Comment on "Experimental Observation of Electrons Accelerated in Vacuum to Relativistic Energies by a High-Intensity Laser"

Malka *et al.* have recently reported the observation of MeV electrons accelerated by a high-intensity subpicosecond laser pulse [1]. Their theoretical interpretation is based on the computation of the trajectories of individual electrons in the field of a linearly polarized electromagnetic wave at focus, described within the paraxial approximation. This leads them to the conclusion that *the scattering will occur only in the* $(\mathbf{E}, \mathbf{k})$ *plane*. They affirm also that at relativistic irradiance, the standard small-amplitude approximation that leads to the concept of ponderomotive scattering can no longer be made.

In this Comment we show the following.

(i) To correctly describe the electron acceleration, it is necessary to take into account the longitudinal components of the fields (essentially the B_x component), which are of order $\epsilon = \lambda_0/w_0$, where λ_0 is the laser wavelength and w_0 the beam waist at focus.

(ii) With this correction, the acceleration is no longer limited in the $(\mathbf{E}, \mathbf{k})$ plane, but occurs almost symmetrically around the laser propagation direction.

(iii) This acceleration is perfectly well described, in the regime of parameters of [1], by the concept of ponderomotive force generalized to the relativistic regime [2,3].

To reach these conclusions, we computed the particle trajectories using three different models based on the following: (1) the paraxial approximation of the fields as Malka *et al.* [1]. We verified that we recovered the same results (in particular their Fig. 3); (2) idem with the inclusion of the longitudinal component of the fields [4]; (3) the relativistic ponderomotive force [3], i.e., the equations $d\mathbf{r}/dt = \mathbf{p}/m\gamma$, $d\mathbf{p}/dt = -mc^2\nabla\gamma$, where $\gamma = (1 + \frac{1}{2}a^2 + p^2/m^2c^2)^{1/2}$, $a = eE/m\omega_0 c$ is the dimensionless field strength parameter, and where $\mathbf{r}$, $\mathbf{p}$, and γ are averaged over the fast time scale.

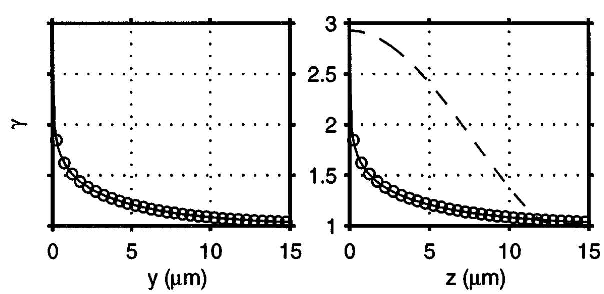

FIG. 1. Final energies of the scattered electrons as a function of their initial transverse position. The $\mathbf{E}$ field is along the y axis. Electrons have an initial longitudinal position $x_0 = -160$ μm and a velocity $v_{0x} = 0.2c$. Other parameters are as in Fig. 3 of Ref. [1]. Dashed line: fields as in Ref. [1]. Solid line: first order correction added. Circles: ponderomotive computation. All three curves coincide on the left part.

Typical results are given in Fig. 1, which shows the final Lorentz factor of electrons moving initially along $\mathbf{k}$ as a function of their initial transverse position, situated either on the y axis (parallel to $\mathbf{E}$) or on the z axis (perpendicular to $\mathbf{E}$). While model 1 correctly predicts the acceleration of the electrons initially on the y axis, it leads to completely wrong results for the electrons initially out of this axis. Moreover, it predicts that the acceleration occurs only in the $(\mathbf{E}, \mathbf{k})$ plane, whereas the second model demonstrates that the scattering is essentially isotropic and purely radial, as also predicted by the ponderomotive model (independent of the polarization). This point is illustrated in Fig. 2, which shows a comparison between the trajectories computed from the second model and from the ponderomotive equations for an off axis electron: as easily seen, the concept of relativistic ponderomotive force is perfectly valid in this regime of parameters. The reason why the first order B_x term has to be kept is that the transverse force $v_y B_x$ has a nonvanishing average, so that it plays in the z direction the same role as the gradient of E_y in the y direction. This is already true in the nonrelativistic regime.

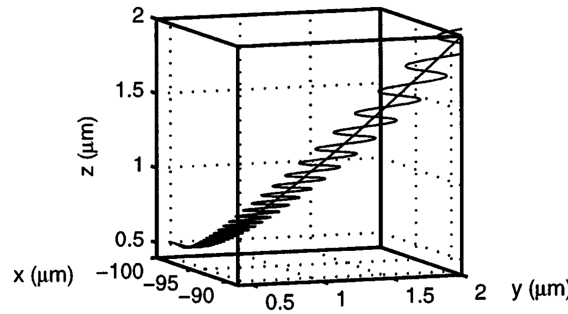

FIG. 2. Sample trajectory of an electron at initial position $x_0 = -100$ μm, $y_0 = z_0 = 0.5$ μm. Other parameters as in Fig. 1.

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