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ULTRASHORT ELECTRON PULSES

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Formation of ultrashort electron pulses in an electrostatic laser reflectron-deflector

S.A. Aseev, B.N. Mironov, S.V. Chekalin, V.G. Minogin

Abstract. **The temporal compression of photoelectron pulses obtained by irradiation of the target by femtosecond electron pulses is analysed by using an electrostatic reflectron with a deflecting pulse laser field. It is shown that the use of a reflectron-deflector allows one both to generate and deflect ultrashort, ~30-fs electron pulses with a countable number of electrons by focusing them into a given region with a focal size about tens of microns. It is found that the laser ponderomotive potential can play a role of a dispersive element in the electrostatic reflectron to spatially separate the electron pulses with different energies.**

Keywords: *electron beam, femtosecond laser pulses, focusing, deflection, pulse compression.*

1. Introduction

Generation of focused ultrashort electron bunches with a high coherence length is of considerable interest for applications in electron diffraction schemes for the purpose of diagnostics of fast physical and chemical processes, including those initiated by high-intensity electromagnetic fields emitted in extremely short time intervals. Three main approaches are used in the modern studies to form ultrashort electron bunches with duration of several picoseconds or less. In the first approach ultrashort electron bunches are produced by means of intense femtosecond laser radiation acting on a solid photocathode, atomic or molecular gas, or dielectric on the surface of which a strong evanescent field is formed. Under special conditions, this approach allows one to obtain electron bunches of femtosecond and even attosecond duration. In today's global practice, this vast area of research is highlighted in detail in the literature [1 – 7].

The second approach assumes that the object of pulsed irradiation is the electron bunch itself, propagating in vacuum. In this case, high-intensity ultrashort laser pulses create the ponderomotive potentials which modify the distribution of electrons in energies and ensure the conditions for spatial separation of ultrashort electron bunches from the original electron bunch. This approach, in contrast to the first one, has no fundamental limitations dictated by the necessity of using laser radiation with an intensity being less than the damage threshold of the photocathode or dielectric. Herewith, the deformation of the original spatial/velocity distribution of electrons in energies is effected by pulsed optical gradient forces, which are principally inertialess on the time scale of ultrashort laser pulses. The second approach also provides an opportunity to control the parameters of electron bunches because the ponderomotive potential created by a femtosecond laser field in vacuum may possess a multifarious space-time structure [8 – 10].

Finally, the third approach for temporal compressing and spatial focusing of electron bunches uses the pulsed electric fields. According to theoretical estimates, this approach is capable of forming ultrashort electron pulses of sub-femtosecond duration [11, 12]. In recent years the compression of original 7-ps photoelectron pulses down to 280 fs has been already demonstrated [12].

With any method for generating a ultrashort photoelectron bunch, it is of interest to use the techniques which make it possible to reduce the duration of electron pulses. One of such simple approaches employs the reflection of electrons from a stationary electric field, which is often called the reflectron [13 – 16]. The reflectron acts a dispersive mirror for electrons, thus allowing restoration of the initial duration of an ultrashort electron bunch. The known disadvantage of the electrostatic reflectron is significant spatial broadening of the reflected electron bunch, the reduction of which requires the use of additional deflecting and focusing elements.

In this paper we analyse the possibility of simultaneous compressing and focusing photoelectron pulses within the scheme of an electrostatic reflectron-deflector, in which the ultrashort ponderomotive potential performs a nonlinear deformation of the velocity distribution of the electron bunch in the vicinity of its stop point in the reflectron. The results obtained show that it is possible to generate ultrashort, ~30-fs electron pulses with a countable number of electrons and the cross-sectional size of the bunch of about tens of microns. It is also established that the laser ponderomotive potential of ultrashort duration may play a role of a dispersive element, which performs spatial separation of ultrashort pulses with different energies. These new opportunities of controlling the spatiotemporal structure of ultrashort pulses are stipulated by a considerable increase in the time of nonlinear deformation of the distribution of electrons in velocities due to the action of the ponderomotive potential on the slow electrons in the vicinity of the stop point of the electron bunch.

2. Reflectron-deflector scheme for an electron bunch

A scheme of the electrostatic laser reflectron-deflector is presented in Fig. 1. Ultrashort electron pulses are formed by

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S.A. Aseev, B.N. Mironov, S.V. Chekalin, V.G. Minogin Institute of Spectroscopy, Russian Academy of Sciences, ul. Fizicheskaya 5, 142190 Moscow, Troitsk, Russia; e-mail: minogin@isan.troitsk.ru

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photoemission of electrons from a flat solid target irradiated by ultrashort laser pulses. Hereafter, we assume that electron pulses are produced by 100-fs laser pulses, the duration τ_p of electron pulses at the source output being equal to 100 fs. Laser radiation L of ultrashort duration is assumed to be focused near the stop point of the bunch. To analyse the possibility of the joined use of the electrostatic retarding and deflecting laser fields in the reflectron, we have chosen the following realistic parameters of the scheme. Initial photoelectrons are assumed to be distributed in the energy range from $E_1 = 0.4$ eV to $E_2 = 0.6$ eV, centred at $E_0 = 0.5$ eV. The choice of a sufficiently low-energy of the photoelectron bunch is stipulated by the fact that the low-energy electron beams are advisable in electron microscopy to reduce the destruction probability for the samples of organic and biological structures, as well as to improve the image contrast [17, 18].

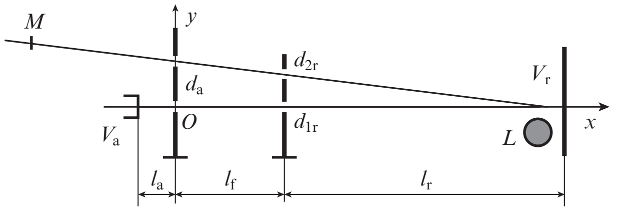

Figure 1. Scheme of an electrostatic laser reflectron-deflector.

It is assumed that the electrons are accelerated by a constant electric field within a small segment of length $l_a = 0.5$ cm, to which the accelerating potential $V_a = -1$ kV is applied. After the acceleration region, the electrons pass through the collimating aperture O. The initial angular distribution of electrons is not fixed because only the electrons that have passed through the collimating diaphragm are taken into consideration. Accordingly, the angle of emission of electrons from the target is completely determined by the diaphragm size, the initial energy of electrons, the length of the accelerating region and the value of the accelerating potential. For the scheme parameters selected, it constitutes 6°. After passing through the diaphragm, the electrons propagate freely within the area of $l_f = 2$ cm. At the end of the field-free region, the electrons enter the decelerating region formed by applying a constant retarding electrostatic field between a thin screen with the holes d_{1r}, d_{2r} and a flat electrode with a negative potential $V_r = -1.1$ kV. In accordance with the selected values of the electrostatic potential, the distance l_r between the reflectron planes was chosen equal to 6 cm. With such a length of the retarding area, slow electrons stop approximately 1 cm away from the plane of the second electrode.

When the laser field is absent in the reflectron, fast electrons, which have a higher speed than the average speed of the bunch and, accordingly, travel in the front edge of the electron pulse, pass longer distances inside the electrostatic retarding field and stop closer to the second plane of the reflectron. As a result, fast electrons spend more time to pass through the reflectron and find themselves behind slow electrons at the reflectron exit. After exiting the reflectron and passing a certain distance which can be optimised by specifying the reflectron parameters, fast electrons overtake the slow ones. Thus, the original duration of an electron pulse in the vicinity of the target M is commonly restored.

If the electron bunch is irradiated by an ultrashort laser pulse at the stop point of the reflectron, the ponderomotive potential thus arising performs deformation of the coordinate and velocity distributions of the bunch due to the two main effects. First, the ponderomotive potential deflects the electrons thanks to the action of the gradient force, which may result in focusing of the beam due to the nonlinear dependence of the gradient force on the electron coordinates transverse to the beam axis. Second, if the ponderomotive potential is symmetrical enough in relation to the spatial distribution of slow electrons, one part of the potential can accelerate those electrons which were slower in the initial photoelectron pulse, while the other part – slow down those electrons which were quicker in the initial distribution. If the parameters of the ponderomotive potential and the reflectron are agreed, such a nonlinear action of the potential on the velocity distribution of electrons near the stop point may result in a decrease in the pulse duration at the reflectron exit, i.e. in the area where the target is placed.

The estimates of the ponderomotive potential and the gradient force given below have served as basis for numerical analysis of the possibility of temporal compression and focusing of the electron bunch.

3. Ponderomotive potential and force

In the scheme under consideration we assume that the pulsed ponderomotive potential is produced by laser pulses localised in the vicinity of the stop point in the reflectron. It is also assumed that the laser bunch has a Gaussian intensity profile

$$I(x,y,t) = I_0 u(x,y,t), \tag{1}$$

where I_0 is the maximum intensity of the laser pulse, and the function $u(x, y, t)$ describes the spatiotemporal envelope of the laser pulse:

$$u(x,y,t) = \exp\left[-\frac{(x-l)^2 + (y-d)^2}{w^2}\right]\exp\left[-\left(\frac{t-t_0}{\tau_{\rm las}}\right)^2\right]. \tag{2}$$

Here w is the laser beam radius at the 1/e level; l and d are the coordinates defining the position of the centre of the bunch in the x and y axes; $2\tau_{\rm las}$ is the pulse duration at the 1/e level; and t_0 is the time delay of the laser pulse maximum. The ponderomotive potential produced by the laser pulse is defined as

$$U(x,y,t) = U_0 u(x,y,t), \tag{3}$$

where

$$U_0 = \frac{e^2\lambda^2 I_0}{2\pi m c^3} \tag{4}$$

is the potential at its maximum; e and m are the electron charge and mass; λ is the laser radiation wavelength; and c is the velocity of light in vacuum. The ponderomotive potential creates the gradient force

$$\boldsymbol{F}(x,y,t) = -\nabla U(x,y,t), \tag{5}$$

which, together with the accelerating electric force, determines the evolution of the spatial-velocity distribution of the electron bunch. The gradient force projections on the x and y axes are as follows:

$$\begin{aligned} F_x(x,y,t) &= \frac{2U_0(x-l)}{w^2}u(x,y,t), \\ F_y(x,y,t) &= \frac{2U_0(x-d)}{w^2}u(x,y,t). \end{aligned} \tag{6}$$

4. Compression, deflection and focusing of the electron bunch

Figure 2 shows the trajectories of electron pulses in the electrostatic laser reflectron-deflectron with the laser pulse parameters given below. The centre of the laser bunch is located at $l = 16.5$ cm and $d = -0.03$ cm; the bunch parameters are as follows: the wavelength $\lambda = 800$ nm, the intensity $I_0 = 1.5\times10^{13}$ W cm^{-2}, the bunch radius at the half height $w_0 = 0.5$ mm, and the pulse duration $\tau_l = 250$ ps. For the given parameters, the electron bunch deflection caused by the ponderomotive potential exceeds the transverse dimension of the bunch. In this case, the bunch itself is focused to a spot of about 50 μm in size, which is located on the longitudinal coordinate $x = -16$ cm.

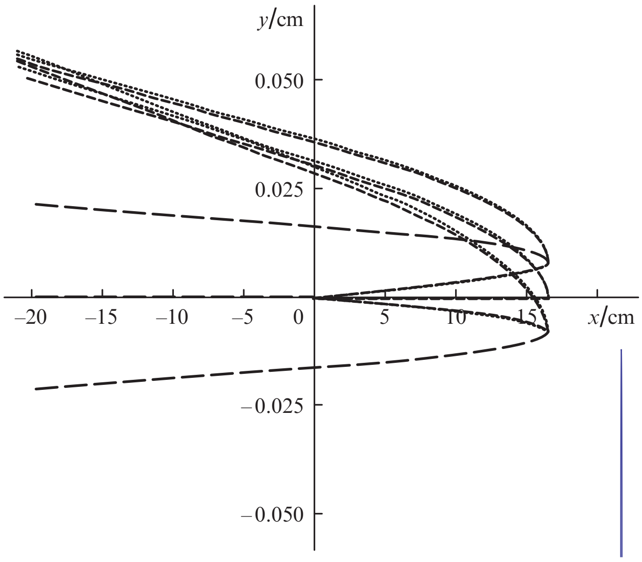

Figure 2. Trajectories of electron pulses in different regions of the reflectron. Long dashes show the trajectories that would occur in the absence of laser radiation (located symmetrically to the x axis), dashed curves – the trajectories of electrons with the energies $E_1 = 0.4$ eV, short dashes – the trajectories of electrons with the energy $E_2 = 0.6$ eV. These trajectories are shifted in the positive direction of the y axis due to the action of the ponderomotive potential. The solid line in the lower right part of the figure shows the laser bunch cross section that has a form of the highly compressed ellipse because of the large difference in coordinate scales.

The scheme under analysis considers the propagation of electron bunches containing a countable number of electrons. Accordingly, if the Coulomb repulsion of electrons is neglected, the main source of electron pulse elongation is the finite width of the initial velocity distribution of electrons. An increase in duration of electron pulses in the course of their propagation inside the decelerating field and in the course of their reverse propagation from the deceleration region is shown in Fig. 3. The figure mainly reflects the impact of the electrostatic potential, which is also slightly affected by the ponderomotive potential, on the electron bunch. Curve (*1*) shows the character of the increase in electron pulse duration while the pulse propagates inside the decelerating region. Since at a constant negative acceleration the slower electrons lose their speed faster, the increase in pulse duration becomes faster when the pulse deepens into the retarding field. In the course of reverse propagation of the pulse, the pulse narrows [curve (*2*)] as a result of spatial redistribution of electrons with different energies. Faster electrons of the initial incident bunch now find themselves behind the front ones which are now slow. Accordingly, the more time they need to catch up with the front ones, the greater their velocity in the initial bunch. As a result, curve (*2*) qualitatively follows the shape of curve (*1*), being however shifted along the ordinate axis towards smaller pulse durations. At the chosen propagation parameters of the electron bunch, its minimum duration is attained at the longitudinal coordinate $x = -16$ cm, which also corresponds to the best focusing of the bunch. With further propagation of the bunch, its front and tail edges change their places, and the bunch duration starts to grow unboundedly.

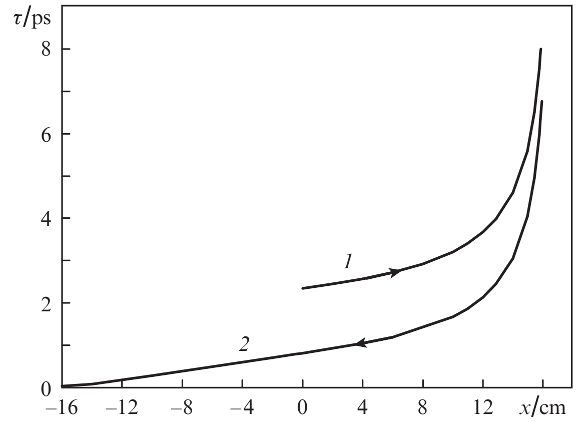

Figure 3. Durations of incident (*1*) and reflected (*2*) electron pulses in the various cross sections of the reflectron, located at different x coordinates. Arrows show the direction of the pulse propagation.

At the chosen duration (100 fs) of initial photoelectron pulses, the value τ_{a1} turns out equal to 2.3 ps at the place where the collimating aperture is located. In case the output hole of the reflectron is reached, the pulses duration increases up to $\tau_{r1} = 2.5$ ps. If the output hole of the reflectron is crossed, this value decreases down to 0.9 ps. The minimal pulse duration ($\tau = 30$ fs) is attained at $x = -17$ cm.

The results of numerical simulation also show that, if the interaction parameters are properly selected, the ponderomotive potential is capable of performing spatial separation of electron pulses with different energies, thus playing the role of a dispersive element for electron pulses.

5. Conclusions

Our analysis shows that the electrostatic laser reflectron-deflector may be simultaneously used both for effective compression of duration of electron pulses and for deflecting and focusing electron pulses in the schemes of 3D microscopy. The results of numerical simulation demonstrate that, at the electron energies of about 1 keV and the reflectron length of about 15 cm, it is possible to compress the electron pulse duration down to 30 fs with the focusing area of about 50 μm. Such parameters of electron pulses can be attained at a relatively high (~10^{13} W cm^{-2}) laser radiation intensity, the radiation power of 10^{11} W and the radiation energy per pulse of ~10 J.

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