

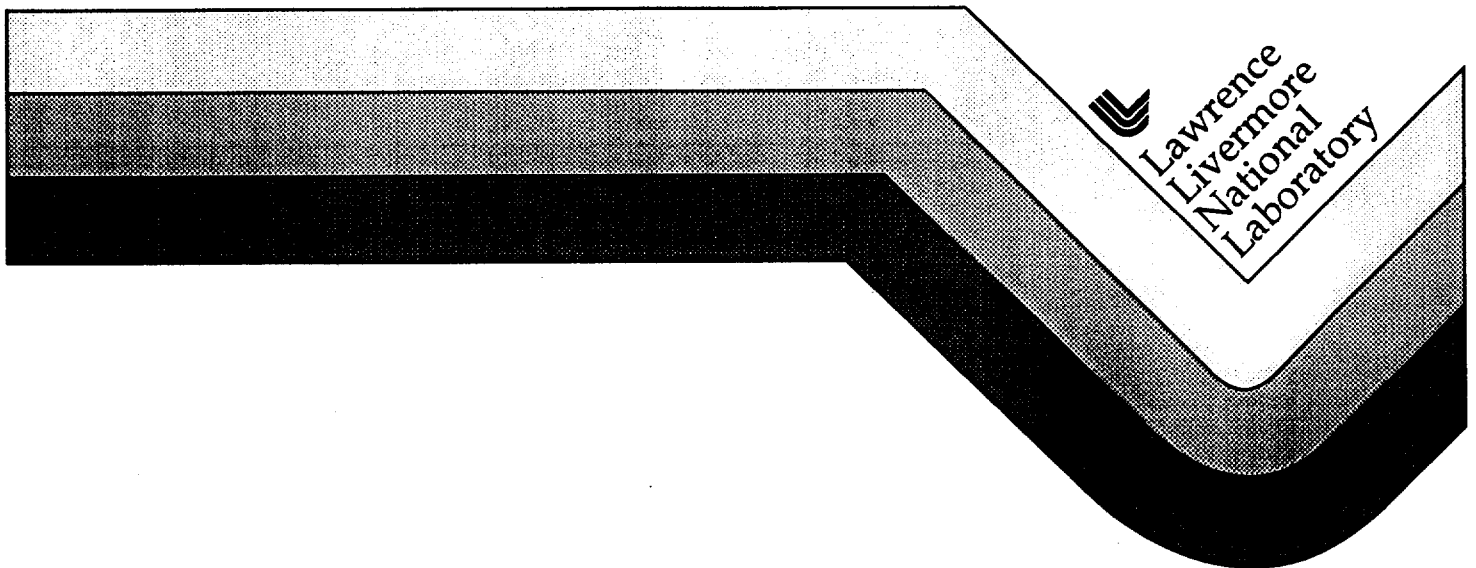
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Study of Laser Plasma Interactions in the Relativistic Regime

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Final Report on the DOE/LLNL Subcontract No. B307953
Covering the Period 2/14/95-6/30/97

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Abstract

We discuss the first experimental demonstration of electron acceleration by a laser wakefield over distances greater than a Rayleigh

range (or the distance a laser normally propagates in vacuum). A self-modulated laser wakefield plasma wave is shown to have a field gradient that exceeds that of an RF linac by four orders of magnitude ($E \geq 200$ GV/m) and accelerates electrons with over 1-nC of charge per bunch in a beam with space-charge-limited emittance (1 mm-mrad). Above a laser power threshold, a plasma channel, created by the intense ultrashort laser pulse ($I \sim 4 \times 10^{18}$ W/cm², $\lambda = 1$ μ m, $\tau = 400$ fs), was found to increase the laser propagation distance, decrease the electron beam divergence, and increase the electron energy. The plasma wave, directly measured with coherent Thomson scattering is shown to damp—due to beam loading—in a duration of 1.5 ps or ~ 100 plasma periods. These results may have important implications for the proposed fast ignitor concept.

Introduction

Implementation of the fast ignitor concept [1] for ICF fusion requires a thorough understanding of the generation and transport of relativistic electrons in dense plasmas. However, it is currently unclear just which of the myriad generation mechanisms will be dominant at the high laser intensities required for fast ignition $I > 10^{19}$ W/cm². Also, hole-boring will require some form of laser channeling. We have recently demonstrated in our lab that—at these high laser intensities—energetic electrons (> 100 keV) with kilo-amp currents can be accelerated into well collimated beams by means of relativistically self-guided laser wakefields in underdense plasmas [14, 11, 13]. We think these results will help to illuminate several important aspects of the fast ignitor problem.

When an intense laser enters a region of gaseous-density atoms, the atomic electrons feel the enormous laser electromagnetic field, and begin to oscillate at the laser frequency ($\omega = 2\pi c/\lambda = ck$). The oscillations can become so large that the electrons become stripped from the atoms, or ionized. At high laser intensity (I), the free electrons begin to move at close to the speed of light (c), and thus their mass m_e changes significantly compared to their rest mass. This large electron oscillation energy corresponds to gigabar laser pressure, displacing the electrons from regions of high laser intensity. Due to their much greater inertia, the ions remain stationary, providing an electrostatic restoring force. These effects cause the plasma electrons to oscillate at the plasma frequency (ω_p) after the laser pulse passes by them, creating alternating regions of net positive and negative charge, where $\omega_p = \sqrt{4\pi e^2 n_e / \gamma m_e}$, n_e is the electron density, e is the electron charge and γ is the relativistic factor associated with the electron motion transverse to the laser propagation. γ depends on the normalized vector potential, a_o , by $\gamma = \sqrt{1 + a_o^2}$, where $a_o = \gamma v_{os}/c = eE/m_o\omega c = 8.5 \times 10^{-10} \lambda[\mu\text{m}] I^{1/2}[\text{W}/\text{cm}^2]$. The resulting electrostatic wakefield plasma wave propagates at a phase velocity nearly equal to the speed of light and thus can continuously accelerate hot electrons [4]. Up to now, most experiments have been done in the self-modulated laser wakefield regime [5, 6, 7], where the laser pulse duration is much longer than the plasma period, $\tau \gg \tau_p = 2\pi/\omega_p$. In this regime, the forward Raman scattering instability can grow; where an electromagnetic wave (ω_o, \mathbf{k}_o) decays into a plasma wave (ω_p, \mathbf{k}_p) and electromagnetic side-bands ($\omega_o \pm \omega_p, \mathbf{k}_o \pm \mathbf{k}_p$).

Recent Results

A small number of relativistic hot electrons were observed in inertial-confinement-fusion experiments with long-pulse duration large-building size lasers and solid-density targets. However, it was shown only recently that electrons can be accelerated by a plasma wave driven by intense ultrashort-duration table-top laser pulses ($I \sim 4 \times 10^{18}$ W/cm², $\lambda = 1$ μ m, $\tau \sim 0.5$ ps) and gaseous-density targets [8, 9]. Under similar conditions, electrons were even observed to have an energies up to 44 MeV, with an energy spread of 100% [10]. Recently, we have shown that the accelerated electron beam appeared to be naturally-collimated with a low-divergence angle (less than ten degrees), and had over 1-nC of charge per bunch [11].

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 μ m. The 43 mm diameter beam was focused with an f/4 off-axis parabolic mirror to $r_o = 8.5$ μ m ($1/e^2$), corresponding to vacuum intensities exceeding 4×10^{18} W/cm². This pulse was focused onto a supersonic helium gas jet with a sharp gradient (250 μ m) and a long flat-topped interaction region (750 μ m). 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.

Moreover, as shown in Fig. 1, acceleration occurred in this experiment [11] only when the laser power exceeded a certain critical value, P_c , the threshold for relativistic self-focusing. 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 $\sim 1.5P_c$, and the total number of electrons increases exponentially and finally saturates beyond $4P_c$ [11]. 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).

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 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),

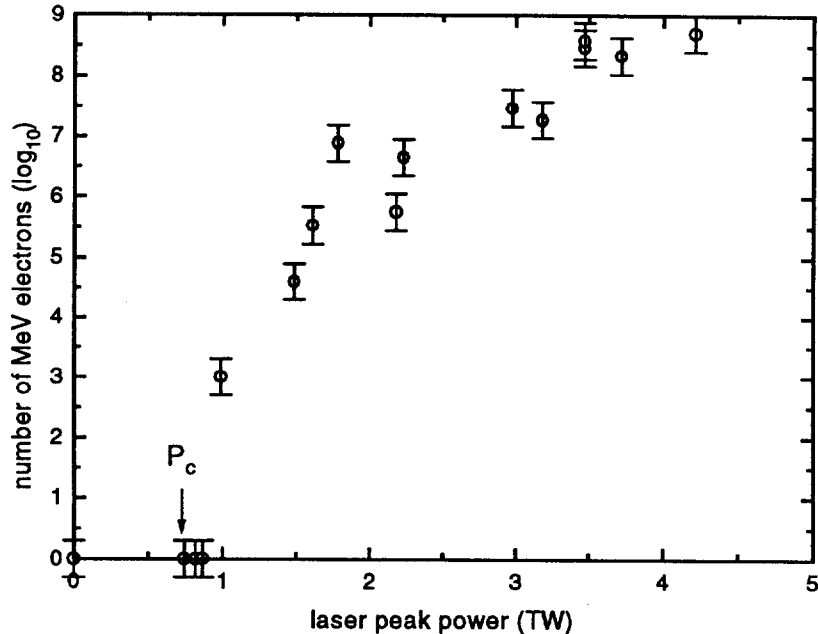


Figure 1: The number of relativistic electrons accelerated as a function of incident laser power focused in a gas of helium at atmospheric density.

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 ($3.1 \times 10^{19} \text{ cm}^{-3}$, 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 only dramatically changes when self-guiding occurs. This indicates that extension in the accelerating length is the primary factor in determining the fitting parameter α .

Measurements of the satellites in the spectrum of the forward scattered light indicated that a self-modulated plasma wave occurred when the laser

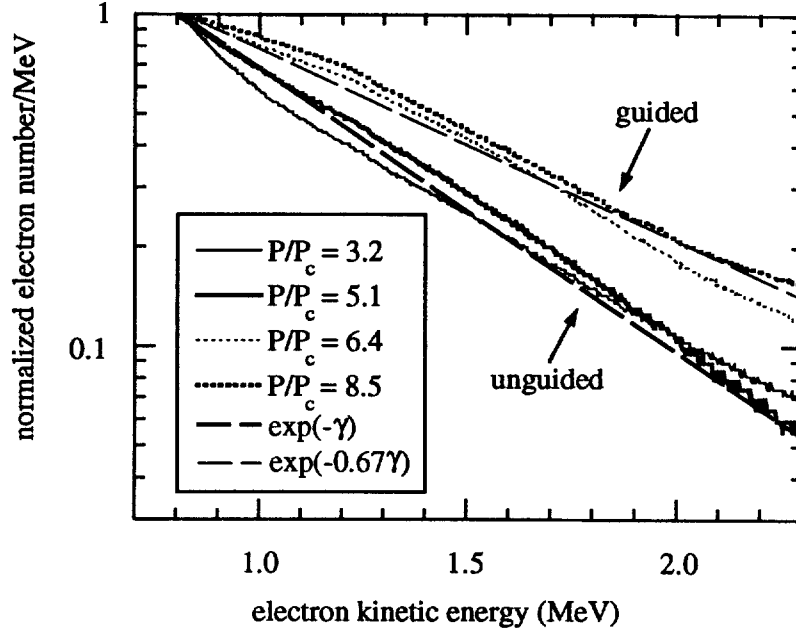


Figure 2: Normalized electron kinetic energy spectrum as a function of laser power at fixed electron density. The upper curves represent the spectra obtained when self-guiding was observed; the lower curves represent unguided spectra. The two exponential fits are also shown.

power exceeded $P_c/2$. Since then, two independent research groups have simultaneously reported direct measurements of the plasma wave amplitude with a Thomson-scattering probe pulse [12, 13]. The field gradient was reported [13] to exceed that of a radio-frequency (RF) linac by four orders of magnitude ($E \geq 200$ GV/m). This acceleration gradient corresponds to an energy gain of 1 MeV in a distance of only 10 microns. The plasma wave was observed to exist for a duration of 1.5 ps or 100 plasma oscillations [13]. It was calculated that it damps only because all of the wave energy was converted to the accelerated electrons. Except for the large energy spread and low average power, these parameters compare favorably with medical linacs. In fact, the much smaller source size of a laser wakefield accelerator compared with that of a conventional linac, 10 microns compared with greater than 100 microns, may permit much greater spatial resolution for medical imaging.

This enormous field gradient would be of limited use if the length over

which it could be used to accelerate electrons were just the natural diffraction length of the highly focused laser beam, which is much less than a millimeter. Fortunately, we recently demonstrated that electrons can be accelerated beyond this distance [14]. At high laser power, the index of refraction in a plasma varies with the radius. This is both because the laser intensity varies with radius and the plasma frequency depends on the relativistic mass factor γ . Above the above-mentioned critical laser power P_c , the plasma should act like a positive lens and focus the laser beam, a process called relativistic self-focusing. This is similar to propagating a low power beam over an optical fiber optic cable, except in this case the intense laser makes its own fiber optic.

In order to diagnose the spatial extent of the plasma, a sidescattering imaging system with a spatial resolution of $15 \mu\text{m}$ was utilized. We were able to resolve the growth of the plasma channel as a function of both laser power and plasma density. Fig. 3 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

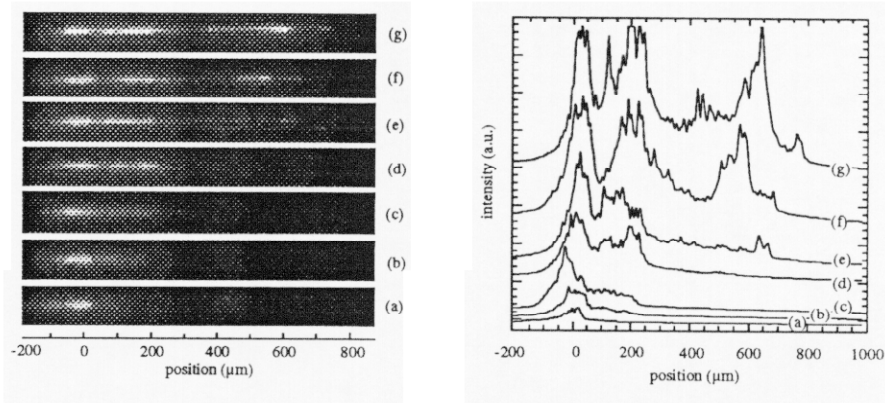


Figure 3: On-axis images (left) and corresponding lineouts (right) of sidescattered light at various laser powers and a fixed initial electron density of $3.6 \times 10^{19} \text{ cm}^{-3}$. The various images and lineouts represent laser powers of $P/P_c =$ (a) 1.6, (b) 2.6, (c) 3.9, (d) 5.5, (e) 7.2,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

length is only $\sim 125 \mu\text{m}$, which is smaller than the confocal parameter ($2Z_R$) of $430 \mu\text{m}$. As the laser power increases for a fixed gas density, the channel length first jumps to $250 \mu\text{m}$ at $3.9P_c$ and then reaches $750 \mu\text{m}$ at $7.2P_c$. The maximum channel length was observed to be $850 \mu\text{m}$ at $9.1P_c$. Note 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 $250 \mu\text{m}$ at 400 PSI backing pressure ($1.4 \times 10^{19} \text{ cm}^{-3}$, $3.2P_c$) and $750 \mu\text{m}$ at 800 PSI ($2.9 \times 10^{19} \text{ cm}^{-3}$, $7.0P_c$). 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 from incoherent Thomson scattering of the blue-shifted 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 CCD camera with a $1.053 \mu\text{m}$ 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 blue-shifting we observe in the scattered spectra. Even though simulations indicate that the laser focuses to $\sim 2 \mu\text{m}$ [15], 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.

A Maxwellian-like energy distribution has been observed in many previous experiments[16] and simulations[17], 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, $L_d = \lambda(\omega_o/\omega_p)^3$, which gives the maximum distance over which acceleration can occur ($170 \mu\text{m}$ 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 $250 \mu\text{m}$ to $750 \mu\text{m}$. Recent PIC simulations[17] 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, increase as the electrons propagate beyond the conventional dephasing length.

The relativistically self-guided channel was found to increase the laser propagation distance by a factor of four (limited thus far only by the length of gas), decrease the electron beam divergence by a factor of two (as shown in Fig. 4), and increase the electron energy. The electron beam profile was mea-

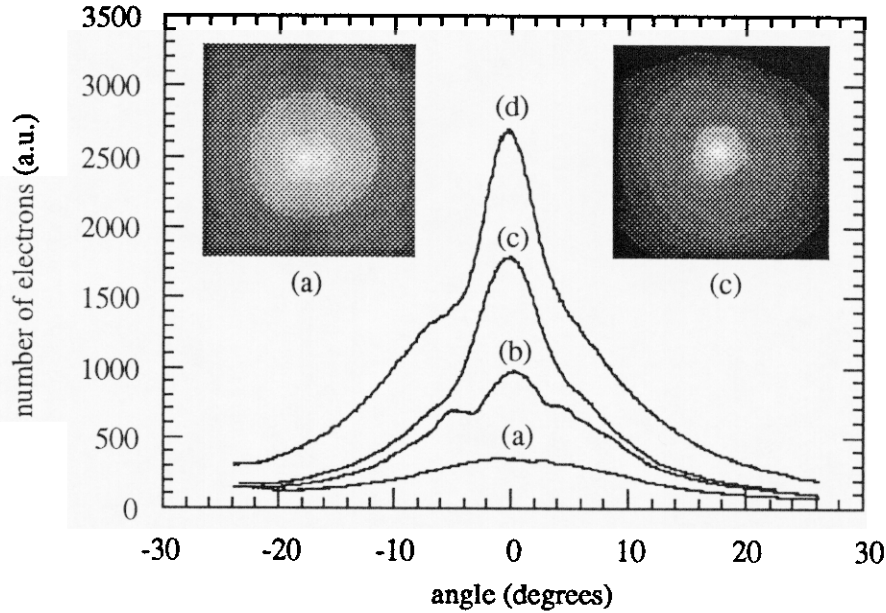


Figure 4: Electron beam divergence as a function of laser power. The various curves represent laser powers of $P/P_c =$ (a) 3.4, (b) 5.0, (c) 6.0, and (d) 7.5. The two insert figures show the complete beam images for curves (a) and (c).

sured using a LANEX scintillating screen imaged by a CCD camera[11]. 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. 4). As the laser power

increases and the plasma channel length increases to $\sim 250 \mu\text{m}$, 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: $\theta_{hwhm} \propto \sqrt{N/\tau_e(\beta\gamma)^3}$, where N is the number of electrons, τ_e is the electron bunch duration, and $\beta\gamma$ is the normalized momentum of the electrons)[18]. 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 $5 \mu\text{m}$ half-max radius), the calculated emittance ($\epsilon = r_o \theta_{hwhm}$) is $0.4 \pi\text{-mm-mrad}$. 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 $360 \mu\text{m}$ and the electron beam divergence is fixed at 12° for all laser powers.

Application to the Fast Ignitor

These results could indicate that relativistic self-focusing may permit the use of only a single pulse in the fast ignitor. If coupled to another laser-produced solid-density plasma, these wakefield generated electrons may eventually be used to study electron transport in high density plasmas in the absence of space charge forces and in the presence of large magnetic fields. By addressing the growth and decay of wakefields, and the nonlinear propagation of intense lasers, this study has already illuminated some of the complexity of the interaction at the laser intensities relevant to the fast ignitor.

Other Applications

Except for the large energy spread and low average power, these parameters compare favorably with medical linacs. In fact, the much smaller source size

of a laser wakefield accelerator compared with that of a conventional linac, 10 microns compared with greater than 100 microns, may permit much greater spatial resolution for medical imaging.

Nontechnical Aspects of the Report

The work was done at the University of Michigan Center for Ultrafast Optical Science (CUOS), where a single graduate student was supported by this contract. Three major scientific papers, published within the last year, acknowledged the support of this contract, two in *Physical Review Letters* and one in *Science*.

Publications

1. D. Umstadter, S.-Y. Chen, A. Maksimchuk, G. Mourou, and R. Wagner, *Science* **273**, 472 (1996).
2. S. P. Le Blanc, M. C. Downer, R. Wagner, S.-Y. Chen, A. Maksimchuk, G. Mourou and D. Umstadter, *Phys. Rev. Lett.* **77**, 5381 (1996).
3. R. Wagner, S.-Y. Chen, A. Maksimchuk and D. Umstadter, *Phys. Rev. Lett.* **78**, 3122 (1997).
4. D. Umstadter, "Laser Acceleration of Electrons: Zero to c in Less than Ten Microns," *New Modes of Particle Acceleration Techniques and Sources*, Z. Parsa, Ed., AIP Conference Proceedings 396 (American Institute of Physics, New York, 1997), pp. 89-94.
5. R. Wagner, S.-Y. Chen, A. Maksimchuk, E. Dodd, J.-K. Kim, D. Umstadter, "A Collimated Beam of MeV Electrons Accelerated by a Terawatt Laser," Quantum Electronics and Laser Science Conference, Vol. 10, OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), p. 70.
6. S. P. Le Blanc, M. C. Downer, R. Wagner, S.-Y. Chen, A. Maksimchuk, G. Mourou, and D. Umstadter, "Temporal characterization of a self-modulated laser wakefield accelerator," Conference on Lasers and Electro-Optics, Vol. 11, OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), p. 313.

7. D. Umstadter, "An Ultrashort-Duration Relativistic Electron Beam Accelerated by an Intense Laser," *Quantum Electronics and Laser Science (CLEO/QELS '97) Conference*, Baltimore, MD, May, 1997, Vol. 11, OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), p. 300.
8. S. P. LeBlanc, M. C. Downer, R. Wagner, S.-Y. Chen, A. Maksimchuk, G. Mourou, and D. Umstadter, "Temporal Characterization of a Self-Modulated Laser Wakefield," *Advanced Accelerator Concepts*, 12-18 October 1996, Lake Tahoe, 4-06 (submitted for publication).
9. S.-Y. Chen, R. Wagner, D. Gustafson, A. Maksimchuk, and D. Umstadter, "Electron Acceleration by Self-Modulated Laser Wakefield Accelerator," *Advanced Accelerator Concepts*, 12-18 October 1996, Lake Tahoe, (submitted for publication).

Invited Conference Presentations

1. "An Ultrashort-Duration Relativistic Electron Beam Accelerated by an Intense Laser," *Quantum Electronics and Laser Science (CLEO/QELS '97) Conference*, Baltimore, MD, May, 1997.
2. "Laser-Driven Plasma Cathode Electron Injector," *Particle Accelerator (PAC '97) Conference*, Vancouver, B. C. Canada, May,
3. "Atomic Processes in Ultrashort-Pulse Laser-Plasmas," *International Conference on Laser Interaction and Related Plasma Phenomena*, Monterey, CA, April, 1997.
4. "Guided Laser Acceleration of Electrons," *Berkeley Workshop on Fast Ignitor Physics*, Berkeley, CA, March, 1997.
5. "Relativistically Self-Guided Laser-Wakefield Acceleration," *Applications of High Field & Short Wavelength Topical Meeting*, Santa Fe, NM, March, 1997.
6. "Laser Acceleration of Particles," *Fourteenth International Conference on the Application of Accelerators in Research and Industry*, Denton, TX, November, 1996.

7. "Electron Injection and Acceleration with Laser Wakefields," *Advanced Accelerator Concepts Workshop*, Lake Tahoe, CA, October, 1996.
8. "Short Bunch Injection, Synchronization and Acceleration in Laser Wakefields," *Institute for Theoretical Physics Conference on New Modes of Particle Acceleration Techniques and Sources*, Santa Barbara, CA, August 1996.
9. "Terawatt Lasers: Probing Unique Material Properties with Novel Diagnostic Sources," *IEEE Lasers and Electro-Optics Society Summer Topical Meeting on Advanced Applications of Lasers in Materials and Processing*, Keystone, CO, August 1996.
10. "Relativistic Electrons from High-Intensity Laser-Plasma Interactions," *Joint Meeting of the American Physical Society and the American Association of Physics Teachers*, Indianapolis, IN, May 1996.

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