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STUDY OF XFEL THIRD HARMONIC RADIATION AT LCLS

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Abstract

In this paper, we focus on characterization of the nonlinear third harmonic radiation properties at Linac Coherent Light Source (LCLS). In addition, we experimentally perform third harmonic self-seeding, using diamond crystal attenuator in the hard X-ray self-seeding chicane. We discuss warm beam effects in such scheme, justifying recently proposed two bunch configuration for harmonic lasing.

INTRODUCTION

In this paper we report on the measurement and spectral characterization of third harmonic radiation at the LCLS. Our analysis describes the radiation properties in the nonlinear harmonic generation (HG) regime and the linear amplification of a harmonic seed in a split undulator with fixed K in both undulator sections and a single spectral filter between them. A schematic of the experiment is shown in Fig. 1. These results are a direct measurement of linear harmonic amplification in a fixed-gap undulator and point towards the realization of more complicated harmonic lasing schemes with multiple bunches or multiple filters/phase shifters [1].

THEORETICAL CONSIDERATIONS

Fundamental photon wavelength in the FEL is defined by resonance condition:

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

where λ is the FEL radiation wavelength, λ_u is the undulator period with magnetic parameter K. In addition, odd higher harmonics generated on axis, obey the following relation:

$$\lambda_h = \frac{\lambda}{h}, \quad (2)$$

where $h = 3, 5, 7$ is the odd harmonic number. Commonly used Ming Xie formalism for FEL gain length calculation, can be also extended to the case of odd harmonics [2]. We have evaluated the gain lengths of both fundamental and third harmonic at LCLS for the range of nominal operational parameters and the results are presented in Fig. 1

Harmonics of the fundamental can be generated in FELs in a planar undulator through two distinct processes: harmonic lasing (HL) and nonlinear harmonic generation (NHG). These processes result in radiation with different properties and have different advantages and disadvantages. In this paper, we attempt to observe both processes and a transition between them. In 1D-theory, the process of harmonic generation can be described by the following system of equations: can be written as follows [1, 3]:

$$\begin{aligned}
\frac{d\theta_j}{dz} &= k_w \times \left(1 - \frac{\gamma_r^2}{\gamma_j^2}\right) \\
\frac{d\gamma_j}{dz} &= \frac{\chi_1}{\gamma_j} * \Re\left\{K_1 E_1(z) e^{i\theta_j} + K_3 E_3(z) e^{3i\theta_j}\right\} \\
\frac{dE_1}{dz} &= -\chi_2 K_1 \left\langle e^{i\theta_j}\right\rangle \\
\frac{dE_3}{dz} &= -\chi_2 K_3 \left\langle e^{3i\theta_j}\right\rangle,
\end{aligned} \quad (3)$$

where (θ_j, γ_j) are the longitudinal phase-space coordinates, $E_1(z)$ is the fundamental electric field, $E_3(z)$ is the third harmonic electric field, $\chi_1 = 1/2m_e c^2$ and $\chi_2 = I/8\pi\epsilon_0 c\sigma_e^2$, the resonant energy $\gamma_r^2 = \lambda_w/2\lambda_s\left(1 + K^2/2\right)$, and $K_h = K * [JJ]_h$ is the harmonic coupling which decreases for higher harmonic number h.

Initially, fundamental and third harmonic evolve independently, due to small coupling in Eqs. (3). When the bunching at the fundamental frequency becomes more prominent, it drives the bunching of the harmonic frequency nonlinearly, therefore harmonic becomes strongly dependent on the fundamental field. In order to keep the linear growth of the third harmonic, one has to disrupt the fundamental bunching, e.g. by means of phase-shifters or crystal attenuators in chicanes, or both.

Harmonic lasing can be used to extend the wavelength range of free electron lasers (FELs), or to reduce the electron beam energy for the same x-ray wavelength. For HL, the FEL instability is driven at the harmonic wavelength and consequently one can theoretically achieve higher intensity ($\sim 1/h$ times the fundamental intensity, were h is the harmonic number) with narrower bandwidth and improved shot-to-shot stability compared to nonlinear HG [2]. In a single-pass FEL, HL can reach high intensity if the gain at the fundamental wavelength is repeatedly disrupted such that the increase in electron slice energy spread does not halt the growth of the harmonic. Previous studies have consid-

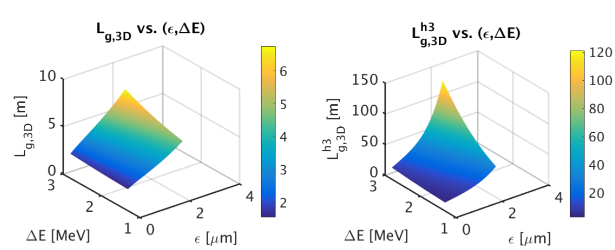

Figure 1: Ming Xie estimate of the gain length for the fundamental (left) and third harmonic (right) at 2 keV and 6 keV respectively as a function of beam emittance and energy spread.

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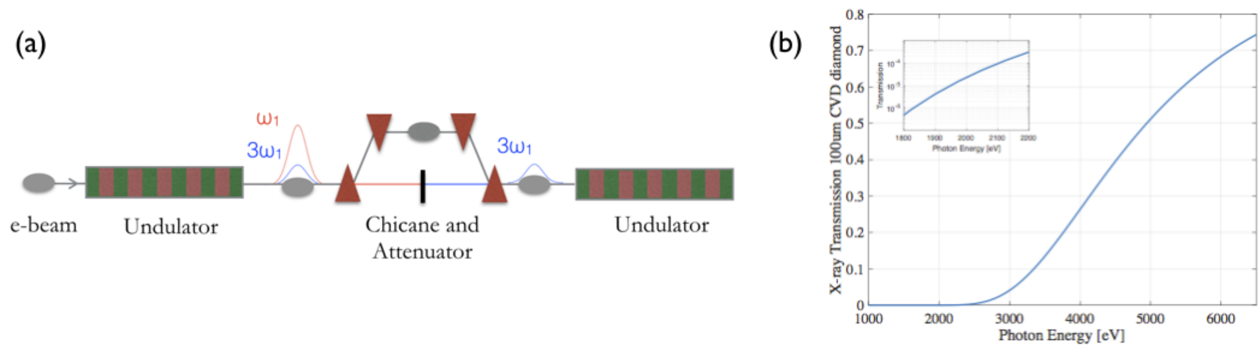

Figure 2: (a) Schematic of the experiment measuring third harmonic radiation at LCLS with a single spectral filter between two undulator sections. (b) Attenuator transmission as a function of photon energy.

ered achieving this by introducing periodic spectral filters or phase shifters in the undulator system (see e.g. Ref. [2]) and various schemes for harmonic lasing and harmonic self-seeding have been discussed in the literature. Specifically harmonic lasing self-seeding, which is possible only using gap-tunable undulators, has recently been demonstrated at EUV wavelengths at the FLASH2 facility [2] and at Pohang Accelerator Laboratory [4].

For LCLS-II or other future FEL facilities, HL is an attractive method for reducing the FEL gain length at short wavelengths and may potentially be used as an improved mode of operation for users [5]. Our measurements characterize the growth of the third harmonic, with results directly applicable to future schemes.

EXPERIMENTAL SETUP

A schematic for the the setup of our experiment is shown in Fig. 2. The LCLS undulator beamline was tuned to 2 keV fundamental photon energy, yielding 6 keV radiation in the third harmonic. We used the gas detector to record total intensity of the fundamental radiation, and a bent crystal spectrometer to measure the third harmonic spectrum. The attenuator used in the experiment was the 100 um thick diamond self-seeding crystal with a transmission of 2.3×10^{-5} at 2 keV and 68.4% at 6 keV.

FEL GAIN MESUREMENTS

We first performed gain measurement of the fundamental and nonlinear third harmonic as a function of undulator length; see Fig. 3. Integrating spectrum over the spectrometer bandwidth yields the total intensity. We used pre-experiment GENESIS simulations to calibrate gas detector readings with the integrated counts of the spectrometer.

We recorded the fundamental and harmonic data between U10 and U15 sections, where the nonlinear third harmonic fully develops while fundamental starts to reach saturation. The gain length of the fundamental was found to be $L_f = 4.1$ m. For the nonlinear third harmonic we measured the gain length to be $L_3^{NL} = 3.3$ m. See Figs. 3, 4 for corresponding measurements.

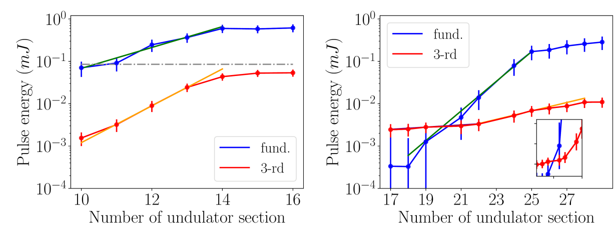

Figure 3: Experimental gain curves before U16 (left) and after U16 with the attenuator inserted (right). Dashed line marks 80 μJ energy level. The inset on the right displays the inflection point of the 3-rd harmonic. Straight lines represent linear gain for corresponding regions.

Afterwards, the first three undulators U1, U2, U3 were then taken out of the FEL process, reducing the fundamental X-ray energy to about 80 μJ to avoid thermal damage of the self-seeding crystal. The diamond crystal was then inserted and the electron beam was sent through the chicane to bypass it. During this process, the fundamental radiation was absorbed by the diamond crystal, while third harmonic was transmitted with 60% efficiency. The electron beam was therefore seeded with the third harmonic radiation, while the bunching at fundamental frequency was smeared out by the chicane. We then performed another gain measurement. Note, the lethargy occurred in the first two undulators; see Fig. 3. Interestingly, the third harmonic integrated counts were consistently increasing during the fundamental lethargy phase in the first few undulators. This process may be attributed to the linear seeded harmonic growth. We note, that with the help of phase-shifters in LCLS-II undulator beamline, currently under commissioning, this setup may lead to direct harmonic lasing. In our experiment, however, the fundamental bunching quickly takes over, turning the process into a nominal nonlinear third harmonic generation. The gain length of the newly generated third harmonic was measured to be $L_3^{NL} = 14.3$ m. Increase in the gain length is expected, as third harmonic is highly susceptible to the warm beam effects [6, 7].

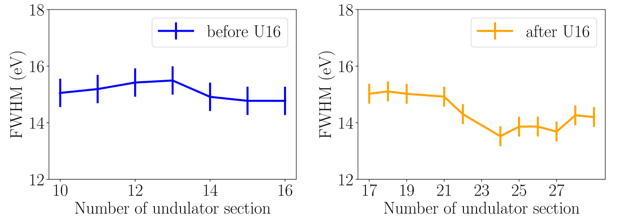

Figure 4: Experimental FWHM of the 3-rd harmonic spectrum as a function of undulator length before U16 (left) and after U16 with attenuator inserted (right).

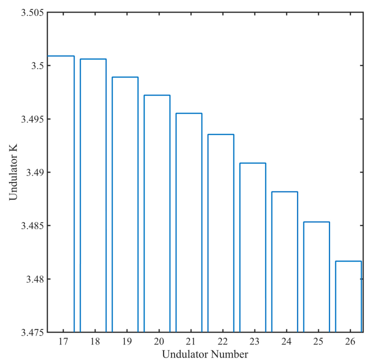

Figure 5: LCLS-II HXR undulator taper profile during the experiment.

EFFECTS OF UNDULATOR TAPERING

First, we notice the saturation of the signal comes after undulator 24, only eight undulators after the HXRSS chicane. This is in contrast with the data shown in Fig. 3 (left) where the SASE saturation with no attenuator inserted occurs around undulator 14. The reason for this early saturation is the taper profile downstream of the chicane; see Fig. 5. The taper favors the growth of the fundamental in U17-24 but causes particle detrapping around U24 consequently saturating the FEL pulse energy around 200 uJ, a factor of 4 less than the saturated power show in Fig. 3 (left). The rapid increase of the fundamental power reduces the number of gain lengths during which the third harmonic can be amplified linearly and thus should be avoided in future harmonic lasing schemes. As mentioned previously, the use of additional spectral filters or phase shifters can alleviate the concerns due to the fundamental growth. Another possibility would be to use a fresh slice [8] or fresh bunch of electrons for which the energy modulation accumulated in the first undulator section is much smaller and the microbunching is much weaker.

GENESIS SIMULATIONS

Finally, we provide a comparison of measured NHG third harmonic spectra with GENESIS simulations; see Fig. 6. We note a very good agreement with the measurements corroborating our numerical model. Detailed statistical analysis of the third harmonic radiation will be reported elsewhere.

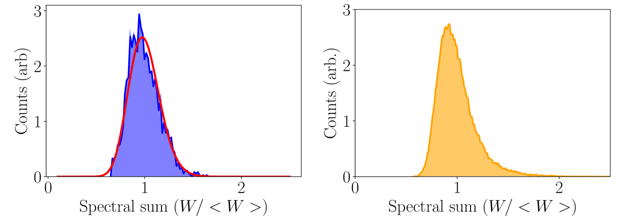

Figure 6: Measured (left) and simulated (right) NHG third harmonic spectrum at U10. Solid red curve represents well-known fundamental Gamma statistics fit [9].

SUMMARY

We experimentally demonstrated the fundamental 2 keV XFEL pulse attenuation using diamond crystal in the HXRSS chicane, followed by third harmonic growth downstream. We foresee this method to be complimentary to the fundamental suppression by phase shifters planned in LCLS-II HXR undulator [10]. We also evaluated, via numerical simulations, the possibility of harmonic lasing scheme at LCLS-II. Finally, we have collected spectral data of the third harmonic and observed very good agreement with the simulations and theory.

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