Guiding of high-intensity laser pulses in a hydrogen-filled capillary discharge waveguide

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Introduction

Optical guiding of laser pulses with intensities of 10^{15} W cm^{-2} or greater is important for increasing the laser-plasma interaction length in applications such as harmonic generation1), laser wakefield accelerators2,3), and x-ray lasers4,5). A wide variety of techniques for guiding intense laser pulses has been investigated, including grazing-incidence reflection at the walls of a hollow capillary tube6-8), relativistic and ponderomotive channelling9,10), and several types of plasma waveguide11-19). However, no single approach has been shown to be capable of guiding high-intensity laser pulses over long lengths with low coupling and propagation losses, minimal distortion of the duration or spectral content of the pulse, and a long device lifetime.

In the present paper we report the first demonstration of guiding of high-intensity laser pulses in a new type of plasma waveguide: the hydrogen-filled capillary discharge waveguide20). We have achieved guiding of femtosecond laser pulses with a peak input intensity of greater than 10^{16} W cm^{-2} through 20 and 40 mm-long hydrogen-filled capillaries, with pulse energy transmissions of approximately 90% and 80% respectively. The waveguide also has a long shot lifetime: in these experiments more than 10^3 laser pulses were guided though the same device.

Before describing our experiments, we briefly discuss the background to this work. In an ideal plasma waveguide a channel is formed in which the radial electron density profile is parabolic: $N_e(r) = N_e(0) + \Delta N_e(r/r_{ch})^2$, where $N_e(r)$ is the electron density at radius r. 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 though the guide with a constant spot-size W_M, provided that $W_M = [\ r_{ch}^2 / (\pi r_e \Delta N_e\ )\ ]^{1/4}$, where r_e is the classical electron radius. Plasma waveguides have been formed by hydrodynamic expansion of a laser-produced cylindrical plasma11-14), ablation of a capillary wall by a slow electrical discharge15-17), and formation by the pinch effect in a fast capillary discharge18-19).

The hydrogen-filled capillary discharge waveguide

The hydrogen-filled capillary discharge is illustrated schematically in the inset to Fig. 1. The two electrodes were mounted at the ends of an alumina capillary of internal diameter 300 μm. Gas was flowed into the capillary through two groups of six, 50-μm diameter holes located 2 mm from each end of the capillary. The discharge was initiated by switching a thyratron so as to connect across the electrodes a 1.7 nF capacitor charged to a voltage between 20 kV and 30 kV.

We have previously measured the radial electron density profile formed in this device and found it to be approximately parabolic20), with a matched spot size of 37.5 μm. The average ionization Z^* of the plasma for $t = 60$ ns after the initiation of the discharge was determined from these measurements to be $0.99^{+0.01}_{-0.12}$.

Magneto-hydrodynamic (MHD) simulations21) of the electron density profiles are in good agreement with the measurements, and demonstrate that under the conditions of the present experiment the pinch effect is negligible. Instead, the guiding electron density profile is formed by conduction of heat to the capillary wall by the plasma electrons. Since radial pressure variations are rapidly equalized, the radially-decreasing plasma temperature corresponds to a radially-increasing electron density. The simulations show the guiding channel to be parabolic near the axis, and predict the hydrogen to be fully ionized for $t > 55$ ns.

Guiding experiments

Figure 1 shows the experimental arrangement employed for the present experiments. Pulses from the Astra Ti:Al$_2$O$_3$ laser at the Rutherford Appleton Laboratory were focused at the entrance of the capillary by a 1.6-m focal-length off-axis paraboloid used at f/27. Considerable care was taken to remove small amounts of astigmatism in the Astra beam by reflecting it from a mirror with an adjustable radius of curvature in one (chosen) dimension. As a result, a high-quality focus was achieved with a measured spot size of 29 μm and $M^2 \approx 3$. During the present experiments the average pulse energy of the laser was 230 mJ. The pulse duration (FWHM) was measured to be (120 ± 40) fs.

The measured energy, duration, and spot size of the input laser pulses correspond to a mean peak input laser intensity of 1×10^{17} W cm^{-2}. However, several months after the completion of our experiments it was discovered that, under certain conditions, the pulses output by the Astra laser system contained significant temporal structure: a train of approximately 8 short pulses separated in time by ~ 100 ps. It is not known whether or not this unwanted temporal structure was present during our experiment. However, even if it had been, the peak intensity of the most intense of the sub-pulses would have been greater than 10^{16} W cm^{-2}.

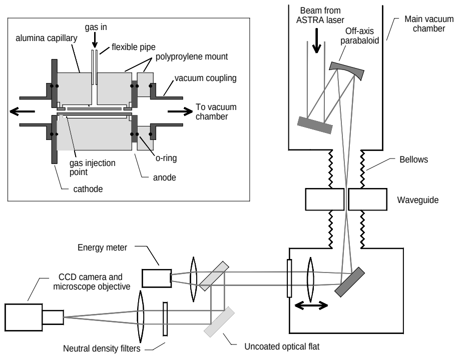


Figure 1. Schematic diagram of the experiment. Inset: Schematic diagram of the hydrogen-filled capillary discharge waveguide.

Radiation leaving the capillary was reduced in intensity by reflections from wedged optical flats and imaged onto a CCD camera. The pulse energy transmission T was measured using energy meters located behind beam-splitters placed before and after the capillary.

For each shot, hydrogen was either flowed into the capillary continuously, or pulsed for 2 s, commencing 1 s before the discharge was initiated.

Results

Figure 2 shows the measured transmission as a function of the delay t for a 20 mm-long capillary waveguide, together with the temporal variation of the discharge current, for a hydrogen pressure of 67 mbar. Note that the small current pulse prior to the main current arose from charging of the coaxial cable connecting the electrodes to the rest of the circuit, and did not pass through the capillary.

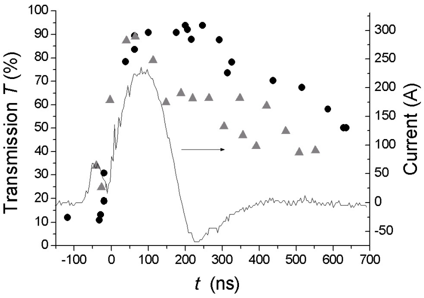


Figure 2. Measured transmission *T* as a function of the delay *t* for 20 mm (circles) and 40 mm (triangles) long capillaries. The solid line shows the discharge current for the 20 mm-long capillary.

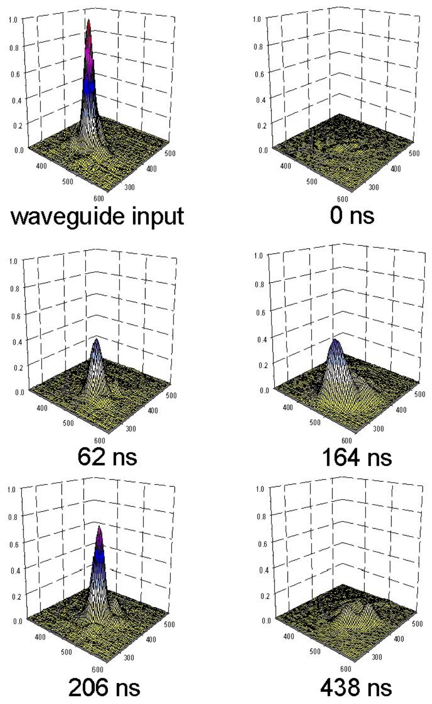
For the 20 mm-long capillaries it is seen that prior to the initiation of the discharge *T* is approximately 12%, the low transmission resulting from ionization-induced defocusing of the laser pulse by the neutral hydrogen inside the capillary. The transmission rises to approximately (90 ± 3)% within 60 ns of the onset of the current pulse, and is maintained at this value for *t* up to approximately 270 ns. For longer delays *T* decreases slowly.

Figure 2 also shows the measured temporal variation of *T* for a 40 mm-long capillary. In order to achieve gas breakdown the charging voltage of the storage capacitor was increased to 30 kV, limited by the thyratron, and the initial hydrogen pressure was reduced to 30 mbar. The temporal profile of the discharge current was very similar to that recorded with the 20 mm capillary, the peak current being 300 A. However, the discharge breakdown was less reliable, which may explain the increased scatter in *T*. It is seen that for the 40 mm capillary the temporal variation of *T* is broadly similar to that of the 20 mm capillary, although the duration of very high transmission appears to be shorter. The best transmission occurs for *t* between approximately 40 and 120 ns, during which *T* = (80 ± 5)%.

Figure 3 shows transverse intensity profiles of the laser pulse measured in the plane of the capillary entrance (with the capillary removed), and in the exit plane of the 20 mm-long capillary for several values of *t*. It is seen that prior to the onset of the discharge current the transmitted laser pulse energy is low, and distributed across the entire diameter of the capillary. For *t* > 0 the transmitted pulse energy initially increases with *t*, and becomes constrained to the axial region of the capillary. For example for the pulse recorded at *t* = 206 ns, the output beam spot size is 33 µm, *T* = 92%, and the peak axial fluence is 70% of that of the input laser pulse. For longer delays the transmission and spot size of the exiting beam decrease and increase respectively.

Discussion of results

Our previous measurements and MHD simulations have shown that the guiding electron density profile is formed within 60 ns of the onset of the discharge current. This is consistent with the observed rapid increase in *T* immediately after the onset of the discharge. The MHD simulations show that the curvature of the electron density profile evolves only slowly during the current pulse. This explains the fact that for the 20 mm capillary high pulse energy transmission is maintained for approximately 200 ns before a decrease in the degree of ionization, loss of plasma, and changes in the curvature of the electron density profile cause the transmission to be reduced, and the transverse profile of the transmitted beam to deteriorate. It is likely that changes in the guiding electron profile are more critical when guiding over 40 mm, which may be the reason that the very high transmission was found to last for a shorter interval in this case.



waveguide input

0 ns

62 ns

164 ns

206 ns

438 ns

Figure 3. Fluence profiles of the pulses transmitted through a 20 mm-long capillary as a function of the delay *t*, together with that of the input pulses. The profiles have been normalized to the mean peak fluence of the input pulses.

It should be emphasized that the plasma channel formed by the hydrogen-filled capillary discharge waveguide is essentially fully ionized, and parabolic. As such ionization-induced defocusing will not occur, and the channel should operate as an almost perfect plasma waveguide. Any mis-match between the input spot size W_0 of the laser pulses and the matched spot size W_M of the waveguide will cause the spot size of the guided laser pulse to oscillate with propagation distance, but the corresponding oscillations in the axial intensity of the guided pulse are relatively small.

Since the guiding channel is essentially fully ionized, temporal distortion of the pulse due to ionization should not occur, and pulse-stretching is restricted to modal dispersion (if the input spot size is mis-matched), and group velocity dispersion (GVD) in the plasma. Calculations show that pulse-stretching caused by GVD is less than 1 fs for the conditions of the present experiment.

As discussed above, it is not known whether unwanted temporal structure on the laser pulses was present during our experiments. However, since the plasma channel is essentially fully ionized, the effect of any individual sub-pulse on the plasma channel would have been negligible: the peak intensity of any sub-pulse would have been too low for any movement of the plasma by the ponderomotive force to occur; and heating of the plasma by ionization, or by inverse bremsstrahlung heating, would be insignificant. Hence, it is expected that if such temporal structure were present each sub-pulse would propagate through the plasma independently. The fact that for the 20 mm-long capillaries the measured pulse transmission was as high as 90% is further evidence for this.

Finally, we note that during these experiments more than 10^3 laser pulses were guided through a single 20 mm capillary at the full input intensity, with no apparent degradation of the guiding performance.

Conclusions

The hydrogen-filled capillary discharge waveguide combines several important features. The plasma channel is composed of fully ionized hydrogen, and so does not suffer from ionization-induced de-focusing22), or temporal and spectral distortion of the laser pulse. The device is relatively simple: no auxiliary lasers are required; and because the plasma channel is long lived, the discharge circuit does not require very low jitter triggering. Furthermore, since the capillary is not ablated by the discharge current, the capillary lifetime is long.

In summary, we have reported the first demonstration of the guiding of high-intensity laser pulses in a new type of waveguide: the hydrogen-filled capillary discharge waveguide. Low-loss guiding of femtosecond laser pulses with a peak input intensity of greater than 10^{16} W cm^{-2} was demonstrated. More than 10^3 laser pulses were guided though the same device with no degradation of the guiding performance.

Finally, we note that very recently we have completed new guiding experiments with the Astra laser in which the unwanted temporal structure, which may have existed in the present experiments, is known not to have occurred. An initial analysis of those results indicates that laser pulses with a peak input intensity of at least 10^{17} W cm^{-2} were guided over distances of up to 50 mm with a pulse energy transmission similar to that reported here. These new results will be described in more detail in a future publication.

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