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Gas bremsstrahlung studies for medium energy electron storage rings using FLUKA Monte Carlo code

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ABSTRACT

Gas bremsstrahlung is generated due to the interaction of the stored electron beam with residual gas molecules of the vacuum chamber in a storage ring. As the opening angle of the bremsstrahlung is very small, the scoring area used in Monte Carlo simulation plays a dominant role in evaluating the absorbed dose. In the present work gas bremsstrahlung angular distribution and absorbed dose for the energies ranging from 1 to 5 GeV electron storage rings are studied using the Monte Carlo code, FLUKA. From the study, an empirical formula for gas bremsstrahlung dose estimation was deduced. The results were compared with the data obtained from reported experimental values. The results obtained from simulations are found to be in very good agreement with the reported experimental data. The results obtained are applied in estimating the gas bremsstrahlung dose for 2.5 GeV synchrotron radiation source, Indus-2 at Raja Ramanna Centre for Advanced Technology, India. The paper discusses the details of the simulation and the results obtained.

1. Introduction

Indus-2 is a 2.5 GeV electron synchrotron radiation source at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, India and is presently being upgraded to install insertion devices. This facility is designed for 300 mA stored current having provision to accommodate 26 synchrotron beam lines for basic and applied research. Out of these beamlines, five beamlines are planned on insertion devices and the remaining beamlines are on bending magnets. The radiation environment in the synchrotron beamlines is dominated by gas bremsstrahlung radiation along with synchrotron radiation. Gas bremsstrahlung is produced in the storage ring due to the interaction of circulating electrons with residual gas molecules inside the vacuum chamber (Tromba and Rindi, 1990). Because of its highly forward emission and the broad energy spectrum ranging up to the electron energy, gas bremsstrahlung poses challenges in detection and dose estimation for radiation protection purposes. Gas bremsstrahlung spectrum and the dose have been discussed in the literature (Ipe and Fasso, 1994; Liu et al., 1994; Ferrari et al., 1993; Tromba and Rindi, 1990). The authors (Tromba and Rindi, 1990) proposed an empirical relation for absorbed dose rate in forward direction using the Monte Carlo code, EGS4. The absorbed dose data were generated for electron energy ranging from 500 MeV to 10 GeV in air target at atmospheric pressure. However due to multiple scattering of electrons with air molecules, the angular distribution of gas bremsstrahlung photons showed larger broadening (Asano, 2000; Ipe and Fasso, 1994; Ferrari et al., 1993). The authors (Ferrari et al., 1993) modified this formula using Monte Carlo code, FLUKA (Fasso et al., 1993) which enabled artificial suppression of multiple Moller scattering effects at atmospheric pressure (760 Torr). An empirical formula was established based on simulation carried out for electron energy ranging between 100 MeV–1 GeV and straight section lengths up to 50 m. Because of highly forward peaked nature, fluence of bremsstrahlung photons was studied with different scoring radii ranging from 0.0005 to 10 cm and converted to dose using fluence to dose conversion coefficient. The authors also pointed out the importance of optimization of the scoring radius with the associated uncertainty and the demanding computation time. They suggested a scoring radius of 0.043 cm for electron energy greater than 500 MeV. A similar study was performed by Ipe et al. for gas bremsstrahlung dose estimation in 7 GeV and 100 mA positron storage ring at Advanced Photon Source (Ipe and

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Fasso, 1994). They performed the simulation studies with a scoring radius of 0.02 cm for 7 GeV electron beam passing through 15 m of straight section using FLUKA code. Basically the scoring radius plays a dominant role in simulating gas bremsstrahlung dose for synchrotron facilities. The absorbed dose increases as the scoring radius decreases. But as the scoring radius is decreased the computation time increases and very small scoring radius is associated with high statistical error in the results. Therefore the scoring radius has to be large enough to save computation time and simultaneously small enough to avoid underestimation of fluence and absorbed dose (Ipe and Fasso, 1994; Ferrari et al., 1993). So each time when the straight section length and/or the detector distances are varied, the optimization of the scoring area has to be performed.

In this paper a recent version of FLUKA Monte Carlo code (Ferrari et al., 2005) was used to study the gas bremsstrahlung angular distribution for different straight section lengths for the beam energy range 1–5 GeV. From the distribution, the scoring radius for dose estimation was optimized for the energy range up to 3 GeV and the absorbed dose in tissue phantom was evaluated. The simulation data were found to be in very good agreement with the reported experimental data. An empirical relation based on the simulation data was then deduced for electron energy up to 3 GeV. This work is applied for evaluating the gas bremsstrahlung dose for 2.5 GeV electron storage ring, Indus-2.

2. Monte Carlo simulation details

A pencil beam of electrons in the energy range 1–5 GeV was allowed to incident on air target at atmospheric pressure (760 Torr) and the angular distribution of gas bremsstrahlung photons was scored. The absorbed dose was scored in an ICRU tissue phantom of radius 15 cm and length 30 cm. The ICRU tissue (⟨http://physics.nist.gov/cgi-bin/Star/compos.pl?matno=262⟩) comprises of four elements: Hydrogen (10.12%), Carbon (11.1%), Nitrogen (2.6%) and Oxygen (76.18%). The schematic of the geometry used for simulation of absorbed dose is shown in Fig. 1.

The simulation was carried out for air targets of lengths in the range 1–10 m. Some authors have recommended the simulation pressure of 0.1 atm for long straight sections greater than 10 m length and 1 atm for smaller straight sections (Ferrari et al., 1993). Therefore, in the present study all the data are generated from air at 1 atmospheric pressure. The average pressure in Indus-2 storage ring is maintained at ~1 nTorr where number of air molecules is significantly lower as compared to that for 1 atmospheric pressure (760 Torr). Hence the multiple scattering effects in air at atmospheric pressure were intentionally suppressed for all 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 (Ferrari et al., 1993). The electrons were killed intentionally at the end of the straight section using a high transport cut-off for electron (primary electron energy considered) in order to avoid its contribution to gas bremsstrahlung dose. Electron, positron and photon transport cut-off for different media

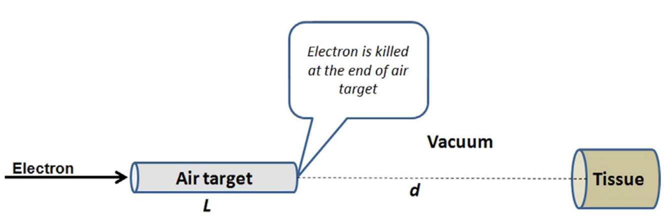

Fig. 1. Geometry used for simulation of absorbed dose due to gas bremsstrahlung in tissue phantom.

Table 1
Transport cut off parameters used in simulation.

Medium	Electron and positron transport cutoff	Photon transport cut off
Air	10 keV	1 keV
Air (electron killing region)	2.5 GeV	1 keV
ICRU tissue	10 keV	1 keV

used in the simulation are shown in Table 1. The output data were scaled to actual pressure of 1 nTorr.

The bremsstrahlung spectrum was transported through vacuum to tissue phantom. The absorbed dose was obtained by scoring absorbed energy density through USRBIN scoring inside the phantom. The scoring area in tissue phantom was decided based on the angular divergence of gas bremsstrahlung emitted from the straight section. The statistical uncertainties in the simulation results achieved are within ±7.4%. Simulations studies for gas bremsstrahlung spectrum, dependency of the straight section length and distance to the tissue phantom are also carried out separately for the case of Indus-2.

3. Results and discussion

The characteristic angle of bremsstrahlung emission is given as $\theta_c = E_0/E$, where E_0 is the rest mass energy of electron and E is the energy of the primary electron (Ban and Hariyama, 1994; Ipe and Fasso, 1994; Rindi and Tromba, 1993). The angular distribution of gas bremsstrahlung photons, generated for electron energies in the range 1–5 GeV is shown in Fig. 2. The distribution of photons shows a nearly flat region up to 0.1 mrad emission angle for beam energy up to 3 GeV. Hence the gas bremsstrahlung dose inside tissue phantom from electron energies up to 3 GeV was calculated using scoring radius, r (mm)=0.1 (mrad)×d (m), where d is the distance of tissue phantom from end of the straight section. Using scoring radius (based on emission angle of 0.1 mrad), the gas bremsstrahlung dose in primary beam energy range of 1–3 GeV for different straight section lengths ranging from $L=1$ to 10 m and target to detector distances ranging from $d=1$ to 50 m are generated and is shown in Fig. 3. The sub-linear dependency of the parameter $L/d(L+d)$ with the absorbed dose is seen from the figure.

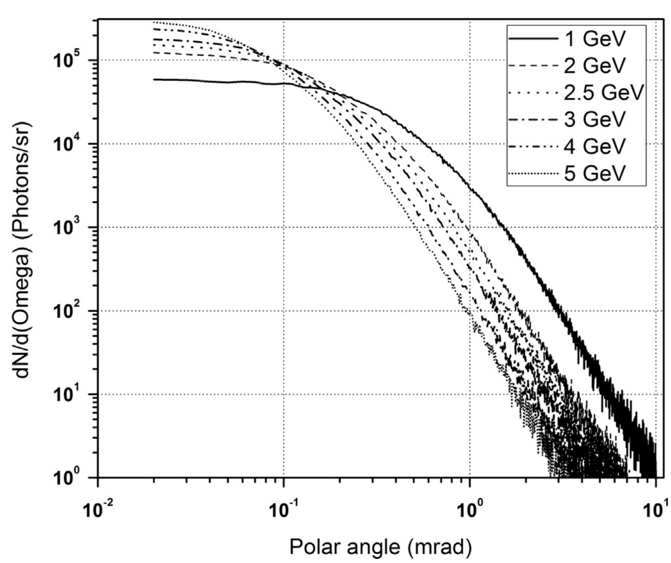

Fig. 2. Angular distribution of the gas bremsstrahlung for electron energies 1–5 GeV (for $L=1$ m).