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Spontaneous emission high-gain harmonic generation free-electron laser

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ABSTRACT

A scheme, spontaneous emission high-gain harmonic generation (SEHG) free-electron laser (FEL), is proposed and analyzed for generating the X-ray FEL. The SEHG scheme works in a similar mechanism as high-gain harmonic generation (HGHG), but without the need for a seed laser. The scheme requires two undulators. The 1st undulator must be sufficiently long so that the energies of electrons are modulated within the bunch, but still away from saturation. A dispersion section is followed to transfer energy modulation into density modulation. The 2nd undulator simply serves as a radiator. A simple, one-dimensional, analytical estimation of SEHG is given to show the process of energy modulation and optimize the system parameters. The three-dimensional FEL simulation code, GENESIS, has been used to simulate, verify, and optimize the SEHG scheme for the soft X-ray free-electron laser (SXFEL) project in China. The simulation results are presented in comparison with the self-amplified spontaneous emission (SASE) and HGHG schemes. At 9 nm radiation wavelength, up to 120 MW of output power can be achieved by the SEHG scheme, with a total length of 47.3 m long undulators. Though the undulator length is comparable with the SASE scheme, the output bandwidth of the SEHG scheme is smaller. Moreover, it is tunable and does not require a seed laser. The SEHG scheme offers an attractive alternative option for the X-ray FEL.

1. Introduction

Significant progress has been made in recent years in the FEL research. More FEL projects worldwide have either been proposed or are currently under construction [1]. The photon flux of a coherent source from the conventional storage ring based 3rd generation light source is not sufficient in the hard X-ray regime to meet ever increasing scientific research needs. However, the FEL can produce radiation from terahertz (THz) up to hard X-rays with high brightness and ultra-fast time structures. It has become one of the most important tools for research in chemistry, biology, material science, and other fields. So far, most of the proposed X-ray FEL projects use either SASE [2,3] or cascading stages of high-gain harmonic generation (HGHG) schemes [4,5].

SASE amplifies the X-ray radiation from spontaneous emission, and there is no need for a seed laser during the process. Since the radiation starts from its own radiation noise, the output pulse of the FEL has typically poor temporal coherence and large power fluctuations. It is also worthy of pointing out that an X-ray SASE scheme requires a relatively longer undulator whose length can exceed 100 m. The HGHG scheme uses a shorter or comparable length of undulator and produces better temporal coherence, but requires a laser as a coherent seed for the energy modulation of electron beams. In addition, the wavelength of the output laser is optimized at one of the harmonic wavelengths of the seed laser. Due to the lack of available and suitable seed lasers, a cascaded HGHG scheme and a fresh bunch technique have been proposed for the X-ray FEL [6], but they have not been experimentally proven yet.

In this paper, we present an analysis of a dispersion-enabled two-undulator FEL scheme, SEHG. The two-undulator FEL scheme with a dispersion section was initially proposed by Vinokurov and Skrinsky [7] in 1977. In 1980, Boscolo and Stagno [8] pointed out that higher harmonic operation is also feasible with the parameter converter. Thereafter, the two-undulator schemes with a dispersion section on higher harmonic operation have been reported as the frequency doubler [9] and the distributed optical klystron [10]. Also, there are some two-undulator schemes without a dispersion section presented on fundamental or higher harmonic operation [11–16]. In Ref. [11], the modulation section (1st undulator) is long enough to reach saturation and to produce the required strong spatial bunching that has rich harmonics. It was intended to obtain high harmonic radiation, and eventually led to the formation of the HGHG scheme [4]. In the HGHG scheme [4], a powerful seed laser is needed, and the 1st undulator can be significantly shortened. A dispersion section is introduced to generate maximum bunching that has rich harmonics. The 2nd

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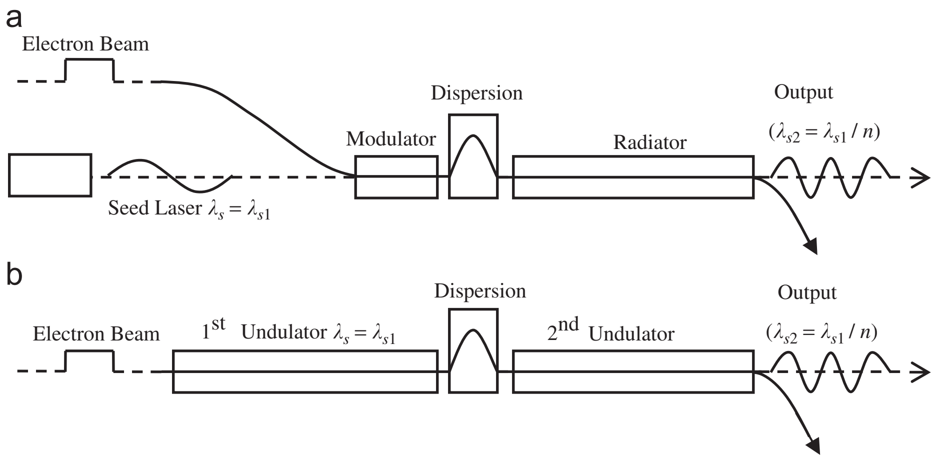

Fig. 1. Schematic layout of two, single-pass FEL schemes with harmonic generation (a) HGHG scheme; (b) SEHG scheme.

undulator serves as a radiator that reaches saturation started by the coherent emission of the partially modulated electron current.

For comparison, a schematic layout of two, single-pass FEL schemes, HGHG and SEHG, is shown in Fig. 1. In the SEHG scheme, the SASE process in the 1st undulator is optimized to modulate the energy of electron beams. Instead of using a seed laser to achieve the needed energy modulation, the 1st undulator must be adequately long; longer than the modulator in the HGHG scheme, but shorter than the saturation length of the FEL. The SASE laser from the 1st undulator is discarded and the energy-modulated electron beam goes through a dispersion section before entering the 2nd undulator.

The rest of the process after the 1st long undulator is similar to the HGHG scheme. No seed laser is needed for the SEHG scheme. Moreover, the X-ray wavelength from the SEHG FEL is tunable, and has a more favorable spectrum than the SASE FEL. Therefore, it offers an attractive alternative option for the X-ray FEL. Taking the SXFEL design as an example [17], we present a design optimized by using the SEHG scheme. The SXFEL is initially proposed to generate a 9 nm soft X-ray using the cascaded HGHG scheme. If it succeeds, it will be the first cascaded HGHG FEL demonstration.

This paper is organized as follows. In Section 2, a one-dimensional theoretical analysis of the SEHG scheme is presented first. The analytical estimation of the SEHG is given to show the feasibility of the high-gain process with harmonics of a modulated electron beam from an unsaturated SASE FEL. Section 3 presents the simulation results of the SEHG scheme using the code GENESIS [18], an optimized design for the SXFEL using the SEHG scheme and comparisons between the SEHG and SASE-HGHG schemes. A conclusion is given in Section 4.

2. Spontaneous emission high-gain harmonic generation FEL

The SEHG is a two-undulator high-gain FEL scheme with a dispersion section that eliminates the need for a seed laser. In the 1st undulator, the SASE process is started without reaching saturation. The energy of the electron beam is modulated to a level comparable to the initial energy spread. Rich harmonic components are obtained with spatial bunching through a dispersion section. The 2nd undulator serves as a radiator where the high-gain harmonic radiation is produced, started by the coherent emission of the partially modulated electron current, and followed by an exponential growth until saturation. A more clean spectrum of the output radiation is expected with proper pre-bunching.

To understand the SEHG scheme, we start with a one-dimensional theory on the energy-modulated electron beam during the SASE process in the 1st undulator. Then the optimization process of the modulator length and dispersion parameters is presented. Some discussions are given based on the bunching factor. The following analysis is based on the planar undulator.

2.1. One-dimensional theory of the SEHG scheme

The electron beam generates spontaneous radiation after it is injected into an undulator. The radiation interacts with the electron beam causing modest energy modulation. The longitudinal motion of the electron beam in the modulator, e.g., the 1st undulator in the SEHG scheme, can be expressed as [19,20]

$$\begin{cases} \dfrac{d\gamma_j}{dz} = -\dfrac{k_s a_s(z) a_w f_B}{\gamma_0} \sin(\theta_j + \phi_s) \\ \dfrac{d\theta_j}{dz} = 2k_w \dfrac{\gamma_j - \gamma_0}{\gamma_0} \end{cases} \tag{1}$$

where γ_j is the relativistic energy factor of particle j and γ_0 is the resonant energy factor. $\theta = (k_s + k_w)z - \omega_s t$ is the ponderomotive phase of the electron in the standing wave field composed by the undulator and laser field. $k_s = 2\pi/\lambda_s$ and $k_w = 2\pi/\lambda_w$ are the wave numbers, λ_s is the fundamental resonance wavelength of the undulator, λ_w is the undulator period, $f_B = J_0(\eta) - J_1(\eta)$ with $\eta = a_w^2/2/(1+a_w^2)$, $a_s(z) = eA_{s0}/(\sqrt{2} m_e c)$, and $a_w = eA_w/(\sqrt{2} m_e c)$ are the dimensionless (rms) vector potentials from the spontaneous radiation and magnetic field of the undulator, respectively. The radiation field can be characterized by $E = \omega_s A_{s0} e^{i(\phi_s - \pi/2)}$, where $\omega_s = 2\pi c/\lambda_s$, and ϕ_s is the initial phase.

It is worth stressing that in the HGHG scheme, the modulator is short, and a_s can be treated to be independent of z. However, in the SEHG scheme the modulator is longer. Therefore the EM field cannot be approximated to be constant anymore. In a high-gain situation, even a_s depends on z, Eq. (1) still can be used. a_s can be obtained from the radiation power P, which is given by the one-dimensional theory [19,21]

$$\begin{cases} P \approx \dfrac{1}{9} \rho m_e c^2 \gamma_0 \dfrac{\sigma_\omega}{\sqrt{2\pi}} e^{z/L_G^{1D}} \\ P_{sat} \approx \rho P_e \end{cases} \tag{2}$$

where $\rho = \sqrt[3]{Z_0 e^2 n_0 K^2 [JJ]^2 / (32 k_w^2 m_e c \gamma_0^3)}$ is the pierce parameter, $L_G^{1D} = \lambda_w/(4\sqrt{3}\pi\rho)$ is the gain length (one-dimensional result), $\sigma_\omega = \omega_s \sqrt{3\sqrt{3}\rho/(k_w z)}$ is the rms value of the relative bandwidth,