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Compact single-pass X-ray FEL with harmonic multiplication cascades

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ABSTRACT

The generation of X-ray radiation in cascaded single-pass free electron laser (FEL), which amplifies high harmonics of a two-frequency undulator, is studied. Power dynamics of FEL harmonics is explored with the help of the phenomenological model of a single pass FEL. The model describes both linear and non-linear harmonic generation, starting from a coherent seed laser and initial shot noise with account for main loss factors for each harmonic in each cascade individually: the energy spread and beam divergence, the coupling losses between FEL cascades, the diffraction etc. The model was validated with the experiment and with relevant 3-D simulations. It is employed for modeling the cascaded FELs with harmonic multiplication and analyzing the evolution of FEL harmonic power with the aim to obtain the maximum high harmonic power in the X-ray band at the shortest possible FEL length with the lowest possible seed frequency. The advantages of two-frequency undulators in HGHG FELs are elucidated. The requirements for the electron beam are studied; the need for low energy spread is evidenced: our evaluations yield $\sigma_e < 2 \times 10^{-4}$. Several cascaded HGHG FELs with two-frequency undulators are modeled. Generation of soft X-ray radiation at $\lambda = 2.71$ nm, reaching ~50 MW power with $I_0 \sim 100$ A in a cascaded FEL at just 40 m with 13.51 nm seed, matching peak reflectivity of Mo/Si, is demonstrated. The generation of 40 MW radiation power at $\lambda = 2.27$ nm with the beam current $I_0 \sim 100$ A, energy $E = 950$ MeV and the energy spread $\sigma_e = 2 \times 10^{-4}$ is studied, using second and third harmonics in three-stage 45 m long FEL. The multistage FEL is modeled for generating radiation in nanometer band: ~40 MW power at $\lambda \sim 2.6$ nm with $I_0 \sim 175$ A current in just ~40 m long FEL with commercially available F_2 excimer UV laser seed at 157 nm. The peak radiation power rises to ~0.5 GW for ~1 kA beam current.

1. Introduction

Undulator radiation (UR) is based on the physical effect of intense emission in narrow angle $\sim 1/\gamma$ from accelerated relativistic electrons with the energy $E \gg mc^2$, $\gamma = E/mc^2$, where m is the electron mass, c is the speed of light. The spontaneous undulator radiation [1] is incoherent, as well as the synchrotron radiation (SR). The latter covers almost the whole electromagnetic spectrum, while the UR spectrum has few distinct peaks. The coherent sources of light – lasers – revolutionized the research in many fields science. They operate in a broad range of electromagnetic spectrum, reaching ~200 nm short wavelength. The wavelength ~200 nm allows study of viruses, the radiation at $\lambda \sim 14$ nm allows distinguishing atomic corrals, the radiation at $\lambda \sim 1$–2 nm could resolve DNA helix, carbon nanotubes etc., while even shorter wavelengths could visualize small molecules and even atoms. For applications, requiring so short and coherent radiation, free-electron lasers (FEL) are good candidates (see, for example, [2–7]). Common lasers and oscillator FELs have optical resonator, which provides high spatial and temporal coherence of the produced radiation. However, in X-ray band the natural lack of reflecting materials imposes limitations on resonator design. For radiating significant power in X-ray range [8–13], mirrorless self-amplified spontaneous emission (SASE) FELs are used. Mirrorless FELs also have their limitations: while mirror FELs benefit from the optical modes of the resonator just as the common lasers do, in SASE the process starts from initial noise with random phase, which triggers the formation of dozens of thousands of micro-bunches, separated from each other by one radiation wavelength. The undulator radiation (UR) then grows exponentially along the undulator and becomes close to coherent; at the end of FEL the saturation is reached. This process is capable of producing trains of very short micro-pulses with high peak power ~10^{10} W and excellent spatial mode. However, random initial noise results in poor temporal coherence, i.e., the coherence time of the produced FEL radiation is much less that the duration of the macro-pulse. To operate in X-ray band SASE FEL needs high quality beam of high energy electrons and the installations reach kilometric length, such as the European XFEL [14], inaugurated in September 2017, has 3.4 km length and it is extremely expensive. Moreover, at such lengths it is hard to contain the beam divergence low and insure proper match of the electron bunch with the FEL radiation.

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An alternative to SASE FEL design is based on the high gain harmonic generation (HGHG) FEL (see, for example, [15,16]), combining the UR high harmonics generation, their multiplication and amplification. Recently it was demonstrated that two-frequency undulators can provide intense high harmonics due to their secondary short-period magnetic field, imposed in addition to the main periodic magnetic field [17–23]. In what follows we will model several cascaded single-pass FELs, operating with relatively low-energy electron beams with $\gamma \sim 10^3$ and low current $\sim 10^2$ A, and demonstrate that with the proper set of parameters they are capable of generating dozens of megawatts of X-ray power at nanoscale wavelengths in 35–50 m long FEL. This is shorter as compared with previously researched for compact SASE FELs [24,25] even in X–UV band. Moreover, the cascaded FELs have one more important advantage over seeded SASE FELs: lower frequency seeding can be employed. We will show that even readily available excimer F_2 laser can be used for seeding multicascaded FEL to generate nanometer radiation. This adds excellent temporal coherence to high intensity and good spatial coherence of SASE FEL radiation.

We will analyze the dynamics of the radiated X-ray harmonic power in the cascaded SASE FELs and explore the requirements for the beam, dependently on the harmonics used in the cascades. To this end we will use simple, though powerful and rather accurate phenomenological FEL model, validated with FEL experiment and with relevant numerical 3-D simulations. Its present form distinguishes from the previous one [26] by the description of the beam energy spread, divergence and diffraction individually for each harmonic in every section, and it assumes noise and proper coupling losses between the sections.

2. Phenomenological model of a cascaded single-pass FEL

For modeling FEL radiation and studying cascaded FELs with HGHG we employ the phenomenological single-pass FEL model, which accounts for linear and nonlinear harmonic generation and for all major power losses. Beam matching has been recently reviewed in [27]; it is a stand alone topic, not treated by the phenomenological model. It can be approached with FEL handbooks [28], books [27], articles [29,30] or relevant software. We assume the matched beam. The present model improves the FEL model [26], which involved basic equations, developed in [31]. In particular, for studying HGHG FELs we need precise account for high harmonic behavior. In reality, high UR harmonics are more sensitive to losses, which makes them more difficult to generate in experiments. To describe accurately their behavior we introduce, following the UR studies [17,18,22,32,33], the harmonic-number dependent account for the beam divergence and for the energy spread in each cascade, as well as the description of the initial shot noise and the account for the coupling losses between the FEL cascades.

The harmonic power in a seeded SASE FEL grows exponentially [21] along its axis z:

$$P_{L,n}(z) \cong P_{0,n} \frac{A(n,z)\exp\left(0.223z/Z_s\right)}{1+(A(n,z)-1)\,P_{0,n}/P_{n,F}}, \tag{1}$$

where

$$A(n,z) \cong \frac{1}{9}\left(3+2\cosh\left(z/L_{n,g}\right)+4\cos\left(\sqrt{3}z/2L_{n,g}\right)\cosh\left(z/2L_{n,g}\right)\right), \tag{2}$$

$P_{0,n}$ is the power of the seed of the nth harmonic, $P_{n,F} = \frac{P_F}{\sqrt{n}}\left(\frac{f_n}{nf_1}\right)^2$ is the saturated harmonic power, $Z_s \cong 1.066L_{1,g}\ln\left(9P_F/P_0\right)$ is the saturated length, $P_F \cong \sqrt{2}\rho_1 P_e$ is the saturated power of the fundamental harmonic, P_e is the electron beam power, $L_{n,g} \cong \lambda_u/\left(4\pi\sqrt{3}n^{1/3}\rho_n\right)$ is the gain length. All these parameters depend on the fundamental for FEL physics Pierce parameter $\rho_n = \frac{1}{2\gamma}\left(\frac{J}{4\pi i}\left(\lambda_u k_{eff} f_n\right)^2\right)^{1/3}$, where γ is the relativistic parameter, λ_u is the main undulator period [m], k_{eff} is the effective undulator parameter [22], f_n are the Bessel factors for the harmonic n (see, for example, [21,26]), J is the electron current density [A/m^2], $i = 1.7045\times10^4$ is the Alfven current [A]. For the FEL cascade, which receives prebunched electron beam, the harmonic power grows as follows [28]:

$$P_{L,n2}(z) \cong \frac{P_{0,n2}F(n,z)}{1+F(n,z)\frac{P_{0,n2}}{P_{F,n2}}},$$
$$F(n,z) \cong \left|2\left(\cosh\frac{z}{L_{n,g2}} - \cos\frac{z}{2L_{n,g2}}\cosh\frac{z}{2L_{n,g2}}\right)\right|, \tag{3}$$

where the index 2 means the second undulator section, $P_{0,n2}$ is the initial power for this cascade, provided directly from the previous cascade, or the equivalent power, provided by the bunching. The renormalization factor $\left(\rho_{1,\sec 1}/\rho_{1,\sec 2}\right)^k$ is used for the bunching in undulators with different from each other parameters, where k is the ratio of the harmonics in them. Besides the linear harmonic generation (1)–(3), the nonlinear harmonic generation develops along FEL; in this regime high harmonics are induced by the fundamental one and they grow as the nth power of the fundamental FEL harmonic (see [21,34]) as follows:

$$Q_n(z) \cong P_{n,0}\frac{\exp\left(nz/L_g\right)}{1+\left(\exp\left(nz/L_g\right)-1\right)P_{n,0}/P_{n,F}}, \tag{4}$$

where $L_g \equiv L_{1,g}$, $P_{n,0} \cong d_n b_n^2 P_{n,F}$ is the equivalent seed power, $d_3 \approx 8$, $d_5 \approx 116$, b_n are the bunching coefficients, induced by the fundamental harmonic, which evolve as follows: $b_n(z) = h_n\left(P_1(z)/P_e\rho_1\right)^{n/2}$, $h_{1,2,3,4,5} \approx 1, 1.5, 2.5, 4.5, 7.5$. The total power of high harmonic generation includes both linear and non linear components: $P_n = P_{L,n} + Q_n$. The Bessel factor f_n [21,28] contains generalized or common Bessel functions, dependently on the undulator. For a common planar undulator the radiation is linearly polarized and $f_{n,x} = J_{\frac{n-1}{2}}(n\xi) - J_{\frac{n+1}{2}}(n\xi)$, where $J_n(\xi)$ are the Bessel functions and $\xi = k^2/4\left(1+k^2/2\right)$, $k = eH_0/\left(k_\lambda mc^2\right) \approx H_0\lambda_u$[T cm].

A two-frequency planar undulator [17,18] has the double periodic magnetic field

$$\overrightarrow{H} = (0, H_0(\sin(k_\lambda z) + d\sin(hk_\lambda z)), 0),$$
$$h \in Z,\ d, h = \text{const}, k_\lambda = 2\pi/\lambda_u. \tag{5}$$

It allows certain regulation of high harmonics, as compared with common undulator. The Bessel factor for the two-frequency undulator [18,19,32,33] with the field (5) is $f_{n,x} = I_{n-1}^{(h)} + I_{n+1}^{(h)} + \frac{d}{h}\left(I_{n+h}^{(h)} + I_{n-h}^{(h)}\right)$, where the proper Bessel functions are

$$I_n^{(h)} = \int_0^{2\pi}\frac{d\theta}{2\pi}\cos\left[n\theta + \frac{k^2}{1+k_{eff}^2/2}\left(\xi_1+\xi_2+\xi_3+\xi_4\right)\right],$$
$$\xi_1 = \frac{\sin 2\theta}{4},\quad \xi_2 = -\frac{d\sin((h-1)\theta)}{h(h-1)}, \tag{6}$$
$$\xi_3 = -\frac{d\sin((h+1)\theta)}{h(h+1)},\quad \xi_4 = -\frac{d^2\sin(2h\theta)}{4h^3}.$$

For common planar undulator $d = 0$. Helical undulators produce elliptically polarized radiation with better possibilities to regulate the phases, rather than the intensities of the harmonics [21,28].

The following ad-hoc function approximately describes the correction to the power due to the initial shot noise:

$$N_{L,n}(z) \approx \frac{P_{NOISE}S(n,z)/9n^3}{1+S(n,z)/50},$$
$$S(n,z) = 2\left|\left(\cosh\frac{z}{L_{n,g}} - \cos\frac{z}{20L_{n,g}}\cosh\frac{z}{2L_{n,g}}\right)\right|, \tag{7}$$

where P_{NOISE} is the shot noise power. The function $N_{L,n}(z)$ was calibrated by comparison with FEL experiment [35] and relevant numerical 3D simulations.

The diffraction of the beam changes the Pierce parameter as follows [34]:

$$\rho_n \to \rho_{D,n} = \frac{\rho_n}{\left(1+\mu_{D,n}\right)^{1/3}},\quad \mu_{D,n} = \frac{\lambda_u\lambda_n}{(4\pi)^2\rho_n\Sigma_{\text{beam}}}, \tag{8}$$