Ultrashort-pulse relativistic electron gun/accelerator

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Abstract

Laser driven plasma waves have up to now been considered exclusively as second stage accelerators. Conventional linacs are used in this case as the first stage of acceleration to inject MeV electrons into the plasma. This paper shows it to be advantageous to instead use laser wake fields in the first stage for greater simplicity and better emittance. The concept presented makes this possible with all-optical generation and acceleration of electrons. It is tested using two dimensional particle-in-cell simulations.

1 INTRODUCTION

In a recent publication [1] we proposed an electron injection scheme for plasma-wave-based accelerators. These types of accelerators are possible because of CPA based lasers [2], which provide the necessary power level, and pulse length. Laser-wakefield plasma waves have a very short wavelength compared to conventional electron beam bunch lengths. Therefore a novel method of injection is called for to inject beams into plasma waves. The actual scheme uses two laser pulses, one for a pump and the other for injecting electrons. LILAC, or Laser Injected Laser ACcelerator, is purely optical, using no external RF electron source. New computer simulation work on LILAC is presented here.

Besides the short bunch lengths, there exist other important characteristics of LILAC. First, the solid state lasers are compact and will fit on a table top, so by purely optical injection this electron gun will also be a table top device. Besides removing the need for an externally triggered RF electron source to make the electron bunch, it also is inherently synchronized with femtosecond accuracy to the laser pulses. The third result of all optical injection is cost. The same laser creates both pulses and no money is spent on a RF injector. LILAC's advantages are not limited to cost and simplicity, the bunch quality created is better than currently available by other means. Both emittance and bunch length are smaller

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than conventional electron guns, as will be demonstrated in the paper.

2 METHODS OF INJECTION

As mentioned previously, LILAC uses two laser pulses to create an ultrashort electron bunch. The first pulse acts as the pump used to create the wave for acceleration. The second, or injection pulse, intersects the wave and alters the electron's motion in such a way as to cause some of them to become trapped and accelerated. In the particular method analyzed here, the ponderomotive force of the injection pulse gives an impulse to electrons in the background so they may be injected. The particles with a large enough velocity in the direction parallel to the pump pulses' propagation fall into the wave's potential and then are trapped. These electrons form the desired beam, without the necessity for an external source.

The method detailed so far is general. In fact, several geometries have been considered. The first is the orthogonal orientation analyzed in the previous paper [1], where the transverse drift of electrons out of the injection pulse causes trapping, Fig. 1a. The most obvious change is to the orientation of the two pulses, with the injection pulse parallel to the pump pulse, Fig. 1b, and its longitudinal ponderomotive force acting on the electrons [3]. This method is currently under study. One can, actually, envision orienting the pulses at any angle between the two extremes talked about. In this paper we will consider the action of the injection pulse to give an impulse to the electrons. At large amplitudes, electrons quivering in the wake have velocities larger than needed for injection. However, these velocities are $\pi/2$ rad out of phase so will not inject until the wave breaking limit is reached. The injection pulse can push electrons into the proper phase for trapping. In the first model, dephasing was not dealt with for simplicity. Another aspect ignored was the fact that the injection pulse creates its own wake, and will modify that of the pump pulse. The motion of electrons in the injection pulses' wake, and alterations to the pump's wake can cause injection. Both cases will cause a modification to the

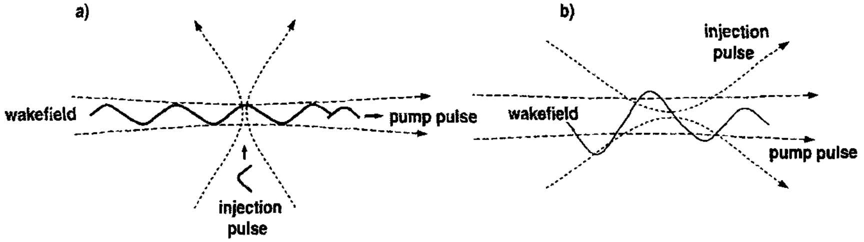

Figure 1: a) Schematic of the transverse LILAC accelerator concept. b) Schematic diagram of the colinear LILAC. Please note that in b) only the contours of intensity are shown.

seperatrix of the wake field, capturing and accelerating electrons. The commonality of all versions, is that we are using a laser pulse's ponderomotive force to affect electrons in the wake, to enhance trapping in a small spatial region. The injection pulse essentially acts as a controllable switch turning on injection at the desired time. Photoionization can also act as a switch for injection [1], if the appearance intensity is between the intensities of the pump and injection pulses. If electrons are produced at the proper phase in the wave from this effect, they will also be trapped and accelerated.

One last aspect that should be addressed is more numerical in nature. The simulation uses very sharp boundaries between vacuum and plasma which will create strong fields at this edge. These fields will oscillate out of phase with the plasma wave and may cause injection. This effect needs to be avoided in simulation so as not to be confused with ponderomotive injection. Though if we could create very sharp boundaries, this would be a physical process.

3 MODEL

In our previous work [1] we approached this problem in a number of ways. First we developed a simple analytic model in order determine the minimum intensity of the injection pulse. The authors were only able to achieve a closed form for an approximate and idealized case. Nevertheless, this model has the benefit of defining the order of magnitude of the problem and providing useful information about laser injection in general, as discussed in Sec. 2 . To fully develop LILAC, we turned to numerical methods for a solution. The simulations will be addressed in a later section.

The wake field of the pump laser moving through the plasma defines an electric potential that can be used to accelerated electrons and is the basis for all laser plasma based accelerator concepts [4]. The problem is that the potential is moving at near the speed of light, and the electrons must start with a velocity in order to become trapped and accelerated. With an impulsive kick the electrons move into the seperatrix defined by the wake field's potential well, and then they may interact with the wave and draw energy from it. Our idea uses the ponderomotive force of the injection pulse to give an electron the necessary velocity. We start by calculating the imparted drift velocity,

$$\Delta(\frac{p_z}{m_e c}) = \frac{b_0^2}{(1+b_0^2/2)^{1/2}}\sqrt{\frac{\pi}{8}}\exp(-1/2). \tag{1}$$

The value, b_0, is the normalized intensity of the injection pulse normally called a_0. Next we calculate the velocity needed by the electron to fall into the wake. This is a previously solved problem [5], analogous to other potential wells, such as the Kepler problem or atomic structure. To be trapped, the electron must be moving in a potential well, such that the well's depth is greater than or equal to the particle's kinetic energy. With the difference that this is true in the moving frame of the wave, so a Lorentz transformation, is needed to define the minimum trapping energy in the lab frame, $\Gamma = \gamma_\phi^2 \left\{ \varepsilon + 1/\gamma_\phi - \beta_\phi \left| (\varepsilon + 2/\gamma_\phi)\, \varepsilon \right|^{1/2} \right\}$, with $\varepsilon = \phi_{max} - \phi_{min}$. The quantity Γ is the minimum trapping energy for an electron in a wake field potential ϕ, and peak to trough value of ε. Trapping now also depends on the phase velocity of the wave γ_ϕ, due to the transformation.

Finally we can say that LILAC injects electrons into the plasma wave when the drift velocity of the electron is larger than the trapping velocity,

$$\Delta\left(\frac{p_z}{m_e c}\right) \geq (\Gamma^2 - 1)^{1/2}. \tag{2}$$

Using Eq. 2 to combine Eq. 1 with the minimum trapping energy, we arrive at the intensity b_{th}, needed to trap. This is represented graphically in Fig. 2. The dashed line is the plotted trapping condition. So our simple model says that assuming we have correctly matched an electron's drift velocity to the phase of the wave, it may now be accelerated by the wave and form a beam. Given an a_0 of a laser pulse, and the amplitude ϕ of the created wake field, we now know the minimum b_0 of the injection pulse for electron to be injected. The problem with our calculation is that it does not take into account that electrons are moving in the wake field at the same time they feel the injection pulse. The more complete problem of calculating the drift velocity at the same time the electrons move in the background has no easy analytic answer. It was necessary to actually do a numeric integration to find a better trapping condition. Also we could then deal with the problem of matching the injection pulse to the wave's phase. This is the solid line in the plot. The inset

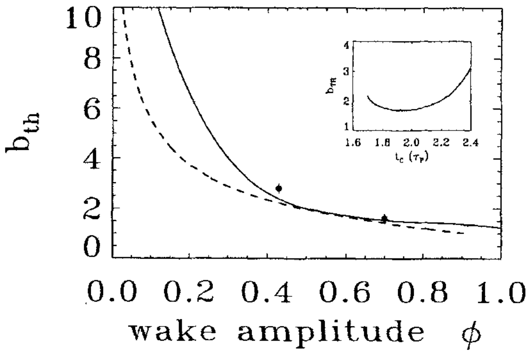

Figure 2: The trapping threshold, b_{th}, plotted versus the plasma-wave amplitude ϕ. The dashed line represents the results of Eq. 2. The trapping region is above of the curves. Inset: $(\gamma\beta)_z$ vs t_c, valid only along $y = 0$.

show the fact that there is one optimal phase at which to inject electrons. The two points on the plot represent 1D particle simulations previously presented [1], to test the trapping.

4 TRANSVERSE LILAC

To test the previous model, before setting up an experiment, we used particle-in-cell simulations to actually try out LILAC. As previously mentioned, we first worked in one dimension. However the problem is inherently multidimensional due the orthogonal orientation of the two laser pulses. So now we have run simulations with two spatial and three velocity dimensions, to better model the physics. They inherently include all electromagnetic, and space charge effects. By performing a series of runs we can find the threshold intensity for the injection pulse. For the beam we may find its final energy, spread of the energy, and the beam emittance. The specific parameters used are $a_0 = 1.6$, $b_0 = 1.6$, and $\tau_{pe} = 5\lambda_l/c$. As before we use the LWFA with the pump pulse resonant with the plasma frequency. For the injection pulse we use $\tau = 2\tau_{pe}$ to reduce ponderomotive forces perpendicular to the direction of acceleration.

The following figures then represent one sample simulation with the excellent characteristics of a LILAC electron beam. In Fig. 3 we can see the electron pulse, highlighted, riding in the plasma wave. Note the separation of the beam electrons from the back ground. Fig. 4 shows the actual volume of phase space inhabited by

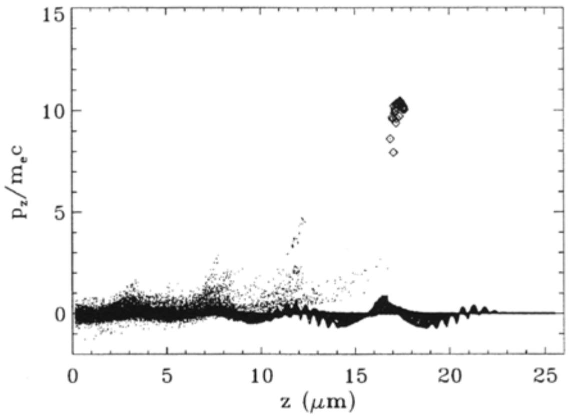

Figure 3: A PIC simulation showing a trapped electron bunch due to laser injection. The trapped electrons are highlighted with diamonds

the beam. As stated before the electron distribution is localized to a small area giving the beam excellent qualities. Empirically we note that during the acceleration

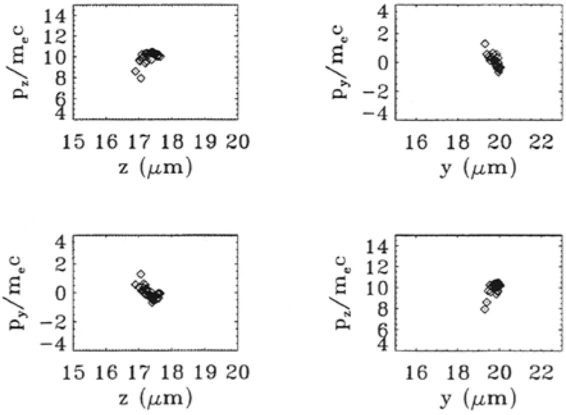

Figure 4: The same PIC simulation as Fig. 3. Plotted is the volume of the bunch for various planes in phase space.

process this volume remains constant, only being altered when the electrons finally outrun the wave. Table 1 summarizes the characteristics found from this particular simulation. Now that it has been shown that an electron beam can be accelerated, it is relevant to compare it with existing ones. To do this we use the emittance, a common quantity used with particle beams to examine their quality. In two dimensions there will be both longitudinal and transverse emittances. Basically they represent the volume of phase space occupied by the beam. In the transverse case we shall calculate the normalized emittance by $\varepsilon_{\perp n} = \pi\gamma\beta 2 r_0 \frac{p_y}{p_z}$, where r_0 is the spot size of the beam, p_y and p_z are the transverse and longitudinal normalized momenta, p/mc. Comparing these results with some recent work on electron guns [6] we see that LILAC is potential as good or better these newer devices. Typical values of newer electron guns are 1 - .5 π mm·mrad. The number of electrons produced by LILAC is 1.5×10^7, smaller than reported for new electron guns. However it should be pointed out that the length of this electron bunch is so short that to achieve high particle numbers would cause the bunch to blow apart due to space charge effects.

$\varepsilon_{\perp n}$	$.16\pi\,\mathrm{mm}\cdot\mathrm{mrad}$
$\varepsilon_{\parallel}$	$.3 \times 10^{-9}\,\mathrm{eV}\cdot\mathrm{sec}$
τ_b	1.3 fs ($.4\mu m$)
$\Delta E/E$@100 MeV	0.5%
n_b	1.5×10^7 per bunch (2 pC)

Table 1: A summary of the results for LILAC

Increasing the plasma wavelength allows more particles to be trapped, thereby increasing the total number in the bunch. At this point in time the electrons have an average energy of 10 MeV, and a relative energy spread of 5%. Since ΔE appears to be invariant with increasing energy, if the electrons reach 100 MeV the relative energy spread reduces to .5%. This spread in the energies is consistent with the change in accelerating gradients over the bunch length. For the purposes of this paper we will represent the longitudinal emittance by the integral $\varepsilon_{||} = \oint dp_z dz$. It is also observed to be a constant of the motion, with a value from the simulation of $.3 \times 10^{-9}$eV · sec. This small value is partly to do with the bunch length on the order of 1.3 fs. Even with a large energy spread, the area in phase space will be small with such a short bunch length. The two dimensional simulations again show that LILAC works in theory, and produces a beam of excellent quality.

Fig. 4 shows a number of plots, including $p_y/m_e c$ by y, or the transverse dimension. The positive y-axis is the direction in which the injection pulse travels. From inspection it can be seen that the particles have a much smaller transverse velocity than in the longitudinal direction. By making the injection pulse longer, the ponderomotive force longitudinal to the injection pulse (and transverse to the pump's wake), is reduced. Enough so that particles do not drift out of the wake, decreasing the number of electrons in the accelerated bunch. Also, the radial wake is necessary for the injection process. During injection, electrons are simultaneously kicked sideways and forward. With a large enough radial wake, electrons are unable to drift transversely out of the accelerating region. One can calculate the velocity needed to escape the wake in the radially given the depth of the potential, in this case about $\gamma\beta = 1.7$.

5 COLINEAR LILAC

Now we consider the other variation of LILAC which employs a different geometry where the injection pulse shares the same axis of propagation of the pump pulse. More tightly focused than the pump, it can act as an injection "switch" by turning on and off the wakefield enhancement. The schematic diagram of this idea appears in Fig. 1b. Injection occurs due to the ponderomotive force interacting with electrons through collective effects. Contribution from the longitudinal and transverse wakefield components will lead to wave breaking, or trapping of background electrons into the wave. Longitudinally, the accelerating phase of the wakefield has a larger value of the gradient for the time interval during which the injection pulse is at its focus. Accordingly, the separatrix, which determines the trapping of electrons, is expanded in phase space. It allows a certain group of electrons to be captured if those electrons satisfy the trapping condition. Inward transverse wakefield breaking by the injection pulse plays a role, in that it actually drags the electrons from outside the channel into the central region near the axis. The longitudinal fields were well below the one dimensional wavebreaking limit, nevertheless we still observe significant amounts of electron trapping. We believe this is inherent in two dimensional wavebreaking. Since this relatively small fraction of electrons, if injected at the optimal acceleration phase, satisfy the trapping condition, they can be accelerated along a narrow region on axis. The optimization of the injection process was done by adjusting the pulse delay between the injection and pump pulses. This wavebreaking process is observed in 2D and 3D PIC simulations, where the constant-phase wave front develops a horseshoe-like shape. In the 1D limit of pump pulse and plasma wave, an injection pulse could introduce transverse wave-breaking in the plasma channel, eventually leading to the generation of fast electrons on axis.

Fig. 5 and Fig. 6 show the longitudinal and transverse momentum of trapped electrons respectively. These are simulations with similar plasma and pulse parameters as in the previous section, except the injection pulse's spot size is smaller, $a_0 = 1.5$, and $b_0 = 3.0$. The injection pulse travels on axis with the pump, and delayed behind it. The large transverse momentum spread is believed to be coming from the steep transverse profile of the injection pulse at its focus. In Fig. 5, the electrons, after trapping, are accelerated up to several MeVs, filling the multiple "buckets" 5 plasma periods (80 fs) behind the pump. Each bunch has a well-defined linear chirp in the momentum over the bunch length, which makes possible the ultrashort compression of these electrons. The problem of filling up multiple buckets might be resolved by using a second pump pulse and driving down the wakefield after the first pulse. An additional improvement can be achieved if the injection pulse uses a smaller laser wavelength than the pump so that the on-off time for the injection switch, from diffraction, is reduced. The beam characteristics of colinear LILAC may be improved if the Rayleigh range of the injection pulse is small compared to the plasma wavelength. We suspect that a lower density is easiest

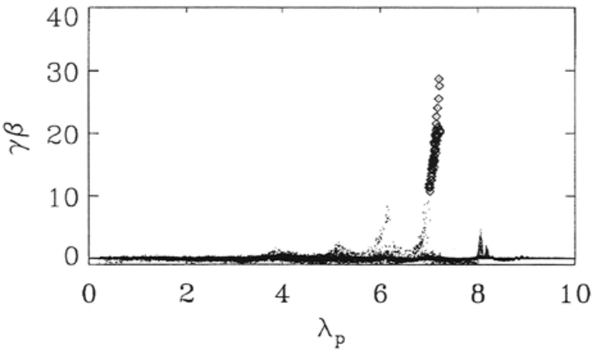

Figure 5: Longitudinal momentum of electrons: $a_0 = 1.5$, $b_0 = 3.0$

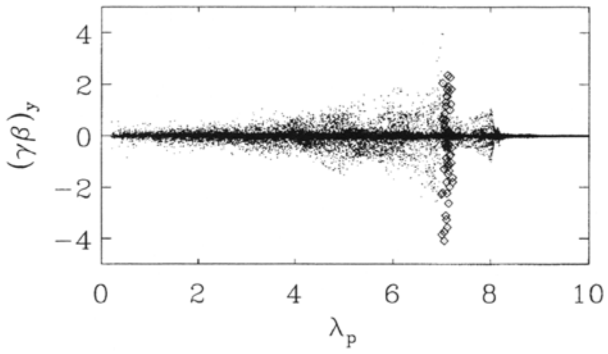

Figure 6: Transverse momentum of electrons from same simulation in Fig. 5

for trying this idea. Our next set of simulations will explore these changes to the LILAC parameters.

6 CONCLUSION

We have defined and analyzed a method for injecting electrons into plasma waves. As demonstrated in this paper, the initial analysis produces a beam of excellent quality, achieving characteristics equivalent or better than presently possible by other means. Starting with the general idea of using ponderomotive forces to inject electrons into plasma waves, we have investigated two particular methods of interest. Particle-in-cell simulations were used to test a model of transverse LILAC, and see if it provides accurate parameters. Normalized intensities of $a_0 = 1 - 2$ are predicted by the model, and do appear to cause injection in the simulations. These numbers are correct within an order of magnitude for transverse LILAC. There are more possible variations to LILAC, and they may be varied to find the best possible way to implement an all optical electron gun. The two particular versions reported in this paper are under study in preparation for experiment.

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