Energy Compression and Stabilization of Laser-Plasma Accelerators

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Laser-plasma accelerators outperform current radio frequency technology in acceleration strength by orders of magnitude. Yet, enabling them to deliver competitive beam quality for demanding applications, particularly in terms of energy spread and stability, remains a major challenge. In this Letter, we propose to combine bunch decompression and active plasma dechirping for drastically improving the energy profile and stability of beams from laser-plasma accelerators. Realistic start-to-end simulations demonstrate the potential of these postacceleration phase-space manipulations for simultaneously reducing an initial energy spread and energy jitter of $\sim$1–2% to $\lesssim$0.1%, closing the beam-quality gap to conventional acceleration schemes.

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Laser-plasma accelerators (LPAs) [1] can give rise to a new generation of ultracompact particle accelerators with a wide range of applications. Among others, they could enable cost-effective coherent light sources [2,3] or injectors for storage rings [4,5]. Improvements in beam quality such as the demonstration of peaked energy spectra [6–8], GeV energy [9–11], high current [12], and low emittance [13–15] bring the performance of these devices closer to that of radio frequency (rf) accelerators. Still, challenges limiting their applicability remain, particularly regarding the beam energy spread and stability.

Applications such as free-electron lasers (FELs) require an energy spread $\lesssim$0.1% [16], yet current LPAs typically operate in the $\sim$1% range [17]. The main source behind this is typically the steep slope of the accelerating fields, which leads to beams with a strong longitudinal energy correlation (chirp), together with various contributions to the slice energy spread [18–20]. Many techniques have been proposed for reducing the energy chirp of plasma beams, either within the acceleration stage [21–23] or in a dedicated external device [24–31]. A promising approach is the use of beam loading [32–34] for flattening the average accelerating gradient along the LPA [35–38]. This has enabled the demonstration of the first subpercent energy spread beams capable of generating FEL radiation [3]. Nonetheless, reaching the performance of conventional machines demands further improvements to the energy spread as well as to the shot-to-shot energy jitter, which currently ranges in the few percent [3,17].

The energy stability is critical for the beam transport downstream of the LPA, and thus for virtually any application. Especially demanding is the injection into diffraction-limited storage rings, where particle energy deviations up to $\sim$1% [39] are tolerated. This requires an energy jitter and energy spread $\lesssim$0.1% rms. Recent developments in machine learning and active feedback loops [37,40,41] offer a path toward LPAs of improved stability, particularly with the onset of kilohertz lasers [42–44], but a per-mille energy jitter is yet to be demonstrated.

In this Letter, we propose a technique for drastically—and simultaneously—reducing the energy spread and energy jitter of LPA beams in a two-step process. First, longitudinal decompression in a magnetic chicane is used to imprint a linear correlation between the particles' arrival time and energy [23,45–48]. Second, a linear longitudinal electric field is applied to remove the imprinted correlation and correct deviations with respect to the target energy. This is carried out by an *active* plasma dechirper (APD), a dedicated plasma stage where the wakefields are generated by a fraction of the LPA driver. In contrast to *passive* plasma dechirpers [24–27], where the wakefields are generated by the electron beam itself, an APD takes advantage of the intrinsic synchronization between the LPA and APD drivers for correcting the central energy jitter, and not only the energy spread. This combination of chicane and APD is the first demonstration of a plasma-based energy compression system [49,50]. Its working principle resembles that of chirped-pulse amplification in lasers [51]. Realistic start-to-end simulations show that this

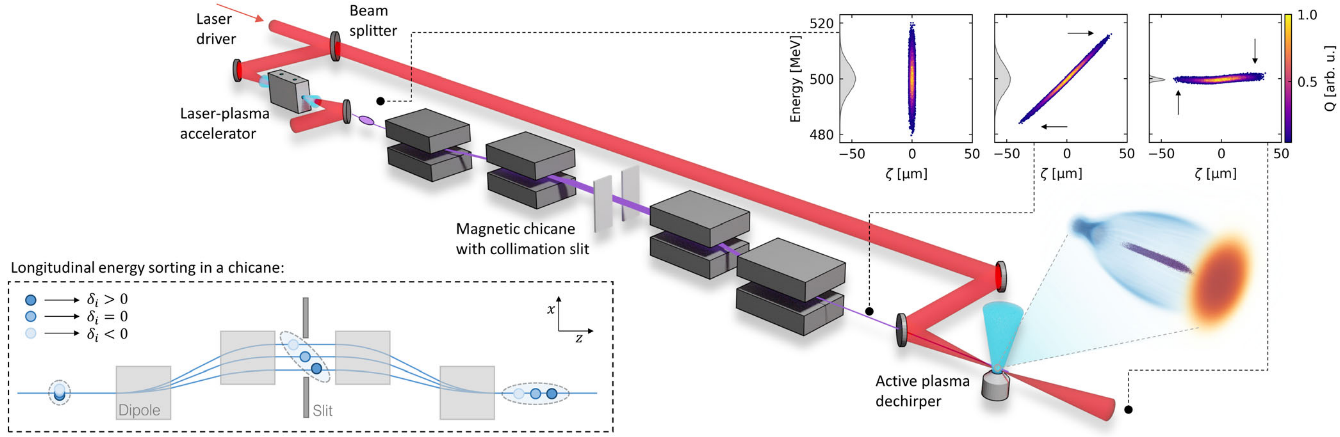

FIG. 1. Basic layout and working principle of an LPA energy compressor and stabilizer. Only the LPA source and the relevant beam line components (laser, chicane, and APD) are shown. The longitudinal phase space of the beam at different locations is also displayed, as well as the 3D [53] wakefield structure in the APD.

method can be incorporated into state-of-the-art LPAs [36,37] for improving the energy spread and stability by an order of magnitude, closing the performance gap to rf accelerators.

The combined effect of decompression and dechirping can be studied by investigating the single-particle dynamics. By establishing a reference energy $\gamma_{\rm ref}$ as the desired beam energy of the accelerator, a relative energy deviation $\delta(t) = (\gamma(t) - \gamma_{\rm ref})/\gamma_{\rm ref}$ and longitudinal coordinate $\zeta(t) = z(t) - z_{\rm ref}(t)$ can be defined for each particle. Here, $\gamma = \sqrt{1 + (\boldsymbol{p}/m_e c)^2}$ is the relativistic Lorentz factor, with $\boldsymbol{p}$ and m_e being, respectively, the momentum and rest mass of an electron; c is the speed of light in vacuum; t is time; z is the longitudinal position; and $z_{\rm ref}$ is the position of a reference particle with $\delta = 0$ initially located at the beam center. A dispersive section transforms the phase-space coordinates of a particle initially at (ζ_i, δ_i) to a final position $\zeta_f = \zeta_i + R_{56}\delta_i + \mathcal{O}(\delta_i^2)$ [52], where R_{56} is the linear dispersion coefficient, while leaving the energy unchanged. Thus, to first order in δ_i, a beam with no initial correlation between ζ_i and δ_i is longitudinally stretched by a factor

$$S \equiv \frac{\sigma_{\zeta_f}}{\sigma_{\zeta_i}} = \sqrt{\left(\frac{R_{56}\sigma_{\delta_i}}{\sigma_{\zeta_i}}\right)^2 + 1}, \tag{1}$$

while developing a linear chirp $\chi \equiv \sigma_{\zeta\delta}/\sigma_\zeta^2 = R_{56}^{-1}(1 - S^{-2})$, which is $\chi \simeq R_{56}^{-1}$ for $S^2 \gg 1$. Here, σ_ζ and σ_δ are the standard deviations of ζ and δ, and $\sigma_{\zeta\delta}$ is their covariance. After decompression, the beam enters a dechirper of length L that applies a linear longitudinal electric field $E_z(\zeta) = -(m_e c^2/e)\mathcal{E}'(\zeta - \zeta_0)$ with normalized slope $\mathcal{E}'$ centered at ζ_0, where e is the elementary charge. Assuming a highly relativistic beam ($\gamma \gg 1$), ζ_f stays constant throughout the dechirper and the particle energy is transformed into a final value:

$$\delta_f = \frac{1}{R_{56}}(\zeta_f - \zeta_i) + \frac{\mathcal{E}'L}{\gamma_{\rm ref}}(\zeta_f - \zeta_0). \tag{2}$$

Therefore, the energy correlation imprinted by the linear dispersion can be removed by the dechirper if

$$\mathcal{E}'L = -\frac{\gamma_{\rm ref}}{R_{56}}. \tag{3}$$

This results in a net reduction of the beam energy spread, whose final value is fully determined by R_{56} as

$$\sigma_{\delta_f} = \frac{\sigma_{\zeta_i}}{R_{56}} \simeq \frac{\sigma_{\delta_i}}{S}, \tag{4}$$

where the last equality holds if $S^2 \gg 1$.

This technique is ideally suited for LPA beams. As Eq. (4) shows, the typically ultrashort ($\sim$1 μm) length and large ($\sim$1%) energy spread allow for a factor 10 decompression and energy spread reduction with minimal dispersion ($R_{56} \sim 1$ mm). In addition, the high initial peak current (up to $\sim$10 kA [12]) means that a final current in the $\sim$1 kA range can still be achieved after decompression, allowing for FEL applications. When high current is not required, such as in storage ring injectors, an even more drastic energy spread reduction could be realized.

As illustrated in Fig. 1, the bunch decompression can be performed by a magnetic chicane, where path length differences arise due to an energy-dependent transverse deflection. This results in $R_{56} = 2\theta^2(L_d + 2L_m/3)$ [52], where L_m and θ are, respectively, the magnet length and bending angle (for $\delta = 0$), and L_d is the distance between the central and outer dipoles.

When Eq. (3) is satisfied, Eq. (2) also yields that the final deviation of the average beam energy is given by

$$\langle\delta_f\rangle = \frac{\zeta_0}{R_{56}}. \tag{5}$$

Therefore, if $\zeta_0 = 0$, the final beam energy is stabilized to $\gamma_{\rm ref}$ regardless of its initial value. This requires the ability to control ζ_0 independently of the beam position, i.e., with an *active* dechirping medium where the fields are not generated by the beam itself. An APD accomplishes this in a compact, plasma-based setup. It is conceptually similar to a laser-plasma lens [54,55], but aimed at the generation of longitudinal, instead of transverse, fields with a fraction of the LPA driver. The intrinsic synchronization between the LPA and APD drivers allows for a precise control of ζ_0, independently of the electron beam arrival time. This setup is also robust against realistic timing jitters between both drivers. As obtained from Eq. (5), if $R_{56} \sim 1$ mm, a state-of-the-art timing jitter of $\lesssim 10$ fs [56,57] is sufficient for achieving a per-mille energy jitter.

When the peak normalized vector potential of the APD driver is sufficiently high (i.e., $a_0 \gtrsim 2$), large plasma electron cavitation occurs and a trailing wakefield with uniform $\mathcal{E}'$ is generated [cf. Fig. 2(a)]. The length of the cavity is approximately given by the plasma wavelength $\lambda_p = 2\pi/k_p$, where $k_p = (n_p e^2/m_e \epsilon_0 c^2)^{1/2}$ and n_p are the plasma electron wave number and density and ϵ_0 is the vacuum permittivity. As depicted in Fig. 1, a slit in the center of the chicane removes particles beyond a maximum, $\delta_{\max}$, and minimum, $\delta_{\min}$, energy deviation for ensuring that the stretched beam fits within the cavity. Imposing a total beam extension $\lesssim \lambda_p/2$ yields the condition $\lambda_p \gtrsim 2(\delta_{\max} - \delta_{\min})R_{56} = 2(\delta_{\max} - \delta_{\min})\sigma_{\zeta_i}/\sigma_{\delta_f}$, which determines the maximum plasma density for achieving a certain final energy spread. For $\sigma_{\delta_f} = 10^{-3}$, $\sigma_{\zeta_i} = 1$ μm and $\delta_{\max} - \delta_{\min} = 0.06$, $n_p \lesssim 8 \times 10^{16}$ cm^{-3} is obtained. The field slope $\mathcal{E}'$ can be estimated from the nonlinear cold fluid equation [58] for the wakefield potential, ψ, behind the driver, i.e., $\mathcal{E}'(\zeta) = \partial_\zeta^2 \psi(\zeta) = -k_p^2(1 - 1/[1+\psi(\zeta)]^2)/2$. At ζ_0, which occurs around the center of the cavity, ψ is maximum and given approximately by $\psi_0 \equiv \psi(\zeta_0) \sim \hat{w}_0^2/4$ [59], where $\hat{w}_0 = k_p w_0$ and w_0 is the spot size of the laser at focus. This implies that $\mathcal{E}'(\zeta_0) \sim -k_p^2(1 - 1/(1+\hat{w}_0^2/4)^2)/2$. Coupled with Eq. (3), this expression allows for an estimate of the required APD length, under the assumption that $w \sim w_0$ throughout the dechirper. Relative to the laser Rayleigh length, $Z_R = \pi w_0^2/\lambda_0$ [58], the APD length is found to be $L/Z_R = 2\gamma_{\text{ref}}\lambda_0(4+\hat{w}_0^2)^2/[\pi R_{56}\hat{w}_0^4(8+\hat{w}_0^2)]$, where λ_0 is the laser wavelength. For $R_{56} = 1$ mm, $\gamma_{\text{ref}} = 10^3$, and $\lambda_0 = 800$ nm, this expression yields $\hat{w}_0 \gtrsim 1$ for ensuring $L \lesssim Z_R$ (i.e., $w \sim w_0$). Under this condition, a compact, mm-long APD can be realized without external laser guiding. Given the typically low density and narrow driver, no self-injection and, thus, no dark current is expected from the APD [60,61].

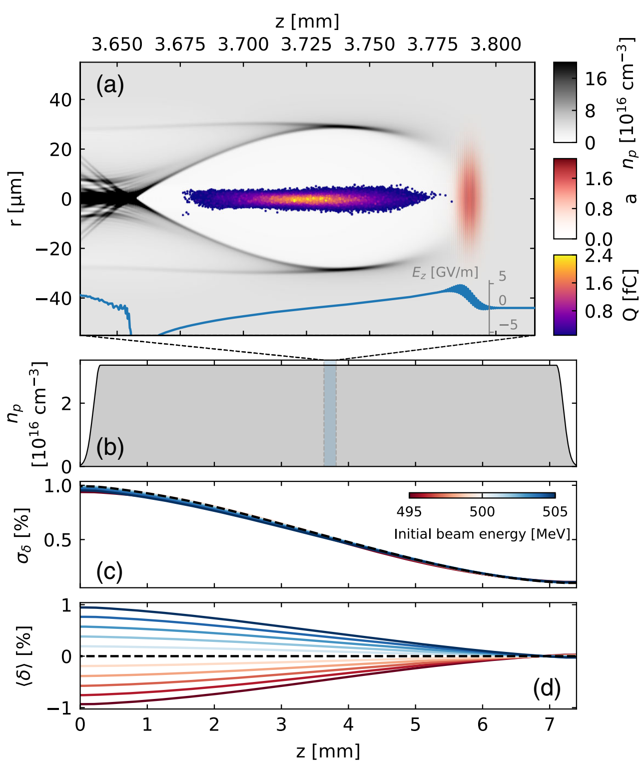

FIG. 2. (a) Plasma wakefields and electron beam at the center of the APD. (b) APD density profile. (c) Energy spread and (d) average energy deviation along the APD of beams with initial energy deviations between ±1%. The black dashed line corresponds to a reference initial energy of 500 MeV.

The performance of the technique is demonstrated by means of two comprehensive simulation studies of an energy compression system. First, the setup is probed with an ideal Gaussian electron bunch to generally assess the energy spread and jitter correction. Second, a full start-to-end study including a realistic LPA and relevant experimental jitters validates its efficacy under real-world conditions. The initial beam capture and final focus into the APD are carried out by active plasma lenses [62]. This enables a compact setup with minimal chromatic emittance growth [63], but other options are also possible [5,64]. After initial prototyping with WAKE-T [65], the plasma elements are simulated with the quasi-3D particle-in-cell code FBPIC [66] and the conventional elements with OCELOT [67], including the effects of 3D space charge and 1D coherent synchrotron radiation. Using LIBENSEMBLE [68], the jitter of the setup is comprehensively evaluated with hundreds of simulations. See Ref. [69] for additional simulation details.

The parameters of the probe Gaussian electron beam are representative of current state-of-the-art LPAs [3,36–38], having a 500 MeV energy with 1% rms shot-to-shot jitter, 1% rms energy spread, 1 μm normalized emittance, 2 μm transverse size, 0.5 mrad rms divergence, 10 fs FWHM duration, and 10 pC charge. The chicane has a total length of 2 m, with $L_d = 50$ cm, $L_m = 20$ cm, and $\theta = 34.4$ mrad, resulting in $R_{56} = 1.5$ mm and $S = 11.8$. It includes a collimating slit with a 1.4 mm horizontal aperture for filtering particles with $|\delta| > 3\%$. The APD has a 6.8 mm plateau with a 3.2×10^{16} cm^{-3} density and two 0.3 mm Gaussian ramps at the entrance and exit. The APD driver is a 2 J Gaussian laser pulse focused at the center of the plateau with $a_0 = 2.15$, $\lambda_0 = 0.8$ μm, $w_0 = 22$ μm, and a 25 fs FWHM duration. The plasma lenses have a 1 cm length, $1.62\ \mathrm{kT\,m^{-1}}$ focusing gradient, and $10^{15}\ \mathrm{cm^{-3}}$ density. They are placed 10 cm down and upstream of the initial beam and the APD, respectively.

Figure 2 shows the evolution of the decompressed Gaussian beam within the APD for initial energy deviations between $\pm 1\%$. The wakefields generated by the driver effectively reduce the energy spread while simultaneously correcting the initial energy deviations. The reference beam has a final energy spread of ∼0.10% (total) and ∼0.084% (slice average). This agrees with Eq. (4), which predicts a value of 0.085%. The total energy spread is larger due to nonlinearities in E_z arising mostly from beam loading. The efficacy of the energy compression can be clearly seen in Fig. 3. The results from 300 simulations show that the initial energy jitter of 1% is reduced to 0.023%. Similarly, the initial energy spread of 1% is reduced by a factor of ∼10 to $(0.1072 \pm 0.0059)\%$. The final normalized emittances of (1.22 ± 0.13) μm (horizontal) and (1.179 ± 0.086) μm (vertical) show only a slight increase dominated by chromatic effects during capture and focus. These values correspond to the average and rms deviations of all simulated shots. Ultimately, this study demonstrates that the energy compressor behaves as expected from theory, improving the energy spread and stability by at least an order of magnitude.

The real-world applicability of the energy compressor is validated through a full start-to-end study including a realistic LPA as well as relevant experimental jitters. The LPA used for this study is based on downramp-assisted ionization injection, a well-proven technique that can be accurately simulated [36,37] and where the dominant sources of jitter are well-known: laser focal position, energy, and pulse duration [17,36]. It is designed as an evolution of the LUX target [17,36,37] aimed at generating 500 MeV beams with maximum stability to laser jitters. The density profile, displayed in Fig. 4(a), contains a mixture of H_2 and N_2 (1%) for electron injection, a $1.46 \times 10^{18}\ \mathrm{cm^{-3}}$ plateau for acceleration, and a low-density tail ($4 \times 10^{16}\ \mathrm{cm^{-3}}$) for divergence minimization [69]. The laser driver is a 130 TW Ti:Sa system with a total energy of 4.68 J, split between the LPA (2.68 J) and the APD (2 J). Its longitudinal profile is Gaussian with a FWHM duration of 34 fs, while its transverse profile is modeled as a so-called flattened Gaussian [74]. This consists of a sum of Laguerre-Gauss modes that accurately describes flattop high-power lasers in experiments [75]. The laser is subject to realistic jitters in the focal plane position (100 μm rms), energy (0.5% rms) and pulse duration (1% rms) [36,76]. Transverse and longitudinal (i.e., timing) jitters between the LPA and APD pulses of 5 μm [75] and 5 fs rms, respectively, are also included at the APD entrance. The LPA driver is focused to $w_0 = 21$ μm, with $a_0 = 2.21$, at $z_{\mathrm{foc}} = 4.68$ mm into the target. The data from 1000 simulations shows that the resulting LPA beams have an energy of (494.3 ± 4.9) MeV (i.e., 1% jitter), an rms (Gaussian fit) energy spread of $(2.13 \pm 0.67)\%$, a normalized emittance of (2.48 ± 0.12) μm (horizontal) and (0.749 ± 0.062) μm (vertical), a divergence of (0.762 ± 0.026) mrad (horizontal) and (0.350 ± 0.029) mrad (vertical), a charge of

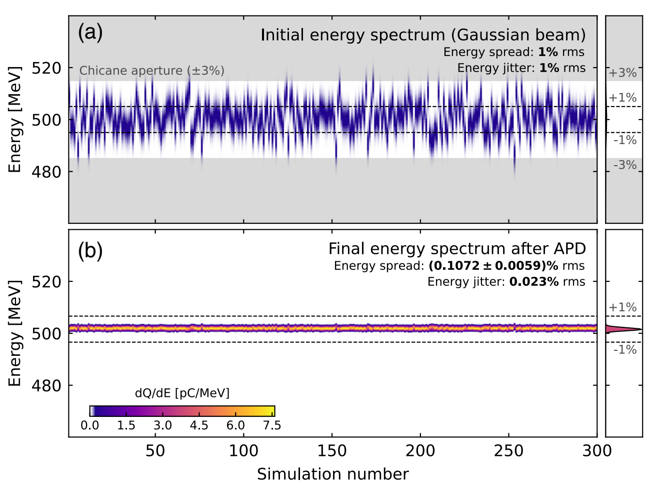

FIG. 3. (a) Initial energy spectrum of 300 Gaussian beams with a 1% rms energy jitter and energy spread. The gray area represents the energies filtered out by the slit in the chicane. (b) Final energy spectrum after the APD.

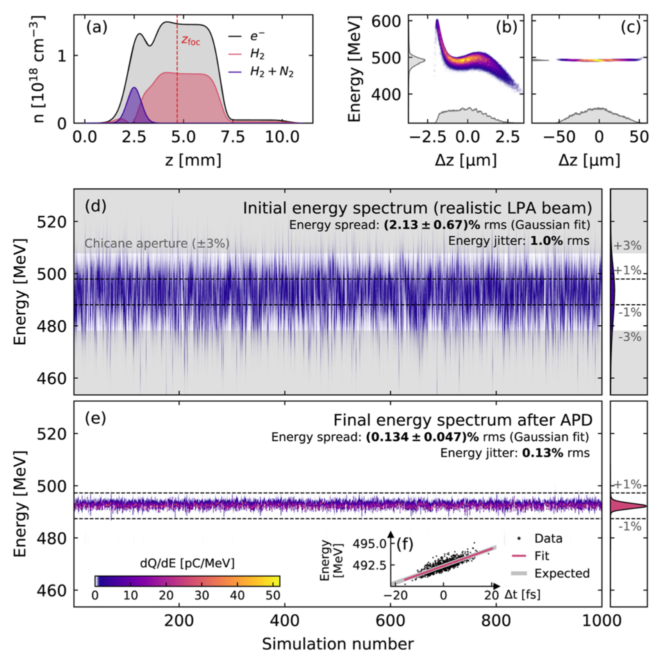

FIG. 4. Results from the start-to-end jitter study. (a) LPA density profile; longitudinal phase space of the reference beam (i.e., no jitters) at the exit of the (b) LPA and (c) APD; beam energy spectra at the (d) LPA and (e) APD exits; (f) average beam energy versus laser arrival time jitter (Δt), including the expected correlation and a linear fit to the data.

(49.8 ± 5.6) pC, a FWHM duration of (8.96 ± 0.57) fs, and a peak current of (5.63 ± 0.87) kA. A realistic pointing jitter of 0.5 mrad, consistent with experiments [36], is externally added. To transport this beam, the focusing gradient in the first and second plasma lenses is tuned to $1.6\ \mathrm{kT\,m^{-1}}$ and $2.37\ \mathrm{kT\,m^{-1}}$, respectively. The APD is placed 6.6 cm downstream of the second lens and has a 5.4 mm plateau with a $4.1 \times 10^{16}\ \mathrm{cm^{-3}}$ density. The laser driver is focused at the center of the APD with $w_0 = 27.5\ \mu\mathrm{m}$ and $a_0 = 1.48$.

The results of this jitter scan can be seen in Fig. 4. After the APD, the beams have an average energy of (492.41 ± 0.63) MeV (i.e., 0.13% jitter) and an rms (Gaussian fit) energy spread of $(0.134 \pm 0.047)\%$ (total) and $(0.071 \pm 0.012)\%$ (slice). This is an order of magnitude improvement over the initial values, and demonstrates a dechirping strength of $\sim 62\ \mathrm{GeV\,mm^{-1}\,m^{-1}}$, a factor $> 10^3$ higher than with rf technology [5]. The final energy variability is dominated by the timing jitter between the two laser pulses. This can be seen in Fig. 4(f), where the observed time-energy correlation is in full agreement with Eq. (5). The final beam emittances of $(5.4 \pm 1.2)\ \mu$m (horizontal) and $(1.78 \pm 0.85)\ \mu$m (vertical) experience an increase mostly due to chromatic effects in the transport line and transverse offsets of the laser at the APD entrance, which also lead to an increased pointing jitter of 1.91 mrad (horizontal) and 1.84 mrad (vertical). The final beam charge of (34.8 ± 5.6) pC is reduced due to the collimating slit in the chicane, resulting in a peak current of (0.180 ± 0.038) kA for a bunch duration of (193 ± 46) fs. This study demonstrates the feasibility and robustness of the proposed concept under real-world conditions, paving the way toward the experimental demonstration of reliable and high-quality plasma accelerators. Side effects such as emittance growth or charge loss can be greatly minimized by a lower initial energy spread, and the final energy stability can be further improved if the laser timing jitter is reduced.

In conclusion, the presented concept of bunch decompression and active plasma dechirping effectively corrects the energy spread and jitter of LPAs in a compact setup. Large-scale realistic start-to-end simulations demonstrate that the beam energy spread and energy jitter of state-of-the-art LPAs can be reduced by an order of magnitude to the per-mille and sub-per-mille range. This would enable LPAs as compact beam sources for future storage rings or free-electron lasers.

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