Section
Signal Processing, Systems Simulation and Complex objects control for Space Applications

AN INFLUENCE OF STRONG PULSED LASER FIELDS ON THE RESONANT PROCESSES OF QUANTUM ELECTRODYNAMICS

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Abstract: The review on the quantum electrodynamics (QED) processes proceeding in strong pulsed light fields, realized in modern powerful pulsed lasers is presented. Resonant processes of quantum electrodynamics in strong laser fields are considered. Following QED processes in the pulsed laser field are considered: resonant scattering of ultrarelativistic electrons, resonance of exchange amplitude of a photon by an electron. The resonant peak altitude and width are defined by the external pulsed wave properties. It is demonstrated that the resonant cross sections may be several orders of magnitude greater than the corresponding cross sections in the absence of an external field.

Introduction

Use of a powerful coherent light source in modern applied and fundamental research has stimulated study of the external strong field influence on quantum electrodynamics (QED) processes [1–2]. A characteristic feature of electrodynamics processes of second order in the fine-structure constant in laser fields is associated with the fact that such processes may occur under both coherent and resonant conditions [1–9]. The resonant character relates to the fact that lower-order processes, such as spontaneous emission and one-photon creation and annihilation of electron-positron pairs, may be allowed in the field of a light wave. Therefore, within a certain range of energy and momentum, a particle in an intermediate state may fall within the mass shell. Then the considered higher-order process is effectively reduced to two sequential lower-order processes [1–9]. The appearance of resonances in a laser field is one of the fundamental problems of QED in strong fields.

As a result of laser technology development, different types of coherent light sources have become available, with intensities that have increased up to $10^{24}\,\mathrm{W/cm^2}$ in recent years. The new experimental conditions have required constant improvements in calculations and model development. The amplitude of the field intensity of powerful ultra-short pulsed lasers changes greatly in space and time. In the description of QED processes in the presence of a pulsed laser the external field is usually modeled as a plane non-monochromatic wave, when a characteristic pulse width τ obeys the condition [1–9]

$$\omega\tau \gg 1. \tag{1}$$

There are two characteristic parameters in these processes of QED in the field of a pulsed electromagnetic wave. The first one is the classical relativistic-invariant parameter [1–9],

$$\eta_0 = \frac{eF_0\lambdabar}{mc^2}, \tag{2}$$

which in the pulse peak equals numerically to the ratio of work done by the field within the distance equal to a wavelength to the electron rest energy (e and m are the charge and the mass of an electron, F_0 and $\lambdabar = c/\omega$ are the strength and the wave-length of an electric field in the pulse peak respectively). The Bunkin-Fedorov quantum parameter is specified [1–9]:

$$\gamma_i = \eta_0 \frac{mv_i c}{\hbar\omega}. \tag{3}$$

(v_i is the electron speed). We treat these problems of QED within the range of moderate-strong-field intensities, when

$$\eta_0 \ll 1, \quad \gamma_i \gtrsim 1. \tag{4}$$

Consequently, the quantum Bunkin-Fedorov parameter is the main parameter which determines multiphoton processes. Hereafter, we use the relativistic system of units $\hbar = c = 1$.

Resonant scattering of ultrarelativistic electrons in the strong field of a pulsed laser wave

Here we describe the resonant scattering of ultrarelativistic electrons at small ingoing–outgoing angles in a strong pulsed laser field. It is well known that it is precisely the case of small-angle scattering that makes the largest contribution to the cross section for the ultrarelativistic energy of particles. (see Fig.1) [6].

We study the scattering of an electron with the four-momentum $p_{1i,1f} = \left(E_{1i,1f}, \mathbf{p}_{1i,1f}\right)$ by an electron with the four-momentum $p_{2i,2f} = \left(E_{2i,2f}, \mathbf{p}_{2i,2f}\right)$ in the case of ultrarelativistic energy and small angles in a field of a pulsed laser wave. In the center-of-mass frame we have

$$1 \ll E_i / m \ll m / \omega, \quad E_i \approx \left|\mathbf{p}_i\right|, \tag{5}$$

$$\theta_{i,f} = \angle\left(\mathbf{e}_z, \mathbf{p}_{i,f}\right) \ll 1. \quad \delta_{i,f} = \theta_{i,f}\left(E_{i,f} / m\right) \tag{6}$$

Here m is the electron mass; $\theta_{i,f}$ are the incoming and outgoing polar angles of electrons; $\delta_{i,f}$ are the characteristic parameters appearing in the scattering of ultrarelativistic articles.

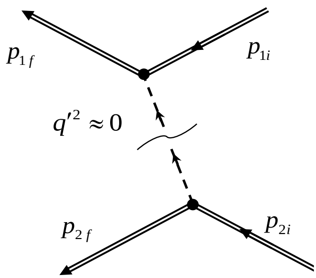

Fig. 1. The direct Feynman diagram of resonant scattering of an electron by an electron in the field of a pulsed laser wave.

The external pulsed field is taken into account accurately. We consider the field of a pulsed laser wave as a plane non-monochromatic wave, propagating along the z-axis with a polarization plane xy. The four-potential of such a field has the form

$$A(\varphi)=g\left(\frac{\varphi}{\omega\tau}\right)\frac{F_0}{\omega}\left(e_x\cos\varphi+\delta_{\text{ell}}e_y\sin\varphi\right), \tag{7}$$

$$\varphi=kx=\omega(t-z). \tag{8}$$

Here, φ is the wave phase; τ is the characteristic duration of a laser pulse; F_0 is the strength amplitude of the electric field in the pulse peak; ω is the characteristic frequency of the laser wave; $k=(\omega,\mathbf{k})$ is the wave vector; δ_{ell} is the wave ellipticity parameter ($\delta_{\text{ell}}=0$ corresponds to the linear polarization, $\delta_{\text{ell}}=\pm 1$ corresponds to the circular polarization); $e_x=(0,\mathbf{e}_x)$, $e_y=(0,\mathbf{e}_y)$ are the four- vectors of wave polarization. The function $g(\varphi/\omega\tau)$ in (7) is the envelope function of the four- potential of an external wave that allows to take into account the pulsed character of a laser field.

The process is studied in the frame of the quasimonochromatic approximation when a laser wave performs a lot of amplitude oscillation, i.e. the following condition is met:

$$\omega\tau\gg 1. \tag{9}$$

The condition (9) is satisfied for the majority of modern lasers [1–2]. The given paper is devoted to studying of the strong field case, when

$$\eta_0>>1,\quad \eta_0 m/E_i\gtrsim 1 \tag{10}$$

The suitable laser fields depend on the energy of ultrarelativistic electrons $\left(\gtrsim 10^{19}\,W/\text{cm}^2\right)$. The fields with such intensity are accessible for modern laser facilities functioning in the pulsed regime [1]. The condition of Oleinik resonance assumes the form [2–8]:

$$q'^2\lesssim\frac{(kq')}{\omega\tau}\ll\omega^2. \tag{11}$$

The resonant scattering angle for the fields with great intensity and small incoming angles in the ultrarelativistic case can be expressed as:

$$\theta_{\mathrm{res}} = \left(l + 2|r|\right)\frac{\omega m}{E_i^2}\delta_i \,. \tag{12}$$

The resonant cross section of laser-assisted Möller scattering into the element of the solid angle is obtained in the form:

$$\frac{d\sigma_{\mathrm{res}}}{d\Omega_f} = \frac{r_e^2 m^2}{E_i^2 \theta_{\mathrm{res}}^4}\left(\frac{\eta_0 m}{E_i}\right)^4 \frac{(\omega\tau)^2}{8}\left(1+\delta_{\mathrm{ell}}^2\right)^2 \sqrt{\frac{\pi}{2}}\cdot P_{\mathrm{res}} \,, \tag{13}$$

$$\begin{aligned} P_{\mathrm{res}} &= \frac{1}{2\rho}\int\limits_{-\rho}^{\rho} d\phi_1 \exp\left(-\phi_1^2\right)\left(1 - \mathrm{erf}\left(\sqrt{2}\phi_1\right)\right) \\ &\times \int\limits_{-\rho}^{\phi_1} d\phi_1' \exp\left(-\phi_1'^2\right)\cos\left(2\beta\left(\phi_1 - \phi_1'\right)\right). \end{aligned} \tag{14}$$

Here β is the resonant parameter, which determines the nature of electron-electron scattering in the field of a pulsed light wave:

$$\beta = \frac{q'^2}{4(kq')}\omega\tau \approx \frac{\omega\tau}{2}\left(\frac{\theta}{\theta_{\mathrm{res}}} - 1\right). \tag{15}$$

We are interested in estimation of the ratio of the resonant cross section of ultrarelativistic electrons in the field of a strong pulsed laser wave to the corresponding cross section in an external field absence. This ratio has the form

$$\frac{d\sigma_{\mathrm{res}}}{d\sigma_{Moller}} = \left(\frac{\eta_0 m}{E_i}\right)^4 (\omega\tau)^2 \left(1+\delta_{\mathrm{ell}}^2\right)^2 \frac{\pi^2}{72\rho} \tag{16}$$

For further study we consider the case of the frontal collision in scattering of ultrarelativistic electrons with equal energy. Consequently, the c. m. system coincides with the laboratory reference system. The laser wave at that, according to the problem statement, propagates under the small angle to the collision axis. We also consider the external wave circular polarization. Let us carry out analysis of the cross section of resonant scattering for several laser systems (see, the Table I). We note that laser systems PHELIX and Vulcan concern to the class of petawatt optical lasers generating within the sub-picoseconds range of duration [1]. Laser systems Vulcan and ELI because of their parameters will concern to multipetawatt lasers generating within the femtosecond range. The basic characteristics of the laser systems are provided in the Table I. Figure 2 represents the ratio of the resonant scattering of electrons in the strong laser field to the cross section of electron scattering in an external field absence as a function of the initial energy in the units of the electron rest energy for concrete laser systems (see, Table I). One can conclude from (16) and Figure 2 that the dependence of the cross sections ratio on the electron initial energy is linear for logarithmic scales. Thus, for both electron MeV-energy and petawatt optical lasers the ratio of the resonant cross section of electron-electron scattering in the field of a strong pulsed laser and the cross section in an external field absence amounts to 5-6 orders of the magnitude. In the same case for multipetawatt lasers within the femtosecond range the ratio (16) may reach 8-9 orders of the magnitude. The resonant cross section becomes of the same order with the Moller cross section for the electron energy of the order 102 MeV for the 1PW range of laser field intensity, and for the electron energy up to 1 GeV in the case of the multupetawatt range.

Table 1. The basic characteristics of the modern laser systems.

Laser system	Pulse duration, ($\omega\tau$)	Peak intensity, (η_0)
PHELIX	500 fs (900)	$2\cdot10^{20}$ W/cm^2 (9)
Vulcan	500 fs (900)	10^{21} W/cm^2 (20)
Vulcan 10	30 fs (60)	10^{23} W/cm^2 (170)
ELT	15 fs (35)	10^{24} W/cm^2 (500)

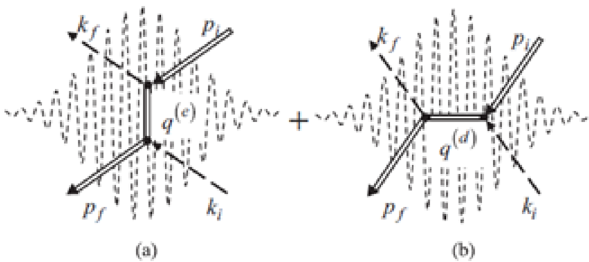

Fig. 2. The ratio of the resonant cross section of scattering of an electron by an electron in the strong pulsed laser field to the cross section of electron-electron scattering in an external field absence as a function of the initial energy for concrete laser systems (Table I).

The obtained results can be verified experimentally on the said facilities with using of highly monochromatic beams of electrons and detectors with high angular resolution.

Resonance of exchange amplitude of a photon by an electron scattering in the pulsed laser

Here we study of laser-modified Compton scattering (see [7], Fig.3). We consider the external field as a circularly polarized pulsed electromagnetic wave, propagating along the *z*-axis with a polarization plane *xy*. The four potential of such a field has the form (7) and (9).

We search for the resonance probability of the exchange diagram using the resonance approximation $\left(q^{(e)}\right)^2 \approx m^2$. The ratio of the differential resonance probability of the scattering of the photon by electron via exchange diagram and to the differential probability of the Compton effect in the absence of the external field in the same scattering kinematics is

$$R^{(\mp)} = \frac{\mathrm{dW}_{\mathrm{res}}^{(\mp)}}{d\mathrm{w}_{\mathrm{Compt}}} = \frac{16}{\left(u_1^{(\mp)}\right)^2} \frac{K^{(\mp)}}{f\left(\tilde{u}', \tilde{u}_1\right)} \cdot \eta^4 \varphi_0^2 \frac{\tau_{\mathrm{imp}}}{T} P_{\mathrm{res}}\left(\beta_i^{(\mp)}\right), \qquad (17)$$

$$P_{\mathrm{res}}\left(\beta_{\mp}\right) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left| I_1(\beta_{\mp}, l_*) \right|^2 d\left(\varphi_0 l_*\right), \qquad (18)$$

Analysis of laser-modified Compton scattering through the exchange diagram has demonstrated the following. The resonant probability of the Compton scattering in the field of the weak intensity wave may exceed the corresponding probability in the external field absence in several orders of the magnitude. Thus, for the electron energy $E_i = 5\mathrm{MeV}$, the photon frequency $\omega_i = 11.7\ \mathrm{eV}$, the intensity in the pulse peak $I = 7 \times 10^{16}\ \mathrm{Wcm}^{-2}$, and arbitrary angles of the entrance of both electron and photon, the ratio $R^{(-)}$ amounts to seven orders of the magnitude. The excess of the resonant probability of the Compton effect for the case of ultrarelativistic energy of the electron moving in the narrow cone with the direction of the external wave propagating, may amount to ten orders of the magnitude.

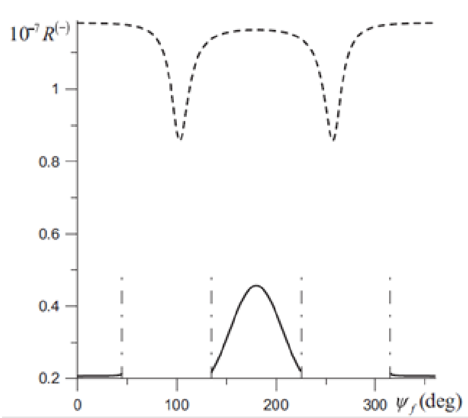

Fig. 3. Feynman diagram for the Compton effect in the field of the pulsed light wave for the direct (a) and exchange (b) parts. Incoming and outgoing double lines correspond to the Volkov function of an electron in initial and final states, and the dashed lines represents the wave function of a photon; inner lines designate the Green's function of an electron in the pulsed field.

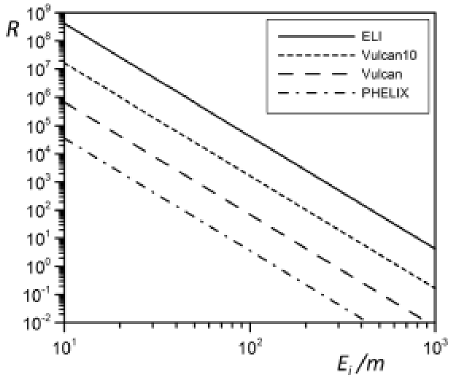

Fig. 4. The ratio (17) of the resonant probability of scattering of the photon by an electron in the field of the pulsed wave ($I = 7\times10^{16}$ Wcm^{-2}, τ/T = 1, ω = 2.35 eV) in the resonant peak $\beta\pm = 0$ to the probability of the Compton scattering, when the external field influence is absent, as a function of the photon output azimuthal angle ψ_f . The dashed line corresponds to the photon entrance angle $\theta_i = 130^\circ$ and the solid line corresponds to the case $\theta_i = 164^\circ$, $E_i = 5\text{MeV}$, $\omega_i = 11.7$ eV .

Conclusions

In review the resonant QED processes in strong pulsed laser field are considered. Significant influence of a pulsed field on the processes was shown.

The obtained results may be experimentally verified, for example, by the scientific facilities at the SLAC National Accelerator Laboratory and FAIR (Facility for Antiproton and Ion Research, Darmstadt, Germany).

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