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RADIATION PROTECTION ISSUES IN UNDULATOR UPGRADES FOR THE EUROPEAN XFEL*

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Abstract

European XFEL is the first free electron laser operating at MHz repetition rate with electron beam energy up to 17.5 GeV. The high repetition rate together with the high electron beam energy provides unique opportunities for users in different domains. To further extend the operation schemes, some upgrades have already been implemented and several more are planned. The advanced operation schemes may require devices inserted into the beam (e.g. slotted foil) or narrow vacuum chambers (e.g. corrugated structure, Apple-X undulator, superconducting undulator), and due to the high beam power, there are concerns about increased radiation loads. Therefore, simulations and measurements have been carried out to study the radiation dose rates that may be generated. We give an overview of the simulations and measurements for the case of the Apple-X undulators, and briefly consider the implications for other schemes.

INTRODUCTION

The SASE3 beamline [1] at the European XFEL (EuXFEL) delivers FEL beam in the photon energy range 0.25–3 keV. Photon pulses are generated by an electron beam with energy up to 17.5 GeV in a planar undulator, consisting of 21 modules each of length 5 m. To allow control of the polarisation of the X-ray beam, during the winter 2021/22 shutdown an Apple-X undulator (consisting of four modules each of length 1.98 m) was installed in the beamline following the planar undulator [2]. First lasing with the Apple-X undulator in place was achieved in early April 2022 [3]. However, after a short period of operation, faults began to occur with the linear and rotary encoders and cam movers used in the control of the magnet arrays in the Apple-X undulator. It was suspected that the damage was caused by spontaneous synchrotron radiation from the SASE3 planar undulator, and to prevent further damage the Apple-X undulators were removed in the summer shutdown 2022, and the new (narrower aperture) vacuum chamber in the Apple-X section was replaced by the original vacuum chamber. Simulation and experimental studies were begun to understand the cause of the radiation damage, and to plan potential mitigations to allow reinstallation of the Apple-X: in this paper, we summarise the studies and outline the results. Other upgrades of EuXFEL, planned or in progress, also raise concerns regarding the effects of increased radiation loads on components in the machine, and we conclude this paper by considering briefly the lessons and implications of the Apple-X studies for these upgrades.

SYNCHROTRON RADIATION MODEL

The study reported here aimed to develop an understanding, through simulations and measurements, of the radiation loads on the Apple-X undulators in EuXFEL (in particular, the loads on the damaged encoders) arising from spontaneous synchrotron radiation from the SASE3 planar undulator. Note that it is assumed that FEL radiation from the undulator can be cleanly extracted along the beamline, and is therefore not included in this study: where we refer to synchrotron radiation in the present paper, it should be understood that (unless stated otherwise) the term refers only to spontaneous radiation. Following construction of a radiation model, the simulations can be developed to investigate possibilities for additional protection, allowing to reinstall the Apple-X undulators. As a first step, a model for the distribution of synchrotron radiation photons was constructed: this distribution was then tracked through a model of the machine (including detailed representations of relevant apertures and components) to the Apple-X undulators using a suitable simulation code, which can be used to estimate the radiation dose rates. We used analytical formulae verified with SPECTRA [4] for generating the photon distribution, and BDSIM [5] for the tracking simulations and radiation dose rate calculations.

For tracking photons in BDSIM, the initial distribution (at the mid-point of an undulator module) is modelled as a set of macroparticles over a 200×200 uniform grid of points in the transverse angular space, up to 0.5 mrad. The initial transverse spatial coordinates were assumed to be negligible, since the beam size towards the end of the undulator is dominated by the initial divergence. The electron beam emittance and energy spread are also neglected. Each macroparticle contains a number of photons with a range of energies: the number density and energy spectrum were calculated analytically as a function of angle using standard

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Table 1: Parameters used to calculate the spontaneous radiation photon distribution in a SASE3 undulator module.

Parameter	Value
Electron beam energy	14 GeV
Bunch charge	250 pC
Average beam current	250 pA
Undulator period	68 mm
Number of periods per module	73
Undulator parameter, K	8.2

formulae (see, for example, Ref. [6]), and the results of the calculations were confirmed by comparison with simulations in SPECTRA. Relevant parameters are shown in Table 1. Note that constraints on machine operation (in particular, from simultaneous operation of hard and soft X-ray beam lines [1]) mean that the undulator parameter for SASE3 under normal operating conditions is relatively large, with the consequence that a large number of harmonics of the fundamental radiation frequency, extending to high photon energy, need to be included in the tracking. The electron beam current is an arbitrary parameter, since it is assumed that the radiation dose rates from simulation can simply be scaled to the actual beam current in machine operation.

RADIATION DOSE RATE SIMULATIONS

Having calculated the initial photon distribution in each module of the planar undulator, the distributions are tracked using BDSIM: this code provides a convenient tool for this purpose, since it also allows (through integration with GEANT4) modelling of the photon interactions with machine components. For the simulations, the machine model includes accurate representations of the vacuum chamber geometry and the photon absorbers designed to limit the synchrotron radiation impacting critical components such as the undulators. Photon absorbers, constructed of copper, are located after each module of the planar and Apple-X undulators. Simulations were performed under a variety of machine conditions: first, corresponding to the machine with the Apple-X undulator installed, to estimate the dose rates at key locations, and to allow comparison with dose rates monitored under standard machine operation; and second, with conditions corresponding to those used for more detailed dose rate measurements, performed following removal of the Apple-X undulators, and designed to provide data for validating the simulations.

Dose rates calculated using BDSIM with the Apple-X undulator installed are shown in Fig. 1. The results show dose rates building up along the initial section of the planar undulator, as expected from the divergence of the synchrotron radiation: the photons generated in an undulator module travel some tens of metres before photons reach the edge of the aperture in a photon absorber. Eventually, a balance is reached between the generation of new photons in successive undulator modules, and photons stopped by

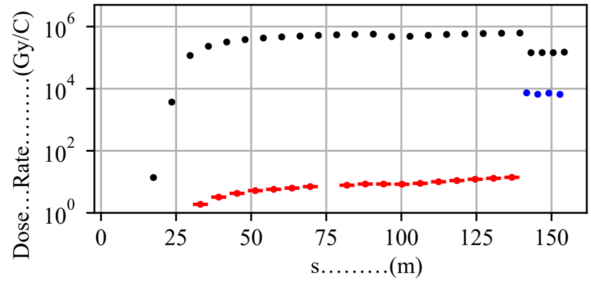

Figure 1: Dose rates in the copper absorbers (black), the planar undulators (red) and the Apple-X undulators (blue).

the absorbers. Significantly, the radiation dose rates in the Apple-X are larger by more than two orders of magnitude than the dose rates along the planar undulator: detailed inspection of results from photon tracking shows that this is due to the narrowing of the vacuum chamber aperture in the Apple-X, particularly in the horizontal dimension. The chamber in the planar undulator is elliptical to allow for efficient transport of synchrotron radiation (with a wide horizontal divergence) to the photon absorbers, but because of the geometry of the Apple-X devices, the chamber in these undulators is circular, with a narrow aperture.

The simulation model was used to investigate the effects of machine imperfections, including steering errors on the electron beam and alignment errors on the vacuum chamber and other components. The results suggested that under realistic assumptions for the scale of the errors, the effects of steering and alignment errors on the dose rates will be relatively small. The high dose rates observed in the Apple-X undulators come mainly from aperture limitations.

DOSE RATE MEASUREMENTS

In the winter shutdown 2022/23, after the Apple-X modules had been removed, the smaller vacuum chamber for the first Apple-X module was reinstalled to allow investigation of the radiation loads with the reduced aperture. Radiation dose rate measurements along the planar undulator and at the intended location of the Apple-X were made using MARWIN, a robot that can be driven along the accelerator tunnel (approximately 2 m from the beamline). MARWIN is equipped with a detector (LB6419) capable of measuring neutron and gamma radiation [7, 8]. To allow comparison with MARWIN data, iron blocks (width 0.1 m, height 0.5 m and length 1 m) were placed in the simulation along the beamline, 2 m from the beam: the dose rate in each block from synchrotron radiation (taking into account interaction with the vacuum chamber and photon stops) was calculated in BDSIM. Figure 2 shows a comparison between simulated and measured dose rates. The different colour lines show the dose rates with different sections of the planar undulator closed: the results from these measurements provide information on the contribution of different undulator sections to the radiation dose rates at the Apple-X.

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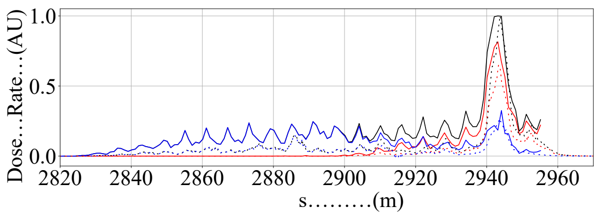

Figure 2: Normalised radiation dose rates simulations (solid) and measurements (dashed) for first 11 cells closed (blue), last 10 cells closed (red) and all cells closed (black).

The radiation dose rates along the beamline from the simulations are in good agreement with the MARWIN measurements. Good agreement is also found in comparing simulations with measurements made using fixed RADFETs [9], of dose rates at different points along the undulator beamline. Finally, simulations of the dose rates at the Apple-X location resulting from individual modules of the planar undulator are also in good agreement with measurements. Overall, the results provide confidence in the simulations as a means of developing a detailed understanding of the origins of the radiation loads on the Apple-X, and as a tool for investigating possible ways of enhancing the protection of the Apple-X undulators to prevent radiation damage.

MACHINE PROTECTION OPTIONS

Protecting the Apple-X from radiation resulting from photons generated in the planar undulator is a challenging problem for several reasons. First, constraints on the geometry limit options that would otherwise be attractive, such as increasing the vacuum chamber aperture in the Apple-X modules. Second, the high electron beam energy results in the production of a significant flux of high-energy (of order 1 MeV) photons from the planar undulator: such photons are highly penetrating, and difficult to stop using photon absorbers. Detailed inspection of simulations show that a significant contribution to dose rates on the Apple-X encoders comes from photons back-scattered from absorbers at the end of each module. Finally, the penetrating nature of high-energy photons also makes it difficult effectively to shield sensitive components.

Ideally, the radiation loads in the Apple-X should be reduced to levels comparable to those in the planar undulator (which has been operated for a number of years without problems from radiation damage). This would mean reducing the dose rates in the Apple-X by two orders of magnitude. To see whether this might be achieved by modifying the absorbers, simulations were carried out with the absorber aperture reduced (from 9 mm×8 mm elliptical, to 6 mm circular) in just the final two absorbers in the planar undulator and the four absorbers in the Apple-X section. It was found that although the dose rates in the Apple-X RADFETs and encoders were indeed reduced, the reduction was only about a factor of two, far short of the two orders of magnitude required. One possible reason for this is that photons back-scattered from the absorbers contribute to the radiation loads on these components: reducing the aperture therefore has limited impact, and can even (under some conditions) make the situation worse.

To try to improve on the benefit from the aperture reduction in the absorbers, two further absorber modifications were investigated in simulation: first, increasing the narrow-aperture section length from 3 mm to 9 mm; and second, changing the material from copper to tungsten. As an additional option, the effect of lead shielding around the RADFETs and encoders was investigated. Results (shown in Table 2) suggest that some combination of changes (including shielding of sensitive components) would likely be needed to reduce the dose rates to safe levels.

Based on the simulation results, new absorbers (6 mm aperture and 15 mm length) were installed in the final two cells of the planar undulator, together with new, narrow-aperture quadrupole vacuum chambers (copper, 6 mm aperture, 150 mm length). Lead shielding (between 3 mm and 6 mm thickness) has also been added to the absorbers, to increase their effectiveness. Preliminary measurements (using MARWIN) show a reduction in dose rates by an order of magnitude in the region of the Apple-X undulators; results from detailed studies will be reported in due course, and will be used in planning the re-installation of the Apple-X undulators.

Table 2: Effect of modified photon absorbers on Apple-X radiation dose rates. The absorber aperture is 6 mm in all cases. Dose rates are expressed as a fraction of the rates with the current absorbers.

Absorber type/length	Shielding	Dose in first RADFET	Mean dose in encoders
Cu / 3 mm	No	0.726	0.680
Cu / 9 mm	No	0.262	0.565
Cu / 3 mm	Yes	0.170	0.629
W / 3 mm	No	0.031	0.071

IMPLICATIONS FOR OTHER UPGRADES

The tools and techniques used for the Apple-X studies build on and will support studies for other upgrades for Eu-XFEL that are planned or proposed. The experimental work to validate the simulations and the improved understanding of radiation issues generally will be of significant value. Simulations of radiation effects have already been reported for the slotted-foil scheme for generating short (femtosecond-scale) X-ray pulses [10]. Work is also in progress on a superconducting undulator to be installed after the current SASE2 undulator [11, 12]. In preparation for this upgrade, a test absorber with 4 mm aperture was installed downstream of the last modules in the present SASE2 undulator in the winter shutdown 2022/2023. Tests with electron beam were successful. Radiation sensitive detectors have been placed downstream and radiation effects on nearby devices are under investigation. Initial results show low radiation levels.

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