STUDIES OF RADIATION BACKGROUND AT THE SYNCHROTRON LIGHT SOURCE DELTA

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Abstract

The 1.5-GeV electron storage ring of the synchrotron radiation source DELTA at TU Dortmund University is surrounded by a 1 m thick concrete radiation shielding wall with a height varying between 3.0 and 4.3 m and with open top. The installation of a new 7-T superconducting wiggler and tentative plans for a new building in the vicinity motivated recent studies of background radiation either directly escaping the open-topped radiation shield or being scattered by air or the roof of the hall (the so-called radiation skyshine). Spectra of gamma radiation were recorded under different conditions using a high-purity germanium detector. Long-term measurements were made with photoluminescence dosimeters. The paper presents the results together with calculations of the spectral distribution of wiggler radiation as well as a model for the spatial distribution of radiation emitted by the whole storage ring.

INTRODUCTION

If a particle accelerator facility is surrounded by a radiation shielding wall with open top, particular care has to be taken regarding radiation safety. One potential hazard is excessive skyshine, i.e., ionizing radiation scattered from air or the roof of the facility. Another point of concern is radiation reaching elevated positions in the vicinity, e.g., adjacent buildings or the operating cabin of a tower crane.

The 1.5-GeV electron storage ring of the synchrotron radiation source DELTA at TU Dortmund University is surrounded by a 1 m thick open-topped concrete wall with a height varying between 3.0 and 4.3 m - see Fig. 1. The replacement of a superconducting wiggler (SCW) with a maximum magnetic field of 5.3 T, critical photon energy 7.9 keV and 5 periods by a new device with 7 T critical energy 10.5 keV and 9 periods in 2020 [1, 2] as well as tentative plans for a new building west of the DELTA hall motivated the radiation studies presented below. The general goal is to keep the dose level at any accessible position in the accelerator hall and elsewhere well below the legal limit of 1 mSv per year and to avoid any unnecessary radiation exposure. Since a Monte-Carlo calculation including all details of the facility and the electron loss mechanism is prohibitively complex and the result of such an attempt would be doubtful, simulations were based on simplified assumptions and scaled by measured data as described in the following.

SKYSHINE FROM A 7-T WIGGLER

While the new 7-T superconducting wiggler was installed and commissioned in 2020, the delivery of vacuum components to match the radiation power and angular distribution are still delayed. To investigate the permissible magnetic field of the SCW under these conditions and at the nominal beam current of 130 mA, photon spectra were measured in the DELTA hall outside of the radiation shielding wall (approximately at the position marked with X in Fig. 1, bottom) while the beam current was limited to 10 mA. Figure 2 shows photon spectra recorded using a recently commissioned high-purity germanium detector [3, 4] with the magnetic field of the SCW set to 5.0, 6.5, and 7.0 T.

Figure 1: Floorplan of the DELTA facility showing the linac, the booster synchrotron (BODO) and the storage ring surrounded by a 1 m thick concrete wall (gray). The superconducting wiggler (SCW) serves three beamlines (BL 8-10).

Figure 2: Photon spectra of skyshine from the SCW with magnetic field 7.0 T (blue), 6.5 T (red), and 5.0 T (green) at a beam current of 10 mA as well as background without beam (magenta).
The spectral flux emitted by the SCW was calculated from 10 to 100 keV using the code SPECTRA [5]. To reproduce the measured spectra, Compton scattering near the inner surface of the vacuum chamber, energy-dependent absorption in the chamber wall, and Compton scattering in air was taken into account. To reach the detector outside the radiation shielding wall, the first scattering process was assumed to point upward (scattering angle $\varphi = 90^\circ$) and the second one downward ($\varphi = 180^\circ$), shifting the photon energy twice according to

$$E' = E \left( 1 + (1 - \cos \varphi) \cdot \frac{1}{m_e c^2} \right),$$

where $E$ and $E'$ is the photon energy before and after the scattering event, respectively, and $m_e$ is the electron rest mass, see e.g. [6]. The resulting spectra scaled to the measured spectrum at 7 T are shown in the left part of Fig. 3. The suppression of the low-energy spectral region is a combination of absorption in the vacuum chamber wall and the detector efficiency. The right part of Fig. 3, shows the calculated spectra individually scaled to the measured, smoothed and background-subtracted data at different SCW fields, which result in a reduction factor of 0.43 for 6.5 T and 0.03 for 5.0 T. Given the simplicity of the model, the excellent agreement of the spectral shapes is certainly coincidental, but the increase of count rate with magnetic field is significant and matches the expectation. The root-mean-square width of the radiation fan is [7]

$$\sigma_\theta = K / \gamma \quad \text{with} \quad K = 93.4 \cdot B \ [\text{T}] \cdot \lambda_W \ [\text{m}],$$

where $\gamma = 2935$ is the Lorentz factor and $\lambda_W = 0.125$ m is the wiggler period. The present vacuum chamber limits the emission angle to $\pm 23$ mrad, which is consistent with a low scattering rate at a field of 5.0 T ($\sigma_\theta \approx 20$ mrad) and the observed strong increase at 6.5 and 7.0 T ($\sigma_\theta \approx 26$ and 28 mrad, respectively). An increased temperature of the vacuum chamber is observed at similar field values. As a result, the SCW is presently operated at a reduced magnetic field of 5 T, and the new vacuum chamber with larger opening angle and suitable absorbers is expected to be installed later this year. Furthermore, the wiggler beamline will be enclosed by lead-aluminum sandwich panels.

**SIMULATION AND MEASUREMENT OF RADIATION DOSES**

Given the plan of a new building west of DELTA, the question arises whether the radiation shielding wall surrounding the accelerator complex is sufficient to keep the radiation at the upper floors of that building below 1 mSv/year. To this end, flat glass photoluminescence dosimeters [8,9] were placed on the west wall of the DELTA accelerator hall from April to July 2022 - see Fig. 4. As a first-order estimate of the relative radiation distribution, simulations were performed assuming a homogeneous emission from equally spaced points along the storage ring. Presuming that electromagnetic showers from lost electrons and ejectiles from direct nuclear reactions remain in the plane of the storage ring, only isotropic emission as from compound nucleus reactions is considered. The radiation shielding wall is modeled by upright rectangles. Radiation is assumed to arrive at the observation point, if the line-of-sight from the source point does not intersect any of these rectangles. Figure 4 shows a top view of the simulation geometry with $(x, y, z) = (0, 0, 0)$ on floor level at the center of the storage ring. For a selected observation point (green dot), the contributing source points basically form two line sources in the northern and southern part of the ring, while the eastern arc is mostly surrounded by the booster tunnel and radiation from the western arc is shielded by the adjacent wall.

Figure 4: Example of the simulation geometry. Green dot: Observation point at $(x, y, z) = (-36.5, 11.5, 7.3)$ m. Blue: Storage ring, where sources contributing to radiation at the observation point are marked in red. Black: Radiation shielding wall, where segments blocking the line-of-sight between source and observation point are shown in magenta. Black circles: Dosimeter positions. Arrow: Geographic north.
Figure 5: Color-coded distribution of radiation (fraction of total emission per m²) on the west wall of the DELTA hall at $x = -36.5$ m as seen from the storage ring. White: Projection of the radiation shielding wall.

Figure 6: Color-coded distribution of radiation in a plane at $x = -114$ m as seen from the storage ring. Note the factor >20 between the color scale here and in Fig. 5.

The considered observation points form a grid in a $y$-$z$-plane, e.g., at $x = -36.5$ m (the west wall of the DELTA hall, where the dosimeters were placed) and at $x = -114.0$ m (the closest position of the planned building). The resulting fraction of emitted radiation hitting 1 m² of these two planes is shown in Figs. 5 and 6. Scattering and absorption processes are ignored. Furthermore, no assumption is made on the absolute amount of emitted radiation. The total energy of lost electrons is given by the number of injected electrons per year and the beam energy, usually 1.5 GeV, but its fraction escaping the vacuum vessel and the storage ring plane via electromagnetic or particle radiation is a priori unknown.

While dosimeters at low elevation outside the radiation shielding wall are dominantly exposed to skyshine, i.e., radiation scattered from air or the roof of the hall, dosimeters above the wall can be used to estimate the radiation distribution at the planned building by scaling the measured values to one year of DELTA operation and to the radiation fraction according to the simulation. Figure 7 (left) shows the measured doses at an elevation of 7.3 m, where direct radiation from the storage ring is assumed to dominate over skyshine. A natural dose level of 0.11 mSv as deduced from four reference dosimeters away from the accelerator hall was subtracted [10]. The red curve indicates the scaled simulation result at $z = 7.3$ m from Fig. 5. Despite the large absolute errors specified for the dosimeters, the measured data seem to follow the trend given by the simulation, i.e., a slightly higher radiation level in the northwest (positive $y$ values), where the radiation shielding wall is lower. Given the operation schedule of DELTA (20 weeks/year for users and 10 weeks/year for accelerator studies), the dose for a full year has to be scaled by a factor of 4.3, as shown in the right part of Fig. 7. Scaling the calculated dose at $x = -114.0$ m by the same factor for the maximum considered elevation of 14.3 m results in a radiation dose of 14 $\mu$Sv per year at the prospective building. Assuming a personal exposure of 40 working hours per week compared to 100 hours of scheduled accelerator operation further reduces the dose. Despite large systematic uncertainties, it can be safely stated that the value is far below the natural dose level and the legal limit.

**SUMMARY**

Two examples of radiation safety issues were addressed by combining simulations under simplified assumptions with measurements. This approach yields reasonable estimates where explicit Monte-Carlo simulations are not feasible due to the complexity of the problem or insufficient knowledge of the boundary conditions. For final conclusions, however, the results will be verified by further measurements.

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REFERENCES


[8] OD FGD-203&SC-2, type approval 23.51/02.01.
