Title
Staging of independent laser plasma accelerators

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We present results of an experiment where two laser-plasma-accelerator stages are coupled at a short distance by a plasma mirror. Stable electron beams from the first stage were used to longitudinally probe the dark-current-free, quasi-linear wakefield excited by the laser of the second stage. Changing the arrival time of the electron beam with respect to the second stage laser pulse allowed reconstruction of the temporal wakefield structure, determination of the plasma density, and inference of the length of the electron beam. The first stage electron beam could be focused by an active plasma lens to a spotsize smaller than the transverse wake size at the entrance of the second stage. This permitted electron beam trapping, verified by an 100 MeV energy gain.

I. INTRODUCTION

In a laser-plasma accelerator (LPA), an intense, short-pulse laser deposits energy into an underdense plasma via excitation of plasma waves. These plasma waves can provide field gradients exceeding 100 GV/m, enabling extremely compact accelerating structures. The laser energy depletion into plasma waves constitutes a fundamental limitation to particle beam energy gain in an LPA. If particle energies beyond the single stage limit are desired, e.g., for collider-relevant applications, operation of LPAs in stages, where each stage is powered by a fresh laser pulse, is required. Obtaining TeV-scale electron beam energies is possible in a single stage; however, this requires operating at low plasma density (on the order of \(10^{15} \text{ cm}^{-3}\)), resulting in low accelerating gradients, km-scale acceleration distances, and requires tens of kJ of laser energy. An efficient LPA at such low densities would also require a high bunch charge, increasing beamstrahlung beyond acceptable limits for high-energy physics applications. Hence, LPA staging is critical to application of LPAs to future colliders. In addition to high-energy physics applications, LPA staging can be important to decelerate electrons after photon production to mitigate shielding needs in compact photon sources.

After the first demonstration of percent-level energy spread and small divergence in mm-scale plasmas in 2008, GeV electron beams were obtained with 40 TW laser pulses, and subsequently electron beams with multi-GeV energies were reported with PW-class laser systems and few-cm plasmas. Controlling the injection of electrons into plasma waves enabled precise tunability of the accelerator. Beam emittances of 0.1 mm rad were reported, as well as fs bunch durations. Such electron beams represent a suitable source for compact x-ray free-electron laser or Thomson x-ray sources.

Here, we present experimental results from a compact, modular staging setup applying two separate laser pulses to drive two independent LPAs. These experiments employed injector electron beams generated from a gas jet target via ionization injection to longitudinally probe the wakefield exit in a second stage target (see Fig. 1). Changing the relative delay of the injector pulse and the second stage laser pulse resulted in a charge modulation of the electron beam that allowed determination of the plasma wavelength \(\lambda_p\) and, hence, the plasma density \(n_e\). An active plasma lens was introduced to the setup to focus the injector electron beam at the entrance of the second stage target for maximum coupling to the wake (see Fig. 1b). Numerical modeling was compared against experimental measurements to infer the temporal structure and to investigate the influence of the transverse plasma profile in the second stage.

II. EXPERIMENT CONFIGURATION

To establish a stable injector stage, 70% of the BELLA center TREX 40 TW laser pulse (i.e., 1.3 J laser energy, 45 fs duration) was focused by a 2 m focal length parabola down to a beamwaist \(w_0 = 18 \mu\text{m}\) onto a supersonic deLaval gas get of 700 \(\mu\text{m}\) diameter. A mixture of two gases (99% Helium and 1% Nitrogen) was used to increase the amount of trapped charge. Injection was achieved by ionizing deeply bound electrons from the high atomic number gas (Nitrogen) around the peak of the laser pulse, i.e., at a phase inside the wakefield that allows them to be trapped.

Stable electron beams were routinely produced over hours of run time (corresponding to thousands of laser shots and more than 10 days). By changing the distance of the laser focus and the gas jet nozzle, the beam parameters could be tuned in energy and charge. For the two experiments presented in this paper (section II and III), this injector was adjusted to generate beams with two different sets of parameters. For the exper-
The experimental setup. (a) In stage I, a laser pulse is focused on a gas jet, producing the injector electron beam. In stage II, the beam enters a discharge capillary. A second laser pulse modulates the electrons; this laser is coupled to the second discharge capillary via a plasma-mirror tape. A magnetic spectrometer is used to obtain an energy-dispersed electron profile. This setup was used for the experiments discussed in section III. (b) An additional discharge capillary is introduced in the setup, acting as a plasma lens to refocus the electron beam to the entrance of stage II. This setup was used for the experiments discussed in section IV.

In the experimental configuration without the plasma lens, corresponding to Fig. 1, the delay of the two laser pulses was varied by an optical delay stage in the laser beam line of the injector stage. Electron spectra were recorded as a function of the delay between the two laser pulses driving the first- and the second stage (see Fig. 2).
FIG. 2. (a) Injector electron beams probing the wakefield of the 2nd stage: waterfall plot of normalized electron spectra shown horizontally in color code. Each row represents a 5-shot averaged spectrum. Positive delay: The injector electrons arrive before the 2nd stage laser pulse and propagate unaffected by the laser. Negative delay: The 1st stage electrons are influenced by the presence of the wakefield generated by the 2nd stage laser pulse. (b) Averaged electron spectra (5 shots) for three different delays (see plot legend for details) plotted along with in the input spectrum. (c) Integrated electron beam charge as a function of the delay of the electron beam with respect to the wake-driving laser pulse. (d) FFT of (c).

In the case of a positive delay, the first stage electrons propagated only under the influence of the discharge magnetic field without the impact of the second laser pulse. After the second laser pulse arrived (negative delay), the electron spectra were periodically modulated in energy and charge (Fig. 2a). The bandwidth of the modulation is illustrated by means of electron spectra at the extrema in Fig. 2b. Where, at the delay for maximum charge throughout, 50% of the input charge distribution reached the magnetic spectrometer, almost no charge is transmitted 60 fs later. In Fig. 2b, the integrated charge is plotted showing the persistence of the modulation for delays corresponding to more than 10 plasma wave periods. In Fig. 2c, the Fast Fourier Transform (FFT) of the charge modulation is shown, verifying the constant period of the modulation of 18 μm. This is consistent with a plasma frequency ωp at a density of 3.4 x 10^18 cm^-3.

Accompanying numerical modeling with the code INF&RNAG allow interpretation of the experimental findings. A laser pulse similar to the experiment with an energy of 360 mJ was modeled with a Gaussian shape in time with a duration of 45 fs (FWHM) and an Airy profile in space with a spot size of 23 μm. The plasma density profile in the capillary of 33 mm length was linearly increasing for 3 mm (to account for the gas supply slots in the experiment) followed by a plateau region of 27 mm length with a density of 3.4 x 10^18 cm^-3 and a linearly decreasing ramp for another 3 mm. The focal plane of the laser was located at the beginning of the density plateau. A radially varying external magnetic field B(r) = μ0I0r/(2πR^2) was applied, for a discharge current of 325 A to account for the electron beam focusing.

To obtain more information on the the temporal structure of the input electron bunch, the delay scan was repeated with different bunch lengths (cf. Fig. 2). The distinct charge/energy modulation obtained with short initial bunches became indistinct if the bunch length exceeds λp/2, as expected. Best agreement with the experimental values is achieved at a bunch length of ≤ 5 μm (see Fig. 3).

When the laser is present, the transverse force of the laser-induced wake prevents a complete focusing of the electron bunch. The waist of the electron bunch is smaller than the transverse size of the wake only in the region where the laser is defocused due to mismatched guiding, and hence, the longitudinal wakefield is small. This results in a relatively small energy gain/loss of the electron beam of ±25 MeV. However, when the transversal size of the wake is small, i.e., the field amplitude is high, most electrons are deflected since they experience defocusing fields due to their oblique incidence as they approach the wake. As a result, only a very small fraction of the electrons experience an appreciable accelerating wake.

FIG. 3. Electron spectra as a function of the delay between the arrival of the electron bunch and laser pulse driving the wake for different electron bunch lengths: (a) 2.5 μm and (b) 20 μm. The electron bunch charge for different initial bunch lengths as function of the delay between electron bunch and laser: 2.5 μm (black), 5 μm (red), 10 μm (green), and 20 μm (blue). Only electrons within a full divergence of 5 mrad were taken included.

IV. MULTISTAGE COUPLING OF INDEPENDENT LPAS

In order to efficiently trap the electron beam in the second stage wakefield, an active plasma lens was inserted after the gas jet (see Fig. 1). The relative phasing of the electron beam and the second stage laser was controlled by the delay of the two driving laser pulses.
FIG. 4. Spectra of electron beams from staged acceleration: (a) maximum electron energy (blue) and total electron beam charge (red) as a function of the delay of the two driving laser pulses. A single data point represents an average of 5 measurements, and the error bar is the standard deviation. (b) 100-shot average unperturbed reference for delays of 100-300 fs before arrival of the second laser pulse. (c)-(f) 2D charge maps (5-shot average) subtracted by the reference (b) for the first two maxima and minima of the energy oscillation shown in (a), i.e., for delays of -107 fs, -153 fs, -193 fs, and -240 fs, respectively. Partially reproduced with permission from Nature 530, 190 (2016).

and electron spectra were again recorded for each delay. Similar to the case without the plasma lens, the electron spectra were periodically modulated in energy (Fig. 4a). The period of the modulation was (80 ± 6) fs, consistent with a plasma wavelength \( \lambda_p = 24 \mu m \) at a density of \((1.9 \pm 0.3) \times 10^{18} \) cm\(^{-3}\). The constant periodicity of the observed modulation as a function of the delay behind the driver pulse further indicates a quasi-linear wake, consistent with expectations for the experimental parameters including laser intensity and plasma density.

To investigate the influence of the second stage wakefield on the electron beam in detail, a reference spectrum of an unperturbed beam (positive delay) was subtracted from the spectrum at each delay to emphasize the effect while maintaining absolute charge information. The resulting electron distributions are plotted in Fig. 5b in the form of a waterfall plot of electron spectra where each horizontal line corresponds to a 5-shot averaged energy spectrum. Background-subtracted 2D charge maps, also averaged over 5 shots, are shown in Fig. 4c-f for significant delays. The presence of the second-stage laser results in a reduction of total beam charge of up to a factor of 3 (see Fig. 4b). For appropriate timing of the second stage laser, however, charge was detected beyond the energy cut-off of the input electron spectrum, i.e. > 200 MeV. This charge accelerated beyond the cutoff of the input spectrum, shown by the red and yellow areas in Fig. 4d,f, indicates acceleration in the second stage. The integrated charge in this region of 1.2 pC represents the charge trapped in the accelerating phase of the wake and respectively, a trapping efficiency of 3.5%. At delays of \( \lambda_p / 2 \) after the times of maximum energy gain, \( \sim 1 \) pC of additional charge was detected around 110-150 MeV (Fig. 4b,c). This could correspond to electrons decelerated or to electrons deflected by the transverse wake fields into the spectrometer acceptance. The broad energy spread of the first stage electron beam prevents unambiguous observation of the decelerating phase of the wake under these conditions.

V. STAGING SCALING TOWARDS PW-CLASS LASER

As discussed above, there were two regions of increased laser intensity, and hence higher wake amplitude, in the capillary due to mismatched laser pulse guiding. In Fig. 4a the electron energy evolution is plotted as function of propagation in the capillary for two different electron populations. One population of electrons focused by the active plasma lens to a spotsize < 15 \( \mu m \) had an initial energy in the interval 89–130 MeV at a delay of −304 fs, gained 95 MeV of energy in the region \( z = 2 – 5 \) mm,
but were strongly defocused by the transverse wakefield in $z = 5 - 8$ mm.

The population of electrons with a final energy above 200 MeV experienced a 100 MeV energy gain at a delay of $-252$ fs in the vicinity of the 2nd laser focus, corresponding to a propagation distance of $z = 24 - 29$ mm in the plasma, where, due to the focusing induced by the discharge current and the laser-induced wake, they reach a spot-size of 5 µm and interact strongly with the laser-driven plasma wake. This is shown Fig. 6b, where we plot (red solid line) the evolution of the transverse electron bunch size as a function of the propagation distance. The red dashed line in the same figure shows the evolution of the bunch spot size without the influence of the laser pulse, indicating that the contribution of the external magnetic field induced by the discharge current of the second capillary on the trapping of the electrons cannot be neglected.

For energy gains of multiple GeV per stage, as required for collider applications, lasers with PW power such as BELLA are required. In order to model such a multi-GeV staging prototype, we adapted the setup sketched in Fig. 1 for two identical Gaussian (temporally and spatially) laser drivers, with 15 J pulse energy, 80 fs (FWHM) pulse duration and $w_0 = 53$ µm beam waist. An electron beam with beam parameter similar to the one obtained in Ref. [13] with a central energy of 400 MeV, 4% energy spread and 10 pC charge was accelerated in the first LPA stage (LPA1): a discharge capillary of 30 cm length and a parabolic channel with a matched radius of 70 µm and a plasma density of $2.2 \times 10^{17}$ cm$^{-3}$. The injector beam is trapped completely and accelerated to energies of 4.5 GeV at an energy spread of 2.5% and 0.11 mrad divergence, consistent with the experimental results reported in Ref. [10]. A 9 cm long active plasma lens with a radius of 250 µm and a current of 800 A is applied to provide the focusing fields required to couple the electron beam to the second stage (LPA2, identical to LPA1) at a total coupling distance of 40 cm. The second stage laser pulse laser pulse is introduced by a plasma mirror (PM) situated 20 cm upstream of LPA2. For proper timing of the two laser pulses, the first stage electron beam can be trapped entirely in the quasi-linear wakefield excited by the second laser pulse and accelerated to energies of 9.5 GeV while maintaining low relative energy spread and divergence. In Fig. 7b, energy spread and bunch energy are plotted for 3 different timings to demonstrate the robustness with respect to jitter in the system.

![FIG. 6. (a) Evolution of the laser intensity expressed as the normalized laser vector potential $a_0$ (black) and evolution of electron energy as function of propagation in the capillary for two different electron populations: electrons with an initial energy in the interval 89 – 130 MeV at a delay of $-304$ fs (blue) and electrons with a final energy of 200 – 300 MeV at a delay of $-252$ fs (red). (b) evolution of the electron beam rms spotsize for the same electron beam subsets as in (a) and the electron beam rms spotsize of the electrons with final energy 200 – 300 MeV without the influence of the laser field. Partially reproduced with permission from Nature 530, 190 (2016).](image1)

![FIG. 7. (a) electron spectra at the different stages of the simulation. (b) mean electron energy and relative energy spread as a function of propagation in the second stage capillary for 3 different timings: -434.6 fs (black), -430.8 fs (red) and -426.9 fs (blue).](image2)

VI. CONCLUSION

In summary, we have presented an experimental study of staging of two LPAs independently driven by two synchronized laser pulses. Electron beam injection and capture into the second stage wake was demonstrated by means of an $\sim 100$ MeV energy gain recurring at delays corresponding to multiples of $\lambda_p$. The observation of temporally well-defined energy modulations further directly implies a bunch length of the input electron beam shorter than $\lambda_p/4m$. This experimental result represents a major milestone in the development of laser-driven plasma-based accelerators towards future colliders, as well as other LPA application that requires electron energies beyond the single stage limits and/or that requires deceleration of electrons after use to mitigate shielding requirements. Numerical modeling indicates that multi-GeV en-
energy boosts to high quality electron beams (with 100% trapping) can be achieved by operating at lower densities (i.e., larger transverse wake size).

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