HARMONIC LASING AT THE LCLS

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INTRODUCTION

The fundamental of the Linac Coherent Light Source (LCLS) produces X-FEL radiation to above 10 keV photon energy. Users that require even harder X-rays can make use of the third harmonic, which typically represents 0.5-2% of the total lasing power. This non-linear harmonic radiation is driven by lasing at the fundamental; the resulting microbunching includes sharp density modulations that include high harmonic components. It has been pointed out [1, 2] that linear harmonic production, in which the FEL lases independently at the third harmonic, can produce even higher power radiation.

This paper describes plans to test harmonic lasing using the methods of Ref. [2]. The first half of the FEL produces radiation at both the fundamental and the third harmonic. Inserting an attenuator into the path of the X-ray beam removes the SASE power at the fundamental. A chicane bends the electrons around the attenuator and also resets the microbunching to shot noise. The remaining third harmonic then dominates the startup process in the second half of the FEL. Harmonic lasing will be tested during commissioning of the soft x-ray self seeding system. If tests are successful, it is possible to add additional attenuators or phase shifters to further increase power and create a new LCLS user mode.

LINEAR VS. NON-LINEAR LASING

The normal FEL process produces sharp microbunching of electrons, with each microbunch separated by the resonant wavelength of the undulator. If the microbunching is sufficiently sharp, the Fourier transform of the current density will include strong harmonic components. As a result, we expect exponential growth of coherent emission at the harmonics of the resonant wavelength. This process is known as non-linear harmonic generation. While harmonic bunching is strongest at the second harmonic, the symmetry of a planar undulator suppresses on-axis radiation at even harmonics, so the strongest harmonic radiation is expected at the third harmonic. At LCLS, the third harmonic can typically produce on the order of 1% the power of the fundamental [3].

An alternative approach is to drive the FEL process itself at a harmonic of the undulator's resonant wavelength. At LCLS, the undulators have a K value of 3.5, produces strong coupling at the third harmonic. Typically harmonic lasing would not be observable, because the gain length is shortest at the fundamental; the fundamental saturates and stops the FEL process before the harmonics can grow to a useful level. However, in principle it is possible to suppress the fundamental so that the harmonics are free to saturate. Ref. [1] proposed inserting periodic $2\pi/3$ or $4\pi/3$ phase shifts into the undulator line. The phase shifts suppress the fundamental radiation by forcing the electrons into an inverse-FEL phase, but they have no effect on the third harmonic. As a result, the third harmonic is able to saturate before the fundamental.

The periodic phase shifts are largely ineffective for SASE FELs, where the offset in phase merely shifts the resonant wavelength [2]. However, Ref. [2] shows that it is possible to suppress the SASE fundamental by varying the phase shift between $0, 2\pi/3$ and $4\pi/3$. Inserting an attenuator that preferentially blocks the fundamental further enhances the relative level of the harmonics.

At LCLS, FEL photon energy changes are made through the electron energy, so there are no phase shifters between the undulators and the harmonic phase shift option is not available at this time. However, a chicane is currently under development for the soft X-ray self seeding (SXRSS) project, and it is possible to fit an attenuator into the SASE path where the electrons have been displaced to one side. In addition, the hard X-ray self-seeding chicane [4] can be used as a phase shifter. We propose to use both an attenuator and phase shift to preferentially select lasing at the third harmonic (Fig. 1). We aim to demonstrate and study the principle of harmonic lasing, and if successful motivate development of a new harmonic operation mode at LCLS.

HARDWARE

The attenuator consists of a 450 μm thick piece of sapphire, which can be inserted into the SASE line to establish harmonic operation mode (Fig. 2). The sapphire absorbs all but 10^{-5} of the radiation at 6 keV, but lets through 60% of the 18 keV photons (Fig. 3). The 6 keV fundamental photon energy was chosen as the lowest energy at which the sapphire can be inserted without danger of damaging the crystal. Switching to a diamond attenuator would extend operation to lower photon energies. The upper end is limited by the beam line mirrors, which stop transmitting radiation around 24 keV [3].

The R_{56} of the chicane scrambles the electron phase space, removing any bunching from the upstream undulators, so following the chicane the FEL process restarts from the strong SASE harmonic radiation that remains. The chicane delay must be more than 10 fs to avoid hitting the sap-

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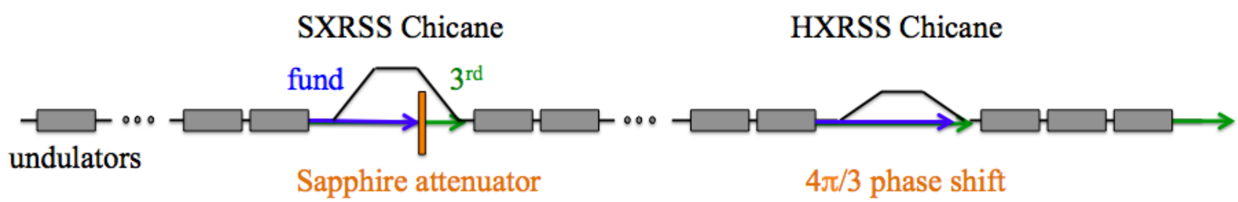

Figure 1: Schematic of the harmonic lasing scheme. The first undulator section produces SASE FEL that includes non-linear third harmonic radiation. The attenuator absorbs the fundamental, and the chicane washes out upstream microbunching. The remaining third harmonic seeds a new FEL process in the second half of the undulators. A second chicane can be used as a phase shift to further suppress the fundamental.

phire with the electron beam and to effectively suppress the upstream microbunching. Larger delays are possible, but require long pulse operation so that the remaining third harmonic SASE still overlaps in time with the electron beam.

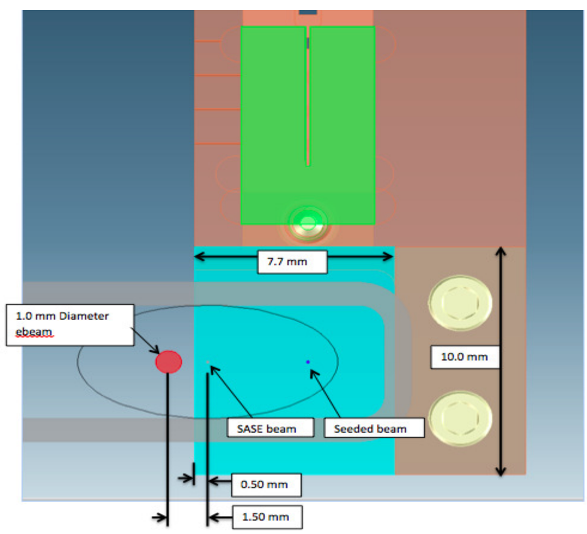

Figure 2: Schematic of the sapphire attenuator. The chicane redirects the electron bunch to one side so that the sapphire can intercept the SASE X-rays without spoiling the beam or damaging the crystal. The 'seeded beam' is used only during operation of the soft x-ray self seeding mode.

SIMULATIONS

To compare the results of non-linear harmonic generation and harmonic lasing, we simulate both cases with the code GINGER [6]. (GINGER is now upgraded to include harmonic lasing simultaneously with the fundamental.) The particle mixing from the chicane that redirects the electrons around the sapphire is approximated with a strong R_{56} component of the transfer matrix. The sapphire is simulated by dropping the fundamental power by a factor of 2×10^{-5} and the third harmonic power by 60%. The delay of the second chicane (HXRSS) is set to minimize the fundamental power and maximize the third harmonic. Though the final harmonic power is similar in both cases,

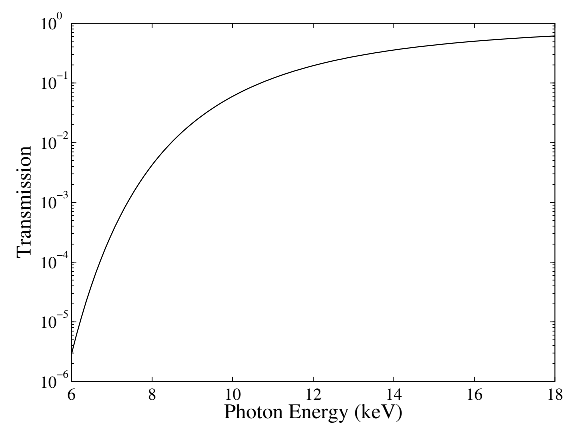

Figure 3: Transmission through a 450μm thick piece of sapphire for the range 6 keV to 18 keV [5].

with harmonic lasing there is an undulator position (around 85 meters) at which point both the fundamental and third harmonic are producing approximately $\sim$1 GW of power at the same time (Figs. 4 and 5). Simulation parameters are given in Table 1. Observation of this large percentage third harmonic would be clear evidence of harmonic lasing.

Table 1: Parameters for SASE GINGER simulations of LCLS.

Electron energy	11.6 GeV
3rd harmonic photon energy	18 keV
Slice energy spread	1.4 MeV
Emittance	0.4 μm
Peak current	3 kA
Sapphire transmission at 6 keV	2×10^{-5}
Sapphire transmission at 18 keV	60%

The spectra from non-linear harmonic and harmonic lasing are expected to be different even with the same level of total radiation power. Simulations show that the non-linear harmonics have a factor of 3-4 wider bandwidth than generated from the harmonic lasing (Figs. 6 and 7). The narrower spectrum of harmonic lasing should be easily measurable with the hard x-ray single-shot spectrometer [7].

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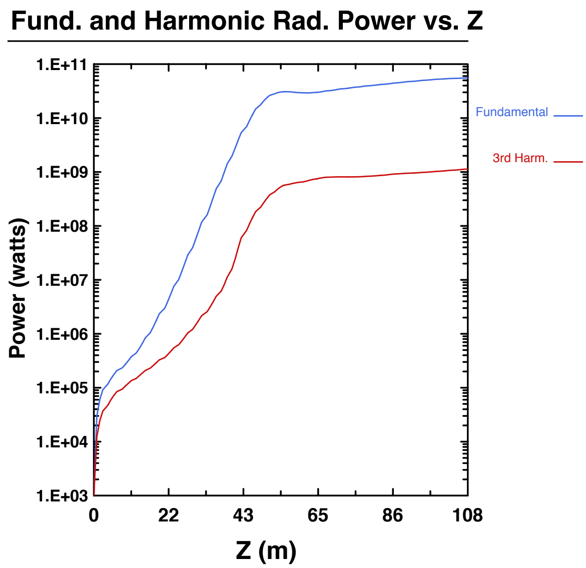

Figure 4: SASE simulation of nominal conditions at LCLS, with parameters from Table 1.

Figure 5: SASE simulation of harmonic lasing conditions at LCLS, with parameters from Table 1. After 85 m, the harmonic and fundamental power is approximately the same.

Some users may benefit from the narrower harmonic lasing spectrum even if the final power levels are similar for the two methods.

LONG TERM IMPROVEMENTS

If the harmonic lasing demonstration is successful, in principle it is possible to upgrade LCLS with either phase shifters or an additional attenuator in the HXRSS chicane.

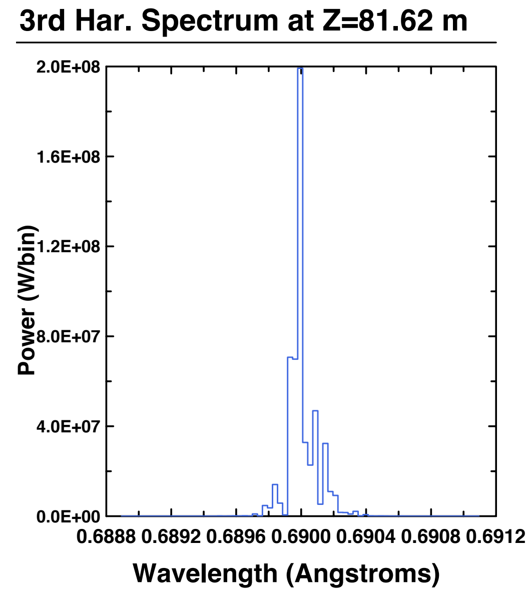

Figure 6: Spectrum of third harmonic for SASE simulation of nominal conditions at LCLS, parameters from Table 1.

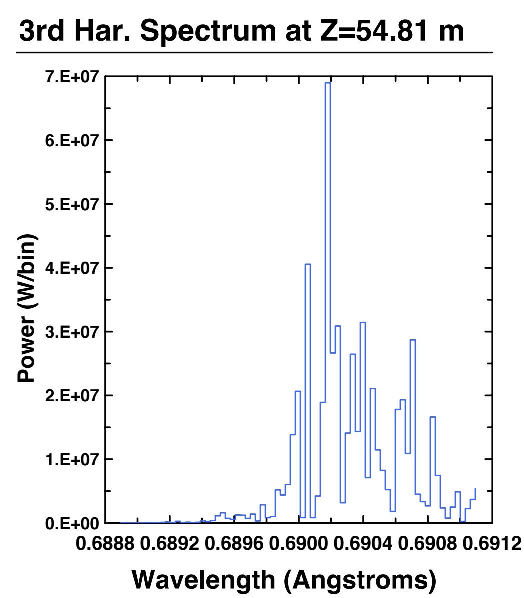

Figure 7: Spectrum of third harmonic for SASE simulation of harmonic lasing conditions at LCLS, parameters from Table 1. Spectrum is a factor of 3-4 narrower than from nominal conditions (Fig. 6).

While there are no phase shifters currently installed at LCLS, there are 'long' breaks every three undulators with enough room to insert a phase shifter without making any other modifications. The current HXRSS chamber also has a free port which could be used to insert a second attenuator. With stronger suppression of the fundamental, the third harmonic can saturate at a higher level, enhancing the total

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level of third harmonic power.

Using fresh-bunch seeding may also help harmonic lasing. The optimal number of undulators upstream of the sapphire is determined by balancing the need to generate nonlinear harmonic radiation and avoid the detrimental effects of increased energy spread as the FEL nears saturation. By using two bunches, one bunch can generate the seed harmonic radiation while the second bunch maintains its initial small energy spread [8]. By adjusting the separation of the two bunches, it is possible to use longer chicane delays and still use short electron bunches.

CONCLUSION

Harmonic lasing is an attractive approach to extending high power LCLS operation to beyond 10 keV photons. We plan to demonstrate harmonic lasing as part of the SXRSS commissioning. Our goal is to observe harmonic lasing and show that the spectrum is narrower than from nonlinear harmonic generation. If the test is successful, we will pursue improvements to establish a harmonic lasing user mode.

ACKNOWLEDGEMENTS

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