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MONTE CARLO SIMULATIONS AND NEUTRON AND GAMMA FLUENCE MEASUREMENTS TO INVESTIGATE STRAY RADIATION IN THE EUROPEAN XFEL UNDULATOR SYSTEM

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Abstract

Monte Carlo simulations have been performed with electrons hitting the beam pipe in order to characterize the radiation field inside the magnetic structure of the undulator and nearby the undulators at the European X-ray Free Electron Laser (EuXFEL). In addition, the measurement of gamma radiation in the vicinity of the undulators is also presented. We show that simulations may complement measurements for characterization of the radiation field, which is important for the investigation of magnets demagnetization caused by stray radiation.

INTRODUCTION

The light source facility EuXFEL produces X-ray pulses with wavelengths as short as 0.1 nm. These flashes are generated as electron bunches of GeV energies travel through the undulator system. The radiation field outside the beam pipe can come from spontaneous undulator radiation, electron interactions with gas molecules and electrons hitting the beam pipe wall. Electrons hitting the beam pipe may be a consequence of the beam steering or the particles further away from the main beam, referred to as beam halo. Those interactions result in the emission of stray radiation, which is damaging to the magnets located a few millimeters above the pipe. The demagnetization of permanent magnets is a well-known issue that may seriously affect machine performance [1].

The area monitor located nearby the undulators segment can measure both neutrons and photons [2]. The gamma signal dominates during the normal operation. Nevertheless, an increased number of neutrons is observed in the case of particle loss. Since the detector registering this signal is situated about 0.5 m in the horizontal plane from the interaction point, the question arises whether photons and neutrons are also present in the volume of the magnets, where they can cause demagnetization [3].

In this work, the Monte Carlo simulations were conducted to investigate the particles present both inside and outside of the magnetic structure as the result of electrons hitting the beam pipe. The simulations are presented together with gamma measurements, and the results are discussed.

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METHODS

Monte Carlo Simulations

In this work, the Monte Carlo code Geant4 [4] was used to simulate electrons hitting the beam pipe in the vicinity of the undulator segment. Three cells were included in the simulation. Each cell consists of a 5 m long undulator segment and a 1.1 m long intersection. The undulator geometry was simplified by including only quadrupole magnet and phase shifter in the intersection. The beam pipe is made from a rectangular aluminum block with dimensions of 70 mm and 10 mm. The aperture of the beam pipe was elliptical along the undulators (9 mm x 15 mm) except for the part of the intersection near the quadrupole magnet, where it was circular (⌀ 9 mm).

The 14 GeV electron beam interacted with the beam pipe at several points along the undulator sector. The particles hit the wall only in the vertical plane, on the axis of the beam.

To obtain information about the fluence within the undulator magnets and outside the vacuum pipe, command-based scoring was applied. The defined mesh point was defined as the cube with dimensions of 1 cm × 1 cm × 1 cm.

Gamma and Neutron Detector

The neutron and gamma components in the pulsed radiation field near the undulators segments at EuXFEL are measured with the LB 6419 area monitor. This detector consists of two parts. The first is a ^{3}He proportional counter tube, which allows to detect thermal neutrons. The radius is 20 mm, and the active detection length is 40 mm. The second part of the monitor is a plastic scintillator with photomultiplier tube readout for gamma radiation identification. It has a length of 41 mm, with 41 mm diameter [2].

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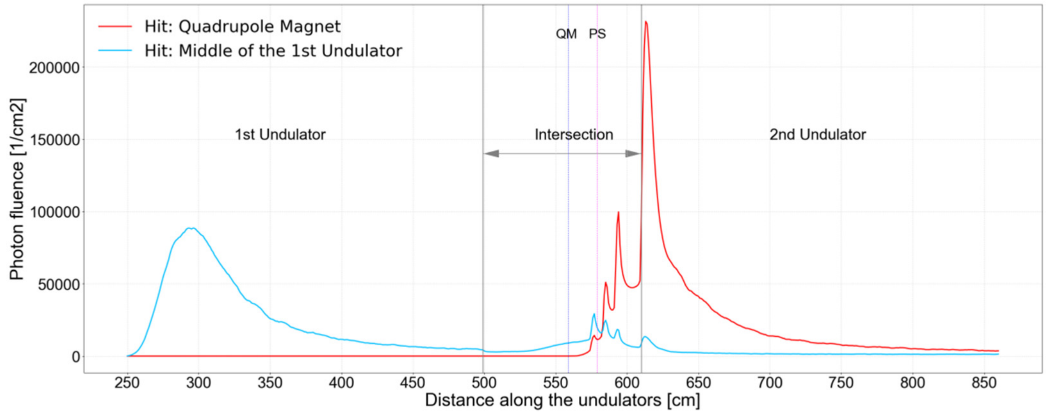

Figure 1: Photon fluence distributions inside the magnetic structure for photons, obtained with Geant4 simulations. QM - quadrupole magnet, PS - phase shifter.

RESULTS

Fluence Distributions

Figure 1 shows the fluence distribution inside the undulator magnets for photons arising from the beam interaction with the vacuum vessel wall. The signal is shown from the middle of the 1st undulator, as no particles were registered before that point. The distribution is plotted along the central axis of the magnets, which is also the central axis of the beam propagation. If the interaction takes place in the middle of the undulator, the maximal signal is shifted approximately 50 cm down the undulator. The peak at the beginning of the magnetic structure was observed for electrons hitting the wall at the previous quadrupole magnet. In both cases, there is an increase in the number of photons as the radiation hits the phase shifter. In the simulations, the phase shifter consists mainly of iron, and therefore it is suspected that the observed rise is related to the creation of low-energy photons.

Similar distributions were obtained for the neutrons and electrons, both inside and outside the magnetic structure. The fluence patterns were similar in each case. The signals for electrons and neutrons were lower by one and four orders of magnitude, respectively. More particles were observed inside the undulator magnets than next to the beam pipe.

Fluence Decrease towards the Detector

During standard operation of the EuXFEL, LB 6419 detector is located approximately 50 cm in the horizontal plane from the undulators. Therefore, simulations were run to investigate how the photon and neutron fluences decrease outside the beam pipe, perpendicularly to the beam propagation. The analyzed fluence was the result of the particle interactions with the wall at the position of the quadrupole magnet. The simulation points were obtained from the beginning of the 2nd undulator, at the height of the beam pipe, because the signal is maximal at this point. Figure 2 shows the exponential decrease of the signal.

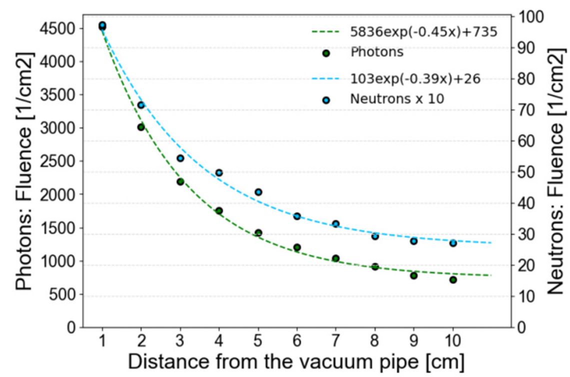

Figure 2: Fluence decrease for photons and neutrons at the beginning of the 2nd undulator.

This indicates that the radiation would be much higher in the magnetic structure than measured by the detector.

Fluence Energy Spectra

Electrons hitting the wall create a shower of different kinds of particles inside the permanent magnets and nearby the undulator segment. One way to characterize the radiation field in this area is to investigate the particles energy spectra. In the simulations, the initial electrons hit the wall at the position of the quadrupole magnet. Figure 3 shows the spectra of photons, neutrons, electrons and positrons inside one of the permanent magnets in the undulator. One undulator cell consists of approximately 250 pairs of magnets, and the fluence was obtained for the 3rd magnet from the electron entrance side. The investigated undulator cell is located directly after the intersection which contains the quadrupole magnet, where electrons hit the beam pipe. The spectra were also investigated 1 cm outside the vacuum pipe in the horizontal plane (see Fig. 4). The signal was integrated over the whole undulator length.
The signal is dominated by the photons in the energy range starting approximately from 10 keV, both inside the magnet's volume and outside the segment. A peak visible around 500 keV is suspected to come from the pair production events. The neutrons are dominant in the energy range from 100 keV up to 1 MeV, after which their signal decreases.

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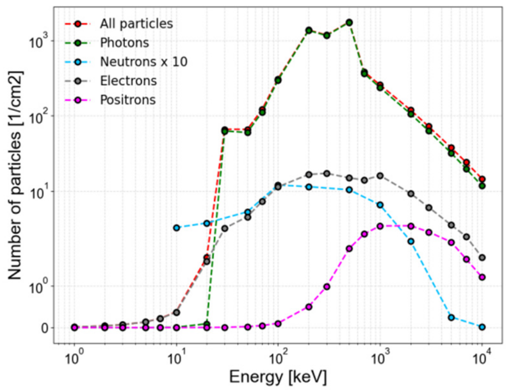

Figure 3: Energy spectra for particles inside the 3rd magnet of the undulator.

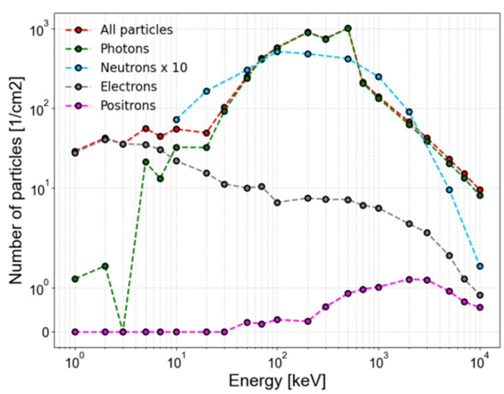

Figure 4: Energy spectra for particles 1 cm outside the vacuum pipe, integrated over the length of the undulator.

LB 6419 Measurements

Figure 5 shows the gamma signal measured with the LB 6149 detector during normal operation and in case of enhanced beam losses. Such events, besides the halo electrons hitting the beam pipe, could be caused by a misalignment of the beam. The entire undulator system is approximately 230 m long and consists of 35 undulator cells. Signal was obtained at the beginning of the whole undulator section (cell 3).

The range for energy spectra measured by the detector is limited on the low energy side by the pulse discrimination threshold. On the high energy side, the response is limited by the size of the plastic scintillator. During normal operation, the energy spectrum is flat in the lower energy range, and the muon peak is visible around 8 MeV. However, in the case of the beam loss event, an additional peak comes up. It is shifted towards the lower energies, which is consistent with the energy spectrum from simulations.

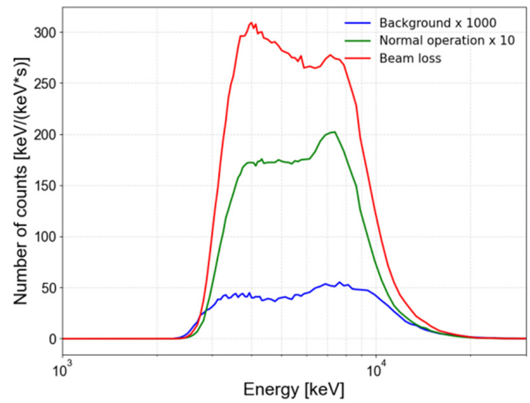

Figure 5: Gamma radiation measured with LB 6419 detector.

SUMMARY

Monte Carlo code Geant4 was used to investigate the radiation field nearby the undulators at EuXFEL. The simulations indicated that various particles are present in the undulator magnets and outside the segment, and they result from electron beam interactions with the beam pipe. The number of electrons and neutrons decreases exponentially, as the distance from the vacuum pipe increases. Energy spectra obtained from simulations showed a dominance of photons, but also the presence of neutrons. The gamma radiation measurements indicate, that during the beam loss event signal peaks at lower energies. The results show, that Monte Carlo simulations may complement radiation measurements nearby the undulators at EuXFEL It is important to emphasize that the work presented here should be treated as a basis for further studies. Questions that came up during the analysis, *i.e.* how the particle spectra would change depending on the measurement position or for the different energy of initial electrons, should be addressed in the future to give a better understanding of the radiation field in the vicinity of the undulators.

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