

UNDULATOR RADIATION DAMAGE EXPERIENCE AT LCLS*

H.-D. Nuhn^{#,1}, C. Field¹, S. Mao¹, Y. Levashov¹, M. Santana¹, J.N. Welch¹, Z. Wolf¹,
¹SLAC National Accelerator Laboratory, Menlo Park, CA 94025, U.S.A

Abstract

The SLAC National Accelerator Laboratory has been running the Linac Coherent Light Source (LCLS), the first x-ray Free Electron Laser since 2009. Undulator magnet damage from radiation, produced by the electron beam traveling through the 133-m long straight vacuum tube, has been and is a concern. A damage measurement experiment has been performed in 2007 in order to obtain dose versus damage calibrations. Radiation reduction and detection devices have been integrated into the LCLS undulator system. The accumulated radiation dose rate was continuously monitored and recorded. In addition, undulator segments have been routinely removed from the beamline to be checked for magnetic (50 ppm, rms) and mechanic (about 0.25 μm , rms) changes. A reduction in strength of the undulator segments is being observed, at a level, which is now clearly above the noise. Recently, potential sources for the observed integrated radiation levels have been investigated. The paper discusses the results of these investigation as well as comparison between observed damage and measured dose accumulations and discusses, briefly, strategies for the new LCLS-II upgrade, which will be operating at more than 300 times larger beam rate.

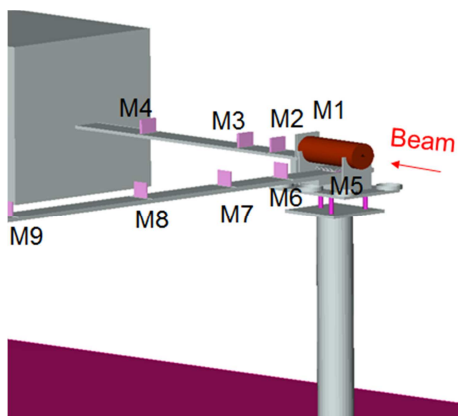


Figure 1: Layout of the SLAC End-Station A (ESA) undulator magnet block damage experiment. M1 to M9 indicate the placement of the individual magnet blocks relative to the copper cylinder. M5 is located underneath the copper cylinder.

INTRODUCTION

The Linac Coherent Light Source (LCLS) has been delivering intense ultra-short x-ray beams to international users at the SLAC National Accelerator Laboratory (SLAC) since 2009 [1]. These x-ray beams are generated

* Work was supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract DE-AC02-76SF00515.

[#] nuhn@slac.stanford.edu

with fixed, canted gap hybrid ($\text{Nd}_2\text{Fe}_{14}\text{B}$) permanent magnet undulators [2].

MAGNET DAMAGE CALIBRATION

In July 2007, a radiation damage experiment was conducted on nine LCLS-I type ($\text{Nd}_2\text{Fe}_{14}\text{B}$) permanent magnet blocks, mounted well separated from one another, behind a solid Cu cylinder, which was bombarded with a 13.6-GeV electron beam (see Figure 1). The experiment was located inside SLAC's ESA (End-Station A) enclosure. During the 12 days of irradiation the magnet blocks stayed at a temperature of $23.8^\circ\text{C} \pm 0.8^\circ\text{C}$. The estimated accumulated maximum radiation doses in each block, based on a FLUKA [3,4] model, ranged from about 1500 kGy to less than 1 kGy and the corresponding measured reduction in total magnetic moment from about 9.6% to less than 0.1%. In fact, the two magnet blocks with the lowest amount of accumulated radiation dose showed a slight increase in total magnetic moment. Linear fitting resulted in a scaling factor of 70 kGy/%. This simple scaling seems not to describe the low-dose behaviour with sufficient detail. Other radiation damage studies and experiments have been conducted in other laboratories around the world, answering a wider range of questions with more detail [5,6,7].

LCLS UNDULATOR RADIATION DOSE MEASUREMENTS

A record of the integrated radiation dose, as actually received by the LCLS undulator magnets, has been kept over the entire operational period with the help of thermoluminescent dosimeters (TLDs). The TLDs have been shielded in small Pb-casings and were mounted in front of each undulator segment with the sensitive element about 25 mm above and horizontally centered on the beam axis. The Pb-casings were added in order to filter out the low energy and non-damaging radiation background coming from synchrotron radiation during the FEL process. Each TLD is left in place for some time (originally several weeks, now several months), before it is replaced by a fresh TLD. Some of the readings are shown in Figure 2 versus the total amount of beam energy that passed through the beam pipe during the same time period. Beam energy is the integral of the product of particle energy, number of particle per bunch and bunch repetition rate. The figure shows a fairly consistent loss rate over about a 3-year period. Three different regions along the undulator line (girder numbers) can be distinguished. The higher levels in the front end (girders 1-10) come from LTU scattering events from inserted wires, screens or the tune-up stopper (TDUND). The higher levels at the back end of the undulator line (girders 17-33) come from events within the undulator vacuum chamber, especially from a

misaligned vacuum chamber in the HXRSS chicane that was in place between January and October 2012. The low level part in the center (girders 10-16) is attributed to a general loss of halo particles.

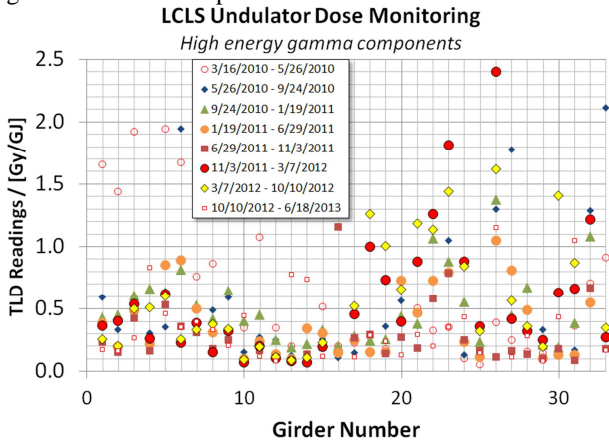


Figure 2: Radiation dose measurements by Pb-cased TLDs placed in front of each LCLS undulator segment. The readings are plotted against the beam energy passed through the undulator beam pipe during the same period. Note: 2 readings for girder 32: 4.9 Gy/GJ and 4.0 Gy/GJ for the last 2 periods, respectively, are cut off.

While TLDs are quite reliable in accumulating dose, they are not readily available for investigating the sources of radiation events. Recently, remotely readable electronic dosimeters (RADFETs) [8] have been installed together with Lucite detectors. Following a small experimental installation of RADFETs, a more extensive installation has been made in 2014, and this time the units were biased to enhance their sensitivity and further reduce their already slow rate of fade. Since readings are made every 10 minutes, it has been possible to follow the influence of beam conditions on the dose rate. Downstream of the self-seeding chicanes, it has been noticed that, when operating with higher energy electron beams (9 – 15 GeV), the dose rate is higher than typically seen with beams at 4 – 5 GeV. Upstream of the chicanes, the tendency, if anything, is reversed. The relative amplitudes of the beam losses can also be measured pulse by pulse with an array of acrylic Cherenkov counters using photomultiplier tubes, installed along the undulator. Some are distributed to intercept the off-axis radiation away from the undulator segments; others monitor the showers close to the vacuum chamber and the undulator material. A few hours of beam time have been available for an initial study of the settings of the machine's collimators with respect to their effect on these counters. Adjusting the collimators for then-current beam conditions has shown the potential for reducing the dose accumulation by factors of ~ 10 at the upstream end of the undulator, but no dose reduction was observed further downstream along the undulator. The RADFET dose rates corroborated these observations. Further work is anticipated.

LCLS UNDULATOR K MONITORING AND RECALIBRATION

The LCLS undulator segments have been designed to be easily removed and reinstalled on any of the girders without the need for special alignment. This was done by machining the individual feet blocks for each undulator such that one of the blocks' vertical surfaces and the bottom surfaces are machined to have fixed distances to the magnetic axis of the undulator segment. Segments have been removed from the tunnel and replaced with standby segments at a rate of roughly 1 segment per month since the end of commissioning.

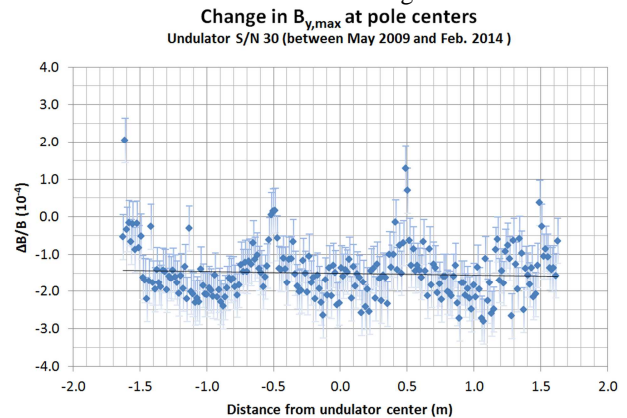


Figure 3: Differences between two Hall probe measurements (taken in 5/09 and in 2/14) of the absolute on-axis peak magnetic fields at 218 core poles (of the total 226 poles) of LCLS undulator segment SN30.

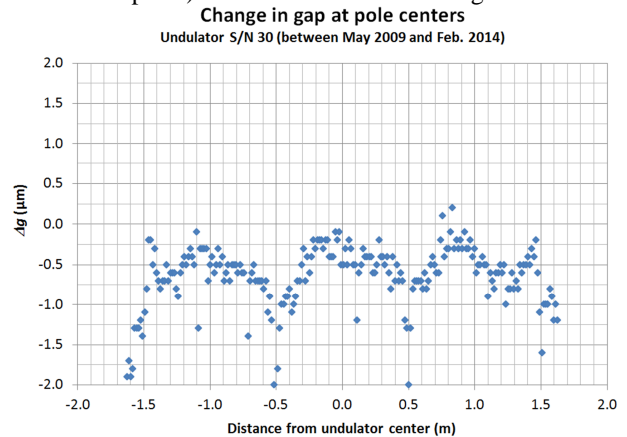


Figure 4: Differences between two CMM measurements (taken in 5/09 and in 2/14) of the gap heights at 218 core poles (of the total 226 poles) of LCLS undulator segment SN30 at the same x location relative to the eight device tooling ball sockets. At each pole, the value shown in the graph is based on an average over 8 – 10 individual measurements taken at horizontally different locations.

These segments have been re-measured in the LCLS magnet measurement facility and compared with earlier measurements for changes in $\Delta K/K$ ($\sigma=6 \times 10^{-5}$) (see example in Figure 3), phase shake and total phase ($\sigma=0.1$ degXray), field integrals ($\sigma=5$ G cm), and gap

changes ($\sigma=0.25\ \mu\text{m}$) (see example in Figure 4). The latter is done in the same x - z plane as earlier, defined by the 8 tooling ball sockets that are part of each segment, using a large coordinate measurement machine (CMM). A detailed description of the measurement technique is given in a different paper [9].

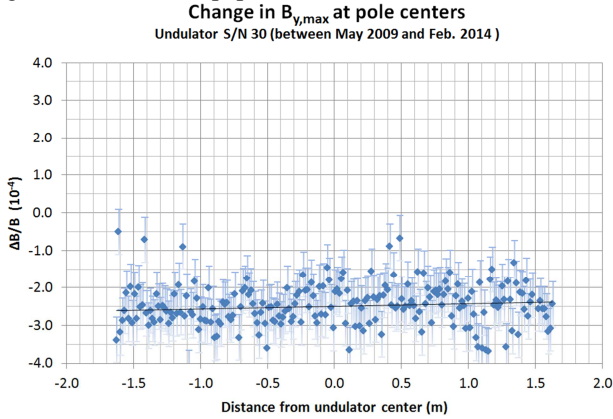


Figure 5: Magnetic field measurements shown in Figure 4 after correction by the CMM gap measurements shown in Figure 5. The remaining change in relative field amplitude is $-(2.5\pm 0.5)\times 10^{-4}$.

Both, changes in $\Delta K/K$ and in gap height have been observed. The former have been corrected by the latter, using the known dependence of relative undulator strength, $\Delta K/K$, on small undulator gap changes, Δg : $\Delta K/K/\Delta g = -(1.46\pm 0.15)\times 10^{-4}/\mu\text{m}$, for the LCLS undulator segments (see example in Figure 5).

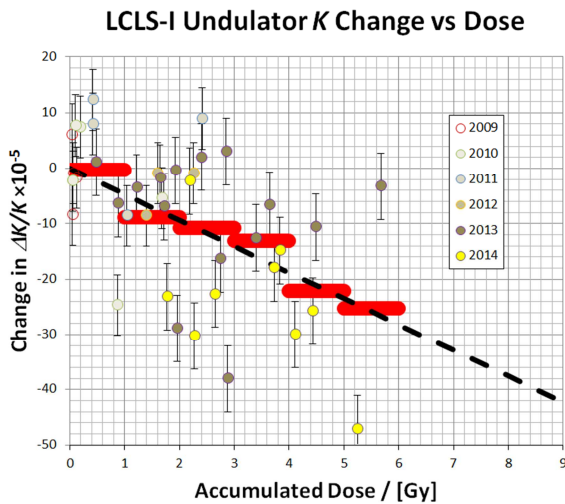


Figure 6: Change in the strength ($\Delta K/K$) of undulator segments vs. the amount of beam energy transported through the beam pipe during the periods in which they were installed in the beam line.

The corrected values of $\Delta K/K$ have been attributed to radiation damage. Note: One undulator has been kept inside the magnet measurement facility since it first finished tuning in 2007. It has been regularly measured over the years as a reference of the measurement process.

This reference undulator does not show the reduction in $\Delta K/K$ as observed on the undulator segments that have spent time in the radiation environment. The averages for the individual undulator segments are plotted in Figure 6 against the radiation dose as accumulated by the TLDs. (see above). In spite of the large spread in the data points, a reduction in segment strength with increased accumulated radiation dose can be seen. Whenever an LCLS undulator segment is re-measured it is recalibrated, i.e., the K polynomials, which translate between the horizontal (x) positions of the canted undulator segments and the K values, are recalculated based on the new measurements. This simple recalibration technique works because of the observed homogeneous z -profile of the K value reduction (see Figure 5).

LCLS ELECTRON BEAM COLLIMATION

Collimator systems appear to be the essential tool for reducing average radiation dose. They remove beam halo, i.e., the large-emittance background that accompanies the electron bunches. Collimators need to be carefully designed and strategically placed to remove out-of-core particles in 5 phase space dimensions (x, x', y, y', E), i.e., transverse (horizontal, x, x' , and vertical, y, y') and energy, E .

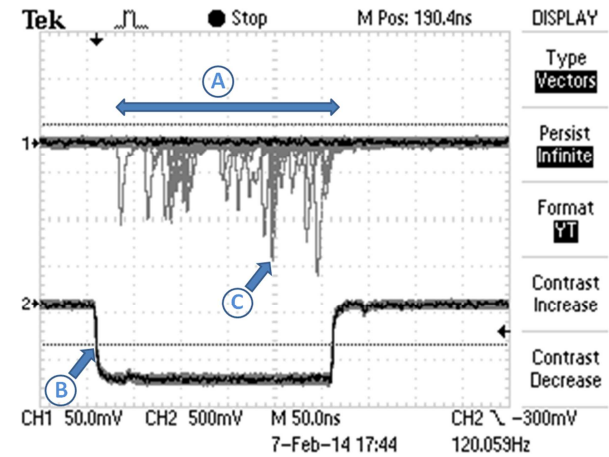


Figure 7: Lost particles from dark current pulses (A) and from the laser driven beam (C) observed at a position along the undulator by a beam loss detector (accumulated over about 500 beam pulses), showing the time spread loss events relative to the true beam time. The lower signal is the oscilloscope trigger from the accelerator timing system (B). The full width of the plot is 500 ns. The rf bucket separation is 0.3 ns.

Recent analysis has shown problems with the current LCLS collimator system. One of the problems is that the LCLS collimators are too short (3 X_0), the LCLS-II collimators will be 15 radiation lengths (X_0). Another problem comes from the fact that collimators both remove and create halo. The creation comes from converting core particles that interact with the collimator but are not removed from the beam by the collimator, itself, to halo particles. A third problem comes from the fact that halo

reduction requires the collimator jaws to get quite close to the beam core such that changes in steering and/or beam optics matching can result in transmission rate changes for core particles. For each of the two transverse planes there need to be two collimators separated by 90 degrees of betatron phase advance. The energy collimator needs to be located at a position of high dispersion (such as inside a chicane or a dogleg). In order to avoid that halo particles, produced by the collimation system, will be able to reach the undulator segments, multiple collimation systems will be used and positioned such that there is at least one dipole between the last collimator and the first undulator segments.

A significant source of radiation can come from dark current in out-of-time buckets, i.e., that are generated in the RF photocathode gun when the electric field is right for acceleration but no laser pulse is present. Those losses have been detected along the LCLS undulator beam pipe (Figure 7). It has been shown that the losses, shown in the figure, can be suppressed by switching the gun rf to be out of time with the accelerator rf; they were not much affected by removing the drive laser, which generates the desired bunches, from the gun. In operation, the dark current bunches could be removed by a fast kicker system that should be located after the first accelerator section (L0) when the electron beam energy is still low. Such a kicker system does not exist for LCLS-I but is planned for LCLS-II, for which it is considered essential because of the much larger number of extra rf bucket due to the DC mode of beam operation.

LCLS-II UNDULATOR RADIATION ISSUES

While LCLS operates currently at a maximum beam power of 324 W, (120 Hz, 15 GeV, 180 pC), LCLS-II is being designed for a maximum beam power of 120 kW (100 kHz, 4 GeV, 300 pC) or (1 MHz, 4 GeV, 30 pC), i.e., a beam power increase by a factor 370.

A new LCLS-II collimation system is being designed, incorporating the lessons learned on LCLS-I, including:

1. LCLS-I halo collimators are too short and close to the undulator line
2. The radiation produced by halo collimators (including gamma and neutron radiation) must be deflected and shielded, i.e., For example, there must be a dipole between halo collimators and undulator segments. Shielding must be added around the halo collimators.
3. Use of beam intercepting devices in front of the undulator line must be limited to low rep-rate operation. They must be fully retrieved from the beam path when not used.
4. A sensitive machine protection monitoring system with correct trip threshold will need to be developed.
5. The understanding of dark current from the gun and L0 during LCLS-II operation needs to be improved. It will be necessary to add a fast kicker in injector area, right after the first linac section.

It is expected that the new system will result in reduction of radiation dose by orders of magnitude compared to the present system for the same beam power. This should allow keeping the segment recalibration rate at roughly 1 segment per month. Initially, LCLS-II will run in mixed-rate operation to keep the average beam power much lower than the planned 120 kW. The average beam power will be slowly increased based on radiation detector readings as halo reduction is improved. This approach will allow high repetition rate to occur early during the start of LCLS-II operations but at a reduced duty cycle.

CONCLUSION

Reduction in magnetic field strength ($\Delta K/K$) as a function of accumulated radiation dose has been observed for the LCLS undulator segments. The existing halo collimation system was found to have a number of insufficiencies. Significant (sometimes the majority of) beam loss comes from out-of-time buckets. Lessons learned with LCLS-I are being used for the design of the LCLS-II undulator radiation protection system at more than 300 times higher beam power levels.

REFERENCES

- [1] P. Emma, *et al.*, "First Lasing and Operation of an Ångstrom-Wavelength Free-Electron Laser", *Nature Photonics* **4**, 641. doi:10.1038 / nphoton.2010.176
- [2] I.B. Vasserman *et al.*, "LCLS Undulator Design Development", *FEL2004*, 367-370
- [3] G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso, J. Ranft, "The FLUKA code: Description and benchmarking" Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6-8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)
- [4] A. Ferrari, R.R. Sala, A. Fasso, J. Ranft *et al.*, "FLUKA: a Multi-Particle Transport Code", CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773
- [5] Y. Asano, T. Bizen, and X. Marechal, "Analyses of the factors for the demagnetization of permanent magnets caused by high-energy electron radiation," *J. Synchrotron Rad.* **16** (2009), 317-324
- [6] A.B. Temnykh, "Measurement of NdFeB permanent magnets demagnetization induced by high energy electron radiation", *Nuclear Instruments and Methods in Physics Research A* 587 (2008) 13-19
- [7] S. Anderson *et al.*, "Fast Neutron Damage Studies on NdFeB materials", PAC05, Knoxville, TN, May 16-20, 2005
- [8] REM Oxford Ltd., Witney, England; A. Holmes-Siedle
- [9] Z. Wolf, Y. Levashov, "Reference Undulator Measurement Results", LCLS-TN-09-3 (2009)