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Beam energy chirp effects in seeded free-electron lasers

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ABSTRACT

Seeded free-electron lasers (FELs) hold great promise for generating high brilliance radiation pulses with a narrow bandwidth, which typically requires an electron bunch with relatively uniform energy distribution. However, it has been pointed out that the beam energy curvature generated in the acceleration process may degrade the output radiation pulse quality of seeded FELs. In this paper, we studied the beam energy chirp effects in various seeded FEL configurations. The theoretical and simulation results show that the performance degradation of high gain harmonic generation scheme is proportional to the beam energy chirp, while the advanced seeding schemes, e.g. echo-enabled harmonic generation and phase merging enhanced harmonic generation, are capable of eliminating the effect of the electron beam energy chirp.

1. Introduction

In recent years, enormous progress has been made in the seeded free-electron lasers (FELs). Seeded FEL schemes hold great potential to deliver high brilliance radiation pulses with excellent longitudinal coherence in the extreme ultraviolet and even x-ray regions. The first seeding scheme, i.e., high gain harmonic generation (HGHG) has been demonstrated in BNL [1,2] and is currently used to deliver coherent FEL pulses to users at FERMI [3]. Meanwhile, the cascaded HGHG and echo-enabled harmonic generation (EEHG) have been intensively demonstrated [4–12], which pave the way to the seeded x-ray FEL user facilities worldwide. More recently, a novel seeded FEL mechanism so-called phase-merging enhanced harmonic generation (PEHG) is proposed [13,14]. Thus it can be seen, the excellent characters of seeded FELs are of great interest, and it permits the scientific application from ultrafast dynamical effects, the nonlinear phenomena to probe matter at extremely small scales.

It has been pointed out in Ref. [15] that the noise amplification in frequency multiplication process is proportional to the harmonic up-conversion number a in seeded FELs, and thus the requirements for the electron beam and the seed laser will become more stringent as the harmonic number increases. The noises introduced by seed laser imperfections have been investigated [16–19], which demonstrates that the slippage effects may relax the distortion induced by the seed laser noise to a large extent. In this paper, we concentrate on the electron beam energy chirp effects in seeded FELs. The energy chirp of the electron beam can be divided into two categories, one is the linear energy chirp due to the radio frequency curvature and wake-field effects in the accelerator, the another one is the random energy chirp due to the nonlinearity of machine and micro-bunching instability. While the linear energy chirp can be used to reduce the output power sensitivity of the beam energy jitter and distinguish radiations from different seeded FEL modes [6,7], it still affects the density modulation efficiency and yields frequency shift in the FEL radiation [20,21]. Similarly, the energy fluctuations along the beam, in other words the random chirp may yield a random phase error in the micro-bunching, then introduce a spectrum broadening and additional noise spikes in time domain and degrade the spectral purity of the output radiation pulse in seeded FELs.

Special design can be accomplished to generate a bunch without linear energy chirp [22], while the random energy chirp is unavoidable even though it can be significantly reduced by adopting a laser heater at the exit of the injector [23]. This paper studies the influences of the energy chirp in HGHG, EEHG and PEHG processes, including theoretical derivation and numerical simulation. Our results indicate that, the beam energy chirp effect is serious for HGHG working at high harmonics, while it may be improved in a cascaded HGHG configuration. EEHG could nearly immune the beam energy chirp by properly setting the dispersive strengths of the two chicanes. Better still, PEHG is zero in response to the beam energy chirp under the optimal condition. Moreover, using a set of typical beam parameters from modern accelerators,

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further studies show that the cascaded HGHG, EEHG and PEHG are capable of generating narrow bandwidth soft x-ray radiation pulses from commercial ultraviolet seed lasers.

2. Energy chirp effects in seeded FEL schemes

First, we assume an initial Gaussian beam energy distribution function with a linear energy chirp h as

$$f_0(p,\zeta)=\frac{N_0}{\sqrt{2\pi}}\exp\left(-\frac{(p-h\zeta)^2}{2}\right),$$

where N_0 is the number of electrons per unit length, $p=(E-E_0)/\sigma_E$ represents the dimensionless energy deviation with central energy E_0 and RMS energy spread σ_E, $\zeta=k_1z$ is the phase of the electron beam with k_1 for the wave number of the seed laser and z for the coordinate of the electron beam, respectively.

Following the notations in ref. [5], the beam energy modulation amplitude induced in the modulators is $A_{1,2}=\Delta E_{1,2}/\sigma_E$,$k_1,k_2$ represent the wave numbers of seed lasers and $K=k_1/k_2$, $B_{1,2}=R_{56}^{1,2}k_{1,2}\sigma_E/E_0$ are the strengths of the dispersive chicanes and $B=B_1+B_2$. Then the bunching factor of HGHG, EEHG and PEHG at ath harmonic can be presented as [5,14,24]

$$b_{HGHG}\frac{1}{N_0}\int_{-\infty}^{+\infty}dpe^{-iapB_1}f_0(p,\zeta)\left\langle e^{-ia\zeta}e^{-iaA_1B_1\ \sin\ \xi}\right\rangle; \tag{1}$$

$$b_{EEHG}=\frac{1}{N_0}\left|\int_{-\infty}^{+\infty}dpe^{-iapB}f_0(p,\zeta)\times\left\langle e^{-ia\zeta}e^{-iaA_1B\ \sin\ \xi}e^{-iaA_2B_2\ \sin(K\zeta+KB_1p+KA_1B_1\ \sin(\zeta+\phi))}\right\rangle\right|; \tag{2}$$

$$b_{PEHG}=\frac{1}{N_0}\left|\int_{-\infty}^{+\infty}dpe^{-iap(TD+B_1)-iaT\chi}f_0(p,\zeta)g_0(\chi)\left\langle e^{-ia(\zeta+A_1B_1\ \sin(\zeta))}\right\rangle\right|. \tag{3}$$

In the PEHG, $D=\eta\sigma_E/\sigma_x\gamma$ is the dimensionless strength used to transversely disperse the electron beam, T is the dimensionless transverse gradient parameter of the modulator undulator, $g_0(\chi)$ shows the dimensionless horizontal beam distribution with $\chi=(x-x_0)/\sigma_x$, where x_0 is the horizontal beam center position and σ_x is the initial horizontal beam size.

For HGHG case, by changing the integration variable from p to $p'=p-h\zeta$, Eq. (1) can be rewritten as

$$b_{HGHG}=\frac{1}{N_0}\int_{-\infty}^{+\infty}dpe^{-iapB_1}f_0(p,\zeta)\left\langle e^{-ia\zeta(1+hB_1)}e^{-iaA_1B_1\ \sin\ \xi}\right\rangle. \tag{4}$$

Then by carrying out the average over ζ, the non-vanishing bunching factor can be obtained only when the harmonic number a reads

$$a_{HGHG}=\frac{k}{1+hB}, \tag{5}$$

With some similar derivations, the optimized harmonic number a for EEHG and PEHG can be presented as

$$a_{EEHG}=\frac{n+mK(1+hB_1)}{1+hB}, \tag{6}$$

$$a_{PEHG}=\frac{k}{1+h(TD+B)}, \tag{7}$$

where n, m and k are integers, $k=n+mK$ is the harmonic number of HGHG and PEHG. The wavelength of FEL radiation can be calculated with Eqs. (5)–(7), hence we define the wavelength shift factor $M=\lambda_{chirp}'/\lambda_{ideal}$, where λ_{chirp}' is the EEHG wavelength with energy-chirped electron beam and λ_{ideal} is the radiation with ideal beam, and the spectral bandwidth variable ΔM to illustrate the linear energy chirp and random energy chirp effects in seeded FELs, respectively.

One can find from Eq. (5) that the energy chirp effects in HGHG or cascaded HGHG is proportional to the total strength of the dispersive chicanes. For HGHG, the optimal dispersive strength is $k_1R_{56}A_1\approx 1.2$[24]. The effective energy spread induced by the energy modulation in HGHG is limited by the FEL parameter ρ for the requirement of exponential amplification in the radiator. And thus, a larger R_{56} is required for higher harmonic number with a single stage HGHG. Then the amplification of energy chirp by a large R_{56} becomes the main obstacle for reaching short wavelength in a single stage HGHG.

The optimal relationship between the two dispersive strengths for EEHG operation is

$$B_2=-\frac{n}{a}B_1-\frac{\xi}{a}, \tag{7}$$

where ξ is the solution of $A_1[J_{n-1}(A_1\xi)-J_{n+1}(A_1\xi)]=2\xi J_n(A_1\xi)$. According to the definition of M and Eq. (6), the wavelength shift factor of EEHG can be written as $M_{EEHG}=1+B_1+B_2-\lambda_{EEHG}'mB_1/\lambda_{s2}$, where λ_{s2} is the wavelength of the second seed laser in EEHG. One can see in Fig. 1, with the increase of energy modulation amplitude A_1 and n, ξ will significantly decrease, then the second dispersive strength from Eq. (7) and M_{EEHG} can be approximately rewritten as:$B_2\approx-(n/a)B_1$ and $M_{EEHG}\approx 1$ for a very large harmonic number, which means EEHG will be insensitive to the beam energy chirp at high harmonics under certain conditions.

In comparison with HGHG, a transverse-longitudinal phase space coupling process happened in PEHG, a dogleg is used to transversely disperse the electron beam before the modulator. When the transversely dispersed electron beam passes through a transverse gradient undulator (TGU), electron of different energy undergoes different orbit and the TGU can be equivalent to a positive longitudinal dispersion. The maximal bunching of PEHG will be achieved when $TD=-B$, where R_{56} induced by the dispersive chicane is fully compensated by the combined effects of dogleg and TGU. It means that PEHG can be completely immune to the random beam energy chirp.

Fig. 2 shows the wavelength shift factor M as a function of the linear energy chirp for three seeded FEL schemes. EEHG parameters used here are $A_1=5.5, A_2=3.5, B_1=10.04, B_2=0.32$ and $K=1$, which are optimized for the 30th harmonic of 264 nm seed laser. HGHG and PEGH are also optimized at 30th harmonic with the method mentioned above. The dispersive strengths for EEHG are quite close to the requirement of Eq. (7). It is shown in Fig. 2 that the central wavelength shift in HGHG is proportional to the

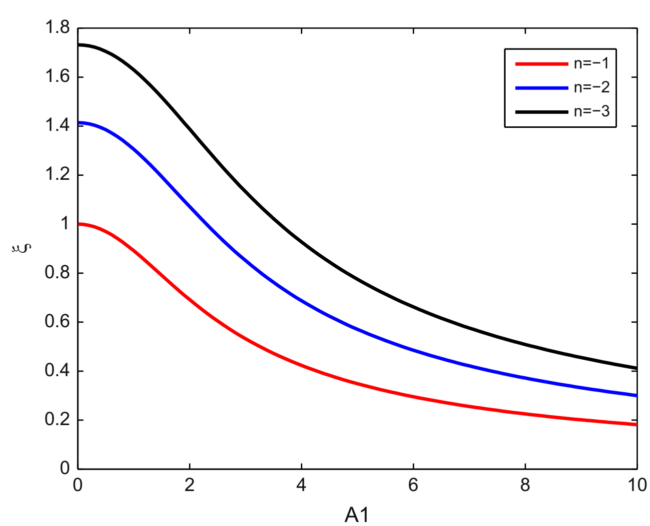

Fig. 1. Decrease of ξ with different n and increasing $A1$.