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Accurate correction field of circularly polarized laser and its acceleration effect

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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 $10^{19\sim21} W/cm^2$. 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.

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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]

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

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

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

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

where

$$w(z)=w_0\left[1+\left(\frac{2z}{kw_0^2}\right)^2\right]^{1/2},\quad R(z)=z\left[1+\left(\frac{kw_0^2}{2z}\right)^2\right],$$
$$\varphi(z)=\tan^{-1}\left(\frac{2z}{kw_0^2}\right),\quad f(ct-z)=\exp\left(-\frac{(t-\frac{z}{c})^2}{\tau^2}\right),$$

w_0 is the radius of the beam width at focus and k is the wave number, f is electric envelope, τ is the pulse duration, "$+$" and "$-$" represent the dextrorotatory and levorotatory CP(Circularly Polarized) lasers, respectively. For simplicity, the dextrorotatory laser is adopted here.

As for tightly focused field, the space diffraction effect is conspicuous. Our previous work shown that the inject electron's trajectory will be severely affected by the diffraction edge field of a tightly focused stationary laser beam at the very start of incidence [12]. Therefore, we should extend to study the high-order correction description instead of that of the paraxial approximation description. According to reference [13, 14], the e-m field components of seventh order in terms of a small dimensionless parameter $s=1/kw_0$ were already obtained. The following is seventh order correction equations about x direction linear polarized laser field.

$$\begin{aligned}E_{x\_7}=&E_0\Big(1+s^2(-\rho^2\Theta^2+i\rho^4\Theta^3-2\Theta^4\xi^2)+s^4[2\rho^4\Theta^4-3i\rho^6\Theta^5-0.5\rho^8\Theta^6\\&+(8\rho^2\Theta^4-2i\rho^4\Theta^5)\xi^2]+s^6[-5\rho^6\Theta^6+9i\rho^8\Theta^7+2.5i\rho^{10}\Theta^8-\frac{i}{6}\rho^{12}\Theta^9\\&-\xi^2(30\rho^4\Theta^6-12i\rho^6\Theta^7-\rho^8\Theta^8)]\Big)\psi_0e^{-i\zeta/s^2},\end{aligned}\tag{5}$$

$$\begin{aligned}E_{y\_7}=&E_0\Big(s^2(-2\Theta^2\xi\eta)+s^4[\xi\eta(8\rho^2\Theta^4-2i\rho^4\Theta^5)]\\&+s^6[-\xi\eta(30\rho^4\Theta^6-12i\rho^6\Theta^7-\rho^8\Theta^8)]\Big)\psi_0e^{-i\zeta/s^2},\end{aligned}\tag{6}$$

$$\begin{aligned}E_{z\_7}=&E_0\Big(s(-2\Theta\xi)+s^3(6\rho^2\Theta^3-2i\rho^4\Theta^4)\xi+s^5(-20\rho^4\Theta^5+10i\rho^6\Theta^6+\rho^8\Theta^7)\xi\\&+s^7(70\rho^6\Theta^7-42i\rho^8\Theta^8-7\rho^{10}\Theta^9+i\rho^{12}\Theta^{10}/3)\xi\Big)\Psi_0e^{-i\zeta/s^2},\end{aligned}\tag{7}$$

$$\begin{aligned}cB_{x\_7}=&E_0\Big(s^2(-2\Theta^2\xi\eta)+s^4[\xi\eta(8\rho^2\Theta^4-2i\rho^4\Theta^5)]\\&+s^6[-\xi\eta(30\rho^4\Theta^6-12i\rho^6\Theta^7-\rho^8\Theta^8)]\Big)\Psi_0e^{-i\zeta/s^2},\end{aligned}\tag{8}$$

$$\begin{aligned}cB_{y\_7}=&E_0\Big(1+s^2(-\rho^2\Theta^2+i\rho^4\Theta^3+i\rho^4\Theta^3-2\Theta^2\eta^2)\\&+s^4[2\rho^4\Theta^4-3i\rho^6\Theta^5-0.5\rho^8\Theta^6+\eta^2(8\rho^2\Theta^4-2i\rho^4\Theta^5)\\&+s^6[-5\rho^6\Theta^6+9i\rho^8\Theta^7+2.5i\rho^{10}\Theta^8-\frac{i}{6}\rho^{12}\Theta^9\\&-\eta^2(30\rho^4\Theta^6-12i\rho^6\Theta^7-\rho^8\Theta^8)]\Big)\Phi_0e^{-i\zeta/s^2},\end{aligned}\tag{9}$$

and

$$cB_{z\_7} = E_0[s(-2\Theta\eta) + s^3(6\rho^2\Theta^3 - 2i\rho^4\Theta^4)\eta + s^5(-20\rho^4\Theta^5 + 10i\rho^6\Theta^6 + \rho^8\Theta^7)\eta \\ + s^7(70\rho^6\Theta^7 - 42i\rho^8\Theta^8 - 7\rho^{10}\Theta^9 + \frac{i}{3}\rho^{12}\Theta^{10})\eta]\Psi_0 e^{-i\zeta/s^2}. \quad (10)$$

In order to develop a CP laser description, for which the electric and magnetic field components are symmetry, according to the above expression, we can derive y direction linear polarized laser field

$$E'_{x\_7} = E_0\Big(s^2(-2\Theta^2\xi\eta) + s^4[\xi\eta(8\rho^2\Theta^4 - 2i\rho^4\Theta^5)] \\ + s^6[-\xi\eta(30\rho^4\Theta^6 - 12i\rho^6\Theta^7 - \rho^8\Theta^8)]\Big)\psi_0 e^{-i\zeta/s^2}, \quad (11)$$

$$E'_{y\_7} = E_0\Big(1 + s^2(-\rho^2\Theta^2 + i\rho^4\Theta^3 - 2\Theta^2\eta^2) + s^4[2\rho^4\Theta^4 - 3i\rho^6\Theta^5 - 0.5\rho^8\Theta^6 \\ + (8\rho^2\Theta^4 - 2i\rho^4\Theta^5)\eta^2] + s^6[-5\rho^6\Theta^6 + 9i\rho^8\Theta^7 + 2.5i\rho^{10}\Theta^8 - \frac{i}{6}\rho^{12}\Theta^9 \\ - \eta^2(30\rho^4\Theta^6 - 12i\rho^6\Theta^7 - \rho^8\Theta^8)]\Big)\psi_0 e^{-i\zeta/s^2}, \quad (12)$$

$$E'_{z\_7} = E_0\Big(s(-2\Theta\eta) + s^2(6\rho^2\Theta^3 - 2i\rho^4\Theta^4)\eta + s^5(-20\rho^4\Theta^5 + 10i\rho^6\Theta^6 + \rho^8\Theta^7)\eta \\ + s^7(70\rho^6\Theta^7 - 42i\rho^8\Theta^8 - 7\rho^{10}\Theta^9 + i\rho^{12}\Theta^{10}/3)\eta\Big)\Psi_0 e^{-i\zeta/s^2}, \quad (13)$$

$$cB'_{x\_7} = E_0\Big(1 + s^2(-\rho^2\Theta^2 + i\rho^4\Theta^3 - 2\Theta^2\xi^2) + s^4[2\rho^4\Theta^4 - 3i\rho^6\Theta^5 - 0.5\rho^8\Theta^6 \\ + \xi^2(8\rho^2\Theta^4 - 2i\rho^4\Theta^5)] + s^6[-5\rho^6\Theta^6 + 9i\rho^8\Theta^7 + 2.5i\rho^{10}\Theta^8 - \frac{i}{6}\rho^{12}\Theta^9 \\ - \xi^2(30\rho^4\Theta^6 - 12i\rho^6\Theta^7 - \rho^8\Theta^8)]\Big)\Psi_0 e^{-i\zeta/s^2}, \quad (14)$$

$$cB'_{y\_7} = E_0\Big(s^2(-2\Theta^2\xi\eta) + s^4[\xi\eta(8\rho^2\Theta^4 - 2i\rho^4\Theta^5)] \\ + s^6[-\xi\eta(30\rho^4\Theta^7 - \rho^8\Theta^8)]\Big)\Psi_0 e^{-i\zeta/s^2}, \quad (15)$$

$$cB'_{z\_7} = E_0\Big(s - (-2\Theta\xi) + s^3(6\rho^2\Theta^3 - 2i\rho^4\Theta^4)\xi + s^5(-20\rho^4\Theta^5 + 10i\rho^6\Theta^6 + \rho^8\Theta^7)\xi \\ + s^7(70\rho^6\Theta^7 - 42i\rho^8\Theta^8 - 7\rho^{10}\Theta^9 + \frac{i}{3}\rho^{12}\Theta^{10})\xi\Big)\Psi_0 e^{-i\zeta/s^2}. \quad (16)$$

where $\xi = x/w_0$, $\eta = y/w_0$, $\zeta = z/w_0^2$, $\rho^2 = \xi^2 + \eta^2$, $\Theta = 1/(i+2\zeta)$, $\psi_0 = i\Theta\exp(-i\rho^2\Theta)$.

Therefore the CP field components can be derived as follows

$$
\begin{aligned}
E_{cx\_7} &= E_{x\_7} + (\pm i)E'_{x\_7},\\
E_{cy\_7} &= E_{y\_7} + (\pm i)E'_{y\_7},\\
E_{cz\_7} &= E_{z\_7} + (\pm i)E'_{z\_7},\\
cB_{cx\_7} &= cB_{x\_7} + (\pm i)cB'_{x\_7},\\
cB_{cy\_7} &= cB_{y\_7} + (\pm i)cB'_{y\_7},\\
cB_{cz\_7} &= cB_{z\_7} + (\pm i)cB'_{z\_7},
\end{aligned}
$$

where "$+$" and "$-$" represent the dextrorotatory and levorotatory CP lasers, respectively.

With the high-order corrected laser fields, the interaction between free electron and Gaussian beam in vacuum could be studied by solving the following relativistic Lorenz equation

$$\frac{d\vec{p}}{dt} = -e(\vec{E} + \vec{v} \times \vec{B}), \tag{17}$$

where $\vec{v}$ is the electron velocity in units of c, $\vec{p}$ is the electron momentum. The above non-linear equation can only be solved numerically. Here the fourth-order Runge-Kutta method together with the Richardson's first-order extrapolation procedure are used. For simplicity, throughout this paper, electron momentum $\vec{p}$ in units of $m_e c$, length in units of $1/k$, and time in units of $1/\omega$.

3 Results and discussion

First we extend our previous study to high-order correction CP field. We will present typical electron-laser interaction in laser field. Fig.1 presents a detailed demonstration of the dynamic variables for CAS electrons occurring in CP laser field. In CP field, the electron is not expelled from the intense-field region. An electron with the initial energy of 5 MeV, finally obtains about 100 MeV energy from the field. Fig.1(c) shows that the laser phase φ experienced by the electron, varies relatively slowly even in the acceleration stage, therefore the electron can remain in the acceleration phase for a long time and get considerable energy. According to the CAS scheme [14], for acceleration particles, the subluminous phase velocity of the field, and the acceleration field strength, i.e., the amplitude of the longitudinal electric field are two important factors. Therefore, we can confirm that this case which Fig. 1 showed is typical CAS.

We next study the difference of the electron dynamics between in CP field and in LP(Linearly Polarized) field. It was also confirmed that there exist the region of subluminous phase velocity in CP field in our previous work [15]. This in conjunction with a strong longitudinal electric field component, the chief acceleration field, this region forms an acceleration channel that shows similar characteristics to that of a waveguide tube of conventional accelerators. Relativistic electrons injected into this field can remain in the acceleration phase and synchronous with the laser for a sufficiently long. In Fig. 2, under the intensity $a_0 \sim 10$, the characteristics of electron's energy in CP field and in LP field have been shown. Comparing CP field with LP field, we can find the acceleration platform of CP is wider than that of LP, and that the platform of CP is higher than that of LP. Therefore, the acceleration is more effect of CP field than that of LP field.

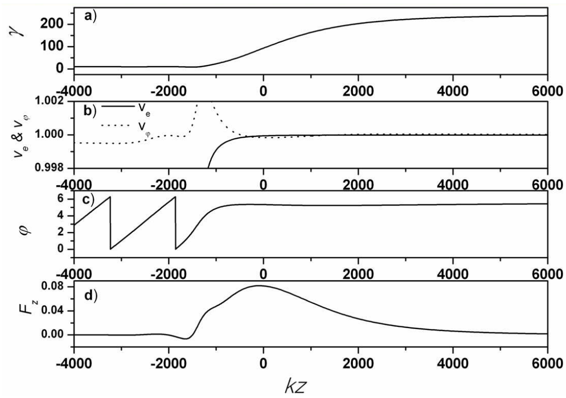

Figure 1: Typical CAS dynamic characteristics in the circularly polarized field. The parameters used are $kw_0 = 60$, $a_0 = 10$, $p_{xi} = 0.99$, $p_{yi} = 0.099$, $p_{zi} = 10$. a) CAS electron's energy γ vs. kz coordinate; b) A comparison of the CAS electron velocity (solid line) and the phase velocity of the laser wave (dotted line) along the electron trajectory vs. z coordinate; c) Phase experienced by the CAS electron; d) Longitudinal force experience by the electron vs. z coordinate.

Why are the energy gains so different? To explore the physics behind this energy phenomenon, in this high-order correct field, we also use a quantity Q which represents the ability of the laser field to accelerate charged particles. We call it the acceleration quality factor. It is defined as $Q = Q_0(1 - v_{\varphi m/c})|E_{cz}|$ for $v_{\varphi m} \leq c$ and $Q = 0$ for $v_{\varphi m} > c$. Here Q_0 is a normalization constant chosen to make Q of the order of unity and the minimum phase velocity $v_{\varphi m} = ck/|\nabla\varphi|$, where

$$\varphi = kz - \omega t - \varphi(z) - \varphi_0 + \frac{k(x^2+y^2)}{2R(z)}.$$

From Fig. 3, we know that the acceleration channel is like a cylindrical shell surrounding the laser beam, symmetric with respect to the beam axis for CP field, while for a LP field [16], it is concentrated in two regions near the plane $x=0$. Obviously, the acceleration channel of CP field is wider than that of LP field, these distinctively different distributions of acceleration channels suggest that much more injected would be accelerated through the CAS scheme in CP fields than in LP fields. In other world, greater efficiency of CAS electrons can be obtained in CP fields than in LP fields.

Now we go on to study the effect of the high-order correction to CP laser field, especially the effect on CAS scheme. In this paper, the following abbreviations, PAF for the paraxial approximation field, FAF for fifth-order corrected approximation field, and SAF for seventh-order corrected approximation field. In Fig. 4, the energy final energy (γ_f) as a function of the laser initial phase at different beam widths are presented. The

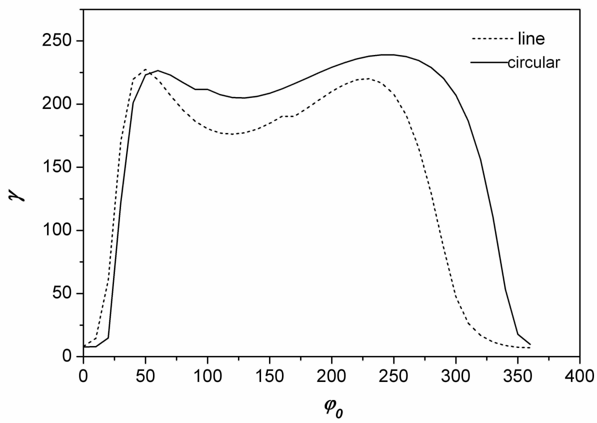

Figure 2: Electron final energy γ_f vs. laser initial phase φ_0 in CP and LP fields at the same parameters. The parameters used are: the incident angle $\theta_i = \tan^{-1}(0.1)$, $kw_0 = 60$, $a_0 = 10$, $p_{xi} = 1$, $p_{yi} = 0$, $p_{zi} = 10$. The solid line stand for CP field and dotted line for LP field.

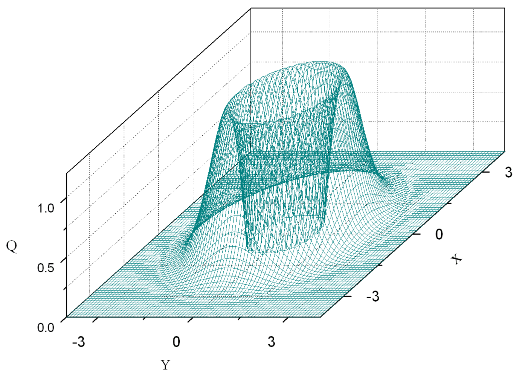

Figure 3: The acceleration quality factor Q versus x and y coordinates in the $z = 0$ plane of focus laser field $kw_0 = 60$.

numerical results reveal that the average discrepancies between the three models. In order to study this problem in more extended parameter range, a comparison of the three corrected models is kept for laser intensity of $a_0 = 10$. In Fig. 4(a), as for $kw_0 = 60$, the mean discrepancies are:0.5% for FAF compared with PAF, and 0.005% for FAF with SAF. In Fig. 4(b), for $kw_0 = 55$, the mean discrepancies are:5% for FAF compared with PAF, and 0.8% for FAF with SAF. In Fig. 4(c), for $kw_0 = 50$, the mean discrepancies are:10% for FAF compared with PAF, and 4% for FAF with SAF. With the laser beam width decrease, the quantity of parameter $s = 1/kw_0$ increases in the laser field formulae, so the larger discrepancies among the results of the three corrected models can be found. 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 con-

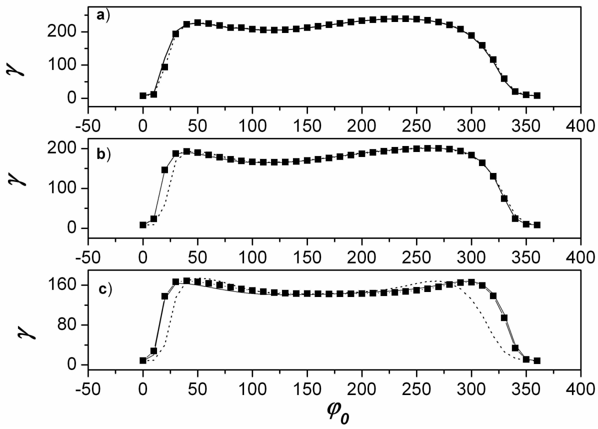

Figure 4: A demonstration of the electron final energy γ as function of the laser initial phase φ_0 at different beam width kw_0. The solid line denotes SAF calculation's result, the symbol line for FAF and the dotted line for PAF. (a) The parameters used are $kw_0=60$, $a_0=10$, $p_{xi}=0.99$, $p_{yi}=0.099$, $p_{zi}=10$; b) $kw_0=55$, the other parameters are the same as in (a); c) $kw_0=50$, the other parameters are the same as in (a).

spicuously for $kw_0 \leq 50$. Based on these results we conclude that when $kw_0 \leq 55$, the PAF should not be used any more, whereas the FAF and the SAF may still depict the laser field adequately for $50 \leq kw_0 \leq 55$, and the PAF should not be used any more. Whereas for very tightly focused laser beams $kw_0 < 50$, one has to utilize seventh-order or higher order corrections to describe more accurately the field of a Gaussian beam.

It should be emphasized that the above judgments depend critically on the criterion chosen. The criterion we adopted to judge the applicability of a corrected field is by comparing its prediction with that by a higher order corrected field. We consider a corrected field applicable if there is less than 5% discrepancy in quantitative comparisons for individual cases.

The domain of the initial momentum of CAS electron had been studied about LP field in our previous work. We necessary extend to explore the domain of CAS in CP field now. Figs. 5 and 6 show the momentum range of two kind fields. Fig. 5 shows the required momentum range as function of beam width w_0. The shaded area presents the optimum incident momentum range. Obviously, those ranges are strongly dependent on the laser beam width. These features can be understood by noting that in order to inject electrons into the CAS acceleration channel and trap these electrons in the acceleration phase, the electron incident momentum should match the subluminous phase velocity of the laser field in the channel. The phase velocity in the channel can be estimated by

$$\frac{v_{\varphi m}}{c} \sim 1 - \frac{1}{(kw_0)^2},$$

which is strongly related to the laser beam width. Due to the $v_{\varphi m}$ increase along with the beam width being wider, the initial electron momentum should be changing larger so as to catch up with the laser phase velocity $v_{\varphi m}$. Fig. 6 presents the required momentum

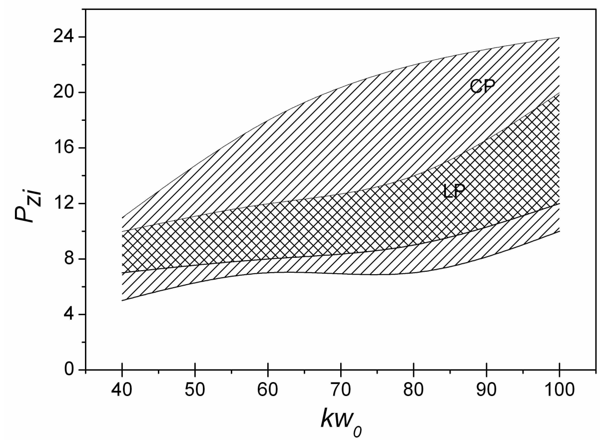

Figure 5: The optimum range of electron incident momentum for the CAS scheme to emerge as a function of beam width kw_0. The laser intensity $a_0 = 10$ and the electron incident angle $\theta_i = \tan^{-1}(0.1)$.

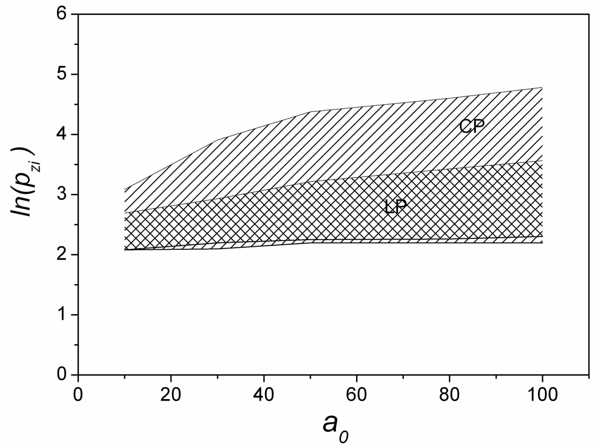

Figure 6: The optimum range of electron incident momentum for the CAS scheme to emerge as a function of the laser intensity a_0. The laser beam width $kw_0 = 60$ and the electron incident angle $\theta_i = \tan^{-1}(0.1)$.

range as function of the laser intensity. The larger the intensity is, the wider the required momentum range becomes. In Figs. 5 and 6, the domain of initial momentum is wider of CP than that of LP. This phenomenon occurs due to difference of the acceleration channel between CP and LP field. The acceleration channel of CP is wider in phase space than that of LP, therefore much more electrons with wider momentum range can get opportunity to enter the channel. In addition, the laser ponder motive potential is larger in CP field than that of in LP field at the same laser intensity a_0, so the top initial momentum curve is higher in CP field than that of in LP field.

4 Conclusions

In summary, the symmetric high-order corrected field equations (up to seventh order in terms of small dimensionless parameter $s=1/kw_0$) for tightly-focused circularly polarized Gaussian laser field have been derived. These fields not only describe accurately the laser, but also are useful for theoretical investigations and simulations as well. It is confirmed that the CAS phenomenon can be observed in high-order correction CP fields as well as in high-order correction LP fields with similar properties. When laser intensity at $a_0\sim 10$, greater acceleration efficiency of acceleration in CP fields than in LP fields. By comparing the electron dynamics features obtained with the results calculated with the PAF, FAF and SAF models, we found that the correction in $s=1/kw_0$ must be taken into account in a tightly focused Gaussian laser beam. The domains in which the three models can be applied have been investigated. The ranges of initial momentum in CP fields are also researched. These studies are significance in designing laser accelerator.

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