COMPARISON OF HARD X-RAY SELF-SEEDING WITH SASE AFTER A MONOCHROMATOR AT LCLS*

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Abstract

Self-seeding using hard x-rays was demonstrated at LCLS in January 2012 and produced a factor of 40-50 bandwidth reduction from normal SASE operation. For many hard x-ray users, the photon intensity after a monochromator is an important performance parameter, whether or not the beam is seeded or SASE. In this paper, we report results from a study of self-seeding performance using the Si (111) K- monochromator with a full bandwidth of 1.2 eV at 8.2 keV. These include a direct comparison of the average intensity of the monochromatized seeded beam with that of a monochromatized fully tuned-up SASE beam, in both cases using 150 pC bunch charge.

SEEDING AT LCLS

The main goal of the hard x-ray self-seeding project at LCLS is to increase the peak spectral brightness. Near-monochromatic beams of hard x-rays can be manipulated efficiently using bragg reflection, rather than low incidence angle x-ray mirrors and long drift spaces, and allow for complex beam manipulation such as split and delay [1] similar to what is done with conventional laser beams.

LCLS [2] was designed to operate in the SASE mode, where shot noise in the electron beam is amplified by the FEL process producing x-ray beams with RMS bandwidths that are typically of order the FEL ρ parameter [3, 4]. By seeding the FEL with near-monochromatic x-rays, the output bandwidth can be drastically reduced, provided the seed power is sufficient to overcome the relatively broad band power fluctuations due to shot noise.

In an upgrade to LCLS [5], originally proposed by Geloni, et. al. [6], a seed pulse is generated by sending the SASE output from the first $\sim$ 45 m of undulator, called 'U1', through a thin diamond crystal set at the bragg angle. The effect of the crystal is to generate a near-monochromatic 'ringing' in the transmitted x-ray beam which forms the x-ray seed. A short 4 m electron beam chicane diverts the electron beam around the crystal, smears out any micro-bunching from U1, and provides the proper time delay between the electron bunch and the seed x-rays. The downstream $\sim$ 68 m of undulator amplify the seed ultimately to reach saturation levels. An overview showing the seeding chicane and the LCLS undulator is given in Fig. 1.

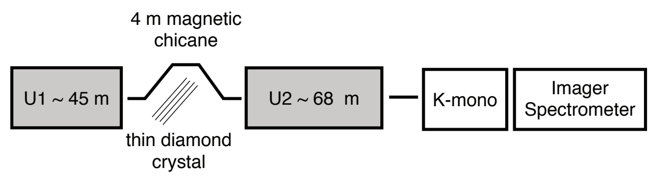

Figure 1: Schematic of hard x-ray seeding at LCLS.

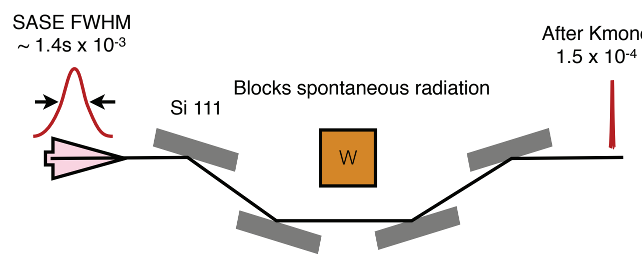

Figure 2: Functional schematic of the K-monochromator.

Since the seeding chicane and crystal were installed in LCLS and commissioned [7] various configurations for seeding have been investigated. These include seeding with relatively long pulses, different crystal planes including 004, 220, 133, and 111; and simultaneous seeding from 004 and 220. All of these configurations have produced seeded beams.

The K-monochromator (Kmono)

A single purpose monochromator was originally developed and installed in LCLS for precision measurement of undulator K-parameters [8]. It has found a new function as a tuning aid for self-seeding operation. The device, shown schematically in Fig. 2, is designed so that there are four bragg reflections of x-ray beam from Si 111 planes resulting in no net deflection of the beam. Because of the four bounce arrangement the device only transmits one energy (8194 eV) with a bandwidth of 1.2 eV and for one angle of incidence. It has a large acceptance area, no cooling, and is located about 90 meters from the end of the undulator

The Kmono transmits only about one-tenth of the output SASE spectrum, but essentially 100% of a seeded spectrum. Thus, when tuning on the intensity seen through the Kmono the SASE contribution to the overall transmitted intensity, which can otherwise dominate, is greatly reduced, and the peak spectral brightness is optimized rather than the overall pulse energy.

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Other Diagnostics

Two spectrometers have also been employed for seeding studies, both based on the same bent-crystal technique [9]. A semi-permanent spectrometer is available for use for, or very near, 8450 eV, while a temporary spectrometer can be set up in the XPP experimental area to work at other x-ray energies. In addition a gas detector and a YAG screen provide measures of the total x-ray pulse energy, though without any spectral information.

MEASUREMENTS

Peak Spectral Brightness

Besides the amplified seeded line, the broad-band SASE power generated in U1 and U2 is also present in the output beam. Depending on the detailed tune-up of the electron beam and the undulator, the overall pulse energy can be predominately either seeded or SASE.

Using the Kmono the relative peak spectral brightness of seeded vs SASE beams can be measured directly and optimized. In Fig. 3 are histograms of two sets of data. The data labeled "SASE" was taken with LCLS tuned for maximum pulse energy for normal SASE operation (about 2 mJ at the time); the seeding chicane was turned off, and the FEL phase optimized for maximum pulse energy. The data labeled "Seeded" was taken shortly afterward with LCLS tuned for maximum seeding power and normalized to the SASE data to account for a small difference in the attenuation used. The data show that after the Kmono the Seeded beam was an average of 3.4 times more intense than the tuned-up SASE beam.

Measurements of the spectrum of the seeded beam typically show a reduction from the SASE bandwidth of about a factor of 40-50, yet the Kmono measurements indicate an increase of peak spectral brightness of only ≈ 3. There are several factors which help explain factor of ≈ 15 difference from what one would expect if all the beam were seeded.

- Jitter in the electron beam energy, discussed in the following section, causes most of the shots to be off-resonace and not to seed well, thus reducing the average brightness of the seeded beam. This typically results in about a factor of two reduction in the average intensity of the seeded beam. Reduction in the electron energy jitter would therefore increase the average seed beam brightness.
- The Kmono bandwidth is 2-4 times larger than the typical seeded bandwidth, so the apparent peak spectral brightness is diluted by a factor of $1/2 - 1/4$.
- The length of the seeding undulator U2, is considerably shorter than the length of the SASE undulator, which is effectively U1+U2. As a result the seeded beam is not as saturated as the SASE beam. Additional undulator segments in U2 would drive the beam further into saturation and increase the seeded beam intensity.

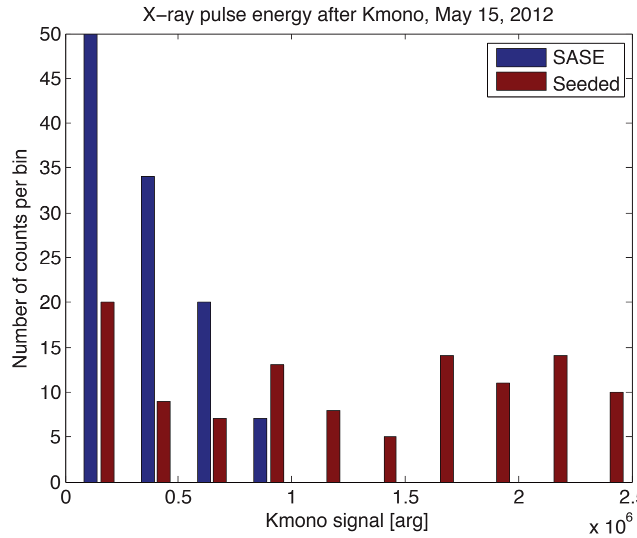

Figure 3: Histograms of intensity after the Kmono for tuned-up SASE operation and for a seeded beam.

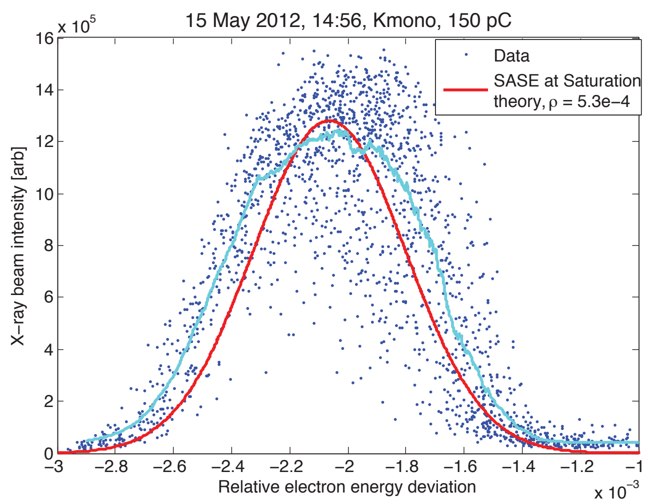

Figure 4: Correlation of electron energy with the x-ray intensity (pulse energy) after passing the seeded beam through the Kmono. The cyan curve is a running average while the red curve is a theoretical curve shown for reference.

Electron Energy Jitter

Considerable information may be gleaned from a study of the data shown in Fig. 4. Plotted is the correlation of the intensity of x-ray beam that passes through the Kmono, against the relative electron energy deviation. For reference a gaussian with a standard deviation equal to $\rho/2$ is plotted in red, and a moving average of the data is plotted in cyan. Electron energy jitters from shot to shot due to small fluctuations in the phase of RF in the Linac. Typically for hard x-ray operation, the electron relative energy jitter is less than, but comparable to $\rho/2$, so it contributes to the overall average spectral width but does't dominate it.

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In seeded operation there are two effects of electron energy jitter: one is to detune the electron beam from resonance at the seeding wavelength, the other is to add fluctuations to the seed power beyond the statistical fluctuations from shot noise. In either case the net effect is to reduce the peak spectral brightness as seen through the Kmono. If the Kmono were not present when taking the data as in Fig. 4, the total x-ray pulse energy would be detected and unseeded pulses would be difficult to distinguish from seeded pulses. The flattened shape of the cyan curve (moving average) in Fig. 4, compared with the reference gaussian, is suggestive of saturation effects.

Thus the Kmono helps to show the real effect of the electron energy jitter on the peak spectral brightness. From Fig. 4 one can infer that reducing the electron energy jitter to an RMS of approximately $\rho/2 \approx 2 \times 10^{-4}$, will both substantially increase the average seeding power and reduce the level of fluctuations from shot to shot. If all the data in Fig 4 is included, the ratio of the RMS to average intensity is 71%. If only the central core representing shots with low electron jitter is included, the ratio is reduced to 21% and the average intensity approximately doubles.

SASE Bandwidth

SASE spectrum measurements made using the HXSSS spectrometer [9] at 8465 eV with the seeding chicane in SASE mode (no crystal and chicane turned off, FEL phase set to maximize the SASE output) are shown in Fig. 5. The SASE radiation from U1 incident at the seeding chicane was measured by kicking the orbit at the chicane, effectively turning off FEL gain from U2. The spectrum at the output of the undulator is primarily generated by U2, after the seeding chicane, but includes a small contribution from U1. The width of the spectrum from U1, 22 eV, is almost three times larger than the SASE output from U2, 9 eV. And the measured output spectral width, 9 eV, can be compared with the calculated value for the spectral width at saturation (eq. 85 in [3]) which is about 6 eV FWHM. Note in SASE mode, electron energy jitter can contribute to the average spectral width.

Intensity vs. Crystal Angle

One of the first steps is setting up seeding operation is to adjust the seeding crystal angle to center the bragg reflection wavelength on the SASE spectrum. When the Kmono is present the angle must be very precisely found because the bragg angle must correspond to the relatively narrow range of wavelengths the Kmono will pass. Examples of this tuning are shown in Fig. 6 where the crystal planes associated with the peaks have been identified, going from left to right, as 004, 133, and 220. The normals to the 004 and 220 planes are both perpendicular to the crystal rotation axis. The 133 plane is an asymmetric bragg reflection.

Spatial Profile

When seeded, the average spatial distribution of the FEL beam is typically narrower than for SASE, and when the Kmono is inserted into the seeded beam the profile becomes even narrower and more uniform. One example of measurements made on the seeded beam with the NFOV imager yields beam sizes in microns without (with) the Kmono inserted of: $\sigma_x = 246(166)$ $\sigma_y = 163(142)$. It is thought that the effective source point of the SASE radiation is further upstream than it is for the seeded radiation, so the SASE contribution to the x-ray pulse tends to generate larger spot sizes.

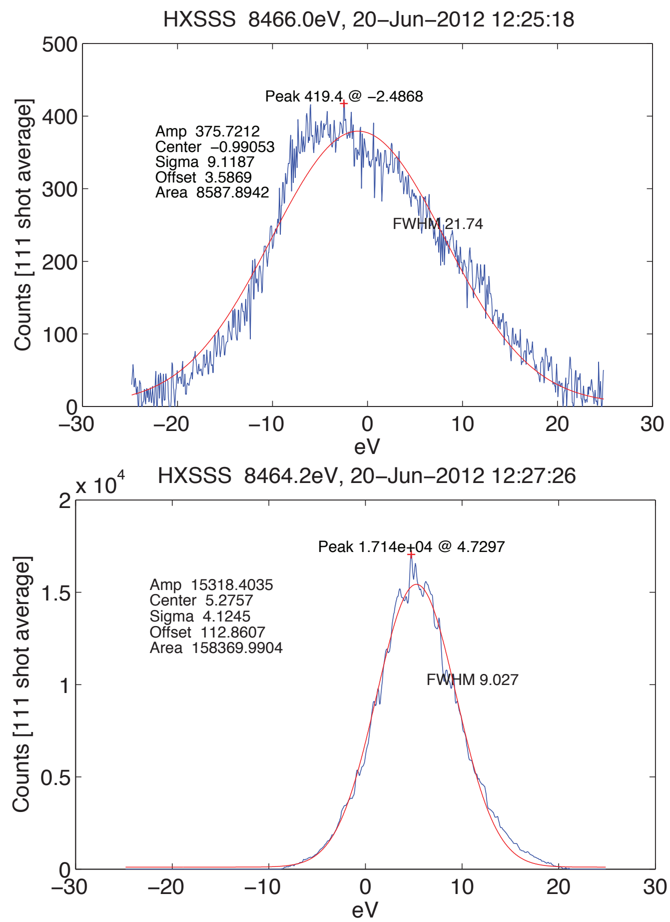

Figure 5: Average SASE spectrum at the seeding chicane (top) and at the output of LCLS (bottom) for normal SASE operation.

CONCLUSION

Self-seeding works well for long pulses as well as short, and for various crystal planes. Measurements with the Kmono facilitate tune-up and interpretation by reducing the SASE contribution and by providing a fixed direct measure of the peak spectral brightness. Comparing the intensity seen through a monochromator, self-seeding beams are typically at least 3 times stronger that the best tuned-up SASE beams without self-seeding. This increase in average spectral brightness in hard x-rays will be available for LCLS experimenters to use starting in the Fall of 2012.

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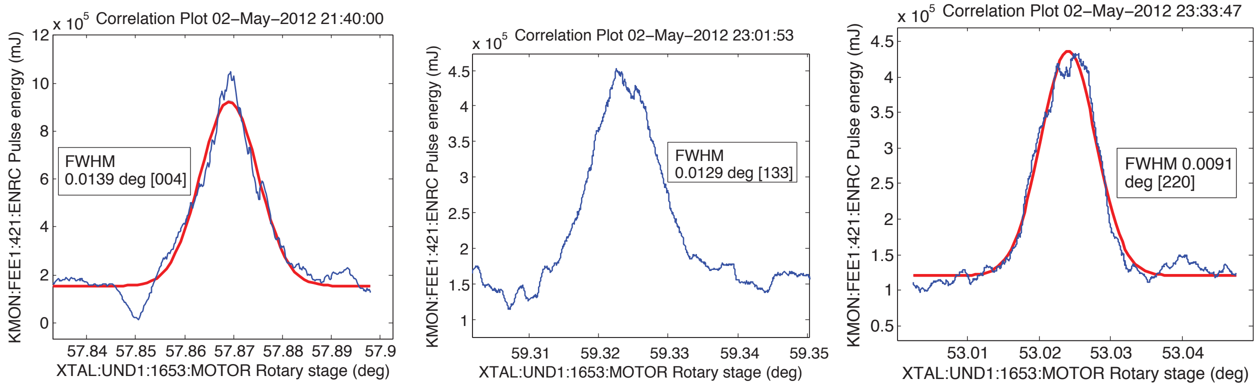

Figure 6: Intensity after the Kmono as a function of the seeding crystal angle for three different crystal planes.

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