ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-TUPS094

DIAGNOSING AN IN-VACUUM UNDULATOR IN THE ALS STORAGE RING*

D. Bertwistle†, J. Dickert, T. Hellert, M. Kritscher, S.C. Leemann, F. Sannibale, T. Scarvie, C. Steier, S. Trovati, E. Wallén
Lawrence Berkeley National Laboratory, Berkeley, CA. USA

Abstract

The Advanced Light Source (ALS) has an in-vacuum undulator named "LEDA". It was installed in 2019 and provides high-brightness, high-energy photons for the ALS macromolecular crystallography beamline, GEMINI. The undulator is a hybrid design with a minimum gap of 4.3 mm, a magnetic period of 15 mm, and a photon energy range of 5–19 keV. When the device was commissioned in the ALS storage ring, it had a negligible impact on ring operations. Recently, there has been a measured degradation in storage ring performance and an increase in radiation at the beamline, both correlated with the LEDA gap. Prior to conducting an invasive magnetic measurement, we performed a suite of beam-based measurements to characterize LEDA. Herein, we detail these measurements and share them with the accelerator community, who may find them useful when encountering similar challenges.

BACKGROUND

GEMINI, an ALS [1] beamline, was commissioned, with beam, at the end of 2020 to a gap of 4.5 mm. At first light, the radiation levels were slightly higher than expected but still below the regulatory limits and remained constant for over a year. A tune shift vs. gap measurement taken in May 2021 shows a significant change in undulator focusing suggesting a deterioration in LEDA performance.

On September 21st 2021 LEDA suffered a mechanical incident where its gap collapsed, in the process deforming the bolts serving as its hard stops. Repair work restored functional hard stops and a close inspection including borescope scanning revealed no obvious damage to liner, poles, rf fingers, or transition pieces. Nevertheless, subsequent user operations revealed an increasingly deteriorating injection efficiency and a reduction in lifetime, both of which were correlated to small LEDA gaps. Radiation measurements (Figs. 1 and 2) on the experimental floor in the GEMINI area showed increasing dose at smaller LEDA gaps, primarily driven by injection losses. A beam-based measurement campaign was initiated to better understand what damage LEDA might have sustained.

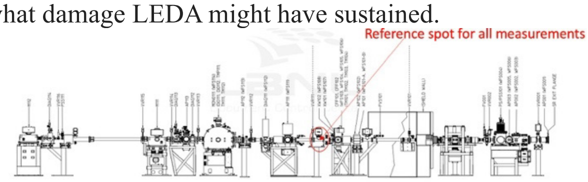

Figure 1: Dose measurement location.

* This work was supported by the Director, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
† bertwistle@lbl.gov

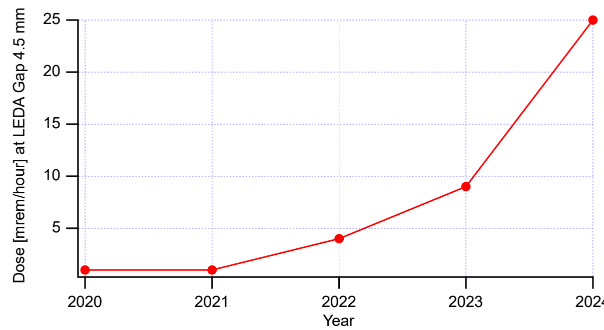

Figure 2: Measured dose at GEMINI beamline.

UNDULATOR PARAMETERS AND MAGNETIC MEASUREMENTS

LEDA was designed for a protein crystallography beamline that requires high photon energies with a 1.9 GeV electron beam. Thus, LEDA has a short period of 15 mm and is of the in-vacuum hybrid type to achieve a high effective magnetic field of 1.053 T (Fig. 3) at a minimum gap of 4.386 mm and practically operate on a high harmonic number. It has 131 periods and an overall magnetic material length of 1995.1 mm.

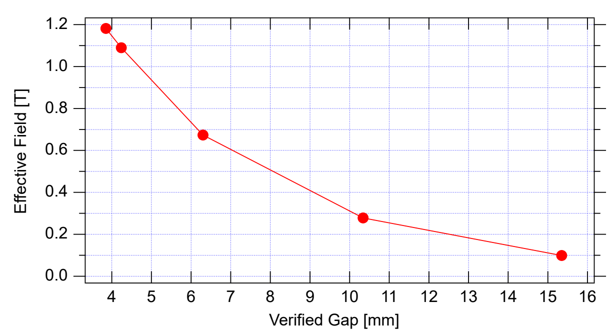

Figure 3: Measured B_{eff} as a function of LEDA gap.

The magnet blocks are Dysprosium infused $Nd_2Fe_{14}B$ (NMX-S43SH + Dy) with a minimum remanence of B_r =1.28 T and an intrinsic coercivity $H_{cj} > 2149$ kA•m^{-1} at room temperature. Their transverse widths are 70 mm (H) x 56 mm (V) and have 6 µm thick TiN coating. The pole piece material is Permendur with a saturation strength of 2.3 T. Their dimensions are 2.5 mm (L) x 56 mm (H) x 27.5 mm (V).

The simulated transverse roll-off of the magnetic field, in the transverse range of ±15 mm, in the magnetic midplane, is < 0.25% for gaps from 4 mm to 10 mm. The simulations support the pre-installation magnetic field integral measurements (Fig. 4) during the factory acceptance tests.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-TUPS094

The multipole distribution is relatively flat over LEDA's transverse width. It also serves as a timestamp for the nominal optics of the undulator before insertion into storage ring. The measured RMS phase error was lower than 3 degrees for gaps less than 15 mm (Fig. 5).

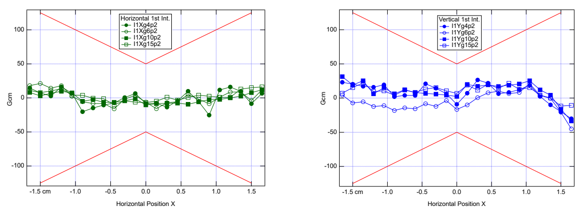

Figure 4: Horizontal (left) and vertical (right) 1st field integrals from FAT.

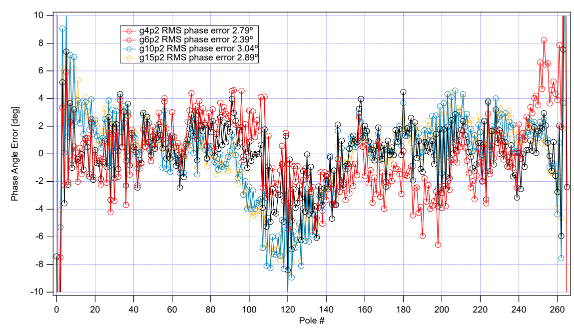

Figure 5: RMS phase error as a function of pole number.

UNDULATOR PROTECTION

LEDA was installed in the first long straight after the injection straight. In order to protect its permanent magnets from lost beam particles, particularly loss during errant injection shots, two pairs of vertical collimators are installed upstream of LEDA and downstream of the injection septa (Fig. 6) [2]. These collimators are separated in vertical betatron phase by roughly 90° and have been calibrated with beam-based measurements to render roughly 1 mm-mrad vertical acceptance, which is sufficient to protect LEDA down to gaps lower than 4 mm with only limited impact on stored beam lifetime.

Figure 6: LEDA scraper positions circled in red.

BEAM BASED MEASUREMENTS

Insertion devices in the straights of 3rd or 4th generation synchrotron storage rings are designed to be transparent to the injected and stored beam. But there is often a residual magnetic field that, when integrated, induces non-negligible gap dependent kicks. All things being equal these kicks are eliminated, reproducibly, by using feedforward tables integrated into an orbit correction system. In the case of LEDA there are two combined function magnets that flank the straight section, one upstream, and one downstream. They are chromatic sextupoles with additional skew quad coils, horizontal dipole coils, and vertical dipole coils. At the ALS the look-up tables are measured by determining dipole corrector strengths that minimize the closed orbit distortion around the ring. This is done for the range of operational gap settings. The data is collected bi-annually during a dedicated machine studies shift.

In-vacuum undulators are close to the beam and more susceptible to radiation damage. The look-up tables can track changes in the integrated magnetic field capturing changes in the undulator termination magnets and/or changes in the magnetic field periodicity field over time. The authors emphasize the utility of storing and managing this data over the lifetime of the insertion device. A planar in-vacuum undulator has 1 degree of freedom, the gap, so look-up table measurements are relatively quick to do and can be done with more frequency for improved statistics. ALS has kept such datasets and upon review (Figs. 7 and 8) we note the LEDA look-up tables have changed over time, especially below 8 mm gap, indicating possible deterioration of the magnetic field of the undulator.

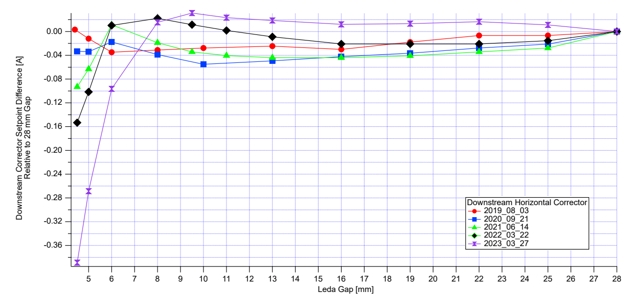

Figure 7: Downstream horizontal dipole correction values, for different years, as a function of gap.

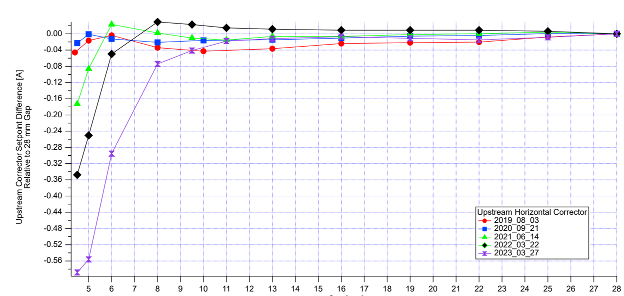

Figure 8: Upstream horizontal dipole correction values, for different years, as a function of gap.

During a shift performing LEDA gap dependent measurements we observed changes in the storage ring coupling using ALS diagnostic BL3.1 beam spot camera. We used LOCO [3] measurements to understand if a previously absent gap dependent skew quadrupole is present in the machine optics of the undulator. We scripted LOCO measurements on the entire storage ring to enforce the desired 2% machine coupling for various LEDA gaps. In this case the flanking combined function magnet skew quadrupole coils were incorporated into the fit. The upstream/downstream skew quadrupoles flanking LEDA require relatively strong changes to maintain the coupling (Fig. 9). This conflicts with the integrated multipole measurements (Fig. 4). Based on this measurement we presently employ a feedforward

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-TUPS094

table that uses the flanking skew quadrupoles to nullify the ID induced skew quadrupole.

We have systematically measured the LEDA gap-dependent tune shifts since it was installed. A change in these tune shifts can be an indication of change in impedance or magnetic field quality. LEDA gap-dependent tune shifts indicate the focusing has changed between 2019 to 2022 then stabilized thereafter.

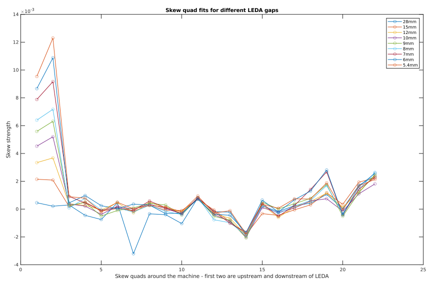

Figure 9: LOCO fits to ALS skew quadrupoles for 5.4 to 28 mm gap. Point 1 is the upstream skew quadrupole and point 2 is the downstream skew quadrupole.

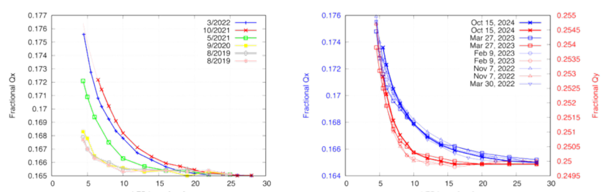

Figure 10: LEDA gap dependent tune shift measurements from 2019 to 2024.

Our penultimate measurement results in a reconstruction of the LEDA integrated multipoles using a beam-based method. At maximum LEDA gap we stepwise add either a vertical or horizontal parallel bump through the straight. We then closed the gap to 5.5 mm and observe the change in corrector strength at the flanking combined function corrector magnets. For each applied bump we obtain an effective 1st field integral for LEDA. The integrated multipoles are derived from the resulting measurements (Fig. 11). From the horizontal field integral fits, we derive a normal and skew quadrupole of 1116 G and 287 G respectively. From the vertical field integral fits, we obtain a normal quadrupole of 95 G and a skew quadrupole of 208 G. There is a strong qualitative change of the field integrals about the centreline of LEDA.

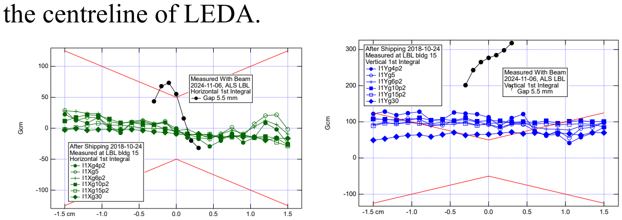

Figure 11: Beam-based measurement (black) of LEDA horizontal/ field integrals (left/right) at fixed gap.

The final beam-based diagnostic method we pursued was to measure the photon spectrum of LEDA and compare that to a simulated spectrum using ALS electron beam parameters. The GEMINI beamline consists of a series of beam defining apertures, a double crystal monochromoter, and an Al foil flux monitor immediately after the monochromoter. In this measurement (Fig. 12) the LEDA gap is set to 6.0 mm. The limiting aperture was 1.6 mm (H) x 1 mm (V) and approximately 16235 mm from the LEA centre. The flux monitor was 19434 mm from the LEDA centre. We used the python-based simulation package XrayTracer (XRT) [4] to propagate the photon beam from the source point (no applied phase errors) to the flux monitor. If there was sufficient radiation damage along the undulator, effectively introducing phase errors to the periodic undulator field, then we would expect the undulator peaks become shorter and wider with increasing spectral harmonic number. Yet the measured higher harmonic numbers such as 9 and 11 have a similar form factor and height compared to the simulated distribution.

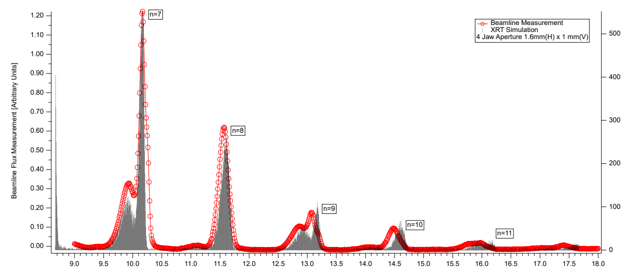

Figure 12: Simulated/measured LEDA spectrum (grey/red). The simulated spectrum is scaled to the measured 7th harmonic peak height and shifted to its energy.

CONCLUSION

The LEDA beam-based measurements included integrated multipoles, tune shifts, LOCO fits, feedforward tables, radiation floor measurements, and x-ray spectra. The data suggest possible radiation damage. The year-to-year changes in the historic gap dependent feedforward tables and tune shift data highlight their utility as diagnostic tools. Finally, the measurements in this article make a compelling case to perform Hall probe and stretched wire bench measurements on LEDA.

REFERENCES

[1] T. Hellert *et al.*, “Status of the Advanced Light Source”, in *Proc. IPAC’24,* Nashville, TN, May 2024, pp. 1309-1312. doi:10.18429/JACoW-IPAC2024-TUPG37

[2] S.C. Leeman, “ALS Internal Note”, Feb. 8th, 2019.

[3] J. Safranek, “Experimental determination of storage ring optics using orbit response measurements,” *Nucl. Instrum. Methods Phys. Res*., Sect. A, vol. 388, no. 1–2, pp. 27–36, Mar. 1997. doi:10.1016/s0168-9002(97)00309-4

[4] K. Klementiev and R. Chernikov, “Powerful scriptable ray tracing package xrt,” in *Advances in Computational Methods for X-Ray Optics III*, M. Sanchez del Rio and O. Chubar, Eds., Sep. 2014, p. 92090A. doi:10.1117/12.2061400.