OPERATING OF SXFEL IN A SINGLE STAGE HIGH GAIN HARMONIC GENERATION SCHEME

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Abstract

The beam energy spread at the entrance of undulator system is of paramount importance for efficient density modulation in high-gain seeded free-electron lasers (FELs). In this paper, the dependencies of high harmonic bunching efficiency in the high-gain harmonic generation (HGHG) schemes on the electron energy spread distribution are studied. Theoretical investigations and multi-dimensional numerical simulations are applied to the cases of uniform and saddle beam energy distributions and compared to a traditional Gaussian distribution. It shows that the uniform and saddle electron energy distributions significantly enhance the performance of HGHG-FELs. A numerical example demonstrates that, with the saddle distribution of sliced beam energy spread controlled by a laser heater, the 30th harmonic radiation can be directly generated by a single-stage seeding scheme for a soft x-ray FEL facility.

INTRODUCTION

In recent years, enormous progresses have been achieved in the seeded free-electron lasers (FELs), which 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 fully demonstrated at BNL [1-4] and is currently used to deliver coherent extreme ultraviolet FEL pulses to users at FERMI [5]. For a long time, it is thought that the frequency multiplication factor of a single-stage HGHG is usually limited within ~10 [1,6], due to the tradeoff between the energy modulation and the energy spread requirement for exponential amplification process of FEL. Therefore, a complicated multi-stage HGHG scheme [7-9] has been theoretically proposed and experimentally demonstrated for short wavelength production from a commercially available seed laser.

Up to now, the bunching performance assessment for seeded FELs is on the basis of assumption that the electron beam at the entrance of undulator has an energy spread of Gaussian distribution, which however is not true, e. g., in the specific case with a laser heater in the LINAC [10-11]. Laser heater is widely utilized in high-gain FEL facilities to suppress the gain of the micro-bunching instability via Landau damping by controllable increasing the beam energy spread. It is found that a non-Gaussian energy distribution can be induced by a laser heater and inherited in the main LINAC section, depending upon details of the transverse overlap between the laser beam and the electron beam in the laser heater system. A recent experiment at FERMI [5,12] demonstrates that the non-Gaussian beam energy spread induced by the laser heater may expand the harmonic number of a single-stage HGHG to several tens [13-14]. Meanwhile, one cannot exclude other unknown schemes lie beyond the horizon for controlling beam energy spread distribution in future.

Considering that the initial energy distribution of electron beam is one of the most critical elements in the bunching process of seeded FELs, in this paper, the possible beam energy distribution influences on density modulation efficiency in various seeded FEL schemes have been studied. In Section II, by using a set of nominal parameters of Shanghai soft x-ray free-electron laser facility (SXFEL) [15], the bunching efficiencies in HGHG schemes with different electron beam energy spread distribution are theoretically derived and numerically simulated, which shows that the uniform and saddle cases may significantly enhance the bunching performance of HGHG. It indicates that the beam energy distribution is of great importance for HGHG scheme, the frequency up-conversion number of a single-stage HGHG can be improved to 30 or even higher with a uniform or saddle electron energy distribution. A followed start-to-end example in Section III demonstrated that the saddle distribution of sliced beam energy spread controlled by a laser-heater can be maintained in the following accelerations of LINAC, and the saddle beam energy distribution is capable of driving a 30^{th} harmonic up-conversion in a single-stage HGHG operation of SXFEL, even though it has a larger sliced beam energy spread than a Gaussian case. Finally, we present our conclusions in Section IV.

ENERGY SPREAD DISTRIBUTION EFFECTS ON SEEDING SCHEME

In order to obtain a comprehensible idea of the energy spread distribution effects on different seeded configurations, by using the nominal parameters of SXFEL, uniform and saddle energy spread distributions are investigated for the density modulation process and compared to the previous Gaussian distribution case in this section, under the same RMS deviation, i.e., beam energy spread. SXFEL aims at generating coherent 8.8 nm FEL pulses from 264 nm seed laser through a two-stage HGHG. In the nominal design of SXFEL, an 840 MeV electron beam with sliced energy spread of 84 keV, i.e., a relative energy spread of 1×10^{-4},

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normalized emittance of 1.0 μm-rad, bunch charge of 500 pC, and peak current of 500 A is expected at the exit of the LINAC for efficient FEL lasing. The sliced beam energy distributions used in the frame of analysis of this section are summarized in Fig. 1.

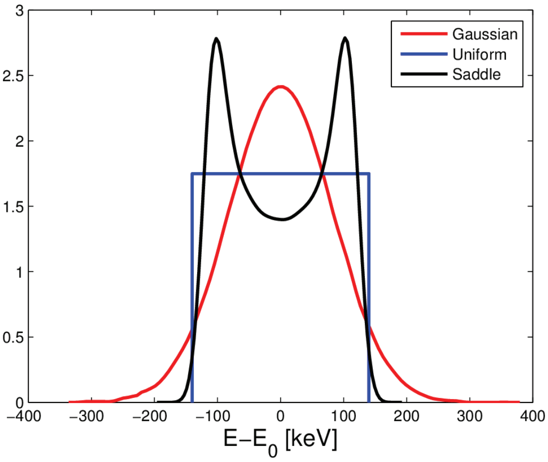

Figure 1: The different beam energy distributions with RMS energy spread of 84keV for the studies in this Section.

It is necessary to take some words to describe the saddle distribution before we step forward, while the Gaussian and uniform distributions are quite straight. As is well known, laser-heaters used for micro-bunching instability suppression in modern high-brightness LINACs have shown the possibility to control the RMS deviation and the distribution shape of sliced beam energy spread by choosing the laser spot size and the peak power [10,13]. In more detail, in the LINAC of SXFEL, electrons from the photo-injector are firstly accelerated up to 130 MeV, and then sent into the laser heater system where a 792 nm Ti-sapphire laser with the pulse length of 10 ps are used to increase the RMS energy spread from 2 keV to about 8.4 keV. After a total longitudinal compression factor of about 10, the sliced RMS energy spread should be about 84 keV at the undulator entrance (at 840 MeV) in the absence of impedance effects. If one supposes a fundamental Gaussian mode laser with spot much larger than the electron beam size co-propagates with a Gaussian electron beam in the laser heater undulator, the energy modulation amplitude is almost the same for all electrons, and the energy profile of heated beam is possibly a saddle distribution, as the black shown in Fig. 1.

Among the various seeding schemes, HGHG is the most compact and pioneering. The high harmonic bunching of HGHG can be described as [16]:

$$b = J_h(h\Delta\gamma_s D)\int dp f(p) e^{-ihD\sigma_E p}, \quad (1)$$

where h is the harmonic number, $D = k_s R_{56}/\gamma$, k_s is the wave number of the seed laser, R_{56} is the strength of the dispersive chicane, γ is the electron beam Lorentz factor, $\Delta\gamma_s$ is the seed laser-induced energy modulation amplitude and J_h is the h^{th} order Bessel function, $p = (E - E_0)/\sigma_E$ is the dimensionless energy deviation of a particle with an average energy E_0 and RMS energy spread σ_E, $f(p)$ is the initial longitudinal phase space distribution. For a Gaussian energy distribution, following Eq. (1), the bunching factor can be written as,

$$b_G = J_h(hD\Delta\gamma_s)\exp\left(-\frac{h^2 D^2 \sigma_E^2}{2}\right). \quad (2)$$

For a saddle distribution, which is caused by the energy modulation process in laser heater, using the notations in ref. [13], i.e., the net longitudinal bunch length compression between the laser heater and the main undulator C, the energy modulation induced in the laser heater system $\Delta\gamma_h$ and the energy spread at the exit of the photo-injector σ_H, the bunching factor can be written as [10, 13],

$$b_S = \left| J_h(hD\Delta\gamma_s)\exp\left(-\frac{h^2\sigma_H^2 C^2 D^2}{2}\right)\times J_0(hCD\Delta\gamma_h)\right|. \quad (3)$$

The predictions made by Eq. (2) has been analyzed intensively in Ref. [11]. The bunching factor draw back fast for a Gaussian energy distribution and this feature limits the feasibility of HGHG at high harmonics. For the non-Gaussian case, FERMI's experiment results show an FEL output pulse energy oscillation with the increase of the laser heating [13], which is a meaningful demonstration of Eq. (3).

If we assume a more ideal case that the electron energy is uniformly distributed between [E_0-τ/2, E_0+τ/2], the RMS energy spread is then changed to $\sigma_E = 0.5\tau/\sqrt{3}$. According to Eq. (1) and the law of Fourier transform for a rectangular pulse [17], the bunching factor for the uniform energy distribution at h^{th} harmonic can be presented as

$$b_U = J_h(hD\Delta\gamma_s)\left|Sinc(hD\tau/2)\right|. \quad (4)$$

To verify the abovementioned theoretical predictions and compare different cases, we carry out the single frequency simulations using the universal FEL simulating code GENESIS [18]. In these simulations, we take the main parameters of SXFEL as an example to illustrate the effects of different energy distribution on FEL density modulation process. Considering that the effective energy spread induced by the seed laser in HGHG is limited by the FEL parameter ρ for the requirement of exponential amplification in the final 8.8nm radiator, the energy modulation amplitude $A = \Delta E/\sigma_E$ is chosen to be about 5, and the optimal dispersive strength is chosen to be $k_1 R_{56} A \approx 1.2$ here.

Figure 2 shows the bunching factor distributions at various harmonic numbers for different cases. The bunching factor oscillations are clearly seen for the uniform and saddle energy spread distribution cases. The

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amplitudes of the oscillations can be adjusted by setting the energy modulation amplitude and the strength of dispersive chicane. The simulation dots are all at the vicinity of the theoretical value, which is in good agreement with the derivation of Eqs. (2)-(4). This kind of bunching factor oscillation can be used to significantly extend the tuning range of the output wavelength of a single-stage HGHG down to very high harmonics, and makes the generation of soft X-ray FEL pulses in a single-stage HGHG possible.

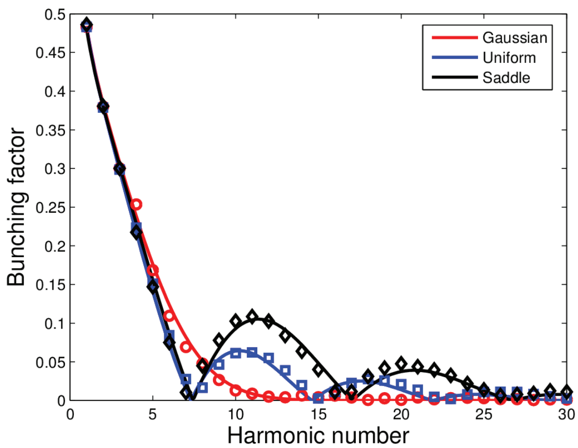

Figure 2: The evolution of bunching factor with the harmonic number, the red circle is Gaussian results, blue square and the black diamond is for uniform and saddle respectively, the corresponding color line is theoretical derivation of Eqs. (2)-(4).

OPERATING SXFEL WITH SINGLE-STAGE HGHG

It has been widely discussed that, seeded FELs with total frequency up-conversion factor of 30, e.g., SXFEL. In this section, we discuss the feasibility of operating SXFEL with a single-stage HGHG, by properly handling the distribution of the sliced beam energy spread with the laser heater.

It is widely known that, the Landau damping of the micro-bunching instability in the electron beam with a Gaussian energy spread is much more efficient than that with a saddle one. It means that, in order to achieve the same suppression of the micro-bunching instability, a larger laser energy in the laser heater, or equivalently a larger RMS deviation of the electron energy distribution could be needed for the non-Gaussian case. Therefore, to clearly understand and state the tradeoff of using a saddle-like energy distribution instead of the Gaussian one for seeded FELs, start-to-end tracking of the electron beam, including all the components of SXFEL has been carried out. The electron beam dynamics in the photo-injector was simulated with ASTRA [19] to take into account space-charge effects. ELEGANT [20] was then used for the simulation in the remainder of the LINAC. For simplicity, one bunch compressor setup of SXFEL is considered.

In the simulation, the total energy spread of about 20 keV is obtained in the absence of all the impedance effects, i.e., the energy sliced energy spread at the exit of photon injector of ~2 keV and the bunch compression factor of 10. In further micro-bunching studies, we first switch off the laser heater, and it is found that the typical sliced beam energy spread is 54 keV at the exit of LINAC. Then two laser-heater cases with the laser size of 0.3 mm and 1.2 mm are considered, respectively, while the electron beam size in the heater is 0.3 mm in both cases. The laser energy is independently optimized to obtain a better micro-bunching suppression, i.e., a lower sliced beam energy spread here for each case. The energy distribution at the exit of the LINAC is shown in Fig. 3. According to the simulation, the beam energy distribution shape controlled by the laser-heater can be maintained in the LINAC. The optimal energy spread is about 27 keV and 38 keV for Gaussian and saddle case, which are both better than the case without laser heater. In other words, it results more micro-bunching and larger energy spread in the saddle case than in the Gaussian one.

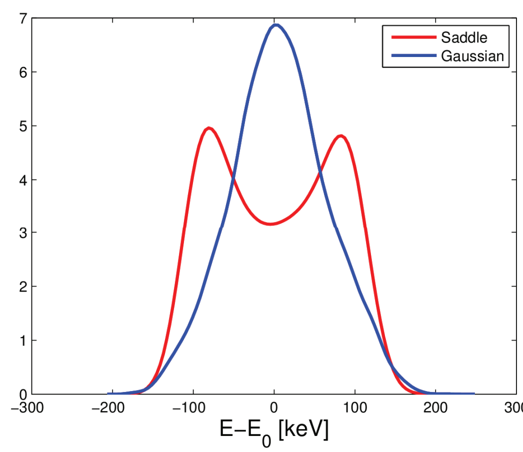

Figure 3: The saddle and Gaussian sliced beam energy distribution at the exit of the LINAC.

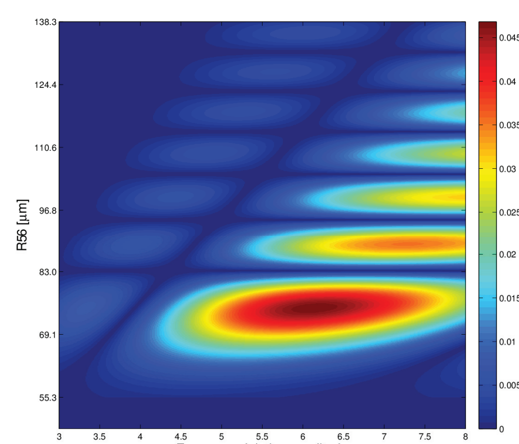

Figure 4: The 30th harmonic bunching factor in a single-stage HGHG v.s. the energy modulation amplitude and the strength of the dispersion. A saddle-like energy distribution from ELEGANT with a RMS energy spread of 38 keV is used.

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According to the previous results, the bunching factor of HGHG can be significantly enhanced with a saddle energy distribution. Using the tracked saddle-like energy distribution, the optimized 30th harmonic bunching factor as a function of the HGHG scheme setup is shown in Fig. 4. One can find that the 30th harmonic bunching factor could be more than 4% for energy modulation amplitude A around 6, which is strong enough for driving intense coherent radiation at the beginning of the radiator. Moreover, in view of the tradeoff between the seed laser induced energy spread and the available bunching factor, a moderate modulation amplitude of A = 6.5 is chosen for FEL gain process in the radiator.

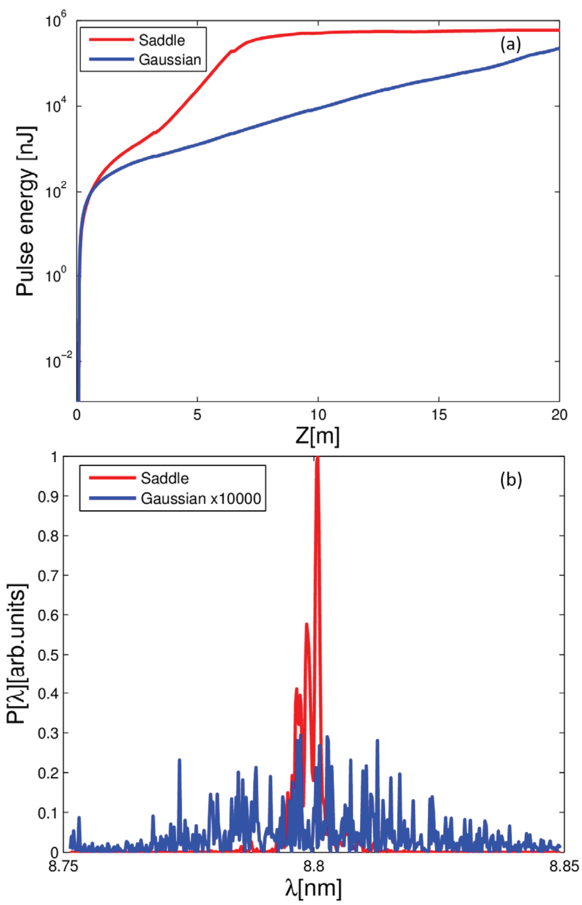

Figure 5: Comparison of final 8.8 nm radiation pulse energy (a) and spectra (b) of SXFEL with a single-stage HGHG. The spectra are exported at the undulator position of 10 m, where the saddle distribution is almost saturated, while the Gaussian one is still in exponential gain regime.

In the FEL simulation, the saddle energy distributions from ELEGANT are artificially imported to GENESIS [18] at the entrance of the modulator undulator. The FWHM pulse duration of the 264nm seed laser is supposed to be 500fs. In order to fairly compare the HGHG performance for both Gaussian and saddle distributions, the energy spread induced by the seed laser is assumed to be same in both cases. Figure 5 shows the comparison of output pulse energy along the radiator and the output spectra. The saddle energy spread beam drives a strong coherent radiation at the beginning of the radiator and the saturation length is about 10m, while the Gaussian one almost starts from shot noise and a much longer radiator is required. After passing through 10 m long radiator, the relative FWHM bandwidth of saddle case is about 0.05% and 5 times narrower than the Gaussian distribution. The noisy spike and FEL spectrum broaden in the saddle case is induced mainly by the nonlinear energy chirp in the electron beam [21-24]. It is worth stressing that with the recent technology [25-26], the FEL performance can be future improved by removing the beam energy curvature [27].

CONCLUSION

In this paper, the sliced energy distribution effects on the bunching process in seeded FELs are investigated by using theoretical analysis and numerical simulations. It is found that a bunching factor oscillation happens in HGHG for uniform and saddle distributions. Moreover, such a bunching factor oscillation in HGHG can be adjusted by setting the energy modulation amplitude and the strength of the dispersive chicane, thus to obtain a large bunching factor at high harmonics.

For the single-stage HGHG operation of a soft X-ray FEL, the start-to-end example in this paper demonstrates that the 30th or even higher harmonic is possible with a moderate energy spread control by using the laser-heater system in the LINAC, even though the saddle distribution has a larger sliced beam energy spread than a Gaussian case. Thus, by manipulating the energy spread distribution, a single-stage HGHG may be used to cover much larger harmonic range than the theoretical predictions under the assumption of Gaussian beam energy spread distribution. However, in order to avoid the temporal coherence degradation due to the nonlinear beam energy curvature, a much shorter seed laser is preferred for high harmonic operation of single-stage HGHG.

Finally, it is worth emphasizing that the control of the sliced beam energy spread, both RMS deviation and shape is quietly related to many issues, e.g., the required suppression of the micro-bunching instability, the detailed LINAC setup, and the FEL performances in pursuit. In general, larger laser heater energy, or equivalently a larger RMS for the electron energy distribution may be needed in non-Gaussian case. Then for a real FEL machine, except the robust design and self-consistent start-to-end beam tracking, it is likely that the machine flexibility, the accuracy of beam energy spread measurement, the commissioning experiences and efforts will determine the frequency up-conversion limit achievable for different seeded FELs.

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REFERENCES

[1] L. H. Yu, Phys. Rev. A **44**, 5178 (1991).
[2] L. H. Yu et al., Science **289**, 932 (2000).
[3] L. H. Yu et al., Phys. Rev. Lett. **91**, 074801 (2003).
[4] T. Shaftan, and L. H. Yu, Phys. Rev. E **71**, 046501 (2005).
[5] E. Allaria et al., Nature Photonics **6**, 699 (2012).
[6] R. Bonifacio et al., Riv. Nuovo Cimento, **17**, 9 (1990).
[7] J. Wu and L. H. Yu, Nucl. Instrum. Methods Phys. Res., Sect. A **475**, 104 (2001).
[8] B. Liu et al., Phys. Rev. ST Accel. Beams **16**, 020704 (2013).
[9] E. Allaria et al., Nature Photonics **7**, 913 (2013).
[10] Z. Huang et al., Phys. Rev. ST Accel. Beams **7**, 074401 (2004).
[11] Z. Huang et al., Phys. Rev. ST Accel. Beams **13**, 020703 (2010).
[12] G. Dattoli et al., arXiv:1410.6614.
[13] E. Ferrari et al., Phys. Rev. Lett. **112**, 114802 (2014).
[14] S. Spampinati et al., Phys. Rev. ST Accel. Beams 17, 120705 (2014).
[15] J. Yan, M. Zhang, and H. Deng, Nucl. Instrum. Methods Phys. Res., Sect. A **615**, 249 (2010).
[16] K. J. Kim, Z. Huang, and R. Lindberg, Synchrotron Radiation and Free Electron Lasers, Principles of Coherent X-Ray Generation, (2014).
[17] Bochner S., Chandrasekharan K., Fourier Transforms, Princeton University Press, (1949).
[18] S. Reiche, Nucl. Instrum. Methods Phys. Res., Sect. A **429**, 243 (1999).
[19] K. Flottmann, ASTRA User Manual, http://www.desy.de/~mpyflo
[20] M. Borland, ANL Advanced Photon Source, Report No. LS-287, 2000.
[21] E. L. Saldin et al., Optics Communications **202**, 169 (2002).
[22] D. Ratner, A. Fry, G. Stupakov, and W. White, Phys. Rev. ST Accel. Beams **15**, 030702 (2012).
[23] C. Feng et al., Phys. Rev. ST Accel. Beams **16**, 070605 (2013).
[24] G. Wang et al., Nucl. Instrum. Methods Phys. Res., Sect. A **753**, 56 (2014).
[25] K. Bane and G. Stupakov, Nucl. Instrum. Methods Phys. Res., Sect. A **690**, 106 (2012).
[26] P. Emma et al., Phys. Rev. Lett. **112**, 034801 (2014).
[27] H. Deng et al., Phys. Rev. Lett. **113**, 254802 (2014).

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