STATUS UPDATE OF THE SASE3 VARIABLE POLARIZATION PROJECT AT THE EUROPEAN XFEL

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Abstract

The SASE3 Variable Polarization project is intended to offer polarization control of the X-ray FEL pulses at the European XFEL. The project was completed in early 2022. During the winter shutdown 2021-2022, all four APPLE-X helical undulators were placed in the tunnel and first lasing was achieved in April 2022. Unfortunately, further use of the helical afterburner proved impossible, as the encoders used to position the magnetic structures of the undulator were damaged by radiation. To carry out repairs, all undulators were removed from the tunnel in the summer 2022, and investigations were carried out to determine the cause of the radiation damage. This article presents measures taken to minimize further radiation damage in order to ensure the continued operation of the helical afterburner.

INTRODUCTION

The European XFEL was designed and commissioned with three undulator systems. Two of them, SASE1 and SASE2, generate hard X-rays, while the third, SASE3, generates soft X-rays. All three systems were equipped with planar undulators that generate linearly polarized radiation in the horizontal plane. Soon after the start of SASE3 operations, users expressed a desire for a variable polarization option. To address this need, an afterburner capable of producing variable polarization was developed. This project, SASE3 Variable Polarization (SASE3-VP), carried out in close collaboration with the Paul Scherrer Institute (PSI) involved installation of four APPLE-X undulators directly after the planar undulator system [1].

Commissioning of SASE3-VP began in spring 2022, with successful lasing in various polarization modes quickly achieved [2]. Later, however, elements of the APPLE-X undulator control system began to fail. Measures were taken to determine the cause, restore functionality, protect against further damage and put the project back into operation.

CAUSE OF RADIATION DAMAGE

It was early suspected that the malfunction of the control electronics was caused by radiation damage. The reasons for this can be understood from the changes that were made to the vacuum system of the undulator section during the design of the afterburner project.

APPLE-X Undulator Section Vacuum System

The vacuum chamber of the planar undulators has an elliptical opening of width 15 mm and height 8.8 mm, followed by an elliptical absorber with an opening of width 9 mm and height 8 mm and then a quadrupole vacuum chamber with a circular cross-section of diameter 10 mm. Following the quadrupole chamber, another undulator chamber with an elliptical opening is positioned. In the case of the interface between the planar and the APPLE-X undulator, there is a section of the undulator vacuum chamber of length 20 cm for the phase shifter located downstream of the quadrupole vacuum chamber. This is followed by a bellows with two circular copper tubes with an internal diameter of 9.4 mm and a total length of 8 cm. The bellows is then connected to the circular vacuum chamber of the APPLE-X undulator, which has an internal diameter of 9.4 mm [3]. Thus, an essential difference between the planar undulator section and the afterburner is the change in the aperture of the tubes in the bellows and the change in the horizontal aperture of the vacuum chamber of the APPLE-X undulator.

Radiation Dose Rate Simulations and Comparison With Measurements

The planar undulators and the APPLE-X undulators are each equipped with radiation-sensitive metal-oxide-silicon field-effect transistor (RADFET) online dosimeters,

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mounted on the upstream side of each magnet girder. The first signals of increased radiation following installation of the APPLE-X undulators were measured with these dosimeters. The normalized dose in the APPLE-X undulators was hundreds of times higher than the dose measured in the planar undulators. However, no activations of beam loss monitors were observed, indicating that photons were the source of the increased radiation. It should be noted that the linear and rotary encoders that were damaged were located on the downstream side of the undulator. This suggested that the source of radiation was backscattered photons.

In order to understand the causes of increased radiation, simulation studies were carried out [4]. The SPECTRA program was used to simulate the spontaneous (not FEL) synchrotron radiation from the planar undulators. The photon flux as a function of energy and angular power distribution were calculated for an electron beam energy of 14 GeV, using a wiggler approximation for the undulator, with undulator parameter K = 8 (see Fig. 1).

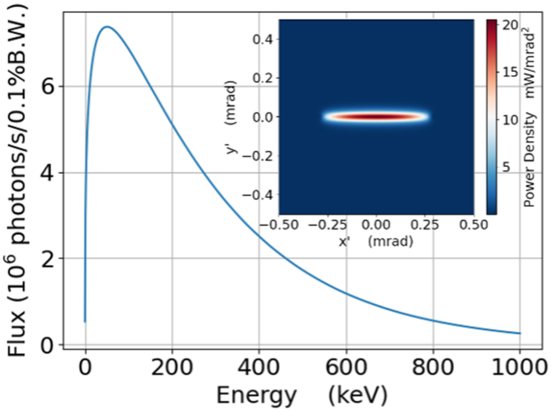

Figure 1: Photon flux as a function of energy (main plot) and angular power distribution (inset) for spontaneous synchrotron radiation from the planar undulator in SASE3.

The flux curve in the range from zero to 1 MeV was integrated to determine the number of photons in each of 100 energy bands of width 10 keV. A different input distribution for the tracking code was created for each energy band. The input distribution was determined from the angular power distribution, with a weight added to each grid point corresponding to the number of photons in that angular range. The tracking code BDSIM, which uses GEANT4, was used to model the interactions between photons and beamline components from the beginning of SASE3 up to the APPLE-X undulators, taking into account the geometric constraints of the vacuum system in the APPLE-X undulator section. The input distribution was added at the center of each SASE3 undulator. The RADFETs were represented by a block of material surrounding the vacuum chamber at the RADFET locations; dose rates were calculated from the dose deposited in the material. The simulation thus allowed calculation of the dose deposition at individual undulators along the beamline, and results could then be compared with measured dose rates.

Figure 2 shows simulation results for the dose absorbed by the material at the RADFET positions in the planar and APPLE-X undulators. The RADFET measurements in the SASE3 undulator beamline showed an increase of hundreds of times between the dose absorbed in a RADFET in the last planar undulator and the dose absorbed in the first RADFET in the APPLE-X. This difference is consistent with the simulation results, and is the result of many more photon interactions, which in turn results from the reduction of the horizontal aperture of the vacuum chamber from 15 mm to 9.4 mm in the APPLE-X.

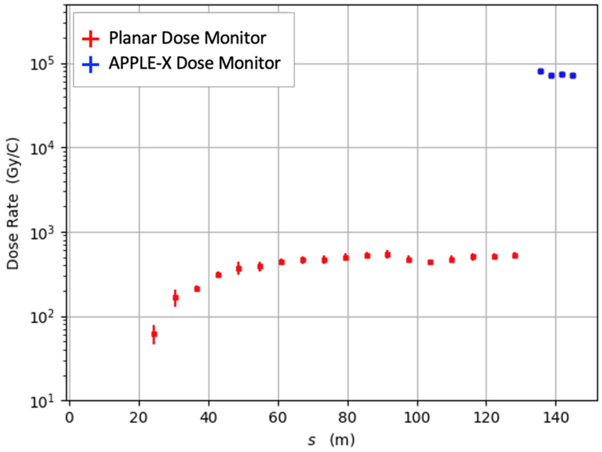

Figure 2: Simulation results of the dose absorbed by the material at the RADFET positions in planar (red) and APPLE-X (blue) undulators.

Radiation Studies

As the aluminum vacuum chamber is an integral part of the APPLE-X undulator, a spare vacuum chamber identical to the APPLE-X chamber was installed in place of the first APPLE-X undulator. In place of the other three chambers, temporary stainless-steel chambers with a diameter of 40.5 mm were installed. At the same time, the SASE3 tunnel was equipped with a MARWIN4 robot, carrying a photon and neutron dose rate meter LB 6419 [5] and capable of moving along the entire tunnel. This made it possible to measure the radiation profile along the electron beam at a perpendicular distance of ~2 m.

Following these installations, a series of measurements were performed. No increased radiation level was observed when the gap of all planar undulators was fully open. If all undulators were closed to the minimum gap, the radiation peaks in the region of the planar undulators coincide with the positions of the photon absorbers. The highest peak (by about a factor of ten over the other peaks) was observed at the location of the APPLE-X vacuum chamber.

Another series of measurements investigated the contribution of single planar undulators. The undulators were closed individually one after the other to a gap of 10.5 mm. The radiation level along the tunnel was then measured with the movable LB 6419 detector. The same measurements were carried out when the gap was closed to 22 mm. The measurements showed that with a gap of 10.5 mm, the undulators in cells 22 and 23 have no influence on the radiation level. With a gap of 22 mm, the undulators in cells 20 to 23 have no influence on the radiation level. Thus, there is a clear dependence of the radiation level on the angular distribution of the power generated by the planar undulators.

A simple geometric model of the integrated photon flux from the individual planar undulators describes very well the measurement results (Fig. 3). An integrated angular power distribution of the spontaneous radiation generated by the planar undulators at 10.5 mm gap was used for the calculation from the geometric model. The calculation of the individual contribution from each cell is based on the flux reaching the wall of the two-meter-long vacuum chamber of the APPLE-X undulator.

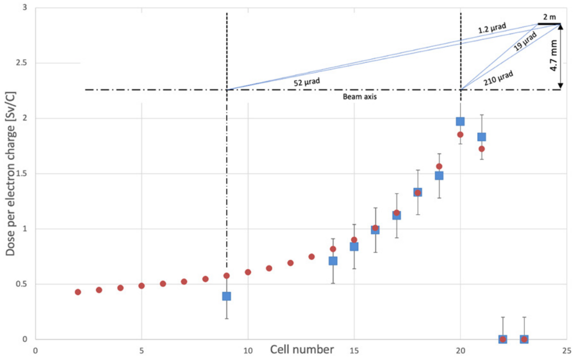

Figure 3: Normalized dose measured by closing a single undulator to a gap of 10.5 mm (blue), compared with the dose calculated (red) from a simple geometric model (shown in the upper part of the plot).

RESULTS OF THE REINSTALLATION

Once the causes of the increased radiation dose rates had been identified, a series of steps were taken to bring the APPLE-X back into operation.

Measures to Improve Radiation Protection

Measurements and modelling showed that reducing the absorber aperture to a diameter of 6 mm would block the spontaneous radiation, which can propagate at a maximum angle of 300 µrad (the largest opening angle for photons generated with the smallest gap of planar undulators).

A new absorber design with a 6 mm aperture and 15 mm length was realized. The simulations showed that the best locations for the new absorbers would be behind cells 22-25. These new absorbers were installed before the APPLE-X undulators were reinstalled in the tunnel. In addition, the linear and rotary encoders of the undulators were covered with a lead shield, and all absorbers in the SASE3 tunnel were equipped with protective shields made of lead and non-magnetic tungsten.

Magnetic Measurement Results

New magnetic measurements were necessary for two reasons. First, it was necessary to recalibrate the undulators as the shift and gap positions of the undulator girders had been lost after exchanging the control components. Second, it was necessary to verify whether the radiation had affected the properties of the permanent magnets. After recalibration and shimming, the final magnetic measurements showed no effect of the absorbed radiation on the magnetic properties of the undulators [6].

Reference Measurements of the Magnet Girders

As the magnetic material in the undulators is less susceptible to radiation than the electronic components, it would make sense to be able to replace the electronic components if needed without new magnetic measurements. To this end, a method was developed and the design of the undulator was adapted so that reference measurements could be made of the position of the magnetic girders in both the longitudinal and transverse directions [7]. After reinstalling the undulators in the tunnel, reference measurements were carried out on all APPLE-X undulators. This means that a damaged encoder can now be replaced (if necessary) in situ within a few hours without having to remove the undulator from the tunnel.

Reinstallation and Commissioning Results

Measurements with the LB 6419 detector showed a reduction in radiation exposure by a factor of 100 (Fig. 4) compared to radiation exposure with an APPLE-X vacuum chamber installed in cell 24 (in place of the APPLE-X) and without modified absorbers. Both measurements were taken at a gap of 10.5 mm for all planar undulators and an electron beam energy of 14 GeV.

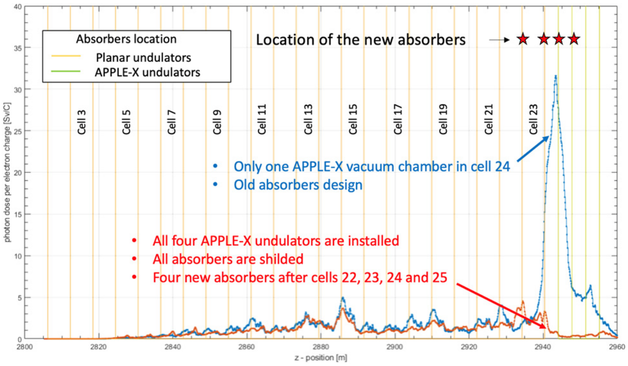

Figure 4: Reduction of the radiation level after replacing the absorbers and reinstalling the APPLE-X undulators.

The RADFET dosimeters also do not show any significant increase in radiation, either in the area of the last planar undulators or in the area of the APPLE-X undulators.

The first lasing after the reinstallation of the helical afterburner was achieved on January 25, 2024. for the circular mode at 1 keV photon energy, the resulting intensity is 1.2 mJ/pulse. A reliable contrast between linear and circular polarization of 40 was achieved by further optimizing the lasing.

CONCLUSION

As a result of an investigation to determine the causes of radiation damage, and measures taken to reduce radiation levels, protect electronics, repair and recalibrate the undulators, it was possible to reinstall the APPLE-X undulators in the tunnel during the winter shutdown period of 2023-2024. The SASE3 Variable Polarization project is back in operation and ready for the experimental program from the second half of 2024.

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