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ABSORBED RADIATION DOSES ON THE EUROPEAN XFEL UNDULATOR SYSTEMS DURING EARLY USER EXPERIMENTS

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Abstract

The European XFEL GmbH (EuXFEL) is a FEL user facility based on a superconducting accelerator with high duty cycle. Three movable gap SASE Undulator Systems using hybrid NdFeB permanent magnet segments are in operation. We observed in a dedicated diagnostic undulator for radiation damage doses up to 4 kGy and 3% demagnetization effect during the commissioning phase. In this work we present characteristics of the absorbed radiation doses in undulators during photon beam delivery for users. Lower absorbed doses are measured since the start of user operation. While ramping up electron beam parameters and repetition rates, individual segments located at the downstream end of the SASE systems show persistent absorbed doses which are proportional to the transmitted charge. In addition, the dose per charge ratio shows photon energy dependence. Portable magnetic flux measurement systems allow in-situ tunnel assessment of undulator magnetic properties in order to estimate radiation dose limits for future user operation.

INTRODUCTION

The European XFEL GmbH is a free-electron laser user facility which started operation in 2017. Its superconducting accelerator is designed to operate at energies up to 17.5 GeV and has the highest duty cycle machine currently in operation with a repetition rate of up to 27000 bunches per second and at 1nC [1]. The EuXFEL operates three separate undulator systems named SASE1, SASE2 and SASE3 to produce FEL radiation with tunable wavelengths from 0.05 to 5.2 nm and pulse lengths of less than 100 fs [2]. These Undulator Systems are built with 91 5-m long undulator segments based on hybrid NdFeB (VACODYM 776AP) permanent magnets, which are tuned to to optimize the SASE effect [3].

De-magnetization effects of the permanent magnets due to radiation damage have been reported [4-8] in several facilities through the years and have been also observed at EuXFEL [9]. Dedicated passive and active machine protection systems have been designed to minimize such effects and the EuXFEL operates a collimation system [10], an array of on-line readable dosimeters [11], and diagnostic undulators (DU) installed at the upstream extremity of each SASE system. These permit to investigate, reduce and/or minimize the demagnetization effects on the undulator systems.

Table 1 summarizes the starting date of accelerator commissioning, first lasing and start of user program in each SASE system. The EuXFEL has adopted a ramping up schedule for the beam parameters and the currently used electron and photon parameters available for users are also indicated in Table 1. In this work we consider the commissioning phase for each SASE system stretching from the first beam transmission through the undulators until the start of the early user operation and therefore it also includes the beam delivery for the beamlines commissioning phase. It is important to note that the electron beam transmitted through SASE1 necessarily travels through SASE3 before reaching the nearest dump.

Table 1: Main Event Dates for SASE1-3 and Typical Beam Parameters for User Experiments

System	SASE1	SASE2	SASE3
1st beam transm.	27.04.2017	13.03.2018	27.04.2017
1st lasing	02.05.2017	01.05.2018	02.08.2017
1st Early user exp.	14.09.2017	20.03.2019	28.11.2018
Typical e-beam user par.	14 GeV 250 pC 2000 bps	14 GeV 250 pC 2000 bps	14 GeV 250 pC 2000 bps
Typical photon user par.	6-12keV	6-14keV	0.7-1.6keV

In this manuscript we report on the evolution and characteristics of the absorbed doses during the initial phase of photon beam delivery for users. In particular we discuss time, charge, and photon energy dependences of the absorbed doses. Additionally, we present further enhancement on magnetic measurement capabilities allowed by in-situ tunnel measurements.

ABSORBED DOSES DURING COMMISIONING AND USER OPERATION

The importance of on-line dosimetry system and diagnostic undulators in the EuXFEL Undulator Systems was demonstrated in the commissioning phase. We have measured de-magnetization effects associated to magnetic field degradation in the diagnostic undulators [9] and to a change in the vertical entrance kick of a 5-m undulator

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segment [3]. As shown in Figure 1, magnetic degradation higher than 4% for absorbed doses up to 4.8 kGy was observed in the SASE1 and SASE3 DUs. If such levels of magnetic reduction were found in 5-m undulator segments, it may affect the overall quality of the SASE process. We have estimated an initial limit of about 55 Gy for a 4×10^{-4} relative change in magnetic field based in Hall sensor magnetic measurements for K-parameter.

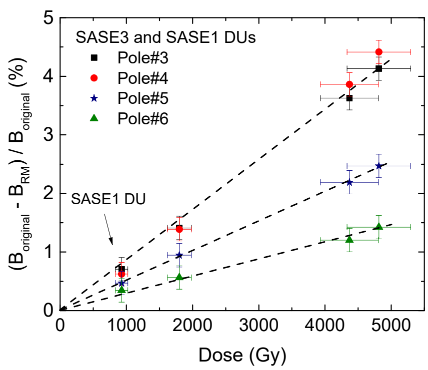

Figure 1: De-magnetization measured on the EuXFEL SASE1 and SASE3 diagnostic undulators.

The absorbed doses in the DUs were mainly generated by localized single e-beam losses and the number of such events could be minimized by extensive commissioning of the collimation system and better understanding and training of operational practices.

Figure 2 presents an overall evolution of the total absorbed doses as function of time for the SASE1-3 Diagnostic Undulators. The time dependence of the total dose increase in DU-SASE1 (black curve) is higher during the commissioning phase between May-17 and September-17 while after the start of user experiments only few single events were mainly responsible for dose increases.

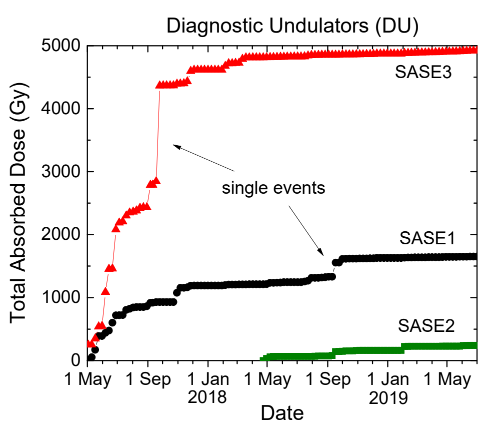

Figure 2: Total absorbed doses in the SASE1-3 Diagnostic Undulators up to July-2019.

The SASE3 Diagnostic Undulator (red curve) shows greater dose increases in 2017 than 2018 or 2019. During the SASE1 commissioning phase the electron beam travels through SASE3 before reaching the dump. Better work practices in beam steering and beam collimation resulted in fewer single events and consequently lower absorbed doses since the start of 2018. The DU-SASE2 (green curve) shows very low absorbed doses since its first beam transmission. At the present, absorbed doses in the diagnostic undulators are only originated from orbit corrections and/or beam based alignment activities. As the Fig. 2 clearly shows, beam losses deposited in the diagnostic undulator have successfully been minimized.

Figure 3 shows the evolution of the absorbed doses in selected 5-m undulator segments in all 3 SASE systems. It is important to note that the dosimeters are attached in the movable girders and move accordingly to the gap changes. Cell#3 corresponds to segments located at the upstream side of a SASE system, nearly 18 m behind a DU, while SASE1-cell#31, SASE2-cell#29 and SASE3-cell#23 are segments located towards the downstream end.

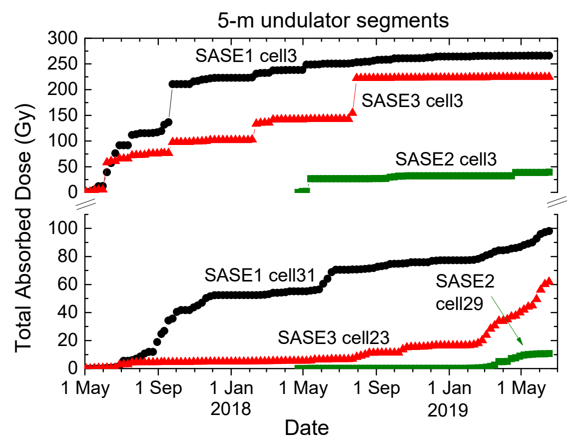

Figure 3: Absorbed doses at upstream (top) and downstream (bottom) 5-m undulator segments.

The absorbed doses in the 5-m undulator segments show different behaviour depending on the segment location along the SASE system. The upstream undulators in cell#3 have similar behaviour as the DUs with higher absorbed doses during the commissioning phase for SASE1 and SASE3. During user operation, the dose increases are mostly seen during eventual singular losses. In contrast, the SASE1-3 downstream undulator segments show an increase of absorbed doses as function of time which nearly coincides with the start of user operation and results from steady dose increases during beam delivery. These findings remain valid for other segments located either at the upstream or at the downstream end of the SASE systems (not shown here).

DOSE PER CHARGE RATIO

We monitor the total transmitted charge through the three undulator systems with the aid of toroids. Figure 4 shows the total transported charge through SASE1-3 since the start of operation.

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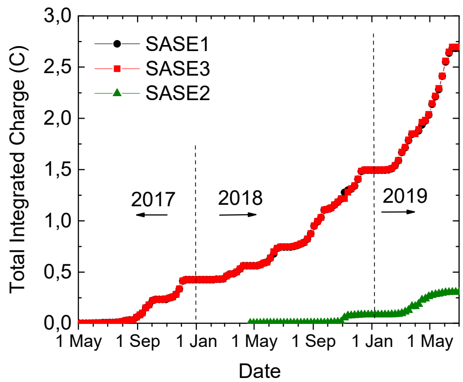

Figure 4: Total transmitted charge in SASE1 and 3 and SASE 2 since start of operation.

SASE1 and 3 have transmitted charge higher than 2.5 C as of July 2019. As comparison, LCLS-I has transmitted a total charge of about 2.5 C during the 10 years of operation [12]. We observe the total transmitted charge rate at EuXFEL has been ramping up as function of time: more than 1 C has passed through SASE1 and SASE3 in 2019 alone. This reflects the experiment and user's demand for higher repetition rates – resulting in higher transmitted charge. Due to safety restrictions the operation is currently limited to 4000 bunches per second and more will be allowed for operation in 2020 after an upgrade in the safety system. As the dose increase as function of time is proportional to the charge rate [9], we expect to observe higher doses associated with higher repetition rates. The SASE2 transmitted charge also has a similar profile resulting in faster increase after the start of beam delivery for user experiments.

The movable gap undulator systems have been operated with fixed gaps corresponding to particular photon energies. The allocated beam time for users at EuXFEL consists of 12 hours shifts for each instrument belonging to a SASE system and typically the photon energy remains constant in a shift. Contrarily, the repetition rate (bunches per second) is frequently changed according to the experiment needs. In order to observe the effects of different operational user modes, we have monitored the transmitted charge (Figure 5a) and the absorbed dose increase (Figure 5b) during a SASE1 user operation period where FXE and SPB/SFX beamlines requested photon energies at 9.3keV and 6.0 keV, respectively.

As the accelerator operated continuously at 14.5 GeV and 0.25nC, the slope change in the transmitted charge in SASE1 reflects only the beamlines choice of number of bunches. Nevertheless, the linear behavior during a 12 hours shift permits to determine a temporal charge rate. Figure 5b shows the total absorbed doses for undulator segments located at cell#17 and cell#31. These are the segments that showed higher absorbed doses during these user shifts. The steady increase in absorbed doses is seen during user operation mode [9] and its origin will be discussed elsewhere. From these plots we can determine the temporal absorbed dose rates for both 9.3 and 6.0 keV operational modes.

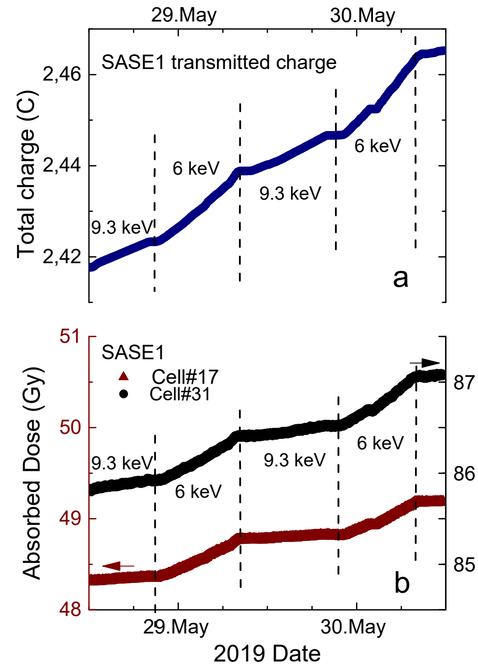

Figure 5: SASE1 total transmitted charge (a) and total absorbed dose in cells #17 and #31 (b) during photon beam delivery for users at 9.3 keV and 6.0 keV.

From the charge and dose rates calculated with linear fits in the plots exemplified in Figure 5 we determined the dose per charge ratio at each individual shift and Table 2 summaries these results.

Table 2: Dose per charge Rate at 9.3 and 6.0 keV in Selected SASE1 Undulator Segments

Photon Energy	**SASE1-Cell#17 (Gy/C)**	**SASE1-Cell#31 (Gy/C)**
9.3 keV	8.2	17.4
9.3 keV	6.2	14.9
9.3 keV	4.9	15.9
6.0 keV	27.1	31.7
6.0 keV	21.0	29.0
6.0 keV	21.7	31.8

For cell#17, the dose per charge ratio is between 5 to 8 Gy/C at 9.3 keV (gap ≈ 13.7 mm). At this gap, the distance between the outer vacuum chamber surface and the undulator magnetic structure is about 2 mm. When clos-

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ing the gap for producing FEL at 6.0 keV (gap ≈ 10.7 mm; top and bottom girders are moved closer to the vacuum chamber by 1.5 mm) the ratio is augmented nearly by a factor 4. Further operational modes will provide data for further studies on the dose ratio as function of photon energy/vertical distance between vacuum chamber and magnetic structure.

The cell#31 shows the dose per charge ratio roughly increases a factor 2 between the 9.3 and 6.0 keV photon energy modes. However, during the operation time here discussed, the cell#31 segment was not used for FEL generation and was positioned at the so-called "parking position" at a gap = 210 mm, meaning the magnetic structure and dosimeters were nearly 100 mm distant to the vacuum chamber. So, there is a clear effect on the dose per charge ratio due to the photon energy. This also suggests the measured absorbed doses in cell#31 are originated from low energy radiation. Nevertheless, the reason for the dose ratio change found in an open undulator requires additional studies and could be associated to X-rays or synchrotron radiation emitted in prior segments.

IN-SITU MAGNETIC MEASUREMENTS

Magnetic measurements performed in the laboratory premisses are time consuming in the case of installed components. Typical procedures of de-installation, transport, magnetic measurements, installation and re-alignment range between 4-5 days (for a DU) to a couple of weeks (for a 5-m segment). Therefore, faster in-situ magnetic measurements are of importance when taking into account the constraints imposed due to machine operation for beam delivery to users. Among considered options, we started by developing a measurement setup based in the so-called "flux coil" method, where an integrated voltage signal measured with a coil is proportional to the magnetic flux induced in a pole. If the magnetic flux through the coil changes, e.g., when changing the undulator gap, a voltage is induced. An analog integrator with accuracy of 10^{-6} V.s integrates the induced voltage over from initial time $t1$ to final time $t2$. The magnetic flux through the fluxcoil is therefore given by:

$$\Phi = N \int_{t1}^{t2} V(t)dt \quad , \qquad (1)$$

where N is the number of windings.

Figure 6 shows the flux coil placed around a magnetic pole for measurements in tunnel. The coil is mounted in a non-magnetic holder with a hollow in the center which fits the pole dimensions and permit reproducible mounting and alignment. In one working hour we obtain representative data in 15 magnetic poles distributed along the 5-m undulator, allowing measurements to be performed in a temporary tunnel access during maintenance days, for example. On the DU's fixed gap, measurements are taken by moving the coil from a field free location to the magnetic pole.

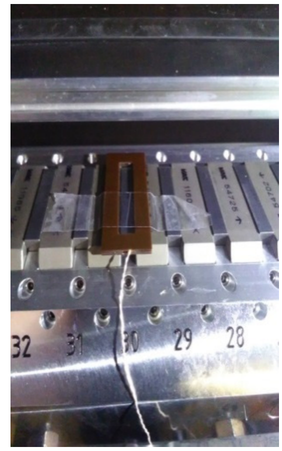

Figure 6: The flux coil is used to perform magnetic measurements on different poles loacted along the 5-m undulator.

The accuracy and repoducibility of the flux coil measurements was tested on reference undulators/DUs located in the magnetic laboratory or in devices installed in the tunnel while performing the same measurement protocol in different days/weeks. The system shows a relative reproducibility better than $\pm 5.10^{-4}$, being in the same order of magnitude as compared to measurements performed with Hall sensor in the magnetic laboratory. This makes it suitable to monitor preliminary de-magnetization effects due to possible radiation damage. To maintain such measurement precision levels, it is important to consider possible temperature effects on the NdFeB magnetic properties at tunnel conditions, in which temperature differences of 0.1 °C will result in 1.10^{-4} change in magnetization. Consequently we compute the undulator temperature during the flux coil measuremets and make appropriate corrections.

Magnetic measurements in selected undulators have been performed between Dec.-2018 and July-2019. Figure 7 compares two distinct measurements on the SASE1-DU and SASE3-DU. These diagnostic undulators have absorbed 20 and 50 Gy, respectively, during the operation time between the measurements. The DUs have a total of 4 magnetic periods and the same permanent magnet grade used in the 5-m segments. The temperature in the tunnel was monitored during the measurements and show agreement in the order of 0.1 °C.

The magnetic relative change in the SASE1-DU after absorbing 20 Gy has shown virtually no change in magnetic flux based in the measurement setup accuracy. In contrast, after absorbing 50 Gy, the SASE3-DU has shown a slightly change in the order of 5.10^{-4} on the measured flux of poles #3 and #4 . These results obtained with the flux coil in the SASE3-DU have a similar behaviour as previously reported [9] where Hall sensor measurements performed in the magnetic laboratory showed higher de-magnetization effects in poles #3 and #4 and permitted to estimate an initial limit of 55 Gy for relative magnetic field changes of 4.10^{-4}.

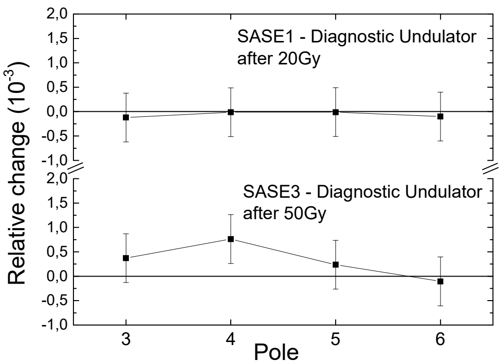

Figure 7: The flux coil is used to perform magnetic measurements on different poles loacted along the 5-m undulator.

The initial results obtained with the flux coil method reveal the potential of this technique. We have performed measurements on several 5-m long segments. These segments have absorbed doses lower than 20 Gy since the first reference measurements were taken and no relative change in flux have been found for these dose levels. Further developments in data acquisition, signal-to-noise ratio and absolute calibration are ongoing.

CONCLUSION

Since the start of the early user experiments we have measured the total absorbed doses in the undulator segments. The absorbed radiation doses during user experiments are proportional to the transmitted charge. The EuXFEL has transmitted more than 2.5 C in SASE1 and SASE3 in the first two years of operation and the ramping up of beam operational parameters towards the facility design may increase the transmitted charge rate by a factor higher than 10. In addition, operating the undulator systems at lower photon energies will increase the dose rate. Currently dose per charge rates of up to 5-17 Gy/C (at 9.3 keV) and 21-32 Gy/C (at 6 keV) are seen in 5-m segments. The development of in-situ magnetic measurements will permit faster measurements of the magnetic properties of the undulator segments and enable to accurately determine damage thresholds for undulator segments located at any position of a SASE system. De-magnetization effects in the order of 5.10^{-4} were measured in the SASE1-DU after absorbing 50 Gy.

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