Radiation safety studies at synchrotron radiation beamlines of Indus-2

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Abstract

Indus-2 is a 2.5GeV, 300mA Synchrotron Radiation Source (SRS) at Raja Ramanna Centre for Advanced Technology, India. The facility is designed to accommodate 21 bending magnet (BM) and 5 insertion device (ID) beam lines. Presently twelve bending magnet beamlines are regularly operated and several others are under various stages of installation and commissioning. The facility is being upgraded to third generation SRS with recently installed insertion devices (Undulators). Radiation safety issues of the synchrotron beamlines are complex due to the high flux & broad spectrum of synchrotron photons ranging up to hard x-ray region with a critical energy of 6 keV and high energy bremsstrahlung photons ranging up to 2.5 GeV. Photo-neutrons generated by the bremsstrahlung radiation also contribute to the radiation environment. The paper describes the radiation environment of synchrotron radiation beamlines of Indus-2, the methodology adopted for the evaluation of radiation dose and shield design. The maximum absorbed dose rate due to synchrotron and gas bremsstrahlung radiation in synchrotron beamlines are simulated and found to be ~ 10^5 Gy/h and 67.0 x 10^{-3} Gy/h respectively for design parameters of Indus-2 SRS. The details of simulation of absorbed dose using FLUKA Monte Carlo code with the results and conclusions are described in the paper.

1. Introduction

Synchrotron Radiation sources (SRS) are being used worldwide for various scientific research studies in material science, biology, industries etc. Indus-2 is a 2.5 GeV electron SRS at Raja Ramanna Centre for Advanced Technology situated at Indore in India. This facility consists of 20 MeV Microtron (electron injector), a booster synchrotron and 2.5 GeV electron storage ring. 20 MeV electron beam is ramped up to 550 MeV in booster synchrotron and is then injected to the storage ring. The energy of the electron beam is then ramped to 2.5 GeV in the storage ring. The storage ring is commissioned up to 200 mA circulating current at design energy of 2.5 GeV. The facility was originally designed for 300 mA stored current at 2.5 GeV beam energy. The facility is planned for accommodating 26 synchrotron beamlines, out of which 21 are from bending magnets and rest are from insertion devices. Twelve beamlines on bending magnet are regularly operating at 150mA at 2.5 GeV beam energy and several beamlines are under various stages of installation and commissioning. The synchrotron radiation (SR) from the bending magnet in Indus-2 is having broad energy spectrum ranging up to hard X-ray region with critical energy at 6 keV. High energy gas bremsstrahlung radiation (BR) along with the synchrotron radiation also channel to beamline posing radiation hazard to beamline users [1,2]. Gas BR radiation is produced by high energy electrons interacting with residual gas molecules inside vacuum chamber of storage ring. This gas BR has a broad spectrum ranging up to the energy of primary electron beam. Hence gas BR is treated as major radiation hazard in synchrotron beamlines. Radiation safety issues of the synchrotron beamlines are complex due to the high flux and broad spectrum of synchrotron photons and high energy bremsstrahlung photons. On further interaction with the beamline components this high energy photons produce photo-neutrons. The intensity of the gas BR depends on the path length of electrons in vacuum chamber. Effective electron beam path for an insertion device beamline is much higher than that of bending magnet case and therefore the intensity of gas bremsstrahlung is many orders magnitude higher than that of a bending magnet. Several optical elements will be used for transport of SR beam to the experimental station. These beamline components act as scatterer for the bremsstrahlung and synchrotron radiation. In order to protect the working personnel from radiation hazard, the beamlines are housed in shielded hutch along with additional local shielding. The radiation scenario in beam lines are different from each other in aspects of design specifications of the beamlines i.e. synchrotron source type, its energy range and the beamline components. Monte Carlo techniques are widely used to simulate the radiation scenario and shielding evaluation for SRS facilities. FLUKA Monte Carlo code [3] was used to evaluate radiation dose in Indus-2 due to synchrotron and gas bremsstrahlung radiation and accordingly the shielding requirement was also evaluated.

2. Radiation Shielding Evaluation

2.1 Synchrotron Radiation

Most of the bending magnet beamlines are using water cooled beryllium window of 200 μm thick for vacuum isolation of the beamline with the storage ring. Therefore the span of synchrotron energy reaching the beamline ranges from 4 to 100 keV however, the useful flux at the experimental station is limited up to 50 keV. The absorbed dose rate due to the synchrotron radiation spectrum in Indus-2 was simulated using FLUKA Monte Carlo code. The synchrotron radiation spectrum in the energy range 4-100 keV for 2.5 GeV electrons bending through 5.5 m bending radius was generated using a fortran program developed by Alberto Fasso, SLAC [4] and is shown in figure-1.

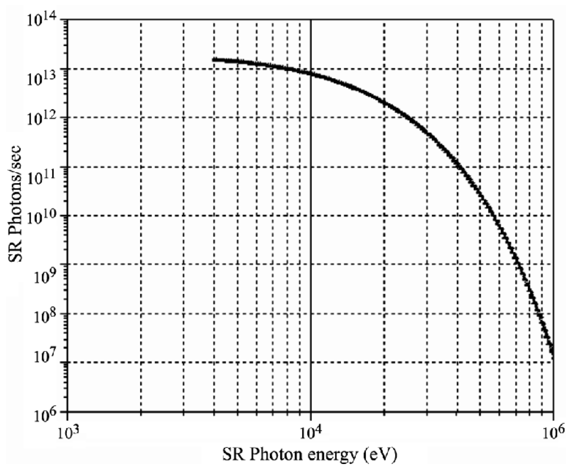

Fig.1 –Synchrotron radiation spectrum from bending magnet in Indus-2 for 300mA at 2.5GeV.

The SR spectrum as shown in figure-1 was incident on water phantom of size (10 mm × 10 mm × 300 mm). The energy absorbed in water phantom was scored along the width in 100 bins (i.e. bin width of 3mm) using USRBIN scoring card. The calculated depth dose profile is shown in figure-2. The statistical uncertainties in all data points are less than 1%.

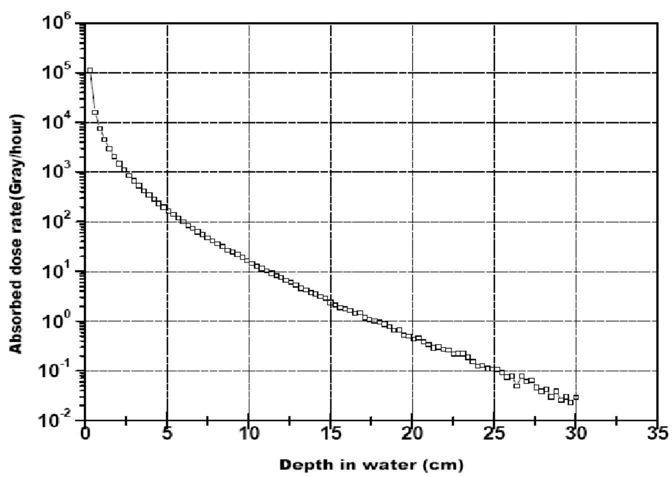

Fig.2 – Depth dose profile inside water phantom due to synchrotron spectrum at 300 mA stored current in Indus-2.

The depth dose curve in figure-2 shows a maximum absorbed dose rate of 1.12×10^5 Gray/h at the surface of the water phantom for 300 mA stored current in Indus-2. Being low energy photons, synchrotron photons get attenuated significantly with the depth of water.

To evaluate the shielding requirement for the absorbed dose from radiation, lead was introduced before the water phantom and the corresponding absorbed dose rate in water phantom was calculated. The surface dose rates obtained in water phantom with respect to different lead thicknesses are given in table-1. Lead thickness of 3 mm is found to be sufficient to achieve the shield criteria (1 μSv/h) for accessible areas [5].

Lead thickness (mm)	*Surface dose rate in water (μGray/hour)*
1	*27.25*
2	*01.67*
3	*00.32*
4	*00.07*

Table 1 – Surface dose rate in water phantom at different lead thicknesses.

2.2 Gas Bremsstrahlung Radiation

FLUKA simulation was performed to estimate gas bremsstrahlung dose due to 2.5 GeV electrons passing through 5 m air target. A pencil beam of electrons of energy 2.5 GeV was incident on air target at NTP and the absorbed energy was scored in an ICRU tissue phantom of radius 15 cm and length 30 cm 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-3.

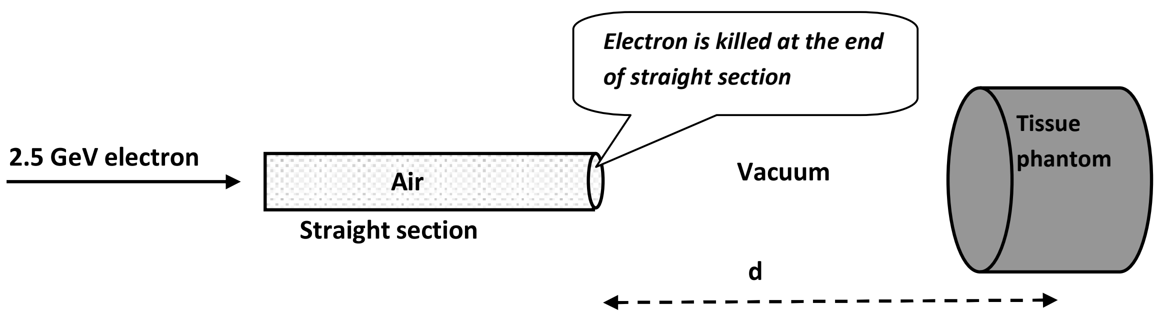

Fig.3 – Schematic of gas bremsstrahlung dose estimation in water phantom.

Simulation was performed at 1 atm pressure of air in straight section where large number of air molecules will lead to the widening of emitted gas bremsstrahlung cone [7, 8]. However actual pressure in Indus-2 is maintained at 1 nTorr during normal operation and the number of air molecules at this pressure is significantly lesser in compared to 1 atm pressure. So the beam interactions with gas molecules are very less and will lead to highly forward peaked bremsstrahlung photons. Therefore the multiple scattering effects in air at atmospheric pressure were intentionally suppressed for the simulation studies. The threshold for Moller scattering of the electrons was set at 10 MeV to minimize the angular divergence due to production of δ-rays [8]. The output data was scaled to actual pressure of 1 nTorr. The electron was killed intentionally at the end of the straight section using high transport cut off as 2.5 GeV in order to avoid its contribution in the gas bremsstrahlung dose. The transport cut off for photon in air and tissue media was set at 1 keV and for electron and positron was set at 10 keV.

The gas bremsstrahlung spectra simulated for a straight section of 5 m length (close to straight section length in Indus-2) is shown in figure-4. The gas bremsstrahlung spectrum ranges up to 2.5 GeV and shows fall in fluence for photon energy less than 20 keV due to the strong photoelectric absorption by air molecules like oxygen. The fluence follows approximately k^{-1} where k is the photon energy which can be attributed to a thin target bremsstrahlung spectrum since the air target thicknesses used for simulation study are much smaller than the radiation length in air [9].

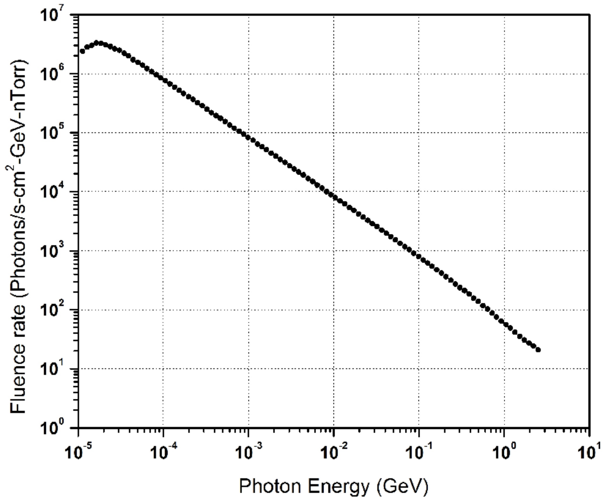

Fig.4 –Gas bremsstrahlung spectrum in Indus-2.

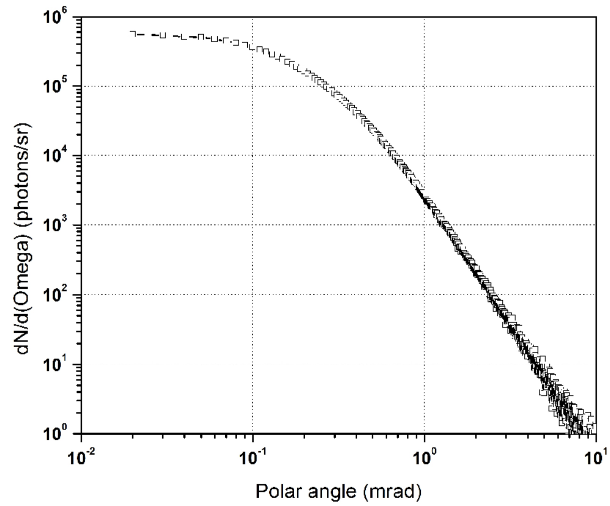

Fig.5 –Angular distribution of gas bremsstrahlung spectrum in Indus-2.

The angular distribution of the gas bremsstrahlung emerging out of the vacuum chamber is shown in figure-5. The distribution of photons shows nearly flat portion up to 0.1 mrad emission angle and falls rapidly in higher emission angles. Therefore an optimized value of emission cone of 0.1 mrad was set as reference for calculating scoring radius in tissue phantom for absorbed dose simulations. Hence the scoring radius in the tissue phantom is calculated as r(mm) = 0.1*d(m), where r is scoring radius in tissue phantom and d is the distance of the tissue phantom from the end of the straight section. The maximum absorbed dose (normalized for 300 mA stored current) inside the tissue phantom as a function of distance from straight section is shown in figure-6. The maximum absorbed dose rate for Indus-2 storage ring at a closest approach of d= 20 m from the straight section is found to be 67.0 ± 0.07 mGy/h. Using attenuation coefficient of lead for gas bremsstrahlung radiation as 0.6 cm^{-1}[10], the lead thickness of 18.5 cm is found to be sufficient to achieve the shield criteria for accessible areas.

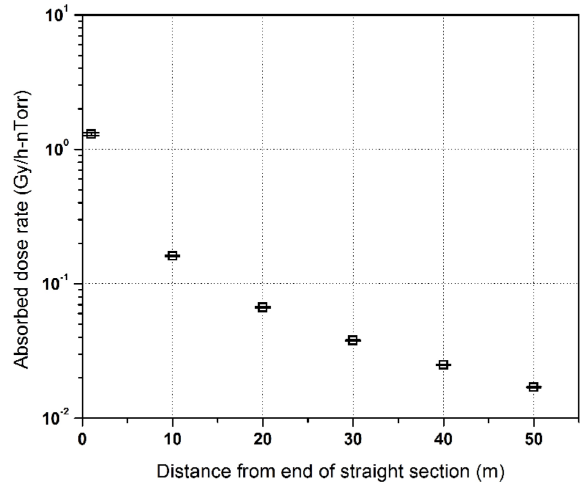

Fig.6 –Gas bremsstrahlung dose as a function of distance from straight section in Indus-2.

3. Conclusion

Indus-2, 2.5 GeV electron storage ring is now at commissioning phase at Indore, India. The facility is planned to accommodate 21 bending magnet and 5 insertion device beamlines. Twelve bending magnet beamlines are now operational and some are in design phases. However the facility is gearing up for addition of two insertion device beamlines in near future. The radiation shielding in Indus-2 beamlines for high intense synchrotron radiation and high energy bremsstrahlung radiation was evaluated using Monte Carlo code, FLUKA. The maximum absorbed dose rate due to synchrotron inside beamline hutches of Indus-2 was estimated to be 1.12×10^5 Gy/h for 300 mA stored current in Indus-2 SRS. It was also found that 3mm lead shield was sufficient enough to reduce the dose rate to permissible dose limit. The energy spectrum and angular distribution of gas bremsstrahlung radiation for insertion device beamlines were studied. The scoring radius in tissue phantom was calculated for an optimized emission angle of 0.1 mrad and the absorbed dose rate at different distances from the straight section were evaluated. The maximum absorbed dose rate for Indus-2 storage ring at a closest approach of 20 m from the straight section is found to be 67.0 ± 0.07 mGy/h. The lead shielding required to reduce the gas bremsstrahlung dose to the permitted dose level is calculated and found as 18.5 cm.

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