COLLIDING PULSE INJECTION EXPERIMENTS IN NON-COLLINEAR GEOMETRY FOR CONTROLLED LASER PLASMA WAKEFIELD ACCELERATION OF ELECTRONS*

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Abstract

An optical injection scheme for a laser-plasma based accelerator which employs a non-collinear counterpropagating laser beam to push background electrons in the focusing and acceleration phase via ponderomotive beat with the trailing part of the wakefield driver pulse is discussed. Preliminary experiments were preformed using a drive beam of $a_0 \simeq 2.6$ and colliding beam of $a_1 \simeq 0.8$ both focused on the middle of a 200 μm slit jet backed with 20 bar, which provided $\simeq$ 250 μm long gas plume. The enhancement in the total charge by the colliding pulse was observed with sharp dependence on the delay time of the colliding beam. Enhancement of the neutron yield was also measured, which suggests a generation of electrons above 10 MeV.

INTRODUCTION

Plasma based electron accelerators [1] have succeeded in producing a few orders larger acceleration gradient (up to several hundred GV/m) [2] than RF-structure based accelerators, which have several hundred MV/m maximum gradient due to the material breakdown. Such large gradients make this new concept attractive as the basis for next generation accelerators. The resultant dense and ultrashort beams [3] may also provide unique light sources with high maximum brightness. A significant breakthrough has been made recently in the generation of the monoenergetic ($\simeq$ 10%) electron beams rather than beams with 100 % energy spread, by extending propagation length of the intense laser pulse (up to 1×10^{19} W/cm^2) by either using a preformed plasma channel [4] or larger F number optics [5] to increase the diffraction range $Z_R = \pi w_0^2/\lambda$ with w_0 being the spot size. The generation of high quality beams (i.e., with low energy spread and low emittance) is important for future plasma based accelerators and for applications.

In any particle accelerator, particle injection into the accelerating structure is a key technology. In all current laser-plasma based accelerators, the electron injection relies on passive physics such as wave breaking [6] or Raman-type instabilities [7] while RF based accelerators use external electron guns synchronized with accelerating field [8]. Taking full control of the injection or trapping process is necessary to produce a high quality beam in a reproducible manner. Electron injection into the accelerating field of the plasma wave, however, is challenging using conventional RF technology, since the characteristic scale length of the wake field in a plasma-based accelerator is the plasma wave length λ_p (typically $\leq$ 100 μm), i.e., much shorter than in conventional RF accelerators. In addition, the femtosecond synchronization between the injection process and the phase of accelerating field is required to achieve good pulse-to-pulse energy stability, which is beyond the performance of current accelerator technology.

In order to perform such highly precise injection, jitter-free all-optical schemes have been proposed [9, 10] which rely on laser trigged injection of background plasma electrons into a plasma wakefield. The colliding pulse injection (CPI) scheme [10] relies on the ponderomotive force associated with the beating of two lasers to inject electrons into the plasma wave. This CPI method requires lower laser intensity to inject, compared to the LILAC scheme [9] which uses the ponderomotive force associated with the laser envelope. Recently, controlled injection by using a two-pulse collinear scheme was reported [11], where $\simeq$ 100 MeV - 20 pC beams with $\simeq$ 10% energy spread (FWHM) were observed. In this paper, we consider a two-pulse CPI scheme with non-collinear configuration to achieve even higher quality beams. In this geometry, the drive beam intersects a second laser pulse (the colliding pulse) at an angle. This has several important advantages and was the first colliding pulse scheme that had been implemented [12, 13]. Firstly, the injection laser does not disturb the plasma acceleration structure prepared by the main driver beam. Secondly, the non-collinear scheme eliminates the risk that injection laser beam propagates back upstream into the amplifier, then damages the optics. Thirdly, no optics are on the electron beam line, avoiding emittance degradation. However, the non-collinear method is more challenging as overlap in space and time needs to be achieved within micrometer and femtosecond precision, respectively. Here, preliminary experimental results are presented and discussed.

EXPERIMENTS

The experiments described in this paper were performed with the 10 Hz multi-arm Ti:Al$_2$O$_3$ CPA laser system of the LOASIS facility at the Lawrence Berkeley National

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Laboratory [14]. Originated from an oscillator (of wavelength $\lambda \simeq 800$ nm), low energy laser pulses were first temporally stretched, then split into three beam lines. The first was amplified up to 1 J/pulse level before compression and used for driving a plasma wave (Driver). The second beam was amplified up to 0.2 J/pulse and used as counter-propagating pulse to trigger injection (Collider), and the third beam was frequency-doubled and used for the plasma diagnostics. A schematic of the experimental configuration is shown in Fig. 1. In previous experiments charge enhancement of the amount of injected electron by the collider beam was observed [12], where the ratio of the enhanced beam (signal) and self-trapped beam by the Driver (noise) was $\simeq 1$. In order to enhance this signal-to-noise ratio, a shorter plasma plume was employed by using a slit nozzle (4 mm x 200 μm) in transverse orientation, which was backed with up to 70 bar of Hydrogen. The Driver beam was compressed to 42 fs and focused to a spot size $r_{0,D} = 6.2$ μm with an $f/4$ off-axis parabolic mirror (OAP0), and the Collider was also compressed to 42 fs and focused to $r_{0,C} = 9.5$ μm with an $f/6$ off-axis parabolic mirror (OAP1). The Collider beam intersected with the Driver from the downstream direction at an 18-degree angle from head-on.

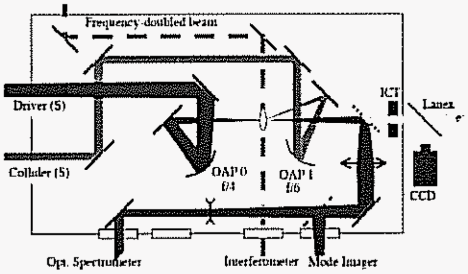

Figure 1: Schematic of the experimental setup. Driver (<500 mJ, >40 fs) and Collider (<100 mJ, >40 fs) beams were focused with 18 degree intersect angle using off-axis parabolic mirrors (OAP0, OAP1) to spot sizes of $r_{0,D} \simeq 6$ μm and $r_{0,C} \simeq 9$ μm onto a high pressure pulsed gas jet operating with up to 70 bar Hydrogen backing pressure. An integrating current transformer (ICT) was used to measure the charge per bunch of the electron beam, and plasma densities were measured with the interferometer. The spatial profile of electron beam as well as the beam charge were monitored by the CCD camera imaging onto a phosphor screen (Lanex).

The two-pulse CPI experiments were performed with both Driver and Collider beams focused onto the middle of the 200 μm long supersonic hydrogen gas jet, backed with 20 bar. The plasma density profile was measured by the side-on interferometry of the folded-wave type, using a frequency-doubled 50 fs duration laser pulse, and the peak plasma density was $5.5 \times 10^{18}/\text{cm}^3$. The interferometer was also used for temporal (z or t: 100 fs resolution) and spatial (y: 5 μm resolution) alignment of the two laser beams. Horizontal alignment (x: 20 μm resolution) was performed using plasma recombination radiation from the top view of the interaction point. This diagnostic was also used to overlap foci by aligning the dumbbell-shape plasmas in a Nitrogen back-filled chamber ($\simeq 4$ mbar). The relativistic laser intensity parameters for the Driver and Collider beams were $a_0 = 2.6$ and $a_1 = 0.8$, respectively. The laser intensities and the plasma density were scanned to optimize the amount of injected electrons by the Collider beam. The electron beam properties were measured by an integrating current transformer (ICT) for the total charge of the beam, a combination of the phosphor screen (Lanex fast, Kodak) and CCD camera for the charge and spatial profile of the beam (beam phosphor screen, BPS [15]), and gamma-ray and neutron detectors as a rough measure of electron energy. Note that the ICT had the collection angle of ±130 mrad while BPS had ±50 mrad against an electron beam.

Measured electron charge on the BPS against the timing delay of Collider is shown in Fig. 2(a) with simultaneously measured neutron yields (b). One can see the enhancement of the acquired charge by the colliding laser beam at -500 fs of the timing delay as well as enhanced neutron yield, which suggest the generation of electrons above 10 MeV [16]. However, the obvious enhancement in total charge was not measured through the ICT, which showed charge of 300 pC during the whole scan of the Collider timing delay. This may be because the electron beam from self modulated laser wakefield accelerator (sm-LWFA) has an energy dependence in the spatial profile, with low energy electrons having larger divergence than high energy ones [16]. As already shown, the ICT had a larger collection angle and so could collect more the low-energy, large-divergence electrons (dark current), than the BPS. Therefore, the enhancement due to injection was within the fluctuation of the ICT measurement (~10%). The BPS is more sensitive and only sees high energy, obvious enhancement of the total charge was not measured by the ICT in contrary to the BPS. Neutron signal implies ~10's pC of injected charge. The BPS observed only the well-collimated part of the beam which was responsible for the generation of the neutrons.

To increase the signal to noise ratio (i.e., CPI beam against self-trapped electrons), it is desirable to perform a dark current free injection. The Raman-type stability or wave-breaking might be responsible for the dark current in the experiments. As originally proposed [10], the CPI scheme is based on the standard regime, where the plasma wavelength $\lambda_p = 2\pi c/\omega_p$ is comparable to the laser length $c\tau_l$. In the standard regime, less Raman-type instability is expected. Therefore, lowering plasma density is an option for a low dark current injection system. Simply having a lower power for the Driver beam would help to reduce the injection from wave-breaking. Although, in either case, one has to pay a cost in the shortening acceleration length since those beam will not be self-guided. Using a pre-formed channel to extend interaction length would pro-

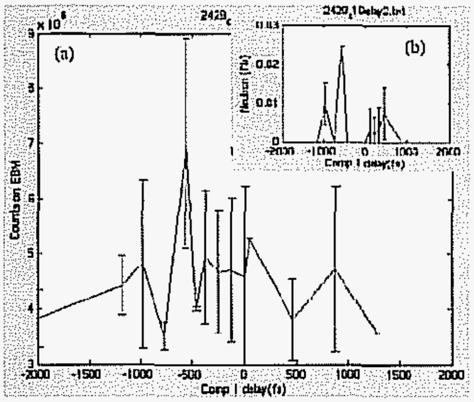

Figure 2: (a) Measured total charge by the beam phosphor screen (BPS), which consists of a phospor screen (Lanex fast, Kodak), and a CCD camera, against the timing delay of Collider beam. (b) Measured neutron yield against the timing delay of the Collider beam.

vide a dark current free accelerating structue [17]. The resonant drive pulse is expected to generate a wakefield inside the plasma channel without trapping significant amounts of background electrons [18]. The future experiments will pursue this scheme to realize dark current free injection for LWFA.

SUMMARY

We have discussed preliminary experiments on the two-pulse non-collinear colliding pulse injection method. Using a transversely orientated slit jet improved signal-to-noise (S/N) ratio so that the enhancement of injected charge and its dependence on Collider time delay could be observed [12]. Employing a Driver beam of $a_0 = 2.6$ and a counterpropagating Collider beam of $a_1 = 0.8$ intersected at an 18 degree angle, enhancement of the electron injection by 10's of pC as well as enhancement of the neutron yield were observed.

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