

Plasma dechirper and lens for electron beams from laser wakefield acceleration in a tailored density profile

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Achieving high-quality electron beams from laser wakefield accelerators critically relies on density tailoring to control electron dynamics during injection, acceleration, and extraction. We report on the experimental observation of electron beam acceleration and shaping, in transverse momentum and longitudinal phase space, controlled by plasma density tailoring in a gas cell. Electron beams with a FWHM charge of 40 pC at an energy of 190 MeV, 3.4% energy spread and an rms divergence of 0.46 mrad, corresponding to a transverse momentum spread of 0.2 $m_e c$, have been measured. These beams have a peak spectral brightness of up to 8 pC/MeV/mrad. Simulations using experimental parameters as input show that acceleration in the plasma plateau leads to chirped electron beams which then undergo transverse momentum spread reduction in a plasma down-ramp followed by dechirping in a 10 mm long plasma tail, leading to the measured peaked spectra. The comparison of experimental results with and without long plasma tail confirms this analysis.

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In laser wakefield acceleration (LWFA) [1,2], a high intensity, short laser pulse (a few 10 fs level) travels through an underdense plasma, generating plasma waves. Under the effects of the accelerating electric field sustained by these waves, trapped electrons can gain energies in excess of hundreds of MeV over a few millimeters [1–3]. Due to strong accelerating gradients, different longitudinal parts of the electron beam may experience different accelerating field amplitudes, resulting in large energy spreads.

However, small energy spread electron beams are needed for applications, and several mechanisms to decrease it have been investigated. Correlated energy spreads can be minimized during acceleration using mechanisms such as beam loading [4,5], which flattens the accelerating field [6,7]; rephasing [8,9], which shifts the relative phase of the

wakefield accelerating the electron beam to compensate for chirps; and quasi-phase-stable acceleration [10], in which the electron beam remains in an almost stable phase during acceleration. Alternatively, postacceleration compensation methods, such as plasma dechirpers, can be used to mitigate energy chirps. In a plasma dechirper, the wakefield driven by the front of the electron beam causes the rear of the beam to experience a decelerating field, decreasing the overall energy spread. Plasma dechirpers for ps-time duration beams originating from rf-accelerators have been demonstrated [11,12]. While schemes have been proposed to dechirp beams from an LWFA using a plasma dechirper [13], they have not yet been demonstrated experimentally.

To successfully transport or utilize electron beams from LWFA, reducing their divergence is essential [14–17]. This is achieved by minimizing the beam's transverse momentum spread (TMS). Passive plasma lensing is a key method to decrease this TMS, utilizing the transverse focusing forces of plasma waves to collimate the charged particle beam [18]. Implemented downstream of an LWFA using separate components or shaped density profiles, these lenses [9,19–21] have been observed to reduce beam divergence by a factor of 2. Plasma lens accompanied by emittance preservation is referred to as adiabatic

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matching [22–25]. In the beam driven regime, it has been theoretically shown that the electron beam driving its own wakefield can impart a focusing force on the rear part of the beam [26].

Here we report the first experimental demonstration of postacceleration spectral and transverse shaping, drastically improving the quality of a chirped beam produced by LWFA, achieving both transverse lensing and longitudinal dechirping within a single, tailored plasma structure. A plasma density down-ramp is used to reduce adiabatically the electron beam transverse momentum spread; it is followed by a long, low-density plasma tail (LPT), where the beam drives its own wakefield and undergoes further collimation and energy spread compression. This process ultimately yields relativistic electron beams with a low TMS of $0.2\ m_e c$ and energy spread of 6 MeV.

Experiments were performed using the DRACO laser at Helmholtz-Zentrum Dresden Rossendorf, a Ti:Sa laser system with carrier wavelength $\lambda_0 = 0.8\ \mu\text{m}$ providing up to 2.5 J energy on target, in 30 fs FWHM pulse length with a repetition rate of up to 0.1 Hz. This laser was focused to a spot size of $24\ \mu\text{m}$ FWHM into a double compartment gas cell, as illustrated in Fig. 1. This is achieved using an off-axis parabolic mirror ($f/20$) with a focal length of 2 m. Shot-to-shot fluctuations from the nominal conditions were monitored using a local pressure gauge on the gas cell, spectral-phase interferometry for a direct electric-field reconstruction (SPIDER) for laser spectral phase, and three focus-imaging cameras [27,28].

We designed a gas cell with variable and replaceable mechanical parts to allow for shaping the density profile, as illustrated in the insets in Fig. 1. The density profile used in the first experiment, with fixed LPT, is shown in Fig. 1(b) where injection and acceleration occur in the high density region ($0 < x < 3.5\ \text{mm}$), which is divided into two compartments. A nitrogen-hydrogen mixture is injected into the first compartment and pure hydrogen into the second. Ionization injection [20,21,32–38] is used to trap electrons in the wakefield, while fine control of injection location is achieved by tailoring nitrogen density between the two compartments [7,39]. The two filling pressures are controlled independently, and pulsed gas injection at equal pressures ensures proper confinement [40] of the nitrogen component in the first part of the density profile. The plateau gas densities were obtained from interferometer measurements. The gas density distribution resulting in the plasma density shown in Fig. 1 was derived by a parameterization of results obtained with the computational fluid dynamics code OpenFOAM [41,42] using the multicomponentFluid package combined with the PIMPLE solver for modeling supersonic multi-component flows. The second density down-ramp, following the plateau of density n_2 , is created by an $800\ \mu\text{m}$ orifice at the outlet. This orifice leads to a cylinder of 4 mm diameter and 10 mm length, which creates an

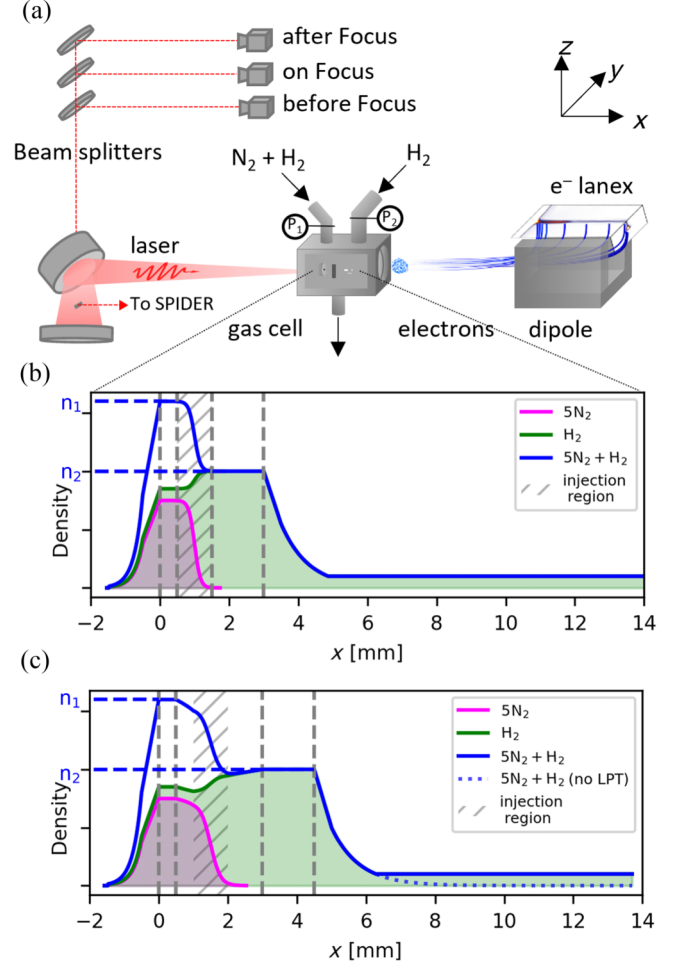


FIG. 1. Schematic of the experimental setup. (a) The laser pulse, propagating along x and linearly polarized along y , is focused onto a gas cell target with two compartments, which provides the desired density profile. Three cameras monitor the laser focus shot-to-shot; a SPIDER tracks the laser spectrum; and two gauges monitor shot-to-shot pressure. The focus position is defined relative to the entrance of the cell, which is at $x = 0\ \text{mm}$. In the inset, blue: electron density from hydrogen and the first five levels of nitrogen, composing the background plasma; magenta: density of the electrons from the first five levels of nitrogen. n_1 and n_2 are the plasma electron densities on the density plateau of the first and second compartments, respectively. Insets: density profiles along the laser propagation axis (b) with fixed LPT for first experiment, (c) with removable LPT and differential pumping [29] between compartments for second experiment. Electron beams are characterized with a spectrometer which has a readout error of 1.4% and 2.2% in divergence and energy, respectively [30,31]. The distance between the gas cell exit and the dipole is 65 cm.

LPT of almost constant low electron density [$n_{\text{LPT}} \approx 4 \times 10^{16}\ \text{cm}^{-3}$ for the case of Figs. 2(a) and 2(e)] [28].

For the gas cell shown in Fig. 1(b), achieving optimized electron spectra requires tuning of the laser focal position and plasma density parameters. The optimum is found for

a pressure of 20 mbar in both compartments and a 15% nitrogen concentration in the first, corresponding to plateau densities $n_1 = 1.6 \times 10^{18} \text{ cm}^{-3}$ and $n_2 = 1 \times 10^{18} \text{ cm}^{-3}$, with laser focus at $x = 2.4 \text{ mm}$.

The characteristics of 130 shots recorded during the first experiment for nominally constant input parameters (laser energy, focus position, and gas pressure) are shown in Fig. 2 ordered by increasing mean energy: spectrum (a) and for each shot the corresponding total charge Q_T (b), median absolute deviation (MAD) energy spread (c), and transverse momentum spread (d). The shot-to-shot pointing standard deviation is 0.26 mrad.

Figure 2(e) shows the divergence-energy space of the optimal beam (ii) of Fig. 2(a). This specific shot is characterized by a peak spectral density approaching 8 pC/MeV and a spectral brightness approaching 6 pC/MeV/mrad.

The divergence-energy space distributions for each shot are matrices $dQ/d\theta_y dE|_{ij}$ in pC/MeV/mrad for each energy $E_j = \gamma_j m_e c^2$, and angle $\theta_{y,i}$, where γ is the Lorentz factor. For ultrarelativistic beams ($\beta_x \approx 1$), $\theta_y \approx p_y/p_x$, where p_y (p_x) is the transverse (longitudinal) momentum. At the indices i, j the transverse momentum along y is $p_{y,i,j} \approx \theta_{y,i} \gamma_j$. The TMS of these distributions was computed as $\sigma_{p_y}^2 = \langle (p_y - \langle p_y \rangle)^2 \rangle$, where $\langle p_y \rangle$ is the average of p_y , calculated over the indices ij using $dQ/d\theta_y dE|_{ij}$ as the statistical weights. We plot the TMS determined from this discretization in Fig. 2(d) for all charge above 100 MeV. The TMS is almost independent of the spectral energy. The spectra in this set have an average $\sigma_{p_y} = 0.23 \pm 0.03 m_e c$.

When the peak energy is increased from 140 MeV [Fig. 2(e)] to 190 MeV [Fig. 2(f)] the divergence is decreased from 0.67 to 0.46 mrad while the TMS remains constant. This peak energy increase was achieved by increasing the density in both compartments by a factor of 1.7 (i.e., $n_2 = 1.7 \times 10^{18} \text{ cm}^{-3}$), which also increased the density of the LPT by a factor of 1.7. The laser focus was adjusted to $x = 2.9 \text{ mm}$, while all other parameters remained unchanged [28]. The total charge and the charge in the FWHM are similar to the lower density case, as shown in Table I. The resulting decrease of divergence leads to peaks with an increased spectral brightness of 8 pC/MeV/mrad compared to the 20 mbar case.

To gain insight into the physical processes leading to measured electron spectra, we performed particle-in-cell (PIC) simulations [43] using the code Smilei [44], with a quasi-cylindrical geometry with azimuthal Fourier decomposition [45], employing two azimuthal modes [28]. Experimental laser and plasma parameters were used as input, together with the longitudinal hydrogen and nitrogen density profiles obtained from the parameterization of corresponding fluid simulations. The laser field distribution was modeled as a focused flattened Gaussian beam (FGB) [46] with an order $N = 8$, a waist parameter of

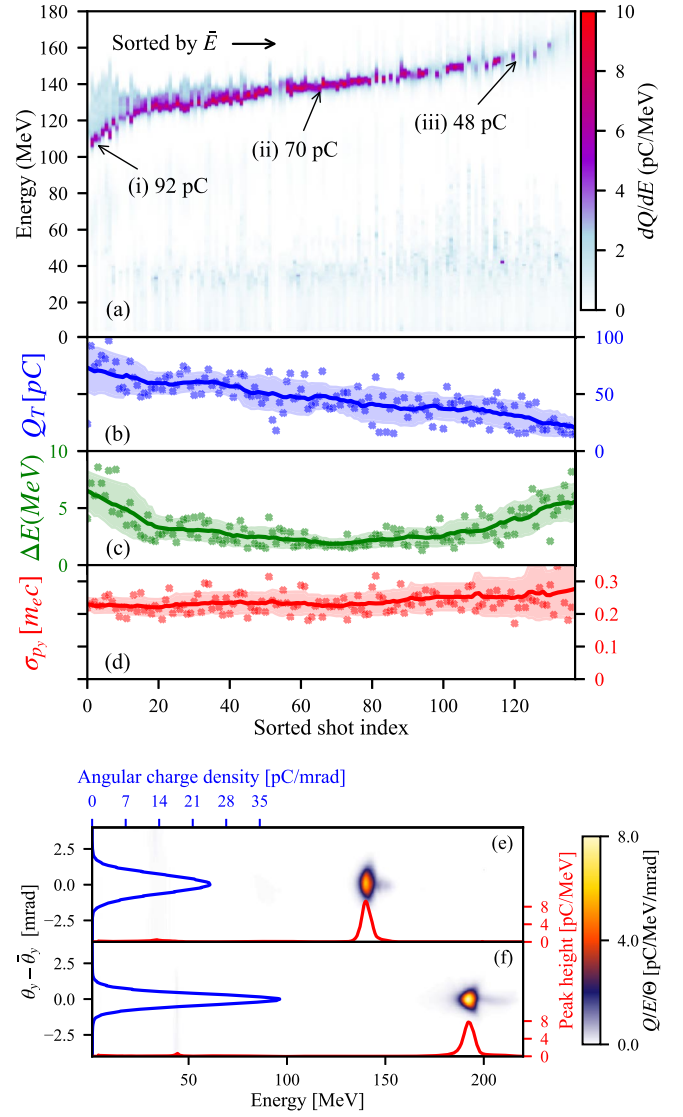


FIG. 2. Experimental results showing the energy spectrum and energy-angle distribution of measured electron beams. (a) Water-fall graph of energy spectra, ordered by increasing mean energy in the spectrum for a pressure of 20 mbar ($n_2 = 10^{18} \text{ cm}^{-3}$); spectra labeled (i)–(iii) are compared with simulations in Fig. 4; (b) corresponding total charge Q_T ; blue line and shaded area are the moving average and standard deviation computed across 15 adjacent shots, respectively. (c) MAD energy spread; (d) transverse momentum spread along laser polarization direction y ; (e) and (f) are the energy-angle distributions of two electron beams obtained at 20 and 35 mbar ($n_2 = 1.7 \times 10^{18} \text{ cm}^{-3}$), respectively. The pointing, $\bar{\theta}_y$, is -0.57 mrad for (e) and -0.45 mrad for (f).

$w_0 = 14 \text{ }\mu\text{m}$, and a Gaussian temporal profile with a pulse duration (FWHM of intensity) of 30 fs. This FGB fit was determined from fluence measurements taken at various positions along the laser axis around the focus [47,48]. The fitting procedure provides a shot-to-shot estimate of the longitudinal focal-position jitter of between ± 100 and

TABLE I. Summary of electron beam parameters for first experiment. [Exp] and [Sim] refer to measured and simulated parameters extracted at the end of the simulation. E_{peak} : energy of the spectrum peak; ΔE : FWHM width of the energy spectrum peak; Q_T : total charge in the spectrum; Q_{FWHM} : charge in the FWHM peak of the energy spectrum; θ_{rms} : rms divergence along the direction y for the FWHM energy slice; σ_{p_y} : rms spread in the normalized transverse momentum along y for the FWHM energy slice.

Parameter	Unit	2(e) [Exp]	2(f) [Exp]	3 and 4(ii) [Sim]
E_{peak}	MeV	140	193	140
ΔE	MeV	5.6	6.5	9.0
Q_T	pC	70	72	74
Q_{FWHM}	pC	41	41	41
θ_{rms}	mrads	0.67	0.46	1.07
$\sigma_{p_y}^{\text{FWHM}}$	$m_e c$	0.18	0.17	0.30

$\pm 200 \mu\text{m}$. The normalized maximum laser electric field component along y , $a_0 = \max[|E_y|]/(2\pi m_e c^2/e)\lambda_0$, was set to be $a_0 = 2.3$ in vacuum at the focal plane.

In order to compare simulation and experimental results, we focus on the characteristics of the particles in the FWHM energy slice, in particular, ΔE : FWHM width of the energy spectrum peak, Q_{FWHM} : the amount of charge in this energy slice and $\sigma_{p_y}^{\text{FWHM}}$: the transverse momentum spread of electrons within the FWHM energy slice. For the optimal shot in Figs. 2(a-ii) and 2(e), the comparison of the results of the simulation and experiment is given in Table I.

Figure 3 illustrates the laser normalized peak electric field propagation along the plasma density distribution (a), the electron beam longitudinal and transverse phase space (b), and the associated emittance (c) for the optimal shot in Figs. 2(a-ii) and 2(e). In Fig. 3(a), the points where the ionization of N^{5+} and N^{6+} starts and ends are shown by a blue disk and a red star, respectively. Injection occurs within the first plasma density down-ramp of length $500 \mu\text{m}$. The decrease of plasma density in the first down-ramp elongates the plasma wave and facilitates the trapping of nitrogen electrons from the sixth and seventh energy levels released by ionization [7,17,49,50]. The laser intensity drops rapidly in the second down-ramp ($x \simeq 4 \text{ mm}$), decreasing below the relativistic threshold ($a_0 < 1$) toward the end of the down-ramp. However, it remains intense enough ($a_0(x = 15 \text{ mm}) = 0.2$) to ionize hydrogen gas in front of the electron beam. The total charge Q_T injected into the first plasma cavity (74.4 pC) is conserved throughout acceleration in the plateau, the second down-ramp, and the LPT.

Figure 3(b) shows the evolution of the transverse momentum spread within the FWHM energy slice in the directions parallel ($\sigma_{p_y}^{\text{FWHM}}$) and perpendicular ($\sigma_{p_z}^{\text{FWHM}}$) to the laser linear polarization direction y . Betatron oscillations are clearly visible in the injection and acceleration

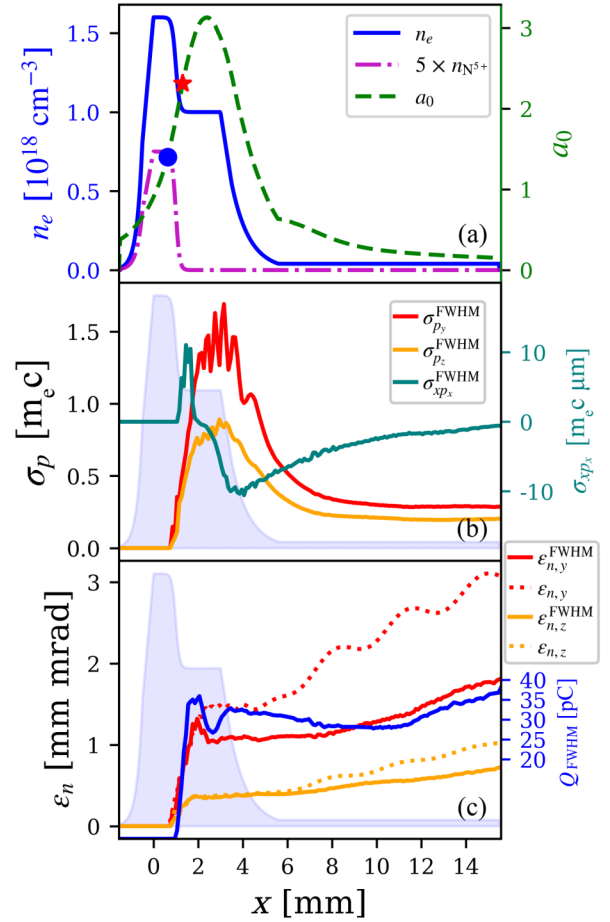


FIG. 3. Simulation results showing the laser maximum electric field and electron beam evolution during the propagation in the plasma. (a) Electron density profile, for all the electrons (blue) and those from the first five levels of nitrogen (magenta); the green line shows the evolution of the laser maximum normalized transverse field a_0 . The blue and red markers denote the start and the end of the ionization of the last two levels of nitrogen, respectively. In panels (b) and (c), the total electron density profile is shown as a shaded area. (b) Evolution of the TMS, perpendicular to the laser polarization direction $\sigma_{p_z}^{\text{FWHM}}$ (orange), parallel to the polarization direction $\sigma_{p_y}^{\text{FWHM}}$ (red), and the longitudinal phase space correlation $\sigma_{x p_x}^{\text{FWHM}}$ (green). (c) Evolution of normalized emittance for the y (red) and z (orange) axes, respectively, for the full beam and for the FWHM energy slice in dotted and solid lines, respectively. The charge in the FWHM energy slice is plotted in blue.

regions. For $3 < x < 6 \text{ mm}$, the down-ramp acts as a plasma lens due to the laser-driven wakefield, which reduces $\sigma_{p_y}^{\text{FWHM}}$ to $0.5 m_e c$. For $x > 6 \text{ mm}$, electron beam dynamics are determined by the fact that the beam density exceeds the plasma density ($n_b > n_p$), and the laser intensity has significantly decreased. The simulation shows that the ratio of the longitudinal electric field driven by the beam exceeds the laser driven one by a factor of at least 5 throughout the LPT. In this region ($x > 6 \text{ mm}$),

$\sigma_{p_y}^{\text{FWHM}}$ is further reduced to $0.3 m_e c$. The spread in the longitudinal phase correlation of those particles in the FWHM energy slice is defined as $\sigma_{xp_x}^{\text{FWHM}} = \langle xp_x \rangle$. This correlation $\sigma_{xp_x}^{\text{FWHM}}$ decreases down to $-10 m_e c \mu\text{m}$ at the end of the acceleration plateau and then increases monotonically to zero in the LPT. This is a signature of the evolution of the chirp of the electron beam, showing that dechirping in the LPT compensates the chirp acquired during acceleration.

The full beam normalized emittance [51] in the k direction is defined as

$$(\epsilon_{n,k})_{\text{rms}} = \frac{1}{m_e c} \sqrt{\langle k^2 \rangle \langle p_k^2 \rangle - \langle kp_k \rangle^2} \quad (1)$$

and $\epsilon_{n,k}^{\text{FWHM}}$ is the emittance of the FWHM energy slice. Here k is either y or z .

Figure 3(c) shows the evolution of emittance for the full beam and for those particles in the FWHM energy slice, as well as the amount of charge contained within the FWHM energy slice. The whole 74 pC beam is transported through the down-ramp without emittance degradation and is thus adiabatically matched. Afterward, the analysis of the longitudinal fields achieved in the simulations shows that beam dynamics in the LPT are governed by beam-driven wakefield, due to the drop of laser amplitude in the LPT [see Fig. 3(a)]. As a result, electrons at the rear of the beam experience a higher focusing field than those at the front, leading to emittance growth for the full beam. In contrast, for particles in the FWHM energy slice, which are primarily located at the front of the beam (see Fig. 4), emittance changes in proportion to the amount of charge added to the FWHM energy slice due to dechirping.

The simulation also indicates that the transverse beam size σ_y (σ_z) increases from $1 \mu\text{m}$ (0.5) at the beginning of the down-ramp ($x = 3.5$ mm) to $6 \mu\text{m}$ (4) at the end of the LPT.

The dechirping mechanism is illustrated in Fig. 4, showing the longitudinal phase space distribution (a) and corresponding energy spectra (b) at three longitudinal positions after the plateau from the respective simulation and the experimentally measured spectra. The figure indices (i)–(iii) correspond to the experimental spectra identified in Fig. 2(a). Figure 4(ii) is the optimal shot corresponding to the simulation analyzed up to this point and shown in Fig. 2(e).

For the optimum case (ii) at $x = 6$ mm, the whole beam has a chirp of $10.9 \text{ MeV}/\mu\text{m}$ (linear fit). Dechirping in the LPT reduces this chirp to $7.5 \text{ MeV}/\mu\text{m}$ over the following 9 mm of propagation. This effect corresponds to a substantial dechirping strength of $380 \text{ GeV}/\text{mm}/\text{m}$. Considering only the particles in the final FWHM energy slice gives a similar dechirp strength; however, these particles have a final residual chirp of only $0.28 \text{ MeV}/\mu\text{m}$. This dechirping strength is 2 orders of

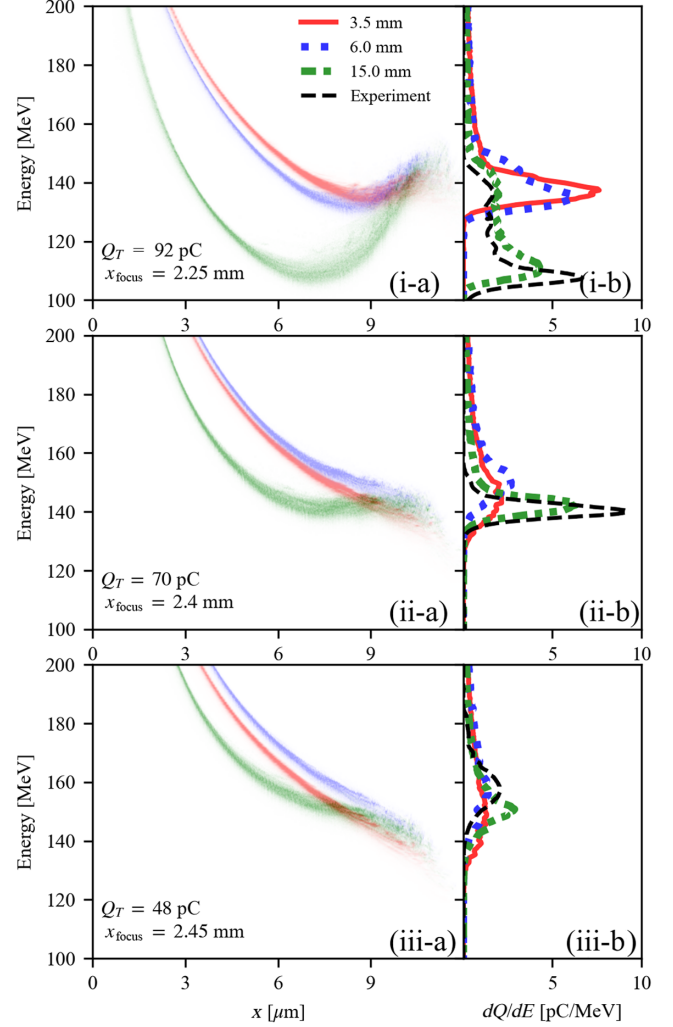


FIG. 4. Evolution of the accelerated electron beam in the plasma after the plateau. (a) Saturated longitudinal phase space distribution in the PIC simulation at selected positions reported in the legend along density profile. The longitudinal position on the horizontal axis is relative to the simulation moving window. (b) Corresponding energy spectra and the experimental spectrum of the beam shown in Fig. 2(e) (black dashed line).

magnitude larger than what has previously been reported for cases involving picosecond beams [11]. The resulting peaked energy spectrum is in good agreement with the one experimentally measured (black dashed line). The phase space analysis confirms that the FWHM energy slice corresponds to the leading part of the bunch, which is the portion with the lowest near zero longitudinal energy chirp.

Simulations are used to illustrate the difference between the optimum case (ii) and the suboptimal cases (i) and (iii). Although the input longitudinal laser focus position is unchanged for the 130 shots shown in Fig. 2, there is a jitter around this nominal position on the order of $\pm 100 \mu\text{m}$. Case (i) is obtained by shifting the focus in the simulation by $-150 \mu\text{m}$ relative to the optimum: at this

focus, the laser ionizes and injects additional charge leading to a total charge of 92 pC. For case (iii), the focus is shifted by +50 μm , which decreases the injected charge to 48 pC. Comparing spectra for the 3 cases at $x = 6$ mm, before any dechirping occurs, the effect of beam loading [7] is visible. At $x = 6$ mm, case (i), with 90 pC, has the smallest amount of chirp, and is thus optimally beam loaded. In cases (ii) and (iii), the charge is reduced to 74 and 48 pC, respectively, which leads to sub-optimal beam loading and residual chirp at the end of the down-ramp. Comparing the beams at $x = 15$ mm shows the effect of dechirping on these beams. The dechirping effect scales with increasing charge, and case (i), with the largest charge, experiences the largest dechirping. However, because the beam entering the LPT had a small chirp, the resulting beam now has a negative chirp. Case (iii) has the lowest charge and as such experiences the lowest dechirp strength, and in this case it is insufficient to compensate the initial chirp. Case (ii) thus represents the optimum where simultaneously the charge and the initial chirp are such that they can be optimally compensated in the dechirper, leading to a narrow energy spread beam. This optimum occurs where the charge and chirp of the beam are matched to the density and length of the dechirper. Finally, this analysis shows that the final phase space is a combination of beam loading in the accelerating section and dechirping in the LPT.

In summary, the simulations reproduce the measured beam characteristics across the observed charge range. They show that the LPT acts as both a dechirper and a lens, and that the strength of these effects depends on the total beam charge.

In order to demonstrate experimentally the role of the LPT, a second experiment was performed using a gas-cell geometry enabling the LPT section to be installed or removed, while keeping other parameters constant. The LPT is established using the same cylinder as in the first experiment. The LPT is removed by removing the cylinder, allowing free expansion of the gas to the experimental chamber. The experiment was carried out with the same laser system and parameters as in the first experiment, with the same plateau densities ($n_1 = 1.6 \times 10^{18} \text{ cm}^{-3}$ and $n_2 = 1.0 \times 10^{18} \text{ cm}^{-3}$); when the LPT was installed, its nominal length and density were set to match the first experiment. Differential pumping [29] was added between the two compartments: this improved the hydrodynamic stability of the density profile, but also introduced a change in the density distribution at the interface between the two compartments as shown in Fig. 1(c). Focus-camera measurements provided clear evidence that laser-focus fluctuations drive variations in total charge, with a Pearson correlation coefficient of up to $r = 0.73$ between focus position and Q_T [28]. The electron characteristics, with and without LPT, are shown in Fig. 5.

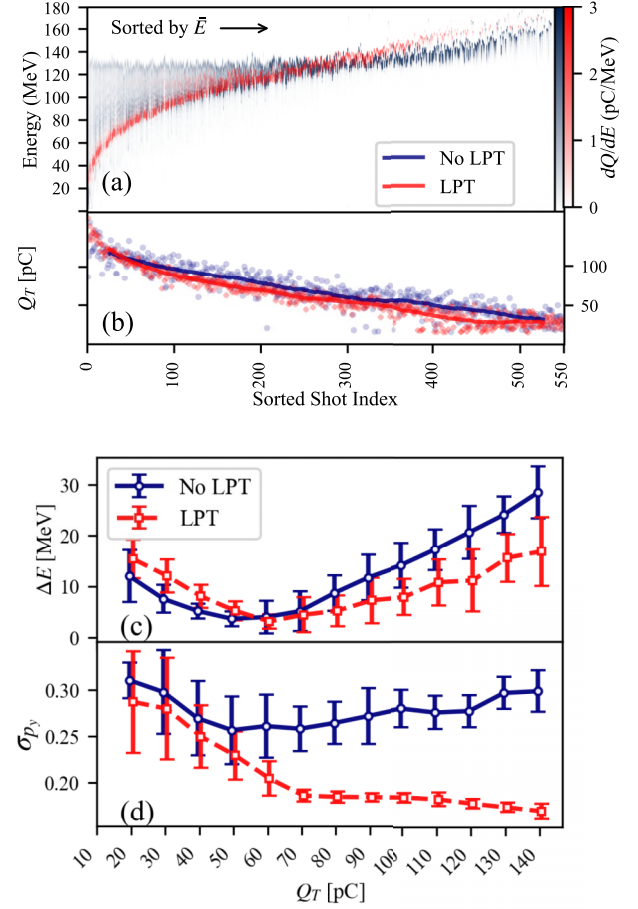


FIG. 5. Comparison of datasets acquired with (red) and without (blue) the long plasma tail (LPT) in the second experiment. (a) Overlaid waterfall plot of single-shot energy spectra, shots are ordered by increasing mean energy. (b) Corresponding total charge Q_T for each shot. The averages and standard deviations of (c) MAD energy spread ΔE and (d) transverse momentum spread σ_{p_y} are computed in Q_T bins of width 10 pC and plotted as a function of total charge; the bin labels indicate the bin centers. The pointing jitter is 0.42 and 0.50 mrad for the no-LPT and LPT cases, respectively.

We recorded 550 consecutive shots for each case, with and without the LPT. Figure 5(a) shows overlaid waterfall spectra for datasets acquired with and without the LPT, with shots ordered by increasing mean energy; Fig. 5(b) shows the corresponding total charge Q_T . To enable a like-for-like comparison, each dataset is grouped into Q_T bins of width 10 pC. Figures 5(c) and 5(d) show, for each bin, the mean and standard deviation of the MAD energy spread ΔE and transverse momentum spread σ_{p_y} as a function of total charge. ΔE is smaller in the presence of LPT at high charge. A clear reduction in σ_{p_y} is also observed for the LPT case, particularly for $Q_T > 50$ pC. These results experimentally confirm that the long plasma tail modifies both the energy spread and the transverse

momentum spread of the beam, and that these effects are the strongest at high charge, consistent with simulations.

In conclusion, reported results show that transverse lensing and longitudinal dechirping achieved within a single, tailored plasma structure significantly improve the quality of chirped beams produced by LWFA. Experimental demonstration was achieved in a gas cell, providing a suitable plasma density distribution. The electron beam transverse momentum is reduced adiabatically in a down-ramp by the transverse laser-driven wakefield.

Lensing and energy compression by dechirping are achieved in a subsequent low density LPT, where the electron beam drives its own wakefield. This process is adiabatic for the leading part of the beam and a dechirping strength of 380 GeV/mm/m has been achieved. This process yields relativistic electron beams with a low transverse momentum spread of $0.2 m_e c$, an energy spread of 6 MeV and a peak brightness of 8 pC/MeV/mrad. This demonstration of compensating the chirp of LWFA beams based on plasma tailoring provides an alternative path toward the narrow energy spreads required for applications such as compact free-electron lasers or multistage accelerator development.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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