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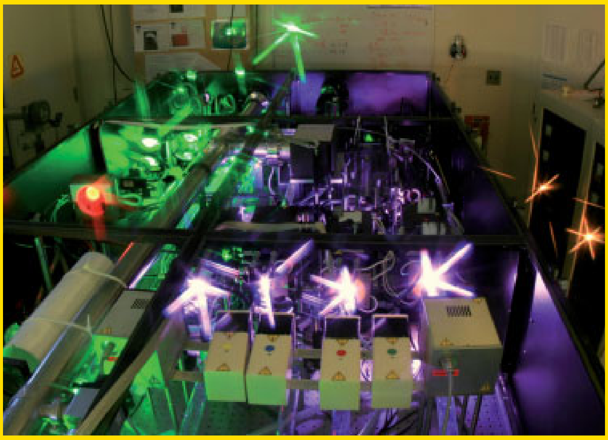
**Abstract** Over the past several years there have been significant advances in research towards generating compact relativistic electron beams using high power short pulse laser produced plasmas (i.e., laser wakefield accelerators). In particular, an explosion of interest was generated in this field following the discovery in 2004 of a method to create such beams with low energy spread using a "plasma bubble" shaped wake. Recent work has increased the energy of these beams to the GeV range by extending the acceleration distance from a few millimetres to several centimeters. From both experimental and theoretical work, a more complete understanding of this "plasma bubble" regime for electron acceleration has also been obtained, enabling a significant improvement in the output electron beam quality and stability. There is ongoing work to further improve the parameters and stability of these beams with the goal of constructing "table-top" 4th generation sources of coherent x-ray radiation.



Pump lasers firing for the final amplifier stage of the 300 TW HERCULES laser at the University of Michigan.



# Laser wakefield plasma accelerators

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## 1. Introduction

Since their invention in the early 1960's the power of pulsed laser beams has increased tremendously. Using the technique of Chirped Pulse Amplification [1] lasers today are capable of producing ultra-short pulses having durations on the order of a few tens of femtoseconds ($10^{-15}$ sec) which can have instantaneous powers in the Petawatt range ($10^{15}$ Watts) [2] (see Fig. 1). Indeed laser systems capable of generating Exawatt ($10^{18}$ Watt) peak power levels are in the planning stages for potential construction sometime over the next decade [3, 4]. However even the smaller scale Terawatt-level lasers which are now commonplace can be focused to high intensities such that the laser electric field immediately rips off electrons from the atoms it encounters – immediately forming a plasma. The electric field of the laser then wiggles these electrons violently – consequently transfering energy from the laser field to high energy electrons.

In 1979, it was realized by Tajima and Dawson of UCLA [5] that such intense laser pulses can also efficiently generate electron plasma waves in their wake as they travel through a low density plasma. Electron plasma waves can be simply thought of as displacements of free electrons in the plasma oscillating at the plasma frequency ($\omega_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_o m_e}}$ where $n_e$ is the electron density, $e$ is the

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**Figure 1** (online color at: www.lpr-journal.org) The 300 TW HERCULES laser system at the University of Michigan. Shown is the vacuum chamber (open) containing the large diffraction gratings used to compress the pulse to very short durations.

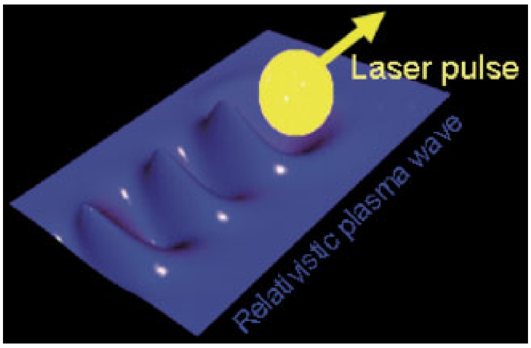


**Figure 2** (online color at: www.lpr-journal.org) Schematic of laser wakefield acceleration. An ultrashort duration laser pulse propagates through a low density plasma. In the wake of the pulse large amplitude plasma waves are formed which have relativistic phase velocities. Such waves are suitable for accelerating electrons to high energy.

electron charge and $m_e$ is the electron mass) with respect to the neutralizing background of slower moving, positively charged ions. These displacements of electrons within the plasma give rise to large electrostatic fields – which can be much larger than any fields possible in a non-ionized material. Tajima and Dawson showed theoretically that by using the light pressure of a focused laser pulse, *relativistic* waves (i.e., having a phase velocity close to the speed of light) can be generated. They found that the criterion for generating a large amplitude relativistic plasma wakefield was that the pulse duration of the high intensity laser pulse be less than the relativistic plasma wavelength (which is only dependent on plasma density). The waves produced thus meet the requirements for efficient high gradient acceleration for charged particles [6, 7]. In this situation an electron can "surf" on the electric field of a plasma wave picking up energy from the wave just as a surfer picks up energy from a water wave in the ocean (see Fig. 2).

When they wrote their paper however, the lasers which Tajima and Dawson postulated to be necessary to generate this acceleration did not exist. Most of the research on laser-based accelerators in the 1980's and early 90's concentrated on generating relativistic plasma waves via the laser "beatwave" accelerator scheme which used a relatively long pulse (hundreds of picoseconds) "dual frequency" laser operating at two infrared frequencies having a separation resonant with the background plasma density. This technique enabled the generation of plasma waves and the acceleration of injected electron bunches. However scaling of this scheme to very high energy is difficult due to the fundamental limitations on the amplitude of the plasma waves which could be obtained in this way [8].

Subsequent work using much higher intensity picosecond-duration laser beams (i.e., without the "beatwave" frequency structure) showed that relativistic plasma waves could also be generated via a high intensity laser plasma instability [9, 10] during the interaction. Although such lasers can generate a plasma wave structure capable of accelerating charged particles it was also found that the electrons to be accelerated by these plasma waves could also be simultaneously produced from within the plasma. In such cases relativistic electrons are generated through the "wavebreaking" of the large amplitude relativistic plasma waves themselves [11]. These electrons can then be "trapped" in the fields of adjacent plasma waves and consequently accelerated to much higher energy. Previously it was demonstrated that such electron beams could be generated with energies up to several hundred MeV – but only having a very broad energy spread ($\Delta E/E \sim 100\%$) [12].

However, now, the technology to produce very high intensity, very short pulse (less than 50 fsec) lasers is indeed becoming routine at major research universities and at national laboratories. In fact, it is presently possible to obtain focused intensities greater than $10^{22}$ W/cm$^2$ [13] using laser systems which have reasonably high repetition rates and which can fit into a university scale lab. These lasers are also capable of producing plasmas with very unusual properties – for example, they can have relativistic "temperatures" (i.e., the average energy of electrons in the system is higher than the electron rest mass) and they can also contain ultra-strong (Gigagauss) magnetic fields [14]. As intensities increase further, QED effects resulting from the high electric fields in the laser focus may also begin to affect the interaction [15].

So using such laser systems in 2004 it was shown that with these much shorter pulses (in the tens of femtoseconds regime) at powers greater than about 10 TW it is possible to generate true "beams" of relativistic electrons which have low divergence and which have a small energy spread ($< 5\%$) [16–18]. This is an extremely important result since only if beams with narrow energy bandwidths can be produced will the full range of applications become possible. With these results the use of plasma acceleration consequently now offers the potential of significantly smaller and

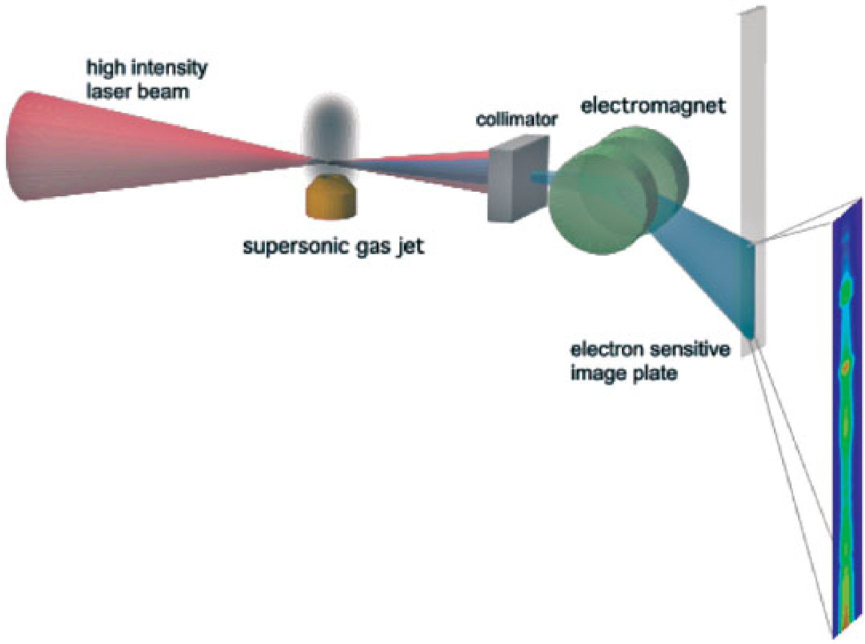


**Figure 3** (online color at: www.lpr-journal.org) Experimental set up for laser wakefield acceleration experiments. The high intensity laser beam is focused onto the front edge of a low density helium gas jet target. The electron generated travel along with the laser pulse as it exits the target and they are subsequently dispersed using a magnetic spectrometer to determine the energy spectrum.

cheaper facilities for generating energetic high quality electron beams, which, when considered along with the current rapid developments in laser technology, may soon allow the construction of laboratory sized high energy accelerators for use in a wide range of experiments and applications. For example, table-top narrowband femto-second x-ray sources and free-electron lasers could become a reality – which may potentially lead to significant advances in both medicine and materials science. It may also be possible to use electron bunches generated in this way for injection into conventional RF accelerators (linacs) or into subsequent plasma acceleration stages.

This paper will provide a brief review of the advances made in the past few years in the understanding of the physics of laser wakefield accelerators (LWFA) operating in the "bubble regime" (Sect. 2). Sect. 3 will describe the recent advances in making these beams more stable. Sect. 4 will discuss the use of laser guiding techniques to increase the acceleration distance. Sect. 5 will describe the innovative methods which have recently been employed to control the acceleration processes more precisely through external injection of electron beams. Sect. 6 will discuss how these accelerators can be scaled to higher energy, while Sect. 7 will describe some of the ongoing work on producing electromagnetic radiation from these laser generated electron beams. Finally Sect. 8 will provide an outlook with regard to the future of this field.

It should be noted that there is a parallel effort to use relativistic beams themselves to generate plasma wakefields for accelerating trailing electron beams to much higher energy (Plasma Wakefield Accelerators, PWFA). This technique also is extremely promising, in particular for scaling to very high energy accelerators [8]. Recent experiments at SLAC have demonstrated the doubling of energy of a 42 GeV beam [19].

## 2. Acceleration in the "bubble" regime

A typical modern LFWA experiment uses a long focal length optic to focus a laser pulse having a duration of less than 50 fsec (at powers above 10 TW) onto the edge of a supersonic jet of helium/hydrogen gas thus producing intensities around $10^{18}$ Wcm$^{-2}$ (see Fig. 3). The plasma electron density ($n_e$) in the first experiments in 2004 [16–18] had a "threshold" for electron beam generation of about $10^{19}$ cm$^{-3}$. In this density range the wavelength of relativistic plasma waves produced (i.e., $\lambda_p = 2\pi c/\omega_{pe}$) was similar to the laser pulse length in space ($c\tau_L$) where $\omega_{pe}$ is the electron plasma frequency, $\tau_L$ is the laser pulse duration, and $c$ is the speed of light. For laser pulses which are less than the plasma wavelength, relativistic plasma waves can be generated "resonantly" in the wake of the pulse – while in the regime in which the laser pulse length is much longer than the plasma wavelength, much higher laser intensity interactions are required to drive an instability in which the plasma waves are produced via "self-modulation" of the laser pulse envelope at the plasma frequency.

However in experiments using a combination of ultrashort pulses and very high intensity, the wakefield assumes the form of a single "bubble" in the plasma which is devoid of electrons. Normally electrons in the plasma cannot be trapped and then accelerated in such waves since they are much slower than the phase velocity of the plasma wave – which is near the speed of light. However at high intensities the bubble shaped wakefield can grow in amplitude until "wave-breaking" or "electron injection" also occurs in this system [20]. This takes place at large amplitudes such that the wave motion becomes so non-linear that wave energy is transferred directly into particle energy (i.e., the trajectories of electrons oscillating in the wave cross so that the electron no longer feels a restoring force to keep them within the wave). Electrons which reach relativistic energies from wavebreaking of the plasma wave can therefore be "injected" into the "bubble" where they can pick up much more energy (the "cold" wavebreaking electric-field amplitude for electron plasma waves is given by, $E = m_e c\omega_{pe}/e$).

The energy spectra of the electron beams produced are typically measured with on-axis magnetic spectrometers using high resolution image plates or scintillating screens as detectors (Fig. 3). The spectrometer is typically set up to measure the spectrum over a wide energy range in a single shot because of relatively large energy fluctuations in the beams. Other standard diagnostics used in such experiments include the simultaneous measurement of the transmitted laser spectrum and transverse optical probing of the interaction with an ultra-short pulse laser probe beam. This can be used to produce time-resolved images of the laser pulse traveling through the plasma via shadowgraphy and/or interferometry, and can be independently timed to also measure pre-pulse effects and plasma channel formation.

The breakthrough experiments in 2004 [16–18] showed electron acceleration over a range of electron densities (which is controlled by varying the target gas pressure). With the plasma density below a "threshold" value no energetic electrons were observed, however as the density was increased, very high energy electrons suddenly could be produced with the most energetic electrons reaching greater than 100 MeV in energy and having an output beam divergence of less than 1 degree. However the most interesting aspect of the energy spectra from these first experiments was that, in this regime, the electron energies were "quasi-monoenergetic" and, indeed, generally consisted of a single narrow spike – which could have an energy bandwidth of less than 5% (Fig. 4). As mentioned previously this is in contrast to the energy spectra of all previous laser acceleration experiments in which essentially 100% energy spreads were observed. As the density was increased, the peak energy of the observed electrons was observed to decrease and the spectra begin to assume the broad "Maxwellian" shape which was characteristic of previous experiments and which the number of energetic electrons drops off rapidly towards higher energy (Fig. 5).

The explanation for the difference observed in these spectra is due to the timing of the "injection" of electrons into the relativistic plasma wave. It appears that as the plasma wave reaches an amplitude which is just sufficient for wavebreaking only a few electrons are able to "fall" into the accelerating portion of the bubble shaped plasma wave. Consequently these electrons all see an almost identical acceleration gradient. The electrons injected into the plasma wave have an electric field themselves which affects the accelerating electric field of the bubble itself via "beam loading". This then stops the injection or "wavebreaking" process.

At low densities these electron bunches are not "dephased" since the propagation distance of the laser through the plasma is less than the "dephasing distance" which is the length over which an electron outruns the plasma wave – and begins to be de-accelerated by the wave. This is given as $L_d = 2\pi c\omega_L^2/\omega_{pe}^3$ where $\omega_L$ is the laser frequency. In contrast, at higher densities the de-phasing distance is much shorter than the interaction distance and so a "randomized" or quasi-Maxwellian distribution of electrons emerges from the plasma.

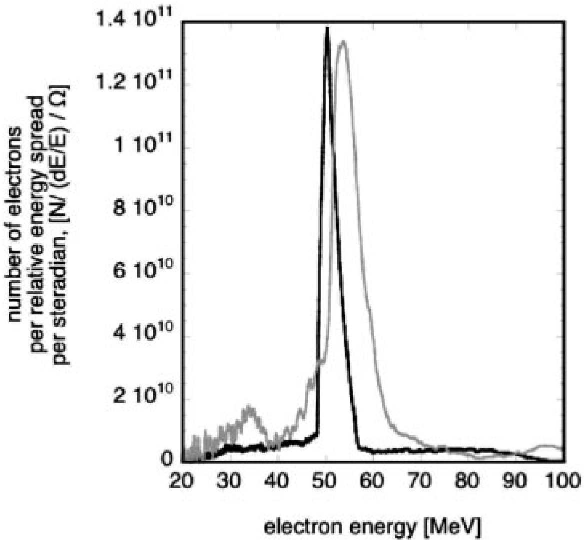


**Figure 4** Two measured electron spectra with $E = 500$ mJ laser at a density of $2 \times 10^{19}$ cm$^{-3}$. Shots are taken from the same shot series. The spectra show the relatively narrow energy spread of the electron beams directly generated by the short pulse laser interaction. The spectra show data taken under similar experimental conditions showing the shot-to-shot variability of the electron beams produced.

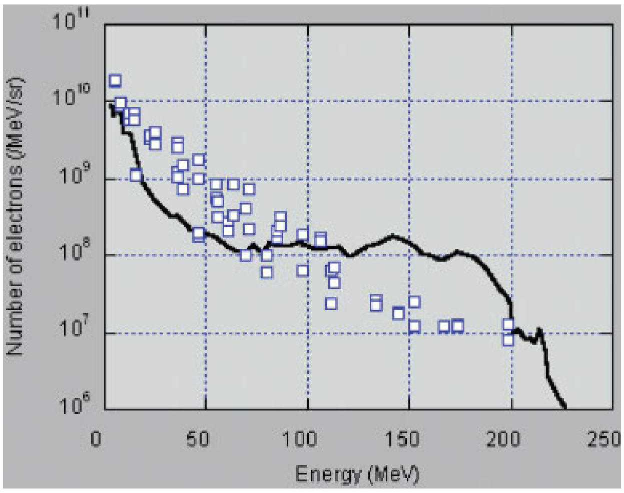


**Figure 5** (online color at: www.lpr-journal.org) Simulated (line) and experimental spectra (squares) at a density of $2.5 \times 10^{19}$ cm$^{-3}$. This spectrum demonstrates the very energetic but broad electron energy spectrum obtainable from the interaction of intense laser pulses with high density plasmas [12].

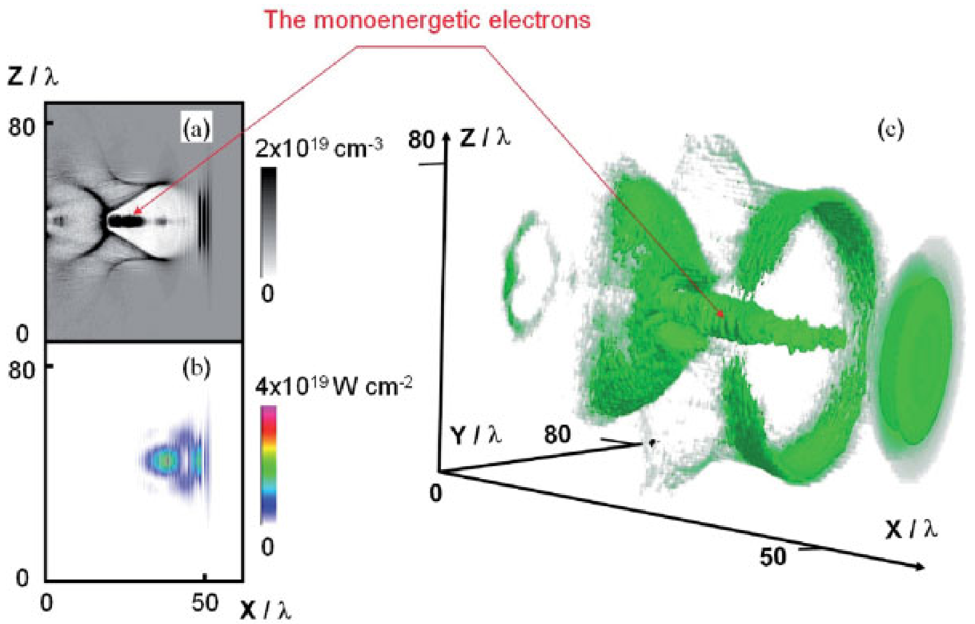


**Figure 6** (online color at: www.lpr-journal.org) 3D PIC simulation results for the case $n_e = 6 \times 10^{18}\,\text{cm}^{-3}$. Frames (a) and (b) show distributions of electron density and laser intensity in the XZ-plane which is perpendicular to the polarization direction and passes through the laser axis. Frame (c) provides a 3D volume view on the electron density distribution in the bubble. The image shows an isosurface at $n_e = 2 \times 10^{19}\,\text{cm}^{-3}$.

This process is indeed what is observed when particle-in-cell (PIC) computational simulations of the interaction are performed. It was found that for relatively low plasma densities the plasma waves increase in amplitude and the laser pulse evolves – self-focusing and self-compressing [21]. When the pulse is fully self-focused, some relativistic electrons have appeared, but at relatively low energies. This is where wave-breaking or injection occurs. As the laser pulse front begins to steepen, the wakefield amplitude grows and the electron energies increase until the pulse reaches its maximum peak intensity. At this point the electrons are clearly "bunched" at a particular energy. After this time the average electron energy begins to drop and the distribution of electron energies is randomized – since the propagation distance is beyond the dephasing length for this interaction.

It is clear from simulations that in these experiments the "bunches" of electrons are produced due to "wavebreaking" in the immediate vicinity of the laser pulse. These electrons are then accelerated through the entire length of the plasma. If this distance is shorter than the dephasing distance, the bunch of electrons can remain relatively mono-energetic after leaving the plasma. The requirements for this regime are that the plasma density has to be high enough so that wave-breaking is easily achieved for an interaction at a given density – but low enough so that the electron bunches produced are not de-phased before they leave the plasma. Subsequent experiments have shown that as the power of the laser is increased the density threshold of generating electrons is reduced and consequently this allows the energy of the accelerated electron bunch to be increased.

The use of PIC simulations has therefore been critical to permit insight into the mechanisms of electron acceleration in the plasma which leads to the observed monoenergetic spectra and of the transition to a Maxwellian spectra at higher density as experimentally observed. Fig. 6 illustrates the bubble injection and the formation of the quasi-monoenergetic electron beam for a plasma density $n_e = 6 \times 10^{18}\,\text{cm}^{-3}$ [22]. The simulation reveals that the laser pulse self-focuses as it propagates through the plasma. As the effective radius of the laser pulse decreases, the laser intensity increases and finally becomes sufficient to generate the bubble. The laser ponderomotive force expels the plasma electrons radially and leaves a cavitated region behind the pulse. At this time, the cavity elongation due to the charge of the trapped electrons then becomes visible: the beam charge becomes comparable with the ion charge in the cavity. The beam's transverse field slows down the radial motion of electrons at the bubble boundary and delays their return to the X-point at the bubble base. This nonlinear "transverse beam loading" leads to the formation of a monoenergetic electron beam. The transverse fields of the cavity squeeze the electron beam down to the transverse diameter (at FWHM) of merely 4 µm. Thus, the normalized transverse emittance of the beam can be computed to be $\varepsilon_\tau \approx 4\pi$ mm mrad (here we have assumed the mean $\gamma$-factor of the electron beam to be $\langle\gamma\rangle = 350$) which is similar to that of conventional electron accelerators. Simulations also show that the electron bunch duration is generally less than the laser pulse duration. Since the electron distribution is quasi-monoenergetic, the bunch can stay short upon propagation through the plasma and exiting into the surrounding vacuum.

In this regime, the laser pulse fits completely into a single plasma wave. As a consequence, the laser-plasma interaction in this regime is largely free from various instabilities such as Raman Scattering or the self-modulation instability and consequently the laser pulse generates a regular and stable plasma wave. Electrons accelerated in this wave demonstrate well-structured spectra with a monoenergetic peak. It is also important that the accelerated electron beam is located behind the main part of the laser pulse, oth-

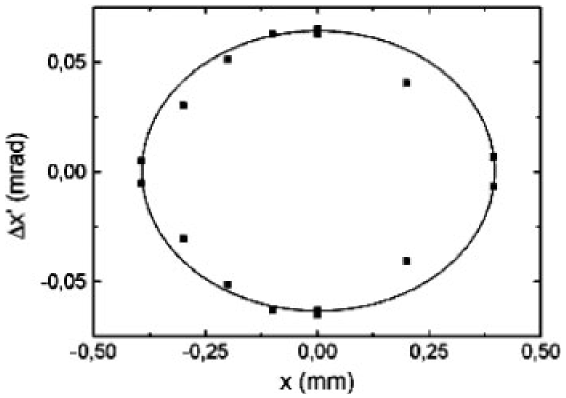


**Figure 7** Electron beam energy as a function of the injection position in counter propagating injection scheme (see [25]).

erwise interaction with the laser electric and magnetic fields can degrade the quality of the electron beam. In addition, the trapped electrons are accelerated not only by the plasma wave field, but can also be accelerated directly by the laser at the so-called betatron resonance. The very complex interplay of these two mechanisms can lead to a broad electron energy spectrum that usually is usually quasi-thermal. At higher density, since the dephasing length is shorter than the interaction length, electrons can be decelerated, this can also lead to a broad spectrum with a quasi-thermal distribution. For those conditions electron emittance has been measured accurately using the "pepper pot" technique [23] as presented on Fig. 7 and was found to be similar to the emittance of beams produced in conventional linear accelerators.

Recent theoretical work has developed scalings for acceleration in the bubble regime [24]. However the main questions which remain outstanding for the further development of such sources in this regime are typically those of experimental control of the acceleration process. How can the laser and plasma parameters be adjusted to enable control of the electron beam energy, charge, energy spread, divergence, emittance and pointing? These properties have all been observed to vary more than desired – and consequently the most significant results of the research reported recently involved insights into improving the stability of these critical beam parameters.

## 3. Stability and tunability

One of the main issues with the electron beams generated by high power laser interactions in the bubble regime has been stability. The measurements of the output electron beams have shown that these beams, under similar experimental conditions, are subject to variations in the energy spread, in the peak energy of the electron beams, in the divergence of the beam, in the charge of the electron beam and in the pointing of the beam. Indeed although excellent quality beams can be generated, the main obstacle to the widespread use of this technology is in this lack of control.

There is significant recent work suggesting that such issues are beginning to be addressed in research centers around the world and that significant progress is being made on this front. Recent results by the LOA group from Laboratoire d'Optique Appliquée (LOA) in France as published in *Nature* in 2006 [25] have shown that the control of electron beam parameters and the reproducibility of the generated electron beams can be greatly enhanced through the use of counter propagating laser beams which can produce a standing wave as the laser pulses pass through each other – thus enabling a significant amount of control over the electron injection process. The electrons in this standing wave pick up relativistic energies and can be injected directly in the the "coexisting" relativistic plasma waves which can then accelerate them further to very high energy. Depending on the timing between the two counter-propagating beams the peak energy and the energy spread can be varied as desired. Further evidence of the effectiveness of this process has also recently showed that superior stability in many of the beam parameters can be obtained using this technique. For example, Fig. 8 shows the variation of the electron beam energy at the collision point between the two laser pulses is varied in space. This effectively allows excellent control of the acceleration length – and the ultimate energy.

Other experiments at LBNL Berkeley, at APRI in South Korea [26] as well as at the Lund Laser Center in Sweden [27] also showed that vast improvements in stability have been achieved over the past few years through precise control over the laser and target parameters. It appears that small shot-to shot changes in the focal spot quality of the laser beam, the level of preionization (due to laser prepulse) and in the density profile can give rise to large changes in the parameters of the electron beams generated. Consequently close attention is required to optimize these parameters during experiments. When the beams are well controlled in such situations, it is possible to manipulate the spectrum and profile of the electron beam simply through changes in the experimental parameters (as shown in Fig. 9 from experiments at Lund) [28].

Although gas jets have been used as the main target medium for this work, recent experiments at the Max Planck Institute for Quantum Optics (MPQ) in Germany have also shown that gas cell targets can potentially provide greater stability for electron beam production [29]. Gas cell targets can be constructed to create accelerating distances which are much longer than those obtainable with gas jets and at low density gas cells can have sufficiently uniform density profiles for laser wakefield accelerator applications. The use of gas cells may also be beneficial for operating these experiments at very high (kHz) repetition rates in the near future.

In addition, work at MPQ has also shown that control of the laser pulse front tilt can change the direction of the electron beam pointing which is often observed to fluctuate experimentally and is not always observed to follow precisely along the axis of laser propagation. These results may

 

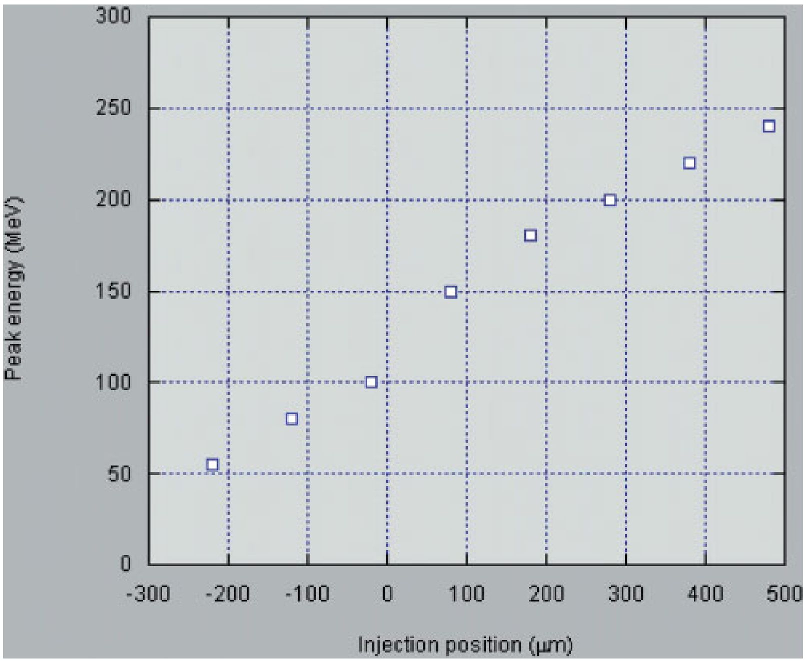


**Figure 8** (online color at: www.lpr-journal.org) Emittance measurement of laser generated electron beam. Two dimensional $(\Delta x', x)$ phase-space distribution for electron energy of 55 MeV. Dots represents the maximum extend of the beam, solid line is the fit for $3\pi$ mm mrad phase space ellipse (see [23]).

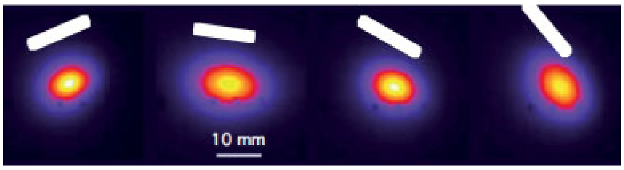


**Figure 9** (online color at: www.lpr-journal.org) Electron beam profile measurements from LWFA acceleration experiments. The polarization of the laser is indicated as a white line. The interaction of the laser pulse with the beam increases the beam divergence in the plane of laser polarization [28].

lead to improvements in the control of this parameter of the beams generated. In other recent experiments in Japan it has even been shown that the use of an external magnetic field surrounding the plasma could dramatically reduce output electron beam divergence [30] even with relatively low power laser beams.

## 4. Guiding

One of the obstacles for generation of high energy electron beams using a single stage LWFA is the necessity for a long acceleration length if very high energies are to be obtained. The peak energy scales as the inverse of the electron density – however since the accelerating electric fields within the plasmas decrease with decreasing density this means that the acceleration distance required to achieve maximum energy as the density is decreased needs to be very long. In fact the acceleration distance increases like $n_e^{-3/2}$ and is just due to classical "dephasing" considerations. Limitations to the acceleration distance in experiments are also often due to laser pump depletion effects which are caused by the laser energy needed to generate the large amplitude wakefields in the plasma. Consequently there have been many previous experiments to demonstrate that high intensity lasers can be guided over longer propagation distances [31–35].

A particularly significant result was the recent demonstration of extended laser acceleration distances using a hydrogen filled capillary discharge plasma waveguide at LBNL – which was shown in 2006 to be able to generate accelerated electron beams to 1 GeV over a distance of only 3 cm [36] using a laser power of 40 TW. This was the first measurement of laser produced electron beams in the GeV range.

There has subsequently been research to improve understanding of the details of plasma wave production and electron acceleration in such plasma waveguides. There have been additional experiments using hydrogen filled capillary waveguides which have shown similar acceleration. In particular at the Max Planck Center for Quantum Optics in Germany it was shown that beam of about 400 MeV could be consistently generated using the ATLAS laser incident onto a similar plasma waveguide [37]. Another experiment using the Astra laser system in the UK demonstrated that high quality electron beams could be generated but that the mechanism for generating these beam was more complex than previously suspected and that electron injection was intimately related to the process of ionization of the target plasma by the intense laser pulse [38]. In these experiments good guiding and an extended propagation distance of the high power laser pulse was a necessary but not sufficient condition for the production of relativistic electron beams from the capillary discharge plasma waveguides. In this work it was found that only when the laser pulse (at

15 TW) was observed to be ionizing the plasma could accelerated electron beams be measured. However it is not clear whether this effect would still be important for experiments at higher laser power such as the earlier experiments performed at LBNL which obtained GeV energies.

Other types of plasma waveguides have also been explored and have been the subject of a significant amount of recent research including the use of gas filled hollow glass capillary waveguides [39] and well as plasma waveguides with modulated density profiles which could potentially induce electron acceleration using slow wave field structures [40].

## 5. Injection and diagnostic development

There has also been significant work on understanding and controlling the injection process in the LWFA accelerators. The successful counter propagation laser injection scheme has already been discussed [25] - however there has also been work to examine how electrons could be injected into a "linear" wakefield structure which would not rely so heavily on the nonlinear processes of wavebreaking and "bubble" formation. A novel injection method is that proposed by the group from the US Naval Research Lab who showed that the process of ionization and ponderomotive acceleration could produce a highly directional beam suitable for injection into a subsequent acceleration stage [41]. Another recently discovered method to increase control of this process used a lower intensity laser pulse beam which co-propagated slightly behind the main pulse which was then guided by the wakefield and was also able to perturb the plasma wave sufficiently to induce injection [42].

One of the obstacles to an increased understanding of LWFA in the bubble regime has been the lack of detailed diagnostics of the laser interaction, and in particular the self-injection mechanism and electron beam generation processes. Simple measurements of the generated electron beam can be compared to the output of large particle in cell simulations of the interaction and consequently insight could be obtained. However for more progress in improving the simulations as well as in experimental parameters it is necessary to develop innovative experimental diagnostic techniques which would enable an even greater degree of comparison between simulation and experiment. There has been notable progress in this regard.

In the UK at the Rutherford Appleton Lab there have been measurements of the wave-breaking radiation [43] which occurs just at the point of electron injection into the plasma "bubble" as well as measurements of the propagation and self-focusing effects of such laser pulses in underdense plasmas [44]. It appears that the size of the focal spot of the laser needs to be well-matched to the plasma wavelength to avoid laser-plasma propagation instabilities at high power. In addition the technique of frequency-domain holography has been used to directly measure the details of the plasma wakefield structure by a University of Texas/ University of Michigan collaboration [45] for the first time.

## 6. Scaling

With the advent of many new even larger laser systems under construction, one of the interesting aspects of this research is how the properties of the accelerated electron beams will scale with this additional energy. Consequently there has been recent significant work to examine the electron beam energy and beam quality with even higher power interactions.

There exist possibilities for laser accelerators using Petawatt and higher power levels which suggest that very high beam energies should be possible without requiring the use of plasma guiding structures. At recent workshops in this field, the first experiments at such powers were reported using lasers at the Rutherford Appleton laboratory on the UK (Astra Gemini) where energies greater 800 MeV were observed [46], as well as at the University of Michigan (HERCULES laser system) [47]. There are also planned Petawatt class laser systems which will be used for LWFA experiments at the University of Texas, LBNL, at LOA in France, in Japan (JAEA), and South Korea (APRI). Simulations of these interactions suggest that electron beam of up to several GeV should be attainable using only a single stage of plasma acceleration.

However to go beyond this – i.e., to obtain energies extending to many tens of GeV or beyond it is necessary to have several acceleration stages which are "linked" together. This raises many significant technological challenges with regard to coupling such electron beams from one stage to another in particular with regard to issues such as collection and refocusing of the electron beam. There has been significant work to address this at LBNL both experimentally and with numerical modeling. The use of plasma targets with a density "down-ramp" gradient was also found to be potentially useful for generating the initial high charge relativistic electron bunches required for injection into subsequent acceleration stages [48].

Another important set of experiments was recently performed at the University of Michigan in which collimated relativistic beams of electrons were produced at kHz repetition rates. Ultimately almost every proposed application of these electron beam sources will require the operation of the electron beam at very high repetition rates. The results from Michigan used a very low energy laser pulse - about 2–3 mJ which was incident onto a rapidly rotating solid target. This showed that good quality reproducible electron beams could be generated – potentially useful for injection into an adjacent plasma wakefield accelerating structure [49].

## 7. Radiation generation

One of the main uses for relativistic electron beams at present is at synchrotron facilities – in which electron bunches of up to 5 GeV are bent by magnetic undulators to emit x-rays for applications in biological, medical or materials science. Consequently if "table-top" multi-GeV beams could be generated and manipulated in a smaller scale university setting this would potentially widen access to such experimental techniques and potentially enable a huge range of additional applications. There is ongoing work in this area in the US [50], Japan [51] and in the UK [52].

There has been recent notable progress in "demonstration" experiments using laser generated electron beams to generate radiation. Recently optical undulator radiation has been measured by passing a laser produced monoenergetic electron beam through a conventional accelerator at the University of Jena [53]. Also recent results from JAEA in Japan have shown that soft x-ray radiation can be produced by reflecting a counter propagating laser beam from the curved density structures in the plasma wakefield [51].

Similarly there has been a significant amount of work recently in the measurements of harder x-ray radiation due to the betatron motion of electrons undergoing acceleration in these experiments [54] as well as in the generation of very energetic (up to 40 keV) synchrotron radiation from ultra-high intensity interactions [55]. There has also been significant recent work to model such effects numerically [56].

## 8. Outlook

The use of high repetition rate lasers has been shown over the past several years to lead to the generation of compact sources of monoenergetic, electron beams having high bunch charge. Because of the use of the extreme accelerating fields available in plasmas, typically of the order of TV/m, this approach has the potential to transform the technology of particle acceleration. Furthermore, it has been shown that the high-quality, low-emittance particle beams already produced in these experiments can today be utilized for measurements of ultra-rapid phenomena in physics, chemistry or for the production of gamma ray beams which have extremely small source sizes [57, 58]. This work is leading to the production of high rep rate, sub-10 fsec, high quality electron beams in the GeV range. With further work to reduce the energy spread of these beams they will be well adapted for the production of compact X-FEL radiation.

Theoretically such waves could also be used for accelerating other relativistic charged particles such as positrons or ions. However development of an all-optical acceleration system for these other types of charged particles will need to wait for the development of techniques to generate significant fluxes of such particles at relativistic energies so that they could be injected into a wakefield structure – although there is presently significant research work for laser acceleration of both positrons [59] and ions [60].

However it should be noted that for high energy physics applications in which very high luminosity electron beams having TeV energies are required, significant further work to develop this technology is necessary - and conceptual designs of such laser based accelerators would require many high energy lasers and would be far from compact. The dramatic improvement in the energy and beam quality of laser based plasma accelerators seems promising for this approach for the generation of very high energy for high energy physics research. But electron energy is not the only important parameter and it is also necessary to consider the extremely high luminosity value required for such applications. For this application, the luminosity requirement for the beam must be greater than $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This value corresponds to the production of electron bunches at kHz rep rates with 1 TeV in energy and with at least 1nC per bunch. The corresponding electron energy per time unit is therefore of about 1 MJ/s. Assuming in the best case a coupling of 20 % from the laser to the electron beam one has to produce at least 5 MJ/s of photons. Since the laser wall-plug efficiency is below 1%, one needs 500 MJ/s, i.e., 500 MW of electrical power to reach this goal. The laser efficiency conversion could be increased up to 50% by using diode pumped systems, thus reducing the needed power to 10 MW. These considerations were done neglecting several other issue such as the propagation of electron beams into a plasma medium, laser plasma coupling problems, laser depletion, emittance requirements and others. Nevertheless, before reaching an objective and more accurate conclusion on the relevance of the laser plasma approach for high energy physics, it will be necessary to design a prototype machine (including several modules) in coordination with accelerator physicists. An estimation of the cost and an identification of all the technical problems that are to be solved will permit an estimate of the risk with respect to other approaches (particle beam interaction in plasma medium, hot or cold technology, or others).

In conclusion while a significant amount of work remains to be done, the electron beams generated by laser wakefields are on the verge of enabling the development of important applications [61]. In particular, the parameters of the electron beams as they presently exist are adequate for "proof of principle" experiments on radiation generation, injection and staging. Over the next few years it is expected at this field will become even more exciting as understanding of how to control and optimize the electron beam parameters grows and many of the promised applications become reality.

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Victor Malka, born in 1960, received the M. S. degree (1987) and the Ph. D. degree (1990) on atomic physics of warm dense plasmas. In 1990, he became a staff researcher with CNRS at LULI working on implosion experiments, on parametric instabilities for inertial fusion and since 1994 on laser plasma accelerator physics. In 2001 he moved to LOA, where he formed his own group dedicated to laser produced particle sources. Since 2003, he has been a Professor with Ecole Polytechnique, France. Victor Malka has been an elected member of the Scientific Council of the European Phyical Society since 2005. He is a member of EPS, SFP and SFO, and a Fellow of the APS. In 2007 he received the international IEEE/NPSS particle accelerator science and technology award for "For groundbreaking work on laser-plasma accelerators" and in 2008 received an Advanced Investigator Grant from the European Research Council (ERC).

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