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Revealing the nonlinear transition of beam-driven plasma wakefield

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Plasma wakefield accelerators, powered by high-current particle beams, are rapidly emerging as a revolutionary platform for both compact light sources and the next generation of high-energy colliders. A critical aspect that remains unresolved in advancing these accelerators is the precise characterization of the field structure and its intricate correlation with the drive particle bunch. In this article, the drive electron bunch is produced by a laser-plasma accelerator, while the plasma wakefield it generates is probed by an ultrashort electron bunch from a separate laser-plasma accelerator. This configuration allows for the simultaneous extraction of both the induced wakefield and the space-charge field of the driving bunch in a single shot. As the charge of the driver is increased, two fundamental phenomena emerge: first, the electric wakefield structure transitions from a linear, sinusoidal pattern to a nonlinear, sawtooth pattern; second, the shape of the field is modified due to the influence of the trailing tail of the driver. Additionally, these observations reveal a strong correlation between the strength of the driver and the wakefield, which aligns closely with quasi-three-dimensional simulations and classical wakefield theory. These findings not only deepen our comprehension of beam-driven plasma wave dynamics but also provide crucial quantitative insights for high-quality plasma wakefield acceleration optimization in real time.

Particle accelerators have been instrumental in probing the origins of matter and have played a pivotal role in advancing frontier particle physics since their inception. Their applications extend beyond the realm of basic research, impacting various societal sectors including medicine, in-

dustry, and security. Despite their widespread utility, traditional particle accelerator technologies grapple with challenges of scale and cost. Consequently, for over three decades, there has been a dedicated effort to explore new acceleration principles that offer greater accelerating power. A particularly promising development in this field is plasma-based wakefield acceleration [1, 2], which leverages intense laser pulses or relativistic charged particle beams to excite plasma waves. These plasma accelerators, capable of sustaining electric fields exceeding 100 GV/m without breakdown, mark a significant advancement over traditional methods.

Laser-driven wakefield acceleration (LWFA) studies, conducted in numerous high-power laser laboratories, have successfully delivered GeV-level electron beams [3–6] with ultra-short bunch durations [7, 8] and small source sizes [9–11] over just centimeter scale. Despite many breakthroughs over the past decades, the maximum energy gain in a single LWFA stage is constrained by dephasing due to the subluminal wake velocity [12, 13]. Particle beam-driven wakefield acceleration (PWFA), on the other hand, does not face this limitation, as the high-energy driver bunch travels nearly at the speed of light. This feature makes PWFA especially appealing for the high-energy physics community, seeking to build compact particle colliders. Leading accelerator institutions like SLAC, CERN, DESY, and INFN have made substantial strides in PWFA research, achieving milestones such as energy doubling of 42 GeV electron beams [14], high energy-transfer efficiencies [15], GeV energy gains in positrons [16], pioneering proton-driven wakefield acceleration of electrons [17] and the demonstration of PWFA based free-electron-lasing [18]. Recent advancements also show that electron beams generated from LWFA can effectively drive strong plasma wakefields [19–22]. This all-optical hybrid approach, operating at a much smaller scale, offers a complementary solution to large radio-frequency accelerators, facilitating fundamental studies of beam-plasma dynamics in university-scale laboratories and promising ultra-high brightness electron beams.

Previously, the strength of PWFA fields has been inferred from the energy gain or loss of the electron bunches [23] based on multiple shots, with subsequent techniques measuring longitudinal phase space or energy-divergence correlations using energy-chirped bunches in single shot [24, 25]. However, these methods relies on the integration over the entire acceleration distance and only provide the longitudinal distribution of the wakefield near the central axis, losing multi-dimensional and instantaneous information. Recent use of few-cycle optical shadowgraphy for diagnosing the two-dimensional shape and size of a plasma wave, on the other hand, lacked direct field measurements [20, 26]. As such, the transient field structure of a beam-driven wakefield

and its correlation with the drive bunch, which is crucial for precise acceleration optimization, remained elusive.

In this article, we present the quantitative two-dimensional mapping of the beam-driven plasma wakefield by using our recently developed technique called *femtosecond relativistic electron microscopy* (FREM) [27], which applies a few-femtosecond high-energy electron bunch generated from another laser-plasma accelerator as a probe to cross the investigated wakefield in the transverse direction [28], and has been successfully tested for diagnosing several important LWFA related phenomena [11, 22, 27, 29]. With this technique, the PWFA field structures are retrieved in both linear and nonlinear regimes, and the measured correlation between the driver bunch and the resulting wakefield strength shows good agreement with both theoretical and simulation predictions.

The experiment was conducted using the HIGGINS dual 100 TW laser system at the Weizmann Institute of Science [30]. As shown in Fig. 1, a 0.6 J, 30 fs laser beam was focused into into a 3 mm-long helium gas jet doped with 1% nitrogen, resulting in a peak plasma density of approximately $8 \times 10^{18} \text{ cm}^{-3}$ measured by an off-line Mach-Zehnder interferometer. The ionization-injected electron beam [31, 32], first accelerated in the LWFA, subsequently drove its own plasma wakefield as the laser energy depleted. A second laser pulse, of 1.2 J, 30 fs was focused into a gas jet of the same type to produce an electron probe, characterized by a quasi-monoenergetic energy spectrum peaking at $295 \pm 30 \text{ MeV}$ and an FWHM spread of $60 \pm 25 \text{ MeV}$, where the error bars come from shot-to-shot fluctuation over 30 consecutive shots and measurement errors such as divergence-induced position uncertainty in the energy spectrometer. Upon exiting the gas jet, the probe bunch drifted in the vacuum for 10 cm and intercepted perpendicularly the plasma wakefield to be probed and getting deflected. Following an additional 6 mm drift, the resulting deflections, which evolved into periodic density variations, were observed using a $50 \mu\text{m}$ thick Ce:YAG scintillator (protected by a $50 \mu\text{m}$ thick stainless steel foil) together with a high-resolution imaging system.

The detailed properties of the PWFA driven by the laser-accelerated electron beam, was measured in the low-density rear down ramp (plasma density around $1 \times 10^{17} \text{ cm}^{-3}$), where the laser field is already insignificant. Fig. 2 showcases five shots of energy spectra of the drive electron beams in (a) and corresponding driven plasma waves captured by the probe in (b) for different on-target laser energies ranging from 230 mJ to 550 mJ. When the laser energy was at its lowest (230 mJ), no accelerated electrons were detected by the energy spectrometer [Fig. 2(a1)], and

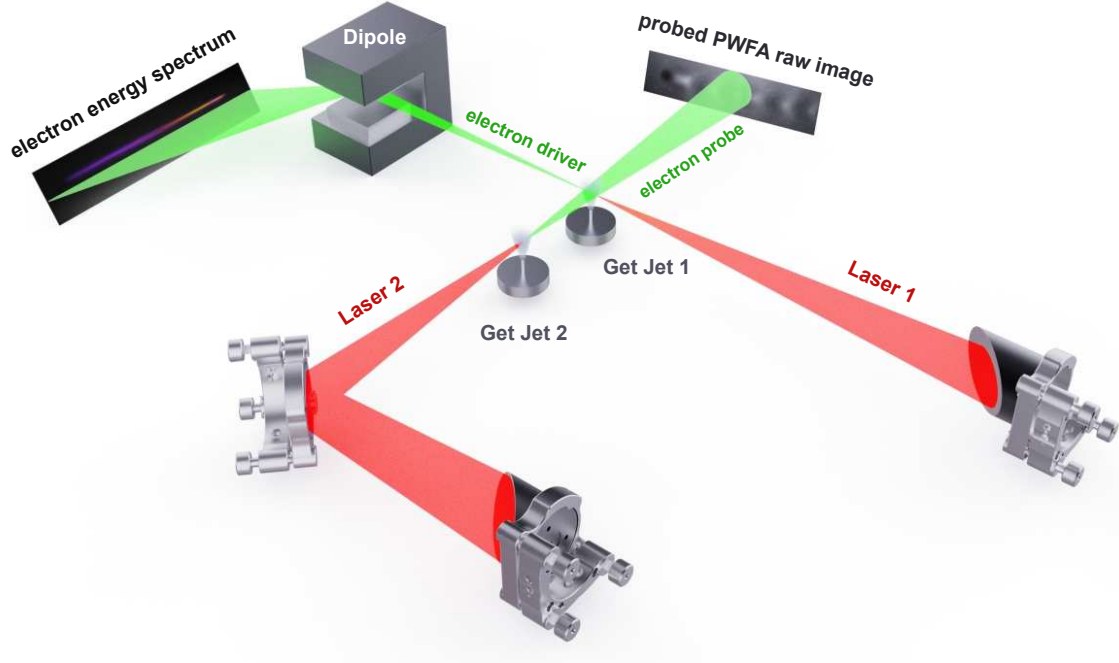


FIG. 1. **Experimental setup.** Laser 1 of 0.6 J, 30 fs was focused into a gaseous target (Jet 1) and accelerated an electron bunch through launched wakefield. After some propagation, the laser intensity became too weak and the electron bunch started to driven its own wakefield. This was diagnosed by another electron bunch as a femtosecond probe generated by Laser 2 of 1.2 J, 30 fs in Gas Jet 2. After crossing the beam-driven wakefield and gaining some momentum modulation, the probe bunch drifted a further 6 mm distance and developed into a corresponding density modulation that contains the key information of the investigated wakefield (see the raw probe image). After exiting the Jet 1, the electron driver was diagnosed by a energy spectrometer consisting of a dipole and a scintillator screen located 1 m downstream of the gas jet.

only a bright-dark periodic pattern was evident in the probe image [Fig. 2(b1)], indicative of a linear wakefield solely driven by the laser [29]. As the laser energy increased, the charge of the laser-accelerated electrons rose to approximately 120 pC, with their maximum energy reaching close to 200 MeV [Fig. 2(a2-a5)]. The probed wakefield images in Fig. 2(b2-b5) revealed an elliptical hollow structure at the front of the periodic pattern, corresponding to a beam driving its own wakefield [11, 22].

As the driver charge increased, two distinct features emerged in the probe images. Firstly, both the darkness of the front hollow structure (representing the driver's lateral charge density [11]) and the brightness of the periodic structure (indicative of the wakefield strength [29]) significantly heightened, aligning with the qualitative understanding of driver-wakefield strength correlation.

Additionally, the shape of the wakefield appeared curved, and elongation of the wake period was observed [from Fig. 2(b2) to Fig.2(b5)], indicating a transition from linear to nonlinear regime [33, 34].

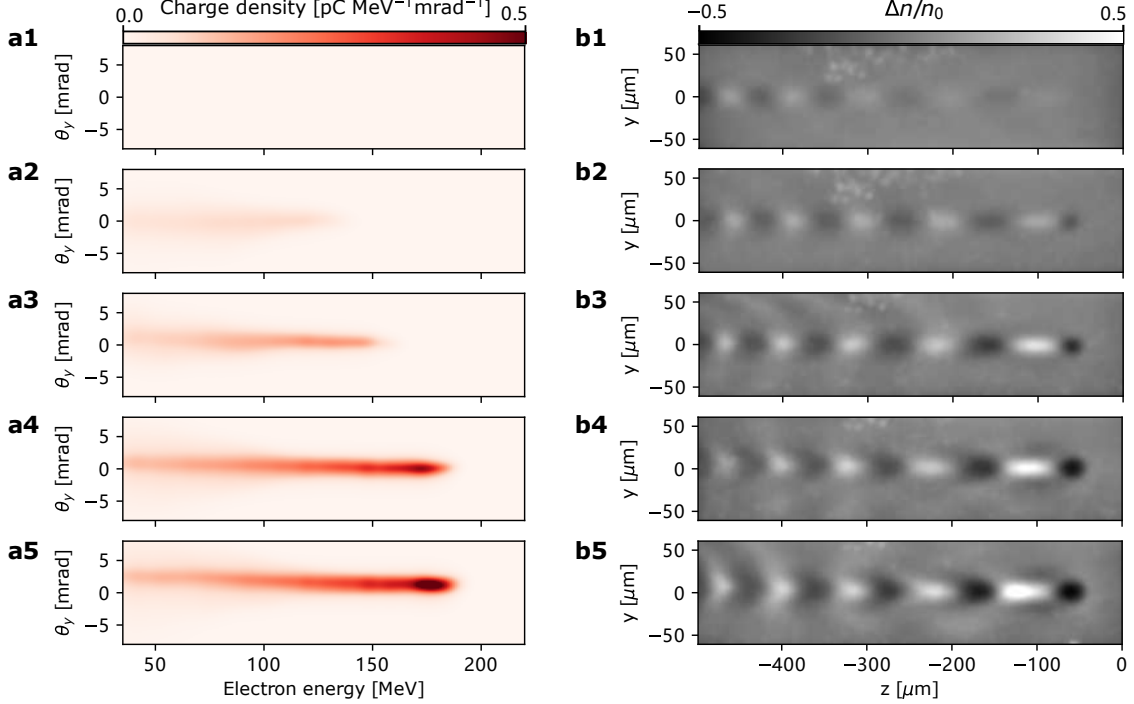


FIG. 2. **Measured energy spectra of the electron driver (a1-a5) and corresponding wakefield snapshots (b1-b5) for five different on-target laser energies.** The used laser energy from up to down, is about 230 mJ, 280 mJ, 380 mJ, 500 mJ, 550 mJ, respectively.

To obtain more quantitative information about this transition, we retrieve the observed driver and wakefield structures. In Figure 3a and 3b, we have selected two representative probe snapshots from Figure 2b for comparison. In terms of the driver parameters, taking into account an ionization-injected LWFA electron bunch with a duration of only a few femtoseconds [8], it is noted that its lateral size typically expands to a few micrometers in the down ramp region [10, 35], which is much larger than its longitudinal size. As a consequence, the lateral charge density distribution of the electron bunch can be directly estimated from the front hollow structure [11]. Assuming a bi-Gaussian distribution, the bunch in Fig. 3a contains a total charge of 21 ± 2 pC, with transverse RMS sizes of $\sigma_x = 7.4 \mu\text{m}$ (horizontal) and $\sigma_y = 7.6 \mu\text{m}$ (vertical), while the one in Fig. 3b contains a much larger charge of 124 ± 12 pC with slightly bigger sizes $\sigma_x = 9.3 \mu\text{m}$ and $\sigma_y = 8.1 \mu\text{m}$.

Furthermore, the wakefield structure of these two images can be reconstructed using the modified algorithm described in the Methods section, which, compare to the previous one [28], takes into consideration both the probe density modulation and coordinates variation [36], while also removing the contribution from residual laser effects. The periodic intensity pattern observed in the probe image is actually *a projection of the plasma wave density perturbation integrated along the probe propagation direction* (see Methods). The wakefield potential ϕ and thus the longitudinal electric field E_z was then calculated based on the Poisson equation. The results are depicted in Figure 3c and Figure 3d, respectively. By analyzing the distribution of their on-axis lineouts displayed as blue solid curves in Figure 3e and 3f, it becomes evident that the left panel depicts a linear wave with a simple sinusoidal pattern, whereas the shape of the right panel becomes skewed, indicating that the wave has become nonlinear [37, 38]. The field strengths of the first period for these two cases are 1.2 ± 0.1 GV/m and 6.7 ± 0.7 GV/m, respectively.

In Figure 3f, it is notable that, aside from the characteristic sawtooth waveform, the electric field of the first period exhibits a significant flattening. This unexpected phenomenon is intriguing, and can predominantly be ascribed to the emergence of an extended tail in the driving electron bunch, potentially due to a too long injection distance. This extended tail bunch employs its space-charge force to further displace the plasma electrons, thereby inducing alterations in the field structure. This effect, commonly referred to as the *beam loading* effect [39, 40], has never to our knowledge been directly observed experimentally.

To validate all these reconstructed findings, we conducted quasi three-dimensional (3D) particle-in-cell (PIC) simulations using the code FBPIC [41], with input density profile mimicking the experimental one. For the linear scenario depicted in Figure 3a, a single electron bunch with a charge of 18 pC, RMS radii of $8 \mu\text{m}$, and a pulse duration of 10 fs was utilized. As evidenced in Figure 3e, the simulated electric field component E_z (represented by the orange solid curve) aligns well with the retrieved experimental data.

In terms of the nonlinear case illustrated in Figure 3b, we initially simulated the scenario using a single electron bunch of 100 pC with RMS radii of $8 \mu\text{m}$ and a pulse duration of 10 fs. The resulting longitudinal field shape was a simple sawtooth waveform (as shown by the blue solid curve in Supplementary Figure 3c). Subsequently, we introduced a second, longer electron bunch of 200 pC positioned behind the initial bunch, with $20 \mu\text{m}$ RMS radii of and 120 fs pulse duration mimicking the long tail dark current. The resulting field shape, as evidenced by the orange solid curve in both Supplementary Figure 3c and also Figure 3f, gets flattened obviously, as similar

behaviour of the reconstructed one. We note that estimating the transverse extent of the second bunch presented a challenge, which based on our observation, was only known larger than the driven wakefield transverse size. Consequently, the parameters selected were only aimed at shaping the wakefield to closely resemble the experimental data. It is important to note that there may be additional viable options for parameter selection.

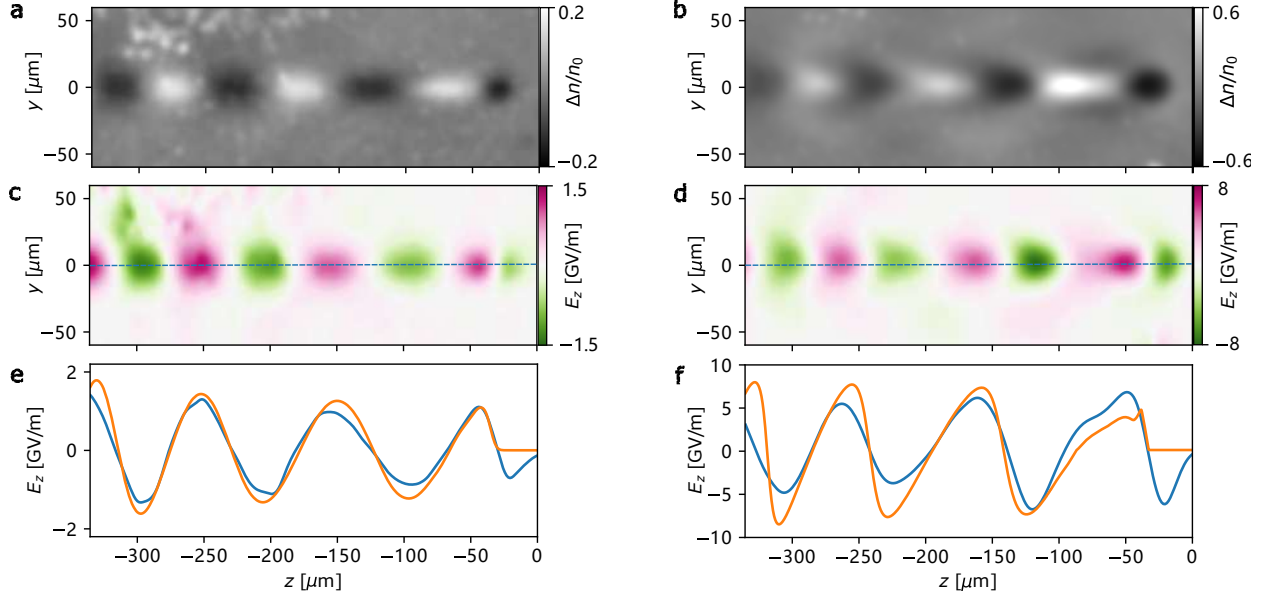


FIG. 3. Experimental wakefield snapshots and retrieved E_z field for linear and nonlinear regimes. (a)(b) Background subtracted probe images of Fig.2b2 and 2b5. (c)(d) Reconstructed 2D map of E_z fields for (a)(b). (e)(f) Lineouts of retrieved E_z (blue solid curve) along the blue dashed line in (c)(d) and the comparison with simulated E_z field (orange solid curve).

In addition to analyzing the field structure, we have also studied the dependence of the wakefield strength on the driver. In our case, the plasma wavelength of the observation region is around $100\ \mu\text{m}$, significantly larger than the drive bunch length of only a few microns for the LWFA electron beam. Consequently, the impact of the driver on the plasma electrons resembles more of a kick, resulting in the launched wakefield strength being primarily dependent on the total charge of the driver if similar transverse widths are assumed [2, 42]. Based on this insight, we have plotted the relationship between the estimated driver charge Q_{driver} and the estimated maximum longitudinal electric field amplitude $E_{z,\text{max}}$ (for the first wake period) using green circles in Figure 4. This data is then compared to results obtained from 3D PIC simulations (red triangles). The results illustrate that as the driver charge increases up to approximately 120 pC, the field grows almost

linearly to nearly 7 GV/m, suggesting that the probed wakefield remains within quasi-linear or weakly-nonlinear regime. This affirms the applicability of classic linear theory in further verifying the correlation, where the $E_{z,max}$ can be represented as $Q_{driver} k_p^2 \exp(k_p^2 \sigma_r^2 / 2) \Gamma(0, k_p^2 \sigma_r^2 / 2)$, with k_p denoting the plasma wavenumber, σ_r representing the averaged transverse RMS driver width, and $\Gamma(a, b) = \int_a^\infty x^{a-1} e^{-x} dx$ [42]. The theoretical estimation is depicted as the black solid curve in Figure 4, demonstrating excellent agreement with both simulation data and experimental measurements.

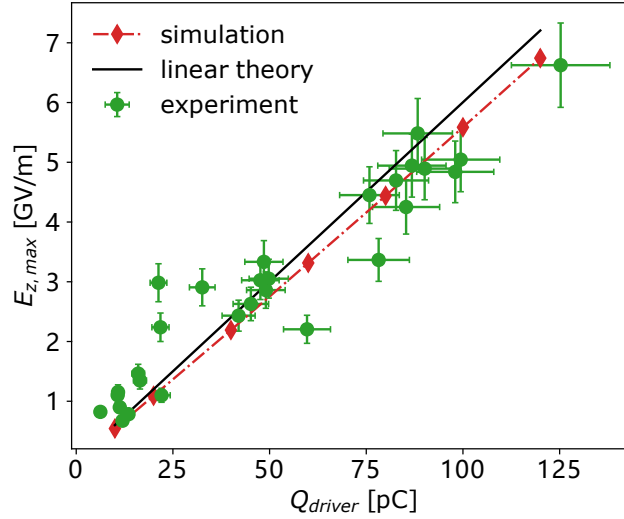


FIG. 4. **The scaling of wakefield strength on driver charge.** The amplitude of E_z of the first wake period for different driver charges ranging from few pC to over 100 pC was compared between experimental measurements (green circles), simulated values (red lozenge) and classic linear theory (black curve). The error bars of the experimental data come from the probe peak energy uncertainty.

In summary, we have conducted measurements of the 2D field structure of a plasma wakefield generated by a laser-accelerated electron bunch using the FREM technique. We have managed to retrieve both the instantaneous information of the driver and the wakefield from just one probe image, enabling direct characterization of the driver-wakefield correlation. As the charge of the driver increased, it is observed that the beam-driven wakefield structure transitions from a linear sinusoidal pattern to a weakly nonlinear sawtooth shape, together with a clear beam loading effect due to the appearance of the trailing long tail of the driver, while the field strength grows almost linearly. With a larger driver charge or higher plasma density, it may be possible to expand this investigation to explore highly nonlinear beam-driven wakefields [43]. These findings offer valuable quantitative insights into beam-driven plasma wakefields, which could help inform real-time

experiments in plasma wakefield acceleration for addressing many key challenges including high-brightness electron injection [44–47], high-efficiency acceleration [15, 40], high-transformer-ratio acceleration [48], positron acceleration [16], hosing instability mitigation [49], staging acceleration [50] etc., important for generating high-energy, high-quality electron and positron beams efficiently.

METHODS

Particle-in-cell simulations. PIC simulations are done using the pseudo-spectral code FBPIC [41] with a quasi-cylindrical geometry simulated with $N_m = 2$ azimuthal modes. For the simulations presented in Fig. 3 and Fig. 4 of the manuscript, the cylindrical simulation box has 350 μm length and 200 μm radius, with the mesh sizes of $\Delta z = 100$ nm and $\Delta r = 300$ nm. The electron bunch for driving PWFA is initialized with a peak energy of 150 MeV and 40% FWHM energy spread. For Fig. 4, the charge is set in the range of 10 to 120 pC. The target is set as pre-ionized plasma with a 150 μm up-ramp and a constant density of $2 \times 10^{17} \text{ cm}^{-3}$ with 300 μm length, followed by a density downramp extracted from the estimation of plasma period based on experimental wakefield snapshots.

Modified algorithm for wakefield reconstruction. Previously, an algorithm for reconstructing the structure of a quasi-linear wakefield was developed [22, 28], based on a perturbation theory derived from the fluid continuity equation. However, this approach didn't account for variations in particle coordinate and thus was mostly valid for very small perturbation (i.e., $|\delta n/n_0| \ll 1$). To address this limitation, we have integrated parts of proton imaging reconstruction techniques [36, 51] into our algorithm, which now is capable to handle moderate perturbation (i.e., $|\delta n/n_0| \leq 1$). The general idea can be outlined as follows:

Considering an ultra-relativistic probe bunch with an initial momentum p_0 that traverses in the x direction a plasma wave travelling along z axis, it gains an additional lateral deflection angle as $\theta_{y,z} = \nabla \int_{-\infty}^{\infty} e\phi(z-x, x, y)dx/cp_0$ with ϕ representing the wakefield potential, e the elementary charge, and c the light speed in vacuum. After the probe bunch drifts a further distance L , based on the paraxial assumption, the original position (z_0, y_0) maps to a new position in the image plane as, $z_f = Mz_0 + \theta_z L$ and $y_f = My_0 + \theta_y L$, with $M = 1.06$ as the magnification factor. By conserving the proton numbers in the absence of trace crossing, we have, $n_f(z_f, y_f)dz_f dy_f = n_0(z_0, y_0)dz_0 dy_0$ with $n_f(n_0)$ as the proton density before (after) drifting.

Therefore, $n_f = n_0/D(x_0, y_0)$ where D is the Jacobian determinant of $\partial(x_f, y_f)/\partial(x_0, y_0)$. By neglecting the second order and assuming n_0 as a constant, we find a simplified correlation between n_f and n_0 as,

$$n_f(z_f, y_f) \simeq \frac{n_0}{M^2} \left[1 - \frac{L}{M} \left(\frac{\partial \theta_z}{\partial z_0} + \frac{\partial \theta_y}{\partial y_0} \right) \right] \quad (1)$$

Based on Eq. 1, the relative density modulation of the probe $I(z_f, y_f) = (M^2 n_f - n_0)/n_0$ can be expressed as,

$$I(z_f, y_f) \simeq -\kappa \nabla^2 \int_{-\infty}^{+\infty} \phi(z_0 - x_0, x_0, y_0) dx_0 \quad (2)$$

where $\kappa = eL/Mcp_0$ is the coefficient. Since the longitudinal and transverse components of a quasi-linear wakefield are mostly decoupled, Eq. 2 can be further simplified as below,

$$I(z_f, y_f) \simeq -\kappa \eta \nabla^2 \phi(z_0, y_0) = \kappa \eta \rho_p(z_0, y_0)/\epsilon_0 \quad (3)$$

where ϵ_0 and $\rho_p(z_0, y_0)$ represent the vacuum permittivity and the slice plasma charge density along the center axis, respectively, and η is a shape factor related to the longitudinal and transverse profile of the wakefield. For a simple linear wakefield with transverse Gaussian profile, $\eta = \sqrt{2\pi} \sigma_E e^{-k_p^2 \sigma_E^2/2}$ with σ_E denoting the RMS width of the electric wakefield. Eq. 3 presents an interesting interpretation that *the probe density modulation is in fact proportional to the density variation of the plasma wave*.

If we assume $z_f \simeq Mz_0$ and $y_f \simeq My_0$, Eq. 3 simplifies to the original form of [22, 28]. However, the ignorance of $\theta_{z,y}L$ can lead to an inaccurate retrieval of the field structure, especially for non-sinusoidal shapes. Here based on the work in [36], we expand the left hand of Eq. 3 in coordinates (z_0, y_0) to the first order and multiply it with e^{MI} , obtaining

$$e^{MI} I = -\kappa \eta \nabla \cdot (e^{MI} \nabla \phi) \quad (4)$$

This is a steady-state diffusion equation, and can be solved using numerical methods, such as the standard Gauss-Seidel iteration. The initial guess can be the solution of Eq. 3 by setting $z_f = Mz_0$ and $y_f = My_0$. After obtaining the wakefield potential ϕ through iterations, the electric field component can be recovered by taking the gradient of the potential and multiplying an reconstruction coefficient 1.3 estimated from simulations.

It is noted that the retrieved field E_{total} for each probe data of Fig. 3 and Fig. 4 contains both PWFA and LWFA components, and the LWFA one needs to be substracted. This is done by first estimating the LWFA contribution, which also requires two steps. First, calculate the field strength

$E_{lwfa,max}$ through a reference LWFA image [e.g., Fig. 2(b1)] with certain laser energy; then, scale it by the ratio of applied laser energy to the reference one. This process is mostly valid for a linear LWFA [52]. After that, the PWFA field is estimated by $E_{total} \times (1 - E_{lwfa,max}/E_{total,max})$.

DATA AVAILABILITY

Source data are provided with this paper. All other data that support the findings of this study are available upon reasonable request to the corresponding authors.

CODE AVAILABILITY

The codes that support the findings of this study are available from the corresponding authors upon reasonable request.

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AUTHOR CONTRIBUTIONS

Y.W. and V.M. conceived the idea and designed the setup. Y.W., O.S., and S.T. together carried out the experiment with support from E.Y.L. and E.K.. Y.W. and B.P. analyzed the data and performed the simulations. Y.W. and V.M. wrote the paper. All authors discussed extensively the results and commented on the manuscript. V.M. provided overall guidance to the project.

COMPETING INTERESTS

The authors declare no competing interests.

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