CHANNELING AND TIME EVOLUTION OF LASER WAKES AND ELECTRON ACCELERATION IN A SELF-MODULATED LASER WAKEFIELD ACCELERATOR EXPERIMENT

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Abstract

Large amplitude plasma wakefields produced by a high power laser pulse in an underdense plasma were studied in a self-modulated laser wakefield accelerator (SM-LWFA) experiment. A pump-probe coherent Thomson scattering (CTS) technique was used and the lifetime of the wakefield was measured to be less than 5 psec. A plasma channel was observed to form in the wake of the pump laser pulse. The trailing probe laser pulse was observed to be guided by this channel for about 20 Rayleigh lengths. High energy electrons (up to 30 MeV) have been measured using a magnetic spectrometer. Highly non-linear plasma waves were also detected using forward Raman scattering diagnostics and were observed to correlate with the electron signals.

Significant progress has been made in recent years [1] using laser–produced plasmas as a medium for accelerating electrons to high energies. In the Laser Wakefield Accelerator (LWFA) [2], a high intensity laser pulse is focused into an underdense plasma with a pulse duration, τ_L, close to the electron plasma period (i.e., $\tau_L \sim 2\pi/\omega_{pe}$ where ω_{pe} is the electron plasma frequency). Large amplitude plasma waves (wakefields) are generated with strong longitudinal electric fields and relativistic phase velocities which are capable of accelerating injected electrons. For laser powers approaching or exceeding the relativistic self-focusing threshold (i.e., $P > P_c = 17\,(\omega_0/\omega_{pe})^2$ GW; where ω_0 is the laser frequency), it is not necessary to match the pulse duration to the plasma period. At laser powers for which $P \geq P_c$ and $\tau_L > 2\pi/\omega_{pe}$, the laser envelope undergoes an instability and becomes "self-modulated" at the plasma frequency [3, 4]. This effect resonantly enhances the creation of wakefields and allows use of higher electron densities and generates stronger accelerating fields [5]. Recent experiments in this Self-Modulated Laser Wakefield Accelerator (SM-LWFA) regime have measured the production of high energy electrons where the source of accelerated particles was either background electrons from the target plasma [6-9] or electrons injected into the interaction region from an adjacent laser-produced plasma [10]. Direct observations of wakefields in the conventional LWFA configuration were recently reported using interferometric techniques, in which the spatial and temporal waveforms of the wakefield were measured [11].

In order to obtain high final energies of the accelerated electrons in a LWFA, it is necessary that the laser propagates long distances at high intensity in the plasma. This implies that the laser pulse must be "guided" for distances significantly greater than the vacuum diffraction length (Rayleigh range), which is typically less than a hundred microns if the beam is tightly focused. Guiding of intense laser pulses in plasmas has been demonstrated by a variety of mechanisms. Laser light with intensities of up to 5×10^{15} W/cm^2 has been channeled in a 3 cm waveguide structure created by the hydrodynamic expansion of a preformed plasma [12] and intensities of 10^{16} W/cm^2 have been propagated for up to 3 cm in evacuated glass capillary waveguides [13]. In addition, a preformed plasma generated by a capillary discharge has been used to guide 10^{16} W/cm^2 laser pulses [14]. For laser pulses above the critical power for relativistic optical guiding, self–channeling of laser pulses in plasmas has been experimentally observed [15,16] and has been the subject of extensive theoretical examination [1,3-5, 17,18]. Self-focusing of intense laser pulses in plasmas can also be enhanced by the expulsion of plasma electrons (cavitation) produced by the extreme ponderomotive force of a focused laser pulse [18].

Large amplitude relativistic plasma waves generated in the SM-LWFA have axial accelerating electric fields with extremely high gradients (~100 GeV/m) [5]. The phase velocity of the plasma wave is approximately equal to the group velocity of the laser pulse (~c), and hence, these plasma waves are very suitable for high energy particle acceleration. Nakajima *et al.* [10] have observed high energy electrons (~17 MeV) being accelerated in a SM-LWFA experiment where ~1 MeV electrons were injected. Coverdale *et al.* [6] and Umstadter *et al.* [8] have observed 2 and 5 MeV accelerated electrons respectively from self-trapping of background plasma electrons. Recent SM-LWFA experiments by Modena *et al.* used a 25 TW laser pulse to drive nonlinear wakefield plasma waves in a helium plasma resulting in the capture and acceleration of background plasma electrons to 44

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MeV [7]. Their experiments showed a broadening of the anti-Stokes lines in the forward Raman scattering (FRS) spectrum concurrent with the onset of high energy electron production at approximately 7 TW. This broadening and high energy electron production was attributed to the onset of wavebreaking.

The SM-LWFA experiments at the Naval Research Laboratory (NRL) were performed using a Ti:Sapphire/Nd:Glass CPA laser system (λ = 1.054 µm) which generates 400 fsec pulses with an energy of 800 - 1200 mJ (P = 2 - 3 TW). The beam was focused with an f/3 off-axis parabolic mirror into a 3 mm diameter hydrogen or helium gas jet. The gas jet was used to reduce the effects of ionization induced defocusing [19] which may occur during interactions in static-filled gas chambers. The focal spot radius measured in vacuum was 4.5 µm which corresponds to a vacuum Rayleigh length of 60 µm.

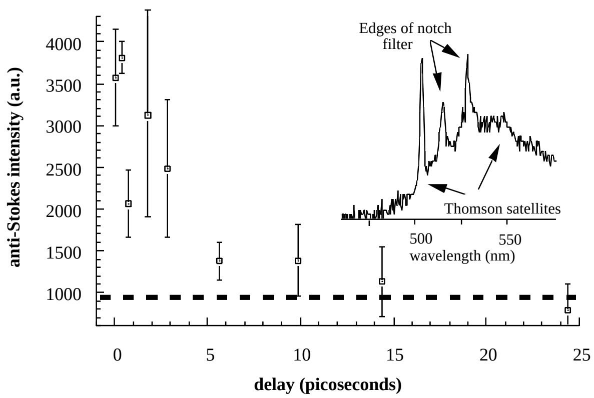

Figure 1: Evolution of electron satellites from zero-degree coherent Thomson scattering. The background level is shown by the dashed line. Data are not shown for pump-probe delay times less than zero since blueshifting of the probe laser spectrum saturates the detector for early times. Insert is a typical spectrum (anti-Stokes at 506 nm, Stokes at 550 nm).

The plasma electron density was measured to be n_0 = 1-1.5x10^{19} cm^{-3}. For a plasma density of $n_0 = 10^{19}$ cm^{-3}, the critical power is P_c = 1.8 TW, and the plasma wavelength is $\lambda_{pe} = 2\pi c/\omega_{pe}$ = 10 µm. Hence, $P \geq P_c$ and $c\tau_L \sim 12\ \lambda_{pe}$, which are necessary for operation in the SM-LWFA regime.

A pump-probe experimental arrangement was used to monitor the temporal characteristics of the high intensity laser produced plasma [20]. Approximately 10 % of the main beam was frequency doubled (to 527 nm) by a 1 cm thick KD^*P crystal for use as the probe. The probe pulse timing was varied relative to the pump using an optical delay line. The spatial overlap of the two beams was accomplished by alignment to a series of apertures prior to the off-axis parabolic mirror, which focused the probe beam at f/6 and the pump beam at f/3, and by observation of scattered light in the focal region. Temporal synchronization was achieved by examining the probe frequency. When the probe arrived before the pump, the probe frequency was blue shifted [21]. Otherwise the frequency was unshifted. This measurement resulted in synchronization to better than 1 psec.

Directly forward scattered light was recollimated by a parabolic mirror, while radiation scattered at off-axis angles was collected by a single lens and imaged onto the slit of a 0.25 m Czerny-Turner spectrometer. The interaction was also monitored by transversely imaging Thomson scattered laser light on a CCD positioned at 90 degrees to the laser axis.

Coherent Thomson scattering (CTS) of the probe laser pulse was used to measure the temporal behavior of the wakefields. Coherently scattered light has a wave vector $\mathbf{k}_{sc}$ and a frequency ω_{sc} that satisfy the Bragg scattering conditions of frequency and wavenumber matching. For electron plasma waves with ω_{pe} and $\mathbf{k}_{pe}$, the conditions require $\omega_{sc} = \omega_1 \pm \omega_{pe}$ and $\mathbf{k}_{sc} = \mathbf{k}_1 \pm \mathbf{k}_{pe}$, where ω_1 is the frequency and $\mathbf{k}_1$ is the wave vector of the probe laser. The plasma wakefields in an SM-LWFA have relativistic phase velocities, $v_\phi \sim c$, such that they are capable of accelerating electrons to high energies. For correct matching of **k** vectors, both the probe and the Thomson scattered light must therefore propagate in the same direction as the relativistic plasma wave (i.e., pump, probe, and scattered light propagating collinearly). The majority of the 527 nm probe light was not scattered and was blocked before the slit of the spectrometer by a notch filter in the beam path. However, the Thomson scattered electron plasma satellites of the probe light (shifted by ω_{pe}) are positioned beyond the edges of the absorption band of the notch filter and detected by the spectrometer. The principal result in this configuration was the observation of these plasma satellites for about 5 psec after passage of the pump laser (see Figure 1). The full width at half maximum (FWHM) of the wakefield lifetime is ~2 psec which is similar to the wakefield lifetime measured by similar techniques reported by LeBlanc *et al.* [22]. As shown in the insert in Figure 1, the anti-Stokes line was typically more intense than the Stokes line, perhaps indicating that the **k**-vectors of the electron plasma waves in the wakefield are primarily in the forward direction [23]. These measurements confirmed the generation of wakefields with $v_\phi \sim c$ [24].

The probe pulse was also observed to be affected by the formation of a plasma channel. The propagation of the probe pulse was monitored by imaging the Thomson scattered emission at 90 degrees to the laser propagation direction onto a CCD through a 527 nm filter ($\Delta\lambda$ = 5 nm). When only the probe pulse was injected into the gas jet, very little Thomson scattered emission was observed even though a plasma was created. However, if both pump and probe pulses were incident simultaneously on the gas jet, a bright image of scattered probe light was observed in the region where the pump beam was channeling, *i.e.*, over the width of the gas jet or approximately 20 Rayleigh lengths. This emission is probably caused by coherent Thomson scattering of the probe laser from ion acoustic waves generated in the turbulent decay of the large amplitude plasma waves in the wakefield [20]. This emission was observed even as the temporal separation between the pump and probe laser pulses was increased by more than the laser pulse width (see Figure 2). In fact, the brightness of the Thomson scattered image from the probe reached a maximum approximately 15 psec after passage of the pump pulse. Thomson scattered emission from the probe continued for pump-probe delays of more than 40 psec before decreasing significantly. The guided intensity was $5x10^{16}$ W/cm^2 with a transmission efficiency of approximately 75%.

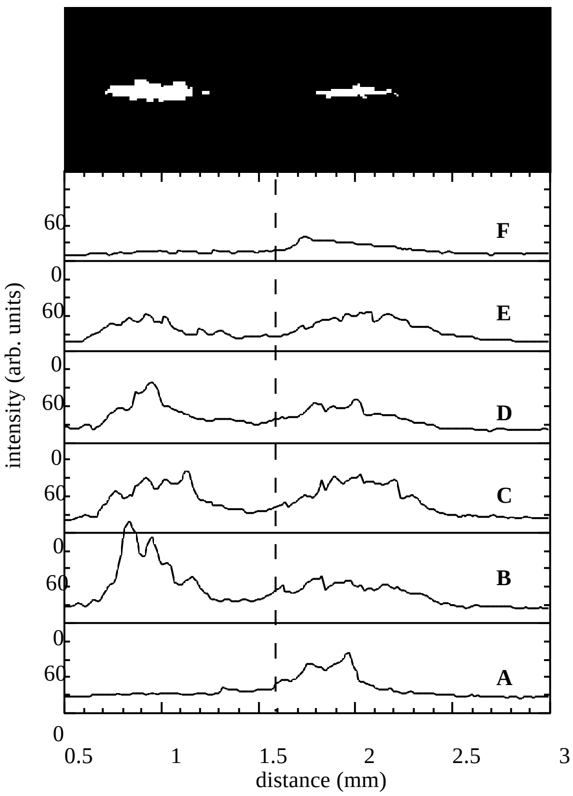

Figure 2: Thomson scattering images of interaction of picosecond probe beam (527 nm) for various delay settings between pump and probe beam in hydrogen gas jet. A) 0, B) 6, C) 14, D) 22 E) 30, F) 46 psec (propagation from right to left). Typical CCD image (Δt = 19 psec) shown at top. Dashed line indicates approximate position of vacuum focus (centered in gas jet).

The "guiding" of the probe pulse is most likely due to formation of a plasma channel in the wake of the pump pulse due to charge displacement effects. As the pump expels electrons by the ponderomotive force, the space charge force on the ions starts a slow radial expansion of the plasma away from the pump laser axis. This expansion causes a density depression on axis and forms a plasma channel capable of guiding the following probe pulse. The observed time scales for formation and decay of the channel are consistent with a simulation and analytical calculations of this hydrodynamic expansion.

Electron measurements and Raman scattering measurements of the pump were also performed. Raman scattered laser light at 40° to the laser axis was imaged on the entrance slit of a spectrometer to measure the relative wakefield amplitude and linearity. An inline spectrometer configuration measured the energy distribution of electrons accelerated from the background plasma. The electron spectrometer consisted of an electromagnet for electron deflection and a plastic scintillator directly coupled to a photo-multiplier tube (PMT) for electron detection. The electromagnet used a 0 to 2500 Gauss magnetic field in a field region 5.5 cm long. Graphite and carbon shielding were arranged with a small gap centered on the laser axis which allowed only high energy electrons with less than an 8° deflection in the magnet to strike the scintillator. Electrons with lower energies were deflected more than 8° and dumped in a graphite block to minimize x-ray production. This inline spectrometer configuration therefore detects all electrons above a cutoff energy which is determined by the magnetic field strength and the maximum acceptance angle of the gap in the shielding (8°).

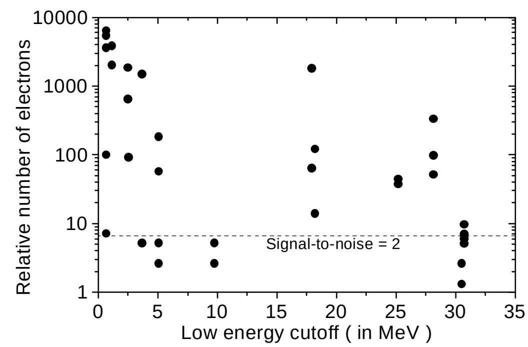

Figure 3: The relative number of electrons above the cutoff energy of the spectrometer. A signal-to-noise level greater than 2 (dashed line) represents a clearly discernible signal from electrons striking the scintillator.

An energy scan is shown in Figure 3. This is raw data showing the electron signal at a range of cutoff energy settings (1-30 MeV). The data points are the total relative number of electrons above the energy specified on the x-axis. The large fluctuations are believed to be shot-to-shot fluctuations caused by the highly non-linear growth of the plasma waves from the self-modulation and the forward Raman instabilities which are seeded from noise. The source of the background accelerated electrons may also contribute to the large fluctuations. A possible source of the background accelerated electrons other than from wavebreaking is the interaction of backward Raman scattered light with the laser wakefield [25, 26].

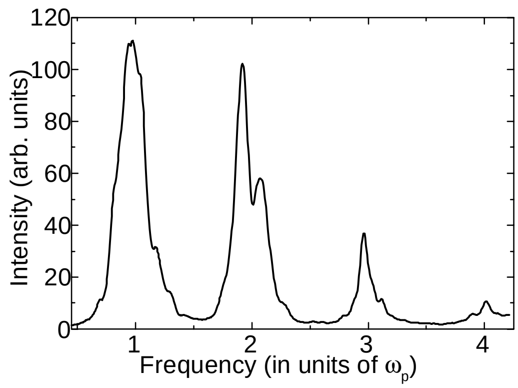

Figure 4: Typical Raman scattering spectrum.

Concurrent with electron measurements we examined the spectrum of Raman scattered light. A typical spectrum is shown in Figure 4 where the strong non-linearity of the plasma wave is obvious from the presence of comparable intensity harmonics in the spectrum [6-8]. Also important is the absence of line broadening in any of the measured spectra. For example, the width of the 1st order anti-Stokes line shown in Figure 4 is the same as those we observed in the linear plasma wave regime (where only the 1st order anti-Stokes line is observed). This indicates that although the wave has steepened, it has not begun to break as was observed by Modena *et al.*. and Umstadter *et al.* at higher powers [7, 8].

The correlation of 2nd order anti-Stokes signal to electron production has been studied. For these experiments, the electron spectrometer measured the number of electrons with greater than 1 MeV of energy. For each laser shot the electron number and forward Raman scattering spectrum were recorded. The 2nd order anti-Stokes signal vs. electron signal is shown in Figure 5. A strong correlation between 2nd order anti-Stokes and electron signal was observed. This perhaps indicates that electrons are only accelerated from the background plasma as the plasma wave becomes non-linear.

Coherent Thomson scattering of a picosecond probe laser was used to measure the time evolution of plasma wakefields produced by a high intensity laser pulse in an underdense hydrogen or helium plasma in the SM-LWFA configuration. Large amplitude plasma wakefields are observed to last for approximately 5 psec.

A plasma channel was observed to be formed behind the relativistically self-guided, subpicosecond, high power pump laser pulse in the gas jet plasma. The channel is probably produced from the radial expulsion of plasma ions due to charge separation created in the displacement of plasma electrons by the large ponderomotive force of the laser. A trailing, frequency doubled probe laser pulse is observed to be guided throughout the length of this channel for about 20 Rayleigh lengths.

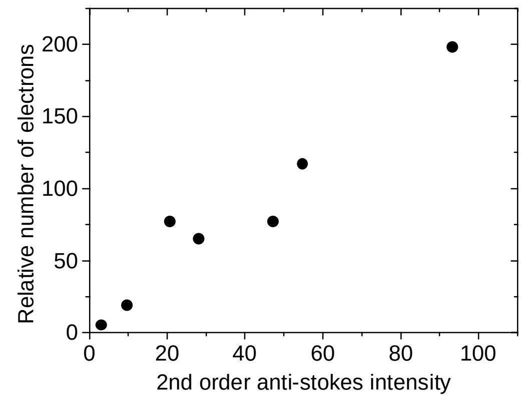

Figure 5: The correlation between the 2nd order anti-Stokes signal and the number of high energy (>1 MeV) electrons.

High energy electrons (up to 30 MeV) have been measured using a high sensitivity detector — a scintillator coupled to a PMT. Highly non-linear plasma waves have been detected using forward Raman scattering as a plasma diagnostic and a correlation between the non-linear plasma waves and electron signal has been observed.

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