Channel Guided Lasers for Plasma Accelerators

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ABSTRACT

The recent demonstration of optical guiding of high intensity laser pulses in plasma waveguides [C.G. Durfee III and H.M. Milchberg, Phys. Rev. Lett 71, 2409 (1993)] has opened the way to new advances in the development of compact laser-driven electron particle accelerators. We review plasma waveguide properties relevant to intense pulse guiding and electron acceleration and show that the shock driven channels described here are well suited for stabilization of a large class of laser-plasma instabilities deleterious to high intensity guiding over long distances.

1. INTRODUCTION

Calculations show that a typical requirement for producing a 1 GeV/cm laser-plasma wake field is to propagate a 10^{18} W/cm^2 laser pulse for ~1 cm in a plasma of electron density 10^{18} cm^{-3} [1]. Until recently, achieving such extended propagation distances for intense pulses was an unsolved problem. Our demonstration [2] of high intensity optical guiding has made possible the serious investigation of laser-plasma-based accelerator schemes, as well as the development of nonlinear optics based short wavelength light sources [3] and soft X-ray lasers [4]. To date, pulses of intensity above 10^{15} W/cm^2 have been guided up to 90 Rayleigh lengths (~3 cm) in our experiments, and this constitutes the highest intensity-interaction length product ever achieved. Up to this intensity range, guiding has appeared to be approximately linear. However, accelerator applications require the guiding of laser pulses which are short and relativistically intense ($\gtrsim 10^{18}$ W/cm^2 at λ~1µm), where the electron response to the field has relativistic corrections, charge (electron) displacement becomes significant, and strong Raman instabilities can be excited in the underlying plasma medium. We show below show that under conditions characteristic of our plasma waveguides, these instabilities can be greatly reduced or eliminated.

2. PLASMA WAVEGUIDE

As an illustration of how the plasma waveguide is formed, Fig. 1 shows a calculation of gas response under typical pressure and laser conditions used in our experiments. The model [1] includes tunneling ionization in the laser field, inverse bremsstrahlung heating, thermal conduction (gradient based or flux-limited), and collision-based ionization and recombination. The breakdown spark drives a radial shock wave in the ion density, leaving a plasma density minimum on axis appropriate for guiding a laser pulse. The important hydrodynamic timescales of experimental relevance are those for shock generation, $\tau_s = \lambda_{ii}/c_s$, and for column evolution, $\tau_c = w_0/c_s$. Here, λ_{ii} is the ion-ion collisional mean free path, c_s is the local sound speed, and w_0 is the laser spot size. For typical experimental parameters of gas pressure 5-300 torr and laser spot size w_0=1-10µm, τ_s ~10-100 ps and τ_c~0.1-1 ns [5].

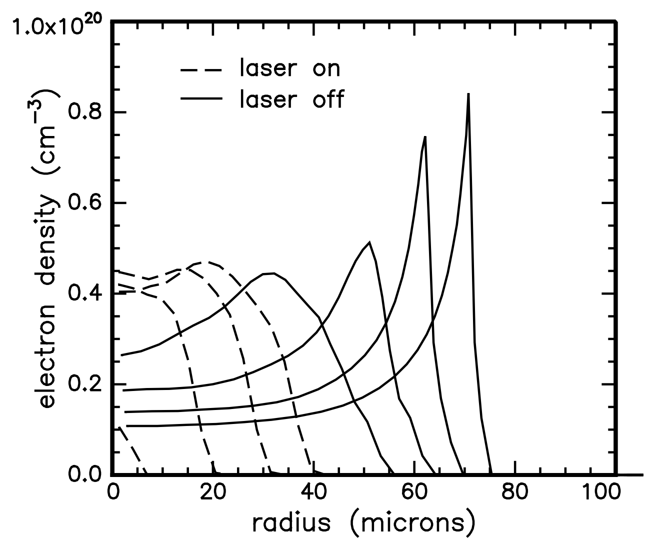

Figure 1: Calculation of 150 torr N_2 response to a 100 ps FWHM pulse of peak intensity 5x10^{13} W/cm^2, spot size w_0 = 10 µm, and λ =1 µm.

The laser used in the initial experiments is a 10 Hz Nd:YAG regenerative amplifier system which can produce 400 mJ, 100ps pulses at λ=1.064µm and 200 mJ, 70 ps pulses at 0.532µm. The pulses are split, with ~200-300 mJ total in 0.532 and 1.064 µm directed to an axicon lens, and up to 100 mJ directed to a waveguide coupling lens. Alternatively, a synchronously amplified dye laser pulse of up to 5 mJ energy at 250fs pulsewidth can be coupled into the plasma waveguide. An optical delay provides -1 to 12 ns delay between the axicon (waveguide generating) pulse and the lens (coupling) pulse. The axicons used are glass cones, with base angles 20° to 35°.

An incident beam refracts at the cone surface, forming a conical wave which interferes with itself, resulting in a Bessel function field profile $E(r,z)=|E_0(z)|^2 J_0^2(kr\sin\gamma)$, where $|E_0(z)|^2$ depends on the transverse field profile incident on the axicon and γ is the angle with the optical axis of the conical wave normal [5]. The first radial field zero is independent of z for a conical axicon surface and a parallel input beam, resulting in an extended focus of constant spot size. For the 35° axicon, the first zero occurs at r_0~1μm and the focus length is L~1 cm for an input beam radius of 0.8 cm. The τ_p < 100 ps pulses used here are well-suited to the plasma dynamics, since $\tau_p \le \tau_s$ and $\tau_p < \tau_c$, and the plasma is heated by the channel creation pulse before it evolves hydrodynamically.

3. WAVEGUIDE MODE PROPERTIES

A condition on the modes that will be supported by a plasma channel can be estimated by assuming a refractive index $n(r)= 1- 1/2\, N_e(r)/N_{cr}(r)$ with a parabolic electron density profile $N_e(r)=N_e(0)+N_{cr}(r/a)^2$, where a is a curvature parameter. For a "finite" parabolic channel with constant electron density beyond a radius r_m ($n(r)=n_{min}$ or $N_e(r)=N(r_m)=N_e^{max}$ for $r>r_m$), approximate cutoff and guiding conditions, respectively, are [6]:

$$N_e(r_m) - N_e(0) \ge \frac{(2p+m+1)^2}{\pi r_e r_m^2} \;; \qquad N_e(w_{ch}) - N_e(0) = \Delta N_e = \frac{1}{\pi r_e w_{ch}^2} \qquad \textbf{(1)}$$

Here r_e is the classical electron radius (2.8x10^{-13} cm), $N_e^{min}=N_e(0)$, $\Delta N_e(w_{ch})=N_e(w_{ch})-N_e(0)$, $p\ge0$ and $m\ge0$ are radial and azimuthal mode indices, and w_{ch} is the $1/e$ field radius of the $p=0$, $m=0$ mode. For a non-parabolic infinite channel, these conditions are still a good approximation [6]. From Eqn. (1), lowest order propagation of a spot size $w_0=w_{ch}$=10μm requires $\Delta N_e \approx 10^{18}$ cm^{-3}. Guiding of higher order modes requires a greater electron density difference and/or channel radius r_m. As seen in Fig. 1, the electron density of the real channel decreases beyond the shock for $r>r_m$ so that a mode below but near the cutoff of Eqn. (1) should tunnel or "leak". Waves close to cutoff appear to be guided, but have non-negligible amplitude outside r_m, where the radiation diverges at a small angle with respect to the channel axis [6].

As indicated by Eqn. (1), adjusting the gas pressure and thus the plasma density should determine the mode structure supported by the waveguide. We have demonstrated experimental control over single mode, multimode and leaky mode propagation regimes [6]. Evidence of leaky mode propagation is shown in the logarithmic-scaled lineouts of Fig. 2. The scattered intensity is observed to decrease exponentially along the channel, with reduced attenuation and increased exit scattering as delay increases (indicating greater channel throughput). This attenuation is not due to inverse bremsstrahlung absorption, for which calculations show a bleaching effect as the guided pulse heats the plasma [5]. The enhanced scattering at the entrance and exit is due to Fresnel reflections of the guided pulse from the near-discontinuity in index at the shock wave interface which propagates away from the channel ends. This index change, however, is not enough to refract the entering and exiting pulse [5].

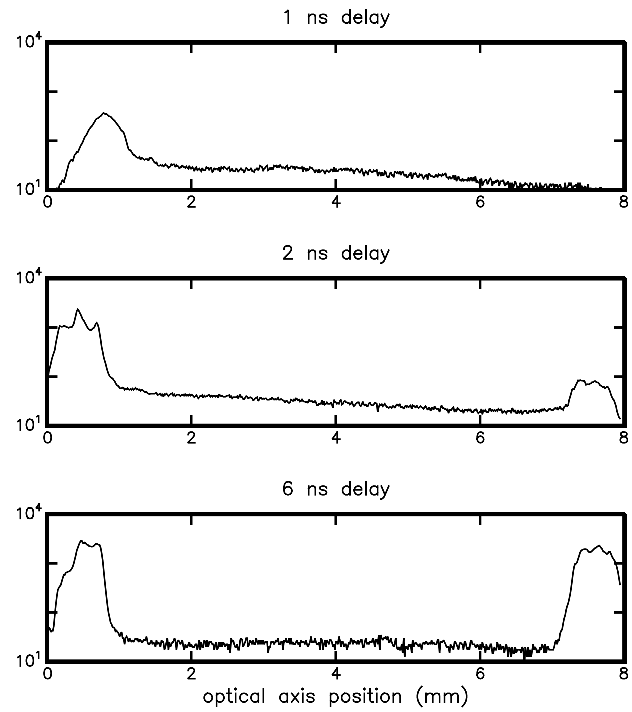

Figure 2: Full channel scattering image lineouts showing leaky mode propagation, for a channel in which the lowest order mode is not well confined at early delays. Confinement improves with increasing delay (and r_m), consistent with Eqn. (1). The injected pulse enters from the left.

4. ULTRA-INTENSE PULSE PROPAGATION

Recently, it has been shown that intense laser pulses suffer from instabilities of the Raman type in which the plasma spontaneously generates modulations at the plasma frequency and the laser light is scattered [7-12]. These instabilities prevent the propagation of smooth pulses of duration significantly greater than the plasma period and have been the subject of theoretical and experimental investigation.

One of the most dangerous instabilities involves the coupling of the Raman and self-focusing mechanisms [7-9]. It results in the scattering at small forward angles of the laser light. If the transverse structure of the laser pulse is initially the lowest order Gaussian mode of propagation, one can think of the small angle forward scattering of the laser light as the excitation of higher order transverse modes of propagation. To the extent that diffraction is weak these higher order modes are not significantly damped and the instability which excites them is strong. In fact, for pulses of peak power P close to the critical power P_c for self-focusing [12] ($P_c = 16.2(\omega/\omega_p)^2\, 10^9$ W, where ω is the frequency of the laser, $\omega_p = (4\pi N_e e^2/m)^{1/2}$ is the plasma frequency based on the ambient electron density N_e , and e and m are the charge and mass of the electron), the pulse will acquire modulation in a time

$$t_m \approx T_R \frac{1}{k_p L} \frac{P_c}{P} \qquad \textbf{(2)}$$

where $T_R = kw_0^2/2c = z_0/c$ is the Rayleigh time, $k=(\omega^2-\omega_p^2)/c$ is the laser wave number in a uniform plasma, w_0 is the laser spot size ($1/e$ electric field radius), z_0 is the Rayleigh length, L is the length of the pulse and $k_p = \omega_p/c$ is the plasma wave number. Thus, for relativistically intense pulses no shorter than the plasma period, the modulations appear in a Rayleigh time. Propagation of pulses over distances greater than a Rayleigh length will be more effective if these instabilities are avoided.

Recent theoretical studies [13] have shown that propagation in leaky channels has important consequences for ultra intense pulses which might exhibit the previously mentioned side scattering instabilities. In particular, as the instability can be regarded as the excitation of a higher order radial mode of propagation, the instability will be suppressed in a leaky channel where the higher order modes are poorly confined, and essentially damped. This stabilization mechanism can be expected to be important not only for the coupled Raman-self focusing instability, but also for the 'laser hose' instability [11] in which the centroid of the laser light is displaced. The mechanism should not seriously influence the growth of either pure forward [10] or the large angle Raman side scattering perturbations [7]. However, these instabilities are less severe in their effects on the laser pulse. In particular, the large angle side scatter instability is only convectively unstable in the pulse frame and may saturate at low amplitude due to particle trapping, while the growth rate for the pure forward instability is smaller than that of the coupled Raman-self focusing instability in a tenuous plasma.

In order to illustrate the effect of a leaky channel on the propagation of an intense pulse we show the results of a numerical simulation of the laser pulse evolution. The system of equations solved describes the interaction of the laser with a weakly nonlinear, weakly relativistic, cold fluid plasma. The following parameters were chosen: normalized laser amplitude, $a_0 = eA/mc^2 = 0.33$, normalized pulse length $k_pL = 60$, and width $k_pw_0 = 10$, where A is the vector potential of the laser field. These parameters correspond to a 100 femtosecond laser pulse of energy 0.15 Joule and $\lambda = 0.8$ μm (corresponding to the Ti:Sapphire laser under construction at the University of Maryland), focused to a 10 μm radius in a plasma of density $2.83\times10^{19}\text{cm}^{-3}$. Figure 3 shows plots of the laser intensity at four times during the simulation for a case in which the ambient plasma density is uniform. This pulse is moderately long, $k_pL = 60$, and is expected to be subject to the Raman - self focusing instability [7]. Indeed, the plots illustrate the development of the instability and show its detrimental effect on laser pulse propagation. After several Rayleigh times a large fraction of the pulse energy has been scattered out of the simulation region. It can also be seen that the head of the laser pulse diffracts [14] even though the body self-focuses.

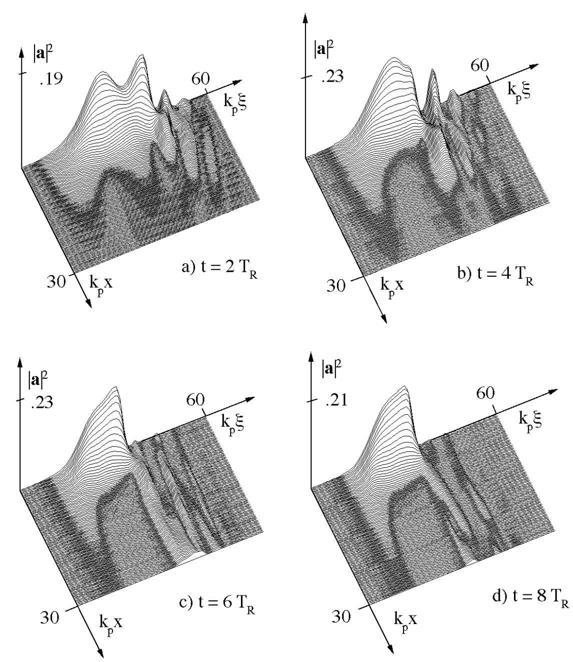

Figure 3: Time evolution of the laser pulse for a uniform plasma. A position coordinate local to the pulse is $\xi=ct-z$. The laser pulse propagates to the left.

Figure 4 shows intensity plots for the same laser parameters for propagation in a leaky channel. Here the peak density is taken to be $2.83\times10^{19}\text{cm}^{-3}$ and the density on axis is 91 % of the peak value. The density profile is quadratic out to a radius $r=r_m=15$ μm, and decreases linearly to zero at $r=21$ μm.

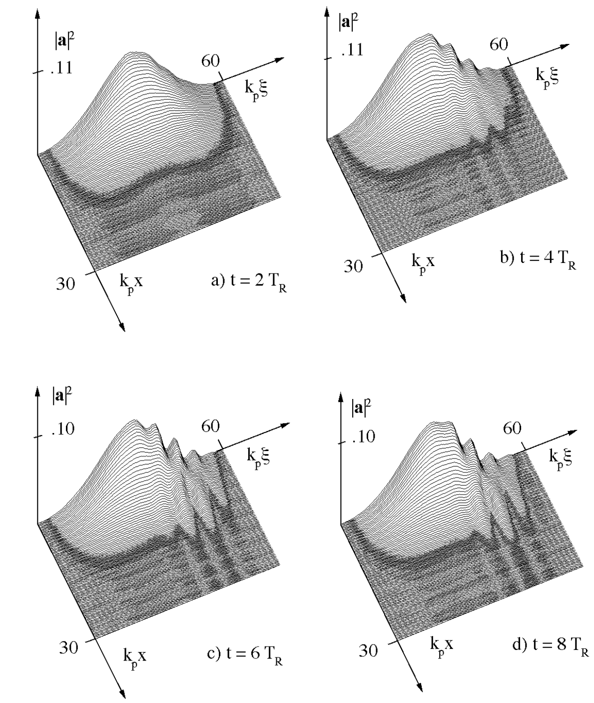

Figure 4: Time evolution of the laser intensity for a leaky channel. The laser pulse propagates to the left.

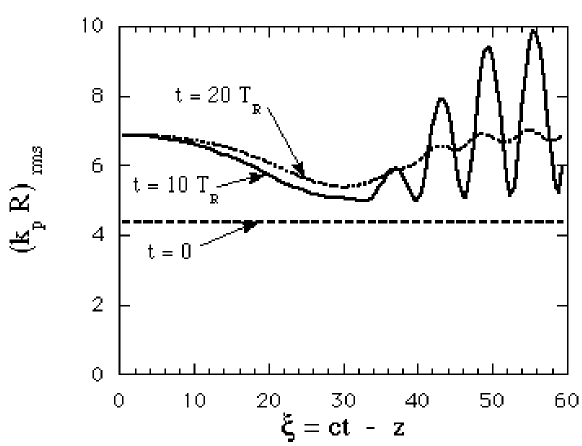

Figure 5: Root mean square radius of laser pulse as a function of distance back from the head for three different times. Here R=w_0.

Compared with the simulations of Fig. 3, the laser pulse retains its shape and energy. Small ripples are visible on the trailing edge of the pulse, indicating the presence of some residual instability. However, the pulse propagates intact for a long period of time as seen in Fig. 5, in which the root mean square 1/e field radius is plotted for three different times. By t=20 T_R , the pulse has reacquired a relatively smooth shape with only a slightly reduced amplitude ($|a|^2$ =0.08).

The above simulations are based on a cold plasma fluid model. Use of this model prevents one from treating situations where the plasma motion reaches the wavebreaking limit and where fast electrons are generated in the interaction. In addition, fluid models contain a mathematical singularity at zero plasma electron density which prevents their use when the electrons are totally expelled from the axis of the laser propagation (electron cavitation). Such features are strong limitations of the fluid models in the high intensity regime. An alternative to the fluid models is the particle-in-cell technique [15]. This technique follows the evolution of the laser radiation on the short timescale associated with the laser period, and thus is computationally intensive and restrictive in the parameters that can be studied.

We have developed a novel particle model to describe the long-time plasma behavior under the action of an ultrahigh intensity (of the order of 10^{18} W/cm^2 or more), short laser pulse (1 psec or less). Among the effects we are able to simulate are the following: (i) Relativistic focusing for short laser pulses over long distances (> 30 z_0) with total electron cavitation in the laser channel and strong modification of the Raman type plasma instabilities; (ii) acceleration of plasma electrons to relativistic energies in the wake of the laser pulse; (iii) plasma wave breaking; (iv) electromagnetic plasma wakes; and (v) high field ionization of background gas.

We illustrate this code with the following parameters: a_0 =1, k_pL=40, k_pw_0=4, for propagation in a uniform plasma. The pulse is about twice the critical power for relativistic self focusing [12]. Figure 6 shows a plot of the laser intensity after 8 Rayleigh lengths of propagation. As expected, trailing ripples are seen, indicating that the pulse is subject to the Raman-self focusing instability, and the pulse head diffracts as usual due to a cancellation between the effects of relativistic self-focusing, and forward charge displacement due to the ponderomotive force of the pulse [9]. However, the instability develops slightly slower than predicted by the weakly nonlinear model of Ref. 7. In this case, we observe a total expulsion of the electrons and stabilization of the Raman instability in the bulk of the laser pulse. As a result, the pulse propagates over a large distance (more than 30 Rayleigh lengths). Figure 7 shows the electron density corresponding to Fig. 6. One observes total electron cavitation where the laser intensity is large, enhancement of the density on the sides, and a strong peak behind the laser pulse due to electrons which return towards the pulse axis under the action of the charge separation field. Suppression of Raman instabilities may be attributed to a number of effects.

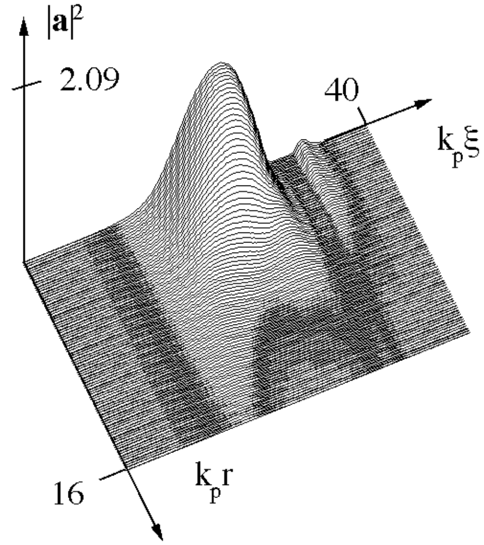

Figure 6: Pulse intensity at z=8z_0 for a pulse with initial length k_pL=40, width k_pw_0=4 and amplitude a_0=1.

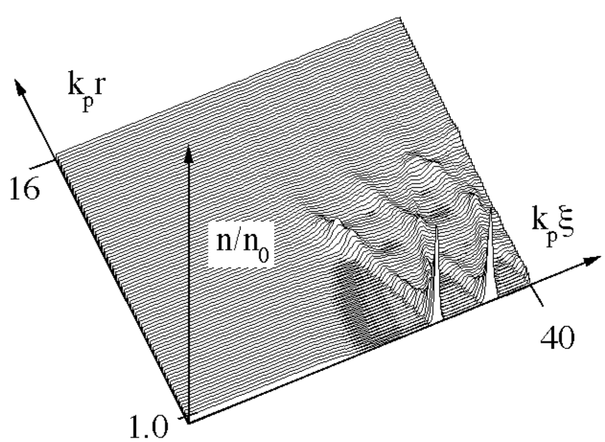

Figure 7: Electron density corresponding to Fig. 6, showing complete cavitation, and leading and trailing peaks.

The electron density is reduced where the laser intensity is greatest so that the plasma channel is inhomogeneous (disturbing the plasma wave resonance), and the channel density has a maximum at a radius just greater than the spot size. This last effect may contribute to enhancing the diffraction of radiation which is sidescattered, and thus suppresses side scattering instabilities as in the leaky channel case shown above in Figs. 4 and 5.

Successful stabilization of Raman instabilities and elimination of diffraction of the head of the pulse via preformed channel guiding will increase the ultimate propagation length of the laser pulse, and both experiments and calculations involving preformed channels are underway. In a tenuous plasma, the laser pulse loses energy while conserving the quantity $\int d^3\boldsymbol{r}\, \omega|\boldsymbol{A}|^2$, the laser "action". In the process, the frequency of the laser light is steadily down shifted and the amplitude of the laser electric field decreases with propagation distance, but the vector potential and plasma electron quiver momentum increases. Thus, as the pulse propagates, the plasma wake becomes more relativistic, as desired for accelerator purposes.

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