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Short Communication

# The Progress of Laser Assisted Charged Particle Acceleration

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Due to the incessant development in the short pulse laser technology ($10^{18}$-$10^{19}$ W/cm$^2$) accessible today, electron beams can be generated and accelerated with higher efficiency and low divergence in vacuum and plasma for various applications in medicine, science and technology, material science, industry, cancer therapy and fusion. Earlier, conventional methods proved to be unsuccessful in vacuum to accelerate electron with high energy due to bulky size. Recently, chirped pulse amplification process improves the power ($\geq$10 TW) of ultra-high short pulse tabletop laser. These ultra-short intense laser pulses are utilized for the generation of monoenergetic electron beams of mega electron volts. electron beam to excite ions to high energy. The key idea to excite large amplitude electron plasma waves by using short laser pulse (LWFA) in high density plasma was proposed by Tajima and Dawson in 1979 (Tajima & Dawson, 1979). The exciting results that have so far been accomplished; present great assurance for future plasma accelerators by providing compact 'table-top' electron accelerators. However, there was no such a short pulse laser in that era, and therefore experiments involve beat wave to excite the plasma waves.

In 1983, a new acceleration mechanism was explored, later called Cross Field Acceleration (or $\vec{v}_p \times \vec{B}$ acceleration. This was the first and novel mechanism observed of high energy acceleration phenomena. A comparatively long pulse laser was employed in the actual plasma-based acceleration experiments conducted in the era of 1980s and 1990s as the short pulse laser does not exist.

A striking innovation in the electron acceleration took place when Strickland and Mourou implemented Chirped Pulse Amplification (CPA) technique from microwaves to lasers. In vacuum, the key idea of laser induced particle acceleration has been proposed (Hora, 1988) by chirped pulse amplification technique. The introduction of CPA rapidly pushed laser-electron optics into relativistic regime led to the possibility of laser wavelength shorter than plasma wavelength. No doubt, the study of nonlinear phenomena in plasmas has proved a big challenging area of research over last few decades. The contributions in the areas of formation of coherent structures such as solitons, double layers, shocks, parametric instabilities and wave induced particle acceleration etc. have not only advanced our perceptive of plasma behaviour but also help ultrashort ultra-intense pulse lasers have made possible to touch new horizons in producing high quality beams by high accelerating energies, and now reached from conventional RF (Radio Frequency) accelerators to dream table top accelerators.

One major drawback of conventional RF accelerators is that the electric field intensity is limited (~30 MV/m). On the other hand, table-top terawatt laser produces highly intense electric fields (~ 100 TV/m), which is approximately million times more intense. In order to reach the TeV range; which has not been done so far in case of electrons and positrons in synchrotron configuration; the accelerator needs to be approximate 30 Km long. Here the plasma-based electron acceleration is important because of larger accelerating gradients in plasma, which in turn produces much shorter acceleration length. Hence, plasma-based accelerators have the capability to be inexpensive and much smaller alternative. As the pulse propagates through plasma, a longitudinal charge (ions and electrons) separated wave, Langmuir wave produces; that trails the electrons or laser pulse. So, depending upon the density of plasma, this wave is able to produce electric fields of 1 GV/m to 1 TV/m range. This was proposed thirty-two years back by Tajima and Dawson with short laser pulse. Laser beam propagates in plasma, excites a plasma wave and for being longitudinal wave, excites electron effectively. Ionised plasmas can uphold electron plasma waves through electric fields of the order of non-relativistic wave breaking field. The schemes to excite longitudinal plasma waves for electron acceleration employ Plasma Wake Field Acceleration (PWFA), Plasma Beat Wave Acceleration (PBWA), Laser Wake Field Acceleration (LWFA), Resonant Laser Plasma Acceleration (RLPA) and Self-Modulated Laser Wake Field Acceleration (SMLWFA).

### Plasma wake field acceleration

As discussed earlier that RF accelerators are limited by power and electric breakdown, so the only way to achieve higher energy from an RF accelerator is to enhance its length, which turn out to be an expensive one. So, plasma Wakefield accelerator proves out to be much efficient over RF accelerators. Plasma based accelerators are able to sustain huge electric fields (~ tens of GV/m). Due to high-speed electron bunch propagation in neutral plasma, causes ionization in plasma and the space charge field of electron bunch create a wake in the in the vicinity of plasma by displacing plasma electrons. This "wake" oscillates with electron plasma frequency, and also referred as plasma wave. It serves as a carrier for the suitably injected electrons, which accelerates due to the huge electric field of this wake of charge.

### Plasma beat wave acceleration

In the plasma beat wave accelerator (PBWA), a relativistic plasma wave is produced by the ponderomotive force of two co-linear laser pulses beating at plasma frequency. The energy and momentum conservation relations are satisfied $\omega_1 - \omega_2 = \omega_p$ and $k_1 - k_2 = k_p$, $\omega_1, \omega_2$ and $k_1, k_2$ are the frequencies and wave numbers of the two lasers respectively. Clayton., *et al*. (1985) was the first to explain the theory of plasma wave in the PBWA process via Thomson scattering, and later several researches were done in that era.

### Laser wake field acceleration

In this process, plasma wake is produced by a short (< 1 ps) terawatt ($I \sim 10^{18}$ W/cm$^2$) laser pulse. The ponderomotive force of the laser pulse drives a plasma wave, which propagates with the group velocity of the laser, i.e. $v_g = \omega_p$, where $v_g$ is the group velocity of the laser and $\omega_p = 4\pi n_0 e^2 / m$ is the plasma frequency, $n_0, e,$ and $m$ are the equilibrium density, charge and mass of the electron respectively. This plasma wave exhibits high electric field (TV/m) in the longitudinal direction. The LWFA was initially proposed by Tajjima and Dawson (1979) by using high power laser.

### Resonant laser plasma acceleration

In this process, multiple laser pulses are employed, which can be independently controlled. Moreover, the width of each pulse is adjustable. By optimizing the space and length of the pulses, the resonance can be quickly established with the plasma waves and hence, maximum wake field amplitude can be achieved.

### Self-modulated laser wake field acceleration

Similar to the LWFA, the SMLWFA also employs a short (< 1 ps) terawatt ($I \sim 10^{18}$ W/cm$^2$) laser pulse. However, self-modulated LWFA works for higher densities and the laser pulse length is longer that the plasma wavelength.

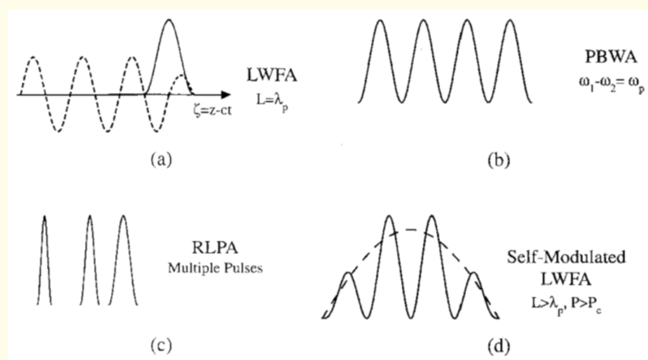


**Figure 1:** Schematic of Plasma based accelerators.

The laser induced electron acceleration up to high energy explores an extensive range of applications in the fields of medicine, therapy for tumours, radiation - chemistry, material-characterization, and ultrafast phenomena studies. Laser-plasma interaction has numerous applications in different areas such as inertial confinement fusion, particle acceleration, resonance absorption, generation of X-rays, gamma rays, generation of THz radiation etc.