ACCURATE ALIGNMENT OF PLASMA CHANNELS BASED ON LASER CENTROID OSCILLATIONS*

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Abstract

A technique has been developed to accurately align a laser beam through a plasma channel by minimizing the shift in laser centroid and angle at the channel outptut. If only the shift in centroid or angle is measured, then accurate alignment is provided by minimizing laser centroid motion at the channel exit as the channel properties are scanned. The improvement in alignment accuracy provided by this technique is important for minimizing electron beam pointing errors in laser plasma accelerators.

INTRODUCTION

Laser-driven plasma accelerators [1] have shown acceleration gradients orders of magnitude higher than those found in conventional accelerators, offering the potential for a significant reduction in accelerator length and cost. Recent progress, such as the production of high-quality GeV electron beams in just a few cm [2] has increased interest in laser-plasma accelerator technology as a driver for radiation sources – ranging from coherent THz to free electron laser (FEL) x-ray sources and Thomson scattering gamma ray sources – and as a path towards a TeV-class linear collider [3, 4].

For both radiation source and high energy physics applications, precise control over electron beam pointing is essential. Current state-of-the-art laser plasma accelerators (LPAs) have rms pointing fluctuation at or below the $1\,\mathrm{mrad}$ level. Although this is tolerable for some applications, it is at least one order of magnitude larger than deemed necessary for light source or staging applications.

Laser pointing errors are one potential source of electron beam pointing errors that must be controlled (others include laser mode asymmetry, pulse-front tilt [5], and plasma gradients). Fluctuations in laser pointing cause the laser centroid to be offset from the plasma channel and to undergo transverse oscillations about the channel axis. Electrons accelerated by the plasma wakefield will then undergo betatron oscillations centered on the trajectory of the laser provided the electron energy is sufficiently low [6], and the electron beam will exit the plasma in the laser beam direction. In this way laser centroid oscillations can result in large exit angles of both the laser and electron beams. For the parameters presented here, $\mu\mathrm{rad}$ jitter in laser pointing (typical of current laser systems) at the input of the waveguide can cause mrad deviations in the laser electron beam pointing.

In this paper, the centroid location of low-intensity ($< 10^{14}\,\mathrm{Wcm^{-2}}$) laser pulses at the output of a plasma channel is used to achieve accurate alignment. Whereas laser pulses of intensity $> 10^{18}\,\mathrm{Wcm^{-2}}$ are used for laser plasma acceleration, the intensity was kept low in these experiments so that ionization-induced diffraction and nonlinear effects such as self-focusing, wake formation, and hosing could be neglected. The method provides increased precision in channel alignment to improve laser guiding and minimize pointing errors in LPA applications.

LASER PROPAGATION IN A PLASMA CHANNEL

A laser pulse initially offset from a plasma channel will undergo oscillations about the channel axis that depend only on the density profile. Consider a parabolic density profile of the form $n(x) = n_0 + 0.5br^2$, where n_0 is the on-axis density and b is the second derivative of the electron density. The matched spot size of the channel is defined as $r_\mathrm{m} = (0.5\pi r_\mathrm{e} b)^{-1/4}$, where r_e is the classical electron radius. For low intensity where non-linear effects can be neglected, the evolution of the centroid (x_c) of a short laser pulse with initial transverse offset x_ci and injection angle θ_i is

$$x_\mathrm{c} = x_\mathrm{i} \cos\left[(k_{\beta\mathrm{c}} z) - \varphi\right], \tag{1}$$

where the initial phase and oscillation amplitude are $\varphi = \arccos(x_\mathrm{ci}/x_\mathrm{i})$ and $x_\mathrm{i} = [x_\mathrm{ci}^2 + \theta_\mathrm{i}^2 k_{\beta\mathrm{c}}^{-2}]^{1/2}$ [7]. Here $k_{\beta\mathrm{c}} = \lambda/(\pi r_\mathrm{m}^2)$ is the wavenumber of the laser centroid oscillation about the plasma channel axis, where λ is the laser wavelength. The period of the centroid oscillation depends only on the depth of the plasma channel.

Figure 1 shows the laser offset normalized by input offset $x_\mathrm{c}/x_\mathrm{ci}$ (solid line) and the laser angle (dotted line) at the output of a plasma channel of length $15\,\mathrm{mm}$ as a function of r_m as calculated from Eq. (1) for $\theta_\mathrm{i} = 0$, $x_\mathrm{ci} = 10\,\mu\mathrm{m}$, and $r_\mathrm{i} = 80\,\mu\mathrm{m}$.

Accurate alignment of the laser beam to the plasma channel can be achieved by ensuring $\theta_\mathrm{c} = 0$ and $x_\mathrm{shift} = x_\mathrm{c} - x_\mathrm{ci} = 0$, since this means no oscillation occurred. If only x_shift is measured, as is common for many LPAs, then alignment can be achieved by varying the properties

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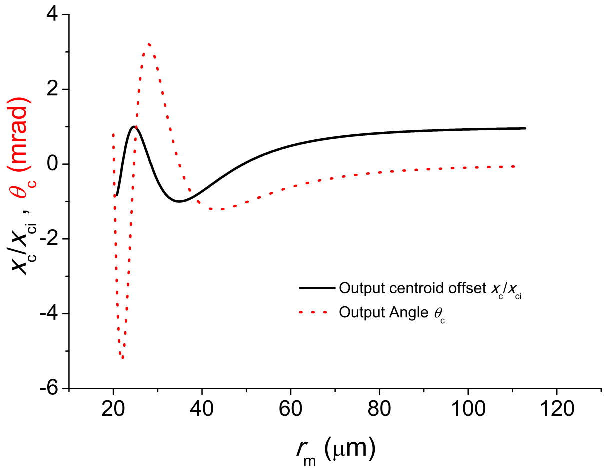

Figure 1: Laser beam parameters at the output of a plasma channel of length 15 mm as a function of matched spot size. Normalized laser centroid offset x_c/x_{ci} (solid line) and angle (dotted line) are shown for an input centroid offset of $x_{ci} = 10\,\mu m$, input injection angle $\theta_i = 0$, and $r_i = 80\,\mu m$.

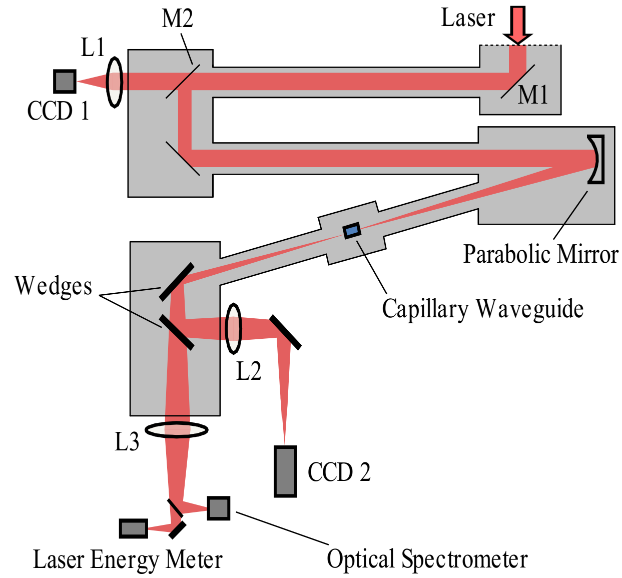

Figure 2: The experimental layout used for investigating laser beam propagation in a capillary waveguide. Laser pointing input to the capillary was measured by CCD 1.

of the plasma channel. One approach is to vary the length of the plasma channel and measure the centroid shift for constant laser and plasma conditions. This could be done in gas jet experiments with laser-produced channels, but is more difficult to achieve in the case of a capillary discharge waveguide. For capillary discharge waveguides an experimentally more straightforward method is to vary the delay t_{delay} between the onset of the plasma channel and arrival of the laser pulse, since this scans the matched spot size from infinity at long delays where there is no discharge current to finite sizes (i.e., scanning right to left in Fig. 1). Thus channel alignment can be accomplished in a straightforward way by scanning the discharge timing. For a properly aligned channel there will be no dependence of the centroid shift on t_{delay}.

EXPERIMENTAL SETUP AND RESULTS

The experimental layout is shown in Fig. 2. Low energy pulses (<5 mJ) from a Ti:sapphire laser system were focused onto the entrance of a hydrogen-filled capillary discharge waveguide by a 2 m focal length off-axis parabolic mirror. The hydrogen-filled capillary discharge waveguide has been described in detail elsewhere [8], along with its use for laser wakefield acceleration of electrons to energies up to 1 GeV [2].

An aperture 2 cm in diameter was used to increase the effective f-number of the focusing system compared to previous experiments [2], resulting in beams with a spot size of $r_i = 70\,\mu m$ at the capillary entrance. The large focal spot and resulting reduced diffraction allowed for the unguided beam to pass through the 15 mm-long and 300 μm-diameter capillary with minimal wall interaction. Thus the centroid location at the output of the capillary when there is no plasma channel ($r_m = \infty$) (i.e., when no current flows through the capillary) was the same as when the capillary was removed. The laser energy on target was 0.5 mJ, corresponding to a peak intensity of $5 \times 10^{13}\,\mathrm{Wcm^{-2}}$ for a pulse length of 120 fs.

Hydrogen gas filled the capillary to a pressure of 46 Torr via slots located 0.5 mm from each end. Due to the hydrodynamic evolution of the plasma channel on the tens of nanosecond timescale, varying the delay time between arrival of the laser pulse and initiation of the discharge allowed various channel conditions to be explored. The on-axis density for delays after which a stable plasma channel is formed was calculated to be $1.4 \times 10^{18}\,\mathrm{cm^{-3}}$ using the scaling given in Ref. [8].

Laser radiation emerging from the capillary was attenuated by reflection off two optically flat glass wedges. The pulses were refocused by a lens of focal length 500 mm and diameter 100 mm, allowing for imaging of the output of the capillary onto a 12-bit CCD camera that measures the centroid location and spot size of the laser beam.

The laser centroid shift x_{shift} was determined by measuring the laser centroid at the output plane of the capillary without plasma channel. Precise alignment was then achieved by measuring the laser centroid location shift as a function of transverse capillary position x_{cap}. For any x_{cap}, the input offset x_{ci} can be calculated using $x_{ci} = x_{shift}(dx_{shift}/dx_{cap})^{-1}$, assuming $\theta_i = 0$. The capillary was displaced horizontally to create an offset of $x_{ci} = 30\,\mu m$ and example images of the output mode of the laser pulses at the capillary exit for different delays are shown in Fig. 3 (a-d). During the discharge, the laser centroid is shifted and the spot size reduced, consistent with the existence of a plasma channel.

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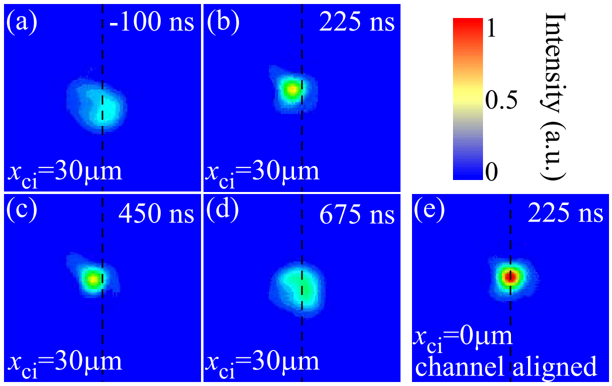

Figure 3: Typical laser modes at the output of the capillary as a function of discharge delay and input offset. The delay between the discharge and laser pulse and input offset is shown on each image. The dashed line represents the location of the beam with and without plasma channel. The centroid shift and spot size reduction is clear for delays during the discharge current with the misaligned capillary (a-d). For the aligned capillary (e), the spot size is reduced (guiding) but the centroid of the laser pulse is not altered.

When the capillary was translated to the aligned position ($x_{\rm ci} = 0$), the creation of the plasma channel (as evidenced by the spot size reduction) does not shift the laser centroid, as shown in Fig. 3 (e).

The alignment error is dominated by the accuracy of centroid determination, which was approximately $5\,\mu$m, limited by the level of magnification of the imaging system for the capillary output. This is significantly better than other techniques that rely on optimizing throughput or modal shape and typically allow for alignment precision to within $\sim 20\,\mu$m. With a higher magnification of the imaging system, it is expected that the alignment accuracy of the centroid motion based technique could be lowered to $\sim 1\,\mu$m. This improvement in accuracy of capillary alignment is expected to prove crucial for LPAs since a μm change in alignment can lead to a mrad change in electron beam pointing.

DISCUSSION

The laser centroid oscillation about a misaligned plasma channel axis was exploited to provide accurate alignment. This is not only important for optimizing laser guiding, but for minimizing electron beam pointing errors in LPAs since laser centroid motion can result in electron beam centroid motion. If the betatron wavelength of an injected electron beam is less than the laser centroid oscillation wavelength, which is the case for typical LPA parameters, then the electron beam will track the laser pulse and likewise undergo oscillations in the channel, exiting the plasma in the laser direction. Laser pointing jitter is therefore a mechanism for increasing electron beam pointing jitter in a channel-guided laser plasma accelerator and it might be expected that use of a waveguide would increase electron beam jitter. However, the lowest reported value for electron beam pointing jitter of $0.7\,$mrad rms was achieved through the use of a capillary waveguide [9]. Pointing jitter of $1.4\,$mrad rms has been achieved in a gas cell [10], which is several times lower than that typically observed in unguided experiments [11]. Other effects such as the stability and homogeneity of the plasma and laser profiles will need to be investigated to understand the differences in electron beam pointing jitter between the guided and unguided LPA experiments.

In the limit that the laser betatron oscillation wavenumber is greater than that of the electron beam, i.e., $k_{\beta c} > k_\beta$, the induced amplitude of the electron beam centroid oscillation is given by $x_c = (k_\beta/k_{\beta c})x_i$. This electron beam centroid oscillation may lead to emittance growth through phase mixing processes, provided the mixing length is less than the stage length. To keep the growth in emittance small, the ratio of x_c to the matched beam radius must be small, which is a restrictive constraint since the matched beam radius is typically small as a result of the strong focusing forces of the wake. Minimizing x_c requires minimizing k_β which can be achieved by decreasing the wake focusing forces in the linear regime through, for example shaping of the transverse laser mode [12]. For high energy electron beams coupled into subsequent LPA stages, the increase in betatron wavelength ($k_\beta \propto \gamma^{-1/2}$) reduces the impact of the laser beam centroid movement on the electron beam pointing and any emittance growth.

To minimize laser and electron beam pointing errors in LPAs, several other strategies can be followed. Laser beam pointing control will need to be improved to well below the μrad level to ensure that x_i is minimized. In addition, the plasma channel length should be tailored to allow for an integer number of betatron oscillations. This ensures that even in the presence of spatial offsets of the laser beam centroid, angular deflections at the exit of the plasma channel will be near or at zero value.

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