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Propagation of super-intense and ultra-short laser pulses in plasmas

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Abstract

The propagation of super-intense and ultra-short laser pulses in plasmas is a main concern in several applications of the laser-plasma interactions, from Inertial Confinement Fusion (ICF) to High Energy Physics (HEP). During the propagation in the plasma the light beam deeply changes its parameters due the onset of non-linear effects, among them the relativistic regime of the electron quivering motion. These extreme conditions are suitable for the electron acceleration in high field gradient, opening the way for the realization of compact secondary sources of X-gamma rays.

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1. Introduction

The CPA (Chirped Pulse Amplification) technique (Strickland and Mourou, 1985) of mode-locked fs laser pulses opened the way for the studies of the propagation of super-intense and ultra short laser pulses propagating in plasmas in unprecedented intensity regimes, overcoming 10^{18}W/cm^2. The electric field, associated to the intensity I,

$$E_{V/cm} \approx 27.5\, I_{W\cdot cm^{-2}}^{\frac{1}{2}}$$

largely exceeds the atomic field, so producing a very fast ionization of the matter (d'Humieres, 2008) in which the laser pulse is propagating. The free electrons of the plasma so produced oscillate under the action of the electric field with relativistic quiver velocity. The relevance of the relativistic effects can be evaluated considering the relativistic parameter *a*, from which the Lorentz factor γ depends:

$$\gamma = \left(1 + \frac{\alpha a^2}{2}\right)^{\frac{1}{2}} \quad \alpha = 1\,(lin.\,p.)\,;\,2\,(circ.\,pol.)$$

$$a = \frac{eE}{m\omega c} \approx 8.5 \cdot 10^{-10} \cdot I_{W\cdot cm^{-2}}^{1/2} \cdot \lambda_{\mu m}$$

The physical phenomena considered in the following paragraphs are not exhaustive to fully describe the interaction of super-intense and ultra-short laser pulses with the matter; therefore, due to the limited extension of the paper, I will restrict to the major effects relevant for the Laser Plasma Acceleration (LPA) experiments.

2. Plasma refractive index at laser relativistic intensities.

The laser, propagating in a plasma, induces a quivering motion on the irradiated electrons. When the relativistic parameter *a* approaches or overcomes the unity in the maximum of the radial intensity distribution of the laser (bell shaped), the electrons in the center of the laser beam are more "heavy" of the ones in the margins, as a consequence of their relativistic motion (γ>1) and the refractive index *n* becomes locally larger. So the laser beam bends due to the radial dependence of the refractive index on the local laser intensity. In fact, the plasma refractive index in the center of the laser beam becomes larger than in its margins, because the plasma frequency ω_{pe} depends on the Lorentz factor, related to the quivering motion of electrons in the laser electromagnetic fields.

$$n = \left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{\frac{1}{2}} \qquad \omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m \gamma}\right)^{\frac{1}{2}}$$

In these conditions the plasma acts as a focusing lens that, concentrating the laser radiation, increases its intensity which in turns increases the refractive index effects, so producing a positive feed-back process of beam self-focusing. The onset of this physical process (Esarey, 1997) demands to overcome the critical value for the laser power:

$$P_{cr} = \frac{mc^5\omega^2}{e^2\omega_{pe}^2} \approx 17\left(\frac{n_c}{n_e}\right) GW$$

As we can see, the critical power decreases as the plasma density increases as a consequence of the major refractive effects. Once the relativistic self-focusing take place, the laser beam can be focused over distances much larger than the Rayleigh length, Z:

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