EXPERIMENTAL INVESTIGATION OF SELF-GUIDING USING A MATCHED LASER BEAM IN A CM SCALE LENGTH UNDERDENSE PLASMA

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Abstract

High-intensity short-pulse laser guiding in plasma channels has extended the length over which acceleration occurs in laser wake field accelerators[1]. Recent multidimensional nonlinear plasma wave theory[2] predicts a range of optimal characteristics for self-guiding of laser pulses in the blowout regime for pulses shorter than a plasma wavelength. This theory predicts a robust, stable parameter space for self-guiding and wake production and has been verified through multidimensional particle-in-cell simulations. We experimentally explore the plasma dynamics and laser pulse propagation using a 50 fs multi-terawatt Ti:Sapphire laser in a helium plasma at plasma densities, laser powers, and spot sizes within this parameter space. Our parameters are in the range where the plasma is underdense and the laser power is much greater than the critical power for self focusing. The evolution of the laser pulse and plasma channel will be followed over several Rayleigh lengths.

INTRODUCTION

Since the seminal paper by Tajima and Dawson [1] introducing the possibility of electron acceleration using the ultra high longitudinal electric field of a relativistic plasma wave was demonstated, steady experimental progress has advanced the idea towards a usable technology. If a high power short pulse laser ($\tau_{FWHM} \sim \lambda_p/2$) is used to drive the relativistic plasma wave, thisx scheme is commonly refered to as the laser wakefield acceleration (LWFA) . In this regime, plasma electrons are mostly pushed out transversely by the pondermotive force of the laser and rush back in a plasma wavelength later after the laser has passed. Ions can be considered as static on this short time scale. As the electrons rush in they react to the longitudinal field created by the ion channel where some get trapped in the strong longitudinal electric field and are accelerated.

BACKGROUND

In order to achieve very high energies, the wakefield should extend until the laser drive pulse has been fully depleted. Solving this problem goes hand and hand with advances in guiding of laser pulses in a plasma. Thus far, progress has been made through creating a preformaed plasma chanel to guide the high power laser pulse, using a channel created through hydrodynamic expansion after a capillary discharge or a laser prepulse has preionized a plasma column[2,3]. Self-guiding has also been demonstrated[4].

Recent interest has focused on the blow-out or bubble regime. In this regime, the pondermotive force of an ultra-intense short pulse laser pushes out all the electrons creating a region behind the laser pulse deviod of electrons[5,6,7]. Simulations in this regime have have produced high energy monoenergetic beams of electrons[5] and demonstrated self-guiding as well. Recent experiments in which shortening of the pulse pulse in the plasma lead to LWFA being in the blow out regime have produced high gradients and monenergic beams [3,9,10] which were later confirmed through simulation[10]. Despite these advances, a 3D theory did not exist until Lu et. al. 2006[11]. This theory outlines a parameter space for stable laser propagation until the pump pulse is fully depleted. In this paper, the goals for on going experiments at UCLA are outlined in which examining the predictions of this theory and present preliminary evidence for self-guiding of a matched short laser pulse without the need for preformed plasma channels.

Theory

The approximate refractive index of the plasma in the vicinity of a high intensity laser pulse is expressed as [12,13].

$$\eta = 1 - \frac{1}{2}\frac{\omega_p^2}{\omega_o^2}\left(1 - \frac{\langle a^2 \rangle}{2} + \frac{\delta n}{n} + \frac{\Delta n}{n}\right) \qquad \textbf{(1)}$$

Here the electron plasma frequency is given by $\omega_p = (4\pi ne^2/m_e)^{1/2}$. The laser frequency is given by ω_0. The average of the normalized vector potential over one laser period is given by $\langle a \rangle$, n is the background plasma density, δn is the change in density due to pondermotive blow out of electrons in the wake created by the laser and Δn is any preformed density profile from a preformed channel. For the special case of self-guiding, the last term is zero. The condition for self-guiding a laser in plasma is given by [5].

$$\left(\frac{\delta n}{n}\right) = \frac{4}{\left(k_p W_0\right)^2} \qquad \textbf{(2)}$$

Here δn /n is the channel depth normalized to n, W_0 is the spot size of the laser pulse and k_p is the plasma wavenumber. Complete electron cavitation results in $\delta n/n \sim 1$, therefore from equation 2, $k_pW_0>2$ for guiding. In Lu et. al. it is shown that when focusing and diffraction forces are balanced in the blowout regime, the condition on the spot size can be obtained for the case of $a_0 > 1$ as.

$$k_p W_0 \approx k_p R_b \sim 2\sqrt{a_0} \qquad \textbf{(3)}$$

In equation (3), R_b is the radius of the blown out electrons for the matched beam case and a_0 is the normalized vector potential of the laser pulse. The blowout radius for the matched beam case is very close to the matched spot size W_0 given the laser pulse duration is shorter than half a plasma period and the laser pulse does not under any spot size oscillations.

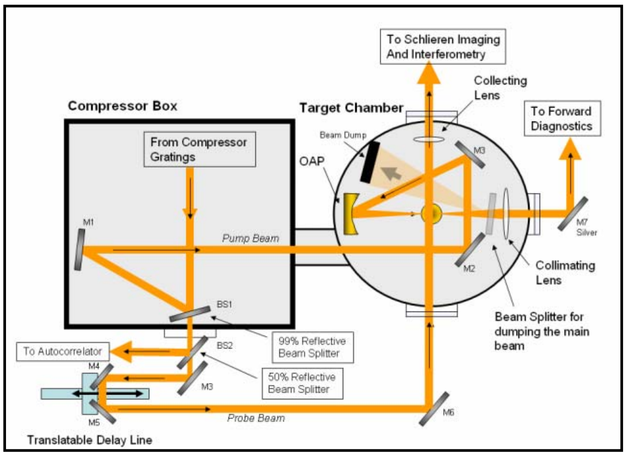

Figure 1: Experimental Setup showing the vacuum compressor, the target chamber and probe delay line, OAP, and beam dump.

Experiment and Diagnostics

On going experiments at UCLA examine propagation and evolution of a multiterawatt Ti:Sapphire laser centered at 815 nm in a 40fs pulse in a plasma with experimental conditions approaching the matched conditions according to the blow out theory [11] described above. A schematic diagram is presented in figure 1. Supersonic gas jets are used to examine propagation of the laser pulse varying distances up to 1 cm by using several nozzles of varying diameter. Nozzles were analyzed using a Mach-Zehnder interferometry setup[14] (see figure 2). All nozzles used have density ramps which are shorter than one Rayleigh length.

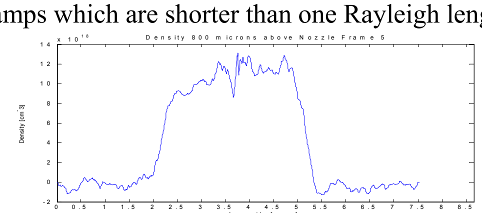

Figure 2: Neutral density profile of a 3mm Supersonic Nozzle at a distance of 800 microns.

The pump beam is focused to a 10 micron spot on the edge of the gas jet using an off axis parabolic mirror with focal length of 22 cm. The setup utilizes a pump with a transverse probe pulse split off of the main pulse and timed through a delay line to arrive simultaneously with the pump as shown in figure 1. Schlieren images provide the time resolved spatial dimensions of the plasma, the distance above the nozzle, spatial structure and location of the ionization front.

Measurements of the plasma density for each shot are determined using a Lloyd mirror type folded wavefront interferometer in the probe arm which has the benefit of being inherently temporally matched[15]. The Lloyd mirror interferometer interferes an image at the plasma image plane where no plasma exists with one where plasma exists and is time resolved on the order of the 60 fs probe duration see figure (3). The shape of the plasma is assumed to be cylindrically symmetric so that Abel's inversion can be used to obtain the transverse density profile of the plasma. Density information provides a shot-to-shot determination of the plasma period.

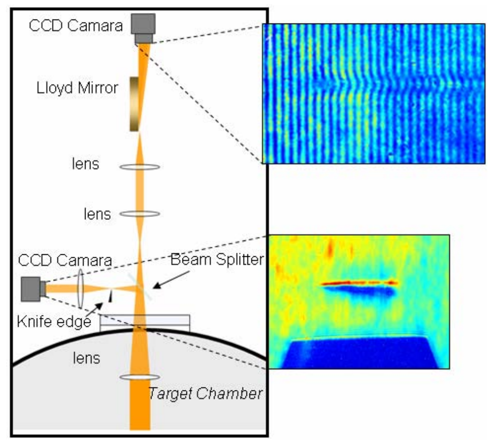

Figure 3: Diagram of the probe diagnostic setup showing Schlieren imaging and Lloyd mirror interferometry.

The beam in the forward direction passes through a dielectric beam splitter which transmits 2% of the beam centered at 800 nm.

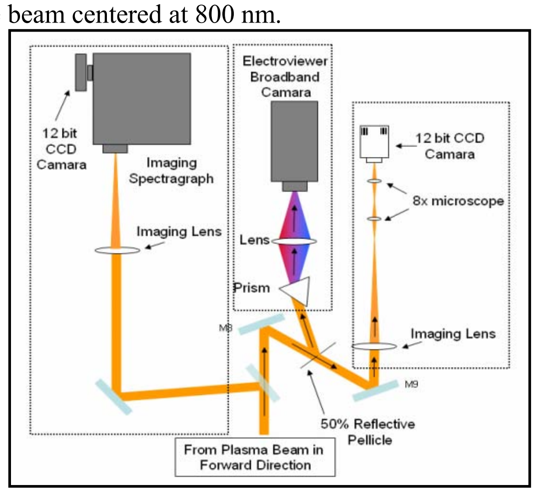

Figure 4: Schematic diagram of the forward diagnostic setup showing the imaging spectrometer, the prism spectrometer and the microscope for imaging the spot.

A lens collimates the transmitted beam before it is sent to the three forward diagnostics (see figure 4). A prism spectrograph is used to detect wavelengths from approximately 400 nm to 1600 nm.

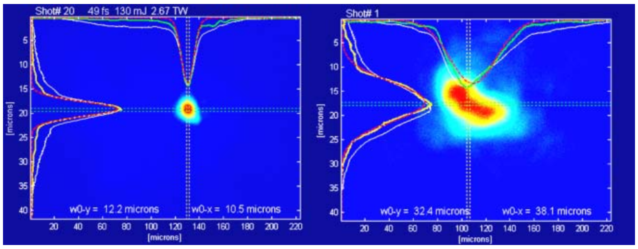

Figure 5: Images of the laser spot. The left image shows the self-guided 2.5 TW laser beam at the exit of a nominally 2mm long plasma with a denstiy of $1.5*10^{19}cm^{-3}$. The image to right shows the beam imaged at the same location with no gas jet.

The forward imaging microscope can be translated to image the exit of the plasma. This allows for determination of the quality and mode structure of the self-guided pulse. A comparison of a guided and unguided laser pulse image is shown in figure (5).

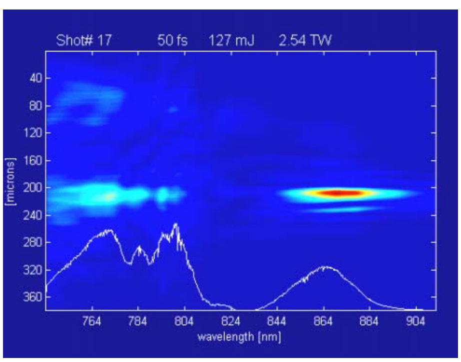

Figure 6: Data showing characteristic red shift (photon deceleration) from self phase modulation in the plasma wake.

Monitoring of self-trapped electrons is accomplished by indirectly by recording the level of X-Rays detected using a surface barrier detector (SBD).

The imaging spectrograph is used to resolve frequency modulation of the laser pulse in the region near 815 nm. The image on the slit of this spectrograph can be moved from the entrance to exit of the plasma. This can indicate nonlinear frequency shifts as a result of self phase modulation resulting from the wake. Figure (6) shows the characteristic red shift induced by self phase modulation in the 1st plasma wavelength. To diagnose guiding, the exit of the gas jet is imaged on to the slit of the imaging spectrograph allowing an image of the wavelength shift across the guided beam. Additionally, by summing over the spectrum of the guided portion and after accounting for the transfer function of the optical system, the transmitted spectrum can be used to determine the percentage of guided energy.

Conclusion

By monitoring the laser energy, pulse duration and initial spotsize, the initial normalized vector potential can be calculated for each shot. The plasma density can be changed by controlling the backing pressure on the supersonic nozzles. The distance of pulse propagation and guiding distance is determined by using several different length gas jets. The mode structure of the output of the plasma is imaged using the forward microscope. The forward imaging spectrograph provides spectral information about the laser propagation in wake which may be used to determine wake amplitude. Large frequency shifts are monitored using the prism spectrograph. Using these diagnostics, a systematic study of the self-guiding of matched laser pulses in plasmas of varying lenths and densities is planned for stable operation of a laser wakefield accelerator in the blow-out regime.

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