Precision Measurement of the Undulator K Parameter using Spontaneous Radiation

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Topics

- Motivation
- Basic Scheme
- Theory of Two-Undulator Spectrum
- Details & Simulation
- Summary
Motivation for in-situ K Measurements

- The LCLS Undulator consists of 33, essentially identical, independent undulator segments.
- Errors in segment K (= 0.934 B [T] \( \lambda \) [cm]), cause errors in the phase between the electron beam wiggle and the x-ray radiation.
  - Loss of microbunching and FEL gain.
- Tolerance of \( \Delta K/K \leq 1.5 \times 10^{-4} \) is initially challenging, and must be maintained for years.
  - Temperature, alignment, radiation, presently unknown effects?... can easily change effective K.
- Direct in-situ magnetic measurements infeasible.
2-Segment Scheme

- Measure synchrotron radiation spectrum produced by two undulator segments, and scan K of one segment
  - Other schemes compare spectra from individual segments. (Pinhole technique, angle-integrated edge measurement, reference undulator)
- K’s are matched when spectrum has the steepest slope on high energy side of 1st harmonic peak.
- Match segments pairwise until all segments are measured.
Theor{y of Two Segment Spectrum

Spectral intensity depends on relative detuning and phase difference

Detuning parameters, $\nu_{1,2}$
Phase difference, $\phi$
Angle parameter, $\xi$
Spectral intensity, $I$
Includes angle energy correlation

$$\begin{align*}
\nu_1 &= \pi N \frac{\omega - \omega_1(0)}{\omega_1(0)} \\
\xi &= \pi N \theta^2 \frac{\omega}{2\omega_u} \\
\lambda_1 &= \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2\right)
\end{align*}$$

$$I(\nu_1, \nu_2, \xi, \phi) \propto \left| e^{i(\nu_1 + \xi)} \frac{\sin(\nu_1 + \xi)}{\nu_1 + \xi} + e^{-i(\nu_2 + \xi) - i\phi} \frac{\sin(\nu_2 + \xi)}{\nu_2 + \xi} \right|^2$$
Theory - Angle Integration

- Two identical segments
- Most signal comes from first 7-8 \( \mu \text{rad} \)
- 20 \( \mu \text{rad} \) is max angle for 1st segment (chamber limit)
- Maximum negative slope for \( K \) measurement doesn't depend on angle of integration much for angles \( \approx 7-8 \, \mu \text{rad} \) or more.

Steepest (negative) slope
Theory - Angle Integrated, 2 Detuned Segments

- Detuning segments produces slight slope/linewidth change
- 3% slope change for 0.1% K change
- Steepest negative slope will be used to track K.

![Graph showing the effect of detuning segments on photon energy distribution](image)
Details and Simulation

- Energy Jitter
- Alignment of Central Rays
- Phase difference
- Computer generated spectra plus noise
- Fitting details
Details

- Beam energy jitter, 0.1% rms.
  - Detector is assumed to be narrow bandwidth (<< 1/N), high efficiency, Si crystal, Bragg diffraction
  - Measure each pulse to $3 \times 10^{-5}$ and use to reconstruct the spectrum
  - Natural beam energy jitter is sufficient to sample region of steepest slope.

- Phase differences between segments
  - Shown to be negligible

- Alignment/Pointing errors
  - More than about 8 μrad beam angle will scrape core SR on the vacuum chamber and distort the high energy edge of the measured spectrum.

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Simulated Data

- Theoretical angle-integrated spectrum was generated for 9 different K values
- "Data" points include effects of resolution and statistics

![Graph showing simulated data with different K values and annotations for ΔK/K = +0.2%, ΔK/K = 0, and ΔK/K = -0.2%](image)
Noise effects that add error to the number of detected photons or the frequency

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Charge meas res.</td>
<td>0.5%</td>
</tr>
<tr>
<td>Energy jitter</td>
<td>0.1% rms</td>
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<tr>
<td>Energy meas. Res.</td>
<td>0.003% rms</td>
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<tr>
<td>E- angle jitter</td>
<td>0.5 μrad rms</td>
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<tr>
<td>Detector noise</td>
<td>100 photons rms</td>
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<tr>
<td>Peak signal</td>
<td>$10^5$ photons</td>
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Simulation - Steepest Slope Determination

- Steepest slope depends on $K$ difference, but not on spectrum absolute shift.
- Third order polynomial fit to truncated spectrum data easily yields steepest slope.

\[ N = N_0 + a(\Delta \omega / \omega) + b(\Delta \omega / \omega)^2 + c(\Delta \omega / \omega)^3 \]

\[ \left( \frac{dN}{(\Delta \omega / \omega)} \right)_{\text{max}} = a - \frac{b^2}{3c} \]
Finding $\Delta K = 0$

- Scan $K$ of one segment and find value that maximizes the steepest slope.
- Neglecting small energy loss between segments, the extremum value is when the segment $K$ values are identical.
- Simulation shows resolution of $\Delta K / K$ of 0.004% rms.
Summary

- Scanning K of one segment, keeping a second segment fixed, and fitting the measured spontaneous radiation spectrum, appears to be a useful method for determining the relative K values of nearby segments.

- Energy jitter is measured each pulse and used to reconstruct spectra.

- Beam angle/energy correlations are dealt with through angle integration and alignment of central rays.

- Phase difference effects are expected to be negligible.