Laser Wakefields at UCLA and LLNL*

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Abstract

We report on recent progress at UCLA and LLNL on the nonlinear laser wakefield scheme. We find advantages to operating in the limit where the laser pulse is narrow enough to expel all the plasma electrons from the focal region. A description of the experimental program for the new short pulse 10 TW laser facility at LLNL is also presented.

1 Introduction

In the laser wakefield accelerator (LWA) concept the large transverse electric fields of present day lasers are converted into the longitudinal electric fields of plasma waves. This conversion arises when the ponderomotive force of a short laser pulse generates a plasma wave wake behind the pulse. The longitudinal plasma wave is then used to accelerate a trailing bunch of charged particles. This was the original plasma accelerator concept of Tajima and Dawson.[1, 2, 3] At the time, short pulse lasers with large enough peak intensities to efficiently generate a wake were not available. As a result the Beat Wave excitation[4, 5] method was proposed. However, with the rapid progress in laser technology[6] there has been renewed interest in the laser wakefield scheme.[7] The most recent investigations have been concerned with the nonlinear laser wakefield concept.[8, 9, 10, 11, 12] The theory of the nonlinear generation of wakes is well developed in one-dimension. The 1-D scaling laws indicate that with present day technology extremely large accelerating gratients (10 Gev/cm) can be generated. However, in order to obtain large energies it is necessary to optically guide the intense driving pulses over many Rayleigh lengths. This was thought to be possible from relativistic self-focusing.[13] Sprangle et al.[7] have argued from a 1-D analysis that relativistic optical guiding will not work for pulses of $\sim \omega_p^{-1}$ in duration. However, this is a 1-D analysis of a 3-D process. Experimental investigation and 2-D and 3-D modeling are needed. At UCLA and LLNL relativistic self-focusing and other related optical guiding ideas are being studied. Part of this investigation involves experiments at the new 10 TW laser facility at LLNL. In this proceeding we will describe planned experiments on wake excitation and self-focusing.

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2 Scaling Laws

Before describing the experimental arrangement, we provide some scaling laws used in planning the experiments. The parameter of the laser which determines the amplitude of the wake is $\frac{v_o}{c}$. This is the non-relativistically defined quiver velocity of an electron in the laser's field normalized to c. If $\frac{v_o}{c} < 1$ then the wake's electric field is $\frac{1}{4}(\frac{v_o}{c})^2 \frac{mc\omega_p}{e}$ where $\frac{mc\omega_p}{e} \simeq \sqrt{n_{cm^{-3}}}$ V/cm. If $\frac{v_o}{c} > 1$ then $E_x \simeq \frac{1}{2}\frac{v_o}{c}\frac{mc\omega_p}{e}$. Since the wake is $\propto \frac{v_o}{c}$ then for a fixed laser power, the largest wake is made with the smallest laser spot size.

If no optical guiding takes place then the maximum energy gain (ϵ) is roughly given by the product of the accelerating gradient and the Rayleigh length $\frac{\pi\sigma^2}{\lambda}$ where σ is the laser spot size. For the linear, $\frac{v_o}{c} \ll 1$, case this gives $\epsilon_{mev} = 60\frac{\omega_p}{\omega}P_{TW}$ where P is the laser's power and it is implicitly assumed that the pulse duration is π/ω_p. This expression is independent of σ since the dependence with E_x is cancelled by a reciprocal dependence with the Rayleigh length. If $\frac{v_o}{c} > 1$ then the energy gain does depend on σ and is given by $\epsilon_{mev} = 50\sqrt{P_{TW}}\ \sigma\frac{\omega_p}{c}$.

In order for a light pulse to relativistically self-focus its power must exceed $P \geq 20\frac{\omega^2}{\omega_p^2}$ GW.[13] In the planned experiments this condition cannot be simultaneously satisfied with the requirement that the pulse duration be $\frac{\pi}{\omega_p}$. Therefore, wake excitation and relativistic self-focusing will be studied in separate experiments with different densities.

When the laser power exceeds the relativistic self-focusing threshold it can either whole beam self-focus or break up into filaments.[14] If whole beam focusing occurs the beam may focus to a spot size of c/ω_p. For this spot size and laser power the radial ponderomotive force is large enough to expel all of the plasma electrons.[14] This radial expulsion will clearly influence the wake formation and forming a wake in this manner provides advantages for beam loading.[15] Interestingly, the peak ac-

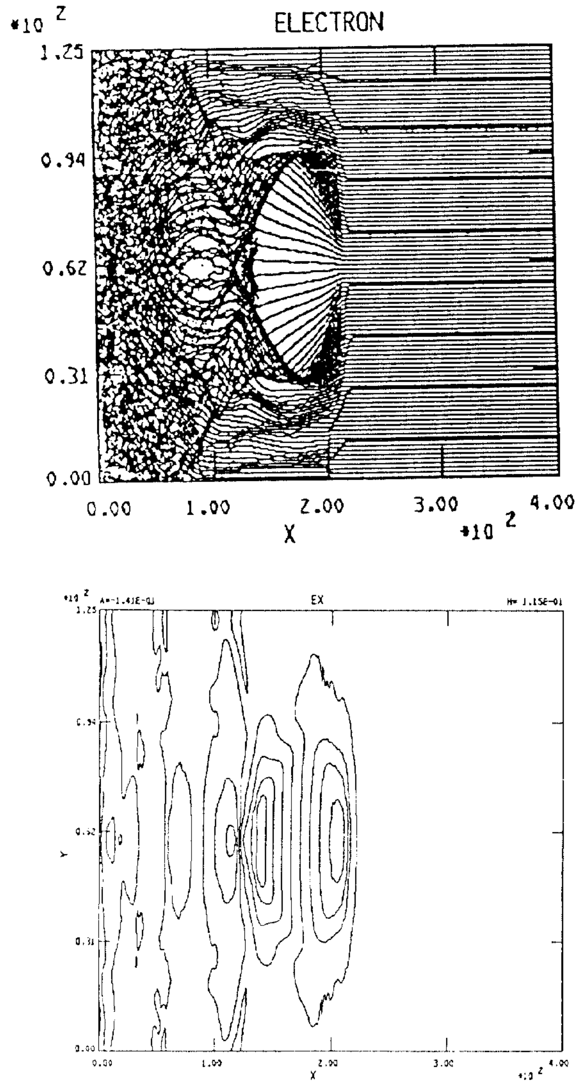

Figure 1: a) The x-y phase space of the plasma electrons. b) The accelerating electric field.

celerating field is still given by the 1-D nonlinear scaling laws. However, the wave fronts are perfectly planar with no variation of E_x across the front. This eliminates longitudinal energy spread while providing a linear focusing force. These points are illustrated in Fig. 1 where results from a 2-D simulation are given. These results are completely analogous to those obtained for the plasma wakefield accelerator.[16]

We will study the possibility of expelling the electrons in both the wake excitation and the self-focusing experiments. In the former we will focus the beam to a spot size considerably less than $\frac{c}{\omega_p}$ while in the latter we will determine if whole beam focusing occurs.

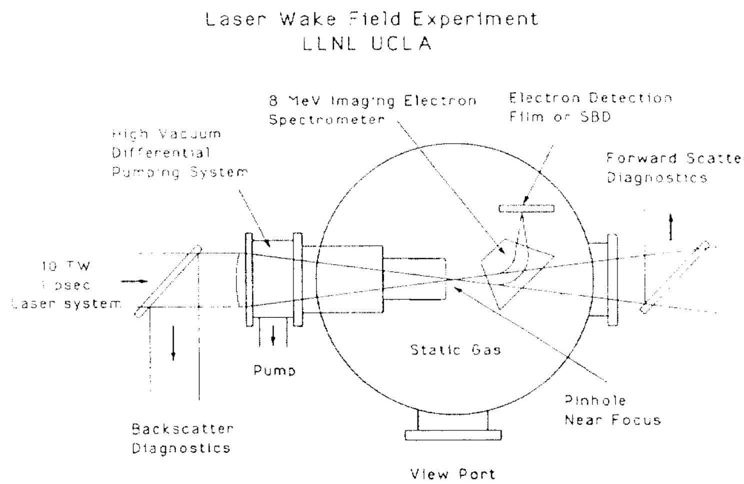

Figure 2: Schematic of Experiment

3 Experimental Set-Up

The scaling laws given in Sec. 2 will be tested with experiments at the new 10 TW laser facility at LLNL.[17] This is a 1 μm laser which provides 4-8 J in .75 ps for a peak power of $\sim$ 10 TW. A schematic of the experimental chamber is shown in Fig. 2. The plasma will be self-generated by the laser through tunneling ionization.[18] Computer simulations indicate that this will not complicate the experimental interpretation.

In the self-focusing experiments the plasma density must be larger than 3×10^{18} in order for the power threshold to be exceeded. In addition, the pulse width should by less than an ion plasma period so that ponderomotive self-focusing will not occur. This condition requires $n < 5 \times 10^{14}\frac{M}{m}$. For nitrogen this gives $n_e < 3 \times 10^{18}$ which is consistent with the self-focusing requirement.

The diagnostics will consist of sampling the back and forward scattered light as well as photographing the recombining plasma. The Raman and Brillouin backscattered light will diagnose the plasma density and temperature. The forward scattered light should contain frequency modulation as well as harmonics. These will be correlated with the plasma pictures.

The wake excitation experiment will require a density of $\sim 5 \times 10^{15}$ in order for the pulse duration be matched to π/ω_p. A gas jet and a differential pumping system will be used to isolate the region where the wake is generated. Initially, with an f-7 focusing lens we will be studying the limit where the wake is generated from a radial expulsion of the electrons. We expect energies from 1-10 MeV and an 8 MeV imaging electron spectrometer will be used. We plan to eventually use larger f numbers so that linear wake excitation can be studied. In this case the plasma wave will be probed using Thomson scattering.

4 Summary

Analytic and computational results indicate that the LWA holds considerable promise. Therefore we have begun a set of experiments at the 10 TW laser facility at LLNL. We plan on investigating wake excitation and relativistic optical guiding in two separate experiments.

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