Guiding of High-Intensity Laser Pulses with a Hydrogen-Filled Capillary Discharge Waveguide

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(Received 10 April 2002; published 14 October 2002)

We report guiding of laser pulses with peak input intensities greater than 10^{17} W cm^{-2} in 30 mm and 50 mm long H_2-filled capillary discharge waveguides. Under conditions producing good guiding the coupling and propagation losses of the waveguide were <4% and (7 ± 1) m^{-1}, respectively. The spectra of the transmitted pulses were not broadened significantly, but were shifted to shorter wavelength. It is concluded that this shift is not associated with significant temporal distortion of the laser pulse.

DOI: 10.1103/PhysRevLett.89.185003 PACS numbers: 52.38.Hb, 42.55.Vc, 52.38.Kd

A range of important applications such as x-ray lasers, laser wakefield acceleration, and high-harmonic generation rely on the interaction of intense laser radiation with a plasma. The laser-plasma interaction length of a focused beam is limited fundamentally by diffraction to the order of the Rayleigh range, and is often further restricted by ionization-induced refraction. In order to overcome the limitations imposed by these processes, techniques for channeling laser pulses with intensities of 10^{15} W cm^{-2} and higher must be developed.

A number of approaches for guiding intense radiation have been investigated, including guiding in hollow capillaries [1,2], relativistic channeling [3,4], and several types of plasma waveguide [5–9]. Of these, plasma waveguides are particularly promising since the medium responsible for guiding is not damaged by the laser radiation, and, in principle, they are able to guide pulses with a wide range of intensities and wavelengths.

In an ideal plasma waveguide the radial electron density profile is parabolic: $N_e(r) = N_e(0) + \Delta N_e(r/r_{\text{ch}})^2$, where $N_e(r)$ is the electron density at a distance r from the axis of the beam and ΔN_e is the increase in the electron density at $r = r_{\text{ch}}$ compared to the axial value. In the absence of further ionization of the plasma by the guided laser pulse, and where ponderomotive and relativistic effects can be neglected, a Gaussian laser beam will propagate through the guide with a constant spot radius W_M, provided $W_M = [r_{\text{ch}}^2/(\pi r_e \Delta N_e)]^{1/4}$ where r_e is the classical electron radius [10]. For the present experiments the peak normalized vector potential is less than 0.2, indicating that relativistic and ponderomotive effects may be neglected.

To date plasma waveguides have been produced by hydrodynamic expansion of a laser-produced cylindrical plasma [7], discharge or laser ablation of an initially evacuated capillary [6], and z-pinch capillary discharges [8]. However, ablation of a capillary wall does not usually produce a fully ionized plasma channel, leading to temporal and spatial distortion of the guided pulse [11], and z-pinch discharges are relatively complex and generate short-lived plasma channels. We have recently described a simple technique for producing a fully ionized plasma waveguide: the H_2-filled capillary discharge waveguide [12]. In this device, a current is pulsed through a capillary prefilled with H_2 gas. Interferometric measurements [12] and magnetohydrodynamic (MHD) simulations [13] have shown that the plasma channel produced is approximately parabolic and is essentially fully ionized.

In the first guiding experiments with this waveguide [9], we demonstrated low-loss guiding over lengths of up to 40 mm. Unfortunately, owing to the possibility of unwanted temporal structure on the input laser pulses, the peak input intensity in those experiments was uncertain by approximately an order of magnitude. With the experiments described in this Letter that uncertainty is removed. We demonstrate guiding of laser pulses over lengths of up to 50 mm for pulses with a peak input intensity of 1.2×10^{17} W cm^{-2}. The results of this experiment correspond, to our knowledge, to the lowest losses yet reported for guiding of laser pulses with peak input intensities of 10^{17} W cm^{-2} or greater. We also present the first measurements of the spectra of the pulses transmitted by a H_2-filled capillary discharge waveguide. The spectra are found not to be broadened significantly, but are shifted to shorter wavelengths. Simulations show this blueshift to be consistent with laser-induced ionization of low levels of impurity species from the capillary wall, and that the temporal profiles of the laser pulses are not distorted significantly.

Figure 1 shows schematically the design of the gas-filled capillary discharge waveguide used in the present experiments. This design differed somewhat from our earlier experiments [9,12] in that the discharge was "double ended," the main advantages being improved electrical shielding of the cathode and increased discharge length.

The alumina capillary had internal and external diameters of 400 μm and 1 mm, respectively. Slots were machined through the wall of the capillary near its ends. H_2 gas was flowed through the slots and out to the surrounding vacuum chamber, such that the steady-state pressure between the injection slots was uniform.

A stainless-steel earth electrode was located coaxially at each end of the capillary, laser radiation entering or

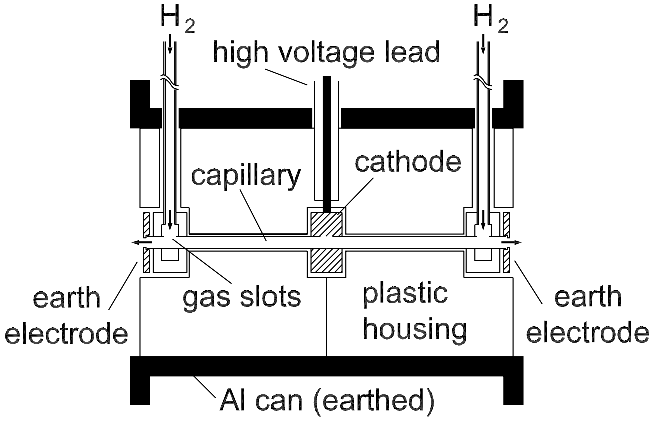

FIG. 1. Schematic diagram of the gas-filled capillary discharge waveguide used in the present experiments.

leaving the capillary through 500 μm diam holes. The cathode, also stainless steel, was located at the midpoint of the capillary. Four slots were drilled at the center of the capillary in order to allow current to flow through the capillary wall to the cathode. The discharge circuit was similar to that employed in our earlier experiments [9,12]. For the present work the storage capacitance was 7.5 nF, charged to between 17 and 30 kV. As shown in Fig. 2, the discharge current pulse had a damped, approximately sinusoidal profile, with a peak of approximately 550 A per arm and a quarter period of approximately 190 ns.

The guiding experiments used radiation of central wavelength 790 nm from the Astra Ti:Al_2O_3 laser at the Rutherford Appleton Laboratory. The experimental layout employed was as described previously, with the addition of a spectrograph located after the waveguide. Circularly polarized radiation from Astra was focused to

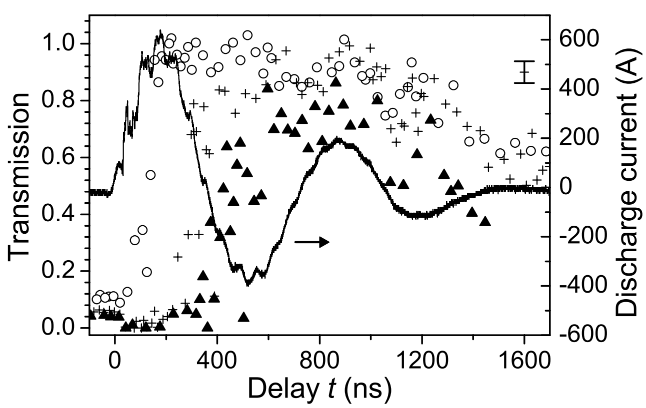

FIG. 2. Measured temporal variation of the pulse energy transmission for a 30 mm long capillary for initial H_2 pressures of 110 mbar (circles) and 330 mbar (crosses), and for a 50 mm long capillary for an initial H_2 pressure of 330 mbar (triangles). The discharge current (per arm) is also shown. A typical error bar for the measured transmission is indicated at the top right.

the entrance plane of the capillary by an off-axis parabolic mirror, used at $f/27$, to a spot of radius 31 μm. The measured Rayleigh range of the focused beam was 1.2 mm, a factor of 3.2 shorter than a diffraction-limited beam with a 31 μm waist.

The intensity of the transmitted radiation was reduced by reflections from three wedged optical flats before being imaged onto a 12-bit CCD camera. The duration of the input laser pulses was measured using a single-shot autocorrelator to be 70 ± 20 fs. Pyroelectric energy meters measured the energies of the input and transmitted laser pulses, the average energy of the laser pulses input to the capillary during the guiding experiments being 162 ± 18 mJ. The spatial profiles recorded by the CCD camera were normalized to the mean input pulse energy and converted to intensity profiles by assuming that the transmitted and input pulses were of the same duration. The peak normalized input intensity of the laser pulses used in the present experiment was $(1.2 \pm 0.4) \times 10^{17}$ W cm^{-2}.

The gas-filled capillary discharge waveguide was operated with a pulsed gas flow of duration 2.0 s, the initial H_2 pressure in the central section of the capillary being measured by a cross-calibrated gap flowmeter [12]. For the present experiments the waveguide was operated at a pulse repetition frequency of approximately 0.2 Hz, the repetition rate being limited by the pumping speed of the vacuum system.

Figure 2 shows the measured pulse energy transmission as a function of the delay t between the onset of the discharge current and the injection of the laser pulse. Data are presented for a 30 mm long capillary, with initial H_2 pressures of 110 and 330 mbar, and for a 50 mm long capillary with an initial H_2 pressure of 330 mbar. For laser pulses injected before the onset of the discharge current the pulse energy transmission was small owing to refractive defocusing in the neutral H_2. Immediately after the onset of the discharge current the transmission decreased to very low values, and remained low for up to approximately 350 ns, the duration of this delay increasing with the initial H_2 pressure. After this initial delay the transmission increased to approximately 90% and 80% for the 30 and 50 mm long capillaries, respectively. The duration of the rising edge in transmission ranged from 100 to 300 ns, the duration increasing with the initial H_2 pressure and capillary length. Once established, the high pulse energy transmission was maintained for many hundreds of nanoseconds. The level and duration of this "plateau" region of high transmission was relatively insensitive to the initial H_2 pressure. The plateau region was modulated slightly, minima in the transmission occurring at 375, 755, and 1100 ns, corresponding closely to times when the discharge current was zero.

Figure 3 shows, for various delays t and for an initial H_2 pressure of 330 mbar, the normalized transverse spatial intensity profiles for the laser pulses in the entrance

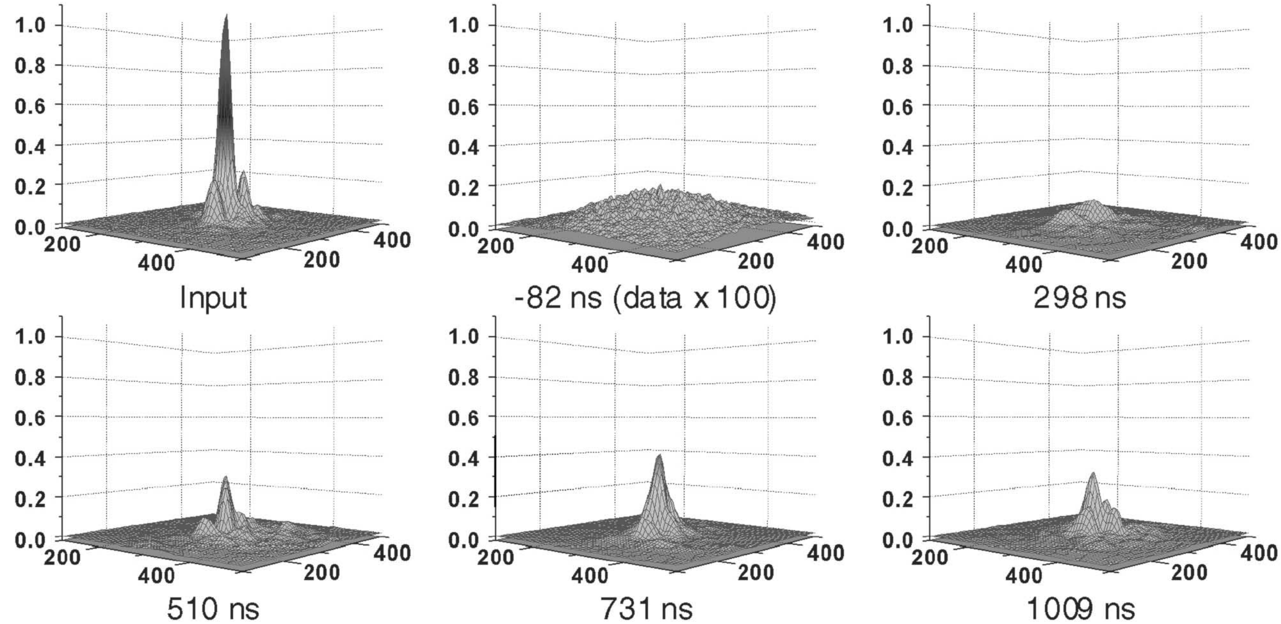

FIG. 3. Normalized transverse intensity profiles in the entrance plane of the capillary, and in the exit plane of the 30 mm long capillary for various delays t and for an initial H_2 pressure of 330 mbar. For all plots the spatial scale is in μm and the vertical scale is in units of 10^{17} W cm^{-2}. The intensity profile for $t = -82$ ns has been multiplied by 100.

and exit planes of a 30 mm long capillary. It is seen that when the laser pulse was injected prior to the onset of the discharge current the transmitted beam filled the entire aperture of the capillary, the peak intensity being nearly 3 orders of magnitude below that of the input pulse. As the discharge developed the transmitted beam was constrained to the axial region, large axial intensities being observed for delays in the range 500 to 1200 ns. For example, in Fig. 3 the pulse recorded at $t = 731$ ns had a pulse energy transmission of 83%, a spot radius of approximately 41 μm, and a peak axial intensity of 0.4×10^{17} W cm^{-2}, some 36% of that of the input pulse. For longer delays the transverse spatial extent of the pulses increased and the peak axial intensity decreased. The temporal variation of the output transverse spatial intensity profiles was broadly similar for the 50 mm long capillary, the peak axial intensities reaching 23% of that of the input pulse.

Figure 4 shows the spectra of pulses transmitted by a 30 mm long capillary for a range of initial H_2 pressures up to 330 mbar and for $t = 730$ ns, corresponding to the conditions giving the highest axial intensity of the transmitted pulses. The spectrum when the capillary was removed is also shown. It is seen that the spectral widths of the transmitted laser pulses were approximately equal to that of the input laser pulses. However, the spectra were shifted to shorter wavelengths by (12 ± 2) nm, the shift being essentially independent of the initial H_2 pressure. Similar results were obtained for 50 mm long capillaries, the wavelength shift being (22 ± 2) nm. We note that the spectra of the transmitted pulses show some modulation that varied on a shot-to-shot basis under otherwise identical conditions.

The results presented above show clearly that the H_2-filled capillary discharge waveguide is able to guide laser pulses with high peak input intensities over long lengths with high pulse energy transmission. Since the plasma channel is expected to be essentially fully ionized, ionization-induced defocusing should be negligible. In this case, longitudinal variation of the spot radius of the guided pulse is restricted to oscillations [10] arising from a mismatch between the input spot radius and W_M. Measurements and MHD simulations suggest that 33 μm$< W_M <$ 43 μm, and hence the spot radius of the

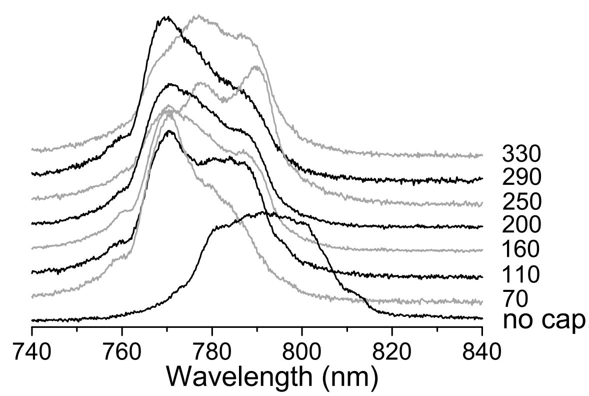

FIG. 4. Measured spectra of the transmitted laser pulses for $t = 731$ ns for a 30 mm long capillary and initial H_2 pressures in the range 70–330 mbar. The spectrum recorded by the output spectrograph with the capillary removed is also shown.

propagating pulse is expected to increase to no more than $W_M^2/W_0 = 60$ μm within the waveguide.

We now consider the extent to which the pulses transmitted by the waveguide were distorted temporally. The observed spectral blueshift was found to be essentially independent of the initial H_2 pressure, and was insensitive to the delay t, which suggests that it was not caused by laser-induced ionization of residual neutral hydrogen. However, the shift $\Delta\lambda$ in the central wavelength of the spectra of the transmitted laser pulses was approximately proportional to the length l of the capillary, a linear fit giving $\Delta\lambda[\mathrm{nm}] = -(492 \pm 200)l[\mathrm{m}] + (2 \pm 8)$.

The observed wavelength shifts can be explained by rapid ionization of impurity species introduced into the plasma from the capillary wall. The wavelength shift experienced by a laser pulse propagating through an ionizing plasma is given by [14] $\Delta\lambda = -(1/2\pi) \times (e^2\lambda_0^3/4\pi\varepsilon_0 m_e c^3) l \partial N_e/\partial t$, where λ_0 is the central (vacuum) laser wavelength and the other symbols have their usual meaning. From the linear fit of $\Delta\lambda$ versus l we find $\partial N_e/\partial t = 7 \times 10^{29}$ cm^{-3} s^{-1}. Assuming that the laser-induced ionization occurred for the 70 fs duration of the laser pulse, the associated increase in electron density is $\Delta N_e = 5 \times 10^{16}$ cm^{-3} corresponding to only 0.3% of the total electron density for an initial H_2 pressure of 330 mbar.

We have simulated [11] the propagation of the laser pulses through parabolic plasma waveguides containing low concentrations of Al and O ions. The initial ion states of Al and O formed by the discharge were calculated to be Al^{3+} and $O^{2.8+}$, by assuming Saha equilibrium. The calculated spectra of the transmitted laser pulses were found to be in good agreement with the measurements presented here for an initial Al_2O_3 density of approximately 1.5×10^{16} cm^{-3}, the calculated ΔN_e being approximately 1×10^{17} cm^{-3}, in reasonable agreement with the estimate above. The calculated temporal profiles of the transmitted laser pulses showed a slight steepening of the leading edge that was responsible for the blueshift, but the peak intensity was largely unaffected.

The data allow us to estimate the waveguide losses. For both capillary lengths investigated the peak axial intensity of the transmitted pulses was found to be greatest for $t \approx 730$ ns and an initial H_2 pressure of 330 mbar. Under these conditions the pulse energy transmission was $(82 \pm 4)\%$ and $(70 \pm 4)\%$ for the 30 and 50 mm long capillaries, respectively. Assuming that the transmission of the capillary may be modeled by $T = T_0 \exp(-\alpha l)$, we find $96\% < T_0 < 100\%$ and $\alpha = (7 \pm 1)\mathrm{m}^{-1}$. To our knowledge these results correspond to the lowest coupling and propagation losses reported for any waveguide able to guide laser pulses with peak input intensities of 10^{17} W cm^{-2} or greater.

Finally, we note that the lifetime of the capillary is long: in the present work some 10^3 high-intensity laser shots were guided through the same capillary with no degradation of guiding performance.

In summary, we have presented the first unambiguous demonstration of guiding of laser pulses with a peak input intensity above 10^{17} W cm^{-2} in a H_2-filled capillary discharge waveguide. The pulses were found to be guided with low coupling and propagation losses, and with little spatial or temporal distortion, over lengths of up to 50 mm, corresponding to 42 times the measured Rayleigh range. The simple construction of the H_2-filled capillary discharge waveguide, together with the long device lifetime, suggests that his device is well suited to applications, such as laser wakefield acceleration, requiring the propagation of intense laser pulses through fully ionized plasmas. Further, it should be possible to dope the channel with target species in order to drive x-ray lasers within the waveguide.

The authors acknowledge invaluable technical assistance from the Astra laser and target area staff at the Rutherford Appleton Laboratory. A. B. and D. J. S. are grateful to the EPSRC and Rutherford Laboratory for support. S. M. H. greatly appreciates the assistance of the Royal Society. This work was funded by the EPSRC via Grant No. GR/M88969.

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[1] S. Jackel *et al.*, Opt. Lett. **20**, 1086 (1995).
[2] F. Dorchies *et al.*, Phys. Rev. Lett. **82**, 4655 (1999).
[3] A. B. Borisov *et al.*, Phys. Rev. Lett. **68**, 2309 (1992).
[4] P. Monot *et al.*, Phys. Rev. Lett. **74**, 2953 (1995).
[5] C. G. Durfee and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993).
[6] Y. Ehrlich *et al.*, Phys. Rev. Lett. **77**, 4186 (1996).
[7] E.W. Gaul *et al.*, Appl. Phys. Lett. **77**, 4112 (2000).
[8] T. Hosokai *et al.*, Opt. Lett. **25**, 10 (2000).
[9] D. J. Spence, A. Butler, and S. M. Hooker, J. Phys. B **34**, 4103 (2001).
[10] E. Esarey *et al.*, IEEE J. Quantum Electron. **33**, 1879 (1997).
[11] D. J. Spence and S. M. Hooker, J. Opt. Soc. Am. B **17**, 1565 (2000).
[12] D. J. Spence and S. M. Hooker, Phys. Rev. E **63**, 015401 (2001).
[13] N. A. Bobrova *et al.*, Phys. Rev. E **65**, 016407 (2001).
[14] E. Yablonovitch, Phys. Rev. Lett. **60**, 795 (1988).