Laser-Driven Plasma Accelerators Operating in the Self-Guided, Blowout Regime

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(Invited Paper)

***Abstract*—In this paper, some recent developments in the area of laser-driven plasma wakefield accelerators are reviewed. In particular, we discuss the acceleration of electrons by laser-induced plasma wakes in the so-called blowout regime. In this regime, the laser pulse is sufficiently intense to completely blowout all the plasma electrons and create a cavity or a bubble comprising plasma ions. The plasma electrons are attracted back toward the axis of propagation and form a thin sheath around the ions. The transverse and longitudinal electric fields of this cavity have desirable characteristics for accelerating a high-quality electron beam. In this blowout regime, the laser pulse can be self-guided by the wake it creates over tens of Rayleigh lengths until it is fully pump depleted. The mechanisms for producing such nonlinear wakes in plasmas, injecting electrons into the wakes so that they can be accelerated, competing instabilities that can adversely affect the beam quality, and recent experimental progress are discussed.**

***Index Terms*—Laser acceleration, plasma, wakefield.**

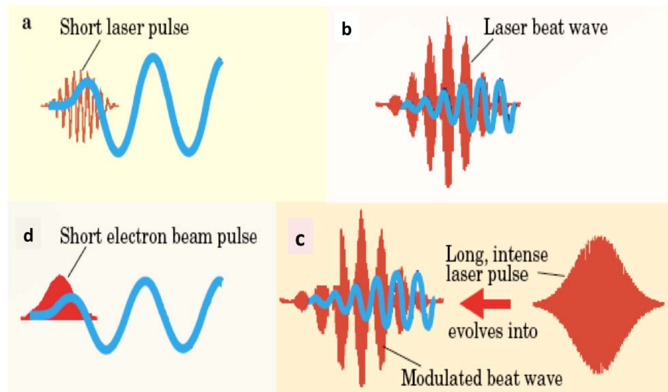

Fig. 1. Four ways of exciting a relativistic plasma wave or a wake (blue). In all cases, (a)–(d) Drive pulse (red) travels from right to left.

I. INTRODUCTION

SINCE the invention of the laser over half a century ago, lasers have become indispensable in advancing many subfields of physical sciences and technology [1]. These include optical communications, optoelectronics, nonlinear optics, spectroscopy, quantum optics, ultrafast science, and charged particle acceleration. In this tutorial review article, I will discuss how intense laser pulses are being used for accelerating electrons far more rapidly than by any other technique [2], [3]. After over three decades of sustained basic research, laser-particle acceleration is poised to turn into a useful driver technology for compact accelerators and possibly light sources [4].

It is well known that the oscillating electric field of a focused (Gaussian) laser pulse can have a significant longitudinal component $E_z \sim E_r/kw_0$. Here E_r is the transverse electric field, $k = 2\pi/\lambda$, and w_0 is the spot size of the focused laser pulse of wavelength λ. The basic requirement for a large energy gain ΔW is that the particle propagating in the z-direction should interact with E_z for a long distance L since $\Delta W = -\int_0^L eE_z dz$. However, since the phase velocity v_ϕ of the electromagnetic wave near the focus in vacuum is $\sim c\ (1 + 1/kZ_R)$, highly relativistic electrons moving at the speed of light will dephase (slip) with respect to the accelerating field in a distance $\sim Z_R$. Here, relativistic electrons are assumed to move at c and $Z_R = \pi w_0/\lambda$ is the Rayleigh length. This continuous dephasing will limit the energy gain to $\Delta W \sim eE_r w_0$ even if the electron can somehow be extracted from the laser beam. Even if we consider the most intense laser pulses (1-PW pulse focused down to a spot size w_0 of 1-μm for instance), the maximum energy gain is limited to about a gigaelectronvolt. How then can one use intense laser pulses as drivers for high-energy accelerators?

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II. LASER-GENERATED PLASMA WAKES: BASIC CONCEPTS

When an intense but short laser pulse is propagated through an underdense $\omega_0 > \omega_p$ plasma, it can leave behind a disturbance or a wake whose longitudinal electric field can be comparable to the transverse electric field of the laser pulse [5]. This scheme is, therefore, known as the laser wakefield accelerator (LWFA) [6] [see Fig. 1(a)]. This wave is rather efficiently generated if the laser pulselength $c\tau \sim \lambda_p$ and the normalized vector potential of the laser $a_o \sim 1$. Here $\lambda_p = 2\pi c/\omega_p$ with ω_p is the plasma frequency, $a_0 = eA/mc^2$ is the normalized laser strength parameter, and A is the vector potential of the laser pulse with frequency ω_0. Here Gaussian units are used unless otherwise stated.

For a laser pulse whose $w_0 \gg \lambda_p$, the mechanism of generating the wake is as follows. The laser pulse exerts a longitudinal, radiation-driven "ponderomotive force" $F_p \propto -\nabla I$ on the plasma electrons pushing them forward and backward from regions of high to low laser intensity. These electrons are, however, pulled back by the Coulomb force of the ions—that are essentially stationary because they are far more massive compared with the electrons—as the short laser pulse passes. The electrons overshoot their initial position setting up an E_z field and oscillate through the ions at approximately ω_p. The phasing of these oscillations is such that the υ_ϕ of this wake is equal to the group velocity υ_g of the laser pulse. This is simply a consequence of causality since after all it is the laser pulse that generates the wake. A relativistic electron moving in the same direction as the wake can remain synchronous with the accelerating portion of E_z for a distance $L \gg \lambda_p$ (in the lab frame), and therefore gain a significant amount of energy. If we assume that the group velocity of the laser pulse in the plasma remains constant then the accelerating electrons moving essentially at c dephase with the wave after they have overtaken the wake by $\lambda_p/2$ in the wave frame. The dephasing length now is $L_d = (c\lambda_p/(2(c - \upsilon_\phi)))$, and therefore maximum energy gained $\Delta W = eE_z L_d = (E_z/E_0)(\omega_p/c)L_d mc^2$. Here $E_0 = (mc\omega_p/e)$ is the wave breaking field limit [7], the maximum value of the longitudinal electric field for a 1-D cold-plasma oscillation with $\upsilon_\phi = c$. A useful expression is $E_0(\text{eV/m}) = 96.2\sqrt{n_0}$ (cm^{-3}) where n_0 is the unperturbed or initial plasma density. Thus $E_z \sim 100$ GV/m (MKS) may be produced in a 10^{18} cm^{-3} density plasma. Such electric fields are more than three orders of magnitude greater than those currently used in microwave powered accelerating cavities and thus hold the key to miniaturizing particle accelerators.

For small amplitude wakes [7], the normalized dephasing length $k_p L_d$ is given by ω_0^2/ω_p^2 which is inversely proportional to plasma density. If L_d is longer than $\sim 2Z_R$—where Z_R is the distance over which the intensity of a focused laser beam drops by a factor of two on either side of the best focus—the laser must either be self-guided by the plasma [8] or propagated in a preformed plasma channel [9]–[11] such that particles gain close to the dephasing-limited energy. As the laser pulse gives energy to the wake, it is depleted and eventually no longer able to excite a wake. The distance over which the energy depletion occurs is called the pump depletion length L_{pd}. For extremely nonlinear wakes in dilute plasmas, L_{pd} and $L_d \gg Z_R$, therefore the laser pulse must be either externally or self-guided.

Typical (dephasing limited) energy gains in an LWFA are limited by the available laser power to tens of megaelectronvolt to a few gigaelectronvolts. Therefore, for a future plasma accelerator operating at the energy frontier of high-energy physics (one to a few teraelectronvolts) many such stages of laser-plasma accelerators need to be combined in series [4]. In order to preserve the beam quality, namely, the small energy spread and the beam emittance, exquisite control on the longitudinal phase ($O \sim$ fs) and transverse spatial (submicrometer) alignment from one stage to the next is needed.

There are other ways to excite relativistic $\upsilon_\phi \sim c$ plasma waves including using a two-frequency laser pulse such that their frequency difference $\Delta\omega = \omega_1 - \omega_2$ is equal to ω_p. In this scheme [Fig. 1(b)] known as the plasma beat-wave accelerator (PBWA), the plasma wave is resonantly excited over many plasma periods to a large amplitude (E_z) using a modest intensity ($a_0 \sim 0.1$) laser pulse [12]–[17]. Alternatively, a single intense, $a_0 \sim O(1)$, laser pulse that is many plasma periods long can generate a plasma wave via the stimulated (forward) Raman scattering instability [Fig. 1(c)] or by the self-modulation instability [18]–[25]. These instabilities generate a series of Stokes and anti-Stokes sidebands that are frequency shifted from the initial laser frequency by $\pm\omega_p$. These sidebands beat with the pump and produce an amplitude-modulated waveform that can then further lead to the growth of the wake via the ponderomotive force. In this sense, all three laser-plasma schemes described here are "Raman accelerators"—PBWA and LWFA can be thought as resonant Raman scattering and impulse Raman scattering, respectively, except that unlike the usual solid, liquid, or gaseous Raman media, the plasma medium affords an additional degree of freedom—the plasma wave is able to exchange energy with free charges.

Here we should also mention that wakes in plasmas can also be excited by an intense, short electron bunch [Fig. 1(d)] [6], [26]–[34]. Now, it is the Coulomb repulsion force of the electron bunch (extra negative charges propagating through an initially charge neutral plasma) that induces the wake. This scheme known as the plasma wakefield accelerator has become a very active subfield of research within the beam physics community in recent years. Both electron and positron bunches [35]–[38] have been used to generate wakes with great success.

There are other novel approaches to particle acceleration. We mention a few here. One scheme uses hollow dielectric tubes as accelerating structures powered by charged particle beams [39]. Another uses a laser pulse to excite a TM-like electromagnetic mode in a miniature photonic bandgap structure [42], [43] or in a slow-wave structure ($\upsilon_\varphi \cong c$) (accelerator on a chip concept) [39], [40] or in a plasma [44]. In principle, any mechanism that causes a charge particle to radiate can be configured to accelerate a charge particle [45]. All these approaches are being investigated experimentally.

III. Linear and Highly Nonlinear LWFAs

The wake induced by a short laser pulse is said to be in the linear regime if $E_z/E_0 \ll 1$. This is equivalent to saying that the plasma electron density modulation associated with the wake $\delta n/n \ll 1$. Laser driven wakes with $c\tau \sim \lambda_p$, and $a_0 \ll 1$ typically excite wakefields in the linear regime. The electron density modulation is sinusoidal, and the accelerating E_z and transverse focusing E_r fields of the wake are $\pi/2$ out of phase with one another [46]. Thus, there is a quarter wavelength ($\pi/4$ radians) region of phase where the fields are both accelerating and focusing and therefore useful for acceleration. The actual L_d is, thus, one half of the value mentioned earlier. In the linear regime, this is true for both electrons and positrons except that the accelerating and focusing region for the positrons is π radians out of phase with that for the electrons.

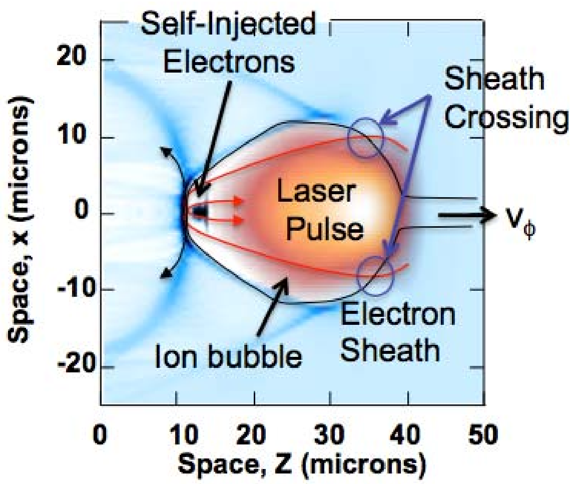

Fig. 2. PIC code simulation of a laser-wakefield accelerator operating in the blowout or bubble regime. A "matched" 60-fs (FWHM) laser pulse with $a_0 \cong 4$ propagating through a preformed 6×10^{18} cm^{-3} plasma is seen to completely evacuate the region surrounding it of plasma electrons (blue) and leave behind an ion cavity or a bubble (white). Cartoon trajectories of two plasma electrons (black lines) are shown as they stream toward the laser pulse, are then blown out by it, and form part of a negatively charged sheath around the ion cavity. These electrons cross the axis of the laser pulse, overshoot, and form the wake. If the laser pulse is intense enough $a_0 > 4$, some electrons (red lines—cartoon) that started out farther from the laser axis can cross the sheath and gain enough energy from the accelerating field to be injected and trapped inside the potential well of the wake.

When the short laser pulse becomes so intense that $a_0 \geq 1$, the wake produced becomes extremely nonlinear. The on-axis E_z profile is no longer sinusoidal but has a saw-tooth shape while the electron density perturbation $\delta n/n$ is strongly spiked. The power needed to excite such nonlinear wakes typically approaches and even exceeds the so-called critical power for relativistic self-focusing P_c given by [47]

$$P_c(\text{GW}) = 17.4\left(\omega_0^2/\omega_p^2\right)$$

where the transverse intensity profile $I(r)$ of the laser pulse causes the plasma to act like a convex lens due to the relativistic increase of the electron mass. If the laser pulse is not "matched," (i.e., its spreading by diffraction is exactly balanced by relativistic self-focusing) and its power is above P_c, the laser pulse will continue to focus until the plasma electrons are completely expelled by the ponderomotive force of the laser, thus saturating the process. The concept of matching has a very powerful physical significance. If $P > P_c$ but w_0 is larger/smaller than the matched spot size (R_m) the laser spot size at the middle of the pulse will oscillate until it asymptotes to R_m. For simplicity, here, we will assume that the laser spot size $w_0 = R_m$, i.e., it is initially matched to the plasma.

IV. Blowout or Bubble Regime

If the laser $a_0 \geq 2$ and $c\tau \sim \lambda_p/2$, matching occurs when $k_p w_0 \cong k_p R_m = k_p R_b = 2\sqrt{a_o}$. Here $R_b(R_m)$ is the blowout (matched) radius. As the laser intensity rises, all the plasma electrons may be blown out creating an ion cavity [48]. The transversely blown-out electrons form a sheath around this nearly spherical cavity with a radius $R_b \cong w_0$, as shown in Fig. 2. This is why this regime is sometimes referred to as the bubble regime. It was observed by Pukov and Mayer-ter Vehn [49] in particle-in-cell (PIC) simulations of LWFA in the very high a_0 limit. Most experiments to-date have used $a_0 < 5$, therefore the scaling laws of [48] are more applicable to these moderately large a_0 experiments.

The electric field structure of this cavity has many desirable properties for accelerating charged particles. First, the transverse focusing force increases linearly with the radial position—a very desirable situation for minimizing any emittance growth of electrons contained in a longitudinally thin slice of the accelerating bunch at that position. Furthermore, once the plasma electrons are blown out, the accelerating cavity comprises only of plasma ions, therefore the focusing force on all the slices of the accelerating electron bunch can be constant; i.e., $\partial_\xi F_r \approx 0$. Here $\xi = (z - v_\phi t)$ is the distance measured in the frame moving with the wake. Here F_r is the radial or transverse focusing force and $F_z = -eE_z$ is the longitudinal accelerating force. As in the case of hollow metallic cavities the Penofsky–Wenzel theorem [50], $\partial_\xi F_r \approx \partial_r F_z$ holds for a plasma cavity and therefore F_z is independent of r and all the particles in a single-slice gain energy at the same rate [33]. If the accelerating bunch contains a significant amount of charge, it can extract a significant fraction of the energy stored in the wake. In this process of beam loading, the electric field of the wake tends to become flat and the particles in all the longitudinal slices are accelerated at nearly the same gradient [51], thereby reducing the energy spread of the electron bunch.

The ion cavity has another beneficial effect of assisting in the guiding of the laser pulse [52], [53]. It can be shown that the minimum density depression of a plasma channel needed to guide a laser pulse is roughly $(\delta n/n) \leq 4/(k_p w_0)^2$ [54]. In the bubble regime, most of the laser pulse resides within the ion cavity, as shown in Fig. 2, i.e., $\delta n/n \sim 1$, so it can be guided by the co-propagating wake itself. However, the very front of the laser pulse as it is blowing out the plasma electrons and creating the wake is weakly guided and continues to diffract [55]—albeit slower than the usual vacuum expansion rate (see Fig. 3). The rate at which the front portion of the pulse is etched away is approximately $v_{\text{etch}} = c(\omega_p/\omega_o)^2$. This etching of the laser pulse causes it to lose energy. Eventually, it cannot excite a wake that has the minimum density perturbation needed for guiding. This pump depletion distance [48] is given by $L_{\text{pd}} = (c/v_{\text{etch}})c\tau$ (FWHM) $\approx c\tau$ (FWHM)$(\omega_0/\omega_p)^2$. Here τ (FWHM) is the full-width at half-maximum (FWHM) time duration during which the pulse is intense enough to produce the minimum wake amplitude necessary to guide the pulse.

Up until now, we have assumed that the laser pulse frequency spectrum is unaffected by the formation of the wake, and that only the laser pulse energy is depleted. However, this is not the case if the cavity is only partially depleted of plasma electrons. In forming the wake by pushing out the plasma electrons, the laser photons are frequency downshifted: process called photon deceleration [56], [57]. Laser photons in the back of the pulse on the other hand can be frequency upshifted (photon acceleration), especially if they reside in the electron density spike at the end of the ion cavity where

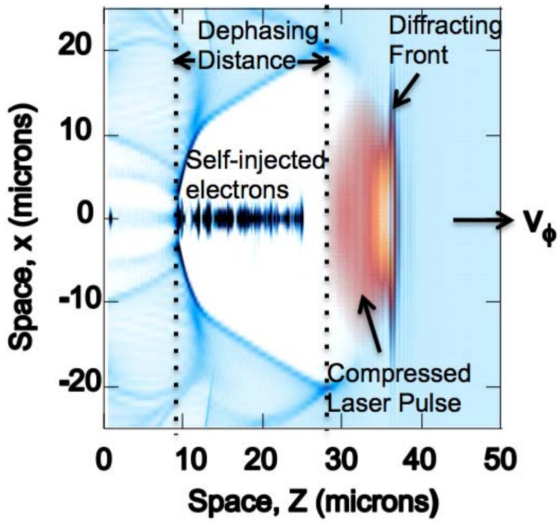

Fig. 3. Injected electrons reach their maximum energy gain when they reach the center of the bubble shown here by distance between the two black dotted lines. The distance over which this happens in the laboratory frame is the dephasing length. The laser pulse here is close to laser pump depletion due to gradual diffraction and wake generation. The front of the laser pulse continues to diffract away while the rest of the pulse gets compressed.

the returning plasma electrons cross the axis [49], [53], [54]. The group velocity of a higher frequency photon packet in plasma is greater than that of a lower frequency packet; hence, the process is called photon acceleration and deceleration. The higher frequency photons at the back now travel faster than the lower frequency photons at the front, causing the laser pulse to compress longitudinally. This pulse compression and photon deceleration in the leading edge of the pulse increase the local a_0 of the laser pulse. This in turn exacerbates the electron blowout even further and can cause self-injection and trapping of electrons. This regime where the laser pulse undergoes significant spatial and spectral evolution is sometimes referred to as forced LWFA [58]. Eventually, the laser pulse is significantly depleted; the phase velocity of the wake itself begins to decrease and the accelerating electrons can overtake the reduced amplitude wake and escape the plasma.

In the matched-blowout regime, simple scaling laws [48] can be derived for $E_{\max}$ and ΔW assuming a spherical cavity radius R_b. Using Gauss' law, the maximum electric field at the edge of this sphere is given by $E_{\max} \propto (en_e/\varepsilon_0)R_b$. This can be rewritten using the matching condition as $(eE_{\max}/m) \propto (\omega_p^2(\sqrt{a_0})/k_p)$ or in normalized units, $(eE_{\max}/mc\omega_p) = \sqrt{a_0}$. The amount of energy gained by an electron from this field can be found by integrating the force $-eE_z(z)$ from the edge of the spherical blowout where $E_z = E_{\max}$ to the center where $E_z = 0$. Since the "useful" (neglecting the spike in E_z due to the spike in electron density) E_z is approximately linear with ζ, the average electric field is $E_{\max}/2$, and therefore the energy gain is given by $(\Delta W/mc^2) = (2/3)a_0(\omega_0/\omega_p)^2$. One can see that for a given laser frequency the energy gain increases as the plasma density is decreased [48]. This is because at lower densities the phase velocity of the wake increases, thereby increasing the dephasing length. The nonlinear dephasing length is longer than the linear one because the bubble radius R_b or the cavity size itself depends on a_0 of the laser pulse giving $k_pL_d = 4/3\ (\omega_0/\omega_p)^2\sqrt{a_0}$ [48].

One can estimate the maximum number of electrons (charge) that can be accelerated in a linear LWFA. The accelerating charges extract energy from the wakefield. The maximum number of electrons also called the "beam load" that can be placed in a small longitudinal slice of a wakefield can be estimated by calculating the wake generated by these electrons. If this wake is π radians out of phase with the laser-produced wake, it will destructively interfere with the laser pulse-induced wake. The number of electrons required to produce a wakefield that will cancel the accelerating field is called the limiting beam load [59] and is given by

$$N_{\max} = \frac{n_0 A_b}{k_p}\frac{E_z}{E_0} \approx 5 \times 10^5 \frac{E_z}{E_0} A_b(\text{cm}^2)\sqrt{n_0(\text{cm}^{-3})}$$

assuming $k_p\sigma_z \ll 1$, $(E_z/E_0) \ll 1$ and A_b is the cross-sectional area of the bunch with longitudinal width σ_z. As $N \to N_{\max}$ the energy spread $(\Delta\gamma/\gamma) \to 1$. This is because the first electron in the beam load sees the unperturbed E_z whereas the last electron sees zero E_z. From energy conservation arguments, the beam loading or energy extraction efficiency $\eta = (N/N_{\max})/(2 - (N/N_{\max}))$. Thus, as $N \to N_{\max}$ the energy extraction efficiency (from the wake) by the beam load approaches 100%.

Theory for beam loading in the blowout regime has been developed. It turns out that a trapezoidal electron bunch (where charge density drops from the front to the back) can flatten the approximately linearly increasing the E_z field [51]. It is possible to achieve an extremely small energy spread (<1%) and high (wake to accelerating beam) energy transfer efficiency (>90%) by crafting the current profile of the beam. A self-consistent theory for positron beam loading is still lacking.

V. Electron Injection and Acceleration

In the linear regime, the longitudinal electric field and hence the plasma wake potential is periodic. Actually for relativistic wakes, we use the pseudopotential $\psi = (\phi - A_z)$ where ϕ is the electrostatic potential and A_z is the z component of the vector potential. In the case of the nonevolving wake, the energy gained by a charged particle from the wake is returned to the wake if the particle subsequently traverses the decelerating phase of the field. However, the energy gain occurs while the particle is sampling the negative E_z, which mostly happens when the particle has a velocity that is equal to or greater than the phase velocity of the wake. Such a particle is "trapped" by the potential well or bucket of the wake. Particles that are either too slow or too energetic execute the so-called passing orbits exchanging far less energy with the wave. The minimum energy that an electron must have to be trapped is called the trapping threshold. This threshold is dependent on the wave amplitude [60]. The larger the wake, the smaller the energy needed to trap and accelerate the electron: however, the larger the phase velocity of the wake, the higher is the trapping threshold.

For highly relativistic wakes $\gamma_\phi \gg 1$, the plasma electrons are not easily trapped unless the cavity size and thereby v_ϕ is "breathing" due to laser spot size oscillations due to imperfect matching or plasma density gradients or plasma density inhomogeneity [61]. Another way of injecting electrons in such wakes is to preaccelerate and then bunch the electrons using a traditional accelerator followed by an inverse free-electron laser (IFEL) so that they are already moving at the same speed as the wake [62], [63]. A third method is to create the electrons by ionization within the wake [64]. Alternatively, if the passing orbit of the electron is too slow to be trapped or if the phase velocity of the wake is too high, one of these must be perturbed by some technique so that the plasma electrons may become trapped [65]–[67]. I will briefly elaborate on some methods used for injecting the electrons into the relativistically moving wakefield.

A. Self-Injection

In an extremely nonlinear wakefield (typically produced by $a_0 > 4$ laser pulses), the trajectories of some of the electrons forming the sheath around the ion cavity can cross the sheath and these electrons find themselves in the accelerating phase of the wakefield, as shown in Fig. 2. These electrons are initially moving backwards in the wave frame. If they can gain sufficient energy from the wakefield to move at the phase velocity v_ϕ of the wake as they reach the near the $E_{z,\max}$, they will be trapped and further accelerated by the wakefield.

B. Ionization-Induced Injection

The self-trapping threshold can be considerably reduced by producing the electrons inside the wakefield [68]–[70] by laser ionization.

How is this done in practice? The laser pulse ionizes a mixture of gases. The mixture contains one (majority) species of atoms that is rather easily ionized by the rising edge of the laser pulse and form the wake. The second (minority) species of atoms (comprising ~0.1—few percent of the total number density of atoms) typically has a large step in the ionization potential between two closed shells. The outer shell electrons of these minority atoms are also ionized during the rise time of the laser pulse and contribute to the formation of the wake. The inner-shell electrons, however, are not ionized until the laser intensity exceeds their ionization threshold near the peak of the pulse. This is illustrated in Fig. 4.

The ionization of the inner (K) shell electron(s) occurs first near the laser axis. These electrons now see a much greater wake potential difference $\Delta\psi = \psi_i - \psi_f$. Here ψ_i is the initial potential where the electron is produced by ionization and ψ_f is the final or maximum potential at the very back of the wake. It has been shown [64] that if $\Delta\psi < -1$ electrons may be trapped in the cavity. For the outer shell electrons produced at the very front of the laser pulse when the potential is $\sim\psi_0$, this is difficult but for the inner-shell electrons born near the peak of the laser pulse it is far easier to fulfill this trapping condition [68].

By choosing an appropriate minority species atom having an ionization threshold close to an $a_0 \sim 2$ (nitrogen K-shell electrons for instance), the laser power requirement for injecting and trapping electrons into the wake can, thus, be reduced considerably. The use of plasmas produced using N atoms alone to inject electrons into the wake has also been demonstrated [71].

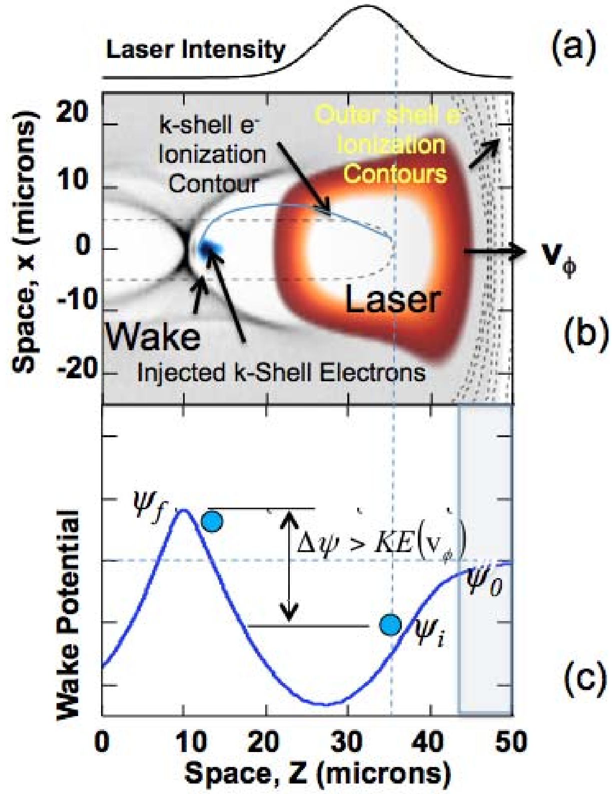

Fig. 4. Ionization injection of electrons in the wake. (a) Intensity variation of an initially Gaussian laser pulse. (b) As the laser pulse propagates through a gas such as nitrogen, the outer shell electrons are readily ionized early during the rise time of the pulse and blown out to form the wake. The inner-shell (K-shell) electrons are ionized close to the peak of the pulse, within the fully formed wake and thus injected near the back of the wake. (c) Wake pseudopotential ψ versus z. The potential difference $\Delta\psi$ between the initial position where the outer shell electrons are ionized ψ_0 and the final maximum value of the potential ψ_f is insufficient for trapping these electrons. However, for the K-shell electrons, $\Delta\psi = \psi_i - \psi_f < -1$ which is large enough to cause trapping. Trapping occurs if the potential difference $\Delta\psi$ is greater than the kinetic energy of the electron moving with the phase velocity of the wake, KE (v_ϕ) [63].

C. Optical Injection Techniques

Several optical injection schemes have been proposed for assisting electron injection into plasma wakes. We briefly discuss two here. In the first scheme, a second transversely propagating intense laser beam is tightly focused to overlap with the wake [72]. The ponderomotive force of the injection pulse can accelerate some of the plasma electrons so that they have enough energy to be trapped.

In a second scheme known as colliding pulse injection, two or even three laser pulses are used [73], [74]. In Fig. 5, we show the case where two colliding short laser pulses are used. The first "pump pulse" with frequency and wavenumber (ω_1, k_1) and a high a_1 excites the wake. The second "injection pulse" with (ω_2, k_2) and $a_2 < a_1$ is collided with the pump pulse. The beating of the two colliding pulses at $\Delta\omega = \omega_1 - \omega_2$ and $\Delta k = k_1 + k_2$ excites a short wavelength, low phase velocity plasma wave that perturbs the normally

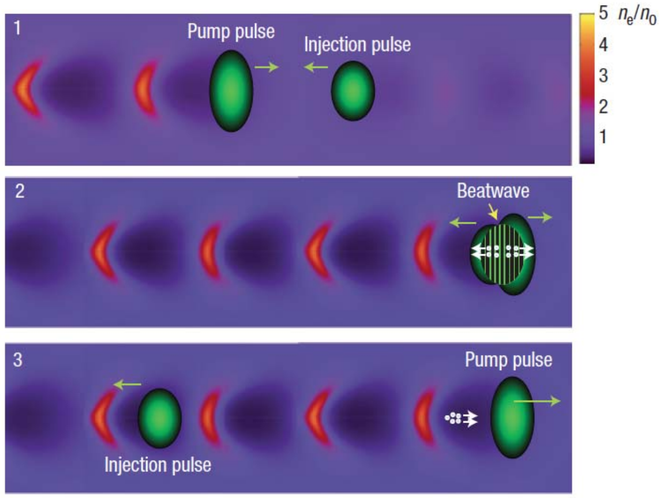

Fig. 5. Colliding pulse injection scheme employed by the LOA (France) group using a counter propagating injection pulse. (a) Pump laser produces a wake, but the wake is not intense enough to trap plasma electrons. (b) Beat wave generated by the overlap of pump and injection pulses pushes the remaining plasma electrons longitudinally. (c) As the injection pulse passes, some of these electrons can be injected into the first "bucket" of the wake to be accelerated (white dots).

passing trajectories of the plasma electrons so that they cross the separatrix to be injected into the wakefield for acceleration to high energies. The scheme works even if the pump and the injection pulses are frequency degenerate ($\Delta\omega = 0$, $\Delta k = 2k_1$).

D. Other Methods for Electron Injection

In analogy to a conventional traveling-wave accelerating structure, a witness beam of electrons or other charged particles may be preaccelerated and injected into a plasma wake to increase their energy. To minimize the energy spread of the accelerating particles, the injected beam should have a longitudinal width that is much less than λ_p and contain a sufficient charge to flatten E_z by beam loading. Additionally, the external electron beam must be synchronized with the wake such that it is injected into the correct accelerating and focusing phase of the wake. For a plasma density of 1×10^{17} cm^{-3}, the wake wavelength is roughly 100 μm so the externally injected electron bunch has to be much shorter than $\lambda_p/4$ or 25 μm and synchronized with an accuracy of a few femtoseconds.

One method for producing such a short synchronized bunch for injection is to prebunch the electrons exiting from a conventional accelerator using the IFEL [75] action. If the seed wave in the IFEL has the same wavelength as—and is phase locked to—the plasma wake then the bunched beam will be deterministically synchronized to the wake. A second method is to use an LWFA itself as an injector [76].

Both methods will require a significant effort to match the electron from the preaccelerator to the main plasma acceleration stage [63] in order to maximize the charge throughput and minimize the emittance growth of the beam [77].

VI. Instabilities and Radiation Loss

No paper on laser-plasma interactions would be complete without some discussion on instabilities and other energy loss mechanisms. In the case of laser-plasma interactions, the interaction of intense short laser pulses with plasmas can lead to many of the same parametric instabilities as those observed in conventional nonlinear optics [14], [78].

In the case of the LWFA, however, the laser pulse duration is on the order of one plasma period and the laser pulse continually moves into undisturbed plasma at the speed of light. Thus many of the instabilities that require many plasma or even ion periods to grow are suppressed. There are, however, two detrimental effects that can grow sufficiently during the formation of the wake that can degrade the emittance of the accelerating electron beam. These are hosing instability [79] and ion motion [80]. The hosing instability is a "head-to-tail instability" which means that any transverse displacement of a longitudinal slice of the accelerating electron beam is exponentially amplified when the drive pulse/wake propagates in the plasma. Consequently, the longer the accelerating beam propagates in the plasma, the greater the hosing amplification and thus emittance growth of the electron beam.

Ion motion is not a laser-plasma effect. It is rather the effect of the accelerating beam on the plasma ions, which in turn affects the emittance of the accelerating beam. Thus far we have been assuming that in the LWFA the more massive plasma ions remain stationary. However, if the accelerating electron beam is dense enough or is further focused by the space charge force of the ions such that the electron beam density exceeds the ion density by a factor greater than m_i/m_e, then the ions can react to the transverse electric field of the electrons and implode inward. The ion focusing force is now no longer perfectly linear and can lead to emittance growth. Study of these deleterious effects using PIC code simulations has shown that they do occur but their effect on the emittance growth may be acceptable [81] or mitigation strategies [82] may be possible. Careful experiments are needed to quantify the role of these effects on the accelerating beam emittance.

In addition to the two undesirable effects mentioned above, accelerating particles radiate energy. As particles are being accelerated, they also oscillate transversely [83], [84]. The physical reason for this oscillation is that an individual accelerating electron that is off axis experiences a focusing force due to the plasma ions, and is attracted inward. It overshoots the axis and oscillates about the axis at the betatron frequency $\omega_\beta = \omega_p/\sqrt{2\gamma}$. As the electron oscillates, it emits synchrotron-like radiation—mostly in the forward direction for a highly relativistic particle. The energy loss gradient is given by [85]

$$\frac{dW_{\mathrm{loss}}}{dz} = \frac{1}{3} r_e \gamma^2 \omega_\beta^2 K^2$$

where r_e is the classical electron radius, γ is the relativistic Lorentz factor, and the strength-parameter $K = \gamma(\omega_\beta/c) r_0$, with r_o being the displacement of the electron from the axis. Clearly at high enough γ, and/or r_o the rate of energy loss to radiation can approach the rate at which the electrons gain energy from the wakefield. This then is the ultimate limit to the maximum energy gain in a plasma accelerator. In practical terms particles with different radii will radiate different amounts of energy, causing the root-mean-squared energy spread of the beam to increase.

VII. Experiments

The current work in the LWFA field can be grouped in two broad subgroups: LWFAs operating in externally produced plasma channels [86], [87] and LWFAs operating in the self-guided, blowout regime [88]–[94]. In this section, I will mainly discuss the latter regime with examples from our own research in the last decade. The goal of our program was to develop a robust platform that can be scaled up to generate 10-GeV class beams [95] using the self-guided, fully blown-out regime of the LWFA by employing the PW class Ti-sapphire laser systems now operational or under construction without the need for employing plasma channels.

But first a brief history: The first demonstration of a wake produced by a single-short laser pulse was in 1996 by Ecole Polytechnique and the University of Texas at Austin groups [96], [97]. In these two early experiments, the laser spot size was much smaller than λ_p and the wake oscillation was dominated by radial motion of the electrons. Such wakes were mapped using a technique known as frequency domain interferometry. The Ecole Polytechnique group followed their work by externally injecting 3-MeV electrons into the wake and observed a maximum longitudinal field of 1.5 GeV/m [98].

These demonstrations were soon followed by several other experiments where the laser power was increased to about 10 TW. The laser pulse lengths were still longer than $\lambda_p/2$ but at the high plasma densities used in many of these experiments, the laser pulses rapidly evolved and shortened due to a combination of self-phase modulation (often called photon acceleration/deceleration), and group velocity dispersion while the front of the laser pulse etched away by local pump depletion. As these longer laser pulses propagated through the plasma, they became shorter and more intense and excited nonlinear wakefields which eventually self-trapped background plasma electrons. However, since the early experiments relied on laser pulse evolution before trapping could occur it was very difficult to control the injection and termination points of the electrons in the wakes. Nonetheless in a major breakthrough for the field three groups in 2004 observed the formation of quasi-monoenergetic electron beams in an LWFA [99]–[101]. In these experiments, beam loading and dephasing played an important role in producing a narrow-energy spectral peak at more-or-less the highest energy observed in the spectrum. Two of these three experiments used a gas jet as a target [99], [100]. The third experiment was carried out in a preformed plasma channel [101].

Extensive PIC code simulations were done to understand the mechanism of quasi-monoenergetic beam formation [102], [103]. Initially, quasi-monoenergetic referred to beams with FWHM energy spreads of smaller than 20%. Eventually, the energy spreads from LWFAs have been reduced to one to a few percent. Concurrently, a phenomenological theory of 3-D nonlinear wakefields was developed and scaling laws [48] derived for various important parameters such as the dephasing length, pump depletion length, the useful wake gradient and the energy gain as a function of laser a_0, laser to plasma frequency (ω_0/ω_p) ratio, and the laser pulse duration. The theory and supporting 3-D PIC code simulations showed that in the blowout region, an intense enough laser pulse with a spot size matched to the plasma, could be self-guided over the entire pump depletion length, which could be tens of vacuum Rayleigh lengths. Such self-guiding should therefore enable one to reduce the plasma density and yet guide the laser beam over a centimeter scale without the need for a preformed plasma channel thereby simplifying a practical LWFA device. This was one of the key breakthroughs that followed the observation of quasi-monoenergetic beams in LWFA. Until this realization, there was an erroneous perception that the front of the laser pulse would rapidly erode away [104], [105] because of diffraction at a rate of $\sim c/\omega_p$ per Z_R. Thus for a laser pulse with $c\tau \sim \lambda_p/2$, the maximum propagation distance would be only $\sim 3Z_R$.

The key issues in developing a 1-GeV class LWFA in the self-guided, blowout regime were as follows.

1) Prove that a short laser pulse could be self-guided over the pump depletion length that was far greater than $3Z_R$.
2) Show that the maximum energy gained by self-trapped electrons scales inversely with n_e.
3) Determine the power threshold and density threshold at which self-trapping occurs for existing 100-TW class lasers.
4) Find new methods of injecting electrons into the wake to lower this power/density threshold for trapping.
5) Generate a high-quality gigaelectronvolt class electron beam with sufficient charge.

In the first of a series of experiments, the UCLA/Lawrence Livermore National Laboratory (LLNL) groups [52], [53] showed that wake-enabled self-guiding of an ultra short, O (λ_p), relativistically intense laser pulse does indeed occur. Using gas jets of various lengths, they generated wakes in plasmas of different densities by controlling the backing pressure of the gas. For each case, they determined the range of densities over which self-guided propagation of the laser pulse occurred by imaging the exit spot size of the laser pulse. A summary of the results is plotted in Fig. 6. There is a minimum density below which laser pulse of a certain spot size w_0 will not be guided because the wake will not produce the necessary density depression to confine the pulse against diffraction. The results clearly showed that at a given plasma length the maximum density at which the laser guiding was observed scaled as $1/n_e$ and that a 50 ± 5 fs laser pulse could be guided over 1.5 cm in a 3×10^{18} cm^{-3} plasma. In these experiments, the maximum laser power was sufficient to produce wakes in the blowout region but the laser a_0 was not sufficient to induce electron self-trapping.

To check the scaling of the maximum energy gain with plasma density as well as to determine the density threshold for self-trapping for a 100-TW class laser, the UCLA/LLNL, collaboration carried out a series of experiments [106], [107] using the nominally 150 TW, Callisto laser at LLNL. These experiments were done using gas jet or gas cell targets

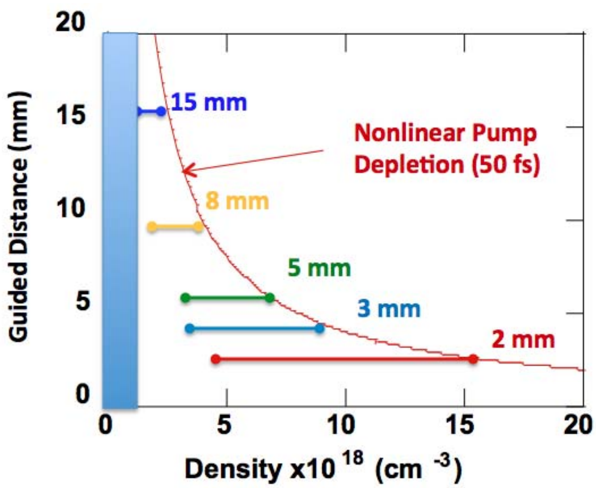

Fig. 6. Distance over which a short laser pulse is guided is limited by nonlinear pump depletion that scales inversely with plasma density. All the measurements were carried out using gas jets except for the 15-mm plasma, which used a gas cell. For the 15-mm case, no guiding could be observed below a density of 1.5×10^{18} cm^{-3} (the blue shaded region). In all other cases, the lowest density is the density at which the guiding measurements were taken [49].

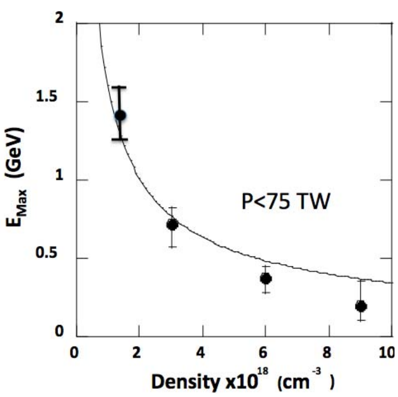

Fig. 7. SCALING of the maximum energy $E_{\max}$ gained by electrons as a function of plasma density predicted by the 3-D nonlinear theory [45] for 0.8-μm laser and a_0 of 5 after beam evolution and experimentally measured maximum energies at four selected densities where the length of the plasma was increased at lower densities to allow dephasing-limited energy gain. The vertical error bars result from the uncertainty in determining the maximum energy because of the transverse size of the electron beam.

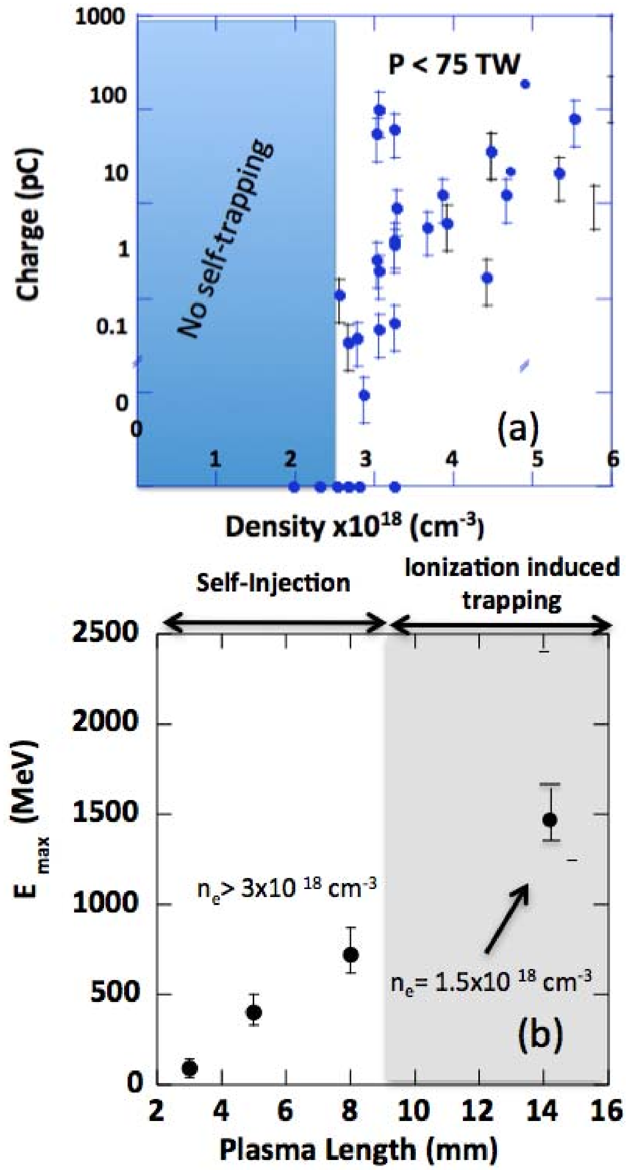

Fig. 8. Experiments on LWFA in the blowout regime [106], [107]. (a) Density threshold for observing self-injected electrons at a laser power of <75 TW. No self-injected electrons were observed below a density of 3×10^{18} cm^{-3}. (b) Maximum observed electron energies as a function of plasma length. In each case, the plasma density was reduced from typically 1×10^{19} cm^{-3} until the highest energy electrons were observed. For the 15-mm-long plasma, ionization injection was employed.

of various lengths and the plasma density was varied until electron energy was maximized. This presumably happened when the pump evolution distance (when injection occurs) plus the dephasing distance were equal to the length of the quasi-uniform density region of the gas jet. The results are summarized in Fig. 7. Here the lowest density point was obtained using a gas cell target and ionization injection scheme (described as follows), whereas all other points were obtained using gas jet targets and self-injection. Fig. 7 shows that the maximum energies observed followed the expected dephasing-limited energy gain trend. Although nominal laser powers of up to 150 TW were used, the laser power in the central "Gaussian" spot was only about 1/2 or, <75-TW in these experiments. At this power no self-trapping of electrons below a density of 3×10^{18} cm^{-3} was observed, as seen in Fig. 8(a). Furthermore, for a given plasma length, the plasma density was varied to get the maximum energy gain, as shown in Fig. 8(b). Quasi-monoenergetic peaks were often observed in the vicinity of the maximum energy but these were frequently seen on the top of a continuous energy spectrum.

Similar results have been obtained on the Vulcan laser at the Rutherford Laboratory in U.K. [108]. Using the PW laser systems, the GIST group in South Korea and the University of Texas Austin groups have produced gigaelectronvolt-class electron beams [109], [110] in a few centimeter scale LWFA operating in the quasi-self-guided, blowout regime that we have been discussing. At this point, I should mention that using the channel guided laser propagation, the LBNL group has shown electrons with up to 4-GeV energy gain in a few percent energy spread beam [111], [112] using a PW-class laser.

Several groups have been employing the ionization induced injection method to trap electrons in the wake at a reduced laser power [113], [114], as discussed earlier. For instance, in 2010, the UCLA-Livermore-UCSD team demonstrated greater than 1-GeV electrons using the Callisto laser by combining the concepts of self-guiding and ionization injection [107]. A 1.8-cm-long gas cell was filled with helium gas with a 3% CO_2 additive to give a fully ionized density of 1.8×10^{18} cm^{-3}. At a laser power of 110 TW, the nominally 50-fs laser pulse was guided over the entire length of the gas cell. No accelerated electrons were observed when the cell was only filled with helium gas. However, with the addition of the minority CO_2 species, high-energy electron with a continuous energy spread that extended well beyond 1 GeV was observed. PIC simulations showed that the ionization of K-shell oxygen electrons within the wake leads to trapping and acceleration. The broad energy spread of the electrons (with considerable structure) indicated that inner-shell electrons of oxygen continued to be ionized over an extended length of the gas cell.

In order to reduce the energy spread, the same team did an injector accelerator experiment using a single gas cell that had two compartments with a small hole between the compartments. The first 3-mm-long compartment contained a mixture of majority He and minority N_2 gas to enable ionization injection [see Fig. 9(a)]. With this compartment alone electrons with a broad energy spectrum out to 150 MeV were generated, as shown in Fig. 9(b) (top). However, when these electrons were further accelerated in the second 7-mm-long compartment that contained only He plasma, the energy spread was reduced to <5% (FWHM) and the maximum energy was increased to ∼500 MeV [102] [see Fig. 9(b) (bottom)].

The ionization injection concept also allows one to investigate the possible use of the ions contained within the wake as a strong wiggler for relativistic electrons. As discussed earlier, the electrons oscillate at the betatron wavelength and emit a fairly low-divergence beam of X-rays in the forward direction. This radiation was first observed by Wang *et al.* [84] using a beam-driven wakefield accelerator and has since then been observed in LWFA experiments by many groups [115]–[119]. Among many possible applications, there is considerable interest in developing such a capability for diagnosing matter under extreme conditions of temperature and pressure generated by high-energy, nanosecond-class laser facilities. The LLNL/UCLA collaboration measured the spatial and spectral distributions of the forward emitted betatron radiation and showed that the critical energy of the synchrotron-like spectrum was in the 10 s of kiloelectronvolt range [120], [121] in the exact forward direction and fell off away from the axis. Many high-energy lasers used for the high energy density science (HEDS) research have picosecond (rather than sub-100 fs) lasers synchronized to multikilojoule lasers, so, for application of betatron X-rays to HEDS, our effort has shifted to generating betatron X-rays using the self-modulated LWFA regime [122], [123] using a picosecond pulse.

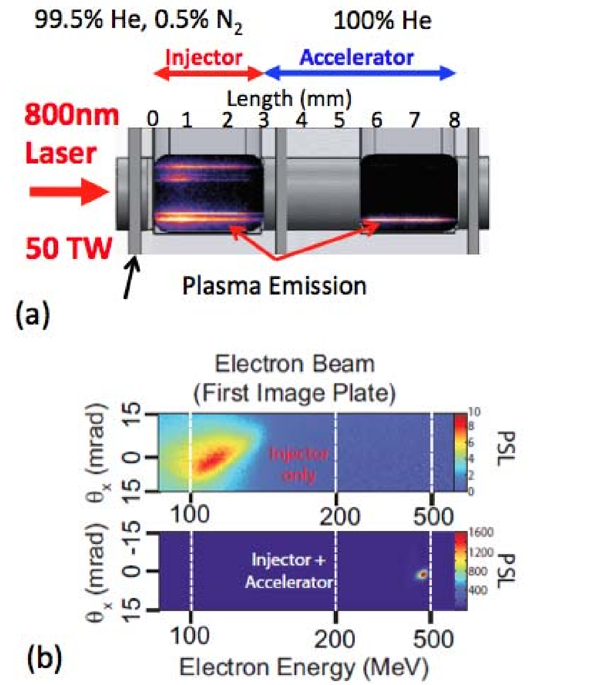

Fig. 9. (a) Dual-compartment gas cell used in an injector accelerator demonstration in [114]. The first compartment has a mixture of N and He, whereas the second has only He. The density is uniform within the entire gas cell. Plasma emission lines show the presence of He and N emission from the first compartment but only He emission from the second compartment. (b) Electron spectrum exiting the injector compartment (top) and after the injector beam is further accelerated in the second, accelerator, compartment (bottom).

The discussion of the LWFA in the blowout region would not be complete without briefly discussing the contribution of direct-laser acceleration (DLA) in this configuration. The process has similarities to the IFEL acceleration mechanism [75], [124]–[126].

Here trapped electrons executing betatron oscillations in the plane of polarization of the laser can gain additional energy directly from the electric field of the laser. This was recently demonstrated in an elegant experiment by Shaw *et al.* [127], who used the ionization injection method to inject electrons in an LWFA (in the blowout regime) before the laser pulse had a chance to longitudinally compress. In this case, the highest energy electrons exhibited a "forked structure" at the spectrometer plane, as expected from the DLA process [127].

The status of the experimental work on the self-guided, blowout regime of LWFA discussed above is not claimed to be comprehensive. The author has focused on the body of work done by the UCLA/LLNL collaboration whose goal was to demonstrate a robust platform for delivering approximate gigaelectronvolt energy electrons from an LWFA without the need for an external plasma channel for guiding the laser pulse. Other groups have done beautiful work on beam loading [128], wake engineering [129], down ramp injection [130], wake diagnostics [131]–[135], etc. Similarly there is a body of theoretical work [136], [137] and several review papers [138], [139] and the references contained therein that the reader is referred to for completeness.

VIII. Future Challenges

What are some of the next challenges for the community of researchers working in this area? The foremost physics challenge is the reliable measurements of the transverse and longitudinal beam emittances [141]–[143] and identifying the factors that degrade the quality of the electron beam by causing emittance growth in an LWFA [144]. Transverse emittance growth may occur as a result of the hosing instability and also ion motion. Even if the electrons have a very small emittance inside the wake, such a beam must be extracted and matched either to another plasma acceleration stage or to conventional magnetic optics [77], [145], [146]. Longitudinal emittance will depend on how small the energy spread of the beam can be, which in turn depends on optimizing the beam loading to give a constant E_z field. Methods for improving the laser-to-wake energy coupling efficiency have been proposed but remain to be demonstrated. Continued development of diagnostic techniques to visualize the fields of the highly nonlinear wake and the injected electrons is also needed. Finally, it seems highly likely that with the availability of multipetawatt, high repetition rate Ti-sapphire systems it will be possible to generate 10-GeV class beams using the self-guided, fully blown-out regime of the LWFA discussed here in a reproducible manner in the near future.

IX. Conclusion

The self-guided, fully blown-out LWFA cavity provides a robust accelerating structure for high gradient acceleration of electrons. The concept and the experiments carried out by the author and his colleagues on this promising regime of the LWFA are summarized.

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Chan Joshi (F’93) is currently a Distinguished Professor of electrical engineering with the University of California, Los Angeles (UCLA), CA, USA. He started the first research group on Plasma Acceleration at UCLA in 1982. This work has now spread worldwide; yet after three decades, his group continues to make breakthrough contributions to this grand challenge in engineering. He has made many fundamental contributions to our understanding of extremely nonlinear optical effects in plasmas. Notably, his first experimental demonstrations are in plasmas of four-wave mixing, stimulated Raman forward instability, stimulated Compton scattering, resonant self-focusing, quasi-resonant modes, and frequency up shifting by ionization fronts and nonlinear coupling between electron and plasma waves. His research group is best known for its involvement in the field of ultrahigh gradient acceleration of charged particles using space charge density waves in plasmas using a laser or a particle beam pulse. Such wakes are being considered as accelerating structures for the next generation of particle colliders and compact light sources to make these critical instruments of scientific discovery compact and affordable. His current research interests include plasma physics, lasers, and electromagnetics, and particularly, laser fusion, laser acceleration of particles, nonlinear optics of plasmas, high-power lasers and particle beams, and basic plasma phenomena.