ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL044

HIGH-POWER AND FEMTOSECOND FREE-ELECTRON LASER PULSE GENERATION WITH CHIRPED PULSE AMPLIFICATION IN EEHG

Li Zeng, Xiaofan Wang*, Yifan Liang, Huaiqian Yi, Weiqing Zhang[1]†, Xueming Yang[2]
Institute of Advanced Science Facilities, Shenzhen, China
[1] also at Dalian Institute of Chemical Physics, CAS, Dalian, China
[2] also at Southern University of Science and Technology, Shenzhen, China

Abstract

Ultrafast science has developed rapidly nowadays thanks to the development of optical and laser technologies, like chirped pulse amplification and high-harmonic generation. In this work, a simulation has been performed to generate high-power femtosecond free-electron laser pulses with chirp pulse amplification in echo-enable harmonic generation. Frequency chirped seed pulses are used to create frequency-chirped bunching at laser harmonic in the electron beam. The generated FEL pulses which inherits the chirped frequency can be compressed to provide ultra-intense ultrafast pulses. Numerical modeling shows that the peak power reaches tens of gigawatts and pulse duration is about several femtosecond.

INTRODUCTION

High-power and ultrafast free-electron laser (FEL) pulses are nowadays an indispensable tool for a multitude of disciplines, ranging from physics and chemistry to biology and material science. To increase the peak power and shorten the pulse duration of FEL pulses, several methods have been proposed and developed in recent years [1–4].

An alternative approach to generate high-power and ultrafast FEL pulses is applying chirped pulse amplification (CPA) to FELs. The feasibility of CPA-SASE have been studied both theoretically and experimentally [5, 6]. However, it is difficult to guarantee the phase relationship starting from the shotnoise, leading to limited compression ratio. Hence, the choice of seeded FELs seems to be a more promising scheme to integrate the CPA technique. CPA-HGHG has been studied theoretically and femtosecond UV pulses (~260 nm) with peak power of tens of MW can be generated [7]. In Ref. [8], researchers demonstrate the possibility of carrying out CPA-HGHG at FERMI@Elettra. But the low transmission of the compressor (~5%) and relatively low harmonic number limited the obtained peak power and pulse duration. To improve the transmission efficiency and to push the power into TW scale, a "self-seeding" CPA scheme has been proposed. It can potentially deliver femtosecond hard X-ray pulses with peak power of ~1 TW, using the Bragg crystals instead of gratings [9].

In this paper, the CPA operation of echo-enable harmonic generation (EEHG) for high-power and ultrafast FEL pulses has been studied. This technique has the potential of generating tens of gigawatts EUV pulses with pulse duration of about several femtosecond.

PROPOSED METHOD

The schematic layout of CPA-EEHG is illustrated in Fig. 1. The frequency chirped seed laser pulses are optically stretched with a pair of gratings. These chirped seed laser pulses interacts with the electron beam in modulators and imprint a chirped bunching at laser harmonics in the electron beam. When passing through the radiator, the bunched electron beam produced FEL pulses which inherit the chirped frequency of the seed laser. Such chirped FEL pulses can be compressed by double-grating compressor in grazing incidence.

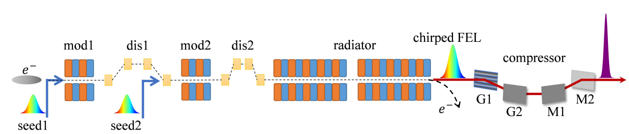

Figure 1: The schematic layout of CPA-EEHG.

The linearly chirped Gaussian pulse can be written mathematically as:

$$E(t) = E_0 \exp\left(-(t/\tau_t)^2\right) \exp i(\omega_0 t + \beta t^2). \quad (1)$$

Hence, the instantaneous frequency is $\omega_{ins} = \omega_0 + 2\beta t$, where β determines the chirp rate. To amplified this chirped pulse, the electron beam should has an energy chirp in order to match the resonance condition:

$$\gamma(s) = \sqrt{\frac{n\lambda_u}{2\lambda_{seed}(s)}(1 + a_w^2)}, \quad (2)$$

where n is the harmonic number, $\lambda_{seed}(s)$ denotes the seed laser wavelength distribution along the longitudinal position s, λ_u and a_w denote the undulator period and strength.

As demonstrated in Ref. [8], when the seed pulses have a significant frequency dispersion, the FEL pulse bandwidth, $(\Delta\omega)_{FEL}$, scales according to the relation

$$(\Delta\omega)_{FEL} \approx n^{1-\alpha}(\Delta\omega)_{seed}, \quad (3)$$

where $(\Delta\omega)_{seed}$ denotes the seed pulse bandwidth, α is a factor depending on the FEL amplification process which is about $1/3$ when FEL reaches saturation. The above equation points out that the frequency up-conversion at higher harmonics will increase the FEL pulse bandwidth leading

* wangxf@mail.iasf.ac.cn
† weiqingzhang@dicp.ac.cn

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL044

to a smaller FEL pulse duration after compression. This indicates that, in principle, the compressed FEL pulse in CPA-EEHG will be much shorter compared with CPA-HGHG.

SIMULATION RESULTS

In order to investigate the feasibility of CPA-EEHG, a simulation has been carried out based on the parameters listed in Table 1. Two 270 nm laser pulses which are stretched to 300 fs(FWHM) are used as seed laser. The Wigner distribution of seed lasers are shown in Fig. 2. Two lasers have the same linear chirp with a bandwidth ($\Delta\lambda/\lambda$) of about 1.5%.

Table 1: Simulation Parameters

Parameter	Value	Unit
Electron beam		
Beam energy	2.5	GeV
Peak current	800	A
Emittance	0.4/0.4	mm·mrad
Bunch length	600	fs
Seed laser		
Wavelength	270	nm
Pulse length	300	fs
Peak Power	~100	MW
Modulator		
Period length	0.09	m
Length	~2	m
Dispersion		
Dipole Length	0.5	m
Length	10/5	m
Radiator		
Period length	0.043	m
Resonant wavelength	13.5	nm
Length	4	m

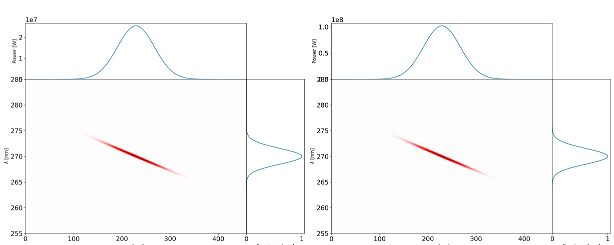

Figure 2: The Winger distribution of seed lasers, the projections show the power profiles and spectra of seed lasers.

To match the resonance condition, a 3.2% energy chirp has been imprinted on the electron beam in the simulation. The distribution of electron beam energy and current are demonstrated in Fig. 3. It is noteworthy that there might be a quadratic component in energy chirp due to the RF curvature in acceleration experimentally, which will broaden the FEL pulse bandwidth. This effect will degrade the quality of the radiation pulse and affect the performance of CPA. The dispersion strengths R_{56} of two chicanes are ~2.20 mm and ~0.12 mm, respectively. After second dispersion section, the electron beam generates micro-bunching which contains frequency components at high harmonics of the seed laser. With this kind of electron beam, coherent 13.5 nm (n = 20) radiation pulses are generated and amplified in the radiator.

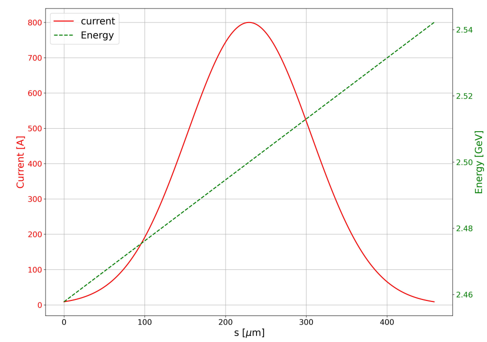

Figure 3: The distribution of electron beam energy and current at the entrance of modulator1.

Figure 4 shows the β-function along the lattice. The maximal field strength of quadrupoles is less than 20 T/m and the average β-function along the radiator is ~10 m. The FEL performance is simulated by GENSIS based on this lattice.

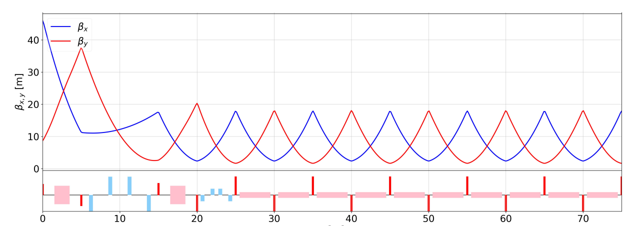

Figure 4: The β-function along the lattice.

The simulation results along the radiator are shown in Fig. 5. The red and gray lines show the evolution of FEL pulse energy and electron beam bunching factor, respectively. The optimized 20^{th} bunching factor at the entrance of radiator is about 8.30%. The pulse energy reaches 651 μJ only after two undulators.

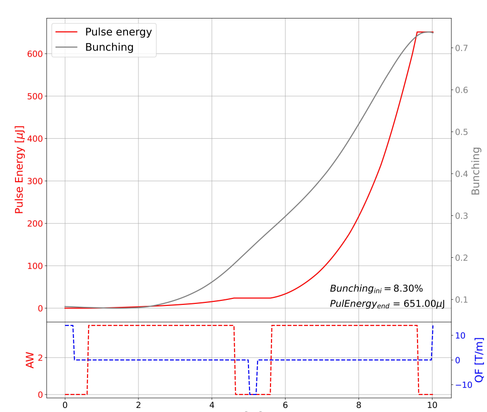

Figure 5: The simulation results along the radiator.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL044

The 20^{th} bunching factor distribution along the electron bunch at the entrance and power profile after two undulators are shown in Fig. 6(a). The peak power of output radiation is around 3.94 GW and the FWHM pulse duration is about 186.43 fs. As shown in Fig. 6(b), the spectrum bandwidth of the radiation pulse is about 0.81%, which is close to the theoretical expectation of 0.55%. The difference may result from the fact that the simulation stopped before saturation. The Wigner distribution of the radiation pulse after radiator is shown in Fig. 7. The linear frequency chirp in the seed laser is well maintained and this kind of laser pulse can be easily compressed by the optical pulse compressor.

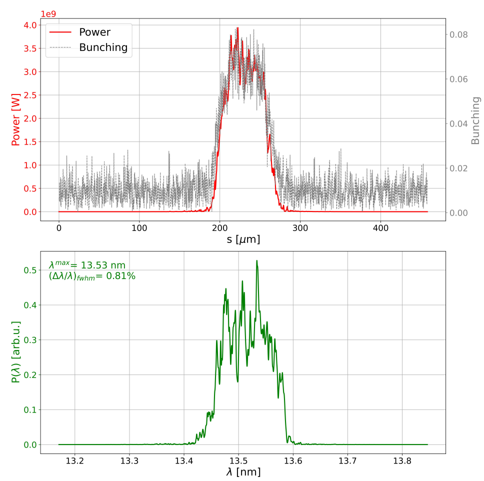

Figure 6: The simulation results along the electron bunch.

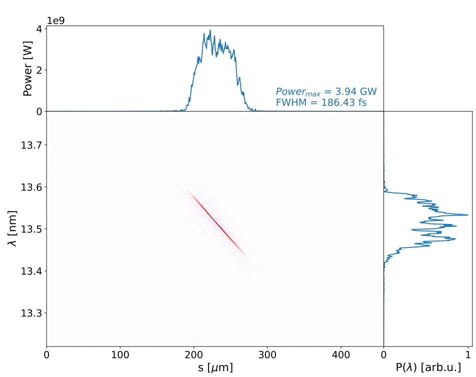

Figure 7: The Wigner distribution of the FEL pulse before the compressor.

The frequency chirped FEL pulse propagates through a double-grating compressor as shown in Fig. 1. If the group-delay dispersion (GDD) introduced by the compressor is equal and opposite to the intrinsic GDD of the input FEL pulse, the pulse duration is reduced since the second-order effects on the phase are corrected. By adopting the off-plane mount (OPM) geometry of the gratings, the expected total efficiency of the compressor is up to 15% at the central wavelength of 13.5 nm [10]. Figure 8 gives the Winger distribution of the FEL pulse after compressor. Assuming that the transmission efficiency of the compressor is around 15%, the pulse length is compressed by about 70 times, from 186.43 fs to 2.70 fs, and the peak power is accordingly enhanced by about 6 times, from 3.94 GW to 23.93 GW. The time-bandwidth product (~0.486) is only a factor of 1.1 above the transform limit for a Gaussian pulse, which is in satisfactory agreement with the experiment result in Ref. [8]. It is worth mentioning that the peak power of compressed pulse can reach 15.95 GW even the transmission efficiency of the compressor decreases to 10%.

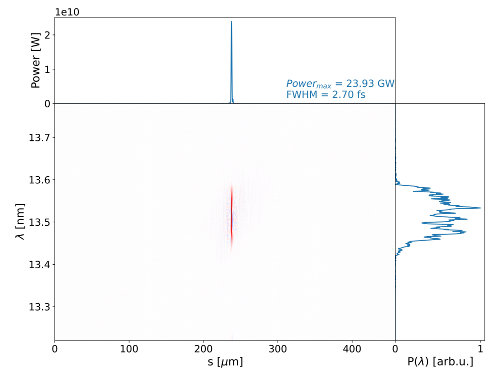

Figure 8: The Wigner distribution of the FEL pulse after the compressor.

The GDD introduced by the compressor is about $-160\,\mathrm{fs}^2$. This kind of GDD can be achieved by increasing the distance between the first and the second gratings. The compressor also gives a spatial chirp of the pulse which may degrade the quality of the final compressed pulse. For the compressor designed in the simulation, the spatial chirp calculated in the FWHM bandwidth is 0.55 mm according to Ref. [10], which is much smaller than the FEL pulse diameter at the compressor entrance and therefor negligible.

CONCLUSIONS

The feasibility of CPA-EEHG has been study analytically and numerically mainly based on S^3FEL parameters. Simulation results show that this technique has the potential of generating high-power XUV FEL pulses with pulse duration of several femtosecond. A compressor adopting OPM geometry is designed at central wavelength of 13.5 nm. The spatial chirp introduced by the compressor is discussed.

ACKNOWLEDGEMENTS

This work is supported by the National Key R&D Program of China (Grant No.2018YFE0203000) and the National Natural Science Foundation of China (Grant No.22288201).

REFERENCES

[1] V. Grattoni *et al.*, "Control of Seeded FEL Pulse Duration Using Laser Heater Pulse Shaping", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2654–2656. doi:10.18429/JACoW-IPAC2017-WEPAB034

[2] E. Prat, *et al.*, "Simple Method to Generate Terawatt-Attosecond X-Ray Free-Electron-Laser Pulses", *Phys. Rev.*

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL044

Lett., vol. 114, p. 244801, 2015. doi:10.1103/PhysRevLett.114.244801

[3] T. Tanaka and P. R. Ribič, "Shortening the pulse duration in seeded free-electron lasers by chirped microbunching", *Opt. Express*, vol. 27, pp. 30875–30892, 2019. doi:10.1364/OE.27.030875

[4] N. S. Mirian, *et al.*, "Generation and measurement of intense few-femtosecond superradiant extreme-ultraviolet free-electron laser pulses", *Nat. Photonics*, vol. 15, pp. 523–529, 2021. doi:10.1038/s41566-021-00815-w

[5] J. Wu *et al*., "Interplay of the chirps and chirped pulse compression in a high-gain seeded free-electron laser", *J. Opt. Soc. Am. B: Opt. Phys.*, vol. 24, p. 484, 2007. doi:10.1364/JOSAB.24.000484

[6] Y. Li, J. Lewellen, Z. Huang, V. Sajaev, and S. V. Milton "Time-Resolved Phase Measurement of a Self-Amplified Free-Electron Laser", *Phys. Rev. Lett.*, vol. 89, p. 234801, 2002. doi:10.1103/PhysRevLett.89.234801

[7] C. Feng *et al.*, "Chirped pulse amplification in a seeded free-electron laser for generating high-power ultra-short radiation", *Nucl. Instrum. Meth. Phys. Res. Sect. A*, vol. 712, pp. 113-119, 2013. doi:10.1016/j.nima.2013.01.063

[8] D. Gauthier *et al.*, "Chirped pulse amplification in an extreme-ultraviolet free-electron laser", *Nat. Commun.*, vol. 7, p. 13688, 2016. doi:10.1038/ncomms13688

[9] H. Li *et al.*, "Femtosecond-Terawatt Hard X-Ray Pulse Generation with Chirped Pulse Amplification on a Free Electron Laser", *Phys. Rev. Lett.*, vol. 129, p. 213901, 2022. doi:10.1103/PhysRevLett.129.213901

[10] F. Frassetto and L. Poletto, "Grating configurations to compress extreme-ultraviolet ultrashort pulses", *Appl. Opt.*, vol. 54, pp. 7985–7992, 2015. doi:10.1364/AO.54.007985