Report on laser guiding techniques for laser-plasma accelerators

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Abstract

In many cases the length over which particles can be accelerated in a laser-driven plasma accelerator is limited by refraction or diffraction of the driving laser pulse. In order to overcome this limitation the driving pulse must be guided or channeled through the plasma. In this paper we briefly review of the techniques used to guide laser pulses with peak intensities up to 10^{19} W/cm^2, and describe recent experimental results.

Introduction

The energy to which particles can be accelerated in a laser-driven plasma accelerator is determined by the shortest of: the propagation distance over which the energy of the driving laser pulse, or pulses, is depleted (the depletion length); the distance for which the particles are correctly phased with the plasma wave (the dephasing length); and the distance for which the intensity of the driving laser pulse remains focused (defocusing length) [1]. For many acceleration experiments, particularly those aimed at demonstrating controlled acceleration of an injected bunch, the acceleration length is limited by defocusing of the pump radiation.

A laser beam of power P propagating along the z axis with a Gaussian transverse intensity profile of the form $I(r,z) = (2P/\pi w(z)^2)\exp\{-2[r/w(z)]^2\}$, where r is radial distance from the axis, has a spot size that varies as $w(z) = w(0)\sqrt{1+(z/z_R)^2}$, where $z_R = \pi w(0)^2/\lambda$, λ is the wavelength of the radiation, and we have assumed that the beam is focused at $z = 0$. The Rayleigh range, z_R, is equal to the distance from the focus at which the axial intensity is reduced by a factor of two from its value at focus, and consequently gives a measure of the length over which diffraction causes the beam to defocus significantly. For the parameters of interest to many laser-driven accelerators (i.e. $\lambda \approx 1\ \mu\text{m}$, $w(0) \approx 10\ \mu\text{m}$) the Rayleigh range is less than 1 mm.

A second cause of defocusing, refraction, occurs in partially ionized plasmas. Since the rate of ionization of a plasma increases with intensity, laser-induced ionization will usually result in the transverse profile of the additional electron density being peaked on axis where the laser intensity is highest. For laser intensities such that relativistic and ponderomotive effects may be ignored (see below), the refractive index of a plasma is given by $\eta = \sqrt{1 - n_e(r)e^2/m_e\varepsilon_0\omega^2}$, where $n_e(r)$ is the electron density, and ω is the angular frequency of the radiation. Consequently, an electron density peaked on axis will cause the refractive index to exhibit an axial minimum, leading to refractive defocusing of the laser pulse. The extent to which this occurs depends on the intensity of the laser and the constitution and density of the plasma, but often ionization-induced refraction defocuses the beam much faster than diffraction.

In order to overcome the limitations on the laser-plasma interaction length set by diffraction and refraction, it is necessary to guide or channel the laser pulse through the plasma. In general, guiding electromagnetic radiation requires a channel to be formed in which the refractive index is a function of radial distance from the axis of propagation. For the more familiar case of guiding low intensity radiation, this has led to the development of step- and gradient-index optical fibers. Related approaches have also been used to guide intense laser pulses, and in addition guiding by self-focusing is important. In this paper we outline the techniques that have been employed and briefly review experimental results.

Guiding in hollow capillaries

For low laser intensities, step-index guiding is achieved by surrounding a cylindrical core of material by a cladding layer of lower refractive index. In this configuration, light propagating along the core can be totally internally reflected from the core-cladding boundary, leading to guiding with very low losses. However, at the high intensities of interest to laser-driven accelerators a solid core would be destroyed, and hence the core must be a plasma or vacuum. In this case a solid cladding will have a higher refractive index so that

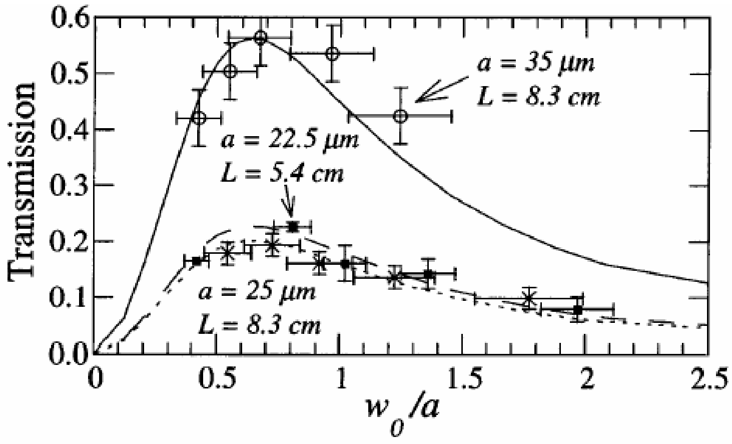


FIGURE 1. Measured and theoretical pulse energy transmission as a function of the ratio of the spot size of the input pulse, w_0, to the capillary radius, a, for capillaries of three different radii. (From Dorchies et al. [5]).

reflection of radiation at the boundary between the two media will no longer be a total reflection. In such cases the guiding will be lossy [2], although the losses are usually small since the angle of incidence with the cladding is close to 90°. In addition, if the capillary wall is ionized by the laser radiation the refractive index is decreased below unity, allowing total internal reflection to occur.

Guiding of high-intensity laser pulses with this approach was first investigated [3] by Jackel et al. in 1995. In that work 1 J, 0.9 ps laser pulses were focused to a peak input intensity of 2×10^{17} W cm^{-2} at the entrance of capillaries up to 126 mm long and with a diameter of 100 μm or 266 μm. High pulse energy transmission was observed: for example, for 30 mm long, 266 μm diameter capillaries the pulse energy transmission was measured to be 26%. In 1998 this work was extended to peak incident powers up to 10 TW by Borghesi et al. [4].

In that early work the spot size of the laser pulses at the entrance to the capillary was small compared to the diameter of the capillaries employed. Consequently several modes of the capillary were excited, and the transverse intensity profile of the transmitted radiation was not smooth. In addition to this problem, multimode guiding of this type is not suitable for laser-driven accelerators since the losses are fairly high, and the group velocity relatively low.

The properties of the eigenmodes of a hollow dielectric capillary have been investigated by Cros et al. [2], who showed that linearly-polarized incident radiation would excite the EH_{1s} family of hybrid modes. For a Gaussian beam focused at the entrance of the capillary, a maximum of 98% of the incident laser energy can be coupled into the lowest-order of these modes, EH_{11}, when $w(0) = 0.645 R_0$, where R_0 is the radius of the capillary. This mode is characterized by a smooth transverse intensity profile, low losses, a high group velocity, and high contrast between the axial intensity and that at the capillary wall.

Experimental demonstration of monomode guiding in hollow capillaries was first reported by Dorchies et al. [5]. The measured pulse transmission as a function of the ratio of the spot size of the input beam to the capillary radius was found to agree very well with theory, as shown in Fig. 1. These measurements show clearly that coupling into the lowest-loss mode occurs when $w(0) \approx 0.6 R_0$, as expected. In the same work monomode guiding through 105 mm long, 50 μm diameter capillaries was achieved for pulses with an input intensity of up to 5×10^{16} W cm^{-2}. The energy of the guided pulse was found to decrease exponentially with propagation distance as $\exp(-\alpha z)$ with a damping coefficient $\alpha = 0.17\ \mathrm{cm}^{-1}$, in good agreement with theory. In later work the same group demonstrated monomode guiding of pulses with peak input intensities up to approximately 10^{18} W cm^{-2} using radiation at the fundamental [6] and second harmonic [7] wavelength of the laser system.

Recently, Kitagawa et al. [8] have reported acceleration of electrons by intense laser pulses guided through evacuated capillaries. That group guided pulses with a peak input intensity of 3×10^{18} W cm^{-2} through evacuated capillaries of 60 μm diameter and 10 mm length. Electrons, from plasma formed by ablation of the capillary wall, were observed to be accelerated to energies up to approximately 100 MeV.

Plasma waveguides

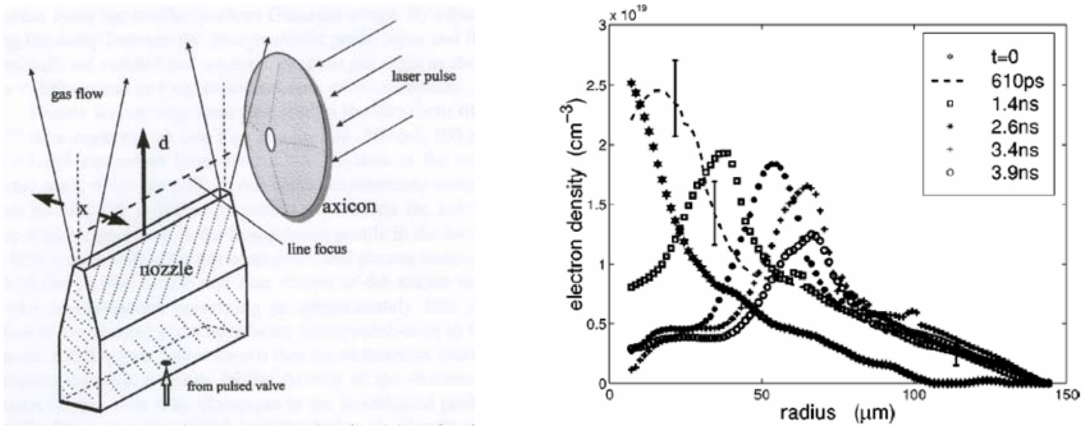
In a plasma waveguide, guiding is achieved by pre-forming a plasma channel with a transverse electron density profile that increases with radial distance from the axis – corresponding to a radially-decreasing refractive index, as employed in gradient refractive index optical fibers. Of particular interest are parabolic plasma channels in which the electron density is given by $n_e(r) = n_e(0) + \Delta n_e (r / r_{ch})^2$, where Δn_e and r_{ch} conveniently parameterize the curvature of the profile. In the absence of further ionization, and provided that relativistic and ponderomotive effects may be ignored, a Gaussian beam can propagate through such a channel with a constant spot size $w = w_M \equiv \left(r_{ch}^2 / \pi r_e \Delta n_e \right)^{1/4}$ where r_e is the classical electron radius [9]. If the spot size of the laser pulse focused at the entrance to the channel $w(0) \neq w_M$, the spot size of the beam within the channel will oscillate between $w(0)$ and $w_M^2 / w(0)$ with a length period of $\pi^2 w_M^2 / \lambda$.

We emphasize that it is important to avoid further ionization of the plasma channel by the propagating laser pulse. Even if the spot size of the laser is matched to that of the plasma channel, laser-induced ionization will cause the spot size of the propagating pulse to oscillate (potentially severely) with propagation distance [10] or even destroy the plasma channel completely. Hence the plasma channel should be fully ionized, or at least stable against further ionization for the laser intensities of interest.

Before describing some of the various techniques that have been developed to generate parabolic plasma channels, we note that step-index plasma waveguides – in which a low density core is surrounded by a cladding layer of higher density plasma – have been considered for laser-driven plasma accelerators [11]. However, to date it has proved hard to make such a channel in practice.

Channels formed by hydrodynamic expansion

The first plasma waveguide for high-intensity laser pulses was formed by hydrodynamic expansion of a plasma column [12]. In this approach ~100 mJ, ~100 ps laser pulses are focused with an axicon to generate a line focus in a gas at an ambient pressure of about 100 mbar, as illustrated in Fig. 2(a). The intensity at the line focus, 10^{13} – 10^{14} W cm^{-2}, is sufficient to ionize the gas and heat the resulting plasma by inverse bremsstrahlung (IB). The hot plasma column so formed then expands in a nanosecond time-scale, driving a shock wave into the surrounding cold gas and leaving a plasma channel behind the shock front. The measured evolution of the electron density in a plasma column formed in an Ar gas jet target is presented in Fig. 2(b), showing clearly the formation of a channel 1 – 2 ns after the laser



(a) (b)

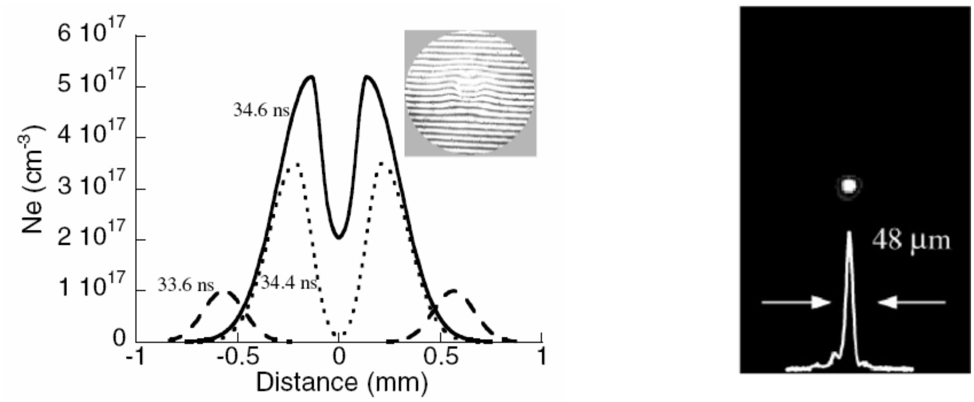
FIGURE 2. (a) Arrangement for forming a plasma channel by hydrodynamic expansion, and (b) the measured temporal evolution of the transverse electron density profile after the formation of a cylindrical plasma column in Ar at *t*=0. (From Fan et al. [17] and Nitikin et al. [13]).

pulse. Analysis of this data shows that the Ar is ionized to Ar^{8+} by the channel-forming laser pulse.

This approach has been used to guide [13] 50 mJ, 110 fs laser pulses with a peak input intensity (in vacuum) of approximately 1×10^{17} W cm^{-2} through 15 mm long plasma channels with an energy transmission of slightly greater than 50%. Most of this energy loss is thought to arise from poor input coupling owing to tapering of the plasma channel at its entrance.

The plasma channels formed by this method are not fully ionized, and so may only be used below the intensity at which substantial further ionization of the channel would occur. For example, for an Ar^{8+} channel, ionization to Ar^{9+} occurs by optical field ionization (OFI) at an intensity of 1.6×10^{18} W cm^{-2}. In addition, coupling losses will be greater for channels formed in gases with a high atomic number owing to laser-induced refraction by unionized gas prior to the plasma channel [14]. It is desirable, therefore, to make fully ionized channels in gases with low atomic number. The difficulty in so doing arises in the conflicting requirements that the laser pulse forming the channel should be: (i) of sufficiently high intensity ($> 10^{14}$ W cm^{-2}) to create initial ionization of, say, H or He by OFI and (ii) of low intensity ($< 10^{13}$ W cm^{-2}) and long duration to heat the plasma by IB. This challenge has been met by several extensions of the hydrodynamic expansion technique. In the ignitor-heater method [15], developed by Wim Leemans' group at Lawrence Berkeley National Laboratory, a short (< 100 fs), intense ($> 5 \times 10^{14}$ W cm^{-2}) 'ignitor' pulse produces initial ionization by OFI. This initial plasma is then heated and further ionized by a long (~ 100 ps) 'heater' pulse of relatively low intensity. In practice this approach is implemented by overlapping the line foci produced by focusing the ignitor and heater beams with cylindrical mirrors. Cylindrical channels are formed if the ignitor and heater beams propagate perpendicular to each other and the common line focus. Recently this approach has been used [16] to guide laser pulses with a peak input intensity as high as 10^{19} W cm^{-2} over 4 mm to generate near-monoenergetic beams of electrons with an energy of approximately 85 MeV.

Alternative extensions of the hydrodynamic expansion scheme have been investigated by Michael Downer and his group [14], [18]. They have used a simple discharge to partially ionize He gas before heating and further ionization by a ~100 ps, 0.3 J laser pulse. The same group has also found that increasing the energy of the laser pulse to 0.6 – 1.0 J, and stretching it to 400 ps, gave sufficient time for avalanche ionization and IB heating to build up from OFI of trace contaminants. This latter approach has been used [14], [18] to channel laser pulses



(a) (b)

FIGURE 3. Experimental results for a fast capillary discharge in Ar. (a) Measured temporal evolution of the transverse electron density profile. The times indicated are with respect to the beginning of the current pulse, and the inset shows the interferogram corresponding to the 34.4 ns profile. (b) The transverse intensity profile of a laser pulse with a peak input intensity of 2×10^{17} W cm^{-2} measured at the exit of a 55 mm long capillary. (From Luther et al [21].)

with a guided intensity of approximately 2×10^{17} W cm^{-2} through fully-ionized He channels with a matched spot size of 8 μm.

Finally, Howard Milchberg and his group have investigated a novel extension to this scheme in which the plasma column is produced in a gas of Ar clusters [19]. The use of a clustered medium has distinct advantages: the medium undergoes partial ionization for short laser pulses of low intensity, and the optical properties of the ionizing and expanding clusters serve to guide the channel-forming pulse over many millimeters. As a consequence the plasma channel can be generated by longitudinally focusing femtosecond pulses from the same laser system that produces the laser pulse to be guided. In recent work, this approach has been used to guide pulses with a peak intensity of 3×10^{17} W cm^{-2} through 15 mm long plasma channels [20].

Channels formed by hydrodynamic compression

Plasma channels have also been formed by the opposite process, hydrodynamic compression, using fast capillary discharges. In this approach a capillary of a few millimeters diameter is filled with gas at low pressure and ionized by a discharge current with a rise time of 10 – 50 ns, and a peak of 5 – 20 kA. Since the current rises rapidly, the skin effect ensures that the initial ionization occurs close to the capillary wall. The large magnetic field generated by the current then compresses the plasma through the $\mathbf{J} \times \mathbf{B}$ force to drive a strong shock towards the capillary axis. A plasma channel is formed just before the rapidly collapsing annulus of plasma reaches the axis, and since the volumetric compression is close to 100%, the axial plasma density is much greater than the initial density of the gas. This process is illustrated in Fig. 3(a) which shows interferometric measurements of the transverse electron density profile formed in a fast capillary discharge in Ar.

This approach has been used [21], [22] to guide intense laser pulses channels formed by fast capillary discharges in He and Ar. For example, Luther et al. [21] have demonstrated guiding of pulses with a peak input intensity and spot size of 2×10^{17} W cm^{-2} and 30 μm respectively through 55 mm long Ar^{8+} plasma channels with an axial electron density of approximately 2×10^{17} cm^{-3}. Fig. 3(b) shows the measured transverse intensity profile of the transmitted beam. The pulse energy transmission was measured to be 75%.

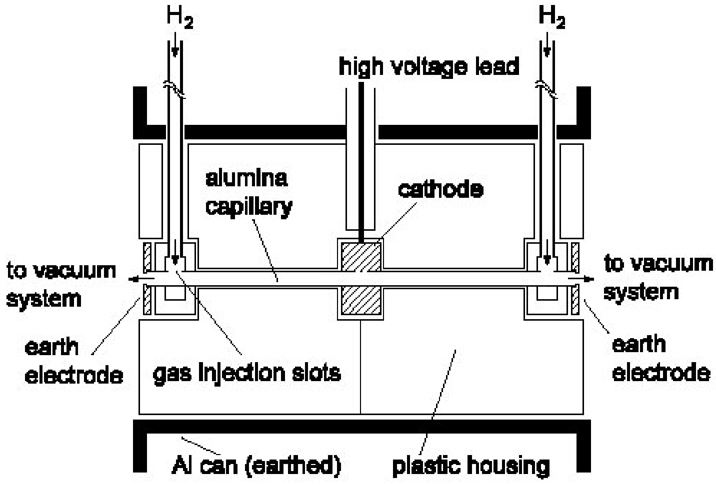


FIGURE 4. Schematic diagram of the H_2-filled capillary discharge waveguide.

Channels formed by slow capillary discharges

Plasma channels have also been formed in slow capillary discharges, an approach pioneered by Arie Zigler and his group at Hebrew University, Jerusalem [23]. In that technique a discharge pulse with a rise-time of order 100 ns and a peak current of a few hundred amperes is passed through an initially evacuated capillary formed in a soft material such as polypropylene. The discharge current ablates and ionizes the wall material to fill the capillary with plasma and forms a plasma channel by radiative and collisional heat transfer to the capillary wall. This causes the temperature of the plasma to be greater on axis and, since the pressure across the capillary is uniform, an axial minimum in the plasma density.

Discharge-ablated capillaries of this type have been used in a wide variety of guiding experiments. For example, pulses with a peak input intensity greater than 10^{16} W cm^{-2} have been guided [24] through capillaries 66 mm long with an energy transmission of approximately 10%, and pulses with a peak input intensity of approximately 4×10^{17} W cm^{-2} have been guided [25] through 20 mm long capillaries with an energy transmission of 75%.

The plasma channels formed by discharge-ablation of a capillary wall are typically only partially ionized. For example, discharge-ablated polypropylene capillaries form a plasma comprised of fully-ionized hydrogen and carbon ionized to a variety of stages up to C^{4+}. As a consequence, laser-induced ionization can cause severe modulation of the spot size of an intense laser pulse propagating along the plasma channel [10].

This problem can be overcome using the hydrogen-filled capillary discharge waveguide developed by S.M. Hooker and his group [26]. As shown schematically in Fig. 4, the capillary is formed from a refractory material, such as alumina, to avoid ablation of the wall. The plasma channel is formed by discharge ionization of gas injected into the capillary through holes machined 1 – 4 mm from each end of the capillary. The mechanisms leading to the formation of the plasma channel have been investigated in magnetohydrodynamic simulations of the capillary discharge [27]. These show that for a 300 μm diameter capillary filled with 67 mbar of H_2, and with a half-sinusoidal discharge pulse of full width 200 ns and 300 A peak, the gas is fully-ionized approximately 60 ns after the onset of the discharge. Approximately 80 ns after the onset of the discharge current the plasma is in a quasi-equilibrium in which the pressure is uniform across the diameter of the capillary, and Ohmic heating of the plasma is balanced by conduction of heat to the wall. The electron density profile so-formed is found to be approximately parabolic with a matched spot size in good agreement with measurements [26] made under these discharge conditions.

Fig. 5 shows the measured transverse intensity profiles at the entrance and exit of a 30 mm long, 400 μm diameter H_2-filled capillary discharge waveguide for laser pulses with a peak input intensity of 1×10^{17} W cm^{-2}. Laser pulses injected prior to the onset of the discharge current are strongly defocused by ionization-induced refraction in the neutral hydrogen, and have a low pulse energy transmission, as shown in (b). The transmission is found to increase rapidly during the discharge, reaching approximately 90% once the hydrogen gas becomes essentially fully ionized. This is accompanied by a reduction in the transverse dimensions, and a corresponding increase in intensity, of the transmitted laser pulse as a plasma channel is formed. For example, for the transmitted pulse shown in (c) the energy transmission and peak axial intensity are 83% and 36% of that of the input pulse respectively [28].

Relativistic and ponderomotive guiding

At laser intensities of order 10^{18} W cm^{-2} the quiver motion of electrons oscillating in the electromagnetic field of the laser becomes relativistic. The refractive index of the plasma is then modified to $\eta = \sqrt{1 - n_e(r)e^2 / \gamma m_e \varepsilon_0 \omega^2}$, where $\gamma \approx \sqrt{1 + a^2/2}$ and $a = p_\perp / m_e c$ is the normalized vector potential – equivalent to the normalized transverse quiver momentum of an electron [9]. Since a increases with the laser intensity, a laser pulse with a transverse intensity profile which is peaked on axis experiences a refractive index which has an axial maximum, leading to guiding. This relativistic self-guiding exactly balances diffraction of the laser pulse at a critical power $P_c = 17.4(\omega/\omega_p)^2$, where ω is the angular frequency of the laser radiation and $\omega_p = \sqrt{n_e e^2 / m_e \varepsilon_0}$ the plasma frequency.

In addition to channeling arising from modification of the refractive index by the quiver motion of the electrons, guiding can also occur through changes induced in the plasma density. The energy of the quivering electrons and ions is proportional to the intensity of the laser radiation, and the gradient of this quiver energy corresponds to a force – the ponderomotive force – which expels electrons and ions radially, reducing the plasma density on axis and thereby enhancing the guiding. Owing to their much greater mass, the motion of the ions under the ponderomotive force is much slower than that of the electrons, and hence for short laser pulses the modification to the plasma density arises solely from expulsion of electrons from the axial region, reducing the critical power [30] for relativistic self-focusing to $P_c = 16.2(\omega/\omega_p)^2$.

Ions are expelled by the ponderomotive force over a much longer time scale, and hence ion motion is only important for self-channeling of long laser pulses. Ion motion is important, however, in forming plasma channels after the passage of an intense laser pulse.

Relativistic and ponderomotive self-channeling has been reported by several groups [31], [32], [33]. For example, Monot et al. demonstrated channeling of 6.8 TW laser pulses over a length of approximately 2 mm in a hydrogen gas jet [32]. Comparison of the observed Thomson scattered light with theory suggested that the peak laser intensity in the channel was greater than 10^{19} W cm^{-2}. The temporal evolution of plasma channels formed ponderomotively during and after the passage of an intense laser pulse has been investigated by Sarkisov et al. [29], as shown in Fig. 6.

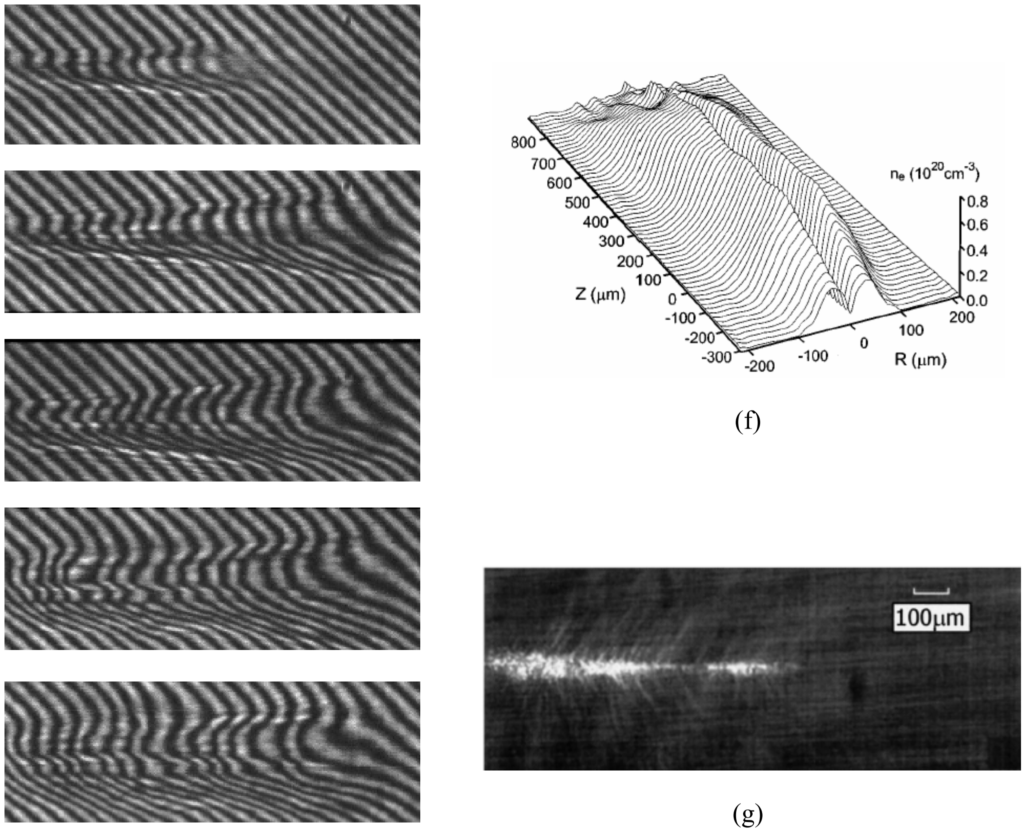


FIGURE 5. Interferomgrams of a plasma in the regime of relativistic self-focusing: (a) 0 ps, (b) 5 ps, (c) 15 ps, (d) 35 ps, and (e) 45 ps after the passage of a 4.3 TW laser pulse through a He gas jet with an atomic density of 4×10^{19} cm^{-3}. In (f) is shown the reconstructed electron density profile of the channel formed 35 ps after the passage of the pulse. An image of the Thomson scattered radiation from the passage of the driving laser pulse through the He gas jet is shown in (g). (From Sarkisov et al. [29])

In that work 400 fs, 4.3 TW laser pulses with a wavelength of 1.053 μm were focused into a He gas jet with an atomic density of approximately 4×10^{19} cm^{-3}. Fig. 6(a) shows the formation of a plasma channel during the laser pulse, and extended propagation over a length of approximately 1 mm is evident in Fig. 6(g) which shows Thomson scattered radiation from the pulse. The development of a plasma channel on a picosecond time-scale after the passage of the driving pulse is shown clearly in Fig. 6 (b)-(e). Ponderomotively-formed channels of this type have been used to guide a second laser pulse injected after an intense channel-forming pulse. For example, Krushelnick et al. [34] have observed guiding of pulses with a peak intensity of 5×10^{16} W cn^{-2} through a 2.5 mm long channel formed by a pulse with a peak intensity of approximately 6×10^{18} W cm^{-2}.

Conclusions

In this section we make some remarks on the techniques reviewed briefly above.

Hollow capillary waveguides are attractive since the method is simple and requires no auxiliary laser or electrical discharge systems. The main issue to be addressed with this technique is the low shot lifetime of the capillaries. Theory suggests that pulses with a peak axial intensity of order 10^{18} W cm^{-2} can be guided by this approach without damage to the glass capillary wall [2]. However, the transverse intensity profile of pulses from a real laser system often deviate from Gaussian, exposing the wall or front face of the capillary to high intensities [6]. To avoid this problem, the spatial profile of the input beam must be carefully controlled, or the beam must be coupled in through a tapered section of capillary. Recently, the use of capillary tubes with thick walls has permitted to extend considerably the lifetime of the capillaries, to several thousand shots: the shot to shot pointing instability of the laser beam ablates only part of the entrance of the tube, and creates a tapered structure.

A second issue for this method is the fact that the coupling and propagation losses of the capillary increase when gas is introduced into the capillary. For example, the addition of 20 mbar of He gas decreases the energy transmission of a 40 mm long capillary by a factor of 4 from that achieved under vacuum [5]. As a consequence, this technique is likely to be most useful for guiding intense pulses in low density, low atomic number gases [35], corresponding to plasma densities less than approximately 5×10^{17} cm^{-3}. Simulations of the wakefield excited in capillary tubes filled with hydrogen gas [36] have demonstrated the efficient generation of a plasma wave with homogeneous amplitude over several centimeters, for plasma densities of 6.9×10^{17} cm^{-3}.

The main advantages of using **hydrodynamic expansion to generate a plasma channel** are that the matched spot size of the channel is small (of order 10 μm), the shot lifetime of the channel is essentially infinite, and there is good optical access for diagnostics. It has also recently become possible to form fully-ionized channels with this approach. To date the axial electron density of the channels has been limited to the range 10^{18} – 10^{19} cm^{-3}, and their length has not exceeded 15 mm. This last limitation partly reflects the fact that it is difficult to make very long plasma columns using an axicon lens, and the energy of the laser pulse (and cost of the laser system) required to generate the channel increases linearly with the length of the plasma. In this regard the use of clustered media is an encouraging development which may allow long plasma channels with axial densities less than 10^{18} cm^{-3} to be generated using small fractions of the energy of the main driving laser pulse used in an acceleration experiment.

Several types of capillary discharge have been used to create plasma channels. These all have the advantages that no auxiliary laser system is required to form the channel, long plasma channels can be created, and it may be possible to generate tapered or structured channels. However, with these approaches transverse optical access to the channel is restricted – although in slow capillary discharges it is possible to probe transversely using capillaries with a square cross-section [37], [38]. It is also the case that to date the matched spot size of the plasma channels produced by capillary discharges are relatively large, approximately 30 μm.

Significant advantages of using hydrodynamic compression in fast capillary discharges to generate plasma channels are that the channels can be made to be fully ionized, and with a reasonably small matched spot size at low axial electron densities. Disadvantages are that the discharge circuitry is relatively complex and the channels evolve on a nanosecond time-scale, which means that the discharge must be triggered with very low jitter. It should also be noted that this approach is likely to be limited on the high density side by difficulties in driving a shock wave at high gas pressures.

The electrical circuit employed in slow capillary discharges is extremely simple. Further, gas-filled ceramic capillaries offer a long shot lifetime and are able to form fully-ionized plasma channels. The main issue remaining to be investigated with this approach is scaling to low electron densities. To date guiding in channels with axial electron densities in the range 10^{18} – 10^{19} cm^{-3} has been demonstrated. However, it is not clear that it will be possible to use this approach to generate plasma channels at lower densities whilst maintaining a reasonably small matched spot size [37].

Relativistic and ponderomotive guiding are, by their nature, able to guide very intense laser pulses. However, these guiding mechanisms are ineffective at guiding short laser pulses with a duration $\tau < 2\pi / \gamma\omega_p$ owing to the fact that the refractive index of the plasma is modified on the time-scale of the plasma, rather than that of the laser pulse [9]. In addition, long laser pulses are prone to modulation instabilities; indeed this mechanism is used in the self-modulated laser wakefield acceleration scheme. It is likely to be difficult, therefore, for relativistic or ponderomotive guiding to be used to accelerate particles over long lengths. It can, however, play an important role in experiments to produce beams for subsequent injection into an accelerator stage. Furthermore, the laser intensities employed in such a stage will be at least mildly relativistic, and as such relativistic and ponderomotive focusing will be important effects.

We conclude by noting that much ingenuity has been used in developing a wide variety of techniques for guiding intense laser pulses. However, there is as yet no 'perfect' technique able to guide laser pulses of arbitrary intensity over any desired length through a plasma density which may be freely chosen. As such, the particular conditions of an experiment will be the main factor determining the most appropriate guiding technique – and this is likely to remain the case for the foreseeable future.

Acknowledgements

S.M. Hooker would like to thank D. J. Spence for helpful comments, and the Royal Society for financial support through a University Research Fellowship. This work was supported in part through the Basic Technology Research Programme of the UK Research Councils (GR/R88090). We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395)

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