Plasma-based generation and control of a single few-cycle, high-energy and ultrahigh intensity laser pulse

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Introduction and motivations

A wide range of novel studies in vacuum nonlinear optics as well as the major new regimes of extreme field physics require laser pulses which **simultaneously** exhibit three key features: few-cycle duration, high energy and ultrahigh intensity. Already in nonrelativistic atomic physics, quantum processes can be **controlled** by manipulating the shape of few-cycle laser pulses [1]. In order to achieve the same goal also in the realm of strong-field QED, few-cycle laser pulses with **tunable** carrier-envelope-phase (CEP) are required with peak intensities largely exceeding 10^{20} W/cm^2 [2-4]. Although next-generation 10-PW optical laser systems are expected to generate laser pulses with 150-300 J energy and 15-30 fs duration [4, 5] (FWHM of the pulse intensity), the limited bandwidth renders the generation of few-cycle pulses with multi-joule energy very challenging [6]. Indeed, the only foreseen laser system aiming at 1-PW power and few-cycle duration is the petawatt field synthesizer (PFS) [7].

Here, we put forward the concept of a solid-density paraboloidal relativistic "mirror" accelerated by a "driver" laser field, interacting with a superintense counterpropagating "source" pulse, to generate a **CEP tunable** few-cycle reflected pulse with multi-joule energy and peak intensity exceeding 10^{23} W/cm^2 [8]. Contrary to intuition, it is found that a heavy and therefore relatively slow mirror should be employed to maximize the intensity and the energy of the reflected pulse, since its larger reflectivity compensates for the lower velocity [8]. In addition, the short duration of the reflected pulse is achieved by employing a superintense source pulse, which abruptly disperses the plasma mirror after only the first few cycles (see Fig. 1). Multidimensional PIC simulations indicate both the feasibility of the presented set-up by employing next-generation multi-PW laser systems and a considerable amplification and shortening (temporally and in the number of laser cycles) even of **already** few-cycle source pulses [8].

Multidimensional particle-in-cell (PIC) simulation results

In our first simulation both the driver and the source pulse have a $\sin^2$-function temporal field profile with 15.5 fs duration (FWHM of the intensity), Gaussian transverse profile, wavelength $\lambda = 800\,\mathrm{nm}$ ($T = \lambda/c$) and propagating along the x-direction. The driver (source) pulse is circularly (linearly along the y-axis) polarized with intensity $I_d = 3.4\times10^{22}\,\mathrm{W/cm^2}$ ($I_s = 5.6\times10^{22}\,\mathrm{W/cm^2}$) and spot radius $\sigma_d = 3.8\lambda$ ($\sigma_s = 1.2\lambda$), corresponding to a power $P_d \simeq 9.9\,\mathrm{PW}$ ($P_s \simeq 1.6\,\mathrm{PW}$). These parameters are indeed expected at the Apollon 10P laser system [4-5].

Initially, the foil consists of fully ionized carbon with density $\rho = 2.3\,\mathrm{g/cm^3}$. The foil is shaped transversely with a thickness distribution $\ell = \max[\ell_1, \ell_0 \exp(-y^2/2\sigma_f^2)]$, with $\ell_1 = 0.02\lambda$, $\ell_0 = 0.20\lambda$, $\sigma_f = 2.6\lambda$ and localized at $x = 5\lambda$. At $t = 22\,T$ a single few-cycle reflected pulse separated from the foil remnants is observed. The peak intensity (power) of the reflected pulse is: $\hat{I}_r \simeq 2.3\times10^{23}\,\mathrm{W/cm^2}$ ($\hat{P}_r \simeq 2.2\,\mathrm{PW}$), with 5.8 fs duration (FWHM intensity) and 6.8 J energy (see Fig. 2).

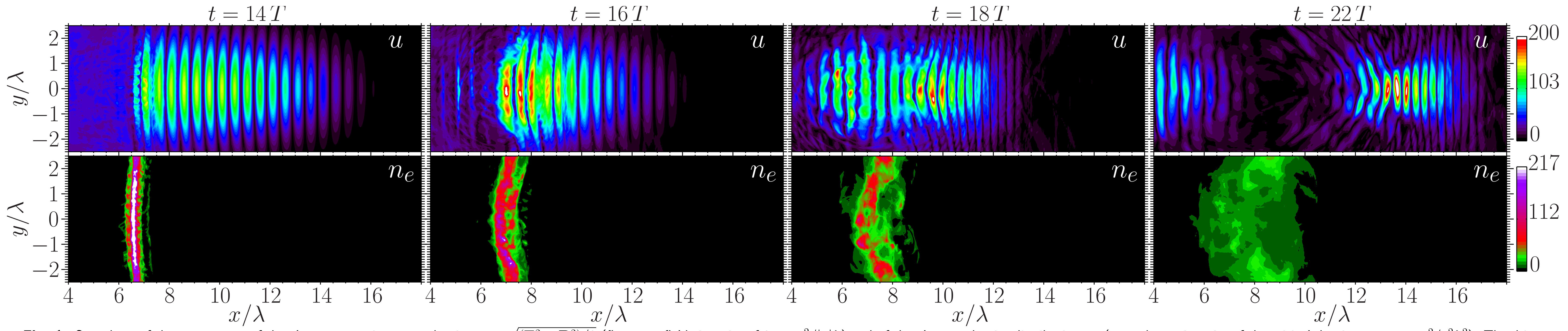

Fig. 1: Snapshots of the square root of the electromagnetic energy density $u = \sqrt{(\mathbf{E}^2+\mathbf{B}^2)/2}$ (first row, fields in units of $2\pi m_e c^2/|e|\lambda$) and of the electron density distribution n_e (second row, in units of the critical density $n_c = \pi m_e c^2/e^2\lambda^2$). The driver pulse reaches the edge of the foil at $t = 0$, while the source pulse reaches the foil at nearly the end of the acceleration phase ($\sim 10\,T$). Although instabilities have developed and density fluctuations are clearly visible before the source pulse impinges on the foil, the foil remains sufficiently compact to reflect the first part of the source pulse ($t \le 16\,T$).

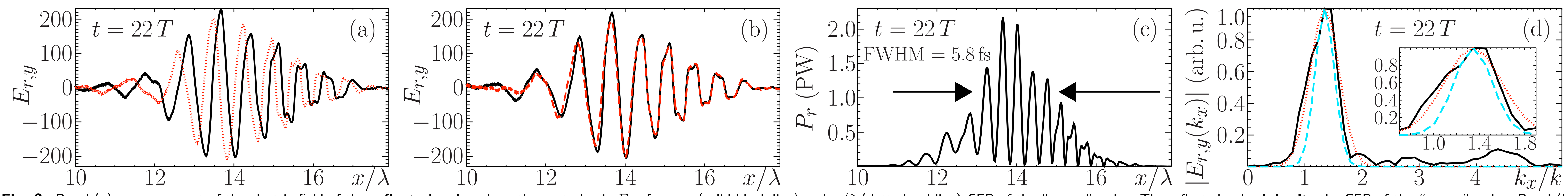

Fig. 2: Panel (a): y-component of the electric field of the **reflected pulse** along the central axis $E_{r,y}$ for zero (solid black line) and $\pi/2$ (dotted red line) CEP of the "source" pulse. The reflected pulse **inherits** the CEP of the "source" pulse. Panel (b): $E_{r,y}$ along the central axis with radiation reaction effects (solid black line) and with a randomly distributed preplasma on the front surface of the foil (dashed red line) [8]. Panel (c): Power contained in a spot with 1λ radius centered on the axis. Panel (d): modulus of the Fourier transform of the y-component of the electric field along the central axis $|E_{r,y}(k_x)|$ (solid black line) and the corresponding quantity for a Gaussian pulse with two (dotted red line) and three (dashed blue line) cycles FWHM of the **field** profile. The inset shows a zoom of the main peak region.

A 1.5-cycle (FWHM of the **field** profile), 2.1 fs, 2 J energy, 1.8 PW peak power and 1.4×10^{23} W/cm^2 peak intensity **reflected pulse** can be generated (see Fig. 3) by employing a 5.8 fs (FWHM of the intensity), 1-PW power **source pulse**, i.e. with parameters close to those expected for the PFS [7], and the driver pulse parameters reported prior to Fig. 1.

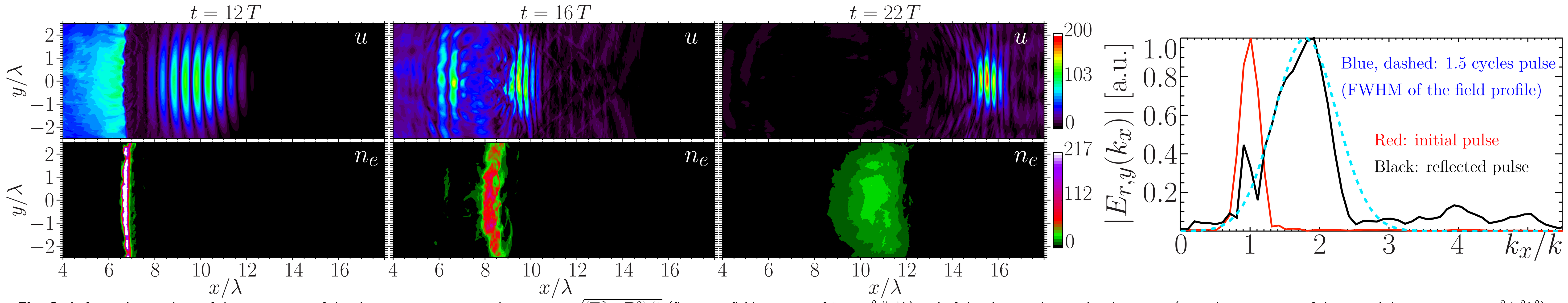

Fig. 3: Left panel: snapshots of the square root of the electromagnetic energy density $u = \sqrt{(\mathbf{E}^2+\mathbf{B}^2)/2}$ (first row, fields in units of $2\pi m_e c^2/|e|\lambda$) and of the electron density distribution n_e (second row, in units of the critical density $n_c = \pi m_e c^2/e^2\lambda^2$). Right panel: modulus of the Fourier transform of the y-component of the electric field along the central axis $|E_{r,y}(k_x)|$ of the source pulse at $t = 10\,T$ (solid red line) and of the generated reflected pulse at $t = 22\,T$ (solid black line). For the sake of comparison, the modulus of the Fourier transform of the electric field along the central axis of a Gaussian pulse with 1.5 cycles FWHM of the **field** profile (dashed blue line) is also reported on the right panel.

References

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