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Bremsstrahlung source term estimation for high energy electron accelerators

M.K. Nayak [a,*], T.K. Sahu [a], H.G. Nair [a], R.V. Nandedkar [b], Tapas Bandyopadhyay [a], R.M Tripathi [a], P.R. Hannurkar [c], D.N Sharma [d]

[a] Health Physics Division, Bhabha Atomic Research Centre, Mumbai 400085, India
[b] Raja Ramanna Centre for Advanced Technology, Indore 452013, India
[c] Indus Operations and Accelerator Physics Design Division, Raja Ramanna Centre for Advanced Technology, Indore 452013, India
[d] Health, Safety & Environment Group, Bhabha Atomic Research Centre, Mumbai 400085, India

HIGHLIGHTS

- Experimental determination of bremsstrahlung source term at 450 and 550 MeV electrons.
- Monte Carlo calculations performed for validation of experimental data.
- Thick and thin target bremsstrahlung source term is studied.
- Brensstrahlung Source term is determined up to 3 GeV electron energies.

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ABSTRACT

Thick target bremsstrahlung source term for 450 MeV and 550 MeV electrons are experimentally determined using booster synchrotron of Indus facility at Raja Ramanna Centre for Advanced Technology, Indore, India. The source term is also simulated using EGSnrc Monte Carlo code. Results from experiment and simulation are found to be in very good agreement. Based on the agreement between experimental and simulated data, the source term is determined up to 3000 MeV by simulation. The paper also describes the studies carried out on the variation of source term when a thin target is considered in place of a thick target, used in earlier studies.

1. Introduction

Bremsstrahlung source term for accelerators is usually expressed as dose equivalent rate or absorbed dose rate per unit beam power at 1 m distance from a high atomic number (Z) thick target (Ferrari et al., 1993). Estimation of source term is important for evaluation of shielding requirement for particle accelerator facilities. The most widely used source terms for electron accelerators are those suggested by Swanson (1979). It is based on experimental data obtained from the measurement of absorbed dose rate in a 30 cm tissue equivalent phantom. The bremsstrahlung radiation for these experiments were generated by bombarding high energy electrons on high Z thick target. For thick targets, the target thickness considered is equivalent to the range of electrons in the medium (Wyckoff et al., 1971). Experimentally obtained maximum absorbed dose data for 20, 30 and 100 MeV electron energies in a polymethyl methacrylate (PMMA) phantom generated by Wyckoff et al. was used by Swanson in formulating a semi-empirical relation for thick target bremsstrahlung source term. The empirical relations suggested for forward and lateral source terms are available up to 100 MeV. For energies in the range 20–100 MeV, the suggested relations for thick target source term in the forward direction are found to be linear in energy. Whereas, for higher energies the relations are assumed to be linear (Swanson,1979; NCRP, 2003).

When an accelerated electron beam moving in vacuum envelope is lost, it encounters a thin target of few millimeter thickness, instead of a thick target, which has been studied earlier. For thin targets, generated bremsstrahlung photons in the forward direction are of higher energies compared with those of thick targets (Haridas et al., 2006). Bremsstrahlung photons generated by thin

* Corresponding author.
E-mail address: nayak@rrcat.gov.in (M.K. Nayak).

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targets further generate electromagnetic shower (ICRU, 1978) when incident on shield structures. Moreover as the thickness of vacuum chamber is less, substantial electrons are also transmitted along with bremsstrahlung photons and the source term is different from that obtained from the empirical relations for the thick target case. The absorbed dose rate from tungsten target at 200 MeV electrons incident as *a* function of angle of emission of bremsstrahlung and thickness calculated by Fasso. et al. (1984), shows that as the thickness of the target is reduced, the absorbed dose rate increases at low emission angles (forward direction). For larger emission angles, the dose rate is higher from thick targets. Thus the target thickness plays an important role in source term determination.

The forward source term for 100 MeV–1000 MeV electrons have been calculated using Monte Carlo simulation code FLUKA by Ferrari. et al. (1993). It has been found that the forward source term is higher by 7 times at 100 MeV and 22 times at 1000 MeV when compared with the values obtained by Swanson's empirical relations. Tromba et al. (1990) also proposed empirical relation for the thick target source term using Monte Carlo calculations performed with EGS4 code for electron energies from 100 MeV up to 10 GeV.

In the present work, thick target source term is experimentally determined from the depth dose data for 450 MeV and 550 MeV electrons in the forward direction on booster synchrotron at Indus synchrotron facility of Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. The experimental data is also simulated using EGSnrc code and is found to be in excellent agreement with the experimental results. Subsequently, the source term data is simulated for higher energies up to 3000 MeV. Source term simulations are also performed for thin targets at two electron energies, 450 MeV[1] and 2500 MeV[1]. The simulated data for 450 MeV is experimentally verified at the booster synchrotron. The thin target source terms are found to be higher than the thick target source term obtained from empirical relations by Swanson.

2. Experimental details

2.1. Materials and methods

$CaSO_4$: Dy TLD disks of size 6 mm diameter and 1 mm thickness used for the experiments are annealed for 1 h at 400 °C in air. The sensitivity of these TLDs is checked by exposing the disks uniformly to a known dose of 5 mGy from a Co-60 source. TLDs within $\pm 3\%$ sensitivity are selected and used for these experiments. A cuboid water phantom of size 30 cm × 30 cm × 30 cm made from 10 mm thick Perspex sheet (with top open) is used for measuring the depth dose in water. The phantom has been placed 1 m away from a lead target in the forward direction with TLDs placed at different depths at the mid plane of the phantom. It is ensured that the geometrical center of the target, the center of the water phantom and the axis of the TL disks within the phantom are in a straight line. The schematic diagram of the experimental setup for the measurement of forward source term is shown in Fig. 1.

2.2. Experiments

The electron beam at 450 MeV from the booster synchrotron is extracted to a transport line via an extraction septum and the electron beam is allowed to come out through a thin (1 mm aluminum) window. The extracted beam is allowed to fall on the center of the lead target of 25 mm[2] (1 CSDA range of 450 MeV electrons) (ICRU,1984). The position of beam at the center of the target is ensured by observing the fluorescence, emitted from a fluorescence screen placed before the target, with the help of a charge-coupled device (CCD) camera. The TLDs are exposed for a period of 900 s (the time of exposure was decided based on a preliminary dose rate measurement with ion chamber). The circulating beam current in the booster synchrotron is 1.5 mA. During the exposure period, the beam pulse from the booster synchrotron is measured with the help of a Wall Current Monitor (WCM) which gave a pulse height of 25 mV/beam pulse. Two pulses per second are fired on the target. From the pulse height data, the extracted electrons per second is calculated to be 3.26×10^8. Similar experiments are repeated for 550 MeV electrons with a 26.3 mm (1CSDA range) lead target and dose is measured with a new set of TLDs. The extracted electrons per second obtained from the WCM data was 1.66×10^8.

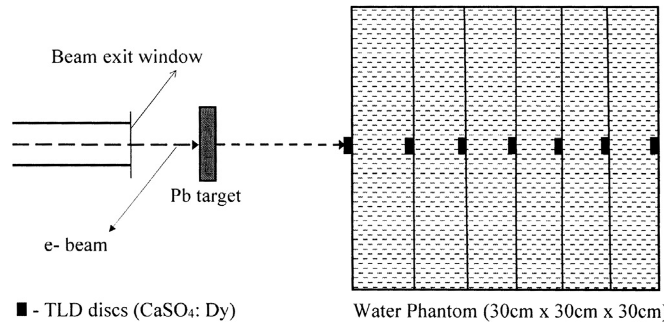

Fig. 1. Experimental set up and geometry used for simulation.

The experiments for thin target source term for 450 MeV electrons are also carried out by allowing the electrons to be incident on a 2 mm Stainless Steel (SS) target close to the vacuum chamber thickness of Indus-1 storage ring. TLDs are exposed within the water phantom for 600 s. The exposed TLDs for each set of experiments are analyzed using a TLD reader (Laboratory Reader-Analyzer RA'94, RADPRO, POLAND). From the TL counts the relative dose per unit beam power with respect to Co-60 is found out.

3. Monte Carlo simulations

The experimental results obtained are simulated using EGSnrc Monte Carlo code. The geometry for the experimental setup (Fig. 1) is made using DOSERZ user code from EGSnrc. In the simulation of depth dose curve, a parallel beam of 3.5 mm radius (which is the electron beam radius) of 450 MeV is allowed to incident on 25 mm thick lead target and absorbed dose per incidence fluence was scored in the TLD disks (scoring area $0.363\ cm^2$), placed in different depths of the water phantom. For radiation transport, an electron cut off (Ecut) of 521 keV and a photon cut-off (Pcut) of 10 keV are used in the simulation with a history of 10^6. Simulation for 550 MeV electron case is carried out by changing the lead target thickness to 26.3 mm. The statistical accuracy obtained in the present simulation is within $\pm 1\%$.

The simulations of depth dose in phantom with thin targets (2 mm Stainless Steel and 30 mm Aluminum) are also performed for calculating the source term for Indus-1 and Indus-2 storage rings (vacuum chamber of Indus-1 and Indus-2 are made of 2 mm

[1] The 450 MeV and 2500 MeV are the electron beam energies in the storage rings, Indus-1 and Indus-2 respectively at RRCAT, Indore.

[2] It is equivalent to ~4.5 radiation length, which is more than enough to develop electromagnetic cascade fully in the lead.