Guiding of Intense Laser Pulses in Plasma Waveguides Produced from Efficient, Femtosecond End-Pumped Heating of Clustered Gases

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We demonstrate intense pulse guiding in efficient femtosecond end-pumped waveguides generated in clustered gases. This novel scheme provides a route to significantly lower on-axis plasma density ($< 10^{18}$ cm^{-3}) more than is feasible in conventional hydrodynamic plasma waveguides. Self-focused propagation and strong absorption of intense femtosecond laser pulses are used to produce long centimeter scale channels in an argon cluster jet, and a subsequent pulse is guided with 3×10^{17} W cm^{-2} intensity and $\sim$50% coupling efficiency. Preliminary results with hydrogen clusters also show guiding.

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Some of the most promising applications of intense laser fields, viz., laser wakefield accelerators, x-ray lasers, and high harmonic generation, demand long interaction lengths with plasma. But for a Gaussian beam of given energy and pulse duration, the product of intensity ($\sim 1/\omega_0^2$) and the interaction length (the confocal parameter, $2z_0$, where $z_0 = \pi\omega_0^2/\lambda$) is a constant, forcing a trade-off between the two. Several schemes for guided propagation have been proposed to counter this limitation, wherein the refractive index of the medium balances the diffractive spreading and the intense pulse is guided at a constant (small) radius over many Rayleigh lengths. Apart from the length of the guide, the ability to control the on-axis plasma density is also critical for these applications. Finally, the waveguide should ideally be formed in an easily renewable target.

Meeting all these goals is a challenging task. The methods developed to date fall into two broad classes—self-focused propagation and preformed plasma waveguides. The first method relies on either ponderomotive charge displacement or relativistic corrections to electron mass, which modify the refractive index of the plasma. These effects require $\geq 10^{18}$ W cm^{-2} intensity for optical and near infrared lasers. However, the propagation lengths achieved (≤ 2 mm) have been strongly limited by refractive erosion or Raman scattering of the pulse [1].

In a preformed waveguide, the plasma density profile must be tailored to match the guided beam. A Gaussian pulse with spot size ω_0 is optimally guided in a channel if the electron density difference ΔN_e between $r = 0$ and $r = \omega_0$ is $\Delta N_e = 1/\pi r_e \omega_0^2$, where r_e is the classical electron radius [2,3]. The desired on-axis density is determined by the application. For resonant wakefield generation, the optimum laser pulse width scales as $N_e^{-1/2}$, with optimum density $<10^{18}$ cm^{-3} for $\sim$100 fs pump pulses [4]. Thus the maximum guide density at its walls should not exceed a few times $\sim 10^{18}$ cm^{-3}. Most of the available schemes for guide generation have been limited to significantly higher densities. Those that can potentially operate at lower density [5,6] are limited to large waveguide diameter. Applications such as electron acceleration and phase matching for coherent short wavelength light generation [2,4,7] would benefit from both small guided modes (if laser energy is limited) and widely adjustable plasma density (for resonance or phase-matching optimization).

To date, several schemes for preformed plasma waveguide formation have been demonstrated. Guided propagation of high intensity pulses in a preformed channel was first demonstrated by Durfee *et al.* [3]. Channels up to 3 cm long, generated by radial evolution of a hydrodynamic shock, were produced in the axicon line focus breakdown of a gas using a 100 ps laser pulse. Subsequently, femtosecond pulses from a Ti:sapphire laser synchronized with the waveguide-generation laser were guided through these channels at $\sim 10^{17}$ W cm^{-2} [8]. A variant of the hydrodynamic shock technique has also been developed, in which collisional gas breakdown is promoted by an auxiliary femtosecond pulse which generates the initial free electrons by optical field ionization (OFI) [9]. Monoenergetic acceleration of electrons has recently been demonstrated in these waveguides [10] (and in unguided configurations [11]). In another, similar, scheme, gas breakdown is assisted by an electrical discharge [12]. Short ($\sim$1 mm) plasma waveguides have also been generated by laser-induced ponderomotive expulsion of electrons from a self-focused channel [13]. Non-laser-generated waveguides have also been formed in vacuum and gas-filled capillary discharges [5,6], in gas discharges [14], in Z pinches [15], and, for lower intensity, in hollow capillaries without electrical discharge [16].

Among these methods, the laser-driven hydrodynamic scheme has the advantages of providing the narrowest channels and smallest guided modes in infinitely renewable targets. But this method, when used with conventional backfill or gas jet targets, has three significant drawbacks. First, efficient collisional breakdown for channel generation requires high gas density N_0 due to the early exponential growth of electron density $N_e(t) \sim N_{e0} e^{SN_0 t}$, where N_{e0} is the initial electron density and S is the collisional ionization rate. In practice, this has resulted in typical waveguide central densities higher than $\sim 5 \times 10^{18}$ cm^{-3}, which is not optimum for some applications as noted above. The high gas density requirement is not mitigated by auxiliary ionization schemes [9,12] which increase N_{e0} but not the exponent. Second, the requirement for adequate ionization and heating for channel formation demands the use of high energy, long duration pulses from an auxiliary laser. At best, the channel heating efficiency of such pulses is 10%–15% [17]. Finally, there is significant taper at the waveguide ends, which results in inefficient coupling of injected pulses. This is due to the falloff of gas density at the edges of gas jets [8], where reduced ionization and heating result in slower radial expansion of the guide ends.

In this Letter, we demonstrate a new scheme for generating plasma waveguides that addresses all three issues. Instead of a gas of monomers, we use a gas of clusters as our starting medium. The cluster gas introduces two novel features of paramount importance: efficient absorption of femtosecond pulses [18,19] and their self-guided propagation [20,21]. The laser breakdown of a cluster is initiated by OFI, which produces the first generation of free electrons, followed by efficient collisional ionization under local solid density conditions, where the local atomic density N_0 is $\sim$1000 times greater than in typical gas targets. Clusters have been used as a medium for waveguide generation [22] in a scheme that was substantially different from the one demonstrated here; clusters along the axis were disassembled with a low intensity prepulse, and the main pulse then strongly ionized an annular region where clusters were still present. Since the plasma density profile corresponds to a radial variation in the degree of ionization, this method cannot be used to generate fully ionized waveguides.

The heated clusters explode on a sub-ps time scale, eventually expanding and merging to form a locally uniform plasma in $\sim$10–100 ps [19,23]. This hot plasma expands radially, leading to the formation of a shock wave and subsequent waveguide structure over a nanosecond time scale. The clusters radially surrounding the hot plasma of the laser interaction region are preheated by a precursor from radiation and fast electrons [24], which ionizes and disassembles them in advance of the shock wave arrival. The cluster method provides a route to control waveguide density: since efficient heating is local to a cluster, independent of the cluster density in the gas, cluster size and density can be adjusted to give desired levels of merged plasma density.

A gas of clusters also has unique optical properties due to the dynamics of the laser-cluster interaction. According to a 1D hydrodynamic model developed by Milchberg *et al.* [23], the real part of the polarizability of the cluster is positive during the early parts of cluster evolution after irradiation by an intense femtosecond pulse, when its dominant optical response is that of a supercritical plasma. This reflects the fact that the heated cluster excludes the laser field when it is above critical density. In a laser beam with intensity peaked on axis, the evolving gas of clusters local to the beam cross section has a positive and concave-shaped refractive index profile during this phase, which induces self-focusing. As the cluster expands to critical density, the imaginary part of the polarizability increases and reaches its peak. Thus the process of self-focusing of the pulse is accompanied by its efficient absorption. The predictions of the model for the complex polarizability and self-focusing have been experimentally confirmed [19–21]. The combination of highly efficient absorption with self-focusing of femtosecond pulses makes possible the generation of femtosecond end-pumped waveguides much longer than the Rayleigh range of the focused pulse. We use jets of argon and hydrogen clusters to realize this scheme, and demonstrate the guiding of $>10^{17}$ W cm^{-2} pulses over $\sim$40 Rayleigh lengths, with a coupling efficiency of $\sim$50%. We also show that waveguide taper at the entrance is reduced, and that plasma density in the channel can be controlled over a wide range to suit various applications.

Pulses (100 mJ, 70 fs) from a Ti:sapphire laser were split to generate three pulses. A small portion ($\sim$1 mJ) was used as a variably delayed transverse interferometry probe of the plasma evolution. The remainder was split into two variable energy pulses with adjustable delay and recombined using thin film polarizers. The first pulse was used as the pump (channel-generating pulse) and the second was used as an injected probe to be guided by the resulting waveguide. Both pulses were focused using an $f/5$ lens into the end of an elongated cluster jet. A negative-positive lens pair in the pump beam path allowed independent fine control over the position of the pump pulse focus for optimizing the coupling of the injected pulse into the waveguide. A telescope was used to monitor the end mode of the guided pulse after the pump pulse was removed using a polarizer. The transverse probe was sent through a Michelson interferometer and a telescope to record shadowgrams and interferograms of the evolving channel. Electron density profiles were extracted from interferometric images using fast-Fourier-transform–based phase extraction followed by Abel inversion [25].

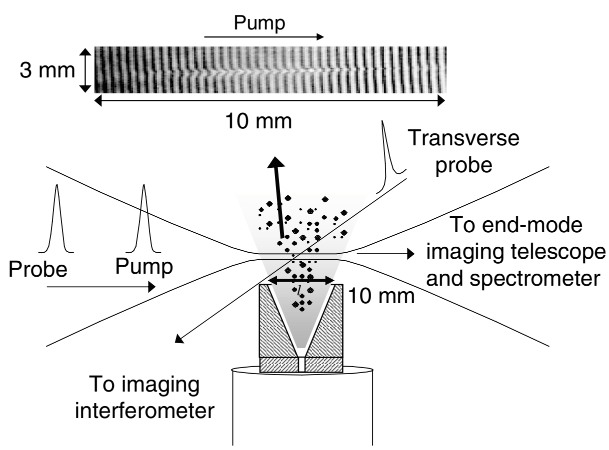

FIG. 1. Schematic diagram of experimental layout. An interferometric image of the full plasma channel is also shown.

Figure 1 shows the experimental layout. This arrangement not only eliminates the need for a synchronized auxiliary long-pulse laser for channel generation, as used in the axicon case [3,8], but the optical setup and alignment are much less complex.

Two different liquid-nitrogen-cooled gas jets were used for these experiments. Clusters are formed when high pressure gas expands adiabatically through a small orifice into vacuum. High valve backing pressures and low temperatures favor the formation of large clusters. An all-optical method to measure cluster size and density was developed to characterize the jet [26]. For argon gas, which clusters easily, a 10 mm $\times$ 0.25 mm slit nozzle was used to produce a long interaction region. Valve backing pressure and temperature ranged from 10 to 50 bar and from 150 to 300 K. However, the slit nozzle could not efficiently produce hydrogen clusters, which requires lower temperature and higher gas density. Hence, for hydrogen, we used a conical nozzle cooled to 90 K to generate jets 3 mm across.

The inset of Fig. 1 is an interferogram of an $\sim$8 mm long plasma waveguide produced by the pump pulse in the elongated argon cluster jet. The slight axial taper of the guide is caused by absorption of the pump as it propagates. Because of self-focusing of the pump pulse in the clustered gas, these channels are considerably longer than the Rayleigh range ($\sim$200 μm). These channels constitute the longest and most uniform hot plasma structures ever produced by laser end pumping. Figures 2(a) and 2(b) show time-resolved electron density profiles of the resulting waveguide near its center for high (190 K, 27 bar) and low (170 K, 20 bar) gas densities. Pump pulse absorption was measured to be 85% and 70%, respectively, for the high and low density jets. Mean cluster radius was measured to be $\sim$6 and $\sim$2.5 nm, respectively (the jet was optimized after these measurements, so these values represent lower limits). A central minimum in electron density develops in $\sim$1 ns. These results illustrate the ability to control the guide density to low levels of $\sim 10^{18}$ cm^{-3}. Note that the pump pulses are only 30 mJ, approximately 10 times less energy than required for heating conventional gas targets for plasma waveguide generation [3]. We note that the radial wings of the electron density profiles extend considerably farther out than for channels generated in nonclustered gases [25]. This is evidence of the precursor heating of the surrounding cluster gas [24]. Figure 2(d) shows the electron density profile measured at the entrance of the waveguide. The channel develops into a waveguide over a short distance ($\sim$100 μm) along the pump laser propagation direction. This represents a substantial improvement over waveguides generated in conventional gas jets, where $\sim$500 μm tapering at the entrance hinders efficient coupling of the injected pulse [8]. Even though the cluster density gradient at the edge of the gas jet can be as large as $\sim$500 μm [26], the strong heating of individual clusters ensures an axially uniform rate of radial plasma expansion, and a much-reduced waveguide-entrance taper.

Delayed probe pulses were injected into and guided by these channels, and exit modes of the probe were relay imaged to a CCD camera. Figure 2(c) shows the exit mode of the laser pulse at the optimum delay (1.3 ns), for a 25 mJ pump, and a 40 mJ injected probe. The guided mode is quite stable on a shot-to-shot basis, and this image is a 50-shot average. The coupling efficiency and channeled intensity of the guided pulse were determined using such images. The highest transmitted intensity is 3×10^{17} W cm^{-2} at 1.3 ns delay, with 50% coupling efficiency. At shorter delays, the energy transmitted is lower, and at longer delays, the mode becomes larger.

The pump pulse is intense enough to ionize argon atoms in the clusters to Ar^{8+} [23]; further ionization by the probe would require $>10^{18}$ W cm^{-2} intensity. The probe pulse is therefore not expected to further ionize the channel. To verify this, the spectrum of the guided pulse was measured using an imaging spectrometer. Figure 2(e) shows the measured input and output spectra of the probe pulse when guiding was optimum. The absence of an ionization-induced blueshift indicates that the intense guided probe does not cause significant additional ionization of the waveguide.

In order to avoid ionization due to even higher intensity pulses than guided here, it is desirable to form the wave-

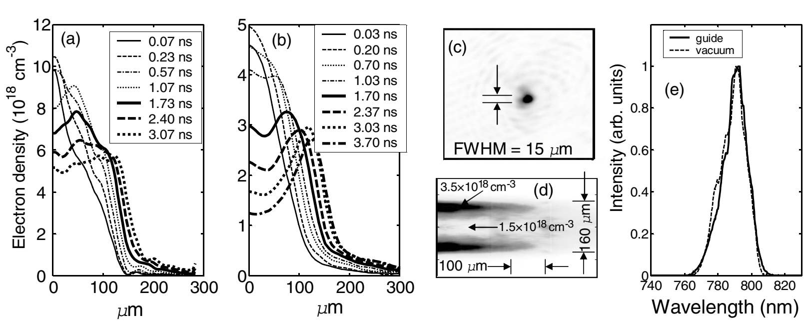

FIG. 2. (a),(b) Electron density profiles from 8 mm long plasma channels, with the argon gas jet at 193 K and 27 bar, and 113 K and 20 bar, respectively. (c) Laser mode at the exit of the waveguide (173 K, 40 bar, 1.3 ns delay). (d) Electron density profile at the waveguide entrance (150 K, 13 bar jet). Note the $\sim$100 μm length scale over which the waveguide develops from the edge of the gas jet. (e) Guided pulse spectrum at optimum delay (193 K, 27 bar). The spectrum shows negligible additional ionization by the guided pulse in the waveguide.

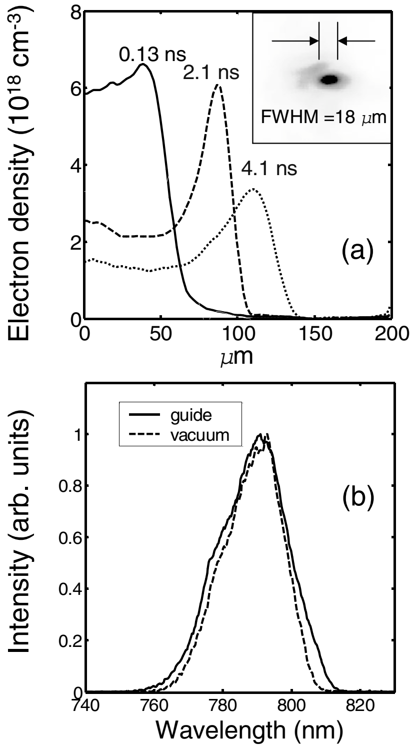

FIG. 3. (a) Electron density profiles, with mode image in the inset, and (b) the spectrum of guided probe at the exit of a 3 mm plasma waveguide from the short hydrogen cluster jet (54 bar, 95 K). Guided intensity is 10^{16} W cm^{-2}. The spectrum shows negligible additional ionization by the guided pulse in the waveguide.

guide in a low-Z medium which can be fully ionized. A clustered hydrogen gas jet was used for this purpose. As discussed above, efficient clustering in hydrogen was achievable only with a cooled conical nozzle, giving a 3 mm long target. Figure 3(a) shows electron density profiles as a function of delay, with a 50-shot-averaged mode image of the optimally coupled pulse in the inset. The coupling efficiency was only ~5%, and the maximum guided intensity was 10^{16} W cm^{-2}. In Fig. 3(b) are shown the vacuum and guided spectra of the probe pulse. Here, too, the absence of significant blueshifts indicates a fully ionized plasma channel. The reason for the weak coupling in these short hydrogen waveguides is not understood at present. One possibility is that the hydrogen jet is incompletely clustered, with high monomer densities near the jet edge, giving rise to OFI-induced pulse refraction in advance of the channel entrance. If it is strongly enough refracted, little of this light would enter the channel and contribute any blueshifting to the measured spectrum. While the guided intensity in the hydrogen waveguide is smaller than demonstrated using existing methods [10], these preliminary experiments serve to indicate the viability of the technique to generate longer hydrogen channels using an improved cluster source. Such a source is currently under development.

In conclusion, we have successfully guided 3×10^{17} W cm^{-2} laser pulses in 8 mm long waveguides produced in a clustered argon gas jet. The use of clustered jets realizes the possibility of achieving on-axis plasma densities less than 10^{18} cm^{-3} by making local pump laser heating independent of average gas density. Preliminary experiments with hydrogen clusters indicate that long fully ionized waveguides may be formed with a more efficient cluster source.

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