OPTIMIZATION OF NONLINEAR WAKEFIELD AMPLITUDE IN LASER PLASMA INTERACTION

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Abstract

Nonlinear, large amplitude, plasma waves are excited in the wake of an intense laser pulse propagating in a cold plasma, providing acceleration gradients ~ GeV/m. Linear analytic theory has shown that the wakefield amplitude is optimal for a certain ratio of the pulse length and plasma wavelength [1,2]. Here we present simulation studies to optimize the wake amplitude. The wake amplitude of a Gaussian pulse profile is maximized with respect to the laser pulse length. Using two dimensional simulations, it is seen that for a Gaussian pulse profile, the optimal pulse length derived from linear theory is also close to optimal (higher charge, smaller energy spread) for the generation of a quasi-monoenergetic electron beam in the bubble regime of laser plasma interaction. We also show, by varying the spot-size but keeping the intensity constant, that the magnitude of the trapped charge is a function primarily of the ratio P/P_c.

INTRODUCTION

Plasma-based charged particle acceleration [1] is a subject of great importance due to its potential in developing a new generation of compact high-energy accelerators. The generation of quasi-monoenergetic, dense, short bunches of relativistic electrons with up to GeV energies in laser driven acceleration has been reported [3]. Along with experimental breakthroughs, much theoretical and simulation work has been performed to understand the physics as well as to generate good quality electron beams with significant energy. In a laser wakefield accelerator a short laser pulse ($L \le \lambda_p$ where L and λ_p are the pulse length and plasma wavelength respectively) generates large amplitude plasma waves (wakefields). A charged particle can be accelerated by the wakefields generated behind the laser pulse. As the laser amplitude increases, the plasma wave becomes highly nonlinear due to which the wave steepens and its period changes. If the wake amplitude is sufficiently high, breaking of waves (longitudinal wave-breaking [4]) takes place. Along with this longitudinal wave-breaking, since the electrons are also expelled radially due to the transverse ponderomotive force of the laser, a radial density inhomogeneity, is created inside the plasma. Due to this inhomogeneity the wavefronts of the plasma wakes curve, leading to transverse wave-breaking [5]. Self-trapping of background plasma electrons and generation of quasi-monoenergetic electron beams due to propagation of intense, short laser pulses has been explored due to wake wave-breaking in the so called 'bubble regime'. In the present paper the dependence of pulse length on wake amplitude, and generation of electron beam has been studied.

ONE-DIMENSIONAL SIMULATIONS

With the help of linear wakefield theory it has been shown that the wake amplitude is maximum if the laser pulse length and plasma wavelength have a definite relation. For Gaussian and half-sine pulses maximum wakefield amplitude can be obtained if $L \approx \lambda_p / \pi\sqrt{2}$ [2] and $L \approx \lambda_p / 2$ [1], respectively. Although analytic determination of optimal pulse length for a particular pulse shape in the nonlinear regime is not possible, linear theory gives a suitable starting point for the choice of pulse length for a given plasma density. In the present analysis we have performed simulation studies using code VORPAL [6] to obtain the optimal value of pulse length for nonlinear wakefield amplitude. Assuming a Gaussian laser pulse of the form $a = a_0 \exp[-y^2/r_0^2 - (t-t_0)^2/2\tau_L^2]$ where τ_L ($\tau_{FWHM} = 2\sqrt{2\ln 2}\,\tau_L$), t_0 and r_0 are the pulse duration, pulse centre and spot-size, one dimensional simulations were performed for 20,000 simulation steps at various plasma densities. We chose a laser strength parameter $a_0 = 3$, and a laser wavelength of 0.8 μm. Plots of pulse length versus maximum wakefield amplitude at plasma wavelengths of 8 μm, 16 μm, 24 μm, 32 μm and 40 μm are shown in Fig. 1. For these values of λ_p, the optimal pulse length can analytically be estimated from the relation $L \approx \lambda_p / \pi\sqrt{2}$, as 1.8 μm (6 fs), 3.6 μm (12 fs), 5.4 μm (18 fs), 7.2 μm (24 fs) and 9 μm (30 fs), respectively. However for these values of λ_p the graph shows that optimal pulse lengths, corresponding to maximum nonlinear wakefield amplitudes, are 18 fs, 12 fs, 18 fs, 20 fs and 25 fs, respectively. Thus it is seen that linear theoretical values give good estimates for optimizing the pulse length to obtain maximum nonlinear wakefield amplitude, except in the high density (low λ_p) regime. The large deviation in the high density regime occurs on account of instabilities, such as self-phase modulation due to which the laser pulse compresses. Also, an ultrashort pulse undergoes strong group velocity dispersion and broadens in time. Thus due to large variation of pulse length in the high density regime, the linear theory is not expected to give a good estimate of the optimal pulse length. Thus one-dimensional simulations show that, for a Gaussian pulse, the linear theoretical optimal pulse relation gives a somewhat suitable estimate for obtaining large amplitude wakefields.

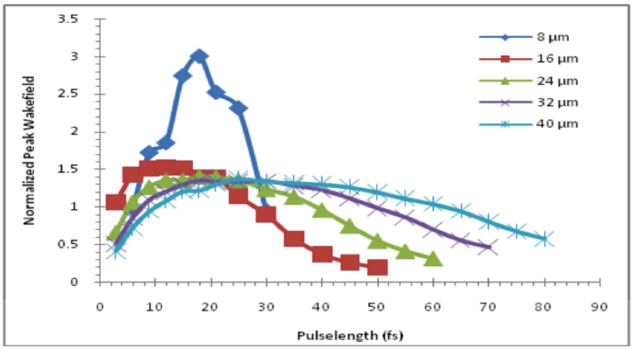

Fig. 1: Maximum wake amplitude vs laser pulse length

TWO-DIMENSIONAL SIMULATIONS

Since laser pulses as well as their wakefields are three-dimensional, a one-dimensional theory is not expected to give a good estimate of the optimal pulse length. A laser pulse having finite transverse width (spot size) undergoes strong self-focusing in the nonlinear regime, which in turn affects the generation of wakefields and vice versa. Here we consider two cases for which $P/P_c(=\pi^2 a_0^2 r_0^2/8\lambda_p^2)$ is the same. This can be achieved by adjusting the plasma density and spot size. The plasma wavelengths are considered to be 16 µm and 40 µm and spot sizes are 11 µm and 28 µm respectively, all other parameters being the same as in the 1D simulations. Since the value of the laser strength parameter lies in the bubble regime where self-generation of accelerated electron beams is possible, we also study the characteristics of the generated beam, as a function of the pulse length, which is an important requirement in laser wakefield accelerators. Figures 2(a) and (b) respectively show the variation of maximum wakefield amplitude and the peak intensity of the laser with propagation distance, for various pulse lengths, with λ_p =16 µm. It is seen that in all cases the wakefield initially increases, attains a maximum value and then starts decreasing. Peak amplitude occurs earlier in shorter pulses as compared to longer pulses. Maximum intensity versus propagation distance is plotted in Fig. 2(b), from which it can be seen that the intensity of laser pulses initially increases and then decreases. The increase and decrease in intensity is due to oscillatory behaviour of the spot-size of the laser beam which undergoes focusing and defocusing in the self-created density inhomogeneity. Along with self-focusing of the spot, compression of laser pulse also takes place. It can also be observed that maximum intensity occurs in shorter pulses at smaller distances as compared to longer pulses. Since the wake amplitude directly depends upon the laser intensity, a similar behaviour of wake amplitude with pulse length is observed in Fig. 2(a).

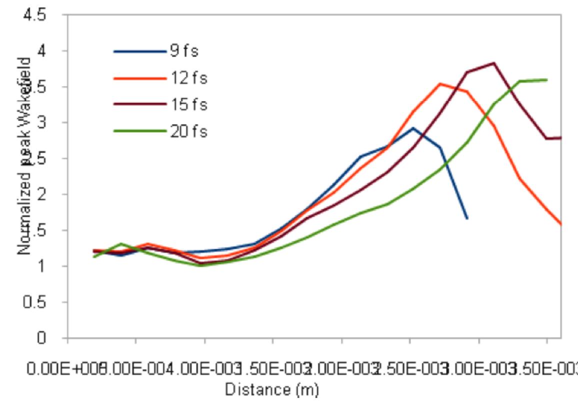

Fig. 2(a): Maximum wakefield amplitude as a function of propagation distance.

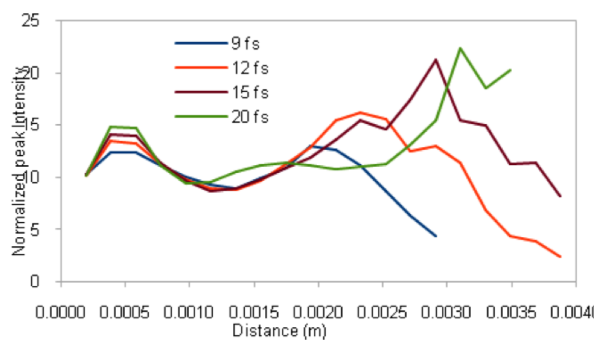

Fig. 2(b): Maximum laser intensity as a function of propagation distance.

In all these cases initially an electron beam is generated which after a certain distance separates from the rear boundary of the bubble and gets accelerated. After a certain distance this beam starts decelerating (dephasing of the electron beam with respect to the wakefield). It has been observed that saturation in energy occurs in longer pulses at a later time as compared to shorter pulses i.e., the dephasing distance of the generated electron beam is larger in longer pulses as compared to shorter pulses. The generation of electron beams with energies between 200-300 MeV has been observed. Longer pulses generate more energetic electrons.

To investigate the quality of the beam, the number of macroparticles versus energy has been plotted in Fig. 3. A nearly quasi-monoenergetic peak with a large number of electrons is observed in the case of the theoretically predicted optimized case. The pulse lengths larger than that shown in Fig. 3 give very low charge. To study the behaviour of laser and plasma dynamics at various pulse lengths at low density (λ_p = 40 µm) we consider the same P/P_c by adjusting the spot size. Decrease of plasma density increases the dephasing length which can lead to increase in acceleration. Figures 4(a) and 4(b) show the variation of peak wakefield amplitude as well peak intensity of the laser pulses with propagation distance for various pulse lengths.

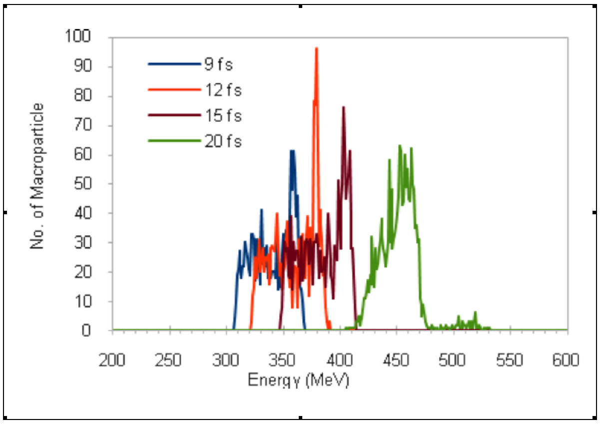

Fig. 3: Number of macroparticles as a function of energy.

Similar behaviour is observed between intensity and wake amplitude as in our earlier simulation, but in this case stable propagation over a large distance is observed.

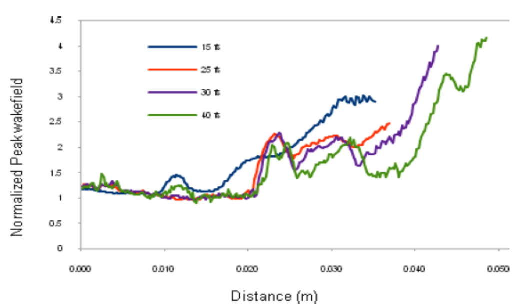

Fig. 4(a) : Maximum wake amplitude as a function of propagation distance.

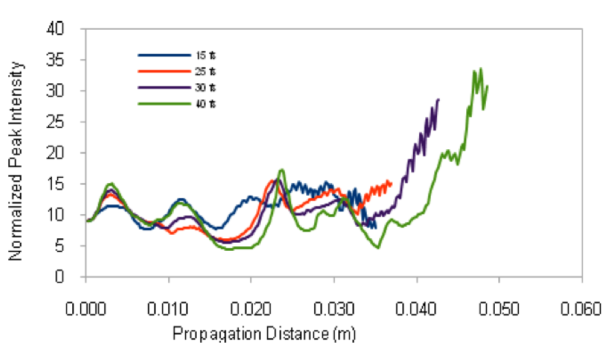

Fig. 4(b): Maximum laser intensity as a function of propagation distance.

In all these cases a self-generated quasi-monoenergetic beam has been observed. As expected, due to larger dephasing length in this case, the energy gain is much higher than the earlier case. Generation of monoenergetic electrons having energy between 1.8 GeV to 3.0 GeV has been observed for various pulse lengths. Longer pulses generate more energetic electrons. To analyze the beam quality, the number of macroparticles against energy is plotted for various pulse lengths. It is observed that the pulses closer to the theoretically optimized value show a larger number of electrons (i.e. greater charge), with low energy spread (Fig. 5). A comparison of Figs. 3 & 5 (for λ_p = 16 μm and 40 μm respectively, and P/P_c = 5.4), shows that the trapped charge is roughly the same, suggesting that P/P_c is the primary parameter in determining the magnitude of the trapped charge (given constant a_0).

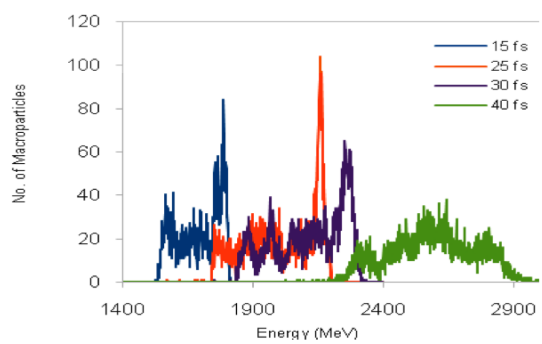

Fig. 5: Number of macroparticle as a function of energy.

CONCLUSION

Optimization of wake amplitude depending upon ratio between laser pulse length and plasma wavelength has been studied. For a Gaussian pulse profile the linear optimized pulse length required for the maximum wake amplitude gives better choice of pulse length in the nonlinear regime. For self generated electron beam the pulse length closer to theoretical optimal case gives better charge and monoenergetic beam compared to other shorter or longer pulses. The magnitude of trapped charge scales roughly with the parameter P/P_c. We plan to investigate this issue in detail in the future.

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