High-Gradient Plasma-Wakefield Acceleration with Two Subpicosecond Electron Bunches

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A plasma-wakefield experiment is presented where two 60 MeV subpicosecond electron bunches are sent into a plasma produced by a capillary discharge. Both bunches are shorter than the plasma wavelength, and the phase of the second bunch relative to the plasma wave is adjusted by tuning the plasma density. It is shown that the second bunch experiences a 150 MeV/m loaded accelerating gradient in the wakefield driven by the first bunch. This is the first experiment to directly demonstrate high-gradient, controlled acceleration of a short-pulse trailing electron bunch in a high-density plasma.

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Plasma waves can sustain extremely large electric fields that are orders-of-magnitude larger than those in conventional radio-frequency accelerators, which are limited by vacuum breakdown to accelerating gradients of up to 150 MV/m [1]. Such large amplitude electron density waves, or wakes, can be excited in plasmas by a laser pulse (laser wakefield acceleration—LWFA), or a relativistic particle beam (plasma-wakefield acceleration—PWFA). Recent LWFA experiments demonstrated quasi-monoenergetic acceleration of self-trapped plasma electrons [2]. Further scaling of LWFA to higher energies, by using higher laser power but larger spot sizes and lower density plasmas, will probably require injecting relativistic electron bunches into a plasma wave, rather than starting with plasma electrons at zero energy. So far, this approach to potentially monoenergetic particle acceleration using plasmas has not been explored. Experiments using PWFA methods similarly face the challenge of producing low-energy-spread acceleration of an injected relativistic particle bunch. In previous PWFA experiments (see, for example, Refs. [3–5]), a single relativistic electron-bunch both drove the wake and provided the electrons to be accelerated. Using this scheme at SLAC, a record-high energy gain of 42 GeV over 85 cm of plasma was demonstrated [3], albeit with an undesirable ~100% spread of the electron energy spectrum. To realize a future collider, such as one incorporating the PWFA afterburner concept [6], a well-defined bunch is required that is suitably phased on the plasma wake of a preceding drive bunch thereby to achieve high efficiency and a small energy spread (~0.1% which is typical for conventional accelerators). In this Letter, we detail a double-bunch PWFA experiment that allows, for the first time, to achieve a controllable high-gradient acceleration of a witness relativistic electron bunch injected into a plasma wave.

Earlier double-bunch PWFA experiments [7] utilized relatively long, picosecond electron bunches in low-density (10^{13} cm^{-3}) plasmas; wakefields up to $\approx$4 MV/m were inferred. Our experiment differs substantially from these studies. First, the driver and witness bunches have subpicosecond lengths ($\sigma_z \sim 100$ fs), and are both shorter than the plasma wavelength. Consequently, the energy shift of both bunches can be directly observed rather than mathematically extracted, as was required in earlier works. Second, the shorter bunch lengths and the higher plasma densities employed (up to 10^{17} cm^{-3}) result in generated wakefield amplitudes that are two orders-of-magnitude larger compared to those studies. We show here that, for a fixed bunch-spacing, the plasma density can be chosen such that the drive electron-bunch loses energy that it is transferred through the plasma wave to the second bunch, which, in turn, gains energy with a minimum energy spread. In the experiment, the drive bunch loses about 1.0 MeV over 6 mm propagation in a plasma of 10^{16} cm^{-3} density, and the witness bunch, delayed by 500 fs, gains $\approx$0.9 MeV corresponding to an average loaded accelerating gradient of $\approx$150 MeV/m. The measured energy gain and loss agree well with 2D linear theory calculations. This experiment is the first to generate and directly probe large plasma accelerating gradients (>100 MeV/m) utilizing a trailing electron bunch.

The experiment is performed at Brookhaven National Laboratory's (BNL's) Accelerator Test Facility (ATF). A photocathode rf gun followed by a conventional 2.856 GHz (S-band) accelerator produces a 1.5 ps-long (rms), 500-pC, 60 MeV single electron bunch [8] that is compressed and split into two distinct (in time and energy) subpicosecond bunches after traveling through a chicane compressor and "dog-leg" dipoles downstream from the linac [Fig. 1]. These two bunches are focused transversely to $\sigma_r \approx 100$ μm at the entrance of a 10^{14} cm^{-3}–10^{17} cm^{-3} density plasma produced by an ablative capillary discharge [9]. A magnetic spectrometer at the end of the beam line records the energy change imparted to the bunches by the plasma.

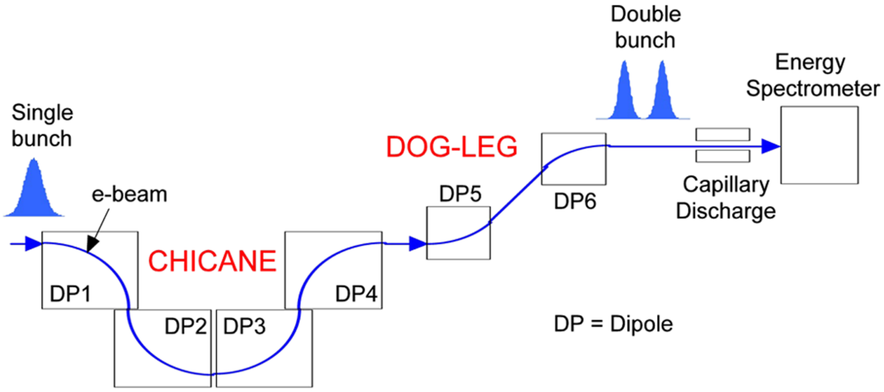

FIG. 1 (color online). Layout of the double-bunch PWFA experimental setup.

Production of subpicosecond driver-witness electron bunch pairs separated by a distance appropriate for PWFA experiments in high-density plasmas (10^{16}–10^{17} cm^{-3}) is challenging [10]. The breakup of the electron beam into two distinct bunches at ATF is attributed to the combination of a nonlinear energy chirp introduced by the linac, over-compression of the bunch in the chicane, and coherent synchrotron radiation effects in the chicane and the dog-leg dipole magnets, the exact details of which are still being studied. Therefore, although the breakup of the bunch is repeatable and consistent [11], control of its characteristics is limited. The two bunches are separated by approximately 1.8 MeV in energy and have a typical full-width-at-half-maximum (FWHM) of 0.4 MeV, thus allowing direct observation of their energy shifts caused by their interaction with the plasma. In addition, coherent transition radiation interferometry [12] is used to diagnose the two bunches in time. Assuming each bunch has a Gaussian shape, it is found that the high-energy and the low-energy bunches, respectively, are roughly 45 μm (150 fs) and 27 μm (90 fs) long (rms), and are separated by $\Delta z = 150$ μm (500 fs). Beam-position monitors and a Faraday cup also indicate that the total charge is preserved during the break up, with the low-energy bunch having about 60% (180 pC) of the charge of the high-energy bunch (300 pC). Finally, observations of the interaction between the bunches and the plasma show that the high-energy bunch loses energy in the plasma independently of the presence of the low-energy bunch, thus implying that the former precedes the latter, which acts as the witness bunch.

The plasma source is a 16.5 kV pulsed electrical discharge through a readily available 6 mm long polypropylene capillary with a 1 mm inner diameter, although there is no fundamental limitation in using a longer, centimeter-scale capillary to reach a larger energy gain. The breakdown in the vacuum ablates the capillary walls creating a carbon-hydrogen plasma. The discharge light is collected and guided by an optical fiber into a spectrometer that measures the hydrogen Balmer H_α linewidth, and the plasma density is derived from the well-tabulated Stark broadening [13]. An intensified time-gated camera collects spectral measurements with a resolution of 300 ns. They show that the plasma reaches a maximum density of approximately 3×10^{17} cm^{-3}, after which it exponentially decays due to diffusion through the capillary openings [4,14] at a nominal rate of one order-of-magnitude per 1.5 μs. Therefore, the required plasma density, n_p, can be selected by tuning the time delay of the e-beam after the discharge starts. The peak electric field of the discharge is about 3 MV/m, which is much smaller than the typical plasma-wakefields in this experiment (>80 MV/m) and does not affect the energy spectra of the electron bunches significantly.

The peak beam density, n_b, of the two compressed bunches is approximately 10^{14} cm^{-3}, so placing the physics of the beam-plasma interaction in the linear overdense regime ($n_b < n_p$) for the range of plasma densities used in these experiments [15]. In this regime, each bunch independently creates a wakefield with a spatial period equal to the plasma wavelength. While the drive bunch only loses energy due to its own wakefield, the witness bunch samples the superposition of the two fields, and loses or gains energy depending on its relative phase in the wakefield driven by the first bunch. This phase is controlled by tuning the plasma density (and hence the plasma wavelength). Specifically, energy gain is expected at plasma densities such that the witness bunch samples the second half-period of the plasma wave driven by the first bunch, i.e., when approximately $\lambda_p/2 < \Delta z < \lambda_p$; here, $\lambda_p = 2\pi c/(n_p e^2/\varepsilon_0 m_e)^{1/2}$ is the wavelength of the relativistic plasma wave, e is the electron charge, ε_0 is the permittivity of free space, m_e is the mass of the electron, and c the speed of light in vacuum.

To model the behavior of the witness bunch, a 2D numerical program was developed to calculate the linear wakefields driven by two Gaussian-shaped bunches [16] with the aforementioned experimental parameters. The validity of the modeling was verified by comparing the findings with the fully-explicit 2D particle-in-cell code

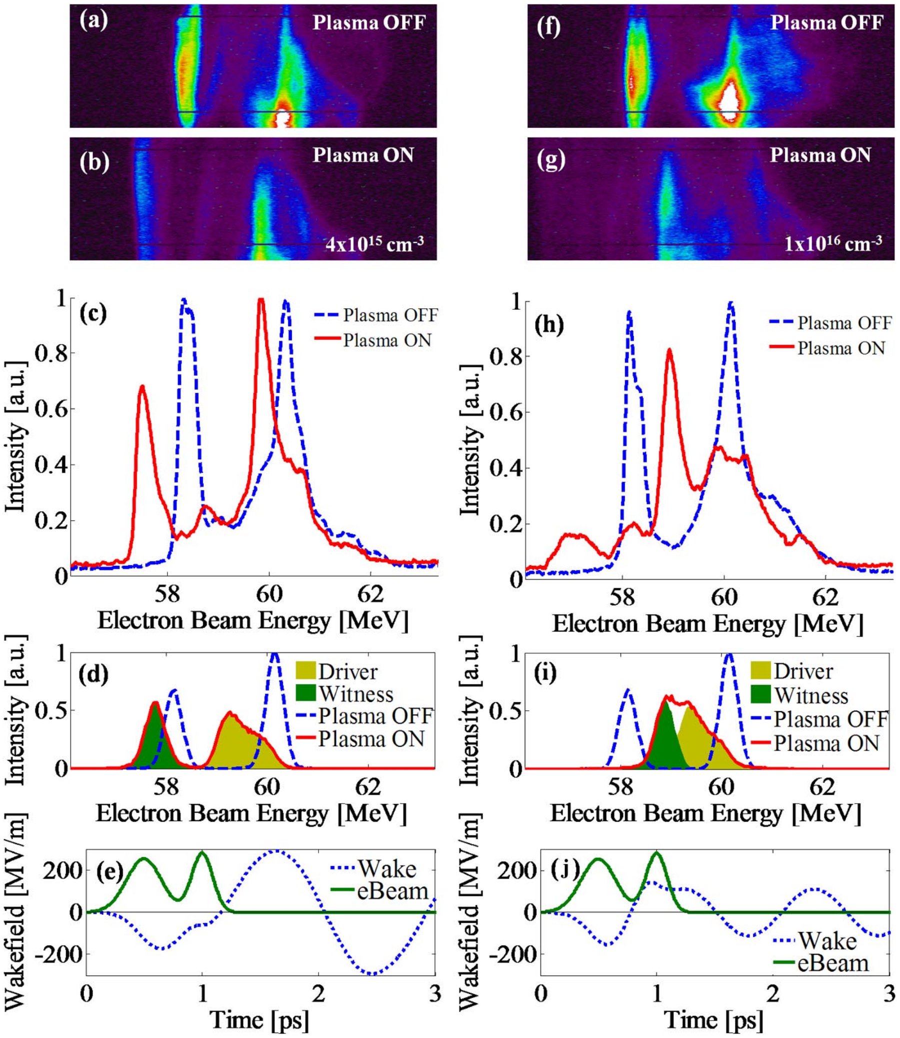

FIG. 2 (color online). Experimental and simulated energy spectra of the double-bunch beam after the 6 mm long capillary discharge at 4×10^{15} cm^{-3} plasma density (left column), and at 1×10^{16} cm^{-3} density (right column): (a),(f) raw energy spectrum without plasma; (b),(g) raw energy spectrum with plasma on; (c),(h) experimental energy profiles; (d),(i) simulated energy profiles; (e),(k) simulated plasma-wakefield and position of the bunches inside the wake.

OSIRIS [17]. The amplitudes of the wakefields simulated by both methods agreed within 10%, thus justifying the use of the thousand-times-faster numerical calculation.

The left-hand side column in Fig. 2 presents experimental energy spectra of the *e*-beam with the plasma discharge turned off [Fig. 2(a)] and as measured after the 4×10^{15} cm^{-3} density plasma [Fig. 2(b)], together with plots of the area-normalized line profiles integrated vertically (across the beam's profile) in Fig. 2(c). At this plasma density, both bunches clearly lose energy, since the plasma wavelength is longer than the separation between the bunches ($\lambda_p = 529$ μm $> 2\Delta z \approx 300$ μm). The drive bunch loses $\approx$0.5 MeV, and the witness bunch loses $\approx$0.8 MeV, corresponding to average wakefield amplitudes (over the 6-mm capillary length) of 83 MV/m, and 133 MV/m. Figure 2(d) plots the simulations of the predicted energy spectra before and after the plasma interaction; they confirm that both bunches should lose energy. Figure 2(e) shows simulated combined plasma-wakefield and longitudinal phasing of the two bunches in this field.

The right-hand side column in Fig. 2 shows the experimental energy spectra recorded when the plasma density is increased to 1×10^{16} cm^{-3}, therefore reducing the plasma wavelength to $\lambda_p = 334$ μm $\approx 2\Delta z$. The witness bunch now mainly gains $\approx$0.9 MeV in energy [Fig. 2(g) and 2(h)]. The simulation illustrates that the observed peak in the energy spectrum around 59 MeV results from the superposition of both accelerated electrons from the witness bunch and decelerated electrons from the drive bunch (which only loses energy) [Fig. 2(i) and 2(j)]. Some residual charge of the drive bunch is recorded around 60.5 MeV, probably reflecting the non-Gaussian initial energy distribution.

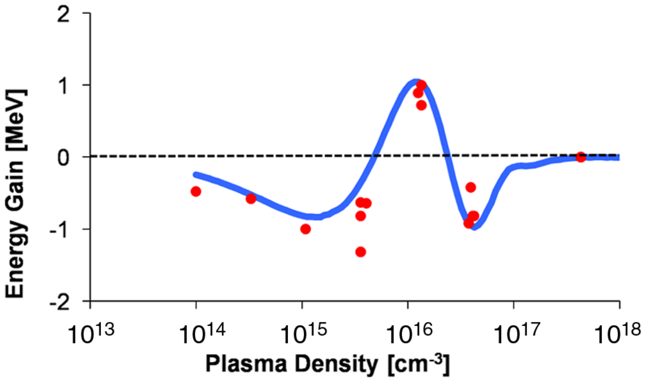

FIG. 3 (color online). Experimental data points for the energy shift of the witness electron-bunch centroid for a range of plasma densities. The solid curve represents 2D numerical calculations for the centroid energy shift.

To confirm that the witness bunch is indeed affected by the drive bunch, the higher-energy bunch is partially blocked by closing a slit located at the dispersion plane inside the dog-leg. Then, when the plasma density is 1×10^{16} cm^{-3}, the witness bunch has an average energy loss of $\approx$1 MeV. Since the witness bunch loses 1 MeV due to its own wake and gains 0.9 MeV in the presence of the drive bunch, we conclude that the net energy shift due to the drive bunch is 1.9 MeV, corresponding a $\approx$315 MV/m unloaded accelerating wakefield amplitude driven by the first bunch.

Figure 3 depicts the measured energy shift of the witness-bunch centroid as the plasma density is scanned from 1×10^{14} cm^{-3} up to 4×10^{17} cm^{-3}. Comparison of the recorded shifts with the 2D numerical calculation of the corresponding predicted energy shifts demonstrates good agreement with the simulation. The experimental points show that the witness bunch progressively loses more energy as the plasma density rises from its minimum value, provided that the plasma wavelength remains longer than the bunch separation ($\lambda_p > \Delta z$) and both bunches reside at the decelerating phase of the wake [see Fig. 2(e)]. As the density increases further to approach the 10^{16} cm^{-3} range, the plasma wavelength decreases and the witness bunch now samples the second, accelerating half of the plasma wave period [$\lambda_p \approx 2\Delta z$; see also Fig. 2(j)], and therefore it gains energy while simultaneously loading the wake since its charge is comparable to that of the drive bunch. Energy loss is observed again at an even higher plasma density ($>4 \times 10^{16}$ cm^{-3}) where the witness-bunch samples the decelerating first half of the second period of the excited plasma wake ($\lambda_p < \Delta z$).

In summary, by adjusting the plasma density, we demonstrated tunable energy gain or energy loss of a short ($\sigma_z < \lambda_p$) witness bunch that samples the wakefield generated by a leading subpicosecond drive bunch. The measured energy gain of 0.9 MeV over a 6 mm long, 10^{16} cm^{-3} density plasma corresponds to an unloaded average accelerating gradient of 315 MeV/m. This work demonstrates that short-pulse accelerated trailing electron beams can be produced with a double-bunch PWFA scheme, and hence, the method constitutes a promising step forward towards producing monoenergetic bunches in next-generation ultra-high gradient plasma accelerators.

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