Plasma-Density-Gradient Injection of Low Absolute-Momentum-Spread Electron Bunches

C. G. R. Geddes,[1,*] K. Nakamura,[1] G. R. Plateau,[1,†] Cs. Toth,[1] E. Cormier-Michel,[1,‡] E. Esarey,[1,‡] C. B. Schroeder,[1] J. R. Cary,[2,§] and W. P. Leemans[1,∥]

[1]*Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, California 94720, USA*
[2]*Tech-X Corporation, 5621 Arapahoe Ave. Ste. A, Boulder, Colorado 80303, USA*
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Plasma density gradients in a gas jet were used to control the wake phase velocity and trapping threshold in a laser wakefield accelerator, producing stable electron bunches with longitudinal and transverse momentum spreads more than 10 times lower than in previous experiments (0.17 and 0.02 MeV/c FWHM, respectively) and with central momenta of 0.76 ± 0.02 MeV/c. Transition radiation measurements combined with simulations indicated that the bunches can be used as a wakefield accelerator injector to produce stable beams with 0.2 MeV/c-class momentum spread at high energies.

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Laser wakefield accelerators (LWFAs) [1] sustain gradients of hundreds of GV/m, enabling reduction of accelerating distances by 1000-fold compared to conventional technologies. The laser ponderomotive (radiation) pressure drives a plasma density wave or wake, whose longitudinal field accelerates electrons [1,2]. If the wake exceeds a threshold amplitude, electrons can be self-trapped from the bulk plasma and accelerated. Recently, such experiments produced bunches with few MeV/c momentum spreads near 100 MeV/c momenta by extending the laser propagation distance using a guiding channel [3] or large spot size [4,5] in combination with self-guiding [6]. Channeled LWFAs have now also produced bunches with ~20 MeV/c longitudinal and 2 MeV/c transverse momentum spread at 1 GeV [7].

The GeV energies obtained in compact LWFAs are sufficient for applications including free electron lasers [8] and THz [9,10] and x-ray [11] radiation sources, and multiple units could be staged for high energy physics applications. However, the 1–20 MeV/c (few %) longitudinal and ~0.2–2 MeV/c transverse momentum spreads of present experiments need to be reduced, and pulse-to-pulse stability and tunability improved, for these applications. In self-trapped experiments, beam quality was best when operating at the trapping threshold [4,5,12], and relatively stable operation [7,13] was only observed in a narrow parameter window, restricting tunability.

To improve bunch momentum spread and stability, several methods have been proposed to control electron injection. The short plasma wake wavelength, $\lambda_p = \sqrt{\pi c^2 m/e^2 n_e}$, typically ~10–100 μm, requires injection of a femtosecond electron bunch with femtosecond timing. Here n_e is the plasma density, m and e the electron mass and charge, and c the speed of light. Experiments [14] demonstrating injection using the colliding laser pulse method [15,16] showed the usefulness of controlled injection in tuning the electron bunch energy, but so far have not reduced bunch momentum spread.

An alternative method to control trapping has been proposed using plasma density gradients with density decreasing in the laser propagation direction, or downramps [17–19]. In a downramp, λ_p increases with propagation. This causes the wake fronts behind the laser to fall further behind as the laser propagates, decreasing the wake phase front velocity v_ϕ even though the laser group velocity v_g is increased due to the decreased density. This reduces the threshold for trapping by reducing the velocity electrons must achieve, and allows control over the trapping process by tailoring the gradient.

In this Letter, control of particle trapping in an LWFA using plasma density gradients is demonstrated for the first time, resulting in the production of stable electron bunches suitable for use as an injector with more than tenfold lower momentum spread and jitter than previous experiments. Momentum of the bunches was stable at 0.76 ± 0.02 MeV/c, longitudinal (transverse) momentum spread was 0.17(0.02) MeV/c FWHM, and pointing stability was 2 mrad or 0.002 MeV/c rms, over hundreds of shots. Bunch charge was on the order of 0.5 nC. Simulations show that the bunches are indeed produced through modification of the trapping threshold by the density gradient in the gas jet target. Measurements further show that the laser mode is well transmitted, and data and simulations also indicate that the bunch is ultrafast. This allows coupling of the gradient to a low density plasma to post-accelerate the bunches, and simulations show that such coupling pro-

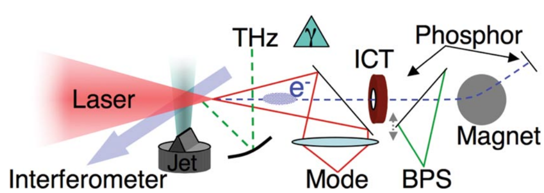

FIG. 1 (color). Setup for density gradient controlled injection using a laser focused on the gas jet downstream edge.

duces high energy bunches with greatly reduced momentum spread, as required for applications.

In the experiments, a pulse from the LOASIS Ti:sapphire laser [20] was focused on the downstream edge of a thin slit gas jet oriented transversely to the beam line (Fig. 1). The peak power was 10 TW (0.5 J in 47 fs FWHM), focused to a 7.5 μm FWHM spot. The plasma density profile along the laser propagation direction, measured by an interferometer [21], was approximately Gaussian with a peak density of $2.2 \pm 0.3 \times 10^{19}$ cm^{-3} and a FWHM of 750 μm ± 100 μm. The laser ionized the hydrogen gas and drove the plasma wake. The wake is excited strongly within a Rayleigh range $Z_R \sim 200$ μm of the laser focus [2], allowing effective selection of the density gradient using the laser focus location. Focusing upstream produced an increasing or flat density, published previously [12], while focusing downstream produced a decreasing density to control trapping.

Electron bunches were characterized using a magnetic spectrometer with a bend angle of 55°. The bunch was dispersed onto a phosphor screen (LANEX) imaged by a CCD, covering a range of $\pm 14\%$ about a central momentum determined by magnet current. The momentum resolution was $\pm 5\%$. Beam divergence was observed in the out-of-plane direction. An insertable bunch phosphor screen (BPS), imaged by a CCD, measured the spatial profile. Charge was determined by cross correlating the phosphor signals with an integrating current transformer (ICT). Gamma ray detectors monitored bremsstrahlung radiation from the electron beam dump, and this was used as a simple online identification of high energy electron production due to the restricted spectrometer acceptance [22]. Electron bunch length was inferred from THz radiation emitted from the plasma edge [9,10]. A 10 μm silver coated nitrocellulose pellicle transmitted the electron bunch and diverted the laser to a mode imager CCD [21] to measure the laser profile at the plasma exit.

Scanning the jet position relative to the laser focus (Fig. 2) demonstrated control of trapping and acceleration by selecting the density gradient at focus. Focusing upstream optimized production of high momentum electrons via conventional self-trapped acceleration, evidenced by the peak in the gamma signal [22]. The magnetic spectrum here was exponential up to tens of MeV/c (see [12]). The mode imager showed strong self-modulation and filamentation of the laser into multiple spots, also consistent with past results [12].

Focusing at the downstream edge of the jet produced stable electron bunches with an order of magnitude lower absolute momentum spread and jitter than previously observed in LWFAs [23]. The charge measured on the ICT increased slightly, but the gamma signal decreased, indicating lower momentum electrons. Magnetic spectrometer data (Fig. 3) showed bunches with central momentum stable at 0.76 MeV/c ± 0.02 MeV/c rms and momentum spread stable at 0.17 MeV/c FWHM (20%) ± 0.02 MeV/c rms over 28 sequential and 45 total diagnostic shots. In the undispersed plane, the vertical bunch divergence was measured to be 20 mrad FWHM ± 1.8 mrad rms, with 1.5 mrad rms pointing deviation.

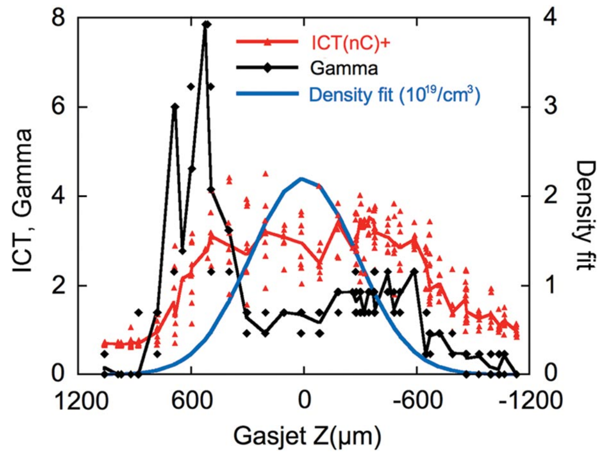

FIG. 2 (color). Charge measured by the ICT and Gamma signal versus gas jet Z position with respect to the laser focus. The Gaussian fit to the plasma density indicates the laser focus position in the profile. Correlation of the ICT and phosphor data showed that the MeV bunch charge was ~0.3–1 nC.

Bunch divergence (all momenta) was measured on the BPS (Fig. 4) [24], showing a small divergence bunch surrounded by a broad background. The narrow feature has a divergence of 26 (14) mrad in the horizontal (vertical) plane with rms deviations of $\pm 1.8(2.5)$ mrad over 30 shots. Bunch pointing was stable, with 1.8 (1.2) mrad rms and 8 (5) mrad peak-to-peak deviations in the horizontal (vertical) plane. Vertical data agree with the magnetic spectrometer, indicating that this narrow feature is the MeV

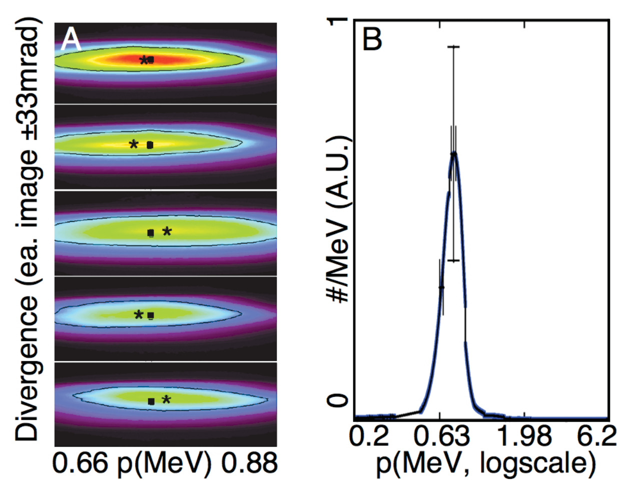

FIG. 3 (color). Magnetic spectra at a jet position of -300 μm, with the laser focus in the density downramp. Sequential shots (A), show the centroid (*) with respect to the average (square) over 45 shots, displaying bunch stability. The contour scale is fixed (see Fig. 4). The integrated magnetic spectrum (B), obtained by scanning the magnet current, shows rms error bars for charge and central energy (top of curve), and FWHM (at half max.). Data points (blue) are connected by a black line.

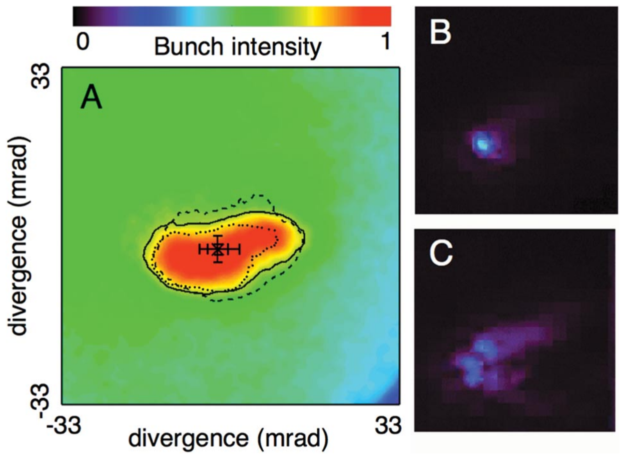

FIG. 4 (color). Electron bunch and transmitted laser profiles. In the electron profile at a jet position of -300 μm (A), the black solid contour indicates the small-divergence feature (70% of peak). Dotted (dashed) contours indicate the sizes and displacements of the smallest (largest) area bunches observed. The (*) indicates the centroid, and inner (outer) error bars display rms (peak-to-peak) pointing deviation over 30 shots. The transmitted laser is unaberrated at this location (B), in contrast to the mode when focused upstream (C).

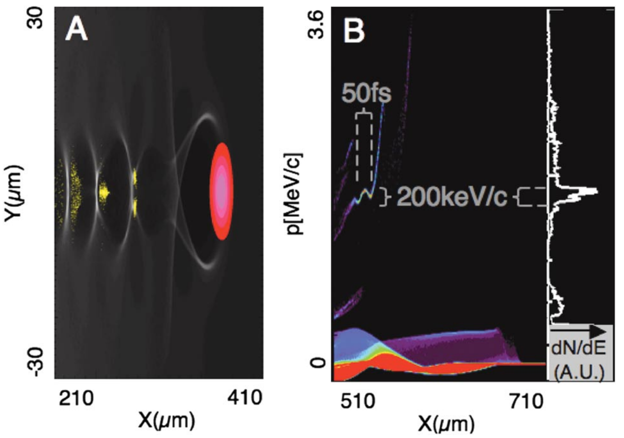

FIG. 5 (color). Simulated wake and phase space. The laser [(A), red] drives a plasma density wake (gray) in the downramp, trapping and accelerating electrons (yellow). Phase space [(B), color bar in Fig. 4] shows formation of an ultrafast, narrow momentum spread bunch at 1.5 MeV$/c$, also visible in the momentum spectrum lineout at right.

bunch, while the broad background is likely lower momentum electrons. The observed divergence indicates transverse bunch momenta of $\sim$0.02 MeV$/c$.

Correlation of the signal on the magnetic spectrometer and BPS to the ICT was used to determine the charge of the bunch at 0.76 MeV$/c$, giving Q_{bunch} of 0.3–1 nC. Charge stability was 40% rms in this sequence.

Accelerator performance was stable over three runs and 7 days; such stability will be crucial for LWFA applications and has not been previously observed. Central momentum was stable between 0.76 and 0.78 MeV$/c$, FWHM energy spread between 0.16 and 0.19 MeV$/c$, and divergence between 17 and 23 mrad. Similar bunches were observed on eight run days, and were stable for at least hundreds of shots at a time (as long as observed).

The experiments were modeled [25] with 2D particle-in-cell simulations (VORPAL [26]), which show that the ramp decreased v_ϕ as described in [17], producing trapping without significant plasma modulation of the laser (which is unstable), and yielding trapping and acceleration to $\sim$1.5 MeV$/c$ (Fig. 5). Trapping of electrons occurred where the density was $\sim 5 \times 10^{17}$ cm^{-3}, such that λ_p was resonant to the laser pulse length. At this density v_ϕ is too high in a homogeneous plasma to allow trapping by this laser, emphasizing the ramp's effect. Absolute momentum spread was $<$0.2 MeV$/c$, as observed in experiments. Consistent with experimental stability, the simulation parameters were scanned and MeV-class beams were observed for plasma lengths 0.5–1 mm, densities 1.8–2.2 $\times 10^{19}$ cm^{-3}, and laser powers 8–10 TW.

In the simulations, the low trapping threshold decreased transverse wake fields during trapping, yielding low transverse emittance. Transverse momentum was $\sim$0.05 MeV$/c$ (divergence 30 mrad) compared to 0.2–2 MeV$/c$ observed in homogeneous plasmas. The simulated bunch size of $\sim$10 μm long by 5 μm diameter, together with the experimental and simulated divergences, indicated a normalized emittance $\epsilon_n \sim 0.2 - 0.4\pi$ mm mrad. As λ_p lengthens in the downramp, the bunch expands to $\geq$50 μm in dimension, explaining the absence of space-charge blowup [27] of the experimental bunches. Remaining differences with experiments may result from the 2D nature of the simulations or parameter uncertainties.

The absolute momentum spread and the transverse momentum inferred from the divergence are tenfold to 100-fold below values obtained in homogeneous plasmas, and the measurements and simulations below indicate that the momentum spread is not significantly degraded in acceleration, so that use of these bunches as an injector may greatly improve LWFA beam quality.

Suitability of the bunches as an LWFA injector was evaluated using THz emission from the vacuum-plasma boundary [9,10] to infer bunch length τ_b. THz energy was measured using a bolometer, and emission in four wavelength bands was measured using Teflon and Fluorogold filters to cut the spectrum. Ratios of emission in each band were used to infer τ_b, assuming Gaussian bunch profiles. Fluorogold measurements were consistent with $\tau_b \sim$ 210 $\pm$ 100 fs, and Teflon with $\tau_b \sim 300 + 600, -200$ fs, agreeing within error bars (Fluorogold has a sharper cutoff, giving better precision) [28]. Simulations indicated that the bunch expands to order 200 fs as it propagates to the emission surface, consistent with data, and show that the length at production is $\leq$30 fs, allowing use as an LWFA injector.

Acceleration of the bunches to high energy will be facilitated by high laser transmission, which allows the transmitted laser to drive a wake in a subsequent plasma. Mode imager data [Fig. 4(b)] showed that the transmitted laser mode was similar to the vacuum mode, with no filamentation and with laser intensity and energy transmission of more than 70% when using a prepulse [21] to preionize the gas jet. Simulations showed similar high transmission. Stable electron bunches were measured with laser prepulse levels below the hydrogen ionization threshold and at levels sufficient to create a fully ionized preformed plasma, but not with intermediate levels, likely because a small preplasma can diffract the laser pulse [29,30], preventing it from reaching focus.

The simulations showed that the bunch can be accelerated to high energy while preserving its low momentum spread by ending the downramp in a plasma channel with uniform axial density immediately after the particles are trapped. The transmitted laser pulse then excites a wake in the channel that accelerates the beam to high energy. The wake is effectively excited because of the high laser transmission through the downramp, and the bunch is efficiently trapped because it is shorter than a plasma period. These simulations have so far shown acceleration to beyond 20 MeV/c (limited by computational time) with 0.18 MeV/c longitudinal and 0.15 MeV/c transverse momentum spread, corresponding to $<1\%$ energy spread and <10 mrad divergence. Other simulations predicted that such post-acceleration nearly preserves absolute momentum spread and normalized emittance [31,32] to high energies, which could enable much lower momentum spread and emittance than previous LWFA experiments, potentially with 0.2 MeV/c class momentum spread and low transverse emittance at GeV and greater energies.

In conclusion, experiments demonstrated a plasma gradient based technique to control injection in LWFAs, producing bunches with 10 to 100 fold lower momentum spread and variation than previous LWFAs. The bunches displayed central momentum stability of 0.76 ± 0.02 MeV/c, momentum spread in the longitudinal (transverse) direction of 0.17(0.02) MeV/c FWHM, and pointing stability of 2 mrad or 0.002 MeV/c rms. Normalized emittance was inferred to be on the order of 0.2–0.4π mm mrad, approximately tenfold better than previous LWFAs. THz measurements and simulations indicated the bunches are short enough (≤ 30 fs at production) for use as an LWFA injector. Such bunches may directly benefit applications such as ultrafast electron diffraction. Simulations of coupling these bunches to subsequent LWFAs showed that their low absolute momentum spread was preserved as the bunch accelerated, resulting in high energy beams with 0.2 MeV/c momentum spread and low emittance. This may allow bunches at GeV energies and beyond with $<0.1\%$ energy spread. Together with the observed stability over many run days, these properties will be important to collider or 4th generation light source applications of LWFAs.

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*cgrgeddes@lbl.gov
†Also at École Polytechnique, France.
‡Also at U. Nevada, Reno, USA.
§Also at U. Colorado, Boulder, USA.
‖Also at U. Nevada, Reno, and U.C. Berkeley, USA.

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[25] Laser focusing through the jet required a large simulation domain of 400 μm (240 μm) with 12 000 (900) cells in the longitudinal (transverse) direction with 5 particles/cell. Peak density was 1.8×10^{19} cm^{-3} with a Gaussian profile of 900 μm FWHM. The laser started 750 μm into the ramp and focused 600 μm downstream of center, in the range that produced MeV bunches experimentally.
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