UNDULATOR RADIATION MEASUREMENTS AT LCLS USING *K*-EDGE X-RAY ABSORPTION TECHNIQUES*

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Abstract

The sharp *K*-edge absorption energies in nickel and yttrium were exploited at LCLS to measure spectral features of spontaneous and FEL x-rays. By scanning the electron beam energy so that the first and third harmonic x-rays scanned across the nickel and yttrium *K*-edges, the resulting spectral features allowed the precise determination of the position of central ray and the resonant photon energy.

BACKGROUND

The LCLS is in the final stages of commissioning. We have been producing strong FEL x-ray beams with most of the complement of undulator segments installed, but the full suite of x-ray diagnostics has not yet been available. However, we are getting information about the x-ray beam properties from a temporary YAG crystal/camera combination and an insertable nickel foil. This timely information serves to confirm our expectations for the properties of the undulator radiation, provides initial photon-energy calibrations, and provides pointing data needed for precise undulator-strength comparisons to be made in coming weeks as the new x-ray diagnostics are commissioned.

THEORY AND METHOD

X-rays that have energy just sufficient to excite electrons bound in the *K* shell of an atom (the *K*-edge energy) are preferentially absorbed by the atom compared to x-rays whose energy is just below the *K*-edge. Figure 1 shows an example of the sharp change in transmission at the *K*-edge of yttrium in a YAG crystal. At the LCLS FEL facility we generate both FEL and spontaneous undulator x-rays whose energy depends on the electron beam energy. By changing the electron beam energy, the energy of the resulting x-rays can be made to sweep across the *K*-edge energy either of the yttrium component of a cerium doped YAG crystal, or of a nickel foil that can be inserted into the x-ray beam.

X-rays absorbed in the YAG crystal generate visible photons, detected by a camera. If the photons have energies just above the yttrium *K*-edge, they are preferentially absorbed in the YAG and therefore cause a brighter area. When the nickel foil is inserted in front of the YAG crystal, photons with energy above the nickel *K*-edge are preferentially absorbed by the nickel and leave a relatively dark area on the YAG. In either case, the *K*-edges provide precise x-ray energy discrimination.

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Of the two sources of x-rays used, FEL radiation is much simpler in that it consists mainly of a narrow beam of x-rays, primarily at the first harmonic. The spontaneous undulator radiation is more complex: spatially broader and consisting of many comparably strong harmonics. The on-axis, fundamental photon energy is determined from the resonance equation:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\tfrac{1}{2}K^2\right) \quad (1)$$

where λ is the x-ray wavelength, λ_u is the undulator period, γ is the electron energy in units of electron rest mass, and K is the undulator strength parameter (3.5, with some tunability, for LCLS). In the case of spontaneous undulator radiation, for angles small compared to K/γ, the spectrum contains many harmonics and is shifted by angle according to:

$$\lambda = \frac{\lambda_u}{2m\gamma^2}\left(1+\tfrac{1}{2}K^2+\gamma^2\theta^2\right) \quad (2)$$

Here θ is the angle from the central ray to the observation point and m is the harmonic number. From symmetry arguments, even harmonics must have no field on axis, while odd harmonics have a maximum on axis.

INSTRUMENTATION

The temporary diagnostic system shown in Fig. 2 is approximately 50 m downstream from the last undulator. This system contains, in order: a remotely controlled 1-µm-thick Be foil to block visible coherent light, a remotely controlled 10-µm Ni foil for *K*-edge measurements, and a fixed 100-µm-thick Ce-doped YAG crystal

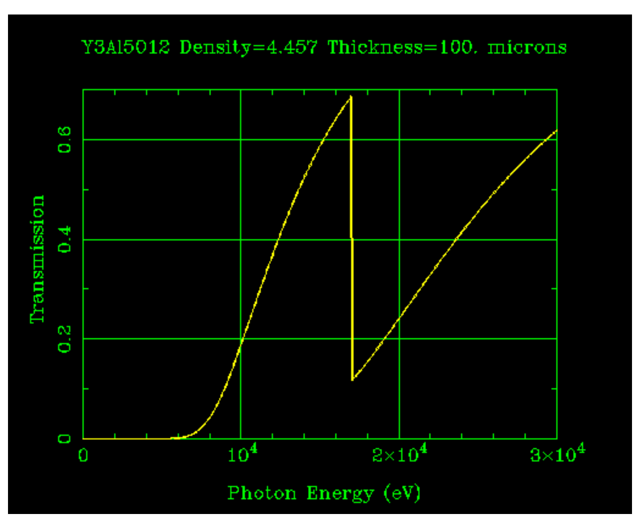

Figure 1: Transmission coefficient versus photon energy for YAG [2]. The yttrium K-edge occurs around 17 keV.

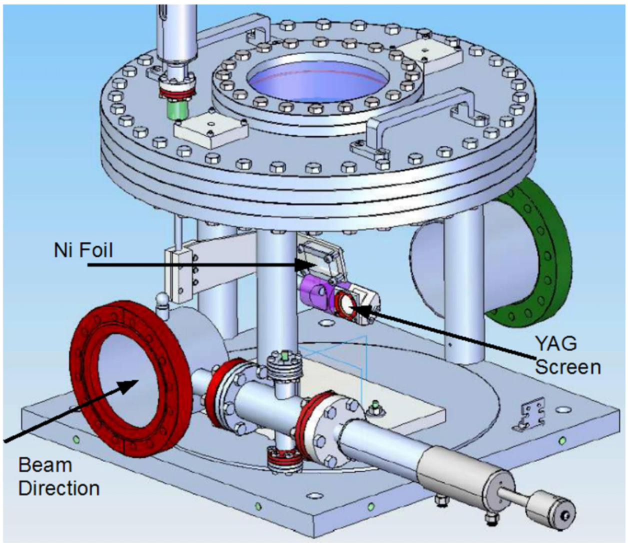

Figure 2: Temporary diagnostic assembly used in the measurements described this paper.

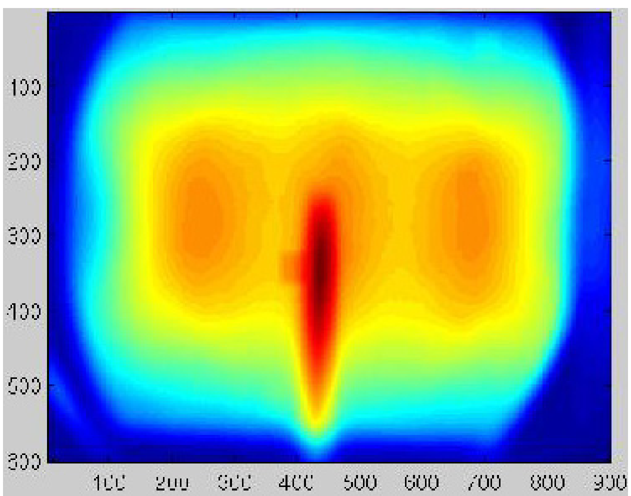

Figure 3: Spontaneous x-rays from one undulator segment as seen on the YAG crystal about 50 m downstream of the undulator. The central red stripe is cause by synchrotron radiation from the last dipoles. The three orange “humps” are the spatial signature of the 3rd harmonic.

as a fluorescence detector. A camera with 12-bit intensity resolution images the YAG at normal incidence using a mirror directly behind the crystal.

MEASUREMENTS

X-ray spatial and spectral measurements are described in this section. Most involve very effective image subtraction and smoothing techniques.

Harmonic Spatial Distributions

Angle-energy correlation of spontaneous synchrotron radiation, combined with the spectral discrimination of *K*-edges can be used to image various spatial harmonics present in the undulator spontaneous radiation. For

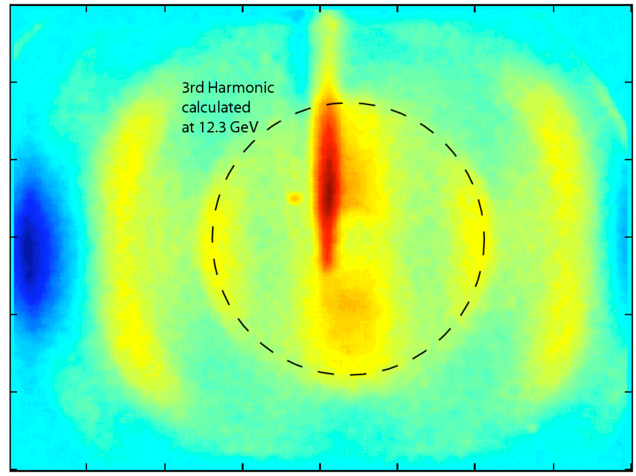

Figure 4: Difference of images taken with 12.3- and 11.3-GeV beams of spontaneous emission from one undulator segment. The dashed ring shows the predicted peak of 3rd-harmonic radiation, coinciding with the two partial rings in the image. Additional harmonics are also visible: the 2nd has two lobes above and below the middle, and the 5th harmonic appears as partial rings at higher angles.

example, even without image subtraction, third-harmonic structure is clearly visible in the image of Fig. 3.

Off-axis rays can be highly red-shifted. At high enough angles, several harmonics will have a resonant energy that is near the *K*-edge of the nickel foil. By subtracting images made with suitably chosen electron-beam energies, these harmonics become visible, as shown in Fig. 4, where we see three harmonics with the expected symmetries.

Determination of the Central Ray

Determining the central ray of spontaneous radiation is important in calibrating the x-ray energy spectrum and avoiding systematic errors when comparing two spectra. Even small errors, of order a few microradians, will shift the energy spectrum outside the tolerance of a few parts in 10^4 needed for undulator strength measurement.

The central ray has the most blue-shifted photon-energy spectrum. Figure 5 shows two images, taken with central energies just above and just below the nickel *K*-edge. While the central ray cannot be determined in either image alone, the difference image below gives a clear measurement of the position of the central ray from an undulator segment. X-rays emitted on axis have the highest energy spectrum and are the first to be preferentially absorbed by the nickel as the electron-beam energy is scanned upward. Figure 6 shows this clearly, with a dark central spot corresponding to the central ray. (Darkening also depends, of course, on using the appropriate sign in the image subtraction.)

FEL Spectrum

A calibration of the FEL photon energy around the first harmonic is shown in Fig. 7, where total intensity of the FEL image was plotted against the electron-beam energy

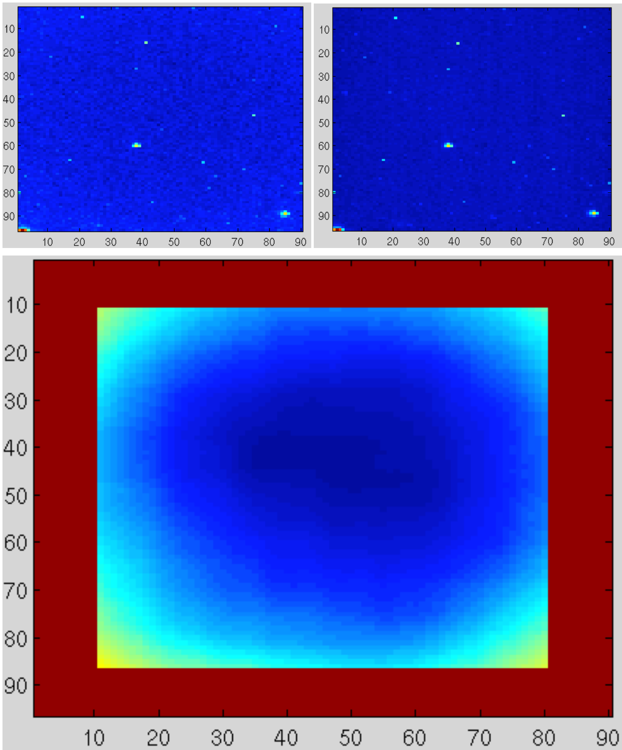

Figure 5: The upper two images were taken at slightly different electron energies corresponding to on-axis x-rays above (left) and below (right) the Ni *K*-edge. These are combined and filtered to produce a relatively clean image, shown enlarged in the lower frame, of only photons near the *K*-edge. The center of the resulting hole can be determined to within a few pixels.

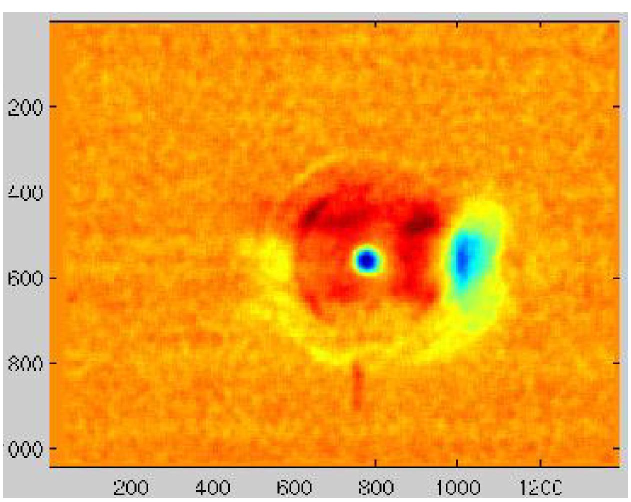

Figure 6: Difference image taken across the nickel K-edge. The dark central spot occurs coincides with the central rays from the undulator segment.

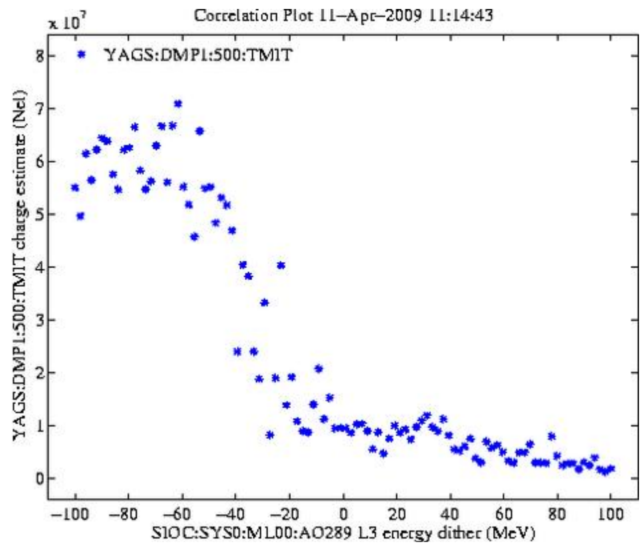

Figure 7: Energy scan of the FEL radiation, which is mostly 1st harmonic, incident on a 10-µm nickel foil. This scan calibrates the machine energy in GeV and the strength of the undulator segment against the nickel *K*-edge, where the transmission drops.

shift. When the electron energy is such that the central photon energy is right on the nickel *K*-edge, the signal drops by half. This occurs around −30 MeV relative to the electron reference energy of 13.740 GeV, i.e., at 13.710 GeV. Tabulated values give the *K*-edge of Ni at 8330 eV. If the true electron energy is 13.710 GeV, (the value derived from magnetic measurements of dipole magnets), then based on the design undulator period and measured strength, the resonant photon energy should be at 8363 eV—about 0.4% higher than the tabulated value. The difference could be explained by an error in the electron beam reference energy of 0.2%.

REFERENCES

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[2] http://henke.lbl.gov/optical_constants/filter2.html