GENERATION OF SINGLE PULSE PARTICLE BEAMS IN A PLASMA CHANNEL BY LASER INJECTION IN LASER WAKEFIELD ACCELERATORS

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Abstract

A laser injection mechanism that generates a single pulse, high quality beam is described. In the past, different all-optical injection schemes for the generation of ultrashort electron bunches were proposed. A very promising scheme proposed by E. Esarey [1] uses the collision of two counterpropagation laser pulses to inject particles. However, the results of ours 2D particle-in-cell (PIC) simulations have shown that in addition to the bunch created by pulse collision, a train of pulses is also generated by a different mechanism. In this paper we show that is possible to achieve a single pulse, high quality beam if the generation of the plasma wakefield takes place in a channel and particles are injected by a phase-kick mechanism [J. Cary at this conference]. We have performed 2D PIC simulations of our proposed injection scheme using the code VORPAL [C. Nieter at this conference]. We have obtained a high quality 11 MeV., 6 fs. single electron bunch with energy spread of4% and emittance of $0.01\pi - mm - mrad$.

INTRODUCTION

Plasma-based accelerators [2] - [3] have received much theoretical and experimental attention in the last decade due to the large longitudinal electric fields that can be excited in a plasma without the limitations found in conventional accelerators. One widely investigated and very promising concept is the laser wakefield accelerator (LWFA) [6], in which a laser drives a wake field in the plasma and the wake field then accelerates electrons. Self-trapping and acceleration of electrons have been demostrated through many experiments [6] - [7] in the self-modulated (long pulse) LWFA. In this case the wake field grows through the modulation instability to the point where wave-breaking occurs. The resulting electron beams typically have 100% energy spread. In the short pulse regime, where the length of the laser pulse is of the order of the plasma wavelength c/ω_p, one can create clean wake fields, but then one has the problem of injecting electron bunches into those accelerating fields. Such bunches would have to be extremely short, with length of the order of the laser pulse length, i.e., multiple femtoseconds. These requirements are beyond current technology including that of photocathode radio-frequency electron guns. The rest of the paper is organized as follows: in Sec. 2 we describe our injection scheme and give a brief description of the VORPAL code. In Sec. 3 we present the results of the simulations, and summary and conclusions are presented in Sec. 4.

PARTICLE INJECTION SCHEME IN A PLASMA WAKE FIELD

The accelerating electric field (or gradient) in conventional radio frequency linear accelerators is limited to around 100 MV/m, partly due to heating or breakdown on the walls of the structures. In order to accelerate electrons to very high energies (greater than 1 TeV), it is necessary to develop new acceleration concepts providing a higher electric field. Plasmas can support large high longitudinal electric fields. More precisely, ionized plasmas can sustain electron plasma waves (EPW) with longitudinal electric field on the order of the nonrelativistic wavebreaking field [5], $E_0 = cm_e\omega_p/e$. For an electron density of $n_e = 10^{18}cm^{-3}$ the electric field is $E_0 \approx 100GV/m$ (which is approximately three orders of magnitude greater that obtained in conventional RF linacs) with a phase velocity close to the speed of light.

In the laser wakefield accelerator (LWFA), a single short ($\leq 1ps.$), ultrahigh intensity ($\geq 10^{18}W/cm^2$) laser pulse injected in an underdense plasma excites an EPW behind the pulse. The plasma wake is excited by the ponderomotive force created by the photons. A correctly placed trailing electron bunch can be accelerated by the longitudinal electric field and focused by the transverse electric field of the plasma wake.

For this reason, all-optical injection schemes have been proposed. Recently E. Esarey and coworkers [1] proposed a colliding laser pulses scheme that uses three laser pulses. An intense pump pulse generates a fast ($v_{p0} \approx c$) wake field. A forward going and a backward going injection pulses collide at some distance behind the pump pulse generating a slow ponderomotive beat wave with phase velocity $v_{pb} \approx \Delta\omega/2k_0$. During the time in which the two injection pulses overlap, the slow beat wave injects plasma electrons into the fast wake field for acceleration to high energies.

In any of the optical injection schemes, one beamlet of electron is supposed to be generated. However our 2D PIC simulations of the colliding pulses scheme and phase-kick injection show that multiple beams are generated instead of a single beamlet (see Fig. 1).

In all these schemes the wake field has to be high enough

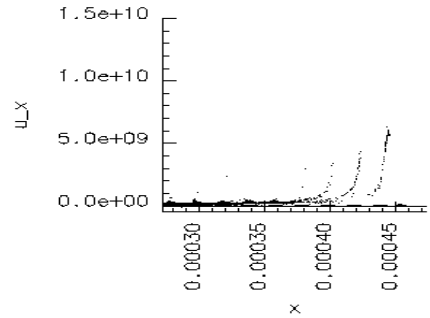

Figure 1: Particles in $x - v_x$ phase-space phase-kick injection. We observed that a train of beamlets is formed.

that transverse wakebreaking takes place and we get particles injected in each accelerating bucket. We propose to modify the structure of the wake field such that only one wavelength has high intensity (therefore, only one accelerating bucket will be suitable for injection). In order to reduce the wake field the pump pulse is propagated in a plasma channel. With the right plasma parameters, the wakefield will be rapidly dumped and only one beamlet will be generated. Particle injection is conducted by a second conterpropagating laser pulse which will beat with the pump and kick particles into an invariant curve that is accelerated, longitudinal trapped and transversely focused.

To carry out our simulations, we have made use of the VORPAL simulation code [10]. VORPAL is a fully relativistic fluid/PIC code that can be run in 1, 2, or 3 dimensions. (The work presented here consists of 2-D simulations). Among other situations, the VORPAL code can be used to simulate the self-consistent dynamics of relativistic particles in electromagnetic fields. Because only the region of the plasma near the pulse is of interest, it is possible to implement a moving window algorithm [9],such that the simulation follows the small region of interest and ignores the rest of the device. The code is also implemented in parallel through the Message Passing Interface(MPI). Parallel computation is critical for these computationally intensive simulations. The laser pulses used in the simulation were modeled as linearly polarized Gaussian in the transverse direction and have an amplitude variation that at the focus is longitudinally a half-sine pulse,

$$\begin{aligned} E_i &= \frac{m_e c \omega_i a_i}{e} \cos\left(\pi(x - x_0 - v_{gi}t)/L_i\right) \\ & \quad exp\left(-y^2/2w_i^2\right) \cos(k_i x + \omega_i t) \end{aligned} \tag{1}$$

For $|x - x_0| \leq L_i/2$, where the subscript i is either p, f for the pump or the forward pulse (with the - sign in the argument of the last cosine), or b for the backward pulse (with the + sign in the argument of the last cosine). The amplitude a_i is in units if $m_e c$. The length of the pulse is L_i, and w_i is the rms width of the pulse.

SIMULATIONS RESULTS

The electron plasma density was $n_{e0} = 2.78 \times 10^{17} cm^{-3}$ which corresponds to a wavelength of $\lambda_p = 20\mu m$ and to a plasma frequency $\omega_p = 9.4 \times 10^{13} s^{-1}$. The laser pulses were linearly polarized with transverse Gaussian profile. The minimum laser spot size was $20\mu m$ and the Rayleigh length was about $31\lambda_p$. The laser pulse length was chosen to be about $\lambda_p/2$. The pump laser intensity was $I_L = 5.8 \times 10^{17} W/cm^2$ and the laser wavelength $\lambda_0 = 2.0\mu m$. the backward pulse had $\lambda_2 = 2.0\mu m$ and intensity $I_L = 5.8 \times 10^{17} W/cm^2$ and pulse length was λ_p. The plasma channel radius is $8.0\mu m$.(see Fig. 2).

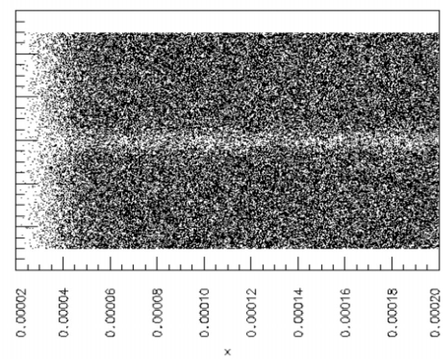

Figure 2: Electron density distribution at $t = 0$ shown in $x - y$ phase-space

The length of the simulation box was $L_x = 200\mu m$ in the X and $L_y = 100\mu m$ in the Y direction. The computational mesh consisted of 1200 cells in the X direction and 200 cells in the Y direction. The simulation used about 1,200,000 computational particles.

The pump pulse is launched into a vacuum region of 20 μm. It follows a (1 - cosine) rise density of 40 μm, and then a flat density region of 120 μm. At $ct = 195\mu m$, the moving window is turned on. The pulses collided at $ct = 155\mu m$.

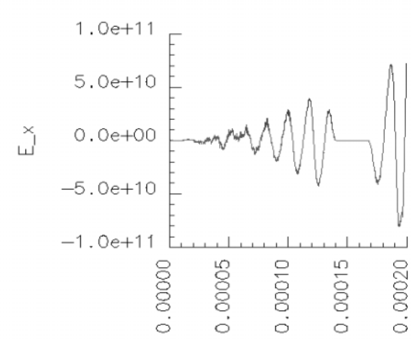

Figure 3: Longitudinal Electric field as a function of distance of propagation right before collision takes place. Notice the fast decay of the plasma wake field due to the channel.

Figure 3 shows the longitudinal electric field on axis before collision takes place. We observe the pump pulse propagating to the right and behind the wake field that creates. We clearly see the rapid decay of in the wakefield intensity due to the propagation in the channel.

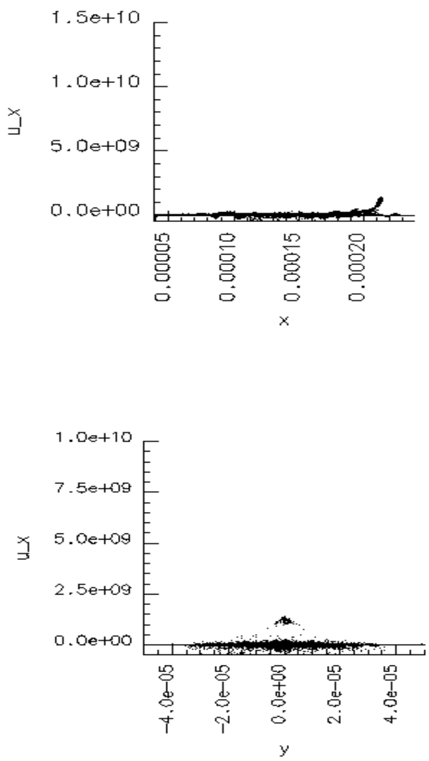

Figure 4: (a) Snapshot of electrons in $X - V_x$ phase-space. (b) Snapshot of electrons in $Y - V_x$ phase-space right after collision.

Figures 4 and 5 are snapshots of electrons in $X - V_x$ and $Y - V_x$ phase-space at right after collision occurs and after close to one Rayleigh length of propagation respectively. We observe that after close to one Rayleigh length of propagation a high quality, single beam is obtained. The beam pulse length is 6.6 fs., while the relative rms energy spread $< \sigma_{px} > / < p_x >$ is 4%. The faster particles are at a relativistic factor of $\gamma = 22$ in about $600\mu m$, which corresponds to an accelerating gradient of $24 GeV/m$. The quality of the beam is also good. The transverse emittance is $0.01\pi - mm - mrad$, which implies a normalized emittance of $0.33\pi - mm - mrad$.

CONCLUSIONS

We have shown 2D PIC simulations performed with the code VORPAL of a new particle injection into a plasma wakefield scheme. PIC simulations of previous all-optical injection schemes produced a train of beamlets instead of a single beam. We have managed to avoid the multiple beam injection by propagating the pump laser pulse in a plasma channel to allow a rapid dacay of the plasma wake field. A second counterpropagating laser pulse is used to inject particles into the first accelerating bucket through a phase-kick mechanism. After almost one Rayleigh length of propagation a high quality, single beam is obtained. The beam pulse length is 6.6 fs, with rms energy spread of 4% and normalized transverse emittance of $0.33\pi - mm - mrad$.

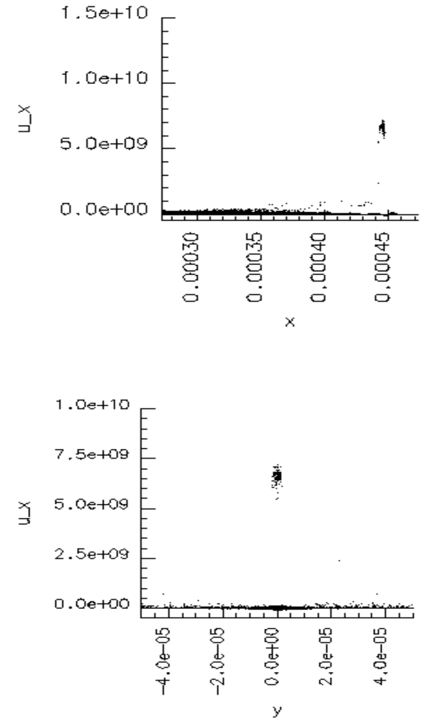

Figure 5: (a) Snapshot of electrons in $X - V_x$ phase-space. (b) Snapshot of electrons in $Y - V_x$ phase-space after about one Rayleigh length of propagation.

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