

Self-adaptive stabilization and quality boost for electron beams from all-optical plasma wakefield accelerators

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(Received 30 June 2025; accepted 1 February 2026; published 10 March 2026)

Shot-to-shot fluctuations in electron beams from laser wakefield accelerators present a significant challenge for applications. Here, we show that instead of using such fluctuating beams directly, employing them to drive a plasma photocathode-based wakefield refinement stage can produce secondary electron beams with higher quality and greater stability. Our simulation-based analysis reveals that drive beam jitters are partially compensated by both the insensitivity of beam-driven plasma wakefield acceleration and the decoupled physics of plasma photocathode injection. While beam-driven, dephasing-free plasma wakefield acceleration mitigates energy and energy-spread fluctuations, intrinsically synchronized plasma photocathode injection compensates charge and current jitters of incoming electron beams, and provides a simultaneous quality boost. Our findings suggest that plasma photocathodes could be ideal injectors for hybrid laser-plasma wakefield accelerators, and nurture prospects for demanding applications such as free-electron lasers.

DOI: [10.1103/p6ss-vgq5](https://doi.org/10.1103/p6ss-vgq5)

I. INTRODUCTION

Laser wakefield acceleration (LWFA) [1–5] utilizes a laser pulse with an intensity $I_L \gtrsim 10^{18} \text{ W/cm}^2$ to expel plasma electrons transversely, thereby driving a collective plasma wave in its wake. This resulting plasma structure supports longitudinal electric fields exceeding several hundred gigavolts per meter (GV/m), enabling rapid electron acceleration over short distances.

Electrons can be captured into the wake and subsequently form an injected electron “witness” beam. This injection can be achieved through various processes, ranging from self-injection [3–5] to more elaborate methods involving local modifications of plasma density [6–9], multiple intense laser pulses [10], using higher ionization levels and dopants [11–14], as well as combinations of these methods [15,16].

A common feature across these schemes is that electron injection is tightly coupled to the wake excitation process. Fluctuations in the drive laser’s characteristics—such as power, polarization [17], or wave front quality [18]—along with the inherently nonlinear and relativistic nature of the laser-plasma interaction [19], significantly influence the evolution of the plasma wakefield. These coupled dynamics, in turn, affect injection rates and charge yield, resulting in shot-to-shot variations in the properties of the injected electron beam.

Once injected, the LWFA-inherent challenges of diffraction of the laser driver, and dephasing with the injected electrons, are further complications that can change the longitudinal and transverse phase space of the injected electron beam throughout the subsequent acceleration process [19]. While meticulous control and fine-tuning of the laser-plasma interaction can improve stability, state-of-the-art systems still exhibit fluctuations in charge, energy, and energy spread on the order of a few to 10% shot to shot [16,20,21].

However, engineering optimization of LWFA is not the only path toward improved stability. Here, we explore intrinsic compensation mechanisms when using fluctuating LWFA electron beam output to power a subsequent electron beam-driven plasma wakefield acceleration (PWFA) [22,23] refinement stage [24–30]. In PWFA, strong plasma waves are

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excited by the unipolar Coulomb force of an electron beam, but with peak driver fields orders of magnitude lower than in LWFA. This environment enables controlled electron injection via a plasma photocathode [31–33], where a low-power laser pulse with $I_L \sim 10^{15}$ – 10^{16} W/cm², just above the tunneling ionization threshold, releases electrons directly into the wake, with negligible momentum imparted by the injection laser [34].

The plasma photocathode can thus potentially generate well-defined electron bunches with ultralow normalized emittance $\epsilon_n < 100$ nm rad root mean square (r.m.s.) [31–35], while the release process and injection rates are decoupled from the driver and wakefield configuration. While staging of plasma wakefield accelerators is usually associated with challenges in capture efficiency and beam quality preservation [36], here we show that staged electron beam utilization from LWFA into plasma photocathode-based PWFA can yield electron output bunches with significantly higher stability, in addition to substantially enhanced bunch quality. These improvements come at the cost of total electron beam charge, but for applications such as light sources where electron beam quality thresholds are crucial, this is a valuable trade-off [37].

To explore the stabilization mechanisms, we perform high-fidelity, quasi-three-dimensional (3D) particle-in-cell (PIC) simulations of plasma photocathode PWFA using Fourier-bessel particle-in-cell (FBPIC) [38]. The electron driver beams may be produced from LWFA via a variety of methods such as self-truncated ionization injection [12–14] or shock-front injection [8,39–42]. For the showcase PWFA configuration, the plasma density is set to $n_e \approx 1.12 \times 10^{17}$ cm^{−3}, corresponding to a cold plasma wavelength $\lambda_p = 2\pi c/\omega_p \approx 100$ μ m, where the plasma frequency is $\omega_p = \sqrt{n_e e^2/(m_e \epsilon_0)}$.

The baseline electron driver beam is bi-Gaussian with charge $Q_D = 500$ pC, length $\sigma_z = 6.0$ μ m (r.m.s.), radius $\sigma_r = 4.0$ μ m (r.m.s.), mean kinetic energy $W_D = (\gamma_D - 1)m_e c^2 = 500$ MeV, where γ_D is the beam's Lorentz factor, relative energy spread $\Delta W_D/W_D = 10\%$ (r.m.s.), normalized emittance $\epsilon_n = 2.0$ μ m rad (r.m.s.), and peak current $I_p \approx 10$ kA.

By choosing these values, neither the longitudinal resonance condition [43] $\sigma_{z,m} = \sqrt{2}/k_p \approx 22.5$ μ m nor the transverse matching condition [44] $\sigma_{r,m} = \sqrt{2/\gamma_D} \sqrt{\epsilon_n/k_p} \approx 1$ μ m is fulfilled, where $k_p = \omega_p/c$ is the plasma wave number. This is intentional, to account for nonideal conditions that may arise from unoptimized beam transport between stages, and to underscore the robustness of the plasma photocathode-enhanced PWFA stage. This choice is also appropriate because, in present day hybrid LWFA $\rightarrow$ PWFA [45] setups, the electron beams emerging from the LWFA stage are short, carry multi-kA currents [46–48], and expand rapidly.

Nevertheless, the driver beam's peak density $n_b = Q_D/[e(2\pi)^{3/2}\sigma_r^2\sigma_z] \approx 2.1 \times 10^{18}$ cm^{−3} exceeds n_e by more than an order of magnitude, allowing it to safely enter the nonlinear blowout regime of PWFA [49]—a prerequisite for preserving the normalized emittance during acceleration [49].

Utilizing intrinsically short driver beams from LWFA furthermore eliminates potential contributions of the driver fields on the plasma photocathode laser field ionization rate, as well as transverse momentum and witness beam emittance growth

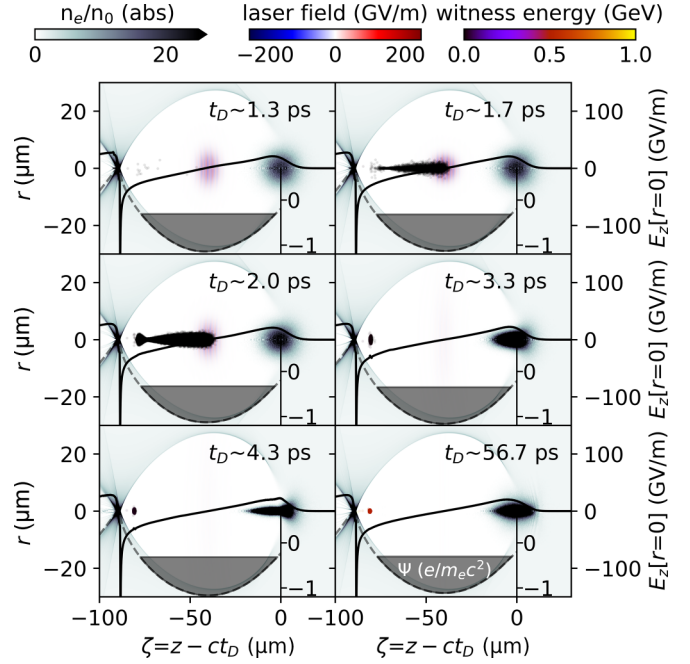


FIG. 1. PWFA showcase simulation: Simulation snapshots illustrate plasma-photocathode injection within a helium plasma wave. The electrostatic pseudopotential Ψ is shown as a gray dashed line, and the shaded region indicates the longitudinal trapping window ($\Psi - \Psi_{\max} \leq -m_e c^2/e$) within the blowout structure. The corresponding on-axis electric field E_z is plotted as a solid black line. An electron beam drives the wakefield as it propagates to the right. A copropagating laser pulse (blue to red) ionizes He^{2+} , releasing witness electrons that are color coded by energy (black to yellow).

[32–34]. The radial electric field of the driver beam $E_r(r) = (Q_D/[(2\pi)^{3/2}\sigma_z\epsilon_0 r]) \times (1 - \exp(-r^2/2\sigma_r^2))$ peaks at approximately 67 GV/m, sufficient to field-ionize helium from its ground state (low ionization threshold: 24.6 eV), while leaving its second, higher ionization threshold level (HIT: 54.4 eV) unperturbed. We assume controlled preionization of the first helium level, as demonstrated experimentally [28–30,41].

This hybrid LWFA $\rightarrow$ PWFA configuration is then equipped with a collinear plasma-photocathode laser of energy $W_L = 0.1$ mJ and pulse duration of $\tau = 30$ fs full width at half maximum, delayed by approximately 133 fs with respect to the driver centroid, and focused to an r.m.s. spot size of $w_0 = 5$ μ m in the blowout center. This setup enables witness bunch generation by controlled ionization of the HIT (He^+) ions.

Figure 1 illustrates the baseline PWFA configuration, showing the plasma-photocathode process through consecutive PIC simulation snapshots in the comoving coordinate system $\zeta = z - ct_D$, where t_D denotes the driver's propagation time.

The electrostatic pseudopotential Ψ and the corresponding longitudinal component of the on-axis electric field ($E_z = \partial_\zeta \Psi$) are shown, with the zero crossing at $\zeta \approx -40$ μ m. As the electrons are released and slip backward, the electrostatic pseudopotential is converted into kinetic energy, accelerating them.

TABLE I. Summary of driver and laser parameters used in Figs. 1–6.

Driver parameter	Figure					
	1	2	3	4	5	6
Driver charge	500 pC	(a) 200–650 pC and (b) 500 pC	500 pC	500 pC	500 pC	300–650 pC
Driver energy	500 MeV	500 MeV	125–3500 MeV	500 MeV	500 MeV	500 MeV
Relative driver energy spread	10%	10%	10%	0%–50%	10%	10%
Laser energy	0.1 mJ	(a) 0.1 mJ and (b) 0.098–0.102 mJ	0.1 mJ	0.1 mJ	N/A	0.1 mJ

Electrons released at ζ_{inj} will be trapped as long as the condition $\Psi_{\text{inj}} - \Psi_{\text{max}} \leq -m_e c^2 / e$, indicated by the gray shaded region in Fig. 1, is satisfied [50,51].

The parabolic shape and symmetry of the electrostatic potential, combined with the decoupled nature of the plasma photocathode injection, form key foundations of the stability mechanisms analyzed in this work. The primary fluctuations investigated are the electron driver energy, energy spread, and current, as well as the plasma-photocathode injector laser energy and its spatiotemporal synchronization with the driver. A summary of the parameters varied and the scan ranges is provided in Table I.

II. WITNESS CHARGE IS FULLY DECOUPLED FROM DRIVER BEAM CHARGE

To reflect shot-to-shot jitter, first we simulate significant variations in the driver beam density by varying its charge Q_D . We note that the driver charge density, which is the key parameter responsible for the wakefield excitation, could also be changed by varying the driver length or its transverse extent, but this would be largely redundant with changing the driver charge.

It will be shown that, in contrast, the released and trapped witness charge is essentially independent of drive beam charge fluctuations, as it is governed by the plasma photocathode injector laser field strength and the helium density, which together determine the number of electrons that can be released from He^+ ions.

With a baseline dimensionless light amplitude $a_0 = eE_L / (\omega_L m_e c) \approx 0.0611$, where E_L is the peak amplitude of the laser's electric field and ω_L is the laser frequency, the pulse will tunnel ionize the He^+ ions and will release He^{2+} electrons with $Q_W \approx 4.9$ pC of charge.

The simulation results shown in Fig. 2(a) reveal that a witness charge capture efficiency of 100% is achieved, as long as the driver charge amounts to $Q_D \gtrsim 290$ pC, corresponding to a current of ~ 5.8 kA, the threshold where the electrostatic potential becomes large enough to trap all electrons released around the blowout center.

In principle, the wakefields could also contribute to the charge yield through superposition with the laser field, locally increasing the total electric field. However, wakefields are minimized in the blowout center, making their contribution negligible. Furthermore, using the second ionization level of helium requires higher laser intensity, further reducing contributions from shot-to-shot wakefield variations. Consequently, the produced witness bunch charge is fully decoupled from

the driver beam charge and, respectively, current over a very wide range.

While charge capture stability can thus be a natural outcome of the laser-dominated collinear plasma photocathode, it remains a major challenge in other LWFA or PWFA injection and staging schemes. For example, in plasma density downramp injection [30,39,52–54], injection rates depend strongly on driver strength and are therefore highly sensitive to shot-to-shot fluctuations. Likewise, in LWFA staging [36] or external injection [55], full charge capture is difficult due to the strong sensitivity to beam-wake alignment, with spatiotemporal and angular offsets significantly impacting subsequent acceleration.

While driver beam electron density is the key parameter for wakefield excitation, the corresponding critical parameter for the plasma-photocathode injector is the laser intensity. It is therefore worthwhile to investigate the witness beam charge when the laser energy is varied, but the driver beam charge density is assumed constant.

Varying the laser energy by $\pm 2\%$ around the baseline produces witness charges of 4.9 ± 0.5 pC ($\pm 10\%$) as shown in Fig. 2(b), right y axis. The slightly different charge has a very

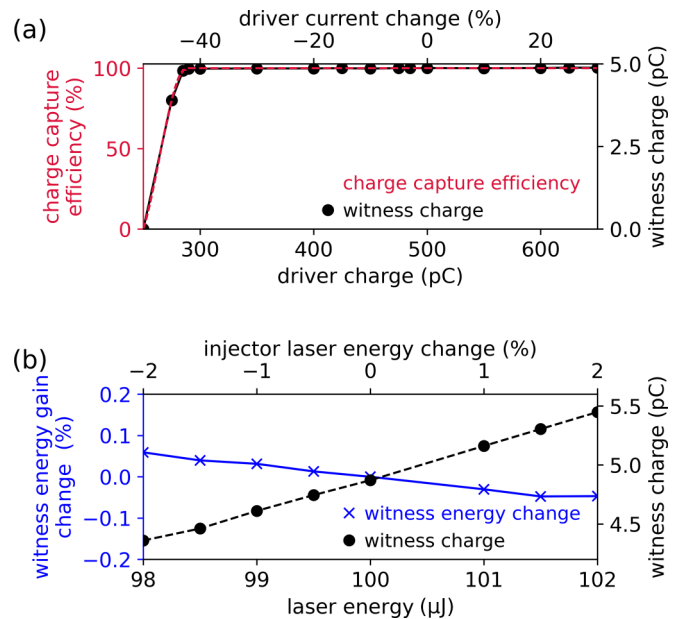


FIG. 2. Witness charge when driver charge or laser energy varies. The stability of the injected witness charge versus varying driver charge and current is shown in panel (a) at constant laser energy, while panel (b) shows witness energy stability versus injector laser energy variation at constant, baseline driver beam charge.

small effect on the energy gain, which due to beam loading is smaller for higher laser energy than for lower laser energy [see Fig. 2(b), left y axis].

Since $\pm 2\%$ significantly exceeds the shot-to-shot energy stability of commercial high-power lasers, this parameter should be regarded more as a tunable knob for adjusting the witness beam charge—and compound quality metrics such as brightness [56]—rather than a source of jitter. Moreover, various techniques may be explored to further stabilize the pulse energy, such as cross-polarized wave normalization, reverse saturable absorbers [57], nonlinear optical limiters [58], etc.

III. WITNESS ENERGY GAIN IS INDEPENDENT OF DRIVER BEAM ENERGY

Next, we investigate the impact of energy fluctuations of the LWFA-generated driver beam by varying its central energy from 125 MeV to multi-GeV levels, while keeping its current, transverse properties, and the injection laser properties fixed.

Figure 3(a) reveals that the witness energy gain rate is linear and nearly constant across the driver parameter sweep, despite the order of magnitude variation in driver energy. Fundamentally, this is because at sufficiently high electron energies W_{kin} and corresponding Lorentz factors $\gamma = 1 + W_{\text{kin}}/(m_e c^2)$, the individual electron velocities v are all very similar and close to c , due to $v = c\sqrt{1 - (1/\gamma^2)}$. Therefore, the driver beam current profile remains similar, and in turn the produced wakefield. That said, higher-energy drivers can sustain the wake over longer distances, allowing the witness to reach higher final energies.

Figure 3(b) shows the spectral charge densities of witness bunches, revealing slightly higher energies for higher-energy drivers, and differences in transverse divergence. This asymmetry originates from the linear polarization of the injector laser, which increases thermal emittance [35] along the polarization (y) direction, yielding normalized projected emittances $\epsilon_{n,y} \approx 29.0$ nm rad and $\epsilon_{n,x} \approx 12.3$ nm rad, respectively.

Additional spectra, including the driver beam signal, are provided in Appendix A. These spectra are taken at the cutoff location marked by the black dashed line in Fig. 3(a), representing a potential experimental extraction point designed to obtain stabilized witness energy even under extreme experimental conditions of wildly varying driver beam energies from shot-to-shot at mean witness energies exceeding the baseline driver value ($W_W > W_D$). Such a tunable extraction point could be realized using tunable-length gas cell targets [59].

Driver energies of ~ 450 – 550 MeV yield witness beam energies with a precision better than $\pm 0.1\%$, while driver energies above ~ 360 MeV can still maintain witness energy stability within $\pm 1\%$. This shows witness energy stability can exceed driver stability by over an order of magnitude.

The longitudinal phase space plots in Fig. 3(c) show effects of the driver's baseline 10% energy spread. The lowest-energy electrons within the driver beam that are located in its strongest decelerating region are slowed down most rapidly. This leads to a progressive lengthening of the driver beam, which in turn reduces its peak current and weakens the wake-field strength during driver depletion.

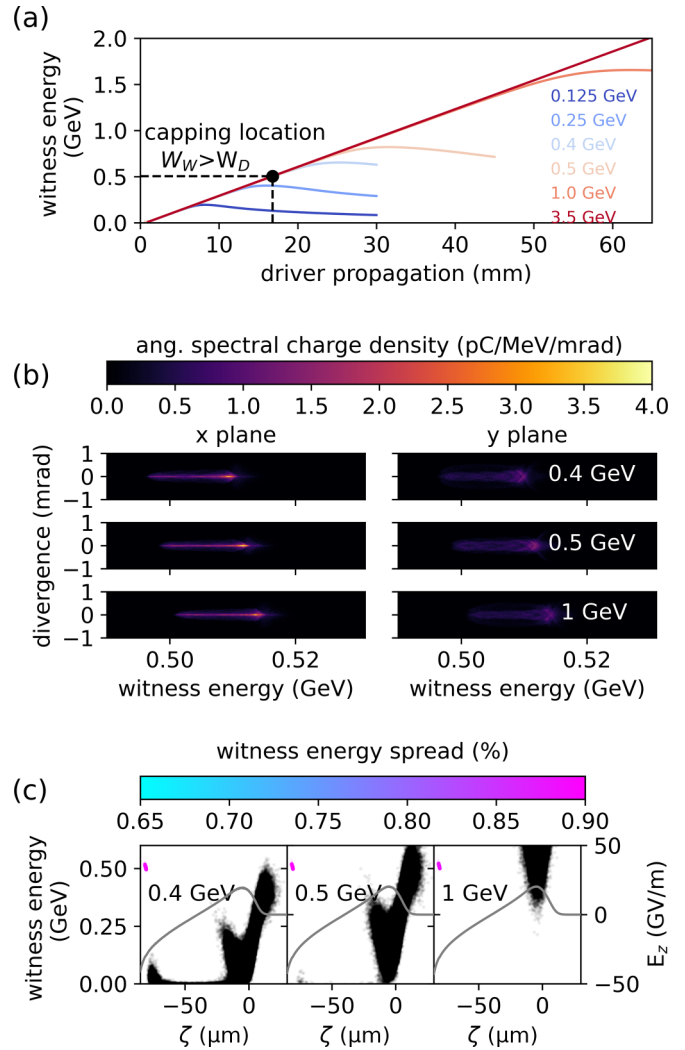


FIG. 3. Impact of driver beam electron energy (0.125–3.5 GeV) on witness energy gain. Panel (a) shows the energy gain of the witness beam as the driver beam energy varies. Panel (b) presents the spectral charge density projections of the witness beam in both the x and y planes for driver energies of 0.4, 0.5, and 1 GeV, at a potential cutoff location indicated by the dashed line in panel (a). Panel (c) displays the energy phase space plots of both the driver (black) and witness beams (left y axis), color coded by relative energy spread, corresponding to the conditions in panel (b) and the values contained within a range of 0.88%–0.9% for the example drivers shown. The longitudinal accelerating on-axis field is shown as a solid gray line (right y axis).

Eventually, driver beam electrons are fully depleted and slip into the accelerating phase of the wake. This effect, already observed in simulations [24,60] and seen experimentally [61,62], is naturally most pronounced for low-energy driver beams with large energy spreads. Accordingly, it is most visible in Fig. 3(c) for the case of a 0.4 GeV driver. In detail, the 0.4, 0.5, and 1.0 GeV driver beams produce witness beams with mean energies of 0.506, 0.508, and 0.510 GeV, and projected relative energy spreads of 0.89%, 0.90%, and 0.88%, respectively. This reduction of energy spread by more than an order of magnitude—jointly with the much

better emittance—demonstrates significant quality enhancement potential.

The hybrid LWFA $\rightarrow$ PWFA platform, therefore, can act as an energy and beam quality transformer [26,27]. While there is a trade-off in energy efficiency between the input LWFA and output PWFA beams, improved driver reproducibility allows optimization, ultimately limited by the depletion length of the lowest-energy driver.

IV. WITNESS ENERGY GAIN IS INDEPENDENT OF DRIVER BEAM ENERGY SPREAD

It is well known that the energy spread of LWFA-generated electron beams can also fluctuate significantly. To determine the effect this may have on the plasma photocathode-generated witness bunch in the PWFA stage, the driver's relative uncorrelated energy spread is varied between 0% and 50% baseline level of $W_D = 500$ MeV. Figure 4(a) shows the corresponding witness energy gains, with selected longitudinal phase space plots displayed in Fig. 4(b).

Figure 4(a) shows that the witness energy gain remains nearly unaffected by even large driver energy-spread variations during early stages of the acceleration. With increasing acceleration distance and driver beam deceleration, the witness energy gains begin to reduce in plasma waves driven by beams with larger energy spreads such as 50%, for reasons similar to those seen with varying driver beam mean energies. Notably, lower driver energy spreads allow the witness beam to reach its maximum energy earlier.

While the largest energy-spread drivers yield the lowest peak witness energies, drivers with moderate energy spread such as 10% can actually achieve slightly higher maximum energy gains than the hypothetical zero-spread case [see Fig. 4(a) inset]. The acceleration distances at which these maxima occur vary nontrivially, reflecting the complex interplay of wakefield dynamics and pump depletion effects.

Again, introducing a capping point—e.g., where the witness energy exceeds the driver energy—helps ensure stable witness energy output. In this case, the lowest-energy-spread cases reach the target energy before those with higher-energy spread. At the chosen extraction point, the mean witness beam energy is 507.0 MeV. Our analysis shows that if the driver energy spread remains below 26.5% r.m.s., the extracted witness energy stays within a $\pm 1\%$ tolerance, demonstrating the hybrid LWFA $\rightarrow$ PWFA scheme's broad tolerance to energy-spread jitter. Additionally, all resulting witness bunches exhibit projected energy spreads below 1%, reducing the witness energy spread by more than an order of magnitude compared to the baseline driver beam.

The selected working point ensures witness trapping occurs in comparatively advanced wakefield phases, rather than at the wake's vertex. While the vertex offers higher initial wakefields—and thus the potential for greater energy gains—trapping in the chosen region provides enhanced beam stability, reducing susceptibility to wakefield evolution and minimizing the risk of electrons slipping out of the focusing or accelerating phases.

Another consequence of positioning the witness bunch in a more advanced phase of the wakefield is the potential for spatial overlap with decelerated electrons from the driver beam.

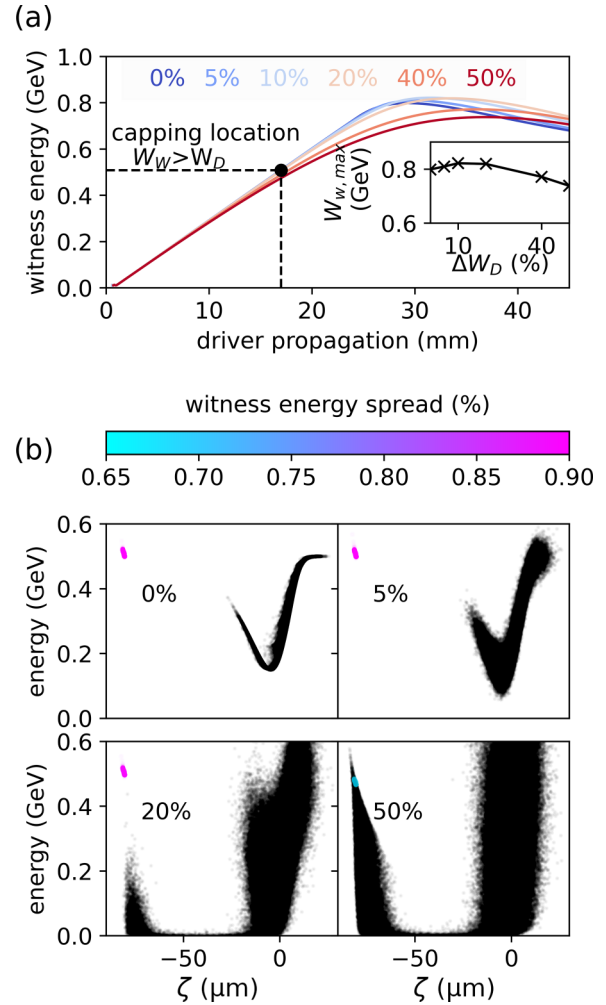


FIG. 4. Impact of driver beam energy spread on witness bunch energy gain. Panel (a) illustrates the witness energy gain as a function of driver energy spread for a fixed driver energy of $W_D = 500$ MeV. The dashed line indicates the threshold at which the witness energy exceeds the driver energy. The inset shows the maximum mean energy gain trend for the witness bunch. Panel (b) presents longitudinal phase space plots for the driver and witness bunches at different driver energy spreads (0%, 5%, 20%, 50%), while the witness bunch maintains a relative projected energy spread of less than 1%. The plots demonstrate the influence of driver energy spread on the longitudinal distribution of both bunches.

Here, they may contribute to beam loading [63], which may be exploited for an interesting effect in particular in context of ultralow emittance electron beams. As shown in Ref. [56], an “escort” beam overlapping an already relativistic, ultralow emittance witness can reduce or compensate its energy chirp without degrading emittance.

In the present configuration, decelerated driver fraction may serve this role. Figure 4(b) illustrates this for 50% driver energy spread. Here, the witness' projected energy spread is significantly lower ($\sim 0.68\%$ versus $\sim 0.9\%$) than in the other three snapshots (see Appendix B). For completeness, the 0%, 5%, 20%, and 50% driver energy-spread cases yield mean energies of 0.509, 0.508, 0.506, and 0.474 GeV, and corresponding projected relative energy spreads of 0.90%,

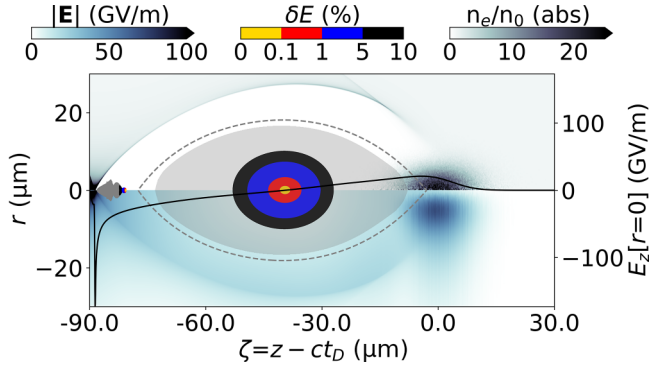


FIG. 5. Intrinsic robustness of witness bunch production against photocathode laser spatiotemporal jitter, shown as a function of longitudinal and radial release position within the blowout. Plasma and driver electron densities are shown in a white-light blue-green gradient, and the localized electric field magnitude is depicted in a white-dark blue gradient. Electrons released within the color-coded energy bands around the 2D trapping ellipse (gray area) are trapped in small volumes at the back of the blowout. The dashed gray line represents the one-dimensional theoretical trapping ellipse, with energy deviations (δE) marked by contour boundaries and the on-axis longitudinal electric field shown as a solid black line.

0.90%, 0.89%, and 0.68%. This creates an opportunity to purposefully reduce the witness beam's energy spread while increasing its energy, provided there is sufficient control over the driver beam. Hybrid LWFA $\rightarrow$ PWFA-plasma photocathodes may be uniquely suited for this, as they combine large driver energy spreads with ultralow emittance witness beams in advanced wake phases. Improving the energy spread while keeping the low emittance could be crucial for applications such as free-electron lasers, which impose strict thresholds on both parameters [64,65].

V. WITNESS PRODUCTION HAS HIGH SPATIOTEMPORAL RELEASE TOLERANCE

We now examine the influence of the spatiotemporal release position of electrons by the plasma photocathode.

Using the baseline driver and a test-particle approach, all possible electron release positions are simulated simultaneously, independent of specific laser parameters. All electrons released within the solid gray ellipse (see Fig. 5) are captured. This agrees with the analytical solution (dashed gray) for trapping from negligible initial velocity, corresponding to the region satisfying the simplified trapping condition discussed earlier, here applied in two dimensions (2D).

Application-specific witness energy stability targets then inform the acceptable spatiotemporal plasma photocathode release region trapping ellipse. Isocontour lines show where released electrons would obtain 0.1% (yellow), 1.0% (red), 5.0% (blue), and 10.0% (black) energy deviation with respect to electron release at electrostatic potential minimum. The symmetry of these isocontours reflects the underlying symmetry of the electrostatic potential. In hybrid LWFA $\rightarrow$ PWFA configurations, the temporal synchronization jitter of the injection laser may be less critical than its pointing jitter. To achieve a 1% witness energy stability target, the transverse

shot-to-shot pointing fluctuation must be below $\pm 3 \mu\text{m}$, which is within reach of emerging high-power laser system capabilities [20,66,67].

The positive gradient of E_z , in concert with linear focusing fields, E_r , facilitates automatic longitudinal and transverse compression of electrons (likewise color coded) at the end of the plasma wave bucket. This autocompression naturally produces ultrashort witness bunches with multi-kA peak currents, exceeding 2.2 kA in the showcase configuration.

Off-axis injection induces betatron oscillations due to the focusing fields, but these rapidly damp as particle γ increases, causing the witness to follow the driver orbit. This offers a significant advantage over external injection schemes of relativistic witness beams, where even minor transverse offsets or pointing errors can severely compromise the acceleration process [68]. Recent studies have indicated [69] that already micrometer-scale emittance growth becomes difficult to control with even submicrometer misalignment. Simulations indicate that plasma photocathodes can limit emittance growth to the nanometer level—over two orders of magnitude lower—even with substantially larger transverse offsets [34].

VI. WITNESS BEAM ENERGY GAIN SELF-ADAPTS TO DRIVER CHARGE DENSITY FLUCTUATIONS

In Sec. II, the driver charge density was varied to demonstrate that witness beam injection rates are independent of the driver charge density. However, as is well known from theory [44,70,71], experiments and even directly observable via shadowgraphy [72], variations in the driver density relative to the plasma density n_D/n_p due to driver charge Q_D , length σ_z , transverse size σ_r , or shape variations from shot-to-shot, can also strongly vary the peak wakefield amplitude, the plasma wavelength and hence the plasma wave cavity size. Therefore, while the accelerating wakefield is only marginally dependent on driver beam energy and its energy spread as discussed in Secs. III and IV, in contrast it is strongly dependent on driver charge density variations [41].

It is also well known that injection rates in LWFA are difficult to control [73,74], and the slice and total current values of electron beams produced by LWFA therefore often exhibit even larger shot-to-shot variations than in energy or energy spread. While total charge is easy to measure, variations in electron beam length and shape are notoriously difficult to quantify. Consequently, shot-to-shot variations in LWFA-produced driver beam charge density represent a very significant, yet often elusive and challenging to measure, source of variation for wakefields in hybrid LWFA $\rightarrow$ PWFA, ultimately influencing the energy gain experienced by witness beams injected in the PWFA stage.

In the hybrid LWFA $\rightarrow$ PWFA scenario, we can realistically assume charge release occurs at a fixed distance behind the driver beam, due to the intrinsic synchronization with the injector laser pulse.

How does the witness energy gain change in this scenario as consequence of driver beam density jitter? To investigate this, we vary the drive beam density as in Sec. II and set the plasma photocathode release position to the electrostatic minimum for the case of the driver charge of $Q_D = 500 \text{ pC}$. The

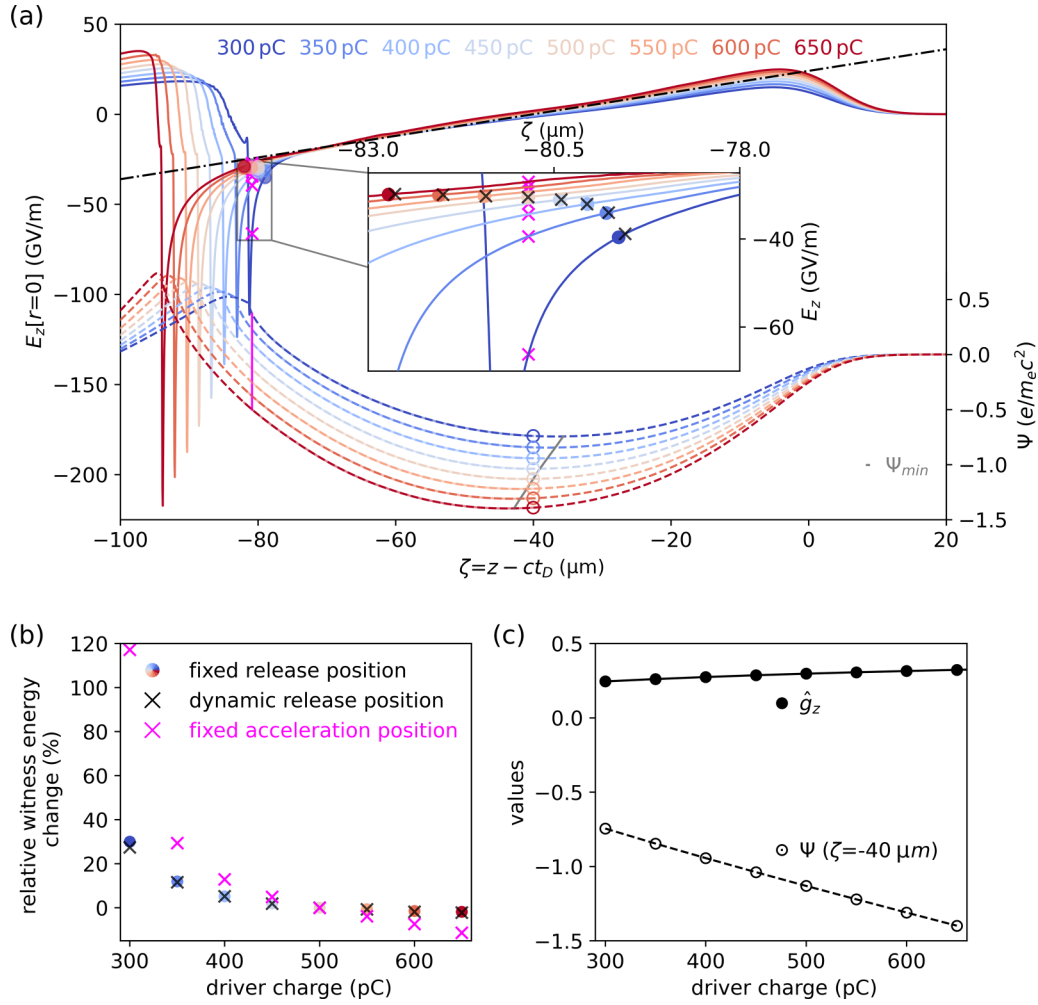


FIG. 6. Intrinsic mitigation of witness energy fluctuation arising from driver density-induced wakefield jitter. Panel (a) presents wakefield line outs for various driver charges, highlighting changes in the electrostatic potential and shifts in the location and magnitude of the minima for both E_z and $\Psi_{\min}$. The dash-dot black line denotes the theoretical normalized gradient $\hat{g}_z$ of the reference driver. Overlaid are color-coded hollow circles indicating fixed injector release positions, with corresponding trapping locations marked by solid circles of the same color. Black crosses represent injection at local $\Psi_{\min}$ positions, while magenta crosses correspond to injection at fixed trapping locations. Panel (b) compares the relative changes in witness energy gain: releasing electrons at a fixed location near the blowout center closely matches injection at the local $\Psi_{\min}$, whereas the variation of mean energies is significantly larger when the acceleration location would be fixed. Panel (c) shows Ψ assuming a fixed injector release position at $\zeta = -40$ μm (hollow black circles) and the normalized slope $\hat{g}_z$ (solid black circles) approaching an asymptotic value of $1/2$, as a function of driver charge.

variation of charge from $Q_D = 300$ to 650 pC corresponds to a relative change of -40% to $+30\%$.

Figure 6(a) visualizes the significant variation in electrostatic potentials and longitudinal wakefield configurations as a response to changes in driver charge (density). The color coding emphasizes that wakefields are stronger (red) and weaker (blue) for driver charge higher/lower than the baseline driver charge $Q_D = 500$ pC. The color-coded hollow circles represent the plasma photocathode release position ζ_{rls} , and highlight that on the one hand the electron release positions are located at electrostatic potentials that are significantly different for the range of Q_D considered. On the other hand, for all cases other than the baseline driver charge, they are also not located at the electrostatic potential minimum of the waves, but to the right (red, stronger waves) and left (blue, weaker waves) of their individual minimum, represented by the dashed gray dotted line. However, the positions in the

wakefield where the electrons are trapped (ζ_{trap} , semitransparent solid circles) are closer to the release position for weaker waves (blue) than for stronger waves (red). This may be counterintuitive, because in a constant wakefield, release positions outside the electrostatic potential minimum result in trapping positions ζ_{trap} farther behind in the plasma wave. In phase-constant PWFA, the wakefield at the trapping position ζ_{trap} then determines the energy gain.

These findings highlight an intrinsic stabilization mechanism inherent to the plasma-photocathode injection scheme, rendering it particularly advantageous in the context of charge variability characteristic of hybrid LWFA $\rightarrow$ PWFA systems.

The inset in Fig. 6(a) zooms in on the trapping region, highlighting that, compared to a hypothetical fixed acceleration position (magenta crosses), for comparison taken here to be the same as the trapping position resulting from plasma photocathode release for the baseline driver case, the range

of electric wakefields at the individual trapping positions ζ_{trap} is significantly reduced across the range of driver beam strengths. This represents a self-adaptive mechanism that decreases the energy gain fluctuations of the witness beam despite significant fluctuations in drive beam and wakefield amplitudes.

In other words, while weaker waves have smaller electrostatic potential and peak wakefield amplitudes than stronger waves, at fixed wake phase positions, the accelerating field—and hence the acceleration rate—is significantly *larger* in weaker waves than in stronger ones. This is a challenge for the output energy stability of externally pre-accelerated and then injected electron beams, in addition to timing jitter. While in the plasma-photocathode mechanism, the resulting accelerating wakefields $E_{z,\text{trap}}$ at individual trapping positions ζ_{trap} are also larger for weaker waves than for stronger ones, the difference is significantly mitigated: Trapping positions ζ_{trap} automatically shift to later positions within the wake for stronger waves—where $E_{z,\text{trap}}$ is larger than at fixed trapping position. This dynamic shift partially compensates for variations in driver beam strengths from shot to shot, providing intrinsic mitigation of the actual witness acceleration gradient fluctuation, and hence the witness energy gain fluctuation. In further detail, the inset in Fig. 6(a) shows that as the driver charge is linearly increased, the variation of ζ_{trap} increases, while the change in $E_{z,\text{trap}}$ decreases nonlinearly. This leads to the bow-shaped distribution of wakefield versus trapping position displayed in the inset.

Figure 6(b) quantifies the witness energy fluctuation mitigation by comparing the resulting witness energy change obtained for beams released by the plasma photocathode with those that would be obtained at a fixed acceleration position in the wakefields. The y axis shows the relative change compared to the baseline driver case of $Q_D = 500$ pC. The magenta plot represents the hypothetical fixed wakefield position case. The colored circles show the electric fields at trapping positions resulting from plasma photocathode emission at a fixed release position, and the black crosses show the slightly different electric fields at trapping positions when release occurs at the individual potential minima of each driver-generated plasma wave. This comparison highlights the intrinsic energy stability advantage of electron beams that may be found in plasma-photocathode injectors.

The—to some extent—*self-stabilizing* behavior of the witness energy—and its robustness to increasing driver current, which leads to saturation of the energy gain in the high-current limit—can be understood from first principles. Consider an accelerating electric field with constant slope, $g_z \equiv dE_z/d\zeta > 0$, defined along the comoving coordinate $\zeta = z - ct_D$. We assume that the electron is released at the zero crossing of the parent wakefield, ζ_0 , corresponding to the center of the blowout region where $E_z(\zeta_0) = 0$. The field is then given by

$$E_z(\zeta) = g_z(\zeta - \zeta_0). \quad (1)$$

Applying the trapping condition, $\Psi(\zeta_0) - \Psi(\zeta_f) = -mc^2/e$, and using $E_z = \partial_\zeta \Psi$, integration yields the trapping offset

$$\zeta_f - \zeta_0 = -\sqrt{\frac{2m_e c^2}{e g_z}}. \quad (2)$$

The accelerating field at the trapping location then evaluates to

$$E_{z,\text{trap}} = -E_0 \sqrt{2\hat{g}_z}, \quad (3)$$

where $E_0 \equiv m_e c^2 k_p / e$ is the cold wave-breaking field and $\hat{g}_z \equiv g_z / (E_0 k_p)$ is the normalized slope of the wakefield. This result shows that the final accelerating gradient depends solely on $\hat{g}_z$.

As established by theory and simulations [44,70], the parameter $\hat{g}_z$ asymptotically approaches 1/2 for high-current drivers ($\gg 10$ kA). In the regime of moderate currents (around ~ 10 kA), $\hat{g}_z$ exhibits only a weak dependence on the driver's current, typically settling near 0.3, in agreement with earlier findings [75].

Due to the square-root dependence in Eq. (3), the influence of current on $E_{z,\text{trap}}$ is further diminished, resulting in a slow convergence toward $E_{z,\text{trap}} \rightarrow -E_0$ as the beam current increases.

This behavior is further illustrated in Fig. 6(c): The difference of Ψ at plasma photocathode release position of $\zeta = -40$ μm (hollow circles) shows a strong dependence on driver charge, whereas $\hat{g}_z$ (solid circles)—and by extension also $E_{z,\text{trap}}$ —converges toward increasing driver charges.

For lower driver currents, trapping occurs increasingly deeper within the nonlinear blowout region, where deviations from linear theory become significant. Nevertheless, the injected beam remains more stable compared to trapping at a fixed location, further illustrating the resilience of this injection mechanism.

VII. DISCUSSION AND OUTLOOK

The plasma photocathode is a path toward electron beams with ultralow emittance ϵ_n on the order of tens of nm rad in both planes, kA-level current I , and in turn ultrahigh electron beam brightness $B_{5,n} = 2I/(\epsilon_{x,n}\epsilon_{y,n})$. While not discussed above, also in the present study, the witness beam brightness exceeds the driver beam brightness by orders of magnitude, and hence acts as a brightness transformer for PWFA. The projected five-dimensional brightness consistently reaches values of $B_{5,n} > 10^{19} \text{ A m}^{-2} \text{ rad}^{-2}$, and projected six-dimensional brightness on the order of $B_{6,n} > 10^{18} \text{ A m}^{-2} \text{ rad}^{-2} / 0.1\% \text{ BW}$. Although emittance, brightness, and energy spread are fundamentally decisive parameters for applications such as light sources, the stability and reproducibility of electron beams are also important. Plasma photocathodes can be realized with driver beams from conventional linacs [33], but as of today very few linacs offer PWFA capabilities, in particular high-field PWFA capabilities with plasma wakefields > 10 GV/m. Only one linac engaged in PWFA research—SLAC FACET [33,76]—so far offered a capability crucial for hosting plasma photocathodes, namely, producing a driver beam current $\gtrsim 6$ kA.

Fortunately, LWFAs can produce beams with very large currents, allowing hybrid LWFA $\rightarrow$ PWFA systems to even operate in the high-field PWFA regime, and to mature from concept [24] to experimental reality in recent years [28–30,41,72]. These systems were quickly envisioned as platforms capable of hosting plasma photocathodes, with their intrinsic synchronization capability recognized as an

important additional advantage [31]. Very recently, the first plasma photocathode in a hybrid LWFA $\rightarrow$ PWFA system was realized, at HZDR's DRACO facility, utilizing a 90° geometry [77].

With these advances, and the global number of high-power laser installations now reaching into the triple digits, the availability of LWFA-capable facilities that can be leveraged for PWFA and plasma-photocathode research has grown substantially. This makes it both timely and necessary to investigate in greater depth the specific conditions and parameters governing this hybrid plasma-photocathode scenario.

In this study, we have identified and explored principal sources of input jitter anticipated when implementing an LWFA $\rightarrow$ PWFA equipped with a collinear plasma-photocathode setup. The dominant shot-to-shot variations of electron beams from today's LWFA systems originate from fluctuations in the electron beam's energy, energy spread, and charge or current. Then, plasma-photocathode injection jitters in plasma waves driven by these beams may result from spatiotemporal jitter between the plasma photocathode laser and the electron beam-driven plasma wave, and from shot-to-shot changes in the laser intensity.

Our findings show that plasma-photocathode electron injection rates are purely dependent on the injection laser, and the witness electron beam charge, therefore, is decoupled from the driver beam strength shot-to-shot. This is in stark contrast to injection methods such as downramp injection or drive beam- or wakefield-induced ionization-based methods, where injection rates are strongly dependent on driver and wakefield strength.

Regarding the acceleration gradient, fluctuations in the driver beam energy and energy spread exhibit negligible impact until driver depletion occurs. Lower-energy driver beams deplete earlier; thus, limiting the length of the PWFA stage can stabilize the output witness energy and operational reproducibility, as alternative to higher witness beam energies, but reduced reproducibility.

Targeting the center of the blowout for plasma photocathode release benefits from the symmetry and flatness of the electrostatic wake potential in this region. This symmetry provides intrinsic robustness against shot-to-shot spatiotemporal relative jitter, as small variations in the electrostatic potential at the release position result in only minimal shifts in the trapping position. Consequently, the associated electric fields and accelerating gradients at the trapping position remain similar shot by shot.

It shall be emphasized that an injection location in the center of the wave is a feature uniquely available for plasma-photocathode injection. In contrast, other internal injection methods typically either inject in earlier (e.g., driver pulse-induced ionization injection) or in later (wakefield-induced or density downramp injection) wake phases, resulting in trapping positions further toward the rear of the wake. In contrast, plasma photocathodes naturally enable earlier trapping positions within the plasma wave, offering significant advantages on multiple fronts. First, the wakefields at the release position are minimal, ensuring that their contribution to the witness charge yield due to superposition with the plasma-photocathode laser fields is negligible. Second, witness beams are trapped and accelerated in a “safe zone” sufficiently well

separated from the vertex of the wake. On the one hand, this allows robust, full capture of the released charge, as well as avoiding witness beam vulnerability to longitudinal and transverse wake evolution and potentially even charge loss. On the other hand, the wakefield amplitude differences at neighboring wake positions rather deep into the blowout are rather small, minimizing the spread of accelerating gradients in case of jitters. Third, our study reveals that in combination with the intrinsic synchronization of hybrid systems and the minimized temporal jitter between plasma photocathode and driver beam, an automatic significant stabilization mechanism against driver charge variation can be harnessed. At lower driver beam charges, the electrostatic wake potential is smaller than at higher driver beam charges; however, the concurrent shift in trapping positions significantly alleviates the spread of accelerating gradients of the witness beams—an effect that is favorable for witness beam energy stability.

Plasma density variations are not considered in this study. A brief sensitivity analysis of plasma density and entrance ramp-length variations indicates that, within realistic experimental fluctuations, these effects induce only marginal changes in the wakefield structure and witness beam parameters.

In summary, our findings show that counterintuitively, the high beam quality feature of plasma photocathodes does not come at the price of reduced stability, but is, according to our analysis, concomitant with improved stability. It is revealed that the plasma photocathode can act not only as a brightness and electron energy transformer but also as a stability transformer. These benefits are made as a trade-off with beam charge. In this study, driver to witness charge ratio is about 1%. We note similar charge ratios have recently been used in the generation of brighter witness beams using density downramp injection, and this demonstration is regarded as a promising route toward light sources and even high-energy physics [37]. We further note that in scenarios where higher witness beam charge is released and direct beam loading is exploited, this ratio can be much higher [78], while trapping tolerances are reduced. The scenario of intrinsic synchronization but significantly varying driver beam from shot-to-shot, the reality of today's LWFA systems, is complementary to the scenario of limited synchronization but state-of-the-art driver beam stability in linac-driven PWFA systems.

The plasma photocathode thus emerges as an ideal injection mechanism for hybrid LWFA $\rightarrow$ PWFA systems, offering a unique combination of three key performance enhancements—brightness, energy, and stability—delivered simultaneously. The concurrent optimization of these beam qualities is essential for demanding applications such as driving free-electron lasers, thus making this avenue an attractive route toward compact, yet high-performance accelerator systems.

ACKNOWLEDGEMENTS

B.H., D.C., A.D., T.H., A.F.H., and A.S. were supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme NeXource, ERC Grant Agreement No. 865877. The project was supported by European Union's Horizon Europe

research and innovation programme under grant agreement No. 101073480 EuPRAXIA and 101188004 PACRI, and by the German BMBF Project. No. 05K25PFA HyBright. This work was supported by the Science and Technology Facilities Council (STFC) (Grant No. ST/S006214/1, PWFA-FEL). A.P., T.W., and L.R. were supported by the German BMBF Project No. 05P24PF2. This research used resources of the National Energy Research Scientific Computing Center (NERSC), a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231, using NERSC award HEP-ERCAP0031797. Computational resources at JUWELS [79] were also utilized.

D.C. performed the simulations and the analysis. D.C., T.H., and B.H. wrote the manuscript, aided by input from all coauthors. The external laser in FBPIC was implemented by T.W. B.H. supervised the project.

DATA AVAILABILITY

The data that support the findings of this article are openly available [80].

APPENDIX A: DEMONSTRATION OF WITNESS STABILIZATION USING ARTIFICIALLY ANGULARLY RESOLVED ENERGY SPECTRA

The primary instrument currently used in all LWFA and PWFA facilities for electron bunch data collection and characterization is the dipole electron spectrometer. In LWFA, the inherent absence of any driver charge allows for a clean witness-only signal. However, in PWFA, this cannot be guaranteed, as driver electrons may cause an energy phase space overlap with the witness signal [e.g., Figs. 3(c) and 4(b)]. While the driver typically has much more charge than the witness beam, driver energy depletion and emittance and divergence growth nevertheless allow identification of the witness signal in almost all cases, even without background subtraction that is usually performed in experiment postprocessing.

Examples of the stabilization outcome are demonstrated in the form of “artificial” spectra generated at the “capping location,” as discussed throughout the main text body of this article, shown in Figs. 7 and 8.

Figure 7(a) shows the case of variation of the driver charge as discussed in context of Figs. 2(a) and 6. The spectra show that the witness energy is stable, despite the large driver charge variation.

Figure 7(b) shows artificial spectra corresponding to the case of variation in laser energy as discussed in Fig. 2(b). All other parameters kept the same; the minimal alteration in injected witness charge produces almost identical signal on the artificial spectrometer.

The case of energy variation of the driver beam is shown in Fig. 8(a), amending the discussion in context of Fig. 3 in the main text. This visualization highlights the energy stability of the witness beam, even as the driver beam transitions through regimes where its electrons are either all less energetic than the witness electrons, partially overlap in energy due to deceleration, or entirely more energetic than the witness beam.

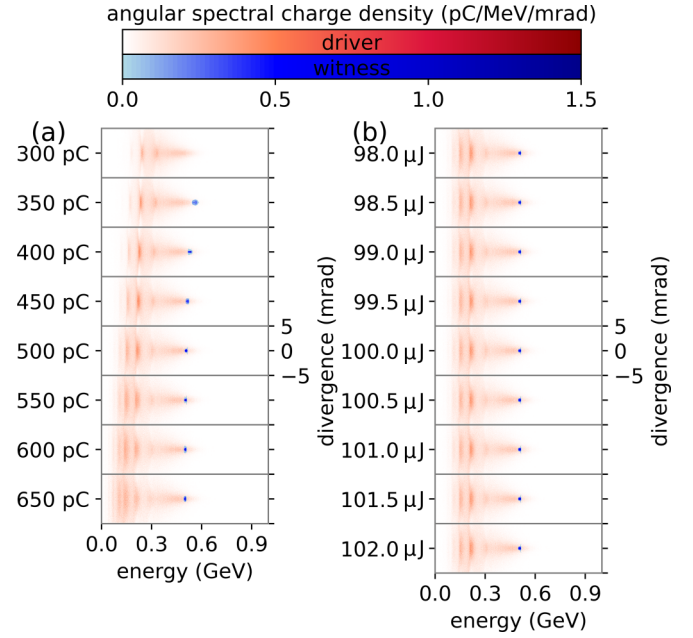


FIG. 7. Exemplar artificial charge density spectra of electron beams from simulation data. Impact of driver charge variation in panel (a) and plasma-photocathode laser energy variation in panel (b) on artificial charge density spectra for driver (white-red colorbar) and witness (white-blue colorbar). The driver energy and energy spread are set to 500 MeV and 10% r.m.s., respectively. In panel (b), the driver charge is set to 500 pC.

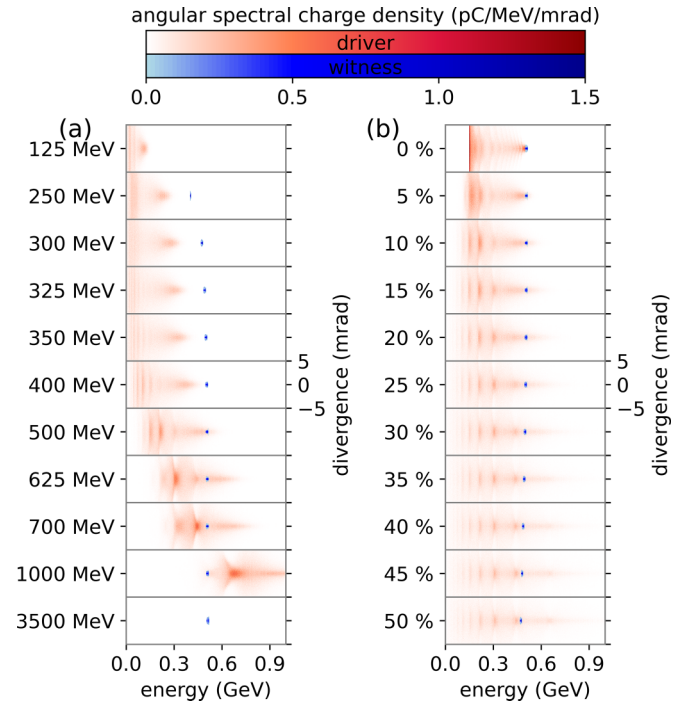


FIG. 8. Further artificial electron charge density spectra from simulation data. Impact of driver mean energy variation in panel (a) and driver energy spread variation in panel (b) on artificial charge density spectra for driver (white-red colorbar) and witness (white-blue colorbar). The driver charge is set to 500 pC. In panel (a), the driver energy spread is 10% r.m.s. In panel (b), the initial driver energy is set to 500 MeV.

Figure 8(b) illustrates the effect of variations in the driver energy spread, complementing the discussion of Fig. 4 in the main text and emphasizing the robustness of the witness beam against such variations. All figures substantiate the fact that the witness beam divergence is much lower than the driver beam divergence, and that its angular spectral charge density—an experimentally robust observable—is enhanced.

APPENDIX B: BEAM LOADING AND WITNESS CHIRP REDUCTION BY DRIVER BEAM DEPLETION

As discussed in the main text, certain latent effects that have an observable impact on the witness beam's energy spread become noticeable at longer acceleration distances. Figure 9 shows the underlying cause of the reduced energy-spread behavior observed in the energy phase space diagrams in Fig. 4(b). The top three panels show the longitudinal driver and witness current profiles at the capping point, and the longitudinal wakefield profiles generated by a driver beam of 5%, 10%, and 50% energy spread at injection (black solid line) and at the capping point (dashed line). The initial driver energy is 500 MeV and its charge is 500 pC.

While there is no difference between the wakefields at the beginning of the acceleration and the end for the low-energy-spread cases, the 50% energy-spread case shows that there is significant difference in wakefield amplitude at the witness position.

As the driver beam depletes due to the self-created decelerating phase of the field, it causes the lowest-energy electrons to eventually be recaptured at a phase of the wakefield that overlaps with the witness beam. This additional, significant current at witness position provides local beam loading, and flattening of the longitudinal wakefield at this position.

The bottom three panels are enlarged, highlighting the change of the wakefield due to this decelerated and reaccelerated charge. This flattened wakefield is responsible for the reduction in witness energy spread.

APPENDIX C: PARTICLE-IN-CELL SIMULATIONS

Simulations were performed using the quasi-3D PIC code FBPIC. The drive beam was modeled as a normally distributed bi-Gaussian distribution with 1 million equally weighted macro-particles. The laser was approximated as a Gaussian pulse, solved at each time step. Its fields were applied to the macro-particles, enabling the recovery of ionization charge yields, which closely agreed with analytical Ammosov-Delone-Krainov (ADK) predictions. The background plasma (He^+) was modeled as an electron-only species [16 macroparticles per cell (PPC)], with convergence tests performed for all parameters before the production runs. Witness macroparticles were generated using the built-in ADK module, with all fields incident on the helium ions kept safely below the ADK critical field (~ 400 GV/m), negating the need for a tunneling and barrier suppression ionization tandem code. These particles represented He^{2+} ions (32 PPC). A total of 3.24 million cells were used, with a cell size of 50 nm in the longitudinal direction (z) and 100 nm in the radial direction (r). This grid resolution allowed for accurate modeling of all key physical

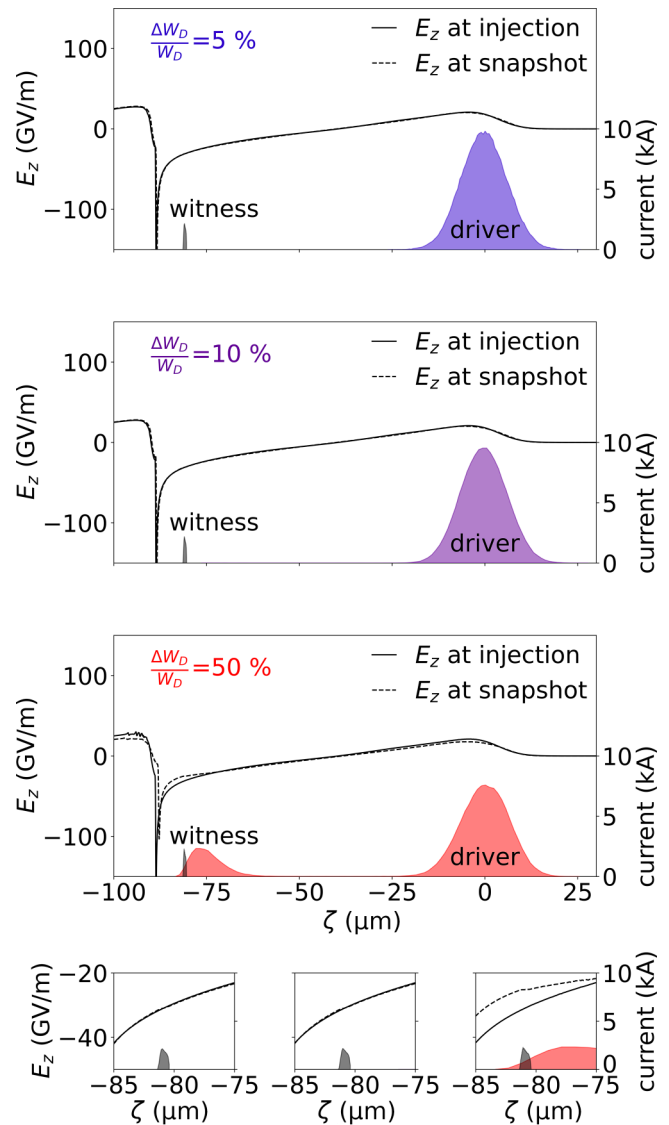


FIG. 9. Wakefield evolution showing beam-loading effects from driver energy spread. Top panels: On-axis accelerating field at injection (solid black) and at 17.0 mm (dashed black), shown with color-coded driver current profiles and shaded black witness current. Increased driver energy spread accelerates depletion, causing field flattening around the witness beam position. Bottom panels: Detailed view of the flattened accelerating field region across the witness bunch, demonstrating how driver depletion contributes to reduced energy spread in the witness beam.

effects while considering the available simulation resources. All simulations were performed using a moving window and utilized the same box accompanied by two azimuthal modes with open box boundaries and default matched absorption layers applied transversely to the $(135 \mu\text{m} \text{ by } 120 \mu\text{m})$ simulation box. A Galilean transformation of the comoving grid was used to suppress the numerical Cherenkov instability and its spurious field emissions to prevent artificial degradation of the witness. Cross deposition current correction and an infinite stencil were used in all simulations, where the latter allowed for a more accurate solving of the dispersion relation compared to when using multi-MPI processes. A cosine

flat-top cylindrically symmetrical plasma channel was used in all simulations, with a $2\lambda_p$ entrance ramp implemented. Injection occurred in all cases with a fixed laser focal position of 0.5 mm in the laboratory frame, with the delay expressed in the main text behind the driver for the linked comoving coordinate. Figure 5 used test particles, which were spaced every dz and $dy = dx = dr$ in Cartesian space. The center of the distribution was placed at the laser focus position, and the particles were instantaneously loaded at the appropriate simulation time step from precalculated arrays of momentum (all zero) and particle positions. To prevent these particles from influencing the simulation fields, their weight and subsequent current deposition were set to zero in this simulation set only.

Simulation postprocessing used the same set of spatial and energy macroparticle cuts for laser injection runs.

APPENDIX D: TABLE SUMMARIZING SIMULATION SCAN PARAMETERS

Table I summarizes the driver-beam and laser parameters used in the simulations corresponding to Figs. 1–6. For each case, the table lists the driver charge, driver energy, relative energy spread, and the laser energy used for the plasma photocathode. In all simulations, the normalized driver beam emittance was held constant at $\epsilon_n = 2.0 \mu\text{m rad (r.m.s.)}$, and the plasma density was set at $n_e \approx 1.12 \times 10^{17} \text{ cm}^{-3}$.

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