# Colliding Laser Pulses for Laser-Plasma Accelerator Injection Control

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**Abstract.** Decoupling injection from acceleration is a key challenge to achieve compact, reliable, tunable laser-plasma accelerators (LPA) [1, 2]. In colliding pulse injection the beat between multiple laser pulses can be used to control energy, energy spread, and emittance of the electron beam by injecting electrons in momentum and phase into the accelerating phase of the wake trailing the driver laser pulse [3, 4, 5, 6, 7]. At LBNL, using automated control of spatiotemporal overlap of laser pulses, two-pulse experiments showed stable operation and reproducibility over hours of operation. Arrival time of the colliding beam was scanned, and the measured timing window and density of optimal operation agree with simulations [8]. The accelerator length was mapped by scanning the collision point.

**Keywords:** laser-plasma accelerators, controlled injection, colliding pulses
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## INTRODUCTION

Laser-plasma accelerators (LPAs) rely on the excitation of an electron density wave by a laser in a plasma, whose longitudinal field accelerates electrons [1, 2]. Capillary-guided LPAs have demonstrated high-quality electron beams at 1 GeV [9] with 2.5% *r.m.s.* energy spread. However, most of present LPAs [10, 11, 12] still relie on transverse wavebreaking effects [13] of highly nonlinear waves [14] to inject electrons into the accelerating phase of the electron density wave. In this scheme, injection and acceleration are coupled, limiting control of the accelerated electron beam which is essential for LPAs' applications such as free-electron lasers [15], THz [16, 17] and x-ray radiation sources [18, 19]. Several methods to control trapping of the electrons have been proposed and demonstrated: external injection of an electron beam from a conventional accelerator [20, 21, 22], triggering injection in plasma density gradients with density decreasing in the laser propagation direction [23, 24], and using additional laser pulses [3, 7, 5, 6, 25].

In this paper, a single off-axis counter-propagating laser pulse is used to simplify the implementation of a laser triggered injection technique, minimize the risk to the laser system when doing a co-linear counterpropagating geometry, and to facilitate secondary radiation extraction [26, 27]. Using active beam pointing, initial colliding pulse injection (CPI) produced stable, reproducible few-MeV electron beams. The length of the accelerating structure was scanned by varying the intersection point of the collider beam. Two-dimensional particle-in-cell (PIC) simulations reproduce the observed timing window for the experimental parameters [28]. Both plasma density and intensity of the collider beam were scanned. Injection reaches a plateau for a normalized vector potential, $a_1$, of the collider laser pulse greater than 0.9 as predicted by simulations. To provide higher energy electron beams in coming CPI experiments, guiding of the driver laser pulse alone through several Rayleigh lengths by a third laser pulse was successfully demonstrated. Combined with CPI, 2–400 MeV beam of several pC and with narrow energy spread could be produced [8].

## EXPERIMENTAL SETUP AND DIAGNOSTICS

In the LOASIS facility at the Lawrence Berkeley National Laboratory, two ultrashort 800-nm laser pulses were focused into Helium or Hydrogen gas (3–9 $10^{18}$ $e^-/\text{cm}^3$) from a 2.2 mm inner diameter supersonic nozzle. Both laser

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pulses were produced using a 10 Hz Ti:$Al_2O_3$ chirped-pulse-amplification laser system. The first laser pulse, called the "driver" beam, an s-polarized pulse of $\simeq 0.4$ J/pulse in $\simeq 45$ fs FWHM, was used to drive the plasma wave. The second laser pulse, referred to as the "collider" beam, an s-polarized pulse of $\simeq 0.25$ J/pulse in $\simeq 45$ fs FWHM, intersected the driver at both foci from the downstream direction at a 19 degree angle. The experimental setup is shown on Fig. 1. Series of single-shot diagnostics are used to characterize the generated electron beams: integrating current transformer (ICT) for the electron beam charge, magnetic dipole spectrometer for the electron bunch energy distribution, spectral analysis of coherent transition radiation from the plasma-vacuum boundary for the electron bunch duration [29], and x-ray radiation distribution from betatron motion of accelerating electrons for the electron beam divergence and transverse size.

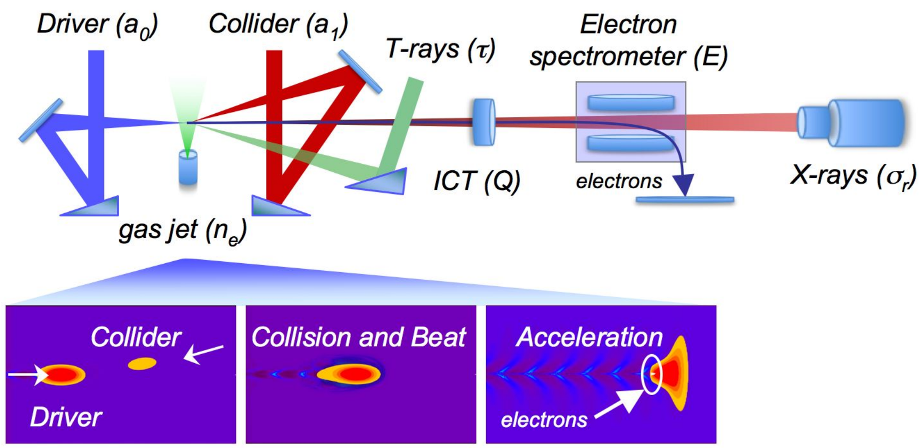


**FIGURE 1.** Schematic of the experimental setup. The laser beams, with strengths $a_0$ and $a_1$, are focused using off-axis parabolic mirrors onto a supersonic gas jet of neutral electronic density $n_e$. Temporal duration ($\tau$), charge ($Q$), energy ($E$) distribution, and source size ($\sigma_r$) can be monitored. The inset describes the principles of colliding pulse injection: at overlap a ponderomotive beat wave provides momentum and phase kick to some background electrons which are then accelerated.

Esarey *et al.* [4] provides a theoretical description of CPI. A driver laser pulse, with normalized vector potential $a_0 \propto \sqrt{I}$, where $I$ is the laser intensity, drives a plasma wave. In the self-injection regime, very high wakefield amplitudes are generated leading to wavebreaking and self-injection of the background electrons. In this regime, injection and acceleration are coupled [30], limiting control of the accelerated electron bunch. In CPI experiments the self-trapping threshold is not reached and a collider beam is used to move background electrons from fluid orbits to trapped orbits. When the collider beam intersects the driver beam their interference creates a zero phase velocity laser beat wave whose ponderomotive force $F_{bw} \propto a_0 a_1$ can accelerate a fraction of the plasma electrons such that they become trapped in the wakefield. In this paper, the driver was focused to a 4.4 $\mu$m focal spot ($1/e^2$ intensity radius) which gave a peak intensity of $3 \times 10^{19}$ W/cm$^2$ and $a_0 = 3.75$. The collider beam energy had a focal spot of 5.7 $\mu$m ($1/e^2$ intensity radius), and its energy was lowered down to $\sim 0.1$ J, which gave $a_1 \simeq 1$.

## EXPERIMENTAL RESULTS

Experimental parameters were chosen so that, when the driver was fired alone, no electron beam was produced. To operate below self-injection threshold, the plasma density was set below $5 \times 10^{18}$ $e^-$/cm$^3$. Prior to lowering the plasma density, by varying the backing pressure of the gas jet, the longitudinal position of the gas jet was adjusted so that the focus of the driver beam lay on the upstream edge of the density plateau where, at higher pressures, self-injection was maximum.

By scanning the arrival time of the collider beam, one could scan the location of the beat wave in phase space. As the collider timing was scanned, the injection was successively turned on and off as illustrated in Fig. 2. The experiments show the expected timing signature as the collider timing was scanned with respect to the drive beam. The experiments also showed dependence of injection on density reasonably consistent with simulations. Colliding pulse experiments were conducted and have demonstrated reproducible injection of electron beams using the colliding pulses, so far at low energies (Fig. 3).

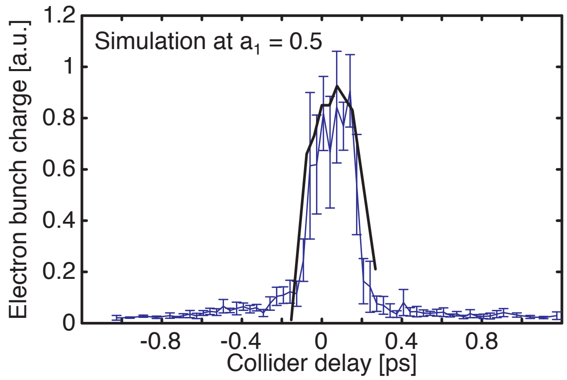


**FIGURE 2.** Timing scan of the collider beam ($a_1 \simeq 1$) arrival time relative to the driver beam ($a_0 \simeq 3.5$). The timing window is consistent with simulations ($a_1 \simeq 0.5$). At overlap, charge stability is $\simeq 20\%$.

A possible explanation for this low energy electron spectra is the combination of a short ($\simeq 75\ \mu$m) defocusing length of the driver beam, and the non-uniformity of the plasma density profile, with a $\sim 25\%$ rise from the upstream to the downstream edge of the profile, which would prematurely stop the injection. Future experiments will include guiding [12] of the driver beam to increase the acceleration length of colliding pulse injected beams. Recently, in the self-trapping regime, firing the driver beam alone, 90-MeV electron beams were generated by guiding the driver, with a pre-ionizing igniter laser pulse, over many Rayleigh length ($\simeq 1.6$ mm), similar to [12]. Combined with CPI, 2–400 MeV beams of several pico-coulombs of charge and narrow energy spread should be anticipated based on simulations.

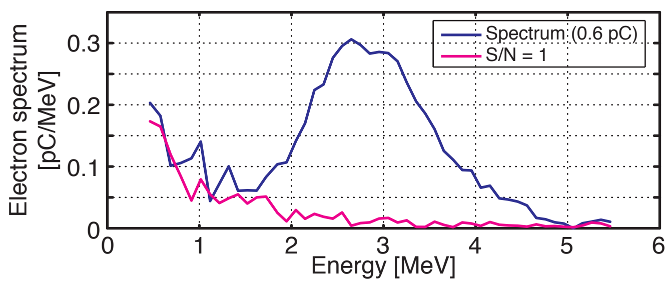


**FIGURE 3.** Example of colliding pulse injection produced electron beam distribution. The total charge in the beam, at the dipole magnetic spectrometer, is 0.6 pC.

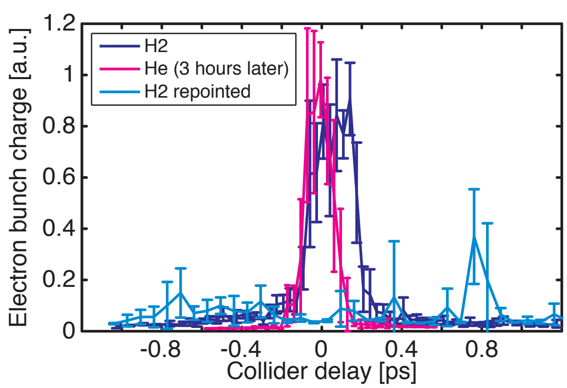


**FIGURE 4.** Three timing scans of the collider beam arrival time relative to the driver beam. The first and third curves show the importance of having an active beam pointing system. Using active beam pointing, the first and second curves, conducted using respectively Hydrogen and Helium gas, show a good stability of the timing window over several hours.

Because CPI experiments rely on the spatiotemporal overlap of the colliding beams, an active beam pointing system was developed in order to provide amplifier and target pointing stability, and consequently stability of electron beam properties. Relative arrival time and focus positions of the two beams were measured using a conventional folded-wave interferometer [31], also used to measure the density profile of the plasma. Few micron on-target stability was achieved, with less than 50 fs timing drift over an hour, and $\sim 100$ fs over 8 hours. To illustrate this stability, Fig. 4 shows two timing scans, one using Hydrogen gas and the other using Helium gas, which were conducted 3 hours from each other. Because of differences between the two gases, timing windows differed from each other but the overlap stayed identical, and both cases showed an *r.m.s.* charge stability of $\simeq 20\%$. Finally, Fig. 4 displays a case, using Hydrogen gas, where the collider beam had been purposely detuned to show correlation between charge, timing overlap and laser pointing.

In addition to the timing scans, both pressure and collider strength ($a_1$) were scanned, and in both cases results were consistent with simulations. In Hydrogen, colliding pulse injection occurred turned on at about $2 \times 10^{18}$ $e^-/\mathrm{cm}^3$ and turned off about $5 \times 10^{18}$ $e^-/\mathrm{cm}^3$, before self-trapping mechanisms started to produce low energy, broad-band, high charge electron beams. While scanning the collider beam intensity, injection reached a plateau for $a_1 > 0.9$ as predicted by simulations, with high charge, low energy electron beams.

## CONCLUSION

In conclusion, the successful implementation of an active beam pointing system lead to the production of stable ($\simeq 20\%$ *r.m.s.* charge stability) electron beams in the colliding pulse injection scheme. Timing scans in both Hydrogen and Helium were performed, showing consistent timing window with two-dimensional PIC simulations. Pressure and collider beam intensity were scanned as well, showing CPI occurring for plasma densities below $5 \times 10^{18}$ $e^-/\mathrm{cm}^3$, with a driver strength of $a_0 = 3.75$. Injection reached a plateau as simulations predicted for $a_1 > 0.9$. Future experiments will focus on guiding the driver laser pulse over several Rayleigh lengths at the low densities CPI needs to operate at, and the production of stable, high-energy electron beams.

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