Comment on "Electron acceleration by an intense short pulse laser in a static magnetic field in vacuum"

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K. P. Singh [Phys. Rev. E **69**, 056410 (2004)] put forward a scheme of vacuum laser acceleration in a static magnetic field. We point out that one of the assumptions used in their model does not stand on a solid physical ground and that it seriously influences electrons to obtain net energy gains from the laser field.

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To accelerate electrons by intense laser in vacuum, many schemes have been put forward, but it is hard to retain the electrons with high energy after leaving the laser field because of the quick phase slippage. Static magnetic field is always used to tow electrons out of the laser field before entering the deceleration phase. Recently, Singh put forward a novel scheme of static magnetic field [1]. In his paper, Singh's analysis and simulation results show that if an optimum static magnetic field in the same direction as the magnetic field of the laser pulse is externally applied during the trailing part of the pulse, the electron can gain and retain significant energy in the form of cyclotron oscillations even after the passing of the laser pulse. Before this, Salamin and Keitel [2] put forward a vacuum laser acceleration scheme and considered a static magnetic field being located well past the focus and merely serving to bend the electrons out of the laser path so that they do not give back some of their energy to it. The static magnetic field does not participate in the acceleration process. Wang *et al.* [3] put forward a similar scheme without static magnetic field and they did not include a magnetic field in their analysis. What is more, those authors emphasize that using a tightly focused laser beam makes it necessary to consider diffractive effects up to fifth order to get accurate results. We would like to point out that the laser spot size in Singh's paper and in the Comment is safely larger than the radius that Salamin and Keitel identified as the limit below which fifth-order terms must be included in the analysis. So we limit our analysis to first-order terms in the optical potential.

However, the field form taken by Singh does not satisfy the free-space Maxwell equation $\nabla \cdot \mathbf{E}=0$. This can hardly make others believe his conclusions [4]. If we consider the other component based on the field form he supposed and make $\nabla \cdot \mathbf{E}=0$, the relation formula obtained by Singh will fail. Three-dimensional (3D) simulation results with other the component considered are also far away from Singh's. The outgoing energy is very sensitive to the initial phase when the laser intensity is strong enough. The initial phase of the laser field may have been taken into account in his model. Without losing generality, Singh's vector potential of a laser pulse can be expressed as

$$\mathbf{A}_L = \hat{x} A_0 \exp\left\{-\left[\frac{ct-(z-z_L)}{c\tau}\right]^2 - \frac{r^2}{2r_0^2}\right\}\exp(i\omega t - ikz + i\phi_0), \tag{1}$$

where ϕ_0 is the initial phase, and other signs are same as those in Singh's paper. We would like to point out that Singh's vector potential does not satisfy the Coulombic gauge because $\nabla \cdot \mathbf{A}_L \neq 0$, nor does it satisfy the Lorentzian gauge because he set the scalar potential to $\Phi=0$. If the Lorentz gauge is used, then there is no problem for $A_y=A_z=0$, but the scalar potential Φ must not be zero. For a linearly polarized pulsed laser beam, the scalar potential of a laser pulse can be assumed as the form [3]

$$\Phi = A_0 \Lambda(x,y,z)\exp\left\{-\left[\frac{ct-(z-z_L)}{c\tau}\right]^2\right\}\exp(i\omega t - ikz + i\phi_0), \tag{2}$$

where $\Lambda(x,y,z)$ is an undetermined time-independent function. Substituting $\mathbf{A}$ and Φ to the Lorentz gauge,

$$\nabla \cdot \mathbf{A} + \frac{1}{c^2}\frac{\partial \Phi}{\partial t} = 0, \tag{3}$$

we can get

$$\Lambda(x,y,z) = \frac{\left(\dfrac{cx}{r_0^2}\right)\exp[-r^2/(2r_0^2)]}{ik - 2[ct-(z-z_L)]/(c\tau)^2}. \tag{4}$$

The corresponding electric and magnetic components can be obtained from $\mathbf{E}=-\partial \mathbf{A}/\partial t - \nabla \Phi$ and $\mathbf{B}=\nabla \times \mathbf{A}$ [3].

Thus, the relationship Eqs. (9) and (10) obtained by Singh [1] does not stand if the longitudinal field components are considered. It is meaningless to study the dynamics of electrons by using these two equations. We used 3D test particle simulations to study the electron dynamics in the laser field. The equations governing electron momentum and energy are [2]

$$\frac{d\mathbf{P}}{dt} = -e(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}), \tag{5}$$

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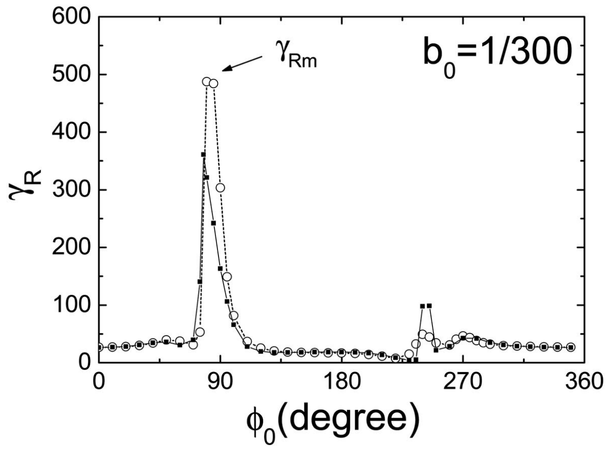

FIG. 1. Retained energy γ_R as a function of the field initial phase ϕ_0, where $1/b_0=300$, $a_0=5$, $\gamma_0=3$, $r_0=85$, $\tau=25$, $z_L=-50$, and $z_m=3200$. The dotted line is for Singh's model and the solid line for our 3D simulation results.

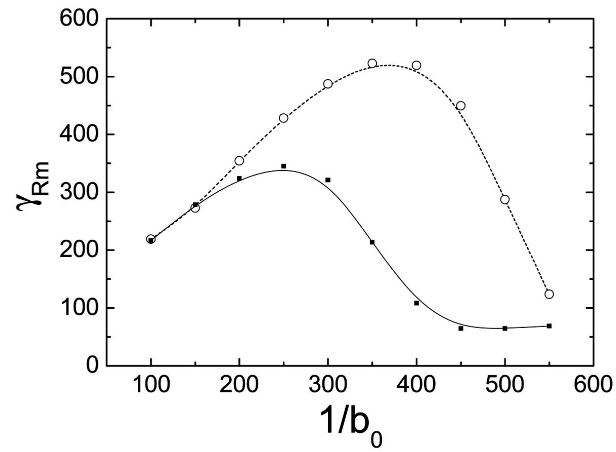

FIG. 2. Maximum retained energy γ_{Rm} as a function of $1/b_0$ for Singh's model (dotted line) and our 3D simulation results (solid line). The parameters are same as those in Fig. 1.

$$\frac{d\wp}{dt} = -e\boldsymbol{\beta}\cdot\mathbf{E}, \tag{6}$$

where $\boldsymbol{\beta}$ is the electron velocity in the unit of c. We used a four-dimensional energy-momentum configuration to specify the electron state $(\wp,\mathbf{P})$, where the momentum $\mathbf{P}=\gamma\boldsymbol{\beta}$ is normalized in the units of m_ec, the energy $\wp=\gamma$ is normalized in the units of m_ec^2, $\gamma=(1-\beta^2)^{-1/2}$ is the Lorentz factor, and m_e is the electron mass. Throughout the paper, time and length are normalized by $1/\omega$ and $1/k$.

Figure 1 shows the retained energy γ_R as a function of the field initial phase ϕ_0, where $1/b_0=300$ and the other parameters are same as those of Fig. 2(a) in Singh's paper, namely, $a_0=5$, $\gamma_0=3$, $r_0=85$, $\tau=25$, $z_L=-50$, and $z_m=3200$. $a_0\equiv eA_0/m_ec$ is a dimensionless parameter specifying the magnitude of field intensities. The solid line is for our 3D simulation results and the dotted line for that of Singh's model, which neglects the longitudinal field component. We can find that the retained energy γ_R is very sensitive to ϕ_0, and the range which induces high energy gain is very narrow.

Figure 2 shows the maximum retained energy γ_{Rm} as a function of $1/b_0$, where γ_{Rm} is the maximum γ_R when ϕ_0 varies in the whole phase range $\phi_0\in[0,2\pi]$. The parameters are same as those of Fig. 2(a) in Singh's paper. The solid line is for our 3D simulation results and the dotted line for that of Singh's model. We can find that the longitudinal field component induces a large difference between these two models. This component is very important and cannot be ignored though it is a relative small quantity.

Finally, we would like to mention that such a plane-wave-like pulse is only an ideal model of the realistic fields, but it is neither a solution of the wave equation nor the paraxial equation. To study what will happen when an electron is driven by a focused laser beam, the diffraction effect should be included. Furthermore, to construct a theoretic optical field must be based on Maxwell equations and one cannot assume its form as one likes. On the other hand, we admit that the method in the original article by Singh is a good one because the electrons can gain considerable net energy in simulation even using this scheme with the fifth-order-corrected laser field equations of a focused laser beam.

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