ALL-OPTICAL BEAMLET TRAIN GENERATION*

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Abstract

One of the critical issues for the development of Laser Wake Field Acceleration (LWFA), which has the promise of creating table-top, GeV accelerators, is the loading of beamlets into the accelerating buckets. All optical injection schemes, which include LILAC [D. Umstadter *et al*, Phys. Rev. Lett. **76**, 2073 (1996)], beat-wave colliding pulse injection [E. Esarey *et al*, Phys. Rev. Lett. **14**, 2682 (1997)], wave breaking injection, and phase-kick injection, provide a technique for doing so. Although a single bunch can have desirable properties such as energy spread of the order of a few percent, femtosecond duration, and low emittance (<1 mm-mrad), recent simulations show that such methods lead to efficiencies of transfer of plasma wave energy to beam energy that are low compared with conventional RF accelerators when only a single pulse is generated. Our latest simulations show that one can improve on this situation through the generation of a beamlet train. This can occur naturally through phase-kick injection at the front of the train and transverse wave breaking for the trailing pulses. The result is an efficiency improvement of the order of the number of beamlets in the train.

INTRODUCTION

Plasma-based accelerators [1,2] can excite and sustain very high longitudinal electric fields that may overcome many of the limitations found in conventional RF accelerators. More precisely, the longitudinal electric fields can be as large or larger than the nonrelativistic wavebreaking field $E_0 = cm_e\omega_p/e$, where ω_p is the electron plasma frequency, and n_e is the electron plasma density. For $n_e = 10^{18}$ cm^{-3}, the electric field is $E_0 = 100$ GV/m, which is approximately three orders of magnitude greater that obtained in conventional RF linacs.

One widely investigated and very promising concept is the Laser Wake Field Accelerator (LWFA) [3], 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 demonstrated though many experiments in the self-modulated (long-pulse) LWFA [4], with recent results [5] showing acceleration to 200 MeV over a distance of 3mm (66 GV/m). In this case the wake field grows through the modulational instability to the point where wave breaking occurs. The resulting electron beams typically have 100% energy spreads. In the short-pulse regime, where the length of the laser pulse is of the order of the plasma wavelength, $\lambda_p \equiv 2\pi c/\omega_p$, 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.

For this reason, all-optical injection schemes have been proposed. Pulse propagation down a density ramp leads [6,7] to wave breaking, which then causes beams to form. In the *LILAC* scheme [8] a second, transversely propagating laser beam crosses the wake field, and the ponderomotive kick of the second beam injects particles up into the accelerating region of phase space. In the *beat-wave scheme* [9,10] three colliding pulses are used. Two pulses propagate in the forward (acceleration) direction. The pump (lead) pulse generates a fast (phase velocity near the speed of light) wake field. A trailing pulse follows the pump. The third, backward pulse passes through the lead pulse transparently, as it has orthogonal polarization, but then interacts strongly with the trailing pulse, which has the same polarization. In the phase-kick scheme (discussed below), there are only two collinear and oppositely propagating pulses. This scheme works when the pump pulse has large amplitude, which makes the generated wake-field have more favorable beam confinement properties. In this case, the backward pulse, of orthogonal polarization, causes a small change in the phase of some electrons, displacing them into the accelerating region of phase space.

In our simulations of phase-kick injection we observed that multiple beamlets could be formed. Through a series of longer simulations we further determined that these beamlets extended back over as many as eight trailing buckets, the total length that we simulated. Ultimately we have concluded that transverse wave breaking is the source of this additional injection. This has been confirmed by simulations with only a single pump pulse. In this case, plasma electrons spontaneously load the wake field. Hence, it may be possible to produce a long train of beamlets, with such perhaps a method for increasing the efficiency of transfer of plasma wave energy to energy of accelerated electrons.

PLASMA TO BEAM TRANSFER EFFICIENCY

Production of only a single beamlet has efficiency disadvantages. The efficiency η of just the conversion from wake field energy to plasma energy is optimistically estimated by the ratio of the energy, $N_b e E_p \lambda_p$, extracted by the N_b particles in the beam by the peak electric field $E_p = k_p \Phi_b$ ($k_p = \omega_p/c$) in one plasma wavelength divided by the plasma wave energy, which is given in linear theory by

$$W = \varepsilon_0 \int\limits_{z}^{z+\lambda_p} dz \int\limits_{-\infty}^{\infty} dx dy E^2 \ .$$

For a wake field with transverse dependence $\exp(-r^2/w^2)$, one obtains the estimate $\eta = f_{tr}(mc^2/\pi e\Phi_p)/(1+4/k_p^2 w^2)$, where $f_{tr} = N_b/n_p\lambda_p\pi w^2$ is the trapping fraction, which is the ratio of the number of beam particles in an accelerating bucket to the number involved in creating one wavelength of the wake field. This is what dominantly determines the efficiency, as the remaining factors are of order unity.

The trapping fraction f_{tr} has been calculated in a number of test-particle and self-consistent simulations. One-dimensional, test-particle calculations [9] find that the trapping fraction can be as high as 19%. However, in two-dimensional calculations, both test-particle [10] and self-consistent [11], it is generally observed that the trapping fraction has a maximum value beyond which the parameters of the beam (emittance, energy spread, etc.) are poor. This trapping fraction is much smaller, more like $f_{tr} = 5 \times 10^{-4}$, thus implying an efficiency that is orders of magnitude below that of conventional accelerators.
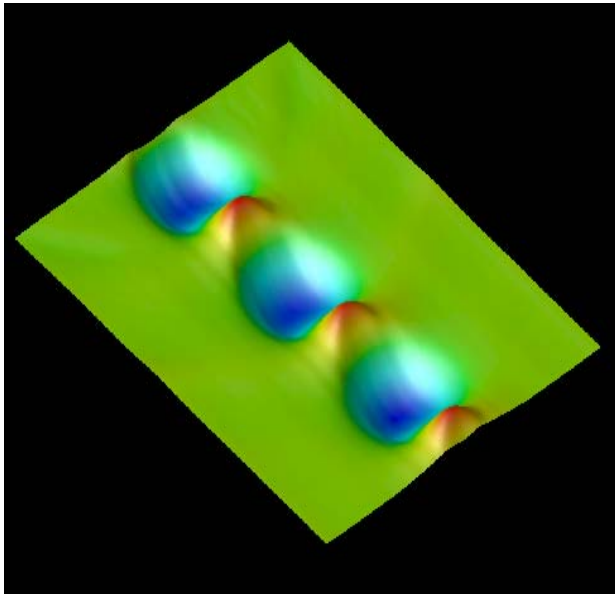

Fig. 1. The potential energy for a pulse with normalized amplitude a=1.7.

PHASE-KICK INJECTION

Phase-kick injection can occur at large pump amplitudes, where the nature of the wake field becomes more favorable to particle capture and confinement. Figure 1 shows the potential energy $e\Phi$ wake field from a 2D simulation where the incoming pulse has a peak amplitude of $a_p \equiv eE_p/m\omega c = 1.7$. (The negative electron charge is denoted by e.) As this figure shows, the region of negative potential expands dramatically. In addition, even the faces of the accelerating phase for positive potential acquire the curvature required for focusing. The

result is that a small phase kick applied to the plasma electrons can put them on an invariant curve that is both accelerating and focused.

This has been verified through two-pulse simulations with the VORPAL code [12]. The pump pulse peak pulse amplitude was given by $a_p = 1.7$ and the backward pulse had $a_b = 0.8$. The plasma wavelength was 40 μm, the laser pulses were 20 μm long and 40 μm wide. The beamlet propagated for of the order of a mm. A full illustration of the dynamics is not possible within this space-limited proceedings, so we show only the final result for the longitudinal phase space in Fig. 2.
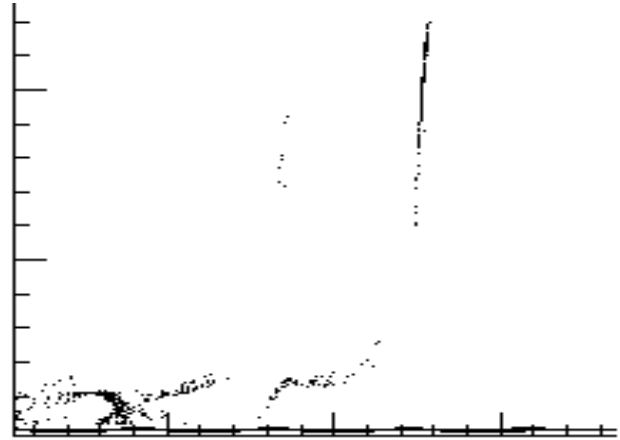

Fig. 2. Longitudinal phase space for a beamlet produced through phase-kick injection. The abscissa shows roughly five plasma wavelengths or 200 μm. The average relativistic factor γ of the particles is about 55.

SPONTANEOUS BEAMLET TRAIN GENERATION

Just behind the first beamlet in Fig. 2 one can see traces of a second beamlet. This seems somewhat reasonable, as phase-kick injection could possibly work for each of the accelerating buckets of the wake field. To test this, we carried out much longer simulations. As a result we found that we were generating beamlets in each of the buckets back through the length of the simulation. At first we thought that each of the trailing beamlets was generated by phase-kick injection interaction with the plasma particles at their oscillation peaks. This, along with a knowledge of the accelerating gradient, allows one to predict the energies of the successive beamlets. As the prediction did not agree with our observations, we began examining new mechanisms. Ultimately we found that the far trailing beamlets were generated with no backward pulse and arbitrarily slow density ramp.

An example of the beamlet train generation by a single pulse is shown in Fig. 3. In this case, the pump pulse has $a_p = 1.7$, with the simulation region being 10 plasma wavelengths long. Other parameters are as mentioned above. After roughly 1 mm of propagation, the spontaneously formed beams found in the 5th to 6th

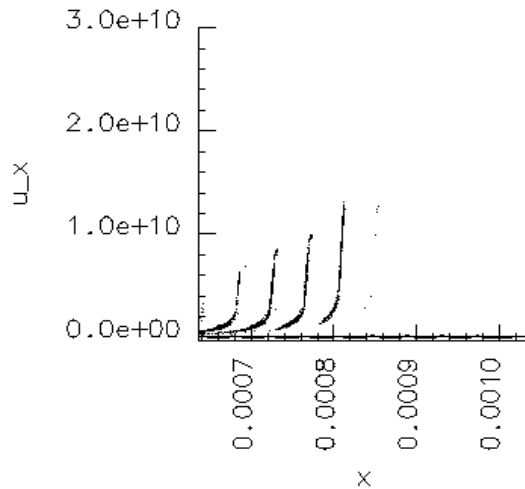buckets back are seen to have been accelerated to relativistic factors of the order of 30.

Fig. 3. Spontaneous injection by a single pump pulse.

We believe that the cause of this is transverse wave breaking [13]. The plasma oscillations have a smaller frequency in the center of the wake field, as average the relativistic factor and, hence, the effective mass is larger. This difference in frequency ultimately causes wavelength shortening to the point of wave breaking, which then injects the particles into the accelerating and focusing region of phase space.

Further work shows that we can combine the spontaneous particle injection with one of the other mechanisms, such as phase-kick or beat-wave injection, to obtain a continuous sequence of pulses.

SUMMARY AND CONCLUSIONS

Our simulations show that one can generate beamlet trains through combining injection due to transverse wave breaking with another form of injection. This has the potential for increasing the efficiency of LWFA systems, as each beamlet then reuses the plasma wave energy. For a case of N generated beamlets, one would then have an efficiency increase by a factor of N. Of course, this would require some method for continuing to energize the plasma wake field so that the trailing beamlets gain the same energy as the leading beamlets. A possibility is to have trailing, smaller laser pulses that re-energize the plasma wake field.

On the other hand, for early experiments our results might indicate that observation of well formed beams will be difficult due to the required temporal discrimination. This can be seen in Fig. 3, in which the beams are separated by 130 fs. Eventually each of the bunches does form a beam through naturally occurring focusing collimation. However, with each successive beamlet of lower energy, the collection after a modest acceleration distance continues to have 100% energy spread.

To improve upon this situation, we have now come up with two methods for obtaining single beamlets. These methods involve modifying the wake field so that it exists over only one or a few plasma wavelengths. In the first method, propagation in an appropriately chosen channel leads to wake field damping in just a few plasma wavelengths. As a result, only the first bucket has sufficient potential energy such that the separatrix extends far enough down that particles can be captured. Giacone et al [14] have now observed this process via simulations with VORPAL. In the second method, we follow the pump pulse with a second pulse that absorbs the wake field generated by the pump pulse, in accordance with the theory of [15]. Again only a single beamlet is produced. We believe that approaches like these may lead to the observation of optically injected, well-formed beams.

ACKNOWLEDGMENTS

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