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Generation of Energetic Electrons in Preplasma via Parametric Instability

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A new mechanism is reported that increases electron energy gain from a laser beam with ultra-relativistic intensity in significantly underdense plasma. The increase occurs when electron oscillations across the ion channel produced by the laser become parametrically unstable. The instability threshold is determined by the product of beam intensity and ion density.

1. Introduction

A common element of applications involving laser-target interactions is the generation of energetic electrons. A laser beam incident onto a solid-density target generates an oscillating force at the target surface. This force injects electrons into the target with characteristic energy of the order of the ponderomotive potential. One way to increase electron energy beyond that level is via multiple interactions with the laser. This requires electron recirculation in the target during the pulse. Another way to increase electron energy is to increase electron interaction length with the laser beam. The conditions for that can naturally occur in a preplasma in front of the target. A laser prepulse often creates a transparent preplasma that extends many wavelength from the target surface along the beam path. The main pulse propagating through such preplasma can then accelerate electrons to energies significantly higher than the ponderomotive potential.

We present a mechanism that increases the electron energy gain in sub-critical preplasma regardless of the beam polarization, which distinguishes this mechanism from the previously discussed betatron resonance [1]. The increase occurs at ultra-relativistic intensities when electron oscillations across the channel formed by the laser become parametrically unstable. The instability threshold is determined by the product of beam intensity and ion density. Our findings suggest that the population of hot electrons and their energy could possibly be increased in laser-target interactions by adjusting the preplasma density and length in order to trigger the instability and provide sufficient interaction length for the enhanced energy gain.

2. Model

We consider interaction of a plane wave with a single electron placed in a straight uniform ion channel. We choose a two-dimensional Cartesian setup, such that the plane wave propagates along the *z*-axis. The static electric field produced by the ion space-charge in the channel is directed along the *y*-axis and it is then proportional to *y*. The ions are assumed to be immobile.

The plane wave is described by a normalized vector potential

$$\mathbf{a} = a(\xi)\left[\mathbf{e}_x \cos\theta + \mathbf{e}_y \sin\theta\right],$$

where θ is the polarization angle and $\mathbf{e}_x$ and $\mathbf{e}_y$ are unit vectors. The dimensionless phase variable ξ is defined as

$$\xi \equiv (ct - z)/\lambda,$$

where λ is the laser wave-length, c is the speed of light, and t is the time in the laboratory (ion) frame of reference. We assume that $a(\xi)$ has a general form

$$a(\xi) = a_0 F(\xi)\sin(2\pi\xi + \psi),$$

where a_0 is the maximum amplitude, $F(\xi)$ is a slowly varying envelope, and ψ is an initial phase.

Starting with the equations of motion for a relativistic electron in electric and magnetic fields, we have derived an equation for electron motion across the channel in the presence of the plane wave:

$$\frac{d^2u}{d\xi^2} - \frac{u}{2\left(C - u^2/2\right)}\left[\frac{du}{d\xi}\right]^2 + \frac{K^2 u}{2\left(C - u^2/2\right)^3}$$
$$+ \frac{K^2 u}{2\left(C - u^2/2\right)} + \frac{K^2 a^2 \cos^2\theta\, u}{2\left(C - u^2/2\right)^3} = \frac{K\sin\theta}{C - u^2/2}\frac{da}{d\xi},$$

where

$$u \equiv \omega_{p0} y/c,$$
$$K \equiv \omega_{p0}\lambda/c,$$

and $\omega_{p0} = \sqrt{4\pi n_0 e^2/m_e}$ is the plasma frequency, n_0 is the density of the single charged ions in the channel, and e and m_e are the electron charge and mass. The constant C for an electron that is initially at rest is determined by its initial displacement,

$C = 1 + u^2(0)/2$. The wave amplitude a_0 enters the equation of motion as a product a_0K, which suggests a convenient dimensionless parameter κ defined as

$$\kappa \equiv a_0 K = \omega_{p0} a_0 \lambda / c .$$

Note that $K \ll 2\pi$ in a significantly underdense plasma, which is the case of our primary interest.

3. Results

In the ultra-relativistic regime (a_0>>1), the K^2 terms that do not involve a^2 can be neglected in the equation of motion. The resulting equation contains only two parameters (κ and θ). The case of an s-polarized wave $(\theta = 0)$ clearly illustrates the instability mechanism. The equation of motion for small oscillations and F=1 reduces to

$$\frac{d^2u}{d\xi^2} + \frac{1}{2}\kappa^2 \sin^2(2\pi\xi + \psi)u = 0 \cdot$$

This is a Mathieu differential equation for a linear oscillator with a periodically changing frequency. Such oscillations are susceptible to parametric instability that causes their amplitude to grow. We find that the instability threshold is $\kappa_* \approx 10.2$.

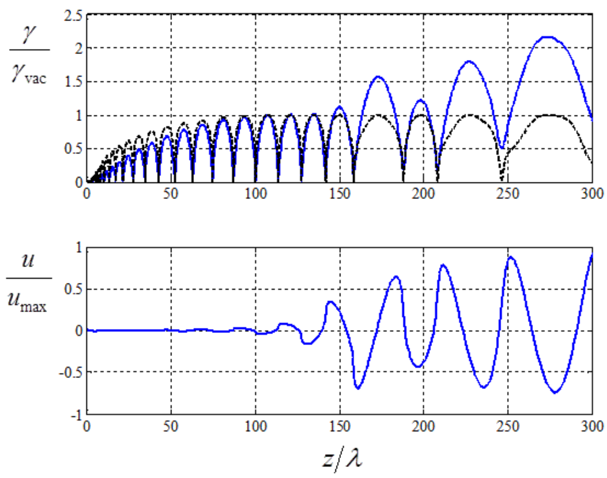

Fig. 1. Parametrically unstable electron oscillations in the s-polarized wave for κ=12 and a_0=10. The dashed curve shows a/a_0 as a function of electron axial location. Note that here $u_{max} \approx \sqrt{2}$ and $\gamma_{vac} = 1 + a_0^2/2$.

The transverse oscillations in the channel change the dephasing rate that determines axial motion of the electron relatively to the wave. The dephasing rate decreases significantly as a result of the instability compared to that in the absence of ions. This allows the electron to stay in phase with the wave for a longer time and thereby gain more energy, with the resulting γ-factor exceeding the maximum value achievable without the ions (in vacuum), $\gamma_{vac} = 1 + a_0^2/2$.

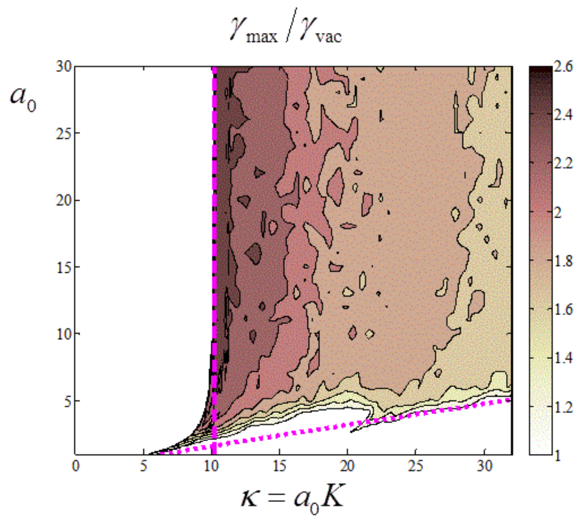

Fig. 2. Maximum γ-factor in the s-polarized wave (θ=0) averaged over the initial wave phase.

The solution of the complete equation of motion and the resulting γ-factor for a set of parameters corresponding to $\kappa = 12 > \kappa_*$ are shown in Fig. 1. The oscillations grow significantly due to the instability. This increase in amplitude causes axial acceleration, reflected by the increase in γ. Figure 2 shows the maximum γ-factor as a function of a_0 and κ. At a_0>10, the instability threshold is indeed determined only by parameter κ since the threshold coincides with the dashed vertical line $\kappa = \kappa_*$. The peak value of γ is roughly 2.6 times greater than the maximum value that can be achieved in the absence of ions.

In summary, we have shown that the parametric instability of an ultra-relativistic electron in the ion channel provides an opportunity for enhanced electron energy gain in the laser beam.

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