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LCLS-II Hard X-Ray Undulator Harmonics

G. Marcus*, T. Raubenheimer
SLAC, Menlo Park, CA 94025

Abstract

The production of harmonics in the LCLS-II hard X-ray (HXR) undulator can potentially provide reasonable average power beyond the high end of the tuning range for the fundamental harmonic, $E_\gamma = 5$ keV. This technical note details a study of the production of harmonics through nonlinear harmonic generation and harmonic lasing in the HXR undulator when fed by the SCRF produced electron beam.

*gmarcus@slac.stanford.edu

1 Introduction

The LCLS-II HXR undulator will support lasing at the fundamental in the tuning range of $E_\gamma = 1.5 - 5.0$ keV with the 4 GeV electron beam supplied by the SCRF linac. The production of harmonics via nonlinear harmonic generation (NHG) and harmonic lasing (HL) from this high repetition rate linac opens the possibility of supplying reasonable average power to users beyond the baseline 5 keV photon energy. We explore the performance of the harmonics in the HXR undulator. Analytic tuning curves for the production of harmonics by means of NHG are presented and are benchmarked to high fidelity numerical particle simulations. In addition, harmonic lasing from a low-charge (20 pC), high-brightness electron beam is explored.

2 Beamline geometry

The baseline LCLS-II HXR undulator nominally consists of 32 individual undulator segments, the parameters of which can be found in Table 1. The HXR undulator beamline

Table 1: Nominal 100 pC electron beam and HXR undulator parameters.

Paramter	**Symbol**	**Value**	**Unit**
e-beam energy	E	4.0	GeV
emittance	ϵ	0.40	μm
current	I	1.0	kA
energy spread	σ_E	500	keV
beta	$\langle\beta\rangle$	13	m
undulator type	-	Hybrid PM, planar	x-pol
undulator period	λ_u	26	mm
segment length	L_u	3.4	m
break length	L_b	1.0	m
# segments	N_u	32	-
total length	L_{tot}	140	m

will also support self-seeding using the high energy CuRF electron beam and the existing LCLS infrastructure. As such, there is a break at the location where the 14th undulator segment would normally be placed to host the monochromator crystal and electron beam bypass chicane. This section is not modeled here in the start-to-end simulations as it has no relevant impact.

3 Electron beam properties

Analytic estimates, based on the M. Xie formalism[6] and the parameters in Table 1, as well as start-to-end (S2E) numerical particle simulations, are used to evaluate the performance of the harmonics. Particles are tracked using `IMPACT-T/Z` from the LCLS-II injector to the entrance of the HXR undulator. Figure 1 shows the detailed slice properties of the a 100 pC electron beam used for this study. The current in the core of the beam is roughly $I \sim 720$

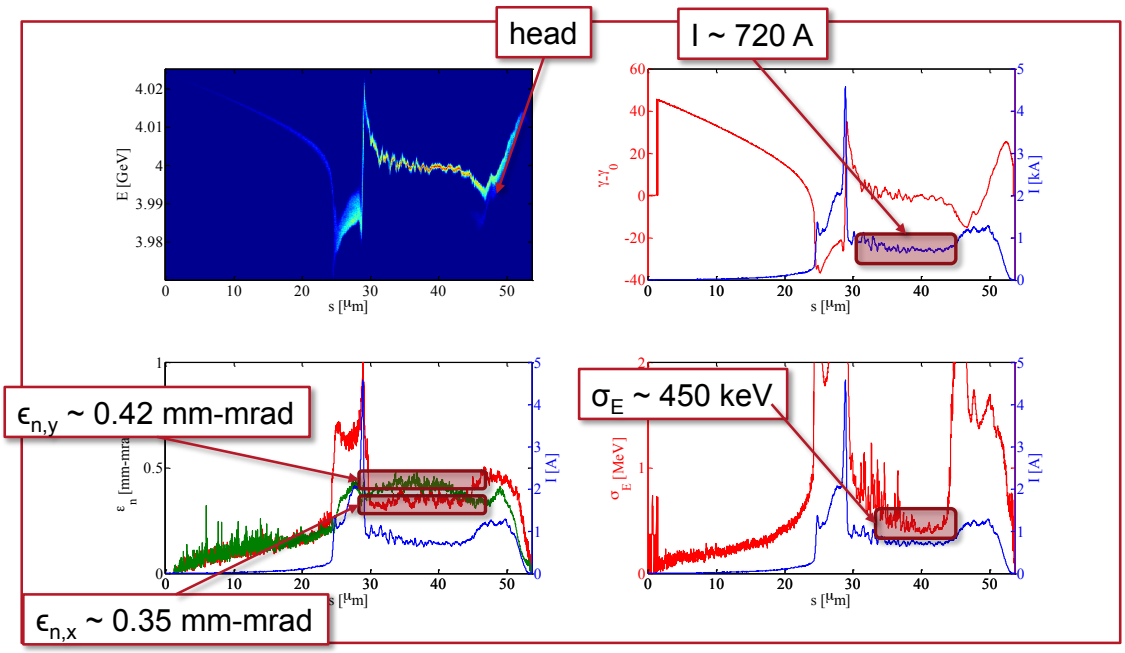

Figure 1: Top left: Longitudinal phase space. Top right: Current (blue) and slice energy (red). Bottom left: Current (blue), slice emittance (green - x, red - y). Bottom right: Current (blue), rms slice energy spread (red).

A while the normalized slice emittance is $\epsilon_{n,(x,y)} \sim 0.40$ mm-mrad and the rms slice energy spread is $\sigma_E \sim 450$ keV. `GENESIS` is used to simulate the FEL performance with this S2E particle distribution.

4 Nonlinear Harmonic Generation

Strong bunching at the fundamental wavelength near saturation can drive substantial bunching and power levels at the harmonics in a high-gain FEL [1, 2, 3]. As a result of this nonlinear harmonic interaction, the gain length, transverse profile, and temporal structure of the harmonics are determined by those of the fundamental. In addition, the powers of the harmonics are subjected to larger fluctuations than the fundamental, while the relative spectral bandwidth is the same.

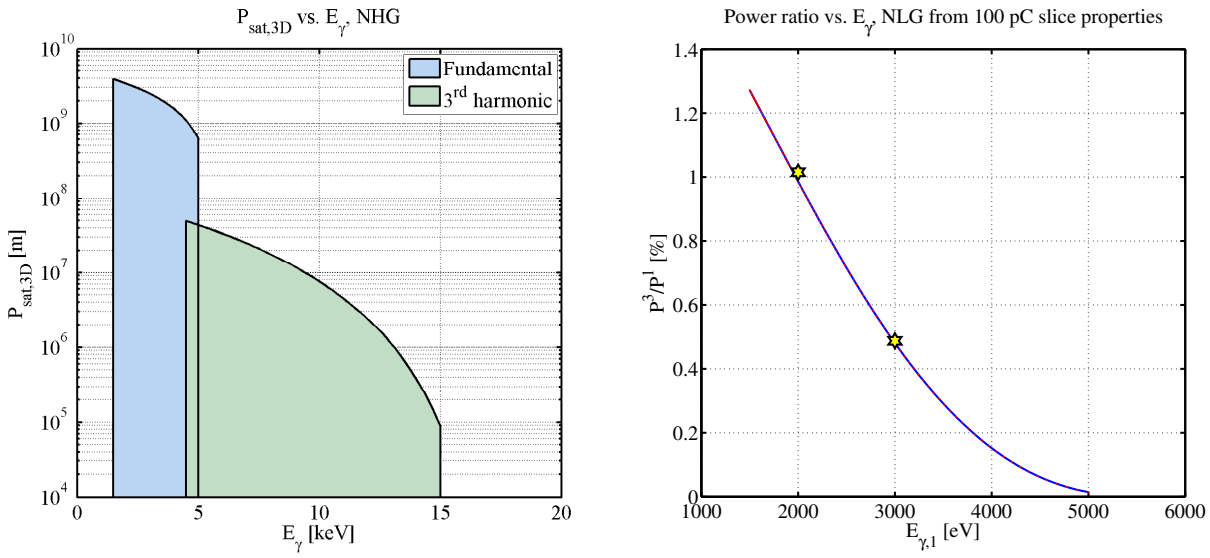

Figure 2: Analytic prediction of the NHG performance. Left: tuning curves. Right: Ratio of the harmonic to fundamental power.

Typical power levels of the third harmonic produced in this way can be on the order of 1-2% for large undulator parameter, K, values (K > 1.5) [3, 4, 5] but can fall off quite dramatically if K is small (K < 1.5) or if emittance or energy spread effects become dominant. Therefore, small power levels can be expected from nonlinear harmonic generation at 7-8 keV photon energies. No modifications to the beamline are needed to leverage these photons, however, attenuation of the fundamental is necessary to isolate the harmonics, which could limit the maximum delivered power.

4.1 Analytic estimates

The estimated HXR NHG performance is shown in Figure 2. The estimated tuning curves for both the fundamental and third harmonic are shown on the left while their power ratio at saturation is shown on the right. The power in the third harmonic begins to drop for large photon energies as the undulator parameter decreases and three-dimensional effects become significant. In addition, the power ratio has been benchmarked to S2E simulations (yellow stars, see below) for two fundamental photon energies, 2 and 3 keV.

4.2 Start-to-end simulations

The electron beam shown in Figure 1 is used to evaluate the performance for a number of intermediate photon energies in the HXR undulator beamline. Figure 3 shows the results when the undulator is tuned to produce 2 keV photons on the fundamental harmonic. The FEL saturates at roughly $z \sim 55$ m with ~ 100 μJ in the fundamental and ~ 1 μJ in the third harmonic. The ratio of the average power of these two pulses is roughly $\sim 1\%$,

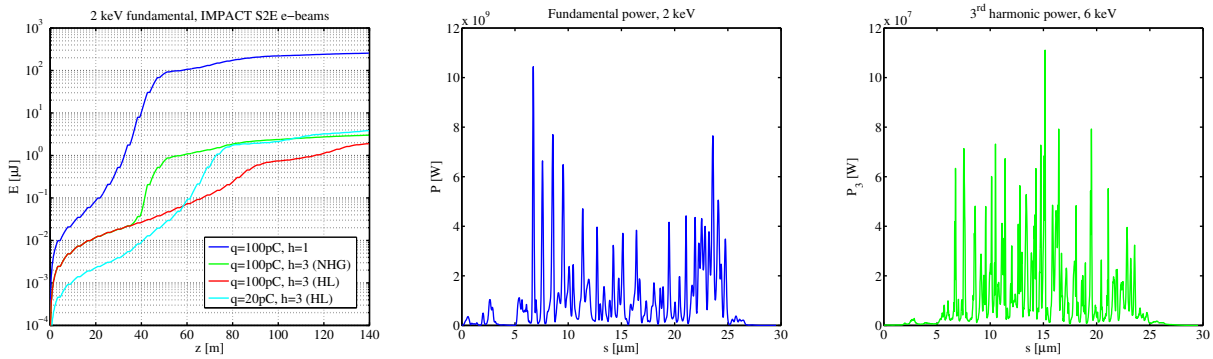

Figure 3: S2E simulation results for the fundamental photon energy of 2 keV. Left: gain curve. Center: fundamental power at saturation. Right: third harmonic power at saturation

which agrees well with the analytic estimate. Figure 3 shows the results when the undulator is tuned to produce 2 keV photons on the fundamental harmonic. In this case, the FEL saturates around $z \sim 70$ m with ~ 50 μJ in the fundamental and ~ 0.25 μJ in the third harmonic. The ratio of the average power of these two pulses is roughly $\sim 0.5\%$, which also agrees well with the analytic estimate (see Figure 2).

5 Harmonic Lasing

Harmonic lasing in FELs, where the collective electron beam/radiation instability of odd harmonics in a planar undulator evolve independently of the fundamental resonant radiation, has generated much recent interest and potentially offers many benefits over nonlinear harmonic generation [7, 8, 9]. Some of these benefits include a more intense, stable, and narrow-band radiation pulse. Harmonic lasing can also be a relatively efficient way of extending the photon energy tuning range of a particular FEL beamline.

The performance of harmonic lasing schemes is contingent on the successful suppression of the fundamental radiation. In this way, incoherent energy spread that is associated with the growth of the fundamental does not interrupt linear growth of the target harmonic, allowing it to reach full saturation. A variety of methods have been proposed to suppress the fundamental radiation including, but not limited to: introducing periodic phase shifts between the field and the electron beam such that the fundamental experiences a non-integer 2π phase shift while the desired harmonic experiences an integer 2π shift; periodically filtering the fundamental with a spectral attenuator while allowing the desired harmonic to pass and simultaneously debunching the electron beam in a bypass chicane; using a combination of detuned/retuned undulators such that the desired harmonic is resonant at different harmonic numbers (third, fifth, etc.) for contiguous undulator sections.

These schemes have been explored in the context of LCLS-II using numerical particle simulations with an ideal electron beam where the slice parameters are specified in Table 1. The results of these simulations are reported in [10]. Initial investigations suggest that

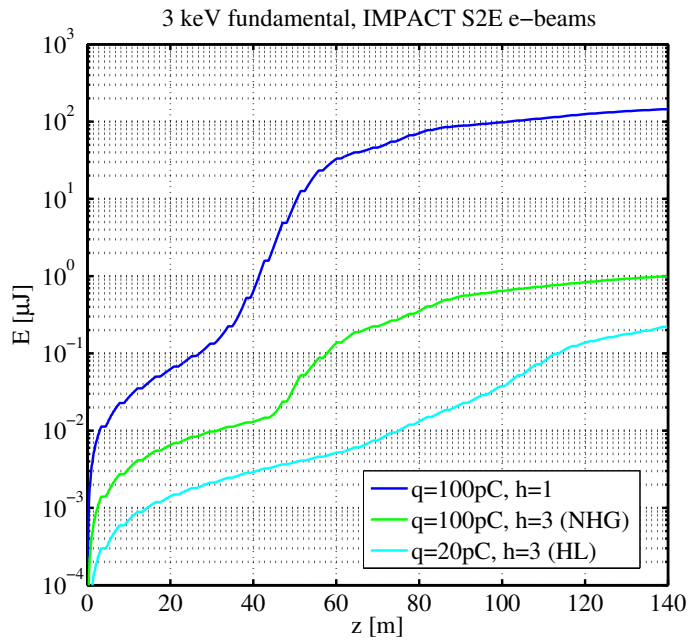

Figure 4: Gain curve for S2E simulations where the fundamental photon energy is tuned to 3 keV.

both the SXR and HXR beamlines would benefit greatly from these concepts. The high end of the HXR beamline tuning range, for instance, could potentially extend to 7 keV with an appropriate distribution of phase shifters and spectral attenuators. Here we report some initial particle simulation results using a low charge (20 pC) electron beam, where the brightness could potentially support lasing for large photon energies.

5.1 20 pC electron beam properties

High fidelity particle simulations are used to evaluate the performance of harmonic lasing with the low-charge, high-brightess beam. Particles are tracked using `IMPACT-T/Z` from the injector to the entrance of the undulator. Figure 5 shows the detailed slice properties of the low charge, 20 pC electron beam at the entrance to the HXR undulator. The current in the core of the beam is roughly $I \sim 350$ A while the normalized slice emittance is $\epsilon_{n,(x,y)} \sim 0.15$ mm-mrad and the rms slice energy spread is $\sigma_E \sim 450$ keV. `GENESIS` is used to simulate the FEL performance with this S2E particle distribution.

5.2 Simulation results

The simulation results showing an idealized harmonic lasing performance for the production of photons at 6 keV and 9 keV (corresponding to 2 keV and 3 keV photon energies at the fundamental, respectively) can be found in Figures 3 and 4. In each of these cases, the

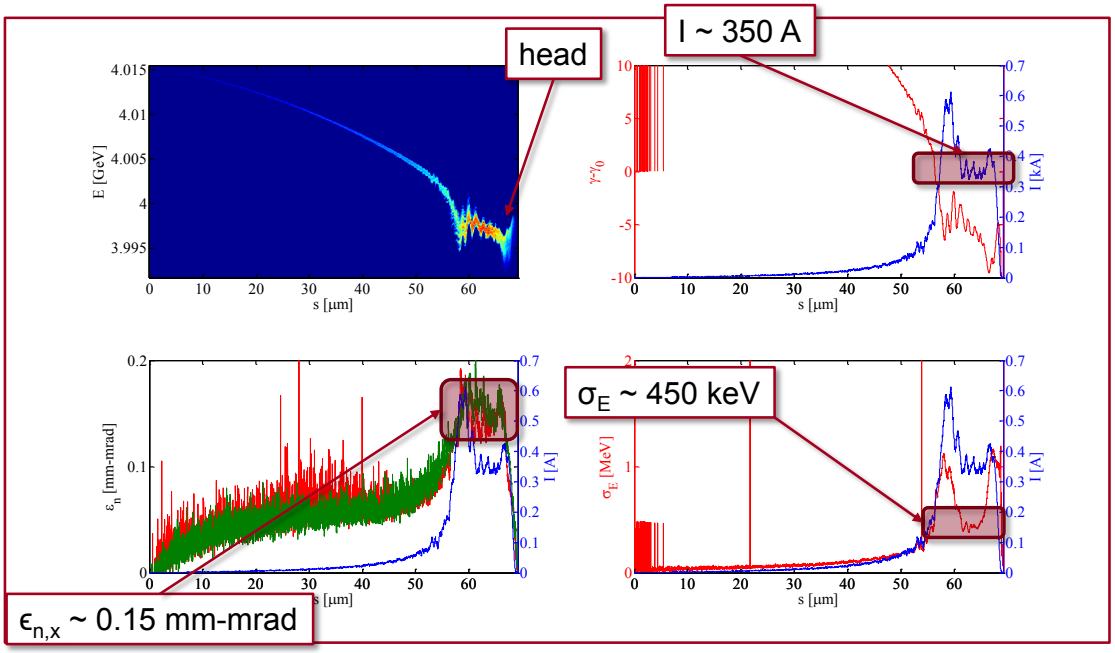

Figure 5: Top left: Longitudinal phase space. Top right: Current (blue) and slice energy (red). Bottom left: Current (blue), slice emittance (green - x, red - y). Bottom right: Current (blue), rms slice energy spread (red).

interaction of the electron beam with the fundamental radiation is artificially turned off in order to simulate the idealized suppression of the fundamental. More realistic cases of suppression, which is detailed in [10], will be studied in the future.

Figure 3 shows that the third harmonic at 6keV reaches saturation around $z \sim 80$ m with an energy of roughly 2 μJ. This is twice the energy at saturation that was produced through NHG with a narrower bandwidth. Furthermore, there is significant room for past saturation tapering to increase the photon yield.

Figure 4 shows the limits of HL for extremely large photon energies. NHG outperforms HL in this case, where lasing at 9 keV is inhibited by large three-dimensional effects.

6 Cost estimate

Harmonic lasing could potentially require a number of spectral filters to suppress the fundamental radiation. The number of filters and their placement along the beamline is still being evaluated. Additionally, the appropriate material for this process is currently under investigation. A detailed cost estimate is not available at this time.

7 Conclusion

The production of harmonics via nonlinear harmonic generation and harmonic lasing has been studied using analytic estimates and numerical particle simulations, which show excellent overall agreement. Significant average power from the harmonics can potentially be produced in the LCLS-II HXR undulator above the high end of the nominal photon tuning range.

Acknowledgments

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References

[1] Z. Huang et al., Phys. Rev. E 62(5), 7295 (2000).

[2] Z. Huang et al., Nucl. Inst. Meth. Res. Sect. A 475 (2001).

[3] E. L. Saldin et al., Phys. Rev. ST Accel. Beams 9, 030702 (2006).

[4] A. Tremaine et al., Phys. Rev. Lett. 88, 204801 (2002).

[5] D. Ratner et al., Phys. Rev. ST Accel. Beams 14, 060701 (2011).

[6] M. Xie, Nucl. Inst. Meth. Res. Sect. A 445, 59 (2000).

[7] B. W. J. McNeil et al., Phys. Rev. Lett. 96, 084801 (2006).

[8] E. A. Schneidmiller et al., Phys. Rev. ST Accel. Beams 15, 080702 (2012).

[9] E. A. Schneidmiller et al., Nucl. Instr. Met. Phys. Res. Sect. A 717, 37 (2013).

[10] G. Marcus et al., LCLS-II-TN-14-12.