HIGH-RESOLUTION UNDULATOR MEASUREMENTS USING ANGLE-INTEGRATED SPONTANEOUS RADIATION*

B. X. Yang†, APS, Argonne National Laboratory, Argonne, IL 60439, U.S.A.

Abstract

The Linac Coherent Light Source (LCLS) is a fourth-generation light source. Its proper operation requires a stringently controlled undulator field. The tolerance for the field parameter K is less than 1.5×10^{-4} for all thirty-three undulator segments totaling 112 meters. The fluctuation of the electron energy (~0.05%) presents a serious challenge to measurement techniques based on electron or x-ray beams. We show that the steep spectral feature in the angle-integrated undulator radiation can be used to measure the field of the undulator one segment at a time. With simultaneous measurement of electron beam charge and energy shot-by-shot, the K-parameter can be determined with required accuracy. We also propose a differential measurement technique that makes use of the radiation intensities from two undulator segments. When the x-ray beams emitted from the two undulator segments are separated but allowed to pass through the same monochromator, the two beam intensities will change almost identically with the change of many electron beam parameters. As a result, the intensity difference becomes a very sensitive and reliable measure for the difference in the fields of the two undulators. Numerical simulations show that a resolution in the range of $\Delta K/K \sim 10^{-5}$ can be achieved.

INTRODUCTION

The undulator is a key component of a free-electron laser (FEL), where an electron beam is forced into sideway oscillations by the periodic magnetic field, which couples the electrons to the transversely polarized electric field of the co-propagating photon beam, resulting in an exchange of energy between the two beams. It is crucial to match the phase of the two beams to attain desired energy transfer from the electron beam to the photon beam. For the LCLS, this phase requirement results in a tolerance for the field parameter K of $|\Delta K/K| < 1.5 \times 10^{-4}$ [1].

Although accurate measurements of undulator magnetic fields are available in high-quality magnetic measurement facilities [2], it is still advantageous to have beam-based undulator measurements for the following reasons: In the initial setup, the beam-based measurements can be used

- to confirm bench measurements,
- to confirm vertical positioning of the undulator (beam-based undulator alignment), and
- to taper the undulators to compensate for the electron energy losses due to longitudinal wakefield [3], or spontaneous radiation.

During FEL operation, stray radiation continues to cause low-level damage to undulator magnets; here the beam-based measurements can be used

- to quickly identify damaged undulator segments,
- to periodically monitor the degradation of the magnets (for $\Delta K/K \sim 10^{-5}$), and
- to help compensating minor magnet damages by adjusting undulator segments.

The angle-integrated spontaneous undulator spectrum shows a stable, sharp transition of photon intensity that is not sensitive to beam positions and divergence. This feature was used at the Advanced Photon Source for measurement of electron beam energy as a function of rf frequency (momentum compaction) [4], and energy spread [5]. It has shown robust, high resolution in the range of 10^{-4}. To apply this technique to LCLS undulator measurements, we need to take into account different beam parameters: single shot, low bunch charge, etc. In this work we will study the technique using two approaches to acquire data: one with a single undulator and another with two undulators in differential mode. Numerical simulation will be used to estimate errors and requirements for taking adequate data.

LCLS UNDULATOR SPECTRUM

The LCLS operates in the photon energy range from 827 eV to 8266 eV. At 8266 eV the electron energy is 13.64 GeV, with a bunch charge of 0.2 – 1.0 nC, at a repetition rate of 10 to 120 Hz. The nominal electron beam size in the undulators is 37 μm, and the nominal beam divergence is 1.2 μrad. This divergence angle is well below the opening angle of the undulator radiation cone near the fundamental photon energy, $\omega_1 = \gamma^2 \omega_u / (1 + K^2/2)$, where $\gamma = E/mc^2$ is given by the electron energy E, $\omega_u = 2\pi c/\lambda_u$ is given by the undulator magnetic period λ_u, and $K = 0.934 \lambda_u B_0$, is the magnetic field parameter. The LCLS undulator is made of thirty-three identical segments, which may be independently inserted. Each segment has 226 poles and its period length is 3 cm. Figure 1 shows a calculated spontaneous radiation spectrum for a single-undulator segment at an electron energy of 13.64 GeV. We notice that the shape of the spectral edge does not change for full aperture sizes greater than 30 μrad. In this photon energy region near ω_1, photons are concentrated in a forward cone. An on-axis aperture with radius ~ $1/\gamma$ would collect all photons emitted, and the spectral data would be independent of electron beam divergence and beam direction jitter (~0.3 μrad). Due to the steep slope of flux intensity changes at this (edge) photon energy,

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†bxyang@aps.anl.gov

$$\frac{\Delta F}{F} \sim -200\frac{\Delta\omega}{\omega_1} \sim -400\frac{\Delta K}{K}, \qquad (1)$$

an intensity (F) measurement of moderate resolution (1%) translates into a high-resolution photon energy measurement (0.5×10^{-4}) or a high-resolution effective-K measurement (0.25×10^{-4}).

The finite energy resolution of the x-ray monochromator (~0.1%) and the electron energy spread (~0.05%) is well below the width of the edge (~1%). They effectively flatten the slope slightly but do not change the center position of slope (Point A in Fig. 1, ~ω_1). In the expression for ω_1, we can see that changes of electron energy will affect photon energy as strongly as changes in the magnetic field parameter K.

In the following sections, we will estimate various beam effects with the aid of numerical simulation.

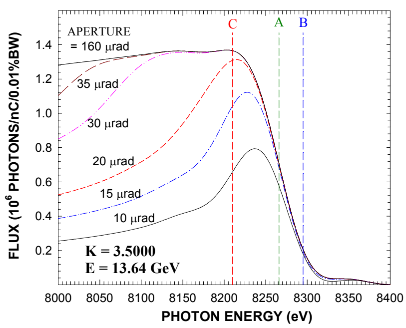

Figure 1: Calculated undulator radiation spectrum through a square aperture. The edge of the spectra is independent of aperture size for total opening > 30 µrad.

SINGLE-UNDULATOR MEASUREMENTS

We start with a conceptual experiment where the x-ray beam passes through a wide aperture (radius ~ $1/\gamma$), is filtered by a monochromator ([ΔE/E] ~ 0.03%), and is received by an integrating detector (total efficiency η ~ 20%). The x-ray photon numbers per bunch F, along with electron bunch charge Q (0.2 nC) and beam position y at a dispersive section (dispersion = D), are recorded shot-to-shot. We simulate these measurements with a MathCAD program. A Gaussian random number generator is used to generate electron bunch charge Q (20% rms jitter) and bunch energy γ (0.1% rms jitter). The angle-integrated photon flux is calculated with a parameterized expression,

$$N_{PH}(\omega) = \eta\cdot\left[\frac{\Delta\omega}{\omega}\right]\cdot Q\cdot\left\{\begin{array}{l} A_1\left(\dfrac{\omega}{\omega_1}\right)^{v}\left[1-\tanh\left(\dfrac{\omega-\omega_1}{\Delta_1}+\phi_1\right)\right] \\ -A_2 e^{-\frac{(\omega-\omega_1)^2}{8\Delta_2^2}}\sin\left(\dfrac{\omega-\omega_1}{\Delta_2}+\phi_2\right)\end{array}\right\}, \qquad (2)$$

where $A_1 = 0.7256\times10^6$, $\phi_1 = 0.0206$, $\Delta_1 = 43.2$ [eV], $v = 3.825$, $A_2 = 0.1120\times10^6$, $\phi_2 = -0.0354$, $\Delta_2 = 25.9$ [eV]. The random number generator is used again to add statistical noise ($\sim\sqrt{N_{PH}}$) to the photon intensity data. A typical spectrum is shown in Figure 2A. After the intensity data is normalized by the "measured" charge data (rms 1% noise added), the nearly horizontal part of the spectrum collapses into a line (Figure 2B). If we define a new correlated photon-electron energy variable,

$$\omega_{corr} = \omega - 2\omega_1\frac{\delta\gamma}{\gamma} = \omega - 2\omega_1\frac{y-y_0}{D} \qquad (3)$$

(with an error equivalent to $\Delta\gamma/\gamma$~10^{-5} added to y), and plot the normalized intensity data against it, the spectrum appears to be very well behaved (Figure 2C).

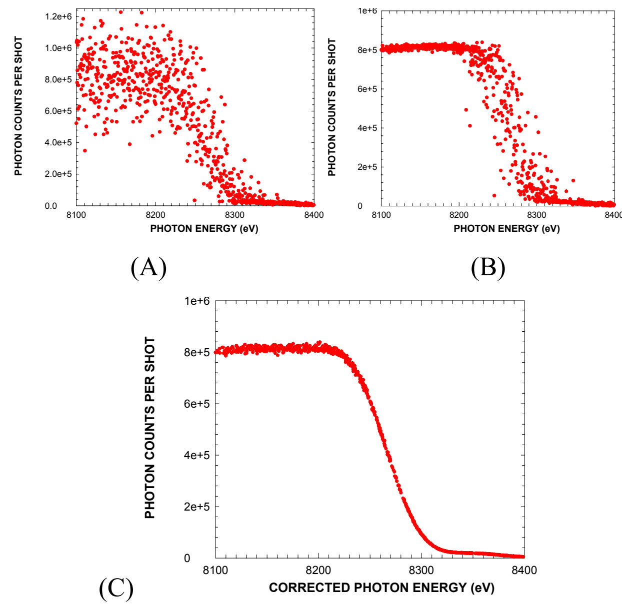

Figure 2: Typical simulated spectra: (A) raw spectrum taken by monochromator scan; (B) raw spectrum normalized by measured bunch charge; (C) charge normalized spectrum with horizontal x-axis changed to correlated photon-electron energy variable.

We then fit the spectra to an expression like the first term in Eq. (2) and use the fitted parameter ω_1 to calculate field parameter K. Statistically, more data points taken near the spectrum edge help improve accuracy of the K-value obtained in the "experiment." Multiple (>10^4) simulations show that it requires a total of 1600 shots or more to obtain the needed accuracy (rms error $\Delta K/K$<10^{-4}) when only charge normalization is used. If we also use the correlated energy variable (Fig. 2C), the rms error is reduced by a factor of about 10, and it needs only ~30 shots to obtain similar accuracy in K. With this improvement, the time of data acquisition is now limited only by the speed of the scanning monochromator.

TWO-UNDULATOR MEASUREMENTS

Inspired by high-precision differential measurements in electronics (Wheatstone bridge, differential amplifiers), we propose a differential measurement using a second, standard undulator in a setup shown in Figure 3. Two undulator magnet segments are inserted: the last undulator

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segment (standard undulator) and one of the 32 segments to be tested (test undulator). A horizontal steering magnet upstream of the standard undulator steers the electron beam so the x-ray beam from the standard undulator is off from the main axis and well separated from the test undulator beam when they reach the same monochromator located ~50 m downstream. Two detectors collect the x-ray beams separately and their intensity difference is used as the (difference) signal.

A typical LCLS electron bunch contains 0.2-nC charge; with a wide-band monochromator (0.03% BW), and 20% overall efficiency, we have ~ 4×10^5 photons/shot at the detector. Hence the statistical (counting) noise is ~ 0.14%. If we have low background noise and good electronics, we can assume the total noise to be 0.4% per shot for two undulators. This translates into an error of $\Delta K/K \sim 10^{-5}$ by virtue of Eq. (1). This simple estimate was supported by numerical simulations, which show that common mode errors, e.g., electron energy jitter, are cleanly cancelled, resulting in a good signal to show minute differences of the two undulators.

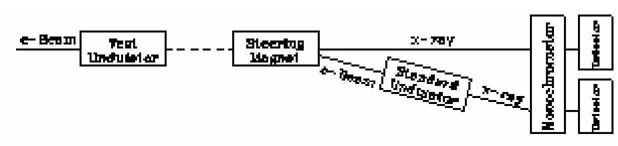


Figure 3: Two-undulator differential measurement.

UNDULATOR VERTICAL ALIGNMENT

From the Maxwell equations, we know the field component satisfies $\Delta^2 B_y = 0$ in the magnetic gap, and the magnetic field increases from mid-gap towards the poles. As a result, the effective K-parameter changes with the electron's vertical coordinates y,

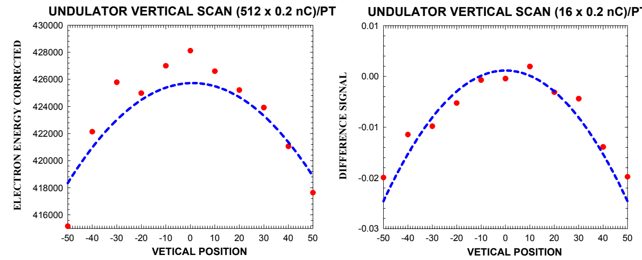
$$\frac{K(y)-K(0)}{K(0)} = \frac{\alpha_y}{2}\left(\frac{y}{\lambda_y}\right)^2, \quad (4)$$

where α_y is a constant of the order of one and is determined by the geometry of the magnetic structure. For LCLS undulator segments, a vertical displacement of 50 μm of the entire undulator results in a change of $\Delta K/K \sim 5\times10^{-5}$, well within the detectable range.

In the simulation, we set the monochromator energy at ω_1, scan undulator vertical position, change the K-value according to Eq. (4) (α_y = 1 for simplicity), and monitor the intensity change shot-to-shot. In one-undulator measurements, we apply the electron energy correction using a simplified spectrum from Fig. 2. In two-undulator measurements, we use the raw normalized difference signal. Figure 4 shows that with multi-shot averaging—512 shots per point for single-undulator and 16 shots for dual-undulator measurements—we can clearly position the undulator at the correct position.

When only one end of the undulator is displaced vertically, the undulator has a slight taper in its magnetic field, and the intensity change is less sensitive to the displacement by about a factor of two.

Results of the simulation show promise for attaining 10-μm resolution for the placement of the center of the undulator and 20-μm resolution for the placement of each end.



(A) (B)

Figure 4: Intensity plots for undulator vertical scans: (A) One-undulator intensity with correction by electron energy data; (B) difference signal of two undulator measurements.

SUMMARY AND DISCUSSIONS

We studied the feasibility of using the angle-integrated spontaneous radiation spectrum for a beam-based undulator setup for x-ray free-electron lasers. Our analysis and initial numerical simulation show that with a scanning monochromator and simultaneous measurements of electron charge and energy centroid, it is feasible to obtain the resolution needed for setting undulators to specifications, including specified K-value and vertical position / orientation. We also proposed a differential measurement technique, which has high resolution ($\Delta K/K \sim 10^{-5}$ or better) and may be used to monitor gradual changes of undulators.

The current studies are based on fairly ideal conditions. Further studies are planned to understand the limitations under realistic conditions, including

- undulators containing field errors,
- electron-beam energy spread and energy centroid modified by the longitudinal wakefield, and by spontaneous radiation, and
- single-shot intensity fluctuation due to longitudinal coherence effect in the electron bunch.

REFERENCES

[1] J. Arthur et al., "LCLS Conceptual Design Report," SLAC-R-593, http://www-ssrl.slac.stanford.edu.

[2] I. Vasserman, S. Sasaki, "Comparison of Different Magnetic Measurement Techniques," Thirteenth Int. Magnetic Measurement Workshop, May 2003, http://www-conf.slac.stanford.edu/immw/.

[3] K. L. F. Bane and G. Stupakov, "Resistive Wall Wakefield in the LCLS Undulator Beam Pipe," SLAC-PUB-10707, http://www.slac.stanford.edu.

[4] B. X. Yang, L. Emery, and M. Borland, BIW'00, Boston, May 2000, AIP Proc. 546, p. 234.

[5] B. X. Yang and J. Xu, PAC'01, Chicago, IL, June 2001, p. 2338, http://www.jacow.org.