

## Guiding of Relativistic Laser Pulses by Preformed Plasma Channels

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Guiding of relativistically intense ( $> 10^{18}$  W/cm<sup>2</sup>) laser pulses over more than 10 diffraction lengths has been demonstrated using plasma channels formed by hydrodynamic shock. Pulses up to twice the self-guiding threshold power were guided without aberration by tuning the guide profile. Transmitted spectra and mode images showed the pulse remained in the channel over the entire length. Experiments varying guided mode power and simulations show a large plasma wave was driven. Operating just below the trapping threshold produces a dark current free structure suitable for controlled injection.

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Controlling the propagation of intense laser pulses is important to many applications including harmonic generation [1], laser fusion [2], and laser wakefield accelerators (LWFAs) [3]. In a LWFA the ponderomotive (radiation) force of an intense laser pulse drives a plasma wave (wake), and particles have been accelerated with gradients of hundreds of GV/m [4–6]. Performance of such accelerators may be greatly enhanced by guiding the drive laser pulse [7], extending the interaction length beyond the diffraction distance  $Z_R$ . Extended length was important to production of low energy spread bunches from self-trapped electrons [8–11], and may allow use of controlled injection to improve beam quality [12,13].

At the high intensities required for acceleration ( $\geq 10^{18}$  W/cm<sup>2</sup>), the guide must control both diffraction and relativistic effects [7,14]. Relativistic self-guiding occurs when the laser power is above the critical power  $P_{\text{crit}}$ , and the quiver motion of the electrons causes their mass to increase, changing the refractive index [14–16]. Self-guiding is unstable [14,16–18], and for short pulses as used for most laser acceleration experiments propagation distance is typically limited to  $\sim Z_R$  [14,17,18]. In the low intensity limit a plasma “channel” with a parabolic density profile can guide a pulse without aberration, compensating for diffraction if the rise in density over a spot size  $w_0$  is  $\Delta n[\text{cm}^{-3}] \sim 1.1 \times 10^{20}/w_0^2[\mu\text{m}]$  [14,19,20]. Channel guiding at powers below  $P_{\text{crit}}$  and input intensities  $\leq 2 \times 10^{17}$  W/cm<sup>2</sup>, where relativistic effects are unimportant, has been demonstrated [19–23]. Whether a suitably shaped plasma could control propagation of a relativistically intense laser with  $P > P_{\text{crit}}$  and in the presence of an intense plasma wake, important regimes for a LWFA, had not been addressed experimentally.

In this Letter, we report guiding of laser pulses for the first time at relativistic intensities over many  $Z_R$ . A plasma channel formed by hydrodynamic shock was tuned to guide input powers up to 4 TW (twice  $P_{\text{crit}}$ ) without distortion of the laser mode, and to compensate for self-guiding. This allowed relativistic intensities to be guided, with intensities above  $10^{18}$  W/cm<sup>2</sup> or  $a_0 > 1$  at the guide output (where the normalized vector potential  $a_0 =$

$eE/m\omega c = \gamma v/c$ ). These pulses are in the relevant regime for LWFA [7]. The pulse remained in the channel over the entire length, and a large plasma wave was driven, providing evaluation of guiding in the strong wake limit.

The plasma channel was created by two laser pulses (Fig. 1) in a variant of the ignitor-heater method [20], using the multiarm LOASIS Ti:Sapphire laser [24] operating at 800 nm with chirped pulse amplification [25]. A supersonic hydrogen gas jet provided a nearly uniform 2.4 mm long target at an atomic density of  $3 \times 10^{19}$  cm<sup>-3</sup>. A 60 fs, 15 mJ ignitor pulse was focused at  $f/15$  near the downstream edge of the jet. Focal location and  $f$ /number were chosen so beam convergence roughly balanced ionization induced refraction [26,27], producing a cylindrical plasma of nearly uniform radius. This plasma was heated to tens of eV by inverse bremsstrahlung using  $\sim 50$  mJ from a 250 ps, 150 mJ pulse cylindrically focused and incident on the jet from the side simultaneously with the ignitor. The hot plasma filament expanded, driving a shock wave in the surrounding gas. This resulted in a density depletion on axis and a nearly parabolic transverse density channel after

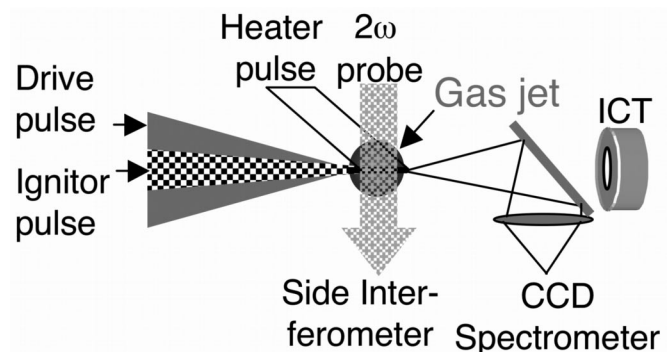


FIG. 1. Experimental arrangement. A plasma was formed by an ignitor pulse in a gas jet, then heated by a heater pulse. Hydrodynamic expansion of the plasma formed a channel which guided the relativistically intense drive pulse focused at its edge. Laser propagation was monitored with an interferometer and mode imager CCD. Accelerated electron bunch charge, if any, was measured by an integrating current transformer (ICT).

$\sim 500$  ps. The drive pulse was coaxial with the ignitor and focused near the entrance of this channel, with a 55 fs pulse width FWHM (full width half maximum, intensity), powers of 0–9 TW, and a spot size of  $7 \mu\text{m}$  FWHM.

The coaxial geometry facilitated guiding at high intensity by allowing the production of guides close to the outlet of the supersonic gas jet with uniform density and hence uniform guiding, and with sharp edge density gradients. This largely avoided the incoupling issues associated with ionization induced refraction [26,27] that limit intensity in experiments using backfilled chambers. Convergence of the coaxial ignitor beam also slightly flared the channel open at the laser entrance, providing good incoupling of the guided mode, which previously required additional laser pulses [21]. Use of two channel formation pulses provided both efficient ionization (high intensity pulse) and heating (longer, low intensity pulse) [20]. This allowed operation in pure low- $Z$  gasses, avoiding ionization refraction which limits intensity in high- $Z$  gasses. Adjustment of heater and ignitor energy and timing provided straightforward tuning of the guide profile by controlling expansion.

Plasma profile and propagation of the drive pulse in the plasma were analyzed using an interferometer, laser mode imager, and a spectrometer. Interferometry using a frequency doubled pulse incident from the side characterized the plasma with fs resolution. To optimize viewing of the long narrow plasma channels, cylindrical optics provided a resolution of  $17 \mu\text{m}$  (axial)  $\times 4 \mu\text{m}$  (transverse). The interferometer phase map was Abel inverted to recover the electron density assuming cylindrical symmetry (confirmed by the guided mode structure, below).

The laser mode profile was measured by imaging the mode onto a CCD (mode imager) camera using an  $f/10$  achromatic lens, and the lens was translated to image the channel entry or exit. Mounting constraints on  $f$ /number meant mode imager resolution was slightly larger than the focused laser spot size so that only a lower limit on guided intensity was obtained from the image. To overcome this, mode imager resolution and imaging response were characterized using laser spots independently measured with a high resolution camera, and with backlit resolution targets. Imaging properties were consistent with diffraction for a circular aperture at  $f/10$ , allowing deconvolution of spot sizes and intensities for laser modes near the lens resolving power. An optical spectrometer simultaneously measured the transmitted spectrum. Trapped and accelerated electrons, if present, were detected using an integrating current transformer (detection threshold  $10^9$  electrons).

The channel profile was optimized to guide the drive pulse and compensate for self-guiding by observing the laser mode at the channel output as the profile was changed. Figures 2(a) and 2(b) show the channel tuned to guide the drive pulse at 4 TW. Axial density was within 10% of  $1.4 \times 10^{19} \text{cm}^{-3}$  over the central 1.7 mm. The drive laser pulselength was thus longer than the linear plasma period, i.e., in the self-modulated regime [17] used for many acceleration experiments. The channel in

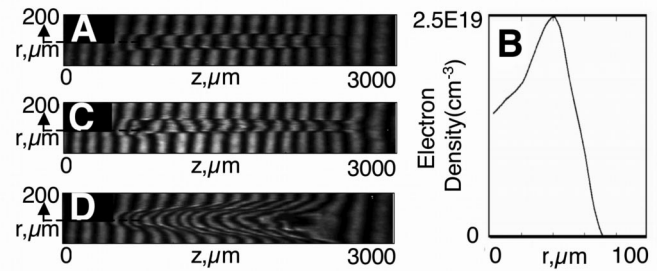


FIG. 2. The plasma profile at the time of drive pulse arrival, measured with an interferometer. The plasma channel interferogram (a) was Abel inverted with symmetry about the  $z$  axis to obtain the transverse density profile (b). When the drive pulse propagated in the channel at 4 TW (c), there was no change in the interferogram, indicating good confinement to the channel. Without the guiding channel (d), the drive pulse diffracted, spreading out as it propagated from left to right.

Fig. 2 had 40% less rise in density over a laser spot size than the matched rise for a low intensity pulse [14,19,20]. This detuning compensated for self-guiding at 4 TW, or twice  $P_{\text{crit}}$  at this density, allowing the mode to be guided without aberration (below). Recovered axial density and density rise over the spot diameter fluctuated by  $\sim 15\%$  shot to shot, driven by variations in the gas jet and channel formation pulses and Abel inversion noise.

The interferometer image of the plasma when the drive pulse propagated in the channel at 4 TW [Fig. 2(c)] is very similar to that of the channel alone [Fig. 2(a)]. Absence of additional plasma ionized outside the channel when the drive pulse is on demonstrates good confinement and minimal leakage over the length of the guide, as laser energy leaking outside the guide would ionize additional plasma. By contrast, the unguided drive beam diffracted rapidly creating a plasma whose radius increased as the beam propagated from left to right [Fig. 2(d)].

The guided laser mode for an input power of 4 TW and intensity of  $7 \times 10^{18} \text{W/cm}^2$  showed no aberration or change in spot size when compared to the input mode [Figs. 3(a) and 3(b)]. This demonstrates control of laser propagation over more than 10 diffraction ranges at twice  $P_{\text{crit}}$  and an intensity useful for acceleration. The output mode was symmetric, indicating that the assumption of channel symmetry (above) was valid. Guide effectiveness is demonstrated by comparison to the vacuum propagated mode, which displayed diffraction, and to propagation through the gas jet without channeling where diffraction was increased by ionization effects [26,27] [Figs. 3(c) and 3(d)]. Energy transmission was near 35%. Deconvolution of imaging system response (above) indicated that because input and output measured mode sizes were identical, the output mode was within  $1 \mu\text{m}$  of the  $7 \mu\text{m}$  input, yielding output intensity of  $2.5 \times 10^{18} \text{W/cm}^2$  (lower limit from the direct image  $I > 1 \times 10^{18} \text{W/cm}^2$ ). For a pulse long compared to  $\lambda_p$ , linear fluid theory predicts self-guiding at this power without a channel, though this is subject to instabilities [7,14]. For the  $\leq 10\lambda_p$  long pulses used in

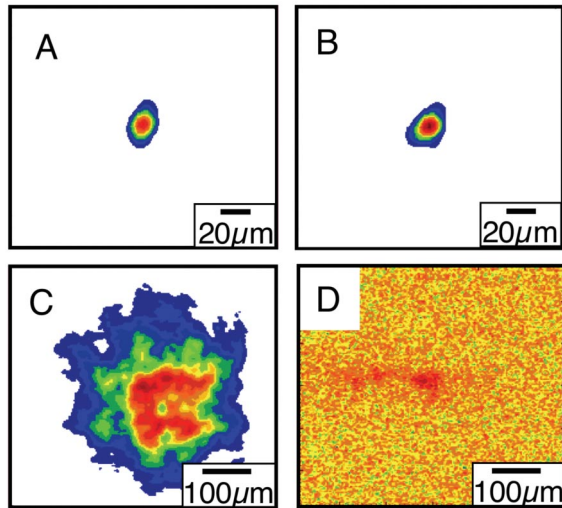


FIG. 3 (color). Mode images of laser propagation at 4 TW, twice  $P_{\text{crit}}$ . The guided output mode after 2.4 mm ( $> 10$  diffraction ranges) of propagation (b) is indistinguishable from the input mode (a). Vacuum propagation over the same distance results in a large output mode due to diffraction (c). With gas jet on but without the guide diffraction is enhanced (d), indicating that self-guiding is not effective. Note enlarged scale in (c),(d).

these experiments, however, self-guiding alone was never sufficient to guide the pulse over  $10 Z_R$ , and the channel detuning required to guide high intensity pulses was modest, indicating the importance of channeling even for high power beams.

Channel plasma profile adjustment allowed guiding of modes at various powers by compensating for changing self-guiding. Figure 4 shows guiding of modes at various input powers by a channel tuned to the low power guiding condition. Energy throughput is up to 50% at 0.5 TW, compared to 35% at 4 TW, indicating that a substantial amount of the laser energy is depleted into the wake at high powers. The low power beam (0.5 TW  $< P_{\text{crit}}$ ) is well guided by this channel, while pulses exceeding  $P_{\text{crit}}$  are distorted. Guided intensity appears clamped for input power  $> P_{\text{crit}}$  in this channel, indicating the importance of compensating for self-guiding, while Figs. 2 and 3 demonstrate that this can be done for  $P \geq 2P_{\text{crit}}$ . Pulses were guided up to 9 TW, but at this power distortion of the mode was always observed, with typical output spots near  $24 \mu\text{m}$  probably due to strong self focusing and coupling to plasma waves in this case [8].

To separate channeling and ionization effects, mode transmission of the high power beam in a preionized plasma without a channel was studied. The ignitor was fired 80 ps before the main beam, preionizing a plasma  $80 \mu\text{m}$  in diameter. Expansion was insignificant, so that the density profile was flat, with no guiding properties. Propagation was similar in preionized and unionized gas jets, indicating that channeling, not ionization, was responsible for the observed propagation differences. This is reasonable since the gas is ionized by the foot of the laser

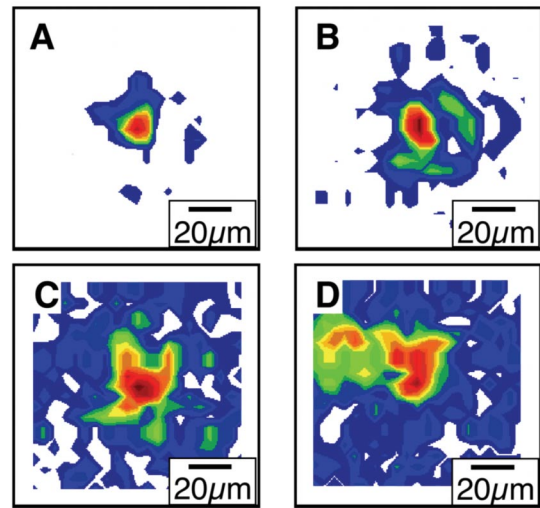


FIG. 4 (color). Channel tuning to compensate for self-guiding. The effect of self-guiding on mode structure is shown by varying the input power in a channel tuned to guide low intensity pulses. For pulses at 0.5 TW, below the critical power for self-guiding, the output mode is undistorted (a). As power is increased to 2 TW (b), some distortion is evident and this becomes more severe as power is further increased to 4 TW (c) and 8 TW (d). Guides were tuned to guide modes up to 4 TW without distortion by adjusting the density profile to compensate for self-guiding (Fig. 3).

pulse at  $I < 10^{-4} I_0$  for the intensities used, and hence should not affect propagation of the bulk of the pulse.

The transmitted laser spectrum indicates channeling efficiency and plasma wave excitation. An intense pulse propagating in an unionized gas suffers a blueshift in spectrum due to the time dependent index of refraction as the gas is ionized by the pulse [28]. The extent of such ionization blueshift is an indicator of the laser escaping confinement in the preionized channel. Coupling of the laser to plasma waves redshifts the pulse as energy is depleted into the wave. Figure 5 shows the normalized transmitted spectrum at 4 TW for the vacuum, unchanneled, and channeled cases. In the unchanneled case, most laser energy is blueshifted, and transmission of the fundamental near 800 nm is a few percent. In contrast, the channeled spectrum shows a small blueshifted shoulder, likely from residual neutral gas at the channel ends. Transmission of the fundamental is  $\sim 30\%$ , compatible with mode imager observations. A redshifted shoulder is visible, and its energy increased to  $> 20\%$  of the fundamental with increasing laser intensity, indicating coupling to plasma waves.

At drive pulse powers above 4 TW, electrons were self-trapped and accelerated [8], verifying the presence of an intense plasma wave that is close to the self trapping field at 4 TW. Just below the trapping threshold, no electrons are self-trapped yet laser intensity and hence plasma wave amplitude are maintained over long scale length. This may enable controlled injection into laser wakefields

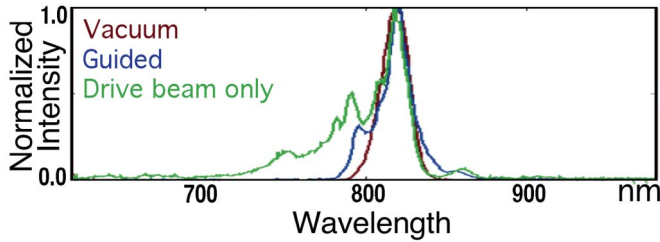


FIG. 5 (color). Normalized transmitted optical spectrum of the drive pulse. The drive pulse propagating in the gas jet has most of its energy blueshifted away from the fundamental by ionization, impairing usefulness for applications. The channeled beam shows almost undistorted propagation, with a redshifted side band indicating depletion of some of the laser energy into plasma waves. Absence of significant blueshift indicates propagation through ionized plasma, and hence that the pulse remained within the channel.

which has the potential to both stabilize and increase quality of beams from laser accelerators [12,13].

Simulations using the particle in cell code VORPAL [29] also indicated good coupling of the laser to plasma waves in the channel. These simulations self-consistently modeled interaction of the laser with the plasma channel including guiding and wake generation using the experimental laser and plasma parameters [30]. The simulations used a window comoving with the laser pulse, 90  $\mu\text{m}$  long by 80  $\mu\text{m}$  transversely, with  $1800 \times 300$  cells and 10 particles/cell. Guided spot size at 4 TW was  $\sim 1 \mu\text{m}$  smaller than the input spot, consistent with experimental observations. The pulse self-modulated, exciting a strong plasma wave with a field averaging  $\sim 300 \text{ GV/m}$  over the last 0.5 mm of the guide and depleting  $\sim 1/4$  of its energy into the wave, close to the experimentally observed decrease in transmission between 0.5 and 4 TW. The wave is below the self-trapping threshold so that there is no dark current, yet would provide energy gains of  $\sim 150 \text{ MeV}$  for injected electrons. Consistent with Figs. 2 and 3, simulations of the 4 TW experiment showed that the laser mode remained nearly Gaussian and did not have sufficient intensity to ionize plasma outside the guide, while stronger self modulation at 9 TW broadened the mode allowing ionization outside the guide consistent with Ref. [8].

In conclusion, experiments demonstrated guiding of relativistically intense laser pulses over many  $Z_R$  in plasmas, and tailoring of the radial plasma profile provided guiding without detectable aberration up to twice  $P_{\text{crit}}$ . Intensities near  $10^{19} \text{ W/cm}^2$  have been guided without self injection of electrons. Experiments and simulations showed that a large plasma wave was excited in the channel, demonstrating guiding in the presence of a large plasma wake. This potentially provides a high gradient, long scale length structure for improving the energy and

quality of beams from laser driven accelerators, and for controlled injection of electrons.

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