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Nonlinear generation of ultra-short electromagnetic pulses in plasmas

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Abstract

When a low-frequency relativistic soliton interacts with the electron density modulations of a wake plasma wave, part of the soliton electromagnetic energy is reflected in the form of an extremely short and ultraintense electromagnetic pulse. By computing analytically the spectra of the reflected and of the transmitted electromagnetic pulses, we show that the reflected wave has the form of a single cycle attosecond pulse.

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Present day lasers produce ultraintense pulses in the ~ 1 μm wavelength range with intensities that approach 10^{22} W/cm^2 [1] and allow us to explore a regime, where the quiver energy of the electrons is equal to, or even significantly greater than, their rest-mass energy. In these relativistic regimes novel nonlinear properties of the laser–plasma interaction come into play (see, e.g., the review articles [1] and [2] and references quoted therein). In the present Letter we address the nonlinear processes that accompany the interaction between the Langmuir waves [3,4] and the relativistic electromagnetic (e.m.) solitons [5–8] that are left in the wake behind the laser pulse and show that such processes can generate high-intensity attosecond pulses.

A new method for generating ultrahigh-intensity e.m. fields was recently proposed in Ref. [9]. This method, which is based on the compression, frequency

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up-shifting and focusing of a laser pulse by a counter-propagating, breaking plasma wave, makes it possible to achieve the critical field of quantum electrodynamics [10] with present-day laser systems. Below, we show that the role of the laser pulse can be taken by a relativistic e.m. soliton. As was shown in Refs. [5–8], a significant fraction of the order of 30%–40% of the laser pulse energy can be trapped in these structures in the form of e.m. energy oscillating at a frequency below the Langmuir frequency $\omega_{pe} = (4\pi n e^2/m_e)^{1/2}$ of the surrounding plasma. The formation mechanism of these relativistic slowly propagating solitons has been identified in Ref. [8] as due to the depletion of the energy of the laser pulse propagating in the plasma and to the consequent frequency downshift and trapping of the laser e.m. energy. As shown, e.g., in Ref. [11], this makes it possible to choose the plasma and laser parameters in such a way as to produce solitons in a controlled manner. The typical size of these solitons is of the order of the collisionless electron skin depth $d_e = c/\omega_{pe}$. The e.m. fields inside the solitons consist of synchronously oscillating electric and magnetic fields plus a steady electrostatic field which arises from charge separation as electrons are pushed outward by the ponderomotive force of the oscillating fields. On a long time scale, when the effects of the ion motion become important, the ponderomotive force forms cavities in the plasma density, which have been denoted as post-solitons [11,12]. For the sake of simplicity here we shall consider conditions when the effects of the ion motion can be neglected. We shall regard the soliton in the reference frame co-moving with the wake wave as a semi-cycle e.m. wave packet propagating against the wake wave. As a result of the packet interaction with the electron density modulations in the wake wave, a portion of its energy is reflected in the direction of propagation of the wake plasma wave. This results in the transformation of the low frequency soliton field into a high frequency ultrashort e.m. burst. In a tenuous plasma the frequency up-shift can be so large that it can provide a new mechanism for generating attosecond pulses, distinct from the mechanisms described in the literature [13,14].

An intense pulse interacting with a plasma forces the plasma electrons to move with relativistic velocities and this motion induces a wakefield in the plasma. The phase velocity $v_{ph} = \beta_{ph} c$ of the wakefield, see, e.g., Ref. [4], is equal to the laser pulse group velocity, which is close to the speed of light in vacuum if the laser pulse propagates in an underdense plasma. The nonlinearity of the strong wakefield leads to the formation a nonlinear wave profile and in particular to the steepening of the wave and to the formation of sharply localized maxima, "spikes", in the electron density [15]. This means that the wakefield enters the wave-breaking regime (see Ref. [2] references therein). From the continuity equation it follows that the electron density is given as a function of comoving coordinate $X = x - v_{ph} t$ by $n_e(X) = n_0 \beta_{ph}/(\beta_{ph} - \beta_u(X))$, where n_0 is the ion density in the plasma and the speed of the electrons (divided by the speed of light) β_u varies from $-\beta_{ph}$ to β_{ph}. As a consequence, the electron density tends to infinity at the breaking points and it is of the order of $n_0/2$ in the regions in between. Thus, close to the wave breaking conditions, we can approximate the electron density distribution as

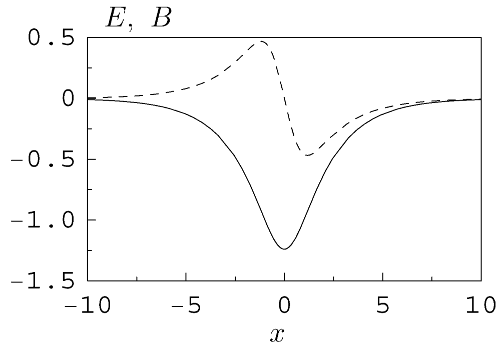

Fig. 1. Dependence of the electric (solid line) and magnetic (dashed line) fields of the initial soliton on x in the laboratory frame; x is measured in units c/ω_{pe}; time is set to zero $t = 0$ and $\omega = 0.85\omega_{pe}$.

$$n_e(X) = \frac{n_0}{2}\big[1 + \lambda_p \delta(X)\big]. \tag{1}$$

Here λ_p is the wavelength in the wave-breaking regime. The density spike in Eq. (1) can be expected to reflect part of the energy of a counterpropagating e.m. wave.

Let us assume that the soliton is formed by a circularly polarized laser pulse and let us describe the transverse components of the vector-potential by introducing the complex dimensionless potential $A = (e/m_e c^2)(A_y + i A_z)$. Requiring that A vanishes at infinity, we can write the stationary solution for the system of the cold hydrodynamic electron equations and