

# SECOND AND THIRD HARMONIC MEASUREMENTS AT THE LINAC COHERENT LIGHT SOURCE

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## INTRODUCTION

The Linac Coherent Light Source (LCLS) started user commissioning in October of 2009, producing Free Electron Laser (FEL) radiation between 800 eV and 8 keV [1]. The fundamental wavelength of the FEL dominates radiation in the beamlines, but the beam also produces non-negligible levels of radiation at higher harmonics. The harmonics may be desirable as a source of harder X-rays, but may also contribute backgrounds to user experiments.

In this paper we present preliminary measurements of the second and third harmonic content in the FEL. We also measure the photon energy cutoff of the soft X-ray mirrors to determine the extent to which higher harmonics reach the experimental stations.

## METHODS

X-ray intensity measurements are obtained either from a gas detector or YAG screen [2]. For each YAG image, we average up to 100 shots from the FEL. Though we subtract a dark (no beam) background, spontaneous radiation is still present. To determine the pulse intensity, we fit a Gaussian profile to the YAG image and calculate the area under the curve.

Our main task is to separate the FEL by photon energy to find the harmonic content. The sum of all higher harmonics represent at most a few percent of the FEL beam, so we consider the total intensity measurements (from the gas detectors or YAG screens) as a first order approximation of the fundamental pulse energy. We measure the third harmonic by inserting a solid attenuator (either beryllium or zirconium) into the X-ray beam (Fig. 1). As an example, the zirconium filter cuts the X-ray intensity by 7 orders of magnitude for 8 keV photons, but cuts the third harmonic (24 keV) by less than an order of magnitude. (Higher harmonics are not suppressed, but are emitted at lower levels by the FEL process.)

The second harmonic, sandwiched between the stronger first and third harmonics, can be measured in the experimental beamlines. Solid or gas attenuators block the fundamental, letting only higher harmonics pass. The mirrors that direct the radiation to the experimental beamlines have a cutoff photon energy, above which the radiation is absorbed. By limiting ourselves to FEL photon energies between  $1/3$  and  $1/2$  of the cutoff, the mirrors pass the second harmonic while absorbing the third harmonic (Fig. 2). With the low energy photons absorbed in the attenuators, and the high energy photons absorbed in the mirrors, only the sec-

ond harmonic remains in the experimental beamlines. An example image of the second harmonic is given in Fig. 3, showing the characteristic double lobe structure.

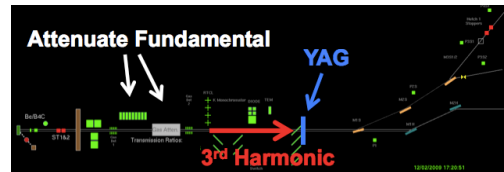


Figure 1: Schematic of the third harmonic measurement. Attenuators block the fundamental and second harmonic, allowing measurement of the third harmonic on a YAG screen.



Figure 2: Schematic of the second harmonic measurement. The fundamental is absorbed by attenuators and the third harmonic is absorbed by the beamline mirrors.

## MIRROR CUTOFF

To determine the level of second harmonic reaching the experimental stations, we measure the photon cutoff energy of the beamline mirrors. A series of three glancing incidence mirrors diverts the X-ray beam to the soft X-ray experimental halls. The mirrors absorb hard X-ray radiation, which does not reach the soft X-ray experimental stations. YAG screens following the second and third mirrors (P2S and P3S respectively) measure X-ray pulse energy. We determined the mirror cutoff energy by two methods. First, we measured the ratio of intensities on P3S and P2S as a function of photon energy. Assuming all three mirrors are identical, we plot the cube of this ratio as the total transmission of the mirrors (Fig. 4). However, we note that the transmission of each stage may differ if the mirror aperture cuts a portion of the beam (Fig. 5). As a semi-independent method, we also compare the signal on P3S to the total incoming power measured in gas detectors, located upstream of the mirrors. Results of both methods are plotted in Fig. 6, showing a cutoff energy of approximately 2.3 keV.

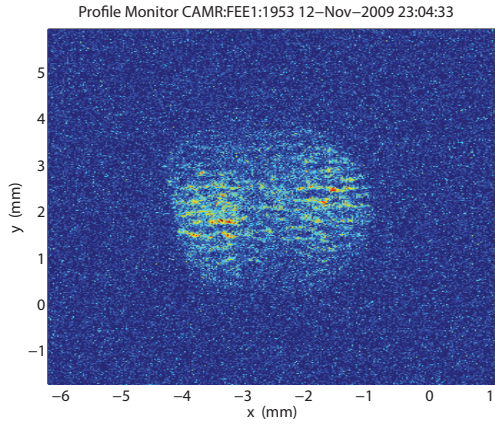


Figure 3: An example image of the second harmonic in the soft X-ray beam line (P3S). The characteristic double lobe structure of the second harmonic is evident. Though gas and solid attenuators strongly suppress the fundamental, a small amount of fundamental radiation remains (gaussian mode background).

A second set of mirrors directs hard X-rays into the X-ray pump-probe hutch. An equivalent study for the hard X-ray line will be completed in the future.

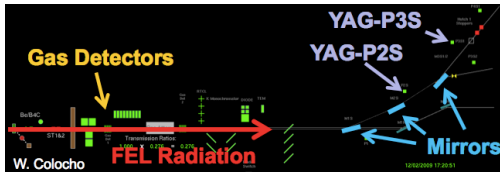


Figure 4: Schematic of the mirror cutoff measurement. The ratio of intensities measured on YAG screens P3S and P2S gives the transmission for a single mirror, and the total transmission is assumed to be the cube of this ratio. Alternatively, the intensity on P3S (downstream of all mirrors) can be compared directly against the intensity at the gas detector (upstream of all mirrors).

## HARMONIC MEASUREMENTS

### Third Harmonic

To measure the third harmonic, we block the fundamental with either beryllium or zirconium attenuators. (The attenuation also blocks the weaker second harmonic.) To find the relative power of the third harmonic, we can simply take the ratio of intensities on the YAG screen when the attenuator is inserted (third harmonic) and removed (fundamental). For 900 eV and 1.7 keV fundamental photons, we find approximately 2% and 3% harmonic content respectively.

Alternatively, we can use the attenuators' dependence on the photon energy to estimate the harmonic content. The total intensity is proportional to

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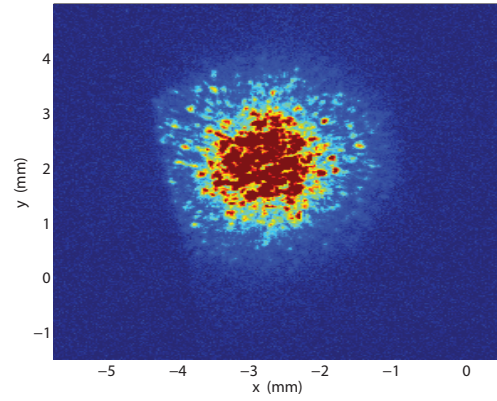


Figure 5: Image of the fundamental FEL signal following the third soft X-ray mirror. The sharp edge on the left side suggests the beam has been cut by an aperture. The speckle pattern is due to diffraction from a beryllium attenuator.

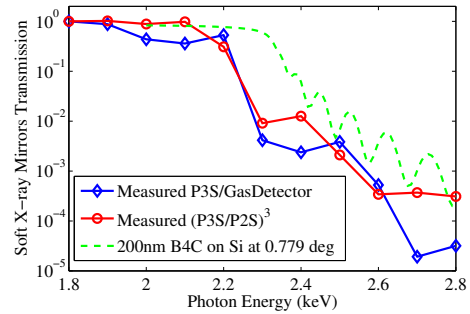


Figure 6: Transmission plot of the soft X-ray optics line as a function of radiation wavelength. The red curve is the cube of the ratio of intensities measured following the third and second mirrors. The blue curve gives the ratio of the intensity following the third mirror to the full pulse energy in the gas detector, normalized to one at 1.8 keV. The slight discrepancy with the theoretical curve (green) may be due to either uncertainty in the electron energy (2.5% higher energy matches) or slight misalignment of the mirror (4% larger matches) [3].

$$I \propto T_1 P_1 + T_2 P_2 + T_3 P_3 + \text{higher harmonics}, \quad (1)$$

with attenuator transmission,  $T_h$ , mirror transmission  $M_h$ , and power,  $P_h$  for harmonic number  $h$ . Neglecting the weaker second and higher harmonics, we find

$$I \propto T_1 + T_3 \frac{P_3}{P_1}. \quad (2)$$

Changing the thickness of the beryllium attenuators ( $T_1$  and  $T_3$ ), we measure the intensity,  $I$ , and then estimate the ratio of the harmonics,  $P_3/P_1$ . The result is found in Figs. 7-9, showing 0.5-2% third harmonic content. For the 6 keV case, we can also measure the third harmonic by

inserting a zirconium filter. The drop in intensity across the 18 keV zirconium K-edge corresponds to the third harmonic, and confirms the approximately 1% third harmonic content.

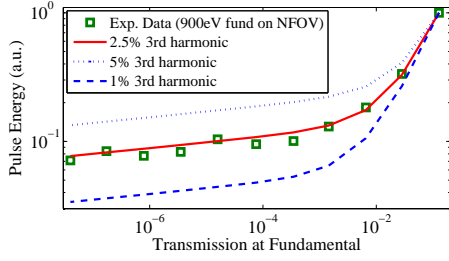


Figure 7: Measured pulse energy vs. gas attenuator strength. Measurement is for a fundamental photon energy of 900 eV, with fundamental pulse energy of 1.4 mJ, and corresponds to approximately 2.5% third harmonic. In all attenuator-scan plots, the analytical curves are guides to the eye, rather than fits to the data.

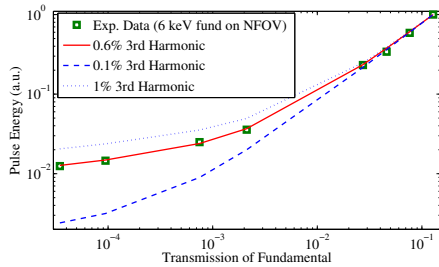


Figure 8: Measured pulse energy vs. gas attenuator strength. Measurement is for a fundamental photon energy of 6 keV, with fundamental pulse energy of 0.6 mJ, and corresponds to approximately 0.6% third harmonic.

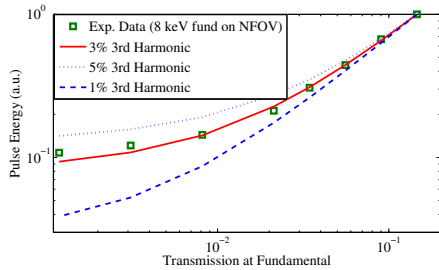


Figure 9: Measured pulse energy vs. gas attenuator strength. Measurement is for a fundamental photon energy of 8 keV, with fundamental pulse energy of 1.5 mJ, and corresponds to approximately 3% third harmonic.

At lower photon energies, we assume the YAG response to the fundamental and third harmonic is equivalent. However, as the photon energy increases, the YAG screen may not fully absorb the third harmonic. For the 6 keV measurement, the third harmonic is still largely absorbed in a 100

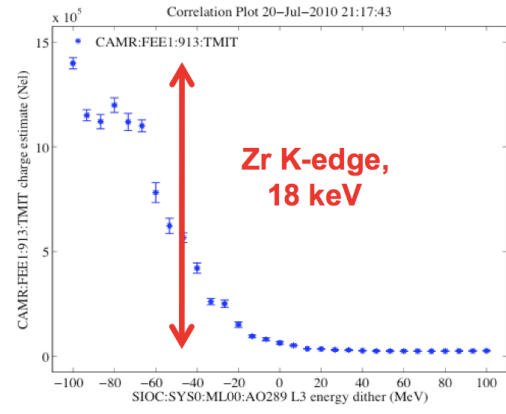


Figure 10: Plot of measured intensity on the YAG screen (Y-axis) vs. electron energy (X-axis), with the FEL tuned to 6 keV fundamental and zirconium filter inserted. The drop-off in signal as the photon energy crosses the K-edge (18 keV) corresponds to the third harmonic. Removing the zirconium filter to measure the fundamental, we find approximately 1% third harmonic, confirming the results of Fig. 8.

$\mu\text{m}$  YAG due to the yttrium K-edge at 17 keV. At 8 keV, approximately 40% of the third harmonic passes through the 100  $\mu\text{m}$  YAG, so we scale the intensity accordingly.

The proportion of harmonics present varies depending on the performance of the fundamental. The lowest and highest harmonic contents were measured with 0.6 mJ and 1.5 mJ fundamental pulse energy respectively. We note that the measured third harmonic content is consistent with the expected level [4, 5].

### Second Harmonic

The second harmonic is expected to be weaker than the third harmonic due to the symmetry of planar undulators. (However, the bunching is stronger at the second harmonic, which can be exploited with second harmonic afterburners if more harmonic radiation is desired [6].)

To measure the second harmonic component we again vary the attenuation and estimate the ratio  $P_2/P_1$  from the intensity

$$I \propto T_1 M_1^3 + T_2 M_2^3 \frac{P_2}{P_1}. \quad (3)$$

To change the attenuation level, we can either directly scan the gas attenuator pressure, or can scan the fundamental energy (which also results in a change of attenuation). The results are shown in Figs. 11, 12, and 13.

Both methods are sensitive to the transmission value at the fundamental. Because the fundamental is suppressed by as many as 7 attenuation lengths, even a 10% error in the attenuation length gives a factor of 2 error in the transmission. When the attenuation is strongest, the proportion of signal at the fundamental is negligible and the error in attenuation can be ignored. However, even at the lowest

level of attenuation (3 attenuation lengths for soft X-rays), the same error changes the transmission by 30%. The gas attenuator is designed for 1% accuracy, but has not been measured independently.

third harmonic content ranging from 0.5% to 3%, which is consistent with expectations. For both second and third harmonics, experimental work is ongoing. More rigorous analysis of the data will be completed soon.

## ACKNOWLEDGEMENTS

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## REFERENCES

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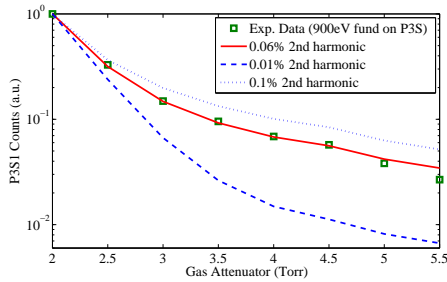


Figure 11: Second harmonic component is estimated by varying the gas attenuator strength for a fundamental photon energy of 900 eV.

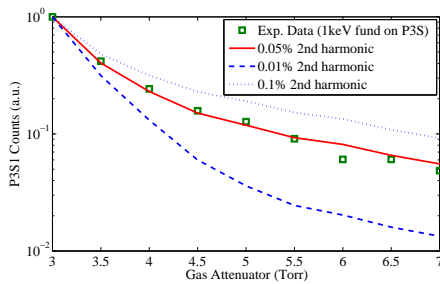


Figure 12: Second harmonic component is estimated by varying the gas attenuator strength for a fundamental photon energy of 1 keV.

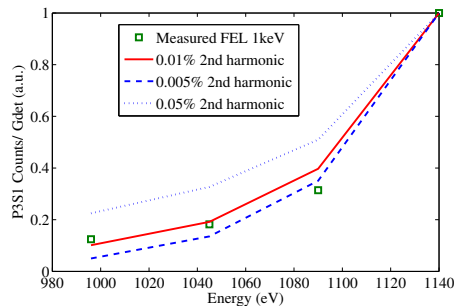


Figure 13: Second harmonic component is estimated by varying the fundamental photon energy.

## CONCLUSION

We present preliminary second and third harmonic measurements for LCLS. At low energies (below 1 keV fundamental) we measure less than 0.1% second harmonic content. The second harmonic will be present in the soft X-ray beam line for fundamental photon energies below approximately 1.1 keV. At low and high energies, we measure