Laser plasma accelerators

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An ultrafast intense laser pulse drives coherent wakefields of relativistic amplitude with the high phase velocity robustly supported by the plasma. The structures of wakes and sheaths in plasma are contrasted. While the large amplitude of wakefields involves collective resonant oscillations of the eigenmode of the entire plasma electrons, the wake phase velocity ~*c* and ultrafastness of the laser pulse introduce the wake stability and rigidity. When the phase velocity gets smaller, wakefields turn into sheaths more suitable for ion acceleration. This short review reports on 4 decades of discoveries on laser plasma accelerators.

1. The Basic Philosophy

In conventional acccelerators, the beam dynamics is determined foremost by each charge particle interacting with the external fields and this is the single particle dynamics[1]. Veksler suggested the idea of collective field acceleration in plasma[2], which triggered research in collective accelerators[3]. Collective accelerators based on the collective interaction involved a large number (N) of particles, which give rise to fields that are collectively composed by these particles and those particles themselves interact with each other. Thus collective fields (as opposed to the single particle interaction) are nonlinear.

We summarize the cardinal differences between the individual and collective forces. Here we contrast the nature of the individual force and acceleration based on this (and thus linear force and the conventional accelerators) with that of the collective force and acceleration based on the collective force. In this review we concentrate on the latter only. The single particle interaction with the externally imposed voltage on the metallic boundary suffers from the surface materials breakdown by sparks and arching. Metallic electrons may be subject to hop out of the metallic chemical potential into a free (with breakdown) state typically the surface field on the order of MeV / cm. But this happens more typically even under much lower field limit. This is because typical materials contain impurities, whose f-center can initiate sparks under a couple of orders of magnitude lower fields. There is an additional inconvenience due to the metallic surface, which causes the waveguide modes to have the phase velocity greater than the speed of light. This necessitates a slow-wave structure with periodically imposing protruding structures into the waveguide to slow down the phase velocity. This unfortunately even help the breakdown from such protruding portions, making the breakdown more susceptible. Because of the accelerating fields are only in the parallel direction, which further projects partial filed strength available for the purpose of the acceleration in the conventional accelerating structure.

Even though collective fields could be huge, as they involve *N* particles, if they are chaotic or random, their effects may be compromised by cancellation and randomization. To address this issue, we need to achieve coherence. In the year of 1956[2] before the invention of laser[4] (1960) such attempts were considered by the use of beams of particles. In fact the many of the experimental endeavors[3] electron beams have been employed. The injection of electron beams into plasma and created accelerating structure in some of these experiments have been examined by Tajima and Mako[5]. In these works the electron beam injection often involved the sheath formation, which could give rise to instability, as the sheath structure is often stuck with the system's boundary condition.

In the 1979 work Tajima and Dawson[6] noticed and introduced a high speed structure (i.e. the phase velocity of the accelerating structure): the principle of high phase velocity. This high phase velocity structure they sought was the wakefield. The wakefield with high phase velocity, unlike the sheath created under the structural constraint above, remains robust and stable. In Table 1 we compare the low phase velocity interaction with the high phase velocity interaction and show our Paradigm of High Phase velocity. We learn that plasma suffers from a large variety of instabilities (see Mikhailovskii[7]) in the conventional situation where the phase velocity of the waves v_{ph} is on the order of the thermal velocity v_{th}. On the other hand our paradigm dictates that the excited wave (wakefields) has the phase velocity far greater than the thermal velocity of the bulk plasma. One of important consequences of this principle is the structure formation. When the phase velocity of the "banging" (large disturbance on the plasma) is large, behind the "banging" we observe a structure called wakefields. These are moving with a large phase velocity (such as near c) that is sustained by electrons while often such a structure has a low (or zero) group velocity (and ions do not move). On the other hand, when the phase velocity of such a "banging" is low (or near zero), the electrons that are "banged" (received a large amount of energy from the disturbance) begin to move but cannot propagate with the large phase velocity characteristic of the high phase velocity counterpart. Therefore, the electrons cannot continuously propagate and instead snap back due to the electrostatic charged restoring force. This is the sheath formation as opposed to the wake formation. See the bottom row of Table 1. Because of this low phase velocity sometimes ions can respond to this. Under certain boundary conditions in turn the entire plasma may begin to move (i.e. ion acceleration is accompanied).

Until the invention of the Chirped Pulse Amplification[8] no laser had reached the ideal requirement of the "bang" (i.e. the strong resonant excitation of the wakefield)[6]. However, it was possible to have the beat wave excitation, self-generated wakefield excitation, or the frequency-modulated wakefield excitation[9-11]. The first experimental demonstration of the self-modulated wakefield acceleration carried out by the use of the CPA was in 1994[12,13]. Since then a large number of experiments demonstrated the above fundamental concept and its ramification far beyond the conceptual basis.

Low phase velocity	**High phase velocity**
Plasma tends to be unstable	Stable state exists (Landau-Ginzburg state)
$v_{ph} \sim v_{th}$	$v_{ph} \gg v_{th}$
Mode interacts with bulk plasma (Landau resonance)	Mode insulated from bulk plasma
Mode-mode coupling ➔ More modes ➔ More turbulence	Mode maintains coherence
Strongly nonlinear regime (large Reynolds' number) → strong turbulence	Strongly nonlinear regime → strongly coherent Relativistic effects further strengthen coherence
Plasma fragile → anomalous transport, structure disintegration	Plasma cannot be destroyed, structures are formed. Violence tolerated
Trapping velocity and trapping width[14]: $v_{tr} \lesssim v_{th} \sim v_{ph}$, $x_{tr} = \sqrt{\frac{cE}{B}\frac{L_s}{k_y v_\parallel}}$	Trapping velocity[15]: $v_{tr} = \sqrt{qE/mk}$ If wave pumped, v_{tr} increases until $v_{tr} \sim v_{ph} \gg v_{th}$ → acceleration or injection Tajima-Dawson saturation[6]: $E_{TD} = \frac{m\omega_p c}{e}$
Characteristic structure: Sheath	Characteristic structure: Wake
Energy gain: by coherent accumulation of electron charges of the sheath (energy amplification of sheath charge accumulation[5] $2\alpha + 1$ (coherence parameter α)	Energy gain: by energy amplification over the trapping width $v_{tr} \sim v_{ph}$

Table 1: High Phase Velocity Paradigm

2. Comparison of wake with high phase velocity and that of low phase velocity

For both the historical development and its relation to the adjacent field of laser ion acceleration, let us compare the commonalities and differences of the wake dynamics with a high phase velocity and that with a low phase velocity. Historically, as mentioned in Sec.1, the experiments that cause a low phase velocity generated a sheath that is unable to comove with the high velocity electrons. The realization of this phenomenon and its analysis[5] prepared for the theoretical foundation and invention of the wakefield[6]. In other words, see Table 1, the dynamics is dictated by the sheath in the low phase velocity ($v_{ph} \sim v_{th}$) of the created plasma wave, while it is governed by the wake in the high phase velocity ($v_{ph} >> v_{th}$). In the latter the high phase velocity wake can robustly propagate for a long distance (the distance such as the dephasing length[6]) so that once electrons that can be trapped in this wake can be accelerated for high energies characterized by the energy gain of $\Delta E = 2\, \gamma^2_{ph}\, \Phi_0$ where $\gamma_{ph}^2 = 1/(1- v_{ph}^2/c^2) = \omega_0^2/\omega_p^2 = (n_c/n_e)$ specifies the relativistic Lorentz factor for v_{ph} on which trapped electrons gain energies and the Lorentz invariant potential height may be the ponderomotive potential of the laser $\Phi_0 = mc^2\, [(1+a_0^2)^{1/2} - 1]$.

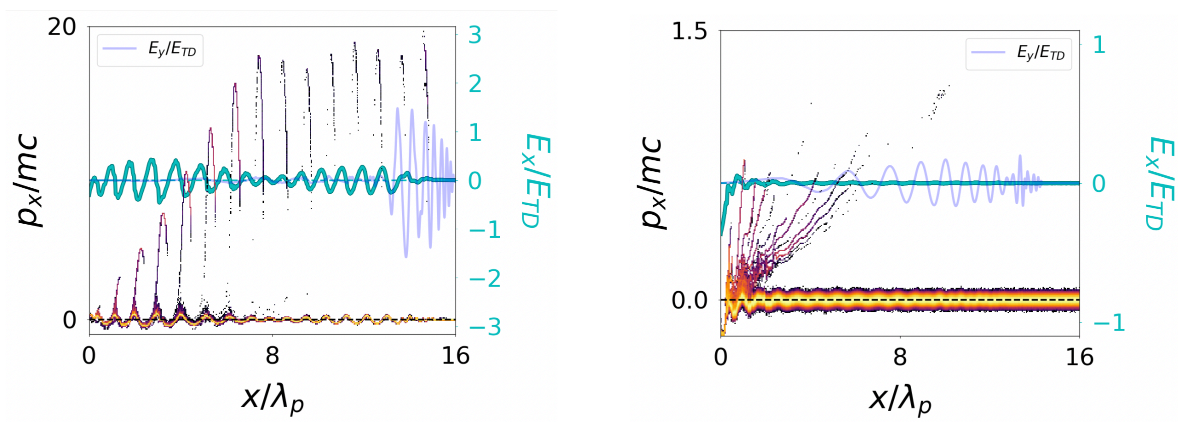

Figure 1: The wake regimes of high phase velocity vs. low phase velocity at the early snap shot time of development. The laser pulse goes to the right. Electron phase space dynamics (dots p_x vs x) and the laser field in light blue and the longitudinal field in blue. (left) high phase velocity (low density $n_c/n_e = 10$), (right) low phase velocity (high density $n_c/n_e = 1$). The electric fields are normalized to the Tajima-Dawson field of $E_{TD} = m_e \omega_p c/e$ (after Nicks[19]).

It is of interest to see the transformation of not only quantitative but also more fundamental qualitative changes of the dynamics when the phase velocity is scanned by gradually reducing it from this "high phase velocity" regime to the "low regime" to understand the laser ion acceleration that started later[16,17], with the transition between the TNSA[16] (Target Normal Sheath Acceleration) and the CAIL[17] (Coherent Acceleration of Ions by Laser) acceleration schemes [18]. In the laser ion acceleration experiments the target has been (mostly) chosen as at a solid density so that the laser upon its immediate interaction on the surface of the solid is overdense, i.e. $n_c/n_e < 1$. In simulations more parameters can be explored for which the phase velocity of the electrostatic waves generated on the surface of this (ionized) plasma on the target is much smaller that the speed of light c, i.e. it belongs to our low phase velocity regime.

In Fig. 2 we show the electron dynamics (along with ion dynamics) in the CAIL regime where the overdense plasma density reaches near critical after sheath formation[20]. The electron dynamics and the sheath formation are similar to those for the case of the high density LWFA early stages (right of Fig. 1). When this nonlinear dynamics was analyzed[5], it was not anticipated that this analysis of the experiment carried out in a much different environment of the electron-beam-driven collective acceleration of ions[21] would have applications to the LWFA in high density and laser driven ion acceleration in ref. 11 and later.

The transition from the wake to the sheath is illustrated on Fig. 1, in which simulations are performed with different values of n_c/n_e. In the former case, of course, we observe the typical well-known LWFA electron dynamics of wakefields. As we gradually decrease toward close to $n_c/n_e = 1$, we observe a gradual onset of the sheath dynamics near the value $n_c/n_e = 1$. In this regime of the high density LWFA what we observe is that the ponderomotive force of the laser creates the electron charge separation on the surface of the solid target, which sets on the sheath of electron-ion layer[5]. This sheath snaps back, which in turn sets up another episode of the charge separation and another snapback of the sheath, and so on, leading to a multiple of layers of sheath. It is cleanly observable of this multiple sheaths in the latter of Fig. 1. These multiple of layers eventually form a single coalesced layer of electron phase space structure[13].

Another important development is to a realization from the energy gain expression that the increase of the ratio n_c/n_e to obtain higher electron energies may be realized not only just by reducing the electron density, but also by increasing the laser photon frequency (thus increasing n_c). The latest laser technology advance such as the Thin Film Compression (TFC)[22] and the Relativistic Compression[23] in conjunction with TFC opens the new path to enable the latter approach to make wakefield acceleration now in solid density (or nanostructures) and “TeV on a chip” [24].

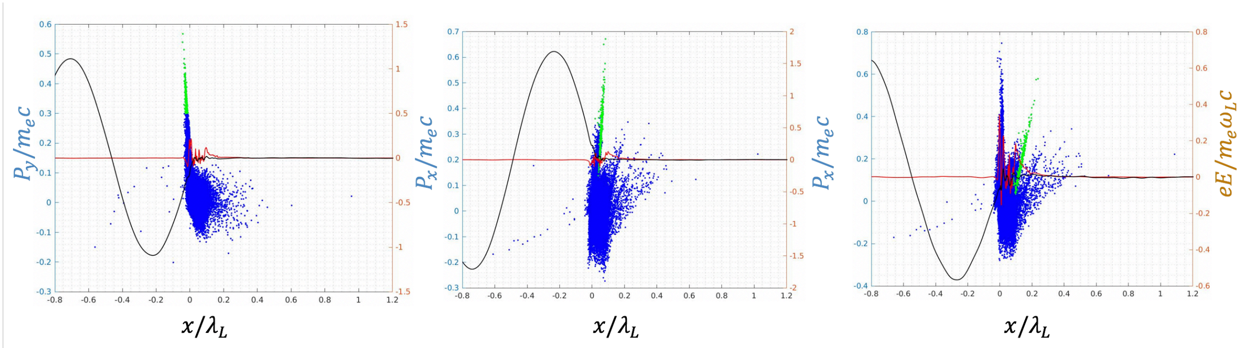

Figure 2: The early time development of the phase space dynamics of electrons (blue dots) and ions (green dots) at the solid target interaction of the CAIL regime. The oncoming laser fields (black) and excited electrostatic fields (red) are normalized to the Tajima-Dawson field E_{TD} (after Necas[14]).

3. From acceleration to accelerators

The original concept by T. Tajima and J. Dawson[6], considered accelerating electrons by the waves generated in gaseous plasma by either one laser, in the Laser Wake Field regime (LWF), or two laser pulses, in the Laser Beat Wave regime (LBW). The proposed scheme, the relativistic electrons externally injected into the accelerating phase of wave's longitudinal electric field, can "surf" on it, and gain high energies over a very short distance.

In the LWF regime, a short and intense laser pulse is focused into a tenuous plasma with a density set to provide the resonance condition of laser pulse duration being a half of the plasma period. The laser ponderomotive force pushes plasma electrons at its leading and trailing edges and the mentioned resonance condition assures the optimal coupling. Electrons injected at 3 MeV have been accelerated by this scheme up to 4.7 MeV[25] in GV/m accelerating field in an experiment performed in France. In the LBW scheme, a train of short pulses, produced by "beating" two laser pulses at two different wavelengths, are propagating in a plasma density chosen in order to match here also a resonance condition that is reached in this case when the plasma frequency is equal to the laser frequencies difference. Electric fields close to the GV/m level were measured for this experimental configuration using mid-infrared laser beams[26] and injected electrons have been accelerated up to 30 MeV at UCLA[27]. In all these pioneering experiments, because of the long duration of the injected electron bunches, which was much longer than the plasma period and even longer than the life time of the plasma wave, only a very small fraction of injected electrons were accelerated and the output beam had a very poor quality with a thermal-like energy distribution.

The first experiment that demonstrated efficient acceleration of self-trapped electrons, i. e. electrons from the background plasma, was performed at Rutherford Appleton Laboratory in 1994[28], in the so-called Self Modulated Laser Wake Field regime (SMLWF) [29-31], that involved a long laser pulse (pulse duration longer than the plasma period) with intensity large enough to excite the stimulated forward Raman scattering with the gain large enough to trigger relativistic wave-breaking limit. In this experiment, for the first time tens of GV/m accelerating gradients were observed, and copious number of electrons were trapped and accelerated in the laser direction, producing tens of MeV electrons on only few millimeter distance. Later on, this regime was also reached in CUOS[32] and NRL[33] in the United States. Further experimental observations of laser electron acceleration were done with at MPQ using a 10 Hz compact laser system[34], for the first time realizing the direct laser acceleration (DLA) scheme, and at LOA in the SMLWF regime[35].

In 2002, another breakthrough was obtained in the Forced Laser WakeField (FLWF) regime where low divergent electron beams with energies up to 200 MeV were obtained with the 1 J "Salle Jaune" laser at LOA[36] in hundred of GV/m accelerating field. In this non-linear regime, the quality of the electron beam was improved by reducing noticeably the interaction between the laser and the electron beam, and by matching the size of the laser pulse (longitudinal and transverse) with the plasma wavelength. The same year, 3D particle-in-cell (PIC) simulations suggested a new so-called *bubble* regime[37] that predicts production of a quasi-monoenergetic electron beam. This regime was observed experimentally in 2004 in UK[38], in the United States[39], and in France[40]. Electrons at the GeV level were observed in this regime using in uniform plasmas[41,42] or in a plasma discharge, where plasma channel with a parabolic density profile guides the intense laser beam over a longer distance of a few centimeters[43]. Recently, the scaling of this scheme to the PW laser power was demonstrated, showing generation of electrons with energies reaching 8 GeV[44]. In those experiments, the electron beam parameters were not yet optimized, and in most cases plasma acceleration exhibits strong shot-to-shot fluctuations that need to be reduced for real applications.

In this respect, since the time of "dream beam" articles, the last decade has been extremely flourishing particularly with the demonstration of high quality electron beam that are delivered now in a reliable way by exploring and demonstrating different injection schemes. The injection schemes that do not involve the external electron beams were made possible thanks to the high accelerating fields produced in the non-linear regime, which greatly facilitate the trapping. Injection process consists in modifying the trajectory of some electrons so that they can remain inside the accelerating part of the wakefield instead of slipping through it. This can be done by changing the wakefield either globally or locally. In addition to improving the reliability of laser plasma accelerator, the control of injection process allows to improve the beam parameters such as charge, emittance, bunch length, energy spread.

To have a synthetic view of electrons injection schemes in non-linear plasma waves, one can divide them into two categories – the cold and the hot injection cases. The injection concept can be understood looking at different electrons trajectories in the laser wakefield potential (see Figure 3). The plasma electrons that are initially at rest, when interacting with the laser follow the blue trajectory in Figure 3, i. e. simply slip through the wakefield, and their longitudinal dynamics corresponds to the plasma oscillations. These are the non-trapped electrons. The gray trajectories in the red area correspond to the trapped electrons that are going to gain energy in the wakefield. The separatrix (black curve) divides the trajectories for which the electrons can be accelerated from the one for which electrons simply slip through the wakefield. Thus the injection process consists in modifying the motion of some of the plasma electrons, in such a way that they cross the separatrix. In hot injection case, electrons get into the accelerating region by an increase in the energy (vertical red arrow), while in the cold, optical injection schemes (horizontal red arrow) such additional energy may be avoided. When trapped those electrons gain energy according to the white curve. Cold injection occurs when electrons are dephased with respect to the wakefield. This occurs when the wakefield wavelength changes, for example due to the relativistic plasma wavelength elongation[45] that results from relativistic self focusing, in the density gradient/shock injection[46-57] due to the density decreases locally, in the case of optical injection with circularly polarized colliding laser pulses[58] (electrons are trapped in the standing wave generated during the pulses collision), or in the transverse optical injection[59] due to the rapid change of the plasma wavelength that results of the pulses collision. Hot injection occurs when local heating with enough longitudinal momentum transfer is achieved for example in optical injection with two linearly polarized colliding laser pulses[60-65].

Demonstrating the injection control mechanisms of electrons in a tiny volume of about one micrometer cube size in an accelerating structure moving at speed of light was the challenge that we have faced this last decade. These methods now permit to produce in a reliable way high quality electrons beams at hundreds of MeV energy with tens of TW laser powers, opening new perspectives for societal applications[66]. In the near term these injection schemes combined with advancement of high power lasers and improving guiding technique will surely allow to produce reliable GeVs and high quality electron beams.

In this mini-review article, many relevant aspects and articles are not referenced because of the length limitation constraints. More detailed review articles[67-70] are suggested to readers interested by this topic.

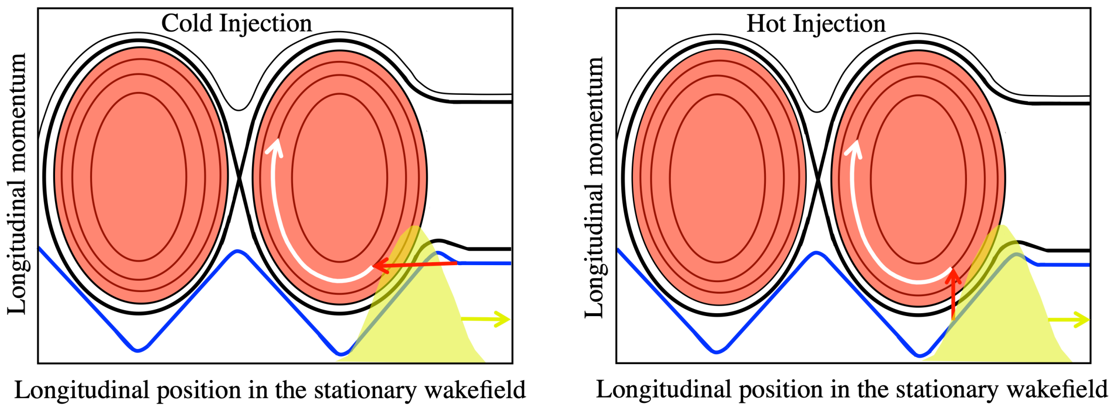

Figure 3: Representation of the possible trajectories for the electrons inside the wakefield for the cold (on left) and hot (on right) injection cases. The black line corresponds to the separatrix, the red area represent the trapping zone, while the blue line represents the trajectory followed by the electrons that are initially at rest. The laser pulse location is represented in yellow. Injection allows electrons at rest (blue line) to move (red arrow) in the trapped region (in red) and gain energy (following the white line).

Author contributions

Part 1 and 2 have been contributed by TT, and part 3 by VM

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