Investigations of Optical Guiding through Hydrodynamic Optical-Field Ionised Plasma Channels

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Abstract

Long, low-density plasma channels can be generated by Hydrodynamic Optical-Field-Ionisation (HOFI) and are capable of operating at kilohertz repetition rates, making them ideal waveguides for multi-GeV laser-plasma accelerators. In this report, the effects of spatial offset at the entrance of the channel are investigated. The pointing jitter of the Gemini South beam was measured to be 6 ± 2 μrad in LA3, corresponding to a transverse offset at the plasma channel entrance of 28 ± 3 μm. As the spatial offset increased, an increase in guided spot size and reduction of energy transmission of the F/40 pulse through the channel was observed. The plasma channel acceptance angle was found to be $\gamma_{acc} \approx 3.7$ μrad, which can inform future experiments of the same type.

1 Introduction

A significant goal for laser plasma accelerators (LPAs) is the development of a multi-GeV energy gain stage capable of operating at kilohertz repetition rates for extended periods [1, 2]. In a single LPA stage, the maximum achievable energy gain scales inversely with the electron density $W \propto 1/n_e$, and the required length of the stage varies as $L_{acc} \propto 1/n_e^{3/2}$. Thus, to attain multi-GeV electron energies in a single stage, low plasma densities ($n_e \sim 10^{17}$ cm^{-3}) and long acceleration lengths ($\sim$ 100 mm) are required. The laser interaction length is limited by diffraction to the distance over which the laser remains focused, which in the absence of a guiding structure is given by the Rayleigh range $z_R = \pi w_0^2/\lambda$ where w_0 and λ are the laser spot size and wavelength respectively.

In order to extend the interaction length of the laser with the plasma to distances comparable to L_{acc}, diffraction of the laser pulse must be mitigated. This can be achieved with a preformed plasma channel. In such a channel, the generated electron density profile acts as a waveguide, overcoming diffraction [2, 3, 4]. For an electron density profile of the form $n_e(r) = n_{e0} + r^2/(\pi r_e w_m^4)$ where n_{e0} is the on-axis electron density, r_e is the classical electron radius, and w_m is the matched spot size of the channel, a Gaussian laser pulse with spot size $w_0 = w_m$ will propagate with constant spot size through the channel. Alternatively, if the power of the laser pulse is large enough, the laser pulse can be self-guided in the plasma, however wakefields driven in this regime are highly non-linear, leading to reduced control over the accelerated bunch parameters. While this has been successfully exploited at the Gemini facility to accelerate electrons to $\sim$ 2 GeV [5], laser pulse guiding in a preformed channel offers greater total electron energy gain and increased control over the wakefield and electron bunch parameters [2].

We recently proposed and demonstrated a new approach to plasma channel formation — hydrodynamic optical-field-ionisation (HOFI) [6, 7]. A column of plasma is formed and heated by an initial laser pulse, and rapid expansion of the plasma drives a radial shockwave outward, generating plasma channels suitable for guiding. Since HOFI channels are free-standing, with no physical structure, they are well suited to kilohertz repetition rates. Unlike previous work which employed collisional ionisation and heating [4], optical-field-ionisation (OFI) is independent of the initial plasma density enabling generation of low-density plasma channels.

A proof-of-principle experiment on the Astra-Gemini TA2 laser demonstrated generation of low-density, 16 mm long HOFI plasma channels [7]. In this report, we describe a recent experiment undertaken at the Gemini TA3 facility in which we aimed to form 100 mm, $n_{e0} \leq 1 \times 10^{17}$ cm^{-3} plasma channels suitable for multi-GeV LPAs. We outline the generation of such plasma channels on the Gemini laser, and examine the effect of pointing jitter and drift on the guided beam.

2 Long Channel Formation

Axicons are well suited to generating long, uniform plasma channels since they generate line foci with a longitudinal, and hence travelling wave, geometry.

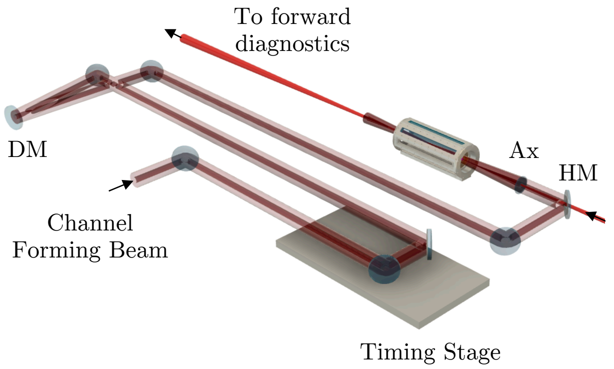

Figure 1: Interaction point setup in TA3. The channel-forming is reflected by a deformable mirror (DM), is coupled into the interaction line by a holed mirror (HM) and focussed into the gas cell by an axicon lens (Ax). The F/40 pulse is focussed to the entrance of the 100 mm gas cell containing hydrogen gas, and guided by the plasma channel to the exit.

Rays passing through the conical surface will be refracted towards the optical axis at approach angle $\alpha = \arcsin(\eta \sin\gamma) - \gamma$, where η and γ are the refractive index and cone base angle of the axicon respectively.

For an incident beam with a top-hat transverse intensity profile I_0, and axicon with approach angle α, the focal intensity profile is described by

$$I(r,z) = \frac{4\pi^2}{\lambda} z I_0 \alpha^2 J_0^2\left(\frac{2\pi}{\lambda}\alpha r\right), \qquad (1)$$

where J_0 is a Bessel function of the first kind. Importantly, although the intensity scales linearly with z, the transverse intensity profile has a constant shape.

Approximately 4% of the Gemini South beam was transmitted through a holed mirror ($D_{hole} = 50$ mm) upon entrance to the target chamber to create the channel-forming beam. This was reflected off a deformable mirror (DM) to flatten the wavefront as shown in figure 1. The beam then passed through a delay stage to allow for adjustment between the arrival of the channel-forming and guided pulse, and a quarter waveplate to circularly polarise the light [6]. It was then reflected off a second holed mirror (HM, $D_{hole} = 9$ mm) and focused into a gas cell containing hydrogen by a fused silica axicon lens (Ax), $\alpha = 2.5°$ as shown in figure 1(a). The radius of the first intensity minima, which sets the initial plasma column size, was 7.0 μm.

Plasma channel formation relies on a high-quality line focus which in turn relies on uniform intensity and wavefront across the surface of the axicon. The wavefront was measured by imaging the near field of the channel-forming beam at the surface of the deformable mirror onto a Shack-Hartmann wavefront sensor. These were used in closed loop to flatten the wavefront and optimise the focus.

Figure 2(a)-(c) shows the transverse and longitudinal

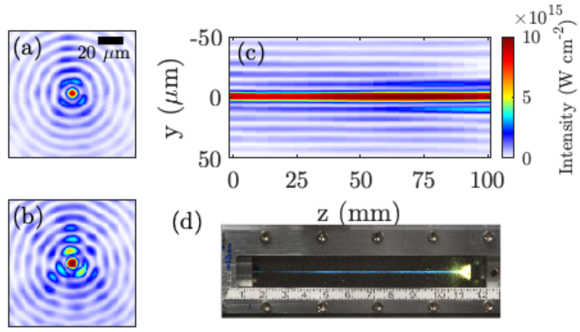

Figure 2: (a) Transverse intensity profile of the channel-forming beam at the start of the line focus. (b) Transverse intensity profile 100 mm downstream. (c) Horizontal slices of the measured transverse intensity taken at 5 mm intervals. (d) SLR image of a hydrogen plasma column ionised by the channel-forming beam.

intensity profiles of the channel-forming pulse measured by the in-chamber focus camera. It can be seen that these profiles match well to equation 1. Figure 2(d) shows a composite image of the hydrogen plasma channel formed in the gas cell. A $\sim$ 100 mm long, uniform column of hydrogen plasma can be seen. The apparent reduction of the intensity of the plasma column observed is attributed to blackening of the gas cell window, not to non-uniformity in the plasma channel.

3 Guiding Experiments

That part of the Gemini South beam which was not used for the channel forming beam was focused to the entrance of the gas cell by an off-axis parabolic mirror used at F/40 to form a focal spot of radius $w_0 = 38$ μm. The Rayleigh length was measured to be 4.6 mm, and the beam had peak intensity 6.1×10^{17} W cm^{-2}, corresponding to $a_0 = 0.54$.

Stability of the F/40 beam far-field was characterised by two separate diagnostics — a leak inside the South compressor in LA3, and by a focus camera inside TA3. The axicon line focus position and pointing was highly stable from shot-to-shot, the standard deviation was just 0.6 μm. For the F/40 beam, the standard deviation of the beam pointing was measured to be $\Delta\theta_{LA3} = 6 \pm 2$ μrad in LA3, compared to compared to $\Delta\theta_{TA3} = 5 \pm 1$ μrad (28 ± 3 μm spatially) in TA3. This indicated the pointing jitter was dominated by contributions from LA3 and earlier in the Gemini laser. As a result, a high proportion of shots were either spatially offset from the channel entrance, or had an angular misalignment with respect to the channel axis.

The exit plane of the plasma channel was imaged onto a CCD to measure the far-field fluence profile of the guided F/40 pulse. When the input F/40 was spatially offset from the axis of the plasma channel, the pulse was only partially guided. The guided spot size increased and

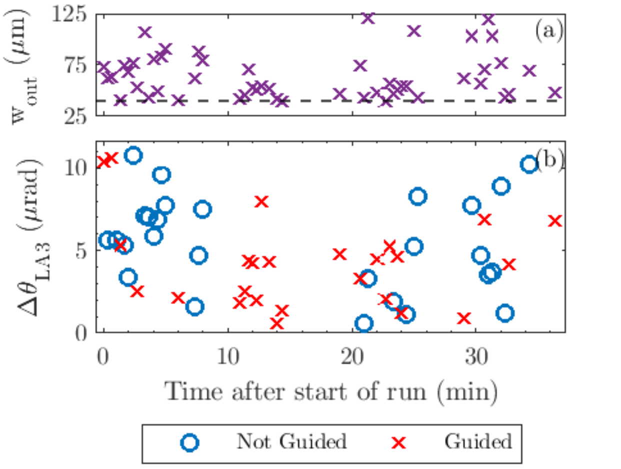

Figure 3: (a) Variation in the guided spot size w_{out}. (b) Graph showing how guiding quality is correlated with time and the LA3 leakage position for 50 consecutive shots.

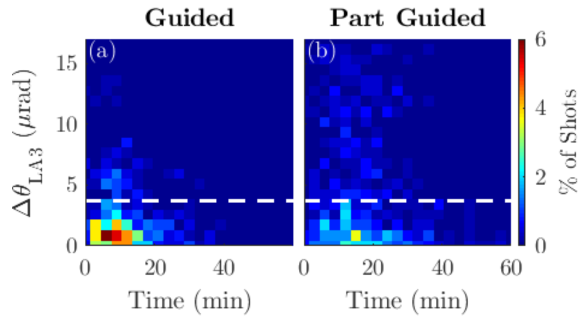

Figure 4: Histograms showing how the guided (a) and partially guided (b) shots were distributed with respect to the pointing jitter observed in LA3 (y-axis) and gradual spatial drift observed in both LA3 and TA3 (x-axis).

energy transmission reduced with increasing offset, consistent with previous findings [4]. At optimum alignment the pulse was well guided, and the lowest order mode of the channel was observed at the output [8]. When the input beam was offset from the axis of the channel, the energy transmission decreased and the transmitted beam exhibited higher-order mode structure.

It was not possible to measure the pointing of the F/40 beam inside the TA3 chamber on-shot. Instead the pointing could only be measured immediately after the South compressor, and hence before all optics in TA3, including the OAP and South extension chamber. Hence, on-shot pointing measurements were only sensitive to movement in LA3, not in TA3. Figure 3 shows how the spot size of the beam transmitted by the HOFI channel changed due to shot-to-shot jitter and drift of the F/40 beam over 50 consecutive Gemini shots. Several effects can be observed here. Shots for which the measured deviation in LA3 was small, but which were not guided could still have been poorly aligned with the channel axis owing to further pointing jitter. Later in the run (> 20 min after alignment), a greater proportion of shots lie further from the centre-point, indicating drift in LA3, whilst a greater proportion of the shots which are well aligned in LA3 are not guided, indicating a drift in the TA3 chamber itself, after the compressor.

Approximately 2700 Gemini shots taken over the course of 4 consecutive days were analyzed in order to estimate the effects of pointing deviations on guiding. Figure 4 shows the proportion of guided (a) and unguided (b) shots as a function of $\Delta\theta_{LA3}$ and the delay since the most recent alignment. Only shots taken shortly after spatial overlap of the two beams and with minimal jitter had a high probability of guiding. The white line indicates one standard deviation of the shot-to-shot pointing variation measured in LA3 for those shots which had guided, $\Delta\theta_{LA3}^{guided} = 3.7$ μrad. By assuming negligible further pointing jitter in TA3 (as measured above), one can estimate the acceptance angle of the channel, that is the maximum pointing offset of an F/40 pulse that is still guided, $\gamma_{acc} \approx \Delta\theta_{LA3}^{guided} = 3.7$ μrad.

4 Conclusions

In summary, we investigated effects of drift and jitter in the pointing of the guided beam on guiding in HOFI channels. The pointing jitter was found to be 6 ± 2 μrad in LA3, corresponding to a transverse offset at the entrance to the plasma channel of 28 ± 3 μm, and jitter in the alignment of the optics in the TA3 vacuum chamber would have increased this further. The pointing jitter, together with pointing drift, meant that in this work that only a small proportion of pulses were guided. We derive an acceptance angle for the plasma channel $\gamma_{acc} \approx 3.7$ μrad.

Future experiments of this type, including electron acceleration experiments, would therefore benefit considerably from active stabilization of the South beam pointing. Importantly, whilst active pointing stabilisation inside TA3 would be optimal, we note that measurements here suggest that an experiment-independent stabilisation system located inside LA3 could be sufficient. Such a setup would significantly reduce the constraints on gas cell design and interaction point geometry for experiments of this type.

5 Acknowledgments

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