UNDULATOR DEMAGNETIZATION DUE TO RADIATION LOSSES AT FLASH

J. Skupin*, Y. Li, J. Pflüger, B. Faatz, T. Vielitz
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Abstract

The free-electron laser FLASH (Free-electron-LASer in Hamburg) was commissioned at DESY in 2004. It is a high-gain, single pass FEL which operates in the VUV and soft X-ray wavelength regime. To monitor the demagnetization of the undulator structures due to radiation losses a small test undulator was installed. This dosimetric undulator consists of a short piece of magnetic undulator structure with only 3 pole pairs and corresponding magnets. It is positioned in front of the first undulator segment where a high dose rate is to be expected.

The accumulated dose of dosimetric undulator and SASE undulator is derived by weekly measurements with thermoluminescence dosimeters (TLDs). The dosimetric undulator is dismounted and magnetically measured regularly. Based on these measurements a (maximum) relative demagnetization rate of about $5 \cdot 10^{-4}$/kGy was derived.

In view of this result magnetic measurements on one of the undulator segments from TTF1 (the predecessor of FLASH) were reviewed. They show a relative demagnetization rate of about $2 \cdot 10^{-4}$/kGy which is lower but still in the same range as the result from FLASH.

FEL simulations to analyze the influence of demagnetization on the SASE process and a lifetime estimate are presented.

INTRODUCTION

Radiation exposure due to electron irradiation leads to demagnetization of permanent magnet material in narrow gap undulators as used in FELs. This might lead to a significant degradation of the SASE process. Therefore, at FLASH radiation doses are measured on a weekly basis with thermoluminescence dosimeters (TLDs) at 5 positions for each of the 6 undulator segments and 2 positions for the dosimetric undulator. By magnetically remeasuring the dosimetric undulator on a regular basis the demagnetization rate of the permanent magnet material is derived. In conjunction with dose measurements the development of field errors in all undulator segments and their impact on the SASE process is simulated. From an extrapolation of the accumulated doses the expected loss of radiation power is calculated and a lifetime estimate is given.

* jochen.skupin@desy.de

DOSIMETRIC UNDULATOR

The dosimetric undulator was installed as a device to investigate radiation damage to magnetic structures. It consists of a short piece of the standard SASE undulator structure with only three poles, two normal magnets and two end-magnets on either side of the electron beam (see schematic drawing in Fig. 1). Its position in the FLASH layout is near the entrance of the first undulator segment where higher radiation doses are to be expected than in the following undulator segments.

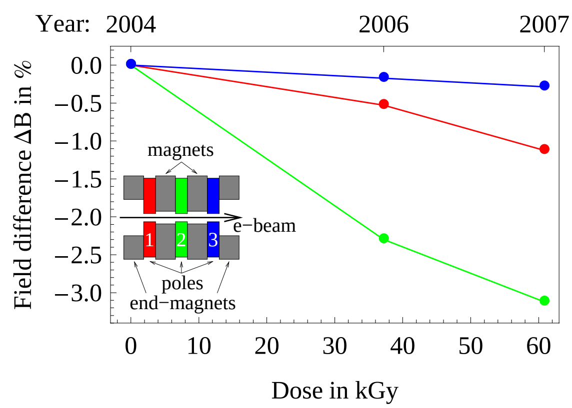

Figure 1: Relative change of peak fields versus accumulated dose of dosimetric undulator (bottom left: schematic structure of dosimetric undulator).

The magnetic field of the dosimetric undulator was measured before its first installation in 2004. In addition, it was dismounted and remeasured in 2006 and 2007. An overview of the measurements is given in Table 1. The dependence between measured dose and relative change of absolute peak fields is shown in Fig. 1. A maximum relative demagnetization rate of about $5 \cdot 10^{-4}$/kGy is found for the mid-pole. This value is taken as a worst-case scenario for the following analysis.

Table 1: Measurement date, accumulated dose and relative peak field change of dosimetric undulator

Date	Dose in kGy	Field change in % on Pole 1	Pole 2	Pole 3
2004-08-13	0	0.0	0.0	0.0
2006-03-21	37	-0.5	-2.3	-0.2
2007-09-29	61	-1.1	-3.1	-0.3

TTF1 REVIEWED

For the TESLA Test Facility Phase-1 (TTF1, the predecessor of FLASH) a complete undulator segment was magnetically remeasured after 3 years of operation. Although a first analysis did not reveal demagnetization [1], in consideration of the FLASH results the TTF1 data were reviewed.

The upper curve in Fig. 2 shows the accumulated dose of the segment and the blue dots in the lower part give the difference between peak field values measured after deinstallation in May 2002 and those taken before installation in 1999. Assuming a linear dependence between accumulated dose and demagnetization two major contributions can be identified, whose sum (blue curve) is a good approximation for the measured field change: 1.) a parabolic field difference due to temperature induced girder deformation (red curve), 2.) a demagnetization proportional to the measured dose (green curve).

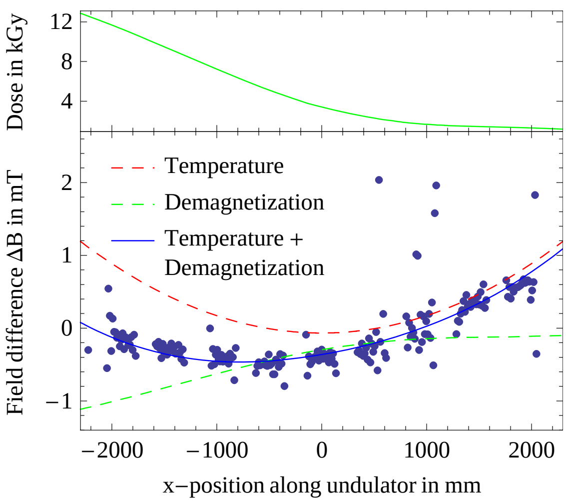

Figure 2: Measured dose (upper plot) and change of peak fields (lower plot) of TTF1 undulator segment.

From the latter one a relative demagnetization rate of about $2 \cdot 10^{-4}$/kGy can be derived. This value is a bit lower than the FLASH result but still in the same range. Possible reasons are changes in energy and geometry of the electron beam from TTF1 to FLASH.

UNDULATOR DEMAGNETIZATION

For FLASH the accumulated dose and beam size along the undulator are shown in Fig. 3. The shape of the loss curve reflects the beam size. Its variation is caused by the focusing structure, which consists of quadrupole doublets in the undulator intersections. Therefore, the variation in beam size is large with its maximum at the quadrupole positions. This is reflected by the larger losses at these positions.

Based on the derived demagnetization rate of the permanent magnet material and the accumulated doses along the undulator (black curve in Fig. 3) the demagnetization along the undulator can be estimated. Assuming a linear

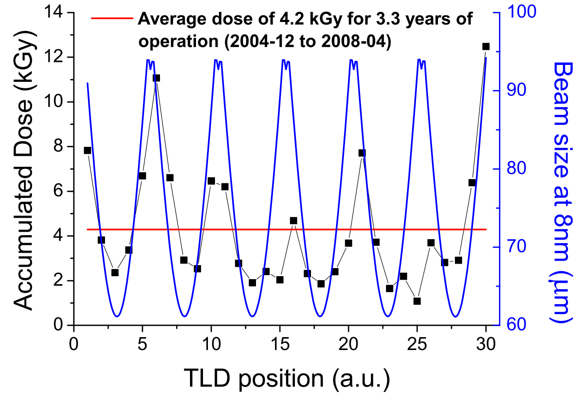

Figure 3: Accumulated dose along the undulator (black curve) and RMS beam size at 8 nm (blue curve).

correspondence between accumulated dose and demagnetization results in a relative change $\Delta K/K$ of the K value along the undulator as shown in Fig. 4.

SIMULATED POWER DEGRADATION

The impact of undulator field errors on the FEL performance has been investigated in various publications [2, 3, 4]. The special case of periodic field errors is discussed in [5]. There different undulator K variations have been simulated in order to estimate tolerances for gap errors of variable gap undulators and girder deformation, and it has been shown that gain degradation can be estimated based on analytical results. For periodic errors that study reveals that only the RMS phase shake is important for the power reduction, not the actual shape of the error distribution.

In order to perform systematic studies and to apply these theoretical results, the variation of K is approximated by the periodic function shown as red curve in Fig. 4. As given in [5] the phase shake $\sigma_{\Delta\phi}$ is proportional to the error am-

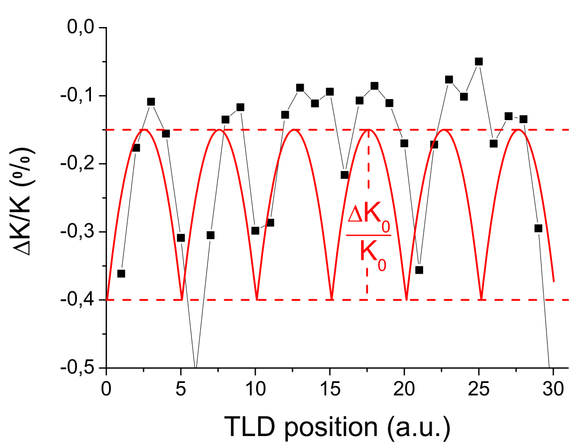

Figure 4: The relative change $\Delta K/K$ of the undulator K value (black curve) and the approximation used for the simulations (red curve).

plitude $\Delta K_0/K_0$

$$\sigma_{\Delta\phi} = A\frac{2\pi K_0^2}{\lambda_u(1+K_0^2)}\frac{\Delta K_0}{K_0}\lambda_\delta \approx 41\frac{\Delta K_0}{K_0},$$

with shape-dependent parameter $A = \sqrt{8/945}$ (derived from the parabolic profile of the error shape), undulator segment length $\lambda_\delta = 4.5\,\mathrm{m}$, undulator period $\lambda_u = 27.3\,\mathrm{mm}$, and $K_0 = 0.87$. Fig. 5 shows the dependence of normalized power on the error amplitude $\Delta K_0/K_0$ for different wavelengths.

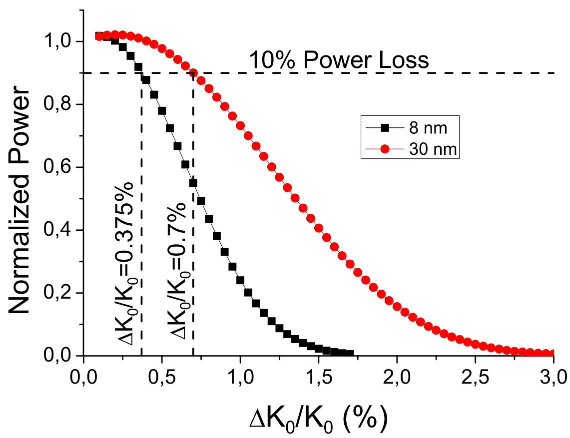

Figure 5: Normalized power vs. error amplitude $\Delta K_0/K_0$ for 8 and 30 nm.

LIFETIME ESTIMATE

Fig. 6 shows the evolution of the averaged accumulated dose of the undulator. It should be noted, that the dose has been accumulated mainly at the beginning of the operation (especially at the undulator entrance) during a time when the optics was not yet well understood, and during a short period with a shortcut in one of the quadrupoles (especially at the end of the undulator) where due to lack of diagnostics a large dose could accumulate before this error was corrected. For an extrapolation of the doses a linear fit based on the complete operation time (red curve in Fig. 6) obviously overestimates the real situation. Therefore, dose extrapolations are done by a linear fit of dose measurements since mid of 2006 (green curve).

Table 2 gives the extrapolations for a loss of power of about 10% for 8 and 30 nm, respectively. This is based on a linear extrapolation of the current state of $\Delta K_0/K_0 \approx 0.25\%$ at an average dose level of 4.2 kGy.

Table 2: Lifetime estimates for 10% loss of power

Wavelength in nm	$\Delta K_0/K_0$ in %	Dose in kGy	Year	Lifetime in years
8	0.375	6.3	2015	10
30	0.700	11.8	2035	30

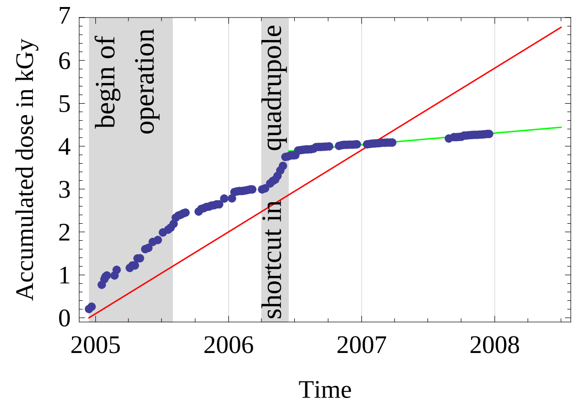

Figure 6: Averaged accumulated dose of the SASE undulator (blue dots) and linear extrapolations based on all data (red curve) and on data since mid of 2006 (green curve).

With the error amplitudes $\Delta K_0/K_0$ for a loss of power of about 10% as given in Fig. 5 the corresponding doses are derived from the dose extrapolation given by the green curve in Fig. 6. From these calculations a lifetime of 10 to 30 years can be estimated, depending on the desired wavelength. It has to be noted that this extrapolation is only valid when events with high dose deposition in the undulator can be circumvented in the future.

SUMMARY

The dose deposition in the FLASH undulator is monitored on a weekly basis by thermoluminescence dosimeters. By magnetically remeasuring a dosimetric device a worst case estimation of $5 \cdot 10^{-4}$/kGy for the demagnetization rate of the permanent magnet material was derived. Based on this demagnetization rate dose dependent field errors and the resulting degradation of the SASE process were simulated. By extrapolating the accumulated doses the lifetime until a 10% loss of power is reached was estimated to 10 and 30 years for radiation wavelengths of 8 and 30 nm, respectively.

REFERENCES

[1] J. Pflüger et al., "Radiation exposure and magnetic performance of the undulator system for the VUV FEL at the TESLA Test Facility Phase-1 after 3 years of operation", Nucl. Instr. Meth. A **507** (2003) 186–190

[2] L.H. Yu, S. Krinsky, R.L. Gluckstern and J.B.J. Zeijts, "Effect of wiggler errors on free-electron-laser gain", Phys. Rev. A **45** (1992) 1163–1176

[3] R.P. Walker, "Interference effects in undulator and wiggler radiation sources", Nucl. Instr. Meth. A **335** (1993) 328–337

[4] H.P. Freund and R.H. Jackson, "Self-consistent analysis of the effect of wiggler field errors in free-electron lasers", Nucl. Instr. Meth. A **331** (1993) 461–466

[5] Y. Li, B. Faatz and J. Pflüger, "Study of Undulator Tolerances for the European XFEL", TESLA-FEL report 2007-07, DESY, Hamburg