Interaction of Intense Laser Pulses with Preformed Density Channels

A. J. Mackinnon, M. Borghesi, A. Iwase, and O. Willi
The Blackett Laboratory, Imperial College of Science, Technology and Medicine, London SW7 2BZ, United Kingdom

(Received 10 March 1997)

The interaction of a high-intensity laser pulse with a plasma density channel preformed in a gas jet target has been studied. At neutral densities below 3.0×10^{19} cm^{-3} a strong interaction between the pulse and the channel walls was observed, there was clear evidence of pulse confinement, and the laser irradiance was significantly increased compared to an interaction with neutral gas. At higher gas densities, however, the radial uniformity and length of the channel were both found to be adversely affected by refractive defocusing of the prepulse used to generate the channel. [S0031-9007(98)06338-8]

PACS numbers: 52.40.Nk, 52.35.Tc, 52.50.Jm

The propagation of intense laser pulses through preformed plasmas is an important area of study for many topical applications of laser produced plasmas, such as the laser particle accelerator [1], x-ray lasers [2], high harmonic generation, and the fast ignitor scheme [3]. These applications generally require an ultrashort high power laser pulse to interact with a neutral gas or plasma at high density (with $n_e > 0.01 n_c$ where n_e and n_c are the electron and critical density, respectively) and high irradiance (10^{14}–10^{19} W cm^{-2}) over distances ranging from a few mm to several cm. At extremely high laser irradiance ($>10^{18}$ W cm^{-2}) self channeling due to relativistic and ponderomotive effects can greatly enhance the propagation length [4]. However, the interaction length can still be increased for applications requiring lower laser irradiance by focusing a low energy prepulse to form a plasma waveguide or channel [5–8]. To date most experiments using this scheme have been carried out at low densities where the length of the guiding channel is limited by the depth of focus of the preforming laser. In fact, guiding over 20× the diffraction limited focal depth has been observed by using an axicon to maximize the length of the plasma channel [6]. Applying this result to higher plasma densities is problematic for short (1–10 ps) prepulses because as the density increases the length of the channel will be limited by ionization defocusing of the preforming pulse [9,10] not diffraction. There is presently little or no information on the effect of ionization defocusing on the formation of preformed density channels using short prepulses. In addition there are very few direct measurements of how the second pulse interacts with and modifies the channel.

This Letter describes the first experimental studies of the interaction of intense laser pulses with plasma channels in the strongly refractive density regime where ionization defocusing influences both the formation of the channel itself and the subsequent propagation of intense pulses through it. In these experiments a 1 μm, 3 ps, laser pulse was focused onto the edge of a neon gas jet with atomic density $>1 \times 10^{19}$ cm^{-3} at a vacuum intensity of 1×10^{18} W cm^{-2}. Quantitative measurements of the electron density profiles produced by focusing the laser pulse either into the neutral gas or preformed density channel were obtained using time resolved optical probing. The confining properties of the channel, observed directly with this diagnostic, were found to be consistent with measurements of the transmitted laser energy. The characteristics of the channel also agreed well with simple analytic calculations and 1D hydrodynamic simulations.

The experiment was performed at the Rutherford Appleton Laboratory using the VULCAN Nd:glass laser [11]. An $f/5$ off axis parabola focused a 1–3 ps pulse onto the gas vacuum boundary with a typical focal spot of 30 μm full width at half maximum. The vacuum intensity was 1×10^{18} W cm^{-2} with a 200 ps pedestal at an intensity of 10^{13} W cm^{-2}. The target (which has been described in detail elsewhere [10,12]) consisted of a solenoid pulsed gas jet with a 1 mm diameter cylindrical nozzle. In this Letter we describe the results of interactions with neon or helium gas with a peak neutral gas density over the range 3×10^{19}–1.0×10^{20} cm^{-3}. The plasma channel was formed by focusing a colinear prepulse (with temporal and spatial characteristics identical to those of the main pulse) into the gas jet. During the experiment the energy of the prepulse was varied from 0.1 to 1 J (1% or 10% of the main beam energy, respectively) and the relative delay between the two pulses was varied from 500 ps to 2.3 ns. The plasma was diagnosed with a temporally independent probe pulse, split off from the main uncompressed heating beam. The probe pulse was compressed to 3 ps with a pair of gratings and frequency doubled to 0.527 μm in a KDP (potassium dihydrogen phosphate) crystal. The plasma was imaged onto the film plane by a collimated telescope, with a magnification of 50×. A moiré deflectometer (comprising a pair of 20 lines per mm Ronchi gratings placed 10 cm apart, near the image plane of the telescope) provided time resolved measurements of the electron density profiles [13], at discrete intervals up to 2.5 ns before or after the interaction pulse. The spatial resolution along the fringe direction was limited by diffractive effects between the gratings to 25 μm [14]. Finally, the laser energy transmitted through the target within a half angle of 5.5° was measured with an absorbing glass calorimeter.

A number of numerical models were used for data interpretation and for detailed comparison with the experimental measurements and analytical estimates. The expansion characteristics of the channel, following the laser heating stage, were compared to an analytic blast wave model [15] and the 1D hydrocode MEDUSA. This gave an estimate of the original electron temperature, which was compared to an inverse bremsstrahlung model [16].

The effect of ionization defocusing on the propagation of a powerful 1 μm laser pulse, through a neon gas jet at a neutral density of 3×10^{19} cm^{-3} has recently been published. Under these circumstances ionization induced density gradients cause the beam to defocus, resulting in a plasma whose radius increases rapidly along the propagation direction [10]. The feasibility of using a preformed density channel to overcome defocusing in such conditions was investigated by focusing a prepulse into the gas ahead of the main pulse and studying the subsequent interaction with moiré deflectometry. Information on the degree of confinement afforded by the channel was obtained by varying the following experimental parameters: (a) the relative delay between the two pulses, (b) the target gas material and density, and (c) the energy content of the prepulse. A deflectogram, taken 6 ps after the interaction of a 5 TW pulse with a preformed channel, is shown in Fig. 1(a). This preformed channel was formed by focusing a 0.1 J prepulse into a neon gas jet with a neutral density of 3×10^{19} cm^{-3}, 2.3 ns ahead of the main pulse. The walls of the density channel can clearly be seen in this figure as the two well defined regions of high-density plasma (shown by strong fringe shifts) running parallel to the laser propagation axis at radii of 100 μm, while the strong filamentary structures within the channel (to the left of the filter block), are the result of optical ionization by the interaction beam. It is important to note that there is no evidence of plasma formation anywhere outside the channel. Consequently, at the channel end (800 μm downstream of the vacuum focus) the pulse is confined within a radius of 100 μm. This is a significant improvement over the neutral gas interaction, where there was plasma formation out to a radius >350 μm. The laser intensity within the channel is thus approximately an order of magnitude greater than could be obtained with the neutral gas interaction. The degree of confinement was found to depend strongly on the relative timing between the two pulses. This is clear from the deflectogram shown in Fig. 1(b), taken 6 ps after a 5 TW pulse was focused into a channel with a prepulse—main delay of 500 ps. It is apparent from this figure that along the length of the channel the walls are not as well developed as in Fig. 1(a). Although strong fringe shifts can be seen close to the propagation axis, there is also significant plasma formation outside the channel. There is clearly less confinement at 500 ps compared to 2.3 ns. The reason for this difference is that the shock wave structure at the channel walls was not properly formed at 500 ps, allowing significant leakage of the main pulse. Hydrocode simulations, which predict a stronger shock structure at 2.3 ns compared to 500 ps, support this interpretation. Further evidence of increased levels of pulse confinement at longer delays was also provided by the transmitted energy measurements. The fraction of laser energy transmitted within the 5.5° angle was found to increase from 2% to 10% as the delay increased from 500 ps to 2.3 ns. Although this increase in transmitted energy was relatively small it demonstrated that the properties of the channel wall, not just preionization of the gas, were the most important factor leading to confinement of the pulse.

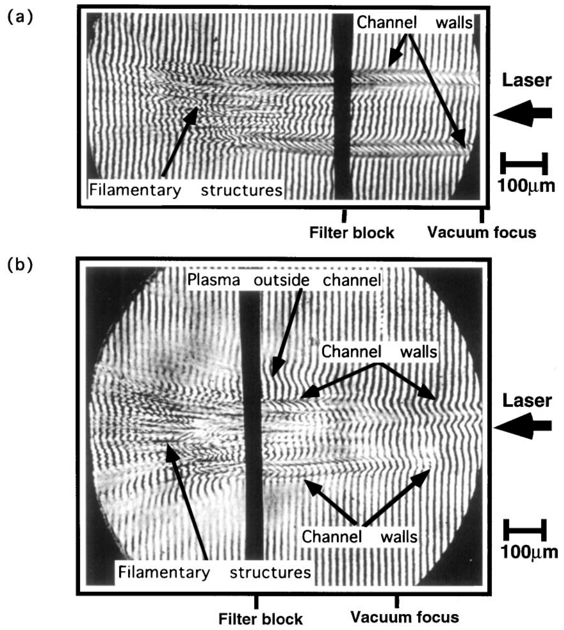

FIG. 1. (a) Deflectogram of the plasma formed by focusing the main beam into the preformed channel with a prepulse-main delay, τ_d of 2.3 ns. The vertical bar near the center of the picture is an imperfection of the filters in front of the film. The laser is focused from the right with a cone angle of 5.7°. The channel walls are well defined; there are strong filamentary structures within the channel and there is no evidence of plasma outside the channel. (b) Moiré deflectogram of the plasma taken 6 ps after focusing a 5 TW, 1 μm laser pulse into a plasma channel formed by a 0.1 J prepulse, with $\tau_d = 500$ ps. The channel walls are not completely formed and there is, consequently, significant plasma formation outside the channel. Note that the center of the field of view has shifted 250 μm towards the laser input.

Further insight into the channel forming process was obtained by examining the 2.3 ns channel a few ps before the arrival of the interaction pulse, as shown in Fig. 2. The deflectogram can be split into two distinct parts: (a) a uniform region clearly showing the strong shock wave structure that confined the beam and (b) a nonuniform region, where the plasma is turbulent and the fringe shifts show a peak on axis, implying an axial density maximum. An electron density profile in the uniform portion of the guide is shown in Fig. 3. The profile is characteristic of

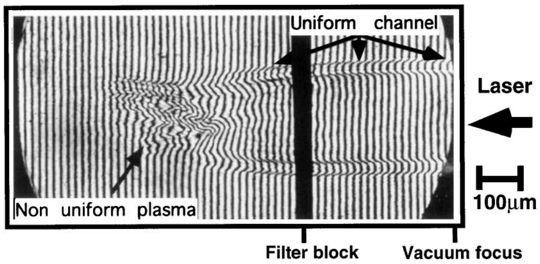

FIG. 2. Moiré deflectogram of the density channel taken 6 ps before the interaction of the main pulse, with $\tau_d = 2.3$ ns. This plasma was formed by focusing a prepulse with $E = 100$ mJ, $\tau_p = 2.5$ ps.

a strong shock wave [15] with an axial density minimum increasing to a sharp maximum at the channel walls. This represents a refractive index profile that is capable of confining an intense laser [5–8]. A simple but instructive estimate of the largest ray angle confined by the uniform part of the channel can be obtained from Snell's law applied to the density profile. Assuming a discontinuity in refractive index at the shock front, the critical angle, $\theta_c = \cos^{-1}(\mu_w/\mu_c)$, where μ_w and μ_c are the refractive indices at the channel wall and center, respectively. For an average density of 5×10^{19} cm^{-3} at the channel wall and 1.0×10^{19} cm^{-3} on axis, $\theta_c \sim 10$–$15°$, which is consistent with the experimental observations.

Another important and novel feature of this data was the significant increase in the fringe shifts at the walls when the main beam interacted with the 2.3 ns channel [this can be seen by comparing Fig. 1(a) and Fig. 2]. A quantitative measurement of this effect was obtained by using helium at a neutral density of 3×10^{19} cm^{-3} as the target gas. Figure 4 shows density profiles taken before and after focusing the interaction pulse into a channel formed 2.5 ns after the 0.1 J prepulse. It can be seen that the electron density at the channel walls increased by a factor of 2.5 when the interaction beam is focused into the channel. For a 4 TW pulse confined within a channel of radius 100 μm an assumption of a top hat laser spatial profile gives an order of magnitude estimate of the mean irradiance within the channel as $\sim 1 \times 10^{16}$ W cm^{-2}. This intensity is near threshold for doubly ionized ($Z^* = 2$) helium and the density increase at the channel walls was therefor consistent with optical ionization increasing $Z^* = 0.8$ to 2. This observation is important because it conclusively shows that the main pulse interacted with the channel walls. Further independent confirmation of the level of pulse confinement was also obtained in a separate experiment using 0.35 ps KrF laser pulses. In this experiment a laser pulse was focused at a vacuum irradiance of 1×10^{17} W cm^{-2} into an identical gas nozzle with a peak neutral density around $0.01 n_c$. The output of the channel was imaged with a quartz $f/2.5$ lens into a CCD camera with a magnification of 10× and spatial resolution of 5 μm. This diagnostic also clearly showed that the interaction pulse was confined within the channel with an irradiance 5 times greater than the neutral density case. These results, together with more details of the 1 μm experiment, will be discussed in a longer article [17].

The nonuniform plasma at the end of the channel in Fig. 2 was due to the finite depth of focus of the preforming laser pulse. Confirmation of this interpretation was obtained by the observations that an increase in the prepulse energy from 0.1 to 1 J resulted in a channel that was uniform over the length of the nozzle ($\sim$1 mm) and the transmitted energy increased from 10% to 25%. This represents an order of magnitude increase in transmission from the 2% value obtained in the neutral gas. The most probable cause of this relatively low transmission within the calorimeter acceptance angle was due to refraction occurring within the channel (for these conditions the absorbed fraction was calculated to be around 5% or less). If, for example, the confined beam expanded at an angle θ_c, then only the fraction $(\theta_a/\theta_c)^2$ would be intercepted within the acceptance angle θ_a of the calorimeter. For these channels $\theta_c \sim 12°$ and with $\theta_a = 5.5°$ giving $T \sim 21\%$, which is consistent with the experimental measurement.

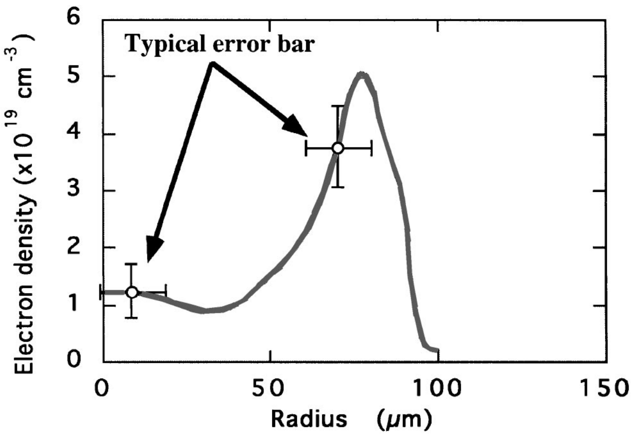

FIG. 3. Radial electron density profile near the vacuum focus. This is an ideal density profile for guiding.

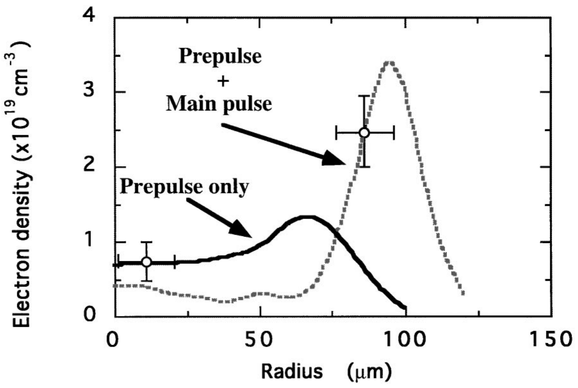

FIG. 4. Electron density profile for helium at best focus before the arrival of the interaction beam (solid line) and after the arrival of a 4 TW pulse (dashed line). Optical ionization at the channel walls is responsible for the increased density.

The mechanism limiting the channel length was examined using the blast wave model of Zel'dovich and Raizer [15]. In cylindrical symmetry this model gives the channel radius as a function of time t: $r(t) \propto (E_d/\rho)^{1/4}t^{1/2}$; where E_d is the energy deposited per unit length and ρ is the gas density. It has been shown in a previous publication described that this model described the channel expansion well for $t > 100$ ps, but a 1D hydrocode was required to simulate the complete temporal evolution of the channel [18]. In this case the asymptotic expansion radius can be directly related to the original laser energy deposited within the center of the channel. With this technique the energy deposited in the uniform part of the channel was estimated. Around the region of best focus the channel expanded from 15 to 100 μm in 2.3 ns and the simulations gave $T_e \sim 300-400$ eV. This agreed well with the value of $T_e = 380$ eV, predicted by the absorption model in these circumstances (a 0.1 J prepulse with an intensity of 1.5×10^{16} W cm^{-2} and neon with a neutral density of 1×10^{19} cm^{-3}) [16]. In contrast at the other end of the channel the radius was only 25 μm after 2.3 ns and a shock wave had not developed at all. The prepulse intensity at this position, due to the cone angle of the focusing optics, was around 3×10^{14} W cm^{-2} resulting in an ionization stage only marginally higher than threshold. For these circumstances the absorption model predicted $T_e \sim 1-5$ eV and the plasma would not undergo any significant radial expansion in the 2.3 ns before the main pulse arrived, in agreement with the experimental observation. This cool, unexpanded plasma region formed a barrier to the interaction pulse and limited the effective confinement length of the channel. This interpretation also explained why an increase in the neutral density led to a reduction in channel length, as this was consistent with enhanced levels of ionization defocusing of the prepulse at the higher neutral density. The variation of channel length as a function of gas jet density is plotted in Fig. 5. As the neutral gas density increased from 3×10^{19} to 1×10^{20} cm^{-3} a 50% reduction in channel length from 550 to 350 μm was observed. This showed that ionization defocusing presented a fundamental limitation on the use of short laser pulses to form plasma waveguides in refracting plasmas.

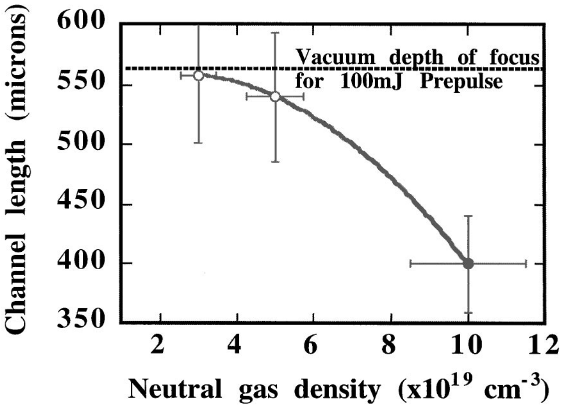

FIG. 5. Graph of the channel length as a function of neon gas density, measured from the moiré deflectograms. The channel length reduces with gas density because of ionization defocusing of the prepulse.

This work has presented direct observations of the interaction of an intense picosecond pulse with a plasma channel preformed in a gas jet target. At low densities the first clear evidence of the interaction between a confined pulse and the channel was observed. These data also demonstrated definite pulse confinement by the channel leading to a laser irradiance that was significantly increased compared to an interaction with the neutral gas. At higher densities, however, the channel length was not limited by the depth of focus of the optical system but by ionization defocusing of the prepulse. The use of a longer duration prepulse (~100–500 ps) could possibly help to overcome this limitation [8].

The authors would like to acknowledge the contributions made by the staff of the Central Laser Facility, especially C. Danson and D. Pepler. The authors are also very grateful to G. J. Pert for the use of his laser absorption code. This work was funded by EPSRC/MoD grants.

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