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Role of stochastic heating in wakefield acceleration monitored by optical injection

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ABSTRACT

It is shown that stochastic heating can play an important role in Laser Wake Field Acceleration. When considering low density plasma interacting with a high intensity wave perturbed by a low intensity counterpropagating wave, stochastic heating can provide electrons with the right momentum for trapping in the wake field. The influence of stochastic acceleration on the trapping of electrons is compared to the one of cold injection by considering several polarizations of the colliding pulses. When the plasma density exceeds some value, stochastic heating becomes important and is necessary in some circumstances to get electrons trapped into the wakefield.

1. Introduction

In this Letter, the role of stochastic acceleration on electron trapping in laser-wakefield acceleration (LWFA) [1–3] when a counterpropagating pulse is taken into account is explored.

We rather select moderate laser intensity $I \leqslant 2\times10^{19}$ W cm^{-2} and plasma density $n_e \leqslant 8\times10^{18}$ cm^{-3} close to values proposed by Lu et al. [4–8] to achieve controlled and stable blowout of the electrons. In this study, dedicated to the analysis of the mechanisms at stake when the two counterpropagating electromagnetic waves collide, we tend to avoid self-injection into the wake by lowering the pump pulse intensity. The relative influence of stochastic heating and beat wave force on the injection mechanism is discussed. Many different combinations of polarizations can be chosen for both waves, each of these possibilities results in particular forces acting on the plasma electrons, when the two waves collide [9]. The goal of this Letter is to discuss the influence of the different forces in the electron trapping by the accelerating cavity versus the different physical parameters.

Two electromagnetic counterpropagating waves with the same frequency are considered, a high intensity one and a perturbing mode. 2Dx3Dv PIC simulations are achieved with code CALDER [10] in which underdense mm-long plasma interact with two counterpropagating laser pulses with the same duration. We focus on the force best suited for injection of electrons into a wakefield, dependence to plasma density is explored. For a given length of interaction of the two waves, at rather high plasma densities, it is found that the case when the two waves are linearly polarized in the same plane is more efficient to trap particles than the case when they are circularly polarized and rotating in the same direction. When one is close or below the cold injection threshold [11] and above threshold for stochastic acceleration, the trapped charge when the two waves are linearly polarized the trapped charge is far more important than in the other case. Moreover, when the intensity of the high intensity wave is higher, the trapped charge can be higher when they are linearly polarized. This is no longer true at lower densities.

A single particle approach is presented first. Then, preliminary PIC code simulations results are given, some of these results are confirmed by a theoretical model next. Finally, it is shown in a discussion that this problem depends on two main parameters.

2. Influence of stochastic heating compared to the one of the stationary force on electron trapping in the wakefield

2.1. Single particle approach

When the two counterpropagating waves are linearly polarized in the same plane (P-linear polarizations), the normalized vector potentials of the two waves can be assumed to be given by: $\hat{\mathbf{a}} = a\cos(\hat{t}-\hat{z})\hat{\mathbf{e}}_x$ and $\hat{\mathbf{a}}_1 = -a_1\sin(\hat{t}+\hat{z})\hat{\mathbf{e}}_x$ ($\hat{z}=k_0 z$, $\hat{t}=\omega_0 t$). When the generalized momentum is such that $\hat{P}_x=\hat{P}_y=0$ ($\hat{P}_{x,y,z}=P_{x,y,z}/mc$). The normalized force acting on the charged particle in the direction of propagation of the waves is given by $d\hat{P}_z/d\hat{t} = -\partial\hat{H}/\partial\hat{z}$, where $\hat{H}$ is the normalized Hamiltonian of an electron in the two waves. One has

$$\hat{f}_z = \frac{d\hat{P}_z}{d\hat{t}} = -\frac{aa_1}{\gamma}\cos 2\hat{z} - \frac{a^2}{2\gamma}\sin 2(\hat{t}-\hat{z}) - \frac{a_1^2}{2\gamma}\sin 2(\hat{t}+\hat{z}). \qquad (1)$$

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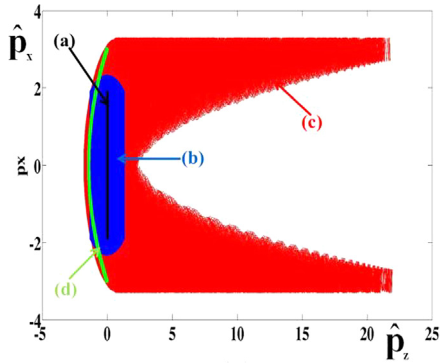

Fig. 1. Coordinates of the mechanical momentum. $a = 3$, $a_1 = 0.3$. (a) C− polarizations, (b) C+ polarizations, (c) P-linear polarizations, (d) S-linear polarizations.

It contains a beatwave term: $\hat{f}_{zBW} = -(aa_1/\gamma)\cos 2\hat{z}$ and other terms which render the problem chaotic, electrons are accelerated to much higher velocities in the z-direction due to the stochastic process (Fig. 1). This situation is, a priori, the most promising to trap electrons in the wake field.

The case when the perturbing mode is polarized perpendicularly to the polarization plane of the high intensity wave is also considered (S-linear polarizations). The normalized vector potentials of the two waves are assumed to be: $\hat{\mathbf{a}} = a\cos(\hat{t} - \hat{z})\hat{\mathbf{e}}_x$, and $\hat{\mathbf{a}}_1 = a_1 \sin(\hat{t} + \hat{z})\hat{\mathbf{e}}_y$. In this case, when $\hat{P}_x = \hat{P}_y = 0$, the normalized transverse mechanical momentum contains no first-order term as $\hat{\mathbf{a}}.\hat{\mathbf{a}}_1 = 0$. These polarizations rule out the electron acceleration in the z-direction due to the beatwave force. Still, some stochastic heating due to the other terms can be found when considering a single particle.

The situation when the two waves are circularly polarized is also considered. Two cases can be considered: the two wave vectors can rotate in the same direction (positive circular polarizations: C+ polarizations) or in two opposite directions (negative circular polarizations: C− polarizations). In both cases the problem is integrable (Appendix A). When the two vectors rotate in two opposite directions, there is no force accelerating particles in the direction of propagation of the high intensity wave (Appendix A) (Fig. 1). When the two vectors rotate in the same direction, the beatwave force $\hat{f}_{zBW} = a_1 a/\gamma \sin 2\hat{z}$ (Appendix A) is the only one to accelerate the electrons in the direction of propagation of the wave. This term can be quite efficient to pre-accelerate plasma background electrons as its spatial scale is $\lambda_0/2$, where λ_0 is the laser wave length [9–12] (Fig. 1).

2.2. Plasma PIC code simulations

2.2.1. Preliminary results

Two 30 fs laser pulses with wavelength $\lambda = 0.8$ μm are considered now. The waves interact with mm-size plasma. The pump pulse which creates the accelerating wakefield is focused to a 18 μm full wiδτh at half maximum (FWHM). The low intensity pulse is counterpropagating and is focused to a 31 μm focal spot.

In the first place, it is assumed that the pump pulse interacts with plasma with a density: $n_e = 4.3 \times 10^{-3} n_c$, where n_c is the plasma critical density. The role of stochastic acceleration is studied by comparing the effect of the collision of two linearly polarized waves (P- and S-linear polarizations) to the one of two circularly polarized lasers considering the cases of positive and negative circular polarizations. To do so, 2D PIC code simulations were performed. The electron energy distribution function is calculated long after the collision of the two waves. It was assumed first that a_1 is above the threshold for stochastic heating [16–20]. In the case when the waves are circularly polarized, the problem of a single electron interacting with them is integrable, as a consequence, no stochastic acceleration is expected when the two waves propagate in low density plasma. In C− polarizations cases and in the S-linear polarizations case, simulation results show that almost no electron is trapped and accelerated in the wakefield (Fig. 2). In these situations there is no beatwave and the stochastic heating in the S polarizations case is very weak. On the contrary, a significant charge is injected and consequently accelerated in the P-linear polarizations case (Fig. 2(a)).

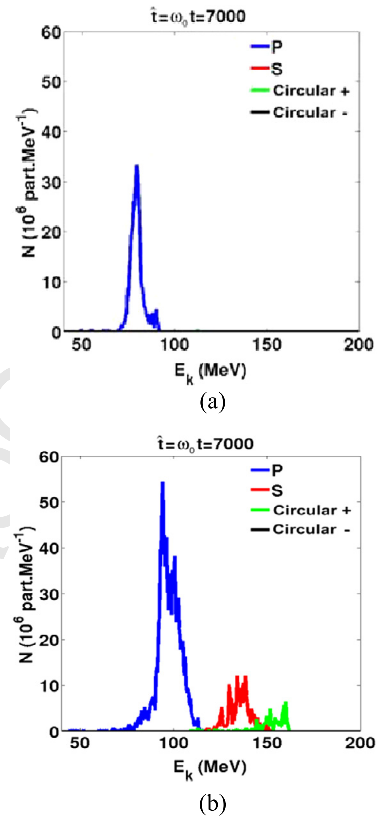

Fig. 2. Electron energy distribution obtained above the stochastic threshold value for a_1. $n_e = 4.3 \times 10^{-3} n_c$. (a) $a = 1.5$, $a_1 = 0.4$, (b) $a = 2$, $a_1 = 0.4$.

In good agreement with previously published theoretical work, the C+ polarized waves do not trap any charge when $a \leqslant 2$ (value below the cold electron trapping: $a = 2$) [11] (Fig. 2). At this plasma density a significant charge can be trapped in the P polarizations case when a_1 is above the threshold. Then, the P polarizations case plays a major role. In this case, stochastic heating provides electrons with enough momentum for trapping in the wake field. Most particles are trapped after passing through the front of the accelerating cavity.

In the case when $a = 2$ and $a_1 = 0.4$, the phase plot which has been perform just at the end of the collision of the two laser pulses do show that one has more particles with a high momentum in the direction of propagation of the wave in the P polarizations case (Fig. 3).

When a_1 is below the threshold, no charge is trapped in the P polarizations case and in the C+ polarizations one.

When $a = 1.5$ (value below the cold electron trapping) and $a_1 = 0.05$ (value below the threshold), no charge is trapped in the P or C+ polarizations cases. When $a = 2$ and $a_1 = 0.05$, just about the same small charge is trapped in both polarizations case.

When $a > 2$, the P polarizations case prevails when a_1 is above the threshold for stochastic heating (Fig. 4). With the P polarization the trapped charge is $Q_P = 25$ pC/μm while it is $Q_{C+} = 17$ pC/mm with the C+ polarizations.