PROPOSALS FOR CHIRPED PULSE AMPLIFICATION IN HGHG AND CHG AT SDUV-FEL

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Abstract

In this paper, proposals to generate intense ultra-short free-electron laser (FEL) pulses at Shanghai deep ultraviolet FEL (SDUV-FEL) by combining the chirped pulse amplification (CPA) technique with the high-gain harmonic generation (HGHG) and coherent harmonic generation (CHG) are presented. In these proposals, frequency chirped seed pulses are used to create frequency-chirped bunching at the laser harmonics in the electron beam. The output radiation pulses which inherit the properties of the seed pulses can be compressed to provide ultra-intense ultra-short radiation pulses. The feasibility and performance of CPA-HGHG and CPA-CHG are studied with start-to-end simulations using the parameters of the SDUV-FEL.

INTRODUCTION

Chirped pulse amplification (CPA) is a well-known technique at optical frequencies in laser physics that can be used to generate extremely high power ultra-short pulses by utilizing solid-state lasers [1]. However, there are technical challenges to extend the wavelength to below 200 nm in standard CPA lasers, because of the strong absorption of the materials used in conventional laser amplifiers. Note that the high-gain free-electron lasers (FELs) hold the capability to produce high-power radiation down to the x-ray wavelength region. It is then natural to apply the CPA technique in high-gain FELs to generate intense pulses with ultra-short durations at shorter wavelengths not accessible with standard lasers.

Applying CPA techniques in a seeded FEL for femtosecond level pulses generation at VUV region has been proposed in Ref. [2]. A preliminary CPA experiment at 800 nm with direct seeding scheme has been carried out at BNL [3]. The CPA experiment has also been carried out in HGHG process at 266 nm, but properties of the FEL output such as frequency chirp has not been characterized [4].

In this paper, we study CPA operation of high-gain harmonic generation (HGHG) and coherent harmonic generation (CHG) [5] for generation of high peak power ultra-short UV pulses and discuss the possibility of carrying out the proof-of-principle experiments of these schemes at SDUV-FEL facility [6].

PRINCIPLE

A schematic layout of the SDUV-FEL with CPA-HGHG setup is shown in Fig. 1. To produce a frequency chirped seed pulse, the seed laser pulse with a bandwidth of a few percent is optically stretched with a pair of gratings. The FEL system consists of two undulators separated by a chicane. The electron beam interacts with the seed laser within the first short undulator, called modulator, to obtain sufficient energy modulation. This energy modulation is then converted into density modulation by the chicane, called the dispersion section. When passing through the second undulator, called the radiator, the bunched electron beam produces FEL through coherent emission. Taking advantage of the fact that the density modulation shows Fourier components also at the harmonics, it is possible to produce coherent FEL radiation at high harmonics of the seed, in which case the radiator is tuned to the harmonic frequency of the seed laser.

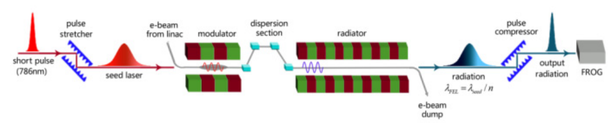

Figure 1: Schematic layout of the SDUV-FEL with CPA-HGHG setup.

Typically the modulator works at the small-gain regime with a bandwidth of about $1/N_m$, where N_m is the period number of the modulator. Similarly, in the CHG scheme, the radiator is relatively short and no exponential growth is expected, therefore the electron beam behaves as a collection of rigid microbunches and the FEL also works in the small-gain region. Accordingly, the relative FEL gain bandwidth is $1/N_c$, where N_c is the period number in the radiator used for CHG. For CPA-CHG scheme with the bandwidth of the seed laser comparable to the gain bandwidths of the modulator and the radiator, the frequency chirped pulse can be directly generated through the CHG process and there will be no need for an initial energy chirp in the electron beam.

For a high-gain FEL with a long radiator, the FEL gain bandwidth is close to the Pierce parameter ▯, which is in the range of 10^{-3} for an ultraviolet FEL. In order to amplify a chirped pulse with a few percent bandwidth, the electron beam need to be prepared with an energy chirp to match the resonance condition as proposed in [2],

$$\gamma(s) = \sqrt{\frac{n\lambda_r}{2\lambda_s(s)}\left(1+K^2/2\right)}, \qquad (1)$$

where $\lambda_s(s)$ is the wavelength distribution along the seed laser pulse, n is the harmonic number, λ_r is the period length of the radiator and K is the strength of the radiator, s is used to denote the longitudinal position along the electron bunch.

The output radiation pulses generated by CPA-CHG and CPA-HGHG inherit the properties of the seed and therefore can be compressed by a system with nonzero

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group delay dispersion, i.e., a grazing-incidence double-grating device as shown in Fig. 1. The minimal pulse duration after compression corresponds to a transform-limited pulse, which can be expressed as [7]

$$\tau = \frac{\lambda_{FEL}}{2cb_w} = \frac{\lambda_s}{2cb_w n}, \quad (2)$$

where λ_{FEL} is the radiation wavelength, c is the speed of light and b_w is the bandwidth of the seed laser. From this equation, one may easily find that the transform-limited pulse duration is mainly determined by the wavelength and bandwidth of the seed laser. For n-th harmonic radiation, the transform-limited pulse duration would be n times shorter than the seed.

To fully characterize the longitudinal properties of the chirped laser pulse in both the time and frequency domains, the Wigner distribution function is routinely used [8],

$$W(t,\omega,s) = \int E(t-\tau/2,s)E^*(t+\tau/2,s)e^{-i\omega\tau}d\tau, \quad (3)$$

Where * denotes the complex conjugate, $E(t,s)$ is the electric field of the laser pulse and ω is the laser frequency. The Wigner distribution can be measured by the frequency-resolved optical gating (FROG) [9].

S2E SIMULATIONS

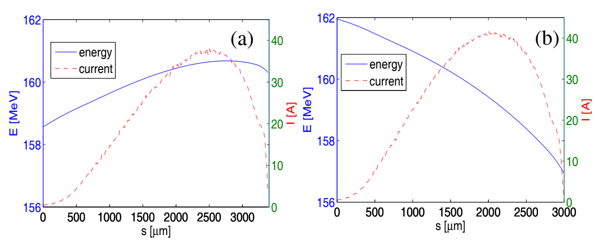

Figure 2: Beam energy and current distributions (bunch head is to the right) at the exit of the linac for two cases: (a) normal electron beam; (b) chirped electron beam.

The Shanghai deep ultra-violet FEL (SDUV-FEL) is a multi-purpose test facility for seeded FEL studies. The layout and parameters of the SDUV-FEL with CPA-HGHG setup are shown in Fig. 1. A 786 nm laser pulse, which is stretched from 82 fs to 4.7 ps (FWHM) with a longitudinal Gaussian profile and peak power of 20 MW, is used as the seed laser. The modulator, a 16×40 mm permanent magnet undulator, is set to fulfill the resonant conditions with beam energy and laser seed. The radiator consisting of six 60-period permanent magnet undulators with 25 mm period length is set in such a way that the FEL wavelength is the 3rd harmonic of laser seed.

Start-to-end tracking of the electron beam, including all components of SDUV-FEL, has been carried out for the CPA-HGHG experiment. The electron beam dynamics in photo-injector was simulated with ASTRA [10] to take in to account of space-charge effects. ELEGANT [11] was then used for the simulation in the remainder of the linac, while tracking in the undulators was performed with GENESIS [12]. The energy and current distributions

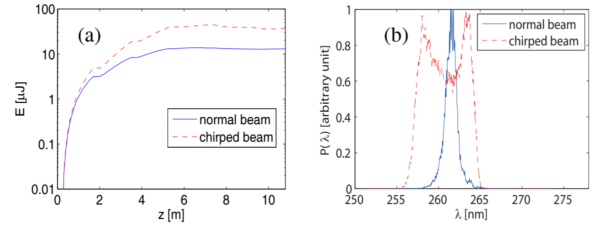

Figure 3: FEL performance for normal electron beam and chirped electron beam: (A) Radiation energy as a function of the radiator undulator length; (B) spectra at saturation.

along the electron beam at the exit of the linac are summarized in Fig. 2. For comparison purpose, two cases have been studied here: one is using a normal electron beam as that used in conventional HGHG, as shown in Fig. 2 (a). The average beam energy is around 160 MeV and the peak currents is about 40 A when the electron beam is compressed by a factor of about 2; another case is adjusting the rf phase of the linac to imprint considerable negative energy chirp on the electron beam to match the resonance condition of the chirped seed laser. The beam energy and current distributions along the electron bunch at the exit of the linac are shown in Fig. 2 (b).

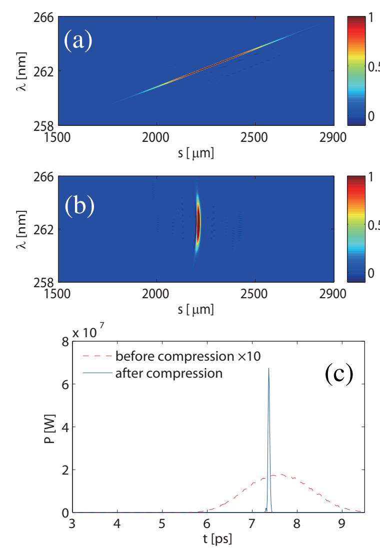

Figure 4: Wigner distributions of the output radiation pulses before (a) and after (b) the optical compressor, and the comparison of output radiation pulses.

For the normal electron beam case, the bandwidth of the seed is much narrower than the gain bandwidth of the modulator (about 6.25%), which means that all parts of the seed spectrum effectively contribute to the energy modulation of the electron beam. The evolutions of pulse energies along the radiator undulator and the spectra of the radiation pulses at saturation are illustrated in Fig. 3. Three FEL gain stages in the radiator are clearly shown. The difference of the output pulse energies is mainly caused by the different gain bandwidths of the radiator for these two cases: the gain bandwidth of the radiator for the normal beam case is much narrower than that of the chirped beam case. As shown in Fig. 3 (b), the spectrum

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bandwidth of the radiation pulse generated by the normal electron beam is about 0.53%, which means that only the FEL frequency within the gain bandwidth of the radiator can be amplified to saturation. For the chirped electron beam case, the bandwidth of the radiation pulse is about 2.7%, which is even broader than that of the seed laser. So nearly the whole electron beam can be used for FEL generation. In particular, there is a pronounced dip near the center of the FEL output spectrum. This is mainly caused by the large energy spread in the central part of the electron bunch from laser modulation. As a result, the FEL emission from the central part is significantly attenuated, creating a dip in the spectrum due to the linear chirp (the spectrum correlates with time). The Wigner distribution of the radiation pulse at saturation is shown in Fig. 4 (a). 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 (Fig. 4 (b)). Fig. 4 (c) gives a comparison of the radiation pulse temporal profiles before and after the compressor without energy loss. The pulse length is compressed by about 110 times, from 3.5 ps to 31 fs, and the peak power is accordingly enhanced by about 100 times, from 12 MW to 1.2 GW. Assuming that the diffraction efficiency of one reflective grating is around 70%, which is commercially available, the transfer efficiency of the compressor will be around 24%. So we can estimate that the output peak power of CPA-HGHG at 262 nm is about 280 MW. As the pulse duration of the seed laser before stretch is 82fs, the minimal pulse duration of the 3^{rd} harmonic radiation is about 2.6 times shorter than that of the seed laser, which is close to the theoretical prediction of Eq. (2).

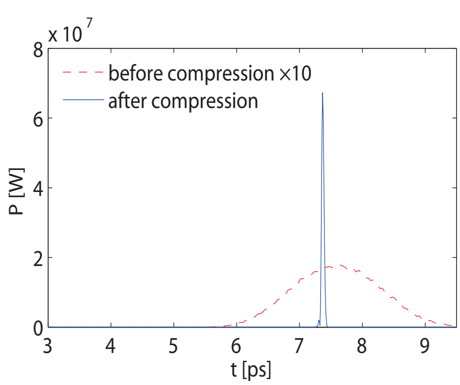

Figure 5: A comparison of the output radiation pulses before and after compressor.

When the FEL works in the CHG regime, the gain bandwidth of the radiator is much broader. For our case, we take the first undulator segment of radiator for the CHG experiment. The gain bandwidth is about 1/60, which is a little narrower than the bandwidth of the seed laser. For this case, there is no need of a chirped electron beam. Fig. 5 shows a comparison of the output radiation pulses before and after compressor when using a normal electron beam. The peak power of the radiation pulse is increased from 1.8 MW to about 67 MW. Considering the transfer efficiency of the grating, the output peak power of CPA-CHG will approach 16MW when the pulse compressor has a 76% loss. The pulse duration is compressed by about 35 times, from 3.3 ps to 94 fs.

It is worth mentioning that the CHG scheme has been widely adopted in storage ring (SR) for the generation of femtosecond coherent radiation pulses in the ultraviolet region. However, the radiation power is relatively low due to the low current of the electron beam used in SR. The CPA technique may be an effective way to enhance the output power of a CHG and can be used to generate ultra-short XUV radiation pulses based on SR [13].

CONCLUSION

Chirped pulse amplification of HGHG has been studied analytically and numerically based on SDUV-FEL. Start-to-end simulation results show femtosecond UV pulses with peak power from tens of MW to hundreds of MW level can be generated directly from a commercial Ti:sapphire infrared seed laser using this technique. It is found that there will be no need for an initial energy chirp in the electron bunch when the FEL is operated in the CHG regime, since the undulators used in CHG are relatively short. One critical issue for operating the CPA-HGHG scheme in the XUV region is to develop suitable high reflectivity laser pulse compressor systems tunable in such a wavelength range.

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