PLASMA ACCELERATORS-PROGRESS AND THE FUTURE

Chan Joshi, University of California Los Angeles, Los Angeles, CA 90095 U.S.A.

Abstract

In recent months plasma accelerators have set new records: The first laser wakefield accelerator (LWFA) to demonstrate a GeV electron beam with a significant charge and good beam quality in a "table-top" device at Lawrence Berkeley National laboratory (LBNL) [1], and the energy doubling of 42 GeV electrons from the SLAC linac in a meter-scale plasma wakefield accelerator (PWFA) by the UCLA, USC, SLAC collaboration known as E167 [2]. These two events happening at two different laboratories represent a very significant advance of the field to be sure, but there have been many other extremely important advances for the field of plasma-accelerators that deserve special recognition. In this paper after reviewing these two major acceleration results, I focus on these latter advances and speculate how the field is likely to develop in the next few years.

LWFA AND PWFA SET ENERGY RECORDS

In both LFWA and PWFA, the longitudinal electric field of a space charge density oscillation, with a phase velocity $v_\phi \sim c$, is responsible for accelerating electrons. In recent years both schemes have been operating in a highly nonlinear regime called the "blow-out" or the "bubble"-regime in which the drive pulse is so intense that it blows out all the plasma electrons which subsequently rush back behind the driver pulse because of the restoring force provided by the ions, overshoot and set-up a plasma density oscillation or the wake. Because the orbits of the transversely blown out plasma electrons encompass an ion bubble, this regime is called the bubble regime.

In most of the LWFA experiments to date, the phase velocity of the wake is moderately relativistic. That is to say as the particles gain energy they slowly overtake the wake. The slippage between the particles and the wake limits the energy gain. However, this dephasing limit also advantageously leads to an accelerated beam with a relatively narrow energy spread. The first evidence for such beams came about three years ago. Since then the l'Oasis group at LBNL has gone to higher phase velocity wakes to increase the energy gain by guiding a 40 TW laser pulse in a 3.3 cm long capillary plasma. They have now observed electrons with a maximum energy out to 1.1 GeV. With this breaking of the psychological 1 GeV barrier the LWFA experimenters are already contemplating how one might achieve 10 GeV energy gain in a single stage of LWFA.

At the time of the PAC 2005 Conference, the PWFA had just reached a milestone of its own: approximately 4 GeV energy gain in a 10 cm long plasma using the 28.5 GeV SLAC electron beam as a driver. At that time first proposals were made to attempt an energy doubling experiment by simply extending the plasma length to about one meter and increasing the beam energy to 42 GeV. There were concerns that the energy gain would not be scalable because of the transverse hosing instability of the drive beam.

In the most recent PWFA experiment, E167 carried out by the UCLA, USC and SLAC scientists, the scalability of the PWFA to achieve energies of interest to high energy physicists was shown . Figure 1 shows the highlight of the results. When the 42 GeV SLAC beam was shot through an 85 cm long, 2.7 × 10^{17} cm^{-3} density lithium plasma, the bulk of the beam was own to lose energy in exciting the wake. The electrons in the tail of the same beam sampled the accelerating portion of the wake and therefore gained energy. The maximum energy seen was 85 GeV indicating that at least some of the electrons had doubled their energy and that the average accelerating gradient was ~ 50 GeV/m.

These two experiments represent a very significant advance for the plasma accelerators field during the past two years.

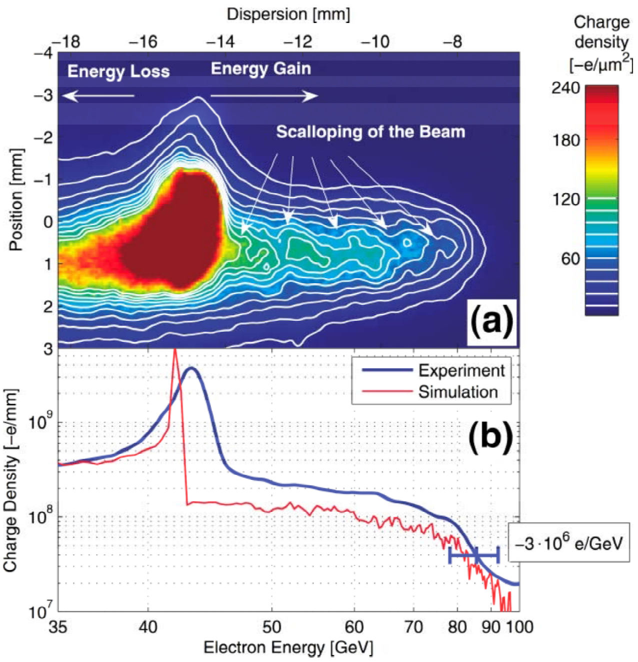

Figure 1. (a) The energy spectrum of the (initially nominally 42 GeV) electron beam after passage through an 85 cm long, 2.7×10^{17} cm^{-3} Lithium plasma and (b) a comparison between the measured spectrum and the simulated spectrum. Reprinted by permission from Macmillan Publishers Ltd: *Nature* 445, 741-744, © 2007.

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VISUALIZATION OF PLASMA ACCELERATING STRUCTURES

A recent major development in diagnosing relativistic wakes in plasmas is frequency-domain holography [3]. The typical wakefield structures visualized using this method have 50-100 μm diameters, 40-100 μm wavelengths, a lifetime of 1-2 ps and propagate at ~c. Until holography was perfected, 3D computer simulations were the only way of visualizing wakes in plasmas.

Frequency domain holographic interferometry of plasma wakefields can be thought of as a classic pump-probe experiment. An intense (a_o ~ 1), 30 fs long, $\lambda = 0.8\ \mu$m laser pulse (pump) is focused at the entrance of a gas jet to produce a plasma and induce the wake. In addition two chirped, $\lambda = 0.4\ \mu$m, 1 ps long laser pulses copropagate with the pump beam. The first chirped pulse which acts as a reference beam is ahead of the pump beam while the second chirped pulse follows the pump and therefore samples the wakefield. The wakefield density modulations impose a phase modulation on this probe beam. Upon exiting the plasma chamber, both pulses are sent to a spectrometer where they produce a frequency-domain interferogram. The wake structure, in the time domain is subsequently recovered from this frequency domain interferogram by Fourier transformation.

An example of the data obtained using frequency domain holography by M. Downer's group at U. Texas at Austin is shown in Figure 2. Using this technique, certain features of the wakefield such as its wavefront curvature and variation of wavelength with plasma density have been experimentally seen for the first time [3].

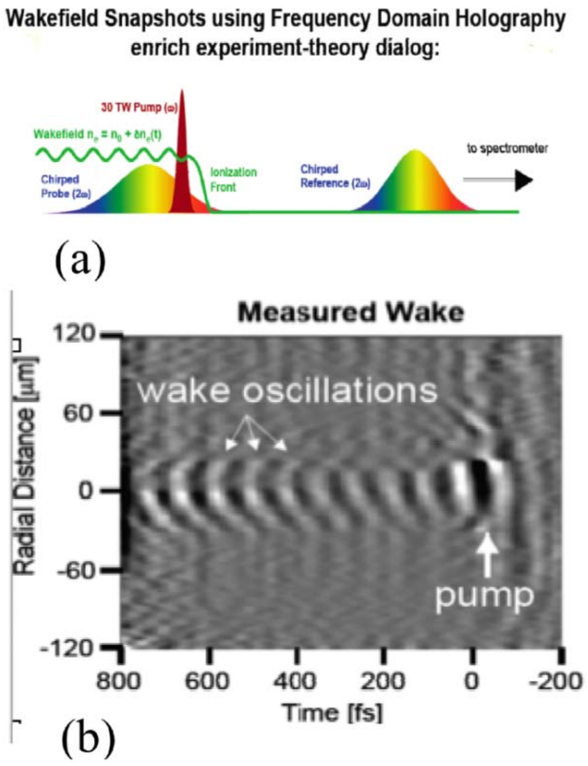

Figure 2. (a) Schematic of frequency domain holography and (b) the reconstructed hologram showing the wake oscillations obtained after Fourier transforming the frequency domain interferogram at the output of the spectrometer. Courtesy of M. Downer.

COLLIDING PULSE INJECTION

From the earliest days of research on plasma accelerators it was well known that when the plasma oscillation became of sufficiently large amplitude it could trap plasma electrons and accelerate them [4]. Such trapped particles were routinely seen to have a monotonically decreasing energy distribution [5]. With the transition of plasma accelerators from the self-modulated to laser wakefield regime, the self-trapped electrons were often seen to have a "monoenergetic" peak if the laser intensity was large enough and the acceleration length was about one dephasing length [6]. However, process that generated a monoenergetic peak was not very reproducible because the exact time and location where plasma electrons were injected into the wake was not deterministic.

It has been known for some time that it is possible to control the injection by sending a second weaker but counter propagating laser pulse such that the wake generating intense laser pulse and the counter propagating laser pulse collide inside the plasma [7]. The beat pattern of the two waves has a zero phase velocity but a significant ponderomotive force associated with it. This force can perturb the phase space orbits of the plasma electrons that are initially untrapped such that they can be trapped by the wake potential.

The technique has now been experimentally demonstrated as shown in Fig. 3 by J. Faure et al. at L.O.A. in France [8]. They found that this all-optical, colliding pulse injection technique improves the reliability of the accelerated beam in terms of its final energy and energy spread.

ONSET OF TRAPPING IN THE PLASMA

When a large amplitude plasma wake initially traps background plasma electrons, there is a violent change in its velocity. Once the electrons become relativistic, v~c, any further gain in their energy is accompanied by a change in their mass. Initially however, as the velocity rapidly increases to c, the electrons emit radiation that is broadband, spatially localized and transverse to the propagation distance of the laser [9]. The observation of this broad spectral band, localized in space is therefore an indication of where in the plasma the trapping occurs.

In a recently reported paper by A.G.R. Thomas et al. from Imperial College, U.K., spectrally and spatially resolved measurements of visible radiation transverse to the direction of the pump laser are reported. In addition to the usual Stokes line and its second harmonic (due to Raman sidescatter) in this transverse direction, a weak but broadband radiation is observed. Furthermore, this latter band is spatially localized and occurs 400 μm in to the plasma consistent with the onset of electron trapping. 2D, PIC code simulations of the experiment have reproduced many features of this radiation at the point of injection giving credibility to the explanation.

This technique is non-perturbative and gives much of the same information that a recent tomographic technique developed by C. T. Hsieh et al. In this tomographic technique a second intense transversely propagating laser beam is used to terminate the plasma wakefield to probe for the injection point [10].

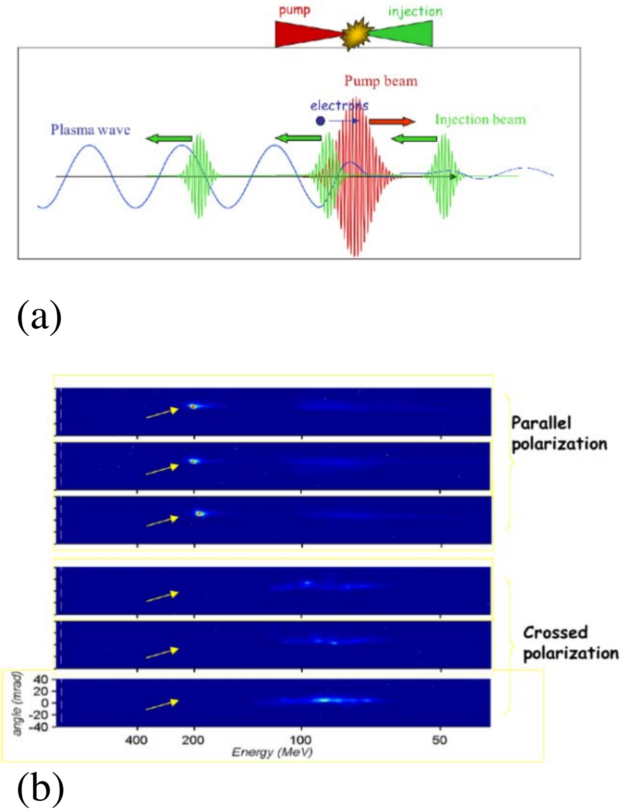

Figure 3. (a) Schematic set-up for controlling the injection of electrons in the wakefield by colliding a pump beam with an injection beam and (b) electron spectra obtained with the pump and the probe beam having parallel polarizations (top three events) and orthogonal polarizations (bottom three events). Only when the polarizations are parallel, a well defined monoenergetic beam can be seen as expected. Courtesy of V. Malka

TRANSITION TRAPPING OF ELECTRONS

In 2001, H. Suk et al. proposed a different technique for controlled injection of electrons in a plasma wakefield [11]. This technique is named "transition-trapping." In this scheme, if a plasma wave is excited across a plasma region where the plasma density suddenly drops from a high value to a low value, over a distance on the order of a plasma skin depth, then electrons can be suddenly trapped. The reason for it is as follows. As the plasma electrons participating in the longitudinal oscillation move from the higher density region, across the transition boundary, to the lower density region they suddenly become dephased and therefore trapped in the longer wavelength plasma oscillation on the low density side. The sharper the density transition region the more dramatic and localized is this effect. In PIC simulations this method of controlling the trapping produces a single trapped bunch of extremely low emittance.

Recently this transition trapping mechanism has been demonstrated in a proof-of-concept experiment by T.Y. Chien et al. [12]. An intense laser pulse propagates through a gas jet plasma to produce a plasma wave via the self-modulated laser wakefield process. The transient density ramp is generated using a second laser pulse propagating transversely to the first. The second heating pulse produces a density depression channel because of ionization and subsequent expansion. Electron acceleration is seen only when there is a spatial overlap of the two pulses and when the pump pulse is delayed by several nanoseconds with respect to the heating pulse for the sudden density transition region to be formed.

MEV BETATRON X-RAYS AND GENERATION OF POSITRONS

Wakefields in plasmas have extremely large transverse (focusing) as well as longitudinal (accelerating) fields [13]. The transverse focusing fields in the so called bubble regime are longitudinally uniform and vary as radius r. Electrons in a finite size particle beam will feel this force and undergo betatron oscillations [14]. These betatron oscillations lead to emission of radiation in extremely narrow angles in the forward direction.

In SLAC experiment 164X, a 30 GeV electron beam with beam density n_b greater than the plasma density $n_p = 2 \times 10^{17}$ cm^{-3}, excited a wakefield in a lithium plasma [15]. The subsequent betatron oscillations of the electrons produced an intense beam of x-rays with a critical energy of about 50 MeV, ideal for e$^+$-e$^-$ pair creation in a thin high z target. An example of the data obtained by D. Johnson et al. [16] is shown in Figure 3. The e$^+$ spectra and absolute yield were found to be in quantitative agreement with calculated values. The experiment also systematically explored the variation of the e$^+$ yield as a function of beam (charge, pulse length and focusing conditions) and plasma length. Once again the measurements and calculations were in excellent agreement.

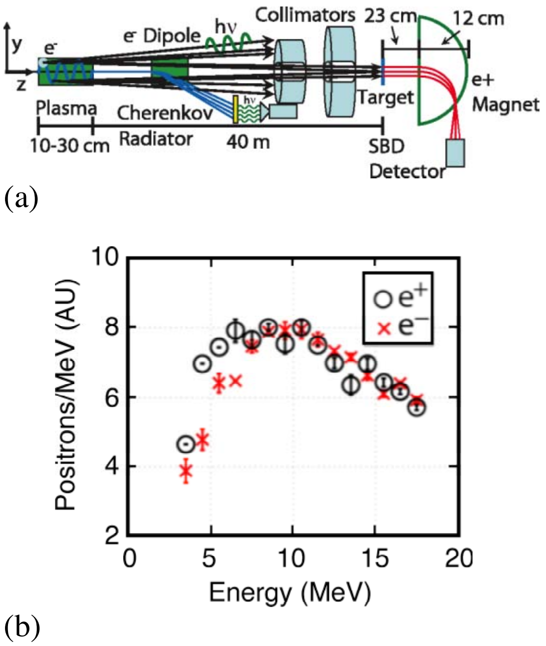

Figure 4. (a) Schematic set-up for the utilization of betatron x-rays for pair-production and (b) both e+ and e- spectra measured for the same plasma and beam conditions.

IONIZATION TRAPPING IN PLASMA WAKES

Earlier I discussed two different techniques for controlling the injection of plasma electrons into relativistic wakes: colliding pulse injection and transition trapping. In wakes produced by an ultra-relativistic beam, experimenters have discovered yet another trapping mechanism that could be used to generate extremely bright beams [17]. This mechanism is known as ionization trapping and it can be explained as follows: In beam driven PWFA experiments at SLAC, the lithium plasma is confined by He buffer gas. The transition region between the Li and He is about 10 cm thick. The ionization potential of Li is only 5.4 eV whereas that of the He is 24.6 eV. As the electron bunch enters the He: Li boundary region it ionizes Li first via field ionization and produces a wake. The Li plasma also focuses the electron beam further causing an increase in the space-charge field of the beam electrons so that He atoms can now be ionized. The He electrons are born inside the wake supported by the Li electrons and are therefore trapped and accelerated [18].

In the experiments a well defined threshold for trapping of the He electrons is observed as shown in Fig. 5.

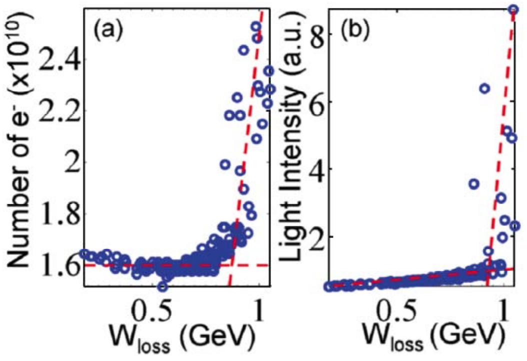

Figure 5. (a) The sudden onset of trapped particles as the wake amplitude (given by energy lost by the drive beam electrons in a PWFA) increases and (b) the sudden increase in the visible light intensity emitted by the plasma at the same value of w_{loss}.

FUTURE DEVELOPMENTS

In speculating about the future, I will confine myself to how the particular advances highlighted in this paper are likely to further contribute to the advancement of the field of plasma accelerators.

The successful demonstration of frequency-domain holography has given us a tool, for the first time, to visualize wakefields in plasmas. Further work in this area will allow one to optimize the wakefields by comparing the experimental data with particle-in-cell (PIC) code simulations. Effects such as the onset of particle trapping, termination of particle trapping because of beam loading, reflection of the electron sheath by the dense beam of trapped electrons and the onset of wave breaking are some of the important effects that (we know must) happen but await direct experimental proof.

It will be interesting to see how the colliding pulse injection will be used in the future. Perhaps it will be used to generate an extremely reproducible, few-tens of MeV beam for injection into a longer LWFA in a plasma channel. Similarly transition trapping and or ionization trapping may play a role of a super-high quality injector for a PWFA.

There is now no doubt that betatron motion of electrons in a plasma accelerator produces collimated x-ray beams. With an ultra-relativistic electron beam driver, joules of energy can be converted into an extremely collimated beam of MeV energy photons. Will it be possible to generate circularly polarized photons that are needed to produce polarized e^+/e^- pairs using a plasma (ion) undulator?

These are among some of the questions that are going to be explored in the next few years. As for the electron acceleration experiments, the next milestone in the LWFA field will likely be the demonstration of acceleration of an externally injected beam while

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preserving its beam quality. In previous experiments using an externally injected beam from a linac, the plasma accelerator output was a continuous spectrum of electrons [19]. To get a narrow energy spread beam from a plasma accelerator, a high quality beam from one plasma accelerator would have to be matched into a second plasma accelerator.

In the PWFA field, high gradient, meter-scale acceleration of positrons is the next great challenge [20]. Such an experiment can only be done at SLAC using the e^+ beam from the SLAC linac. Availability of adequate experimental facilities will be the deciding factor for the long term vitality of this field.

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