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Controllable generation of a single attosecond relativistic electron bunch by a superintense laser pulse with a sharp rising edge

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Introduction. Energetic ultrashort electron bunches can be used in many fields of science and technology: for injection purposes, in spectroscopy, in femtosecond physics and chemistry, for generating bright ultrashort X-ray pulses, including coherent, and others. For controllable generation of ultrashort electron beams, we propose to use a thin plasma layer (either with compensating positive charge or without it) irradiated normally by a super-high intensity laser pulse with a sharp rising edge [1-3]. The electrons of the plasma layer are accelerated during laser pulse action longitudinally to relativistic velocities by the nonlinear component of the Lorentz force, provided a dimensionless field amplitude is large enough. We show analytically and by two-dimensional PIC simulations that it is possible to choose the parameters of the laser pulse and the plasma layer in such a way that only *single short, coherent, and ultracold relativistic electron beam* will be produced (and can survive for some time) rather than a cloud of chaotically moving electrons. First, the transparency of the plasma layer has to be large enough for the electrons to interact with a propagating laser pulse rather than a standing wave. Then, the amplitude of the laser pulse has to be large enough. And at last, the laser pulse has to be nonadiabatic, i.e., with a very sharp rising edge and duration about several periods of the laser frequency. These ensure that the bunch will be compressed by many times in the longitudinal direction at the initial stage of interaction with the front of the laser pulse, giving the resulting bunch duration on the attosecond scale and smaller. As a possible application, frequency up-conversion of the probe laser pulse into *a single, ultrashort (attosecond), and coherent hard X-ray pulse* due to backscattering off such an electron bunch is demonstrated numerically and the spectrum of up-shifted radiation is investigated. In this case, the electron and the X-ray beams are generated synchronously with the laser pulse during the laser-plasma interaction, and three correlated beams of different physical nature are available simultaneously providing a unique opportunity for use.

Formation of relativistic electron mirrors. Let a linearly y-polarized plane electromagnetic wave (amplitude E_0, frequency ω) be incident along the z axis normally at a plasma layer with infinite dimensions in x and y directions. Let the plasma layer be rarefied enough so that the movement of the electrons can be regarded as in the given external field of the laser pulse (this means omitting all collective effects and Coulomb forces in the system). In this model, the solutions for the electrons' equations of motion are well known [4]. Particularly, the invariant $\kappa = \gamma - p_z = \gamma(1-\beta_z) = 1$ exists for the zero initial momenta of the electrons (the normalized momenta and velocities are $p_{y,z} = \gamma\beta_{y,z} = (1-(v/c)^2)^{-1/2} v_{y,z}/c$, besides $\gamma = (1-(v/c)^2)^{-1/2}$, where v and c are the velocities of electrons and light respectively). The equations of motion are similar for all electrons of the plasma layer, the only difference being initial position of electrons and, correspondingly, different phase of the laser field.

During the action of the laser pulse, the electrons can have ultrarelativistic velocities if $a_0 = eE_0/(m\omega c) >> 1$ (the maximum transverse and longitudinal momenta are about $2a_0$ and $2a_0^2$ respectively, the latter being always positive). Let now consider the motion of two electrons, one is being at the left border of the plasma layer with coordinate z_{01}, and the other at the right border with coordinate z_{02}. Let us suppose that the initial length of the plasma layer, $l_0 = z_{02} - z_{01}$, is considerably smaller than the accelerating laser wavelength λ. Then $z_1(t) = z_{01} + z(t)$ and $z_2(t) = z_{02} + z(t - \Delta t)$ are the evolutions of the electrons' coordinates in time, and $\Delta t = l_0 / c$ is the delay, required for the laser pulse to propagate from the point z_{01} to the point z_{02}. For $l_0 << \lambda$, the delay Δt is considerably smaller than the laser period, and the distance between two border electrons is $l = z_2 - z_1 = l_0 + z(t-\Delta t) - z(t) \approx l_0 - (dz/dt)\Delta t = l_0(1-\beta_z(t)) = l_0/\gamma(t)$ because of the invariant value of κ. This equality holds for arbitrary laser pulse envelope provided the motion of the electrons can be considered as in the given field. So the length of the electron mirror will oscillate in the field of external electromagnetic wave due to oscillation of γ, and the smallest length $l_{\min} \approx l_0/(2a_0^2)$ will be achieved for the largest values of γ. In the laboratory frame, the first half-cycle of oscillations corresponds to the time $\omega t \approx 3\pi a_0^2/4$ and can be large enough for $a_0 >> 1$ (hundreds of femtoseconds).

Two-dimensional simulations of mirror dynamics. 2D simulations was done with OSIRIS code. Laser pulse is running from the left to the right and has Gaussian time and spatial profiles with maximum field amplitude $a_0 = 5$, the diameter of the laser pulse is 8λ (FWHM), and the front duration is 3λ. The thickness of the plasma layer is λ, and the density of electrons is $n = 0.003 n_{cr}$, where n_{cr} is critical density for the given laser frequency ω. The simulation results (in the moving window) are presented in Fig. 1.

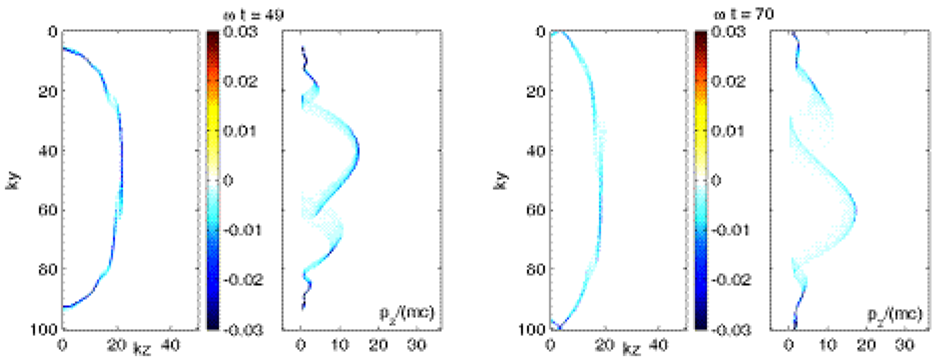

Figure 1: Relativistic electron mirrors for different time from the beginning of interaction.

The minimal thickness of the relativistic electron mirror is realized for $\omega t \approx 49$ and is about 0.1λ that is greater than the possible minimal value $l_0 / \gamma \approx l_0 / 15$, which can be estimated from the right panel corresponding to the same moment of time. This increase in the thickness of the electron mirror is due to the action of the Coulomb force during interaction of a relatively long front of the laser pulse with the plasma layer. The thickness of the electron mirror and the spread of the electrons' longitudinal momenta increase with increasing time due to the action of the Coulomb forces between the electrons in the mirror. However, the mirror is stable at least until $\omega t \approx 90$ that corresponds to about 45 femtoseconds for $\lambda = 1\mu$.

Frequency up-conversion of the probe beam. When the laser beam reflects from a counter-moving ideal relativistic mirror the frequency and the amplitude of the reflected wave increase by the factor $(1+v_z/c)/(1-v_z/c)$ [4]. So for $v_z/c \approx 1$ the frequency up-shift can be very high. It is necessary to stress that the reflected radiation will be coherent if the incident wave is coherent and the thickness of the electron mirror is small enough. Besides, the duration of the reflected pulse can be considerably smaller than the duration of the incident probe pulse due to the Doppler contraction. Additional benefit of such scheme is its tunability because the frequency of the generated radiation depends on the velocity of the mirror, which can be simply adjusted.

The frequency transformation factor for ultrarelativistic electron mirror with $p_z >> 1$ is $f_v = (1+\beta_z)/(1-\beta_z) \approx 2p_z$. Let the motion of electrons can be considered as in the given field. Then, the maximum longitudinal momentum can be about $p_z \approx 2a_0^2$ and $f_v \approx 4a_0^2$ for the sine form of the accelerating pulse with rectangular envelope. So to up-shift the coherent optical radiation into the hard X-ray band the dimensionless field amplitude a_0 has to be at least 70-100. Therefore below, we consider one-dimensional simulation of the up-conversion process for the following parameters: $a_0 = 100$ and $n = 0.003n_{cr}$. Besides, the initial thickness of the target has to be taken as small as possible for to increase the monochromaticity and the amplitude of the reflected field. We take $l = 0.01\lambda = 10$ nm for the accelerating laser wavelength $\lambda = 1\mu$. The frequency of the probe pulse is taken equal to the frequency of the accelerating pulse, and the amplitude a_1 of the probe pulse is equal to 10. For such parameters, the maximum frequency transformation coefficient can be about 40000. The probe pulse has to strike the electron mirror some time after the beginning of the acceleration process for the electrons in the bunch can achieve relativistic velocities; otherwise the lifetime of the bunch will be seriously degraded by the probe pulse. In simulation, we suppose that the probe pulse (a piece of the sine wave) falls at the relativistic mirror at $\omega t \approx 25000$, where p_z is near to the maximum.

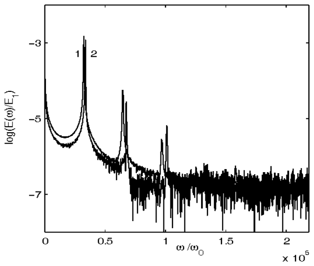

Figure 2.

The spectrum of the up-shifted radiation is presented in Fig. 2. The harmonics of the probe pulse frequency, arising due to the nonlinearity of the interaction, are also up-shifted giving harmonics of the up-shifted frequency. Here, the spectra of two samples (with the same length) from the different points 1 and 2 of the acceleration curve are presented. The longitudinal momenta of the electron bunch changes during the acceleration therefore f_v has to change also (some kind of frequency chirp). This is just what can be seen in Fig. 2, where the frequency transformation coefficient for point 1 is smaller than for point 2 and, consequently, the frequency of the reflected field for point 1 is also smaller. It is necessary to note that the field of the frequency up-shifted harmonics is also coherent so the maximal frequency of the up-shifted radiation is three times larger in this case than the estimate $4a_0^2$ (Fig. 2) reaching the value of 10^5 with respect to the probe wave frequency.

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