STATUS OF THE RADIATION DAMAGE ON THE EUROPEAN XFEL UNDULATOR SYSTEMS

F. Wolff-Fabris†, J. Pflüger, European XFEL GmbH, 22869 Schenefeld, Germany
F. Schmidt-Föhre, Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany
F. Hellberg, Fysikum - Stockholm University, 114 19 Stockholm, Sweden

Abstract

The European XFEL GmbH is a new X-ray FEL user facility and started lasing in 2017. Three movable gap SASE Undulator Systems based on hybrid NdFeB permanent magnet technology were built. Radiation damage due to machine operation affects the magnetic properties of the segments and the quality of the SASE process. Dosimeters monitor the absorbed doses in every undulator segment and each SASE system is equipped with a diagnostic undulator (DU). We report on the profile of the absorbed doses seen in the first year of the Undulator Systems operation. Magnetic field degradation higher than 3.5% in the DU is found and associated to absorbed doses up to 4.4 kGy. An initial limit of 55 Gy for the 5-m undulator segments is recommended based on the precise K-parameter determination for beam operation.

INTRODUCTION AND METHODS

The European XFEL (XFEL.EU) uses a superconducting accelerator to operate at energies up to 17.5 GeV with a repetition rate up to 27000 bunches per second and at 1nC [1]. Its accelerator has the highest duty cycle currently in operation worldwide. Three movable gap SASE Undulator Systems produce FEL radiation with tunable wavelength from 0.05 to 5.2 nm and pulse lengths of less than 100 fs [2]. SASE1 achieved the first lasing in May 2017 and is currently in user operation. SASE3 started lasing in February 2018 and SASE2 started commissioning in March 2018. The facility has successfully reached lasing at 14 GeV with 10-3000 bunches per second and at 0.25-0.5 nC [3]. Typical SASE1 photon energy is 9.2-9.3 keV with 1 mJ intensity.

A total of 91 5-meter long undulator segments based on hybrid NdFeB (VACODYM 776AP) permanent magnets were tuned respecting tight specifications in order to optimize the SASE effect (table 1). The de-magnetization of the permanent magnets has been observed in other facilities [4-10] as an effect caused by radiation damage. However, the mechanisms behind the magnetic degradation are not yet completely understood or controlled and studies have been proposed [11-13] or are subject for current discussions in the accelerator community.

The radiation damage on the XFEL.EU Undulator Systems was expected and dedicated machine protection systems were designed [14,15]. Among them, we have operated an array of dosimeters [16] based on on-line readable Radfets and offline TLD-800 dosimeters. The Radfets permit to monitor the total absorbed doses and beam losses on the upstream side of each undulator segment since first day of beam commissioning. Furthermore, each SASE Undulator System is equipped at its upstream side with a so-called diagnostic undulator (DU). The DU contains the same hybrid NdFeB structure as the 5-meter segments. It has four magnetic periods (table 1) and 12 mm fixed gap. With a total length of about 300 mm and weight of 47 Kg, the DU can be mounted or dismounted in an hour making it suitable for frequent remeasurements of the magnetic properties during maintenance days or weeks.

† f.wolff-fabris@xfel.eu

Table 1: XFEL.EU Magnetic Specifications

5-m Undulators	SASE1 & 2	SASE3
# of Segments	35	21
Max. K-parameter @10mm	≥ 3.9	≥ 8.0
End kicks By and Bz	≤ |0.15T.mm|	
RMS Phase jitter	$\leq 8^{\circ}$	
Diagnostic Undulators		
Period length	40 mm	
Peak Field	0.916 T	
K-parameter	3.28	
Number of poles	8	

In this manuscript we report on the characteristics of the absorbed doses at SASE1 and SASE3 and on the measurable de-magnetization effects observed on the diagnostic undulators and on one 5-m segment during the first year of beam commissioning/operation.

ABSORBED DOSES CHARACTERISTICS

At the XFEL.EU facility, the SASE3 tunnel is located downstream of the SASE1 tunnel. The Radfet doses in both systems are therefore monitored since the start of SASE1 commissioning once the electron beam is necessarily travelling through both SASE systems before being dumped.

Two types of dose exposure have been observed. The so-called "singular events" are defined by a steep rise of the integrated doses during a short time interval, as shown in Fig. 1A for the upper Radfets installed at the undulators in cell#3 and cell#4 in SASE1. These events are mostly seen due to electron beam steering, change of beam energy or correcting the quadrupoles and/or air coils parameters. Usually these singular events are observed simultaneously on several subsequent undulator segments and the total increased doses at each segment reduce towards the downstream direction, as demonstrated in Fig. 1A. Singular events can be mitigated by machine protection counter-measures such as opening undulator gaps during the first beam passage.

The second type for the increase of absorbed doses consists in a slow and steady rise as a function of time and Fig. 1B exemplifies this case for the 5-m segment located at cell#27 in SASE1. This behaviour is particularly seen during stable beam conditions or while continuously lasing in the course of user operation. A clear linear increase with time and number of bunches is seen.

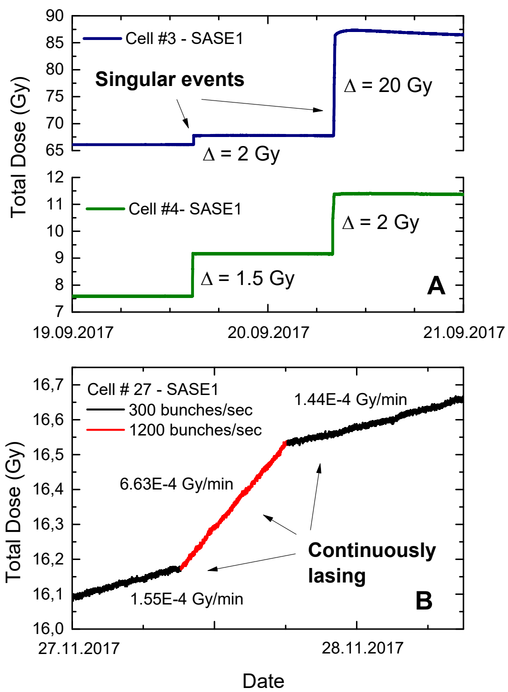

Figure 1: Absorbed dose increases for “singular events” (A) and for continuous lasing (B) at operating modes with 300 or 1200 bunches per second and 0.5 nC.

We have analysed the SASE1 dose increase during stable beam operation with aid of toroids which monitor the total charge which is transmitted through each SASE System. Figure 2 represents at each SASE1 undulator segment the ratio between the dose rates and charge rates for selected time intervals with operation modes from 300 to 5000 bunches per second. During these procedures the segments in cells#3-31 were lasing at 12-13 mm gap while segments in cells#32-37 were maintained opened to 220 mm gap. The results clearly show a tendency of higher absorbed doses at the second half of SASE1 which are independent of the operation mode. The dose increase at each individual segment is found to be approximately proportional to the transmitted charge through SASE1.

Higher absorbed doses may occur for higher repetition modes or higher transmitted charge causing unsafe operation for the 5-m segments. The reasons for the higher dose rates towards downstream direction need to be addressed and studies are presently ongoing. Relations to mechanical misalignments on the segments, intersections components and vacuum chambers were excluded by performing laser tracking re-alignment on maintenance periods and frequent orbit corrections via Beam Based Alignment. The observed tendency of higher radiation doses along the SASE saturation process can be originated by beam losses due to Halo and/or x-ray generation. The depiction of the lower (x-rays) and harmful higher (electrons) energies radiation components to the wideband spectrum of measurable absorbed doses shall be accessed by systematically shielding Radfets dosimeters and/or measuring the radiation spectrum using neutrons and gamma detectors. Effects due to electron beam, such as, Halo particle showers and scattering of electrons by residual gas in vacuum chamber, as well as effects due to high harmonic generations should be calculated via simulations.

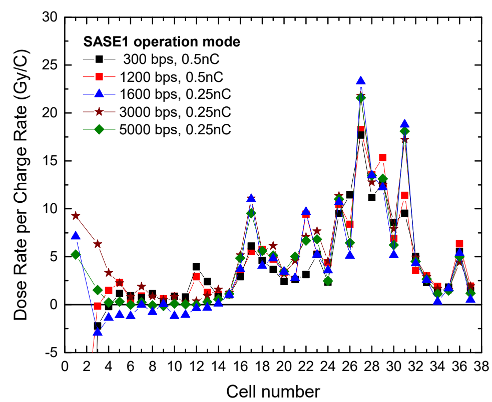

Figure 2: SASE1 dose rate per charge rate during selected operating modes at different repetition rates. Cell#1 corresponds to the DU location.

DE-MAGNETIZATION EFFECTS

Figure 3A exemplifies the relative magnetic field degradation of all poles on the SASE3 DU after wideband absorbed doses up to 4.4 kGy at the upper girder. Pole number 1 corresponds to the upstream side. The first and second poles seem to have lower de-magnetization effects. Poles #3 to #6 are the most de-magnetized with pole#3 and pole#4 presenting magnetic reduction higher than 3.5%. The last two poles show comparatively no magnetic field degradation indicating a shielding effect to the radiation by the previous poles. We assume hits due to scattered high energy electrons cause this magnetic degradation. Figure 3B compiles the de-magnetization seen in poles #3 to #6 as function of the absorbed doses for the re-measurements conducted in the first year of operation on SASE1 and SASE3 Diagnostic Undulators. A linear magnetic degradation as function of absorbed dose seems to occur. This permits to extrapolate an initial wideband dose limit of 55 Gy on the 5-m undulator segments for an approximated change on magnetic fields of $\Delta B/_B = 4.10^{-4}$ based on precise Hall sensor measurements for K-parameter determination. The absorbed dose dependence on the energy-resolved spectrum of Radfet readings and the cross calibration between DU and 5-m segments will permit to further improve the accuracy of this initial wideband limit for future operation.

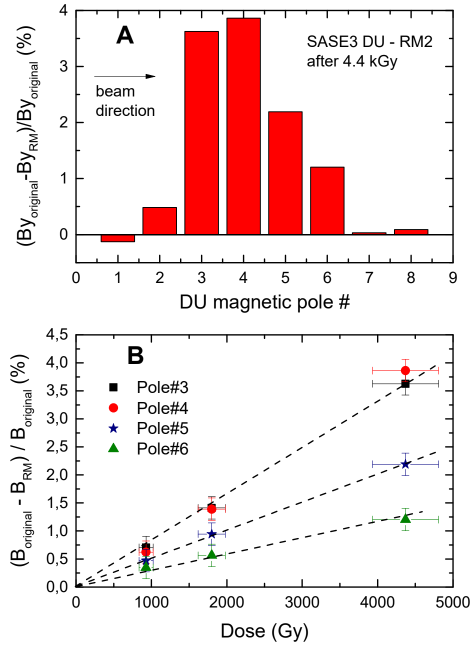

Figure 3: Magnetic degradation on the (A) SASE3 DU and (B) for poles #3 to #6 as function of absorbed doses.

The 5-m segment located at cell#3 in SASE1 was re-measured after 230 Gy wideband absorbed dose. Magnetic field integrals measurements performed with moving wire technique [17] were compared to the ones prior to operation. The horizontal field integrals remained unchanged while the vertical field integrals showed a reduction of up to 0.037 T.mm. This gap dependent change is located only at the upstream/entrance side, as seen in Fig. 4. New factors for the air coil corrector compensation table to the end kicks are calculated to guarantee the beam trajectory straightness. A magnetic field degradation of up to $\Delta B/_{B} = 5.10^{-4}$ for the first 4 magnetic poles at the entrance side of the segment is measured with Hall sensor. This degradation rate at 230 Gy is smaller as compared to the DU for the scatter of the slopes shown in Fig. 3B. It may indicate individual de-magnetization rates per dose to the segments accordingly to differences on the energy spectrum of the incident radiations.

Figure 5 shows current absorbed doses in the upper girder Radfets for SASE1 and SASE3. The total transmitted charge is about 0.5 C with losses of 1.2 and 0.7 mC at SASE1 and SASE3, respectively. Several segments have doses higher than the initial 55 Gy wideband limit. The combination of optimized beam operation with more accurate damage limits will possibly result in a reduction of radiation load on the 5-m segments. Nevertheless, a plan is underway to build spare segments to be used on frequent exchange of undulators during re-measurement or refurbishment campaigns in order to guarantee the XFEL.EU operation ability as a fall-back solution in case of inadvertent singular radiation overloads.

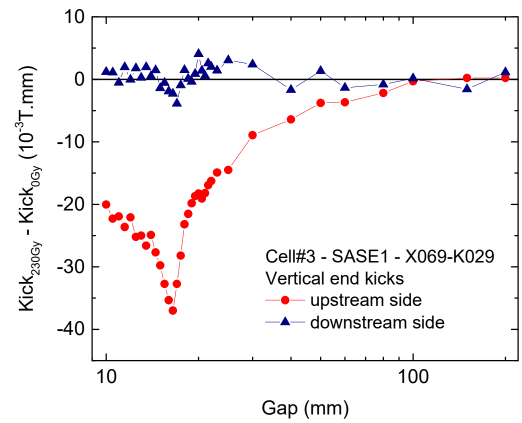

Figure 4: Measurable magnetic field integral changes are seen in Cell#3-SASE1 segment after exposed to about 230 Gy.

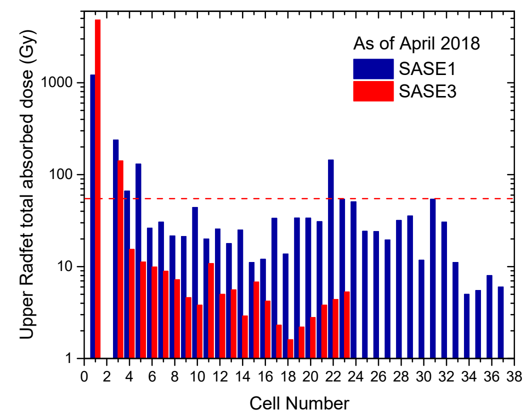

Figure 5: Total absorbed doses in logarithmic scale for SASE1 and SASE3 after the first year of operation.

CONCLUSION

The advent of superconducting accelerators in FEL facilities permits electron beams with higher repetition rate and transmitted charge excursing through Undulators. Radiation damage may pose limitations to insertion devices based on permanent magnet technologies. On the first year of operation we have seen higher absorbed doses in undulators located at the downstream end of SASE1 as compared to segments at the upstream side when lasing at stable conditions. The doses are proportional to the transmitted charge. De-magnetizations higher than 3.5% are observed in the diagnostic undulators and indication of magnetic degradation at the upstream side of a 5-m segment is measured. Different precautions are developed and foreseen to significantly reduce damaging radiation and prevent malfunction of the Undulator Systems.

REFERENCES

[1] *M. Altarelli et al.*, Technical Design Report DESY 2006-097, July 2007.

[2] *E. Schneidmiller et al.*, Technical Design Report DESY 2011-152, Sep. 2011.

[3] *M. Scholz et al.*, FEL performance achieved at the European XFEL, presented at IPAC-2018, Vancouver, Canada, April-May 2018, paper MOZGBD2, unpublished.

[4] *J. Pflüger et al,* "Search for possible radiation damage on NdFeB permanent magnet structure after two years of operation". *Rev. Scientific Instr*. 66, 1946 (1995).

[5] *J. Skupin et al,* "Undulator demagnetization due to radiation losses at FLASH". *Proceedings of EPAC2008*, WEPC129.

[6] *H.-D. Nuhn et al.,* "Undulator radiation damage experience at LCLS" in *Proc. 36th Int. Free Electron Laser Conf. (FEL'14)*, Basel, Switzerland, Aug. 2014, paper MOP046.

[7] *P. Vagin et al.,* "Radiation damage of undulators at PetraIII", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, paper WEPRO035.

[8] *T. Bizen et al,* Radiation-induced magnetization reversal causing a large flux loss in undulator permanent magnets. Scientific Reports 6:37937 (2016).

[9] *M. Santana Leitner et al.,* Life expectancy studies for LCLS-II permanent magnet undulators. Proceedings of IPAC2017, TUPAB134.

[10] *C. Baribeau et al.,* Evaluation of immutability against radiation induced demagnetization for a hybrid wiggler with NdFeB magnets at the Canadian light source. Proceedings of IPAC2016, THPOW036.

[11] *A. Samin et al,* An analysis of radiation effects on NdFeB permanent magnets. Nuclear Instr. and Meth. In Phys. Res. B 342, 200 (2015).

[12] *T. Bizen et al,* High-energy electron irradiation of NdFeB permanent magnets: dependence of radiation damage on the electron energy. *Nuclear Instr. and Meth. In Phys. Res*. A 574, 401 (2017).

[13] *A. Temnykh et al.,* "beam losses due to intra-beam and residual gas scattering for Cornell´s energy recovery linac", in *EPAC'08*, Genoa, Italy, Jun. 2008, paper MOPC064.

[14] *D. Nölle,* "Electron beam diagnostics for the European XFEL", in *DIPAC'09*, Basel, Switzerland, May 2009, paper TUOA04.

[15] *F. Hellberg et al.*, Neutron radiation damage study and cost estimate of a hybrid magnet for the EXFEL. Stockholm University Technical Report MSL-08-1, Sep. 2008.

[16] *F. Schmidt-Föhre et al.*, "Commissioning of the new online-radiation-monitoring-system at the new European XFEL injector with first tests of the high-sensitivity-mode for ultra-tunnel rack surveillance", presented at the *4th Int. Beam Instrumentation Conf. (IBIC'15)*, Melbourne, Australia, Sep. 2015, paper WECLA02.

[17] *F. Wolff-Fabris et al.*, High accuracy measurements of magnetic field integrals for the European XFEL undulator systems. *Nuclear Instr. and Met.* A, 833 (2016) 54-60, July 2016.