COHERENT HARD X-RAY FREE-ELECTRON LASER BASED ON ECHO-ENABLED STAGED HARMONIC GENERATION SCHEME *

C. Feng, Z.T. Zhao#,
Shanghai Institute of Applied Physics, CAS, Shanghai 201800, China

Abstract

A novel approach to producing coherent hard x-ray based on the echo-enabled staged harmonic generation (EESHG) scheme is proposed. This scheme is not a simple cascaded EEHG, but consists of an EEHG, a beam shifter and a conventional HGHG like configuration, which also works in the EEHG principle. In the first stage, all over the whole electron beam is energy modulated by a laser beam in the first modulator and then converts into separate energy bands by a very strong dispersion section. In the second modulator, the seed laser is adjusted so that only the tail half part of the e-beam is energy modulated, and then this beam is sent through the second dispersion section which converts the energy modulated part into a density modulation. The radiation from the first stage serves as the seed laser of the second stage, the beam shifter is so tuned that the head part of the electron beam can exactly interact with the radiation from the first stage in the modulator of the second stage, so the total harmonic number will be hundreds. It is possible to do the proof-of-principle experiment of EESHG on the SDUV-FEL.

INTRODUCTION

Free-electron laser (FEL) holds the promise to produce a short, high intense radiation pulse from THz to hard x-ray. Because of the ultra-high brightness and full coherence properties, a high gain x-ray FEL will bring lots of new understandings to many scientific fields, such as molecular biology, material science, catalysis engineering and medical science. Currently there are several projects of x-ray FEL under operation and construction all over the world, based on either self-amplified spontaneous emission (SASE) [1] or possibly cascaded high-gain harmonic generation (HGHG) scheme [2, 3]. However, because the radiation starts from its own radiation noise, the output of SASE FEL typically has poor temporal coherence and large shot-to-shot power fluctuation. HGHG [2] has the advantages of shorter undulator and produces much better temporal coherence laser pulses, but the frequency up-conversion efficiency is limited to a small number. Due to the lack of available and suitable seed lasers, cascaded HGHG with "fresh bunch technique" [3] or high-order harmonic generation (HHG) [4] seeded HGHG schemes are needed to extend the HGHG scheme to hard x-ray region.

Recently, some novel double-modulator schemes [5][6][7] have been put forward to enhance the bunching factor of higher harmonics. In these schemes, EEHG has unprecedented up-frequency conversion efficiency and allows the generation of ultrahigh harmonic with relatively smaller energy modulation. Up to now, the analytical calculations and simulation results imply that a single-stage EEHG FEL is able to generate high power soft x-ray radiation with narrow bandwidth close to Fourier transform directly from a UV seed laser [7][8].

Here we extend the EEHG FEL to hard x-ray region with the proposed Echo-enabled Staged Harmonic Generation (EESHG) scheme and show the possibility to operate the Shanghai deep ultraviolet FEL (SDUV-FEL) with EESHG scheme.

PRINCIPLE

General Layout

Although the EEHG scheme has a remarkable up frequency conversion efficiency, it is still very difficult to use only one stage to get hard x-ray radiation directly from a VUV seed laser. If borrowing the idea from

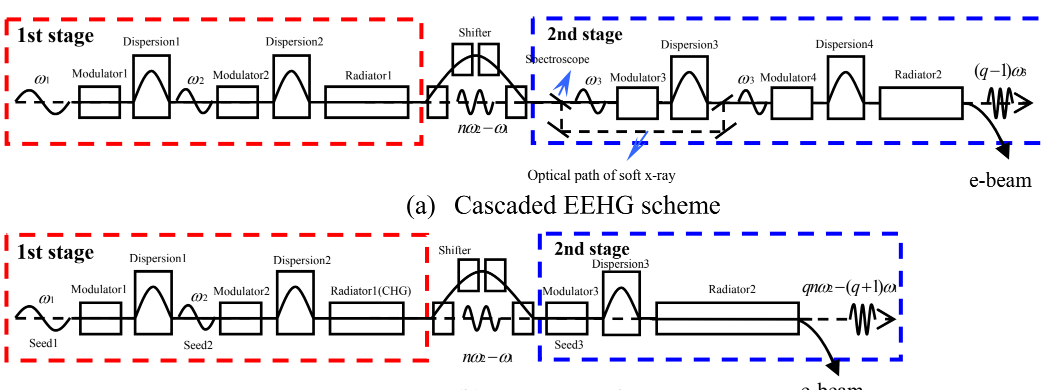

Figure 1: (a) Using usual method to cascade two stages of EEHG scheme. (b) EESHG scheme.

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zhaozt@ssrc.ac.cn

cascaded HGHG to make a cascaded EEHG, as shown in Figure 1(a), how to transport the radiation from the first stage to the two modulators in the second stage might become extremely complicated and a great challenge. To mitigate this problem, we use a novel scheme as Figure 1(b) shows, which consist of an EEHG, a beam shifter and an HGHG like configuration, but the HGHG part is equivalent to an EEHG by jointly using the first modulator and first dispersion section with the EEHG part.

Physical Mechanism

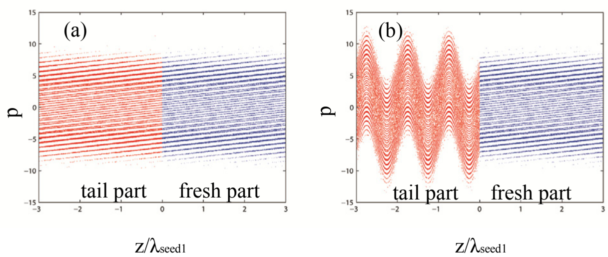

Figure 2: Sketch map of longitudinal phase space in the first stage of EESHG. (a) Phase space after the dispersion section 1. (b) Phase space after the modulator 2.

The evolving process of the longitudinal phase space in the first stage of EESHG is shown in Figure 2. The modulator1 and the dispersion section1 help to obtain separate energy bands all over the whole electron beam (Figure 2(a)). In the modulator2, the seed laser2 is adjusted so that only the tail half part of the e-beam is energy modulated (Figure 2(b)), then this beam is sent through the dispersion section2 which converts the energy modulated part into a density modulation and will be used to produce coherent radiation in the radiator1. This radiation serves as the seed laser of the second stage. The shifter between these two stages is so tuned that the fresh part of the e-beam can exactly interact with the seed laser3 in modulator3. Noticing that the fresh part has already been modulated and shredded to energy beamlets in the first stage, for the fresh part, the second stage together with the modulator1 and dispersion section1 can also be considered as a whole EEHG. In this way, the output from the radiator2, which is tuned at the harmonic of seed laser3, can be extended to even hard x-ray region. In addition, since the needed seed laser power for the second stage is much smaller than the saturation power of the first stage, the length of the radiator1 is so chosen to make it work in the coherent harmonic generation (CHG) [9] regime, which reduces not only the machine size but also its impact on the fresh part.

Analytical and Simulation study

Following the notation of ref. [7], we also assume an initial Gaussian beam energy distribution with an average energy E_0 and use the variable $p=(E-E_0)/\sigma_E$ for the dimensionless energy deviation of a particle, where σ_E is the rms energy spread. We can deduce the bunching factor at the entrance to the radiator2 in the present scheme

$$b_{n,q}=2\left|e^{-1/2[nB_c+(K_cq+n)B_3]^2}J_q[-(K_cq+n)A_3B_3] \times J_n\{-A_1[nB_c+(K_cq+n)B_3]\}\right| \quad (1)$$

where n and q are integer numbers, $A_3=\Delta E_3/\sigma_E$, ΔE_3 is the energy modulated amplitude of the modulator3, $B_3=R_{56(3)}k_1\sigma_E/E_0$, $B_c=(R_{56(1)}+R_{56(2)}+R_{56(s)})k_1\sigma_E/E_0$, $R_{56(3)}$ and $R_{56(s)}$ are the dispersive strength of phase shifter and dispersion3, $K_c=k_3/k_1$ and k_3 is the wave number of seed laser3. To maximum this bunching factor, we limit our considerations to the $n=-1$ and $q>0$ condition. Since A_1, A_2, B_1, B_2 and B_c are determined in the first stage. we have to change A_3 and B_3 to maximize $b_{n,q}$. B_3 should be optimized by $B_3=(B_c-\xi)/(K_cq-1)$ first, where $\xi=B_1-(Km-1)B_2$, and A_3 can be optimized by $A_3=(q+0.81q^{1/3})/(K_cqB_3-B_3)$, after doing this, the beam modulation is observed at the frequency $\omega_c=q\omega_3-\omega_1$. When $m>4$, the maximal bunching factor is

$$|b_{-1,q}|\approx\frac{1.34}{(q+1)^{1/3}}J_1(A_1\xi)e^{-\xi^2/2}. \quad (2)$$

Generally q is a big number, in our scheme $\omega_3 \gg \omega_1$, so the output frequency $\omega_c=q\omega_3-\omega_1$ is nearly only determined by ω_3 , since $\omega_3=m\omega_2-\omega_1$, and the final output frequency can be written as

$$\omega_c=qm\omega_2-(q-1)\omega_1. \quad (3)$$

If we assume the frequency of the seed laser1 and seed laser2 equal, $\omega_1=\omega_2$, then the output frequency satisfies $\omega_c=(qm-q-1)\omega_1$, which means the final output frequency should be $qm-q-1$ times of the initial one.

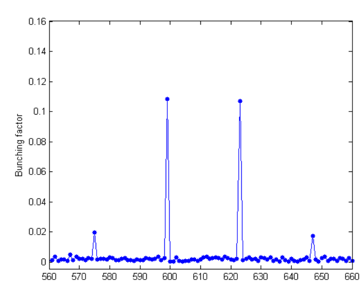

Figure 3: Bunching factors vs. harmonic numbers of the initial seed laser.

As an example, we show that the 599th harmonic of the initial seed laser can be generated with dimensionless parameters $A_1=3$, $A_2=1$, $A_3=0.96$, $B_1=27.91$, $B_2=1.14$, $B_s=0.03$, $B_3=0.0477$, $K=1$ and $K_c=24$. Using our 1D code, we get the bunching factors versus harmonic numbers of the seed laser 1 as Figure 4 shows. Since we choose $m=25,\ q=25$ here, the result agrees well with the prediction from eq. (3). The bunching factor is about 0.12 at 559th harmonic, while most of the others are suppressed to the shot noise level. Some practical issues that may affect the performance of EESHG are studied in ref. [10].

EXPERIMENTAL PLAN

As a test facility for modern FEL R&D, SDUV-FEL is doing the proof-of-principle experiment of EEHG recently [11] and it will be equipped a new HGHG stage to test the cascaded HGHG and EESHG schemes in the near future. The machine parameters and simulation results based on EESHG scheme are summarized in Table 1 and Figure 4&5.

Table 1: Machine parameters for SDUV-FEL with the EESHG scheme.

Electron bunch

$E = 160MeV, I_p = 200A, \varepsilon = 10mm \cdot mrad,$

$\sigma_\gamma / \gamma = 0.03\%, 3-4ps$ length

	Stage 1		Stage 2
Seed laser	1	2	3
$\tau(fs)$	200	200	200
$\lambda_s(nm)$	786	786	393
Modulator	1	2	3
$\lambda_u(mm)$	65	50	30
a_u	1.17	1.44	1.25
$L_m(m)$	0.65	0.5	0.6
Dispersion section	1	2	3
$R_{56}(mm)$	1.64	0.65	0.39
Radiator	1		2
$\lambda_u(mm)$	30		25
a_u	1.25		1.02
$L_r(m)$	3.0		6.0
$\lambda_{sr}(nm)$	393		262

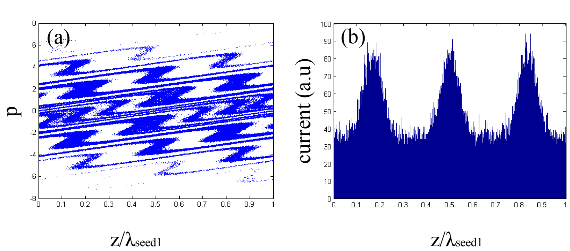

Figure 4: (a) Longitudinal phase space after dispersion section3. (b) Current distribution after dispersion section3.

Figure 4 shows the 1D simulation results of longitudinal phase space and current distribution of the electron beam at the entrance to the radiator of the 2nd stage. From figure 4(b) one can find that there are 3 spikes in one wavelength of the initial 786nm seed laser, so the radiation of the 2nd stage is 1.5th harmonic of seed laser3 as figure 5 shows, which is not possible for classical HGHG scheme.

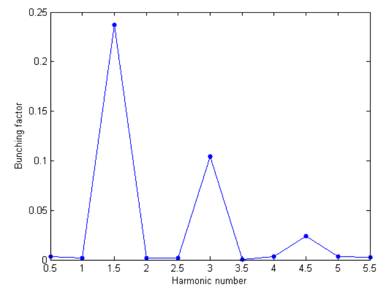

Figure 5: Bunching factors vs. harmonic numbers of seed laser3.

CONCLUSION

The EESHG scheme is an attractive scheme for generating ultra-high order harmonic radiation. It is possible to produced coherent hard X-ray radiation directly from a VUV seed laser. We will operate the SDUV-FEL with EESHG scheme in the near future.

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