EXPERIMENTAL PROGRESS ON STAGED LASER-PLASMA ACCELERATION*

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Abstract

Recent progress on a staged laser-plasma accelerator (LPA) experiment is reported. The experiment utilizes a 40 TW class laser which is split into two pulses. The first laser drives the first LPA stage to produce an electron beam. The second laser drives the second LPA stage in a dark-current free regime and accelerates the electron beam from the first LPA. Injection from the first stage, triggering of plasma mirror and reflection of the second laser, and laser guiding in the second stage have been demonstrated. Optical spectral redshift of driving laser has been analyzed to estimate the wakefield amplitude and electron energy gain in the second stage.

INTRODUCTION

Laser-plasma accelerators (LPAs) have demonstrated accelerating gradients thousands of times greater than those of conventional accelerators [1]. Employing a capillary discharge waveguide, a high-quality GeV electron beam (e-beam) has been produced within a few centimeters, demonstrating that LPAs have great potential for reducing accelerator size and cost.

For applications such as high energy colliders, LPA designs will rely on sequencing multiple acceleration stages, each driven by its own laser [2, 3]. Limitations to the energy gain in a single stage include diffraction, dephasing, and pump depletion. Using a capillary waveguide to create a preformed plasma channel, laser pulses have been guided over many Rayleigh lengths ($z_{\rm R}$), minimizing diffraction and extending the accelerating length. If the laser is guided, and the e-beam dephasing controlled, energy gain is limited by depletion. To overcome pump depletion, staged acceleration is necessary to supply fresh laser pulses. Experiments performed so far utilize a single laser that drives the wakefield for both injection and acceleration. The on-going staging experiment at the LOASIS Program at Lawrence Berkeley National Laboratory will demonstrate driving of two modules with two independent laser pulses and coupling of the e-beam between them. Staged acceleration not only supplies fresh laser pulses to LPAs but it also allows independent control of electron injection and acceleration.

Experimental demonstration of staged LPAs requires understanding electron injection, performance of a plasma mirror (PM), and acceleration of externally injected e-beams. Controlled electron injection is an active area of research and various techniques such as self-trapping, density gradient, and ionization injections have been demonstrated [4, 5, 6, 7]. The PM is triggered when the leading edge of the pulse generates plasma on a solid target, reflecting the remainder of the pulse at the critical surface. The second laser pulse is coupled in to the acceleration beam line using the PM to keep the LPA compact [8]. Post-acceleration of e-beams requires understanding the amplitudes of wakefileds in the second stage. Laser spectra are analyzed as a diagnostic of plasma waves.

This paper reports the recent progress of the staged acceleration experiment at the LOASIS Program. Basic theory of laser propagation and redsfhit are presented to support the use of redshift as a wakefield diagnostic. Then, the experimental setup at the LOASIS Program is described. Initial results for electron injection, plasma mirror in-coupling and wake excitation performed independently of each other are presented in the results section followed by a concluding summary.

LASER PROPAGATION IN A PLASMA CHANNEL

Laser guiding is used to extend acceleration lengths in LPAs. However, accelerating fields, and hence redshifting of the laser, evolve differently depending on the guiding condition. In a capillary waveguide, the laser pulse transverse size can oscillate if the density profile is not matched to the laser spot size. The channel is characterized by a parabolic plasma density profile, $n(r) = n_0 + \Delta n r^2/r_{\rm m}^2$, where r is the radial position, n_0 is the on-axis density [9], and Δn is the channel depth at a matched spot size, $r_{\rm m}$ [10]. Such channels can provide guiding for a laser pulse with a Gaussian intensity profile, $|a|^2 = (a_0 r_0/r_{\rm s})^2 \exp(-2r^2/r_{\rm s}^2)$, where a_0 is the normalized laser vector potential given by $a_0^2 \simeq 7.3 \times 10^{-19}\ (\lambda[\mu{\rm m}])^2 I_0[{\rm Wcm}^{-2}]$, r_0 is the focal spot size, $r_{\rm s}$ is the spot size, and λ is the laser wavelength. Perfect guiding is achieved when $r_0 = r_{\rm m}$ and the laser is focused at the entrance of the channel ($r_{\rm i} = r_0$, ${\rm d}r_{\rm s}/{\rm d}z = 0$). Considering a low power pulse (without self-focusing), the laser pulse propagates in the channel according to

$$r_{\rm s}^2 = \frac{r_{\rm i}^2}{2}\left[1 + \frac{r_{\rm m}^4}{r_{\rm i}^4} + \left(1 - \frac{r_{\rm m}^4}{r_{\rm i}^4}\right)\cos\left(\frac{2\lambda z}{\pi r_{\rm m}^2}\right)\right], \quad (1)$$

where $r_{\rm i}$ is the spot size at the entrance of channel, and z is the propagation distance [10]. Examples of matched and mismatched guiding are shown in Fig. 1. The entrance of the capillary is set at $z = 0$, and the plasma channel is indicated with a cyan box. For matched guiding,

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$r_\mathrm{i} = r_\mathrm{m} = 18\ \mu\mathrm{m}$, the laser retains its spot size as it propagates through the channel. For mismatched guiding with r_i = 18 μm and r_m = 41 μm, the transverse spot size oscillates between r_i and $r_\mathrm{m}^2/r_\mathrm{i}$. The mismatched guiding leads to excitation of significant plasma waves only at localized regions of high intensity, creating an accelerating gradient that depends on the propagation distance. While

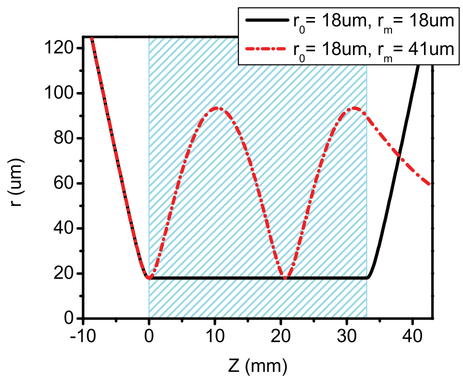

Figure 1: Laser spot size as a function of z.

matched guiding allows the most efficient coupling of laser energy to plasma waves, experimental conditions do not always allow the matched condition.

When the laser excites plasma waves, the laser energy is transferred to the wakefield and spectrally redshifts. In one-dimension, the evolution of the laser energy normalized to initial energy, ϵ, of a short laser pulse propagating in an underdense plasma is related to the amplitude of the wakefield as [11]:

$$\frac{\partial \epsilon}{\partial \omega_\mathrm{p} t} = -\frac{k_\mathrm{p}^2}{k_0^2}\left(\frac{E_\mathrm{max}}{E_0}\right)^2, \qquad (2)$$

where k_p is the plasma wavenumber, k_0 is the central wavenumber of the input laser, ω_p is the plasma frequency, and E_max/E_0 is the maximum accelerating field normalized by the cold nonrelativistic wave breaking field. In addition, the mean wavenumber $\bar{k} = \varepsilon/A$ where A is the wave action, which is constant provided $\bar{k}/k_\mathrm{p} \gg 1$. Therefore, E_max can be estimated through the redshift of optical spectra.

In experiments, the estimation of E_max is much more complex due to the transverse and longitudinal dynamics of the laser pulse. Particle-in-cell (PIC) simulations using INF&RNO were performed to study wake excitation and its relation to spectral redshifting [12]. INF&RNO is a two-dimensional cylindrical (r-z) code that adopts an envelope model for the laser pulse. Details are found in [12]. The laser pulse was focused 4.8 mm into the capillary with vacuum focus of r_0 = 18 μm and the channel was 33 mm long, r_m = 41 μm and $n_0 \sim 1.5 \times 10^{18}\mathrm{cm}^{-3}$. Figure 2 shows simulated peak accelerating field E_max (solid black curve), normalized laser energy ε (dashed black curve) and mean wavenumber $\bar{k}$ (red dots) as functions of z. Since the guiding condition is mismatched, the laser intensity oscillates. There are two regions where the laser is strongly focused to excite a large plasma wave. The ε evolution shows that the majority of laser energy is deposited at locations of large wakefield and $\bar{k}$ tracks the ε. Even with mismatched guiding, one can gain insights into E_max by comparing simulated and measured spectra [13].

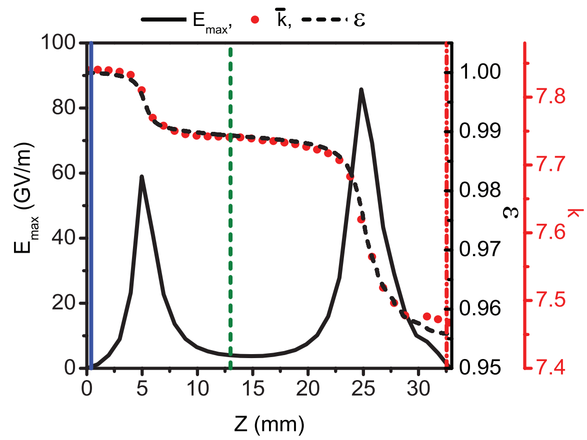

Figure 2: Simulated E_max, ε and $\bar{k}$ as a function of z.

EXPERIMENTAL SETUP

The staged acceleration experiment is on-going at the LOASIS Program and is performed using a 40 TW class Ti:sapphire laser system. A schematic of the experiment is shown in Fig. 3. A laser pulse is split into two pulses.

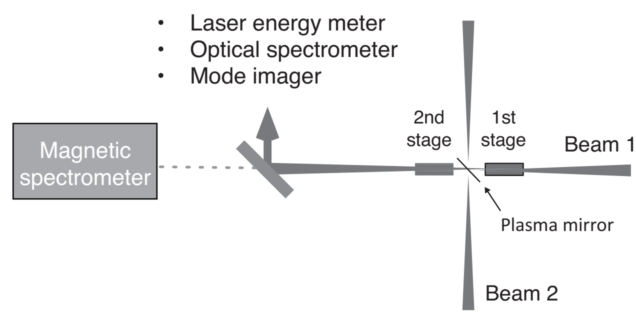

Figure 3: A schematic of the experiment.

Beam 1 drives the first stage to produce e-beams and Beam 2 reflects off the PM and drives the second stage for post-acceleration. Both laser pulses are focused on the entrance of capillary discharge waveguides [14, 15] by off-axis parabolic mirrors used at f/20. Focal spot sizes are $r_0 \simeq 20\ \mu$m. Injection in the first stage was performed with a pulse duration of 67 fs at full width at half maximum (FWHM), resulting in $a_0 \sim 0.9$. Beam 2 underwent a modulation in the splitting optic which lengthened the pulse duration to 130 fs for the initial experiments. Fluence of the Beam 2 impinging on PM was $\sim$ 500 J/cm^2 and excited plasma waves at $a_0 \sim 0.4$. The coupling distance between the two capillaries is $2-3$ cm. Preliminary experiments on electron injection, the plasma mirror reflectivity, and wake

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excitation performed independently of each other will be discussed.

Each LPA module used a capillary waveguide to guide the lasers. The capillaries were 33 mm long and 250 μm in diameter. For the injection experiment, various gases such as hydrogen, helium, and a mixture of nitrogen and helium were studied along with tailored plasma density. For the wake excitation experiment, hydrogen gas was used to optimize the guiding condition. A high voltage discharge ionized the gas and formed plasma $\sim$ 200 ns before the arrival of the laser. The plasma evolved from hydrodynamic motion and formed a plasma channel. The on-axis plasma densities for both experiments were $\sim 3 \times 10^{18}$ cm^3 and $r_{\rm m} \sim 35$ μm based on a scaling law derived from the simulation in [16]. Requirements for the plasma mirror were high reflectivity and good reflected mode [17]. The tape drive based plasma mirror was characterized, and the reflected laser was guided through the second stage.

RESULTS

For the injector study (1st stage), e-beams were produced by ionization of nitrogen atoms with tailored longitudinal plasma density channel. The averaged e-beam spectrum collected for 22 shots is shown in Fig. 4. The charge was 0.15 ± 0.13 pC, mean momentum 221 ± 22 MeV/c with $\sigma_p = 34 \pm 10$ MeV/c. The divergence was $\sigma_\theta = 1.4 \pm 0.2$ mrad. The fluctuation of the peak momentum was 14%. Optimizations to reduce the fluctuation in the e-beam peak energy are currently in progress.

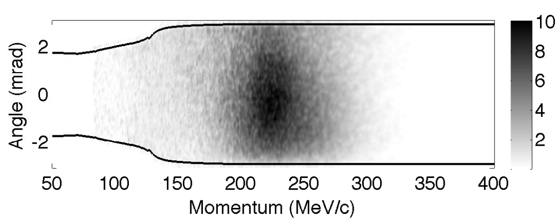

Figure 4: Averaged spectrum [nC/SR/(MeV/c)] of e-beams produced from the first stage.

The PM experiment showed fluence dependent reflective properties. When the fluence was lower than optimum, the PM triggered too late with respect to the arrival of the main pulse, transmitting a larger fraction of laser energy. When the fluence was higher than optimum, the plasma absorbed too much energy, resulting in a lower reflectivity as well as a poor surface quality. Optimum fluence of $\sim 300 - 500$ J/cm^2 resulted in 80% reflectivity and the reflected laser mode was as good as the input mode. This performance is believed to be sufficient for the experiment.

Laser beam 2 reflected off the PM and was coupled into the second stage. Optical spectra of the laser exiting the second stage is shown in Fig. 5 along with an input spectra. Based on a preliminary spectral analysis using simulations, the average accelerating field is $\sim$ 1 GV/m, and the energy gain of the e-beam would be $\sim 10 - 30$ MeV. Since the

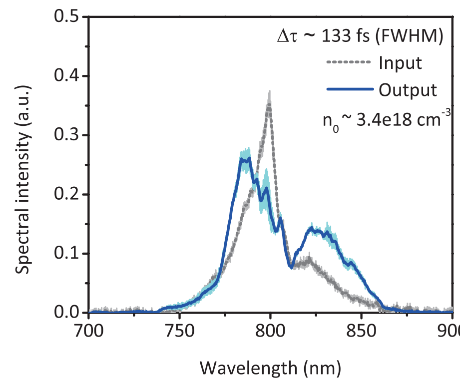

Figure 5: Input and output laser spectra guided through the second stage.

laser pulse duration was not optimized in the experiment shown here, various optimizations for wake excitation are in progress.

CONCLUSION

Recent progress of staged LPA was reported. Electron injection, plasma mirror in-coupling, and wake excitation in the acceleration stage were demonstrated independently of each other. Along with the experiments, the analysis of optical spectra to estimate energy gain from the acceleration stage was discussed. Optimizations to improve e-beam stability and efficiency of wakefield excitations are in progress.

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