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# HARMONIC LASING OPTIONS FOR LCLS-II

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*Abstract*

Harmonic lasing can be a cheap and relatively efficient way to extend the photon energy range of a particular FEL beamline. Furthermore, in comparison to nonlinear harmonics, harmonic lasing can provide a beam that is more intense, stable, and narrow-band. This paper explores the application of the harmonic lasing concept at LCLS-II using various combinations of phase shifters and attenuators. In addition, a scheme by which individual undulator modules are tuned to amplify either the third or fifth harmonic in different configurations is presented in detail.

## INTRODUCTION

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 [1–3]. 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 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 $2\pi$ phase shift while the desired harmonic experiences an integer $2\pi$ 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. This paper explores the application of each of these methods (and combinations thereof) in the case of the LCLS-II design study to not only extend the tuning range of individual beamlines, but to also increase the performance of the hard x-ray (HXR) and soft x-ray (SXR) beamlines at the high end of the tuning range [4]. The performance is illustrated through numerical particle simulations using the FEL code `GENESIS` [5] where we focus primarily on lasing at the third harmonic.

## PARAMETERIZATION

The eigenvalue equation for a high-gain FEL with all of the relevant three-dimentional effects included was was first generalized to the case of harmonics in [6]. More recently [2], Ming Xie fitting formulas for the power gain length [7,8] were also generalized to harmonic lasing:

$$
\begin{aligned}
\frac{L_{1d}^{(h)}}{L_g^{(h)}} &= \frac{1}{1+\Lambda\left(\eta_d^{(h)},\eta_\epsilon^{(h)},\eta_\gamma^{(h)}\right)} \\
L_{1d}^{(h)} &= \left(\frac{A_{JJ1}^2}{hA_{JJh}^2}\right)^{1/3} L_{1d} \\
\eta_d^{(h)} &= \left(\frac{A_{JJ1}^2}{hA_{JJh}^2}\right)^{1/3} \frac{\eta_d}{h} \qquad (1) \\
\eta_\epsilon^{(h)} &= \left(\frac{A_{JJ1}^2}{hA_{JJh}^2}\right)^{1/3} h\eta_\epsilon \qquad (2) \\
\eta_\gamma^{(h)} &= \left(\frac{A_{JJ1}^2}{hA_{JJh}^2}\right)^{1/3} h\eta_\gamma
\end{aligned}
$$

The Xie approach to parameterizing the power gain length is useful for quickly estimating three-dimensional effects using scaled parameters that represent essential system features. Using this formalism, it is possible to quickly estimate electron beam and undulator parameters that are suitable for optimizing harmonic lasing. For instance, it offers a quick estimate on the distance between phase shifters necessary to effectively suppress the fundamental. It is also useful for determining if harmonic lasing is viable for given electron beam and undulator parameters. The harmonics can be extremely sensitive to the slice energy spread and emittance. The Xie formalism quickly quantifies this sensitivity and can illuminate how high in harmonics (and photon energy) the harmonic lasing concept can be pushed.

Table 1: Nominal Electron Beam and Undulator Parameters for the Baseline LCLS-II Scenario

| **Paramter** | **Symbol** | **Value SXR(HXR)** | **Unit** |
|---|---|---|---|
| e-beam energy | $E$ | 4.0 | GeV |
| emittance | $\epsilon$ | 0.45 | $\mu$m |
| current | $I$ | 1000 | A |
| energy spread | $\sigma_E$ | 500 | keV |
| beta | $\langle\beta\rangle$ | 12(13) | m |
| undulator period | $\lambda_u$ | 39(26) | mm |
| segment length | $L_u$ | 3.4 | m |
| break length | $L_b$ | 1.0 | m |
| # segments | $N_u$ | 21(32) | - |
| total length | $L_{tot}$ | 96(149) | m |

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An example of this optimization is illustrated in Figure 1, which shows the dependence on the slice energy spread and normalized emittance (at constant current) of the retuned fundamental gain length (top left), the third harmonic gain length (top right) and their ratio (bottom) for the nominal LCLS-II parameters (see Table 1) for lasing at $E_\gamma = 5$ keV in the presence of three-dimensional effects. The bottom plot illustrates that the third harmonic at 5 keV has a shorter gain length than the fundamental tuned to produce 5 keV photons (through undulator parameter K tuning) regardless of the slice energy spread or emittance around the LCLS-II design point. The middle plot illustrates, however, that these parameters must be reasonably controlled in order for the harmonic to reach saturation within the undulator length constraints. It also shows that the third harmonic is far more sensitive to an increase in the slice energy spread than the fundamental.

## PHASE SHIFTERS

Phase shifters are present in gap tunable undulators in order to maintain a $2\pi$ phase shift between the FEL radiation and electron beam during the break sections that host strong focusing quadrupoles. If, however, these phase shifters are tuned such that the electron's phase delay is either $2\pi/3$ or $4\pi/3$, the third harmonic stays resonant while the fundamental radiation is suppressed.

Figure 2 shows the power gain curves for an ideal electron beam specified by the parameters in Table 1 comparing the production of $E_\gamma = 5$ keV photons through nonlinear harmonics (brown), harmonic lasing (cyan) and the retuned, using K, fundamental (blue) for the LCLS-II baseline scenario in the HXR beamline. Here, we have included additional phase shifters for illustrative purposes in the harmonic lasing scenario that are not in the current iteration of the undulator lattice but are nonetheless needed to effectively suppress the fundamental. We have found that the phase shifter spacing should be less than the fundamental power gain length. The phase shifter distribution is the optimized recipe reported in [3]. As one can see, harmonic lasing saturates at a higher average power than the nonlinear harmonics. While it saturates at about the same power as the retuned fundamental, it does so at a much earlier location, which leaves significant room for post saturation tapering. The current LCLS-II baseline barely reaches saturation at the fundamental at $E_\gamma = 5$ keV. Among other advantages, harmonic lasing enables the consideration of self-seeding at 5 keV with the electron beam from the superconducting linac. Furthermore, the RMS bandwidth of the harmonic lasing photon beam is roughly two times smaller than that coming from the fundamental, producing an overall brighter beam.

While the primary aim of the phase shifters is to suppress the fundamental radiation by shifting it's phase relative to the electrons, what actually ends up happening for self-amplified spontaneous emission is the amplification of well separated frequency bands. The goal of the phase shifters, then, is to

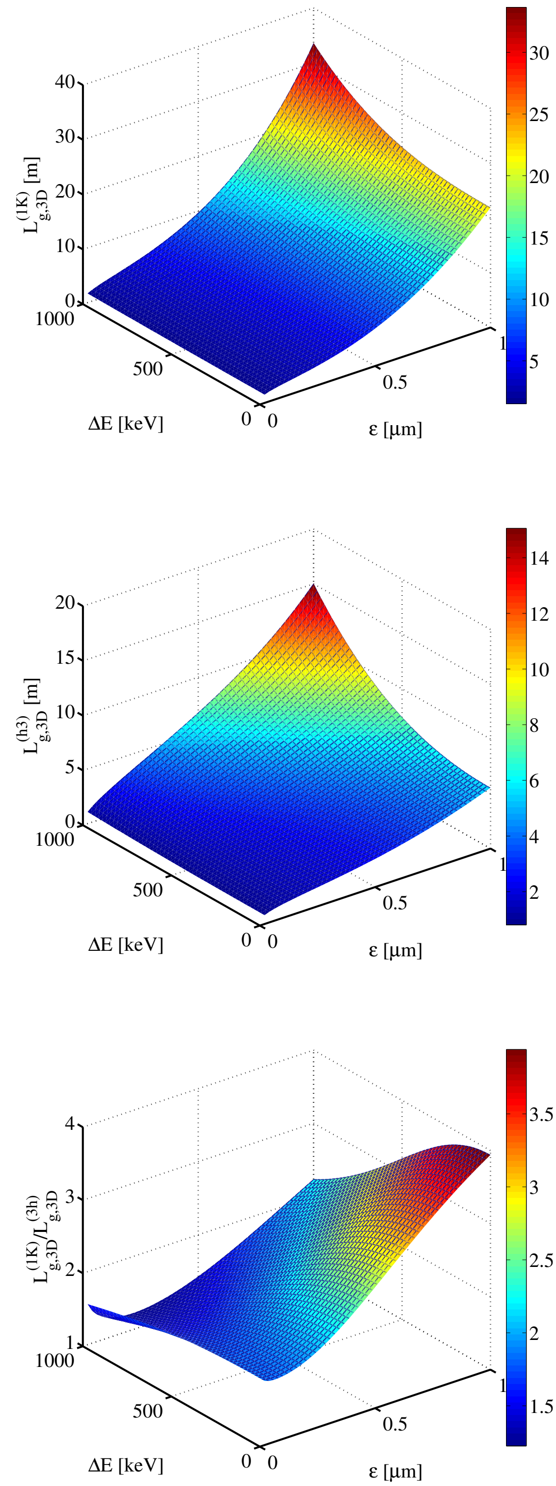


Figure 1: Surface plots illustrating the dependence on the slice energy spread and normalized emittance (at constant current) of the retuned fundamental (using undulator K, denoted (1K)) gain length (top), the third harmonic gain length (middle) and their ratio (bottom) for the nominal LCLS-II parameters for lasing at $E_\gamma = 5$ keV.

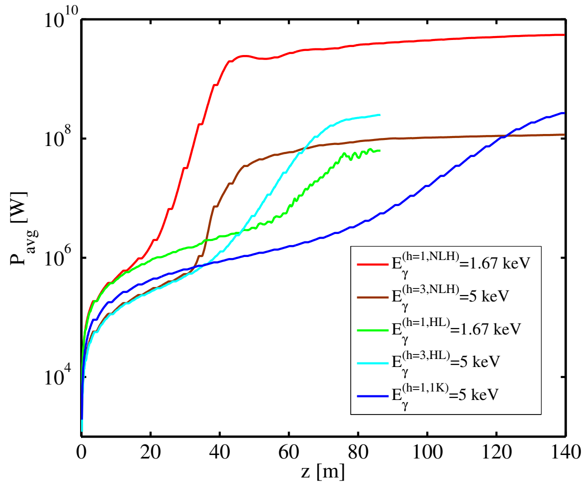


Figure 2: The average power gain curves for the fundemental tuned to $E_\gamma = 1.67$ keV (red), which drives the third harmonic through nonlinear harmonic interaction (brown); The suppressed fundamental (by phase shifters) tuned to $E_\gamma = 1.67$ keV (green) and the third harmonic from harmonic lasing (cyan); the retuned fundamental at $E_\gamma = 5$ keV (blue).

increase the bandwidth of the fundamental by filling these sidebands non-preferentially. While the optimized recipe provided in [3] strategically fills these sidebands, and certainly works for most scenarios, randomized phase shifter recipes can also produce the desired effect. This is illustrated in Figure 3. The top plot shows the fundamental and third harmonic using the optimized phase shifter recipe (blue and green respectively) as well as the fundamental and third harmonic (cyan and red) from a completely random distribution of phase shifters. In this case, the performance is almost identical, with the randomized distribution doing slightly better at saturation. Randomized distributions, however, are often inconsistent in their results as illustrated in the bottom plot for a different random distribution.

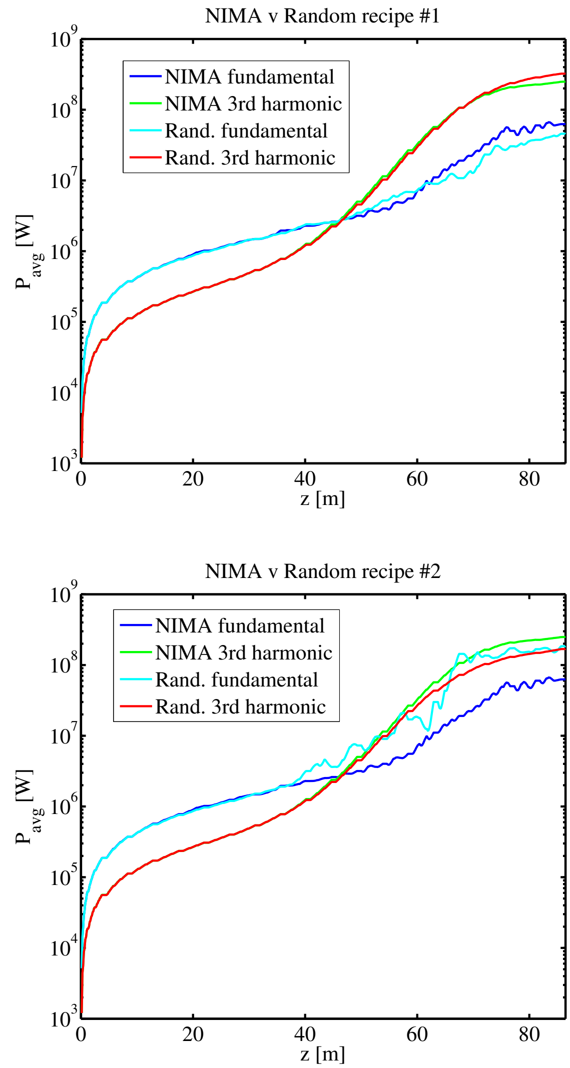


Figure 3: Comparison of the optimized phase shifter recipe detailed in [3] with two independent random phase shifter recipes. The top plot shown a comparable (or even slightly better) performance while the bottom plot shows a clearly worse performance for the random recipes.

## INTRAUNDULATOR SPECTRAL FILTERING

As previously mentioned, the LCLS-II does not have the necessary phase shifter period to effectively suppress the fundamental radiation when the third harmonic is tuned to amplify 5 keV photon. Other methods, however, can be used in concert with the given number of phase shifters to optimize the performance. The results of including several stages of spectral filtering (shown here using a crude model where the filters perfectly absorb the fundamental while passing the third harmonic), along with using the available phase shifters in a randomized fashion, is shown in Figure 5. The filters have to be placed frequently enough such that the fundamental does not increase the energy spread as it amplifies. The top plot shows the average power gain curves for the third harmonic tuned to 5 keV (green) and the fundamental (blue) using two spectral filters and compares the results to the nominal performance of 5 keV at the fundamental using a retuned undulator (red). The slice emittance, energy spread, and beam matching for this particular study were for slightly more pessimistic LCLS-II parameters than what is listed in Table 1, which explains the slightly longer third harmonic saturation length. The third harmonic (green) clearly outperforms the retuned fundamental (red). The addition of a third spectral filter allows for the amplification of 7 keV photons at the third harmonic close to saturation. This photon energy is current beyond the reach of the fundamental in the baseline LCLS-II case.

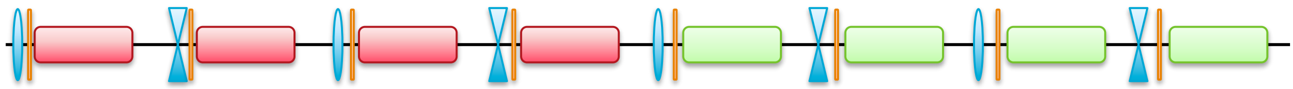

Figure 4: The split undulator scheme where the first half of the undulator (red segments) has the desired photon energy at the third harmonic while the second half of the undulator (green segments) has the desired photon energy at the fifth harmonic. Quadrupoles are shown in blue while adjustable phase shifters are shown in orange.

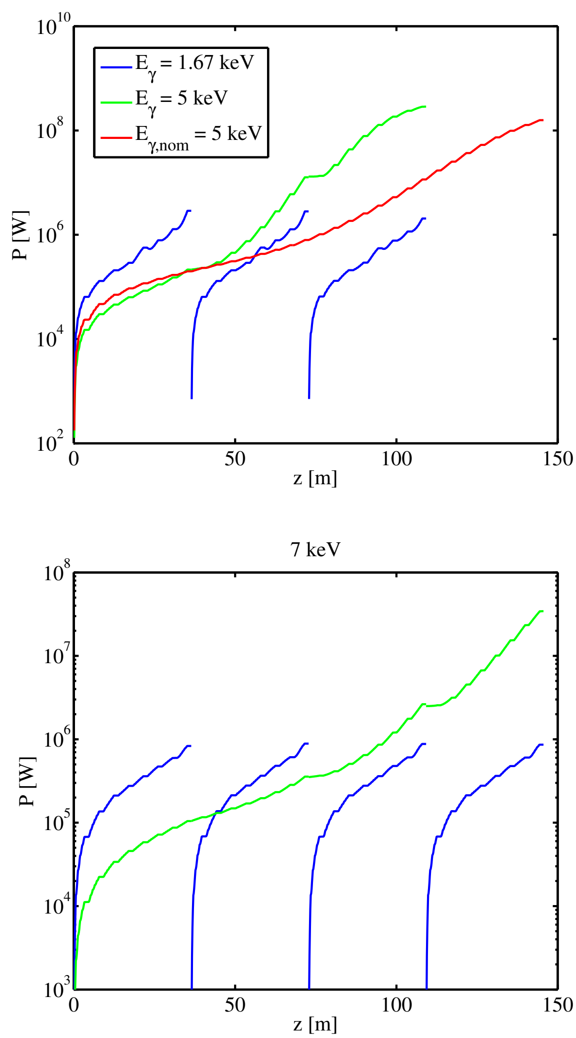


Figure 5: The average power gain curves for the third harmonic tuned to 5 keV (green) and the fundamental (blue) using two spectral filters compared to the nominal performance of 5 keV at the fundamental (red).

## DETUNED AND RETUNED UNDULATORS

More exotic methods of harmonic lasing have also been proposed [9, 10]. If the undulator parameter K is large enough, individual undulator sections can be tuned such that the desired photon energy is resonant at either the third or fifth harmonic (or higher). The scheme presented here uses the first half of the LCLS-II SXR undulator such that the third harmonic is tuned to produce $E_\gamma$ = 4.1 keV photons while the existing phase shifters attempt to suppress the fundamental as efficiently as possible (see Figure 4). The second half of the undulator is tuned such that the fifth harmonic is resonant at 4.1 keV. Here, the fundamental radiation from the first half of the undulator is not resonant with any harmonic. The phase shifters are used in an attempt to suppress both the fundamental and third harmonic radiation while allowing the fifth harmonic to continue to grow. Figure 6 illustrates the performance of the undulator under these conditions.

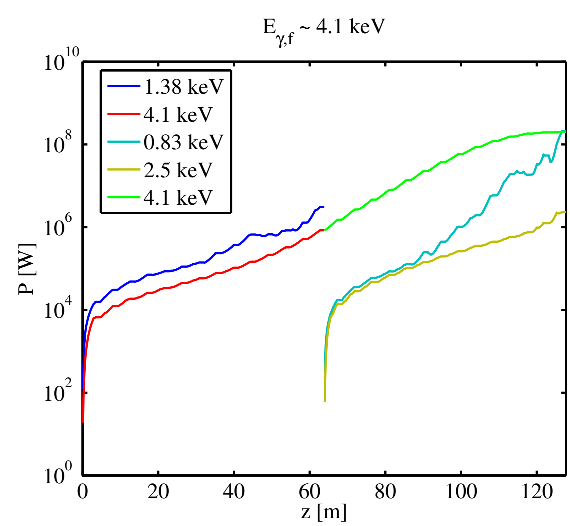


Figure 6: Harmonic lasing scheme where the first.

It should be noted that the FEL resonance condition requires an electron beam energy greater than 4 GeV to produce 4.1 keV photons from the fundamental in the SXR beamline, which is beyond the baseline scenario. It is also clear that the phase shifters in both the first and second half of the undulators are not sufficient to suppress the undesired harmonics completely. However, by the time the fundamental radiation in the second undulator (0.83 keV) begins to amplify, the fifth harmonic at the desired energy has nearly saturated. Of course, ever more complicated arrangements of undulator segments is being explored.

## DISCUSSION

Harmonic lasing using clever combinations of phase shifters, attenuators and detuned/retuned undulators offers an attractive option to both improve the performance of undulator beamlines at the high end of their tuning range and to fully extend the tuning range altogether. Useful formulas exist for quickly estimating the necessary harmonic lasing method needed to reach a desired performance level. However, detailed numerical particle simulations are typically needed to evaluate the efficacy of the implementation [11]. This paper details an initial harmonic lasing performance study in the context of the LCLS-II project. It is worth emphasizing that even though harmonic lasing nominally requires a large number of phase shifters to effectively suppress the fundamental radiation, more exotic methods of suppression using detuned and retuned undulators work for the baseline LCLS-II beamlines without any additional components. More realistic physical models of the spectral filters and chicanes, as was done in [12], will be included in future studies. For the moment, however, it has been shown that the LCLS-II should benefit greatly from these concepts.

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## REFERENCES

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

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

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

[4] G. Marcus *et al.*,"FEL Simulation and Performance Studies for LCLS-II", in *These Proceedings: Proc. 36th Int. Free-Electron Laser Conf.*, Basel, 2014, TUP032.

[5] S. Reiche, *Nucl. Instr. Meth. Phys. Res. Sect. A* **429**, 243 (1999).

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

[7] M. Xie, *Nucl. Instrum. Methods Phys. Res. Sect. A* **445**, 59 (2000).

[8] Z. Huang, Private Communication.

[9] R. Brinkmann *et al.*, DESY-14-025 (2014).

[10] G. Penn, Private Communication.

[11] G. Marcus *et al.*,"FEL Code Comparison for the Production of Harmonics via Harmonic Lasing', in *These Proceedings: Proc. 36th Int. Free-Electron Laser Conf.*, Basel, 2014, TUP031.

[12] D. Ratner *et al.*, "Harmonic Lasing at the LCLS", in *Proc. 35th Int. Free-Electron Laser Conf., New York, 2013*, WEPSO53.