Single-Cycle High-Intensity Electromagnetic Pulse Generation in the Interaction of a Plasma Wakefield with regular Nonlinear Structures

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The interaction of sub-cycle solitons, electron vortices and wake Langmuir waves with a strong wake wave in a collisionless plasma can be exploited in order to produce ultra-short electromagnetic pulses. The electromagnetic field of these nonlinear structures is partially reflected by the electron density modulations of the incident wake wave and a single-cycle high-intensity electromagnetic pulse is formed.

Present day laser technology allows us to generate ultraintense laser pulses with intensities approaching 10^{22} W/cm^2. In this regime the relativistic dynamics of the electrons in the plasma inside which the pulse propagates, introduces a new type of nonlinear phenomena that arise from the nonlinearity of the Lorentz force and of the relationship between particle momentum and velocity and, at very large intensities, from nonlinear quantum electrodynamics effects such as electron-positron pair creation. Such nonlinear processes can be harnessed ("relativistic engineering", as introduced in Ref.[1]) in order to concentrate the e. m. radiation in space and in time and produce e.m. pulses of unprecedented high intensity or short duration that can be used to explore ultra-high energy density effects in plasmas. These new possibilities were emphasized by the results presented in

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[2], where it is shown that synchronized attosecond e. m. pulses and attosecond electron bunches can be produced during the interaction of tightly focused, ultrashort laser pulses with overdense plasmas. The property of nonlinear systems to respond anharmonically to a periodic driving force was exploited in Ref. [3] where the propagation of a high intensity short laser pulse in a thin wall hollow channel was shown to produce a coherent ultrashort pulse with very short wavelength that propagates outwards through the channel walls.

A different method of generating ultra-short e. m. pulses was proposed in Ref.[4]. This method uses the interaction between a relativistic electromagnetic sub-cycle soliton and the density modulations of a Langmuir wakefield in a plasma. The mechanism envisaged is based on the results of Ref. [1], where it was shown, that when a laser pulse interacts with a breaking wake plasma wave, part of the pulse is reflected in the form of a highly compressed and focused e. m. pulse with an up-shifted carrier frequency due to the Doppler effect. The pulse enhancement of the pulse intensity and the pulse compression arise because the electron density modulations in the wake wave act as parabolic relativistic mirrors. In the approach introduced in Ref.[4] the role of laser pulse is taken by a sub-cycle soliton produced by another laser pulse in the plasma. These results were confirmed in Ref.[5] on the basis of two-dimensional (2D) particle-in-cell (PIC) simulations and extended to other types of coherent nonlinear structures: an electron vortex and a wake field.

The reflection of one-dimensional coherent structures can be derived by performing a Lorentz transformation to the reference frame where the wake plasma wave is at rest. In this frame the e.m. fields are Fourier transformed with respect to time and the frequency dependent reflection coefficient

$$\rho(\omega') = -q/(q - i\omega'), \tag{1}$$

where $q = 2\omega_{pe}(2\gamma_{ph})^{1/2}$, derived in Ref.[1] is used, where γ_{ph} is the Lorentz factor corresponding to the phase velocity of the wake wave. The form and amplitude of the reflected pulse in the laboratory frame are then obtained by adding the reflected Fourier components and by performing the inverse Lorentz transformation of the resulting e.m. fields. The structure of the e.m. fields of the soliton and of the vortex before interacting with the wake are described in Refs.[6, 7] and in Ref.[8] respectively, The explicit form of the reflected pulse in the case of a relativistic soliton, a vortex and of a Langmuir wave are given in Ref.[5].

The main conclusion of this one-dimensional analysis is that the amplitudes of the e.m. fields in the reflected pulse are increased by the factor $\gamma_{ph}^{3/2}$, i. e., the pulse intensity is proportional to γ_{ph}^3, while its frequency is up-shifted by $2\gamma_{ph}^2$. This scaling indicates that in a tenuous plasma the frequency up-shift of the reflected pulse, and its related compression, would be so large that it could lead to the generation of attosecond pulses.

The Lorentz factor γ_{ph} of the wakefield generated by a laser pulse in plasma is of the order of $\gamma_{ph} \approx \omega_d/\omega_{pe}$, where ω_d is the frequency of the laser pulse (driver) that generates the wake plasma wave. The frequency up-shift is $2\gamma_{ph}^2\Omega_S \approx 2\gamma_{ph}^2\omega_{pe} \approx 2\gamma_{ph}\omega_d$. Thus, for a $1\,\mu m$ wavelength laser pulse, corresponding to the critical plasma density $n_{cr} = m_e\omega_d^2/4\pi e^2 \approx 10^{21} cm^{-3}$, the factor $2\gamma_{ph}$ that would be required to generate an attosecond reflected pulse is of order 10^3, i. e. the density of the plasma must be order of $4 \times 10^{15} cm^{-3}$.

In order to take into account the effects of multi-dimensional geometry and strongly nonlinear plasma dynamics, as well as the influence of kinetic effects, two dimensional simulations were performed using the code REMP based on the particle in cell (PIC) method and “density decomposition scheme” [9]. These two-dimensional particle-in-cell simulations are reported in Ref.[5] and show that during the interaction of coherent nonlinear structures (such as sub-cycle solitons, electron vortices and wake Langmuir waves) with a strong wake wave in a collisionless plasma a train of single-cycle intense electromagnetic pulses is generated.

We also note that ultrashort e. m. pulses can be generated when a wake wave interacts with plasma in a self-focusing channel, see, e. g., [10]. In a self-focusing channel, an electric field is present due to charge separation and can be transformed into an ultrashort e. m. pulse, similarly to the soliton, vortex or wake wave.

In conclusion, the reflection of coherent structures by a wake wave can be exploited in order to produce ultra-short intense e.m. pulses with presently available lasers. The modulations of electron density in a strong wake wave close to the wave-breaking regime have the shape of spikes and each spike acts as a semi-transparent mirror moving with a relativistic velocity. Such a mirror partially reflects the electromagnetic field of a coherent nonlinear structure and thus generates an electromagnetic pulse. For each spike, the reflected pulse consists of a single cycle oscillation, which results in a train of single oscillation pulses.

As compared to the e.m. field of the coherent nonlinear structure, the reflected pulse has an up-shifted frequency and an increased intensity. The reflected pulse intensity occurs as a result of frequency up-shift, due to Doppler effect, and because of the parabolic profile of the wake wave. An analytical approach and two-dimensional simulations show that the amplitude of the e.m. pulse, reflected by a relativistic flying mirror, scales in all the three case examined as $\gamma_{ph}^{3/2}$, due to a similarity of the reflection process. The reflection leads to a frequency and wavenumber upshift which scales as γ_{ph}^2 and to the formation of an additional spatial scale proportional to $1/\gamma_{ph}^{3/2}$.

Since in all the above cases of wakefield interaction with nonlinear coherent structures in a plasma, single-cycle e.m. pulses are emitted with a characteristic frequency, duration and polarization, their emission represents an important process to be used for diagnostics of laser plasma interactions.

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