UNDULATOR K-PARAMETER MEASUREMENTS AT LCLS *

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Abstract

We report our first in-situ measurements of relative undulator segment K-parameters made at the LCLS. The diagnostics, calibration, procedure, and early results are described. Measurement errors and noise are discussed and the outlook for near-term develop presented.

INTRODUCTION

At the highest design x-ray energy of 8 keV, where undulator field tolerances are most demanding, the LCLS started lasing within a few hours of the time the electron beam was first transported through the undulator, so undulator field quality must be well in hand. Nevertheless, even though advances in magnetic measurements and undulator tuning have produced an undulator of this quality [1], the field quality can change after installation. Field changes are known to occur due to radiation exposure and temperature variation. Similarly, errors in knowledge of the undulator position relative to the beam can occur and have the same net effect as field errors. Position fiducialization errors have occurred when segments of the LCLS undulator were accidentally exposed to temperature excursion of $5° C$. Undulator position errors would also result from diagnostic errors, or errors in configurations used to establish the positions of undulator segments. The *in-situ* undulator measurement techniques described in this paper are being developed to provide periodic assessment of the LCLS undulator field quality.

The 130 m long LCLS undulator is composed of 33 nearly identical segments, each separately tuned to a precise strength denoted by its "K-parameter". The K-parameter is dimensionless and $K = 0.934\lambda_u B\ [T]$, where B is the amplitude of the on-axis magnetic field in Tesla, and λ_u is undulator period in centimeters. Tolerance studies of the FEL process led to a tolerance budget based on FEL power for individual segment K parameters of

$$\frac{\delta K}{K} < 1.5 \times 10^{-4},$$

where δK is the RMS deviation from design. The design K-parameters vary slightly depending on where the segment is to be located, but a typical value is 3.5.

We are developing two techniques to measure *in-situ* segment K parameters, both of which rely on measurements of the x-ray spectrum using a monochromator and the ability to remotely move segments onto and off from the beamline. In the one-segment method, all segments are moved off the beamline except for a single reference segment and a x-ray energy spectrum is measured. The reference segment is then removed and a test segment is put in and its x-ray spectrum is measured. The difference in K between the two segments can be inferred from relative shifts in the spectra. At this early stage in commissioning, most of the measurements have been done with the one-segment technique.

In the two-segment method, all segments are moved off the beamline except for two adjacent segments. One of the two segments is then stepped horizontally over a range of a few millimeters relative to the other, and a spectrum is taken at each position. By design, the gap of the undulator segments has a slight horizontal taper so that the effective K-parameter varies slightly with horizontal position. Based on simulation [2] we find that when the position is such that the effective K-parameters for the two segments is matched, the x-ray spectrum has the steepest slope at the point of inflection on the high energy side. Thus from the measured position of the match and knowledge of the rate of change of the effective K-parameter with position from magnetic measurements, we can calculate the difference in K-parameters for the two segments.

MEASUREMENTS

Diagnostics

Insertable diagnostics used for K-measurements include a special monochromator called the "K-monochromator", followed by a set of photodiodes, and a YAG screen/camera combination called the "Direct Imager". The path of the x-rays through K-monochromator involves four Bragg silicon (111) reflections and forms a chicance around a tungsten block. The spontaneous radiation generated by the undulator contains very high energy x-rays, well over 100 keV, which pass through the silicon crystal of the K-monochromator and are absorbed in the tungsten block. Because of the multiple reflections, the K-monochromator will only transmit x-rays with a single angle of incidence, at a single energy and some of its harmonics. The angle of incidence was made to be remotely tunable. The device was tested at SSRL and found to pass x-rays with energy 8193 eV (0.15 nm), essentially the same as the first harmonic x-rays produced by a typical LCLS undulator segment ($K = 3.497$) when the electron beam is 13.56 GeV. The transmitted bandwidth was found to be 1.2 eV FWHM, and the transmission angle was also measured and related

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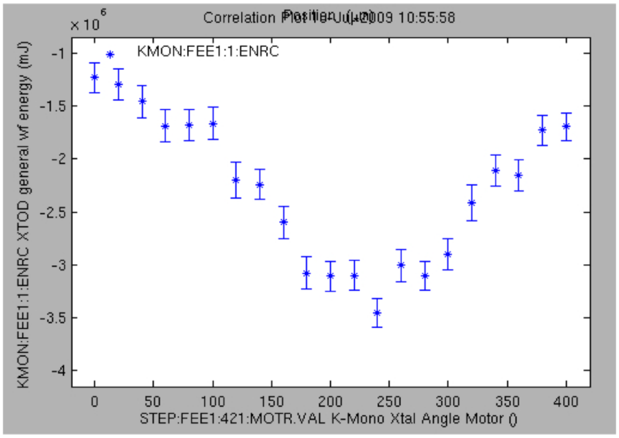

Figure 1: The dependence of the photodiode signal (in this early measurement, it is a negative going signal and has an arbitrary scale) on the K-monochromator angle of incidence, also in arbitrary units.

to fiducials on the K-monochromator for installation alignment.

Commissioning the K-monochromator included two measurements: (1) finding the electron beam energy, as defined by the strength of the LCLS bend magnets required for the ideal orbit, that generates first harmonic x-rays at 8193 eV; (2) finding the angle of incidence that passes the 8193 eV x-rays. Both are precision measurements.

The electron beam energy for transmission was found by scanning the linac output energy ±100 MeV and watching for the appearance of an image on the Direct Imager. It turned out that the bend magnets were well calibrated as we found the machine energy of 13.64 GeV provides maximum transmission. We were also fortunate that the preset angle of incidence was close enough to the ideal that a two dimensional search of angle and energy was not necessary.

The optimum angle of incidence was found in two different ways and yielded the same result. One method simply scanned the angle for maximum transmission while measuring the photodiode signal. The result is shown in Fig. 1. Alternately, we found that the image of the transmitted x-rays, as seen by the Direct Imager, was very sensitive to the angle of incidence, and by adjusting the angle to symmetrize the image we could set the angle precisely. The images in Fig. 2 show the effect of the angle tuning. The images could easily be distinguished to within 30 motor steps, which corresponds to an angular sensitivity of better than 3 microradians.

Results

The x-ray spectrum was measured by inserting the K-monochromator and the photodiode detector, and scanning the electron beam energy over a range of about 200 MeV. Changing the electron beam energy by a small amount, while keeping the undulator segment K fixed, results in a simple linear shift of the x-ray energy spectrum. Since the K-monochromator only transmits 8192 eV, the x-ray spectrum is effectively scanned by scanning the electron beam energy.

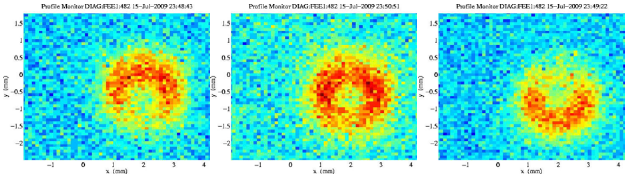

Figure 2: Effect of tuning the K-monochromator angle of incidence on the image of the transmitted x-rays.: left image was taken with angle at -3 μrad, center image at 0 μrad, and right image at $+3\mu$rad.

Measured and simulated spectra/energy scans are shown in Fig. 3, for the case where only the last undulator segment (U33) is on the beamline. The overall shape, width, and resonant electron beam energy, are in reasonable agreement between measurement and simulation. The measured spectrum has noticeably more noise than the simulation.This can come about from either noise in the photodiode signal or fluctuations in the electron beam energy. In fact we believe the latter is responsible for the majority of the excess noise. The effect of energy errors is discussed in the Systematics section below. The spectra in Fig. 3 are over a range of 200 MeV. Normally for K-measurements we concentrate on scanning the rising edge of the spectrum as a function of electron beam energy, because it is insensitive to small changes in electron beam orbit angles and solid angle effects.

K-measurement results presented in this paper used the one-segment technique referred to in the Introduction. So far the noise levels were too high for consistent two-segment results. First the reference segment is moved into its nominal horizontal position and the electron beam energy is scanned to obtain the x-ray spectrum. Rising edge data from 10% to 90% of the peak is extracted and fit to a third order curve and is plotted as the heavy red line in Fig. 4. Next the test segment is moved onto the beamline and set at various equally spaced horizontal positions, typically ranging from -1 to $+1$ mm. The spectra from each of these positions are plotted as the green curves in Fig. 4. Since the undulator gap is slightly non-parallel, with an average angle of 5.5 mrad, the K is slightly different for the different positions and the spectra are shifted in machine energy. Each of the green test spectra is analyzed to extract the electron beam energy that corresponds to the middle of the rising portion where the slope is steepest, “Energy at Mid-slope”. High noise levels can make the Energy at Mid-slope data sensitive to the exact region of the rising edge data that is included in the fit.

In Fig. 5, the “Energy at Mid-slope” data (circles) is fit to a second order polynomial and plotted against the test segment position along with the Energy at Mid-Slope for the reference segment. The energy where the fitted test data matches that of the reference segment defines the horizontal position of the test segment at which the two segments have the same spectrum. If there are no significant sys-

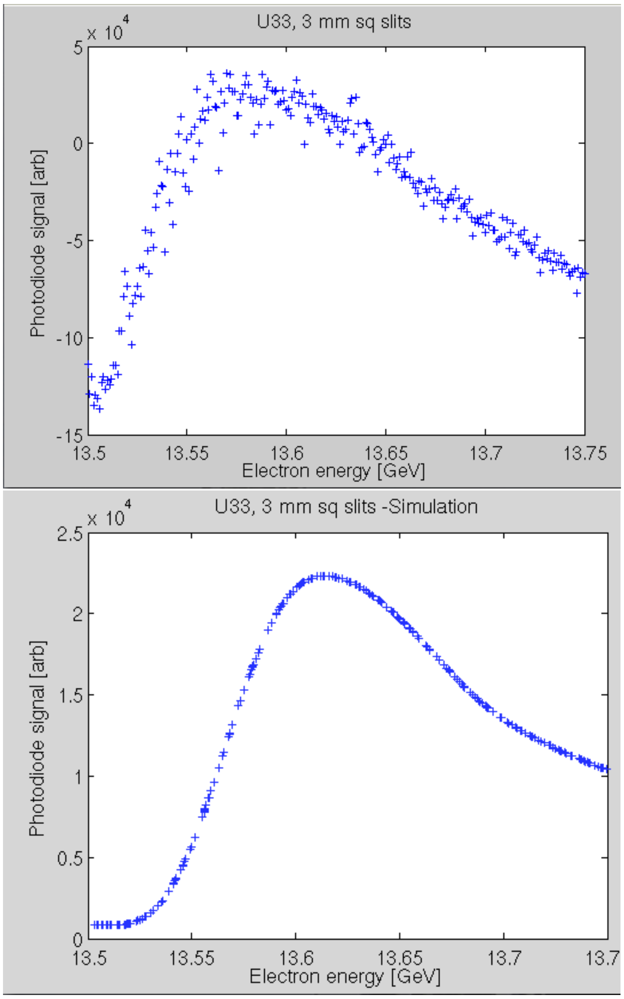

Figure 3: Measured (upper plot) and simulated(lower plot) x-ray spectrum as a function of machine energy.

tematic effects, such as differences in electron energy or the x-ray integration angles, the match position and slope Energy at Mid-slope versus segment position, can be used to determine the difference in K-parameters for any horizontal position. For constant resonant photon energy and angle,

$$\frac{d\gamma}{\gamma} = \frac{K^2}{2+K^2}\frac{dK}{K} \approx 0.86\frac{dK}{K} \qquad (1)$$

where γ is the electron beam energy in units of the electron rest mass.

Early results are shown in Fig. 5 were for segment 14 and segment 15. Measurements indicate the two segments will give the x-ray spectrum when segment 15 is at 0 mm and segment 14 is at 0.4 mm. The measured slope of the segment 14 mid-point energy versus position is approximately $(d\gamma/\gamma)/dx = -7.7 \times 10^{-4}$ mm^{-1}. Prior to installation the gradient of K with respect to horizontal position had been measured at the magnetic measurement laboratory to be $-2.68\times10^{-3}\ mm^{-1}$, which corresponds to an expected $(d\gamma/\gamma)/dx = -6.6 \times 10^{-4}$. The match position and the measured slope imply a $\Delta K/K = -2.7 \times 10^{-4}$ where ΔK is the difference in K between segments when both segments are at 0 mm.

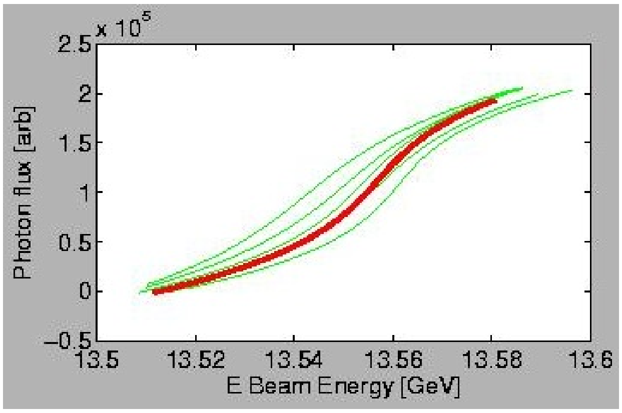

Figure 4: Successive energy scans for different horizontal positions using the one-segment method.

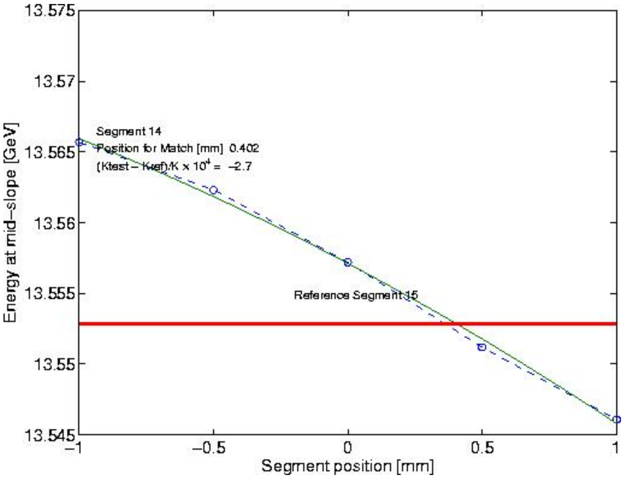

Figure 5: One-segment results of a K measurement scan.

A reproducibility measurement of the one-segment method was made and resulted with a standard deviation of the measurement of $\Delta K/K$ of 4×10^{-4}. Measurements of 14 pairs of segments were made so far and the results are consistent with all being within the required tolerance. As the techniques are developed and the two-segment technique is fully implemented, we expect the reproducibility to approach1 $\times\ 10^{-4}$.

SOURCES OF ERRORS

The undulator resonance equation is

$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + K^2/2 + \gamma^2\theta^2), \qquad (2)$$

where θ is the observation angle of the x-rays relative to the direction of the electron beam in the undulator. In it, K, electron energy, and observation angle are related, so that measuring any two allows the calculation of the third, assuming the wavelength λ through the K-monochromator

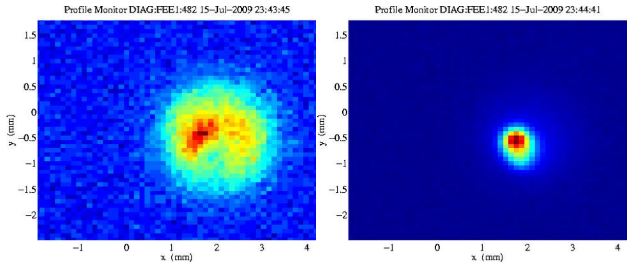

Figure 6: The central ray is determined when the electron beam energy is lowered until only the highest energy x-rays are at the passband energy. The electron beam energy for the right/left image is 15 MeV/10 MeV below 13.64 GeV.

to be constant. This implies that to accurately determine K, one has to accurately know the angle and the energy. The discussion of systematics in this section concentrates on determining limits on the uncertainties of electron beam energy and observation angle.

Observation Angle

The "Central Ray" of the x-ray radiation is defined as the radiation emitted at $\theta = 0$. Experimental determination of the Central Ray is necessary to control the K error associated with the observation angle uncertainty. For an ideal comparison of two spectra the central rays from both segments should coincide on the direct imager screen. In general the Central Rays from the different segment will not coincide due to slight deviations in the electron beam trajectory. We mitigated this effect by the technique we used to establish the shift of the x-ray spectrum from the electron beam energy at which the x-ray spectrum has the steepest positive slope. X-rays in this part of the spectrum come only from the smallest observation angles. In practice, if the electron beam is well aligned, we only have to be sure that we capture the Central Rays in the detectror to avoid significant error associated with observation angle.

We determined the central ray by observing the image of the x-rays on the Direct Imager while the K-monochromator is inserted. When the electron beam energy is tuned such that only x-rays from very near $\theta = 0$ are at 8193 eV, a very narrow image appears as can be seen in Fig. 6. The sensitivity of this method is impressive. The position of the spot for -15 MeV in Fig. 6 is determined to a statistical precision of around 3 microns, which at the distance of about 100 m from the last undulator segment is an angular uncertainty of 0.03 microradians. Since the central ray can be used to infer the angle the electron beam makes as it passes through each segment, it can in principle be used to determine electron beam trajectory straightness.

Electron Beam Energy

Differences in the electron beam energy between the reference segment and the test segment also introduce shifts in the x-ray spectra, and should be accounted for high precision determination of ΔK. Both spontaneous radiation and wakefield energy loss mechanism can contribute to this difference. There is about 0.63 MeV energy loss per electron from spontaneous radiation from a single segment for an electron beam energy of 13.64 GeV. In addition there is a wakefield loss which depends on peak current but not beam energy. For a peak current of 500 A, at which the K measurements are normally done, the total wakefield energy loss was measured to be 5 MeV, or 0.15 MeV per segment. In total, during a normal K measurement, the total energy loss from one segment to the next is about 0.78 MeV. From equation 1, the corresponding apparent K change is 2.3×10^{-4} ($\Delta K/K$ change of about 7×10^{-5}.), with the downstream segment appearing to be lower K.

Pulse-to-pulse fluctuations in the electron beam energy can be measured on a pulse-by-pulse basis and corrected for using beam position monitors in a dispersive region near the end of the linac [2]. In addition, fluctuations in peak bunch current can be measured and the resulting energy fluctuations due to impedance corrected on a pulse-by-pulse basis. At the time of these measurements neither of these techniques was quite ready yet, but they are expected to be working soon.

OUTLOOK

The initial K-measurements made recently are encouraging. The spectrum of the undulator segments seen through the K-monochromator reasonably agrees with the simulation. The photodiode has good sensitivity and the electron energy scans can be done quickly. Systematic effects of observation angle and energy loss are well in hand. Noise levels are higher than expected, but by implementing pulse-by-pulse measurement of energy and peak bunch current, the noise associated with the electron beam energy can be reduced. This will help the fitting algorithm to more reliably find the electron energy with the steepest positive slope and better determine the spectral shift of each measurement.

The initial noise levels were too high for good two segment results. When the noise is reduced the two-segment method in conjunction with the one-segment method should improve the confidence of the results as well. We would also like to try to look at K-measurement using different harmonics, not just the first. The higher harmonics should have narrower bandwidth and more sensitive to electron energy change. Higher harmonics can be tuned onto the transmission energy of the K-monochromator by reducing the electron beam energy or using higher order crystal reflections of the K-monochromator.

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