

A SIMULATION FOR ELECTRON TRAPPING AND ACCELERATION IN PARABOLIC DENSITY PROFILE AND ONGOING EXPERIMENTAL PLAN*

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Abstract

It is known that as a laser wakefield passes through a downward density transition in a plasma some portion of the background electrons are trapped in the laser wakefield and the trapped electrons are accelerated to relativistic high energies over a very short distance. In this study, by using a two-dimensional particle-in-cell (PIC) simulation, we suggest an experimental scheme that can manipulate electron trapping and acceleration across a parabolic plasma density channel, which is easier to produce and more feasible to apply to the laser wakefield acceleration experiment. Also, we present a brief ongoing experimental research plan by using the newly developed high power femtosecond laser in KERI.

INTRODUCTION

The plasma-based accelerators such as laser wakefield accelerators (LWFA) have shown much interest in both theory¹⁻² and experiment.³⁻⁴ In the conventional LWFA scheme, for acceleration of electrons they should be injected externally by using an external injection accelerator or high-power lasers for optical injection.⁵⁻⁶ However, in the self-injection cases,⁷⁻⁹ some background electrons in a plasma can be self-injected and the electrons can be accelerated by the laser wakefield to relativistic high energies over a very short distance. Therefore, the major advantage of the self-injected LWFA is that it may be built with very compact tabletop size because it does not require auxiliary heavy facilities that most conventional accelerators do. That is why people in the advanced accelerator community have shown much interest in the self-injection LWFA method in recent years.

In this study, we propose an experimental scheme with a parabolic plasma density channel, which may be easily obtained experimentally by an intense laser and gas jet interaction. There were some previous LWFA studies performed in a preformed parabolic density channel,¹⁰⁻¹¹ but most of the works were conducted along the axis of the channel in which electron density is minimum to provide optical guiding of an intense laser pulse. In the current study, however, we report a preliminary simulation result of electron trapping and acceleration in a plasma when a short and intense laser pulse passes across a parabolic plasma channel. For this purpose, a 2-dimensional (2-D) particle-in-cell (PIC) simulation has

been performed and fully relativistic and electromagnetic OSIRIS code¹¹ were employed. The simulation box (i.e., moving window) was assumed to propagate with the speed of light, c , in free space.

PLASMA DENSITY MODEL & SIMULATION PARAMETERS

The density profile modelled in the simulation has a typical parabolic shape of $n(r) \approx n_0 + \Delta n r^2 / r_{ch}^2$. Here, n_0 and Δn are the minimum density on axis and density change, respectively and r_{ch} is the channel radius. The full width of the plasma channel (r) and the width of the parabolic density region were set to $3,140 k_0^{-1}$ ($\approx 400 \mu\text{m}$) and $2,512 k_0^{-1}$ ($\approx 320 \mu\text{m}$), respectively. The edges of the plasma channel were set to $314 k_0^{-1}$ ($\approx 40 \mu\text{m}$) for the upward and downward density transitions, respectively. Here, k_0 is the wave number of laser in free space. Assuming the cylindrical symmetry of the plasma channel the density profile shows a density minimum on axis (i.e., $r = 0$) and it increases with r and reaches the highest value at the edge where it decreases to zero with relatively short scale length, L_s of $\approx 40 \mu\text{m}$. 2-D PIC simulations were performed using this parabolic density channel assuming that the peak and minimum plasma density were $n_e = 5 \times 10^{18} \text{ cm}^{-3}$ and $2.1 \times 10^{18} \text{ cm}^{-3}$, respectively and a fully ionized plasma channel was assumed. Also, a short ($= 50 \text{ fs}$, i.e., pulse length $L = c\tau \approx 15 \mu\text{m}$), intense laser pulse (i.e., peak power, $P = 10 \text{ TW}$ and wavelength $\lambda_0 = 1.064 \mu\text{m}$) was assumed to pass through the plasma channel. The normalized vector potential a_0 was set to 2.27 and the laser beam was focused at the centre of the channel to a spot size of $10 \mu\text{m}$.

RESULTS & DISCUSSIONS

In the simulation it was observed that some background electrons are trapped at the first node of wakefield as the plasma wakefield passes just down rim ($\approx 57 \mu\text{m}$) of the parabolic density channel. At further elapsed time, the trapped electrons were injected into the acceleration phase of the wakefield and accelerated further [Fig. 1] until they reach the minimum density position (i.e., $\Delta Z = 1571 k_0^{-1}$ (i.e., $\approx 200 \mu\text{m}$) of the parabolic density channel. In general, accelerated electrons are highly relativistic so its velocity is faster than the phase velocity (v_{ph}) of the

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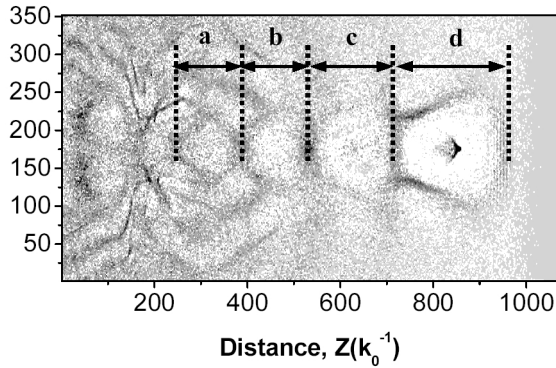


Figure 1: Further acceleration of the trapped electrons at the downward density transition of the parabolic density profile (i.e., $n(r) \approx n_0 + \Delta n r^2 / r_{ch}^2$). Where $a < b < c < d$.

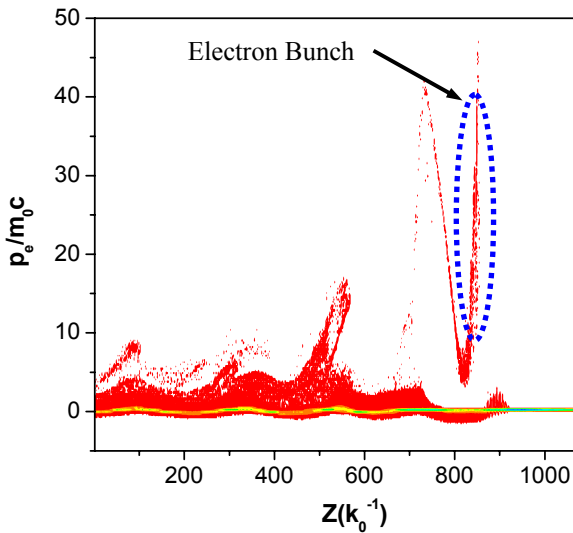


Figure 2: A simulation result of the momentum phase space (p_z, z) of the plasma electrons at the propagation distance $\Delta Z = 2,940 k_0^{-1}$ ($\approx 375 \mu\text{m}$ in plasma).

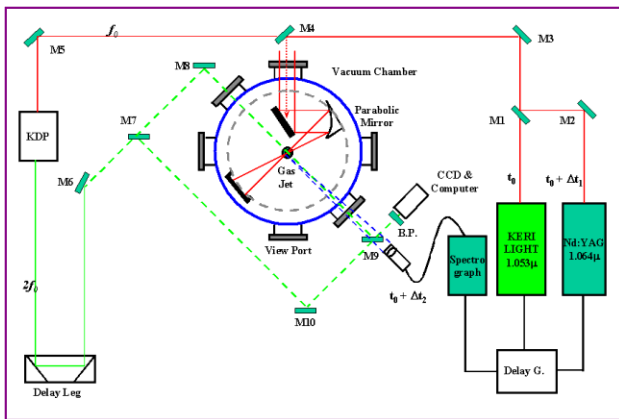


Figure 3: Future experimental schematic for diagnostics of the laser induced plasma.

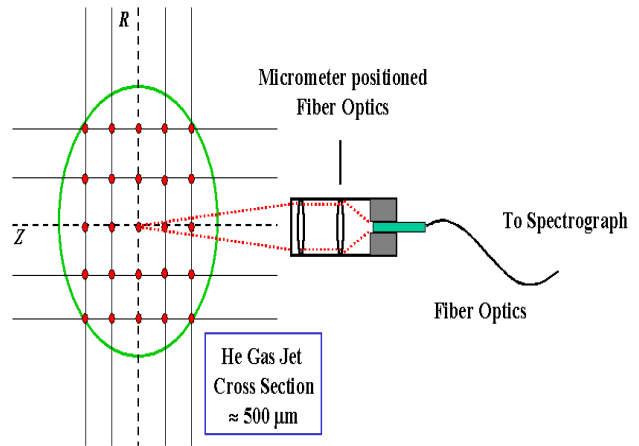


Figure 4: Detailed schematic diagram of the electron density and temperature measurement by using optical emission spectroscopy of seeded copper.

wakefield, which is nearly equal to the group velocity (v_g) of the driving laser.¹² Therefore, it is anticipated the trapped electrons would reach the deceleration phase of the wakefield. However, this is not the case as long as we consider the downward density transition in the parabolic density channel in which increased plasma wavelength can keep the trapped electrons effectively in the acceleration phase of the wakefield.

In Fig. 1, it is clearly seen that the wavelength of the wakefield increases continuously from “a” ($\approx 16 \mu\text{m}$) to “d” ($\approx 25 \mu\text{m}$) as the wakefield passes through the downward density regions of the parabolic density profile. While being accelerated, the trapped electrons have shown so-called “betatron” motion¹³ in which their transverse amplitude is continuously changing from maximum to minimum in the wakefield. On the contrary, as the laser wakefield passes through the upward density transition of the parabolic density profile, situations are quite reversed. Since the plasma wavelength, λ_p , decreases the very front portion of the accelerated electrons are gradually laid in deceleration phase (i.e., slippage or detuning)¹² of the wake field. It should be noted that, however, except for the very few front part of the electron beam most of the electrons are still in the acceleration phase of the wakefield, thus gaining more energy from the field.

Figure 2 shows a typical simulation result of the momentum phase space (p_z, z) of the plasma electrons at propagation distance of $\Delta Z = 2,940 k_0^{-1}$ (i.e., $\approx 375 \mu\text{m}$). The results show that the accelerated electron bunch (denoted as a dotted circle in Fig. 2) has momenta in the ranges of 5 and 20 MeV/c and the beam pulse width of approximately $\approx 31 k_0^{-1}$ (i.e., $\approx 4 \mu\text{m}$). However, it should be pointed out that the accelerated electron bunch shows large energy spread, which is due to the dephasing of the electron beams to the laser wakefield,¹² and it is commonly observed elsewhere.⁹

Figure 3 shows an ongoing experimental schematic for diagnostics of laser-induced plasmas produced in high-density gas jet and high power laser (~2 TW) interaction. The planned research is to study the characteristics of waveguides formed as subsequent two laser pulses are focused in the gas jet with appropriate time delay. For this purpose two lasers will be employed. One of which will be a high power laser, whose peak power, pulse duration, and wavelength are 2 TW, 700 fs, and 1.053 μm , respectively, and the other is a long pulse (7 ns FWHM) Nd:YAG laser. Plasma channels will be imaged by Mach-Zehnder and Schlieren visualization methods. Temporal and spatial evolutions of the electron density as well as electron temperature will be obtained by using optical emission spectroscopy as shown in Fig. 4. Usually, two typical methods in optical emission spectroscopy may be employed in the measurement of electron temperature in plasmas. One of which is the "Boltzmann plot method" and the other is so called "two-line method". Particularly, for this purpose, either a thin copper wire of approximately 20 μm will be installed in the centre of the gas jet or very fine copper powders (i.e., nano or micro-scale copper powders) will be seeded in the gas jet. Since the spectroscopic parameters such as spontaneous emission rate, degeneracy, and lower and upper level electronic energies are well known for the specific copper emission lines, therefore, only relative intensity measurements of copper emission lines are required in

order to deduce electron density and temperatures in the plasma.

In conclusion, we presented on-going experimental plan in KERI by using a recently developed high power femtosecond laser system. The planned research is to study the characteristics of waveguides as subsequent two laser pulses are focused in the gas jet with appropriate time delay and the detailed experimental procedures were introduced. Also, a 2-D PIC simulation study was performed in this study to investigate the electron trapping and acceleration in plasma by using a simple parabolic density model, which may be easily obtained experimentally by a laser and gas jet interaction. The scale length of the density transition used in this simulation is larger than Suk's scheme⁹ but smaller than Bulanov's.⁸ Despite the large momentum spread the trapped electrons can be effectively accelerated with momenta in the range of 5 – 20 MeV/c, which is similar to the previous results that used sharp downward density transition.⁹ It is anticipated that the current work proposes an experimentally easier and more feasible method for the electron trapping and acceleration in a plasma.

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