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Accurate correction field of circularly polarized laser and its acceleration effect

S. Y. Zhang *

School of Sciences and Institute of Condensed Matter Physics, Linyi Normal University, Linyi 276005, China

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Abstract. High-order correction terms to the expression of the field of circularly polarized Gaussian laser are derived. Terms up to seventh order in the small dimensionless spatial parameter are explicitly presented. Using the test particle simulation programs, the CAS (Capture & Acceleration Scenario) phenomenon in the circularly polarized field has been proved, and the difference efficiency of CAS scheme between the circularly polarized field and linearly polarized field has been investigated, further more the electron dynamics obtained by the paraxial approximation, the fifth-order correction, and the seventh-order correction are compared in detail. The numerical calculations show that the results of three corrected models coincide with each other very well for $kw_0>60$, and the difference of the three corrected models is very conspicuously for $kw_0\leq 50$. Then the ranges of the electron incident momentum for the CAS scheme in circularly polarized field to emerge are examined. This study is of significance in designing experimental setup to test CAS and helpful in understanding the basic physics of CAS.

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Key words: laser acceleration, vacuum acceleration mechanism, wave phase propagation

1 Introduction

Due to the recent development of ultra-intense laser with the chirped pulse amplification technique [1, 2], currently laser intensities have increased to as high as $10^{19\sim 21} W/cm^2$. Such intense laser was used to study the interaction of matter and laser. For instance, the research fields of the produce of ultra-short x-ray laser, particles acceleration [3–8], lab astrophysics and fast ignition.

*Corresponding author. *Email address:* `shaoyinzhang@163.com` (S. Y. Zhang)

Based on a 3D simulation model of free electrons interacting with a lowest-order Hermite-Gaussian (0, 0) mode laser polarized in the x direction, we study the inelastic scattering and accelerating effects of the intense laser field on the electron. It has been found that if the laser intensity is very high, e.g. $a_0 \sim 100$ ($a_0 = eE_0/m_e\omega c$ is a dimensionless parameter representing the laser intensity, where $-e, m_e$ are the electron charge and mass, respectively, c is the speed of light in vacuum, ω is the angular frequency of the electromagnetic wave) under some injection conditions, the electron can be captured and violently accelerated to energy ≥ 1 GeV; the electron energy gain is linearly proportional to the laser intensity. A newly discovered electron acceleration mechanism using an intense vacuum laser beam which was named CAS had been presented in detail [8–10]. The above conclusions reveal that CAS is an effective and promising principle for developing a new type of laser-driven accelerator, and the scheme can be tested experimentally with existing laser systems.

For tightly focused beams, the beam waist radius is of the same order of magnitude as the wavelength and the paraxial formula becomes an inaccurate description. It is necessary to extend the paraxial description to corrections of higher order. This work is intended to acquaint us with the structure of tightly focused of circularly polarized Gaussian laser beam and to develop theory of electron acceleration. The main task of this paper present the formulae of the high-order circularly polarized field, we will explore the effect of the high-order correction of circularly polarized Gaussian laser field relation to the CAS phenomenon. We also study the conditions under which the electrons must be injected so that they will enter into this acceleration channel. This study is not only helpful for understanding the physics underlying CAS in this laser field, but also in finding proper experimental parameters to test CAS as well.

2 Formulae of circularly polarized laser fields

As for a circularly polarized field, the electromagnetic field components of the laser in the normal paraxial approximation are expressed by the following equations [11]

$$E_x = E_0 \frac{w_0}{w(z)} \exp\left(-\frac{x^2+y^2}{w^2(z)}\right) \times \exp\left[i\left(kz - \omega t - \varphi_0 + \frac{k(x^2+y^2)}{2R(z)}\right)\right] \times f(ct-z), \tag{1}$$

$$E_y = E_x \exp(\pm i\frac{\pi}{2}), \tag{2}$$

$$E_z = (i/k)(\partial E_x/\partial x + \partial E_y/\partial y), \tag{3}$$

$$\vec{B} = -(i/\omega)\nabla \times \vec{E}. \tag{4}$$