Plasma Cathode Using Single-T^{3}Laser Beam-Wakefield Wavebreaking in Plasmas

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Abstract

Recently *Bulanov et al.* proposed the nonlinear wavebreaking as a mechanism for the electron injection in the laser wakefield accelerator (LWFA) using 1D particle-in-cell simulation code. We confirmed it by more realistic PIC-2D simulations. Our simulation results showed the generation of about 10 fs 25 MeV 59.2 pC electron beam from the background electron plasma, which is called plasma cathode. The simple experimental setup, which is now under construction, is proposed using the 12TW 50fs laser system. The numerical approach and experimental configuration are presented.

1- Introduction

Recent advances in laser technology [1,2] offer the possibility of ultrahigh gradient acceleration of particles in laser-driven plasma waves (wakefields) [3]. The very promising scheme is the laser wakefield accelerator (LWFA), in which [4], electric fields up to 100 GV/m, and acceleration up to 100 MeV of an electron beam injected with 17 MeV has been observed experimentally [5]. Since the phase velocity of the wakefield equals the group velocity of the laser pulse i.e. $v_\varphi \approx v_g \approx c$, it is generally thought that the required pre-acceleration can be done only with an external electron injector (e.g. linear accelerator). *Umstadter et al.* [6] has proposed an all-optical method for electron injection into the accelerating phase of the wakefield. The method uses two laser pulses, the first pulse (*driver*) excite the wake-field, while the second pulse (*injector*) intersects the first wake some distance behind the driver pulse. The ponderomotive force $\sim\nabla a^2$ of the injection pulse can accelerate a portion of the plasma electrons so that they become trapped, where **a** is the laser strength parameter defined as the peak amplitude of the normalized vector potential of the laser field, and is given by a = $(eE/m\omega c) = 8.5\times10^{-10}\ \lambda[\mu m]\times I^{1/2}[W/cm^2]$, I is the laser intensity, and λ its wavelength. *Esarey et al.* [7] has proposed another scheme of optical injection that uses three laser pulses, one high intensity driver, and two counter-propagating injecting laser pulses with moderate intensities. In this method the colliding pulses excite a *slow* phase velocity beat wave that injects electrons into the accelerating phase of the fast wakefield of the driver pulse. However, it seems that the realization of the plasma cathode based on the above schemes with multi-laser beams is rather difficult from technical viewpoints. A difficulty comes from the requirement to tune the wakefield and the injecting laser pulses very precisely (with fs accuracy). In case of lasers with relativistic intensities ($a > 1$), the wavelength of the wakefield depends on the laser pulse amplitude and frequency, which in turn change due to such nonlinear effects as self-focusing, pulse energy depletion, and down-shifting of the carrier frequency. To overcome these synchronization problems, *Bulanov et al.* [8] proposed for injection, the using of the fast electrons generated due to the wavebreaking of the wakefield*s* in inhomogeneous plasma. The effect of the inhomogeneity [9] of the plasma gives rise to wavebreaking (even when the initial wave amplitude is below the wave-break threshold calculated by Akhiezer & Polovin [10]) and the self-injection of electrons into the acceleration phase of a plasma wave. In a strongly inhomogeneous plasma, corresponding to a drop in the density equal to $\delta N = N_o$ (where N_o is the uniform plasma density) over a certain length, the wavebreaking occurs. Figure.1 is a schematic of the wavebreaking injection. The experiment using only single 12TW laser beam to inject and pre-accelerate an electron bunch is going to be performed in our laboratory in end 1999.

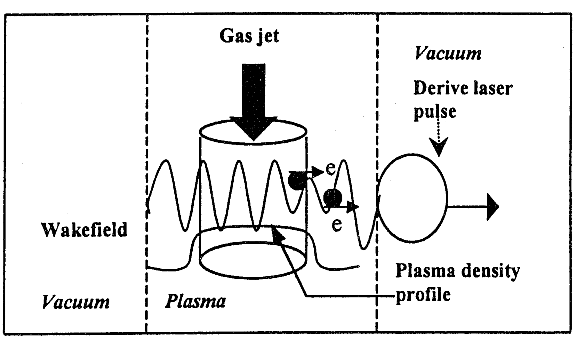

Fig.1. Schematic of the plasma cathode by using single laser beam and *wavebreaking injection* of plasma electrons. The plasma density profile is adjusted using a specially designed gas jet. In the region of density inhomogeneity the wakefiled is locally decayed, hence the plasma electrons are pre-accelerated and injected into the regular region of the wakefield for more acceleration. Our experiment will be based on this scheme.

2-Theoretical Approach

It is well known that *Akhiezer* and *Polovin* [10] calculated the maximum (called *wavebreaking*) amplitude of a non-linear fully relativistic Langmuir wave in a cold plasma, their formula can be written as: $E_m = mc\omega_p / e\ [2(\gamma_\varphi - 1)]^{1/2}$, where $\gamma_\varphi = (1 - v^2_\varphi/c^2)^{-1/2} \approx \omega/\omega_p$, $v_\varphi = c\ (1 - \omega^2_p/\omega^2)^{1/2}$ is the phase velocity of the waves, and ω/ω_p is the ratio of laser and plasma frequencies. For homogeneous plasma and in case of wakefield driven by ultrashort terawatt laser pulse, the maximum laser irradiance beyond which the wakefield breaks is given by [11] $\gamma^2_o = 1 + \mathbf{a}^2 =$

$$= \frac{1+\beta_g^2}{4\beta_g^2}\left[\left[\frac{(1+\beta_g)^3}{1-\beta_g}\right]^{1/2} + \left[\frac{(1-\beta_g)^3}{1+\beta_g}\right]^{1/2} - \frac{2}{1+\beta_g^2} - \beta_g^2\right] \quad (1)$$

where the group velocity of the laser equals the phase velocity of plasma wave, $\beta_g = v_g/c = v_\varphi/c$. For the case of $\beta_g \to 1$ one can see that $\mathbf{a}^2$ scales as $\gamma_\varphi = \omega/\omega_p$. In the 1D cold electron plasma the Langmuir wave break occurs when the quiver velocity of electrons v, becomes equal to the phase velocity of the wave. Using the Lagrangian description, the position of each electron is $x = x_o + \zeta(x_o, t)$, where $\zeta(x_o, t)$ is the displacement of an electron from its initial position x_o. The wavebreaking singularity appears when the Jacobian $J(x_o, t) = |\partial_{xo} x| = |1 + \partial_{xo}\zeta|$ of the transformation form the Euler to the Lagrangian coordinates vanishes. For nonrelativistic wave, the time evolution equation is linear in Lagrangian coordinates. For $\zeta(x_o, t) = \zeta_m \cos(k\, x_o - \omega_p t)$, the Jacobian vanishes when $k\zeta_m = 1$. This condition can be rewritten as $v \equiv \partial_t x = v_\varphi$, where v is the electron quiver velocity in the wave. In an in-homogeneous plasma, the wave number k of the Langumir wave, depends on time through $\partial_t k = -\partial_x \omega$. The resulting growth over time of k results in the break of the wave even if the initial wave amplitude is below the threshold for wavebreaking [8].

3- Simulations

Using PIC-2D simulation code a plane polarized (in z-direction) laser pulse started in the vacuum, then interacts with the plasma. The plasma density profile used in our first study is shown in Fig.2. The plasma density varies smoothly from zero (region. I) at x = 320Δ to $2.43\times10^{19}/cm^3$ at 960Δ(Δ=0.072 μm). The plasma is homogeneous (region. II) in the domain 960< x/Δ<1280, and its density decreases gradually from $2.43\times10^{19}/cm^3$ to $2.12\times10^{19}/cm^3$ in the region 1280 < x/Δ< 1520. Asymptotically, as $x \to \infty$, the plasma is homogeneous with density $2.12\times10^{19}/cm^3$ (region. III). The plasma density is homogeneous in y-direction. The plasma temperature is 1keV, and the ions are assumed to be immobile. The laser pulse shape is assumed to be gaussian, and two pulse lengths in the propagation direction 21fs (6.3μm) and 50fs (15μm) has been considered. The pulse's transverse dimension (spot size) of the pulse in y-direction is 2.04 - 8.6μm. Two laser strength parameters such as **a** = 2, and 4 has been used in different simulation runs. The laser wavelength is 0.793μm, and its intensity exceeds 10^{18} W/cm^2. The laser pulse propagates in the x-direction and focused in the y-direction. The simulations has been performed for a long-run time, in order to see the injection.

and the subsequent acceleration processes in the wakefield of the ultrashort laser pulse focused in the inhomogenous plasma.

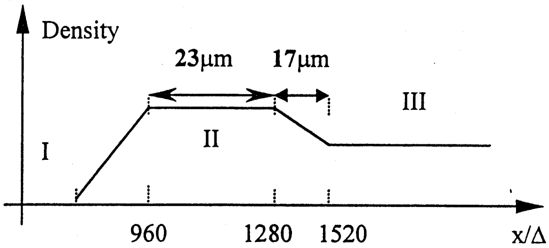

Fig.2. Schematic of the plasma density profile for our simulations, the simulation delta Δ = 0.072 μm.

4- Results

The simulation results are shown in Figs. 3, and 4. In Fig.3a the wake electric field is shown for a laser pulse with **a** =2 and, Fig.3b shows the wakefield for **a** = 4. In both of these cases the laser-pulse length at FWHM is 21fs. As shown in Fig.3 the wakefield of the laser pulse as it crosses the inhomogeneity region located between region II and region III (see Fig.2). It is clear that the wakefield is *locally* decayed in the region of the inhomogeneity. As the laser pulse enters the homogeneous region, a regular large-amplitude wakefield start to develop, and is used for accelerating the electrons injected in the forward direction from the wavebreaking region. For the case of **a** = 4 the maximum value of the wakefield in the homogeneous regions is about 140 GV/m, this value reduced to about 35 GV/m in the wavebreaking region. Trapped electron beam with centered longitudinal momentum of 25 MeV/c, and longitudinal bunch length τ_b = 12 fs (FWHM) with total charge 59.2 pC has been observed in this case (see Fig.4a). For a laser pulse of **a** = 4 propagating only in the homogeneous plasma (starting at x =1600Δ), in this case electron trapping occurs because **a** = 4 exceeds the threshold for wavebreaking in homogeneous plasma, this is in agreement with the theoretical value calculated from Eq. (1). Longitudinal phase space plot for this case in shown in Fig.40b. As we mentioned in a previous section, the experimental device for the plasma cathode is now under construction. Based on the chirped pulse amplification technique (CPA) our table-top tera-watt (T^3) laser system will be able to produce pulses of power of 12 TW and duration of 50 at FWHM fs at 10 Hz repetition rate. Using an off- axis parabolic mirror we can focus the beam down to 10 μm into a high density gas jet, the laser intensity (I) in the focal volume will be $7.63\times10^{18}W/cm^2$. With these parameters, we performed the PIC-2D simulations. The plasma density profile is the same as before, but the densities in region II are $3.16\times10^{18}cm^{-3}$ and 2.72×10^{18} cm^{-3}, respectively, which is one order of magnitude lower that the previous case. Figure.5 shows the longitudinal electron phase space for this case. The electron beam with the longitudinal momentum of 20 MeV/c, the bunch length of 14 fs (FWHM) and of total charge 68.7 pC has been generated. It is clear that the energy spread is very large. We propose the use of momentum filter to get ultrashort bunch with a proper energy spread.

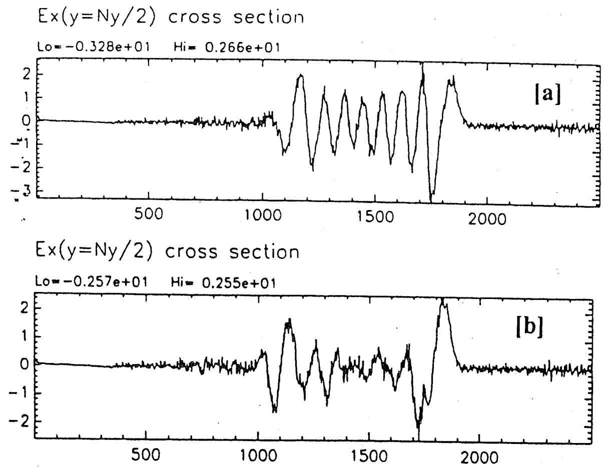

Fig.3. The wake electric field is locally decayed around the region of plasma inhomogeneity (a) for the case of **a** = 2. (b) for the case of **a** = 4.

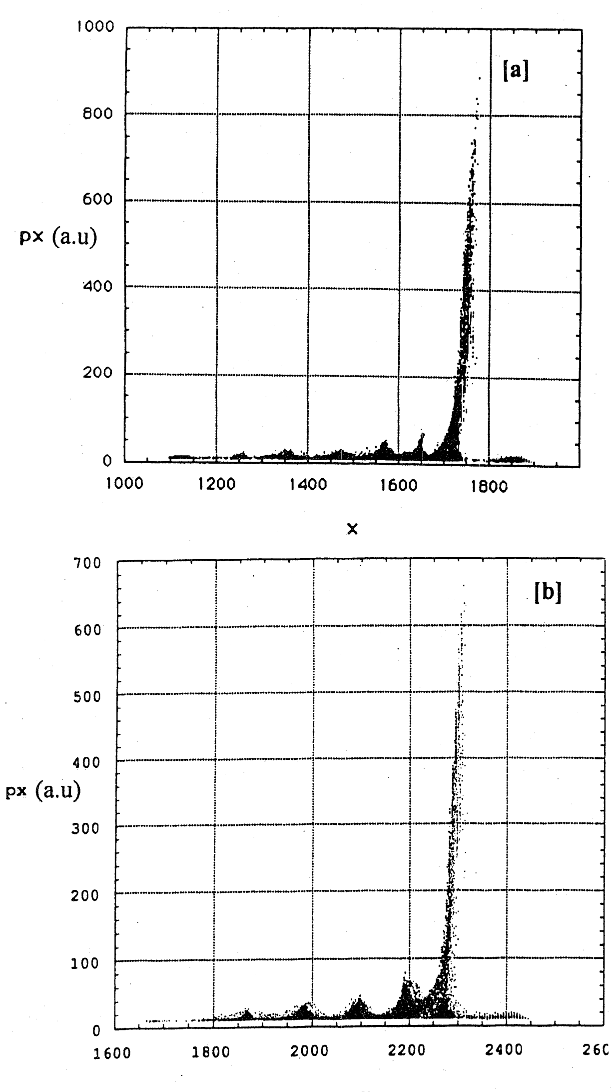

Fig. 4. Longitidinal phase space plot for trapped electrons in case of a = 4. (a) the laser pulse propagating in an inhomogeneous plasma .(b) the pulse propagating only in homogeneous plasma.

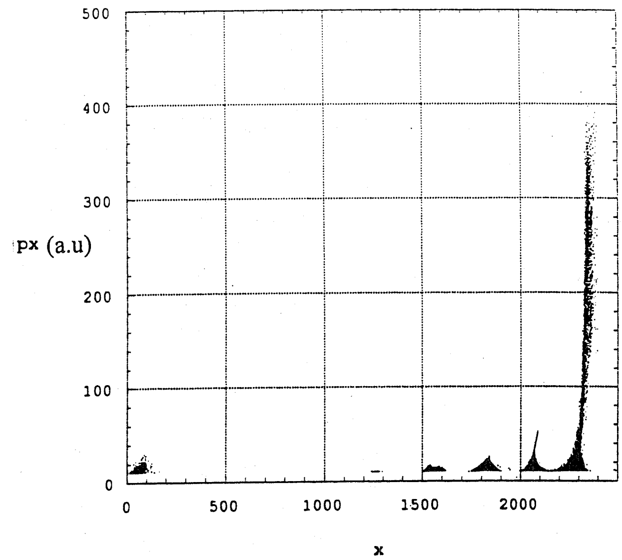

Fig.5. Phase space for trapped electrons in inhomogeneous plasma for the case of **a** = 2.6, 12 TW, 50 fs laser pulse.

Conclusion

According to the PIC-2D simulations, it is feasible to generate 25 MeV 10 fs electron beams from an inhomogeneous underdense plasma by using single laser beam and the phenomenon of wakefield wavebreaking. We plan this December using the 12TW 50 fs laser system to start our experiments on the plasma cathode . As for the problem of energy spread, we propose the use of momentum filter in the second experiment.

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