SIMULATION OF ELECTRON ACCELERATION BY TWO LASER PULSES PROPAGATING IN A HOMOGENOUS PLASMA

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Abstract

We study electron acceleration by two laser pulses co-propagating one behind the other in a homogeneous plasma. We show, using one-dimensional simulations, that the wake amplitude can be amplified or diminished depending on the time delay between the two lasers, in agreement with linear analytic theory [1]. We extend the study to the bubble regime using two-dimensional simulations. We find that the one-dimensional optimization holds in two dimensions also. Trapping and acceleration of quasi-monoenergetic electrons (up to around 300 MeV) is found in the bucket behind the second laser, even for low intensities, where there is no trapping with a single laser. Thus, this scheme could be very useful for achieving a desired accelerated energy with less intense lasers, or, equivalently, increasing the accelerated energy for a given laser intensity.

INTRODUCTION

Acceleration of charged particles [2] by means of laser-plasma interaction has become an interesting area of research. In laser wakefield acceleration (LWFA), a short intense laser pulse interacting with plasma, generates a wakefield behind the laser pulse. The phase velocity of this wakefield is nearly equal to the group velocity of the laser pulse. A particle injected in this wakefield can gain energy up to several GeV. Using a one dimensional theory and numerical simulation it has been shown that, depending upon the delay between the two pulses, the wakefield amplitude can be diminished or enhanced [3]. Use of a train of laser pulses with independently adjustable pulse width and inter-pulse spacing to obtain high amplitude plasma wave with low intensity laser pulses has also been investigated [4]. It has been theoretically shown [1] that the wakefield generated by a single laser pulse can be amplified by using an identical second laser pulse and adjusting the time delay between the two pulses. This scheme of enhancing the wakefield amplitude can be used for obtaining larger energy gain in a laser wakefield accelerator with laser pulses of modest intensity.

All the theory and numerical simulations have been performed in one dimension. Since both the laser pulse and the wakefield which it excites are three dimensional, it is necessary to verify this scheme in more than one dimension. In the present study we first present one dimensional simulations of amplification/attenuation of the wakefield amplitude depending upon the delay between the two pulses, using the code VORPAL [5]. These one dimensional simulations have been performed in the nonlinear wakefield regime. Next, with two dimensional simulations we show that this scheme can be utilized to produce self-generated monoenergetic electron beams, in the bubble regime of the laser-plasma interaction [6], with much lower intensity than is required with a single pulse.

WAKE AMPLIFICATION/ATTENUATION: ONE-DIMENSIONAL SIMULATIONS

The superposition of the two bi-Gaussian pulses can be represented by the envelope

$$a = a_{10}\exp\left[-\frac{y^2}{r_{s1}^2}-\frac{(t-t_{10})^2}{2\tau_{L1}^2}\right]+a_{20}\exp\left[-\frac{y^2}{r_{s2}^2}-\frac{(t-t_{20})^2}{2\tau_{L2}^2}\right] \quad (1)$$

where $a_{10}(a_{20})$, $\tau_{L1}(\tau_{L2})$, $t_{10}(t_{20})$ and $r_{s1}(r_{s2})$ are the laser strength parameter, pulse duration, pulse centre and spot-size of the first (second) laser pulse. The delay between the two laser pulses is given by $\tau_d = t_{20} - t_{10}$. Both pulses are linearly polarized along the y-direction. Figure 1(a) shows the evolution of the wakefield amplitude for two identical laser pulses with $a_{10} = a_{20} = 1.0$, $\tau_{L1} = \tau_{L2} = 15\,fs$, when the plasma wavelength (λ_p) is 20 µm. It is observed that if the delay between the two pulses is 1.25λ_p, 2.0λ_p and 2.25λ_p, the wakefield behind the second laser pulse is amplified, in comparison with the wakefield amplitude obtained for a single laser pulse. However if the delay between the two pulses is 1.5λ_p and 2.5λ_p, the second laser absorbs energy from the wake created by the first laser and the wake amplitude diminishes behind the second laser as compared to the single laser case. It may also be noted that if the delay is 1.75λ_p the wake amplitude behind the second pulse is nearly the same as the single pulse case. Thus, for time delays that are close to integral multiples of the plasma wavelength, the wakes superimpose constructively and the wake amplitude is maximum. For time delays close to half-integer multiples of the plasma wavelength the wakes interfere destructively, and the wake amplitude is minimum. These results agree well with the analytic results of Ref. 1.

When the wake is amplified or attenuated, the energy in the wake is transferred from or to the second laser, and leads to photon acceleration or deceleration. This can be seen in Fig. 1(b), where the frequency spectrum of the second laser pulse after propagating 1 mm, has been shown for two different cases in which amplification or attenuation of the wake has been observed, and these are compared with the initial frequency. It can be seen that if amplification takes place the frequency of the second laser is down-shifted (photon deceleration), whereas if there is attenuation the frequency is up-shifted (photon acceleration).

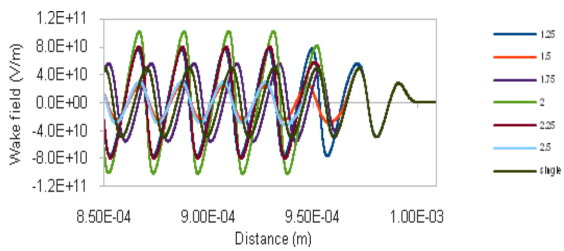

Fig. 1(a): Wakefield amplitude as a function of propagation distance, at various time delays.

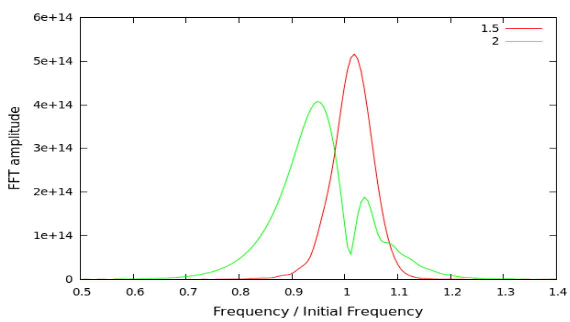

Fig. 1(b): Frequency spectrum of the second laser pulse.

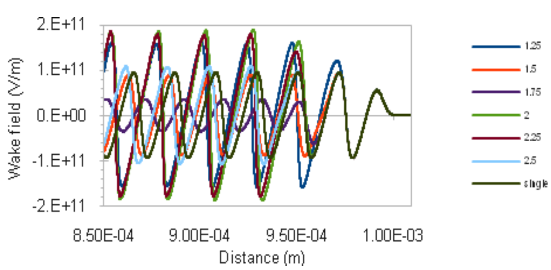

Fig. 2(a): Wakefield amplitude as a function of propagation distance, at various time delays.

Higher intensities. As the laser intensity increases, nonlinear effects set it, such as change in the plasma period/wavelength. Fig. 2(a) shows the simulation results for larger intensity laser pulses ($a_{10} = a_{20} = 1.5$). In this case, the nonlinear wakefields are steepened and the period of oscillation varies. Also the increase in amplitude of the laser pulses causes a change in the laser pulse length on account of enhanced self-phase modulation. Therefore for this case it is expected that the time delay for amplification/attenuation of the wake amplitude will not remain the same as for the low intensity case (Fig. 1(a)). Figure 2(b) clearly shows that when the wake is intensified the laser frequency is down-shifted (photon deceleration), and when the wake is attenuated, the laser frequency is up-shifted (photon acceleration). If the laser intensity is further increased such that the threshold for longitudinal wave-breaking [7] is attained, this scheme will not remain useful for acceleration of an externally injected electron beam via wakefield amplification.

ELECTRON ACCELERATION IN THE BUBBLE REGIME: TWO-DIMENSIONAL SIMULATIONS

When a high intensity laser pulse interacts with a plasma it not only pushes the plasma electrons back and forth but also expels plasma electrons radially outward, creating a density inhomogeneity. Due to this inhomogeneity the plasma wavefront curves, leading to transverse wave-breaking [8]. The transverse wave-breaking threshold is lower than the longitudinal wave-breaking threshold. Under appropriate conditions this plasma wave-breaking can lead to trapping and acceleration of background plasma electrons to generate a quasi-monoenergetic beam of electrons in the so called 'bubble regime'.

Earlier studies have shown that using a single laser pulse, self injection of monoenergetic electron beams is possible if the pulse intensity is significantly large ($a_0 \geq 3$). Motivated by the results of the previous section, it is reasonable to expect that similar acceleration could be achieved using two co-propagating laser pulses each of lesser intensity ($a_0 < 3$). To this end we performed two-dimensional simulations of two co-propagating laser pulses using VORPAL. The intensity of each pulse was kept lower than the minimum intensity required by a single laser pulse for self-injection of electrons. The time delay between the two pulses was optimized for maximum acceleration.

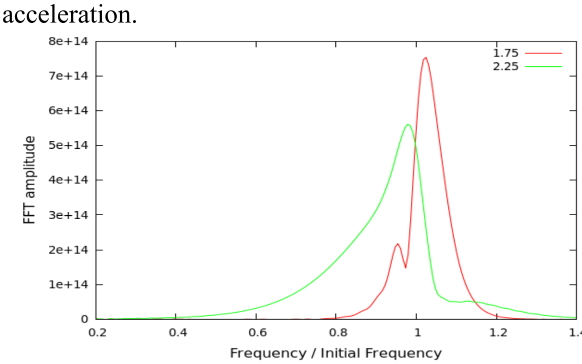

Fig. 2(b): Frequency spectrum of second laser pulse.

The pulse envelopes are the same as defined in Eq. (1), while the laser and plasma parameters are, a_{10}= a_{20}=1.5, τ_{L1}= τ_{L2}=15 fs, r_{s1}= r_{s2}=28 μm, and λ_p=20 μm. The simulation was initially performed for the single laser case (a_{10}=1.5, a_{20}=0), up to a distance of nearly 4 mm. It was seen that no self injection of electrons occurs. Subsequently, two identical laser pulses each having the same intensity as the single laser pulse and separated by a finite time delay were launched into the plasma. The minimum delay considered is such that the two pulses do not overlap with each other. We found that if the delay between the two lasers is $1.25\lambda_p$, $2.0\lambda_p$ and $2.25\lambda_p$, monoenergetic electrons up to 300 MeV are generated in the bubble behind the second laser pulse, after propagating the same distance over which a single pulse is not able to generate monoenergetic electrons. These time delays are identical to the ones for which we observed wake amplification in the one-dimensional simulations. Transverse as well as longitudinal plasma wave-breaking occur due to large amplification of the wake amplitude, behind the second laser pulse, leading to the generation high-energy electron beams. The self focusing leads to increase in laser intensity, and the radial inhomogeneity created by the transverse ponderomotive force of the laser leads to curving of the plasma wave. Thus, after amplification by the second laser pulse the wake amplitude increases, and after a certain threshold wave-breaking occurs, leading to injection of electrons into the bubble behind the second laser. We also find that when the delay between the two pulses is $1.5\lambda_p$, $1.75\lambda_p$ and $2.5\lambda_p$, no self-injection is observed due to reduction of wake amplitude behind the second laser – exactly as in the case of the one-dimensional simulations.

In order to study the beam quality, the number of electrons versus energy gain is plotted in Fig. 3 for all the three cases in which self-injection has been observed. The figure shows that quasi-monoenergetic electron beams are obtained. It may be noted that the electron beam generated for the time delay given by $2.25\lambda_p$ has a large number of electrons with a quasi-monoenergetic peak. The average energy, rms energy spread and normalized emittance of the beams generated for time delays of $1.25\lambda_p$, $2.0\lambda_p$ and $2.25\lambda_p$, are 280 MeV, 240 MeV, and 250 MeV, 10%, 10% and 8%, 59 mm-mrad, 37 mm-mrad and 40 mm-mrad, respectively.

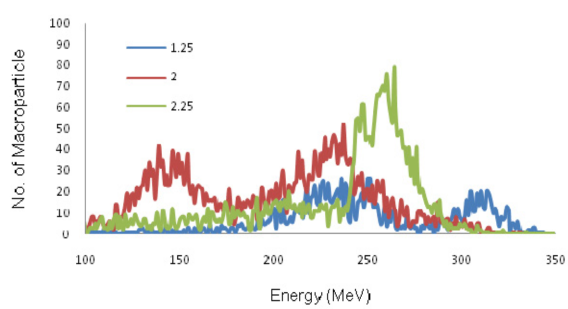

Fig. 3: Number of macroparticles as a function of energy.

CONCLUSION

We have studied, using simulations, electron acceleration by two co-propagating laser pulses. We find, using one-dimensional simulations, that, depending on the delay between the two pulses, the wake behind the second laser is either amplified or attenuated, and at the same time the frequency of the second laser is either down-shifted (photon deceleration) or up-shifted (photon acceleration). We then studied the same scheme with two-dimensional simulations, focusing on electron beam acceleration in the bubble regime. We show that by employing two lasers of modest intensity, one can achieve acceleration equivalent to that achieved using a single laser of much higher intensity, by optimizing the time delay between the two lasers. It is interesting to note that this optimization is identical to that in the one-dimensional case, even though the physical mechanisms are different. The quality of the accelerated electron beam is quite good. Although the parametric regime which we have considered here show the beam acceleration up to 300 MeV, it is clear that by decreasing the plasma density (i.e. increasing the plasma wavelength), self-generated GeV beam can be obtained even with low intensity laser pulses.

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