBS chamber

A separate calculation was carried out to estimate the dose rates outside the bellows (upstream and downstream) of the PBBS chamber. The bellow is considered to be 0.2 mm thick SS with every fold adding the same thickness. From field measurements, it is estimated that the angle of start edge of the bellow subtending at the slit will see 5 folds equivalent to 1 mm thickness. The dose rates are estimated to be negligible (2e-4 mrem/h or lower).

3.1.3 Dose outside the PGM chamber

In the next set of calculations, the dose rates outside the PGM chamber is estimated after the pink beam has been reflected by M2 at different angles with M1 kept fixed at 1.25°. The chamber thickness of 8 mm is assumed as the shield thickness at all angles. Figure 13 shows the variation of the dose with respect to the angle. From the radius of the chamber, it is expected that at 8°, the beam will see only the chamber wall thickness. The size of the PGM exit mask subtends 5° at the center of the mirror. From the figure, the dose rates are seen to be less than 0.05 mrem/h.

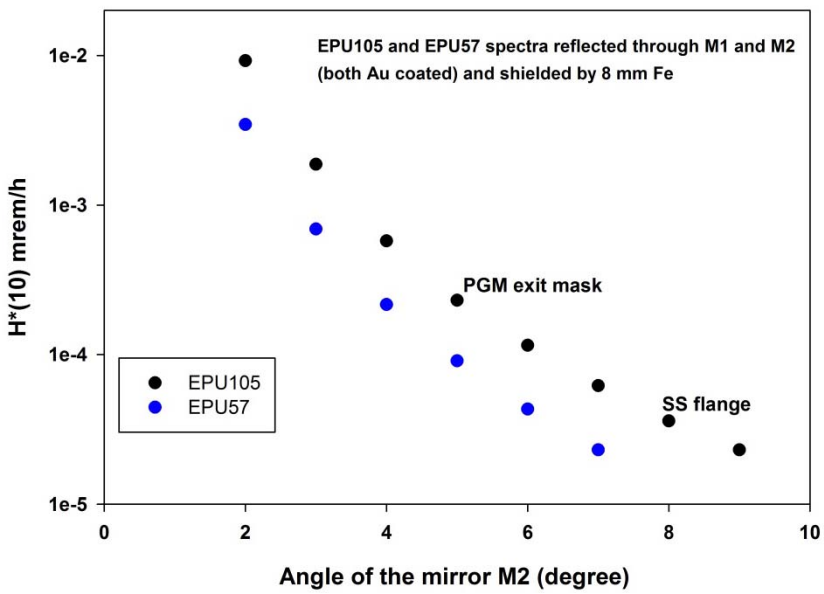

Figure 13. Maximum direct dose from a doubly reflected beam shielded by 8 mm of Fe at various angles of reflection by the second mirror. The first mirror is kept fixed at 1.25°.

3.1.4 Dose outside the beam pipe from the beam emerging from the exit mask and gamma stop

For lower angles of reflection by M2, a line of sight through the openings of the copper PGM exit mask and the tungsten bremsstrahlung is possible (figures 4(a)&(b)). For a worst case scenario, the dose rates outside the exit beam pipe of the PGM chamber is calculated by assuming the mirror M2 as a Si scatterer. The dose rates are then estimated at 2-8° with respect to the beam direction, with 2 mm beam pipe as the shield and are expected to be less than 2e-5 mrem/h.

4 Summary

Ambient dose equivalent rates are estimated for the radiation shielding of the 21-ID-ESM beamline with the introduction of the pink beam baffle slits. Estimation of the GB dose rates with the FLUKA Monte Carlo code shows dose rates are well below 0.05 mrem/h outside the FOE and the beamline. Ambient dose equivalent rates due to the synchrotron radiation calculated by the STAC8 code are not expected to exceed 0.05 mrem/h outside the chamber, beam pipe joint and at the bellows adjacent to the chamber. The white beam spectra provided by the beamline group are used as the input for the STAC8 calculations. Results from the simulations shall be validated by measurements during commissioning as per the radiation survey procedure. The rad survey procedure has been modified to include measurements in the vicinity of the pink beam baffle slits chamber and at the exit of the PGM chamber.

5 References:

1. V.J. Ghosh and M. Benmerrouche, 21-ID ESM Beamline Radiation Shielding Analysis, NSLS II TECHNICAL NOTE 217, 28 June 2016.
2. R. Lee, Photon Sciences Shielding Policy, PS-C-ASD-POL-005.
3. A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft, FLUKA: a multi-particle transport code, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.
4. Y. Asano, "A study on radiation shielding and safety analysis for a synchrotron radiation beamline," JAERI-Research-2001-006, March 2001.
5. Email from E. Vescovo to M. Benmerrouche (June 23, 2016).

6 Acronyms

EPU	Elliptical Polarized Undulator
ESH	Environment, Safety and Health
ESM	Electron Spectrum Microscopy
FE	Front End
FOE	First Optical Enclosure
GB	Gas Bremsstrahlung
ID	Insertion Device
LOTO	Lockout/Tagout
m	Meter
mrad	Millirad
mrem/hr	Millirem per hour
NSLS-II	National Synchrotron Light Source II
PBBS	Pink Beam Baffle Slit
PBS	Pink Beam Stop
PGM	Plane Grating Monochromator
PSD	Photon Science Division
RCT	Radiological Control Technician
rms	Root Mean Square
SAF	Safety Approval Form
SBMS	Standards Based Management System