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INVESTIGATION OF HIGH ABSORBED DOSES IN THE INTERSECTIONS OF THE EUROPEAN XFEL UNDULATOR SYSTEMS

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Abstract

This work presents measurements of the absorbed doses in the vicinity of phase shifter (PS) installed in intersections of the Undulator Systems at the European X-Ray Free Electron Laser (XFEL). In addition, Geant4 Monte Carlo simulations were performed to further investigate the radiation field present in these intersections. Measurements in the downstream undulator cell in SASE3 showed similar doses for the films placed at the PS entrance and near PS motors. Both measurements and simulations indicate that the radiation field near PS motors is not caused by the high-energy electron interactions with the beam pipe close to the PS. The measurements of the absorbed doses at the PS entrance in the upstream undulator cells are also presented.

INTRODUCTION

The European XFEL GmbH is a free-electron laser facility located in Schenefeld, Germany. It operates three undulator systems called SASE1, SASE2 and SASE3 since 2017, and the radiation damage to the undulators is the matter of concern [1]. In each of these systems, electron bunches of GeV energies that propagate along the undulators in the vacuum beam pipe generate high brilliance X-ray pulses. Each system consists of numerous undulator segments (5 m long) separated by intersections (1.1 m long). The intersection together with the undulator segment is called the undulator cell. There are 35 undulator cells in SASE1 and SASE2, while SASE3 consists of 21 cells. Each intersection contains vacuum systems and correction and diagnostic equipment such as beam position monitor (BPM), beam loss monitor (BLM) and quadrupole magnet (QM). Downstream of the QM a PS is located. It has a movable gap and is composed by permanent magnets from the same type as employed in the undulator segments. It matches the phase of electrons and photons produced through the Self-Amplification Spontaneous Emission (SASE) process [2].

At the entrance of each undulator segment, Radfet dosimeters continuously measure the absorbed doses and are online readable [3]. The radiation field close to the beam pipe can arise from several factors, such as spontaneous undulator radiation and electron interaction with gas molecules. In addition, electrons may hit the beam pipe which results in emission of stray radiation. However, no dosimetry system is installed in the intersections. Recently, it was noticed that the movement of gaps in some PS in SASE3 could not be performed due to PS motor or encoder damage. It might be caused by the radiation present between undulator segments.

In this work, we present the results of gafchromic film measurements at the PS entrance and near PS motors. The measurements are presented together with the Monte Carlo simulations of electron beam losses to better understand the radiation field in the intersections.

METHODS

Gafchromic films

The absorbed doses in the intersections were measured with gafchromic film dosimeters. Film dosimetry is mostly used for medical radiation purposes, but they are also useful for measurements in the high-energy radiation fields. They can be cut in various shapes without changing their properties. Therefore, they can be placed in areas that are difficult to access with other detectors. In addition, film dosimeters give information on 2D dose distributions.

The films undergo polymerization during exposure to ionizing radiation. The subsequent colour change is proportional to the absorbed dose, which can be evaluated through Red (R), Green (G) and Blue (B) values of scanned films through multichannel analysis [4].

In this work, the GAFCHROMIC^{TM} EBT3 films were placed at the PS entrance, perpendicularly to the beam pipe (referred later as PS films) in different SASE1 and SASE3 undulator cells. Films were removed from SASE1 and SASE3 after approximately five and two months, respectively. In addition, in SASE3 the absorbed doses were measured next to the PS motors, located approximately 10 cm above the PS and 40 cm above the beam pipe. The PS and position of the PS motor are shown in Fig. 1.

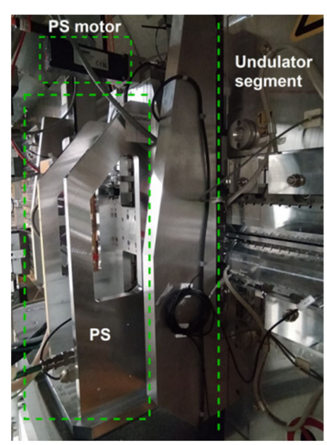

Figure 1: PS and PS motor seen from the downstream side of the undulator system.

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Monte Carlo Simulations

Electrons interactions with the beam pipe were simulated using Monte Carlo code Geant4 [5]. The code consists of 2 undulator segments, each 5 m long, separated by 1.1 m long intersections. The aluminum beam pipe along undulator segments is rectangular (70 mm x 10 mm), with an elliptical aperture (15 mm x 9 mm). In the intersection, the beam pipe is circular, with a diameter of 9 mm and 0.5 mm aluminum wall. Intersection components such as absorber, vacuum pump, BMP, BLM, QM and PS were included in the code with simplified geometry. The simulation geometry is schematically presented in Fig. 2. In the simulations 10 000 electrons with energy of 14 GeV hit the beam pipe at two fixed positions along the beam pipe, which were the end of the 1st undulator segment and the middle of the quadrupole magnet. Therefore, it was possible to investigate the effect that all the components in the intersection have on the absorbed dose at the PS entrance. At this stage, no magnetic field was included in the code.

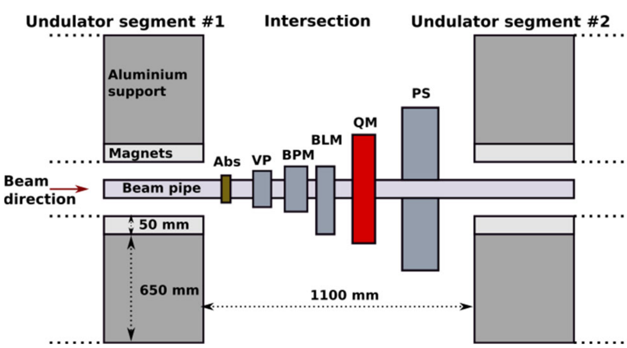

Figure 2: Schematic presentation of the Geant4 code geometry.

RESULTS

The absorbed dose measurements near PS motor in cell #12 in SASE3 is shown in Fig. 3. The measurements show that the radiation near the PS motor after 2 months of irradiation varies between 2 Gy and 3 Gy. The dose is distributed almost homogeneously over the whole film area. Additional measurements near the PS motor in cell #15 in SASE3 showed similar dose distribution pattern. However, the absorbed doses were higher for the same irradiation time and varied between 6 Gy and 8 Gy.

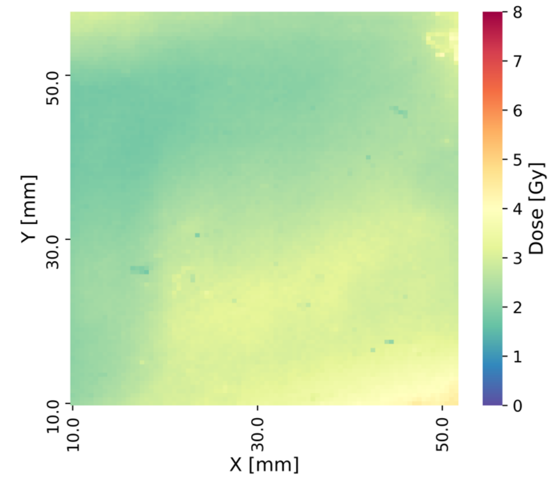

Figure 3: Absorbed dose distribution measured near PS motor in cell #12 in SASE3.

Figures 4 and 5 show dose distributions for the PS film placed in undulator cell #12 in SASE3, above and below the vacuum pipe, respectively. The maximum absorbed dose is almost 8 Gy for the top PS film and 7 Gy for the bottom PS film. The region with the maximum dose is concentrated in a small area near the beam pipe. However, in both cases there is an area with increased dose propagating in the vertical direction of the film. Its shape indicates that this is an effect of the QM, which is located directly upstream of the PS and shields part of the radiation. It suggests that the radiation contributing to the absorbed dose comes from the upstream of the closest QM.

Figure 6 shows the dose distribution at the undulator segment entrance in cell #12 in SASE3. As it can be seen, the maximum absorbed dose is concentrated in a small area near the film's edge. The dose decreases to 0.2 Gy after approximately 10 mm in the vertical direction.

As can be seen from Fig. 4, the absorbed dose measured for the part unshielded by the QM is around 2 Gy. It is comparable to the absorbed dose measured near the PS motor in the same undulator cell.

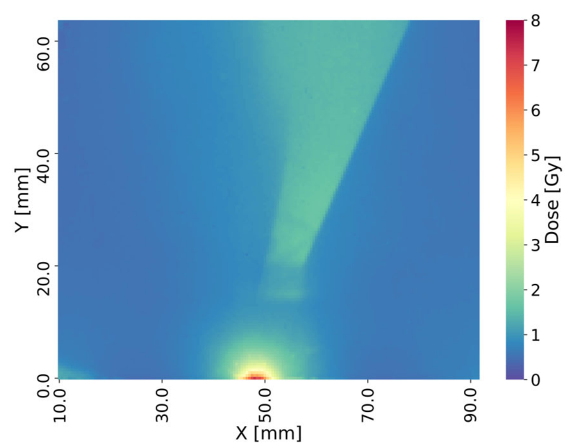

Figure 4: Absorbed dose distribution for the PS film in cell #12 located above the beam pipe in SASE3.

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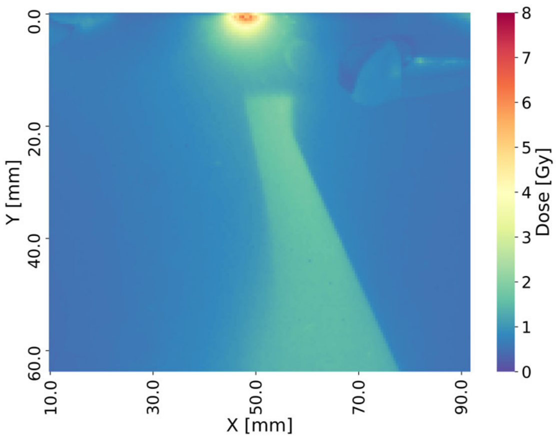

Figure 5: Absorbed dose distribution for the PS film in cell #12 located below the beam pipe in SASE3.

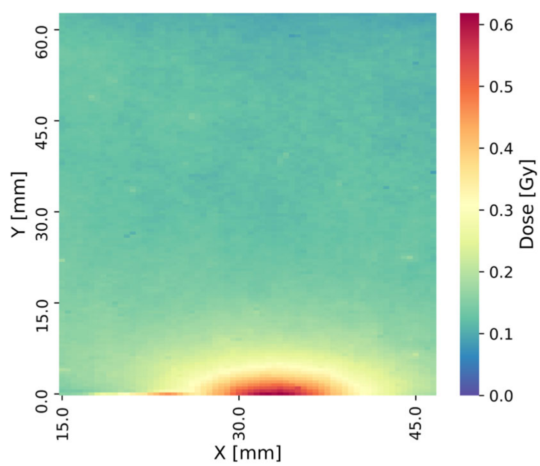

Figure 6: Absorbed dose distribution for the film placed at the undulator segment entrance #12 in SASE3, above the beam pipe.

In order to determine if the interactions of the high-energy electrons with the beam pipe are responsible for the absorbed doses at the PS entrance and near the PS motors in the downstream undulator cells, Geant4 simulations were performed. Figs. 7 and 8 show Geant4 simulations of dose distributions at the PS entrance for electrons hitting the wall at the end of the 1st undulator segment and at the QM, respectively. In this case only electron losses were simulated. In these simulations, electrons hit the beam pipe over its whole aperture at 15° intervals.

The maximum absorbed dose is more than two times higher for electrons interacting with the beam pipe at the end of the upstream segments. It is most likely caused by the fact that the emitted stray radiation interacts with various components along the intersections, creating secondary particles which contribute to the dose. The triangular shape of the dose distribution seen in Fig. 7 is a result of the QM implemented in the code, which shields part of the radiation. However, the shielding effect is not as prominent as in Figs. 4 and 5, and the dose decreases significantly after approximately 20 mm in the vertical direction. As mentioned, the doses measured near the PS motor in cell #12 in SASE3 were similar to the doses measured at the part of the PS not shielded by QM. As only electron losses were simulated, it indicates that they do not contribute to the doses measured near the PS motors in the downstream undulator cells. Therefore, the radiation field in the vicinity of PS motors comes most likely from further upstream of the intersection, e.g. low-energy radiation associated with the SASE process or secondary radiation from the electron interactions with the beam pipe in the upstream undulator cells further away from the PS motors.

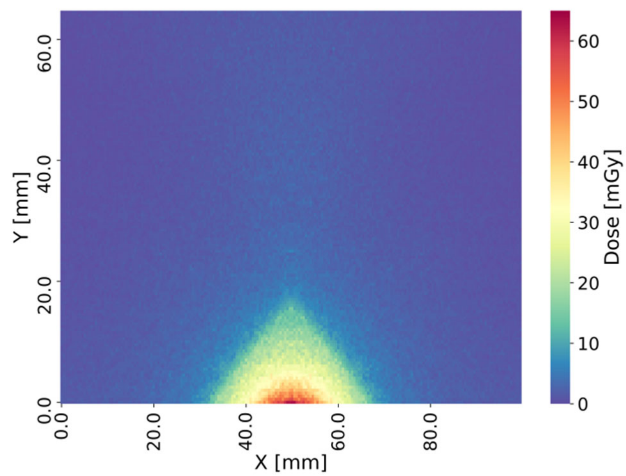

Figure 7: Simulations of the dose distribution at the PS surface for electrons hitting the beam pipe at the end of the 1st undulator segment.

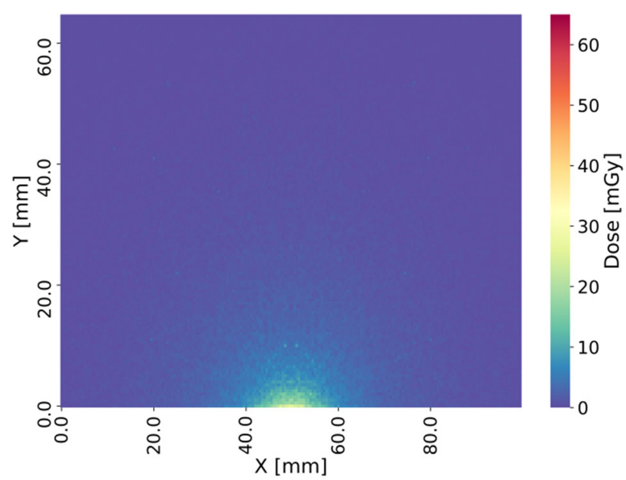

Figure 8: Simulations of the dose distribution at the PS surface for electrons hitting the beam pipe at the QM.

In order to determine if the QM shielding effect is visible in the upstream undulator cells, the films were placed also at the PS entrance in undulator cells #4 – #10 in SASE1, above (top films) and below (bottom films) the vacuum pipe. The measurements showed the highest doses closest to the beam pipe. The maximum absorbed doses were determined as a mean over the area 5 mm in the horizontal direction and 2.5 in the vertical direction around the maximum. The maximum absorbed doses for PS films are presented in Fig. 9. The measurements in cell

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#8 showed significant absorbed doses which exceed 20 Gy both for top and bottom films, and they were not included in Fig. 9.

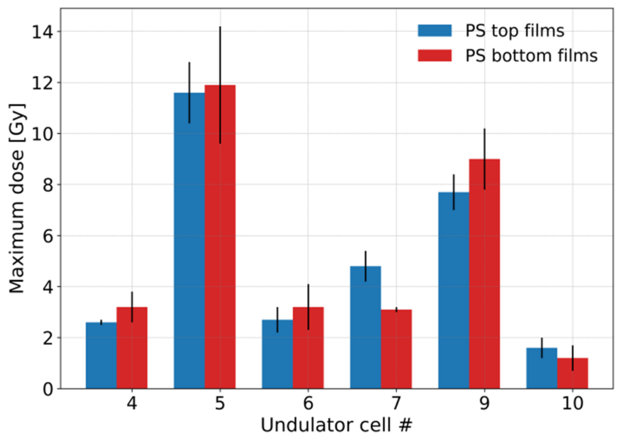

Figure 9: Maximum absorbed doses measured at the PS entrance in different intersections of upstream undulator cells in SASE1.

As seen in Fig. 9, the absorbed doses measured at the entrance of the PS in intersections of upstream cells in SASE1 vary between almost 2 Gy and 12 Gy. However, the QM shielding effect seen in Figs. 4 and 5 was not observed for any of the PS films. As shown in [6], low-energy synchrotron radiation doesn't contribute to the absorbed doses upstream of the undulator cell #13. It suggests that the radiation field in the upstream cells may be a result of high-energy electron interactions with the beam pipe, which creates secondary radiation contributing to the absorbed doses.

CONCLUSION

In this work, gafchromic film measurements were performed in the intersections of the undulator systems at EuXFEL. The measurements in SASE3 showed absorbed doses around 2 Gy and 7 Gy near PS motors in intersections of the undulator cells #12 and #15, respectively. Additional measurements in cell #12 at the PS entrance showed that for the large area of the film propagating in the vertical direction, the absorbed dose is comparable to the dose at the PS motor. The shape of this area indicates that the radiation contributing to the absorbed dose comes from the upstream of the QM.

Geant4 simulations of electron losses were performed in order to determine the source of the radiation field present in the intersections of the downstream undulator cells. The shielding effect of QM is visible in Fig. 7. However it is not as prominent as for film measurements in Figs. 4 and 5. The simulations indicate that the absorbed doses measured near PS motors are not caused by electrons losses, but rather low-energy radiation associated with the SASE process or secondary radiation from the upstream undulator cells further away from the PS motors.

The film measurements at the PS entrance in multiple intersections in SASE1 showed that the radiation field is also present in the intersections of the upstream undulator cells. It is most likely caused by other factors than low-energy synchrotron radiation, e.g. electrons interactions with the beam pipe, which create secondary particles contributing to the dose.

The presented results are preliminary, and a more detailed analysis should be performed in the future to further characterize the radiation field in the undulator system intersections. Additional measurements near PS motors in different undulator cells should be performed in the future in order to identify the source of radiation in this area.

REFERENCES

[1] F. Wolff-Fabris, J. Pflueger, F. Schmidt-Foehre, and F. Hellberg, "Status of the Radiation damage on the European XFEL Undulator Systems", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18),* Vancouver, Canada, Apr.-May 2018, pp. 1776-1779, doi:10.1088/1742-6596/1067/3/032025

[2] H. H. Lu, Y. Li, and J. Pflueger., "The Permanent Magnet Phase Shifter for the European X-Ray Free Electron Laser", in *Nucl. Instrum. Methods Phys. Res. A,* vol. 605, no. 3, pp. 399-408, Jul. 2009, doi:10.1016/j.nima.2009.03.217

[3] F. Schmidt-Foehre, D. Noelle, R. Susen, and K. Wittenburg, "Tests and Measurements with the Embedded Radiation-monitor-system Prototype for Dosimetry at the European XFEL", in *Proc. 3rd Int. Particle Accelerator Conf. (IPAC'12),* New Orleans, LA, USA, May 2018, paper THPPR033, pp. 4041-4043

[4] A. Micke, D. F. Lewis, and X. Yu, "Multichannel film dosimetry with nonuniformity correction", in *Med Phys.,* vol. 38, no. 5, pp. 2523-34, May 2011, doi:10.1118/1.3576105

[5] S. Agostinelli, *et al.*, "GEANT4 – a simulation toolkit", *Nucl. Instrum. Meth. A*, vol. 506, no 3, pp. 250-303, Jul. 2003.

[6] S. Liu, Y. Li, and F. Wolff-Fabris, "Undulator Radiation Dose Caused by Synchrotron Radiation at the European XFEL", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19),* Melbourne, Australia, May 2019, pp. 1724-1727, doi:10.18429/JACoW-IPAC2019-TUPRB021