Optical phase effects in electron wakefield acceleration using few-cycle laser pulses

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Abstract. Simulations performed with the particle-in-cell code Calder Circ show the feasibility of injection and acceleration of electrons in the laser wakefield created by few-femtosecond laser pulses with moderate energy at the few mJ level. A detailed study of the effect of the carrier-envelope phase of the pulse on the injection is presented. It is shown that using ionization injection with nitrogen as the target gas, the control of the optical phase allows production of high-quality and shot-to-shot stable electron beams. The electron bunches obtained have a relative energy spread of a few per cent, a bunch duration in the sub-fs domain, a divergence close to 10 mrad and a peak energy in the 10 MeV range, and could be produced in the near future at kHz repetition rates.

Laser technology has greatly evolved over the last 30 years. Regarding the development of laser chains delivering pulses shorter than 50 fs with power in the 10–100 TW range, this revolution started at the end of the 1990s with as a consequence of the flourishing of the research field of laser-plasma acceleration. Advances in the experimental techniques and in the basic knowledge of the interaction of these laser beams with gas/plasma medium have permitted the production of high-quality ultra-short electron bunches with energies approaching the GeV [1–5]. Electric fields in the wake of the drive laser pulse can reach some hundreds of GeV m$^{-1}$ instead of the tens of MeV m$^{-1}$ attainable in conventional radio-frequency (RF) accelerators, opening the door to a new generation of compact particle accelerators. The external injection of electrons in the wakefield using a second laser beam has been demonstrated [6]. Electron beams obtained in

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this manner are quasi-monoenergetic, tuneable and stable. The production of sub-MeV electron bunches with 25% relative energy spread with a 0.5 J–47 fs laser has also been reported [7].

The power of these sub-50 fs lasers has been continuously growing, attaining values as large as a few hundreds of TW but with a limited repetition rate at the 10 Hz level in the best case. On the other hand, a new generation of ultra-short laser beams able to reach relativistic intensities with durations shorter than 10 fs is being developed. The production of quasi-monoenergetic relativistic electron beams with 40 mJ–8 fs laser pulses has recently been demonstrated [8]. The repetition rate of the laser used in these experiments is still of the order of Hz. A new laser system, named ‘Salle Noire’, delivering few optical cycles long laser pulses at repetition rates of kHz has been developed at LOA [9]. Moreover, this laser is phase stabilized, meaning that the carrier-envelope phase of the laser pulse produced can be locked [10]. Phase-locked pulses as short as 5 fs are already produced by this laser. The laser pulse energy, however, is limited to a few mJ, ten times lower than that in the mentioned 8 fs laser system.

The production of high-quality relativistic electron beams with such modest pulse energies is a challenging issue. The very short laser pulse duration allows one to work in the resonant regime [11] at densities close to 10% of the critical density, for which the threshold for self-injection of electrons in the wakefield is very low. Longer pulses could be used to trap and accelerate electrons even at these high densities via self-modulation, but this regime requires the onset of highly nonlinear instabilities that would affect the reproducibility of the process. The drawback of working at these densities is the strong gradient of the accelerating field due to the small plasma length, which makes the production of quasi-monochromatic pulses difficult.

In this work, we present numerical evidence for the feasibility of self-injection and acceleration of electrons with mJ pulses. It has recently been shown [12] that for pulses with lengths close to a single cycle and at high amplitude ($a_0 \gg 1$) the bubble presents an asymmetry in the polarization plane, which results in a spatially modulated beam. But in this regime the beam quality is low (broad spectrum, high emittance) and the control of the carried envelope phase does not allow one to improve the beam properties. We will show that for few-cycle laser pulses at modest amplitudes ($a_0 \sim 1$), the optical phase plays a role in the injection of electrons, even if the bubble shape does not present any asymmetry. Moreover, we will show that its control permits one to improve the quality and shot-to-shot stability of the electron beams produced.

We perform simulations using the fully electromagnetic particle-in-cell code Calder Circ [13]. In this code, Maxwell equations, written in cylindrical coordinates, are solved by projecting over a basis of Fourier modes. A few modes are enough to accurately describe the laser evolution and wakefield, resulting in simulations needing much less computational resources than fully 3D simulations. Simulations performed here included three Fourier modes. The amplitude of the mode $m = 0$ for the electron density spatial distribution (symmetrical around the propagation axis) is much larger than that for the modes $m = 1$ and $m = 2$, showing that the bubble is roughly symmetrical. Parameters of the simulations correspond approximately to those of the LOA laser ‘Salle Noire’: a laser energy of 5 mJ, a laser wavelength $\lambda_0 = 0.8 \mu m$ and a laser pulse duration of 5 fs full-width at half-maximum (FWHM) in intensity. By focusing this laser beam on a spot size of 5 $\mu m$ FWHM in intensity, a laser intensity $I$ of $2.9 \times 10^{18}$ W cm$^{-2}$ is expected to be reached by assuming that 75% of the laser energy is contained in the focal spot. The corresponding values of the normalized vector potential and laser power are, respectively, $a_0 = 1.1$ and $P = 0.7$ TW. Different values of the optical phase $\phi$ have been used: $\phi = 0$ corresponds to a laser pulse with its maximum of electric field coinciding with the maximum of the envelope.
Simulations were performed using 300 N\(^0\) macroparticles per cell (this corresponds to 2100 electrons per cell in regions where N is fully ionized). The longitudinal and radial sizes of each cell are \(\lambda_0/50\) and \(\lambda_0/10\), respectively. The simulations box is composed of 2500 \(\times\) 300 cells, respectively, in the longitudinal and radial directions.

Preliminary simulations performed indicate that the use of self-injection of plasma electrons as the injection method does not permit us to produce low-energy-spread beams. Self-injection of bound electrons ionized close to the maximum of the laser envelope, known as ionization injection that has been proposed and demonstrated very recently [14–18], appears to be a good method for the production of high-quality electron bunches for the laser parameters used here. In order to produce quasi-monoenergetic electron bunches we try to reduce as much as possible the injection region. We use nitrogen as the target gas, because the element presents a large gap between the ionization potentials of L and K shell electrons (\(I = 96.9\) eV for the most tightly bound L shell electron and 552 eV for the most loosely bound K shell electron) [19]. Electrons coming from the ionization of \(N^{5+}\) will be born close to the peak of the laser amplitude envelope and will be trapped. Electrons coming from the ionization of less charged states \(N^0–N^{4+}\), born far from the peak of the envelope and not trapped, will form the wakefield. Tunnel ionization is described in the particle-in-cell code by the Ammosov–Delone–Krainov (ADK) model [20].

For laser pulses of arbitrary duration but with enough power, the beam propagation results from the interplay of two opposite effects, namely relativistic self-focusing and ionization defocusing [21]. For few-cycle laser pulses at a few per cent of the critical density, another effect plays a major role in laser pulse evolution. Because of the large frequency spectrum associated with these few-cycle laser pulses, the lower-frequency components propagate much more slowly than the highest one. These components are rapidly outrun by the high-frequency ones, resulting in a less intense, longer laser pulse. The interference between the different components can result in a shorter pulse [22], but only over very short distances for the parameters explored here. Thus, to benefit from the ultra-short nature of the laser pulse the plasma must be not longer than a few tens of \(\mu\)m. Getting a well-suited laser propagation requires a careful tailoring of the pulse focusing length and power, as well as the gas density.

Simulations are started with neutral gas composed of 100% nitrogen. The longitudinal density profile (dotted line in figure 1) consists of a 70 \(\mu\)m long plateau at \(n_{\text{atomic}} = 0.009\), \(n_e\), preceded and followed by a 30 \(\mu\)m long ramp. The corresponding plasma density inside the laser envelope, where the gas particles are stripped of their five L-shell electrons, is \(n_e = 0.045\), \(n_c \sim 7 \times 10^{19}\) cm\(^{-3}\). The evolution of the peak absolute value of the normalized vector potential is shown in figure 1 for an optical phase \(\phi = \pi/2\). The maximum vector potential of the laser reached (\(a_0 = 1.4\)) is only slightly larger than the vacuum value, because ionization limits the effect of relativistic self-focusing (the laser power of 0.7 TW is above the critical power for self-focusing at this density, 0.4 TW). All the trapped electrons come from the ionization of \(N^{5+}\) at amplitudes \(a_0 \geq 1.25\). As already mentioned, injection with such a small laser intensity is possible for two reasons. Firstly, the ultra-short duration of the laser pulse allows us to work at relatively high plasma densities close to the resonance condition. The pulse will thus excite a large-amplitude wakefield. Secondly, because of the high density the driven pulse is very slow (\(\gamma_{\text{laser}} \propto 1/\sqrt{n_0} \sim 4.7\)). Thus, the trapping threshold corresponding roughly to \(\gamma = \gamma_{\text{laser}}\) is as low as 2.3 MeV. For example, for a 35 fs laser pulse, the resonance is close to \(5 \times 10^{18}\) cm\(^{-3}\), which corresponds to a trapping threshold of 9 MeV.

Ionization takes place around each maximum of the laser high frequency electric field, i.e. once by optical semi-cycle. Five semi-cycles are responsible for the creation of most trapped
Figure 1. Evolution of the peak absolute value of the normalized vector potential of the laser (the laser beam propagates from the left to the right). The peak amplitude of the individual semi-cycles responsible for the production of self-injected electrons is also shown. The dotted line corresponds to the longitudinal density profile of neutral gas.

electrons. The amplitudes of these semi-cycles, labeled I–V, are also shown in figure 1. At \( t = 0 \), the pulse envelope peak is at \( x = -6 \mu m \). The first semi-cycle (I) is closer to the pulse head than the others, whereas the last one (V) is closer to the pulse tail (see figure 2). Electrons coming from a given optical semi-cycle are packed in a well-defined region of the phase space, forming a small bunch. These bunches are clearly seen in figure 2, which shows the distribution of electrons in the phase space \((x, \gamma)\) at four different times. The number of low-energy or thermal electrons is negligible. Note that electrons produced by two different semi-cycles can be created at the same time. The aggregation of the electron in isolated bunches comes not from different birth times, but from the different initial positions inside the bubble and thus different trajectories in the phase space.

The evolution of the laser pulse visible in figure 2 is rather complex. It results from a superposition of ionization defocusing, relativistic self-focusing and interference of red-shifted components of the pulse that slip backward to the pulse tail. The amplitude of the semi-cycles responsible for creating the trapped electrons varies rapidly, resulting in localized injection of individual bunches. For the final time (340 fs, bottom panel of figure 2), a very red-shifted spectral component of the laser pulse stands over the trapped electrons.

At extraction, the energy dispersion of each individual electron bunch is small due to phase rotation, i.e. electrons at the head of each bunch reach the decelerating region of the bubble. Low-energy bunches are born closer to the bubble center. Phase-space orbits of electrons in these bunches are farther from the separatrix between trapped and non-trapped particles than for higher energy bunches. The maximum energy, reached at the dephasing point, is lower for the inner orbits than for the outer ones. Therefore, phase rotation produces a flattening of the energy distributions of each bunch at a different energy level. The dephasing length is roughly \( 30 \mu m \) for the first bunch injected and \( 15 \mu m \) for the last one. The resulting spectra, shown in figure 3, present narrow peaks, each one corresponding to a given bunch. In this figure, we can see the spectra for three values of the absolute phase, \( \phi = 0, \pi/2 \) and \( \pi \). The energy of the peaks can be continuously shifted by changing the phase, corresponding to the continuous shift of the
Figure 2. Positions in the phase space $x-\gamma$ of trapped electrons at four different times. Electrons coming from ionization produced by a given optical semi-cycle are plotted in the same color. The laser field (dashed line) and the longitudinal field of the wakefield (multiplied by 2, dotted line) are also shown.

injection position. Shifted peaks define an envelope between 10 and 16 MeV, with a maximum around 14 MeV. For $\phi = 0$, the spectrum presents two main peaks, whereas for $\phi = \pi/2$ the low-energy peak shift to the center of the envelope, becoming larger than the others. For $\phi = \pi$, which corresponds to inverting the direction of the electric field, we retrieve the same spectrum as for $\phi = 0$. The total extracted charge is roughly the same for all the phases, $\sim 150$ fC.
Figure 3. Electron energy spectra for three values of the phase, $\phi = 0$, $\pi/2$ and $\pi$. Spectra for $\phi = 0$ and $\pi$ are superposed. The total charge is 150 fC.

Figure 4. Trajectories of electrons belonging to bunches II–IV. The snapshot of electron density (in blue color scale) is taken just before the injection onset.

One way to reduce the energy spread of the electron beam would consist in wiping out all but one of the peaks on the energy spectrum by limiting the injection region to a single optical semi-cycle. For the parameters explored here, at least three semi-cycles are always responsible for the production of injected electrons. Nevertheless, we will show that it is possible to significantly improve the beam quality by taking advantage of a feature of the ionization injection.

Figure 4 shows the trajectories of electrons belonging to bunches II–IV in the plane $(x - v_{laser}t) - y$ for $\phi = \pi/2$, where $y$ is the polarization direction of the pulse. The color scale in this figure shows a snapshot of the electron density at $x = 40 \mu$m, before the beginning of the injection. The laser field points in $-\hat{y}$ in the semi-cycle III and in $\hat{y}$ in the neighbor semi-cycles II and IV. Electrons born in the semi-cycle III receive an extra kick in the $\hat{y}$-direction at the beginning of their trajectories, whereas for electrons born in the semi-cycles II and IV the initial kick is in the $-\hat{y}$-direction. For 30 or 40 fs pulses, ionization takes place in many optical
cycles, and the overall result of the initial finite electric field is an enhancement of the divergence along the polarization direction [23] compared with the case of self-injection. In this case, the initial kick introduces a correlation between the exit angle and the semi-cycle responsible for ionization. As electrons coming from different semi-cycles pack in bunches with a well-defined energy, a correlation between the exit angle and the energy arises.

Even after performing a betatron oscillation, there is still a correlation between the sign of the velocities along \( y \) and that of the initial kick. The electron created in semi-cycle III exits the plasma with \( v_y < 0 \), whereas electrons created in semi-cycles II and IV exit with \( v_y > 0 \). The effect smoothens down to some extent for electrons born farther from the semi-cycle field peak or with a large \( z \)-coordinate. Nevertheless, we will see that the correlation is strong enough to allow the filtering of certain bunches by reducing the spatial acceptance of the system.

Figure 5 shows the spectra obtained by selecting only particles with negative velocity component along \( y \). Far enough away from the gas jet, this corresponds to cutting the upper half of the beam. This can be straightforwardly implemented in the experiment by putting a rectangular foil perpendicular to the laser propagation axis with its lower edge at \( y = 0 \). The spectra for \( \phi = 0 \) and \( \pi \), identical without the mask (see figure 3), become very different from each other with such a foil. For \( \phi = 0 \) the high-energy peak almost disappears, while when inverting the laser field (\( \phi = \pi \)) the high-energy peaks remain almost unchanged and the low-energy one is very small. Note that if the optical phase randomly varies shot-to-shot, the electron peak energy will present a fluctuation of \( \sim 25\% \). Therefore, carrier-envelope phase stabilization is indispensable for avoiding fluctuations of the electron bunch properties in this regime.

For \( \phi = \pi/2 \) (figures 5 and 6) the central peak is close to that obtained without the mask, whereas the charge of both the lower and higher energy peaks is divided by \( \sim 4 \). The resulting electron beam has a charge of 83 fC, an energy spread of 9\% rms and 3\% FWHM. Rms beam duration is close to 0.6 fs, resulting in a current of 140 A. The energy spread of the beam for \( \phi = \pi/2 \) can be further reduced by reducing the acceptance angle, with the drawback of reducing the beam charge. For example, by putting the mask 1 cm far from the gas jet and with its lower edge at \( y = -15 \mu m \), we get an electron bunch with 43 fC and an energy spread of 2.6\% FWHM, and a very low rms energy spread for laser-wakefield acceleration standards, 6\% (full line in figure 6). The rms divergence is 8 mrad in \( y \) and 11 in \( z \).

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Figure 6. Electron energy spectra for $\phi = \pi/2$ for two filtering conditions. Filter I: a mask 1 cm far from the gas jet and with its lower edge at $y = 0$; the upper half of the beam is blocked. Filter II: a mask 1 cm far from the gas jet and with its lower edge at $y = -15 \mu m$.

The simulations we have presented show the promising use of few mJ–5 fs phase-locked laser systems in the production of high-quality relativistic electron beams at kHz repetition rates in the near future. For this regime of injection and acceleration with laser pulses composed of only a few optical cycles, the carrier-envelope phase does affect the injection of electrons in the wakefield, and phase-locking is required for obtaining shot-to-shot stability of the electron bunch. Tuning the phase value and reducing the acceptance angle of the accelerator allow the production of relativistic electron beams with energy spreads smaller than 3% FWHM. The proposed approach will allow us to produce with TW–few mJ laser systems very stable and very-high-quality sub-fs electron beams at kHz repetition rates, of interest for non-destructive material science inspection, medicine and potentially for ultra-fast phenomena studies using electron diffraction techniques [24].

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