PHYSICAL REVIEW E, VOLUME 63, 015401(R)

Investigation of a hydrogen plasma waveguide

D. J. Spence and S. M. Hooker
Department of Physics, University of Oxford, Oxford OX1 3PU, United Kingdom

(Received 2 August 2000; published 18 December 2000)

A hydrogen plasma waveguide for high-intensity laser pulses is described. The guiding channel is formed by a small-scale discharge in a hydrogen-filled capillary. The measured lifetime of the capillary is inferred to be greater than 10^6 shots. The results of interferometric measurements of the electron density in the capillary are presented. The guiding channel is found to be highly ionized with an axial electron density of $2.7\times10^{18}\ \mathrm{cm}^{-3}$, and parabolic, the curvature corresponding to a matched spot-size of 37.5 μm.

DOI: 10.1103/PhysRevE.63.015401 PACS number(s): 52.38.−r

Optical guiding of high-intensity laser pulses can be used to increase the laser-plasma interaction length in applications such as harmonic generation [1], laser wake-field accelerators [2,3], and x-ray lasers [4,5]. In the absence of such guiding, the interaction length is at most of the order of the Rayleigh range, and in many cases is further limited by ionization-induced refractive defocusing.

A promising class of waveguide for high intensity laser pulses is the plasma waveguide, in which, ideally, the radial electron density profile of the plasma is parabolic: $N_e(r)=N_e(0)+\Delta N_e(r/r_m)^2$, where $N_e(0)$ is the axial electron density and ΔN_e is the increase in the electron density at radius $r=r_m$. 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 pulse will propagate through the guide with a constant spot-size W_M, provided $W_M=[r_m^2/(\pi r_e \Delta N_e)]^{1/4}$, where r_e is the classical electron radius. Here spot-size is defined as the radius at which the pulse intensity is $1/e^2$ of the peak value.

Plasma channels suitable for guiding may be formed in several ways. Durfee and Milchberg generated a plasma waveguide in argon following the hydrodynamic expansion of a laser-produced cylindrical spark [6]. Using this technique guided propagation of pulses with intensities up to $5\times10^{16}\ \mathrm{W\,cm}^{-2}$ has been demonstrated over 15 mm, with a pulse transmission of 52% [7]. Volfbeyn *et al.* have created similar channels in hydrogen and in nitrogen using an extension to this scheme employing two lasers [8].

Hosokai *et al.* have observed the creation of a transient plasma channel during the implosion phase of a Z-pinch discharge through a He-filled capillary [9]. By driving a 4.8 kA current pulse rising in 15 ns through the preionized gas, a 70-μm-wide channel was formed 8.5 ns after the initiation of the discharge.

Suitable channels have also been formed by passing slow electrical discharges through initially evacuated polypropylene ($[CH_2]_n$) capillaries [10–12]. In such discharge-ablated capillary waveguides, a discharge current of several hundred amps ablates the capillary wall, and heats and ionizes the resulting plasma to form an approximately parabolic radial electron density profile. In these devices the ablation of the capillary wall results in a finite capillary lifetime, which for polypropylene capillaries is only several hundred shots. Furthermore, owing to the relatively low plasma temperature achieved in the capillary, the plasma is only partially ionized, being composed of H^+, C^+, and C^{2+}. For guided laser pulses with intensities between 10^{14} and $5\times10^{17}\ \mathrm{W\,cm}^{-2}$, ionization-induced defocusing severely impairs the guiding performance of the waveguide, causing strong oscillations of the laser spot-size as a function of propagation distance [13].

Partially ionized plasma waveguides offer greatly improved guiding performance in a regime of quasimatched guiding [13]. Consider a waveguide with a parabolic ion density profile and an initial average ionization of Z_I^*, with a matched spot size of W_M. If the plasma ions are ionized by the guided laser pulse to an ion stage Z_F^* which is stable against further ionization, then a laser pulse with a peak intensity of several hundred times the threshold for creation of that stable ion stage will experience quasimatched guiding. In this regime the leading edge of the pulse creates a wide plateau of the stable ion stage out to a radius significantly greater than the spot size. Within that radius the electron density is raised from the initial value, but maintains a parabolic profile so that the bulk of the pulse experiences a modified guiding electron density profile. The raised parabolic region has a modified matched spot size $W_{\mathrm{QM}}=W_M(Z_I^*/Z_F^*)^{1/4}$.

The intensity range over which quasimatched guiding can be achieved will be particularly wide for a plasma waveguide in hydrogen, since H is fully ionized at a relatively low intensity. For example, for a 50-fs pulse hydrogen is field-ionized to $Z_F^*=0.99$ for a peak pulse intensity of only $2.3\times10^{14}\ \mathrm{W\,cm}^{-2}$. Quasimatched guiding is expected to occur at intensities significantly greater than this, i.e., of the order of $5\times10^{16}\ \mathrm{W\,cm}^{-2}$ and above.

In the present Rapid Communication we describe a hydrogen plasma waveguide formed by a slow discharge through a H-filled capillary. We present the measurements of the electron density, and show that this simple device is able to generate a stable, approximately parabolic electron density profile in a hydrogen plasma with an average ionization Z_I^* of between 0.87 and 1. We present numerical simulations that show that high-quality quasimatched guiding could be achieved over long distances for pulses with peak intensities greater than approximately $5\times10^{16}\ \mathrm{W\,cm}^{-2}$.

Figure 1 illustrates schematically our design of a gas-filled slow capillary discharge waveguide. The capillary is an alumina (Al_2O_3) tube with an inner-diameter of 300 μm. In order to introduce gas into the volume of the capillary, one or more groups of nine closely spaced holes, each 50 μm in diameter, are micromachined through the capillary wall us-

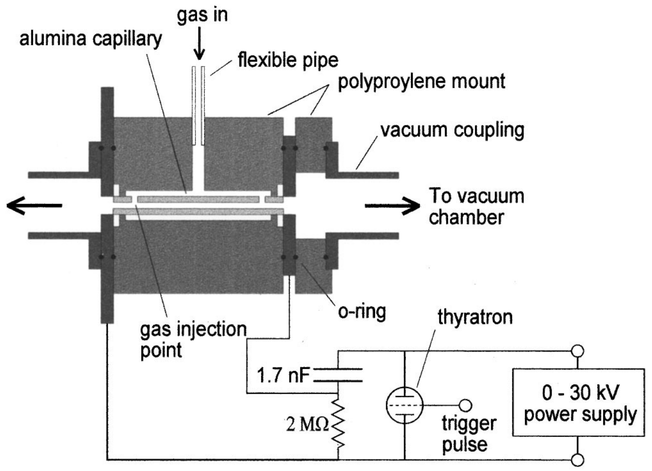

FIG. 1. Schematic diagram of the gas-filled slow capillary discharge, and the associated discharge circuit.

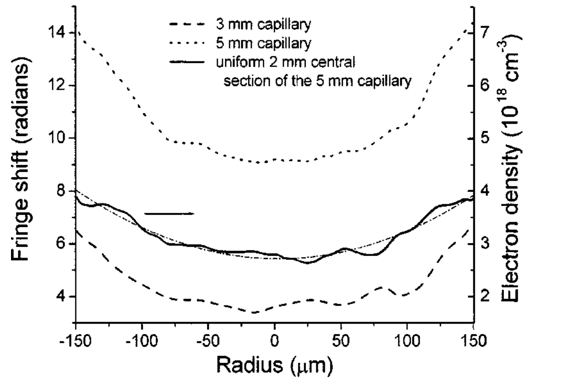

FIG. 2. Fringe shifts measured for 3-mm- and 5-mm-long capillaries. The calculated fringe shift caused by the uniform 2-mm-long central section of the 5-mm capillary is also shown, along with a parabolic fit, as described in the text. The right-hand axis shows the deduced electron density for the central 2-mm-long section.

ing a copper vapor laser. Stainless steel disk electrodes are fixed coaxially at either end of the capillary. After evacuation, gas can be flowed through the micromachined holes into the bore of the capillary, and out to the vacuum chamber.

For long capillaries, gas is injected through the side-wall of the capillary at two points, spaced 1.5 mm from either end. The flow reaches a steady state in which the pressure in the section of capillary between the injection points is axially uniform, while between each injection point and the capillary exit the pressure drops to the background pressure of the vacuum chamber. The hydrogen flow rate was measured using a flow meter, and was set to 300 cm^3 min^{-1} for all experiments described here.

The discharge circuit, shown schematically in Fig. 1, consists of a 1.7 nF capacitor charged to a voltage of between 10 and 25 kV, depending on the capillary length. The discharge is initiated by switching the positive side of the capacitor to ground. The discharge current is found to be an approximately half-sinusoidal pulse with a full width of 200 ns, and a peak of 300 A. Note that, unlike the work of Hosokai *et al.* [9], for such slow discharges the pinch effect is negligible.

We have measured the electron density profile generated in the waveguide using longitudinal interferometry. The apparatus employed has been described previously [14], but, briefly, is as follows. The capillary waveguide is placed coaxially in one arm of a Mach-Zehnder interferometer, illuminated by 355-nm, 8-ns pulses from a neodymium-doped yttrium aluminum garnet laser. Virtual wedge fringes in the exit plane of the capillary are imaged onto a charge-coupled-device camera, and the interference patterns recorded as a function of time t throughout the discharge pulse. The radial electron density profile of the capillary plasma is deduced from analysis of the fringe patterns.

Deflection of the 355-nm probe beam inside the waveguide limits to only a few millimeters the maximum capillary length that can be probed. It is not therefore possible to undertake interferometric measurements using a capillary that is sufficiently long for end effects to be small. Instead, measurements were performed for capillaries of two different lengths. One was a 3-mm-long capillary with a single gas injection point at the capillary center. The second was a 5-mm-long capillary with two injection points, 1.5 mm from either end. In each case the hydrogen flow rate were set to the same value. The form of the discharge current was found to be the same for both capillary lengths. The measurements on the short capillary serve to record the fringe shift caused by the end effects in the capillaries. The long capillary is assumed to cause that same fringe shift plus an extra fringe shift due to the additional axially uniform 2-mm-long section between the injection points. Hence, from these two measurements we can recover the electron density profile in the central section of the capillary. It is this profile that will be created in the uniform central section of longer capillaries which can usefully be used as waveguides.

The fringe shifts are found to be approximately radially symmetric. Figure 2 shows the fringe shifts measured along a capillary diameter for the 5-mm- and 3-mm-long capillaries at $t \sim 60$ ns after the initiation of the discharge, averaged over several shots to reduce noise due to small random shifts of the fringe patterns. The standard deviation of the measured fringe shift was typically 5%. Figure 2 also shows the fringe shift due to the 2-mm-long section in the center of the 5-mm-long capillary, obtained by subtracting these curves. The right-hand axis shows the radial electron density profile in the central section, assuming that the refractive index of the plasma is dominated by free electrons. The recovered electron density profile is fit by $N_e(r)[10^{18}\ \mathrm{cm}^{-3}] = 2.72 + 1.29(r[\mu\mathrm{m}]/150)^2$, shown in Fig. 2, corresponding to a matched spot-size $W_M = 37.5\ \mu$m.

The guiding channel was observed for $t > 30$ ns, and persisted throughout the discharge current pulse with little change in the channel parameters. The axial electron density was found to be at its highest approximately 30 ns after the onset of the discharge, thereafter decaying to zero on a time scale of the order of 650 ns, caused by the hydrogen plasma being expelled from the capillary. It is clear, therefore, that in the results presented in Fig. 2 for $t \sim 60$ ns, there was not time for significant longitudinal changes to occur in the ion and neutral density from that prior to the discharge pulse.

Consequently, the end effect for the 3-mm capillary will be similar to that of the 5-mm capillary, and hence our procedure for eliminating the end effect is correct. Furthermore, since the initial hydrogen density is uniform between the gas injection points, the plasma waveguide will also have a uniform guiding profile in its central section.

The channel is formed due to cooling of the plasma at the walls of the capillary which creates a radially decreasing temperature. Equilibration of pressure across the diameter of the capillary diameter is expected to occur on a time scale of order 10 ns, and hence the temperature profile is associated with a radially increasing plasma density. Longitudinal transport occurs on a time scale much slower than that of radial equilibration, and hence, is not expected to play a significant role in the channel formation in the middle of the capillary.

In our analysis of the fringe shifts we have assumed that the refractive index of the plasma is dominated by free electrons, and that the contribution of ions to the refractive index is negligible. We confirmed that this was the case by performing measurements at wavelengths of 532 and 355 nm, and demonstrating that the observed fringe shift was proportional to wavelength [14].

As discussed above, the degree of initial ionization Z_I^* of the plasma channel is vital in determining the performance of the waveguide. In order to determine Z_I^* for the plasma measured above, it is necessary to know the initial neutral gas density in the capillary. We have measured the gas density in a 20-mm-long capillary, with the gas injection points located 1.5 mm from each end. Using the same flow rate as for the measurements presented above, and hence the same gas pressure in the central section of the capillary, we measured and tracked the fringe shift that occurs when hydrogen is flowed into an evacuated capillary and reaches a steady-state pressure. The longer capillary length was used for this measurement since the refractive index of neutral hydrogen gas is much smaller than that of the plasma. For a flow rate of 300 $cm^{-3}\ min^{-1}$, the H_2 density was measured to be $1.68\times10^{18}\ cm^{-3}$, corresponding to a pressure of 67.0 mbar at room temperature. Using the radial profiles presented above for $t\sim60$ ns we calculate the volume-averaged electron density to be $3.33\times10^{18}\ cm^{-3}$. Assuming that H_2 is fully dissociated by the discharge, we therefore deduce that $Z_I^*=0.99$. The error associated with this measurement, caused mainly by jitter of the fringe patterns during data collection and the accuracy to which the hydrogen flow rate could be set, is estimated to be $\pm12\%$. Hence we conclude that for the plasma in the central 2-mm section of the 5-mm-long capillary, Z_I^* was between 0.87 and 1.

We have determined the lifetime of the 5-mm-long capillary used in the above measurements, under the same hydrogen flow conditions and with the same discharge current. After 10^5 discharge shots, the increase in the capillary diameter was measured to be less than 1 μm. Since an increase of the capillary diameter by 5% will not significantly affect the generated electron density, the capillary will have a lifetime of greater than 10^6 shots. Furthermore, using a capillary ablation rate of 1 μm in 10^5 shots we can calculate that Al and O atoms ablated from the walls can in total account for at most 0.3% of the plasma ions. These impurities will be ionized to Al^{9+} and O^{6+} by a guided laser pulse of intensity of order $10^{18}\ W\,cm^{-2}$, and hence can contribute at most 2.5% of the plasma electrons. This is sufficiently small that the impurities will not affect the properties of the waveguide.

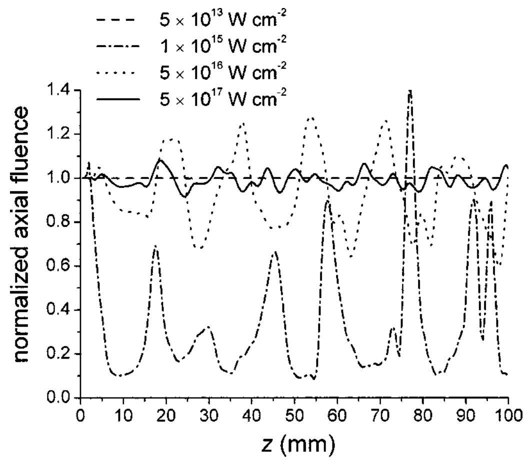

FIG. 3. Calculated axial fluence of intense laser pulses as a function of propagation distance z through the parabolic plasma channel measured for our device, assuming $Z_I^*=0.87$. The results for a range of input intensities are shown. The fluence is normalized to that at the capillary entrance.

We have performed numerical simulations of the propagation of laser pulses in the waveguide characterized above. The numerical code, described previously [13], accounts for further ionization of the plasma waveguide by the propagating pulse, but neglects relativistic effects and plasma motion [15], and modulation instabilities due to bound electrons [16]. Simulations were performed for a longitudinally uniform waveguide with the parabolic radial electron density measured above. The initial ionization Z_I^* of the waveguide was set to 0.87, which is the lowest value consistent with our measurements. Figure 3 shows the calculated normalized axial fluence as a function of propagated distance z for pulses of several different peak intensities. The simulations assume a pulse with a wavelength of 800 nm, and a $sech^2$ temporal profile of 50 fs full width at half maximum. The pulse is taken to be focused at the waveguide entrance with a waist size set to $W_M=37.5$ μm for the pulse of intensity $5\times10^{13}\ W\,cm^{-2}$, but set to $W_{QM}=36.2$ μm for the more intense pulses. It is seen that the waveguide is capable of matched guiding at $5\times10^{13}\ W\,cm^{-2}$, since the plasma is unperturbed by the laser pulse. However, at an intensity of $1\times10^{15}\ W\,cm^{-2}$ the spot-size of the pulse shows strong oscillations as a function of z, due to ionization-induced defocusing. Quasimatched guiding is achieved for peak intensities greater than approximately $5\times10^{16}\ W\,cm^{-2}$. For example, the simulation for a peak intensity of $5\times10^{17}\ W\,cm^{-2}$, corresponding to a pulse energy of 450 mJ, shows very stable quasimatched propagation, with a calculated transmission of 99% over a distance of 100 mm (19.4 Rayleigh ranges).

It is seen that in the quasimatched regime losses due to ionization and interaction with the capillary wall are very small, and furthermore, since the majority of the laser pulse experiences a fully ionized plasma, modulational instabilities due to bound electrons should not be significant. As such the waveguide presented here is an almost ideal plasma waveguide, since any additional losses or instabilities are inherent to plasmas of this density.

The waveguide we have described offers a number of advantages over other techniques. The small-scale discharge circuit is simple and compact. We have operated our waveguide with capillaries up to 60 mm. Longer capillaries will require voltages of greater than 25 kV in order to break down the neutral gas. Since the guiding profile remains stable for ~100 ns, there are no difficulties with injecting the laser pulse at the optimum time, unlike for *Z*-pinch capillary waveguides. By operating at higher initial gas pressure, it is possible to create a waveguide with a smaller W_M. However, it is not possible to characterize such waveguides using the present technique since the increased curvature of the waveguide significantly distorts the probe beam. The longitudinal profile of the waveguide is uniform, thereby allowing true matched guiding along the whole length of the capillary. Finally, the long capillary lifetime, in excess of 10^6 shots, will be important in practical applications.

The hydrogen-filled slow capillary discharge waveguide would seem to be ideal for use in guided laser wakefield acceleration schemes. For example, simulations have shown that a 40-TW laser pulse can accelerate a trailing electron bunch from 1 MeV up to 1 GeV, when guided for 20 cm in a waveguide with a parabolic electron density profile [3].

Our measurements on capillaries filled with either argon or helium show qualitatively similar guiding profiles developing in the same way as those presented above for hydrogen. The prospect of forming a waveguide in an arbitrary gas, or even a mixture of gases, has important implications. For example, a waveguide created in hydrogen gas doped with a small partial pressure of a lasant gas would be capable of high quality guiding. This would allow longitudinal pumping of novel x-ray lasers over much greater lengths than can be achieved in the absence of such guiding [5]. Alternatively, a waveguide could be created in a pure lasant gas. For x-ray lasers in which the lasant ion is sufficiently stable against further ionization (e.g., Ar^{8+}), quasimatched guiding would generate a core of lasant ions along the capillary axis over long lengths.

In summary, we have investigated a hydrogen plasma waveguide formed by a slow discharge in a hydrogen-filled capillary. Using time-resolved interferometry we have demonstrated the formation of a guiding channel in a pure, almost fully ionized hydrogen plasma. Gas-filled capillary discharge waveguides of this type promise to be a versatile tool for extending the laser-plasma interaction length in many applications.

We would like to thank D. W. Coutts for his assistance with laser micromachining. D. J. Spence acknowledges the support of EPSRC, and the Rutherford Appleton Laboratory. S. M. Hooker is grateful to the Royal Society for their support.

[1] H. M. Milchberg, C. G. Durfee, III, and T. J. MacIlrath, Phys. Rev. Lett. **75**, 2494 (1995).
[2] E. Esarey, P. Sprangle, J. Krall, and A. Ting, IEEE Trans. Plasma Sci. **PS-24**, 252 (1996).
[3] E. Esarey *et al.*, Phys. Fluids B **5**, 2690 (1993).
[4] D. V. Korobkin, C. H. Nam, and S. Suckewer, Phys. Rev. Lett. **77**, 5206 (1996).
[5] B. E. Lemoff *et al.*, Phys. Rev. Lett. **74**, 1574 (1995).
[6] C. G. Durfee and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993).
[7] S. P. Nikitin, I. Alexeev, J. Fan, and H. M. Milchberg, Phys. Rev. E **59**, R3839 (1999).
[8] P. Volfbeyn, E. Esarey, and W. P. Leemans, Phys. Plasmas **6**, 2269 (1999).
[9] T. Hosokai *et al.*, Opt. Lett. **25**, 10 (2000).
[10] Y. Ehrlich *et al.*, Phys. Rev. Lett. **77**, 4186 (1996).
[11] D. Kaganovich *et al.*, Phys. Rev. E **59**, R4769 (1999).
[12] S. M. Hooker, D. J. Spence, and R. A. Smith, J. Opt. Soc. Am. B **17**, 90 (2000).
[13] D. J. Spence and S. M. Hooker, J. Opt. Soc. Am. B **17**, 1565 (2000).
[14] D. J. Spence, P. D. S. Burnett, and S. M. Hooker, Opt. Lett. **24**, 993 (1999).
[15] W. B. Mori, IEEE J. Quantum Electron. **33**, 1942 (1997).
[16] P. Sprangle, B. Hafizi, and J. R. Penano, Phys. Rev. E **61**, 4381 (2000).