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Study on the seed laser phase error multiplication in seeded free electron lasers

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ABSTRACT

Seeded free-electron lasers (FELs) hold a great promise for generating high brilliant radiation with a narrow bandwidth. However, it has been pointed out that the initial seed laser noise will be amplified in the harmonic up-conversion process, which may degrade the output radiation pulse quality of a seeded FEL. In this paper, theoretical and simulation studies of seeded FEL schemes with seed laser imperfections are presented. It is found that the slippage effect in the modulator will slow down the multiplication process of the seed laser phase error, which may aid in the production of transform-limited short-wavelength pulses for seeded FELs.

1. Introduction

The success of high-gain harmonic generation (HGHG) [1–4], echo-enabled harmonic generation (EEHG) and [5–9] free electron lasers (FELs) lead to the possibility of generating narrow bandwidth radiation pulses with high brilliance and excellent longitudinal coherence. As the most promising devices for delivering coherent FEL radiation in the ultraviolet and even soft x-ray regions, seeded FEL schemes are arising worldwide. The world's first seeded FEL user-facility FERMI has already been lased in 2010 [10], and several other FEL facilities based on seeded configurations are under construction or consideration [11–13]. Moreover, novel seeded FEL mechanisms are being proposed [14,15]. It is expected that, more scientific opportunities ranging from materials and biomaterials sciences, nano-sciences, plasma physics, molecular science and chemistry will emerge, as seeded FEL sources are fully exploited.

In a seeded harmonic generation FEL, an external coherent laser pulse (seed laser) is usually employed to interact with the electron beam in a short undulator (modulator) to generate sufficient energy modulation. The electron beam is then sent through a magnetic chicane (dispersion section) where the energy modulation is converted into density modulation and the microbunching on the scale of the optical seed laser wavelength is established. Taking advantage of that the Fourier transform of the density modulation contains abundant components at high harmonic of the seed, coherent short-wavelength signal that dominates over the beam shot noise can be amplified by a relatively long undulator (radiator) resonant at the interested harmonic of the seed. Therefore, it is anticipated that the seeded FEL schemes are capable of generating Fourier-transform-limited radiation pulses at short wavelength.

The noise sources in seeded FEL can be divided into two main parts, the intrinsic shot noise of the electron beam and the noise due to the seed laser imperfections. In seeded FELs, the output radiations inherit the coherence characteristics of the high quality seed lasers, while resulting in a noise amplification of the seed laser. Generally, the frequency multiplication process will produce a signal to noise ratio degradation, which is proportional to the square of the frequency multiplication ratio n [16]. Thus, the phase error control is one of the most important aspects in seeded FELs. The investigations in the absence of slippage effect in the energy modulation process [17,18] indicate that the phase errors in microbunching will be roughly amplified by the harmonic number n, then the seed laser phase control requirement may exceed the state-of-the-art laser technology when the harmonic number is extremely high (e.g., hundreds or even higher). The evolution of linear phase chirp with ultra-short seed laser pulse has been reported in an earlier work [19], when considering the slippage

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effect in the modulator. In this paper, we concentrate on the degradation of the random phase error and the correlated phase error with the long seed laser pulse in the FEL process, including theoretical derivation and numerical simulation. Our results indicate that, the multiplication of the random phase error induced by the seed laser can be reduced by a factor of $N_m^{1/2}$ with the slippage effect, where N_m is the period number of the modulator. And the correlated phase error of the seed laser leads to an infinitesimal frequency shift in the FEL output.

2. Slippage effect on random phase error

First, we consider the laser-beam interaction in a planar undulator with a period number of N_m. Assuming a longitudinally uniform seed laser with the slow varying electric filed amplitude of E_0 and the random phase φ_0 in each laser wavelength along the beam coordinate s, the laser field amplitude along the electron beam can be described as

$$E(s) = E_0 e^{i\varphi_0(s)} \tag{1}$$

According to the energy exchange, the beam energy modulation $\Delta\gamma$ at the end of the modulator can be given as

$$\Delta\gamma(s) = \int_0^{z_1} \frac{eK[JJ]}{2\gamma mc^2} E(s)dz, \tag{2}$$

where K is the undulator parameter ($K = 0.934B\lambda_u$ with B in tesla and λ_u in centimeter), $[JJ]$ and z_1 represents the modified Bessel factor $[JJ] = J_0[K^2/(4+2K^2)] - J_1[K^2/(4+2K^2)]$ and the modulator length, respectively. Following the results without considering the slippage effect [20], the maximum energy modulation can be calculated by

$$\Delta\gamma = \frac{eK[JJ]}{2\gamma mc^2} E_0 z_1 \tag{3}$$

According to the undulator radiation theory [21], after electron travels one undulator period, the seed laser overtakes the electron by one resonant wavelength λ_s, thus the influences of seed laser phase error to the electrons should be integrated over $N_m\lambda_s$. And if one considers the slippage effect in the modulator, Eq. (2) then could be expressed as

$$\Delta\gamma(s) = \frac{eK[JJ]}{2\gamma mc^2} \int_s^{s+N_m\lambda_s} E_0 e^{i\varphi_0(s)}\, ds = G_1 E_0 \textstyle\sum_{j=s+1}^{s+N_m} e^{i\varphi_0(j)}. \tag{4}$$

Through the equivalent infinitesimal replacement, $\Delta\gamma(s)$ can be rewritten as

$$\begin{aligned}\Delta\gamma(s) &= G_1E_0[e^{i\varphi_0(s+1)} + e^{i\varphi_0(s+2)} + \cdots + e^{i\varphi_0(s+N_m)}] \\ &= G_1E_0N_m[1 + i\frac{\varphi_0(s+1)+\varphi_0(s+1)+\cdots+\varphi_0(s+N_m)}{N_m}] \\ &= G_1E_0N_m e^{i\sum_{j=s+1}^{s+N_m}\varphi_0(j)/N_m} = G_1E_0N_m e^{i\langle\varphi_0\rangle}\end{aligned} \tag{5}$$

With a total frequency up-conversion factor of n, the phase of the output harmonic radiation is determined by micro-bunching, in other words the distribution of density modulation. Then for a relatively small seed laser phase error, the electric field at the output harmonic is [22]

$$E_n e^{i\varphi_n} = G_2 E_0 e^{in\langle\varphi_0\rangle} \tag{6}$$

G_2 is an arbitrary function of the field amplitude, such as Bessel function bunching factor and the exponential gain, etc. Thus, the phase relationship between the output radiation and the initial seed laser can be represented as

$$\varphi_n(s) = \frac{n}{N_m} \sum_{j=s+1}^{s+N_m} \varphi_0(j) \tag{7}$$

Then, one may write the phase error of the output FEL radiation as follows:

$$\begin{aligned}\sigma^2(\varphi_n) &= \frac{n^2}{N_m^2}\left\langle \sum_{s=-\infty}^{+\infty} [\sum_{j=s+1}^{s+N_m} \varphi_0(j)]^2 \right\rangle \\ &= \frac{n^2}{N_m^2}\left\langle \sum_{s=-\infty}^{+\infty} [\varphi_0^2(s+1)+\varphi_0^2(s+2)+\cdots+\varphi_0^2(s+N_m)] \right\rangle \\ &= \frac{n^2}{N_m^2} N_m \left\langle \sum_{s=-\infty}^{+\infty} \varphi_0^2(s) \right\rangle = \frac{n^2}{N_m}\sigma^2(\varphi_0)\end{aligned} \tag{8}$$

For convenience, we now define the phase noise multiplication factor as $M = ((\sigma(\varphi_n))/\sigma(\varphi_0)) = n/\sqrt{N_m}$. In comparison with the earlier results [17,18], a $\sqrt{N_m}$ reduction is introduced by the seed laser slippage in the modulator. Therefore, the phase noise requirements on seed laser in extremely high harmonic generation may be relaxed by increasing the modulator periods number appropriately. To verify the theoretical analysis above, a 3D time-dependent simulation with GENESIS [23] was carried out. The 30th harmonic in a seeded FEL scheme is investigated to quantitatively describe the phase noise amplification process, where a seed laser with an infinite pulse length interacts with a flat-top electron beam in the modulator. In the simulation, 500 radiation slices were used for the phase error statistics and the electron beam shot noise was switched off. Fig. 1 shows the relationship between the phase error of the output radiation and that of the seed laser, where only one modulator period is utilized and the FEL output phase error $\sigma(\varphi_{30})$ is exported after the first gain length in the radiator. According to Eq. (8), the amplification of phase error is the same as in Refs. [17,18] when $N_m = 1$, then the slope of the theoretical line should be 30. The simulation dots are all in the vicinity of the theoretical value, which is in good agreement with our derivation.

To further compare the simulations with the analytical results, different modulator periods upto 40 are considered, and for each period number case, 10 random phase error samples of the seed laser are carried out. Fig. 2 illustrates the phase noise amplification with respect to the modulator period number. Since the seed laser phase error is averaged over the slippage length in the modulator of a seeded FEL, significant reduction of the noise multiplication is observed.

Fig. 3 shows the spectra of the 30th harmonic radiation after the first gain length in the radiator, where a relatively large phase noise with RMS value of 0.15 rad is assumed for the seed laser to illustrate the noise degradation in the normal and the sub-harmonic

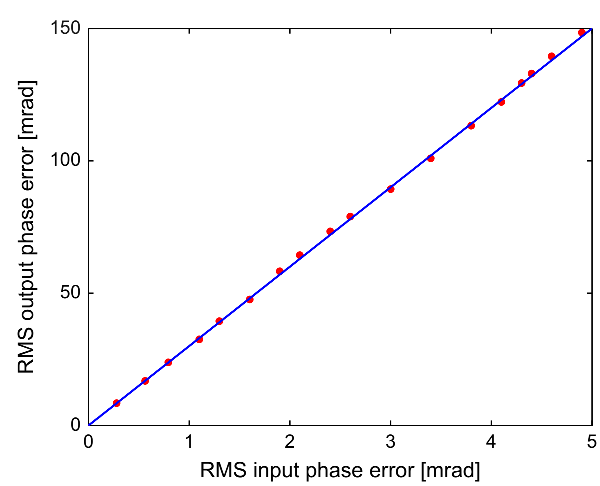

Fig. 1. The output phase error dependence on the seed laser phase error for the case of 1 modulator period, the slope of the blue line is 30, the red dots are the simulation results. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)