ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-MOP014

HARMONIC LASING TOWARDS SHORTER WAVELENGTHS IN SOFT X-RAY SELF-SEEDING FELS

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Abstract

In this paper, we study a simple harmonic lasing scheme to extend the wavelength of X-ray self-seeding FELs. The self-seeding amplifier comprises two stages. In the first stage, the fundamental radiation is amplified but well restricted below saturation, and meanwhile harmonic radiation is generated. In the second stage, the fundamental radiation is suppressed and the harmonic radiation is amplified to saturation. We performed start-to-end simulation to demonstrate third harmonic lasing in a soft x-ray self-seeding FEL at the fundamental wavelength of 1.52 nm. Our simulations show that a stable narrow-band FEL at GW level can be obtained.

INTRODUCTION

X-ray free electron lasers (XFELs) are tunable light sources with high power, coherent radiation over a broad spectral range. Self-amplified spontaneous emission (SASE) [1,2] is a usual operation mode in single pass XFEL which has excellent transverse coherence. However, because of starting from shot noise of electron beams, SASE has poor temporal coherence.

Self-seeding [3] is a way to improve the temporal coherence of SASE which consists of two undulators and an X-ray monochromator between them. The monochromator selects a narrow band of radiation from the SASE in the first undulator as the seed. Then the seed is amplified to saturation in the second undulator. This self-seeding scheme works both for soft and hard x-rays and has been demonstrated recently [4,5]. Generally, the main material for monochromator grating when the photon energy is below 2 keV [4]. While the diamond is used for the monochromator when the photon energy is above 4.5 keV [5]. However, because of lacking proper materials, the energy gap between 2 keV to 4.5 keV for self-seeding FEL has not been achieved now.

A possible way to extend the operating range of a soft X-ray self-seeding FEL is to use nonlinear harmonic generation [6]. The odd harmonics can be radiated in the same undulator [7]. However, the intensity of harmonics is rather small because of the dominance of the interaction at the fundamental radiation [7-9]. In this paper, we study the harmonic lasing in soft X-ray self-seeding FEL which could fill the energy gap not easily achieved by regular self-seeding schemes. By suppressing the fundamental frequency, we can obtain the odd harmonic radiations with higher intensity.

HARMONIC ANALYSIS FOR THE SELF-SEEDED FEL

In a planar undulator, the resonance condition for the radiation is written as

$$\lambda_h = \frac{\lambda_u(1+K^2/2)}{2h\gamma^2} \qquad (1)$$

Here h is the harmonic number, λ_h is the harmonic wavelength, λ_u is the undulator period, γ is relativistic factor, and K is the undulator parameter.

In a high-gain FEL, odd linear and nonlinear harmonics can be radiated on axis [7]. The linear amplification of harmonics is always smaller than the fundamental. The nonlinear harmonic generation occurs when a beam is strongly bunched by the fundamental frequency and the bunch spectrum develops rich harmonic contents. Especially, the growth rate of the nonlinear harmonics is h times higher than that of the fundamental. However, the dominance of the interaction at the fundamental radiation will limit the nonlinear harmonic interaction. So the intensity of harmonics is rather small. Typically, the third harmonic is at the level of a percent of the fundamental.

We study the third harmonic radiation in the soft X-ray self-seeding FEL and our simulation study is based on the LCLS parameters, which are shown in Table 1. Time-dependent simulation result by GENESIS [10] code of the soft X-ray self-seeding is shown in Fig. 1 and Fig. 2. It is clear that after the monochromator, the seed power of radiation is about 200 kW. Fig. 2 shows the evolution of the power of the fundamental and 3rd harmonic in the undulator U_2. It's clear that the linear gain process is at z < 15m and the linear harmonic grows much more slowly than the fundamental.

Table 1: Parameters Used for Soft X-ray Self-seeding FEL Simulation at LCLS

Parameter	Value	Unit
Electron beam energy	4.3	GeV
Peak current	3	kA
Energy spread	1	MeV
Emittance	0.5	mm-mmrad
Mono. central wavelength	1.52	nm
Mono. resolving power	5000	
Mono. power efficiency	0.02	
Undulator period	0.03	m
U_1 length	19.8	m
U_1 parameter K (rms)	2.4749	

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When z > 15m, the nonlinear interaction occurs and the nonlinear harmonic grows faster than the fundamental. However, the power of the 3rd harmonic is rather small, which is 0.4 GW, about 2% of the fundamental saturation power.

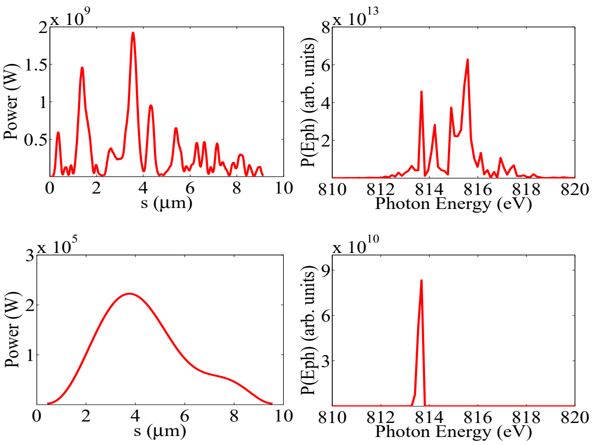

Figure 1: The FEL power at U_1 and monochromatic stage in time (top) and frequency (bottom) domain. At the exit of U_S (left); At the exit of monochromator (right).

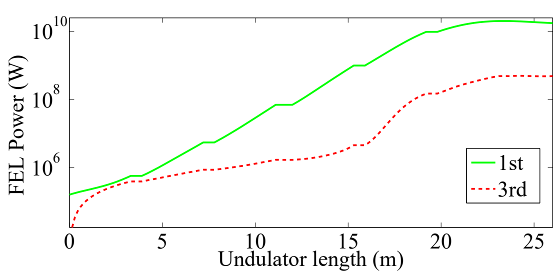

Figure 2: The fundamental (green line) and 3rd (red line) harmonic power evolution along the radiator undulator U_2

SUPPRESSION OF THE FUNDAMENTAL HARMONIC IN AMPLIFIER UNDULATOR

To achieve high output harmonic power, we could suppress the interaction at the fundamental resonance while allowing the harmonics to evolve to saturation, which is referred to as harmonic lasing [11]. The soft X-ray self-seeding harmonic lasing scheme is shown in Fig. 3. It demonstrates that the seeding undulator of normal self-seeding is segmented by a fundamental suppressor, which suppresses the radiation at the fundamental and allow the harmonic radiation to grow in the linear regime toward saturation [4–6], so as to avoid significant nonlinear coupling to the fundamental.

One method to suppress the interaction at the fundamental resonance without affecting the third harmonic lasing is phase shifter [12]. Here we define θ_j as the phase of the electrons with respect to the ponderomotive potential of the fundamental resonant wavelength, where j = 1, 2, …, N is the number of electrons. Then the phase of the nth harmonic is $\theta_{nj} = n\theta_j + \phi_n$, where ϕ_n is the relative phase between the ponderomotive potential of the fundamental and nth harmonic. When the phase of fundamental changes by a relative phase $\Delta\theta_j = 2\pi/k$ then the corresponding phase change for the harmonics will be $\Delta\theta_{nj} = 2\pi n/k$. Here we use k = n = 3, which means the phase delay is $2\pi/3$ for the fundamental and its amplification is disrupt. However, the phase delay for 3th harmonic is 2π. As a result, the fundamental can be expected to disrupt its exponential growth while the 3th harmonic should not affect it's FEL interaction. It continues to get amplified without being affected by phase shifters. In Fig. 4, one can see the evolution of the 1st (at 1.5 nm) and the 3rd (at 0.5 nm) harmonics. The length of U_2 at Fig. 3 is about 11m so that the fundamental radiation is well below saturation. Then the fundamental is suppressed and the 3rd harmonic continues to get amplified to saturation. Power of the 3rd harmonic radiation at the exit is 6.5 GW.

Another method for the fundamental suppressing is intra-undulator spectral filtering [11]. Fig. 5 shows that the electron beam trajectory deviates from a straight line, and a filter is inserted. After transmitting the filter, the radiation will be absorbed in a specific frequency.

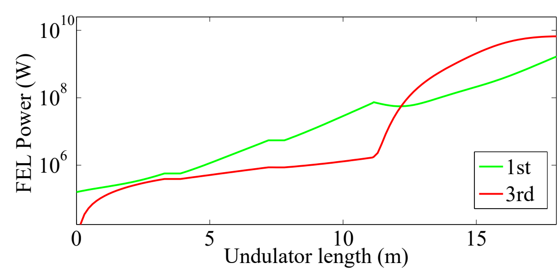

Figure 4: FEL power versus undulator length at U_2(0~11m) and U_3(>11m) in soft X-ray self-seeding harmonic lasing FEL.

After the filter, fundamental mode will be suppressed while the nth harmonic mode is only weakly affected.

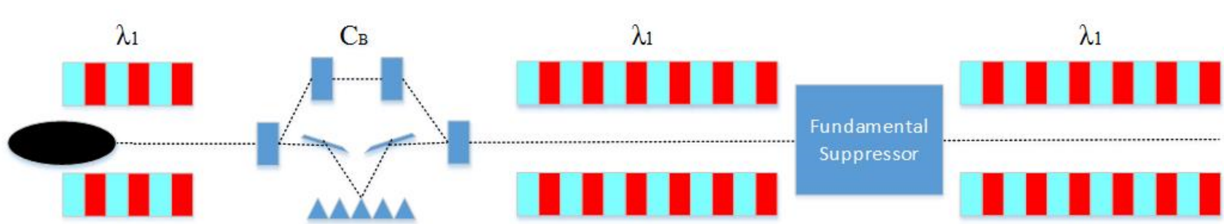

Figure 3: Soft X-ray self-seeding harmonic lasing scheme

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At the same time, beam modulation will be smeared through a chicane due to R_{56}.

Figure 6 illustrates the evolution of 1st and 3rd harmonic using the intra-undulator spectral filter. Here we choose the filter which provides 10000 power attenuation for the fundamental radiation. While the 3rd still get amplified to saturation with a 4 GW saturation power.

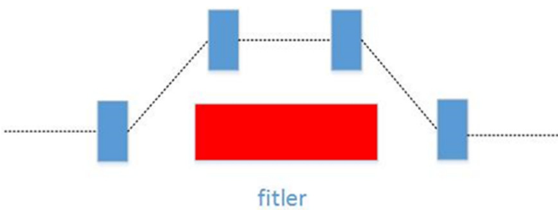

Figure 5: Schematic of intra-undulator spectral filter system.

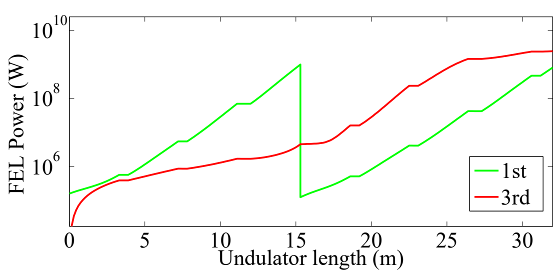

Figure 6: FEL power versus undulator length at U_2 (0~15m).

CONCLUSION

In this paper, we proposed a new simple scheme to extend the wavelength of the soft X-ray self-seeding FEL. With the help of two different ways to suppress the fundamental radiation, the harmonics will get amplified independently. The simulation shows promising results that the output power of the 3rd harmonic radiation (at 0.5 nm) reaches 6.5 GW and 4 GW according to the phase shifter method and intra-undulator spectral filter method, respectively. Further study including optimization and higher harmonic generation is ongoing.

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