Indication of Local Laser Pump Depletion via Transmitted Self-Guided Laser Light

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Abstract. In recent experiments it has been shown that an ultra-intense, ultra-short laser pulse can be self-guided over tens of Rayleigh lengths in an underdense plasma where \( \tau \) (FWHM of the laser pulse) is on the order of the plasma wavelength \( (\lambda_p) \). Using an imaging spectrograph, the frequency of the transmitted laser pulse was spatially and spectrally resolved at the exit of 3, 5, and 8 mm long plasmas. The mechanism of laser pump depletion was studied by observing the amount that the transmitted laser pulse’s spectrum was red shifted in wavelength through the interaction with the self-guiding plasma wave.

Keywords: Local Pump Depletion, Self-Guiding, Photon Deceleration
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Introduction

As an ultra-short (\( \tau \approx \lambda_p / c \)), high intensity (\( I_0 \approx 10^{18} \text{ W/cm}^2 \)) laser pulse propagates through a plasma, its ponderomotive force pushes out electrons around the pulse and sets up an accelerating wakefield. Electrons, which are trapped or injected into these wakefields, can be accelerated by the large space charge electric field of the wake. Much effort has been made to extend the length of these accelerating structures to increase the energy gain of the accelerated electrons. One energy loss mechanism for short pulses, which ultimately limits the length that a pulse can drive a wakefield, is local laser pump depletion. Local laser pump depletion occurs at the front edge of the pulse where the laser pulse is losing energy through driving the wakefield. A characteristic of energy loss from a laser pulse to a wakefield can be observed through the photon deceleration of the laser pulse’s spectrum. In these proceedings the local laser pump depletion of ultra-short ultra-intense laser pulses was experimentally investigated by measuring the spectrum of the laser pulse after it has driven a wake through a plasma.

Local Pump Depletion Theory

Decker et al. [1] were the first to consider the local loss of energy that occurs for intense laser pulses driving strong nonlinear wakes. Initially at the front of the laser pulse, the ponderomotive force pushes out electrons around the envelope of the electric field and sets up a wake. As the pulse propagates while driving a wake through the plasma, energy is continuously being locally depleted from the front of the laser pulse. Due to this local loss of energy, the envelope of the electric field at the front of the pulse
steepens and the pulse duration begins to narrow. The local pump depletion length is the
distance at which the laser pulse’s electric field has been depleted to a point where it is
no longer intense enough to drive a wake. In reference [1], \( V_{etch} \), the rate at which energy
is locally depleted from a laser pulse due to driving an strong wake was found to equal
\( c \left( \frac{\omega_p^2}{\omega_o^2} \right) \). The equation for 3-D nonlinear \( (a_o \geq 2) \) local pump depletion length is given
by the length of the pulse divided by the energy etching velocity, \( L_{PD} = (c \tau_{PD}) \omega_o^2 / \omega_p^2 \)
, (Eqn 1), where \( \tau_{PD} \) is the time scale associated with the laser pulse’s ponderomotive
force being strong enough to start driving a wake. The local pump depletion length varies
inversely with the plasma frequency, which follows from the fact that at higher plasma
densities, the laser pulse pushes out and does work on more electrons while driving a
wake.

**Photon Acceleration / Deceleration**

While the laser pulse must do work and lose energy to drive a wake, the number of
photons in the laser pulse must be conserved [2]. If the number of photons is conserved,
then for the laser pulse to lose energy, the frequencies of the photons doing work must
decrease. Locally at the front of the laser pulse, where the wake is being created, the
frequency of the laser must decrease leading to a red shifting in local wavelength. This
decrease in local laser frequency also leads to a decrease in the local group velocity of
the laser. This is why, as described earlier, the front of the laser pulse moves back and the
envelope of the electric field steepens as it is pump depleted. In general, positive density
gradients, as found at the front of a wakefield, will lead to a decrease in local frequency
of light, while negative density gradients, as found in the back half of wakefields, will
increase the local frequency of light. The local increase in frequency associated with
light interacting with the time changing density of a plasma wave is called photon
acceleration while the local decrease of frequency is called photon deceleration [3].

**Self-Guided Regime**

In these experiments the laser pulse was observed to be self-guided through an under-
dense plasma over tens of laser Rayleigh lengths. Self-guiding of the laser pulse allows
the intensity of the pulse to remain high enough to drive a wake over distances much
longer than the vacuum Rayleigh length. This extended interaction allows the pulse to
propagate and drive a wake to pump depletion. In the self-guided regime, an intense
\( (a_o \geq 2) \), short \( (\tau \approx \lambda_p / c) \) laser pulse expels all the electrons in an ion bubble around it-
self. When laser and plasma conditions are such that the transverse ponderomotive force
of the laser is approximately equal to the restoring force of the ion bubble that is cre-
ated, a matched electron density profile will be created which will minimize diffraction
at the front of the laser pulse and allow the rest of the laser pulse to remain transversely
guided [4]. For matched self-guiding of a laser pulse, a relationship between \( R \), the
blowout radius, \( W_o \), the laser spot size and \( a_o \), the normalized laser vector potential is
given by, \( k_p R \approx k_p W_o = 2 \sqrt{a_o} \) [Eqn. 2]. This relation indicates that for given \( a_o \) and
laser spot size $W_0$, there is a matched plasma density which will allow for the pulse to be self-guided. Conducting experiments in the self-guided blowout regime allows the laser pulse to propagate over many Rayleigh lengths while driving a wakefield. By observing the relative amount of red shifted light that was contained in the self-guided transmitted laser spot, the amount of local laser pump depletion was studied.

**Experiment, Results and Conclusions**

These experiments were conducted at UCLA using a short $\tau_{FWHM} \sim 50$ fs laser pulse with $\sim 200 - 500$ mJ of energy and a center wavelength of $\sim 815$ nm, that was created using a Ti:Sapphire chirped pulse amplification laser system. The laser pulse was focused using an off-axis parabola to a spot size of $6 \mu m$ (1/e of the electric field) onto the edge of a supersonic column of Helium gas. The laser pulse was intense enough to fully ionize the Helium gas. Three different diameter nozzles were used to vary the plasma length from 3 to 5 to 8.5 mm. By varying the backing pressure on the nozzle, the plasma density could also be varied for each length. The range of plasma densities used in these self-guiding experiments was from $4 \times 10^{18} cm^{-3}$ to $1 \times 10^{19} cm^{-3}$. For this range of densities the pulse width of the laser was equal to 1-1.4 plasma wavelengths. This satisfies the condition that the pulse length should be on the order of a plasma wavelength for self-guiding to occur. Additionally, the laser pulse’s $a_0$ was $\sim 2 - 3$ and was sufficiently intense to blow out all the electrons to form an ion bubble which is also required for self-guiding. Equation 2 indicates that for the laser spot size and the range of vector potentials used, perfectly matched self-guiding occurs at a plasma density of $\sim 6.3 \times 10^{18} cm^{-3}$ to $9.4 \times 10^{18} cm^{-3}$.

A figure of the experimental setup is shown in reference [5]. A collection lens in the vacuum chamber collimates the transmitted light out of the chamber and forms half of an image relay system. The collimated light is split in two and imaged onto two separate diagnostics. The first diagnostic used a microscope to further magnify the transmitted image and is called the forward spot diagnostic. The total magnification of this diagnostic was 11x and was capable of imaging the laser spot at best focus as well as being able to be adjusted to image the laser spot at the exit of the plasma. The purpose of the forward spot diagnostic is to image the exit plane of the plasma and determine whether the transmitted laser pulse has been guided. The second forward diagnostic was an imaging spectrograph. The exit plane of the plasma was imaged onto the slit of the imaging spectrograph with a transverse magnification of 4.5x and a resolution of $\sim 13 \mu m$. The imaging spectrometer disperses light in one plane while the other plane images the transmitted light. The imaging spectrograph was operated with a 300 $\mu m$ slit opening to collect a large fraction of the transmitted light. When the transmitted spot was guided, the spectral resolution of the spectrograph was $\sim 2$ nm. Additionally, the transmission function of the optical system to the imaging spectrograph was measured and used to recover the true spectrum of the transmitted light.

Figure 1 illustrates the self-guiding of the short laser pulse through 5 mm of plasma. Figure 1a shows the laser spot at best focus in vacuum. The full width half max of the intensity of the spot size was measured to be $\sim 10 \mu m$ and is resolution limited. This
FIGURE 1.  a) The laser spot at best focus in vacuum  b) The laser spot in the exit plane of a 5mm gas jet in vacuum  c) Self-guided laser pulse imaged at the exit plane of a 5mm gas jet  d) The self-guided laser pulse’s spectrum imaged at the exit plane of 5mm gas jet. The solid curve is the transmitted self-guided spectrum. The dashed curve is the vacuum laser spectrum. Both the transmitted and vacuum laser spectrum are normalized to 1.

image was taken with the forward spot diagnostic set to image the entrance of the gas jet. An image of the vacuum laser spot at the exit of the 5 mm gas jet was also taken and is shown in figure 1b. At the exit of the gas jet in vacuum, the laser spot had a FWHM of \( \sim 150 \mu m \). Figure 1c was taken imaging the same exit plane as 1b, but with the gas jet on. With the gas jet on, the transmitted laser pulse was well guided as compared to the vacuum laser spot. Using the forward spot diagnostic in this manner, self-guided laser pulses were observed at the exit of 3, 5, and 8 mm long plasmas over a range of plasma densities and laser powers [5].

Figure 1d shows the imaged spectrum of the transmitted laser pulse for the self-guided transmitted laser pulse shown in 1c. The solid curve is the normalized spectrum of the guided spot, while the dashed curve is the normalized vacuum spectrum of the laser. As discussed above, in order for the transmitted laser pulse to be self-guided, it must have driven a wake. Additionally, a pulse residing in and being guided by such a wake would have its spectrum modulated via photon acceleration / deceleration. The self-guided transmitted spectrum shown in figure 1d has light that is red and blue shifted in wavelength from the vacuum laser spectrum. Furthermore, the majority of the light which has been red shifted in wavelength is spatially contained within \( \sim 25 \mu m \). This light corresponds to the light which has been self-guided and photon decelerated through driving a wake. The guided un-shifted laser light comes from the middle of the laser pulse which resides in the blown out bubble of the wake and has yet to give energy to plasma. The relative amount of photon decelerated red shifted light to un-shifted laser light is an indication of how much local laser pump depletion has occurred. In these experiments the laser pulse width was on the order of a \( \lambda_p \). Thus, in addition to the
FIGURE 2. Transmitted self-guided laser pulses spectrum at the exit of a) a 5 mm gas jet at 5x10^{18} cm^{-3} b) a 8.5 mm gas jet at 4.3x10^{18} cm^{-3}. The solid curve is the transmitted self-guided spectrum. The dashed curve is the vacuum laser spectrum. Both the transmitted and vacuum laser spectrum are normalized to 1.

photon decelerated light created at the front of the wake, a portion of the laser pulse overlapped the back half of the wake and locally the frequency of these photons were increased. These blue shifted in wavelength photons can also be seen in figure 1d on axis with the self-guided laser light. In addition, off-axis in space of the self-guided light there is ionization induced blue shifted light as well un-shifted laser light. The un-shifted laser light that was not guided comes from light that did not couple into the guiding plasma wave and was located after the ionization front of the laser.

The relative amount of spectral red shifting of the laser pulse due to local pump depletion was explored in two manners, first by varying the length of the plasma at a fixed density and secondly by fixing the length of the plasma and varying the density. Figure 2 compares the transmitted spectrum of a laser pulse after propagating 5 mm at a plasma density of 5x10^{18} cm^{-3} in figure 2a to the spectrum of the laser pulse after propagating ~ 8.5 mm at a plasma density of 4.3x10^{18} cm^{-3} in figure 2b. In figure 2b the relative level of the red shifted light to that of the unshifted laser light centered around the vacuum spectrum is approximately equal. As compared to figure 2a where there is still a large amount of un-shifted laser light, the spectrum in figure 2b indicates that the laser pulse has been significantly pump depleted after 8.5 mm of plasma. It is thought that the spectrum in figure 2b is representative of the spectrum of a laser pulse close to propagating the entire local pump depletion length from the following physical picture. As the laser energy is locally pump depleted, the front edge of the laser pulse’s envelope steepens as the photon decelerated light slips backwards in space with respect to the unshifted laser light. This in effect causes the leading edge of the wake to move back in space with respect to the laser pulse as it is locally pump depleted. As more and more energy is lost from the laser pulse to the plasma wave, there will be less and less unshifted laser light. Therefore, when the laser pulse is close to pump depletion it is expected that the laser pulse’s vacuum spectrum should be almost entirely spectrally red shifted and this is seen in figure 2b. Equation 1 also indicates that at a plasma density of 4x10^{18} cm^{-3} and for a \( \tau_{PD} \) of 70 fs, the local pump depletion length is \( \sim 8.8 \) mm.

Figure 3 shows the transmitted guided spectrum through 5 mm of plasma at densities
of 6, 7, and 8x10^{18} cm^{-3}. The plotted spectra have been normalized to the laser energy and the spectral transmission function of the imaging system so that their spectral content can be accurately compared with each other. The absolute amount of transmitted self-guided light depends on the amount of local pump depletion as well as the coupling efficiency of the laser pulse to the guiding plasma wave at nearly matched densities [6]. As indicated by equation 1 the pump depletion length decreases as plasma density increases. This decrease in pump depletion length is actually due to the increase in the rate at which the laser loses energy to the plasma wave as given by V_{ach}. It is expected that for a fixed length, as the density increases more energy will be given to the plasma wave and therefore more laser light will be spectrally red shifted. This can be clearly seen in figure 3 by the manner in which the amplitude of light centered at the vacuum spectrum decreases, while relative to this amplitude the amount of spectral red shifted light increases with increasing plasma density. At a plasma density of 8x10^{18} cm^{-3} (figure 3d), the amplitude of the spectrally red shifted light is on the order of the light centered around the vacuum wavelength. Therefore, it is thought that the after propagating 5 mm at 8x10^{18} cm^{-3} the pulse is close to being pump depleted.

In these proceedings, initial experimental evidence has been presented indicating local laser pump depletion of a self-guided laser pulse via observed photon deceleration in the transmitted spectrum. Thus far, only a relative comparison has been made between the amount of local pump depletion and spectrally red shifted light. Future work will include a more quantitative analysis, including comparison of the total transmitted energy of a self-guided laser pulse measured in simulation versus experiment.

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REFERENCES