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X-RAY FEL OSCILLATOR SEEDED HARMONIC AMPLIFIER FOR HIGH ENERGY PHOTONS

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Abstract

High power, high energy X-ray pulses in the range of several tens of keV have important applications for material sciences. The unique feature of an X-ray FEL Oscillator (XFELO) makes it possible to seed a harmonic amplifier to produce such high energy photons. In this paper, we present simulation studies using 14.4-keV output pulses from an XFELO to generate harmonics at 43.2 keV (third harmonic) and 57.6 keV (fourth harmonic). Techniques such as undulator tapering and fresh bunch lasing are considered to improve the amplifier performance.

INTRODUCTION

High power, high energy hard X-ray free-electron lasers (XFELs) have important applications for exploring the dynamic properties of materials under extreme conditions. Generation of such high energy photons can be realized using conventional self-amplified spontaneous emission (SASE) [1, 2] scheme and advanced harmonic lasing [3] and fresh-slice technique [4] to improve the performance. An alternative way is to use the proposed XFELO [5], which successively amplifies X-ray pulse trapped in a low loss cavity, to produce coherent, stable hard X-ray as the seed for a high gain harmonic generation (HGHG) [6] type FEL, which is possible to generate stable pulses with high intensity and narrow bandwidth. This concept was studied for third harmonic of 14-keV XFELO and fourth harmonic of 15-keV XFELO using ideal beam [7, 8] for the Matter-Radiation Interactions in Extremes (MaRIE) [9]. Here we use the output from a start-to-end simulated 14.4-keV XFELO operating in fundamental mode [10] to investigate the harmonic performance at third harmonic (43.2 keV) and fourth harmonic (57.6 keV).

LAYOUT

The layout of the proposed scheme is illustrated in Fig. 1, where two photoinjectors are used to generate high brightness interleaved electron bunches for the XFELO and the harmonic amplifier, respectively. Electron beams are kicked from the linac at 8 GeV into the XFELO to generate a 14.4-keV seed. With a proper delay, the seed is sent into a modulator to modulate the 12-GeV, 3.4-kA electron beam. The energy modulation can be converted to density modulation via a small magnetic chicane or a detuned undulator. In a subsequent radiator tuned at third or fourth harmonic of the modulation wavelength, high energy photons are emitted. Fresh bunch technique, where a fresh electron bunch is delayed to interact with the FEL radiation generated in the first part of the radiator, is used to reduce the effect of the increased energy spread after modulation on the FEL performance. The fresh bunch can be provided by accelerating two bunches in one RF bucket, as in Ref. [11], and the delay between two bunches is tens of femtosecond, which can be reached using a small magnetic chicane. Although the XFELO pulse is much longer than the delay of the two bunches, one of the two bunches can be tuned to off resonant in the modulator through energy difference between the two bunches due to wakefields, so that one bunch is modulated and the other remains fresh. Bunch charge is 100 pC for all cases. Normalized emittance is 0.2 µm for 12-GeV ideal Gaussian beam. For the XFELO simulation, the emittance is 0.25 µm. More machine parameters used in this study are listed in Table 1.

Table 1: Electron beam and FEL parameters. Bunch charge is 100 pC for all cases. Normalized emittance is 0.2 µm for 12 GeV ideal Gaussian beam. For the XFELO simulation, the emittance is 0.25 µm.

Parameter	XFELO	Mod.	43.2 keV	57.6 keV
FEL K	1.48	2.79	1.44	1.03
E_b [GeV]	8	12	12	12
I_{pk} [A]	120	3400	3400	3400
σ_s [fs]	317	12.5	12.5	12.5
σ_E [MeV]	0.2	1.8	1.8	1.8
λ_u [cm]	2	1.94	1.55	1.55
L_u [m]	20	8	70	70
harmonic	1	1	3	4

THE XFELO

The XFELO uses high reflectivity, narrow spectral bandwidth crystals as mirrors for the X-ray pulses. In this study we adopt the four crystal configuration as proposed in Ref. [12] to allow for wavelength tunability and C(733) is used for 14.4-keV radiation. GINGER [13] simulation is conducted to evaluate the XFELO performance, with its temporal profile and spectrum shown in Fig. 2. The power of the XFELO output reaches about 37 MW after saturation and the FWHM bandwidth is about 3.4 meV, which is two orders narrower than hard X-ray self-seeding machine.

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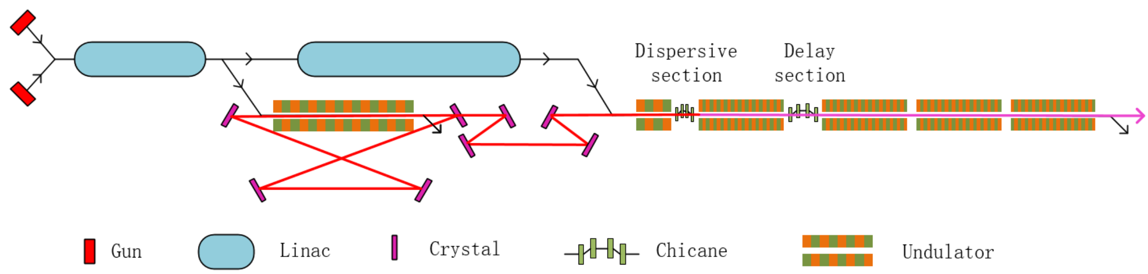

Figure 1: Layout of the proposed XFELO driven high gain harmonic generation scheme.

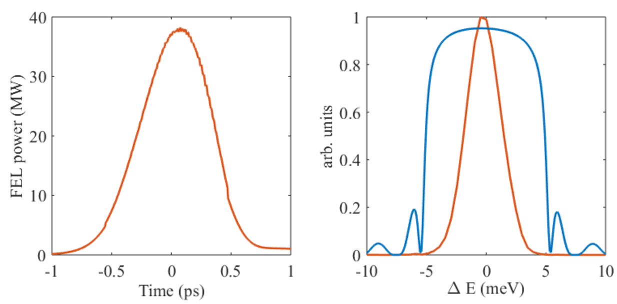

Figure 2: Output pulse temporal profile and spectrum of the 14.4-keV XFELO.

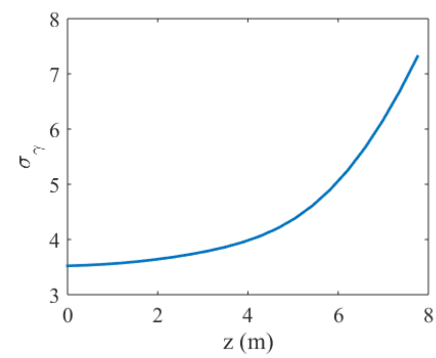

Figure 3: Electron beam rms energy spread evolution along the modulator.

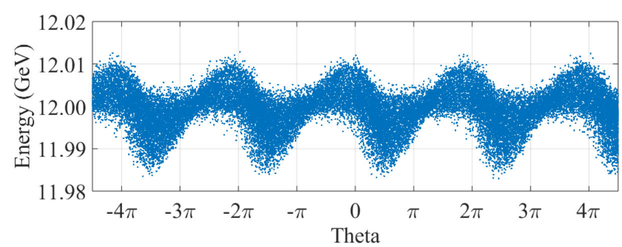

Figure 4: Electron beam longitudinal phase space at the end of the modulator.

HARMONIC GENERATION

Modulator

The XFELO output is converted to GENESIS [14] input as radiation description file for harmonic generation simulation. An 8 m undulator with 1.94 cm period is used to introduce sufficient energy modulation in the beam. To obtain sufficient bunching after dispersive section with R_{56}, an energy modulation amplitude of $h\sigma_E$ is favorable for the h^{th} harmonic. The energy modulation also increases the beam energy spread, which should be smaller than the FEL ρ to ensure sufficient FEL gain. For the 12-GeV beam in this study, the beam energy spread is 1.5×10^{-4} and the Pierce parameter ρ is about 4×10^{-4} for third harmonic and 3.2×10^{-4} for fourth harmonic. As is shown in Fig. 3, the beam rms energy spread is almost doubled at the end of the modulator, with the corresponding electron beam longitudinal phase space shown in Fig. 4. The R_{56} needed to convert the energy modulation into density modulation is about 10 nanometers, which can be achieved with either small magnets (bend angle 1×10^{-4} and length 2.5 cm) or a detuned undulator. The bunching factor reaches about 9% with $R_{56} = 1.4 \times 10^{-8}$ m for third harmonic and 4% with $R_{56} = 1.2 \times 10^{-8}$ m for fourth harmonic.

Third Harmonic

To explore the FEL performance at the third harmonic in the radiator, four cases are simulated using GENESIS: 1) non-fresh bunch, 2) non-fresh bunch, with undulator taper, 3) with fresh bunch and 4) with fresh bunch and undulator taper. The radiator length is 70 m for non-fresh bunch cases and (5 + 65) m for fresh bunch cases. FEL pulse energy evolution along the undulator is shown in Fig. 5. The standard HGHG scheme produce about 100-μJ X-ray pulse at the end of the undulator. After a proper taper, the pulse energy is increased to 500 μJ, corresponding to 7.2×10^{10} photons per pulse. Using the fresh bunch method along with undulator taper, the pulse energy reaches 750 μJ at 70 m, corresponding to 1.1×10^{11} photons per pulse. Compared with non-fresh cases, the improvement of pulse energy using fresh bunch method is less than a factor of two, indicating that the increased energy spread in the modulator is well within favorable range for third harmonic. The temporal profile and spectrum for the case with both fresh bunch and taper are shown in Fig. 6. FEL pulse with 45 GW power and 17 fs FWHM pulse duration is generated. The pulse spectrum is clean and the FWHM bandwidth is about 0.38 eV.

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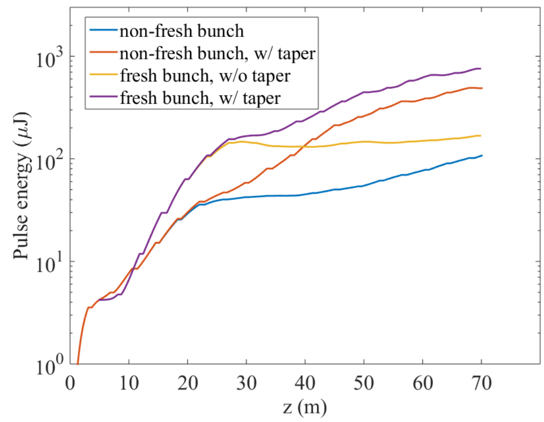

Figure 5: FEL pulse energy evolution in the radiator for 43.2-keV X-rays.

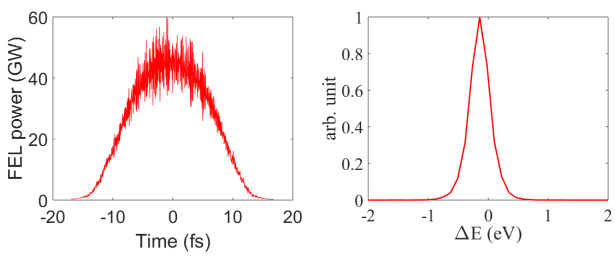

Figure 6: Temporal profile and spectrum for the 43.2-keV X-rays with fresh bunch and undulator taper.

Fourth Harmonic

For the fourth harmonic radiation, it can be seen in Fig. 7 that the increased energy spread after modulation is limiting the FEL performance in the radiator, with only 13-μJ pulse energy at the end of the undulator. With the help of fresh bunch, the output pulse energy is increased to 55 μJ. Undulator taper further increases the pulse energy to 300 μJ, corresponding to 3.3×10^{10} photons per pulse. Temporal profile and spectrum for the case with fresh bunch and undulator taper for the fourth harmonic are shown in Fig. 8. The temporal and spectral characteristics are similar to those of the third harmonic, with 19-GW power, 16-fs FWHM pulse duration and 0.4-eV FWHM bandwidth.

CONCLUSION

We studied the FEL performance of an HGHG-type harmonic amplifier driven by a 14.4 keV XFELO to generate coherent high energy photons for scientific applications under extreme conditions. This scheme takes full advantage of the high-power, narrow-bandwidth hard X-rays from the XFELO. Simulations show that, with the help of fresh bunch and undulator taper, 750 μJ and 300 μJ pulse energy can be generated for third harmonic at 43.2 keV and fourth harmonic at 57.6 keV, respectively. The generated high energy X-ray pulses have $10^{10} - 10^{11}$ photons per pulse and narrow bandwidth down to 10^{-6}. More detailed study should be conducted in several aspects of the proposed scheme, for example, the accelerator system that can deliver two high-

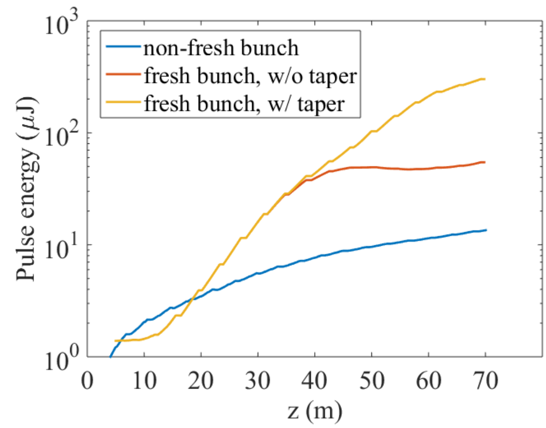

Figure 7: FEL pulse energy evolution in the radiator for 57.6-keV X-rays.

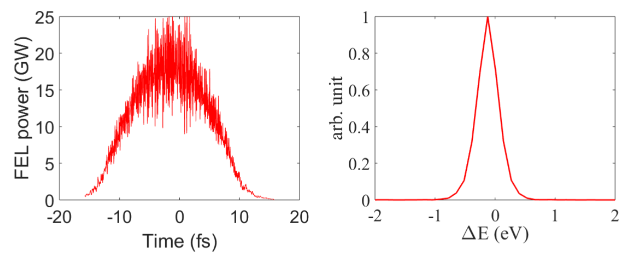

Figure 8: Temporal profile and spectrum for the 57.6-keV X-rays with fresh bunch and undulator taper.

energy, interleaved electron bunch streams with large current difference, the optimization of the undulator taper, the nonlinear harmonic generation in the radiator to produce even higher photon energies.

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REFERENCES

[1] A. Kondratenko and E. Saldin, "Generation of coherent radiation by a relativistic-0electron beam in an undulator", *Part. Accel.* 10, 207 (1980).

[2] R. Bonifacio *et al.*, "Collective instabilities and high-gain regime in a free electron laser", *Opt. Commun.* 50, 373 (1984).

[3] E. A. Schneidmiller *et al.*, "First operation of a harmonic lasing self-seeded free electron laser", *Phys. Rev. Accel. Beams* 20, 020705 (2017).

[4] C. Emma *et al.*, "Demonstration of fresh slice self-seeding in a hard X-ray free electron laser", *Proc. of NAPAC'16*, Chicago, IL, USA, TUB3CO03.

[5] K.-J. Kim *et al.*, "A proposal for an X-ray free-electron laser oscillator with an energy-recovery linac", *Phys. Rev. Lett.* 100, 244802 (2008).

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[6] L. Yu, "Generation of intense UV radiation by subharmonically seeded single-pass free-electron lasers", *Phys. Rev. A* 44, 5178 (1991).

[7] K.-J. Kim, "XFELO Seeded Amplifier" (talk), *MaRIE workshop*, Santa Fe, NM, USA (2016).

[8] L. Gupta *et al.*, "Performance of a Combined System Using an X-Ray FEL Oscillator and a High-Gain FEL Amplifier", *Proc. of NAPAC'16*, Chicago, IL, USA, WEPOB32.

[9] J. W. Lewellen *et al.*, "Technology maturation for the MaRIE 1.0 X-FEL", *Proc. of FEL'15*, Daejeon, Korea, TUP030.

[10] W. Qin *et al.*, "Start-to-end simulations for an X-ray FEL Oscillator at the LCLS-II and LCLS-II-HE", presented at FEL'17, TUC05, these proceedings.

[11] A. Marinelli *et al.*, "High-intensity double-pulse X-ray free-electron laser", *Nat. Commun.* 6, 6369 (2015).

[12] K.-J. Kim *et al.*, "Tunable optical cavity for an x-ray free-electron-laser oscillator", *Phys. Rev. ST Accel. Beams* 12, 030703 (2009).

[13] W. M. Fawley, "A user manual for GINGER-H and its post-processor XPLOTGINH", Version 2.0k, June 2012.

[14] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code", *Nucl. Instr. Meth. A* 429 (1999) 243.