Radiation shielding for undulator beamline in Indus-2 synchrotron radiation source

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Abstract

Indus-2 synchrotron radiation source (SRS) is operational at Raja Ramanna Centre for Advanced Technology (RRCAT), India with electron beam current up to 200mA at 2.5 GeV and is being used for conducting research in basic and applied branches of science and engineering. Two planar undulators and one APPLE-II type undulator have been installed and commissioned in the straight sections of Indus-2 SRS to increase brilliance required for enhancing utilization. One of the insertion devices, a planar permanent magnet (PPM) undulator (U_1) will be used as a source of ultraviolet to soft X-ray photons for a beamline dedicated for atomic, molecular and optical science (AMOS) research. Appropriate radiation shielding enclosure (hutch) is mandatory requirement to operate this beamline for conducting experiments. The shielding requirement of hutch for this beamline in Indus-2 experimental hall was evaluated using FLUKA Monte Carlo code. The radiation dose due to gas bremsstrahlung radiation, photo-neutron and synchrotron radiation were simulated and the shielding parameters were optimized to achieve regulatory dose limit. This paper describes the design and optimization studies of a gas bremsstrahlung stop and shielding hutch using FLUKA Monte Carlo code.

1. Introduction

Indus-2, 2.5 GeV electron storage ring is operational at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, India and is a dedicated synchrotron radiation source (SRS) for scientific and technological research applications. This facility comprises of 20 MeV microtron as electron injector, a booster synchrotron for delivering 550 MeV electrons and a 2.5 GeV electron storage ring. 550 MeV electrons from booster synchrotron are injected, stored and ramped to 2.5 GeV in Indus-2 SRS with an operating beam current of 200 mA. The facility has provision for accommodating 21 bending magnet and 5 insertion device beamlines. At present, thirteen bending magnet based beamlines (10 hard X- ray beamlines & 3 soft X-ray beamlines) are regularly being used for conducting research in medicine, material science, geology, biology etc. As a part of the program for enhancing utilization of Indus-2 SRS to perform advanced experiments requiring higher brilliance over broad energy range (ultraviolet to hard X–ray through soft X-ray), many insertion devices have been planned to be installed. Two planar and One APPLE-II type undulators are installed in 10.4 m long straight sections of Indus-2 storage ring. One such device, a planar permanent magnet (PPM) undulator (U1) has been installed in the LS-2 long straight section. This undulator is going to be used as the photon source for a beamline to conduct Atomic, Molecular and Optical Science (AMOS) research [1]. Operation of this beamline requires commissioning of an appropriate radiation shielding enclosure (hutch) to keep the radiation dose in and around this beamline within permissible limits. Gas bremsstrahlung, produced due to interaction of high energy electron beam with residual gas molecules present inside the storage ring chambers travels in to the beamline (along with the synchrotron radiation) is a potential radiation hazard to the working personnel in beamline [2, 3]. Gas bremsstrahlung is significantly higher in beamlines based on insertion devises compared to bending magnet beamlines as the intensity of gas bremsstrahlung depends on beam energy and length of the straight sections through which the electrons move. Gas bremsstrahlung radiation is highly focused in the forward direction, but on interacting with beamline components, the radiation gets scattered in all directions. Radiation protection at synchrotron radiation beamlines, especially undulator/wiggler based beamlines therefore is challenging due to the presence of high energy gas bremsstrahlung. In addition to the scattered bremsstrahlung, photo-neutrons produced by gas bremsstrahlung complicate radiation issues further. To contain the radiation dose within allowed limits, beamline components are contained in a shielded enclosure made of materials like steel and lead along with additional local shielding for radiation safety. In case of AMOS beamline, the first plane mirror acts as the first scattering element. In the present work, FLUKA Monte Carlo code [4] was used to study the gas bremsstrahlung characteristics like spectrum, angular distribution and dose profile in the beamline. Photo-neutron component is also evaluated and accordingly shielding requirements are finalised.

2. Radiation shielding evaluation

The layout of the AMOS beamline along with the shielding hutch and beamline components are shown in Fig-1. Mirror was kept inside the optics hutch of the beamline and is at a distance of 18.5 m from the centre of U1 undulator. This acts as the first scattering element for gas bremsstrahlung radiation which channels along with synchrotron radiation. Radiation shielding evaluation is carried out in such a manner that radiation is confined within the optics hutch. Monochromator hutch and experimental hutch are made normally accessible. The dose limit for normally accessible areas is kept less than 1 μSv/h as per the regulatory requirement [5].

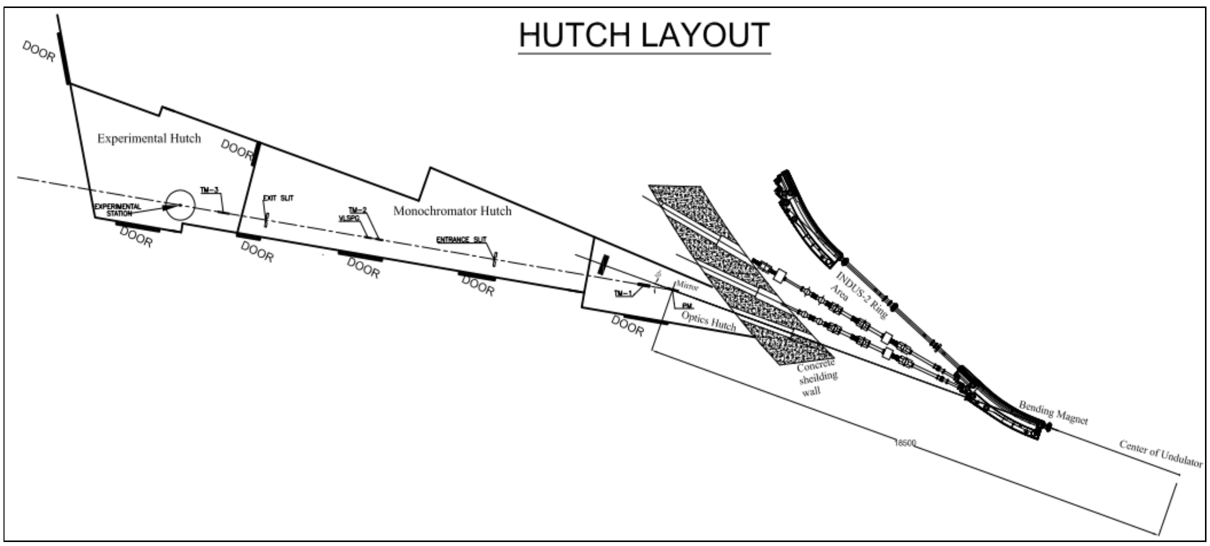

Fig-1: Layout of AMOS beamline with shielding hutch

2.1 Gas bremsstrahlung

2.1.1 Unshielded gas bremsstrahlung dose

FLUKA simulation was performed to estimate the unshielded gas bremsstrahlung dose due to 2.5 GeV electrons passing through 10.4 m air target. A pencil beam of electrons of energy 2.5 GeV was allowed to incident on air target at NTP and the absorbed energy was scored in an ICRU tissue phantom (radius =15 cm and length =30 cm) placed at a distance of 19.5 m from the centre of straight section using USRBIN scoring estimator. The ICRU tissue [6] comprises of four elements: Hydrogen (10.12%), Carbon (11.1%), Nitrogen (2.6%) and Oxygen (76.18%). The schematic diagram of the geometry is shown in figure-2.

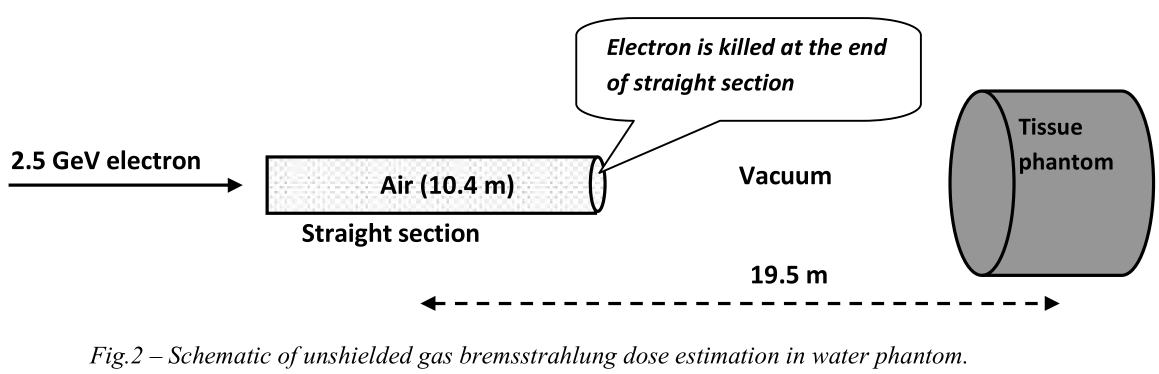

Fig.2 – Schematic of unshielded gas bremsstrahlung dose estimation in water phantom.

The average pressure in Indus-2 storage ring is maintained at 1 nTorr. The number of air molecules present at this pressure is significantly less compared to air at atmospheric pressure. This will lead to widening of emitted gas bremsstrahlung cone due to multiple scattering effects. Therefore multiple scattering effects are suppressed for all the simulation studies. The threshold for Moller scattering of electrons was set at 10 MeV to minimize angular divergence due to production of δ-rays [7, 8]. Results of simulations performed at atmospheric pressure (for better statistics), were then normalized to actual pressure of 1 nTorr. In actual scenario, an electron gets bent by a bending magnet at the end of straight section. In simulation, electrons are killed intentionally at the end of straight section using high electron transport cut off (2.5 GeV) in order to avoid the electron contribution in gas bremsstrahlung dose. The transport cut off for photon, electron and positron in air and tissue media were set at 1, 10 and 10 keV respectively. Tissue phantoms are binned longitudinally into 30 bins (1cm per bin) for estimation of dose equivalent. Dose equivalent rate was scored through USRBIN scoring card using fluence to dose equivalent conversion coefficients through AUXSCORE card. The fluence spectrum was obtained using USRTRACK scoring card and output data were scaled to actual pressure of 1 nTorr. The statistical uncertainties in the results are found to be within ± 3.0 %. The estimated gas bremsstrahlung dose rate is found to be 102.73 mSv/h-nTorr at a distance of 19.5 m from the straight section for 200 mA stored current in Indus-2. Gas bremsstrahlung energy spectrum and corresponding depth dose inside tissue phantom are shown in figure-3.

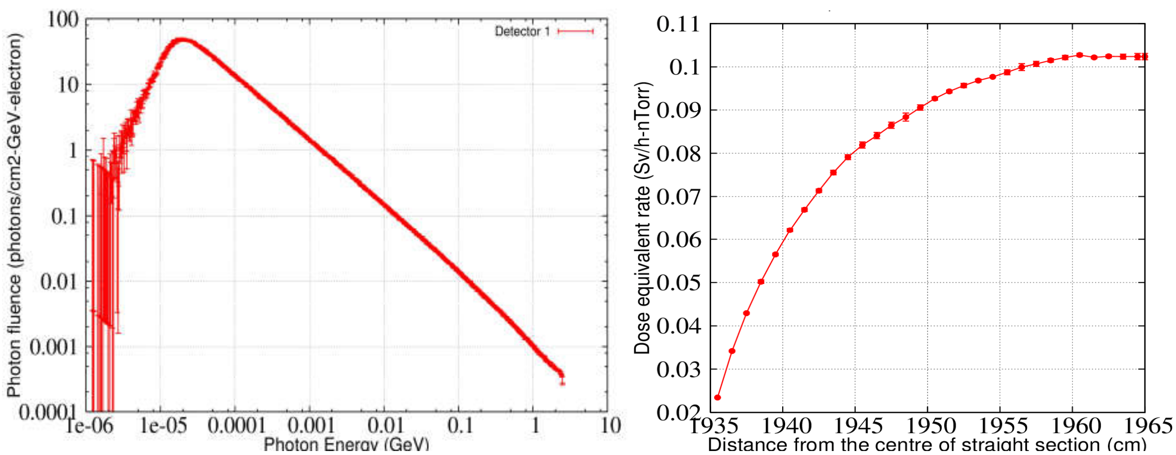

Fig.3- Gas bremsstrahlung energy spectrum (L) and the depth dose profile (R) inside tissue phantom due to 2.5 GeV electrons passing through 10.4 m straight section

2.1.2 Scattered gas bremsstrahlung dose from the mirror assembly

In order to evaluate scattered gas bremsstrahlung contribution from mirror assembly, direct spectrum is allowed to incident on the silicon mirror which is inclined at 10–degrees with respect to synchrotron beam axis. This mirror is located at a distance of 18.5 m from the centre of the straight section of Indus-2 storage ring. A schematic diagram of the geometry used for the simulation of scattered gas bremsstrahlung dose rate and spectrum is shown in figure-4. Two detectors (tissue phantoms of radius = 15 cm and length= 30 cm) placed at 1 m along forward direction (0^0) and lateral direction (90^0) from the silicon mirror are used to score gas bremsstrahlung dose and spectrum. The gas bremsstrahlung energy spectrum along 0^0 and 90^0 are shown in figure-5 and the corresponding estimated dose equivalent rate in the detectors placed along (0^0) and perpendicular (90^0) to beam axis for 200 mA stored current are shown in figure-6. Figure-6 shows that the dose in forward direction (0^0) is increasing with respect to depth in tissue phantom whereas a decreasing trend is observed in lateral direction (90^0). This is in consistent with the energy spectrum shown in figure-5. The increase in dose is due to the high energy photons in the forward direction and relatively low energy in lateral direction as shown in figure-5. The maximum dose equivalent rate at 1 m along (0^0) and perpendicular (90^0) to beam axis is found to be 64.3 mSv/h-nTorr and 0.31 μSv/h-nTorr respectively.

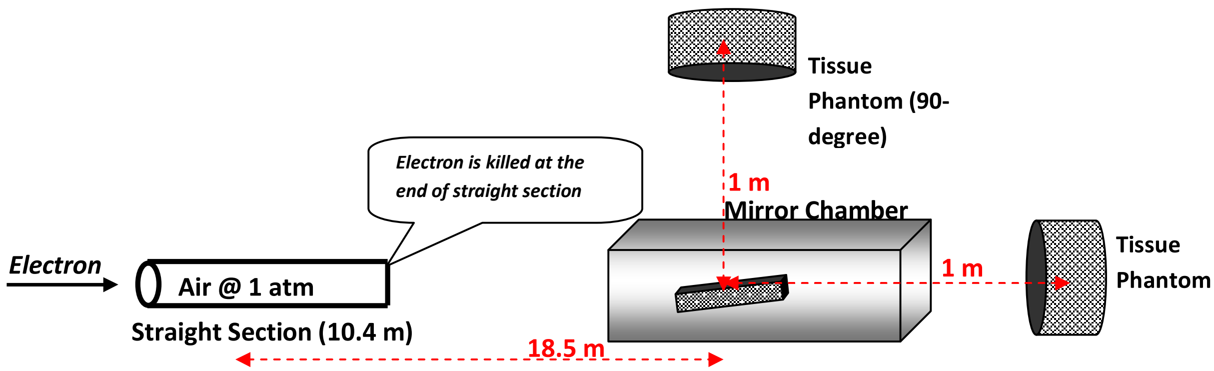

Fig.4- Geometry used for bremsstrahlung dose evaluation in 0 and 90 degree from the mirror

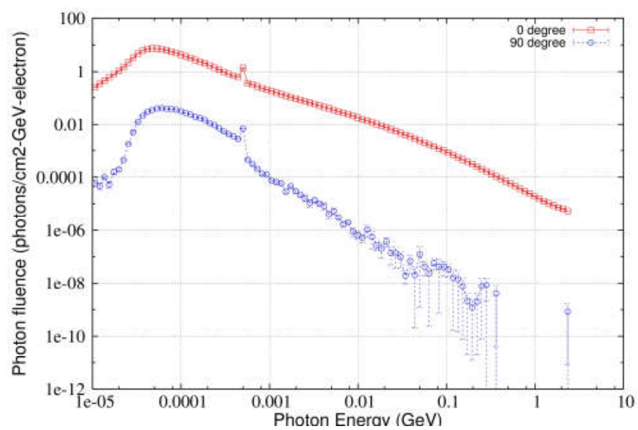

Fig.5 - Scattered gas bremsstrahlung spectra from pre-mirror in 0 and 90-degree direction

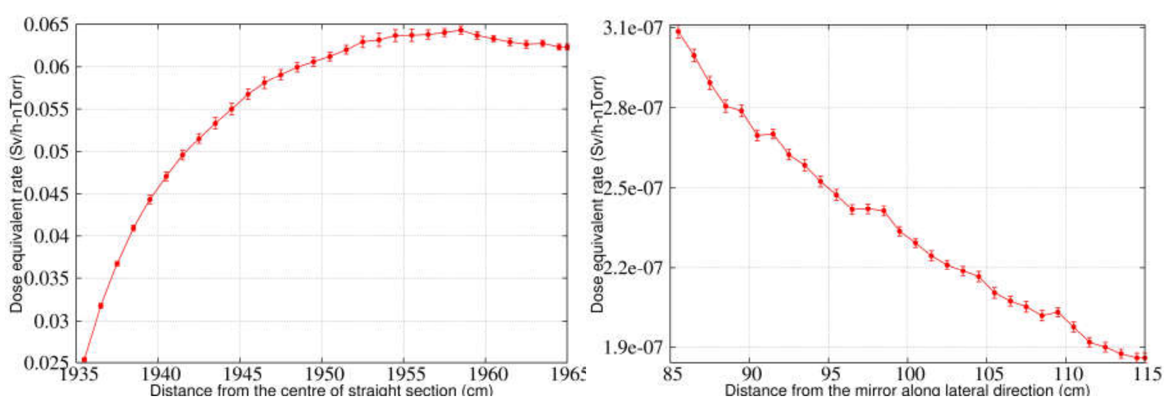

Fig.6- Depth dose profile inside 30 cm tissue phantom in 0^0 (L) and 90^0 (R)

2.1.3 Scattered gas bremsstrahlung dose outside beamline hutch

For optimization of gas bremsstrahlung stop, first beamline component with plane mirror (made of silicon), mirror chamber (made of stainless steel) and complete hutch wall (made of lead) are simulated. Initially the calculation for bremsstrahlung stop is performed with a lead shielding of 10 and 15 cm thickness after the mirror. The direct gas bremsstrahlung spectrum is allowed to fall on the mirror and dose equivalent rate outside the hutch wall is estimated. Preliminary estimates with 10 to 15 cm of lead gave a forward (0^0) dose rate of 254 and 15.4 µSv/h-nTorr for 200 mA stored current at 2.5 GeV. This exercise helped in optimizing the final shielding required for bremsstrahlung stop. An optimized thickness of 20 cm is found out as the bremsstrahlung radiation shield (BR stop) thickness along the central axis. Size of BR stop is optimized in lateral direction taking the advantage of angular distribution of gas bremsstrahlung. In the lateral direction, a thickness of 10 cm is found to be adequate to maintain radiation levels outside the hutch within acceptable limit. In order to evaluate scattered dose around optics hutch, four detectors (Tissue phantoms- D1, D2, D3 and D4) are placed and dose is scored. Schematic layout of the beamline with the proposed lead shielding for optics hutch is shown in figure-7.

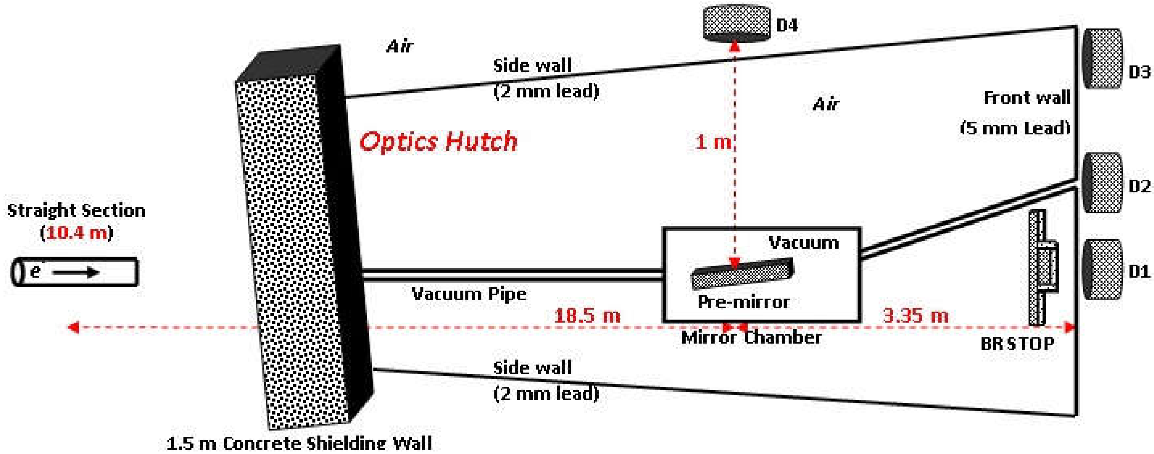

Fig.7- Geometry used for bremsstrahlung dose evaluation outside hutch area.

2.2 Photo-neutron dose outside the beamline hutch

Gas bremsstrahlung on hitting the mirror/mirror chamber will generate photo-neutrons. Photo-neutron dose is scored outside the beamline hutch in the four detectors D1, D2, D3 and D4. For photo-neutron simulation, LAMBIAS card is used for reducing the photon interaction length for nuclear inelastic interactions by a factor of 50, since the photo nuclear cross-section is smaller as compared to cross-section for electromagnetic interactions.

From the study, it has been observed that though 20 cm thick lead (BR stop) is sufficient enough to reduce gas bremsstrahlung dose within regulatory limit (1 μSv/h) but it enhances the photo-neutron dose rate. Therefore 15 cm polyethylene (density – 0.93 g/cc) is added to the BR stop for neutron shielding. The dose equivalent rate due to photons and photo-neutrons with optimized shielding from four detectors for 200 mA at 2.5 GeV are shown in Table-1.

Location & Detector	Dose Equivalent rate (μSv/h-nTorr) for 200 mA stored current in Indus-2							
	Unshielded	With Mirror assembly	With BR stop and hutch walls			With BR stop, Neutron shielding and hutch walls		
	Gas BR	Gas BR	Gas BR	Photo-neutron	Total	Gas BR	Photo-neutron	Total
Forward (0-degree) – D1	102730	64300	0.58	6.63	7.21	0.22	0.07	0.29
Beam pipe hole– D2	-	-	1.12	1.49	2.61	0.94	0.33	1.27
Corner of the hutch – D3	-	-	0.24	0.15	0.39	0.24	0.26	0.50
Lateral (90-degree) – D4	-	0.31	0.06	0.11	0.17	0.06	0.12	0.18

Table-1: Scattered gas bremsstrahlung and photoneutron dose rate around the hutch

2.3 Synchrotron radiation dose evaluation outside the beamline hutch

Synchrotron radiation in the energy range 1 to 100 keV from undulator U1 is generated using SPECTRA [9] code. To evaluate the dose due to direct synchrotron spectrum, this complete spectrum is programmed as incident beam using a subroutine (source.f) in FLUKA input. To evaluate the unshielded synchrotron dose, the spectrum is allowed to incident directly on the 30 cm thick tissue phantom (placed at D1 location). Input synchrotron spectrum and the corresponding depth dose profile inside the water phantom for 200mA stored current in Indus-2 are shown in figure-8. Maximum dose equivalent dose equivalent rate of 7.24 x 10^4 Sv/h for 200 mA stored current in Indus-2 was observed at the surface of the tissue phantom.

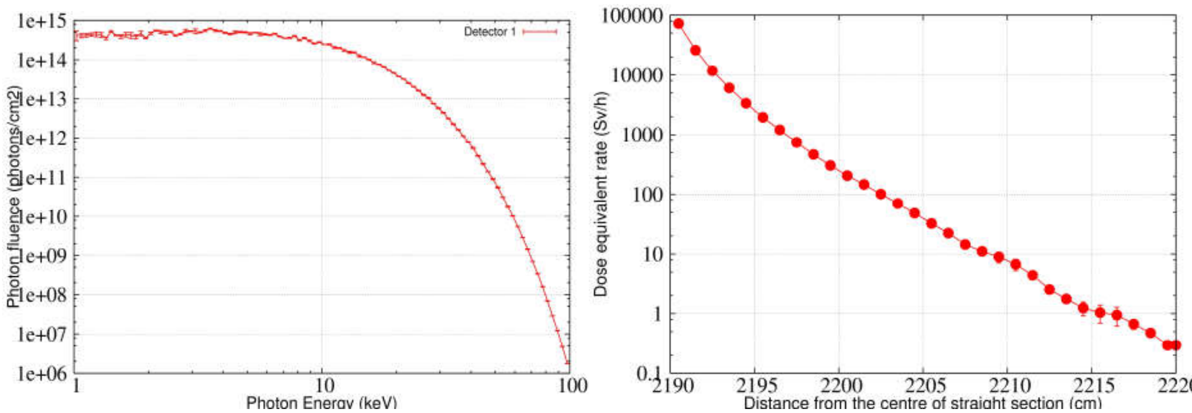

Fig-8: Synchrotron radiation spectrum (L) and the depth dose profile (R) inside tissue phantom for 200mA stored current in Indus-2

To evaluate the scattered dose outside the beamline, the synchrotron photon spectrum (Fig-8) is allowed to transport through the beamline components inside the lead hutch wall (Fig-7). The dose equivalent rate was scored using the tissue phantoms D1, D2, D3 and D4 placed along the hutch wall (5 mm front and 2 mm sidewall). The scattered synchrotron dose rate in all the detectors placed outside the hutch wall are found to be less than 0.1 µSv/h for 200 mA stored current in Indus-2.

3. Conclusion

The radiation shielding requirements for insertion device based AMOS beamline in Indus-2 is evaluated using Monte Carlo code, FLUKA. The dose rate due to direct gas bremsstrahlung, synchrotron radiation and scattered radiation are evaluated. Photo-neutron dose rate is also simulated. Based on the study, the recommendations for shielding enclosure of the beamline are as follows.

- Front and lateral wall of the hutch should have 5 and 2 mm thick lead shielding respectively.
- The optimised gas bremsstrahlung shielding (BR stop) behind the mirror assembly should be 20 cm thick lead along the central axis. Lateral thickness above the central axis (5 cm above) can be reduced to 10 cm. Additional 15 cm Polyethylene should be added to BR stop to reduce photo-neutron dose rate.
- The beam pipe hole showed dose equivalent rate 1.45 µSv/h. Annular space between the beam pipe and the hutch wall near the beam hole needs to be plugged with lead wool to reduce the dose rate to acceptable levels and stop leakage of radiation.
- The scattered synchrotron dose outside hutch was found to be within the permissible limit.
- Beyond optics hutch, there is no shielding requirement for monochromator and experimental hutch of the beam line and the areas will be accessible in beam “ON” condition.

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