Slow wave plasma structures for direct electron acceleration

B D Layer, J P Palastro, A G York, T M Antonsen and H M Milchberg

Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, MD 20742, USA
E-mail: layerbd@gmail.com

New Journal of Physics 12 (2010) 095011 (20pp)
Received 2 May 2010
Published 29 September 2010
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/9/095011

Abstract. Two highly versatile experimental techniques are demonstrated for making preformed plasma waveguides with a periodic structure capable of supporting the propagation of ultra-intense femtosecond laser pulses up to $2 \times 10^{17}$ W cm$^{-2}$, limited by the available laser energy. These waveguides are made in hydrogen, nitrogen and argon plasmas with a length of 15 mm and a modulation period as short as 35 µm. Simulations show that these guides allow direct laser acceleration of electrons, achieving gradients of 80 MV cm$^{-1}$ and 10 MV cm$^{-1}$ for laser pulse powers of 1.9 TW and 30 GW, respectively. It is also shown that the periodic structure in these waveguides supresses the Raman forward instability, which could otherwise interfere with the direct acceleration scheme proposed.
1. Introduction

The extreme focused laser intensities accessible with modern ultrashort pulse, high-energy solid-state lasers have enabled the pursuit of many useful and physics-rich applications, such as laser-driven particle acceleration [1, 2], x-ray lasers [3–5], high-harmonic generation [6–8] and terahertz generation [9]. The efficient generation of these extreme intensities is made possible by squeezing a modest amount of laser energy into an extremely small temporal and spatial region. However, diffraction imposes a trade-off between peak intensity and focal volume; focusing a laser pulse more tightly in free space causes more rapid divergence to a larger beam of weaker intensity. This is a major obstacle, because the simultaneous achievement of ultrahigh intensities and large focal volumes is necessary for the most efficient and useful realization of these applications.

Waveguides are by definition the solution to this problem. However, ultrashort pulse laser systems now routinely exceed intensities of $10^{18}$ W cm$^{-2}$ and even the most durable solids have damage thresholds on the order of $10^{12}$ W cm$^{-2}$. This renders conventional metal or dielectric waveguides useless, since the damage threshold of a solid is fundamentally determined by the ionization threshold of its constituent atoms. Thus, the inescapable solution is to make a waveguide composed of plasma. Although dielectric hollow core waveguides also make it possible to guide intensities that surpass this damage threshold [10], they cannot support the extreme intensities possible in plasma waveguides.

Many groups have developed and demonstrated such plasma micro-optics capable of guiding ultra-intense laser pulses with an effectively unlimited damage threshold. They were first generated using the radial hydrodynamic shock expansion of gas plasma heated with an axicon-focused picosecond laser pulse [11]. Later, plasma waveguides were demonstrated in capillaries using an electrical discharge [12, 13], in variations of the hydrodynamic shock technique [14, 15], and most recently using laser-driven hydrodynamic shocks in cluster jet targets, both end pumped [16] and side pumped [17]. The optical mode structure and dispersion properties of plasma waveguides have been discussed in detail [18].

All the applications mentioned above benefit from an extended interaction volume, but after guiding has maintained focused propagation for several vacuum Rayleigh lengths, phase-matching between the laser pulse and process can become a dominant limitation. Depending
on the application, this refers to the mismatch between either the phase or group velocity of
the driving laser pulse, and the velocity of a relativistic particle beam or the phase velocity of
newly generated electromagnetic radiation. For example, in the case of direct laser acceleration
it is impossible to match the superluminal phase velocity of the driving laser in a plasma with
the subluminal velocity of accelerating relativistic charged particles. This results in the charged
particles being pushed with equal force in alternating directions as the laser field oscillates if
direct acceleration is attempted in an unmodulated waveguide with imperfect phase matching.
Phase matching can become possible when a plasma’s negative contribution to the index of
refraction is balanced by a positive contribution, such as from a neutral gas in a partially ionized
plasma [19] or the transient positive index from exploding clusters [20]. However, it is difficult
to implement these solutions in situations with the highest intensities, where deeply ionized
plasmas with large negative contributions to the index are unavoidable. Quasi-phase matching
(QPM) of the interaction then becomes necessary. Other recent work on QPM methods for use
in plasma waveguides includes interfering the driving pulse with a counterpropagating pulse
train [21] or a counterpropagating infrared beam [22].

We have recently developed two ways of adding periodic modulations to plasma
waveguides generated using the hydrodynamic shock technique in a cluster jet target [23, 24].
This allows us to pursue several exciting lines of research which require QPM, including
direct acceleration of charged particles driven by guided, radially polarized femtosecond
pulses [25]–[27] and the generation of high-power terahertz pulses [9]. There is currently
great interest in laser-based particle acceleration, laser wakefield acceleration (LWFA) in
particular, as it may lead to a new generation of compact, cost effective and energetic particle
accelerators. However, laser systems capable of multi-TW peak powers are necessary to form
the highly nonlinear, ponderomotively driven plasma waves used in LWFA to couple driving
laser energy to relativistic charged particles. Although such laser systems are commonly
referred to as ‘tabletop’, they often stretch the definition of the term. Direct acceleration of
charged particles offers an appealing alternative, as it is possible with much smaller few-mJ
femtosecond regenerative amplifiers incapable of driving such plasma waves. We propose the
use of modulated plasma structures for this application and show that modest laser pulses could
be used to directly accelerate electrons with acceleration gradients of $\sim 100$ MV cm$^{-1}$ [25].
The energy gain in this direct acceleration scheme can be increased by extending the laser
pulse duration. However, this could make the laser pulse susceptible to the Raman forward
instability [28], which could affect the accelerating field. We show that the axial modulations in
these plasma waveguides greatly reduces the growth rate of this instability.

In addition to discussing the effects of channel modulations in the terminology of QPM, we
can view the modulated plasma channel as a ‘slow wave’ structure. This is especially relevant
as we consider particle acceleration applications, as this language is usually used to discuss
the structured copper cavities used in conventional RF-based particle accelerators. Our direct
acceleration scheme is analogous, using plasma structures instead of copper, driven by infrared
optical radiation instead of microwaves.

The phase velocity of a Gaussian beam in an unmodulated plasma channel is $v_p/c = 1 + \tilde{N}_e/(2N_{cr}) + 2\lambda^2/(2\pi\omega_{ch})^2$, where $\omega_{ch}$ is the $1/e$ field radius of the guided mode, $\tilde{N}_e$ is the
average electron density on axis, $N_{cr}$ is the critical density and $\lambda = 2\pi/k_0$ is the laser vacuum
wavelength [29]. For deeply ionized plasmas such as those present in the waveguides considered
here, the phase velocity in a straight waveguide is strictly superluminal. However, a modulated
plasma waveguide adds a negative $m\lambda/d$ term to the right side of the equation, where $m$ is
an integer and $d$ is the axial modulation period. This can balance the positive contribution of the plasma, creating slow wave components of the propagating beam at values of $m$ that yield a subluminal phase velocity. This occurs because the corrugations add additional ‘branches’ to the $\omega$ versus $k$ dispersion diagram, where $k = k(\omega)$ is the axial wave number of the guide and $\omega$ is the angular frequency. More specifically, adding axial modulations allows a new set of solutions to satisfy Maxwell’s equations within the waveguide, given by $u(r_{\perp}, z, \omega) = u(r_{\perp}, z + d, \omega)$ and $k = k_c(\omega) + 2\pi m/d$ (from the Floquet–Bloch theorem), $u$ is an electromagnetic field component, $r_{\perp}$ is transverse position and $k_c$ is the fundamental axial wave number [30]. Direct acceleration becomes possible when the subluminal phase velocity of one of the slow waves components $m$ matches the velocity of copropagating relativistic charged particles.

2. Methods for creating modulated waveguides

Two different techniques are used to make modulated waveguides, both of which involve modifications of the setup used to make an unmodulated waveguide in a cluster jet. In the first, a laser pulse with a radially periodic intensity distribution is brought to a line focus on a uniform clustered gas target using an axicon [23]. This creates and nonuniformly heats a plasma column, leading to periodic diameter modulations that we refer to as a ‘corrugated’ structure. The second uses a spatially uniform laser pulse and a nonuniform clustered target with sharp discontinuous gaps at periodic intervals [24]. These two techniques lead to periodically modulated channels with distinct characteristics that are optimal for different applications. Both of these methods are modified versions of the technique for making unmodulated waveguides.

2.1. Unmodulated waveguides in a cluster jet

Figure 1 shows the experimental setup. A 100 ps Nd:YAG laser pulse (10 Hz, 1064 nm, up to 800 mJ) is focused by an axicon to a 25 mm line-focus positioned 2–3 mm above a cluster jet with an elongated nozzle. This line focus overfills the length of the 15 mm long, 1 mm wide nozzle exit orifice, generating a 15 mm long plasma column. Over a period of several nanoseconds after the arrival of the laser pulse, this plasma column expands radially with a hydrodynamic shock wave, resulting in a tubular plasma profile with an on-axis electron density minimum.

The cluster source used in these experiments was a liquid nitrogen cooled supersonic gas jet with an elongated nozzle exit orifice. Clusters form when a highly pressurized gas undergoes rapid cooling and expansion from the nozzle into vacuum. As this expansion occurs, Van der Waals forces attract the atoms or molecules to one another, leading to the formation of aggregates at solid density of mean diameter anywhere between 1 and 50 nm ($\sim 10^2–10^7$ atoms). We control this mean diameter using nozzle geometry, gas species, jet temperature (115–295 K) and backing pressure (100–1000 psi) [17]. The channel can be extended by increasing the length of the cluster jet and decreasing the base angle of the axicon.

The use of a clustered target in conjunction with a 100 ps Bessel beam is an important aspect of our experimental setup, allowing us to decouple the average gas density from the plasma channel density to some extent through the control of cluster parameters. It was shown [17] that the use of clusters increases the 100 ps Bessel beam absorption efficiency by an order of magnitude compared to an unclustered gas target of the same volume average density.
Figure 1. Experimental layout for generation of modulated channels using a Nd:YAG laser pulse (200–500 mJ, 100 ps, 1064 nm) transmitted through a ring grating (RG) (not shown), then imaged to the axicon line focus, which overfills an elongated cluster jet target making a 15 mm corrugated plasma channel. (a) Ti:sapphire laser pulse (70 mJ, 70 fs, 800 nm) focused to the entrance of the guide through a hole in the axis of the axicon, guiding with an electronically adjustable delay. A 1 mJ portion of this fs pulse was used to probe the channel transversely, then sent through a folded wavefront Michelson interferometer. Extracted phase from these interferograms of argon cluster plasma channels with modulation periods of (b) 300 µm and (c) 30 µm, and air plasma with a (d) 35 µm period. (e) Exit mode from the guide in (b), with $w_{\text{HWHM}} = 13$ µm.

This occurs despite the fact that typical clusters generated by our nozzle in these experiments (~5–30 nm diameter) explosively disassemble and expand below the plasma critical density on a subpicosecond time scale much shorter than the 100 ps channel generating pulse [20]. It is helpful to view this as a two-stage interaction; first the far leading edge of the 100 ps pulse encounters clusters with a near solid density, which are ionized extremely efficiently through electron collisional ionization prior to the arrival of the majority of the pulse energy. These dense, deeply ionized clusters of plasma then expand, cool and merge over several picoseconds to form a uniform plasma that is then efficiently heated by the majority of the pulse that then follows [17].
Waveguides were injected through a hole in the axicon at \( f/10 \), with 70 mJ, 70 fs, 800 nm Ti:sapphire laser pulses. The guided Ti:sapphire pulses and the channel-generating Nd:YAG pulses were synchronized and variably delayed with respect to one another, usually by \( \sim 2 \) ns. Radial electron density profiles of the evolving channel were obtained by probing the plasma with a small portion of the femtosecond pulse (\( \sim 1 \) mJ). After passage through a delay line, this probe pulse was directed transversely through the side of the waveguide and imaged through a folded wavefront interferometer onto a CCD camera, followed by phase extraction and Abel inversion [23].

2.2. Waveguides modulated with ring grating (RG) imaging

Our first method for imposing axial modulations in a plasma channel relies on the use of a RG, an azimuthally symmetric transmissive diffraction grating, which we fabricate by lithographically etching a fused silica disc with a carefully chosen groove period, depth, duty cycle and pattern. We use the RG by centering it in the path of the channel-generating 100 ps laser pulse, then imaging it with appropriate lenses to the line focus of the axicon. This maps the diffraction pattern produced by the RG onto the optical axis and leads to axial intensity modulations. These modulations are caused by interference at the line focus of several Bessel beams, which are generated by the different diffracted orders of the RG. These axial modulations of the central spot intensity lead to axial modulations in the plasma column generation and subsequent heating in the cluster jet. The 100 ps pulse can be thought of as an impulse on the hydrodynamic time scale (\( \sim 0.1–0.5 \) ns) of the heated bulk plasma (formed from merged cluster explosions) that remains after the pulse [17]. The merged cluster plasma then undergoes radial hydrodynamic shock expansion, producing a diameter-modulated corrugated plasma waveguide.

Figures 1(b) and (c) show phase images extracted from transverse interferograms of modulated channels with 300 and 35 \( \mu \)m modulation periods in an argon cluster jet. Since the modulations are caused by the interference pattern of several Bessel beams with different convergence angles, we can control the period of the waveguide by using sets of Bessel beams with different angles. This is accomplished by using a RG with a different ruling density for each desired waveguide modulation period. Corrugated guides can also be generated in backfill gases: figure 1(d) shows a shadowgram of a modulated channel produced in air with a period of 35 \( \mu \)m. However, channels generated in backfill are not useful for guiding high intensity pulses due to ionization-induced defocusing, which prevents the pulse from reaching peak intensity and efficiently coupling into the entrance of the waveguide. We use these backfill plasmas primarily as an alignment diagnostic. Figure 1(e) shows a guided mode imaged from the exit of a typical modulated cluster plasma channel (half-width at half-maximum mean radius 13 \( \mu \)m). The use of cluster targets acts to greatly stabilize plasma generation and is responsible for our ability to ‘sculpt’ fine and consistent modulation features. Note that all density profiles shown are extracted from the average phase of 200 consecutive interferograms, and the shot-to-shot extracted density variation is less than 5%. The high stability of these waveguides is also exhibited in the exit modes of the guided femtosecond pulses. In sequences of 100 consecutive end mode images of guided femtosecond pulses in hydrogen (argon) cluster plasmas, we observed RMS centroid jitter of 2.6 (3.5) \( \mu \)m with a mean FWHM of 15.4 (18.9) \( \mu \)m, as determined by a Gaussian fit to each spot profile. The primary source of jitter is the pointing of the femtosecond laser prior to coupling into the waveguide. By tuning the relative delay between the channel generating 100 ps laser pulse and the guided femtosecond pulse, we can achieve consistent single mode guiding. A sequence of 12 consecutive guided end mode images
Figure 2. A sequence of 12 consecutive end mode images of guided femtosecond pulses in unmodulated hydrogen plasma waveguides. The set of images from which this sequence was taken has an RMS jitter of 2.6 µm and mean FWHM of 15.4 µm. The main source of jitter in these images pointing of the femtosecond laser prior to coupling into the waveguide, the plasma structure itself is extremely consistent.

Figure 3. Abel-inverted radial electron density images of corrugated plasma channels made with a RG imaged to an argon cluster jet (800 psi backing, 22 °C). (a) 3 mm section of channel with (bottom panel) and without (top panel) a right-to-left propagating guided Ti:sapphire pulse (70 mJ, 70 fs, 800 nm) injected 1.5 ns after channel formation. (b) Magnified images of beaded (300 mJ pump, left column (i)) and more continuous (500 mJ pump, right column (ii)) modulations, 2 ns after the channel-forming Nd:YAG pulse. Left (i) and right (ii) columns: (1) radial plasma density of uninjected waveguide, (2) radial plasma density of injected waveguide, (3) Abel-inverted scattering image at 800 nm corresponding to (2).

from an unmodulated hydrogen plasma waveguide is shown in figure 2. The waveguide acts as a spatial filter for the guided pulse.

Results for modulated argon plasma waveguides are shown in figure 3. The modulation period of $d = 300 \mu m$ was chosen because it ensures clearly observable periodic oscillations in plasma channel density. An extended region is shown at 1.5 ns delay in figure 3(a) with and
without guided pulse injection (bottom and top panels, respectively) 10 ps after the guided pulse leaves the frame. The guided pulse has little effect on the preformed plasma waveguide, but a significant electron density ‘halo’ appears approximately 100 µm outside the channel wall after the passage of the guided femtosecond pulse. Sequences of probe images taken at increasing probe delays show that the halo propagates right to left at the speed of light with the guided pulse. The halo’s radial location remains constant over the full 15 mm length of the waveguide, but the initial density of the halo continuously drops with propagation distance from the entrance of the guide. This suggests that it is caused by a portion of the guided pulse leaking through the walls of the waveguide that ionizes neutral clusters around the periphery of the channel [18], rather than by a portion of the driving femtosecond pulse that fails to couple into the channel at the entrance and continues to propagate outside the channel.

Higher-resolution images of modulations near the center of argon cluster channels are shown in figure 3(b), revealing in the left column that using a less energetic axicon-focused pulse (300 mJ) can produce periodic ‘beads’ of plasma separated by zones of neutral clusters and atoms, while the right column shows that using more pulse energy (500 mJ) results in a continuous ionization. The beads act as a series of plasma lenslets, collecting the light emerging from each gap and re-focusing it to the next gap. In beaded guide, strong additional ionization by the guided pulse is observed in the initially neutral gaps in figure 3(b) (panel (2i)) as the beam is focused and collected by successive lenslets. Remarkably, the guided energy throughput of the channel is still ~10%, showing that the plasma lenslets can recapture the guided pulse with reasonable efficiency. Throughput for continuous channels made with more 100 ps energy is ~20%, yielding a peak intensity of $2 \times 10^{17}$ W cm$^{-2}$ at the beam waist, based the fact that the exit mode of the channel is measured at a guide bulge. This peak-guided intensity was limited by available pulse energy in the femtosecond laser system. For comparison, throughput at this injection delay in an unmodulated waveguide is ~60%. Panels (2i) and (2ii) both show in more detail the ionization halo induced by leakage of the guided pulse through the walls of the channel. Thomson–Rayleigh scattering of guided 800 nm light was transversely imaged through the same optics used to record probe images. These scattering images are dominated by regions where there was no measurable plasma density prior to the arrival of the guided pulse (figure 3(b), panels (3i) and (3ii)), making clear that the dominant scatterers are likely clusters that either survived in the gaps between beads or outside the continuously modulated guide.

2.3. Waveguides modulated with wire obstructions in a cluster jet

Our second method for producing modulated plasma channels uses an axially uniform channel generating beam focused upon a modulated cluster target, as shown in figure 4. We accomplish this modulation of the target by stretching thin wires across the orifice of our standard 15 mm by 1 mm elongated cluster jet, parallel to the 1 mm dimension. This array of wires allows us to make a modulated waveguide by disrupting the clusters required for plasma formation at regular intervals.

2.3.1. Effects of single wire obstructions. Initial experiments examined the effects upon the plasma waveguide of a single 25 µm diameter tungsten wire stretched across the short dimension of our cluster jet nozzle. We observed the temporal evolution of the waveguide in the neighborhood of the wire using the same transverse interferometry setup used in the RG channel experiments. It is seen in figure 5 that this obstruction in the cluster flow causes a
Figure 4. Experimental setup for waveguides modulated with cluster jet obstructions. A Nd:YAG laser pulse (200–500 mJ, 100 ps, 1064 nm) is brought to a line focus with an axicon, overfilling an elongated cluster jet target with periodic obstructions, making a 15 mm corrugated plasma channel. A Ti:sapphire laser pulse (70 mJ, 70 fs, 800 nm) is focused to the entrance of the guide through a hole in the axis of the axicon, guiding with electronically adjustable delay. A 1 mJ portion of this fs pulse was used to probe the channel transversely, then sent through a folded wavefront Michelson interferometer. (b) Photograph of channel with 250 µm wires at a 1 mm period and (c) extracted phase image of channel with 25 µm wires at a 200 µm modulation period, both in room temperature argon cluster targets.

50 µm gap in the plasma column immediately after the channel forming pulse is gone. This gap remains remarkably sharp and well defined as the plasma column expands radially and axially, as the gaps between sections of the waveguide shrink and eventually disappear after 6 ns of expansion. These images show that the primary effect of a single wire positioned over at the nozzle exit is to cast a localized downstream ‘shadow’ in the cluster flow. Subsequent guiding experiments, to be discussed shortly, show that this shadow is a manifestation of the absence of clusters, and hence any appreciable plasma. The mean free path for inter-cluster collisions with our jet parameters [31] is $\lambda_{\text{cluster}} = (N\sigma)^{-1 \approx 1}$ mm, where $N \approx 10^{13}$ cm$^{-3}$ is the cluster density and $\sigma \approx 1.5 \times 10^{-12}$ cm$^2$ is the hard sphere collisional cross-section for a 70 Å cluster [31]. The cluster encounter with the wire is thus almost purely ballistic, because $\lambda_{\text{cluster}}$ is much larger than the wire diameter in this experiment. Since the clusters are held together weakly with Van der Waals forces, a collision with a wire will usually be of sufficient energy to dissociate a cluster into its constituent molecules. This would result in a low-density accumulation of monomers near the wire that might impede the ballistic flow of massive clusters, although the magnitude of this effect has not been assessed. It is seen in figure 5 that the edges and gaps in the nitrogen
channels are significantly sharper than those seen in the argon channels. We attribute this to the larger number of available ionization stages in argon, which allows electron density profiles to vary spatially over a larger extent.

The effect of 50, 100 and 250 μm wire obstructions upon the channel was also investigated, and it was found that the breaks in the plasma channel increased with wire diameter (for example, a 300 μm gap for a 250 μm wire). Sharper gaps in the channel were caused by wires of smaller diameter. It is likely that gaps of less than 50 μm can be achieved, but wires smaller than 25 μm were too fragile to mount using the current method. Note that like the corrugated channels generated with RGs, wire-modulated plasma channels are highly stable and reproducible. All density profiles shown in this paper are extracted from the average phase of 200 consecutive interferograms, with a shot-to-shot extracted density variation of less than 5%.

2.3.2. Effects of arrays of wire obstructions. For this method to be useful with applications such as those discussed previously requiring QPM in a plasma channel, an array of regularly spaced wires must be used to make appropriately located breaks in the plasma channel. The first array constructed consisted of 250 μm wires with 1 mm periodicity, seen in figure 4(b). 25 μm wires with a ~200 μm period were then used, which produced argon and nitrogen plasma waveguides (figures 6(a) and (b)) with local density profiles and temporal evolution similar to those observed with single wires. Our method of hand-winding led to slightly nonuniform wire arrays, and a suppression of peak local plasma density was observed in plasma segments between wire pairs that were closer together than the others. It is possible that this is an effect
of monomer interference with cluster flow caused by clusters that have been dissociated by collisions with wires.

Any electron density in the gaps of the channels is below the sensitivity of the transverse interferometer, a clear indication that there were no clusters in that region of the target. However, based on unguided channel images alone, the gaps could still contain significant unclustered gas density, because the 100 ps Bessel beam may not cause detectable ionization at the unclustered gas densities that would be encountered in our jet. A 70 mJ, 70 fs, 800 nm Ti:sapphire laser pulse was then guided in an argon channel, and transverse probe images taken with and without the guided pulse are shown in figures 6(b) and (c). There was virtually no change in plasma density after the high intensity pulse propagated through the gaps, which, given the ion stage of the plasma and the $10^{17} \text{cm}^{-3}$ threshold phase shift sensitivity of the probe in our optical interferometry setup, the gas atom density in the gaps must be $< 10^{16} \text{cm}^{-3}$. An examination of the scattered light from the guided pulse (figure 6(d)) corroborates this conclusion of negligible particle density in the gaps. Note that the slanted gap shadows seen in figures 6(c) and (d) can be attributed to the local direction of the flow from the cluster nozzle near that section of the wire grid.

Also seen in figure 6(c) is a halo of plasma density appearing outside the walls of the plasma waveguide that was also observed in the RG modulated channels in figure 3. The halo is present only after the passage of the guided femtosecond pulse, as also observed in the
corrugated channels formed with RGs. We attribute the plasma halo to leakage of the guided pulse through the walls of the modulated channel, and subsequent scattering/absorption by unionized clusters at the channel periphery. There is no such further ionization in the peripheral regions adjacent to the gaps, reinforcing the conclusion that there are no clusters present in the wire shadows. Figure 6(d) shows Rayleigh scattering of the femtosecond pulse guided in the channel shown in figure 6(c). As was the case for the RG-modulated channel, femtosecond light impinging upon unionized clusters was the primary source of Rayleigh scattering, which in the channel shown in figure 6(c) only occurred after the leakage reached unionized clusters outside channel walls.

3. Direct acceleration of charged particles

Harnessing the powerful electric fields found in femtosecond laser pulses for efficient relativistic particle acceleration is currently a research topic of great interest, especially LWFA. However, LWFA uses highly nonlinear plasma waves to couple laser energy to particle beams that sub-TW laser systems are incapable of driving. This is unfortunate, because the smaller, mJ-scale regenerative amplifiers incapable of LWFA are capable of much higher repetition rates than larger systems, and are much more widespread and affordable by comparison. Directly coupling laser energy to charged particles could completely avoid the requirement of a nonlinear intermediary (such as plasma) for transferring energy to charged particles. However, there are immediate and obvious obstacles to efficient coupling between the laser field and charged particles. The propagation direction of a laser pulse and the direction of its electric field vector are perpendicular, and the laser electric field oscillates. These facts make it difficult to directly couple a substantial fraction of laser pulse energy to the momentum of charged particles in a controlled fashion.

A wide variety of methods have been used to circumvent these obstacles to direct acceleration, including kilometer-scale RF-loaded copper guiding structures, radially polarized Bessel beams focused in a hydrogen gas [32], and a picosecond laser focused on a metal strip [33]. However, all of these techniques are limited to gradients of order 1 MV cm\(^{-1}\), because beyond this level breakdown usually occurs in any dielectric or metal structure and none of these methods can tolerate the presence of plasma in the acceleration region for various reasons. Femtosecond lasers are now capable of generating fields surpassing 10 GV cm\(^{-1}\), and there is no way to harness these field strengths in an un-ionized structure.

One way to make the propagation direction of the laser parallel to a component of the laser electric field \(E_z\) is to use a radially polarized laser pulse in a straight plasma waveguide [34], which allows the acceleration of a copropagating relativistic electron bunch a laser pulse. The dominant component of the guided mode of a radially polarized pulse in a straight waveguide is the radial component \(E_r\), which has a doughnut profile that peaks at \(r = w_{ch}/\sqrt{2}\) and is zero on-axis. The mode radius \(w_{ch}\) is given by \(w_{ch} = (1/\pi r_e \Delta N_e)^{1/2}\), where \(r_e\) is the classical electron radius and \(\Delta N_e\) is the difference in electron density between the axis \(r = 0\) and mode radius \(r = w_{ch}\). Crucially, there is also an axial component to the guided mode \(E_z\) that peaks on axis at \(r = 0\) then drops to zero at the mode radius \(r = w_{ch}\). It is this axial component that allows direct acceleration of a copropagating bunch of charged particles. For a 1.9 TW, 800 nm laser pulse in a channel with a mode radius \(w_{ch} = 15 \mu m\), a properly phased copropagating bunch of electrons would experience a peak gradient of 0.49 GV cm\(^{-1}\) [25] from the \(E_z\) component of the laser field. This gradient is competitive with those achieved using LWFA, but the problem of

New Journal of Physics 12 (2010) 095011 (http://www.njp.org/)
Figure 7. Schematic setup for direct acceleration of electrons using (a) a corrugated plasma waveguide generated with a RG (diffractive optic). (b) Abel-inverted radial electron density for an argon plasma waveguide is shown after 2 ns of expansion. (c) A radially polarized femtosecond laser pulse and copropagating relativistic electron bunch are then injected, allowing quasi-phase-matched direct acceleration of the electron bunch if the corrugation period of the waveguide is matched to $L_d$.

matching the phase velocity of the guided pulse to the velocity of the relativistic electron bunch makes it difficult to maintain this strong gradient over an extended propagation distance.

The positive contribution to the refractive index from neutral gas in a partially ionized plasma channel can be used to achieve phase matching [34], but complete ionization of any neutral gas by the radially polarized pulse would be unavoidable long before the desired gradients could be reached. This newly formed plasma would then give a negative contribution to the refractive index, making the phase velocity of the laser pulse superluminal, rendering perfect phase matching impossible. With mismatched phase velocities, acceleration will only occur for half the dephasing length $L_d/2$, where the dephasing length $L_d = \lambda / 2(N_0/N_{cr} + 2\lambda^2/\pi^2w_{ch}^2)^{-1}$, where $N_0$ is the on-axis plasma density and $N_{cr}$ is the plasma critical density. The electron bunch will then experience equal and opposite acceleration for the next $L_d/2$ as the axial component of the laser field $E_z$ pushes in the other direction. For plasma densities and diameters typically seen in modulated guides generated with RGs, this dephasing length is $\sim 300 \mu m$ for an electron bunch moving at $\sim c$.

The modulated plasma waveguides demonstrated experimentally above can quasi-phase match this direct acceleration process. Laser phase velocity is faster in higher density plasmas; so, if the modulation period of the waveguide is chosen to match the dephasing length $L_d$, cancellation between acceleration and deceleration as the electric field oscillates should no longer be complete. An electron bunch phased such that it is in lower density regions during acceleration and the higher density regions during deceleration will gain energy with each dephasing length. This proposed experimental setup is schematically shown in figure 7.
3.1. Analytic calculations

A scaling law was analytically calculated for this direct acceleration scheme, making appropriate approximations. First we consider the radial component of the laser vector potential:

$$A_r = \hat{A}_r(r, z, t) \exp[i(k_0 z - \omega_0 t)],$$

(1)

where $\hat{A}_r(r, z, t)$ is a slowly varying envelope, $k_0$ is the central wave number, and $\omega_0$ is the central frequency of the laser pulse. Azimuthal symmetry is assumed for all time and channels at much less than critical density are considered. Under these assumptions the laser pulse envelope evolves on a time scale much longer than the laser period, so that the evolution of the pulse envelope can be determined by the slowly varying envelope equation

$$2i k_0 \left( \frac{\partial}{\partial z} + \frac{1}{c} \frac{\partial}{\partial t} \right) + \frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} - \frac{1}{r^2} \hat{A}_r = \frac{\omega_p^2(r, z)}{c^2} \hat{A}_r,$$

(2)

where $\omega_0 = k_0 c$. This also assumes that the plasma responds linearly as a nonrelativistic cold fluid, which should be quite valid in this regime. Our boundary condition at the origin is $\hat{A}_r(r = 0) = 0$. A lossless plasma channel is then assumed, allowing us to set the boundary condition $\hat{A}_r(r = \infty) = 0$. The conditions under which this assumption is valid are determined in appendix B of [26].

To calculate solutions for the slowly varying envelope equation, a channel profile $N_e(r, z)$ must be chosen. Since the dephasing length $L_d$ between laser pulse and electron bunch will change as the electrons accelerate, it would be best to have a plasma structure with a continually varying $L_d$ to compensate and maintain ideal QPM for the full length of the channel. This could be accomplished using a structure with a graded modulation period or an axial taper. However, for simplicity an azimuthally symmetric, axially periodic model plasma channel has been chosen that mimics those experimentally measured

$$N_e(r, z) = N_0(1 + \delta \sin(k_m z)) + N''_0 r^2 / 2,$$

(3)

where $\delta$ is the relative amplitude of the axial density modulation, $k_m$ is the wave number describing axial periodicity, and $N''_0$ determines the radial profile of the channel. This simplifies the investigation of electron bunch dynamics, because exact solutions for the slowly varying envelope equation exist for this channel profile with our boundary conditions and the lowest eigenmode solution is calculated in [26]. An effective phase velocity for the $n$th spatial harmonic can then be found by taking the ratio of $\omega_0$ to $k$

$$v_{p,n}/c = 1 - nk_m / k_0 + \omega_p^2 / 2\omega^2 + 4/(k_0 w_{ch})^2.$$

(4)

This allows the determination of the condition for the existence of a ‘slow wave’ component of the guided pulse with subluminal phase velocity that allows electron acceleration.

By using this expression for the axial field component of a guided radially polarized pulse, then integrating over the pulse length dephasing time, a scaling law for direct acceleration can be obtained. For an electron that starts on axis with no radial velocity and an initial axial velocity close enough to $c$ that the QPM condition is maintained over the acceleration length, the scaling law for energy gain is:

$$\frac{\Delta E}{m_e c^2} \bigg|_{DA} \sim 4\delta a_0 \left( \frac{\sigma_x}{w_{ch}} \right) \left( \frac{\lambda_p}{\lambda} \right)^2 \left( 1 + \frac{2\lambda_p^2}{\pi^2 w_{ch}^2} \right)^{-2},$$

(5)

New Journal of Physics 12 (2010) 095011 (http://www.njp.org/)
where $\lambda_p = 2\pi c / \omega_p$. This scales linearly with the density modulation amplitude $\delta$ and the field amplitude $a_0$. For comparison, the LWFA scaling law is

$$\frac{\Delta E}{m_e c^2} \mid_{WF} \sim \frac{a_0^2}{(1 + a_0^2/2)^{1/2}} \left( \frac{\lambda_p}{\lambda} \right)^2 \left( 1 + \frac{\lambda_p^2}{\pi^2 w_{ch}^2} \right)^{-1}. \quad (6)$$

Plugging in parameters seen experimentally in [23], we see that this scheme can be used to achieve an energy gain of $\Delta E/mc^2 \sim 1000$ using a pulse energy of 1.9 TW (normalized amplitude $a_0 = 0.25$), $\lambda = 800 \text{ nm}$, $w_{ch} = 15 \mu\text{m}$, pulse length $\sigma_z/c = 300 \text{ fs}$, on axis plasma density $N_e = 7 \times 10^{18} \text{ cm}^{-3}$, corrugation amplitude $\delta = 0.9$ and modulation period of $T_m = 349 \mu\text{m}$.

This is similar to the $\Delta E/mc^2 \sim 750$ gain seen in [35] using LWFA driven with a 7.16 TW pulse, but the real strength of this method lies with laser pulse energies below the threshold for any acceleration using LWFA. Gain of $\Delta E/mc^2 \sim 125$ is still achieved if the driving pulse energy of DLA is reduced to 30 GW.

### 3.2. Stimulated Raman forward scattering

The energy scaling law of equation (5) shows that the energy gain in QPMed direct acceleration can be increased by extending the pulse duration. As the pulse becomes longer, however, it can become susceptible to Raman scattering which can degrade the quality of the pulse [28] and as a result the accelerating field. In a corrugated plasma channel, the situation is not as severe as in an axially uniform channel and longer pulses can be guided. We show that adding axial modulations to these plasma waveguides reduces the instability growth rate.

The Raman forward instability occurs when an incident light wave scatters off fluctuations in the plasma density, resulting in a frequency up- and down-shifted scattered light wave. The scattered light wave then beats with the incident wave to enhance the density fluctuations (plasma wave). In an axially uniform plasma channel, every radial point within the channel has a different density and thus a different resonant wavenumber for the excited plasma wave. In a parabolic plasma channel, the resonant radius for a given plasma waves wavenumber is $R = \frac{1}{2} w_{ch}^2 (k^2 - k_p^2)^{1/2}$, where the wavenumber is determined by the phase matching condition and dispersion relation for the scattering process. In a modulated plasma channel, the resonant radius is a function of axial position, $R(z) = \frac{1}{2} w_{ch}^2 (k^2 - k_p^2(z))^{1/2}$ and the instability cannot grow uniformly along the propagation direction, since the modulations disrupt the spatial coherence of the instability.

Simulations with WAKE [36] were conducted to investigate the Raman effect upon the propagation of laser pulses propagating in axially uniform and modulated plasma channels. We used the same synthetic plasma channel profile (equation (3)) and laser pulse parameters as those in the analytic calculations in the previous section. Figure 8(a) shows strong fluctuations in pulse envelope after 7.5 mm of propagation in an unmodulated channel (modulation amplitude $\delta = 0$). However, in a channel with density modulation amplitude $\delta = 0.9$ that emulates the profile of a RG-modulated channel, the effect of the Raman instability upon the pulse envelope is reduced to an acceptable level, as shown in figure 8(b). In addition, propagation of a plasma profile that more closely approximates waveguides modulated with wire arrays was simulated by replacing the $\delta \sin(k_m z)$ term in the synthetic channel profile (equation (3)) with $\delta \sin^{10}(k_m z)$. These results, shown in figure 8(c), clearly show that this modulation profile also effectively suppresses the effect of the Raman instability upon the pulse envelope.
3.3. Electron beam dynamics

To study electron beam dynamics, the electron equations of motion are integrated in the laser field calculated using our model waveguide and the varying envelope equation (2). We also neglect space charge effects, which is valid in the regime where the axial field due to space charge is smaller than the accelerating field. For the channel parameters discussed above, this corresponds to a maximum bunch charge of approximately 40 pC [26]. Consider electron beams with zero initial divergence and a waveguide modeled after those created using RGs that is 18 mm long. In this situation, the interaction time determined by the waveguide length is approximately half the pulse length dephasing time, so particle momentum gain is limited by the plasma channel length.

3.3.1. Scaling law verification. First, these simulations were used to verify the analytically calculated scaling law. This was accomplished by evaluating several electron trajectories, starting from 10 to 11 μm behind the peak of the laser pulse, with initial electron momentum of \( p_z/m_e c = 30, 100 \) or 1000. Since only uniform modulation periods are being considered, we must also choose the \( n = 1 \) slow wave phase velocity of the waveguide by selecting a modulation period. For each of the three initial electron momenta, acceleration in a channel was first simulated with the \( n = 1 \) slow wave phase velocity equal to the initial electron momentum, and then simulated again with the slow wave phase velocity of the channel equal to \( c \). These results are shown in figures 9(a) and (b), along with the prediction of the analytically derived scaling law.

This shows that the scaling law is more accurate for higher initial electron momenta. This makes sense, because the scaling law is derived assuming that perfect QPM is maintained as the
Figure 9. Simulated electron trajectories in the synthetic channel in figure 7(b). Energy gain versus time for initial electron energies $\gamma_0 = 30, 100$ and $1000$ with (a) the slow wave phase velocity matched of the channel matched to the initial electron velocity and (b) with the slow wave phase velocity set to $c$ for all initial electron energies. For an initially uniform distribution of electrons, average final momentum $p_z$ as a function of (c) initial position and (d) final position. The final electron density in (e) shows that the initially uniform distribution has become bunched and focused.

electrons gain momentum, which in practice would require a continually varying modulation period or axial density gradient. However, because a waveguide with a constant modulation period is used in these simulations, as the particle gains velocity it drifts away from (or closer to) the phase velocity of the slow wave. This explains the discrepancy between the scaling law and simulations at lower energies, because at lower energies the same change in momentum results in a larger change in velocity mismatch.

3.3.2. Transverse beam dynamics. Assuming that we can neglect space charge effects, electrons close to the axis will experience transverse forces arising from two different physical mechanisms.

The first is a quasi-phase-matched force caused by the slow wave components of the guided laser pulse responsible for acceleration. Just as the axial component of these slow waves has a net accelerating or decelerating effect depending on the phase of an electron in $z$, there is also a focusing or defocusing effect with the same periodicity. These focusing and defocusing regions are out of phase by $90^\circ$ with the accelerating and decelerating regions. Starting with the equation
of motion for an electron near the waveguide axis and using the phase-matching condition for the \( n = 1 \) slow wave, the expression for the QPMed focusing or defocusing force is

\[
F_{qpm} = \frac{m_e c^2 k_0 \delta a_0}{[1 + 2\lambda_p^2/(\pi^2 w_{ch}^2)]} \frac{r}{w_{ch}} \left[ 1 - \frac{v_z}{c} \left( 1 + \frac{8}{k_0^2 w_{ch}^2} \right) \right] \cos(k_0 z - \omega_0 t). \tag{7}
\]

The other transverse force arises from the ponderomotive force exerted by the driving pulse. Since most of the laser energy is in the ‘doughnut mode’ of the radial electric field, the ponderomotive force focuses electrons closer to the axis than the peak radial field and defocuses those further from the axis. The lowest-order contribution in \( \lambda_p/w_{ch} \) to the ponderomotive force of the of the radial field due to the \( n = 0 \) laser mode is

\[
F_{pm} = -\frac{2 m_e c^2}{\gamma_0} \frac{r}{w_{ch}^2} a_0^2 \left[ 1 - \frac{4 v_0}{c} \left( \frac{\lambda_p}{w_{ch}} \right)^2 \left( 1 + \frac{2\lambda_p^2}{\pi^2 w_{ch}^2} \right)^{-1} \right]^2. \tag{8}
\]

This component of the force is dominant due to the large relative amplitude of the \( n = 0 \) mode. It is inversely proportional to \( \gamma_0 \); so, higher energy electrons experience less ponderomotive focusing.

Overall, electrons that are initially at small radii experience a focusing force. The ratio of the two transverse forces is

\[
\frac{F_{pm}^*}{F_{qpm}^*} \sim \frac{1}{4\gamma_0} a_0 \left( \frac{k_0 w_{ch}}{\delta} \right) \left( 1 + \frac{\lambda_p^2}{\pi^2 w_{ch}^2} \right)^{-1}, \tag{9}
\]

which for our parameters is \( \sim 0.08 \), so it is seen that for this lower-intensity regime the quasi-phase-matched focusing is stronger than ponderomotive focusing effects.

To examine these transverse dynamics, a 10 \( \mu \)m long, axially uniform electron bunch with a Gaussian radial profile of \( \sigma_b = 9 \ \mu \)m was simulated. The start of the bunch was positioned 1 \( \mu \)m behind the peak of the laser pulse, with an initial momentum of \( p_z/m_e c = 100 \), and the phase velocity of the \( n = 1 \) mode of the waveguide set to \( c \). In figure 9, we show radial plots of the number-averaged \( z \) electron momentum as a function of initial (figure 9(c)) and final (figure 9(d)) position, as well as the final electron density (figure 9(e)). As expected, we see that electrons that are initially close to the axis with the proper initial \( z \) position experience focusing and acceleration, while improperly phased electrons and those further from the axis are ejected from the waveguide. This tells us that the profile and phasing of the injected bunch is extremely important, as the highest-energy electrons gain 151 MeV over 1.8 cm, a gradient of 84 MeV cm\(^{-1}\). A 40 pC bunch within a single ‘bucket’ of the beam would absorb about 6 mJ of energy. Since this acceleration scheme scales linearly with the laser field strength, just 30 GW of laser power would give a respectable gradient of 10.6 MeV cm\(^{-1}\).

4. Conclusion

We have demonstrated guiding and dispersive control of intense femtosecond laser pulses in miniature plasma slow wave guiding structures generated with two distinct techniques. The first uses a ring grating to impose axial intensity modulations at the line focus of the channel-generating 100 ps Nd:YAG laser pulse, which lead to diameter modulations in the plasma channel after several nanoseconds of radial hydrodynamic expansion. The second uses a spatially uniform channel-generating pulse and a cluster jet target with array of thin wire
obstructions that remove small sections of the cluster target and thus the waveguide. These channel generation schemes, which exploit the unique properties of clusters and cluster plasmas, make fine control of both the diameter and on-axis refractive index of plasma waveguides possible, allowing both photon and particle applications based on QPM.

Simulations that demonstrate the viability of these channels as a tools for harnessing the fields of intense femtosecond pulses for the direct acceleration of electrons were discussed. This method scales linearly with laser field strength, and can therefore be implemented with few-mJ femtosecond regenerative amplifiers incapable of driving the highly nonlinear ponderomotive plasma waves LWFA requires. By guiding a radially polarized pulse in a modulated plasma channel, the symmetry is broken between the accelerating and decelerating forces due to the axial electric field $E_z$ present due to the radially polarized pulse. This allows a properly phased electron bunch to gain energy with each dephasing length $L_d$. This was shown using an analytic model for laser pulse propagation in a corrugated plasma waveguide developed using the slowly varying envelope approximation. As result of the periodic axial density profile, the guided mode becomes composed of spatial harmonics, and for small enough plasma corrugation periods some of these spatial harmonics are ‘slow waves’ with subluminal phase velocity that make direct electron acceleration possible.

Acknowledgments

This work was supported by the US Department of Energy, the National Science Foundation and the Office of Naval Research.

References

[1] Tajima T and Dawson J M 1979 Laser electron accelerator Phys. Rev. Lett. 43 267–70
[2] Esarey E, Schroeder C B and Leemans W P 2009 Physics of laser-driven plasma-based electron accelerators Rev. Mod. Phys. 81 1229
[3] Milchberg H M, Durfee C G and Lynch J 1995 Application of a plasma waveguide to soft-x-ray lasers J. Opt. Soc. Am. B 12 731–7
[4] Rocca J J 1999 Table-top soft x-ray lasers Rev. Sci. Instrum. 70 3799–827
[5] Butler A, Gonsalves A J, McKenna C M, Spence D J, Hooker S M, Sebben S, Mocen T, Bettaibi I and Cros B 2003 Demonstration of a collisionally excited optical-field-ionization XUV laser driven in a plasma waveguide Phys. Rev. Lett. 91 205001
[6] Lewenstein M, Balcou Ph, Ivanov M Yu, L’Huillier A and Corkum P B 1994 Theory of high-harmonic generation by low-frequency laser fields Phys. Rev. A 49 2117–32
[7] Milchberg H M, Durfee III C G and McIlrath T J 1995 High-order frequency conversion in the plasma waveguide Phys. Rev. Lett. 75 2494–7
[8] Winterfeldt C, Spielmann C and Gerber G 2008 Optimal control of high-harmonic generation Rev. Mod. Phys. 80 117
[9] Antonsen T M Jr., Palastro J and Milchberg H M 2007 Excitation of terahertz radiation by laser pulses in nonuniform plasma channels Phys. Plasmas 14 033107
[10] Arpin P, Popmintchev T, Wagner N L, Lytle A L, Cohen O, Kapteyn H C and Murnane M M 2009 Enhanced high harmonic generation from multiply ionized argon above 500 eV through laser pulse self-compression Phys. Rev. Lett. 103 143901
[11] Durfee C G and Milchberg H M 1993 Light pipe for high intensity laser pulses Phys. Rev. Lett. 71 2409–12
Ehrlich Y, Cohen C, Zigler A, Krall J, Sprangle P and Esarey E 1996 Guiding of high intensity laser pulses in straight and curved plasma channel experiments Phys. Rev. Lett. 77 4186–9

Butler A, Spence D J and Hooker S M 2002 Guiding of high-intensity laser pulses with a hydrogen-filled capillary discharge waveguide Phys. Rev. Lett. 89 185003

Volfheyn P, Esarey E and Leemans W P 1999 Guiding of laser pulses in plasma channels created by the ignitor–heater technique Phys. Plasmas 6 2269–77

Gaul E W, Le Blanc S P, Rundquist A R, Zgadzaj R, Langhoff H and Downer M C 2000 Production and characterization of a fully ionized he plasma channel Appl. Phys. Lett. 77 4112–4

Kumarappan V, Kim K Y and Milchberg H M 2005 Guiding of intense laser pulses in plasma waveguides produced from efficient, femtosecond end-pumped heating of clustered gases Phys. Rev. Lett. 94 205004

Sheng H, Kim K Y, Kumarappan V, Layer B D and Milchberg H M 2005 Plasma waveguides efficiently generated by bessel beams in elongated cluster gas jets Phys. Rev. E 72 036411

Clark T R and Milchberg H M 2000 Optical mode structure of the plasma waveguide Phys. Rev. E 61 1954–65

Rundquist A, Durfee III C G, Chang Z, Herne C, Backus S, Murnane M M and Kapteyn H C 1998 Phase-matched generation of coherent soft x-rays Science 280 1412–5

Kim K Y, Alexeev I, Parra E and Milchberg H M 2003 Time-resolved explosion of intense-laser-heated clusters Phys. Rev. Lett. 90 023401

Zhang X, Lytle A L, Popmintchev T, Zhou X, Kapteyn H C and Murnane M M 2007 Quasi-phase-matching and quantum-path control of high-harmonic generation using counterpropagating light Nat. Phys. 3 270–5

Cohen O, Zhang X, Lytle A L, Popmintchev T, Murnane M M and Kapteyn H C 2007 Grating-assisted phase matching in extreme nonlinear optics Phys. Rev. Lett. 99 053902

Layer B D, York A, Antonsen T M, Varma S, Chen Y-H, Leng Y and Milchberg H M 2007 Ultrahigh-intensity optical slow-wave structure Phys. Rev. Lett. 99 035001

Layer B D, York A G, Varma S, Chen Y H and Milchberg H M 2009 Periodic index-modulated plasma waveguide Opt. Express 17 4263–7

York A G, Milchberg H M, Palastro J P and Antonsen T M 2008 Direct acceleration of electrons in a corrugated plasma waveguide Phys. Rev. Lett. 100 195001

Palastro J P, Antonsen T M, Morshed S, York A G and Milchberg H M 2008 Pulse propagation and electron acceleration in a corrugated plasma channel Phys. Rev. E 77 036405

Palastro J P and Antonsen T M 2009 Interaction of an ultrashort laser pulse and relativistic electron beam in a corrugated plasma channel Phys. Rev. E 80 016409

Antonsen T M and Mora P 1992 Self-focusing and raman scattering of laser pulses in tenuous plasmas Phys. Rev. Lett. 69 2204–7

York A, Layer B D and Milchberg H M 2006 Application of the corrugated plasma waveguide to direct laser acceleration AIP Conf. Proc. 877 807–11

Schachter L 1979 Beam–Wave Interaction in Periodic and Quasi-Periodic Structures (Berlin: Springer)

Kim K Y, Kumarappan V and Milchberg H M 2003 Measurement of the average size and density of clusters in a gas jet Appl. Phys. Lett. 83 3210–2

Kimura W D, Kim G H, Romea R D, Steinhauer L C, Pogorelsky I V, Kusche K P, Fernow R C, Wang X and Liu Y 1995 Laser acceleration of relativistic electrons using the inverse Cherenkov effect Phys. Rev. Lett. 74 546–9

Plettner T, Byer R L, Colby E, Cowan B, Sears C M S, Spencer J E and Siemann R H 2005 Visible-laser acceleration of relativistic electrons in a semi-infinite vacuum Phys. Rev. Lett. 95 134801

Serafin P, Sprangle P and Hafizi B 2000 Optical guiding of a radially polarized laser beam for inverse cherenkov acceleration in a plasma channel IEEE Trans. Plasma Sci. 28 1190–3

Hubbard R F, Sprangle P and Hafizi B 2000 Scaling of accelerating gradients and dephasing effects in channel-guided laser wakefield accelerators IEEE Trans. Plasma Sci. 28 1159–69

Mora P and Antonsen T M Jr 1997 Kinetic modeling of intense, short laser pulses propagating in tenuous plasmas Phys. Plasmas 4 217–29