A MODIFIED SELF-SEEDED X-RAY FEL SCHEME TOWARDS SHORTER WAVELENGTHS

L. Zeng#, S. Huang, W. Qin, K. Liu, J. Chen
Institute of Heavy Ion Physics, School of Physics, Peking University, Beijing 100871, China
Y. Ding, G. Marcus, Z. Huang
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

We present a modified self-seeded free-electron laser (FEL) scheme of harmonic generation to extend soft x-ray FEL towards shorter wavelength. Different from classical HGHG scheme whose seed laser is a conventional laser with a longer wavelength, this scheme uses a regular self-seeding monochromator to generate a seed laser, followed by a HGHG configuration to produce shorter-wavelength radiations. We perform start-to-end simulations to demonstrate the second and third harmonic FELs from a soft x-ray self-seeding case at the fundamental wavelength of 1.52 nm. The FEL performance will be discussed.

*INTRODUCTION

There are two main schemes for single pass short wavelength FELs: SASE [1,2] and HGHG [3,4]. Until recently, most of the modern high-gain FELs in short wavelength (e.g., x-ray) region have been operated in SASE mode (Emma et al., 2010 [5]; Ishikawa et al., 2012 [6]), which is characterized by excellent transverse coherence. However, SASE has poor temporal coherence and large shot-to-shot fluctuations in both the time and frequency domain because it starts from shot noise.

HGHG scheme can generate fully coherent and high gain harmonic radiation of seed laser. However, single stage harmonic number n is limited since the energy spread is increased n times during the energy modulation which makes the induced energy spread exceed the ρ of radiator. So far, the highest harmonic obtained with single HGHG is the 13th harmonic at 20nm using a 1.2 GeV beam at FERMI FEL [7]. In order to reach higher harmonics, so as to obtain ultrashort wavelength and fully coherent FEL, several schemes have been suggested in recent years. Among them, the cascaded HGHG scheme with the help of "fresh bunch" technique was first proposed in 2001 [8]. Recently, 4.3 nm radiation (60th harmonic of a 260 nm UV laser) has been achieved with a two stage HGHG configuration at FERMI [9]. Another harmonic bunching technique, EEHG [10], has been proof-of-principle demonstrated at SLAC [11] and the third harmonic has been observed at SDUV-FEL, then further amplified to saturation (Zhao et al., 2012 [12]). Currently, coherent radiation at 160 nm (15th harmonic of a 2400 nm seed laser) has been produced at SLAC [13].

#zengling@pku.edu.cn

So far, the cascaded HGHG and EEHG have difficulty in generating hard X-ray FEL. For classic HGHG scheme, it cannot reach hard x-ray region due to lack of external seeds with short enough wavelengths [14]. Besides, the optical properties of HGHG FEL are determined by the quality of seed laser, so a high quality seed laser is required. On the other hand, self-seeding [15] starts from SASE, and a monochromator is used before saturation to generate a purified seed. This seed is then well aligned and interact with the electron beam, which is delayed by a bypass chicane, until saturation to produce near Fourier-transform-limited X-ray pulses. This self-seeding scheme works for both soft and hard x-ray FELs and has been demonstrated recently [14]. For x-ray FEL with the photon energy below 2 keV, a grating-based monochromator can be used [14]; while for x-ray FEL with the photon energy above 4.5 keV, diamond-based monochromator is more popular [16]. The self-seeded FEL in the energy region between 2 to 4.5 keV is more difficult due to lack of monochromator materials. In this paper, we study a new scheme combining the self-seeding and HGHG scheme to produce fully coherent x-rays which could fill the above energy gap not easily achieved by regular seeding schemes.

HGHG BASED ON SELF-SEEDING

The proposed scheme, HGHG based on self-seeding, is shown in Fig. 1, which consists of two stages: SASE stage and HGHG stage. In this preliminary work, we are trying to generate 0.76 nm and 0.51 nm x-ray FELs which are the second and third harmonic of the 1.52 nm radiation from SASE undulator, respectively.

The first stage follows the regular self-seeding setup, including a SASE undulator, a monochromator, and a bypass chicane. A 4.3 GeV electron beam is sent to the 19.8-m-long undulator (U_S) which is resonant at 1.52 nm and operates in the linear amplification region, so the output radiation has the usual SASE properties. The monochromator filters out a narrow bandwidth signal from the SASE radiation, which is used as the seed laser for the downstream HGHG.

The second stage FEL uses the seed laser and electron beam from the former stage to generate harmonic radiation. Here we should notice that, different from external seed laser whose peak power is at hundred megawatt level (e.g., 100 MW in FERMI FEL-1 [7]) in classic HGHG scheme, our seed power is limited to be lower than several hundred kilowatts in order to avoid damage to the monochromator optics [14]. As a result, we

ISBN 978-3-95450-134-2

need to use a longer undulator for electron energy modulation. This long modulator has two functions here: the first one is to amplify the few hundred kilowatt seed to few hundred megawatt, which is mainly achieved with the front part of the modulator; the second one is to modulate the electron bunch, as in a normal HGHG modulator.

.

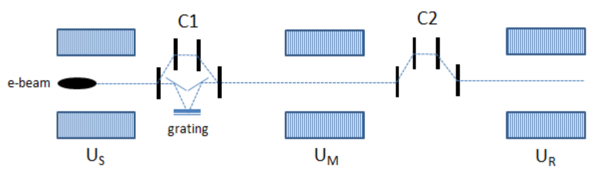


Figure 1: Schematic of HGHG based on self-seeding. U_S is a SASE undulator resonated at 1.52nm. U_M is a modulator resonated at 1.52 nm while U_R is a radiator resonated at 0.76 nm or 0.507 nm. C1 and C2 are chicanes with different values of R_{56}.

FEL SIMULATION

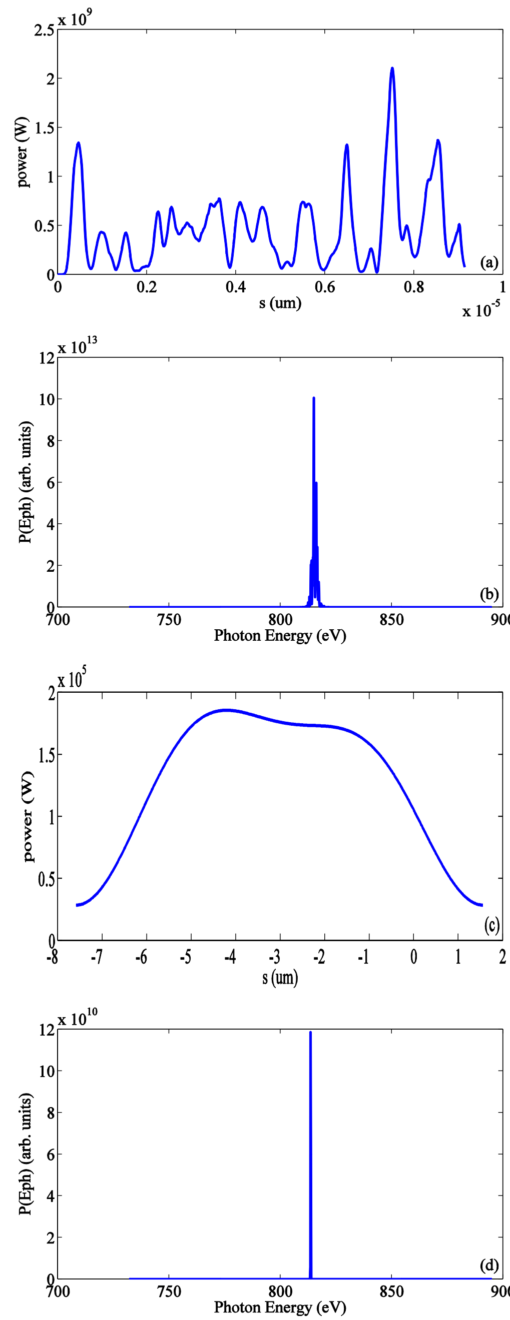
Table 1: Parameters used for HGHG based on Self-seeding Simulation

Parameter	Value	Unit
Electron beam		
Energy	4.3	GeV
Peak current	3	kA
Energy spread	1	MeV
Emittance	0.5	mm-mrad
Mono / Chicane		
Resolving power	5000	
Power efficiency	0.02	
R_{56} of C2	0.28	µm
Undulators		
U_S (U_M and U_R) period	0.03	m
U_S length	19.8	m
U_S strength, A_u	2.4749	
U_M length	9.9	m
U_M strength, A_u	2.4749	
U_R length	39.1	m
U_R strength, A_u	1.6	

We use LCLS parameters as a representative example for start-to-end simulations. The simulations were performed with GENESIS [17]. Table 1 shows the parameters of the scheme which have been optimized for the maximum FEL power at the exit of monochromator. Time-dependent simulation result of the first stage is shown in Fig. 2. It is clear that after the monochromator, the seed power of radiation is about 200 kW.

For modulator, the optimal $\Delta\gamma_m$ is about $n\sigma_\eta$ [18], where n is the harmonic number, σ_η is the relative energy spread and $\Delta\gamma_m$ is the maximum energy modulation amplitude. Three LCLS-type undulator sections are used for modulator which have a total length of 9.9 m. The dispersion of the chicane is chosen to approximately satisfy $R_{56}\Delta\gamma_m/\gamma \approx \lambda/4$[10], where λ is the wavelength of the seed laser. The value of R_{56} here is 0.28 µm.

Figure 3 illustrates the evolution of the peak power of the second harmonic and the third harmonic along radiator. The second harmonic reaches saturation at 39 m and the saturation power is 29 GW, while the third harmonic reaches saturation at 36 m and the saturation power is 0.6 GW. At the position of saturation the 2nd and 3rd harmonic spectrum is shown in Fig. 4. We can see a second harmonic at 0.76 nm whose relative bandwidth is about $2\text{x}10^{-3}$ and a third harmonic at 0.76 nm whose relative bandwidth is about $1.5\text{x}10^{-3}$.



ISBN 978-3-95450-134-2

Figure 2: The FEL power at monochromatic SASE stage in time and frequency domain.(a) temporal profile at the exit of U_S; (b) spectrum at the exit of U_S; (c) temporal profile at the exit of monochromator; (d) spectrum at the exit of monochromator.

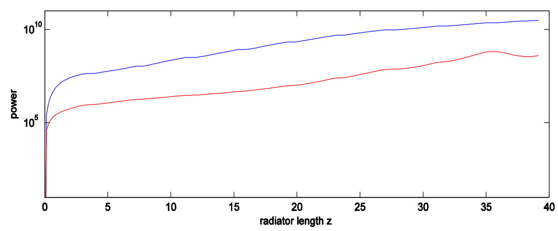


Figure 3: The 2nd (blue line) and 3rd (red line) harmonic power evolution along the radiator undulators (Different A_u values.)

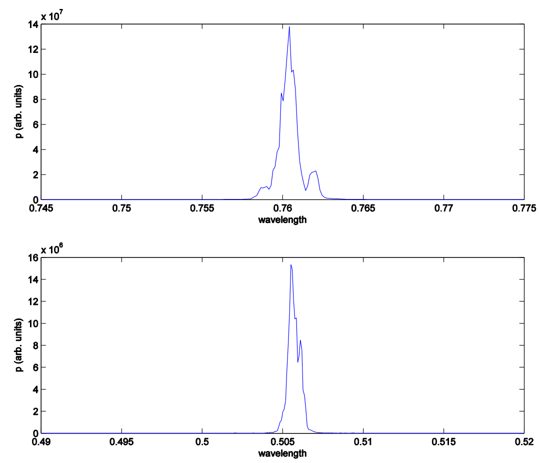


Figure 4: 2nd (a) and 3rd (b) harmonic FEL spectrum at the radiator exit.

CONCLUSION

In this paper, we proposed a new scheme to produce fully coherent shorter-wavelength radiations. It is a modified HGHG setup based on a seed from regular self-seeding scheme. The simulation shows promising results that with wavelength of 0.76 nm (2nd harmonic) and 0.51 nm (3rd harmonic), fully coherent radiation of 30 GW and 0.6 GW are obtained. Further study including optimization and higher harmonic generation is ongoing.

REFERENCES

[1] SLAC Report No. SLAC-R-593, 2002.
[2] DESY Report No. DESY-2006-097, 2006.
[3] I. Ben-Zvi et al., Nucl. Instrum. Methods Phys. Res., Sect. A 304, 181 (1991).
[4] L. Yu. Phys. Rev. A 44. 5178 (1991).
[5] Emma P, Akre R, Arthur J, et al. First lasing and operation of an ångstrom-wavelength free-electron laser, Nature Photonics, 2010, 4(9): 641-647.
[6] Ishikawa T, Aoyagi H, Asaka T, et al. A compact X-ray free-electron laser emitting in the sub-angstrom region, Nature Photonics, 2012, 6(8): 540-544.
[7] Allaria, E., et al., 2012, Nature Photonics 6, 699.
[8] Wu J H, Yu L H. Nucl. Instrum. Methods A, 2001, 475: 10
[9] Allaria, E., et al., 2013, Nature Photonics 7, 913.
[10] Xiang D, Stupakov G. Echo-enabled harmonic generation free electron laser, Physical Review Special Topics-Accelerators and Beams, 2009, 12(3): 030702.
[11] Dunning M, et al. A proof-of-principle echo-enabled harmonic generation FEL experiment at SLAC, Conf. Proc. 2010, C100523 (IPAC-2010-TUPE069).
[12] Zhao Z.T, Wang D, Chen J H, et al. First lasing of an echo-enabled harmonic generation free-electron laser, Nature Photonics, 2012, 6(6): 360-363.
[13] Hemsing, E., M. Dunning, C. Hast, T. Raubenheimer, S. Weathersby, and D. Xiang, 2014, "Highly coherent vacuum ultraviolet radiation at the 15th harmonic with echo-enabled harmonic generation technique", Phys.Rev.ST Accel.Beams 17 (2014) 070702; doi: 10.1103/ PhysRevSTAB. 17. 070702
[14] Ratner D, Abela R, Amann J, et al. Experimental Demonstration of a Soft X-Ray Self-Seeded Free-Electron Laser. Physical review letters, 2015,114(5): 054801.
[15] Feldhaus J, Saldin E L, Schneider J R, et al. Possible application of X-ray optical elements for reducing the spectral bandwidth of an X-ray SASE FEL, Optics Communications, 1997, 140(4): 341-352.
[16] J. Amann et al. "Demonstration of self-seeding in a hard-X-ray free-electron laser", Nature Photonics 6, 693–698 (2012) doi:10.1038/nphoton.2012.180
[17] S. Reiche, Nucl. Instr. Meth. Phys. Res. Sec. A 429, 243 (1999).
[18] Kwang-Je Kim and Zhirong Huang. Introduction to the physics of free electron lasers.

ISBN 978-3-95450-134-2