Studies of Intense Laser Propagation in Channels for Extended Length Plasma Accelerators

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Abstract

Progress on modeling plasma-based accelerator concepts in plasma channels is presented. Such schemes offer the potential for large accelerating gradients, high beam quality and acceleration over many Rayleigh lengths by optically guiding intense laser pulses. Recent results include modeling of non-ideal channels, higher order laser modes, and instabilities . Curiously we find that Raman scatter and laser hosing are to a large extent suppressed in a hollow channel.

I. NON-IDEAL PLASMA CHANNELS AND RESONANT ABSORPTION

Recently we have investigated the propagation of short laser pulses in hollow channels [1,2] ($n_e = n_i = 0$ on axis, $\omega_p = constant < \omega_{laser}$ for $r > a$). We showed that pulses shorter than $\lambda_p\sqrt{1+k_p a}$ (where $k_p = \omega_p/c$ and a is channel radius) effectively excite a large surface wake of frequency $\omega_p/\sqrt{1+k_p a}$. These wakes were found to be attractive because the accelerating fields were large (of the order 10 GeV/m), transversely uniform and with linear focusing.

In the previous discussion, the plasma was assumed to have a step function radial profile. That is, $n_0(y) = 0$ for $y < a$ and $n_0(y) = n_0$ for $y > a$ In this section we consider the more realistic case when there is a finite scale length for the vacuum plasma boundary. As a first approximation, we consider the plasma density $n_0(y)$ to be zero for $y < a/2$, to ramp linearly from $y = a/2$ to $y = 3a/2$ up to the value n_0, and $n_0(y) = n_0$ for $y > 3a/2$.

Since the laser frequency (ω_0) is much greater than the plasma frequency (ω_p), there is no resonant absorption of the laser. However, because the wake frequency ω_{ch} is less than ω_p, there exists a resonant absorption layer in the channel wall which will damp the wakefield seriously. A thorough investigation of this phenomenon have been given in Ref.[3]. In Figs. 1 to 3 we show the simulation results. The damping of the axial wakefield after the first cycle implies that the wakefield accelerator scheme can be effective, but only if the beam load is placed on the first accelerating bucket. The transverse slices of E_z vs. y show the absorption of the wake energy at the resonant layer.

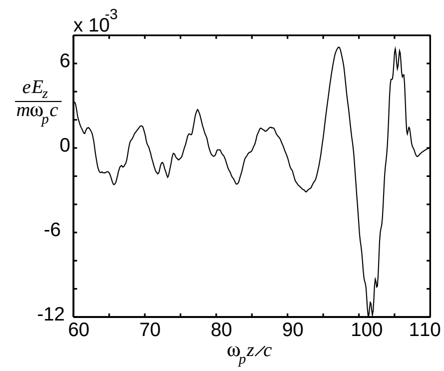

Figure. 1. Axial wakefield $eE_z/m\omega_p c$ vs. z

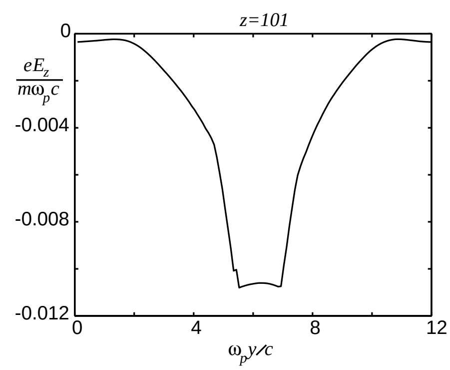

Figure. 2. Axial wakefield $eE_z/m\omega_p c$ vs. y at $z = 101c/\omega_p$

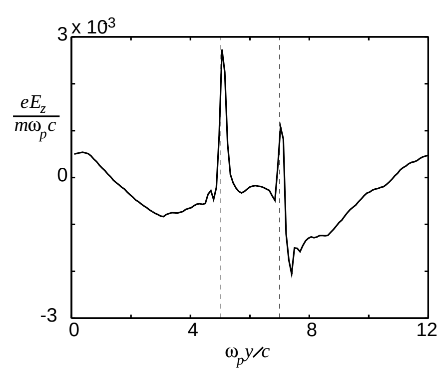

Figure. 3. Axial wakefield $eE_z/m\omega_p c$ vs. y at $z = 80c/\omega_p$

II. HIGHER ORDER OPTICAL FIBER MODES FOR RELAXED CHANNEL REQUIREMENTS

In previous work we found that the accelerating field is large only when the channel width is of order c/ω_p (typically $20\mu m$). For wider channels, the surface wake amplitude decreases because the intensity of the fundamental laser mode at the edge becomes very weak compared to the intensity at the center. This is unfortunate because it may be easier to realize wider channels in actual experiments. Fortunately, there is a solution; namely, we can use higher order guided laser modes in a wider channel. These modes have larger intensity at the edge than does the fundamental mode. Figs. 4 and 5 show the transverse profile of the laser in a plasma fiber at z=0 and z=50 c/ω_p from a PIC simulation. The TE_{01} character is apparent. The laser is well guided and excites a wake very similar to what would be excited by the fundamental TE_{00} mode.

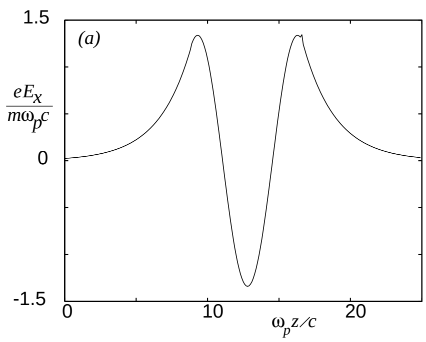

Figure. 4. Transverse electric field of the laser showing its TE_{01} character at z=0 in PIC simulation (for $k_p a = 4$).

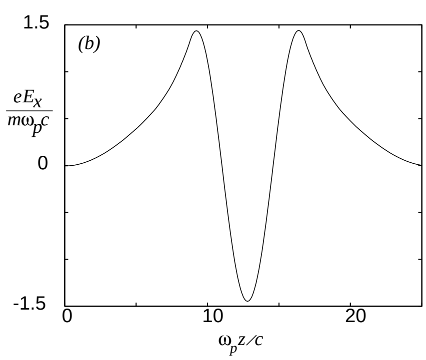

Figure. 5. Transverse electric field of the laser showing its TE_{01} mode character at z=50 c/ω_p in PIC simulation (for $k_p a = 4$).

III. STABILITIES IN CHANNELS

It is well known that the propagation of intense laser pulses in homogeneous plasma is limited to relatively short distances by diffraction, pump depletion and parametric instabilities. Since depressed density channels act as optical fibers to guide the laser, they overcome diffraction. Short pulses excite a large plasma wake as just described that depletes the laser energy over a distance $\lambda_p \omega_0^2/\omega_p^2(1 + 1/(V_{osc}/c)^2)$. However, for pulses longer than $\lambda_p = 2\pi c/\omega_p$, three-wave and four-wave Raman forward [4] and side scatter and laser hosing instabilities [5] limit the intensity that can be stably propagated through the channels. Below we briefly summarize results of analysis and simulation of instabilities in channels.

Analytic solutions for the growth rate of Raman Forward Scatter (RFS) in homogeneous plasma [4] and the hose instability in parabolic channel plasma [5] have been proposed in several articles. We address the same problem in a hollow channel plasma. The derivation will be given in a longer paper. The result is

$$\gamma = \frac{1}{2\sqrt{2}}(\frac{V_{osc}}{c})\frac{\omega_p^2}{\omega_0}\sqrt{1-(\frac{4p}{k_p})^2} \qquad (1)$$

where p satisfies the following dispersion relation for the laser pulse in hollow channel[2],

$$p^2 + h^2 = k_p^2$$
$$p = h\tan(ha) \qquad (2)$$

We see that the growth rate is less than the homogeneous growth rate by a factor $\sqrt{1-(\frac{4p}{k_p})^2}$. It is easy to see that as $k_p a \approx 0$ the growth rate approaches the homogeneous result. In addition, if $k_p < 4p$ or equivalently $k_p a > 0.26$, γ becomes imaginary and even the decaying of the $E_0(\omega_0)$ wave into the body mode ($\omega = \omega_p$) is non-resonant. PIC simulations support the conclusion that Raman instability is suppressed except in very narrow channels ($k_p a < 1$).

Next we examine hosing instability in parabolic channels for various cases of initial laser misalignment. We found through simulations that for a uniform misalignment of the laser centroid defined as $< y_c >= \frac{\int yE^2dy}{\int E^2dy}$, the RFS of the laser will overwhelm the hose instability ,if any, in the parabolic channel. On the other hand, if we seed some wiggle in the laser centroid the laser will execute hosing instability significantly. Fig. 6 shows the initial laser centroid where we have offset sinusoidally by 2 cells. The wiggling wavelength is equal to λ_p. After propagating about 4 Rayleigh lengths, as was shown in Fig. 7, the growth of the laser centroid was evident.

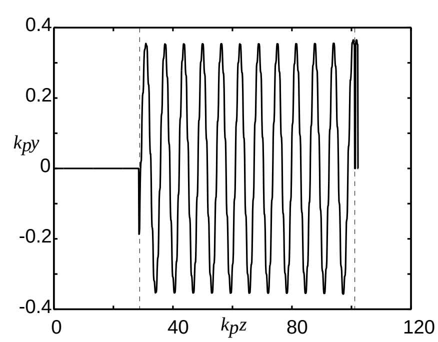

Figure. 6. Centroid of the laser pulse in parabolic channel plasma at z=0. The dashed lines show the position of the laser pulse

IV. Discussion

We have examined the propagation of intense laser pulse through plasmas of various kinds of density profiles. The RFS

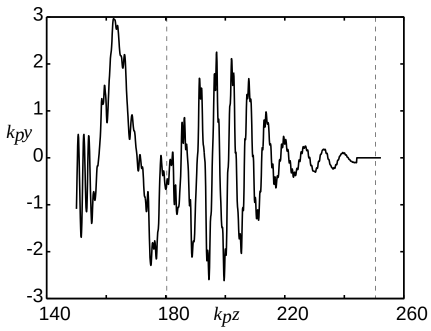

Figure. 7. Centroid of the laser pulse in parabolic channel plasma at z=180 c/ω_p. The dashed lines show the position of the laser pulse

instability in both homogeneous and parabolic channel plasmas are observed in PIC simulations (not shown here). The pulse in parabolic channel seems to be more unstable than in homogeneous plasma. This may be partly due to guiding of Raman side scatter by the channel. In hollow channels, we have found a reduced growth rate for RFS if $k_p a < 0.26$. The instability of the pulse is not significantly affected by the thickness of the channel wall. Overdense channels will be the subject of another work. We comment that underdense channels are of interest because they avoid resonant absorption of the laser by the plasma.

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