

Direct visualization of shock front induced nonlinear laser wakefield dynamics

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Laser-plasma acceleration is considered to be a promising candidate for compactly delivering high-energy high-quality electron beams. One of the most common methods for injecting plasma electrons into the wakefield structure is the shock front injection. Here we present the first direct visualization of the nonlinear laser wakefield dynamics resulting from a tilted shock front using the *femtosecond relativistic electron microscopy* technique. Our observations reveal the occurrence of a split in the wakefield, with the formation of an on-axis laser-driven wakefield and an off-axis beam-driven wakefield just after the passage through the hydrodynamic shock. Using experimental and three-dimensional numerical evidence, we identify the mechanism of this newly observed phenomenon as an off-axis electron injection from the tilted shock, which amplified the betatron oscillations of the bunch until its breakup. These results propel our comprehension of the intricate and nonlinear laser-plasma dynamics within the widely employed shock-front injection scheme, providing crucial information for high-quality beam generation in real-time operations.

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Introduction. Over the last few decades, laser wakefield accelerators (LWFAs) have grown from a theoretical concept [1] into a full, active research field, with applications relevant to high energy physics [2], medical diagnosis [3–6], cancer treatment [7–9], material research and inspection [10,11], and advanced light sources [12,13], among others. In LWFA, a high-intensity, ultrashort laser pulse interacts with an underdense plasma medium, driving plasma oscillations and creating an accelerating structure in its wake [14,15]; electrons placed in the correct location in the cavities, or bubbles, of this structure feel extremely strong forces accelerating them in the direction of propagation of the laser, as well as focusing them radially to the optical axis. Various injection schemes have been used to trap electrons into this wakefield for facilitating their acceleration [16], such as the colliding pulse injection [17,18], the ionization injection [19,20], the shock-front injection [21–24], etc.

Among them, the shock-front injection is considered to be a promising method to generate high-quality electron bunches of very low energy spreads and has been widely studied for more than a decade [22–29]. A sharp longitudinal density downramp is created in the plasma target, increasing the bubble size and reducing the plasma wave's phase velocity at the bubble rear due to the plasma wavelength's dependence on the plasma density, thereby triggering electron injection as the laser pulse crosses the downramp. A common way to produce

this downramp is by placing an obstacle such as a razor blade inside the gas flow, creating a hydrodynamic shock [23,24]. Using this approach, however, the shock is usually not normal to the laser axis [30], unless the setup is specifically designed to make it so. Previous studies [27,28] have investigated the effects of the shock angle on the accelerated electron bunch properties, such as the bunch divergence, steering angle, and pointing stability. However, in all these studies, the electron properties were experimentally measured far from the plasma target, and contain no direct observations of the injection and acceleration processes taking place inside the plasma medium itself. Without such information the bunch behavior might not be fully understood, and key points of it might be overlooked.

In this article, we present the first direct observation of the laser wakefield dynamics after passing through a tilted shock front using the *femtosecond relativistic electron microscopy* (FREM) technique [31–35], which we have previously used for ultrafast probing of other nonlinear LWFA-related phenomena [35–37], and which shows here that under certain conditions the accelerated electron bunch splits into two parts, with one part staying on axis inside the original laser wakefield, and the other part deviating from the laser propagation axis and driving its own wake. This unexpected and interesting phenomenon, supported also by large-scale three-dimensional particle-in-cell (3D PIC) simulations, is attributed to an off-axis injection of the electron beam by the tilted shock front, which triggers strong transverse oscillations in the electron bunch, finally leading to the breakup of the bunch itself.

Off-axis injection has been observed in simulations before (e.g., in [28] following the crossing of a tilted shock, and in [38,39] due to pulse front tilt in the driver laser pulse), but in all of these cases, no bunch splitting was predicted or observed before. In addition, the present analysis uncovers

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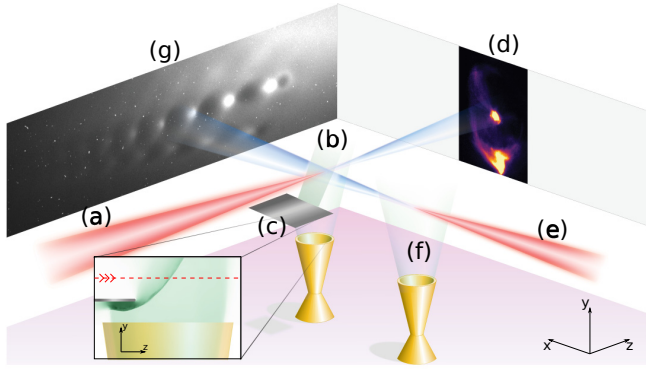


FIG. 1. Experimental setup. A laser beam (a) is focused onto a gas target (b) with a shock front introduced by a razor blade (c). The electron bunch accelerated by this LWFA drifts towards a scintillating screen (d), showing the bunch transverse density distribution. Simultaneously, a second laser beam (e) is focused onto a second gas target (f), accelerating a second electron bunch to be used as a probe. After a 100 mm drift, this bunch passes through the first gas jet's wakefield (b), whose strong electromagnetic fields deflect and modulate the probe bunch density. The modulated electrons reach a Ce:YAG screen (g), forming an image corresponding to the probed wakefield. Inset image (bottom left): central vertical slice of gas density profile, obtained from a 3D hydrodynamic ANSYS® FLUENT® simulation. Also shown in the inset are the laser axis, gas nozzle, and razor blade.

some more details regarding the mechanism by which the shock asymmetry causes the off-axis injection.

Experimental setup. The experiment was performed using the dual 100 TW HIGGINS Ti:sapphire laser system at the Weizmann Institute of Science [40]. One of the two horizontally polarized 30 fs pulsed beams was focused using an off-axis parabola down to a waist size of $30\ \mu\text{m}$ with an on-target peak intensity of above $4 \times 10^{18}\ \text{W}/\text{cm}^2$, driving a nonlinear plasma wake in a pure-helium gas target [see Figs. 1(a) and 1(b)]. Similarly to previous works [23,27,28], a razor blade [Fig. 1(c)] was placed 1 mm above the supersonic 5 mm conical nozzle, such that a tilted hydrodynamic shock front was formed at the entrance of the gas target, where the peak density of the shock front was more than 2 times higher than the undisturbed density plateau. During the experiment, the plateau plasma density was varied between 9×10^{17} and $2.5 \times 10^{18}\ \text{cm}^{-3}$ by regulating the backing pressure (the on-axis density values were measured using the FREM images together with 3D PIC simulations, as explained in the next paragraph). Due to the sharp density drop during the shock traversal [see Fig. 2(a)], plasma electrons were injected into the laser wakefield and accelerated. A scintillator Lanex screen located 225 mm downstream of the gas target recorded the bunch angular profile [Fig. 1(d)]. The energy spectrum of this bunch was analyzed using a dipole magnet and another scintillator located further downstream (not drawn in Fig. 1), showing that the electron energies in this experiment averaged around 180 MeV. The FREM probe was generated by focusing the second laser beam down to a waist size of $26\ \mu\text{m}$ and targeting a second 3 mm gas jet of mixed helium and nitrogen located about 100 mm away from the tilted shock target [Figs. 1(e) and 1(f)]. Using a second dipole magnet

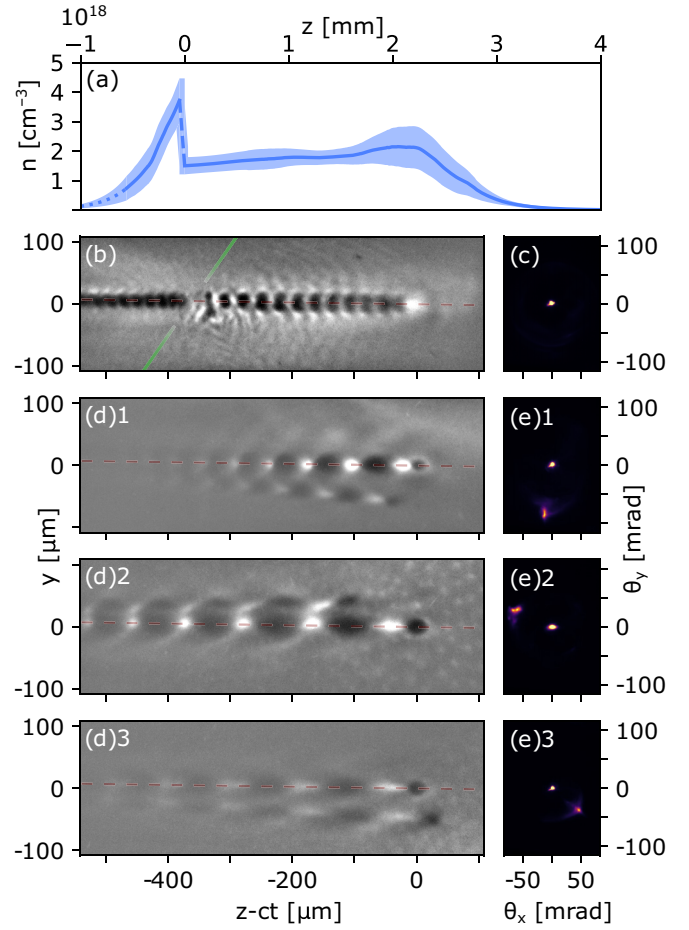


FIG. 2. Experimental results. (a) Electron density profile estimated from the observed bubble sizes along the target with a gas backing pressure of 10.5 bar. (b) Femtosecond relativistic electron microscopy (FREM) image taken at the shock position [$z = 0$ in (a), marked by a green line], demonstrating bubble size modulation with the varying density. The approximate laser axis shown by a dashed red line. Coordinates are relative to the on-axis wakefield's leading bubble, using the comoving coordinate $z - ct$. (c) Far-field bunch profile with a single on-axis electron bunch. See Fig. 1 for the geometry. Coordinates are relative to the optical axis. (d)1–3 Three example shots taken after the wakefield has crossed the shock, all exhibiting splitting wakefields. (e)1–3 Corresponding far-field bunch profiles.

and a second scintillator, the probe bunch was measured to have a continuous energy spectrum reaching around 200 MeV. After passing transversely through the probed wakefield and locally deflecting from its strong electromagnetic fields, the probe electrons drifted for another 15 mm and reached a $100\ \mu\text{m}$ thick Ce:YAG (Ce-doped yttrium aluminum garnet) screen, which emitted visible photons that were collected by a high-resolution imaging system onto a 16-bit sCMOS (scientific complementary metal oxide semiconductor) camera, visualizing the wakefield via the probe density modulations [Fig. 1(g)].

Figure 2(a) presents the on-axis plasma density profile estimated by the measured wakefield period in the FREM images [36] using the relativistic factor obtained from 3D PIC simulations after second degree locally estimated scatterplot

smoothing (LOESS) [41,42] (using the implementation of [43]) (blue solid line), and the shaded region is the rms shot-to-shot density fluctuation. Near the target's end ($z > 3$ mm) the data were averaged by a simple exponential fit, since edge effects made LOESS deviate there from the data. Near the hydrodynamic shock the wakefield structure temporarily collapses, as can be seen in the FREM image of Fig. 2(b), so the plasma frequency in that region could not be measured directly, and the profile in Fig. 2(a) is linearly continued between the preshock and postshock regions (dashed line), with shock position shot-to-shot fluctuations of 10's up to (rarely) a few 100's of μm represented by the shaded region near $z = 0$.

Results. Figure 2(c) shows the accelerated electron bunch angular profile for an example shot, with a single beam on-axis. Contrarily, For most of the shots, we observed at least two electron bunches on the downstream angular profile monitor, as shown in Figs. 2(e)1–3. Correspondingly, FREM also captures the unusual wakefield behavior after crossing the shock front [see Figs. 2(d)1–3], where two wakefields propagate in the plasma, one always along the laser propagation axis and the other off axis. Moreover, these two wakefields exhibit different properties: the on-axis one always has a halo around the first wave bucket, while the off-axis one only shows a pure hollow structure. Based on our previous studies [37], this actually means that the on-axis wakefield is driven by a laser pulse with electrons accelerated inside: the laser pulse is invisible to the FREM probe, so the first wave bucket imaged is the ion cavity, focusing the probe electrons and creating the halo, with the injected bunch repelling the probe electrons from the center and creating the darker hole. For comparison, the off-axis wakefield is driven purely by an electron beam [44], whose FREM signature is a dark hole with no halo, solely created by the repulsion of probe electrons from the electron driver. To the best of our knowledge, this interesting phenomenon has never been observed before. Note that, for off-axis electron bunches with a large horizontal (x) momentum component such as those in Figs. 2(e)2–3, though the probed wakefield images cannot show this dimension explicitly (as the probe propagates along the same direction), the probe electrons traverse the two wakefields at different times, causing a shift in their relative positions on the probe image. For example, in Fig. 2(e)2 we can see that the electron bunch has a split part towards the $-\hat{x}$ direction (against the probe propagation direction), so the probe electrons passed through the off-axis wakefield first, and indeed in Fig. 2(d)2 the off-axis wakefield lags more behind the on-axis one compared to Fig. 2(d)1; while in Fig. 2(d–e)3 the exact opposite effect makes the off-axis wakefield look *ahead* of the on-axis wakefield. Interestingly, in all of the shots with mostly vertical off-axis pointing [such as Fig. 2(e)1, and shots even closer to the vertical axis] where the probe bunch encounters both wakefields at the same time, there is still a nonzero lag between the on-axis and the off-axis wakefields in the FREM image [see for example Fig. 2(d)1]; the front of the off-axis wakefield is aligned with the *rear* of the first bubble of the on-axis wakefield. The reason for this will be explained in the numerical analysis section below.

For a full set of a few hundreds of shots, the wakefield split after the tilted shock front appeared more than half of

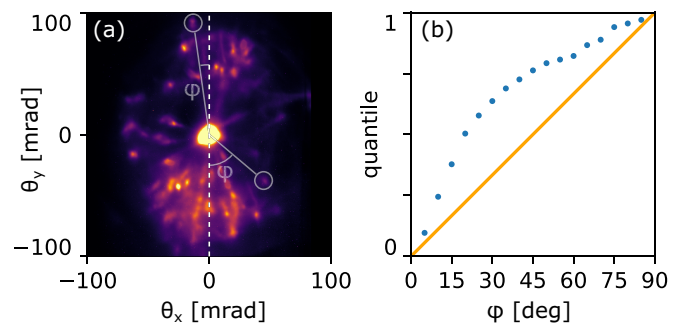


FIG. 3. Angular distribution of off-axis bunches. (a) Sum of about 100 electron profile shots of the same type as Fig. 2(e), all featuring a splitting wakefield; the bright spot at the center is the region of impact of the on-axis bunches. The image is highly saturated to make the off-axis bunches visible. For two of them, the angle φ from the vertical line is shown as an example. (b) Quantile plot of the azimuthal angle φ distribution, sampled every 5 degrees (blue points). The vertical coordinate of every point is the fraction of all the shots depicted in (a) which are angularly closer to the vertical axis than the horizontal coordinate of the same point in (b). The orange line is the quantile plot of an isotropic distribution.

the time. By summing the bunch profile images of more than 100 splitting shots, the pointing distribution of the off-axis bunch was observed to be significantly biased towards the vertical direction, as can be seen visually in Fig. 3(a) and quantitatively in Fig. 3(b), which shows, e.g., that for more than half of the shots, the azimuthal angle is below 20° from the vertical direction, whereas in an isotropic distribution half of the shots have angles extending up to 45° . Since the tilted shock is the only notable vertically asymmetric element in our system, the vertical pointing bias indicates that the shock is the primary cause of the split. It is noted that all of these observations are totally different from a splitting laser pulse with each part driving its own wakefield due to nonlinear filamentation in high-density plasmas [45,46]. It should also be noted that this effect is not caused by interaction with the driver laser, since it is polarized in the normal direction.

To estimate the position where the off-axis bunch branches out of the on-axis wakefield from our experimental data, we plotted the off-axis bunch vertical position as recorded in the FREM image versus the eventual pointing angle as recorded by the far-field profile screen, for many splitting shots, shown in Fig. 4(a). First, we found that for fixed conditions and for a given FREM imaging position within the plasma target, they are linearly related, implying that the split indeed occurs around the same place for all of the shots. Next, we plotted the slopes of these linear relations for various FREM imaging positions within the plasma target, shown in Fig. 4(b), and found that these slopes vary linearly with the longitudinal position. This means that the off-axis bunches follow a straight trajectory (at least between these measured points), and from this relation we can estimate the source of this straight motion—the point for which the slope is zero (i.e., for which off-axis bunches in different far-field angles are all in the same longitudinal position, the origin). The same procedure was also done in the other transverse dimension [Figs. 4(c) and 4(d)]. Since this is the propagation direction of the

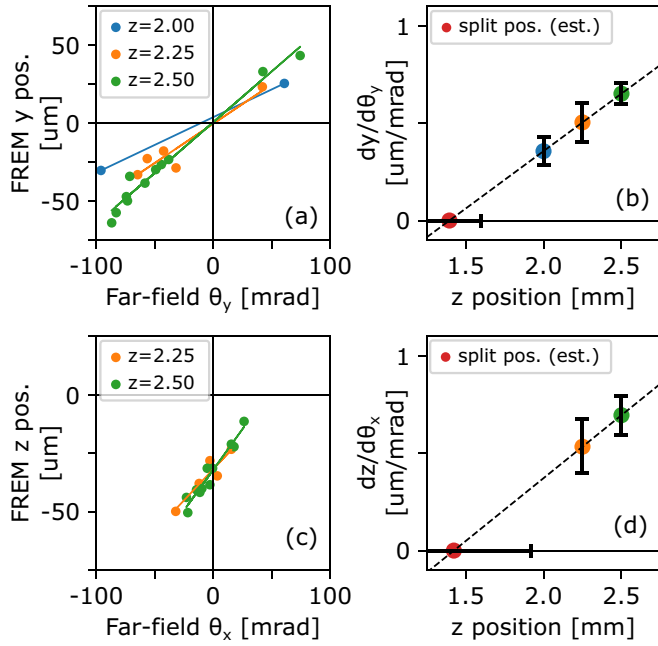


FIG. 4. Finding the split location from the experimental data. (a) Off-axis bunch vertical position y in FREM images [such as Fig. 2(d)] versus vertical far-field angle θ_y in the profile images [such as Fig. 2(e)], showing a linear correlation between them for a given in-plasma longitudinal position z (marked in mm in the labels). Plotting the slopes of these lines versus the longitudinal imaging position (b), the split position can be estimated by the extrapolated zero-slope position; in this case, roughly 1.5 mm after the shock front. (c,d) A similar comparison between the longitudinal (z) position in the FREM images and the horizontal far-field angle (θ_x) yields a similar estimation for the split point. It should be noted that in panel (c), the lines cross the vertical axis below the origin, meaning that the relative longitudinal position of the off-axis bunch on the FREM images is nonzero for zero horizontal off-axis pointing, as explained in the main text. Error bars in (a,c) are smaller than the markers, and represent the uncertainty of the bubble center location in the FREM images and the electron vertical angle in the beam profile images. Error bars in (b,d) represent the standard deviations of the slopes, based on the estimation errors of the individual points in (a,c) as well as on their statistical variation around the regression lines, except for the estimated split point in (b,d), for which the error bars are based on the errors of the points used in the extrapolation.

FREM probe bunch, the in-plasma transverse position in this dimension was estimated from the relative longitudinal bunch lag due to the different encounter times of the FREM probe with the two bunches. This dimension gave similar results.

During the experiment the plasma density was also scanned to check the bunch splitting effect, and it was observed that above a certain density threshold the split phenomenon ceased to occur.

Numerical analysis. To validate our hypothesis about the tilted shock being the cause of the split, we performed 3D PIC simulations using the code PICONGPU [47], allowing visualization of even finer details. We used a simulation box of about $230 (z) \times 100 (x) \times 100 (y)$ μm with a spatial resolution of $30 (z) \times 400 (x) \times 400 (y)$ nm and a time step of 50 as. The on-axis density we used is the one described in Fig. 2(a)

above, and the surrounding features such as shock slope and transverse density gradients were taken from a 3D ANSYS® FLUENT® fluid dynamics simulation [48]. Although not all of the experimental results were reproduced quantitatively, our simulations recreate and confirm the observed qualitative phenomena, uncovering the mechanism responsible for their manifestation.

The snapshots in Fig. 5 track the numerical dynamics of the wakefield during and after passing through the shock. Normally, the sharp longitudinal density downramp causes an abrupt increase in the bubble size both longitudinally and transversely. However, as can be seen in Fig. 5(a), when the shock is tilted, the bubble expansion is asymmetric: the bottom of the bubble (closer to the gas jet) crosses to the low-density region before the top does, resulting in a temporary transverse shift of the effective bubble center downwards. It should be noted that this shift is observed in our simulation to be larger by about an order of magnitude than the shift caused to the laser pulse itself due to the density dependence of the refractive index. Since the bubble expansion triggers electron injection, the electrons are injected out of the laser axis. Immediately afterwards, when the shock crossing is completed, the bubble structure symmetry around the laser axis is regained [Fig. 5(b)]. As a result, the off-axis electrons are strongly pulled towards the bubble central axis by the intense radial focusing forces, and start oscillating with a very large amplitude. Electrons in the wakefield always oscillate radially around the axis, a motion known as betatron oscillation; but the off-axis injection seeds this motion with a very large amplitude, and with the “center of mass” of the electron bunch located away from the axis and not on it, on average.

The amplitude of these oscillations is strongest near the rear of the bunch, similarly to the hosing instability process [49] (an interaction between the oscillating bunch and the shell of electrons surrounding the bubble), and eventually parts of the electron bunch break through the bubble shell [Fig. 5(c)] and drive a secondary wakefield [Fig. 5(d)]. This ejection mechanism introduces an inherent longitudinal lag between the drivers of the on-axis and the off-axis wakefields, since the driver of the off-axis wakefield—located at the *front* of the first bubble—is always aligned with the *rear* of the first bubble of the on-axis wakefield, from which it was emitted. This explains the inherent lag observed in the experimental FREM images, as mentioned above, and as seen in Figs. 2(d) and 4(c).

Figure 6(a) is a zoomed-in version of Fig. 5(c) with a fraction of the simulated electrons colored by their energies, showing that the splitting bunch is highly relativistic (150–200 MeV). It also shows that additional groups of electrons are ejected away, but they are typically of much lower energy, as well as of lower density, as can be seen in Fig. 6(b); such electrons cannot drive a wakefield and eventually scatter. We occasionally saw a third faint bunch experimentally, but for most of the shots only one on-axis bunch and one off-axis bunch have appeared. The polar splitting angle of the main off-axis bunch seen in Fig. 6(b) compares well with the experimental results shown in Fig. 2(e).

It should be noted, as seen in Fig. 6(b) and also experimentally in Fig. 3, that the off-axis bunch is typically not oriented

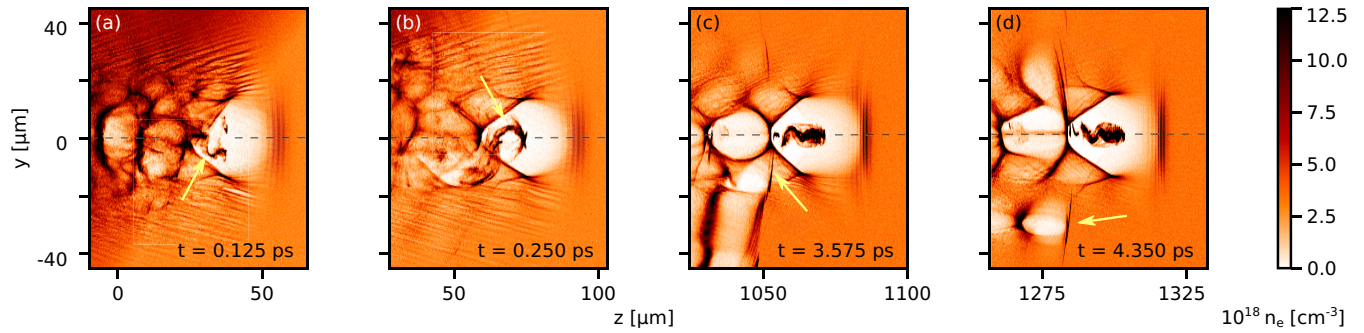


FIG. 5. Numerical results of the wakefield front crossing the tilted shock. During the shock crossing the bubble expands asymmetrically, so that the triggered injection, marked by an arrow in (a), is to the off-axis center of the rear part of the bubble. After crossing the shock, symmetry is regained and restoring forces act on the electron bunch, driving oscillations marked in (b) which are strong enough for part of the bunch to eventually break through the bubble shell, near the arrow in (c), and drive its own wakefield, with the driver marked in (d). The laser axis is marked by a dashed gray line.

exactly inside the vertical plane, having a nonzero horizontal component. This horizontal spread is seemingly the result of fluctuations in the laser parameters and the plasma density profile, and there could also be a secondary effect of the (horizontally polarized) laser interacting asymmetrically with the shock front, causing small shifts to the rear of the bubble in the polarization direction, thereby seeding the oscillations of the injected bunch with a nonzero horizontal component of the initial position. In the numerical simulation, there is the additional error originated in the discretization of the system due to the finite mesh and the macroparticle representation, but the first factor (experimental fluctuations) is irrelevant for the simulation.

To further verify the tilted shock-front effect, we skewed the density profile in another simulation to make the shock normal to the longitudinal axis, while maintaining all other parameters. In these conditions, the electron injection only occurs near the axis and no large oscillations and split wakefields were observed.

Due to this mechanism, the asymmetric bubble expansion from the tilted shock is the major cause of the off-axis electron injection and enhanced betatron oscillations. This is different

from previously described effects which attributed the change in the wakefield dynamics to the laser pulse itself interacting with the refractive index with nonuniform distribution, making it shift [28,50] or distort [45].

The numerical results agree with the experimental findings in many aspects: the wakefield split was recreated, including the on-axis/off-axis characteristic of the split; a laser driver is associated with the on-axis wakefield and a relativistic electron bunch driver with the off-axis wakefield, as we saw in the FREM images; the vertical bias of the off-axis bunch pointing has been explained by the vertically asymmetrical bubble expansion and shifted injection point, seeding the oscillations that eventually lead to the split; the split is indeed caused by the shock, explaining why we only see the split in FREM images taken after the wakefield has crossed the shock; the split position in the simulation agrees with the estimated position from the measured results; since the off-axis bunch originates from the back of the injected electrons in the first on-axis bubble, and is located at the front of the first off-axis bubble (since it drives the wakefield), there will always be a lag between the two wakefields, as has been observed in our experimental results; and additionally, the simulation features a single major split event, in accordance with the vast majority of the experimental shots. It should be noted that, when simulating different density profiles, we saw situations where splits occurred every half cycle of the strong oscillations, upwards and downwards alternatively. These density profiles are not the ones used in this experiment, but this leads to the thought that if such density profiles would be implemented in some experiment, maybe a train of splits could be observed using FREM. One thing seen in the experiment but not verified in the simulation is the density dependence of the wakefield splitting phenomenon (the fact that above a certain density level it no longer occurs, and for many density values below this threshold it does occur).

Discussion. In conclusion, the shock-front induced nonlinear laser-plasma wakefield dynamics were characterized in detail using FREM, supported by 3D numerical results. The shock tilt was found to cause the splitting of the wakefield (observed both in the experiment and in the numerical simulation), via asymmetric bubble expansion and off-axis injection. The bunch split into an on-axis laser-driven wakefield and an

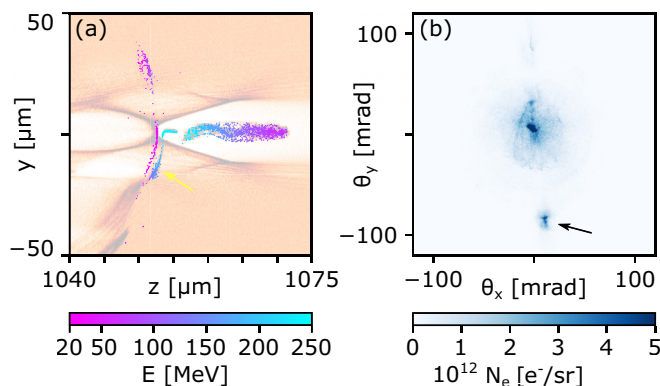


FIG. 6. Numerical snapshot showing the moment of the split. (a) Zoomed version of Fig. 5(c) with electrons above 20 MeV colored by energy. (b) Angular pointing histogram of the same numerical snapshot showing the bunch densities. Arrows mark the main off-axis bunch in both panels.

off-axis beam-driven wakefield, a phenomenon not observed before to the best of our knowledge. The asymmetry and split can be thought of as undesired, but also as beneficial; the asymmetry can be used (alone or combined with other methods) to enhance the betatron radiation emitted from the electron oscillatory motion [39,50], following our result that the amplitude of the oscillations caused by the tilted-shock induced off-axis injection is much larger than the deflection obtained in other asymmetry-based methods. In addition, multiple electron bunches emitted from the same source have many potential usages [51], and with further research one can envisage to control this new phenomenon, opening the way to applications such as converting the two synchronized electron bunches to a double synchronized advanced light source [51], velocity measurement of near-luminal and superluminal phenomena [52], direct measurement of the betatron period by using a parameter regime where such splits occur every half-period of the betatron oscillations (such parameter regimes were found in simulations), and splitting-beam FREM imaging, where this splitting bunch can be used as a double probe that measures a single shot in two positions—an ability that can be highly valuable for systems such as petawatt-class laser-plasma accelerators, typically featuring very low repetition rates, implying that any extra information obtainable for each shot is highly valuable. Already now, this discovery adds to our knowledge of the various processes taking place inside nonlinear wakefields, and in particular sheds light on plasma

dynamics and wakefield behavior around and after density shock transitions.

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The authors declare no competing interests.

Data availability. All data as well as the codes that support the findings of this study are available from the contact author upon reasonable request.

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