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Design of sub-Angstrom compact free-electron laser source

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ABSTRACT

In this paper, we propose for first time practical parameters to construct a compact sub-Angstrom Free Electron Laser (FEL) based on Compton backscattering. Our recipe is based on using picocoulomb electron bunch, enabling very low emittance and ultracold electron beam. We assume the FEL is operating in a quantum regime of Self Amplified Spontaneous Emission (SASE). The fundamental quantum feature is a significantly narrower spectrum of the emitted radiation relative to classical SASE. The quantum regime of the SASE FEL is reached when the momentum spread of the electron beam is smaller than the photon recoil momentum. Following the formulae describing SASE FEL operation, realistic designs for quantum FEL experiments are proposed. We discuss the practical constraints that influence the experimental parameters. Numerical simulations of power spectra and intensities are presented and attractive radiation characteristics such as high flux, narrow linewidth, and short pulse structure are demonstrated.

1. Introduction

The development of a compact, tunable, near monochromatic hard x-ray source has wide-ranging applications in modern medical, commercial, and academic research applications e.g. microscopy and nuclear resonance absorption. Some properties of the x-ray radiation which are important for these applications are narrow spectral width, high photon flux, high-brightness, pulse duration (in the ps to fs range) and variable polarization.

A potentially attractive ultra-short x-ray source has been proposed by replacing the magnetic undulator in the conventional undulator Free Electron Laser (FEL) by ultra-high intensity laser pulses (a laser undulator) [1,2]. Synchrotron radiation is emitted when an electron beam of substantially lower energy interacts with a counter propagating laser undulator. The Compton backscattered process can be treated as that of an undulator FEL operated in the Self Amplified Spontaneous Emission (SASE) mode [2,3]. The quantum regime of SASE FELs is characterized by a dimensionless parameter $\bar{\rho}=\rho(\gamma mc/\hbar k)$, where ρ is the classical FEL parameter, γ is the electron energy (in rest mass units), m is the electron mass, and k is the photon wavenumber [4,6]. Since the maximum induced energy spread $\Delta\gamma\sim\rho\gamma$, hence, $\bar{\rho}$ is understood as the ratio between the classical momentum spread $\Delta\gamma mc$ and the photon recoil $\hbar k$. The quantum effects become apparent when $\bar{\rho}<1$ where the discreteness of momentum exchange becomes significant. In the quantum regime, the broad and spiky classical spectrum is converted to discrete lines due to a distinct transition between two energy levels. This process is called quantum purification. The width of this single emission line in the quantum FEL (QFEL) is $(\Delta\omega/\omega)_{QFEL}=\lambda_r/L_b$ [7] where λ_r is the radiation wavelength and L_b is the electron bunch length. In the classical regime when $\bar{\rho}>1$, many momentum states are occupied and a multi−frequency spectrum with equally spaced lines is observed. The spectral width of the classical FEL (CFEL) spectrum is given by $(\Delta\omega/\omega)_{CFEL}\sim 2\rho$ with the average number of spikes $N_s\sim 2\rho/(\lambda_r/L_b)$ [8].

Recent advances in laser-plasma accelerators have demonstrated generation of low energy spread, low-emittance, and very short electron bunches (fs duration) [9,10]. On the other hand, present day lasers (e.g., Nd:YAG/Nd:glass lasers) can provide laser pulses with high peak power (TW range) and relatively long pulse duration (ns–ps range). These characteristics create a possibility to realize an efficient x-ray QFEL using a Compton backscattering configuration. Such an x-ray QFEL would assist in observing fundamental processes that require fs time resolution and atomic scale spatial resolution. The narrow bandwidth of longer laser undulator pulses is required to achieve a narrow x-ray bandwidth. It is noted that a basic requirement to realize a QFEL is a high quality electron beam with a low normalized emittance and a

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sufficiently small energy spread. This can be achieved using a low charge per bunch (e.g., using short electron bunches with high repetition rate).

In this paper, we present design studies for a compact sub-Angstrom radiation source based on the Compton backscattering configuration. The criteria and constraints that are inherent in the requirements for all experimental parameters are discussed. We use the working equations of FELs in the Compton regime discussed in Ref. [7] to propose experimental parameters of ≤0.5Å–QFELs. In this paper, we assume operation in the quantum regime taking $\bar{\rho}\ll1$. The quantum properties of the radiation such as full temporal coherence are demonstrated. It is confirmed that the experimental parameters of QFELs are attainable using current electron beam and laser undulator technologies.

2. Basic formulas for QFEL experiments

In this section, we present the basic formulae of the laser-electron Compton backscattering scheme (i.e., Quantum SASE FELs). We also discuss the design criteria for the QFEL experiments.

In the Compton backscattering process, the radiation wavelength λ_r is identical to that of an undulator FEL by replacing the undulator period by half of the incident laser wavelength λ_L and the undulator parameter K by the dimensionless laser strength parameter $a_0 = |e|\bar{A}/mc^2$, where $\bar{A}$ is the laser vector potential. The resonance radiation wavelength is then [7]:

$$\lambda_r = \frac{\lambda_L}{4\gamma^2}\left(1+a_0^2\right). \tag{1}$$

The laser undulator parameter a_0 is given in terms of incident laser power P by

$$a_0 = \frac{2.\,4k_L\lambda_L}{R_0}\sqrt{P(TW)} \tag{2}$$

where R_0 is the minimum radius of the laser and k_L is 1 or $\sqrt{2}$ for a Gaussian or for a flat top transverse profile of the laser. It is noted that the position−dependent laser radius $R(z)$ varies due to the intrinsic Gaussian beam diffraction. If the laser diffraction is taken into account, the laser parameter a_0 shown in Eqs. (1) and (2) should be replaced by $a(z)=a_0/\left[1+\left(z/Z_L\right)^2\right]$ where Z_L is the laser Rayleigh range. When $a_0\gtrsim1$, the resonance wavelength given by Eq. (1) becomes spatially dependent broadening the emission spectrum. One important criterion for QFEL optimization is to fulfill the condition $a_0<1$ to overcome the laser diffraction and resultant spectral broadening. From Eq. (2), the constraint $a_0<1$ imposes a limit on the maximum laser undulator power, as discussed later. The diffraction effect can be reduced by guiding the laser pulse in a plasma-filled [11,12] or vacuum [13,14] capillary waveguide or by means of energy chirp in the electron pulse [15]. However, it is beyond the scope of this paper to treat in detail the means of negating the laser diffraction effect.

As discussed above, the transition from the classical to quantum regimes is determined by the quantum FEL parameter $\bar{\rho}$ that is related to the classical FEL parameter ρ given by:

$$\rho = \bar{\rho}\frac{\hbar k}{\gamma mc} = \frac{1}{2\gamma}\left(\frac{I}{I_A}\right)^{1/3}\left(\frac{k_e\lambda_L a_0}{4\pi\sigma}\right)^{2/3} \tag{3}$$

where I is the peak current of electron beam, $I_A\approx17kA$ is the Alfven current, σ is the rms electron beam radius, and k_e is 1 or $\sqrt{2}$ for a Gaussian or for a flat top transverse current profile respectively. Using Eq. (3) with Eq. (2), we can write the peak electron current as:

$$I(A)=50\bar{\rho}^3\frac{R_0^2\sigma^2}{k_e^2k_L^2\lambda_L^4\lambda_r^3}\frac{1}{P}, \tag{4}$$

where λ_r is in Å, λ_L is in μm, R_0 is in μm, σ is in μm, and P is in TW. In Eq. (4), it is noted that $I\propto\bar{\rho}^3$ and $I\propto 1/\lambda_r^3$. Therefore, the peak current required in the FEL experiments operated in the quantum regime ($\bar{\rho}<1$) is much smaller than that required in the classical regime ($\bar{\rho}>1$). This fact indicates the important role of the quantum regime to realize a compact FEL experiments in the x-ray range.

In the classical regime, the gain length L_g and the cooperation length L_c for the field growth are written as [8]:

$$L_g = \frac{\lambda_L}{8\pi\rho},\ L_c = \frac{\lambda_r}{4\pi\rho}. \tag{5}$$

It is considered that the interaction length $L_{\rm int}$ is the saturation length $L_{\rm sat}$ and is given by the laser pulse duration $c\tau_L$. $L_{\rm int}$ is also determined by a factor n_i times L_g, i.e.

$$L_{\rm int} = L_{\rm sat} = c\tau_L = n_iL_g. \tag{6}$$

where n_i is the number of L_g in the interaction length $L_{\rm int}$.

The spectral width due to the finite time of emission when the interaction length $L_{\rm int}\gg L_{\rm b}$ is given by [7]

$$\left(\Delta\omega/\omega\right)_{QFEL} \approx \frac{\lambda_r}{L_b}. \tag{7}$$

The normalized beam emittance must satisfy the restrictive condition [7]:

$$\varepsilon_n \le \sigma\sqrt{\Gamma\left(1+a_0^2\right)}, \tag{8}$$

where Γ is the FEL line width equal to $\rho\sqrt{\bar{\rho}}$.

In the quantum regime, as the peak (or saturation) power of the FEL radiation is approximated by [7]:

$$P_r \approx \frac{I}{e}\hbar\omega, \tag{9}$$

the number of emitted photons per pulse is:

$$N_{\rm ph} \approx \frac{Q}{e}, \tag{10}$$

where Q is the electron bunch charge.

3. Proposal design for sub-Angstrom QFEL experiments

3.1. Criteria and constraints

In the classical regime (i.e., when $\bar{\rho}\gg1$), the number of spikes is $N_s\sim2\rho/\left(\lambda_r/L_b\right) = L_{\rm b}/(2\pi L_c)$. In the quantum regime when $\bar{\rho}<1$, the chaotic temporal structure of the radiated pulse is reduced. In this study, we assume $L_{\rm b}\gg L_c$, so that many radiation spikes would occur in the classical regime. Therefore, when $\bar{\rho}<1$, the improved spectral characteristics of the QFEL interaction should become apparent.

To determine the experimental parameters, we begin by choosing the radiation wavelength λ_r, the laser wavelength λ_L, and an appropriate value for the quantum regime of $\bar{\rho}$=0.2. For saturation, we choose n_i~24.4 (see Figs. 3 and 4). It is noted that for smaller values of $\bar{\rho}$ (i.e., $\bar{\rho}$<0.1,) impractical values for the gain length L_g and the laser pulse width τ_L are necessary. Then, the energy of the laser pulse $U = P\tau_L$ become more challenging. For values of $\bar{\rho}\ge0.4$, the quantum properties of the FEL interaction are greatly reduced.

Using realistic values for the laser power P and the laser