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High efficiency guiding of terawatt subpicosecond laser pulses in a capillary discharge plasma channel

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Transmission efficiencies in excess of 75% were obtained in the optical guiding of subpicosecond, terawatt laser pulses in a 2-cm-long capillary discharge plasma channel at the Naval Research Laboratory. The guided laser beam size at the exit of the channel was measured using far field imaging and Thomson scattering techniques. The guided laser intensity was $>1\times10^{17}\,\mathrm{W/cm^2}$ at a guided beam diameter of 35 μm for a propagation length of 22 Rayleigh ranges. There is evidence that the plasma channel extends beyond the ends of the capillary and affects the far field beam structure of the transmitted laser pulse.

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Optical guiding of intense, subpicosecond laser pulses is important to many applications, such as laser based high energy particle accelerators [1–3] and laser pumped short wavelength coherent radiation generation [4–7]. These applications require optical guiding since an extended interaction distance between the laser and the active medium is crucial to their efficient operation. For example, in the laser wakefield accelerator (LWFA) with no optical guiding, the acceleration distance is governed by the Rayleigh diffraction length of the laser, the length over which the laser has sufficient intensity to generate large amplitude wakefields in the plasma, typically hundreds of micrometers. In spite of the extremely high acceleration gradient (>1 GeV/m) of the LWFA, the final energy of the accelerated electrons is severely limited by the relatively short Rayleigh length of the intense laser pulse that generates the wake field. Another example is the coherent generation of short wavelength radiation in laser plasma interactions, such as harmonic generation [4,5] and x-ray lasers [6,7]. Substantial gain of the laser excited radiation in the plasma can be obtained only if the gain medium has enough length for amplification of the radiation. Extended plasma regions can be obtained with line focusing of very high energy laser pulses, available only at a limited number of institutions [8]. With optical guiding, interaction distances much longer than the Rayleigh length can be achieved with laser pulses of modest energy.

Extended propagation of a laser pulse in plasma to beyond Raleigh diffraction lengths can be achieved with a preformed plasma channel [9–12]. The plasma density is lower in the center of the channel leading to a higher index of refraction. Such a refractive index profile results in optical guiding similar to guiding in gradient index optical fibers. A very promising way of producing a performed plasma channel that can optically guide high-power, subpicosecond laser pulses is by the use of a capillary discharge formed plasma channel. In a previous experiment, Ehrlich *et al.* [12] demonstrated the guiding of a subterawatt, intense laser beam ($10^{16}\,\mathrm{W/cm^2}$, 4 mJ, 100 fsec), focused into a single capillary discharge with ~75% transmission efficiency. Optical guiding of terawatt laser pulses in glass capillaries was previously reported [13], but the transmission efficiency was limited to ~25% for a 2-cm-long capillary. In this Rapid Communication, we are reporting the guiding at high efficiency and high intensity of terawatt laser pulses from the Naval Research Laboratory (NRL) subpicosecond T^3 laser in a 500-μm core diameter, 2-cm-long double capillary discharge plasma channel. The energy transfer efficiency, output mode structure, and the guided laser beam size at the exit of the channel were measured. We found evidence that, at the terawatt power level, even in the absence of the discharge, the laser was guided by a plasma channel that could be formed when the laser ablated the capillary wall. However, the degree of optical guiding was dramatically improved when the plasma channel was generated by the high voltage discharge. We also discovered that the plasma column that extends beyond the exit end of the capillary discharge strongly affects the propagation behavior of the guided laser pulse as it exits the capillary.

The experimental setup of the optical guiding experiment is shown in Fig. 1. The capillary used was a double capillary that allowed easy control of the plasma channel density and profile in order to get the best conditions for guiding [14,15]. The double capillary has been shown to perform well for hundreds of shots. It was composed of two collinear capil-

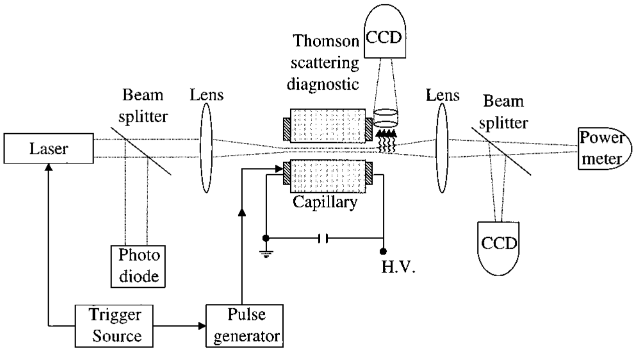

FIG. 1. Setup of experiment for laser guiding in a double-capillary plasma channel.

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laries that were attached together with a ''trigger'' electrode between them and two other electrodes on the opposite ends of each capillary. The first capillary, the trigger capillary, was 3-mm long and 500 μm in diameter. It was at the laser injection end of the double capillary. The second capillary was the ''main'' capillary with a length of 17 mm and also 500 μm in diameter (the length and diameter could be varied). The total length of the entire double capillary was therefore 2 cm with a bore diameter of 500 μm. Approximately 3–5 kV of high voltage was applied to the end electrodes. When a 10 kV, high impedance trigger pulse was sent to the trigger electrode, a breakdown was initiated in the trigger capillary, which subsequently caused the main capillary to discharge. The trigger capillary provided more stable discharges of the main capillary and reduced the timing jitter of the discharges as was monitored by the current probe of the main discharge. The dielectric material used in the capillary was polyethylene and it produced a carbon and hydrogen plasma. The discharge generated plasma temperatures and densities that could create fully ionized hydrogen and doubly and triply ionized carbon ions. The plasma density can be controlled by the amplitude of the discharge current, which is a function of only the voltage applied to the main capillary. Direct measurements of the plasma density profile were performed near the open end of the main capillary [14,15]. These measurements showed a depression in the plasma density on axis, indicating the formation of a plasma channel. The plasma density depression, Δn, varied from 10^{18} to $10^{19}\,\mathrm{cm}^{-3}$.

The laser used in this experiment was the NRL T^3 laser that delivered up to 1 J of energy at 1.054 μm in a 400-fsec pulse. It was focused with a 30-cm-long focal length lens with an F number equal to 7 to produce a focal spot diameter of ~30 μm. The laser intensity at the focus in the vacuum was about $4\times10^{17}\,\mathrm{W/cm}^2$. The laser pulse was aligned through the capillary. Both the timing of the laser relative to the discharge and the input laser energy were monitored with a photodiode, reading from a beam splitter placed before the capillary. The output beam profile was monitored with a charge-coupled device (CCD) camera. The laser energy transmitted through the capillary was recorded with a calorimeter. Another CCD camera, together with an interference filter for 1053 nm, was arranged to image the 90° Thomson scattered (TS) laser radiation at the exit of the capillary. The capillary was positioned inside a vacuum chamber maintained at better than 10^{-4} Torr.

Laser energy measurements indicated that, even without an electrical discharge (no plasma in the capillary), about 20% of a terawatt laser pulse could still go through the capillary. This is in excess of what could have gone through the capillary (~3%) based on simple acceptance angle consideration of the capillary. This is probably due to the direct ionization of the capillary wall by the front of the intense laser pulse thus forming a hollow plasma channel inside the capillary to guide the bulk portion of the laser pulse [13]. This direct ionization of the capillary wall was indicated by a coating of the trigger electrode with polyethylene, which rendered it inoperative after a few shots of the laser pulse with no electrical discharge. When there was an electrical discharge, the electrodes were prevented from dielectric coating by the discharge, and the capillary survived hundreds of shots.

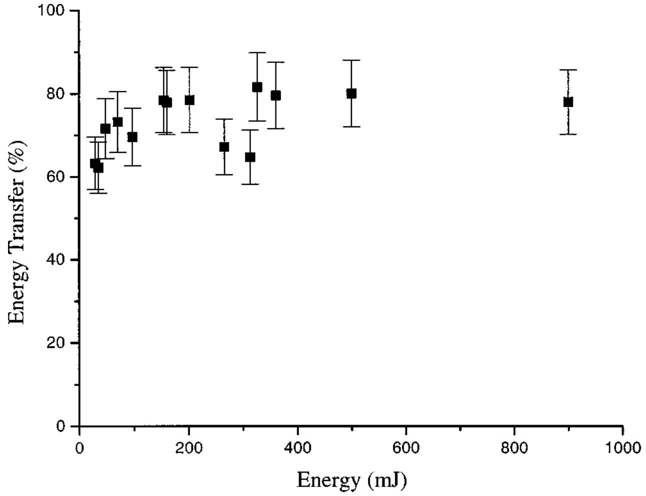

FIG. 2. Energy transfer efficiency as a function of the laser beam energy.

The energy transfer efficiency with the discharge varied deeply with the timing between the discharge and the passage of the laser pulse through the capillary. The best energy transfer was obtained near the peak of the discharge current, which was monitored with a magnetic Pearson probe. As shown in Fig. 2, the energy transfer efficiency was between ~70 and 80%, with maximum transmission at the highest energies. As a contrast, the energy transfer of an unguided beam at the incorrect timing between discharge and laser is negligible, indicating that the plasma inside the capillary with the wrong density profile actually blocks the laser pulse from propagating through. The energy transfer efficiency was also optimized by adjusting the axial position of the input laser focus to achieve maximum coupling of the input laser pulse into the plasma channel.

The guided mode structure of the laser is of great importance to all applications of a guided laser pulse. However, it is difficult to directly image the laser beam profile at the exit of the capillary for two reasons. The first problem is that the plasma and high intensity laser pulse near the capillary could damage the optics of a small F-number imaging system. The second difficulty is that the capillary creates a plasma jet beyond the end of the capillary, which acts like a complicated refractive lens to distort the transverse laser profile. We have monitored the shape and length of the plasma column at the exit end of the capillary by imaging the recombination light from the plasma column onto a CCD camera at 90° to the capillary axis. Depending on the history and number of discharges in a particular capillary, the angle of divergence and extension of the plasma jets varied from narrow and long to wide and short. The plasma density profile in the jet is similar to the profile inside the capillary, but with larger radial dimension due to unconfined expansion of the plasma [15]. Two indirect methods have been employed to overcome these difficulties and to measure the guided beam spot size.

The first method eliminated the first difficulty of placing optics near the capillary by examining the laser beam profile

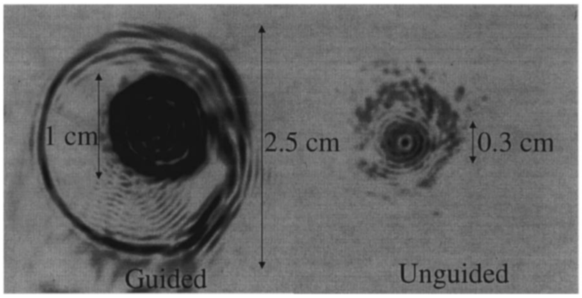

FIG. 3. Far field diffraction images of a 2.5-TW laser beam with a preformed plasma channel (guided) and without a preformed plasma channel (unguided). Images were collected 22 cm from the output of the capillary.

in the far field of the guided pulse. Infrared sensitive ''burn'' paper was placed 22 cm from the end of the capillary. These far field diffraction images are presented in Fig. 3. In the guided beam image on the left, the main part of the laser energy is concentrated in a 1-cm-diameter spot. The angle of divergence ($F^{\#}=22$) corresponded to the diffraction of a two times diffraction limited beam with a focused size of 60 μm. There is also a relatively intense ring with a diameter of 2.5 cm. The angle of divergence corresponds to $F^{\#}=9$, which indicates that a portion of the laser beam originated from a focused spot size of ~ 25 μm. If the laser is guided inside the channel with this smaller laser spot size, the guided laser intensity in the capillary is $\sim 3\times 10^{17}$ W/cm^2. By comparison, the right hand image in Fig. 3 shows the far field laser profile when there is no discharge in the capillary. The divergence angle is $F^{\#}=74$, which corresponds to the diffraction of a 200-μm-diam laser beam guided by the laser ionization of the capillary wall [13]. The corresponding guided laser intensity is only $\sim 5\times 10^{15}$ W/cm^2.

A second method to more accurately measure the guided laser beam size within the capillary is a 90° TS diagnostic. The optical path through the plasma jet at 90° is much shorter and therefore would induce less distortion in the optical image. Using a lens and a 1054-nm interference filter, the 90° TS radiation of the laser beam in the plasma jet was imaged on a CCD camera. The TS intensity image is presented in Fig. 4(a). The end of the capillary is to the left of the image, which explains why the left side edge of the image is saturated because of the hot electrical spark on the end electrode. Figure 4(b) shows the contour plot of the image in Fig. 4(a) and the laser can be seen to be concentrated in the central 30-μm diameter region on the left side. From a lineout profile of Fig. 4(b), the full width at half maximum of the guided laser beam at the exit of the capillary is estimated to be ~ 35 μm. It can be assumed that the guided laser beam diameter inside the capillary is less than or equal to this value. The corresponding Rayleigh length is 900 μm, indicating that the laser has propagated over 22 Rayleigh lengths through the capillary discharge formed plasma channel. The guided laser intensity inside the plasma channel is estimated to be $\sim 2\times 10^{17}$ W/cm^2.

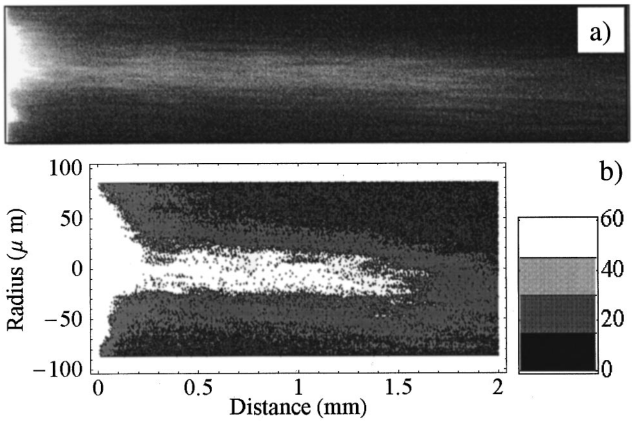

FIG. 4. Thomson scattering image (a) and intensity contour distribution (b) of the laser beam in the plasma jet outside of the capillary.

Apparently, as the guided laser beam exits the capillary, the main part of it follows the expanding plasma column of the discharge plasma and thus expands to a larger beam diameter in the plasma jet. This accounts for the central, intense, but smaller, guided image in the far field picture on the left-hand side of Fig. 3. However, because of the initially large diffraction angle, a substantial amount of the laser energy escapes the narrowly expanding plasma column, which acts like a ''leaky channel'' [16,17]. This portion expands on its own according to the diffraction of its original small guided spot size and forms the larger diameter image in the far field picture. The 90° TS image in Fig. 4 confirmed and measured the guided laser spot size initially to be very small at the exit of the capillary. The subsequent expansion of the laser beam size as the plasma jet expanded is clear from Fig. 4. It is the dynamics of the capillary discharge that determines the characteristics of the plasma jet. When the electrodes of the capillary were modified after a substantial number of discharges, long and narrow plasma jets were developed that continued to guide portion of the laser beam beyond the capillary exit as shown in Figs. 3 and 4. For the short and wide plasma jets of a new capillary, the plasma expanded so rapidly that the laser beam was not guided beyond the end of the capillary and could not be imaged by the 90° TS diagnostic. Correctly tailoring the electrodes of the capillary can therefore either enhance or suppress this extra guiding of the terawatt laser pulses by the exit plasma jets.

We have optically guided a terawatt, subpicosecond laser pulse from the NRL T^3 laser in a 500-μm diameter, 2-cm-long capillary discharge plasma channel. The energy transfer efficiency was measured to be $\sim$80%. The guided laser beam diameter was measured to be ~ 25 μm, using a diffraction angle measurement of the far field laser image and ~ 35 μm using 90° Thomson scattering diagnostics. The guided laser intensity was $>1\times 10^{17}$ W/cm^2 and the propagation length was greater than 22 Rayleigh ranges. There was evidence that the plasma channel extended beyond the ends of the capillary and affected the far field beam structure of the transmitted laser pulse. Part of the guided laser beam was contained in the extended plasma column while part of it leaked out of the channel and expanded at a larger diffraction angle. These experimental results demonstrated the potential of the extended laser interaction length for applications such as advanced laser driven accelerators, harmonics generation, and x-ray lasers.

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