ACCELERATION OF ELECTRONS USING TWO IDENTICAL CO-PROPAGATING LASERS IN A HOMOGENEOUS PLASMA

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Abstract

We study the nonlinear interaction of two co-propagating laser beams in a homogeneous plasma. By adjusting the delay between the two laser pulses the wakefield can be enhanced or suppressed and one can trap and accelerate the plasma electrons to high energies. We show, using PIC simulations, that by optimizing the laser parameters, trapping and acceleration of electrons to 300 MeV can be obtained behind the second laser, even with low laser intensities (a_0=1.5). We also find that the beam quality (energy spread and emittance) is good.

INTRODUCTION

Laser wakefield acceleration (LWFA) [1,2] of electrons is of much current interest because of the ability of plasmas to sustain large electric fields, of the order of 100 GV/m, thus enabling the production of high-energy beams over distances much shorter than in conventional accelerators. Acceleration to ~1 GeV over just a few centimetres [3] has already been demonstrated. These experiments employ just a single laser. Here we explore a new configuration, with two low-intensity, short-pulse lasers that are propagating in the same direction, one behind the other. Both lasers have bi-Gaussian profiles, and are linearly polarized in the same direction. Our emphasis was to look not just for acceleration to high energy, but also for good beam quality, in terms of low energy-spread and emittance, which are essential for applications such as free-electron lasers.

3-D PIC SIMULATION OF TWO CO-PROPAGATING LASER PULSES

We used the code VORPAL [4] to perform a three-dimensional (3-D) PIC (particle-in-cell) simulation study of two identical co-propagating laser pulses, each with an intensity given by a_0=1.5, propagating in a homogeneous plasma. The wavelength of the two lasers was 0.8 μm. The simulation parameters were as follows: a grid size (dx and dy) of 0.04 and 0.8 μm, one macroparticles per cell, and a time-step of 0.13 fs. The laser wavelength (0.8 μm) was resolved over 20 cells in the propagation direction. All simulations were run for 90,000 steps corresponding to a distance of 3.57 mm. We chose a plasma density of 4.34×10^{18} cm^{-3}, corresponding to a plasma wavelength of 16 μm, as an experimentally realisable density. For this plasma wavelength (λ_p), we first optimized the delay between the two pulses. With λ_p delay, the accelerated electron bunch reaches an energy less than 200 MeV and has a large energy-spread. No trapping of plasma electrons occurs when the delay is $1.5\lambda_p$. For a delay of $1.25\lambda_p$, trapping and acceleration of plasma electrons takes place behind the second laser due to amplification of the wakefield. Quasimonoenergetic electrons up to 300 MeV are generated behind the second laser pulse, after propagating a distance of 3.57 mm. The simulation results show that the number of injected electrons is larger than that of the single laser case and the beam energy is higher as well. We have checked for the single laser case that there is very little trapping with these parameters, and the energy achieved is less than 200 MeV.

Next, we tried to optimize the laser parameters by varying the pulse-length and spot-size of the lasers.

OPTIMIZATION OF PULSE-LENGTH

First we varied the pulse-lengths of the two lasers (while keeping them equal). The spot-size was 11 μm. Figure 1 shows the accelerated charge as a function of the energy, at different pulse-lengths, 10, 12 and 14 fs. It can be seen that at all pulse-lengths there is a clear peak in the spectrum, corresponding to a quasimonoenergetic electron beam, with a substantial number of trapped electrons.

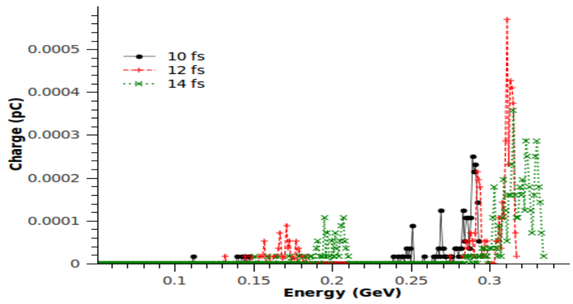

Fig. 1 Electron beam charge (pC) vs. Energy (GeV) at various pulse-lengths, after propagating 3.57 mm.

From Table 1 we can see that as we increase the pulse-length, the energy increases slightly, but at the same time the energy-spread also increases. There is no trapping in the case of 8 fs pulse-length which indicates that the pulse-length is not sufficient to excite a wake for this plasma wavelength of λ_p = 16 μm. This also shows that there is an optimal value of pulse-length for each plasma density. The behaviour of the normalized emittance is more complicated, increasing for a particular value and then decreasing. Although the charge and current also increase with increasing pulse-length, since we are looking for a good-quality beam, *i.e.* one with low energy-spread and emittance, we choose the optimal pulse-length to be 10 fs (3 μm).

Table 1. Data for optimization of the pulse-length, for a plasma wavelength of λ_p = 16 μm, and spot-size = 11 μm.

Parameter	Value			
rms pulse-length (fs)	***8***	***10***	***12***	***14***
Mean Energy (GeV)	....	0.29	0.31	0.32
rms energy spread (%)	....	1.62	1.66	2.72
Normalized emittance (π mm-mrad)	....	2.99	4.93	2.18
Charge (pC)	....	1.66	3.06	3.95
Current (kA)	....	1.2	2.3	3.0

OPTIMIZATION OF SPOT-SIZE

For this value of the optimized laser pulse-length, 10 fs, we then optimized the laser spot-size for the plasma wavelength λ_p = 16 μm.

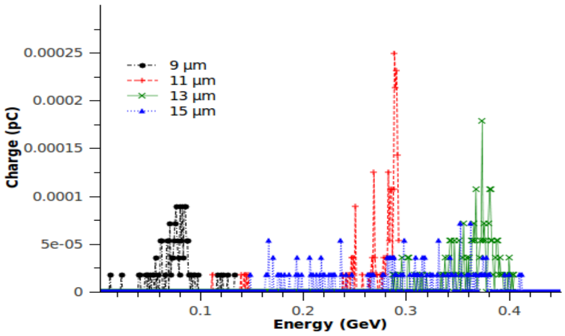

Fig. 2 Electron beam charge (pC) vs Energy (GeV) at various spot-sizes, after propagating 3.57 mm.

The charge as a function of energy at different spot-sizes, 9, 11, 13 and 15 μm, are shown in Figure 2. Here too we can see that there is a quasimonoenergetic electron spectrum. There is a larger peak in the spectrum for the case of 11 μm which shows a good amount of trapped charge compared to all other spot-sizes.

We observe from Table 2 that as we increase the spot-size, the energy increases. Excluding the 9 μm case, where there is negligible acceleration, the energy-spread increases with increasing spot-size. The emittance behaves in a more complicated manner, first increasing and then decreasing. The quantity of charge for the case of 11 μm is more among all other spot-sizes but the current is slightly less compared to 13 μm. Overall, therefore, keeping in mind optimization of all the parameters, energy, energy-spread, and emittance, it is clear from the table that the optimal value of the spot-size is around 11 μm.

Table 2. Data for optimization of the spot-size, for a plasma wavelength of λ_p = 16 μm, pulse-length = 10 fs.

Parameter	Value			
Laser spot-size(μm)	***9***	***11***	***13***	***15***
Mean Energy (GeV)	0.092	0.29	0.38	0.37
rms energy spread (%)	24.65	1.62	3.69	6.22
Normalized emittance (π mm-mrad)	19.8	2.99	3.32	1.60
Charge (pC)	0.34	1.66	1.55	0.62
Current (kA)	0.089	1.218	1.271	0.527

SUMMARY AND CONCLUSION

We have studied, using 3D PIC simulations, trapping and acceleration of plasma electrons in a homogeneous plasma by using two identical low-intensity laser pulses, propagating one behind the other in the same direction. The first laser pulse generates a wakefield and the second one amplifies the wake resonantly. This resonant amplification is quite efficient for self-injection of plasma electrons. We find that in this scheme plasma electrons are initially trapped in the plasma wave and then accelerated to high energy due to wake enhancement behind the second laser. Our focus has been on optimizing the laser parameters, pulse-length and spot-size, to get not just high-energy, but also good beam quality, *i.e.*, high charge, low normalized emittance, and small energy spread. By using two co–propagating lasers, with a_0=1.5, pulse-length 10 fs, and spot-size 11 μm, we find acceleration of a 1.2 kA electron bunch to 300 MeV, with normalized emittance 3π mm-mrad and energy spread 1.6%.

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