



High-throughput injection-acceleration of electron bunches from a linear accelerator to a laser wakefield accelerator

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Plasma-based accelerators driven by either intense lasers¹ or charged particle beams² can accelerate electrons or positrons with extremely high gradients compared with conventional radio-frequency accelerators. For their use as next-generation light sources and in energy frontier colliders³, beams with good stability, high quality, controllable polarization and excellent reproducibility^{4,5} are required. The accelerated electrons can be either internally injected directly from the background plasma or externally injected from conventional accelerators. Despite significant progress^{6–14}, the beam properties obtained with the internal injection scheme fall short of simultaneously reaching these requirements. In contrast, such high-property beams are routinely generated from conventional accelerators. Therefore, it is important to demonstrate the injection from a conventional accelerator into a plasma-based machine followed by further acceleration of the beam. Here we report the demonstration of external injection from a conventional linear accelerator into a laser wakefield accelerator and subsequent acceleration without any significant loss of charge, which is achieved by properly shaping and matching the beam into the plasma structure. The experimental results, combined with three-dimensional particle-in-cell simulations, indicate that this is possible with modest degradation in the beam quality. This work is an important step towards realizing a high-throughput, multistage, high-energy, hybrid conventional-plasma-based accelerator.

Multistage plasma-based accelerators (PBAs) with external injection are inherently difficult to build because of the micrometre-size beams and wake structures, exceedingly large focusing fields and the temporal synchronization precision required at the femto-second scale. This is why in spite of some success, a high overall coupling efficiency or charge throughput of the externally injected beam has been difficult to achieve. Previously, external injection of electrons from a conventional radio-frequency (RF) accelerator and Van de Graaff accelerator to a plasma beat-wave accelerator has been demonstrated at University of California, Los Angeles^{15,16}, and École Polytechnique¹⁷, respectively. However, due to the non-ideal transverse and longitudinal matching between the very long electron bunch (tens of plasma wavelengths or even longer) and the beat-wave-excited plasma wake, the coupling efficiency was well below 1%. Recently, external injection-acceleration of a conventional RF-accelerator-produced electron beam into a self-modulated

proton-beam-driven plasma wakefield accelerator has been demonstrated at CERN (European Centre for Particle Physics)¹¹. Due to the non-collinear matching between the electron bunch and the plasma wake, and both the focusing and defocusing wakefields experienced by the long (several plasma wavelengths) beam, the coupling efficiency was below 0.1%. This issue of low coupling efficiency is not only challenging for external injection from an RF accelerator into a PBA, where two different accelerator technologies must be spatio-temporally synchronized with micrometre/femto-second accuracy, but also for staging between two PBAs. For example, the staged acceleration of two inherently synchronized laser wakefield accelerators (LWFAs) has recently been demonstrated at the Berkeley Lab Laser Accelerator of Lawrence Berkeley National Laboratory¹² and Osaka University¹⁸. Although a plasma lens or a solenoid was installed between the two LWFA stages to refocus the electron beam exiting the first-stage injector into the second-stage booster, the overall coupling efficiency from the injector to the booster was typically at the percent level due to imperfect matching of the focusing and broad energy spread of the first-stage electron beam. On the other hand, although the two-electron-bunch plasma wakefield accelerator experiment (the driving and trailing bunches came from the same beam) at the Facility for Advanced Accelerator Experimental Tests, Stanford Linear Accelerator Center, has achieved roughly 25% coupling efficiency, the remaining ~75% charge was lost due to the oversized width and length of the electron beam, as well as the non-ideal matching of the injected bunch to the plasma wakefield accelerator¹³. In all the above scenarios, such low coupling efficiencies will be problematic for most practical applications of PBAs, especially for a multistage collider, where the coupling efficiency must be near 100% per stage, otherwise the beam charge throughput will approach zero after some stages.

To reach 100% coupling efficiency, a good matching of the injected beam to the plasma wake, not only of the beam size and wake size but also of the beam phase space and wake structure, is critical. Such good matching is also essential for beam emittance preservation. Previous theoretical studies have suggested the use of tailored plasma density structures to fulfil this challenging requirement^{19–21}. However, there has not been any experimental demonstration so far. Here we demonstrate ~100% successful coupling of a high-quality externally injected beam from a conventional RF linear accelerator (LINAC) into an LWFA and subsequent monoenergetic acceleration of the injected charge. The beam divergence measurements,

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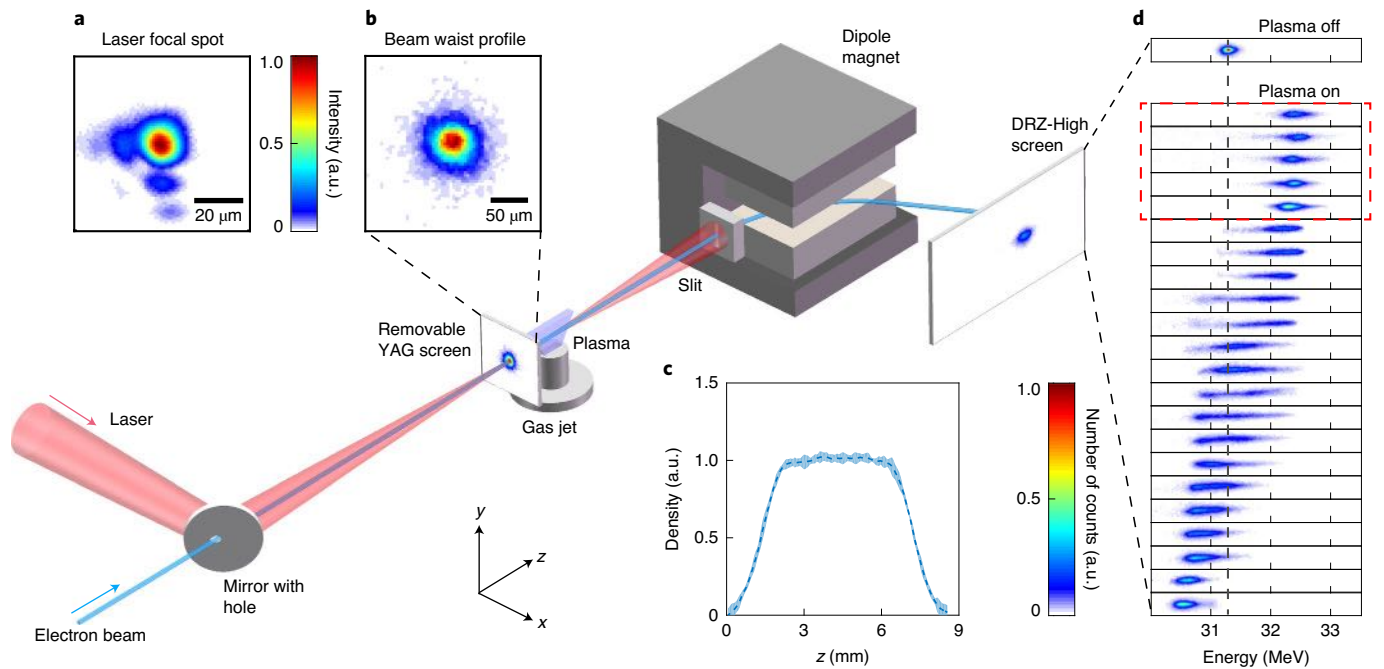


Fig. 1 | Experimental layout. **a, b**, A laser pulse is focused and sent collinearly with the electron beam using a mirror with a 3-mm-diameter central hole. The laser focal spot is shown in **a** and the electron beam waist profile (measured using a removable cerium-doped yttrium-aluminium-garnet (YAG) screen) is shown in **b**. **c**, Measured neutral density profile of the gas jet along the longitudinal axis z (the blurred region shows the r.m.s. spread of five shots). The beam energy spectra are recorded by a spectrometer composed of a 1-mm-wide lead slit, a permanent dipole magnet of ~ 1 T, a 25-μm-thick aluminium foil (not shown) and a phosphor screen (DRZ-High). The lead slit introduces an uncertainty in the incoming beam position relative to the spectrometer, and thus, its width induces an energy measurement uncertainty of ~ 0.05 MeV. The thin aluminium foil is placed between the dipole magnet and the DRZ-High screen (very close to the DRZ-High screen) to block the scattered residual drive laser and ambient light. **d**, A group (sorted by decreasing mean energy) showing the energy-dispersed beam distributions induced by the ~ 100 fs timing jitter under the same experimental condition ($z_i = -4.5$ mm and $n_p = 6 \times 10^{17} \text{ cm}^{-3}$).

combined with three-dimensional (3D) particle-in-cell (PIC) simulations, also indicate that the beam emittance growth is limited during the injection–acceleration process.

A schematic of the experiment is shown in Fig. 1. A 31.30 ± 0.05 MeV electron bunch from a photocathode-RF-gun-driven LINAC^{22,23} co-propagates with an ultrashort (40 ± 2 fs full-width at half-maximum (FWHM)), energetic (600 ± 14 mJ), $0.8\text{-}\mu\text{m}$ -wavelength laser pulse, which is focused by an $f/12.7$ off-axis parabolic mirror (not shown in Fig. 1) to a spot size of $12.2 \pm 0.3\text{ }\mu\text{m}$ (a radius where the laser intensity is e^{-2} compared with the on-axis value) that contains $\sim 55\%$ of the laser pulse energy (Fig. 1a; giving the laser Rayleigh length $Z_R \approx 584\text{ }\mu\text{m}$ and peak intensity $I_{0,\text{peak}} \approx 4 \times 10^{18} \text{ W cm}^{-2}$). The laser pulse creates a plasma in a 6-mm-long helium gas jet and excites a wake throughout the plasma.

To achieve high coupling efficiency, the plasma wake must be wider than the electron beam. The beam is tightly focused to a spot as small as $20.3 \pm 0.9\text{ }\mu\text{m}$ root mean squared (r.m.s.) (Fig. 1b) at the entrance of the plasma via optimization of the normalized beam emittance (~ 1 mm mrad) and the beam-focusing magnets. The distance between the drive laser focal position ($z = z_i$) and the entrance of the plasma ($z = 0$) is scanned from 3.5 mm ($6.0Z_R$) to 5.5 mm ($9.4Z_R$) such that the laser expands in a vacuum to the transverse size w_{input} from $74.2\text{ }\mu\text{m}$ to $115.3\text{ }\mu\text{m}$ when it enters the plasma (the transverse wake size $\approx$ the transverse laser size). For the wake wavelength to be longer than the injected beam, the beam is strongly velocity compressed to ~ 13 fs r.m.s. (near the flat-top current profile) in the photocathode RF gun by properly launching the beam at near-zero phase (far away from the on-crest acceleration phase) to gain a head-to-tail energy chirp and reducing the bunch charge

(~ 20 fC) (ref. ²⁴). The plasma density (plateau value), n_p , is adjusted between 2×10^{17} and $6 \times 10^{17} \text{ cm}^{-3}$ such that a relatively long plasma wavelength $\lambda_p \approx 3.3 \times 10^{10} / \sqrt{n_p (\text{cm}^{-3})} \mu\text{m} \approx 74.6\text{--}43.1\text{ }\mu\text{m}$ ($248.7\text{--}143.6$ fs) can be obtained. This is also beneficial for reducing beam energy spread growth and avoiding beam size modulation resulting from periodic focusing and defocusing fields. In addition to the transverse and longitudinal size matching, the position jitter of the injected beam ($\sim 3.1\text{ }\mu\text{m}$) and the drive laser ($\sim 1.3\text{ }\mu\text{m}$) are kept small compared with their spot sizes to enable a highly collinear overlap of the beam and the wake in space.

Another key to achieving high coupling efficiency is a longitudinally tailored focusing profile to match the beam transverse phase space. Otherwise, poor matching may lead to catastrophic emittance growth, divergence increase and beam loss. In this experiment, the gas jet is properly designed to produce a plasma structure with a density profile (Fig. 1c) for matching the injected beam to the plasma wake.

In the experiment, by tuning the electron beam arrival time relative to the laser pulse, we can place the beam immediately in the first few wake wavelengths behind the driver and control the beam injection phase. Since the beam arrival time has a jitter of ~ 100 fs (r.m.s.) (ref. ²⁵), energy jitter will be induced in the LWFA, as shown in the 22 shots of the energy-dispersed beam distributions (Fig. 1d) measured under the same experimental condition ($z_i = -4.5$ mm and $n_p = 6 \times 10^{17} \text{ cm}^{-3}$), where both beam acceleration and deceleration by the plasma wake can be observed. The first five shots of the plasma-on case (inside the red dashed rectangle in Fig. 1d) show features of both maximum energy gain and minimum energy spread, which can be viewed as the electron beam being at the proper acceleration phase of the plasma wakefield.

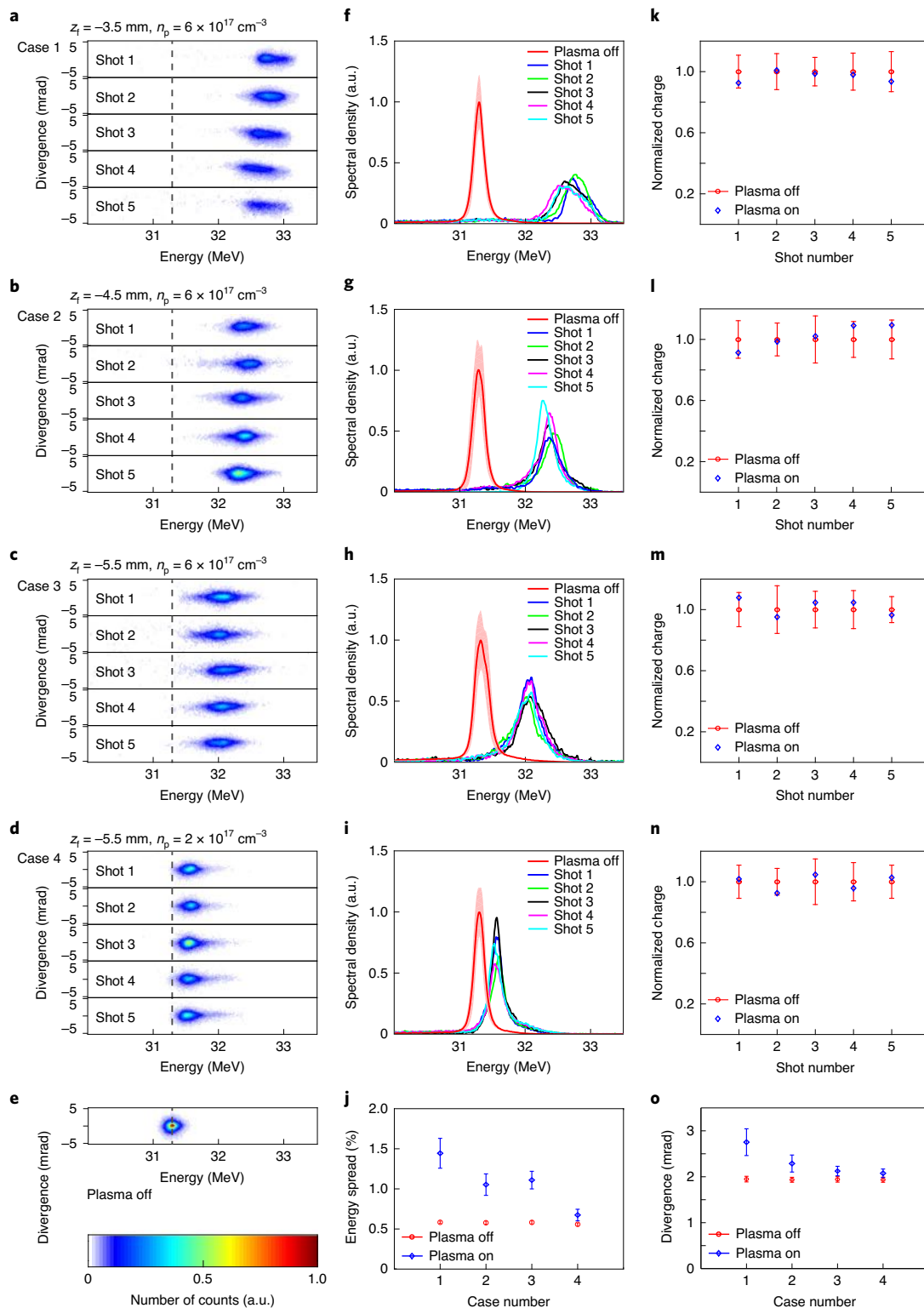


Fig. 2 | Experimental results. **a–e**, Energy-dispersed beam distributions for plasma-on cases with various laser focal plane position z_f and plasma plateau density n_p values (five shots for each experimental condition (**a–d**)) and for the plasma-off case (**e**). The beam vertical distribution corresponds to the beam transverse divergence since the propagation of electrons in this direction is not affected by the magnet. **f–i**, Integrated beam energy spectra corresponding to **a–d**. For comparison, 20 consecutive plasma-off shots for each plasma-on shot are simultaneously recorded within ~4 s. These total 100 plasma-off shots for each experimental condition (5 plasma-on shots) are shown in **f–i** with red lines, where the blurred regions show the r.m.s. spread of the data. **j**, Beam energy spreads (FWHM) corresponding to **a–d** (5-shot average for the plasma-on case and 100-shot average for the plasma-off case under each experimental condition). **k–n**, Integrated beam charge corresponding to **a–d** (normalized to the average value of 20 plasma-off shots for each plasma-on shot). **o**, Integrated beam divergences (FWHM) corresponding to **a–d** (5-shot average for the plasma-on case and 100-shot average for the plasma-off case under each experimental condition). In **j–o**, the error bars represent the standard deviation.

We vary the focal plane position z_f and the plasma density n_p , and find that such monoenergetic acceleration resulting from the proper wake phase is consistent and stable for a certain parameter interval. Examples of the energy-dispersed beam distributions are shown in Fig. 2a–d, where Fig. 2a–c is obtained by decreasing z_f from -3.5 mm to -5.5 mm while setting $n_p = 6 \times 10^{17} \text{ cm}^{-3}$ (cases 1–3) and Fig. 2d is obtained by decreasing n_p to $2 \times 10^{17} \text{ cm}^{-3}$ while setting z_f to be the same as that in Fig. 2c (case 4). For comparison, Fig. 2e shows one typical shot of the beam distribution without plasma interaction.

Figure 2f–i shows the integrated energy spectra corresponding to Fig. 2a–d and Fig. 2j shows the corresponding average energy spreads. The average peak-to-peak energy gain is ~ 1.5 MeV for $z_f = -3.5$ mm and $n_p = 6 \times 10^{17} \text{ cm}^{-3}$. For a plasma length of ~ 6 mm FWHM, this represents an average acceleration gradient of $\sim 250 \text{ MV m}^{-1}$. The average energy spread is as small as 1.4% FWHM (compared with the initial value of 0.6% FWHM). As z_f decreases, the laser intensity and thus the acceleration gradient decreases since the laser diffracts more, leading to a larger w_{input} (Fig. 2f–h). As n_p decreases, both the acceleration gradient and the phase interval occupied by the beam decrease, and therefore, the accumulated energy spread also decreases (Fig. 2h,i). Figure 2k–n shows the integrated beam charge corresponding to Fig. 2a–d. Due to the near-zero launching phase in the photocathode RF gun, the bunch charge is sensitive to the jitter of the RF phase and amplitude, leading to a shot-to-shot fluctuation ($\sim \pm 10\%$) of the bunch charge. For all four cases (Fig. 2k–n), the fraction of captured electrons is nearly 100% (within $\sim 10\%$ uncertainty of the charge fluctuation). If z_f increases further and n_p remains the same, for example, $z_f = -1.5$ mm and $n_p = 6 \times 10^{17} \text{ cm}^{-3}$, the coupling efficiency is reduced to ~ 40 – 50% , as shown in Extended Data Fig. 1.

Figure 2o shows the integrated average beam divergences corresponding to Fig. 2a–d. For the case of $z_f = -3.5$ mm and $n_p = 6 \times 10^{17} \text{ cm}^{-3}$, the divergence growth at the exit of the LWFA is within $\sim 41\%$ (from initial 1.95 mrad to 2.75 mrad FWHM), and this value decreases with decreasing z_f or n_p .

To achieve a deeper understanding of the experiment, full-scale 3D PIC simulations corresponding to Fig. 2a–d are performed using the OSIRIS²⁶ code (Methods). In Fig. 3a,b, the simulated evolution of the laser spot size w and normalized vector potential a_0 ($a_0 = 0.85 \times 10^{-9} / \sqrt{I_0 (\text{W cm}^{-2}) \lambda_0 (\mu\text{m})}$, where I_0 is the laser intensity and $\lambda_0 = 0.8 \mu\text{m}$ is the laser wavelength) is shown as a function of the propagation distance z , respectively. Due to laser diffraction in vacuum, at the entrance of the plasma, w is several times the transverse size of the electron beam and it continues to increase during further propagation since the laser power ($P \approx 9 \text{ TW}$) is less than the critical power for relativistic self-focusing ($P_c (\text{TW}) = 3 \times 10^{19} / n_p (\text{cm}^{-3})$), resulting in a relatively low a_0 ($a_0 < 1$). Such large w and relatively low a_0 lead to a linear plasma wake²⁷ with a transverse size much larger than the beam size, which is beneficial for obtaining a high coupling efficiency.

Figure 3c–f shows the longitudinal wakefields E_z corresponding to Fig. 2a–d immediately at the start of the plasma plateau ($z = 2.4$ mm), where the accelerating gradient is found to be maximum during the whole acceleration process. For efficient acceleration, the beam centre is placed near the crest of the acceleration phase, as shown

in Fig. 3c–f. This near on-crest acceleration also leads to the low accumulated energy spread despite no significant beam loading. Simulations confirm that all the electrons can be fully trapped and subsequently accelerated. The resulting energy-dispersed beam distributions and the corresponding energy spectra are shown in Fig. 3g,h, respectively, both in good agreement with the experimental results. Moreover, by varying the delay between the beam and the laser in the simulations, we can obtain the dispersed beam distributions as a function of the delay; a typical example for $z_f = -4.5$ mm and $n_p = 6 \times 10^{17} \text{ cm}^{-3}$ is shown in Extended Data Fig. 2, which is very similar to the measured results (Fig. 1d).

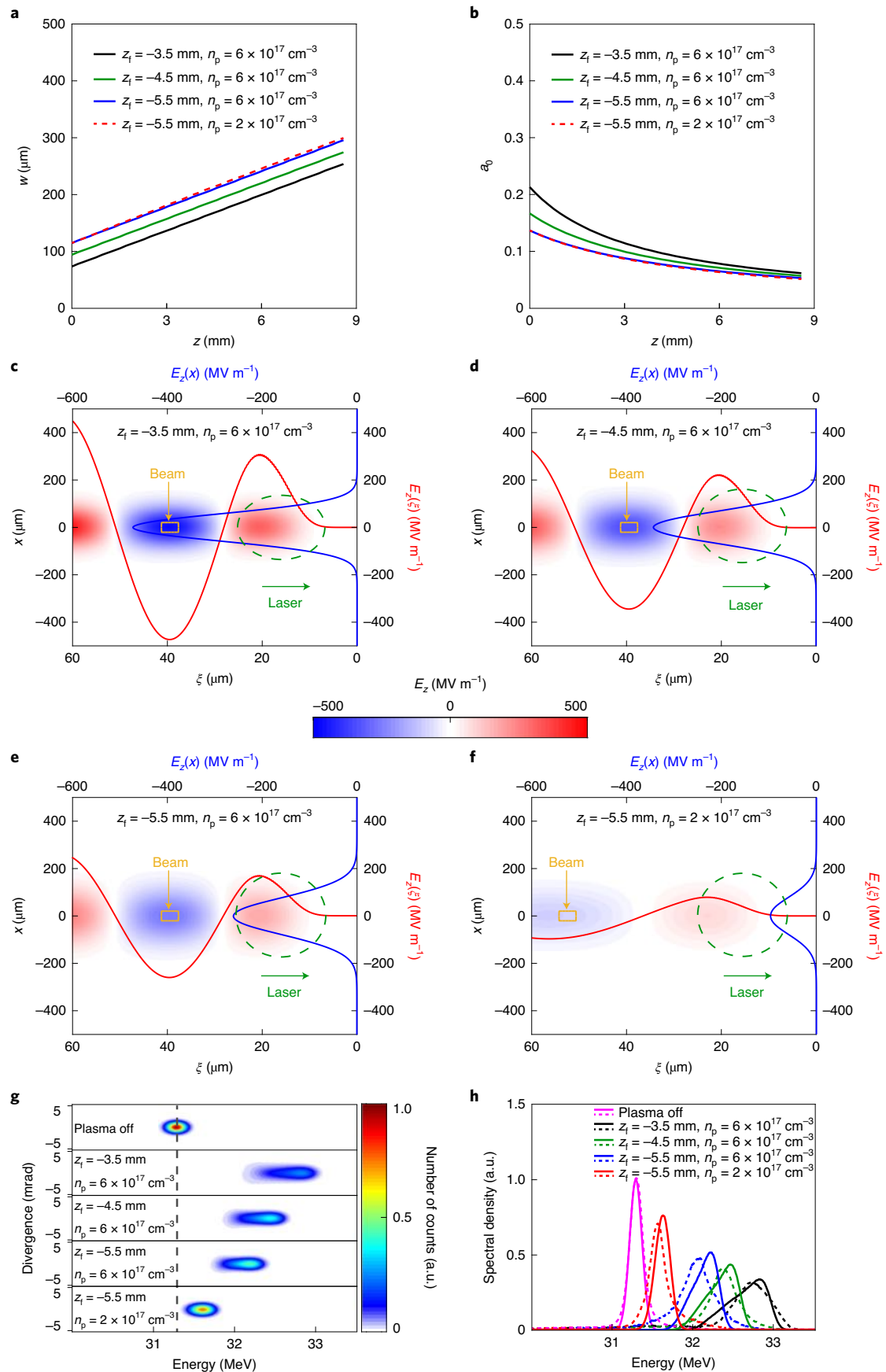
To get a deeper insight into the beam transverse-phase space dynamics and the possible beam quality degradation during the injection–acceleration process, Fig. 4a–c shows the simulated evolutions of beam divergence, spot size and normalized emittance for different z_f and n_p cases. At the exit of the plasma, the simulated divergences agree well with those measured in the experiment (diamonds in Fig. 4a). The small divergence increases and the small variations of the beam spot sizes (Fig. 4b) indicate that the growth of the beam emittance should be limited; this is confirmed by the simulated emittance evolution (Fig. 4c), where for most cases, the emittance growth is only a few percentage points, with the worst case being $\sim 28\%$ for $z_f = -3.5$ mm and $n_p = 6 \times 10^{17} \text{ cm}^{-3}$. This level of emittance preservation is indeed highly non-trivial, which needs a proper focusing phase for the electron beam and careful tailoring of the plasma profile (see Supplementary Information for details). This is because the longitudinal-position-dependent transverse focusing fields in the wake can lead to large phase differences in the betatron oscillation of different beam slices; therefore, significant projected emittance growth can be induced if the beam is not properly matched with a carefully chosen plasma profile^{20,21}. To clearly show the importance of a properly chosen plasma profile, Fig. 4c shows the simulated evolutions of normalized beam emittance for other two different profiles (with a 500- μm up-ramp and a step-function up-ramp) plotted for $z_f = -3.5$ mm and $n_p = 6 \times 10^{17} \text{ cm}^{-3}$, where a significant growth of the projected emittance (a factor of 2.6 and 4.2 for the 500- μm up-ramp and step-function up-ramp cases, respectively) can be seen. In contrast, for the experimental condition where a 2.4 mm up-ramp is adopted, the projected emittance growth is fairly small, where the phase differences induced in the plateau have been partially compensated by the phase differences induced in the up-ramp.

In our experiment, a beam charge of $\sim 20 \text{ fC}$ is adopted for achieving a short bunch length of $\sim 13 \text{ fs}$ r.m.s. by velocity compression, where space-charge-induced longitudinal expansion of the bunch can be mitigated. If the bunch charge is increased by 50 times to 1 pC while all other parameters are exactly identical to those in the experiment, the simulations confirm that the whole physical process is almost the same. If the bunch charge is further increased by 100 times to 2 pC, although the simulations show that the self-excited wakefields of the beam become slightly comparable to the laser-excited wakefields, the beam is still unable to optimally load the wake but monoenergetic acceleration with 100% coupling efficiency and beam quality preservation (an even smaller energy

Fig. 3 | Simulation results of laser evolution, wakefield structure and output-beam energy distribution. **a,b**, Simulated evolutions of the laser spot size w (**a**) and the laser vector potential a_0 (**b**) as a function of the propagation distance z for the plasma-on cases with various laser focal plane position z_f and plasma plateau density n_p . **c–f**, Simulated laser-excited longitudinal wakefields E_z corresponding to Fig. 2a–d immediately at the start of the plasma plateau ($z = 2.4$ mm), where $\xi = ct - z$ represents the position relative to the laser pulse, c is the speed of light in vacuum and t is the time axis. The green and yellow lines show the contours of the laser (e^{-2} of its peak intensity) and the electron beam (r.m.s. bunch length in ξ and r.m.s. spot size in x), respectively. Lineouts of the on-axis E_z and the transverse variation in E_z ($\xi = 39 \mu\text{m}$ (**c–e**) and $\xi = 56 \mu\text{m}$ (**f**)) are shown with red and blue solid lines, respectively. **g**, Simulated angle-resolved energy-dispersed beam distributions for the plasma-off and plasma-on cases with different z_f and n_p values. **h**, Simulated beam energy spectra integrated from **g** are shown with the solid lines. For comparison, the corresponding experimental results obtained from Fig. 2f–i (5-shot average for the plasma-on case under each experimental condition and a total 400-shot average for the plasma-off case) are shown with the dashed lines.

spread and a little larger emittance of the output beam compared with the 20 fC charge case) can still be achieved, as clearly shown in Extended Data Fig. 3.

In the current experiment, the laser power is relatively low (~ 9 TW) and the plasma length is much shorter than the dephasing length and the pump depletion length, especially



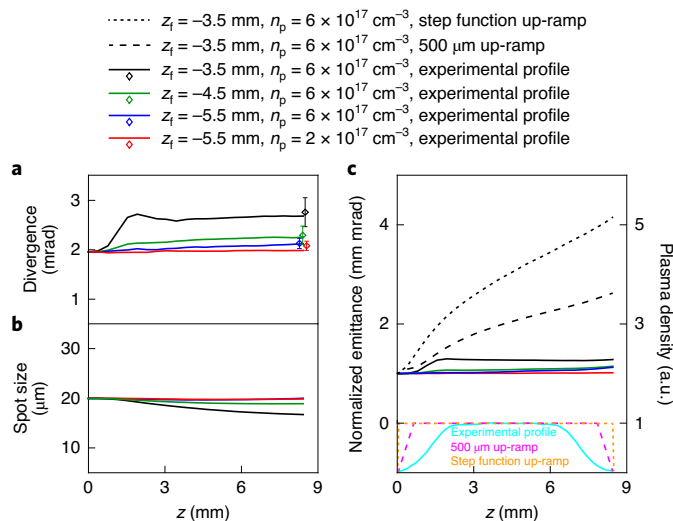


Fig. 4 | Simulation results of transverse beam dynamics. **a–c**, Simulated evolutions of beam divergence (FWHM) (**a**), spot size (r.m.s.) (**b**) and normalized emittance (**c**) for the plasma-on cases with different laser focal plane position z_f and plasma plateau density n_p values. The corresponding measured beam divergences at the exit of the plasma (as shown in Fig. 2o) are shown in **a** with diamonds, where the error bars represent the standard deviation. Evolutions of normalized beam emittance for other two different plasma profiles (dashed line for a profile with a 500 μ m up-ramp and dotted line for a profile with a step-function up-ramp) are also shown in **c**.

for $n_p = 2 \times 10^{17}$ cm $^{-3}$. For this density, a channel-guided LWFA has a dephasing length of ~ 20 cm and a pump depletion length larger than 20 cm. Using a 40 fs, 200 TW laser ($a_0 = 2.2$) interacting with a 20-cm-long plasma channel (while gas jets may not be the best choice, similar characterization and optimization of the density profiles of capillaries, gas ovens, etc. can be applied), 3D PIC simulations show that the energy of the injected beam (a 50 pC, 25 MeV electron beam with a normalized emittance of 1 mm mrad, a focused Gaussian spot of 4 μ m r.m.s. (which can be achieved using a permanent magnetic quadrupole or an active plasma lens²⁸) and a flat-top current profile of 10 fs full duration (which can be achieved using a magnetic chicane)) can be boosted to ~ 4.3 GeV with 100% coupling efficiency, $\sim 0.3\%$ r.m.s. energy spread and negligible normalized emittance growth (Extended Data Fig. 4).

In summary, we have experimentally demonstrated high-efficiency coupling ($\sim 100\%$) and subsequent monoenergetic acceleration between a conventional RF LINAC and an LWFA. The results demonstrated here are also applicable to positron acceleration as well by simply placing the positron bunch (from an external positron damping ring) π radians out of phase with the electron bunch placement location. This is a crucial milestone for realizing future compact electron–positron colliders based on plasma accelerators. Such demonstration also enables some innovative variations in laser-wakefield-based accelerators and radiation sources, such as quasi-phase-matched LWFA²⁹, multiple-pulse LWFA³⁰ and radiation from plasma channel undulator³¹.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41567-021-01202-6>.

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Methods

Electron beam generation and transport. An ~ 20 fC, ~ 13 fs (r.m.s.), 31.3 MeV electron bunch has been produced by a high-brightness S-band LINAC^{22,23} at Tsinghua University. A schematic of the beamline is shown in Extended Data Fig. 5a. The bunch charge is set by tuning the energy of the 300 fs (FWHM), 266 nm photocathode drive laser. The short bunch length is achieved through velocity compression within the photocathode RF gun by launching the beam at the near-zero phase to gain an energy chirp with the bunch tail with energy higher than the bunch head²⁴. High-fidelity particle dynamics simulations with the ASTRA³² code are performed to estimate the bunch length and beam current profile (near the flat top) (Extended Data Fig. 5b). After further acceleration in the accelerating tube, the electron beam is transported to the vacuum interaction chamber (experimental area with setup (Fig. 1)). Two triplets are used to focus the beam to the entrance of the plasma with an r.m.s. transverse waist size of $20.3 \pm 0.9 \mu\text{m}$, detected by a removable yttrium–aluminium–garnet (YAG) screen (Fig. 1). A 180-nm-thick diamond film (not shown in Extended Data Fig. 5a) is inserted between the LINAC and the interaction chamber for creating a differential vacuum pressure. The vertical (y axis) normalized emittance of the beam after the diamond film is directly measured to be ~ 1 mm mrad by using a two-screen method³³ (a YAG screen and a Mitsubishi Chemical DRZ-High screen (Fig. 1)).

Characterization of the plasma. The plasma structure used in the experiment is produced by a supersonic slit-opening gas jet ($6 \text{ mm} \times 2 \text{ mm}$), and its density profile is characterized by combining offline and online measurements with shearing interferometry³⁴ using a wavefront sensor (SID-4, Phasics) (see Supplementary Information for details).

PIC simulations. Computer simulations are carried out using the 3D fully relativistic PIC OSIRIS³⁵ code in the moving-window configuration (the simulation box travels at the speed of light in the laser propagation direction).

The experiment-related simulations (shown in Figs. 3 and 4 and Extended Data Figs. 2 and 3) are carried out in the laboratory frame. A 3D cylindrical geometry with Fourier azimuthal decomposition^{35,36} (the first two Fourier modes) is utilized in these simulations. To compare the simulations and experimental results, parameters of the laser, plasma and electron beam used in the simulations are chosen as close to the experimental conditions as possible. A 40 fs (FWHM with a $\sin^2$ temporal profile) linearly polarized laser pulse is initialized with $a_0 = 1.35$ and a Gaussian focal spot ($12.2 \mu\text{m}$) at the focus. A transversely uniform plasma is initialized with a measured longitudinal profile, as shown in Fig. 1c. A 31.3 MeV electron beam with 0.6% (FWHM) energy spread and 1 mm mrad normalized emittance is initialized with a Gaussian focal spot of $20 \mu\text{m}$ r.m.s. and a flat-top current profile of 52 fs full duration (13 fs r.m.s. duration). The simulation window has a dimension of $571.5 \mu\text{m} \times 108.2 \mu\text{m}$ with $1,500 \times 5,100$ cells in the r and z directions, respectively. This corresponds to cell sizes of $\Delta r = 3k_0^{-1}$ and $\Delta z = 0.167k_0^{-1}$ (where $k_0 = 2\pi\lambda_0^{-1}$ is the laser wavevector). Here 2 macroparticles per cell in the $r-z$ direction and 16 particles in the azimuthal direction are used for both plasma and electron beam.

The simulation of the matching section in Extended Data Fig. 4 is performed within the laboratory frame in 3D Cartesian coordinates. The simulation window has dimensions of $228.6 \mu\text{m} \times 228.6 \mu\text{m} \times 76.2 \mu\text{m}$ with $600 \times 600 \times 4,500$ cells in the x , y and z directions, respectively. To save the computational resources, the simulation of the acceleration section Extended Data Fig. 4 is carried out in a Lorentz-boosted frame^{37,38} with the relativistic factor $\gamma_{\text{boost}} = 5$ in 3D Cartesian coordinates. An electron beam with almost the same parameters as those at the exit of the matching section is initialized. The simulation window (in the boosted frame) has dimensions of $228.6 \mu\text{m} \times 228.6 \mu\text{m} \times 76.2 \mu\text{m}$ with $600 \times 600 \times 4,500$ cells in the x , y and z directions, respectively. For simulations of both the matching and acceleration sections, 1 macroparticle per cell and 8 macroparticles per cell are used for the plasma and electron beam, respectively.

Data availability

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

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

W.L. conceived and supervised the project. J.H. led the development of laser system, plasma structure and diagnostics. Y.D. led the optimization of electron beam. Y.W., Z.Z., S.L., B.P., J.H., Y.D. and W.L. performed the experiments. Y.W. analysed the experimental data and carried out the corresponding simulations. W.L., C.J., Y.W. and J.H. wrote the paper. All the authors contributed extensively to the work presented in this paper.

Competing interests

The authors declare no competing interests.

Additional information

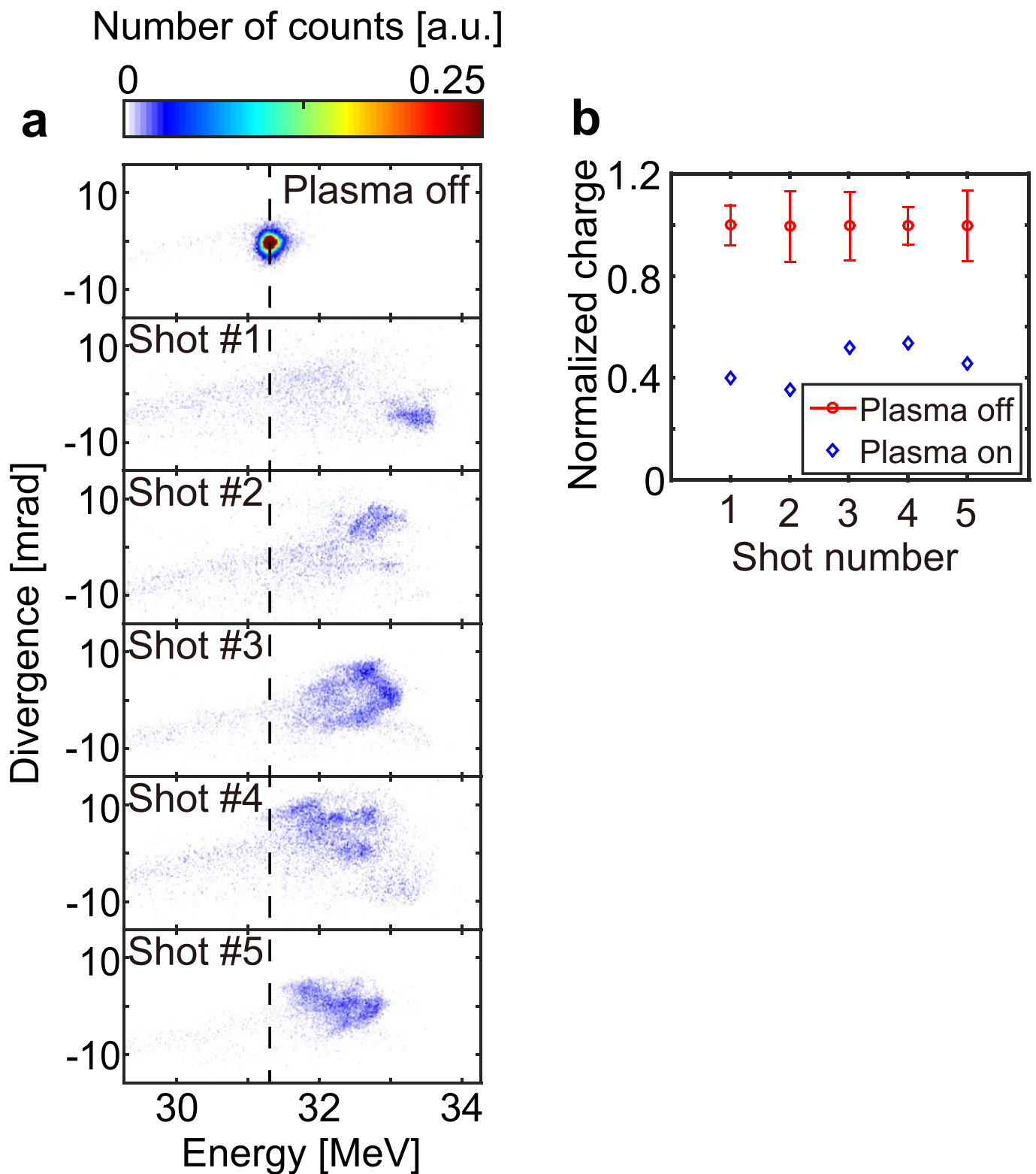
Extended data is available for this paper at <https://doi.org/10.1038/s41567-021-01202-6>.

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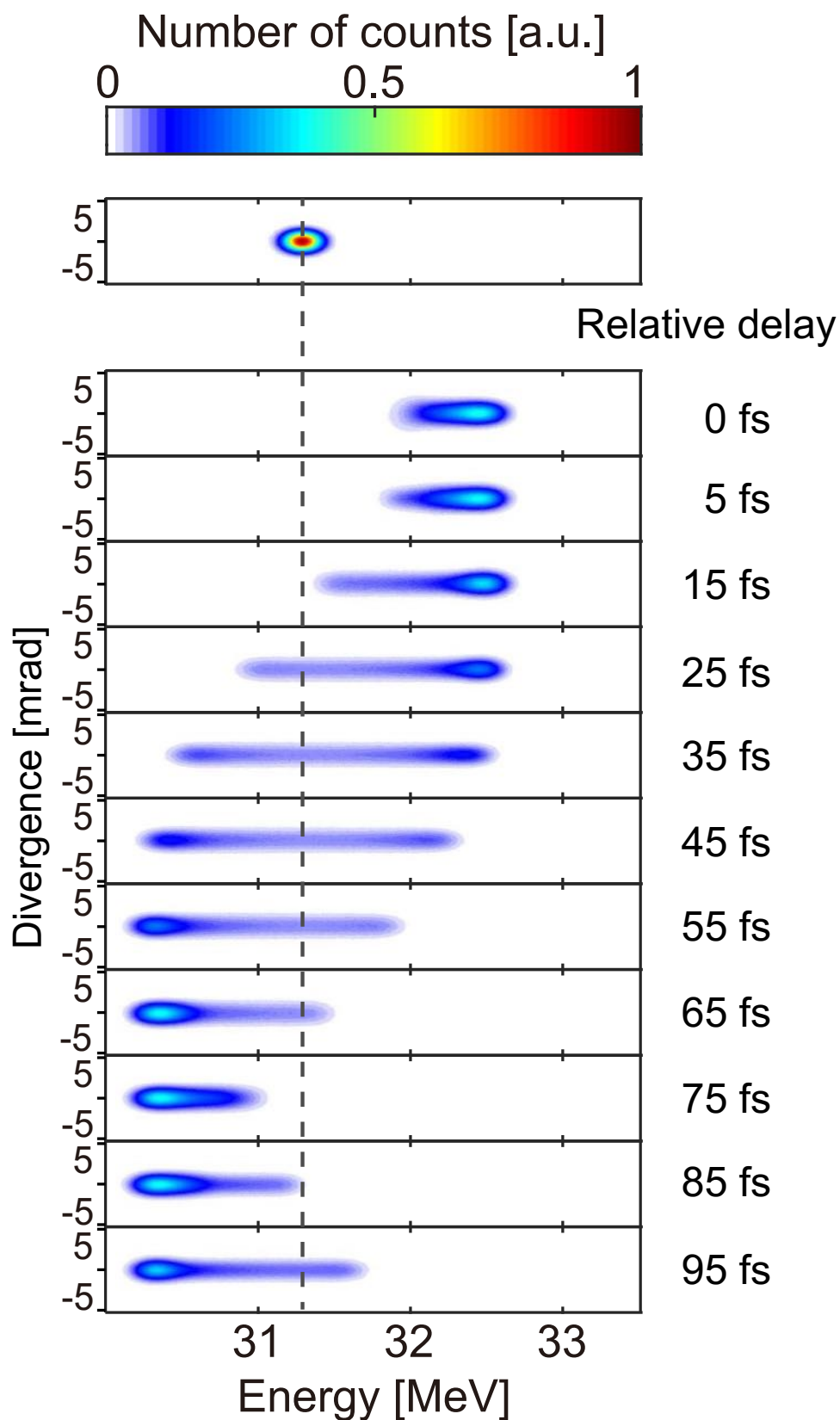
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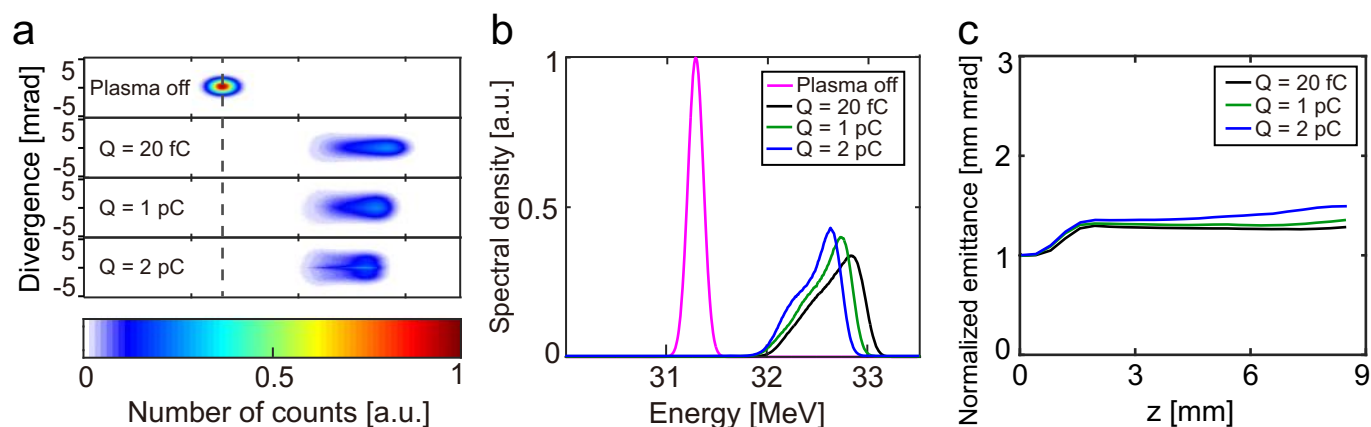
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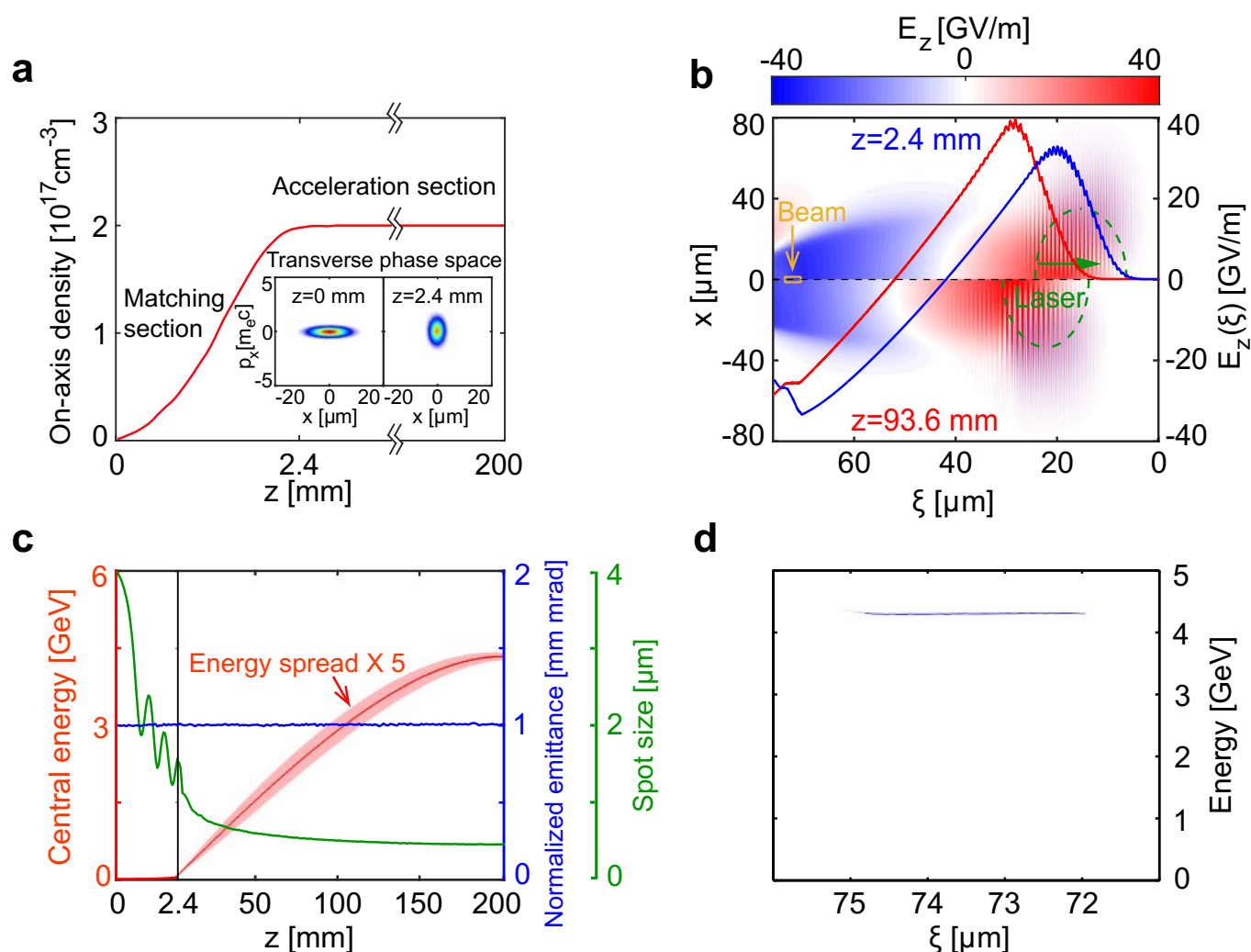
Extended Data Fig. 1 | Experimental cases for non-matched injection. **a**, The measured energy-dispersed beam distributions, with $z_t = -1.5$ mm and $n_p = 6 \times 10^{17} \text{ cm}^{-3}$. **b**, The integrated normalized beam charge corresponding to panel **a** (20-plasma-off-shot average for each plasma-on shot), where the error bars represent the standard deviation.



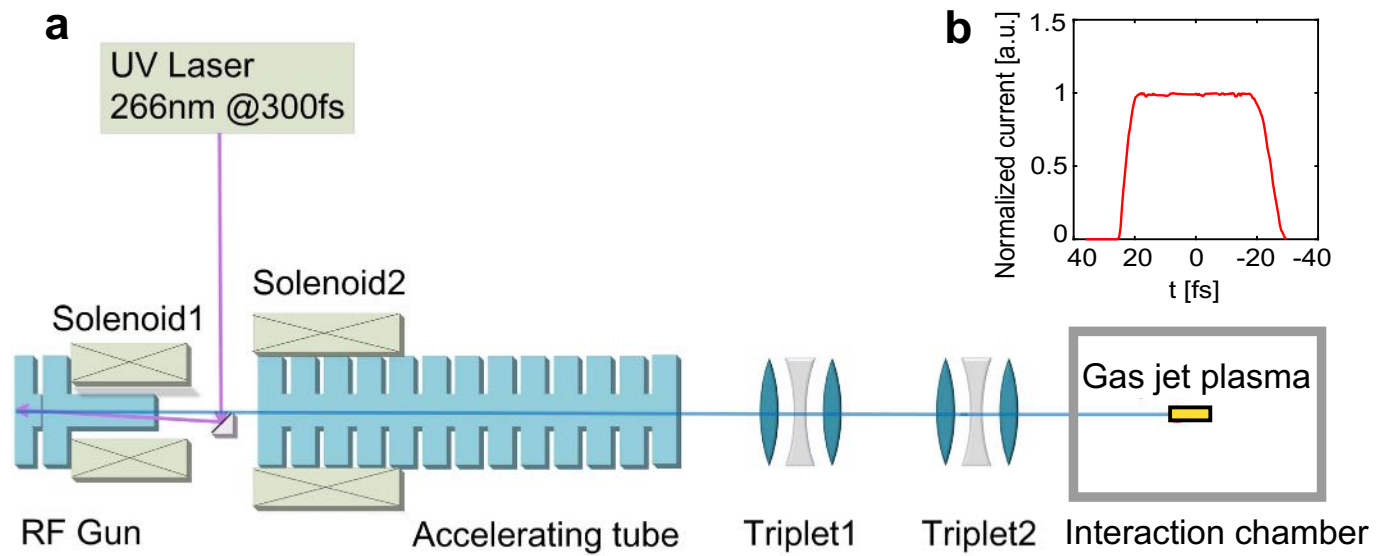
Extended Data Fig. 2 | Simulation results for different relative delays. The simulated energy-dispersed beam distributions as a function of the relative delay between the electron beam and the laser, with $z_i = -4.5$ mm and $n_p = 6 \times 10^{17}$ cm $^{-3}$. Here the relative delay of 0 fs corresponds to the absolute delay as shown in Fig. 3d.



Extended Data Fig. 3 | Simulation results obtained by increasing the beam charge. **a**, The simulated angle-resolved energy-dispersed beam distributions obtained by increasing the beam charge Q from 20 fC to 1 pC and 2 pC, while keeping other parameters invariant, with $z_i = -3.5$ mm and $n_p = 6 \times 10^{17}$ cm $^{-3}$. **b**, The corresponding energy spectra. **c**, The corresponding evolutions of the normalized beam emittance.



Extended Data Fig. 4 | Simulation results for high energy gain when using a longer plasma and a more powerful laser. The plasma has a 2.4 mm-long up-ramp identical to the experimental condition as the matching section, and a 20 cm-long plateau as the acceleration section (see panel **a**). A 200 TW laser is focused to a spot size $w_0 = 35 \mu\text{m}$ with $a_0 = 2.2$ at the beginning of the plateau ($z = 2.4$ mm). The plasma transverse profile is set to a parabolic channel $n_{p,0} \times \left(1 + 0.4 \times \frac{x^2 + y^2}{w_0^2}\right)$ for laser guiding, where $n_{p,0}$ is the on-axis density with the plateau value of $2 \times 10^{17} \text{ cm}^{-3}$. A 50 pC, 25 MeV, 10 fs full duration (flat-top current profile) electron beam with 0.6% FWHM (no chirp) energy spread and 1 mm mrad normalized emittance is focused to $z = 0$ with a transverse waist size of $4 \mu\text{m}$ r.m.s. (left inset in panel **a**). The matching section can transport the beam from this waist to another waist with spot size of $\sim 1.5 \mu\text{m}$ r.m.s. and energy of ~ 50 MeV at $z = 2.4$ mm (right inset in panel **a**), which is nearly matched to the plasma focusing fields in the acceleration section. **b**, The simulated E_z at $z = 2.4$ mm (upper half) and $z = 93.6$ mm (lower half). The blue and red lines show the lineouts of on-axis E_z values for $z = 2.4$ mm and $z = 93.6$ mm, respectively. The electron beam is first over-loaded (blue line), and then as the beam phase slips forward the wake, the longitudinal field within the beam is gradually flattened (red line). After that, the beam is under-loaded. The green and yellow lines show the contours of the laser (e^{-2} of its peak intensity) and the electron beam (full bunch length in ξ and r.m.s. spot size in x), respectively. **c**, Evolutions of the beam r.m.s. spot size (green line), normalized emittance (blue line) and central energy (red line). The shaded regions correspond to the beam r.m.s. energy spread (times 5 for visual clarity). **d**, The final beam longitudinal phase space.



Extended Data Fig. 5 | Ultrashort electron beam generation and transport. **a**, The schematic layout of the high-brightness S-band LINAC beamline at Tsinghua University. **b**, The simulated beam current profile (charge 20 fC) using the code ASTRA according to the experimental settings, where the beam head locates at the right.