All-optical control of electron self-injection in millimeter-scale, tapered dense plasmas.

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\textbf{A B S T R A C T}

It is demonstrated that a laser pulse with an ultrahigh bandwidth ($\Delta \lambda \sim 400$ nm) is an asset for future high-repetition-rate, quasimonochromatic (QME), GeV-scale laser plasma electron accelerators. Manipulating the phase of the driver has a direct impact on evolution of the accelerating bucket (a cavity of electron density maintained by the pressure of the laser pulse radiation), making it possible to control electron self-injection and the final parameters of the QME beam by purely optical means. The large bandwidth makes it possible to compensate for the frequency red-shift accumulated at the pulse leading edge in transit through the plasma. Advancing higher frequencies in time (viz. introducing a negative frequency chirp of the incident pulse) reduces the red-shift, preventing self-compression of the pulse into a relativistic optical shock. This avoids constant expansion of the plasma bucket, suppressing continuous self-injection of copious unwanted electrons, keeping the beam almost free of a high-charge, poorly collimated low-energy tail. In addition, gradually increasing the plasma density in the forward direction locks electrons in the accelerating phase, delaying their dephasing and boosting their energy without increasing the tail. Advantages of this technique are demonstrated here for acceleration in sub-millimeter-length, dense plasmas ($n_0 > 10^{19}$ cm$^{-3}$), using 100-mJ-scale energy laser pulses. Three-dimensional particle-in-cell simulations show that a negatively chirped, 15 TW pulse with a 20 fs length and a bandwidth corresponding to a transform-limited duration below two optical cycles, in combination with a modest density taper (corresponding to 25% linear increase of the density in the forward direction), transfers 3.5% of its energy to a 300 MeV electron bunch with relative energy spread below 4% without increasing the tail. Advantages of this technique are demonstrated here for acceleration in submillimeter-length, dense plasmas ($n_0 > 10^{19}$ cm$^{-3}$), using 100-mJ-scale energy laser pulses. Three-dimensional particle-in-cell simulations show that a negatively chirped, 15 TW pulse with a 20 fs length and a bandwidth corresponding to a transform-limited duration below two optical cycles, in combination with a modest density taper (corresponding to 25% linear increase of the density in the forward direction), transfers 3.5% of its energy to a 300 MeV electron bunch with relative energy spread below 4% and flux a factor 4.5 higher than the average flux in the tail. The acceleration occurs over a 0.6 mm plasma with the electron density at the center of the target $n_0 = 1.3 \times 10^{19}$ cm$^{-3}$. Chirp and taper increase the QME bunch energy by 50% and brightness more than twice, while reducing the average flux in the tail by more than a half. This optically controlled, miniature 100-MeV-scale accelerator naturally affords high-repetition-rate operation important for radiation physics applications.

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1. Introduction

The radiation pressure of a sub-100 fs, relativistically intense laser pulse propagating in a tenuous plasma creates complete electron cavitation, leaving the background ions unperturbed [1–3]. The resulting cavity of electron density (“bubble”) guides the pulse over many Rayleigh lengths while maintaining GV/cm-scale accelerating and focusing gradients. The three-dimensional (3D) structure of electromagnetic fields inside the bubble [4,5] favors conservation of the normalized transverse emittance, whereas electron cavitation relaxes limitations on the charge imposed by beam loading considerations [6]. The shape of the bubble evolves slowly, in lock-step with the optical driver, making it possible to trap initially quiescent background electrons, eliminating the need for an external photocathode [7–14]. Miniature laser-plasma accelerators (LPAs) driven by compact, high-repetition-rate, multi-terawatt (TW) lasers, presently produce tunable, GeV-scale energy, 10–100 pC quasimonochromatic (QME) electron bunches from sub-centimeter plasmas [15,16]. Energy gain and beam quality, which are competitive with conventional linear accelerators [17], and, more importantly, flexibility in electron beam characteristics (inaccessible with standard linacs) make LPAs attractive for various scientific and technological applications [18–21]. This flexibility is rooted in the optical nature of the driver. The nonlinear dynamics of the drive pulse can be controlled by properly shaping its initial phase and amplitude in order to enhance or compensate for nonlinear optical effects within the
plasma. Electron self-injection and the entire acceleration process can thus be controlled by purely optical means [10–15,22–25].

Growing demand for higher electron energies (e.g. for use in compact X-ray sources [20,21]) offsets the main advantage of the LPA—its compactness. Per standard scalings [3], reaching beyond GeV requires cm-length plasmas and petawatt-power lasers [7,26]. Limited availability of the latter, in combination with their low repetition rate and poor beam quality [26–30], presently inhibits progress in the field. Furthermore, increase in the physical dimensions of the experiment greatly complicates predictive modeling [31].

Maintaining high repetition rate implies operation at a modest (10-TW-scale) laser pulse power. At the same time, preserving a mm-scale plasma size and GeV-scale energy gain dictates the choice of a high-density plasma ($n_0 \sim 10^{19}$ cm$^{-3}$) as the accelerator medium. At these high densities, a 10-TW-scale pulse power is sufficient to maintain electron cavitation, yielding important benefits of self-injection and pulse self-guiding through electron dephasing, while keeping the average accelerating gradient, $E_{\text{acc}} > (n_0 \text{cm}^{-3})^{1/2}$ V/cm, in the few-GV/cm range.

With the state-of-art conventional short-pulse laser technology [32], producing fully compressed pulses with a duration of a few tens of fs, this acceleration regime faces two major challenges. First, the short dephasing length (estimated under the assumption of a transform-limited pulse) limits the energy gain in a dense plasma [3,31]. Secondly, massive continuous self-injection (dark current) ruins the beam long before dephasing [9,10,12,13]. This beam quality degradation is very vivid in the experiments conducted with 100-TW-scale lasers at a plasma density above $5 \times 10^{18}$ cm$^{-3}$ [27–30]. Both challenges arise from transformation of the laser driver into a relativistic optical shock (ROS) [33–36], which is physically the same as the soliton effect occurring in optical fibers [37,38]. Ploughing through the plasma increases the laser pulse bandwidth by red-shifting its head, keeping the tail unshifted. The pulse leading edge constantly witnesses a negative gradient in the nonlinear refractive index. The resulting phase self-modulation (PSM) introduces constantly growing frequency red-shift at the location of the index gradient, positively chirping the laser frequency. Negative group velocity dispersion (GVD) associated with the plasma response slows down the red-shifted frequency components, building up intensity at the leading edge, creating a sharp front with a rise time $\sim 1/\omega_0$ (here, $\omega_0 = 2\pi c / \lambda_0$ is the carrier frequency of the pulse, $c$ is the speed of light in vacuum, and $\lambda_0$ is the carrier wavelength). Pulse self-steepening slows down the bubble, reducing the dephasing length and limiting the energy gain [3]. In a dense plasma, $n_0 > 10^{18}$ cm$^{-3}$, the laser frequency downshifts by a large fraction of $\omega_0$ long before electron dephasing. Concurrent self-compression of the pulse forces elongation of the bubble. Continuous injection ensues, which beam loading is unable to terminate, polluting the electron beam with a high-charge, low-energy tail [9,10,12].

To suppress the tail, we propose to delay shock formation using a dispersion compensation technique similar to that employed in fiber optics, compensating for the reduction in frequency (exceeding $-\omega_0/2$) with a proper choice of the initial laser phase. To be practically effective, this approach needs broad frequency spectrum amplifiers delivering few-Joule, near-IR pulses with a bandwidth approaching one-half of the carrier wavelength. One example of this cutting-edge technology is the Petawatt Field Synthesizer presently under development in Max-Planck-Institut für Quantenoptik (MPQ) [39]. Advancing the high frequency components of the incident laser pulse in time (i.e. introducing a negative frequency chirp) reduces the positive chirp due to the PSM. Self-compression of the negatively chirped pulse (NCP) is thus mitigated, continuous injection is suppressed, and the QME electron bunch remains dominant through dephasing. As a bonus, the higher mean frequency of the pulse, together with slower etching of its front, effectively increases the dephasing length, further boosting electron energy [10,12,13].

Here we explore the experimental prospect of using laser systems delivering 100-mJ pulses with an unprecedented broad bandwidth corresponding to the transform-limited duration (TLD) below two optical cycles. Such pulses may become available as a result of upcoming upgrades of the Light Wave Synthesizer (LWS) at MPQ [40]. Presently, the system produces pulses as short as 7.7 fs with peak powers up to 16 TW at $\lambda_0 = 0.8$ μm at 10 Hz repetition rate. Using these fully compressed pulses as LPA drivers allows generation of low-background 20 MeV electron beams from sub-mm-length, very dense plasmas, $n_0 \geq 2 \times 10^{19}$ cm$^{-3}$ [41,42]. Here we demonstrate that increasing the pulse energy by a factor $> 2.5$ (i.e. above 300 mJ) and the bandwidth by a factor 1.5 (TLD $\approx 5$ fs) permits manipulation of the laser phase, helping to control pulse evolution and to optimize the self-injection process without resorting to complicated target geometries, boosting electron energy by an order of magnitude without compromising the beam quality. Our 3D particle-in-cell (PIC) simulations show that stretching the 300 mJ pulse from 5 to 20 fs, introducing the negative frequency chirp, and applying a moderate density taper along the 0.65 mm acceleration distance yields a 300 MeV QME bunch having relative energy spread below 4% and containing $\approx 3.5 \%$ of the incident pulse energy. This QME component dominates the energy spectrum through the entire acceleration process, with flux (number of particles per MeV) more than a factor 4.5 higher than the average flux in the low-energy tail. The beam quality improvements brought about by the manipulations of the laser pulse phase are significant, and are well suited for experimental proof-of-concept. In the longer perspective, raising the pulse energy to the few-Joule level while preserving the frequency bandwidth should enable operation at a repetition rate over 100 Hz, making this miniature 100-MeV-scale LPA an important scientific instrument for radiation physics applications.

The paper is organized as follows. The physical problem is formulated and numerical aspects of reduced and full 3D PIC simulation methods are outlined in Section 2. Results and discussion are presented in Section 3. Section 4 provides concluding remarks and points out directions of future work.

2. Simulation methods and initial conditions

We optimize the laser propagation regime and acceleration process by using a combination of reduced and full 3D PIC simulations. Nonlinear optical dynamics of the driver is explored, and the optimal initial phase is found using the cylindrically symmetric, time-averaged (over the period of laser field oscillations) quasistatic code WAKE [1]. Non-quasistatic simulations with the fully explicit code CALDER-Circ [43] yield a complete kinetic description of the electron beam, demonstrating suppression of continuous injection and increase of final electron energy. WAKE computes the complex pulse envelope using an extended paraxial solver. To preserve GVD over a broad frequency range and to calculate precisely radiation absorption due to wake excitation in the situation with large frequency shifts [44,45], we use the longitudinal grid $\Delta \xi \approx \lambda_0 / 15.5 \approx 51.6$ nm (here, $\xi = ct - z$). The radial grid is three times coarser. We take 30 particles per radial cell and the time step $\omega_0 \Delta t = 0.67$. Under these conditions, WAKE correctly captures all relevant physics of pulse propagation and evolution of the bubble [9,12,44,45]. CALDER-Circ uses the grid

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1. Terminating acceleration before dephasing may reduce or even completely eliminate the tail, preserving the dominant QME feature [8–10,15,27]; however, electron energy and accelerator efficiency cannot be maximized this way.
\[ \Delta z \approx \lambda_0/50 \approx 16 \text{ nm} \text{ and } \Delta r = 15.6 \Delta z, \text{ where } r = (x^2 + y^2)^{1/2}, \text{ with 45 particles per cell and } \omega_0 d t = 0.1244. \]

In all cases, the plasma has a 0.85 mm length [similar to experiments at MPQ [41,46]], with 0.1 mm entrance and exit ramps, and electron density at the center \( n_0 = 1.3 \times 10^{19} \text{ cm}^{-3} \). A linearly polarized Gaussian laser pulse with \( \lambda_0 = 0.8 \mu \text{m (} \omega_0/\omega_p \approx 11.6\text{), 15 TW power [} P/P_\infty \approx 0.9, \text{ where } P_\infty = 16.2(\omega_0/\omega_p)^2 \text{ GW is the critical power for the relativistic self-focusing}], \) and peak intensity 2.72 \times 10^{19} \text{ W/cm}^2 is focused at the plasma border and propagates in the positive z-direction. The complex amplitude of its vector potential (normalized to \( m_e^2 c^2/|e| \)) is \( a(z = 0) = a_0 \exp(-r/r_0^2 - 2 \ln(2(\pi r_1)^2 + i\eta t)), \text{ where } a_0 = 3.545, \tau_1 = 20 \text{ fs (} \omega_0 \tau_1 = 4.07), \text{ and } r_0 = 5.75 \mu \text{m (} \omega_0 r_0/c = 3.9). \text{ Here, } \omega_0 = (4\pi^2 n_0 m_e/\lambda_0)^{1/2} \text{ is the electron Langmuir frequency; } m_e \text{ is the electron rest mass; } e \text{ is the electron charge. The pulse is thus matched for self-guiding, } \omega_0 r_0/c \approx 2\sqrt{\omega_0}, \text{ with estimated dephasing length 0.52 mm and peak electron energy 175 MeV [3].} \text{ The rate of phase variation defines an instantaneous frequency, } \alpha(t) = -d\phi/dt = \omega_0 + (4 \ln 2)\sigma(k/\tau_1)^2 t. \text{ Simulations with a transform-limited, 20 fs-length pulse (} k = 0 \text{) in the flat-top plasma are subsequently referred to as the reference case. To combat ROS formation, we temporally advance high frequencies (} \sigma = -1 \text{) and increase the bandwidth by a factor of } 4 (k = 1.968), \text{ keeping other parameters unchanged. Such NCP may be obtained by undercompressing a 60-TW, 5-fs pulse of the upgraded LWS. Acceleration with the NCP in a flat-top plasma is subsequently referred to as NCP-FTP.} \text{ This case was considered in detail in Ref. [13]. Here, we complement that study by introducing a moderate density taper, raising the plasma density from } 1.15 \times 10^{19} \text{ cm}^{-3} \text{ (at } z = 0.1 \text{ mm) to } 1.45 \times 10^{19} \text{ cm}^{-3} \text{ (at } z = 0.75 \text{ mm) to lock electrons in the accelerating phase, boosting their energy. (A tilt of a gas jet with respect to the pulse propagation direction can produce the necessary taper in an experiment.) This latter case is referred to as NCP-FTP.} \]

### 3. Results and discussion

#### 3.1. Laser pulse evolution

Fig. 1 demonstrates new features of the laser pulse dynamics brought about by the negative frequency chirp and density taper. Most aspects of the pulse evolution, such as depletion, self-compression, frequency red-shift, and spectral broadening, are insensitive to the modest density taper. Conversely, the introduction of chirp fundamentally alters the pulse evolution. Fig. 1(b) shows the pulse length computed as a \( \xi \)-variance of the energy density on axis,

\[
\langle \Delta r(z) \rangle = \sqrt{8} \ln 2 \left( \frac{\int_{-\infty}^{\infty} (\xi - c(t))^2 |a(0, z, \xi)|^2 d\xi}{c^2 \int_{-\infty}^{\infty} |a(0, z, \xi)|^2 d\xi} \right)^{1/2},
\]

where
c(t) = \int_{-\infty}^{\infty} \xi a(0, z, \xi) d\xi \left( \int_{-\infty}^{\infty} |a(0, z, \xi)|^2 d\xi \right)^{-1}

is the position of the pulse centroid. Fig. 1(d) and (e) shows radially integrated mean frequency and frequency variance

\[
\langle \omega(z) \rangle = \int_0^\infty r dr \int_0^{\infty} \omega^2 |a(r, z, \omega)|^2 d\omega \omega_0 \sum_0 \int_0^{\infty} \omega |a(r, z, \omega)|^2 d\omega
\]

\[
\langle \Delta \omega(z) \rangle = \left( \int_0^\infty r dr \int_0^{\infty} (\omega - \omega_0)^2 |a(r, z, \omega)|^2 d\omega \right) / \omega_0^2 \sum_0 \int_0^{\infty} \omega |a(r, z, \omega)|^2 d\omega \right)^{1/2}
\]

Fig. 1(c) and (d) indicates that the pulse energy and mean frequency drop by the end of the interaction by approximately 40% in the reference case, and only by 30% in the NCP case. Fig. 1(e) shows that in the reference case the frequency variance (2) increases more than 10-fold as the pulse depletes. In contrast, the NCP bandwidth is preserved through 65% of the propagation length, and its increase through the rest of the interaction is not nearly as great as in the reference case. Pulse contraction occurs in all cases, with \( \langle \Delta r \rangle \) dropping nearly by half. In the reference case, however, the pulse fully compresses long before the end of the density plateau and then rapidly spreads out as newly generated mid-IR photons slide into the plasma bucket. Conversely, the chirped pulse shrinks steadily and becomes fully compressed only near the plasma exit.

Fig. 2 complements the integral characteristics displayed in Fig. 1(d) and (e). It links longitudinal distortion of the pulse [cf. axial lineouts of normalized intensity in panels (a) and (b)] to the local frequency shift on axis [panels (d) and (e)]. The shift is extracted from the complex envelope of the vector potential, \( a(0, z, \xi) = a(0, z, \xi) \exp[-i(\omega_0 - \omega_0 \xi)] \) \( d\xi \) is the Fourier transform of the vector potential with respect to \( \xi = \xi/c \). The mean frequency (1) is essentially a ratio of the pulse energy to the pulse action [45]. The extended paraxial solver of WAKE approximately conserves the action [44]; therefore, the mean frequency declines in proportion to pulse energy depletion [47].

\[ \rho_\text{photon} = \frac{1}{2} \int_{-\infty}^{\infty} a^2 (\xi + E/2, 2) d\xi \text{ d}z \text{.} \]

yields the distribution of “photon density” in the “photon phase space,” \( (\xi, \omega) \). Secondly, we calculate the “instantaneous” frequency as the rate of the envelope phase change, \( \omega(\xi) = \omega_0 - d\phi/dt = \omega_0 + c\phi/d\xi \).
Fig. 2(a) and (b) shows that the pulse leading edge rides on the co-moving negative gradient in the nonlinear index. The positive frequency chirp develops along the gradient, red-shifting the pulse head by a large fraction of the carrier frequency, while leaving the tail unshifted. Plots of radially integrated spectral power $S(z, \omega) = \int_0^\infty \omega^2 d(\tau, z, \omega)^2 \mathrm{d}\tau$ in Fig. 2(c) indicate that the frequency spectrum extends toward $\omega - \omega_p$. In full agreement with Fig. 1(e), the pulse bandwidth increases by an order of magnitude in the reference case, and nearly doubles in the NCP-TP case.

CVD slows down the red-shifted frequency components, building up the field amplitude in the pulse head, causing a noticeable steepening of the pulse. In the reference case, however, the process goes further than just steepening. By the end of the interaction, the entire pulse becomes red-shifted. As a result, its envelope, depicted in Fig. 2(a), starts oscillating in the tail area. Fig. 2(d) shows that the red-shifted mid-IR photons slide inside the bubble, etching away the pulse front, mixing with the unshifted radiation. Mixing radiation of different frequencies and uncorrelated phases leads to sharp variations of the envelope phase, making the local frequency poorly defined. Not only does this “photon phase space rotation” fill the bubble with mid-IR radiation, $\lambda \approx 0.1\lambda_0$ [48,45]; Fig. 2(a) indicates that it also compresses the pulse to nearly a single cycle [33], producing a ROS. This strong compression, accompanied by $\approx 27\%$ reduction in mean frequency and energy, is consistent with the local frequency bandwidth, $\Delta \omega \approx 0.2\omega_p$, obtained from Fig. 1(e). With this modest energy loss, the fully compressed pulse preserves relativistic intensity $|a| \approx 7.75$, acting on the ambient plasma electrons as a snow-plow, causing elongation of the bubble [10,12]. Indeed, the ponderomotive push of the ROS compresses electrons in front of the bubble into a co-moving slab 4 times denser than the ambient plasma. The resulting strong charge separation increases the positive (decelerating) longitudinal electric field acting on the sheath electrons immediately behind the driver. Passing the ROS, these electrons receive strong backward kick and quickly become relativistic. It takes a long time for them to return back to the axis, which explains elongation of the bubble [cf. Fig. 2(f), top].

The negative chirp mitigates ROS formation. Temporal advancement of high frequencies compensates for the nonlinear red-shift, preserving the pulse bandwidth for a long time, slowing down the photon phase space rotation. Fig. 2(e) shows that the frequency red-shift remains localized at the pulse leading edge, yielding merely a 12% reduction in the mean frequency. There is no sign of photon phase mixing inside the bubble. The instantaneous frequency is thus well-defined and single-valued, showing minimal oscillations. In contrast to the reference case, the pulse in Fig. 2(b) is not yet fully compressed. Its full width at half-maximum in intensity is two optical cycles, and the intensity build-up is only a half of that of the reference case. Weaker compression of the NCP reduces the snow-plow effect thereby suppressing the bubble expansion [cf. Fig. 2(f), bottom]. Fully kinetic CALDER-Circ simulations show that stabilization of the bubble suppresses the dark current.

3.2. Evolution of the bubble and dynamics of electron beam formation and acceleration

Fig. 3 correlates self-injection with the bubble evolution using data from CALDER-Circ simulations. The length of the accelerating phase (the size of the area inside the bubble where the electric field is negative) evolves in lock-step with the optical driver. In the reference and NCP-FTP cases, contraction, expansion, and stabilization of the bubble during the early stage of propagation are followed by continuous expansion caused by the driver pulse transformation into a ROS. In both cases, expansion begins around $z=0.45$ mm. Introduction of the chirp slows pulse self-compression, reducing the bubble expansion rate by half. Addition of the taper extends the interval of bubble stability to $z \approx 0.65$ mm.

Fig. 3(b) indicates that all accelerated particles are collected from a conical cylindrical shell with a radius slightly smaller than the bubble radius; thus they all have initial radial offsets of sheath electrons. This collection volume is insensitive to the chirp, taper, and details of the bubble evolution. There is no evidence of self-injection from the near-axis region [49]. The correlation between electron energy and their initial $z$-positions, displayed in Fig. 3(c), reveals two distinct features of the beam: the highest-energy QME bunch that consists of particles injected during the period of the most rapid bubble expansion between $z \approx 0.2$ and $0.33$ mm, and the continuous tail (dark current) accumulated through the rest of
the plasma. As soon as the bubble stabilizes near $z=0.4$ mm, the electron energy spread drops below 10% via phase space rotation [7–11] and remains at this level. The integrated charge per energy interval shown in the inset in Fig. 3(c) demonstrates that the combination of chirp and taper noticeably reduces the tail, boosting the energy of the QME bunch.

Our first task is to find for how long the QME bunch can be accelerated in plasma and how much energy can it gain without growing a significant low-energy tail (viz. with the flux in the tail not exceeding 10% of the peak). Electron energy spectra and data presented in Fig. 4(a) and Table 1 provide the answer. Table 1 shows: the energy corresponding to the spectral peak, $E_{\text{peak}}$; the root-mean-square (RMS) energy spread, $\sigma_E$; the RMS normalized transverse emittance, $\epsilon^\theta = (\langle r^2 \rangle - \langle r \rangle^2)^{1/2}$, where $\epsilon^\theta = (m_\text{ec})^{-1} (\langle p_x^2 \rangle - \langle p_x \rangle^2)^{1/2}$; the total charge, $Q$; the RMS bunch duration, $(\Delta t_B)$; the average current, $(I)$; and the total energy of the bunch (a measure of accelerator efficiency). We also show the average flux, $(F) = Q/(\sigma E)$, and average brightness, $(B) = (m_\text{ec} c^2)^{-2} (F) (E_{\text{peak}}/\epsilon^\theta)^2$, which is proportional to the particle density in the phase space. These quantities are commonly used in beam physics to assess the quality of the particle source [15,50]. Combination of chirp and taper delays accumulation of the tail by $\approx 12\%$ of the acceleration distance, reducing the charge of the QME bunch nearly by half and boosting its energy by $\approx 40\%$ (from 182.5 to 260 MeV). As regards the beam brightness, advantages of much quieter injection and energy boost outweigh reduction of the charge. Data from Table 1 show that the chirp and the taper together reduce the beam energy spread by 37%, and normalized transverse emittance by 25%, increasing $(B)$ by a factor 2.25 against the reference case.

The LPA beams with parameters presented here are in some aspects superior to those delivered by conventional 100 MeV linear accelerators. As an example, a 75 MeV linac, used in experiments on generation of sub-picosecond THz pulses at the Pohang Accelerator Laboratory [17], produces beams with the energy spread below 1%, $\epsilon^\theta \approx 5$ mm mrad, $Q > 0.2$ nC, $(\Delta t_B) > 75$ fs, and $(B) \approx 3$ kA, at a 10–30 Hz repetition rate. In contrast, the data presented in Table 1 show an order-of-magnitude higher current and 1-fs-scale bunch duration, which makes such LPA beams very attractive as drivers of fs-scale pulsed X-ray sources [20,21]. Besides, in most situations, the LPA beams are produced at a repetition rate similar to that of linacs, and are tunable in a broad energy range [15,16].

The next task is maximizing the beam energy, accelerating electrons through dephasing. At this point, we are also interested in individual contributions of the chirp and the taper to the structure of electron spectrum. In the reference case, electrons

![Fig. 3. Evolution of the bubble and electron self-injection (CALDER-Circ simulations).](image)

(a) Variation of the accelerating phase length (on axis) in the course of propagation in the reference (black), NCP-FTP [green (light gray)], and NCP-TP [red (gray)] cases. The accelerating phase is the region of negative longitudinal electric field inside the bubble. (b) Collection volume: initial radial offsets of accelerated electrons $R_{\text{tot}} = \sqrt{\langle x^2 \rangle + \langle y^2 \rangle}$ vs. their initial longitudinal positions, $z_{\text{in}}$. (c) Collection phase space: longitudinal momenta of accelerated electrons vs. $2z_{\text{in}}$. Markers are the particles with $E > 50$ MeV reaching $z=0.78$ mm in the reference (black) and NCP-TP [red (gray)] cases. Inset shows the normalized integrated charge.

![Fig. 4. Electron energy spectra in the reference (black), NCP-FTP [green (light gray)], and NCP-TP [red (gray)] cases (CALDER-Circ simulations).](image)

Panel (a) shows the highest energy gain achievable without accumulation of a tail. The spectrum in the reference case is taken at $z=0.624$ mm; in the NCP-FTP case at $z=0.663$ mm; and in the NCP-TP case at $z=0.676$ mm. Beam statistics are summarized in Table 1. Panel (b): acceleration in a flat-top plasma. Thin green (light gray) curve is the spectrum in the NCP-FTP case at $z=0.65$ mm. Thick curves are the spectra at the end of the density plateau, $z=0.78$ mm (the dephasing point in the reference case). The negative chirp boosts electron energy by 15% and reduces the flux in the tail roughly by half. Panel (c) shows electron spectra at $z=0.78$ mm (beam statistics are presented in Tables 2 and 3). The taper boosts electron energy, while the chirp suppresses the tail. Panels (a) and (c) demonstrate that the chirp and the taper together maintain, on average, 40% higher electron energy against the reference case through the entire acceleration process.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference</th>
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<th>NCP-TP</th>
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<td>$z$ (mm)</td>
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</table>
reach dephasing just at the beginning of the exit ramp \(z=0.78\) mm). At this point, spectra presented in Fig. 4(b) and (c) (black curves) show a prominent low-energy tail. Fig. 4(b) demonstrates that the introduction of a chirp reduces the average flux in the tail nearly by half by the end of acceleration, boosting the energy by 15%. Statistical data from Table 2 also show reduction of the emittance and energy spread, resulting in \(\approx 50\%\) increase of brightness. Remarkably, the same energy gain as in the reference case near dephasing can be achieved with the negatively chirped pulse sooner (at \(z=0.65\) rather than 0.78 mm), with 15% lower energy spread, and a factor 5 lower in the tail [thin green (light gray) curve in Fig. 4(b)].

Electron energy spectra at the end of acceleration \((z=0.78\) mm\) are presented in Fig. 4(c). At this point, statistics for the QME bunches (Table 2) and the tails (Table 3) make it clear that it is the negative chirp that cleans up the beam, keeping the tail low (also yielding a modest, 15%, energy boost). The density taper, on the other hand, increases the energy by additional 25%, while preserving the tail. Together, the chirp and taper maintain \(\approx 40\%\) higher QME electron energy throughout the entire acceleration process, doubling the brightness against the reference case, allowing 300 MeV energy gain over merely 0.6 mm accelerating distance, transferring 3.5% of the driver pulse energy the bunch, preserving \(\approx 3\) mm mrad emittance and less than 4% energy spread. This significant improvement of the beam quality is well suited for proof-of-principle experiments. Furthermore, poorly collimated electrons from the tail, which are distributed over the energy range 20 times broader than the energy spread of the QME bunch, can be effectively dispersed in vacuum using miniature magnetic quadrupole lenses, further improving the beam collimation and reducing the energy spread \([51,52]\).

4. Summary and outlook

All-optical control of electron beam acceleration in very dense plasmas \((n_0 > 10^{19} \text{ cm}^{-3})\) promises electron beam quality competitive with that of the beams obtained in the same energy range (up to 300 MeV) in experiments on a much larger scale (requiring an order-of-magnitude higher laser energy and a several times longer plasmas \([15,16]\)).

Anticipating exciting developments in the laser technology leading to 100 TW-class pulses of a sub-2-cycle duration \([39,40]\), we demonstrate the advantage of their ultra-wide bandwidth for all-optical control of electron beam quality in the blowout regime of laser-plasma acceleration. Under-compressing the pulse and temporally advancing higher frequencies (i.e. introducing a negative chirp) compensates the red frequency shift produced by wake excitation. This prevents rapid self-compression of the pulse and keeps the dark current low over the entire dephasing length. QME electron beams with the energy above 200 MeV can be thus generated in dense plasmas, \(n_0 \sim 1.3 \times 10^{19} \text{ cm}^{-3}\), over a 0.6 mm distance. Further increase of the laser energy (by an order of magnitude) would allow working at lower densities \((n_0 \sim 5 \times 10^{18} \text{ cm}^{-3}\) ), reaching a GeV energy level over less than 2 mm-length distance \([12]\). Tapering the target (viz. gradually increasing the plasma density along the laser path) should further suppress the bubble expansion, locking electrons in the accelerating phase, boosting their energy, leading to GeV electron beams of uncompromised quality with characteristics suitable for most challenging applications (such as all-optically driven compact γ-ray sources).

We conclude that investment into new pulse amplification techniques allowing for ultrahigh bandwidth (approaching the carrier wavelength) is as important for the design of future compact, high-repetition-rate, GeV-scale LPAs as investments into the approaches increasing the laser pulse energy without increase of the bandwidth.

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