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Generation of short gamma-ray pulses on electron bunches formed in intense interfering laser beams with tilted fronts

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Abstract. **It is shown that in the interference of multiple laser pulses with a relativistic intensity, phase and amplitude fronts of which are tilted at an angle with respect to their wave vector, effective traps of charged particles, which are moving at the velocity of light, are formed. Such traps are capable of capturing and accelerating the electrons produced in the ionisation of low-density gas by means of laser radiation. The accelerated electrons in the traps form a bunch, whose dimensions in all directions are much smaller than the laser radiation wavelength. Calculations show that the energy of accelerated electrons may amount to several hundred GeV at experimentally accessible relativistic laser intensities. As a result of the inverse Compton scattering, gamma-quanta with a high energy and narrow radiation pattern are emitted when these electrons interact with a laser pulse propagating from the opposite direction. The duration of emitted gamma-ray pulses constitutes a few attoseconds. The simulation is performed by solving the relativistic equation of motion for an electron with a relevant Lorentz force.**

Keywords: *relativistic laser pulse intensity, acceleration of electrons, inverse Compton effect, gamma radiation.*

1. Introduction

Theoretical and experimental studies on the mechanisms of gamma-quanta generation are one of the most important areas of modern physics. Currently, different approaches are applied to produce bunches of gamma-quanta, such as the use of the long-lived nuclear isomers as an active medium with hidden population inversion, nuclear reactions leading to the excitation of the final nucleus and bremsstrahlung from electron accelerators. To generate gamma-quanta, the superstrong laser pulses are also used, which produce high-energy electrons in interactions with solid targets. In the process of scattering of these electrons on the target nuclei, a bremsstrahlung occurs and gamma-quanta are emitted. However, this mechanism is characterised by relatively small energies of the emitted gamma-quanta and a significant dependence on the laser pulse parameters. An overview of the mechanisms of the gamma-quanta generation is presented in [1].

Currently, none of these methods allows one to obtain the bunches of coherent gamma-quanta with high energy. For efficient generation of gamma radiation using electron beams, the particles accelerated to high energy with a small energy spread are required, while the angular spread of the electron pulse should be small enough to ensure a small angular divergence of the relevant photon beam.

To develop the methods for producing high-energy gamma beams, the use of the effect of the inverse Compton scattering of laser photons on accelerated electron bunches seems very promising. As a result of such scattering, quasi-monochromatic gamma-quanta with high energy and small angular divergence can be generated.

In this paper, we propose a scheme for generating short gamma-ray pulses, based on the effect of inverse Compton scattering of laser photons on accelerated electron bunches. Such bunches are formed when electrons are exposed to the action of the laser fields of special configuration with tilted fronts. Electrons in these bunches have a narrow radiation pattern, while spatial dimensions of the bunches are significantly smaller than the laser radiation wavelength. Preliminary results of calculations of the generation of partially coherent gamma-quanta were presented in [2].

The use of the multiple interfering laser pulses with tilted fronts and strongly elongated focal spots of different sizes in two dimensions can provide the formation of accelerated electron bunches with the energy and spatial parameters that are required for efficient generation of gamma-quanta [3, 4]. The essence of the approach is the use of the laser pulses to directly accelerate the electrons that are injected or have arisen from the ionisation of a low-density gaseous target. The electromagnetic field compresses the electron beam in spatial coordinates down to the size being smaller than the optical field wavelength. Herewith a higher level of compression is achieved than, for example, when the electrons are accelerated in the wake field [5, 6]. Similar to the previous works [3, 4], the dynamics of electrons in this work is modelled by solving the relativistic Newton equation with the Lorentz force in the right-hand side.

2. A scheme of formation of accelerated electron bunches and gamma-quanta generation

Calculations of the electron dynamics and the gamma-quanta generation are performed for the scheme, which uses five interfering laser pulses (Figs 1a and b) and the sixth pulse propagating toward the accelerated electron bunch (Fig. 1c). Five linearly polarised laser pulses are employed to form a trap for the charged particles that travel at the velocity of

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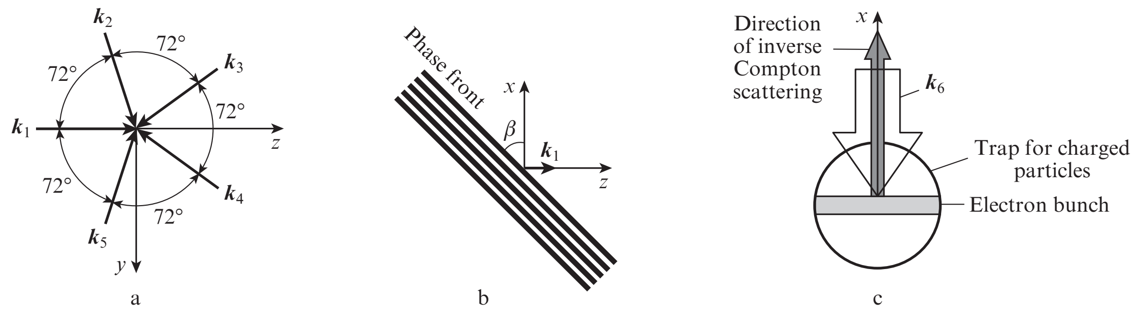

Figure 1. (a) Scheme of summation of laser pulses with the wave vectors $\boldsymbol{k}_1 - \boldsymbol{k}_5$ in the yz plane, (b) the image of the tilted phase front of one of the laser pulses and (c) scheme of inverse Compton scattering of the laser pulse with the wave vector $\boldsymbol{k}_6$ on an electron bunch in the trap.

light c in a certain direction. Such traps capture, accelerate and hold the electrons which form the compressed bunches.

To ensure efficient acceleration of charged particles, the parameters of each of the interfering laser pulses are selected in such a way that the trap moves with the velocity c. This can be achieved by using the beams whose amplitude and phase fronts are tilted relative to the relevant planes that are perpendicular to the wave vectors (the sloping occurs, for example, at the oblique incidence of the laser radiation onto a diffraction grating [7]). Thus, the laser pulse propagates in the direction which differs from the normal to the wave front. The angle between the wave vector of each pulse and its amplitude and phase fronts should be selected to ensure the trap velocity equal to c (the angle between the pulse fronts and the plane perpendicular to its wave vector is denoted as β in Fig. 1b).

It is assumed that one of the five laser pulses that are used to accelerate the electrons propagates along the z axis in the coordinate system selected. The angles in the yz plane between the wave vectors of the five interfering pulses constitute 72° (Fig. 1a). These pulses intersect each other at the origin of the coordinate system. The wave vectors of the laser pulses can be inclined at some angle to the z axis in the xz plane. Let α be the angle between the wave vector of the pulse and the z axis in this plane. Then, for the traps of charged particles moving along the x axis at the velocity c, the relationship $\beta = \alpha/2 + \pi/4$ should be met.

In the interference of the fields of laser pulses characterised by the parameters mentioned above, optical traps of charged particles are formed, which travel at the velocity of light along the x axis in the coordinate system selected. The number of traps (in the row along the x axis) depends on the laser pulse duration. The electromagnetic field gains its maximum in the central traps of the thus formed series. The resulting electric field that accelerates the particles is directed along the x axis in the trap. The electric field strength in the neighbouring traps represents an alternating value. The magnetic field strength in the trap centre is close to zero, while it is maximal at the boundaries between the traps. The magnetic field holds the particles in a transverse direction relative to the x axis from the trap centre. In the case when the acceleration scheme of charged particle employs a large number of laser beams, the magnetic field may be rather close to an axisymmetric one.

Under the action of the fields of interfering laser pulses, the charged particles with different initial positions are shifted to the x axis where the magnetic field is close to zero. The electric field in the trap accelerates the entrapped charged particles along the x axis, while the magnetic field holds the particles that deviate from the x axis in the transverse direction. The traps successively catch the particles with different initial displacements directed both along the x axis and perpendicularly to it. Note that the particles that have initially been displaced in the negative direction of the x axis are accelerated more efficiently due to a greater acceleration length. Owing to the fields having the configuration described above, the electron beam is compressed in all spatial coordinates, and all captured electrons are accelerated to approximately the same kinetic energy.

Due to the fact that the field intensity in the first traps moving along the x axis is small and thus insufficient for acceleration and capture of the particles, the particles slip past these traps. The field strength in the succeeding traps is significantly greater, and the particles are accelerated to high velocities in the direction of the trap motion. At the same time, the electrons do not fall into the traps with maximum potential since their velocity in the traps with a somewhat lesser intensity approaches the velocity of light c with which the traps travel.

When the accelerated electron bunch interacts with the laser field coming from the opposite direction with the amplitude and phase fronts not tilted, the inverse Compton scattering occurs (Fig. 1c). The generated short pulses propagate along the x axis.

3. Equations of motion

In the laser radiation field, an electron is subjected to the action of the high-frequency Lorentz force, and the equation of motion has the form

$$\frac{d\boldsymbol{p}}{dt} = -e\boldsymbol{E} - \frac{e}{c}[\boldsymbol{v}\boldsymbol{H}], \quad (1)$$

where $\boldsymbol{p}$, $\boldsymbol{v}$, $\boldsymbol{E}$, and $\boldsymbol{H}$ are the particle momentum and velocity, and electric and magnetic field intensities, respectively; and $e > 0$ is the absolute charge of the electron. Equation (1) is supplemented by the necessary initial conditions for the position and velocity of an electron and is used to calculate its motion in the field of interfering laser pulses.

The calculations were performed for the linearly polarised beams with plane phase fronts, the field distribution of which depends on the transverse coordinates. The structure of electromagnetic fields for such beams was studied in [8].

The expression for the x-component of the electric field of the beam with two different transverse dimensions, propagating along the z axis in the coordinate system selected (with the fronts not tilted), has the form

$$E_x = E_0(x, y, \xi)\cos\varphi, \quad (2)$$

where $\xi = t - z/c$; $\varphi = (2\pi c\xi/\lambda - \varphi_0)$ is the phase; φ_0 is the initial phase. The field amplitude is

$$E_0(x,y,\xi) = E_m \exp\{-[(\xi - z_d/c)/\tau]^{2s} - (x/\rho_{\|})^{2n} - (y/\rho_{\perp})^{2n}\}, \quad (3)$$

where E_m is the maximum field strength; z_d is the initial momentum shift relative to the position of the electron, which provides a smooth switching of the field in the numerical solution; τ is the pulse duration; and $\rho_{\|}$ and $\rho_{\perp}$ are the transverse dimensions of the beam. The parameters s and n identify, respectively, the temporal pulse shape and its cross section. In case that the laser beam fronts are different from a plane, the electric field component along the direction of the wave vector is taken into account in the structure of the electromagnetic fields. In the scheme described above, as a result of the interaction with the field of the interfering laser pulses, electrons are shifted to the x axis, near which the field components of several laser beams are compensated. Thus, the electric field component along the direction of the wave vector turns out small.

The beam intensity is given by

$$I = \frac{c}{4\pi}\left|\overline{[\boldsymbol{E}(x,y,z,t)\boldsymbol{H}(x,y,z,t)]}\right|, \quad (4)$$

where averaging is performed with respect to high frequency. For each beam, the dimensionless intensity I_m/I_{rel} is used, where I_m is the maximum intensity of the beam and the relativistic intensity I_{rel} is given by [9]

$$I_{rel} = m^2c^3\omega^2/(8\pi e^2) = 1.37\times10^{18}\lambda^{-2}, \quad (5)$$

where I_{rel} is taken in W cm^{-2}, and λ – in micrometers.

For a laser beam with a tilted amplitude and phase fronts, the expressions for the fields are obtained by introducing a dependence of the parameter ξ on β: $\xi = t - (z + x\tan\beta)/c$. In case of a deviation of the beam from the z axis at an arbitrary angle both in the xz and yz planes, the expressions for the fields can be easily derived from (2) and (3) by means of the coordinate system transformation.

The results of calculations of the electron dynamics are presented below in the basic coordinate system for which expressions (2) and (3) have been obtained.

4. Dynamics of an electron in the field of multiple interfering laser

The transverse dimensions at the waist for each of the five interfering beams are different. It is of profound interest to analyse the dependence of the output energy of the electrons on the acceleration length, in other words, on the value $\rho_{\|}$, under condition that the total energy of the laser radiation of the interfering beams is preserved. The calculations have shown that the most efficient particle acceleration is achieved with increasing $\rho_{\|}$, despite the fact that the intensity of the accelerating electric field in the traps decreases. The calculations assume that the amplitude and phase fronts are tilted by the angle $\beta = 45°$ to the plane perpendicular to the wave vector; this ensures the velocity c for the motion of the arising traps.

The coordinates, velocities, accelerations, as well as the trajectories and other parameters of the dynamics of an electron have been determined by numerical solution of equation (1). These calculations were performed for the ultrashort pulses with super-Gaussian temporal and transverse profiles. It is assumed that the pulses are focused so that the transverse dimensions of the beam are $\rho_{\|}/\lambda = 20000$ and $\rho_{\perp}/\lambda = 2.5$.

Calculations show that the motion of electrons in the field of several interfering laser pulses can be separated into two stages. In the first stage, the electrons rapidly move into the region immediately adjacent to the x axis. In a small vicinity around the x axis, the field action of the laser pulses becomes almost symmetrical with respect to this axis. In the second stage, the electrons fall into the trap formed by the interference of laser pulses with tilted fronts and move along a nearly straight trajectory along the x axis at a velocity very close to the velocity of light c. The electrons with different initial positions successively fall into this trap. The length of the trap along the x axis is $\sim 2\rho_{\|}\cos\beta$. The accelerated electrons are concentrated in a small area belonging to one of the traps and form a bunch. At relativistic laser intensities in the case of $I_m/I_{rel} = 6$ and $\rho_{\|} \sim 10^4\lambda$ the size of the accelerated bunch along the x axis amounts to $\sim 10^{-3}\lambda$. The electrons captured by the trap slightly oscillate along the z and y axes symmetrically with respect to the x axis (Fig. 2a). The displacement of the electrons along the x axis in the course of their interaction with laser pulses considerably exceeds the oscillation amplitude of the electrons along the z and y axes (the oscillation amplitudes along these directions constitute a few hundredths of the wavelength). The magnetic field of the trap returns the deviating electrons to the x axis. As a result, the electron beam is compressed along the z and y axes. The cross-sectional size of the arising electron bunch does not exceed $\sim 10^{-2}\lambda$ along these axes.

The kinetic energy of an electron smoothly increases in the course of acceleration and attains its maximum when the interaction of electrons with the laser pulses ends (Fig. 2b). At the relativistic intensity $\sim 10^{18}$ W cm^{-2} of the laser radia-

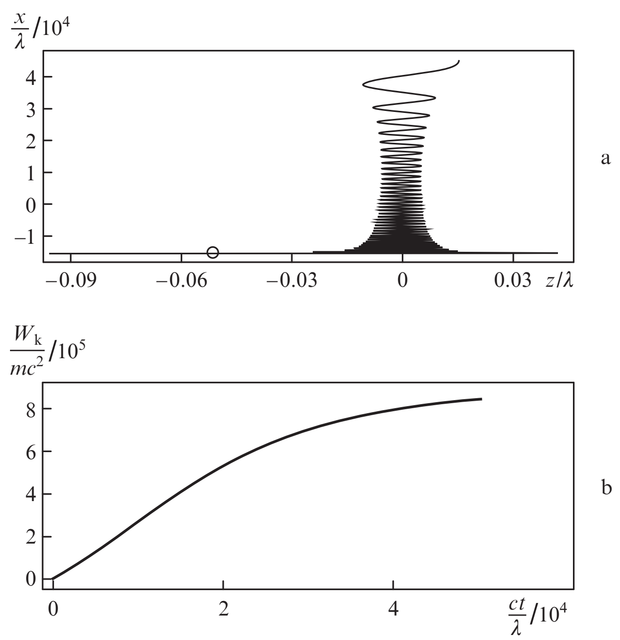

Figure 2. (a) Two-dimensional trajectory of electron motion in the dimensionless coordinates z/λ, x/λ and (b) temporal dependence of the kinetic energy $W_k/(mc^2)$ for $\beta = 45°$. The laser pulse parameters: $s = 2$, $c\tau/\lambda = 20000$, $\rho_{\perp}/\lambda = 2.5$, $I_m/I_{rel} = 6$, total energy of 30 J. Initial coordinates of the electron (shown by a circle in Fig. 2a): $x_0/\lambda = -15000$, $y_0/\lambda = 0.1$, $z_0/\lambda = -0.05$.

tion and the longitudinal size $\sim 10^4\lambda$ of the laser beam in the caustic, the kinetic energy gained by the electrons amounts to 440 GeV at the total energy 30 J of all laser beams.

The initial displacements of charged particles that can be captured by the traps may achieve $\sim\rho_{\parallel}$ and $\sim\rho_{\perp}$ along the x and y axes, respectively. At the difference of 1000λ in initial displacement of electrons along the x axis, the energies gained differ by no more than 2%. The electrons gather in a bunch of the volume of $10^{-7}\lambda^3$ from the region with the cross-sectional sizes of $\sim\lambda$ and the length of $\sim 10^3\lambda$ (the length at which the electron bunch under formation remains monoenergetic). At the initial electron concentration of 10^{15} cm^{-3} in the ionised gaseous target, the concentration of electrons in the bunch may exceed the original one by the factor of 10^{10}, while the concentration of 10^{25} cm^{-3} exceeds the critical value for the Ti:sapphire laser. It is known that, if the concentration of charged particles in the bunch exceeds the critical value, the field can penetrate to a distance of $\sim\lambda/2$. The dimensions of the generated electron bunches do not exceed $\sim 10^{-2}\lambda$. Thus, all electrons of the bunch interact with the field of interfering laser pulses.

The electric field strength in which the electron moves reaches 18 TV m^{-1} on the acceleration length of 3 cm, which is about 200 times greater than the accelerating field strength in the wake field [10] and 10^5 times greater than the intensity of the accelerating field in traditional accelerators. It should be noted that the acceleration of electrons to the energy of $\sim$1 TeV is possible on the acceleration length of less than 5 cm in the scheme proposed, while the size of the traditional accelerator facilities must be tens of kilometres to accelerate the electrons to comparable energies.

The estimates of the Coulomb interaction effect between electrons show that even in the case of their solid-state concentration in the bunch arising in the field of interfering pulses, the force with which the laser field acts on the electrons considerably exceeds the force of Coulomb interaction between them at the laser pulse intensity of $\sim 10^{18}$ W cm^{-2}. The electron concentration in the bunch formed does not exceed 10^{25} cm^{-3}. At the mentioned sizes of the bunch, the value of the electron density and the laser radiation parameters used in the calculations, all the electrons comprising the bunch continue to interact with the interfering laser pulses.

5. Generation of short gamma-ray pulses

The dynamics of electrons accelerated by means of the method described above can be characterised as follows: the trajectory of each electron of the arising bunch is close to a straight line, the velocity of each electron is close to the velocity of light c and the longitudinal size of the electron bunch does not exceed the laser radiation wavelength. The attainment of these conditions leads to the fact that the interaction of the compressed electron bunch with the laser pulse coming from the opposite direction results in generation of gamma radiation with a small angular divergence and pulse duration which is much shorter than the laser pulse duration. At the moment of the gamma-quanta generation, the probability of electron collision with another particle is small due to the inverse Compton scattering.

The expression for the energy of the generated gamma-quanta E_γ (easily obtained from [11]) has the form

$$E_\gamma = E_{\rm las}\frac{1-(v/c)\cos\theta}{1-(v/c)\cos(\theta-\phi)+(E_{\rm las}/E_{\rm e})(1-\cos\phi)}, \qquad (6)$$

where $E_{\rm e}$ is the energy of the accelerated electrons; $E_{\rm las}$ is the energy of the primary photons; v is the electron velocity; θ is the angle between the propagation directions of the photons and electron beam; and ϕ is the angle between the propagation directions of the primary and scattered photons.

As follows from the expressions for the angular distribution (see, for example, [12]), in the event of a frontal collision, when $\theta = \pi$, the generated gamma-quanta propagate in the direction of the electron beam, the angular divergence being found from the expression $\Delta\phi \approx mc^2/E_\gamma$. In the process of inverse Compton scattering of photons by relativistic electrons, a significant loss of the electron energy of occurs. In the proposed scheme, the energy of gamma-quanta is close to the kinetic energy of electrons: $E_\gamma \approx E_{\rm e}$. Since in the case considered the electron energy is 440 GeV, the divergence amounts to $\Delta\phi \approx 1.2\times10^{-6}$ rad.

According to [11], the expression for the Compton scattering cross section can be presented as

$$\sigma = (3/4)\sigma_{\rm T}\zeta^{-1}(\ln\zeta + 1/2), \qquad (7)$$

where $\zeta = [2h\nu/(mc^2)]\gamma[1-(v/c)\cos\theta]$; $\sigma_{\rm T} = (8\pi/3)[e^2/(mc^2)] = 6.65\times10^{-25}$ cm^2 is the scattering cross section; $\gamma = E_{\rm e}/(mc^2)$; and ν is the radiation frequency before scattering. In the scattering of photons on ultra-relativistic electrons ($\zeta \gg 1$), the Compton scattering cross section is close to the Thomson scattering cross section ($\sigma \approx \sigma_{\rm T}$), in other words, classical Thomson scattering takes place in the electron rest frame [11]. For the laser radiation parameter used in the calculations, ensuring the formation of the electron bunch accelerated to a high energy, and in case of the laser pulse of relativistic intensity propagating towards the accelerated electron bunches, 99% of electrons with the energies of several hundred GeV generate gamma-quanta as a result of inverse Compton scattering. The number of gamma-quanta emitted is close to the number of electrons in the bunch and amounts to $\sim 10^5$.

Since the longitudinal size of the electron bunch is much smaller than the wavelength of the additional laser pulse interacting with the bunch and equals $10^{-3}\lambda$, the interaction time between the accelerated bunch and the laser pulse propagating from the opposite direction constitutes a few attoseconds. Consequently, the generated gamma-ray pulses have a very short duration and are partially coherent.

Note that one of the advantages of the method proposed is the possibility of regulating the energy of the gamma-quanta emitted by the electrons by means of varying the parameters of the laser pulses in the field of which the acceleration occurs.

6. Conclusions

Considered is a scheme for the generation of gamma-ray pulses on the compressed electron bunches with a great energy, which are formed in the optical traps arising from the interference of multiple laser pulses with tilted amplitude and phase fronts and converging at a single point. The traps move over the distances comparable with the size of the focal spot in the polarisation direction. The field distribution in the traps provides simultaneously the acceleration of electrons in the direction of the trap motion and the resulting compression of the bunch in three spatial directions. According to calculations, at the experimentally realisable parameters of the laser pulses, the longitudinal and transverse dimensions of the accelerated electron bunch are, respectively, three and two orders of magnitude smaller than the laser radiation wavelength, whilst the electrons gain the energy of a few hundred GeV.

When the electrons of the compressed bunch interact with a laser pulse propagating in the opposite direction, the partially coherent gamma-ray pulses with the duration of several attoseconds are emitted.

The creation of gamma beams based on electron bunches will be of great importance for the development of new ideas and technologies. Gamma radiation is used in various fields of engineering, medicine, radiation chemistry, agriculture, food industry, etc. The use of gamma-ray pulses with very short duration and low divergence opens up the possibilities for the investigation of chemical and physical processes in molecules and allows experiments with the atomic resolution in space and time. The partially coherent monochromatic gamma radiation with high energy can be used to study the structure of nuclei, in medicine for precise irradiation of tumours as well as for the broader theoretical and experimental research in nuclear physics, astrophysics, etc.

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