The development of laser- and beam-driven plasma accelerators as an experimental field[a)]

C. Joshi[b)]
Department of Electrical Engineering, University of California, Los Angeles, California 90095

(Received 10 November 2006; accepted 6 February 2007; published online 15 May 2007)

Since its inception in the early 1980s, the field of plasma-based particle accelerators has made remarkable advances. Robust plasma accelerating structures can now be excited over centimeter scales using short laser pulses and over meter scales using ultrarelativistic particle beams. Accelerating fields in excess of tens of GV/m can be sustained over these lengths. Laser-driven plasma accelerators now routinely produce monoenergetic, low divergence electron beams in the 100 MeV–1 GeV range, whereas electron-beam driven plasma accelerators have demonstrated the ability to double the energy of 42 GeV electrons using a high-energy collider beam in less than one meter. The development of this field is traced through a series of path breaking experiments. [DOI: 10.1063/1.2721965]

I. INTRODUCTON

It is a great pleasure and an honor for me to give you a somewhat personalized account of the development of a new interdisciplinary field: plasma-based accelerators. This interdisciplinary field overlaps the fields of plasma physics, beam physics, and lasers. I am fortunate to have been involved with its development and successes over the past 25 years. Serendipity came to the rescue in the form of technological innovations just when it appeared that the plasma acceleration schemes had gone as far as they were likely to go. These innovations have produced a steady stream of breakthroughs for the field and attracted a talented pool of researchers from around the world. I wish to acknowledge them all and in particular the many critical contributions made to this field by my former and present colleagues and students.

The notion of using "collective fields" to accelerate charged particles can be traced all the way to the 1950s to Budker and Veksler, pioneers in both accelerator and plasma communities. They independently proposed using the "collective fields" generated by a beam of medium energy electrons to accelerate a beam of more massive ions.[1] In the United States, Budker and Veksler's ideas and other related schemes for collective acceleration of ions were intensely investigated in many places over the next 20 years, including at the University of Maryland, Cornell, the University of California Irvine, and Naval Research Laboratory (NRL).[2] Much was learned, but a conceptual breakthrough in the field of collective acceleration came when John Dawson of the University of California Los Angeles (UCLA) proposed the use of a space-charge disturbance or a wakefield created in a plasma to generate collective fields[3] thousands of times greater than those generated by microwaves in a conventional slow-wave structure. A very personal account of how Dawson came to this realization is given in Ref. 3, which the reader may find fascinating. The key advantage to Dawson's proposal was that such a wakefield could be made to have a phase velocity close to c, making it particularly suitable for accelerating electrons to very high energies.

Wakefields in a plasma can be driven by an intense laser pulse that is about half a plasma wavelength long as shown by Toshi Tajima and John Dawson in their now classic 1979 paper, *Laser Electron Accelerator*.[4] For plasma densities in the range $10^{19}-10^{17}$ cm^{-3}, this corresponds to drive beams with full-width at half maximum (FWHM) pulse lengths in the range of $\sim 15-150$ fs. This scheme later came to be known as the laser wakefield accelerator (LWFA).[5] The idea of using a particle beam to drive plasma wakes was also due to Dawson and was published a few years later in a paper authored by Chen and Dawson *et al.*[6] In the laser-driver case, it is the ponderomotive force of the light pulse (proportional to the gradient of the light intensity), whereas in the latter case it is the space-charge force of the electron beam that pushes away the plasma electrons (see Fig. 1). In both cases, the plasma electrons snap back toward the back of the drive pulse because of the restoring force exerted by the more massive and therefore immobile plasma ions, overshoot, and set up the wakefield oscillation. In either case, the drive pulse is approximately half a plasma wavelength long. In the laser case, the wake has a phase velocity equal to the group velocity $v_{\rm gr}$ of the laser pulse, whereas in the beam driver case the phase velocity is the beam velocity v_b. Since $v_{\rm gr}$ and v_b are $\cong$c, such a wake is a relativistic plasma wave. In both cases, an appropriately placed trailing beam of electrons can be accelerated by the longitudinal field of the wake. When one looks back over the past 20 years at the development of the plasma acceleration field, it becomes clear that the critical element that determined its progress was the availability of and access to suitable laser or particle beam drivers.

For me, the journey in these uncharted waters began in 1980 when I came to UCLA to work with Professor Frank Chen as a postdoc on laser-plasma interactions. Our laboratory facilities were very modest and I was looking for something exciting to do. I had read the Tajima and Dawson paper, but intense, short laser pulses needed to excite wakefields did not yet exist. So I turned my attention to

[a)]Paper TR1 1, Bull. Am. Phys. Soc. **51**, 256 (2006).
[b)]Invited speaker.

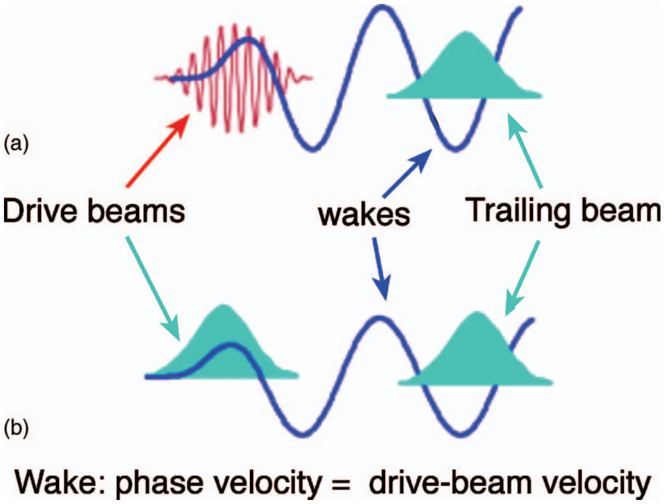

FIG. 1. (Color) A simple one-dimensional picture of the excitation of a relativistic plasma wake by (a) a short laser pulse or (b) a short electron beam pulse propagating through a plasma.

another ingenious way of exciting large amplitude, relativistic plasma waves ($v_{\mathrm{ph}} \sim c$) called beat-wave excitation.[7]

II. PLASMA BEAT WAVE ACCELERATION (PBWA)

In PBWA, two copropagating laser beams, with slightly different frequencies and wave numbers, excite a relativistic plasma wave if the frequency difference $\Delta\omega = \omega_1 - \omega_2$ is equal to the plasma frequency ω_p. In this case, the wave number of the plasma wave is $k_p = \Delta k = k_1 - k_2$ and $\omega_p / k_p \cong c$ with $\gamma_{\mathrm{ph}} = (\omega_1 + \omega_2)/2\omega_p$. Here γ_{ph} is the Lorentz factor associated with the phase velocity of the wave. The physical mechanism for displacing the plasma electrons from their initial position is the so-called ponderomotive force, which is proportional to the gradient of the dot product of the electric fields of the two lasers. Since beat excitation is a resonant process, the laser intensity required to excite a large amplitude ($\varepsilon = n_1/n_o > 0.1$) plasma oscillation is relatively modest and the laser pulse can be fairly long. Here n_1/n_o is the perturbed plasma density. Characterizing laser intensities and pulse length in normalized units of electric field $a = eE/m\omega c$ and collisionless skin depth c/ω_p, respectively, the PBWA typically requires $a_{1,2} = 0.1$ and $\tau \cong 100-500\ c/\omega_p$. This translates to $I_{1,2} = 10^{14}\ \mathrm{W/cm^2}$ and $\tau \leqslant 100$ ps for a CO_2 laser driver and $\gamma_{\mathrm{ph}} \cong 30$ plasma wave.

The PBWA scheme was anticipated in Ref. 4. However, many scientists doubted whether such a scheme would work in practice because of the relatively long and intense pulses used to excite the plasma wave. There was worry that competing laser-plasma instabilities, such as Raman and Brillouin backscatter and the modulational instability, would "kill" the scheme.[8] It was not until 1983 when the first two-dimensional (2D), particle-in-cell (PIC) code simulations of the PBWA scheme[7] were carried out, by Warren Mori of UCLA and David Forslund and Joe Kindel at Los Alamos National Laboratory, that the potential of this method as an ultrahigh gradient particle accelerator became widely accepted. Figure 2 shows one result from Ref. 7 showing that

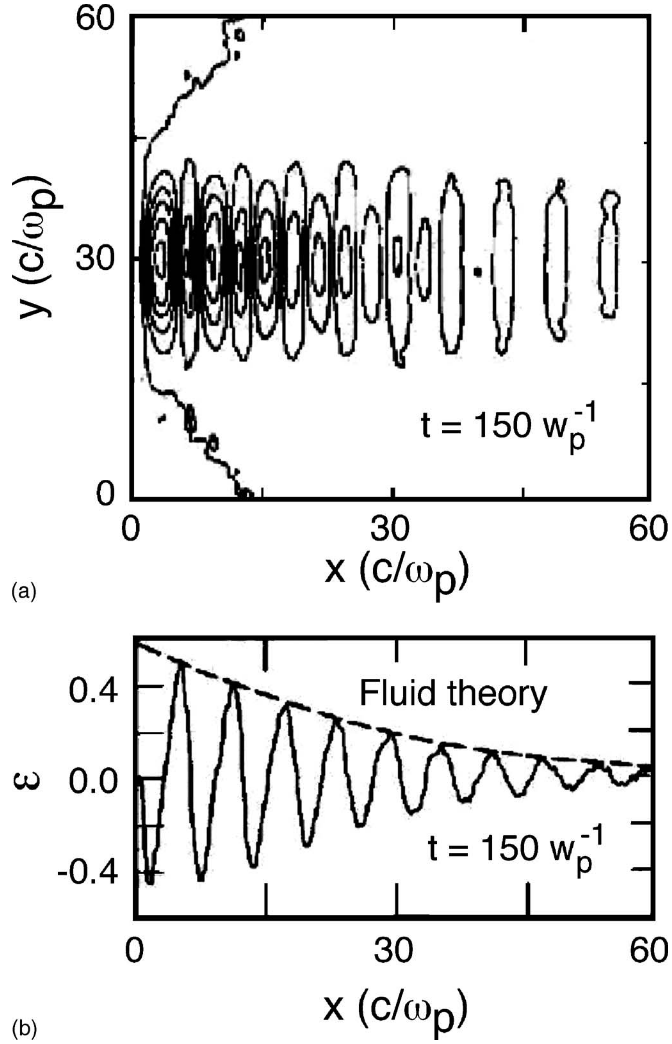

FIG. 2. First, two dimensional PIC-code simulations of a plasma beat wave accelerator carried out using the CRAY-XMP machine at Los Alamos in 1983. (a) 2D contours of the wave potential in space and (b) the growth of the plasma wave as predicted by 2D-PIC simulations of the PBWA (Ref. 1). Reprinted by permission from Macmillan Publishers Ltd: Nature **311**, 525 (1984).

there was a quantitative agreement between the growth rate of the plasma wave seen in the PIC simulations and that predicted by fluid theory developed by Rosenbluth and Liu.[9]

Reference 7 was followed shortly by an experimental verification of the excitation of relativistic plasma waves by collinear optical mixing[10] by the UCLA group. Figure 3 shows key results from this work that demonstrated the expected frequency ($\omega_p = \Delta\omega$) and wave number ($k_p = \Delta k$) relationship for the excited plasma wave: the excitation of the Stokes and anti-Stokes side bands and a proportionate relationship between the amplitude of the first Stokes side band and the amount of Thomson scattering from the plasma wave. The accelerating field deduced from the density fluctuations (measured using the Thomson scattering diagnostic) was greater than one GeV/m for the first time. It was this result that gave credibility to the whole plasma accelerator field and resulted in many experiments being funded around the world on actual acceleration of electrons using such waves.

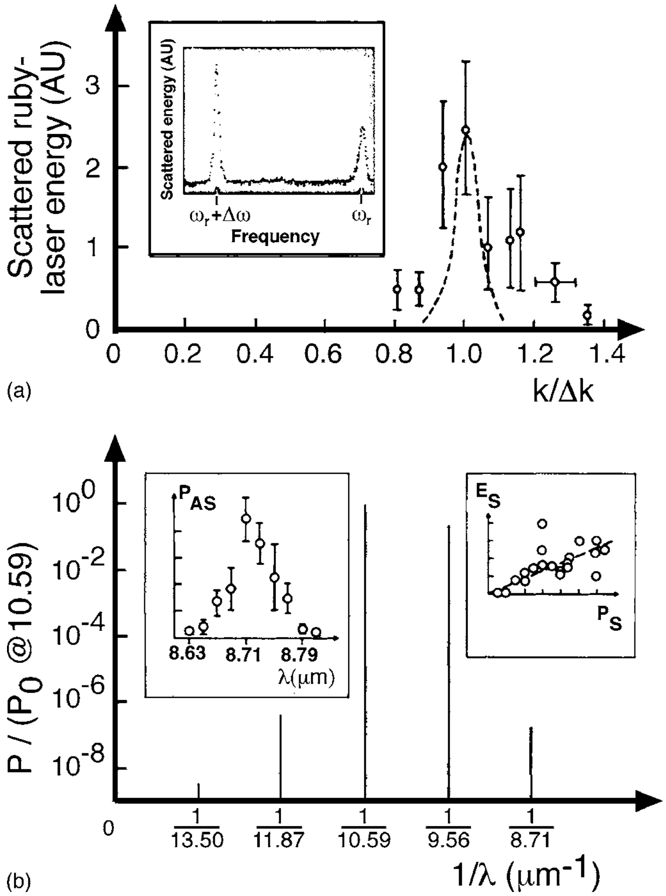

FIG. 3. The first evidence for the excitation of a relativistic plasma wave obtained at UCLA. (a) Frequency and wave-number spectrum of the beat-excited relativistic plasma wave. (b) Stokes and anti-Stokes side bands to the incident laser wavelengths of 10.59 and 9.56 μm, including the anti-Stokes spectrum at 8.71 μm (inset) and linear relationship between Thomson scattered light (E_s) and Stokes light P_s at 11.87 μm (also inset) (Ref. 9).

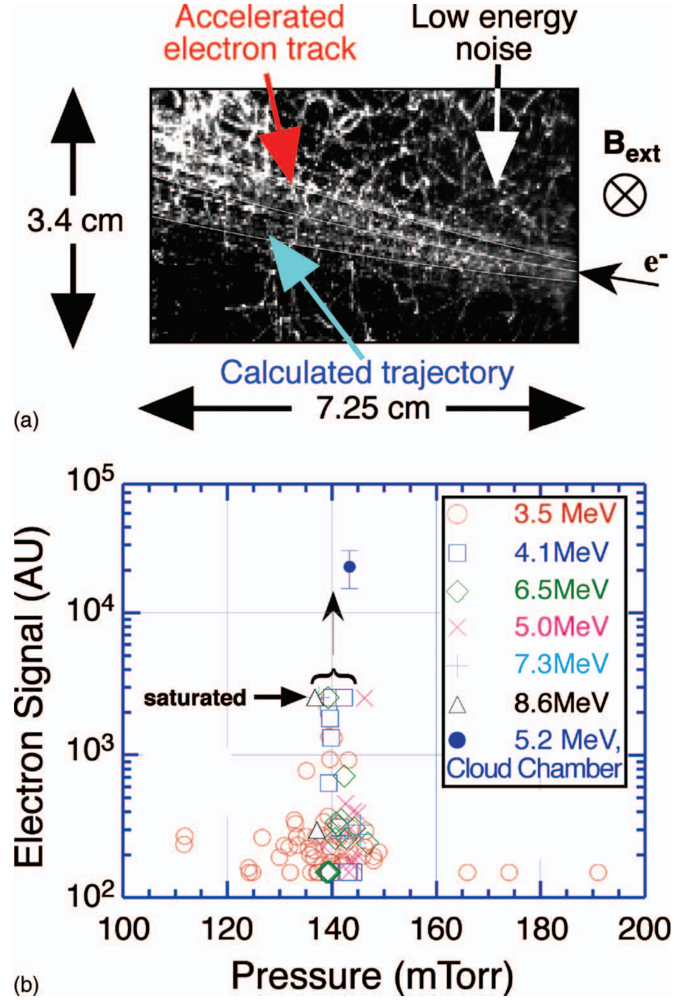

FIG. 4. (Color) The first evidence for the acceleration of externally injected electrons by a relativistic plasma wave. (a) Cloud chamber tracks produced by accelerated electrons and (b) the number of accelerated electron as the gas pressure (plasma density) is varied showing the expected resonance (Ref. 12).

Although it proved to be relatively easy to excite relativistic plasma waves using the beat-excitation technique, conclusive acceleration of externally injected electrons turned out to be far more difficult and would take another 8 years. During this time the UCLA group was fortunate to have a number of talented theorists, such as Tom Katsouleas, Warren Mori, J. J. Su, S. Wilks, and of course John Dawson, whose conceptual and computational advances[11] kept the fledgling field intellectually vibrant even as the experimentalists struggled to sort out how to externally inject preaccelerated electrons into a relativistic plasma wave.

It was 1993 when the first conclusive results were presented by the UCLA group of acceleration and substantial energy gain of externally injected electrons using the PBWA technique.[12] Here I must recognize the contributions of two of my colleagues, Chris Clayton and Ken Marsh, who, together with a group of exceptionally talented students (Wim Leemans, Matt Everett, Ron Williams, Amit Lal, and Dan Gordon), worked for many years, systematically solving problems of uniform plasma production,[13] particle diagnostics, plasma wave diagnostics,[14] and a reliable two-frequency CO_2 laser. Figure 4 shows key results from Ref. 12. Many plasma physicists doubted that one could conclusively demonstrate acceleration of test particles in a turbulent plasma environment. So the UCLA group first used an imaging magnetic spectrometer to momentum select electrons of a certain energy and then an auxiliary cloud chamber to visualize the particles. A secondary orthogonal B field was used to bend the electrons in the cloud chamber and measure their relativistic Larmor radius to confirm the energy gain. Furthermore, both the electron energy gain and the number of accelerated electrons were found to maximize at the resonant density. [In Fig. 4(b), the horizontal axis is pressure but later this was shown to be directly related to electron density.]

In 1994, the UCLA group showed trapping and acceleration of externally injected electrons by the PBWA.[15] The injected electron energy was 2 MeV while γ_{ph} was 33 so the observation of electron energies of greater than 16.5 MeV was conclusive proof that electrons had been trapped by the wave potential (Fig. 5). Maximum electron energies of 30 MeV were observed. The acceleration length was measured to be less than 1 cm long, which implied an acceleration gradient of ~2.8 GeV/m. Furthermore, loss of electron energy was seen as well as gain. This was to be expected

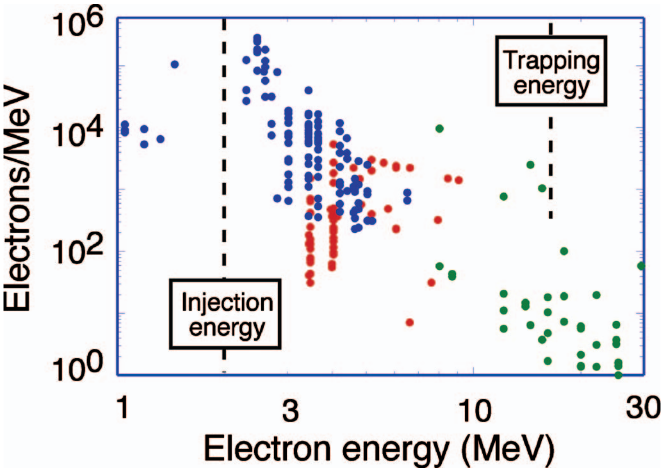

FIG. 5. (Color) Trapping of externally injected electrons in the beat-excited relativistic plasma wave (Ref. 10). The energy of particles moving synchronously with the wave is 16.5 MeV. Therefore, all the electrons with energies greater than this are evidence of trapping in the wave potential. Reprinted by permission from Macmillan Publishers Ltd: Nature **368**, 527 (1994).

because the wavelength of the plasma oscillation was ~300 μm (1 ps duration) whereas the injected electron microbunch was 10 ps long. The data shown in Fig. 5 were obtained over many laser shots, and as there was a ±50 ps jitter between the laser and the electron beam, the electron beam sampled plasma waves of different amplitudes from one shot to the next leading to large variations in the number of electrons that were accelerated.

It took 9 years from the time a relativistic plasma wave was first excited using the beat wave technique[10] to do a convincing acceleration experiment[12] mainly because the new laser acceleration field turned out to be a cross-disciplinary field requiring state-of-the-art expertise in lasers, beam physics, and plasmas. In fact in 1994, the UCLA group proposed a 1 GeV PBWA experiment[16] based on then available 1 μm CPA laser technology, but unfortunately such an experiment was never funded due to a lack of resources. The UCLA PBWA program has therefore turned its attention to injecting externally generated microbunches in beat excited plasma waves to obtain accelerated beams with a reduced energy spread.

This brief historical review of the PBWA would not be complete without mentioning some of the other notable groups that also explored the PBWA scheme, particularly those from University of Osaka (Japan),[17] Imperial College (U.K.),[18] Ecole Polytechnique (France),[19] and Chalk River Laboratory, Canada.[20] These experiments were carried out using both 1 and 10 μm laser pulses and have demonstrated acceleration of self-trapped[17] as well as externally injected electrons.[19,20]

III. THE SELF-MODULATED, LASER-WAKEFIELD ACCELERATION (SMLWFA)

In the early 1990s, a revolution of sorts was taking place in the development of high-power lasers. The so-called "chirped pulse amplification (CPA)" technique was successfully applied to the large energy-storage, Nd:glass laser to

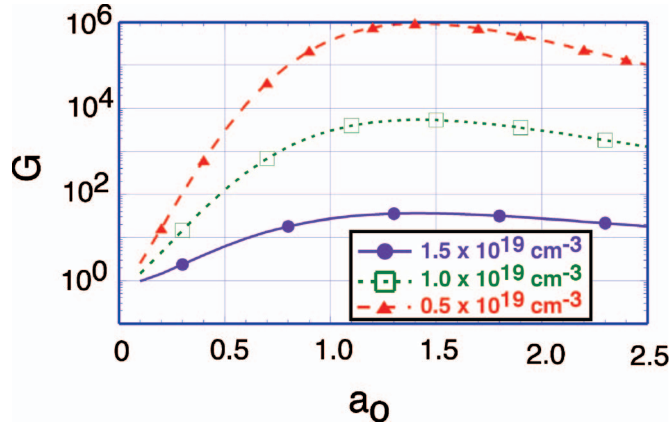

FIG. 6. (Color) Spatio-temporal gain G for RFS (for three different plasma densities) is plotted as a function of laser power in units of normalized vector potential for a 1 μm laser, nominally 800 fs long (Ref. 23).

generate subpicosecond pulses containing a few terawatts of power.[21] These pulses were still almost an order of magnitude too long to excite wakefields (shown in Fig. 1) in a high-density plasma (needed to self-trap the plasma electrons), but they were now intense enough to excite a relativistically propagating plasma wave via a parametric instability known as forward Raman scattering (RFS).[22] This eliminated the need to have a two-frequency laser pulse whose frequency difference had to exactly match the plasma frequency as in the PBWA case. As soon as such lasers became relatively commonplace, the research on plasma accelerators shifted to the exploration of the RFS scheme. In RFS, the laser beam decays into a forward propagating Stokes wave, an anti-Stokes wave, and a relativistic plasma wave. Once the Stokes and the anti-Stokes waves become sufficiently intense, they beat with the pump wave to produce a deeply amplitude modulated envelope of the electric field. This is why this scheme eventually came to be known as the self-modulated laser wakefield acceleration (SMLWFA) scheme. As in the PBWA scheme, the electron density modulation in the SMLWFA scheme has a frequency of ω_p and wave number $k_p = k_o - k_s$, where "o" denotes the pump and "s" denotes the Stokes wave, respectively.

When the laser pulse is short compared to Z_R/c, where Z_R is the Rayleigh length of the focused laser beam, the RFS is in the so-called spatio-temporal regime[23] with the spatio-temporal gain $G = e^g/(2\pi g)^{1/2}$ with

$$g = (a_o/\sqrt{2})(1 + a_o^2/2)(\omega_p/\omega_o)^2(\omega_o/c)\sqrt{x\psi}. \quad (1)$$

Here a_o is the normalized vector potential of the laser with frequency ω_o, x is the distance traveled into the plasma, and ψ/c is the length of time that the assumed constant intensity pulse has interacted with the plasma at position x.

Figure 6 shows the total growth G from an initial noise level of $\varepsilon_{\text{noise}} \sim 10^{-5}$ as the laser intensity (expressed in units of a_o) is varied for different densities assuming a 1 μm laser. One can see that G initially increases with a_o but subsequently remains rather constant or even decreases for $a_o > 1$. On the other hand, G is a strong function of plasma density. There are ~3 e-foldings of growth when $n = 5$

$\times 10^{18}$ cm^{-3} but this number approaches 12 when the density increases to 1.5×10^{19} cm^{-3}. Thus, at these high densities we expect to see self-trapping of background plasma electrons[24] and even catastrophic wave breaking[25] of the plasma oscillation.

The first paper that pointed out the RFS's role in electron acceleration was by Joshi *et al.*,[16] who used a relatively long but intense CO_2 laser pulse ($a_o \sim 0.3$, $\omega/\omega_p \sim 2.1$) to form a plasma using a thin carbon foil and measured the spectrum of forward and backward emitted electrons. Electrons with higher energies (up to 1.4 MeV) were emitted in the forward (laser) direction compared with up to 0.8 MeV in the backward direction and were attributed to RFS through computer simulations of the experiment. Electrons were observed without external injection, which means that they were self-trapped plasma electrons.

It was not until 1995 that research on the SMLWFA scheme began in earnest as TW class lasers became widely available, as mentioned earlier. A typical SMLWFA experiment used a supersonic hydrogen or helium gas jet to produce 1–2 mm long gas plumes of density in the range $(1-10)\times 10^{19}$ cm^{-3}. This gas was field ionized[26] by the leading edge of the subpicosecond laser pulse and the rest of the laser underwent RFS instability and excited the RPW. Because of the modest phase velocities ($\gamma_p \sim 10$), plasma electrons could be rather easily self-trapped and accelerated. The typical electron spectrum was exponential. In addition to the electrons, a comb of Stokes and anti-Stokes sidebands to the laser frequency each separated by ω_p was observed in the forward direction as was expected from a four-wave parametric instability. In 1993, Coverdale and Darrow (an alumnus of the UCLA group) of Lawrence Livermore National Laboratory (LLNL) in collaboration with the UCLA group showed acceleration of electrons via RFS conclusively using a nominally 10 TW, 1 μm laser.[27] In this plasma acceleration experiment, the first to be done using a gas jet plasma, the first two anti-Stokes side bands were seen. Electrons up to 2 MeV energy were seen when an $a_o=0.9$ laser was used to produce and interact with a 10^{19} cm^{-3} gas jet plasma. This experiment ushered in the "jet-age" of plasma accelerators.[28]

The Livermore-UCLA experiment[27] was soon followed by a much more sophisticated experiment at the Rutherford Appleton Laboratory[29] (RAL) in the U.K. by the Imperial College, UCLA, and Ecole Polytechnique groups. The 1 μm Vulcan laser[30] at RAL had the capability of delivering up to 30 TW of power in an 800 fs pulse. Using this laser ($a_o \gtrsim 2$) and a gas-jet plasma target, this group was able to see copious fast electron generation via breaking of the Raman forward plasma wave. The evidence for wave breaking came from the sudden broadening of the comb of satellites in the forward direction (see Fig. 7) as the plasma density was increased from 5.3×10^{18} cm^{-3} to 1.5×10^{19} cm^{-3}. The spatial extent of the relativistic plasma wave was also directly measured using Thomson scattering of a probe beam[31] as was the spectrum of the relativistic electrons that were escaping the plasma in the forward direction (Fig. 8). From the maximum observed energy of 94 MeV, the accelerating gradient was deduced to be greater than 150 GeV/m, which represented, at the time, a record for the highest gradient

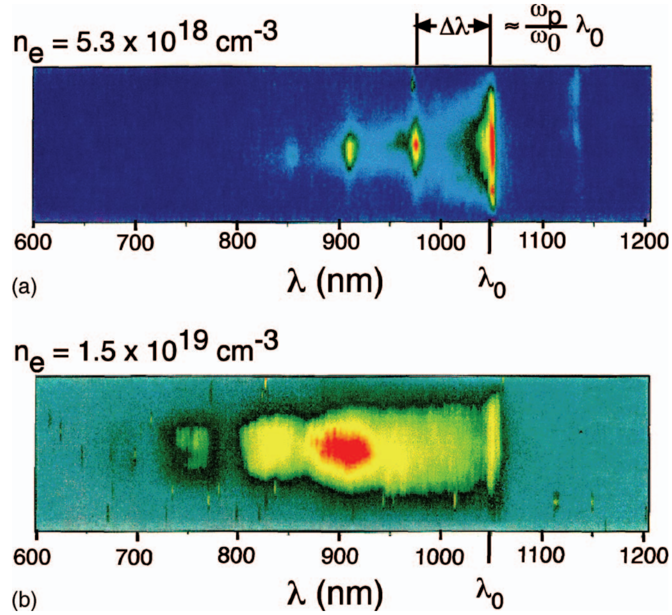

FIG. 7. (Color) Spectrum of satellites to the pump laser in the forward direction at two different densities in the Rutherford experiment (Ref. 29). At the lower density of 5.3×10^{18} cm^{-3}, a series of well defined anti-Stokes satellites were observed each separated by ω_p, whereas at the higher density of 1.5×10^{19} cm^{-3}, a continuous broadening of the spectrum was observed. The broadening coincided with a sudden increase in the number of high-energy electrons ejected from the plasma.

terrestrial acceleration of charged particles. Another interesting aspect of this experiment was that the maximum energies observed were greater than those expected from the phase slippage between the electrons and the accelerating electric field of the plasma wave as given by the linear theory.

Many other groups around the world soon experimented with the SMLWFA scheme. Most notably, the University of Michigan group[32] and the NRL group[33] both observed the anti-Stokes side bands and electrons. The Michigan group led by Don Umstadter, also a UCLA group alumnus, showed that the electrons were emitted in a well-defined beam[32] in the same direction as the laser. The NRL group did coherent Thomson scattering measurements on the plasma wave and determined that it lasts for about 30 ps or roughly 100 oscillations before decaying into ion acoustic waves.[33]

An interesting byproduct of the SMLWFA experiments is the observation of relativistic self-focusing and filamentation of the laser beam in the plasma.[34] This is so because the thresholds for both RFS and relativistic self-focusing are about the same for n_c/n_e of about 100. In the Rutherford experiments[35] where the ratio of P/P_c was about 20 (where P_c is the critical power for whole beam relativistic guiding), a relativistic plasma wave that was about 24 Rayleigh lengths long was observed and was presumed to be inside a filament of similar length that was simultaneously observed by imaging sidescattered incident laser light. The observation of this plasma wave puts a lower bound on the intensity of light inside the filament (Fig. 9) to be around 10^{18} W/cm^{-2}. Experiments at University of Michigan[36] observed the onset of relativistic guiding very close to the theoretically predicted threshold. The experiments spurred theoretical work

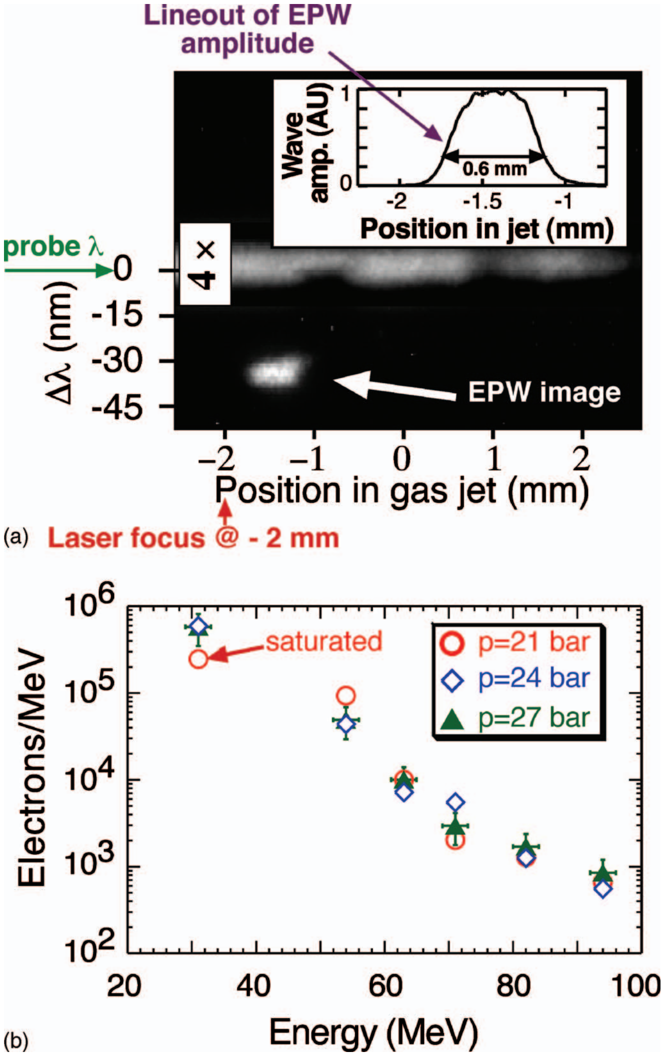

FIG. 8. (Color) A direct measure of the maximum accelerating gradient in a SMLWFA experiment at the Rutherford Laboratory (Ref. 31). (a) Data showing the spectrum and the spatial extent of transverse, small-angle Thomson scattering showing that the spatial extent of the RFS plasma wave was ~600 μm. (b) Electron spectrum emitted in the forward direction showed electrons with a maximum energy of 94 MeV. The maximum accelerating gradient was thus ~ 160 GV/m.

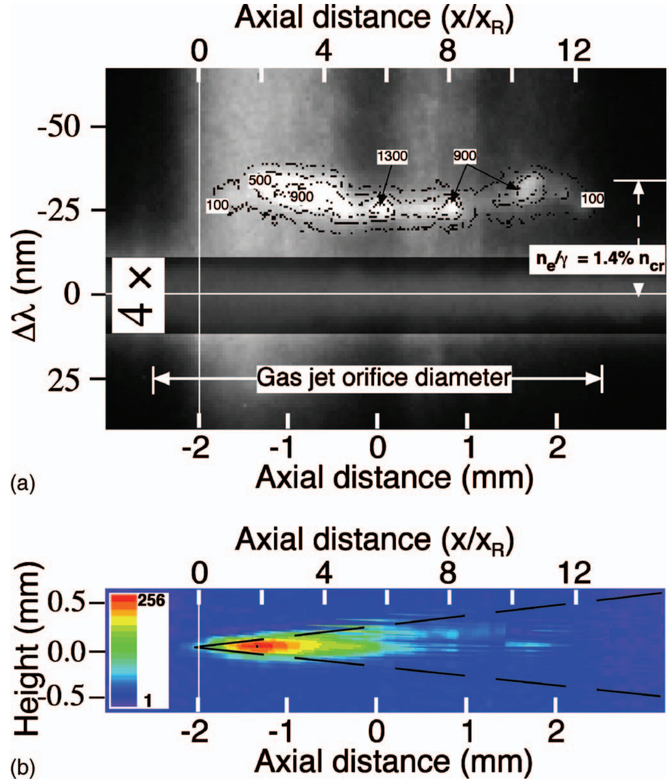

FIG. 9. (Color) Direct evidence for the excitation of a relativistic electron plasma (R-EPW) wave inside a self-focused laser beam (Ref. 35). (a) Frequency-resolved image of (R-EPW) amplitude along the laser propagation axis. Contours are of constant scattered probe energy and are artificially suppressed at the edges relative to $x=0$ due to the temporal profile of the probe pulse. Spatial-modulated bremsstrahlung continuum is also apparent. (b) Side-view sidescatter near 1 μm for the same shot (color) shows the self-focused laser beam propagating over 12 Rayleigh lengths in the 4 mm gas jet plasma.

on how one should propagate a matched beam in a plasma using the relativistic guiding effect so that it propagates until all its energy is depleted by energy transfer to the wakefield.[37] Major advances in laser-plasma acceleration are expected once these ideas are adopted in the next few years.

IV. LASER WAKE FIELD ACCELERATION (LWFA)

By 2002, it appeared as if SMLWFA experiments had run their course. It was clear that RPW could accelerate electrons to several hundred MeV[38] but the continuous energy electron spectra seemed inevitable. Several ingenious all optical injection schemes were proposed that had the potential to make the electron beam more reproducible and produce somewhat narrower energy spread beams.[39]

Fortunately, the next big boost to the field came in the form of the development of the high-power Ti:sapphire laser.[40] Now laser pulses with pulse widths in the range of 50–100 fs that contained tens of terawatts of power could be produced. Such ultrashort intense pulses were exactly what was needed to realize the original vision of the LWFA.

A. Early experiments on LWFA

The first observation of a wake produced by a single short laser pulse was in 1996 by the Ecole Polytechnique[41] and University of Texas at Austin (UT Austin) groups.[42] In both of these experiments, the laser was focused to a spot size much smaller than the wavelength of the plasma oscillation and, consequently, the oscillation was dominated mainly by the radial motion of the electrons. Such “cylindrical” electron wakes were measured, with a temporal resolution much better than ω_p^{-1} by frequency domain interferometry. A very recent diagnostic developed by Mike Downer’s UT Austin group has enabled single-shot, 2D visualization of laser-induced wakes using frequency domain holography.[43] Using this method, fine details such as the wavefront curvature of the wakefield, seen previously only in computer simulations, have now been observed. This powerful technique will provide a better understanding of future experiments by allowing a comparison to be made between the experiment and PIC simulations.

In the Ecole Polytechnique experiments, the cylindrical plasma wakefield excited by a 130 fs Ti:sapphire laser was seen to have a nonlinear increase in oscillation frequency as the plasma density was decreased below the optimum density. The plasma wave was also seen to damp in a few plasma periods.[41] These experiments were followed up by a proof-of-principle acceleration experiment by the same group.[44] By injecting a 3 MeV electron beam into the wake, a maximum energy gain of 1.6 MeV was measured, corresponding to a maximum longitudinal field of 1.5 GeV/m.

Strictly speaking, none of the experiments carried out with intense, short-pulse lasers in the early 2000s have operated in the classical laser-wakefield regime, i.e., the laser pulses were still longer than the optimum $\lambda_p/2$ needed for wakefield excitation. However, at the high plasma densities and laser intensities used in many of these experiments, the laser pulses rapidly self-modulated at the plasma frequency due to a combination of self-steepening caused by diffraction of the front of the laser pulse, an increase in the normalized vector potential (due to both self-focusing and frequency downshifting due to photon deceleration)[45] and local pump depletion. Thus, as these longer laser pulses propagated through the plasma, they became shorter and excited a wakefield in the plasma. An example of such a "forced laser wakefield" acceleration was reported in Ref. 46 by the Laboratoire d'Opique Appliquée (LOA) group. It showed a monotonically decreasing energy spectrum of electrons with a maximum energy of up to 200 MeV. Similar results were obtained at many other laboratories around the world. A key feature of all these experiments was the generation of a well collimated beam of electrons with a normalized emittance of ~1 mm mrad, which is comparable to the state-of-the-art R.F. electron guns based on photocathodes.[47]

B. The blowout or bubble regime

The blowout or bubble regime was first explored in connection with an electron beam driven plasma accelerator.[47] However, its basic features are the same for a laser driver.[48] In the case of an electron beam driver, it is the space-charge force of the electron beam pulse, whereas in the case of the laser pulse, it is the radiation pressure that now radially pushes away all plasma electrons leaving a void or a bubble of ions. In both cases, plasma electrons form a sheath around the ion bubble and return toward the beam axis because of the space-charge attraction force of the plasma ions, overshoot, and set up a three-dimensional wakefield oscillation. The focusing or radial electric field of such a wakefield has certain desirable properties. Once fully formed, it is uniform axially, varies linearly with r, and it is mostly in phase with the accelerating or longitudinal field. In contrast, a linear plasma wakefield has sinusoidal longitudinal and transverse fields that are both accelerating and focusing over only a quarter of a wavelength. Most laser- and particle beam-driven plasma accelerators now operate in this blowout or "bubble" regime, so called because the drive beam appears to be encapsulated inside a sheath of plasma electrons as shown in Fig. 10.

As this point, I would like to emphasize the indispensable role played by computer simulations in the development of the plasma accelerator field. In contrast to the one-dimensional particle-in-cell (PIC) simulations often done using "cartoon" parameters in the early days of the field,[49] it is now possible to carry out fully 3D, one-to-one simulations of the experiment using fully parallel, moving window codes written in modern object programming languages. Of these, OSIRIS,[50] VLPL,[51] turboWAVE,[52] VORPAL,[53] WAKE,[54] and QuickPIC[55] deserve special mention because they are being used extensively to both design and analyze experiments. Figure 10 is from a QuickPIC simulation that uses a quasi-static approximation. In simple terms, it is assumed that the driver evolves on a slower time scale (distance of propagation) than the frequency or wavelength of the wake. In the moving window, the driver and hence the wake evolve on distances on the order of the diffraction length of the driver. This length is much greater than the pulse length of the driver. This approach was first adopted by Whittum for particle beam drivers[56] and by Mora and Antonsen[54] for a laser driver. A good account of the development of different codes used in the modeling of plasma acceleration is given by Mori.[57] QuickPIC and OSIRIS have been used to model the beam-driven PWFA experiments in the blowout regime that have been carried out at Stanford Linear Accelerator Center (SLAC) with a great degree of accuracy.

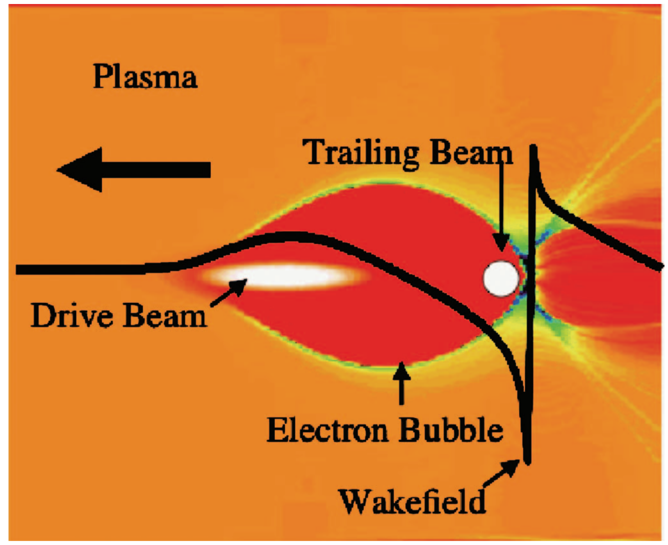

FIG. 10. (Color) As a short laser pulse or an electron drive beam is shot through the plasma, it leaves behind it a charge disturbance or a wakefield. In both cases, the beam blows out all the plasma electrons, which snap back toward the axis behind the beam. This creates a bubble that surrounds both the beam that creates it and the plasma ions that are left behind. The electrical field inside the bubble, shown here with the black curve, resembles an extremely steepened wave that is ready to break. This wave or wakefield can trap some of the electrons from the plasma itself to be accelerated by this field. Alternatively, a distinct trailing electron beam can now be accelerated by the wakefield.

C. Laser acceleration experiments in the bubble regime

In the case of a laser beam driver, even though the phase velocity of the bubble wake structure is relativistic, the accelerating particles can still outrun the wave in a distance

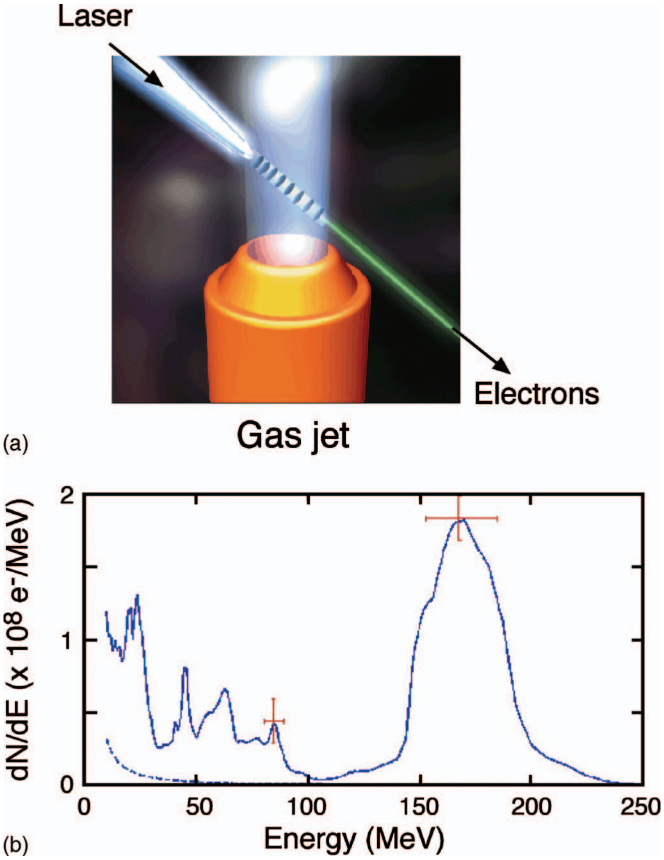

FIG. 11. (Color) (a) A typical setup for a LWFA experiment and (b) a quasimonoenergetic spectrum of electrons observed in the LOA experiments using the setup shown in (a).

known as the dephasing distance. While this limits the maximum energy gain, it beneficially generates an electron beam with a much narrower energy spread (see Fig. 11). The sequence of events that produces this "quasimonoenergetic" bunch is complex. Even though (it was) observed first in 3D PIC simulations,[48,58] there was skepticism about whether it would be observed in practice. To produce this quasimonoenergetic beam, some of the electrons that are blown out by the drive pulse are first trapped by the spike of the accelerating field. This happens because the electron sheath has a finite thickness as the electrons approach the beam axis. Amazingly, a significant number of electrons are trapped so that the wake is beam loaded, the accelerating field drops in amplitude, and further trapping is not possible. The trapped electrons are subsequently accelerated as a group where they initially have a spread of energies. However, as the electrons in the front dephase and begin to lose energy, the electrons behind them continue to gain energy. This phase-space rotation generates a quasimonoenergetic bunch.[58]

The trick to generating such accelerated bunches with a narrow energy spread is to terminate the acceleration process close to the dephasing distance by having a plasma-vacuum boundary. If this is not the case and the plasma is either too long or the plasma density is too high for a given plasma length, the trapped electrons begin to lose energy and the monoenergetic beam is lost.

Such monoenergetic beams have now been seen in at

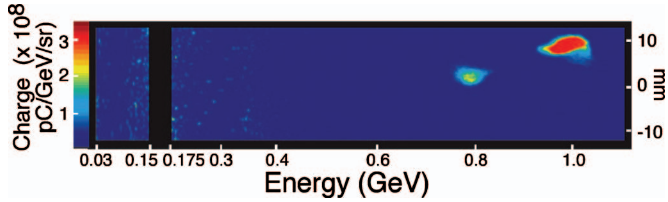

FIG. 12. (Color) Observation of two distinct, monoenergetic electron bunches from a channel guided laser wakefield acceleration experiment at Lawrence Berkeley National Laboratory. Reprinted by permission from Macmillan Publishers Ltd: Nature Physics **2**, 696 (2006).

least half a dozen LWFA experiments including at Lawrence Berkeley National Laboratory (USA) (LBNL), RAL (U.K.), and LOA (France).[59] An example of the data obtained at LOA is shown in Fig. 11. Of the three experiments mentioned, the LBNL work is different from that of the other two groups. The LBNL experiment was carried out in a preformed plasma channel,[60] whereas the RAL and the LOA work was done using a gas jet. To scale the experiment to higher energies, one needs to go to lower plasma densities ($\gamma_{\mathrm{ph}} \sim \omega_o / \omega_p$) and longer plasma lengths. One way to maintain the laser intensity over a longer length, for a given laser power, is to guide the laser beam in a preformed channel as done in the LBNL experiment mentioned above.

D. Development of plasma channels and laser acceleration

The need to employ a plasma channel to guide a laser beam over the full length needed to fully pump deplete the laser beam (typically tens to hundreds of diffraction lengths) was well appreciated since the earliest days of this field. Pioneering experiments were done at the University of Maryland[61] by H. Milchberg's group, which demonstrated that a column of laser-produced plasma can be allowed to expand to produce a transverse refractive index profile that has a maximum on axis. Such a column of plasma can then guide a second much higher intensity pulse and excite a wakefield.[62]

Recently, the LBNL group (led by W. Leemans, yet another alumnus of the UCLA group), in collaboration with Oxford University group, used a 3.3 cm long capillary discharge[63] to produce a hydrogen plasma channel with a density of $\sim 4 \times 10^{18}$ cm^{-3}. When a 40 TW beam was guided through this channel, a monoenergetic electron beam with up to 1 GeV energy was obtained. An example of the electron spectrum taken from Ref. 63 is shown in Fig. 12. In this single shot spectrum, two distinct, monoenergetic electron bunches with energies of approximately 0.8 and 1 GeV are clearly seen. Other groups in Japan[64] and France[65] are using z pinch discharges and gas-filled capillary tubes to propagate intense laser pulses. In the next few years, we will see which approach yields the 10–30 cm long plasma channels in the density range 10^{17} cm^{-3}, needed to produce a 10 GeV energy electron beam.

V. BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATOR

The PWFA scheme is very attractive because of its potential to double the beam energy of a high-energy accelerator beam[66] in a single stage of acceleration that is only tens of meters long. Because of this potential, this advanced acceleration method is a likely candidate for impacting future high-energy colliders at the energy frontier.

A. PWFA work at modest energies

Experimental research on PWFA has been going on at Argonne National Lab (ANL),[67] Fermi National Laboratory,[68] KEK-Japan,[69] and more recently at Brookhaven National Laboratory.[70] Using relatively low energy drive beams, researchers at these facilities were able to demonstrate many aspects of the physics involved in the PWFA concept.

The first demonstration of the excitation of a wakefield by a relativistic beam was at ANL in 1987 by the University of Wisconsin group.[67] The change in energy of a witness beam with a variable delay was used to map the wakefield induced by the drive beam. The peak acceleration gradient was just 1.6 MeV/m, however the experiment clearly showed the wakefield persisting for several plasma wavelengths. In a follow-on experiment at ANL, the wakefield was more carefully mapped out. The energy change of the centroid of the witness beam was increased from ±50 to ±150 keV and the nonlinear steepening of the wake was clearly observed for both the longitudinal and the transverse components of the wake.[71] Both of these experiments were in the linear regime, where the beam density was typically less than the plasma density.

These experiments were followed at ANL by the first experiments in the blowout regime, i.e., $n_b > n_p$. By time-resolving the beam spot size at the end of the plasma column using a streak camera, the beam core was shown to be guided over 12 characteristic diffraction lengths of the beam.[72] The guiding was attributed to the focusing force provided by the ion channel. In 1999, the ANL wakefield facility again produced a drive and a witness beam capability and the wakefield acceleration experiment was repeated this time in the blowout regime with $n_b \sim 2.5 n_p$. Consequently, the average acceleration gradient was increased to 25 MV/m over 12 cm of 10^{13} cm^{-3} plasma. The acceleration gradient was limited by the ~200 ps long drive beam pulse.[73]

More recently at Fermilab's photoinjector facility,[74] a magnetic chicane was used to compress the electron beam to a few picoseconds. Now the acceleration and deceleration gradients dramatically increased to ~150 MeV/m and some particles of the 15 MeV beam lost nearly all their initial energy to the plasma wake.[75]

Another important PWFA experiment was recently carried out at Brookhaven's Accelerator Test Facility (ATF). Here an initial 60 MeV, 3 ps (FWHM) beam was propagated through a 10^{17} cm^{-3} plasma formed in a capillary discharge. The output beam was imaged and energy resolved using an imaging spectrometer. From the transverse size of the beam in the dispersion plane, the variation of the focusing field of the wake was mapped out. As expected, the focusing field was shown to be 90 degrees out of phase with the accelerating field.[70]

Where are the PWFA experiment with modest energy headed? Rosenzweig *et al.* from UCLA are working toward producing shaped drive bunches to increase the transformer ratio of the wakefield.[76] Another idea being pursued by this group is the so-called "transition-trapping injection" proposed by Suk[77] and observed in laser-plasma acceleration experiments.[78] Here a sudden density transition from high to low density, in a distance less than c/ω_p, leads to trapping of plasma electrons into the wake on the lower density side of the transition. Under certain conditions, the self-trapped electrons can have an extremely narrow energy spread and a small emittance.[79]

Finally at ATF, a user group from the University of Southern California (USC) is resonantly exciting a wakefield using electrons prebunched on a 10 μm scale by an IFEL prebuncher.[80] By sending a train of such microbunched pulses into a 10^{19} cm^{-3} plasma, they hope to resonantly excite a large gradient wakefield. A few percent detuning between the drive and the wakefield frequency is sufficient for the later bunches to extract energy from the wake built up by the earlier bunches.

B. Plasma wakefield acceleration experiments with ultrarelativistic beams

By 1995, numerous laser acceleration experiments had confirmed that plasmas could support gradients of tens of GeV/m. Such large gradients were extremely attractive to conventional accelerator builders. At the 1996 Snowmass Workshop on "New Directions in High Energy Physics," Tom Katsouleas and I proposed to use the electron beam driver from the SLAC linac to demonstrate a 1 GeV energy gain in a meter long plasma module. This led to the formation of a very fruitful collaboration between UCLA, USC, and SLAC on developing the PWFA. SLAC is perhaps the only user facility in the world that has high-energy (30–50 GeV) electron and positron beams for exploring advanced acceleration concepts.[81] Since the year 2000, in a series of experiments, a collaboration of scientists have used the high-energy electron and positron beams, at the Final Focus Test Beam (FFTB) facility,[82] to demonstrate focusing and acceleration of both high-energy electrons and positrons using plasmas. Initially, the key goal of these experiments was to demonstrate a one meter long plasma accelerator module that would give an energy gain of 1 GeV. There were three breakthrough developments that allowed this scientific collaboration to far exceed this initial goal. The first was the development of a fully parallel, moving-window PIC code OSIRIS and a reduced description PIC code QuickPIC[55] that enabled one-to-one simulations of the proposed and completed experiments. The second was the use of a perfectly reproducible meter long lithium plasma source that could give plasma densities over a very broad density range of 10^{12} cm^{-3}–5×10^{17} cm^{-3}.[83] The third factor was the ability to compress the nominally 5 ps long SLAC electron beam pulses down to 50 fs.[84]

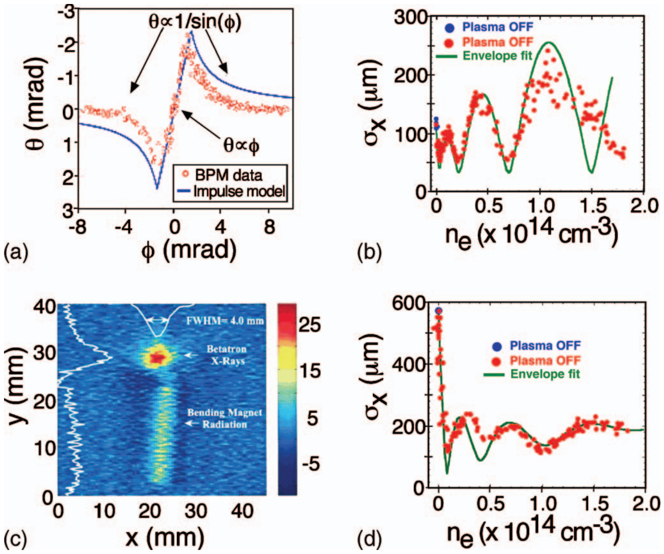

FIG. 13. (Color) (a) Experimental evidence for collective refraction and total internal reflection of an electron beam crossing a plasma-gas interface. For incident angles $\phi > 1.2$ mrad, the refracted angle θ is proportional to $1/\sin\phi$ as predicted by "Snell's law" for refraction of a beam but for ϕ less than 1.2 mrad, $\phi = \theta$ as would be expected for total internal reflection of the beam at the interface. Reference 85. Reprinted by permission from Macmillan Publishers Ltd: Nature **411**, 43 (2001). (b) Oscillations of the transverse spot size of the beam observed on a screen downstream of the plasma, as plasma density is varied. The green curve is a fit to the data using the beam envelope equation (Ref. 86). (c) Image produced on a fluorescent screen as recorded by a CCD camera showing the betatron x rays produced by the 28.5 GeV electron beam in a plasma $n_p = 2 \times 10^{13}$ cm^{-3} (Ref. 87). (d) Demonstration of "beam-matching" (Ref. 88).

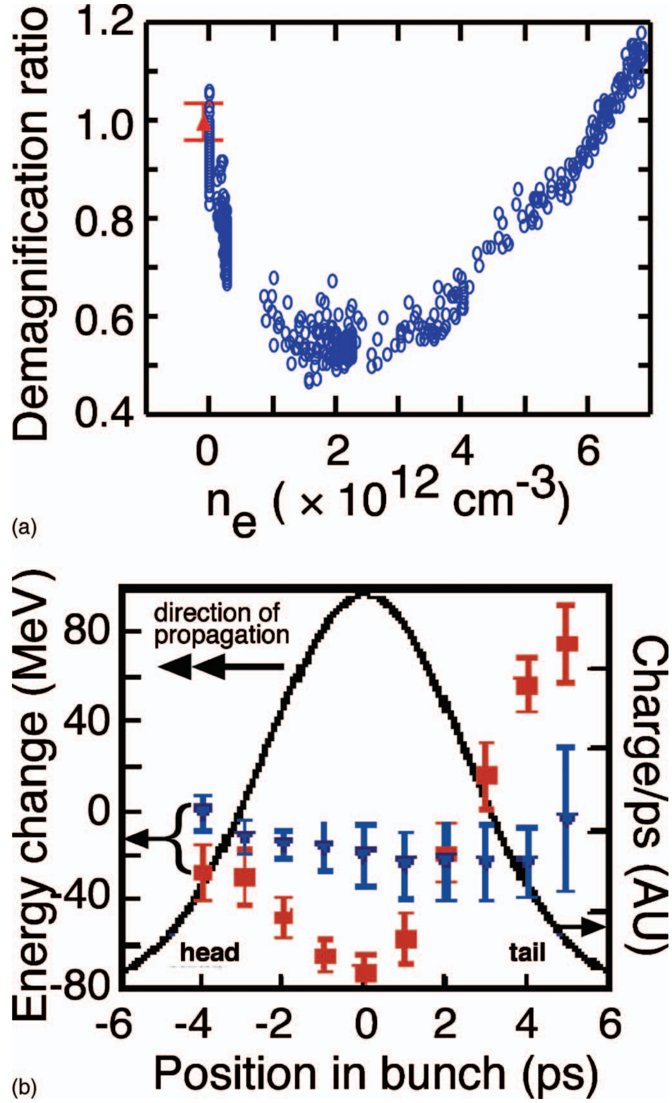

FIG. 14. (Color) (a) Plasma focusing of a 28.5 GeV positron beam from the Stanford Linear Accelerator (Ref. 89) (b) Energy changes to the different slices of a nominally 10 ps long e^+ beam by a 1.4 meter long plasma column. The blue triangles are no plasma condition and red squares are with the plasma. The black curve is the current profile of the positron beam (Ref. 90).

Early experiments (E157 and E162) were carried out with 28.5 GeV electron and positron beams. The physics of wakefield excitation is different for electron and positron beam drivers. In these experiments, both e^+ and e^- beams had densities $n_b > n_p$. However, in contrast to the electron beam driver case (where the plasma electrons are completely expelled by the head of the beam), in the e^+ driver case electrons are pulled in from a plasma region that has a much larger radius than the beam radius. These plasma electrons cross the beam axis at different times and positions. This phase mixing leads to up to a factor 2 smaller wakes for the same e^+ drive beam density compared to when electrons are used. The focusing fields are also qualitatively different for an e^+ driver.

In the SLAC experiments E157 and E162, the changes to the transverse size and energy of various slices of the beam due to the focusing/defocusing and decelerating/accelerating fields of the wake were used to diagnose the wake. Most particles of the beam lost energy in exciting the wake, but particles in the back of the beam sampled the accelerating field and therefore gained energy. The early accomplishments have been documented in several publications and are summarized in Figs. 13 and 14. Figure 13(a) shows the observation of refraction and indeed total internal reflection of a particle beam as it traverses the boundary between plasma and neutral gas.[85] A plot of beam deflection angle θ (measured with a beam position monitor) versus angle between the ionizing laser that produces the plasma and the beam ϕ is shown in this figure. ϕ is therefore also the angle between the beam and the plasma. For incident angle ϕ less than 1.2 mrad, θ is proportional to ϕ and the beam is internally reflected at the interface. The solid line is the prediction of the simple impulse model described in Ref. 85.

Figure 13(b) shows evidence for betatron or envelope oscillations of the electron beam because of the focusing force exerted by a column of ions produced by the head of the beam.[86] Multiple oscillations of the spot-size σ_x due to betatron motion, of the 28.5 GeV electron beam in a 1.4 m long lithium plasma as the plasma density is increased, are clearly evident on a screen placed downstream of the plasma. The oscillation amplitude increases as the density is increased because the plasma focusing force is greater than the beam emittance force. The solid line is a theory fit to the measured data using the beam envelope equation. Figure 13(c) shows the emission of intense, collimated beam of x rays in the 10 keV range by individual electrons executing betatron motion in the ion column.[87] The circle at the top is due to nominally 10 keV betatron x rays, and the vertical stripe is from remnant synchrotron radiation produced by a dipole bend magnet that dumps the beam. Figure 13(d) shows how a beam is "matched" to the plasma.[88] In this case, the beam emittance force is initially greater than the plasma focusing force. As the plasma density is increased, the focusing force due to the ion column increases until it eventually equals the emittance force. As the beam propagates through the 1.4 m long plasma, its spot size variations (seen on an external screen) become smaller until at a density of $\sim 1.5 \times 10^{14}$ cm^{-3} the beam spot size remains unchanged as the beam is matched to the plasma.

The main results obtained using a positron driver are summarized in Fig. 14, which shows the focusing of a positron beam by a plasma column acting as a thick lens.[89] At a fixed distance beyond the plasma lens, the demagnification of the beam diameter, which was initially 50 μm, is plotted against the electron density of the focusing plasma. As the plasma density is increased toward its optimum value of $2 \times 10^{12}/\mathrm{cm}^3$, the focusing strength increases and the beam diameter is pinched to half its initial value. At still higher plasma densities, the beam is overfocused and the spot size grows again. The red error bar indicates the spot size uncertainty of the beam without plasma focusing. Figure 14(b) shows the evidence for the acceleration of positrons with gradients of 50 MeV/m in a meter scale plasma.[90] In this experiment, energy changes were recorded for different temporal slices of the 10-ps, 28.5 GeV initial energy positron beam pulse. Whereas the bulk of the pulse (near $t=0$) showed energy loss of about 55 MeV, its tail (later than +1 ps) demonstrated energy gain of as much as 80 MeV. This was the first demonstration of high-gradient plasma acceleration of positrons.

These results, although impressive in their own right, were eclipsed when sub-100 fs electron pulses became available with the addition of a beam compression chicane. According to linear wakefield theory, for a fixed number of particles in the bunch, the accelerating gradient scales as the inverse square of the electron pulse length.[91] Simulations showed that this scaling held even in the extremely nonlinear blowout region in which the SLAC experiments operated and that accelerating fields on the order of 40 GeV/m were possible by using 50 fs long electron bunches.

Early PWFA experiments with the 28.5 GeV, 10 ps (FWHM) SLAC beam used an ArF laser, preionized Li plasma column with densities in the 10^{14} cm^{-3} range.[86] The bulk of the drive electron beam excited the wake and therefore lost energy, however the electrons in the back of the same beam overlapped with the accelerating portion of the wakefield and thus gained energy. In these early experiments, energy gains of up to 350 MeV were observed in a 1.4 m long plasma. The results were in good agreement with OSIRIS simulations of the experiment.[88]

As much shorter electron bunches in the 50 fs (FWHM) range became available, the prospects of obtaining multi-GeV energy gains using a higher density plasma seemed excellent. Bruhwiler pointed out the possibility of field ionizing the Li to form a plasma using the transverse electric field of the tightly focused short electron bunch.[92] The E164 experiment was devoted to carefully characterizing such field-ionized plasmas using vapors/gases of many different species.[93] This was followed by a series of breakthrough experiments in which the first evidence for multi-GeV energy gain using a 10 cm long plasma was seen.[94] See Fig. 15. This was followed by an experiment in which the plasma length was varied systematically and energy gains of more than 10 GeV were obtained.[95]

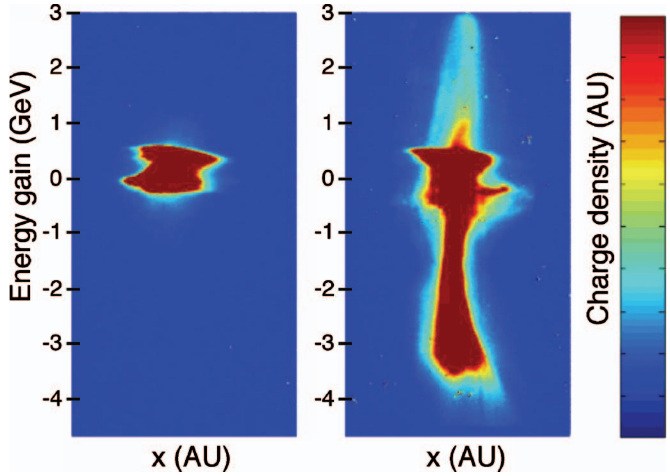

FIG. 15. (Color) Multi-GeV energy gain for electrons was observed using a nominally 10 cm long, lithium plasma with a density of $\sim 3 \times 10^{17}$ cm^{-3}. (a) and (b) above show electron beam spectra after dispersion when no plasma is present and after the beam has traversed the plasma, respectively (Ref. 94).

Even more remarkable experiments followed in which the energy of some of the electrons from a 28.5 GeV beam was shown to double in a 60 cm long plasma, and subsequently by using a 42 GeV beam, electrons with a maximum energy of up to 85 GeV (an energy gain of 43 GeV) were obtained in an $\sim$85 cm long plasma.[96] Figure 16 shows the electron spectrum from Ref. 96. In Fig. 16(a), the head of the electron pulse that drives the wake is at 43 GeV. The core of the pulse that has lost energy in driving the wake is dispersed mostly out of the view of the spectrometer camera and therefore not observable. Electrons in the back of the same bunch are accelerated by the wakefield to reach energies up to 85 GeV and can be seen to the right. In Fig. 16(b), a comparison between the experimentally measured spectrum and that obtained in QuickPIC simulations of the experiment is shown. What was surprising about these experiments was that this doubling of particle energy was possible without any significant growth of the electron hose instability even as the electrons executed approximately 35 betatron oscillations in the plasma.[97] In fact, QuickPIC simulations revealed that the maximum possible pump depletion limited energy gain was only prevented because of the spreading of the front of the beam in a process known as the beam head erosion.[96] At these higher densities ($>10^{17}$ cm^{-3}), the betatron motion of the electrons led to a significant emission of photons in the 5–100 MeV energy range.[98] These photons traversed a thin tungsten target to generate e^+-e^- pairs in the 1–30 MeV range, which may make them useful for a future positron source.[99] (See Fig. 17.)

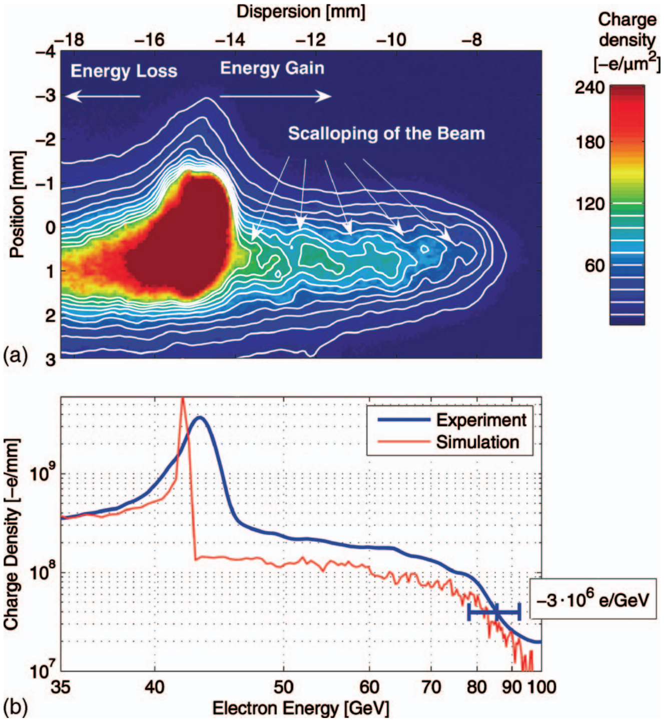

FIG. 16. (Color) (a) The energy spectrum of the (initially nominally 42 GeV) electron beam after passage through an 85 cm long, 2.7×10^{17} cm^{-3} lithium plasma and (b) a comparison between the measured spectrum and the simulated spectrum. Reprinted by permission from Macmillan Publishers Ltd: Nature **445**, 741 (2007).

VI. NEAR-TERM PROSPECTS FOR PLASMA ACCELERATORS

It is difficult to predict how the field of plasma accelerators will develop in the long term, but we can prognosticate its near-term prospects with some degree of confidence. Already Ti:sapphire lasers delivering 200 TW of power at 10 Hz that fit on three optical tables have become a reality. Using such lasers, it seems that electron beams with a relatively small ($\sim 1\%$) energy spread, containing 0.5 nC charge and energy in the 1 to a few GeV range, will be generated using the LWFA scheme. In the next few years, such beams may not have the small energy spreads and emittances needed for coherent x-ray generation via the FEL mechanism, but they will find applications in other fields such as femtochemistry, radiotherapy with electrons, and radiography.

On the research front, laser acceleration will strive to demonstrate staging where the electron beam emanating from one laser accelerator stage is injected into a second stage and further accelerated. Exquisite temporal and spatial control will be required to reproducibly demonstrate staging. If 10–30 cm long plasma channels can be produced and if 200 TW class beams can by guided along such channels, then an electron beam with up to 10 GeV energy seems possible.

With beam driven PWFA, the extent of the progress will be determined by the availability of the short-pulse, high-energy electron and positron beam facilities. It is important to show that high gradient positron acceleration can be achieved over meter scale plasmas. This needs to be followed by the demonstration of acceleration of a substantial number of particles, with a narrow energy spread (while maintaining its emittance) using a distinctly separate trailing bunch. Although I have not dealt with the topic of plasma lenses for focusing high-energy particle beams in this review, I expect much attention to be devoted to this topic in the next few years. Judging by how rapidly the field has evolved in the past five years, I would not be surprised if all these issues are successfully tackled in the next five years.

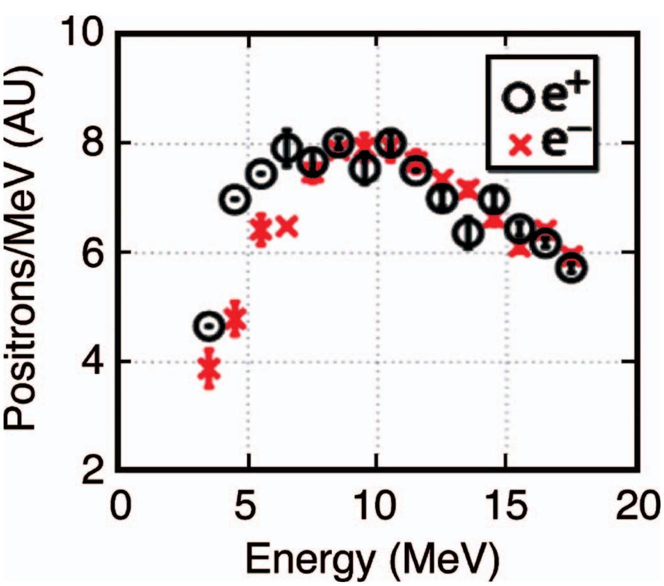

FIG. 17. (Color) The spectrum of positrons produced by $e^{+}-e^{-}$ decay of 10–50 MeV photons produced by betatron motion of 28.5 GeV electrons in an ion column. The electron spectrum (e^{-}) is also shown for comparison (Ref. 98).

ACKNOWLEDGMENTS

In this review paper, I have recollected how Plasma Acceleration has evolved as an experimental field. I am sure that I have inadvertently omitted some important contributions for which I hope that I will be forgiven. I would like to thank all our present and former students and colleagues without whose hard work many of the results described in this paper would not have been obtained. In particular, I am grateful to Chris Clayton, Ken Marsh, Tom Katsouleas, Warren Mori, the late John M. Dawson, Frank Chen, Andy Sessler, Bucker Dangor, Bob Bingham, Tudor Johnston, Sergei Tochitsky, Patric Muggli, Mark Hogan, Rasmus Ischebeck, Dieter Walz, and Bob Siemann for their many contributions and friendship. I would like to thank in particular all my co-workers on SLAC experiments E157, 162, 164, 164X, and 167. Thanks are also due to Wim Leemans, Victor Malka, Zulfikar Najmudin, and Mike Downer for providing me with their latest results. I thank Dr. David Sutter and Dr. Philip Debenham of the U.S. DOE for their unflinching support of the field of plasma accelerators.

This work was supported by the U.S. Department of Energy under Grant No. DE-FG02-92ER40727.

[1]G. I. Budker, *Proceedings of the CERN Symposium on High Energy Accelerators* (CERN, Geneva, 1956), Vol. 1, pp. 68 and 80.

[2]M. Reiser, IEEE Trans. Nucl. Sci. **NS-28**, 3355 (1981); N. Rostoker, *ibid.* **NS-26**, 4156 (1979); P. Sprangle, A. T. Drobot, and W. M. Manheimer, Phys. Rev. Lett. **36**, 1180 (1976); *Collective Methods of Accelerations*, edited by N. Rostoker and M. Raiser (Harwood Academic, New York, 1979).

[3]J. M. Dawson, in *Advanced Accelerator Concepts: Ninth Workshop, Santa Fe, NM, 2000*, edited by P. L. Colestock and S. Keeley, AIP Conf. Proc. No. 569 (AIP, Melville, NY, 2001), p. 3.

[4]T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).

[5]P. Sprangle, E. Esarey, A. Ting, and G. Joyce, Appl. Phys. Lett. **53**, 2146 (1988).

[6]P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, Phys. Rev. Lett. **54**, 693 (1985).

[7]C. Joshi, W. Mori, T. Katsouleas, and J. M. Dawson, Food Sci. Technol. (London) **311**, 525 (1984).

[8]D. W. Forslund, J. M. Kindel, and E. L. Lindman, Phys. Fluids **18**, 1002 (1975); P. Mora, D. Pesme, A. Héron, G. Laval, and N. Silvestre, Phys. Rev. Lett. **61**, 1611 (1988).

[9]M. N. Rosenbluth and C. S. Liu, Phys. Rev. Lett. **29**, 701 (1972); B. I. Cohen, A. N. Kaufman, and K. M. Watson, *ibid.* **29**, 581 (1972).

[10]C. Clayton, C. Joshi, C. Darrow, and D. Umstadter, Phys. Rev. Lett. **54**, 2343 (1985).

[11]T. Katsouleas and J. M. Dawson, Phys. Rev. Lett. **51**, 392 (1983); T. Katsouleas, Phys. Rev. A **33**, 2056 (1986); T. Katsouleas and W. Mori, Phys. Rev. Lett. **61**, 90 (1988); S. Wilks, J. M. Dawson, W. B. Mori, T. Katsouleas, and M. E. Jones, *ibid.* **62**, 2600 (1989); J. J. Su, T. Katsouleas, J. M. Dawson, and R. Fedele, Phys. Rev. A **41**, 3321 (1990).

[12]C. E. Clayton, K. A. Marsh, A. Dyson, M. Everett, A. Lal, W. P. Leemans, R. Williams, and C. Joshi, Phys. Rev. Lett. **70**, 37 (1993).

[13]W. P. Leemans, C. E. Clayton, W. B. Mori, K. A. Marsh, P. K. Kaw, A. Dyson, and C. Joshi, Phys. Rev. A **46**, 1091 (1992); W. P. Leemans, C. E. Clayton, W. B. Mori, K. A. Marsh, A. Dyson, and C. Joshi, Phys. Rev. Lett. **68**, 321 (1992).

[14]M. J. Everett, A. Lal, C. E. Clayton, W. B. Mori, and C. Joshi, Phys. Rev. Lett. **74**, 2236 (1995); M. J. Everett, A. Lal, D. Gordon, K. Wharton, C. E. Clayton, W. B. Mori, and C. Joshi, *ibid.* **74**, 1355 (1995); W. P. Leemans, C. E. Clayton, K. A. Marsh, and C. Joshi, *ibid.* **67**, 1434 (1991); A. K. Lal, D. Gordon, K. Wharton, C. E. Clayton, K. A. Marsh, W. B. Mori, C. Joshi, M. J. Everett, and T. W. Johnston, Phys. Plasmas **4**, 1434 (1997).

[15]M. Everett, A. Lal, C. E. Clayton, K. A. Marsh, and C. Joshi, Food Sci. Technol. (London) **368**, 527 (1994).

[16]C. Joshi, B. Blue, C. E. Clayton *et al.*, Phys. Plasmas **9**, 1845 (2002); S. Ya. 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, Phys. Rev. Lett. **92**, 095004 (2004).

[17]Y. Kitagawa, T. Matsumoto, T. Minamiata *et al.*, Phys. Rev. Lett. **68**, 48 (1992).

[18]A. Dyson, A. E. Dangor, A. K. L. Dymok-Bradshaw *et al.*, Plasma Phys. Controlled Fusion **38**, 509 (1996).

[19]F. Amiranoff, M. Laberge, J. R. Marqués *et al.*, Phys. Rev. Lett. **68**, 3710 (1992).

[20]N. A. Ebrahim, J. Appl. Phys. **76**, 7645 (1994).

[21]P. Maine, D. Strickland, P. Bado, M. Pessot, and G. Mourou, IEEE J. Quantum Electron. **QE-24**, 398 (1988).

[22]C. Joshi, T. Tajima, J. M. Dawson, H. A. Baldis, and N. A. Ebrahim, Phys. Rev. Lett. **47**, 1285 (1981); D. W. Forslund, J. M. Kindel, W. Mori, C. Joshi, and J. M. Dawson, *ibid.* **54**, 558 (1985).

[23]W. B. Mori, C. D. Decker, D. E. Hinkel, and T. Katsouleas, Phys. Rev. Lett. **72**, 1482 (1994).

[24]T. C. Katsouleas and W. B. Mori, Phys. Rev. Lett. **61**, 90 (1988).

[25]J. M. Dawson, Phys. Rev. **113**, 383 (1959); T. P. Coffey, Phys. Fluids **14**, 1402 (1971); A. I. Akhiezer and R. P. Polovin, Sov. Phys. JETP **3**, 696 (1956).

[26]M. V. Ammosov, N. B. Delone, and V. P. Krainor, Sov. Phys. JETP **64**, 1191 (1986).

[27]C. Coverdale, C. B. Darrow, W. B. Mori, C. D. Decker, K. C. Tzeng, K. A. Marsh, C. E. Clayton, and C. Joshi, Phys. Rev. Lett. **74**, 4659 (1995).

[28]T. Katsouleas, Phys. Plasmas **13**, 055503 (2006).

[29]A. Modena, Z. Najmudin, A. E. Dangor *et al.*, Food Sci. Technol. (London) **377**, 606 (1995).

[30]C. N. Danson, L. J. Barzanti, Z. Chang *et al.*, Opt. Commun. **103**, 392 (1993).

[31]D. Gordon, K. C. Tzeng, C. E. Clayton *et al.*, Phys. Rev. Lett. **80**, 2133 (1998).

[32]D. Umstadter, S.-Y. Chen, A. Maksimchuk, G. Mourou, and R. Wagner, Science **273**, 472 (1996).

[33]A. Ting, K. Krushelnick, C. I. Moore, H. R. Burris, E. Esarey, J. Krall, and P. Sprangle, Phys. Rev. Lett. **77**, 5377 (1996).

[34]R. Wagner, S.-Y. Chen, A. Maksimchuk, and D. Umstadter, Phys. Rev. Lett. **78**, 3125 (1997).

[35]C. E. Clayton, D. Gordon, K. A. Marsh *et al.*, Phys. Rev. Lett. **81**, 100 (1998).

[36]S.-Y. Chen, G. S. Sarkisov, A. Maksimchuk, R. Wagner, and D. Umstadter, Phys. Rev. Lett. **80**, 2610 (1998).

[37]W. Lu, M. Tzoufras, C. Joshi *et al.*, "Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime," Phys. Rev. ST Accel. Beams (submitted).

[38]S. P. D. Mangles, B. R. Walton, M. Tzoufras *et al.*, Phys. Rev. Lett. **94**, 245001 (2005).

[39]D. Umstadter, J. K. Kim, and E. Dodd, Phys. Rev. Lett. **76**, 2073 (1996); E. Esarey, R. F. Hubbard, W. P. Leemans, A. Ting, and P. Sprangle, *ibid.* **79**, 2682 (1997).

[40]S. Backus, C. G. Durfee III, M. M. Murnane, and H. C. Kapteyn, Rev. Sci. Instrum. **69**, 1207 (1998).

[41]J. R. Marqués, F. Dorchies, P. Audebert *et al.*, Phys. Rev. Lett. **78**, 3463 (1997); J. R. Marqués, J. P. Geindre, F. Amiranoff, P. Audebert, J. C. Gauthier, A. Antonetti, and G. Grillon, *ibid.* **76**, 3566 (1996).

[42]C. W. Siders, S. P. Le Blanc, D. Fisher, T. Tajima, M. C. Downer, A. Babine, A. Stepanov, and A. Sergeev, Phys. Rev. Lett. **76**, 3570 (1996).

[43]N. H. Matlis, S. Reed, S. S. Bulanov *et al.*, Nat. Phys. **2**, 749 (2006).

[44]F. Amiranoff, S. Baton, D. Bernard *et al.*, Phys. Rev. Lett. **81**, 995 (1998).

[45]S. Wilks, J. M. Dawson, W. B. Mori, T. Katsouleas, and M. E. Jones, Phys. Rev. Lett. **62**, 2600 (1989).

[46]V. Malka, S. Fritzler, E. Lefebvre *et al.*, Science **298**, 1596 (2002).

[47]J. Rosenzweig, B. Breizman, T. Katsouleas, and J. J. Su, Phys. Rev. A **44**, R6189 (1991).

[48]W. B. Mori, T. Katsouleas, C. B. Darrow, C. E. Clayton, C. Joshi, J. M. Dawson, C. B. Decker, K. Marsh, and S. C. Wilks, *Proceedings of the 1991 Particle Accelerator Conference, San Francisco* (IEEE, Piscataway, NJ, 1991), Vol. 1, p. 564; A. Pukhov and J. Meyer-ter-Vehn, Appl. Phys. B **74**, 355 (2002).

[49]R. L. Morse and C. W. Nielson, Phys. Fluids **14**, 830 (1971).

[50]R. G. Hemker, F. S. Tsung, V. K. Decyk, W. B. Mori, S. Lee, and T. Katsouleas, *Proceedings of the 1999 Particle Accelerator Conference, New York, 1999*, edited by A. Luccio and W. MacKay (IEEE, Piscataway, NJ, 1999), Vol. 5, p. 367.

[51]A. Pukhov, J. Plasma Phys. **61**, 425 (1999).

[52]D. F. Gordon, W. B. Mori, and T. M. Antonsen, Jr., IEEE Trans. Plasma Sci. **28**, 1224 (2000).

[53]C. Nieter and J. R. Cary, J. Comput. Phys. **196**, 448 (2004).

[54]P. Mora and T. A. Antonsen, Jr., Phys. Plasmas **4**, 217 (1997).

[55]C. Huang, V. K. Decyk, C. Ren, M. Zhou, W. Lu, W. B. Mori, J. H. Cooley, T. M. Antonsen, Jr., and T. Katsouleas, J. Comput. Phys. **217**, 658 (2006).

[56]D. Whittum, Phys. Plasmas **4**, 1154 (1997).

[57]W. Mori, in *Proceedings of Advanced Acceleration Concepts, Mandalay Beach, CA, 2002*, edited by C. E. Clayton and P. Muggli, AIP Conf. Proc. No. 647 (AIP, Melville, NY, 2002), p. 11.

[58]F. S. Tsung, R. Narang, W. B. Mori, C. Joshi, R. A. Fonseca, and L. O. Silva, Phys. Rev. Lett. **93**, 185002 (2004).

[59]J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.-P. Rousseau, F. Burgy, and V. Malka, Food Sci. Technol. (London) **431**, 541 (2004); S. P. D. Mangles, C. D. Murphy, Z. Najumdin *et al.*, *ibid.* **431**, 535 (2004); C. T. Hsieh, C.-M. Huang, C.-L. Chang, Y.-C. Ho, Y.-S. Chen, J.-Y. Lin, J. Wang, and S.-Y. Chen, Phys. Rev. Lett. **96**, 095001 (2006); B. Hidding, K.-U. Amthor, B. Liesfeld *et al.*, *ibid.* **96**, 105004 (2006); E. Miura, K. Koyama, S. Kato, N. Saito, M. Adachi, Y. Kawada, T. Nakamura, and M. Tanimoto, Appl. Phys. Lett. **86**, 251501 (2005); T. Hosokai, K. Kinoshita, T. Ohkubo *et al.*, Phys. Rev. E **73**, 036407 (2006); C. G. R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Neiter, J. Cary, and W. P. Leemans, Food Sci. Technol. (London) **431**, 538 (2004).

[60]C. G. R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, J. Cary, and W. P. Leemans, Phys. Rev. Lett. **95**, 145002 (2005).

[61]C. Durfee and H. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993).

[62]W. P. Leemans, P. Volfbeyn, K. Z. Guo, S. Chattopadhyay, C. B.

Schroeder, B. A. Shadwick, P. B. Lee, J. S. Wurtele, and E. Esarey, Phys. Plasmas **5**, 1615 (1998).
[63]D. Spence and S. Hooker, J. Opt. Soc. Am. B **17**, 1565 (2000); W. P. Leemans, B. Nagler, A. J. Gonsalves, Cs. Tóth, K. Nakamura, C. G. R. Geddes, E. Esarey, C. B. Schroeder, and S. M. Hooker, Nat. Phys. **2**, 696 (2006).
[64]T. Hosokai, M. Kando, H. Dewa, H. Kotaki, S. Kondo, N. Hasegawa, K. Nakajima, and K. Horioka, Opt. Lett. **25**, 10 (2000).
[65]B. Cross, C. Courtois, and G. Malka, IEEE Trans. Plasma Sci. **28**, 1071 (2000).
[66]S. Lee, T. Katsouleas, P. Muggli *et al.*, Phys. Rev. ST Accel. Beams **5**, 011001 (2002); C. Joshi and T. Katsouleas, Phys. Today **56** (6), 47 (2003).
[67]J. B. Rosenzweig, D. B. Cline, B. Cole, H. Figueroa, W. Gai, R. Konecny, J. Norem, P. Schoessow, and J. Simpson, Phys. Rev. Lett. **61**, 98 (1988).
[68]N. Barov, M. E. Conde, W. Gai, and J. B. Rosenzweig, Phys. Rev. Lett. **80**, 81 (1998).
[69]H. Nakanishi, Y. Yoshida, T. Ueda *et al.*, Phys. Rev. Lett. **66**, 1870 (1991).
[70]V. Yakimenko, I. V. Pogorelsky, I. V. Pavlishin *et al.*, Phys. Rev. Lett. **91**, 014802 (2003).
[71]J. B. Rosenzweig, P. Schoessow, B. Cole, W. Gai, R. Konecny, J. Norem, and J. Simpson, Phys. Rev. A **39**, 1586 (1989).
[72]N. Barov, M. E. Conde, W. Gai, and J. Rosenzweig, Phys. Rev. Lett. **80**, 81 (1998).
[73]N. Barov, J. B. Rosenzweig, M. E. Conde, W. Gai, and J. G. Power, Phys. Rev. ST Accel. Beams **3**, 011301 (2000).
[74]J.-P. Carneiro, R. A. Carrigan, M. S. Champion *et al.*, in *Proceedings of the 1999 Particle Accelerator Conference, New York, 1999*, edited by A. Luccio and W. MacKay (IEEE, Piscataway, NJ, 1999), Vol. 3, p. 2027.
[75]N. Barov, M. C. Thompson, K. Bishofberger, J. B. Rosenzweig, H. Edwards, and J. Santucci, in *Proceedings of Advanced Acceleration Concepts, Mandalay Beach, CA 2002*, edited by C. E. Clayton and P. Muggli, AIP Conf. Proc. No. 647 (AIP, Melville, NY, 2002), p 71.
[76]K. Bane, P. Chen, and P. Wilson, IEEE Trans. Nucl. Sci. **NS-32**, 3524 (1985).
[77]T.-Y. Chien, C.-L. Chang, C.-H. Lee, J.-Y. Lin, J. Wang, and S.-Y. Chen, Phys. Rev. Lett. **94**, 115003 (2005).
[78]H. Suk, N. Barov, J. B. Rosenzweig, and E. Esarey, Phys. Rev. Lett. **86**, 1011 (2001).
[79]M. C. Thompson, J. B. Rosenzweig, and H. Suk, Phys. Rev. ST Accel. Beams **7**, 011301 (2004).
[80]E. Kallos, P. Muggli, T. Katsouleas *et al.*, in *Proceedings of Advanced Acceleration Concepts, Lake Geneva, WI, 2006*, edited by M. Conde and C. Eyberger, AIP Conf. Proc. No. 877 (AIP, Melville, NY, 2006), p. 520.
[81]M. Hogan, R. Assmann, F.-J. Decker *et al.*, Phys. Plasmas **7**, 2241 (2000).
[82]J. Seeman, W. Brunk, R. Early, M. Ross, E. Tillmann, and D. Walz, in *Proceedings of the Linear Accelerator Conference (LINAC)*, Stanford, CA, June 1986 (SLAC, Menlo Park, CA, 1986), p. 441.
[83]P. Muggli, K. A. Marsh, S. Wang, C. E. Clayton, S. Lee, T. C. Katsouleas, and C. Joshi, IEEE Trans. Plasma Sci. **27**, 791 (1999).
[84]P. Emma, I. Iverson, P. Krejcik, P. Raimondi, and J. Safranek, in *Proceedings of the 2001 Particle Accelerator Conference, Chicago, 2001*, edited by P. Lucas (IEEE, Piscataway, NJ, 2001), Vol. 5, p. 4038.
[85]P. Muggli, S. Lee, T. Katsouleas *et al.*, Food Sci. Technol. (London) **411**, 43 (2001).
[86]C. Clayton, B. E. Blue, E. S. Dodd *et al.*, Phys. Rev. Lett. **88**, 154801 (2002).
[87]S. Wang, C. E. Clayton, B. E. Blue *et al.*, Phys. Rev. Lett. **88**, 135004 (2002).
[88]P. Muggli, B. E. Blue, C. E. Clayton *et al.*, Phys. Rev. Lett. **93**, 014802 (2004).
[89]M. Hogan, C. E. Clayton, C. Huang *et al.*, Phys. Rev. Lett. **90**, 205002 (2003).
[90]B. Blue, C. E. Clayton, C. L. O'Connell *et al.*, Phys. Rev. Lett. **90**, 214801 (2003).
[91]C. Joshi, B. Blue, C. E. Clayton *et al.*, Phys. Plasmas **9**, 1845 (2002).
[92]D. Bruhwiler, D. A. Dimitrov, J. R. Cary, E. Esarey, W. P. Leemans, and R. E. Giacone, Phys. Plasmas **10**, 2022 (2003).
[93]C. L. O'Connell, C. D. Barnes, F.-J. Decker *et al.*, Phys. Rev. ST Accel. Beams **9**, 101301 (2006).
[94]M. Hogan, C. D. Barnes, C. E. Clayton *et al.*, Phys. Rev. Lett. **95**, 054802 (2005).
[95]T. Katsouleas, Phys. Plasmas **13**, 055503 (2006).
[96]I. Blumenfeld, C. E. Clayton, F.-J. Decker *et al.*, Food Sci. Technol. (London) **445**, 741 (2007).
[97]C. Huang (private communication).
[98]D. K. Johnson, D. Auerbach, I. Blumenfeld *et al.*, Phys. Rev. Lett. **97**, 175003 (2006).
[99]D. K. Johnson, C. E. Clayton, C. Huang *et al.*, "Positron source from x-rays emitted by plasma betatron motion," in Proceedings of the LINAC 2006 Conference, Knoxville, TN (in press).