Dose Rate Distribution of Photoneutrons in an ID Beamline of SSRF: Simulations and Measurements (Postprint)

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Abstract

Photoneutrons emitted via photonuclear interactions when gas bremsstrahlung impinges upon beamline components represent an additional radiation source that must be considered in beamline shielding design and dose assessment. In this study, simulations and measurements of photoneutron dose rates at beamline BL09U were conducted with the Shanghai Synchrotron Radiation Facility (SSRF) operating in Top-up mode (3.5 GeV, 235 mA). A geometric model of beamline BL09U was constructed, incorporating scattering processes from major optical components. This model was implemented in the Monte Carlo simulation code FLUKA to calculate photoneutron dose distributions. Photoneutron dose rate measurements were performed using an Environmental Neutron Monitor (ENM), with observation points uniformly distributed along the interior and exterior of the BL09U optical enclosure (OE). The calculated results agree with experimental data within measurement uncertainties, thereby verifying the reliability of photoneutron dose simulations. The simulation and measurement methodologies developed herein can be applied to evaluate neutron dose levels at other beamline stations and provide reference data for future shielding design of SSRF beamlines.

Full Text

Preamble

Dose Rate Distribution of Photoneutrons in an ID Beamline of SSRF: Simulations and Measurements

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Abstract: Photoneutrons emitted through photonuclear interactions when gas bremsstrahlung interacts with beamline components represent an additional radiation source that must be considered for shielding design and dose assessment. This paper presents simulations and measurements of photoneutron dose rates at beamline BL09U when the Shanghai Synchrotron Radiation Facility (SSRF) operates in Top-up mode (3.5 GeV, 235 mA). A geometry model was constructed for beamline BL09U incorporating the scattering processes of major optical components, which was then implemented in the Monte Carlo simulation code FLUKA to calculate photoneutron dose distributions. Measurements were performed using an Environmental Neutron Monitor (ENM) at observation points arranged uniformly inside and outside the optical enclosure (OE) of BL09U. The calculation results agree with experimental data within measurement uncertainties, verifying the reliability of photoneutron dose simulation. These simulation and measurement methods can be applied to evaluate neutron dose levels at other beamline stations and provide references for future beamline shielding design at SSRF.

Keywords: Gas bremsstrahlung; Photoneutron; Monte Carlo simulation; Radiation dose; Synchrotron radiation facility
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Introduction

In synchrotron radiation facilities, gas bremsstrahlung (GB) is generated through interactions between high-energy electrons and residual gas molecules in the storage ring vacuum chamber where electron beams circulate. Each straight section of the storage ring contains an insertion device (ID) to generate synchrotron radiation, and GB propagates like a narrow, monodirectional photon beam with an opening angle of just m_0c^2/E_0 and an energy spectrum extending up to E_0 that continuously distributes as $1/E_0$, where m_0c^2 is the electron rest energy and E_0 is the primary electron beam energy [1, 2]. GB, together with synchrotron radiation from insertion devices, travels into beamline stations and interacts with optical components to produce secondary particles. Photoneutrons are produced via photonuclear reactions when photon energy exceeds a certain threshold (5-15 MeV). Three main processes produce photoneutrons from high-energy photons ($E\gamma$): nuclear giant dipole resonance and decay ($10 \text{ MeV} < E\gamma < 30 \text{ MeV}$), quasi-deuteron production and decay ($50 \text{ MeV} < E\gamma < 140 \text{ MeV}$) [3]. Photoneutrons pose a shielding problem in addition to secondary scattered photon radiation and must be considered in shielding design, particularly for beamlines extracted from insertion devices in straight sections.

Many researchers have studied photoneutrons generated from gas bremsstrahlung. Earlier calculations of photoneutron yield were primarily based on photon track length in targets and cross sections for photonuclear giant resonance neutrons [4, 5], with photoneutron yield estimated through separate post-processing rather than integrated simulation. Experiments measuring photoneutron dose from photonuclear reactions with different targets were conducted at some high-energy accelerators [3]; however, these measured only single positions and considered only giant resonance neutrons. Shen et al. calculated photoneutron spectra for all energy ranges but only for lead targets [6].

This paper investigates photoneutron dose rates at a typical ID beamline BL09U of the Shanghai Synchrotron Radiation Facility (SSRF), considering all objects relevant to photoneutron production. The optical enclosure (OE) containing essential optical devices—where most photonuclear interactions occur—was used to construct the geometry model for Monte Carlo simulations. Experiments were performed using a calibrated high-sensitivity Environmental Neutron Monitor (ENM) at positions inside and outside the OE along the beam axis. These methods enable assessment of photoneutron dose distribution at this beamline. In the simulations, photoneutrons across the full energy range were considered, and the dose distribution dependence on GB intensity and slit opening sizes was also evaluated.

Method

A. Beamline BL09U

Beamline BL09U, named the ultra-high resolution wide-range photoemission beamline, produces soft X-ray and low-power synchrotron radiation. As shown schematically in [Figure 1: see original paper], BL09U consists of three parts: two switchable insertion devices installed in a standard storage ring section that produce the radiation source, a beamline that transfers the radiation, and stations that use the light for Photoemission Electron Microscopy (PEEM) and Angle-Resolved Photoemission Spectroscopy (ARPES). Gas bremsstrahlung propagation through the beamline and interaction with key components can be illustrated by the GB ray-tracing map shown in [Figure 2: see original paper].

The effective length of the standard straight section is 12.5 m, and the distance from the insertion device center to the optical enclosure is 17.8 m. Key components from left to right include the safety shutter, ratchet wall, slits, collimators, reflection mirror, OE hutch wall, and monochromator.

B. Simulation of Photoneutron Dose Rate

Photoneutrons are produced through three photonuclear interaction processes as GB transfers through the beamline. This study used the FLUKA Monte Carlo code to simulate particle transport. FLUKA is a fully integrated particle physics Monte Carlo simulation package that includes complete hadronic and electromagnetic interactions, charged particle tracking, low-energy neutron transport, and full secondary particle tracing [7, 8]. The GB transport simulation in FLUKA includes: bremsstrahlung production in the straight section, electromagnetic cascade shower generation from interactions between bremsstrahlung and optical devices, and photoneutron production in photonuclear interactions. Photoneutron dose distributions across the full energy range from these processes were calculated using the method described by Pelliccioni M. [9].

GB transport simulations require the following conditions. Electron beams travel in a vacuum tube 12.5 m long before moving to the next storage ring unit, a deflection magnet of 1.27 T at the straight section end. The straight section has an average vacuum of 0.41 nTorr, with residual gases in the storage ring having a Z value of 3.42, as shown in Table 1 .

In the simulation, a geometry model was constructed including BL09U key components based on the GB ray-tracing map in [Figure 2: see original paper]. The positions of each key component and hole sizes were set according to the bremsstrahlung ray-tracing map, with their materials and geometry structures included in the simulation model. Other devices such as film windows and fluorescent screens have minimal effects on photoneutron scattering, so their influence on calculation results can be ignored and they were omitted from the geometry model. Since BL09U was in commissioning, the slit aperture was set to 0.5 mm × 0.5 mm for device protection. The simulation also considered slit opening sizes at their upper limit of 9.0 mm × 9.0 mm.

C. Measurement of Photoneutron Dose Rate

An experiment was conducted at beamline BL09U to verify the simulation method. A high-sensitivity neutron detector ENM (Beijing High Energy Radiation Protection Technology Co.) was utilized. The BF_3 proportional counter tube in the ENM is a cylinder (Φ 50 mm × 350 mm) filled with 600 mmHg pressure gas, placed in the center of a 6.5-cm wide cylindrical polyethylene moderation tube. The detector has a response range of 0.25 eV–16 MeV, dose rate limit of >1 nSv/h, and sensitivity capable of detecting minute neutron quantities. It is insensitive to γ-rays at photon dose rates <650 μSv/h, with a total uncertainty of 11% [10].

The experiment was performed while SSRF operated in Top-up mode with electron beam energy of 3.5 GeV and current of 235 mA, an average beam lifetime of 16 h, and vacuum of 0.41 nTorr in the straight section. Neutron dose rate background was measured after closing the safety shutter at the front end, yielding 7 nSv/h inside and 5 nSv/h outside the optical enclosure. With the safety shutter opened and GB entering the beamline, neutron dose rate was measured at two sets of seven positions along the beam transmission direction, with the first position placed 0.6 m from the ratchet wall ([Figure 3: see original paper]). Seven monitoring points each were arranged inside the optical enclosure at 0.7 m from the beam axis and outside the optical enclosure at 0.2 m from the OE wall, with 1 m intervals between neighboring points. The ENM detector was placed at each point at beam height (1.3 m), with measurement times of 3–5 minutes per point.

Results and Discussion

The photoneutron dose distribution from FLUKA simulation is shown in [Figure 4: see original paper]. Beyond the ratchet wall, photoneutron dose is found only in the OE area. GB loses energy primarily at the slits (aperture 0.5 mm × 0.5 mm). Photoneutrons are produced from high-energy photons interacting with copper slits, with dose rate showing isotropic distribution centered on the slits. The dose rate exceeds 10 µSv/h at the slits but drops to 0.6 µSv/h at 0.7 m from the center. Outside the GB hutch wall, the photoneutron dose rate is about 0.15 µSv/h. The photoneutron spectrum emitted from the slits, obtained from FLUKA simulation, is shown in [Figure 5: see original paper]. The spectrum peaks at 1–2 MeV, indicating that giant resonance interactions dominate in this case. Since the ENM detector energy range is 0.25 eV–16 MeV, the majority of neutrons detected are giant resonance neutrons. To make simulation and measurement results comparable, dose distribution from photoneutrons produced by nuclear giant dipole resonance and decay was also calculated.

Measurement and simulation results are shown in [Figure 6: see original paper]. Figure 6(a) shows results inside the optical enclosure. Measurement results agree well with dose rates calculated for giant resonance neutrons only. Larger differences (<32%) appear in low dose rate regions, such as data points near the optical enclosure end (5.5–6.5 m), where statistical calculation errors and measurement uncertainties become more significant at low neutron dose levels. Giant resonance neutrons contribute about 83% of the total neutron dose.

In Figure 6: see original paper, results outside the optical enclosure show the same trend as in Figure 6: see original paper. Calculated dose rates for giant resonance neutrons also agree well with experimental results, with giant resonance neutrons contributing about 78% of the total neutron dose.

Dose rates simulated for slit apertures of 0.5 mm × 0.5 mm and 9.0 mm × 9.0 mm are shown in [Figure 7: see original paper], with GB set at maximum intensity for an electron beam current of 300 mA and vacuum of 1 nTorr in the straight section.

Conclusion

In this study, photoneutron doses inside and outside the optical enclosure of the typical ID beamline BL09U at SSRF in Top-up mode were simulated and measured. Calculation results agree well with experimental results, indicating that FLUKA code simulation of photoneutron doses is reliable. These simulation and measurement methods can be applied to evaluate neutron dose levels at other beamline stations and will provide references for future beamline shielding design at SSRF.

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Note: Figure translations are in progress. See original paper for figures.