Laser Plasma Electron Linear Accelerator

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Abstract

The generation of an ultrashort relativistic electron bunch from a strong laser-plasma interaction have been studied by particle-in-cell simulations and observed experimentally. The electron beam was generated from the plasma created by focusing a Ti: sapphire 12 TW (tera watt) laser pulse at the edge of helium gas jet expanded into the vacuum from a pulsed supersonic nozzle. The laser pulse duration was 50 fs (femtosecond).

In the interaction of 50 fs 12 TW laser pulse with plasma of density of $5 \times 10^{18}$ cm$^{-3}$ ($\gamma = \omega_{\text{laser}}/\omega_{\text{plasma}} = 18.6$) the electron beam generation was taking place due to the transverse injection of some portion of the plasma electrons which constitute a large amplitude plasma wave. Such an electron injection and generation took place at the very end of the interaction region with no possible chance for enhanced acceleration. For a relatively higher plasma density at $5 \times 10^{19}$ cm$^{-3}$, ($\gamma = 5.8$) the electron generation with very high energy (up to 100 MeV) was observed in the simulation at the beginning of the interaction region. The relativistic force (in the laser’s propagation direction) of the laser pulse creates relativistic waves with wavelengths of the order of the laser wavelength propagating with the pulse. Due to its short length, the relativistic waves break into the wakefield behind the laser pulse producing energetic electrons. These electrons constitute the injection source for the following relativistic wave so these electrons acquire the maximal energy in the bunch just behind the laser pulse. In the experiment, the electron beam transverse profile and its total charge have been measured in the forward direction by using imaging plate and Faraday-cup, respectively.

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1. **Introduction**

The theory, simulation, and experimental work in the field of electron acceleration by plasma wave excited by intense laser pulse have been addressed over the last two decades [1]. In the standard scheme of the laser wake field accelerator (LWFA), an ultrashort, intense laser pulse propagates through an underdense plasma can generate large amplitude plasma wave by the effect of ponderomotive force associated with the laser pulse envelope $F_p \sim V a^2$. It expels electrons from the region of the laser pulse, where $a$ is the normalized vector potential of the laser and is given by $a = eE\lambda/2\pi m_o c^2$ where $e$, $m_o$ are the electron charge and mass respectively and $E$ is the electric field of the laser beam with wavelength $\lambda$. If the length scale $L_c$ of the axial gradient of the pulse profile is approximately equal to the plasma wavelength, $L_c \sim \lambda_p$, the ponderomotive force excites the plasma wave effectively. The plasma wave (called wake field) forms a train of accelerating buckets behind the laser pulse, each with duration equal to the plasma period. The acceleration gradient resulting from the charge displacement is given by $E_0 = mc(\omega_p/e)$ or $E_0 = n_o^{1/2}$ when $E_o$ is in units of V/cm and $n_o$ is in units of cm$^{-3}$. For example, plasma with density $n_o = 10^{18}$ cm$^{-3}$ is capable of supporting a field of $E_o = 100$ GV/m. In order to accelerate an electron in such high field, it should be injected in the correct phase with respect to the plasma wave. Also it should be moving with nearly the same phase velocity as the plasma wave which is almost the speed of light, $c$. Therefore it is expected that the required injection of electrons into the wave can be done only with an external electron injector (e.g. a linac). Since the plasma wavelength of our interest, is ranging from 10-100 $\mu$m (depending on the plasma density), the longitudinal bunch length of the injected electrons should be within this range. Two schemes based on laser triggered electron trapping in the plasma wave, were proposed for generating such an ultra-short bunch electron beams [2, 3]. In these schemes two or three laser pulses should collide in the plasma, injecting some plasma electrons to get trapped in the wakefield generated by one of these laser pulses. In this case, the laser pulses should be synchronized in space and time very precisely, which is not possible experimentally so far. Instead, we use, one single 12TW 50 fs laser pulse propagating through an underdense plasma, exciting large amplitude waves, and the electron injection process can be done by the wavebreaking of the plasma wave. The plasma will be created in a gas jet by the foot of the laser pulse itself, hence the rest of the laser pulse is moving in a fully ionized plasma, see Fig. (1).

The purpose of the present work is to generate ultrashort relativistic (tens of MeV’s) single electron
bunch in the sub-100fs range. Hence our setup can serve as an accelerator or as an injector for higher energy laser-plasma based or radio frequency conventional accelerators.

The basic idea of generating such an electron bunch is based on the wavebreaking of plasma wakefields as they grow up to very high amplitudes generated in plasma having density gradients. At the wavebreaking point, a large amount of plasma electrons gain highly relativistic energy (originally, the wave’s energy) in the longitudinal direction that make them leave the plasma and emitted as a beam of electrons. The density gradients which we are using, are experimentally available from supersonic gas jets (see Fig. (1)) in contrary to the scheme proposed in Ref. [4] which is based on making very sharp plasma density gradient (of the order of the plasma wavelength $\lambda_p$). However, the beam quality in one of our cases is fairly good, approaching the quality in Ref [4]. In order to obtain very good beam quality, a magnetic chicane should be used just after the gas jet for filtering the electron beam and obtaining relativistic ultrashort single bunch.

2. 2D-PIC Simulation Results

The 2D simulations were done using the recently developed fully relativistic particle-in-cell code OSIRIS [5], [6]. The code is scalable parallel code and can be used for 2D as well as 3D simulations. It contains moving window algorithm that makes it possible to conduct simulations over the distances we have in our experiments with reasonable amount of computing resources. The simulation window, which was moving with the speed of light in the propagation direction of the laser pulse and thereby following the laser as well as any high energy electrons, had in normalized units dimensions of 905 $c/\omega_n$ in the $x_1$ direction and 351 $c/\omega_n$ (or 2111 $c/\omega_n$) in the $x_2$ direction. $\omega_n$ is the frequency used for normalization. For convenience we choose $\omega_n = \omega_L$, the laser frequency. This normalization units corresponds to the length of the laser wavelength $\lambda_L = 0.8 \mu m$. The moving window size is therefore $115 \mu m \times 44.6 \mu m$ (or $269 \mu m$) in MKSA units. The computational grid of the simulations was $2048 \times 768$ with four particles per cell.

The simulations with the gas jet of 1.5 mm diameter were run for a time of $12600 \omega_L^2$, $(5.35\times10^{-12}$ sec) corresponding to a propagation distance of $12600 c/\omega_L$ (1.6 mm). The plasma density profile can be approximately described by a trapezoidal function. Within $500 \mu m$ the plasma density ramps from zero (vacuum) up to $5\times10^{18}$/cm$^3$ (or $5\times10^{19}$/cm$^3$ as will be shown later). The density was kept constant at this value in about $500 \mu m$. At last the density ramped down to zero in $500 \mu m$. In the
simulations we set the laser pulse as 12TW 50 fs with spot size of 10 $\mu m$, initialized in vacuum and propagated through the plasma.

Figure (2) shows the simulation results (the window size is 115 $\mu m \times 44.6 \mu m$) in the case of plasma with density of $5\times10^{18}/cm^3$ (in the flat top region as described earlier). This case corresponds to the standard regime of LWFA. Figure (2a) shows the longitudinal momentum that the trapped electrons gain as a result of the interaction versus their longitudinal distance. The particles at the very end (at $x = 1.31 \times 10^4 (c / \omega_0)$ in the figure) of the simulation box are the ones which leave the plasma first to the vacuum. The average energy of those electrons was 6.5 $MeV$. The mechanism for the electron trapping in the plasma wave is shown in Fig. (2b) and Fig. (2c). They show the phase space $X2-X1$ of the plasma electrons at the very end of the plasma region, exactly after propagating 1.42 mm (in Fig.2b) and 1.47 mm (in Fig.2c). The red semi-circles correspond to the electron plasma wave or wakefield generated due to the propagation of the laser pulse. At the time shown in Fig. (2b) the electrons in wave 1 have started to be injected transversely from the sides of the plasma wave. At the later time of Fig. 2c the electron injection is clear at the centers of both waves. At the injection point, the plasma wavelength increased due to the decrease of the plasma density. Such lengthening of the wavelength had affected and disturbed the regular structure of the wave such that it lost some of its electrons. We call this injection as the ‘transverse wavebreaking’ and occurred only at the end of the plasma. The generation of such beam at the very end of the plasma region is not preferable since they are not going to gain more energy. However, if the electron generation took place at the beginning of the interaction, there will be a chance for them to gain more energy as they move forward in the field of the plasma waves.

Figure (3) shows the results for a run with the same parameters as the previous run except that the plasma density in the flat-topped region is $5\times10^{19}/cm^3$ instead of $5\times10^{18}/cm^3$ (the size of the window in this case was 115 $\mu m \times 269 \mu m$). Figure (3a) and (3b) show the longitudinal phase-space of plasma electrons trapped and accelerated by the plasma waves up to 110 MeV. Such very high-energy electrons were trapped in the wave at the beginning of the interaction. In Fig. (3a), after the laser propagates distance of $ct = 0.49 \text{ mm}$, it is clearly seen that amounts of electrons with high energies were trapped. Now we discuss the electron injection mechanism in this case.

In Ref [4], the plasma-wavebreaking mechanism for such injection has been proposed. The steep plasma density gradient is necessary for the purpose. If the gradient is too long as in our simulations,
the time delay between the maximal intensity wakefield and injected electrons can reduce essentially the efficiency of acceleration. However for a laser pulse with relativistic intensity \( a = eE/m_0 c \omega > 1 \), there is another mechanism for electron injection based on the breaking of waves produced by the relativistic acceleration of electrons into wakefield waves.

The effect of the ponderomotive force on electron acceleration decreases with the relativistic laser intensity because this force has \( \gamma \) as a factor in denominator [8],

\[
\frac{dp}{dt} = -\frac{mc^2}{2\gamma} \nabla a^2,
\]

where the cap means time-averaging. With the laser intensity, this force grows as \( a \) when \( a > 1 \). In contrast to the ponderomotive force, the relativistic force, which acts along to the laser propagation direction, grows as \( a^2 \) [9]. The relativistic force creates waves with wavelengths of the order of the laser wavelength propagating with the laser pulse. The maximal energy of electrons in the waves is determined by the longitudinal component of the electron momentum,

\[
\gamma \sim p_x = a^2 \sin^2 (a \omega + k x)/2
\]

Since the wavelength of these waves is much shorter than the plasma wavelength, \( \lambda_p = \frac{2\pi c}{\omega p} \), the waves break into the wakefields behind the laser pulse producing the energetic electrons. These electrons constitute the injection source for the following relativistic wave so that electrons acquire the maximal energy in the bunch just behind the laser pulse as shown in Fig. (3a).

The short wavelength waves appear behind the laser pulse and break into the wakefield with longer wavelength. This wavebreaking is an injection source for wake-field acceleration. This injection and acceleration mechanism sustain as long as the laser pulse is relativistic and energetic. Fig. (4a) shows the contour plot (the color code indicates the intensity of the laser field in arbitrary units.) of the laser pulse at the same time as in Fig. (3a). As the laser pulse propagates further through the plasma, it filaments, deteriorates and leaves the plasma in a distorted and diffracted shape as shown in Fig. (4b). Consequently the ordering structure and energy of the relativistic wave and the electron trapping in it are all also deteriorated as in Fig. (3b). Disordering of the wave with the maximal energy electrons after the laser pulse deteriorated is a proof for the mechanism proposed.

Despite of the deterioration of the trapped electrons, they leave the plasma as shown in (Fig. 3b) in a single bunch with maximum energy of 110 MeV. The average energy of all electrons was 22.5 MeV. However, an energy spread of 100% was produced. The beam characteristics of this run are preferable because only single bunch was generated, with much more electrons in it, and with higher
average and maximum energies. Using a magnetic chicane, it seems possible to filter this beam in order to get a beam with lower energy spread. For example, in the energy range 82 MeV-110 MeV, the bunch length was 3.5\(\mu\)m (equivalent to \(\approx 10 \text{ fs}\)) and the total charge of accelerated electrons was about 580 \(pC\).

3. Experiment

The experimental setup is shown in Fig.5 and described as follows: an OAP (off-axis parabolic) mirror focused the laser pulse at 1-3 mm above the top of a pulsed supersonic gas jet. The calculated laser spot size and intensity in vacuum above the nozzle were 12.6 \(\mu\)m and \(4\times10^{18} \text{ W/cm}^2\), respectively. The maximum gas backing pressure was \(\approx 1000 \text{ psi}\) and helium and nitrogen gases were used. The high pressure corresponds to high plasma density. The nozzle has a conic shape with a circular base of 2\(mm\) in diameter. The design and performance of the gas jet nozzle are crucial in this experiment.

The 12TW 50 fs laser facility is based on the chirped-pulse amplification (CPA) technique at the wavelength of 0.8 \(\mu\)m. The system consists of an oscillator system (FEMTOSOURCE-20) and a combined optical stretcher- amplifier- compressor system (ALPHA-10 S-12). The oscillator system is a chirped mirror mode locked Ti:sapphire laser, pumped at 5 watts by a solid-state diode-pumped, frequency doubled Nd:Vanadate (Nd:YVO\(_4\)) laser that provides a continuous wave single-frequency green (532\(nm\)) light. The laser oscillator output power is 450 milliwatt with repetition rate of 79 MHz. The laser oscillator pulse duration is 20 \(fs\) at 773 \(nm\) with spectrum width of 44 \(nm\).

The stretcher- amplifier- compressor system consists of (i) single grating stretcher, (ii) 10 Hz repetition rate regenerative amplifier, (iii) multi-pass pre-amplifier, (iv) two multi-pass amplifiers and (v) an evacuated pulse compressor. The regenerative (regen.) amp. and the three multi-pass amps. utilize four Titanium sapphire (Ti: Al\(_2\)O\(_3\)) crystals as gain medium which has broadband tunability (from 670 \(nm\) to 1070 \(nm\)) and all are pumped with three frequency-doubled Nd:YAG lasers. A single Pockels Cell (MEDOX system) is used to seed and dump out the pulse from the regenerative cavity. All the optical components and the cavity design are optimized to provide a high damage threshold.

The laser system briefly works as follows: The 20 fs seed pulse from the oscillator is stretched to 300 \(ps\) in the stretcher, which is a multi-pass single-grating arrangement with a reflective telescope.
A stretched pulse is amplified to 4.5 mJ in the Ti: sapphire regenerative amplifier pumped at 10 Hz by 245 mJ, 3 ns pulses of a Q-switched compact Nd:YAG laser at 532 nm. The output of the regenerative amplifier is further amplified to 35-40 mJ in a Ti: sapphire multi-pass pre-amplifier and to 650-700 mJ through a Ti: sapphire main amplifier both are pumped by two high-power Q-switched Nd:YAG lasers with two channels per one laser head, the output energy per channel is a pulse of 1250 mJ with 6 ns duration at 10 Hz. The amplified pulse is transported to the experimental room via an evacuated transportation line and is compressed in an evacuated two-pass grating configuration compressor system down to about 50 fs with an energy 650-700 mJ, corresponding to a peak power of about 12 TW.

The synchronization between the laser and the gas jet was achieved precisely by using timing electronic units triggered by a signal from the laser control panel. The exact synchronization was confirmed by taking the brightest image of the plasma produced by focusing the laser (at low power) on the gas jet while changing the delay time between them. The gas jet repetition rate was about 0.14 Hz. We have used such a low repetition rate for safety purposes, however the experiment can be done at the laser’s repetition rate, 10 Hz. The perfect focusing above the jet was done in vacuum by remote controlling the jet’s translation stage. The charge per pulse and the transverse profile of the electrons were detected in the forward direction by using a Faraday cup and an imaging plate, respectively. An aluminum foil with thickness of 75 µm was inserted at 200 mm from the gas jet to filter-out electrons below ≈100 keV, and to prevent the intense laser light from reaching the detection system. The whole system was under vacuum down to 10⁻⁵ Torr.

4. Experimental Results

The total charge of the electron beam was measured in the direction of laser propagation by using the Faraday Cup (FC) installed outside of the vacuum chamber. The FC has been installed in the forward direction, 20 cm away from the interaction point. A vacuum flange made of Titanium with thickness about 20 µm was used so that the generated electrons can pass through it and measured outside the vacuum chamber. Using lead collimator in front of the FC then collimated the beam, in this configuration the FC was able to detect electron beam with divergence angle up to 0.07 rad (i.e. 4.2°). In such measurement the average charge was about 15 pC per pulse.

We are planning to measure the beam charge again after adjusting the time jitters more precisely. Also we are planning to measure the electron beam energy spectrum. For this purpose, an on-line
64-channel electron spectrometer for measuring energies from 100 keV to 10 MeV was designed and tested. The transverse profiles of electron beams generated from helium plasma are shown in Fig. (6) for various gas pressures at the laser power of 4 TW. The gas pressures were 42, 52 and 62 atmospheres in Figs. (6a), (6b), and (6c), respectively. The profiles were detected by using imaging plates (IP) inserted in the forward direction inside the experimental chamber at a distance of 20 cm from the gas jet. After each irradiation, a laser scanner read the IP and a two-dimensional distribution of the beam could be viewed on a display through a computer. Each electron image shown in Fig. (6) is an accumulation of about 200 pulses. The electron beams shown in Fig. (6a) and (6b) have approximately Gaussian profile, and were emitted from the plasma in a cone-like shape with angles about 9° and 7° (at HWHM), respectively from the electron source. The beam profile was deviated from Gaussian at higher gas pressure in Fig (6c). In other measurement in this same experiment and at both higher pressures and laser powers, we observed two-component spatial profile of the electron beam. Similar behavior has also been observed in previous experiments using longer laser pulses [7].

5. Conclusion
The 2D-PIC simulations and the first experimental results showed the generation of electron beam from a plasma in its interaction with an ultrashort "50 fs", intense "12 TW" laser pulse. The simulations showed two regimes, the first was the LWFA in which electron generation and trapping took place due to the transverse injection wavebreaking mechanism at the end of the plasma region, and hence the electron beam energy and quality were quite limited. Second, was the regime with relatively higher plasma density. In this case the electron trapping and injection processes were started at the beginning of the interaction due the relativistic force of the laser pulse which creates relativistic waves with wavelengths of the order of the laser wavelength propagating with the pulse. Due to its short wavelength, the relativistic waves break into the wakefield behind the laser pulse producing energetic electron which are then injected into a following relativistic wave for further acceleration. In the experiment, by focusing 12TW 50 fs in a supersonic helium gas jet, we measured the total beam charge and transverse profile. We are planning to perform further experiments for fully diagnosing the electron beam, the laser pulse propagation, and the plasma diagnostics.
Figure (1). Schematic view illustrating the electron trapping by the wavebreaking of the plasma wave excited in the interaction of 12TW 50 fs laser pulse with gas jet plasma.
Figure (2). Simulation results of the standard LWFA formed by the interaction of 12TW 50 fs laser pulse with plasma of density $5 \times 10^{18}$ cm$^{-3}$. (a) The figure shows the longitudinal momentum versus the distance of the accelerated plasma electrons. (b and c) Show the process of transverse injection of some electrons from the plasma wave at the very end of the laser-plasma interaction region.
Figure (3). (a-b) The figures show the phase space of the accelerated plasma electrons after the laser pulse have propagated the distances 0.49 mm and 1.57 mm in the plasma of density $5 \times 10^{19}$ cm$^{-3}$. 
Figure (4). The color contour plot of the laser pulse after propagating into the plasma the distances (a) 0.49 mm and (b) 1.57 mm.
Figure (5) The experimental setup.
Figure (6). The electron beam transverse profiles measured by using imaging plates at fixed laser power of 4 TW. (a), (b) and (c) show the profile of electron beams generated from helium plasma at the gas backing pressures 42, 52 and 62 atmospheres, respectively.