Recent Work on Short Pulse Laser-Plasma Accelerators*

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Abstract

Theory and simulation of short-pulse laser plasma accelerators is presented. The plasma beat wave and laser wakefield accelerators are examined for the parameters of recently developed high-brightness lasers. For typical parameters, energy gains of .3 to 1GeV over a few centimeters length appear feasible with a short pulse beat wave design. Issues important for extending these designs to multi-GeV acceleration of beams with high beam quality are examined, including optical guiding of the lasers, non-linear laser and wake velocity shifts, and long-term stability of the laser pulses.

I. INTRODUCTION

The recent success of the plasma beat wave accelerator at UCLA (see C. Clayton, these proceedings), coupled with the rapid advancement of laser technology point to a promising future for short pulse laser-plasma accelerators. It is natural then to consider what are the key issues for next generation experiments at the 100 MeV to GeV level and beyond. These issues include long-term stability of intense laser pulses, non-linear effects on the laser group velocity and resulting accelerating wake velocity, and techniques for guiding the laser pulses over many diffraction lengths.

First, we illustrate with an example that with present technology it is possible to design a GeV experiment that is a straight forward extension of the UCLA experiment. In the UCLA experiment, it was demonstrated that short pulses could avoid competing instabilities and that the energy gain of approximately 20 MeV was consistent with an acceleration length equal to the laser depth of focus.

Then we take up the long-term stability of laser pulses. The parametric instabilities of radiation in plasmas has been long studied. For pulses shorter than an ion plasma period all of the ion instabilities can be avoided. Thus we consider the coupling to electron plasma noise known as Raman scattering. For pulses shorter than a few times the e-folding time of the Raman backscatter instability ($\tau_B = 2\sqrt{2}\,|(V_{os}/c)\sqrt{\omega_0\omega_p}|^{-1}$, where $V_{os}/c = eA_0/mc^2$ is the normalized laser amplitude and ω_0 is its frequency), this can be avoided. On the other hand, even for pulses shorter than the Raman forward scatter *temporal* growth time ($\tau_F \sim 2\sqrt{2}\,|(V_{os}/c)\,\omega_p^2/\omega_0|^{-1}$) this instability can still be important because the decay waves travel in the direction of the pulse at nearly c. We consider for the first time the *spatial-temporal* growth of the forward Raman instability for arbitrarily intense laser pulses.

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Another possible limitation to the energy gain and beam quality in a plasma accelerator is the dephasing between the particle and the wave. Therefore, in laser plasma accelerators it is important to understand the relationship between the laser's parameters (i.e. shape, amplitude, and frequency) and the excited plasma wave phase velocity. In the limit of small laser amplitude, i.e., $\frac{V_{os}}{c} = \frac{eA_0}{mc^2} << 1$, the plasma waves phase velocity is equal to the laser pulse's group velocity. However, as the laser amplitude increases these relationships become more complicated because the laser's group velocity (υ_g) depends on its amplitude and the wake's phase velocity (υ_w) depends on pump depletion. In Sec. IV we examine the non-linear laser group velocity and wake phase velocity analytically and computationally.

Finally, in Sec. V we examine one technique for guiding laser pulses over many diffraction lengths.

II. DESIGN EXAMPLE

An illustrative example of a short-pulse beat wave accelerator is given in Table 1 and Figure 1. We call this a hybrid design because it uses very short laser pulses like the laser wakefield scheme but two frequencies as in the beat wave scheme.

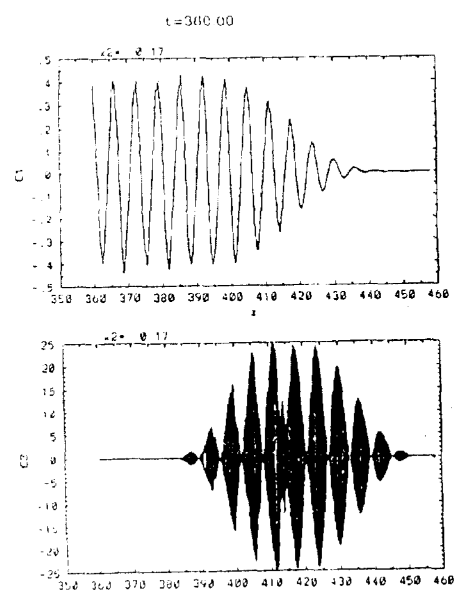

Figure 1. PIC simulation of Plasma wake (above) and laser in hybrid example

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The parameters are typical of a CPA Nd: Yag laser[1]. As shown in the moving PIC simulation in Fig. 1, the plasma wake grows resonantly, but only over a few plasma cycles. So the homogeneity requirement on plasma density ($\Delta n_o/n_o \leq$ one over the number of growth cycles) is greatly relaxed over previous beat wave designs. For this example the energy gain is limited by the laser Rayleigh range to about 300 MeV in 2 cm.

Table 1

Hybrid Wakefield/Beatwave Accelerator An Example:	
Laser Wavelengths	1.05, 1.06 μm
Laser Pulse Length	1.4 psec
Laser Power	10 TW
Laser Spotsize (2σ)	100 μm
Rayleigh Length	0.8 cm
Plasma Density	10^{17} cm^{-3}
Plasma Homogeneity	+/–20%
Accelerating Field	160 MeV/cm
Acceleration Length*	6.4 cm
Energy	1000 MeV

*Assumes optical guiding. Max energy without guiding is 300 MeV

III. FORWARD RAMAN INSTABILITY OF SHORT PULSES

We consider a laser pulse of vector potential $A \equiv mc^2a/e$ propagating in a plasma of density $n_o \equiv m\omega_p^2/4\pi e^2$. The coupled equations for the laser potential A and plasma potential $\phi \equiv (\chi - 1)mc^2$ are found in the coordinates $\psi = t - x/c$ and $\tau = t$:

$$-2\,\partial_\psi\,\partial_\tau\, a = \frac{a}{\chi} \tag{1}$$

$$\partial_\psi^2 \chi + \frac{1}{2}\left[1 - \frac{1+a^2}{\chi^2}\right] = 0_2 \tag{2}$$

This is the quasi-static approximation[2]. We expand these for large a and χ about $\chi = \chi_o + \delta\chi$ where $\chi_o^2 = 1 + a_0^2/2$, $a = \frac{a_o}{2} e^{i\theta_o} + \frac{a_+}{2} e^{i\theta_+} + \frac{a_-}{2} e^{i\theta_-} + \text{c.c}$, $\theta_j = -k_j\psi - (\omega_j - k_j)\tau$, $\delta\chi = \delta\chi_s e^{i\theta}$, and $\theta_\pm = \theta \pm \theta_o$. The details and an exact solution in ψ and τ are given in a longer paper[3]. Here we give the asymptotic growth rate for $\tau > \psi$ (i.e., distance moved through the plasma longer than the pulse length) and large a_o: χ, a grow as e^Γ where

$$\Gamma = 2\,\gamma_{nl}\sqrt{\psi\tau} \tag{3}$$

$\gamma_{nl} = \gamma_o/\chi_0^2$ and γ_o is the usual small-amplitude temporal growth rate ($\gamma_o = a_o\omega_p^2/2\sqrt{2}\,\omega_o$)

IV. NON-LINEAR GROUP AND WAKE VELOCITY

An analytical expression for the nonlinear group velocity is obtained by starting from the conservation of energy equations for a fluid plasma

$$\frac{\partial}{\partial t}\left[\frac{E^2+B^2}{8\pi} + n\,mc^2\,\gamma - n_o mc^2\right] + \nabla\cdot\left[\frac{c}{4\pi}\,E \times B + n\,mc^2\gamma\,\upsilon\right] \tag{4}$$

where υ is the electron momentum and $\gamma \equiv [1 - \frac{\upsilon^2}{c^2}]^{-1}$. A group velocity is given by the ratio of the energy flux to the energy density. For long pulses this provides the expression

$$\upsilon_g = \frac{c^2/\upsilon_\phi}{1 + \frac{\omega_p^2}{2\omega^2}\,\frac{\gamma_{\perp 0} - 1}{\gamma_{\perp o}(\gamma_{\perp o}+1)}} \tag{5}$$

where $\gamma_{\perp o} \equiv (1 + \langle(\frac{e A_o}{mc^2})^2\rangle)^{1/2}$, < > represents averaging of the laser oscillations and Faraday's law was used to relate B to E. An expression for υ_ϕ is provided by the well known results of Ahkiezer and Polovin, $\upsilon_\phi^2 = \frac{1}{1 - \frac{\omega_p^2}{\omega^2\gamma_{\perp o}}}$. Therefore, in the nonlinear limit $\upsilon_\phi\,\upsilon_g$ no longer equals c^2. Note that expression (4) does reduce to the linear results as $\gamma_{\perp o} \to 1$. If we define $\gamma_g \equiv (1 - \frac{\upsilon_g^2}{c_2})^{-1/2}$ then $\gamma_g = \sqrt{\frac{\gamma_{\perp o}+1}{2}}\,\frac{\omega}{\omega_p}$ while if $\upsilon_g = \frac{1}{\upsilon_\phi}$ then $\gamma_g = \sqrt{\gamma_{\perp o}}\,\frac{\omega}{\omega_p}$. The relationship between υ_g and υ_w was investigated using PIC simulations. Analytical results are difficult because the wake's phase velocity is influenced by υ_g, linear and nonlinear dispersion, photon deceleration (pump depletion), photon acceleration and pulse distortion.

It was found that the group velocity of symmetrically shaped pulsed of length $\leq 2\pi\, c/\omega_p$ is always above the linear υ_g but below the nonlinear υ_g of long pulses. However, the wake's phase velocity monotonically decreases from the *linear* υ_g as the laser's amplitude is increased. We believe this arises from pump depletion which causes the front of the pulse to distort. Furthermore, we have found that pulses with slow rise times and rapid fall times provide wakes with phase velocities exceeding the *nonlinear* group velocity. We note different conclusions regarding υ_g and υ_w have been reached when the lowest order non linearities and times exceeding the pump depletion time were considered. Clearly, further work is needed to fully understand the dependence of υ_w on laser parameters.

V. HOLLOW CHANNEL LASER WAKEFIELD ACCELERATOR[4]

In order to guide a short pulse over long distances without diffraction we consider a hollow evacuated channel in the plasma. Since the index of refraction in the channel ($\varepsilon = 1$) is greater than that in the surrounding plasma ($\varepsilon = 1 - \omega_p^2/\omega_o^2$), the channel guides the laser as would an optical fiber. The channel can be formed by a precursor laser (of high frequency, low intensity and long pulse length) or by hydrodynamic means prior to ionization (e.g., a partially blocked gas jet).

The laser excites a wake on the surface of the channel; the fields of the wake extend into the channel where a particle beam can be accelerated. The wake is illustrated in Fig. 2 and the laser pulse, initially and after 13 Rayleigh lengths, is shown in Fig. 3.

The hollow channel scheme presented here has several attractive features: (1) The Rayleigh length limit on acceleration length is overcome. (2) The wake is nearly uniform as a function of radial position in the channel, so beam quality should be good. (3) The laser and wake velocity are higher than in a uniform plasma, so phase slippage is reduced.

Further study of the stability of such pulses is planned.

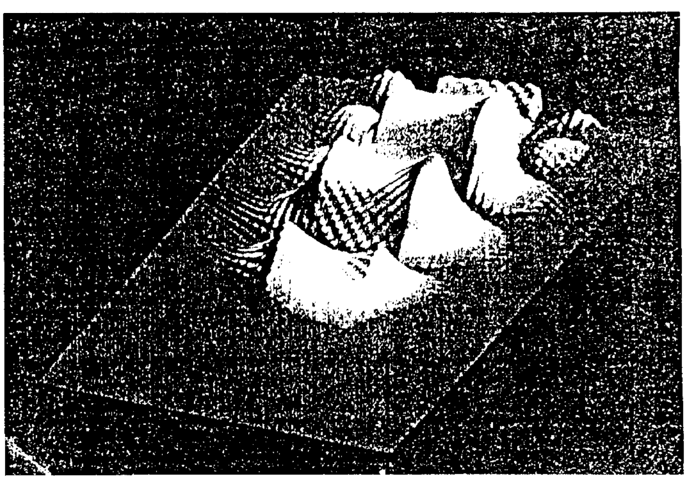
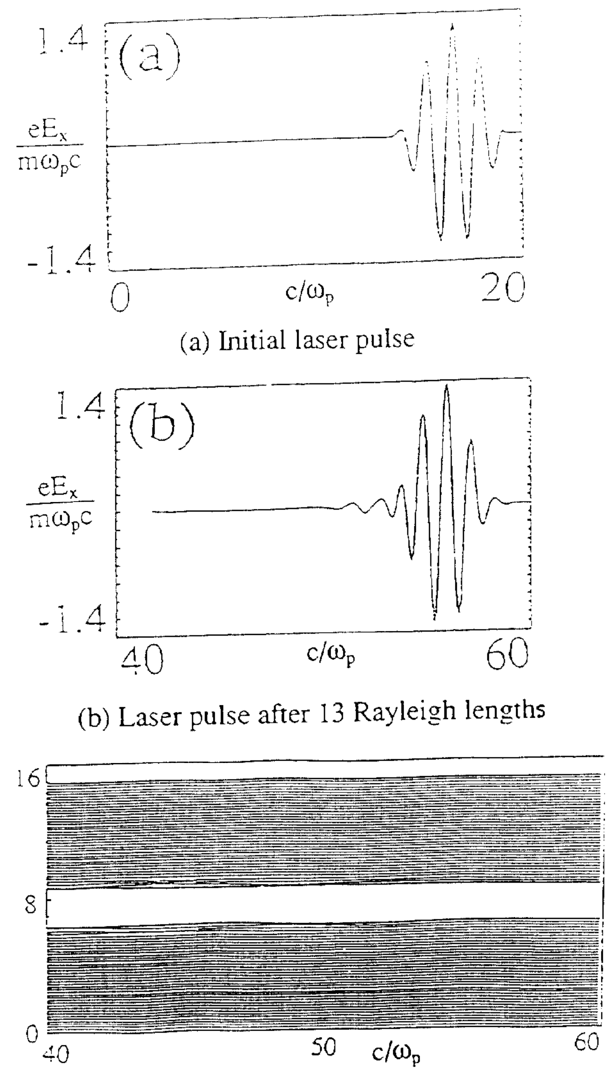


Figure 2. Wake in a hollow plasma channel

Simulations:



(a) Initial laser pulse

(b) Laser pulse after 13 Rayleigh lengths

(c) Plasma channel ($k_p a = 1$)

Figure 3.

REFERENCES

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[2] See for example P. Sprangle, et al., in Ref. 1.

[3] W. B. Mori, et al, to be published.

[4] T. Katsouleas, et al. in Ref. 1.