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INFLUENCE OF RADIATION EXPOSURE ON THE FEL PERFORMANCE AT FLASH

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Abstract

FLASH has been operated as user facility for about 14 years. In this time, the total charge accelerated and transported through the FLASH1 undulator is around 35 Coulomb. Based on detailed monitoring of the radiation loss and reference measurements on degradation of the magnetic field of the undulator, we have performed simulations to study the change in FEL performance and compare the simulations with the changes we observe during operation.

INTRODUCTION

FLASH is the first FEL user facility in the XUV and has been running since 2005 [1]. Continuous upgrades have increased the beam energy from initially about 700 MeV to the present 1.25 GeV, resulting in a wavelength from 13 nm in 2005 to the present 4.2 nm. It is also the only XUV-FEL based on superconducting technology, which produces up to 5000 bunches per second as compared to the typical 50 to 100 for normal conducting machines [2]. And finally, since 4 years FLASH runs two FELs simultaneously from the same accelerator, thus increasing the available beamtime for users [3].

In the foreseeable future, several new facilities will be built with the same superconducting technology, but in this case running in CW mode [4, 5]. Where beam loss in the undulator plays only a minor role for most facilities, for a facility like FLASH or the European XFEL [6], this has resulted in more elaborate systems to detect beam loss and in interlock and machine safety systems that switch off the beam as fast as possible to avoid deterioration of the undulator magnetic field due to radiation damage.

Even after running for 14 years, the accumulated charge produced by FLASH is around 35 C. Had FLASH been running continuously at the highest repetition rate at around 0.3 nC bunch charge, the accumulated charge would have been around 660 C. However, since experiments want different properties and bunch spacing, the machine has been occasionally running 100 kHz or even single bunch and regularly at much lower charge to produce ultra-short pulses with single spikes [7]. Machines running in CW mode at 1 MHz with a charge of 100 pC will produce a similar charge within weeks.

In order to be prepared for this increase in charge and possible damage to the undulators, we have studied the effect of radiation loss on the undulator over the past years [8] and have also gained experience in the magnetic behaviour of radiation-damaged undulators [9, 10]. For this purpose, a one-period, sacrificial undulator is installed in front of the FLASH main undulators. This device is periodically removed from the beamline and the field re-measured on a magnetic bench. At the same time, both in this undulator and in the main undulator, TLDs are regularly exchanged and the accumulated dose is evaluated. This way, a correlation between integrated dose and magnetic field is determined.

In this paper, we will show the dose which has been accumulated over the years in FLASH1.

ACCUMULATED DOSE IN THE FLASH1 UNDULATOR

A dose is accumulated inside the undulator because of Continuous loss of dark current, continuous loss of beam or because of single events due to operation errors.

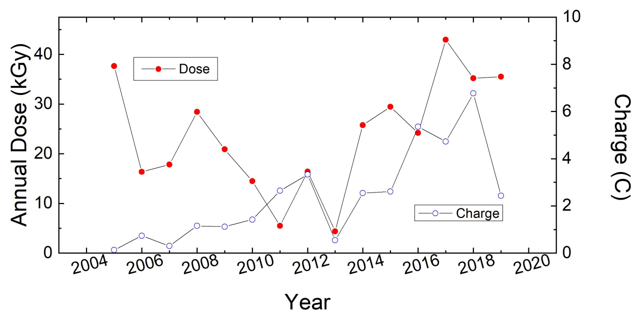

Figure 1: Accumulated annual dose in the sacrificial undulator at two locations since the commissioning of FLASH in 2005 (left scale). Also shown is the charge transmitted through the undulator during the same period (right scale).

As was mentioned, in front of the main undulator a one-period sacrificial undulator is installed. This undulator at FLASH1 has accumulated over the years the largest dose, namely around 350 kGy. As can be seen in Fig. 1, the initial losses are, normalized to the charge, much higher during the first few years. In recent years, the dose is similar to the one in the early years. The transmitted charge has grown by at least an order of magnitude because more users request longer bunch trains. Nevertheless, the increased loss in 2017 can also be observed in the main undulator, as we will see. For 2019, the charge has gone down significantly, but the losses have not. This has not been understood yet.

Losses during the first year of operation (2005) have been exceptionally high. As can be seen in Fig. 2 (top), the loss during the first year has been about half of the total loss, assuming we exclude specific events, that will be discussed below. It becomes even more clear when the data are normalized to the charge, shown in Fig. 2 (bottom). Normalized to the charge the loss in 2005 is up to an order of magnitude more than all of the following years.

Losses during 2006 occurred at the end of the undulator, as can be seen in Fig. 3. The reason was that the beam

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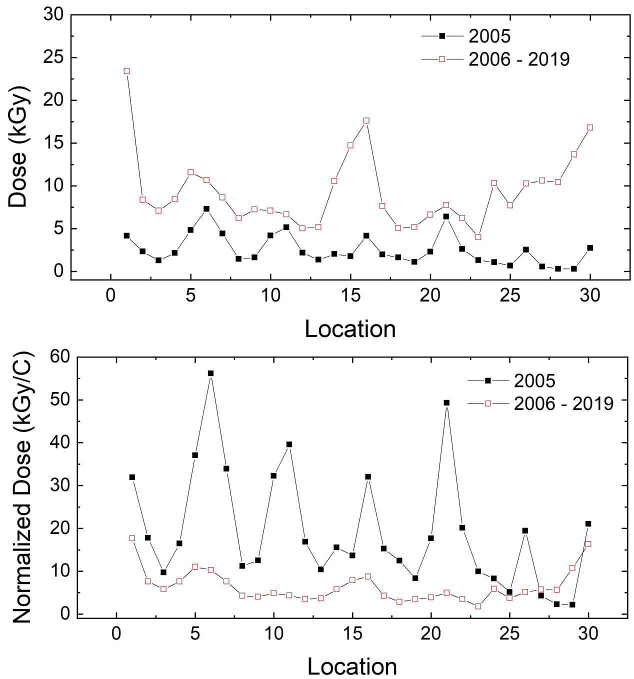

Figure 2: Losses in 2005 (solid black dots) and all following years combined (open red dots) as measured by the TLDs (top) and normalized to produced charge (bottom).

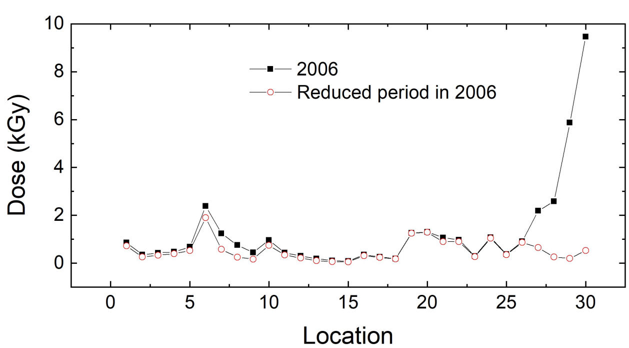

Figure 3: The loss along the undulator in 2006 and during the same period, but excluding 7 weeks of operation from April 11 to June 6.

size was very large at the end of the undulator due to a shortcut in one of the quadrupoles. Since it took several weeks before this was discovered, the accumulated dose was already around 8 kGy. Excluding this 7-week period, the loss along the undulator is more constant (open red dots in Fig. 3).

Fig. 4 shows the losses in 2017 after changing the electronics of the loss system and before the machine protection system thresholds were adjusted. Since also the injector optics was changed, there was for several months a mismatch of the optics, which caused losses in the middle of the undulator. This was only reduced after the thresholds of the machine protection system were changed and the optics was adjusted, as can be seen when the startup period is taken out of the accumulated dose (open red dots compared to

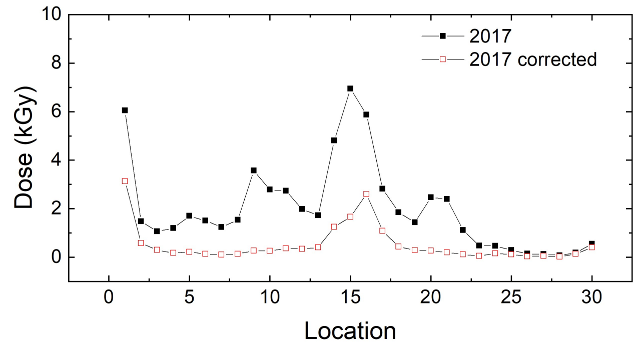

Figure 4: Losses in 2017 (solid black dots) and without startup from July 5 to September 19 (open red dots).

solid black dots in Fig. 4). Since this was only done after a period with long pulse trains, already several kGy were accumulated.

INFLUENCE OF UNDULATOR DAMAGE ON SASE

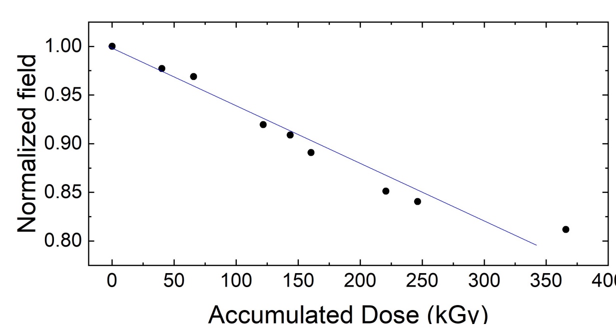

Figure 5: Field degradation due to radiation damage measured by determining at regular time intervals the field of the sacrificial undulator placed in front of the main FLASH1 undulator. Initial absolute field of central pole in 2004 is 0.504T, demagnetization of 1% per 16kGy.

In Fig. 5, the relation between accumulated dose and the reduction of magnetic field is shown. This information was obtained by taking out in regular intervals a one-period sacrificial undulator and measuring the magnetic field on a magnetic bench. The demagnetization rate of 1%/16kGy estimated for this diagnostic undulator can be applied to the accumulated dose in the main FLASH1 undulator. Since the dose is only measured at discrete positions along the undulator, we performed simulations, assuming steps in the magnetic field amplitude between measured TLD-positions or a linear interpolation. The resulting field that is used for the simulation is shown in Fig. 6. As can be seen, the field shows a reduction in amplitude at the beginning, the end and in the middle.

The FEL performance was checked for different field configurations by simulations with Genesis [11]. As can be seen in Fig. 7, the power is around 4 orders of magnitude smaller in case of step errors and almost without power loss in case

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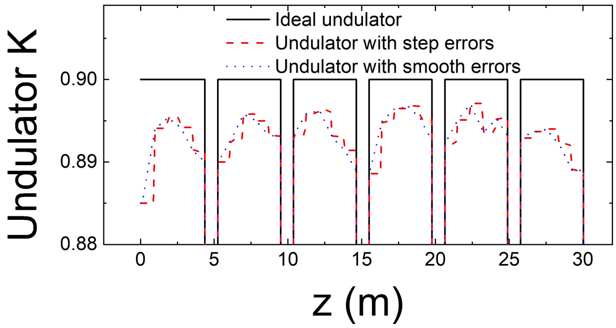

Figure 6: Field along the FLASH1 undulator without errors (black), modeled as a step fuction (red) and with linear interpolation (blue).

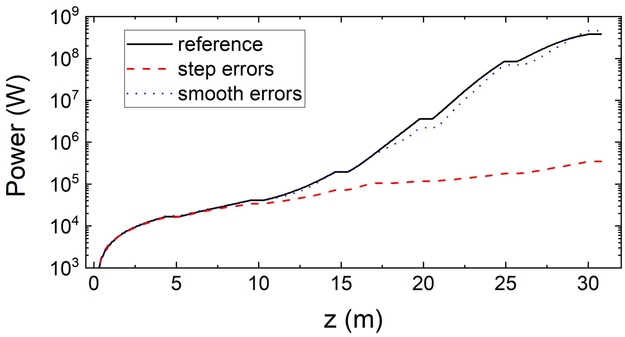

Figure 7: Power gowth along the undulator for an error-free undulator and with the errors included as step (red) and smooth interpolation (blue).

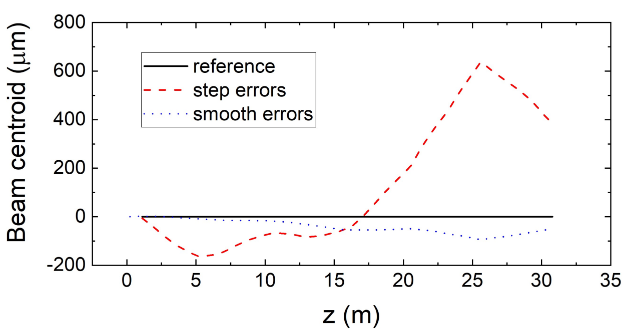

Figure 8: Horizontal orbit along the undulator corresponding to the fields in Fig. 6.

of interpolated errors compared to the case without errors. Although the reduction in pulse energy can be caused by loss of resonance condition and reduced overlap, it is clear from these results that for the assumed fields the dominant effect is a reduction in overlap, as shown in Fig. 8. In case of Genesis, the end fields are not treated correctly. Therefore, it is unclear if the actual orbit is as is described here.

To confirm that the main effect is caused by reduced overlap, we have corrected the orbit with field step-errors. Because the performance with interpolated errors shows very little reduction of the power compared to the ideal case, this is no further optimized. The result of the ideal spectrum is compared with the case of field errors before and after

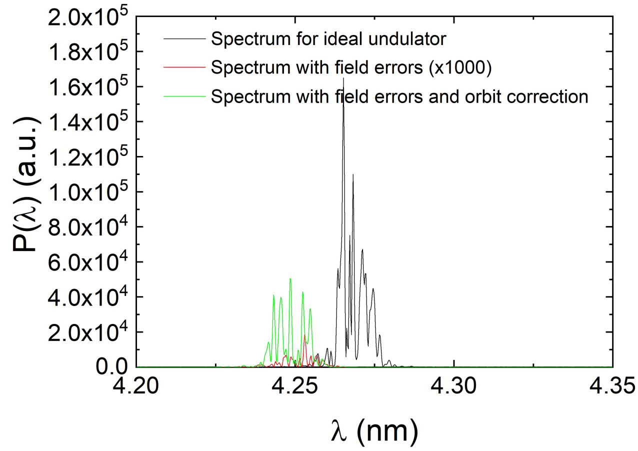

Figure 9: SASE spectrum for an ideal undulator, with step errors, and with step errors and orbit correction.

correction in Fig. 9. Without orbit correction, the spectrum multiplied by 1000 in order to make it visible. As can be seen, after orbit correction the reduction in intensity is only minor. Since the orbit correction is not perfect, even this can still be improved upon.

SUMMARY AND OUTLOOK

As can be seen, most of the beam losses at FLASH1 are produced in single events. With the present TLD readout intervals it is difficult to prove that most of the remaining losses are caused during setup changes for different user experiments. Because FLASH1 has a fixed gap undulator, initial losses cannot be avoided. At FLASH2, where the undulators are closed only after the losses have been reduced, the accumulated dose is much improve. The changed magnetic field has an effect in resonance condition and orbit of the electron beam. For the field profile simulated here, the effect is mainly caused by an orbit deviation, even though the field error exceeds the ρ-parameter.

Extrapolation of these results by two orders of magnitude for FELs running in CW-mode is probably not realistic. In addition, the machines that are planned at the moment or under construction, will run at much higher energies, which probably cause different problems of detecting and avoiding losses. However, based on the results at FLASH, it seems that the undulator lifetime is still at least several years.

ACKNOWLEDGEMENTS

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