Soft-x-ray generation by multiphoton scattering of a laser beam from fast free electrons

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A special type of multiphoton interaction of powerful laser radiation with fast truly free electrons is analyzed. The production of intense soft-x-ray emission is shown to arise due to the large differential cross section of the process and the Doppler shift of the simultaneously scattered photons.

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The use of the Doppler effect to generate single, high-energy photons at Compton scattering of laser beams from relativistic free electrons was suggested by Milburn [1]. This method, first applied to γ photon production by Sinclair and co-workers [2], has been proven a successful experimental technique. Its application to the construction of scattering-type free-electron x-ray lasers or amplifiers is rendered more difficult, among others, by the small cross section of the Compton scattering due to its second-order (absorption-emission) character—relative to the first-order nature of atomic emission—and by the fact that only one high-energy photon per scattering is produced. Nevertheless, new interest is observed in the use of Compton or Thomson scattering due to the availability of high current accelerators and ultrahigh intensity lasers that could be exploited as undulators, leading to the construction of laser synchrotron sources [3]. Instead of Compton scattering the application of resonance photon scattering from relativistic atoms or ions is under current investigation [4] with its own problems mentioned in [5]. X-ray lasers based on optical-field-induced ionization by powerful lasers are also considered theoretically [6,7] and the obtained plasma characteristic measured experimentally [8,9].

Along with the development of ultrapowerful laser sources, increased interest has been shown in multiphoton or nonlinear processes and the appearing phenomena at multiphoton scattering from fast free electrons. So Körmendi [10–12] presented and analyzed a special type of multiphoton interaction of powerful single-mode laser beams (pulses) with truly free electrons, proving that at well defined above-threshold intensities a large number of laser photons may be scattered along with the simultaneous absorption of one or several photons (in a one-step process) by the electron, which basically differs from the Compton effect. The large differential cross section indicates its applicability to the construction of scattering-type free-electron soft-x-ray lasers or amplifiers. Intense research in the field of photon generation by electron beams resulted in the appearance of a variety of techniques of coherent radiation production. So, for example, Luccio and co-workers [13] suggested a new method for the production of coherent x-rays by Compton scattering of laser photons from fast electrons. Its essence is in the periodic modulation of the electron beam by the incident radiation. A similar technique could, in principle, also be used for coherent radiation production when, instead of the inefficient Compton effect, the multiphoton scattering, described in [11], would be exploited at above-threshold incident-laser-beam intensities. These two, put together, could give the preconditions for the construction of an intense, monochromatic, coherent soft-x-ray source. Another potential possibility to obtain coherent radiation is described in [14], where the created energetic photons are used for pumping an appropriate lasing crystal. (We note that this special multiphoton interaction process [11–13] implies another important possibility, namely, laser-driven free-electron acceleration up to multi-GeV energies; our calculations describing this effect will be presented elsewhere.)

The starting equation defining the kinematics of the truly free-electron–multiphoton scattering and simultaneous absorption of N photons, formulated in [11], whose diagrams are given in Fig. 1, is determined by the total four-momentum conservation law

$$p_i + nk_i + Nk_i = p + nk, \tag{1}$$

where p_i and p are the initial and final four-momenta of a free electron, k_i and k the initial and final four-momenta of the parallel propagating single-mode photons, while n and N represent the number of scattered and absorbed quanta, respectively. From (1) the number n can be readily evaluated,

$$n = \left[\frac{NE_0}{\epsilon_{i0}(1-\cos\alpha_0)} + \frac{N}{4} \right]^{1/2} - \frac{N}{2}, \tag{2}$$

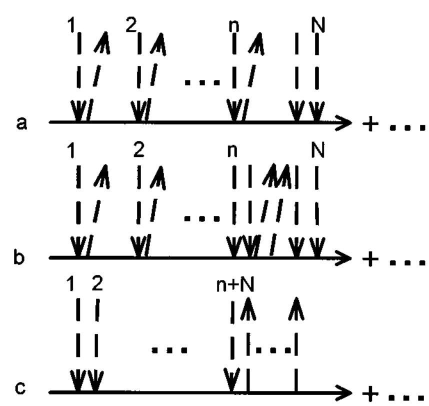

FIG. 1. Diagrams of the simultaneous scattering of n photons and absorption of N quanta by a truly free electron. The solid line represents the electron and the dashed lines the photons.

where E_0 is the electron rest energy, $E_0 = m_0 c^2$, c is the speed of light, m_0 the electron rest mass, ϵ_i the energy of an incident photon, and α the angle between the propagation directions of the incident and scattered photons. The zero subscript indicates the electron rest frame. The incident photon energy in the electron rest frame ϵ_{i0} relative to that in the laboratory frame, in which the laser source and the detectors (observer) are at rest, ϵ_i, given by the formula

$$\epsilon_{i0} = \frac{\epsilon_i (1 - B\cos\theta_i)}{(1-B^2)^{1/2}}, \quad B = \frac{v}{c}, \tag{3}$$

can be easily varied by the appropriate choice of the initial velocity of the electrons v_i and the angle between the propagation directions of the incident laser and electron beams θ_i. The final energies of the n-scattered and simultaneously Doppler-shifted single-mode photons ϵ are determined by the formula

$$\epsilon = \epsilon_i \frac{1 - B\cos\theta_i}{1 - B\cos\theta_f}, \tag{4}$$

where θ_f is the angle between the propagation directions of the electron and the scattered photon beams in the laboratory frame. With these formulas in mind, let us consider a practical case when the incident, linearly polarized, single-mode laser beam is directed relative to the electron beam under an angle of $\theta_i \approx 25°–30°$ and the n photons forward scatter, $\theta_f \approx 0°$. The incident photon energies are $\epsilon_i \approx 1$ eV or $\epsilon_i \approx 0.1$ eV. We shall require the scattered and Doppler-shifted quanta to have energies of $\epsilon \approx 73–100$ eV depending on the chosen angle θ_i. Using formula (4) one obtains for the given values of ϵ_i, ϵ, θ_i the necessary electron energy E.

For $\epsilon_i \approx 1$ eV, $E \approx 10–12$ MeV, while for $\epsilon_i \approx 0.1$ eV, $E \approx 35–40$ MeV. θ_i and θ_f define the angle $\alpha = \theta_f - \theta_i$ and thus α_0 in (2). Substituting α_0 and ϵ_{i0} into (2) we determine the number of simultaneously scattered photons n; so, for example, for $\epsilon_i \approx 1$ eV, $n = 312–373$.

The transition probabilities per unit time and the differential cross sections of the described multiphoton–free-electron interaction processes are evaluated in the electron rest frame. The calculations are carried out in the framework of quantum electrodynamics because the semiclassical or classical treatment with the "external field" model for the intense laser field is inconvenient. This is due to the fact that in that model the intense "external field" remains unaffected by its interaction with the electrons and thus remains unchanged in its propagation direction, intensity and others, while in our model the scattering of a part of the strong laser beam plays a key role, enabling the production of a higher number of energetic photons and hence, cannot be ignored. The diagrams in Fig. 1 describe the multiphoton scattering and N-photon absorption.

The transition probability per unit time P', as was shown in [11], has the form

$$P' = K^n P'_N, \tag{5}$$

where P'_N represents the probability per unit time of the absorption of N photons (depending on n-photon scattering), while the factor K^n has a meaning of probability for the interchange of three-momentum between the laser field and the electron due to the elastic scattering of n photons. At $K \to 1$ the laser field becomes "classical" in the sense that the interchange of three-momentum occurs with certainty, as in the case with electrons in static fields. At above-threshold intensities K^n does not rise above 1 because of the damping effects that hold $K^n = 1$ in a wide range of intensities. From the condition $K \to 1$ the threshold laser beam intensity I_{c0} follows,

$$I_{c0} \approx \frac{4\pi^2 \epsilon_{i0}^2}{n r_0^2 h \cos^2\varphi_0}, \tag{6}$$

where r_0 is the classical electron radius, h the Planck constant, and φ the angle between the polarization vectors of the linearly polarized incident and scattered photons. The threshold laser beam intensity in the laboratory frame is

$$I_c = I_{c0}(\epsilon_i/\epsilon_{i0})^2. \tag{7}$$

For the known values of ϵ_i, n, φ one obtains I_c from (6) and (7), whose order of magnitude for $\epsilon_i \approx 0.1$ eV, $N = 2$, and $\theta_i \approx 25°–30°$ is $I_c \approx 10^{17}$ W/cm^2, and for $\epsilon_i \approx 1$ eV, $I_c \approx 10^{19}$ W/cm^2. The order of magnitude of the energy content of the laser pulse at a pulse width of 0.1–1 ps is 1–10 J. At lower electron energies $E < 10$ MeV the scattered photons will have appropriately lower energies that require, on the other hand, lower incident-laser-beam intensities. At $K = 1$ in (5) the transition probability per unit time becomes

$$P' = \frac{4\pi^2}{h} |M|^2 \rho_F, \tag{8}$$

where M is the transition matrix element and ρ_F the density of final energy states. The classical nonrelativistic theory of the interaction Hamiltonian, to which M is related, consists of two parts,

$$H_{\text{int}} = -e(\vec{p}\cdot\vec{A})/E_0 + e^2 A^2/2E_0, \tag{9}$$

where the first term, proportional to the vector potential $\vec{A}$ and the electron momentum vector $\vec{p}$, corresponds to one-photon absorption, while the second term corresponds to two-photon absorption. e is the charge of the electron. In the framework of quantum electrodynamics one-photon absorption has a differential cross section from (8),

$$\frac{d\sigma_{10}}{d\Omega_{e0}} = 16\pi r_0 h c E_0 \epsilon_{i0}^{-2} \cos^2\beta_{e0}, \tag{10}$$

where β_e is the electron-scattering angle relative to the polarization vector of the incident photons and Ω_e the solid angle into which the electron scatters. For $\epsilon_i \approx 1$ eV, $\theta_i \approx 25°$,

$$\frac{d\sigma_{10}}{d\Omega_{e0}} \approx 1 \times 10^{-11} \ \text{cm}^2/\text{sr}.$$

Two-photon absorption has a differential cross section from (8),

$$\frac{d\sigma_{20}}{d\Omega_{e0}} = 8 r_0^2 h^3 c^2 E_0 \epsilon_{i0}^{-4} \cos^2\varphi_0, \tag{11}$$

where φ is the angle between the polarization vectors of the two absorbed photons. For a linearly polarized beam with parallely moving photons $\cos^2\varphi_0=1$. For $\epsilon_i\approx 1$ eV, $\theta_i\approx 25°$,

$$\frac{d\sigma_{20}}{d\Omega_{e0}}\approx 2\times 10^{-42}\ \text{cm}^4\text{s/sr}.$$

Comparing the transition probabilities for one-photon and two-photon absorption, the latter becomes higher than the former at laser beam intensities $I_i>10^{12}$ W/cm^2. Thus we shall calculate with P'_{20}.

The intensity of the forward scattered radiation ($\theta_f=\theta_{f0}=0$) is given by

$$I_{s0}=\frac{d\sigma_{20}}{d\Omega_{e0}}\,\Delta\Omega_{e0}I_{i0}^2\epsilon_{i0}^{-1}nn_{e0}L_0, \tag{12}$$

where n_e is the density of electrons in the interaction region, L the interaction length, and $\Delta\Omega_e$ the solid angle into which the electron scatters at photon absorption, $\Delta\Omega_e\approx(\epsilon_i/E)^2$. With 10^7 electrons in the interaction volume or ≈ 1 A current pulse of ≈ 1 ps duration the intensity of the generated soft-x-ray radiation in the laboratory frame is $I_s\approx 10^{12}$ W/cm^2. The electron energy conversion efficiency reaches 10%.

The most convenient accelerators for soft-x-ray generation are betatrons. The newer ones [15] produce >1 kA currents with the help of which soft-x-ray pulse energies of 1 mJ can be obtained. As the energy spread of the electrons does not exceed 0.5–1%, the spectral width of the radiation, on similar grounds as in [3], remains within this value. Figure 2 shows a typical schematic arrangement of soft-x-ray pulse generation, based on the considerations described in this work.

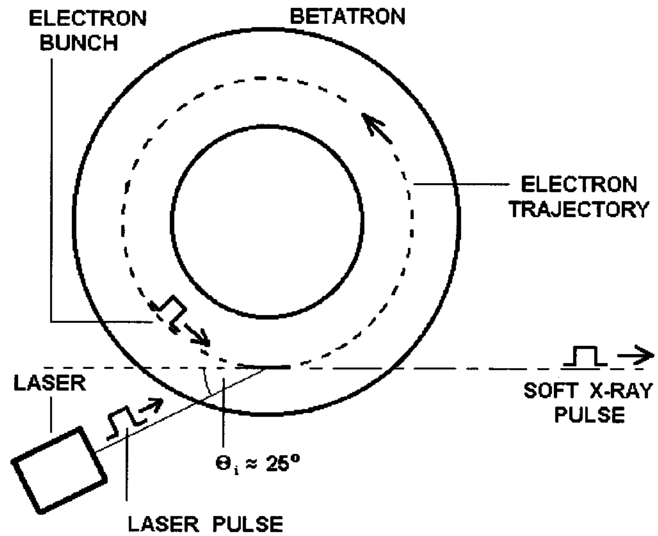

FIG. 2. Schematic diagram of soft-x-ray pulse generation by laser-pulse scattering from a fast electron bunch.

In conclusion, the analysis of multiphoton–free-electron interaction processes shows that simultaneous photon absorption and multiphoton scattering from 10–12 MeV free electrons of 1-A current pulses of 1-ps duration produces 10^{12} W/cm^2 soft-x-ray radiation at well defined above-threshold incident-laser-beam intensities.

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