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Optimized laser vacuum acceleration by static magnetic field

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Abstract

Laser vacuum acceleration can be optimized significantly by applying a static magnetic field which is along the direction of laser magnetic field. This setup can cause a charged particle to be of a periodic, oscillatory-rising velocity, and significantly high kinetic energy. Moreover, the contribution from the motion vertical to accelerating electric field is fully taken into account and is found to be essential to efficient acceleration.

Keywords: Laser; Vacuum acceleration; Static magnetic field

1. INTRODUCTION

Direct vacuum acceleration of charged particle by laser (Brown & Kibble, 1964; Sarachik & Schappert, 1970; Hussein *et al.*, 1992; Haaland, 1995; Moore *et al.*, 1995; Malka *et al.*, 1997; Salamin & Keitel, 2000) is an issue of broad interest (Bochove *et al.*, 1992; Hauser *et al.*, 1994; Ho & Feng, 1994; Ho *et al.*, 1996; Hussein & Pato, 1992; Korobkin *et al.*, 2013; McDonald, 1998; Mora & Quesnel, 1998; Mori & Katsouleas, 1992; Salamin *et al.*, 2003; 1999; Wang *et al.*, 2002) and marked application value. Strict three-dimensional (3D) single-body dynamics determines that a laser will drive a charged particle to be of time-periodic velocity (Scheid & Hora, 1989; Goreslavsky *et al.*, 1995). Therefore, the acceleration is often attributed to incomplete laser cycle experienced by the charged particle (Kawata *et al.*, 1991; Hussein *et al.*, 1992; Rau *et al.*, 1997). In this time-periodic motion, charged particle's energy (denoted as relativistic factor Γ) oscillates between a range whose minimum is usually 1 and maximum Γ_{max} is usually proportional to laser strength (or its peak vector potential A_{max}). When experiencing incomplete laser cycle, a charged particle can leave the laser with an escape energy Γ_{esc}, which is $\leqslant\Gamma_{max}$ but is possible to be >1. Clearly, larger Γ_{max} can allow larger Γ_{esc}.

Therefore, people's attention are focused on the acceleration by higher A_{max} and hence plasma-based acceleration (Esarey *et al.*, 1996; 2009; Yin *et al.*, 2006; Flippo *et al.*, 2007). In contrast, how to upgrade the efficiency of the acceleration, that is, to obtain higher ratio between Γ_{max} and the electromagnetic energy density of the laser (which is proportional to A_{max}^2), receives little attention. If we confine ourselves in time-periodic motion, then the main route of optimizing acceleration will be enhancing A_{max}

We are interested in how to obtain Γ_{max} as high as possible from a given value of the electromagnetic energy density. Time-monotonic motion/velocity is the most desirable to any acceleration scheme. If it is too expensive to establish such a time-monotonic motion, to achieve a combination of time-periodic motion and time-monotonic one is a realistic replacement. Because time-monotonic motion can be driven by the static field, this enlightens us to attention the combination of a laser and a static field.

In a previous work (Lin *et al.*, 2014), we have demonstrated the advantage of multiple stimuli over single stimulus in laser direct vacuum acceleration and found that applying a static electric field can effectively optimize the acceleration. Beside applying a static electric field, whether or not we can optimize the acceleration with other methods, such as applying a static magnetic field, is worthy of investigation. This will be helpful for us to choose the best among different possible methods of optimizing the acceleration.

Many authors have been aware that static magnetic field can ameliorate not only laser wakefield acceleration (Tsakiris *et al.*, 2000; Hur *et al.*, 2008; Vieira *et al.*, 2012) but also vacuum laser acceleration (Apollonov *et al.*, 1990; Singh, 2004; Huang *et al.*, 2007). But for the vacuum laser acceleration, there is a realistic question on the laser electric field. That is, when laser power is dependent on longitudinal coordinate, whether or not the laser electric field have a longitudinal component in order to fulfill Gauss law $\nabla\cdot E_{laser} = 0$.

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Some authors (Singh, 2004) do not take into account this longitudinal laser electric field but the laser electric field they considered violates $\nabla\cdot E_{\text{laser}} = 0$. Some authors (Huang *et al.*, 2007) remedy this inconsistency by introducing a longitudinal component. Exact detailed mathematical form of the laser electric field in vacuum is a profound issue. Here, we put aside the discussion on whether or not the longitudinal component should be introduced and only study the case where the laser electric field is a pure transverse vector (i.e., no longitudinal component). Such a pure transverse field model on the electric field of laser in vacuum is familiar to the physical community. What have been studied by some authors (Apollonov *et al.*, 1990) is just toward this most familiar case but these authors merely proposed approximation treatment, which might lead to in accurate estimation on the acceleration. Actually, stricter theory is not difficult to be obtained.

Here, we study a compound field setup which contains a linear polarized laser beam and a static magnetic field along the direction of laser magnetic field. Clearly, such a compound field is a pure transverse field. In some theories (Esarey *et al.*, 1995*a*; 1995*b*; Hartemann *et al.*, 1995; 1998; Bochove *et al.*, 1992; Hauser *et al.*, 1994; Ho & Feng, 1994; Ho *et al.*, 1996; Hussein & Pato, 1992; Korobkin *et al.*, 2013; McDonald, 1998; Mora & Quesnel, 1998; Mori & Katsouleas, 1992; Salamin *et al.*, 2003; 1999; Wang *et al.*, 2002) the longitudinal electric field laser of a laser (due to Gauss law $\nabla\cdot\vec{E}_{\text{laser}} = 0$) plays an essential effect in acceleration. If no longitudinal field exists, whether or not significant acceleration can occur is a very worthy question. Moreover, because of the relation $d_t\Gamma = \vec{E}\cdot\vec{\upsilon} = E\upsilon_{\parallel}$ ($\vec{\upsilon}$ is the particle velocity and $\upsilon_{\parallel}$ is its component parallel to $\vec{E}$), we often stress the importance of a high-amplitude E to high Γ. Because Γ also depends on $\upsilon_{\perp}$, the component of $\vec{\upsilon}$ vertical to $\vec{E}$, what is reflected by the relation $d_t\Gamma = \vec{E}\cdot\vec{\upsilon} = E\upsilon_{\parallel}$ is merely a relation between $d_t\Gamma$ and E when $d_t\upsilon_{\perp}\equiv 0$ (Lin *et al.*, 2014). Detailed comment will be presented latter. How to fully explore the contribution of $\upsilon_{\perp}^2$ to Γ might be worthy to be studied.

2. THEORY AND RESULTS

Now we study the single-body dynamics of charged particle in a compound field: a static magnetic field $BS_y = BS$ (where BS is a constant) and a laser [$E_x = E_{\text{m}}\sin(kz-\omega t)$, $B_y = B_{\text{m}}\sin(kz-\omega t)$]. Here, the laser propagates in vacuum and hence meets two relations: $E_{\text{m}} = cB_{\text{m}}$ and $\omega = kc$. Dimensionless 3D relativistic Newton equation set (RNEs) read

$$d_s\left[\Gamma d_s\frac{y}{\lambda}\right] = 0, \tag{1}$$

$$d_s\left[\Gamma d_s\frac{z}{\lambda}\right] = -\frac{\omega_{\text{B}}}{\omega}d_s\frac{x}{\lambda}*\sin\theta - \frac{\omega_{\text{D}}}{\omega}d_s\frac{x}{\lambda}, \tag{2}$$

$$d_s\left[\Gamma d_s\frac{x}{\lambda}\right] = -\frac{\omega_{\text{B}}}{\omega}\left[1-d_s\frac{z}{\lambda}\right]*\sin\theta + \frac{\omega_{\text{D}}}{\omega}d_s\frac{z}{\lambda}, \tag{3}$$

where $\lambda = 2\pi(c/\omega)$, $\theta = [(z-ct)/\lambda]^*2\pi$, $s = \omega t$, $\omega_{\text{B}} = (eB_{\text{m}}/m_{\text{e}})$, and $\omega_{\text{D}} = (eBS/m_{\text{e}})$. Same equation set [Eq. (8) in Apollonov *et al.*, 1990], had been studied by perturbation theory, and approximation solutions for cases in which the laser magnetic field is far weaker relatively to the static magnetic field (i.e., cases of $\omega_{\text{B}} = \omega_{\text{D}}$), had been found. Here, their work (Apollonov *et al.*, 1990) is improved by a non-perturbation method of finding strict solutions of Eqs. (1)–(3), which are applicable to cases of arbitrary values of (ω_{B}, ω_{D}).

Equations (1) and (3) will yield

$$\Gamma d_s\frac{y}{\lambda} = 0, \tag{4}$$

$$\Gamma d_s\frac{x}{\lambda} + \frac{\omega_{\text{B}}}{\omega}*\cos\theta - \frac{\omega_{\text{D}}}{\omega}*(\theta+1) = \text{constant} = \frac{\omega_{\text{B}}}{\omega} - \frac{\omega_{\text{D}}}{\omega}. \tag{5}$$

Here, the value of *constant* in Eq. (5) is determined by the initial condition (at $t = 0$, there are $d_s\,(x/\lambda) = 0$, $\Gamma = 1$, and $\theta = 0$), and hence Eq. (5) can be re-written as

$$\Gamma d_s\frac{x}{\lambda} = \frac{\omega_{\text{B}}}{\omega}*2\sin^2\left(\frac{\theta}{2}\right) + \frac{\omega_D}{\omega}\theta. \tag{6}$$

Due to the definition $1/\Gamma = \sqrt{1-(d_s[x/\lambda])^2-(d_s[y/\lambda])^2-(d_s[z/\lambda])^2}$, Eqs. (4) and (6) will yield

$$\left(d_s\frac{x}{\lambda}\right)^2 = \frac{([\omega_{\text{B}}/\omega]*2\sin^2(\theta/2)+(\omega_{\text{D}}/\omega)\theta)^2}{[1+([\omega_{\text{B}}/\omega]*2\sin^2(\theta/2)+(\omega_{\text{D}}/\omega)\theta)^2]}*\left[1-\left(d_s\frac{z}{\lambda}\right)^2\right]. \tag{7}$$

For convenience in expressing formulas, we introduce symbols

$$\Delta = \sqrt{1+\left(\frac{\omega_{\text{B}}}{\omega}*2\sin^2\left(\frac{\theta}{2}\right)+\frac{\omega_{\text{D}}}{\omega}\theta\right)^2}; \tag{8}$$

$$M = \sqrt{1-\left(d_s\frac{z}{\lambda}\right)^2} = \sqrt{-2*d_s\theta-(d_s\theta)^2}, \tag{9}$$

and hence Eq. (7) imply

$$\Gamma = \frac{\Delta}{M}. \tag{10}$$

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Thus, Eq. (2) is re-written as

$$d_s\left[\Delta\sqrt{\frac{1}{M^2}-1}\right]=-\frac{\omega_B}{\omega}*\frac{([\omega_B/\omega]*2\sin^2(\theta/2)+[\omega_B/\omega]\theta)}{\Delta}M*\sin\theta - \frac{\omega_D}{\omega}*\frac{([\omega_B/\omega]*2\sin^2(\theta/2)+[\omega_B/\omega]\theta)}{\Delta}M. \tag{11}$$

From definitions Eqs. (8) and (9), we have

$$d_s\Delta=\frac{\begin{array}{c}4(-[\omega_B/\omega])^2(\sin^3[\theta/2]\cos[\theta/2])d_s\theta \\ +4([\omega_B\omega_D]/\omega^2)(\sin[\theta/2]\cos[\theta/2])\theta d_s\theta \\ +4([\omega_B\omega_D]/\omega^2)(\sin^2[\theta/2])\theta d_s\theta+2(\omega_B/\omega)^2\theta d_s\theta\end{array}}{\Delta}; \tag{12}$$

$$d_sM=-\frac{(1+d_s\theta)}{M}d_{ss}\theta, \tag{13}$$

and re-write Eq. (11) as

$$\begin{aligned}&\frac{\begin{array}{c}4(-[\omega_B/\omega])^2(\sin^3[\theta/2]\cos[\theta/2])d_s\theta \\ +4([\omega_B\omega_D]/\omega^2)(\sin[\theta/2]\cos[\theta/2])\theta d_s\theta \\ +4([\omega_B\omega_D]/\omega^2)\left(\sin^2[\theta/2]\right)\theta d_s\theta+2(\omega_B/\omega)^2\theta d_s\theta\end{array}}{\Delta} \\ &+\Delta\frac{(1+d_s\theta)}{M^2(1-M^2)}d_{ss}\theta \\ &=-\frac{\omega_B}{\omega}*\frac{(-[\omega_B/\omega]*2\sin^2[\theta/2]+[\omega_D/\omega]\theta)}{\Delta}\frac{M^2}{\sqrt{1-M^2}}*\sin\theta \\ &-\frac{\omega_D}{\omega}*\frac{(-[\omega_B/\omega]*2\sin^2[\theta/2]+[\omega_D/\omega]\theta)}{\Delta}\frac{M^2}{\sqrt{1-M^2}}.\end{aligned} \tag{14}$$

We denote the direction of electric field as $\overrightarrow{e_\parallel}$ and the direction vertical to electric field as $\overrightarrow{e_\perp}$. Clearly, the contribution from the motion along $\overrightarrow{e_\perp}$ to Γ_{max} is not clear enough. The formula $d_t\Gamma = E\cdot\upsilon$ reflects that the dependence of Γ on $\upsilon_\parallel$. Because Γ depends on both $\upsilon_\parallel$ and $\upsilon_\perp$, this formula reflects the relation between Γ and $\upsilon_\parallel$ when $\upsilon_\perp$ is given and hence should be denoted more strictly as $d_t\Gamma|_{d_t\upsilon_\perp=0} = E\cdot\upsilon$ (Lin *et al.*, 2014). Namely, we can always obtain $d_t\Gamma = E\cdot\upsilon$ from RNEs if $d_t\upsilon_\perp = 0$. Clearly, once $d_t\upsilon_\perp = 0$ cannot be warranted, $\Gamma(t)$, which should be equal to $\Gamma(0)+\int d_t\Gamma|_{d_t\upsilon_\perp=0}dt+\int d_t\Gamma|_{d_t\upsilon_\parallel=0}dt$, might be different from $\Gamma(0)+\int E\cdot\upsilon\,dt$. (Lin *et al.*, 2014).

The 3D RNEs is ultimately reduced to Eq. (14), a second-order differential equation of $z=\int\upsilon_\perp\,dt$. All related quantities can be calculated from this equation. In this compound field setup, due to the static magnetic field, the motion of a charged particle is no longer periodic even though the laser is a periodic stimulus. As shown in Figure 1, Γ rises with respect to t in an oscillatory manner. If no static magnetic field is applied, that is, $\omega_D/\omega = 0$, Γ will periodically oscillate between 1 and a time-independent Γ_{max}, and $\Gamma_{max}-1$ is proportional to $\omega_B/\omega = (eA_{max}/mc^2)$ (Scheid & Hora, 1989; Goreslavsky *et al.*, 1995; Lin *et al.*, 2013). If $(\omega_D/\omega) \ll \omega_B/\omega$, Γ will do nearly periodical oscillation. Likewise, if no laser is applied that is, $\omega_B/\omega = 0$, Γ will be independent of t. Clearly, the oscillatory rising, which is a combination of periodic behavior and monotonic one, reflects combined effect of the laser and the static magnetic field.

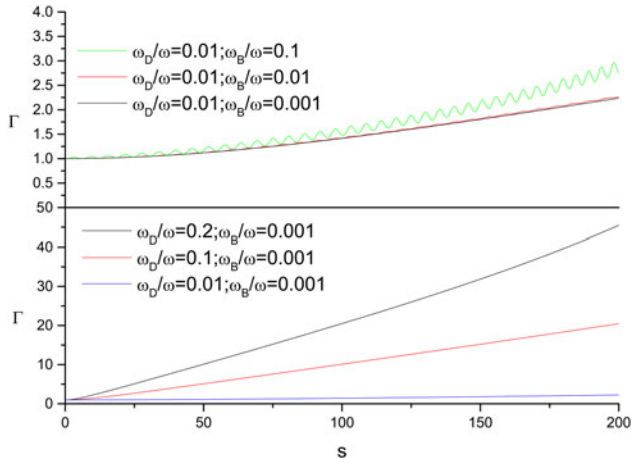


Fig. 1. Examples of time history of Γ.

Because the electromagnetic energy density is $\sim(\omega_B/\omega)^2$, the energy density of a laser beam of $(\omega_B/\omega) = \sqrt{2}a$ will be equal to the summation of those of two laser beams of $\omega_B/\omega = a$. For two cases with nearly same energy density that is $(\omega_D/\omega,\ \omega_B/\omega) = (0,\ 0.15)$ and $(\omega_D/\omega,\ \omega_B/\omega) = (0.1,\ 0.1)$ (here because of $\sqrt{2} = 1.414\sim1.5$, we approximate 0.15 as $0.1*\sqrt{2}$), so obvious contrast shown in Figure 2 well illustrate the advantage of multiple stimuli over single stimulus in acceleration. More interest, high Γ_{max} is mainly contributed by high $\upsilon_\perp^2$ instead of $\upsilon_\parallel^2$. As shown in Figure 3, $d_s\theta$, which is just dimensionless $\upsilon_\perp$ subtracting 1, obviously differs from -1. This implies that $\upsilon_\perp$ obviously differs from 0 and hence have marked contribution to high Γ_{max}-value. Here, we should also note that if $\omega_B/\omega = 0$, there will be always $\upsilon_\perp = 0$. Namely, the laser is necessary for ensuring $\upsilon_\perp \neq 0$.

According to strict theories (Scheid & Hora, 1989; Goreslavsky *et al.*, 1995), the laser enables particle's velocity to be periodic. The periodicity limits Γ to be $\leqslant\Gamma_{max}$ whose value is determined by laser strength E_{max}. Usually people choose to increase Γ_{max} by enhancing E_{max} under same setup (i.e., a single laser beam). Above results have shown that trying different setups might be more effective to find better acceleration scheme. The compound field setup described above has clearly illustrated a typical example of better acceleration. In short, how to harness the motion vertical to the electric field is a worthy issue for ensuring higher Γ_{max}. Because of the formula $d_t\Gamma = E\cdot\upsilon$, the importance of $\upsilon_\perp^2$ to higher Γ_{max} has been underestimated greatly.

A simple estimation can illustrate the effect of $\upsilon_\perp^2$ to Γ_{max}. According to Eq. (7), if $\omega_D/\omega = 0$ and $\upsilon_\perp^2 \equiv 0$ exist, there will be

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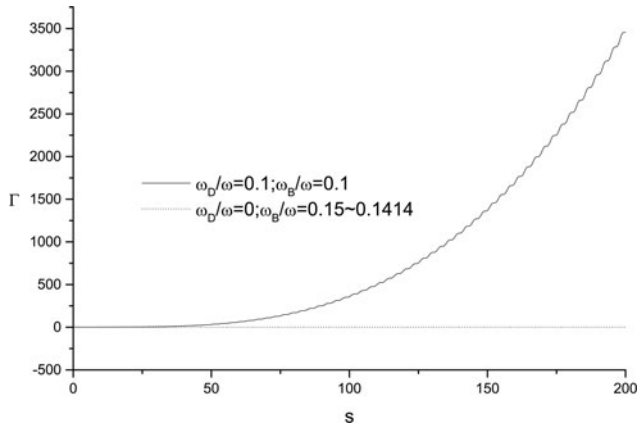


Fig. 2. Examples of time history of Γ.

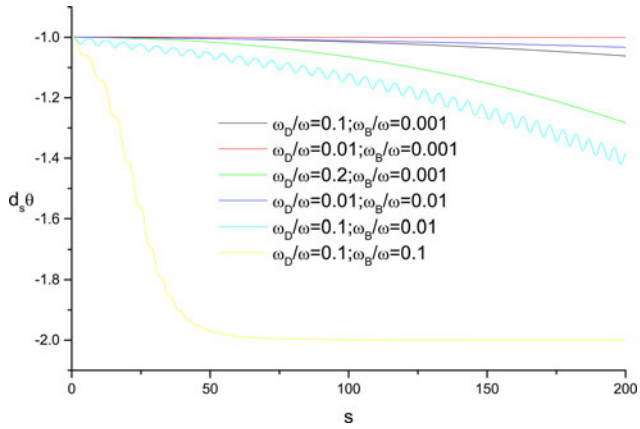


Fig. 3. Examples of time history of $d_s\theta$.

$\Gamma=1/\sqrt{1-(d_s[x/\lambda])^2}=\sqrt{1+(-[\omega_B/\omega]*2\sin^2[\theta/2])^2}$, which can also be derived from $d_s[1/\sqrt{1-(d_s[x/\lambda])^2}]=[\omega_B/\omega]\sin\theta*d_s[x/\lambda]$. In contrast, if $\omega_D/\omega=0$ exists but $\upsilon_\perp^2\equiv 0$ not, Eq. (7) will yield

$$\begin{aligned}\Gamma &= 1/\sqrt{1-\left(d_s\frac{x}{\lambda}\right)^2-\left(d_s\frac{z}{\lambda}\right)^2}\\ &= \sqrt{1+\left(-\frac{\omega_B}{\omega}*2\sin^2\left(\frac{\theta}{2}\right)\right)^2}/\sqrt{1-\left(d_s\frac{z}{\lambda}\right)^2}\\ &> \sqrt{1+\left(-\frac{\omega_B}{\omega}*2\sin^2\left(\frac{\theta}{2}\right)\right)^2}\end{aligned}$$

The > well illustrates the underestimation of Γ, if $\upsilon_\perp^2\equiv 0$ is taken for granted.

Moreover, strict solution in the $\omega_D/\omega=0$ case can be described by a first integral and hence is a periodic function of s. In contrast, Eq. (14) does not have periodic solutions.

3. SUMMARY

A recent work has suggested the advantage of multiple stimuli over single stimulus in laser direct vacuum acceleration (Lin *et al.*, 2014). Because a single stimulus will lead to time-periodic motion of charged particle, our effort for better acceleration is to avoid such a time-periodic motion but instead aimed at obtaining a time-aperiodic motion which is a combination of time-periodic behavior and time-monotonic one. The more the time-monotonic behavior is, the better the acceleration is. The physics basis of our acceleration optimization scheme is to fully harness potential contribution of $\upsilon_\perp^2$ to the increment of Γ. Actually, the increment of Γ is not independent of magnetic field B but instead is complicatedly affected by B through $\upsilon_\perp^2$.

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