RAPID COMMUNICATIONS

PHYSICAL REVIEW E VOLUME 57, NUMBER 5 MAY 1998

Guiding of a 10-TW picosecond laser pulse through hollow capillary tubes

M. Borghesi, A. J. Mackinnon, R. Gaillard, and O. Willi
Imperial College of Science, Technology and Medicine, London SW7 2BZ, United Kingdom

A. A. Offenberger
Department of Electrical Engineering, University of Alberta, Edmonton, Canada T6G 2G7

(Received 5 January 1998)

Efficient guiding of 1-ps infrared laser pulses with power exceeding 10 TW has been demonstrated through hollow capillary tubes with 40- and 100-μm internal diameters and lengths up to 10 mm, with transmission greater than 80% of the incident energy coupled into the capillary. The beam is guided via multiple reflections off a plasma formed on the walls of the guide by the pulse's rising edge, as inferred from optical probe measurements. [S1063-651X(98)50605-8]

PACS number(s): 52.40.Nk, 42.79.Gn, 52.75.−d

Several important applications using short laser pulses, including particle acceleration [1] and x-ray laser studies [2], require short laser pulses to interact with homogeneous plasmas over lengths significantly exceeding the natural defocusing distance of the laser beam (Rayleigh length). The propagation of an ultraintense short pulse through a long region of plasma without considerable energy dissipation is also a basic requirement of the fast ignitor scheme for inertial confinement fusion [3]. In order to confine the laser beam in a small section and achieve the required intensity over several Rayleigh lengths, some guiding mechanism is necessary. For pulses at sufficiently high power, relativistic self-guiding can occur, as has been observed in several experiments [4]. The pulse is guided due to the combination of ponderomotive and relativistic modifications induced in the plasma density profile by the pulse itself. Guiding of short pulses over considerable lengths has also been achieved by using preformed plasma channels [5]. In these experiments, a prepulse, focused in the gas or plasma ahead of the main pulse, provided the necessary refractive index modification.

An alternative approach, not yet widely investigated, is the use of solid guides, namely hollow capillary tubes. In this case the laser pulse is confined within the inner diameter of the guide and propagates through reflections off the inner walls of the tube. The propagation of laser pulses with a power up to 1 TW through glass microcapillary tubes (with diameters in the range 100–200 μm) was first studied by Jackel *et al.* [6]. For energies below the breakdown threshold, the propagation occurs through grazing incidence reflections at the dielectric inner surface [7,8], the reflectivity for each bounce being determined by Fresnel laws. For high intensity pulses, however, an overdense plasma is created at the guide walls ahead of the main pulse, by the pulse's rising edge or by the prepulse. In this case the beam is guided through reflections off the high-density plasma (an obliquely incident beam will be reflected at a density $n_e = n_{\mathrm{cr}} \cos^2\theta$, where n_{cr} is the critical density and θ the angle of incidence [9]). Since, in principle, some energy is absorbed by the plasma at every bounce, a reflection coefficient R can be introduced. The total transmission through the guide will be $T \approx T_{\mathrm{ins}}(R)^N$, where the insertion coefficient T_{ins} represents the fraction of the pulse energy that can be coupled to the guide and N is the number of bounces undergone by the pulse along the length of the guide. Within the guide, a mode structure is established, depending on its transverse size; a detailed modal analysis of hollow cylindrical waveguides can be found in Ref. [7].

The guiding of high-intensity pulses through solid guides appears to be of particular interest in view of alternative approaches to fast ignition. In principle, the igniting pulse can be guided to the high-density core of an imploding target (or at least through the coronal plasma region) in a solid waveguide, provided its walls are thick enough to survive the compression. This approach, also applicable to direct drive compression schemes, seems particularly promising for point ignition following indirect-drive compression of a pellet placed inside a hohlraum. In this case, in order to reach the compressed core, the igniting pulse can be guided inside a solid capillary tube through the hohlraum wall and the gas fill. Considering the size of hohlraums presently in use, the guide lengths of interest for these applications are in the 1–10-mm range.

This paper reports on an experiment studying the guided propagation of 10–20-TW, ps pulses (i.e., in a regime of interest for fast ignitor applications) through hollow glass capillary tubes. From energy-transmission measurements through the waveguide, using capillary tubes of different diameters and lengths, high transmittivity was observed (more than 80% of the energy coupled into the guide).

The experiment was carried out at the Rutherford Appleton Laboratory using the Vulcan laser operating in the chirped pulse amplification (CPA) mode [10]. The experimental setup is shown in Fig. 1. The duration of the 1-μm CPA pulse was 1 ps, with a power on target up to 20 TW. The pulse was superimposed on a 200–300-ps pedestal with a main-to-prepulse contrast ratio better than 10^6. The targets were variable length Pyrex (KG33) hollow capillary tubes. Two different sets of targets were used: (a) 40($\pm$10)-μm inner diameter targets, with an external diameter of 100 μm; (b) 100($\pm$20)-μm inner diameter targets, with an external diameter of 550 μm. The targets were mounted on a translation stage that also allowed rotation in the horizontal and vertical planes. The CPA pulse was focused at the entrance of the waveguide by an $f/4.5$ off-axis parabola. The targets

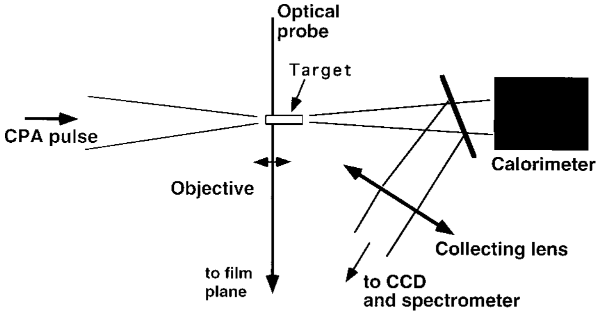

FIG. 1. Schematic of the experimental setup.

were aligned using telemicroscope systems and, also, by optimizing the mode structures observed in the output beam when the continuous wave neodymium-doped yttrium lithium flouride (CW YLF) oscillator beam was focused into the target. The transmitted beam energy was monitored with a contact calorimeter placed inside the interaction chamber. A fraction ($\sim 4\%$) of the transmitted beam was collected by an $f/2.5$ doublet that imaged the end plane of the target onto a charge-coupled-device (CCD) readout system with a spatial resolution ~ 5 μm. A fraction of the uncompressed pulse was recompressed with a separate pair of gratings, frequency doubled in a potassium dihydrogen phosphate KDP crystal and used as a transverse probe. A microscope objective on the probe line imaged the target plane, and shadowgrams of the target were obtained at different times, before and after interaction, by suitably delaying the probe pulse.

The energy fraction transmitted through the target is plotted in Fig. 2 as a function of the target length, for the two different diameters used. The energy transmitted through a platinum pinhole 100 μm in diameter is also shown in the data. Although there is some scatter in the data, a consistent behavior for both sets of measurements clearly emerges from the graph. Even though the transmission appears to decrease with the target length, a sizable fraction of the laser energy is guided through the tube. It has to be noted that, as can be deduced from the measured transmission through a 100-μm pinhole, only a fraction ($\sim 60\%$) of the laser energy could be injected into the waveguide. The relatively low coupling efficiency is a consequence of the poor quality of the focal spot attainable in the high-energy range investigated. As a matter of fact, the focal spot profile appeared to degenerate as the beam energy was increased above 15 J, with a large fraction of the energy being spread in the beam wings (probably due to an increase of the *B* integral of the beam). An image of the beam transmitted through a 100-μm pinhole is shown in Fig. 3. For 100-μm inner diameter targets, transmission as high as 50% of the total beam energy was observed for a target length of 10 mm. If one takes into account the insertion losses, the transmitted fraction corresponds to about 85% of the energy that was coupled to the guide.

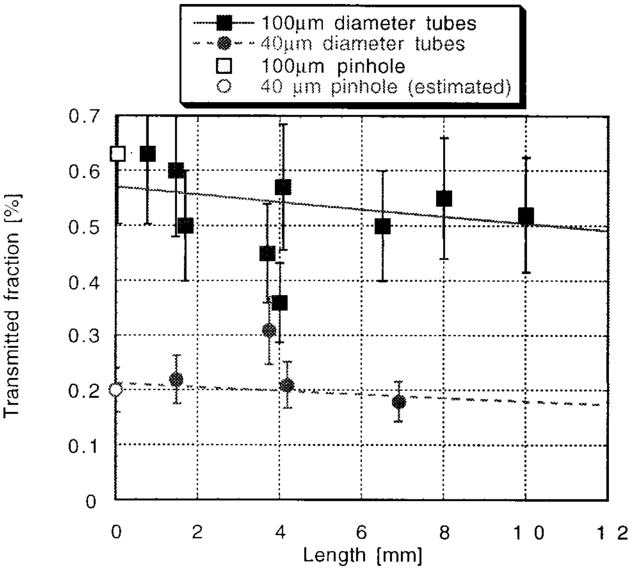

FIG. 2. Transmitted energy vs capillary length for two different target inner diameters, 40 μm (circles) and 100 μm (squares). The measured transmission through a 100-μm pinhole and the estimated transmission through a 40-μm pinhole (see text) are also shown in the graph.

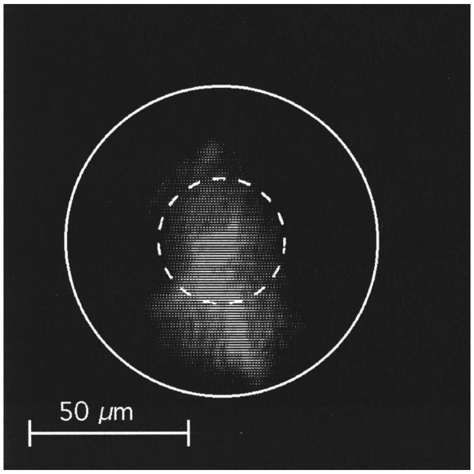

FIG. 3. Profile of the beam transmitted through a 100-μm pinhole (the size of the pinhole is shown as a solid circle). The dashed circle indicates the size of a 40-μm-diam pinhole. By integrating the intensity over the area of this circle, the estimated transmission through a 40-μm pinhole (empty circle in the plot of Fig. 2) is obtained.

The energy fraction transmitted through a 40-μm pinhole, and consequently the energy coupling to a 40-μm inner diameter guide, has been estimated as 20% of the incident energy (by integrating the intensity distribution of Fig. 3 over the area of a 20-μm radius disk, shown in the figure as a dashed line). Even in this case it should be stressed that the low coupling to the guide depends only on the poor quality of the focal spot in the conditions of the experiment, and that about 80% of the energy coupled to the guide is transmitted through it.

A rough estimate of the number of times that the beam is reflected off the plasma walls can be given as $N \approx L/(4f_{\#}r)$, where L is the length of the tube, $f_{\#}$ the focusing f number and r the guide inner radius. Consequently, the transmission through the target depends upon the length through the expression $T \approx T_{\mathrm{ins}} R^{L/(4f_{\#}r)}$. A fit of the data using this function is given in Fig. 2, including the transmission through a 100-μm-diam pinhole (measured) and through a 40-μm-diam pinhole (estimated), but excluding the two points that most deviated from the general trend.

From the best fits (shown in the graph), an approximate value of the reflectivity R can be obtained, i.e., $R = 0.98-0.99$. Consequently, an absorption of 1–2 % of the incident energy for each bounce can be inferred (for a more accurate estimate, one should take into account that the effective f number inside the guide, when the mode structure has been established, will differ from the focusing f number [6]). The energy is thus dissipated at the rate of 0.2 cm^{-1}. Though this rate is the same as measured in Ref. [6], it has to be noted that the measurements reported here are obtained with narrower targets and a smaller focusing f number than in Ref. [6]. This means that, in the experiment reported here, the beam propagated with a higher number of bounces per unit length and consequently with less energy absorption per bounce than in Ref. [6] (1–2 % instead than 10–15 %).

In addition to the transmission diagnostics, transverse optical probing was used to determine the onset of plasma creation on the guide walls. In fact, as soon as the plasma is formed, the target wall—initially transparent to the probe radiation—becomes opaque. By suitably delaying the probe pulse with respect to the main beam, breakdown at the channel walls was observed 8–10 ps ahead of the peak of the pulse. While no plasma was created by the 200-ps pedestal, the breakdown is likely to be initiated by the (relatively) slowly rising edge of the pulse. The breakdown threshold for glass depends on the laser pulsewidth; data available for fused silica show the damage threshold for 1-ps pulses to be $I_b \approx 5 \times 10^{12}$ W/cm^2 [11]. By simply dividing the power coupled to the guide by the area of a section of the guide, one can roughly estimate the laser irradiance at the walls (at the peak of the pulse) as $I_{wp} \approx (1-3) \times 10^{17}$ W/cm^2. Therefore, $I_b \approx (1-5) \times 10^{-5} I_{wp}$. Cross-correlation measurements of the peak-to-pedestal contrast ratio for the Vulcan CPA system [10] indicate that a 10^{-5} level is reached at about 15 ps ahead of the peak of the pulse, in reasonable agreement with the optical probe observations. The plasma, initially cold, is heated up as the laser-pulse power rises, but it cannot expand more than a few micrometers in the short time between the plasma formation and the peak of the pulse. This is confirmed by the fact that plasma closure does not appear to affect the propagation of the pulse. Moreover, measured spectra of the laser radiation transmitted through the guides did not differ significantly from spectra of the incident pulse.

Concerning the low value of absorption per bounce estimated from the data, it is expected that—due to the high laser irradiance and the short scale length of the plasma—collisional absorption will not be very important for the conditions of the experiment. In addition, classical resonance absorption cannot be very efficient due to the large angle of incidence. Even though classical resonance theory [12] is strictly valid only for $L \gg \lambda$ (where L is the scale length of the plasma), numerical results [13] suggest that, for $L = \lambda$, resonance absorption is still described reasonably well by a Denisov-like profile, approximately peaking at $\theta \approx \arcsin[0.8/(2\pi)^{1/3}] \approx 25°$. Under these conditions a resonance absorption value below a few percent can be reasonably assumed for $\theta = 84°$ (i.e., the angle of incidence on the plasma walls corresponding to the focusing f number of the experiment). At high laser irradiance, other collisionless absorption processes could, in principle, become important even at grazing incidence. In recent measurements, performed at irradiances exceeding 5×10^{17} W/cm^2 [14], absorption as high as 80% of the incident radiation was observed at angles of incidence as large as 80°, as predicted for absorption via the anomalous skin effect [15]. However, other experiments performed in similar experimental conditions yielded different results [16], showing a more conventional resonant profile for p-polarized light, with absorption close to zero at very large angles (in agreement with the absorption values inferred from the measurements reported here).

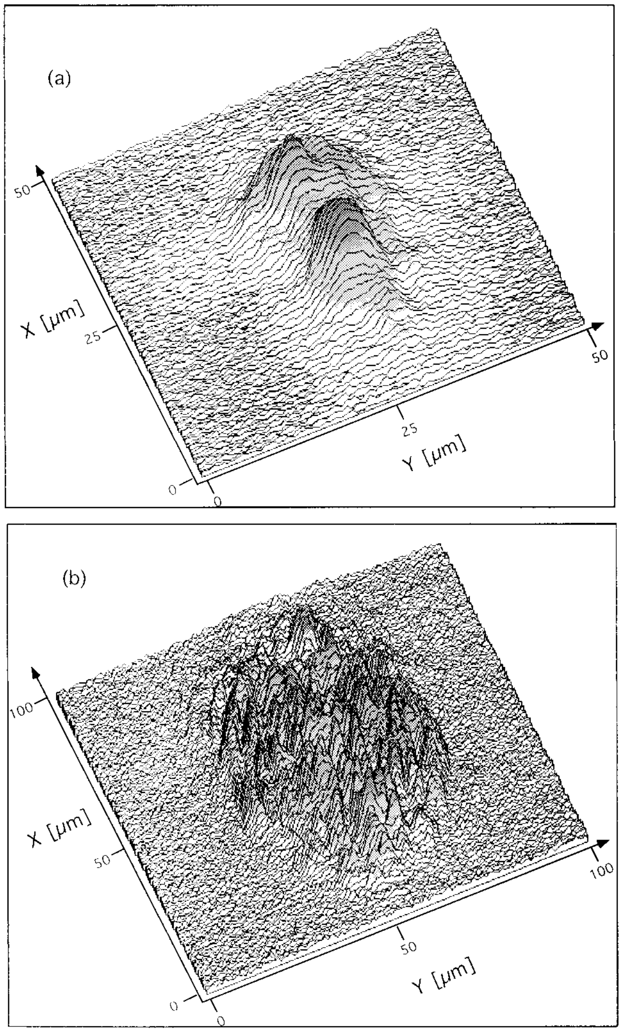

FIG. 4. Intensity profile of the beam at the output of (a) 40-μm diameter, 1.5-mm-long target; (b) 100-μm diameter, 4-mm-long target.

Images of the beam profile at the guide output provided information concerning the mode structure of the beam during propagation. While several modes were seen when the pulse propagated through 100-μm-diam guides, propagation with no more than two modes was observed through the 40-μm-diam tubes. This can be seen in Figs. 4(a) and 4(b), where the beam profiles at the end of a 40-μm-diam guide (1.5 mm long) and of a 100-μm-diam guide (4.0 mm long) are respectively shown. While the different modes present in the multimode structure of Fig. 4(b) cannot be immediately identified, the intensity pattern of Fig. 4(b) is, for example, consistent with a combination of the circular electric mode $\text{TE}_{0,1}$ and of the hybrid mode $\text{HE}_{2,1}$ [17]. The efficiency of guiding is evident if one observes that the size of the unguided beam at such axial positions is much larger, about 150 μm for the case of Fig. 4(a), and 450 μm for the case of Fig. 4(b). For comparison, the Rayleigh length defined by the focusing optics was about 500 μm. In the case of the 40-μm tube the output power is in excess of 5 TW. Again, it should be noted that, for the experimental conditions of this investigation, the limitation in transmitted power is not due to the guiding mechanism, but to the inefficient coupling to the guide. A better quality focal spot would certainly improve the coupling, allowing higher power to be transmitted through the guide.

In conclusion, efficient guiding of 10-TW, picosecond laser pulses through 40-μm and 100-μm-diam glass capillary tubes has been demonstrated over lengths up to 10 mm (i.e., substantially exceeding the Rayleigh length determined by the focusing optics). For both tube diameters, the pulse propagates with an attenuation coefficient of around 0.2 cm^{-1} and an estimated plasma-wall reflectivity of about 98–99 %. Two-mode propagation and output power up to 5 TW has been achieved through the 40-μm-diam guides. Optical probe measurements revealed that a plasma is formed on the guide wall by the rising edge of the pulse 15–20 ps ahead of the pulse peak. Beside their relevance to general applications requiring propagation of high-intensity laser pulses over several Rayleigh lengths, these results are of particular interest for possible application to the fast ignitor scheme for inertial confinement fusion, in which the ignitor pulse could be guided to the compressed core of the pellet through a solid optical guide.

The authors would like to acknowledge inspiring discussions with Dr. T. Afshar-rad, the support of the staff of the Rutherford Appleton Laboratory and, in particular, to thank Paul Bryant of Target Preparation. This work was funded by an EPSRC/MoD grant.

---

[1] E. Esarey *et al.*, IEEE Trans. Plasma Sci. **24**, 252 (1996); A. Modena *et al.*, Nature (London) **377**, 606 (1995).

[2] N. H. Burnett and G. D. Enright, IEEE J. Quantum Electron. **26**, 1797 (1990).

[3] M. Tabak *et al.*, Phys. Plasmas **1**, 1621 (1994).

[4] A. B. Borisov *et al.*, Phys. Rev. Lett. **68**, 2309 (1992); P. Monot *et al.*, *ibid.* **74**, 2953 (1995); P. E. Young and P. R. Bolton, *ibid.* **77**, 4556 (1996); M. Borghesi *et al.*, *ibid.* **78**, 879 (1997).

[5] C. G. Durfee III and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993); K. Krushelnick *et al.*, *ibid.* **78**, 4047 (1997).

[6] S. Jackel *et al.*, Opt. Lett. **20**, 1086 (1995).

[7] E. A. J. Marcatili and R. A. Schmeltzer, Bell Syst. Tech. J. **43**, 1783 (1964).

[8] M. Nisoli, S. De Silvestri, and O. Svelto, Appl. Phys. Lett. **68**, 2793 (1996).

[9] W. L. Kruer, *The Physics of Laser Plasma Interaction* (Addison-Wesley, New York, 1988), pp. 37–43.

[10] C. N. Danson *et al.*, Opt. Commun. **103**, 392 (1993).

[11] D. Du, X. Liu, G. Korn, and G. Mourou, Appl. Phys. Lett. **64**, 3071 (1994).

[12] V. L. Ginzburg, *The Propagation of Electromagnetic Waves in Plasmas* (Pergamon, New York, 1964).

[13] O. L. Landen, D. G. Stearns, and E. M. Campbell, Phys. Rev. Lett. **63**, 1475 (1989).

[14] U. Teubner *et al.*, Phys. Rev. E **54**, 4167 (1996).

[15] A. A. Andreev *et al.*, Sov. Phys. JETP **74**, 963 (1992); W. Rozmus, V. T. Tikhonchuk, and R. Cauble Phys. Plasmas **3**, 360 (1996).

[16] M. Borghesi *et al.*, Rutherford Appleton Laboratory Annual Report No. RAL-TR-95-025, 1995 (unpublished); R. Gaillard *et al.* (unpublished).

[17] T. Sawatari, in *Optical Waveguides* (Academic, New York, 1972).