

RECENT PROGRESS ON LASER DRIVEN ACCELERATORS AND APPLICATIONS

W. P. LEEMANS,^{*†} E. ESAREY,[†] C. G. R. GEDDES, C. B. SCHROEDER and CS. TÓTH

LOASIS Program, Accelerator & Fusion Research Division,
Lawrence Berkeley National Laboratory, Berkeley, California 94720 USA

[†]Also at the Department of Physics, University of Nevada, Reno

^{*}Corresponding author. E-mail : wpleemans@lbl.gov

Received September 1, 2005

Laser driven accelerators promise to provide an alternative to conventional accelerator technology. They rely on the excitation of large amplitude density waves in a plasma by the photon pressure of an intense laser. The density oscillations in which electrons and ions are separated, result in extremely large longitudinal electric fields that can be several orders of magnitude larger than those that are used in today's radio-frequency accelerators. Whereas this principle had been demonstrated experimentally for nearly two decades, it was not until 2004 that the production of high quality electron beams around 100 MeV was demonstrated. Analysis, aided by particle-in-cell simulations, as well as experiments with various plasma lengths and densities, indicate that tailoring the length of the accelerator, together with loading of the accelerating structure with beam, are the keys to production of mono-energetic electron beams. Increasing the energy towards a GeV and beyond will require reducing the plasma density and design criteria are discussed for an optimized accelerator module. The current progress and future directions are summarized through comparison with conventional accelerators, highlighting the unique short and long term prospects for intense radiation sources and high energy accelerators based on laser-driven plasma accelerators.

KEYWORDS : Laser, Plasma, Accelerator, Wakefield, Guiding

1. INTRODUCTION

Directed laser beams provide a very useful way of concentrating energy efficiently. Using them for acceleration of particles however is challenging. An electron in an intense laser beam will behave much like a cork on water as a huge wave passes by-bobbing up and down on the wave but not really going anywhere. In 1979, Tajima and Dawson [1] solved the problem of how to transfer the laser beam energy to an electron: an intense focused laser beam can create a large, fast-moving, plasma wave as it passes through and ionizes a gas. The electron can then "surf" on the plasma "tsunami" and be accelerated to enormous energies. The laser beam in essence generates a large amplitude plasma density wave that ripples through the plasma like a wake behind a boat. The longitudinal electric field associated with this density wave can be in excess of 10's of GV/meter (more than three orders of magnitude beyond conventional accelerator technology).

Experiments conducted during more than two decades that followed the seminal paper by Tajima and

Dawson, demonstrated that, by focusing intense laser pulses onto a neutral gas, relativistic electron beams can be produced [2-4]. The accelerated electron energy spectrum was characterized by an exponential or Boltzmann-like distribution, with the majority of electrons at modest energies (a few MeV). The total accelerated charge was large (up to several nC), but the number of electrons at high energy (tens of MeV) was an exponentially small fraction of the total charge. Over the years, the quality of these bunches improved, and beams were produced with "smaller" lasers, capable of operating at higher repetition rate [5]. Laser pulse shape effects were studied [6, 7], and applications were explored such as radio-isotope production [8-10], THz radiation generation [11, 12], and x-ray generation [13-16]. Although steady progress had been made, the 100 percent energy spread remained a major limitation.

Recent simulations of laser-plasma interaction in an ultra-relativistic regime indicated that the generation of quasi-monochromatic bunches [17] was however possible. The bubble or blow-out regime is well known in plasma wakefield accelerators, when using electron

beams denser than the surrounding plasma [18]. In the case of lasers, it occurs when the ponderomotive potential of the laser is large enough to blow out all plasma electrons. However, the simulations [17] were done for incident laser intensities that were not (yet) achievable experimentally. As it turns out, through an interplay between the laser pulse and plasma, the self-modulational instability leads to laser pulse steepening, which allows this regime to be accessed experimentally.

In 2004 a major new milestone was reported in the journal *Nature*, with the production and measurement of high quality electron bunches. Three different groups [located at the Rutherford Appleton Laboratory-RAL (UK), Lawrence Berkeley National Laboratory-LBNL (USA), and the Laboratoire d'Optique Appliquée-LOA (France)] announced measurement of electron bunches with narrow energy spread containing a significant amount of charge in a beam with a small divergence [19-21]. In the case of the LBNL experiments [20], this was accompanied by the achievement of another major milestone: the guiding of relativistically intense ($>10^{18}$ W/cm²) laser pulses within preformed plasma channels and the self-trapping and acceleration of electrons within these channels.

As will be discussed, guiding of high intensity laser pulses in plasma channels is necessary in order to extend the acceleration length and the energy gain up to the multi-GeV range with reasonable size laser systems that can operate at high repetition rates.

To obtain the mono-energetic bunches, the RAL and LOA groups used relatively large laser spot sizes. This effectively increases the diffraction (or Rayleigh range, Z_R) of the laser beam permitting propagation over distances on the order of the gas jet length. The RAL-AlphaX collaboration used a 16 TW, 40 fs laser pulse focused (25 μ m spot size, 1×10^{18} W/cm²) on a plume of a gas jet with a plasma density of 2×10^{18} cm⁻³. A narrow energy spread bunch was observed at 78 ± 2 MeV with 20 pC of charge [19]. The LOA experiments used a 30 TW, 33 fs laser pulse focused (18 μ m spot size, 3×10^{18} W/cm²) on a plume of a gas jet with a plasma density of 6×10^{18} cm⁻³. A narrow energy spread bunch was observed at 170 ± 15 MeV with 500 pC of charge [21].

The LBNL experiments used a 9 TW, 55 fs laser pulse focused to a relatively tight spot size (8.5 μ m FWHM). To mitigate the short Z_R of the beam, a preformed plasma channel was used to guide the laser beam through the gas jet. Channel guiding, including the method used at LBNL, will be described next. This is followed by a discussion on scaling laws that indicate the importance of development of long plasma channels for GeV-class accelerators.

The manuscript will conclude with a discussion on the state-of-the-art performance of laser wakefield accelerators (LWFAs) and future developments that are needed to enable the use of laser driven accelerators for

various applications.

2. CHANNEL GUIDING: SCALING LAWS AND EXPERIMENTS

The importance of the accelerator length, and how to extend it, has been discussed theoretically for many years. As an example, during the 1995 Kardamyli Workshop on second generation plasma-based accelerators, design studies were carried out in the laser guiding and acceleration working group for a 1 GeV LWFA [22]. The main conclusion of the study was that extending the propagation of a laser pulse beyond Z_R , up to the dephasing distance [4], was an essential element of a future LWFA. Much higher net energy gains can be realized for the same amount of input laser power, by extending the acceleration distance beyond Z_R . Guiding concepts relying on the use of preformed channels are being studied by several groups around the world [20, 23-32]. At LBNL, using the ignitor-heater concept [23], we have recently produced plasma channels that have guided, to our knowledge, the highest peak power in a preformed channel [20]. This result demonstrates the ability of plasma channels to guide laser beams, at intensities relevant for particle acceleration, over many Z_R . After a brief review of scaling laws in Section 2.1, experimental results from the LOASIS group on laser guiding and electron acceleration will be summarized in Sections 2.2 and 2.3, respectively.

2.1. Scaling laws

There are several mechanisms that can limit the effective accelerator length, and, therefore, the energy gain in a LWFA [4]. One of the most severe is diffraction of the laser pulse, but this can be overcome through the use of a plasma channel to guide the laser pulse [20, 33-35]. The two main limitations for a channel-guided LWFA are then electron dephasing and pump depletion. Electron dephasing is a result of a highly relativistic electron outrunning the wakefield, which typically has a phase velocity $< c$. In this low intensity (or linear) limit, $a_0^2 \ll 1$, the dephasing length is $L_{\text{deph}} \sim \lambda_p^3 / \lambda_0^2$, assuming an axially uniform, wide plasma channel, where λ_p is the plasma wavelength, λ_0 is the laser wavelength, and a_0 is the normalized peak vector potential of the laser field, which is related to the peak intensity of a linear polarized laser pulse by $a_0 = 8.5 \times 10^{-10} \lambda_0 [\mu\text{m}] (I_0 [\text{W/cm}^2])^{1/2}$. In the high intensity (or nonlinear) limit, $a_0^2 \gg 1$, the dephasing length is $L_{\text{deph}} \sim (\lambda_p^3 / \lambda_0^2) a_0$, where a constant of order unity has been neglected.

The laser pulse excites a wake as it propagates. Wake excitation leads to loss of laser pulse energy. The pump depletion length (the distance over which the pump loses a significant fraction of its energy) can be estimated by equating the laser pulse energy to the energy left behind in the wake [36, 37]. In the linear limit ($a_0^2 \ll 1$), the

pump depletion length is $L_{pd} (\lambda_p^3 / \lambda_0^2) a_0^2$, whereas in the nonlinear limit ($a_0^2 \gg 1$), $L_{pd} (\lambda_p^3 / \lambda_0^2) a_0$. Once pump depletion occurs, staging with a fresh pump pulse is necessary.

Scaling laws describing the energy gain in a standard LWFA (where the laser pulse length L_L is on the order of the plasma wavelength λ_p) can be derived under idealized assumptions [4, 22]. Three different cases are considered. The first is for a uniform plasma wherein the acceleration length is limited by vacuum diffraction, i.e., $L_{acc} \simeq \pi Z_R$, where $Z_R = \pi r_0^2 / \lambda_0$ and r_0 is the laser spot size. The second is for a plasma channel wherein the acceleration length is limited by electron dephasing, and the third is a plasma channel wherein the acceleration length is limited by pump depletion. In all cases, the laser power is assumed to be less than the critical power for self-focusing and the effects of instabilities are neglected. Furthermore, the laser pulse and plasma are assumed to be wide and axially uniform, and the accelerating field is assumed to be that for an optimized flat-top pump pulse, i.e., $E_{max}/E_0 = (a_0^2/2) (1+a_0^2/2)^{-1/2}$, where E_{max} is the maximum electric field amplitude of the wake behind the laser pulse and $eE_0 = 2\pi mc^2/\lambda_p$. The ideal energy gain W is given by multiplying E_{max} by the acceleration length. In the linear limit ($a_0^2 \ll 1$), $L_{deph} \sim L_{pd}$ and $W \sim mc^2(\lambda_p^2/\lambda_0^2)a_0^2$. In the nonlinear limit ($a_0^2 \gg 1$), $L_{deph} \sim L_{pd}$ and $W \sim mc^2(\lambda_p^2/\lambda_0^2)a_0$. Note that the nonlinear (or mildly nonlinear regime) is advantageous, since $L_{deph} \sim L_{pd}$ which implies efficient use of the pump laser pulse energy in a single stage. Furthermore, the energy gain and accelerating gradients are higher compared to the linear regime.

The scaling laws for the ideal energy gain in a channel-guided LWFA, as obtained from analytic theory, can be summarized as follows [38]. If the acceleration distance is limited by diffraction, $L_{acc} \simeq \pi Z_R < L_{deph}$, L_{pd} , the energy gain in practical units is

$$\Delta W_{diff} [MeV] \simeq 740(\lambda/\lambda_p)(1+a_0^2/2)^{-1/2} P [TW]. \quad (1)$$

If the acceleration distance is limited by the dephasing length, $L_{acc} \simeq L_{deph}$, the energy gain in practical units is

$$\Delta W_{deph} [MeV] \simeq \frac{630 I [W/cm^2]}{n [cm^{-3}]} \times \begin{cases} 1, & a_0^2 \ll 1, \\ (2/\pi)/N, & a_0^2 \gg 1, \end{cases} \quad (2)$$

where N is the number of plasma periods that the bunch is located behind the laser pulse.

If the acceleration distance is limited by the depletion length, $L_{acc} \simeq L_{pd}$, the energy gain in practical units is

$$\Delta W_{pd} [MeV] \simeq \begin{cases} 3.4 \times 10^{21} / (\lambda^2 [\mu m] n [cm^{-3}]), & a_0^2 \ll 1, \\ 400 I [W/cm^2] / (n [cm^{-3}]), & a_0^2 \gg 1. \end{cases} \quad (3)$$

As an example, consider the nonlinear regime $a_0^2 \gg 1$. This is favorable since the dephasing length is approximately equal to the depletion length, which implies higher efficiency, in addition to larger accelerating fields and larger energy gains. For a laser with $P=100$ TW, $a_0=3$, $\lambda=0.8 \mu m$, $r_0=18 \mu m$, $I=1.9 \times 10^{19}$ W/cm², 55 fs, and 5.5 J; along with a plasma with $\lambda_p=33 \mu m$ ($n_0=10^{18}$ cm⁻³) such that $L_L=\lambda_p/2$, gives a wakefield of $E_z=190$ GeV/m, an acceleration length of $L_{acc}=3.8$ cm, and an energy gain of $\Delta W=7.2$ GeV.

In the next section recent experimental results will be discussed that demonstrate that radially shaped plasmas can indeed guide intensities relevant to large amplitude wake excitation and particle acceleration.

2.2. Guiding Relativistic Intensities in Plasma Channels

As discussed in the previous section, the ability to guide intense laser pulses over many Z_R is an essential element of a high energy LWFA. Plasma channel guiding of short laser pulses was first demonstrated in hydrodynamically formed plasma channels produced by focusing a relatively intense beam with an axicon lens [34, 39]. In these pioneering experiments, high Z-gases were used to facilitate the ionization process. High Z-gases, however, are susceptible to further ionization when used with ultrahigh intensity lasers, and, therefore, a method was needed to allow the use of low Z-gases. By separating out the ionization and heating phase of the channel formation, channels were produced in hydrogen gas with the ignitor-heater method [23].

Recently, channeling at relativistic intensities was realized with the 10 TW multi-beam LOASIS laser [20]. Preformed guiding channels were created using a variation of the ignitor-heater method [23]. A plasma was formed in a 2.5 mm long supersonic H₂ gas jet with an atomic density of $3-4 \times 10^{19}$ cm⁻³ by an ignitor pulse (15 mJ, 60 fs) that is co-axial with the drive pulse, then heated by a heater pulse (150 mJ, 250 ps). Hydrodynamic expansion of the plasma formed a channel [34, 39] that guided a relativistically intense drive pulse that was focused at the entrance to the channel. The drive pulse (500 mJ, 55 fs) was focused with an off-axis parabola to a spot of 7-8.5 μm FWHM resulting in a laser intensity of 1.1×10^{19} W/cm². Propagation of the laser was monitored with a side interferometer, mode imager CCD, and transmitted light spectrometer. Electrons accelerated by the plasma wake of the drive beam were analyzed using an integrating current transformer (ICT), a phosphor screen, and a magnetic spectrometer. A 55° dipole magnet permitted energy distribution measurements up to 92 MeV with about 1% resolution and a range of 25% around a chosen central momentum. Higher energies (up to 150 MeV) were measured by operating the spectrometer at a 5° angle, at the cost of resolution (10% level).

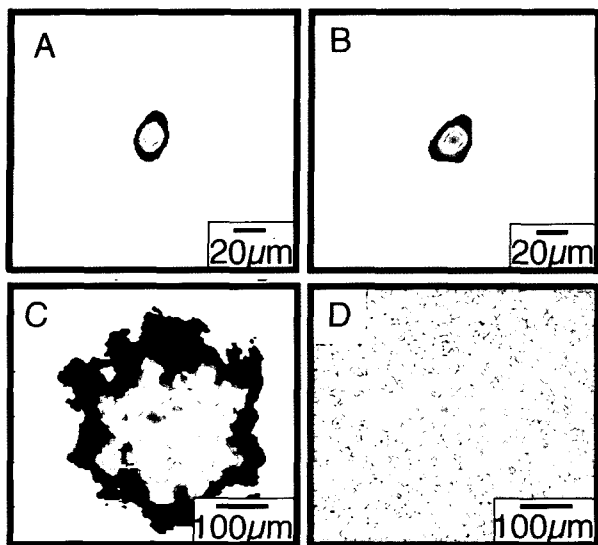


Fig. 1. Mode Images of Laser Propagation at 4 TW, or Two Times the Critical Power for Self Focusing. The Guided Output Mode after 2.5 mm ($10 Z_R$) of Propagation (B) is Indistinguishable from the Input Mode (A). The Effect of the Channel Can Be Seen by Comparison to Vacuum Propagation over the Same Distance Where the Output is Severely Diffracted (C). Self Guiding Also Does Not Maintain the Spot over This Distance Due to Instability, and the Output Mode with Gas Jet on but without the Guide Displays Enhanced Diffraction (D). Note Enlarged Scale in (C) and (D).

The ignitor-heater method provided several tuning knobs to tailor the channel properties. Varying the time delay between the heater and drive pulses, energy of the heater pulse and spatial overlap, channels can be created with different radial density profiles. Figure 1 shows an example of mode images of laser spots at 4 TW ($7 \mu\text{m}$ input spot, $7 \times 10^{18} \text{ W/cm}^2$). With the channel on, the output spot (B) matches the input (A). The mode imager resolution is restricted by $f\#$ constraints in the target chamber, and measures a $12 \mu\text{m}$ FWHM spot size for both input and output. Hence, the guided intensity is between 10^{18} and $2.5 \times 10^{18} \text{ W/cm}^2$, with the lower limit set by the $12 \mu\text{m}$ mode imager observation and the upper limit set by the input spot size. In the absence of any plasma, a large mode size consistent with vacuum diffraction is observed (C), and with the gas jet on but the channel off (D) diffraction is increased by ionization effects [40, 41], showing that self guiding alone is insufficient to efficiently guide the beam. Transmission at 4 TW was 35%, a reduction of one third from the low power case, indicating that substantial power was deposited in plasma waves. The depletion observed, is consistent with particle-in-cell simulations, run with the experimental parameters. The simulations also indicate

that a plasma wave averaging 200-300 GV/m is excited, in the last 0.5 mm of guide length. No electrons are self trapped at 4 TW, making this an attractive structure for controlled injection experiments [42-44], as will be discussed below. When increasing the laser power up to the 10 TW level, electron beams were produced with unprecedented properties, as discussed in Section 2.3.

2.3. Production of Low Energy Spread Bunches

With the preformed channels and laser input powers at the 8-10 TW level, electron beams with narrow energy spread were observed [20]. Using the 55° fine resolution magnetic spectrometer, beams containing 2×10^9 electrons with two percent energy spread around 86 MeV were observed with a divergence on the order of 3 mrad. Beams containing 10^9 electrons at energies between 135-170 MeV were observed using the 5° port of the magnetic spectrometer. An example of a narrow energy spread spectrum is shown in Fig. 2. The normalized geometric emittance, obtained from assuming that the bunch comes from a source approximately the size of the laser spot, is 1-2 π mm-mrad, competitive with state of the art radio-frequency facilities.

To understand the details of the LWFA, particle-in-cell simulations using the code VORPAL [45] (developed at the University of Colorado and Tech-X Corporation) were conducted in parameter regimes relevant to the experiments [20]. In these simulations, it is observed that in the first few hundred microns of

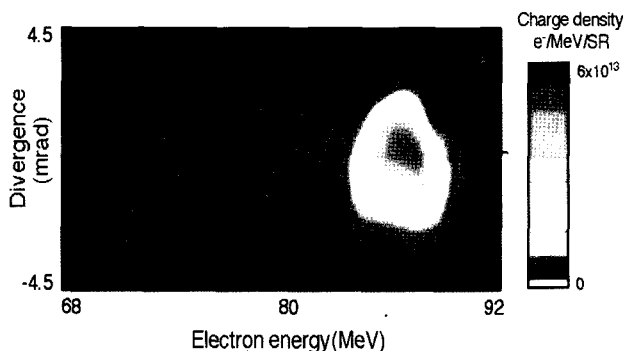


Fig. 2. Electron Energy Spectrum of a Bunch Produced by the Channel Guided Accelerator. The Spectrum was Obtained by Dispersing the Electron Beam with the 55° Magnetic Spectrometer and Recording the Beam Image on a Phosphor Screen Imaged with a High Resolution CCD-Camera. The Energy Range Covered in this Single Shot is from 68-92 MeV and Shows the Appearance of Monoenergetic Features, here with 3×10^9 Electrons in a Bunch with Energy Spread of 4% FWHM at 86 MeV. In the Vertical (non-dispersive) Plane, the Divergence was Near 3 Mrad FWHM for this Bunch

propagation of the laser pulse in the channel, the wake amplitudes (and hence the amount of trapped particles) are small. As the laser pulse envelope starts distorting through the self-modulation instability, developing features that have rise times on the order of or shorter than the plasma period, a plasma wake is excited that is large enough to trap and accelerate particles. Once enough charge is accumulated in the accelerating bucket, the injection process can be terminated due to beam loading, i.e., the field of the accelerated bunch modifies the wakefield and reduces its amplitude to below the trapping threshold. Pump depletion of the laser pulse energy (lost to wake excitation) can also reduce the wake amplitude below the trapping threshold. If the trapped electrons propagate beyond a dephasing distance, the electrons lose energy, which leads to a broad energy distribution.

The electron energy spread is minimized, however, if the acceleration process is terminated after a dephasing distance, i.e., when the bunch is at its maximum energy at the top of the phase space separatrix. The momentum bunching that occurs at the top of the bucket results in high quality electron beams. By carefully controlling the accelerator length to match the dephasing distance, high energy electron beams with narrow energy spread can hence be obtained.

Reaching the dephasing distance was also put forward by the RAL and LOA groups as the mechanism behind their observation of narrow energy spread bunches [19, 21].

3. SUMMARY AND FUTURE DEVELOPMENTS

3.1. High Intensity Laser Guiding and Mono-energetic Electron Beams

During the past few years, two important milestones towards the development of a laserplasma accelerator have been achieved: laser guiding and production of mono-energetic beams. Using preformed plasma channels, laser beams of relativistic intensities (i.e., $a_0^2 \gg 1$) have been guided over $> 10 Z_r$ [20]. Two regimes were found at LBNL. In the first regime, intense laser pulses at the 4 TW power level were guided and transmission levels approaching 50 percent were obtained. No significant amount accelerated charge was detected. This result shows that it is possible to guide laser pulses over macroscopic distances at relativistic intensities without generating self-trapped electrons or “dark current”. This is an important result for future development of laser accelerator modules that rely on the use of wakefield excitation.

In the second regime, intense laser pulses were guided and high energy electron beams were observed that had an energy distribution with narrow structure.

Using a magnetic spectrometer, isolated intense monoenergetic beams were produced at the 100 MeV energy level with energy spread at the level of a few percent, containing several 100's of picoCoulomb of charge. Transversely, these bunches were found to have a normalized emittance of 1-2 π mm-mrad, limited by the resolution of the diagnostic. In this regime, the transmitted laser pulse was severely depleted.

Narrow energy electron beams were also observed without guiding using 20 μ m scale laser spot sizes with long, lower density plasmas (LOA, RAL) or, alternatively, 8.5 μ m laser spots and short, higher density plasmas (LBNL unguided) or long, lower density plasmas (LBNL self-guided). The fundamental reason for the observation of these narrow energy spread beams seems consistent with matching the acceleration distance to the dephasing distance of an electron in the plasma wave bucket. This was confirmed via particle-in-cell simulations and via experiments at LBNL in which a single beam was used in gas jets of various lengths and gas densities.

Based on experiment, simulation, and theory, the production of monoenergetic bunches in a laser-plasma accelerator requires the following four steps: Step 1 consists of exciting a wakefield. For a self-modulated LWFA, this typically occurs after the laser has propagated a sufficiently long distance within the plasma, such that the self-modulation instability (i.e., the feedback of the wake on the pulse and the self-consistent evolution of both the wake and the pulse) excites a large amplitude wakefield. Step 2 consists of a method for trapping and the initial injection of the electrons into the wake. For a self-modulated LWFA, this can be the result of wake wave-breaking. Step 3 consists of termination of the self-trapping or injection process. If trapping is not terminated, low energy electrons would continuously be injected into the wake over the entire length of acceleration, resulting in a large energy spread. One mechanism to accomplish this is by beam loading, i.e., the injected electron bunch is of sufficient charge so as to reduce the amplitude of the wake below the self-trapping threshold. Step 4 is acceleration of the electron bunch over a distance equal to the dephasing length. If acceleration occurs over distances longer than the dephasing length, the trapped bunch will continue to circulate around the separatrix, losing energy and increasing its energy spread. Optimum acceleration would occur over a distance equal to the dephasing length, such that the trapped bunch exits the plasma near the top of the separatrix (i.e., the accelerating phase-space bucket), with maximum energy and minimum energy spread.

In the LBNL experiments, matching of the acceleration length and the dephasing length was obtained by using a preformed plasma channel. The length of the channel can be adjusted to control the acceleration length, whereas the channel depth and radius can be adjusted to control the dephasing length (via the wake phase velocity). In the

LOA and RAL experiments, matching of the acceleration length to the dephasing length was the result of using a larger laser spot size (i.e., a larger Z_r and a longer acceleration length) along with the use of lower plasma densities, which increases the dephasing length. If a large Z_r is used in combination with high plasma densities, then the acceleration length would exceed the dephasing length, and large energy spreads are expected. This was in fact observed in the LOA and RAL experiments, as well as in the LBNL experiments that relied on self-guiding [46] (i.e., no preformed channel). At high densities, a continuous Boltzmann-like distribution was observed. As the density was decreased, narrow energy spread peaks began to emerge in the energy spectrum.

It should be noted that, without detectors capable of covering the entire dispersive area of the spectrometer, narrow energy spread features can easily be missed. Many previous experiments used diodes, with limited energy resolution, for electron detection.

3.2. Quantifying the Progress

To quantify the progress made in laser driven accelerators, Figs. 3 and 4 show the total beam energy and brightness versus particle energy, respectively, for the beams produced in the three papers published in the September 30, 2004 issue of *Nature*. Expected performance of 1 GeV and 10 GeV modules are also plotted. The spread in beam energy and brightness is due to the uncertainty in predicting the normalized emittance and total charge of the beam for those two cases. The upper limit in brightness

assumes that the normalized emittance measured for the 100 MeV-class beams will be conserved when accelerating to 1 or 10 GeV, whereas the lower limit assumes that the divergence angle will be conserved. For comparison, the same quantities are plotted for a conventional thermionic gun, a photo-cathode radio-frequency gun, and the 30 GeV beam at the Stanford Linear Accelerator Center (SLAC). As can be seen in Fig. 3 beam energy is comparable for the different 100 MeV-class linacs, but, for the > 10 GeV laser accelerators, considerable progress must be made in increasing the total beam energy to become competitive. From Fig. 4 it can be seen that in the shorter term, laser driven accelerators can have an advantage over conventional accelerators due to the high peak brightness which is a direct result of the ultra-short pulse nature of the bunches and the competitively low normalized emittance.

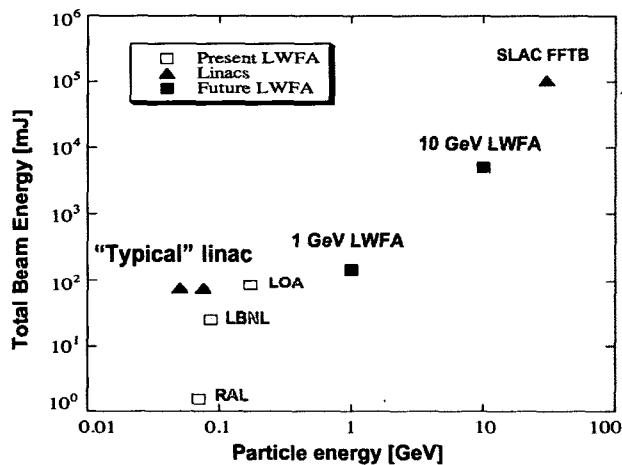


Fig. 3. Electron Beam Energy (number of particles times mean particle energy per bunch) vs. Particle Energy for a Conventional RF Linacs (thermionic gun and a photo-cathode RF gun), the SLAC FFTB Beam, Beams Reported in the September 30, 2004 *Nature* Issue and Expected Performance of a 1 GeV and a 10 GeV Laser-Driven Plasma Accelerator

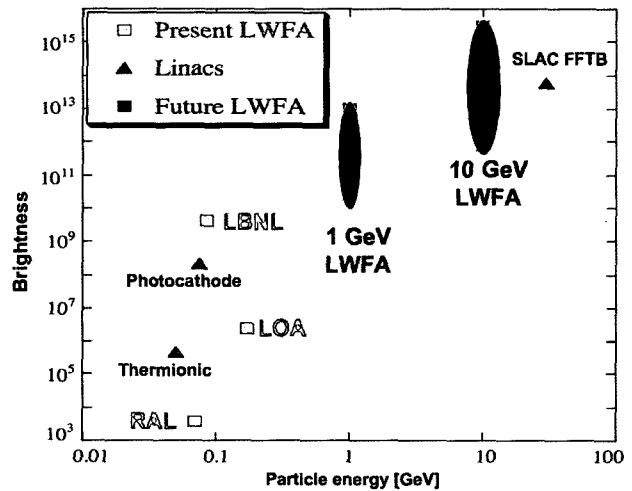


Fig. 4. Electron Beam Brightness Vs. Particle Energy for a Conventional Thermionic Gun, a Photocathode RF Gun, the SLAC FFTB Beam, Beams Reported in the September 30, 2004 *Nature* Issue, and Expected Performance of a 1 GeV and a 10 GeV Laser Driven Accelerator. The Brightness is Calculated by Multiplying the Total Number of Particles with the Mean Bunch Energy and Dividing by the Bunch Duration, the Relative Energy Spread and the Square of the Unnormalized Emittance (in $\text{mm}^2\text{-mrad}^2$)

3.3. Future Challenges

The immediate challenge ahead is to stabilize the performance of the accelerator. The charge per bunch integrated over all energies is found to be relatively stable, at the few percent level, in the high repetition LBNL experiments. The bunch energy and amount of charge in the narrow energy spread beams, however, fluctuates. This is

expected to be remedied with sophisticated control over the electron trapping process as well as the laser and plasma source operation. Since the energy depends linearly on laser intensity [see, e.g., Eq. (2)], control of the pulse length, pulse energy, and spot size is needed at the few percent level. Pulse length control requires spectral and pointing control. In the laser pulse stretcher and compressor, for example, pointing fluctuations translate into pulse duration fluctuation. To minimize pointing fluctuations, great care must be taken during the construction of future systems to precisely control the environment (temperature and vibration). Pointing errors can also translate into pulse energy changes, due to changes in overlap between the gain medium and the amplified pulse. Novel methods for controlling laser pulse energy are being developed in industry for short pulse systems that may meet these requirements. The origin of spot size fluctuations is not entirely understood, but may also be affected by pump laser changes that can affect the divergence, and overall spot size of the amplified beam (as well as beam pointing).

Plasma densities must be controlled at the percent level to ensure that the wake amplitude ($\propto n^{1/2}$), dephasing length ($\propto 1/n^{3/2}$), and energy gain ($\propto 1/n$) remain constant. In addition to the development of plasma density diagnostics capable of providing this level of accuracy, efforts are required to engineer pulsed gas jet systems that limit the shot-to-shot variation. When using statically filled chambers, such as in the case of a hydrogen based capillary discharge system [28], gas densities should be controllable to a sufficient level. This should result in reproducible plasma densities, provided the electrical discharge is reproducible.

As has been discussed, matching the accelerator length to the dephasing length can produce narrow energy spread beams, even when relying on self-trapping. However, accurate control of the performance of the accelerator will most likely require a method for triggering the trapping process. Various methods for injecting electrons into the wake with one or more additional laser pulses have been proposed [42-44, 47, 48]. Experiments are underway to study laser triggered injection, and are predicted by theory to produce narrow energy spread bunches with greater stability.

Combined with channeling technology, optically triggered injection, we believe, forms the basis of an all-optical GeV accelerator. As can be seen from the basic scaling laws, reducing the density and lengthening the distance over which the plasma channel extends is essential to reach GeV energies. To achieve multi-cm scale plasma channels, novel methods relying on hydrogen capillary discharges developed by Hooker *et al.* [28] are being tested with the 100 TW LOASIS amplifier. To reduce the amount of energy required from the laser system in schemes that use inverse Bremsstrahlung to heat the plasmas (hydrodynamically formed channels), cluster jets will be tested such as being developed by Milchberg *et al.* [49].

The next challenge will be to go beyond GeV energy levels, requiring a demonstration of staging different modules, as well as development of laser systems capable of delivering high peak power, and large amounts of energy, at high repetition rate (i.e., high average power). As a simple example, consider producing a 10 GeV electron beam, containing 1 nC of charge (6×10^9 electrons). This represents 10 J worth of energy and assuming a laser to particle beam efficiency between 1-10%, requires therefore 100-1000 J/pulse of laser energy. It is obvious from this simple calculation that it is essential for both accelerator and laser development to be pursued, if one wants to realize the goal of all-optical linacs. Such an accelerator holds the promise of offering unique beams, having femtosecond duration and containing 100's of pC of charge, with an emittance that equals or surpasses conventional linacs. If the development continues to be successful, it will serve as a compact multi-GeV injector for high energy physics applications, as well as the basis for novel radiation sources including next generation femtosecond light sources.

3.4. Is the Use of a Channel the Only Way to Go?

Can channeling be avoided by using ever more powerful laser beams? Based on the first three experiments that demonstrated the production of mono-energetic electron beams, it is clear that for fixed laser power unchanneled experiments accelerated less charge and reached lower energy than channeled experiments; increasing the laser spot size decreased its intensity and hence the wake amplitude. To further study this question, consider the high intensity limit, $a_0 > 1$, along with the constraint $r_0 \propto \lambda_p$, since $k_p r_0 \sim 1$. Recalling that the self-field of a point charge extends out to a radius of order $k_p^{-1} = \lambda_p / 2\pi$, this last constraint is necessary to ensure efficient coupling between the wakefield and the electron bunch. For the diffraction limited case, the energy gain can be written as $\Delta W_{\text{diff}} [\text{MeV}] \approx 0.8(k_p r_0) (P[\text{GW}])^{1/2}$. For this to apply, it is necessary for $P < P_c = 17(\lambda_p / \lambda)^2 \text{ GW}$, so that the effects of relativistic self-focusing can be neglected, and for $Z_R < L_{\text{deph}} \approx a_0 \lambda_p^3 / (2\lambda^2)$, so that dephasing can be neglected. Note that $Z_R < L_{\text{deph}}$ can be written as $(k_p r_0)^2 < 2\pi a_0 \lambda_p / \lambda$ or $(k_p r_0)^3 < 8.5(P[\text{GW}])^{1/2}$. Since $Z_R < L_{\text{deph}}$ is easily satisfied and $\Delta W_{\text{diff}} \propto P^{1/2}$, the energy gain will be strongly limited without some form of guiding.

Using a density channel for laser pulse guiding the dephasing-limited energy gain can be written as $\Delta W_{\text{deph}} [\text{MeV}] \approx 0.9(k_p r_0)^2 P[\text{GW}]$ (for $a_0 > 1$ and $k_p r_0 \sim 1$), e.g., $P \approx 100 \text{ TW}$ and $k_p r_0 \approx 4$ give $\Delta W_{\text{deph}} \approx 6 \text{ GeV}$.

For sufficiently high powers $P \gg P_{cr}$, it may be possible to guide the laser pulse over multiple Z_R without the use of a density channel due to a combination of relativistic selffocusing and ponderomotive self-channeling. This is the case in the so-called blow-out or bubble regime [17] Assuming that the energy gain is limited by dephasing with $a_0 > 1$ and $k_p r_0 \sim 1$ again implies

$\Delta W_{\text{deph}}[\text{MeV}] \simeq 0.9(k_p r_0)^{-2} P[\text{GW}]$, only now with the additional constraint $P \gg P_{cr}$. Note that if $P = R_{cr} P_{cr}$, where $R_{cr} \sim 10$ is a constant, then this implies $a_0 = 5.6 R_{cr}^{1/2} / (k_p r_0)$. Similar scalings for the energy, i.e., $\Delta W \propto P$, can also be obtained through analytical and numerical studies of the blow-out regime. For example, Gordienko and Pukhov [50] obtain $\Delta W_{GP}[\text{MeV}] \simeq 0.1(c_{TL}/\lambda)(P[\text{GW}])^{1/2}$, but, if $c_{TL} = R_p \lambda_p$, where $R_p \sim 1$ is a constant, and $P = R_{cr} P_{cr}$, then $\Delta W_{GP}[\text{MeV}] \simeq 0.03 R_p R_{cr}^{-1/2} P[\text{GW}]$. Mori [51] obtained $\Delta W_M[\text{MeV}] \simeq 0.5(\lambda_p/\lambda)^{4/3}(P[\text{GW}])^{1/3}$, which can be written as $\Delta W_M[\text{MeV}] \simeq 0.02 R_{cr}^{2/3} P[\text{GW}]$ assuming $P = R_{cr} P_{cr}$.

Although $\Delta W \sim P$ when limited by dephasing for both a channel-guided LWFA or a self-guided LWFA with $P \gg P_{cr}$, there may be additional advantages to using a channel over relying on self-guiding. One obvious difference is that the additional constraint $P \gg P_{cr}$ need not be satisfied when using a channel. This implies that the channel-guided LWFA may be operated at lower intensities (lower a_0), which may be a more stable regime. The channel may also provide some resistance to instabilities, such as the laser-hose instability. Without a channel, the laser pulse will be subject to some amount of diffractive erosion, since the head of the pulse will not be self-guided, which can limit the propagation distance. For example, if the pulse is self-guided for a distance of $L = R_R Z_R$, where $R_R \gg 1$ is the number of Z_R , then erosion will limit the energy gain and not dephasing when $R_R Z_R < L_{\text{deph}}$, or $R_R (k_p r_0)^3 < 8.5 (P[\text{GW}])^{1/2}$. Lastly, it is hoped that by operating a channel-guided LWFA in the “dark-current-free” mode (no self-trapping), a high quality electron bunch can be obtained by injecting a low energy spread, low emittance bunch into the LWFA. If the LWFA is to be operated in the self-guided mode (i.e., the blow-out or bubble regime), it may not be possible to operate in this regime without self-trapping, which may limit the achievable energy spread and emittance of the accelerated bunch.

Acknowledgements

The authors acknowledge Catalin Filip, Gwenael Fubiani, Estelle Michel, Pierre Michel, Bob Nagler, Kei Nakamura, Brad Shadwick, Jeroen van Tilborg, Simon Hooker, Tony Gon-salves, John Cary, David Bruhwiler, Dimitre Dimitrov, and Chet Nieter for all their help. This work was supported by the Director, Office of Science, High Energy Physics, U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

REFERENCES

- [1] T. Tajima and J. M. Dawson, “Laser Electron Accelerator,” *Phys. Rev. Lett.*, **43**, 267 (1979).
- [2] A. Modena, Z. Najmudin, A. E. Dangor, C. E. Clayton, K. A. Marsh, C. Joshi, V. Malka, C. B. Darrow, C. Danson, D. Neely, and F. N. Walsh, “Electron acceleration from the breaking of relativistic plasma waves,” *Nature*, **377**, 606 (1995).
- [3] D. Umstadter, S.-Y. Chen, A. Maksimchuk, G. Mourou, and R. Wagner, “Nonlinear optics in relativistic plasmas and laser wake field acceleration of electrons,” *Science*, **273**, 472 (1996).
- [4] E. Esarey, P. Sprangle, J. Krall, and A. Ting, “Overview of Plasma-Based Accelerator Concepts,” *IEEE Trans. Plasma Sci.*, **24**, 252 (1996).
- [5] V. Malka, S. Fritzler, E. Lefebvre, M. M. Leonard, F. Burgy, J. P. Chambaret, J. F. Chemin, K. Krushelnick, G. Malka, S. P. D. Mangles, Z. Najmudin, M. Pittman, J. P. Rousseau, J. N. Scheurer, B. Walton, and A. E. Dangor, “Electron acceleration by a wake field forced by an intense ultrashort laser pulse,” *Science*, **298**, 1596 (2002).
- [6] W. P. Leemans, P. Catravas, E. Esarey, C. G. R. Geddes, C. Toth, R. Trines, C. B. Schroeder, B. A. Shadwick, J. van Tilborg, and J. Faure, “Electron-yield enhancement in a laser-wakefield accelerator driven by asymmetric laser pulses,” *Phys. Rev. Lett.*, **89**, 4802 (2002).
- [7] C. B. Schroeder, E. Esarey, C. G. R. Geddes, C. Tóth, B. A. Shadwick, J. van Tilborg, J. Faure, and W. P. Leemans, “Frequency chirp and pulse shape effects in self-modulated laser wakefield accelerators,” *Phys. Plasmas*, **10**, 2039 (2003).
- [8] M. I. K. Santala, M. Zepf, F. N. Beg, E. L. Clark, A. E. Dangor, K. Krushelnick, M. Tatarakis, I. Watts, K. W. D. Ledingham, T. McCanny, I. Spencer, A. C. Machacek, R. Allott, R. Clarke, and P. A. Norreys, “Production of Radioactive Nuclides by Energetic Protons Generated from Intense Laser-Plasma Interactions,” *Appl. Phys. Lett.*, **78**, 19 (2001).
- [9] W. P. Leemans, D. Rodgers, P. Catravas, C. G. R. Geddes, G. Fubiani, E. Esarey, B. Shadwick, R. Donahue, and A. Smith, “Gamma-neutron activation experiments using laser wakefield accelerators,” *Phys. Plasmas*, **8**, 2510 (2001).
- [10] K. W. D. Ledingham, P. McKenna, and R. P. Singhal, “Applications for nuclear phenomena generated by ultra-intense lasers,” *Science*, **300**, 1107 (2003).
- [11] W. P. Leemans, C. G. R. Geddes, J. Faure, C. Tóth, J. van Tilborg, C. B. Schroeder, E. Esarey, G. Fubiani, D. Auerbach, B. Marcellis, M. A. Carnahan, R. A. Kaindl, J. Byrd, and M. Martin, “Observation of Terahertz Emission from a Laser-Plasma Accelerated Electron Bunch Crossing a Plasma-Vacuum Boundary,” *Phys. Rev. Lett.*, **91**, 074802 (2003).
- [12] C. B. Schroeder, E. Esarey, J. van Tilborg, and W. P. Leemans, “Theory of coherent transition radiation generated at a plasma-vacuum interface,” *Phys. Rev. E*, **69**, 016501 (2004).
- [13] W. Leemans, S. Chattopadhyay, E. Esarey, A. Zholents, M. Zolotarev, A. Chin, R. Schoenlein, and C. Shank, “Femtosecond X-ray generation through relativistic electron beam-laser interaction,” *Comptes Rendus de l’Academie des Sciences Serie IV Physique Astrophysique*, **1**, 279 (2000).
- [14] P. Catravas, E. Esarey, and W. P. Leemans, “Femtosecond x-rays from Thomson scattering using laser wakefield accelerators,” *Meas. Sci. Technol.*, **12**, 1828 (2001).
- [15] E. Esarey, B. Shadwick, P. Catravas, and W. P. Leemans, “Synchrotron radiation from electron beams in plasma-focusing channels,” *Phys. Rev. E*, **65**, 056505 (2002).
- [16] A. Rousse, K. T. Phuoc, R. Shah, A. Pukhov, E. Lefebvre, V. Malka, S. Kiselev, F. Burgy, J.-P. Rousseau, D. Umstadter, and D. Hulin, “Production of a keV X-ray Beam From Synchrotron Radiation in Relativistic Laser-Plasma Inter-

- action,” *Phys. Rev. Lett.*, **93**, 135005 (2004).
- [17] A. Pukhov and J. Meyer-ter-Vehn, “Laser wake field acceleration: the highly non-linear brokenwave regime,” *Appl. Phys. B*, **74**, 355 (2002).
- [18] J. B. Rosenzweig, B. Breizman, T. Katsouleas, and J. J. Su, “Acceleration and focusing of electrons in two-dimensional nonlinear plasma wake fields,” *Phys. Rev. E*, **44**, R6189 (1991).
- [19] S. Mangles, C. Murphy, Z. Najmudin, A. Thomas, J. Collier, A. Dangor, E. Divali, P. Foster, J. Gallacher, C. Hooker, D. Jaroszynski, A. Langley, W. Mori, P. Norreys, F. Tsung, R. Viskup, B. Walton, and K. Krushelnick, “Monoenergetic beams of relativistic electrons from intense laser-plasma interactions,” *Nature*, **431**, 535 (2004).
- [20] C. G. R. Geddes, C. Tóth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans, “High quality electron beams from a plasma channel guided laser wakefield accelerator,” *Nature*, **431**, 538 (2004).
- [21] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.-P. Rousseau, F. Burgy, and V. Malka, “A laser-plasma accelerator producing monoenergetic electron beams,” *Nature*, **431**, 541 (2004).
- [22] W. P. Leemans, C. W. Siders, E. Esarey, N. E. Andreev, G. Shvets, and W. B. Mori, “Plasma guiding and wakefield generation for second-generation experiments,” *IEEE Trans. Plasma Sci.*, **24**, 331 (1996).
- [23] P. Volfbeyn, E. Esarey, and W. P. Leemans, “Guiding of Laser Pulses in Plasma Channels Created by the Ignitor-Heater Technique,” *Phys. Plasmas*, **6**, 2269 (1999).
- [24] I. Alexeev, T. M. Antonsen, Jr., K. Y. Kim, and H. M. Milchberg, “Self-Focusing of Intense Laser Pulses in a Clustered Gas,” *Phys. Rev. Lett.*, **90**, 103402 (2003).
- [25] M. C. Downer, C. Chiu, M. Fomyts’kyi, E. W. Gaul, F. Grigsby, N. H. Matlis, B. Shim, P. J. Smith, and R. Zgadzaj, “Plasma Channels and Laser Pulse Tailoring for GeV Laser-Plasma Accelerators,” in “Advanced Accelerator Concepts. Eleventh Workshop,” **647**, 654 (2003).
- [26] S. Y. Tochitsky, R. Narang, C. V. Filip, P. Musumeci, C. E. Clayton, R. B. Yoder, K. A. Marsh, J. B. Rosenzweig, C. Pellegrini, and C. Joshi, “Enhanced Acceleration of Injected Electrons in a Laser-Beat-Wave-Induced Plasma Channel,” *Phys. Rev. Lett.*, **92**, 095004 (2004).
- [27] P. Sprangle, B. Hafizi, J. R. Peñano, R. F. Hubbard, A. Ting, C. I. Moore, D. F. Gordon, A. Zigler, D. Kaganovich, and T. M. Antonsen, Jr., “Wakefield generation and GeV acceleration in tapered plasma channels,” *Phys. Rev. E*, **63**, 056405 (2001).
- [28] D. J. Spence and S. M. Hooker, “Investigation of a hydrogen plasma waveguide,” *Phys. Rev. E*, **63**, 015401(R) (2001).
- [29] A. Zhidkov, J. Koga, T. Esirkepov, T. Hosokai, M. Uesaka, and T. Tajima, “Optical-fieldionization effects on the propagation of an ultraintense laser pulse in high-Z gas jets,” *Phys. Rev. E*, **69**, 066408 (2004).
- [30] N. C. Lopes, G. Figueira, L. O. Silva, J. M. Dias, R. Fonseca, L. Cardoso, C. Russo, C. Carias, G. Mendes, J. Vieira, and J. T. Mendonça, “Plasma channels produced by a laser-triggered high-voltage discharge,” *Phys. Rev. E*, **68**, 035402 (2003).
- [31] Y.-F. Xiao, H.-H. Chu, H.-E. Tsai, C.-H. Lee, J.-Y. Lin, J. Wang, and S.-Y. Chen, “Efficient generation of extended plasma waveguides with the axicon ignitor-heater scheme,” *Phys. Plasmas*, **11**, L21 (2004).
- [32] B. Cros, C. Courtois, G. Matthieussent, A. D. Bernardo, D. Batani, N. Andreev, and S. Kuznetsov, “Eigenmodes for capillary tubes with dielectric walls and ultraintense laser pulse guiding,” *Phys. Rev. E*, **65**, 026405 (2002).
- [33] P. Sprangle, E. Esarey, J. Krall, and G. Joyce, “Propagation and Guiding of Intense Laser Pulses in Plasmas,” *Phys. Rev. Lett.*, **69**, 2200 (1992).
- [34] C. G. Durfee III and H. M. Milchberg, “Light pipe for high intensity laser pulses,” *Phys. Rev. Lett.*, **71**, 2409 (1993).
- [35] E. Esarey, P. Sprangle, J. Krall, and A. Ting, “Self-focusing and guiding of short laser pulses in ionizing gases and plasmas,” *IEEE J. Quantum Electron.*, **33**, 1879 (1997).
- [36] W. Horton and T. Tajima, “Pump depletion in the plasma-beat-wave accelerator,” *Phys. Rev. A*, **34**, 4110 (1986).
- [37] S. V. Bulanov, I. N. Inovenkov, V. I. Kirsanov, N. M. Naumova, and A. S. Sakharov, “Nonlinear Depletion of Ultrashort and Relativistically Strong Laser Pulses in an Underdense Plasma,” *Phys. Fluids B*, **4**, 1935 (1992).
- [38] E. Esarey, C. B. Schroeder, B. A. Shadwick, and W. P. Leemans, “Non-Linear Pump Depletion and Electron Dephasing in Laser Wakefield Accelerators,” in V. Yakimenko, ed., “Advanced Accelerator Concepts. Eleventh Workshop,” *AIP Conf. Proc., Amer. Inst. Phys.*, **737**, 578, New York (2004).
- [39] H. M. Milchberg, T. R. Clark, C. G. Durfee III, and T. M. Antonsen, Jr., “Development and Applications of a Plasma Waveguide for Intense Laser Pulses,” *Phys. Plasmas*, **3**, 2149 (1996).
- [40] R. Rankin, C. E. Capjack, N. H. Burnett, and P. B. Corkum, “Refraction effects associated with multiphoton ionization and ultrashort-pulse laser propagation in plasma waveguides,” *Optics Letters*, **16**, 835 (1991).
- [41] W. P. Leemans, C. E. Clayton, W. B. Mori, K. A. Marsh, P. K. Kaw, A. Dyson, C. Joshi, and J. M. Wallace, “Experiments and simulations of tunnel-ionized plasmas,” *Phys. Rev. A*, **46**, 1091 (1992).
- [42] E. Esarey, R. F. Hubbard, W. P. Leemans, A. Ting, and P. Sprangle, “Electron injection into plasma wake fields by colliding laser pulses,” *Phys. Rev. Lett.*, **79**, 2682 (1997).
- [43] C. B. Schroeder, P. B. Lee, J. S. Wurtele, E. Esarey, and W. P. Leemans, “Generation of Ultrashort Electron Bunches by Colliding Laser Pulses,” *Phys. Rev. E*, **59**, 6037 (1999).
- [44] G. Fubiani, E. Esarey, C. B. Schroeder, and W. P. Leemans, “Beat wave injection of electrons into plasma waves using two interfering laser pulses,” *Physical Review E*, **70**, 016402 (2004).
- [45] C. Nieter and J. Cary, “VORPAL: a versatile plasma simulation code,” *J. Comp. Phys.*, **196**, 448 (2004).
- [46] C. G. R. Geddes, C. Tóth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans, “Production of high-quality electron bunches by dephasing and beam loading in channeled and unchanneled laser plasma accelerators,” *Phys. Plasmas*, **12**, 056709 (2005).
- [47] D. Umstadter, J. K. Kim, and E. Dodd, “Laser Injection of Ultrashort Electron Pulses into Wakefield Plasma Waves,” *Phys. Rev. Lett.*, **76**, 2073 (1996).
- [48] R. G. Hemker, K. C. Tzeng, W. B. Mori, C. E. Clayton, and T. Katsouleas, “Computer simulations of cathodeless,

- high-brightness electron-beam production by multiple laser beams in plasmas," *Phys. Rev. E*, **57**, 5920 (1998).
- [49] T. Taguchi, T. M. Antonsen, Jr., and H. M. Milchberg, "Resonant Heating of a Cluster Plasma by Intense Laser Light," *Phys. Rev. Lett.*, **92**, 205003 (2004).
- [50] S. Gordienko and A. Pukhov, "Scalings for ultrarelativistic laser plasmas and quasimonoenergetic electrons," *Phys. Plasmas*, **12**, 043109 (2005).
- [51] W. B. Mori (2005), private communication.