Electron Acceleration by a Laser Wakefield in a Relativistically Self-Guided Channel

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Acceleration of electrons to relativistic energies by a multidimensional self-modulated laser wakefield is discussed. Above a power threshold, a relativistically self-guided channel from an intense ultrashort laser pulse ($I \sim 4 \times 10^{18}$ W/cm^2, $\lambda = 1$ μm, $\tau = 400$ fs) was found to increase the laser propagation distance, decrease the electron beam divergence, and increase the energy of the electrons. These electron beam effects occurred even though the propagation distance became significantly longer than the conventional dephasing length. [S0031-9007(97)02922-0]

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Because of recent advances in laser technology [1], there is much current interest in the interactions of high-intensity and ultrashort-duration laser pulses with plasmas. Applications include advanced fusion energy, x-ray lasers, and ultrahigh-gradient electron accelerators [2]. In the latter case, the field gradient of a plasma wave has been demonstrated to exceed that of a rf linac by 4 orders of magnitude ($E \geq 200$ GV/m) and has been used to accelerate electrons with over 1 nC of charge per bunch in a low-emittance beam (1 mm mrad) [3]. In this paper, we demonstrate electron acceleration beyond the current limitation of laser-plasma accelerators, the natural diffraction length of the laser.

A plasma wave is driven by the displacement of plasma electrons by the ponderomotive force of the laser light. Because of their greater mass, the ions remain stationary, providing an electrostatic restoring force. The electrons will then oscillate and create regions of net positive and negative charge. This forms an electrostatic wakefield that propagates with the laser pulse at nearly the speed of light, which can trap and accelerate hot electrons. We have explored the self-modulated laser wakefield regime [3–8], where the laser pulse duration is much longer than the plasma period, $\tau_p = 2\pi/\omega_p$, where $\omega_p = \sqrt{4\pi e^2 n_e/\gamma m_e}$, n_e is the electron density, e is the electron charge, m_e is the electron mass, and γ is the relativistic factor associated with the electron motion transverse to the laser propagation. γ depends on the normalized vector potential, a_0, by $\gamma = \sqrt{1 + a_0^2}$, where $a_0 = \gamma v_{0s}/c = eE/m_0\omega c = 8.5 \times 10^{-10}\lambda[\mu\text{m}]I^{1/2}[\text{W/cm}^2]$. In this regime, the forward Raman scattering instability can grow, where an electromagnetic wave $(\omega_0, \mathbf{k}_0)$ decays into a plasma wave $(\omega_p, \mathbf{k}_p)$ and electromagnetic side bands $(\omega_0 \pm \omega_p, \mathbf{k}_0 \pm \mathbf{k}_p)$. This instability can be one dimensional or multidimensional, depending on the experimental conditions [9]. In the 1D case, the laser energy is bunched only longitudinally [10]; however, in the multidimensional case, transverse effects lead to focusing and defocusing of different sections of the laser pulse [4]. This leads to modulations in the laser pulse which can drive high-amplitude plasma waves. Andreev *et al.* have calculated thresholds for these regimes and found that mixed 1D/3D behavior should occur whenever $a_0^2 k_p c\tau > 16(\omega_0/\omega_p)^2/(k_p L_\perp)^2 > 1$, where $L_\perp$ is the transverse extent of the plasma wave and τ is the laser pulse duration [note, $a_0^2 k_p c\tau = 380$ and $16(\omega_0/\omega_p)^2/(k_p L_\perp)^2 = 3.9$ for our conditions]. In this mixed regime, it is expected that 1D effects will dominate early in the laser pulse, and mixed (1D/3D) effects will dominate in the rear part of the laser pulse. Our experimental observation of the plasma channel confirms, for the first time, the importance of 3D effects in this parameter range.

Even though the accelerating gradients can be very large in these laser-plasma-based accelerators, the overall energy gain will be modest if the interaction length is short. In order to reach the high intensity necessary to create the plasma wave, the laser pulses must be focused tightly, and thus the interaction length will be short, limited by diffraction to the Rayleigh range ($Z_R = \pi r_0^2/\lambda$). Several methods have been proposed or demonstrated to extend the propagation distance beyond the diffraction limit, most notably preformed channels [4,11] and relativistically self-guided channels [12–16]. In this Letter, we report, for the first time, laser wakefield acceleration in a self-guided channel.

When a laser propagates through a plasma, the index of refraction, $n = (1 - \omega_p^2/\omega_0^2)^{1/2}$ depends on the laser frequency, ω_0, and the plasma frequency, ω_p. For low laser power, the index is essentially constant; however, for higher laser power, the index varies with the radius, since the laser intensity varies with radius and the plasma frequency changes with the relativistic mass factor. Under these conditions, the plasma acts like a positive lens and focuses the beam (relativistic self-focusing). This effect has been shown to have a power threshold given by $P_c = 16.5 n_c/n_e$[GW], where n_c is the critical density (when $\omega_p = \omega_0$) [4]. Recent simulations [13] have shown that this effect has different properties, depending on the laser power. At the critical power threshold, only the focal intensity increases. However, as the incident laser power is increased (about $P/P_c = 3$–4), the beam extends and forms a second focus. As the laser power is increased further, multiple foci should occur, which eventually merge into a single channel.

In this experiment, we used a Ti:sapphire-Nd:glass laser system based on chirped-pulse amplification that produces 3 J, 400 fs pulses at 1.053 μm. The 43 mm diameter beam was focused with an $f/4$ off-axis parabolic mirror to $r_0 = 8.5\ \mu$m $(1/e^2)$, corresponding to vacuum intensities exceeding 4×10^{18} W/cm^2. This pulse was focused onto a supersonic helium gas jet with a sharp gradient (250 μm) and a long flat-topped interaction region (750 μm). The maximum density varies linearly with backing pressure up to the maximum backing pressure of 1000 PSI, and an underdense plasma at 3.6×10^{19} cm^{-3} is formed by the foot of the laser pulse tunnel ionizing the gas. This plasma density corresponds to a critical power of $P_c = 470$ GW. A sharp gradient and long interaction region are found to be essential for producing an electron beam and for self-guiding to occur.

Under these conditions, a large amplitude plasma wave was driven through the self-modulated laser wakefield instability. This was inferred by observing a highly modulated forward Raman scattered spectrum with up to the fourth anti-Stokes side band visible [3]. The onset of the Raman scattering occurred at $0.5P_c$ [3] which is consistent with the theoretical onset of 3D Raman scattering [16]. The absolute plasma wave amplitude was measured using a collinear collective Thomson scattering probe [8] that was split off from the main pulse after the compressor stage. This pulse was frequency doubled by a type-I potassium dihydrogen phosphate (KDP) crystal and then recombined with the main pulse. By measuring the spectrum of the scattered probe light, we found that the plasma wave lasts for approximately 1.5 ps (FWHM), and the spatial averaged peak plasma wave amplitude varies from $\delta n_e/n_e = 0.1-0.4$ at laser powers of 2–3 TW. The plasma frequency gradually decreases from 3.3×10^{14} rad/s to 2.5×10^{14} rad/s with increasing laser power, and we attribute this decrease primarily to the relativistic mass dependence on laser power in the plasma frequency [17]. Other effects, such as the nonlinear plasma wavelength when the plasma wave is driven to larger amplitudes or the expulsion of electrons from on axis (electron cavitation) which reduces the electron density, are calculated to be small (on the order of a few percent). The decreasing plasma frequency was not observed in our prior experiments with a different gas jet, where self-focusing was not observed [3].

In order to diagnose the spatial extent of the plasma, a sidescattering imaging system with a spatial resolution of 15 μm was utilized. We were able to resolve the growth of the plasma channel as a function of both laser power and plasma density. Figure 1 shows the sidescattered intensity distribution as a function of laser power, and the plasma channel clearly extends as the laser power increases. In the lower power cases ($<2.6P_c$), the channel length is only $\sim$125 μm, which is smaller than the confocal parameter ($2Z_R$) of 430 μm. As the laser power increases for a fixed gas density, the channel length first jumps to 250 μm at $3.9P_c$ and then reaches 750 μm at $7.2P_c$. The maximum channel length was observed to be 850 μm at $9.1P_c$. Note that this is limited by the interaction length of the gas jet. At $5.5P_c$, the sidescattered image formed has two distinct foci, and when the power exceeds $7.2P_c$, either multiple foci or a channel are observed, depending on shot-to-shot fluctuations and the gas jet position. A similar channel extension occurs if the gas density is varied at fixed laser power. For a 3.9 TW laser pulse, the channel extends to 250 μm at 400 PSI backing pressure (1.4×10^{19} cm^{-3}, $3.2P_c$) and 750 μm at 800 PSI (2.9×10^{19} cm^{-3}, $7.0P_c$). The consistent behavior at specific values of P_c for varying laser power or plasma density indicates that the channeling mechanism is relativistic self-focusing.

The sidescattered light was spectrally analyzed by an imaging spectrometer, and the bulk of the emission comes

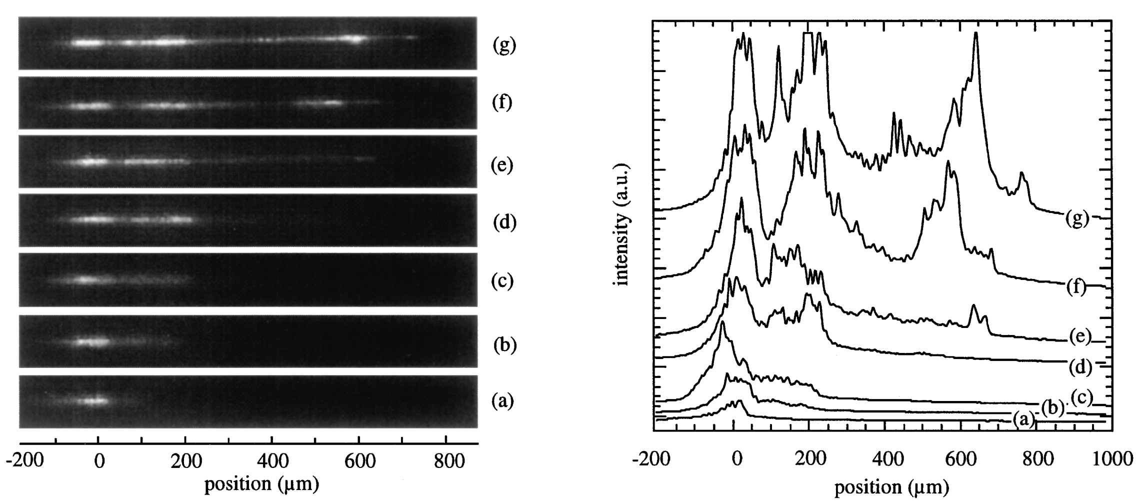

FIG. 1. On-axis images (left) and corresponding lineouts (right) of sidescattered light at various laser powers and a fixed initial electron density of 3.6×10^{19} cm^{-3}. The various images and lineouts represent laser powers of $P/P_c =$ (a) 1.6, (b) 2.6, (c) 3.9, (d) 5.5, (e) 7.2, (f) 8.4, and (g) 9.1. Note, the curves have been displaced vertically for ease of viewing.

from incoherent Thomson scattering of the blueshifted laser pulse. We were unable to obtain any information about the plasma density or temperature from this measurement. The divergence of the laser beam transmitted through the plasma was measured using a diffusing screen and a charge-coupled device (CCD) camera with a 1.053 μm narrow bandpass filter. At all laser powers, the laser expands to twice the vacuum divergence, and we attribute this expansion to ionization defocusing. This is consistent with the strong blueshifting we observe in the scattered spectra. Even though simulations indicate that the laser focuses to ~ 2 μm [13], the complex dynamics that occur as the laser continually focuses and defocuses in the plasma make it impossible to determine the minimum self-focused beam width from the far field divergence angle.

The total number of accelerated electrons (at all energies) was measured using either a Faraday cup or a plastic scintillator coupled to a photomultiplier tube, and the results were found to be consistent with each other. There is a sharp threshold for electron production at $\sim 1.5 P_c$, and the total number of electrons increases exponentially and finally saturates beyond $4P_c$ [3]. At $6P_c$, 6×10^9 accelerated electrons were measured coming out of the plasma in a beam. By using aluminum absorbers, we determined that 50% of the electrons detected have energy greater than 1 MeV (corresponding to 0.5 mJ of energy in the electron beam). Even though self-guiding extends the plasma channel length, we cannot observe any noticeable change in the total number of electrons. This is not unexpected since the electron number increases exponentially, and shot-to-shot fluctuations are large.

The electron energy spectrum (see Fig. 2) was measured using a 60° sector dipole magnet by imaging a LANEX scintillating screen with a CCD camera. The results obtained with this spectrometer supersede those reported in our earlier experiments [3], in which a peak in the electron spectrum turned out to be an artifact of the spectrometer used in that case. The normalized distribution is found to have a functional form of $\exp(-\alpha\gamma)$, where α is a fitting parameter. In the low-power case ($<6P_c$, no channeling), the normalized distribution follows $\exp(-\gamma)$, and when the laser power increases ($>6P_c$, with channeling), the electron energy distribution discretely jumps to follow $\exp(-0.67\gamma)$. The abrupt change in the electron distribution also occurs if the laser power is held fixed and the density is increased, as it should, given the critical power threshold dependence on density. Below 850 PSI (3.1×10^{19} cm^{-3}, no channeling), the electron distribution follows the same trend as the lower power distribution, and above 850 PSI (with channeling) it follows the higher power distribution. For the electron energy distribution greater than 3 MeV, a significantly less steep slope that extends to 20 MeV was measured using aluminum absorbers. Even though the plasma wave amplitude increases as the laser power increases, the distribution dramatically changes only when self-guiding occurs. This indicates that extension in the accelerating length is the primary factor in determining the fitting parameter α.

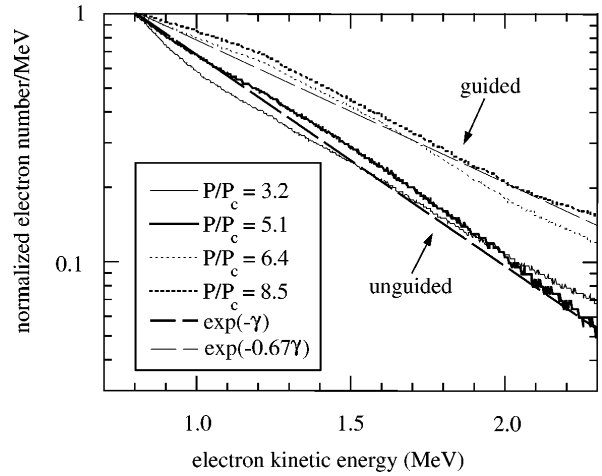

FIG. 2. Normalized electron kinetic energy spectrum as a function of laser power at fixed electron density. The upper curves represent the spectra obtained when self-guiding was observed; the lower curves represent unguided spectra. The two exponential fits are also shown.

A Maxwellian-like energy distribution has been observed in many previous experiments [18] and simulations [19], however, no theoretical justification for it has been found to date. Because the energy distribution is exponential, a temperature in the longitudinal direction can be defined. The temperature of the low energy distribution changes from 500 keV (without guiding) to 750 keV (with guiding). In these plasmas, many different plasma waves can grow from various instabilities and local conditions. The interactions between these waves can lead to stochastic heating of the electron beam, so by extending the plasma length, the various waves will interact longer and heat the beam more. However, the dephasing length, $L_d = \lambda(\omega_0/\omega_p)^3$, which gives the maximum distance over which acceleration can occur (170 μm for our conditions), is significantly shorter than our accelerating length. From this expression, we would think that there would be no noticeable change in the electron spectrum when we extend the plasma length from 250 μm to 750 μm. Recent particle-in-cell (PIC) simulations [19] indicate that this expression is too conservative for these highly nonlinear plasma interactions, and, in fact, the actual dephasing length may be many times longer. Consistent with our experimental results, these simulations indicate that the electron temperature, as well as the maximum energy, increases as the electrons propagate beyond the conventional dephasing length.

The electron beam profile was measured using a LANEX scintillating screen imaged by a CCD camera [3]. The LANEX is placed behind an aluminum sheet which blocks the laser light, so only electrons greater than 100 keV can be imaged. Analysis of the electron spectrum indicates that the bulk of the electrons that create an image on the screen are in the 100 keV to 3 MeV range. We have found, using aluminum absorbers, that the electron divergence does not depend on electron energy in this range. At low power ($<5P_c$), the electron beam has a Gaussian-like profile with a 10° radius at half maximum (see Fig. 3). As the laser power increases and the plasma channel length increases to $\sim$250 μm, a second peak seems to grow out of the low-power profile. Ultimately, at the highest laser powers and longest channel lengths, the divergence decreases to 5°, and the profile becomes more Lorentzian-like. The electron beam divergence should decrease as the longitudinal energy of the electrons increases since space charge will be less and the relative transverse momentum decreases due to the longer accelerating length. However, there should be a minimum divergence due to the space charge effect after the electrons leave the plasma. This effect is significant since the electrons are in the few MeV range (small γ) and the peak current is high (large number of electrons in a short bunch). We have roughly estimated the space charge divergence to be 6° by assuming 10^9 electrons at 1 MeV in a 1 ps bunch [note, $\theta_{\mathrm{HWHM}} \propto \sqrt{N/\tau_e(\beta\gamma)^3}$, where N is the number of electrons, τ_e is the electron bunch duration, and $\beta\gamma$ is the normalized momentum of the electrons] [20]. The electron beam emittance can be found from the measured divergence angle and the radius of the plasma channel, and in the best case (5° half angle and 5 μm half maximum radius), the calculated emittance ($\epsilon = r_0\theta_{\mathrm{HWHM}}$) is 0.4π mm mrad. To verify that the reduction in the beam emittance is due to the extension of the plasma channel, another gas jet with a narrower width was used and the same measurements repeated. In this case, the sidescattered images show that the channel length is limited to 360 μm, and the electron beam divergence is fixed at 12° for all laser powers.

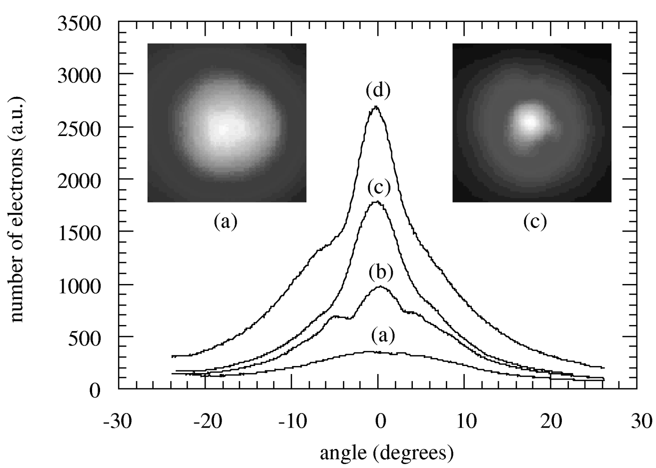

FIG. 3. Electron beam divergence as a function of laser power. Note the smaller divergence component growing out of the low-power profile as the laser power increases. The various curves represent laser powers of $P/P_c =$ (a) 3.4, (b) 5.0, (c) 6.0, and (d) 7.5. The two inset figures show the complete beam images for curves (a) and (c).

In this paper, we have shown the effect of self-guiding on a beam of relativistic electrons produced from a multidimensional self-modulated laser wakefield. The laser was channeled for four times the Rayleigh range (limited by the gas jet), and the self-guiding was found to increase the electron energy and decrease the electron beam emittance to the space charge limit even though the electrons propagated beyond the conventional dephasing limit.

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