Inverse-Bremsstrahlung Electron Acceleration

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A single-particle computation, simple analysis, and a particle simulation show that energy gain of an electron in a vacuum is possible using a laser and a weak perpendicular static electric field ($E_{\rm app}$). This simple system does not need any structure to accelerate the electron. If $E_{\rm app}=0$, an electron will just oscillate, with no net acceleration, because of the symmetry of the laser's electromagnetic wave in space and time. The static electric field breaks the symmetry of the wave so that the electron is accelerated in both half wavelengths of the wave.

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Various new ideas for particle accelerators with plasma or without plasma have been proposed[1-17] in order to break through the limitation of the acceleration gradient of the current linear accelerators. Laser accelerators[15-17] without plasma and any structure use a strong laser field directly for the particle acceleration and are free from the ambiguity or difficulty of plasma control. In this paper, we present a new mechanism for electron acceleration using a laser and a weak perpendicular static electric field. This means that a plane electromagnetic (EM) wave travels across a static electric field. If the system has no static electric field, the electron just oscillates, with no net acceleration: When a laser wave passes through an electron by a half wavelength, the electron can absorb laser energy. However, in the remaining half wavelength, the electron loses the energy gained. As a result, the electron cannot be accelerated. This is a result of the symmetry of the EM wave in space and time. Our idea is to remove this symmetry by applying a static electric field $E_{\rm app}$ so that the electron is accelerated in both half wavelengths of the wave. Previously we proposed another mechanism[16,17] for electron acceleration using a laser and a perpendicular static magnetic field, which also has the role of removing this wave symmetry. This paper proposes a new mechanism using a laser and a static electric field, under a similar idea.

Figure 1 shows the mechanism proposed for electron acceleration. A plane EM wave propagates at the speed of light c in the $+x$ direction. The magnetic component (B_z) of the wave is in the x-z plane and the electric one (E_y) is in the x-y plane. The static electric field ($E_{\rm app}$) is applied in the $+y$ direction. The electron speed is less than c. Therefore the EM wave propagating with c in a vacuum catches up with the electron and leaves it behind. The electron equation of motion and the energy equation are

$$dP_x/dt=F_x=-e\beta_y B_z=-e\beta_y E_y\,,$$
$$dP_y/dt=F_y=-e[(E_y+E_{\rm app})-\beta_x B_z]$$
$$=-e[(1-\beta_x)E_y+E_{\rm app}]\,,$$

and $d(mc^2\gamma)/dt=-eE_y v_y$. Here $\beta_x=v_x/c$, $\beta_y=v_y/c$, $E_y=B_z=-E_{y0}\sin[k(ct-x)]$, and E_{y0} is the amplitude of the EM wave. From the energy equation, it is clear that the speed v_y parallel to E_y is important for the electron acceleration and v_y is determined by the y component of the above equation of motion. In order to accelerate an electron in both half wavelengths in one period of the laser wave, we choose an appropriate value of $E_{\rm app}$ so that v_y becomes zero at $k(ct-x)\simeq\pi$; this means that in the half wavelength of $0<k(ct-x)<\pi$, $v_y>0$, and in the remaining half wavelength, $v_y<0$. As a result, in the half wavelength of $0<k(ct-x)<\pi$, the electron is accelerated in the $+y$ direction and can absorb wave energy. Then v_y decreases according to the force F_y and becomes zero at $k(ct-x)\simeq\pi$. In the remaining half wavelength the electron has the velocity $v_y<0$ and can again absorb wave energy. In addition, the electron is accelerated in the $+x$ direction by the force $F_x>0$ in both half wavelengths and the interaction between the electron and the EM wave becomes longer. Consequently, the electron can absorb wave energy efficiently by this mechanism.

First, we numerically perform a single-particle analysis in order to demonstrate the viability of this mechanism. In this case the plane EM wave is infinitely

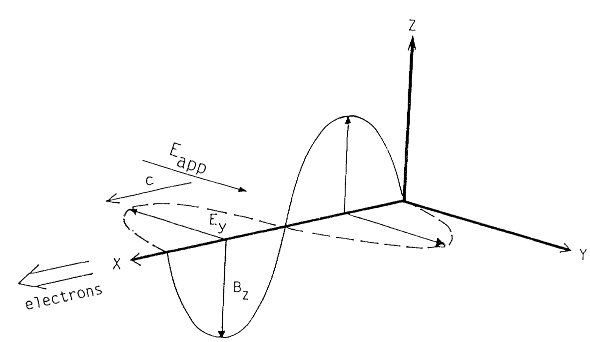

FIG. 1. The system of inverse-bremsstrahlung electron acceleration. The electron is efficiently accelerated in a vacuum by applying a weak static electric field $E_{\rm app}$.

continuous in the x direction. Figure 2 shows electron energy versus time t (solid line). The initial electron speed v_0 is $0.9999c$. The electron has the optimal initial velocity v_{y0} in the $+y$ direction and equivalently the optimal incident angle, that is, 0.608° with respect to the laser axis for this specified case. The amplitude of the EM wave is $E_{y0}=AE_0=0.1E_0$, where $E_0=mc^2/(e\lambda/32)=1.636\times10^7/\lambda$ V/cm, λ is the wavelength in cm, and $E_{\rm app}/E_{y0}=4.28\times10^{-5}$ which is the optimal value of $E_{\rm app}$ for this specified parameter set. It should be noted that the optimal $E_{\rm app}$ is quite small compared with the laser amplitude. The laser power employed is 3.54×10^{15} W/cm^2 for $\lambda=10$ μm. In the figure the time t is normalized by $1.01\times10^6 l_0/c$, that is, the time interval during which the laser passes through the electron by one wavelength, where $l_0=\lambda/32$. Figure 2 shows clearly that the electron is accelerated in both half wavelengths. The final electron energy becomes about 5.91 times as large as the initial energy and the final relativistic factor γ is 418. Here the final values are evaluated at $k(ct-x)=2\pi$. The acceleration gradient is 0.564 GeV/m. (When $E_{\rm app}=0$, the electron can be accelerated only in a half cycle of the wave. In this case γ/γ_0 is 2.64 at the half cycle with the same initial conditions as employed in the above example, except $E_{\rm app}$. Here γ_0 is the initial γ.[18]) Figure 2 also shows an oscillation of γ after the first period because of the effect of the continuous wave field, though the lowest value of γ is rather high compared with the initial γ_0. This fact suggests letting the electrons leave the laser beam appropriately after one period of acceleration. Figure 3 shows an electron trajectory in the x-y coordinates, normalized by $\lambda/32$; it should be noted that the trajectory does not bend much and is rather straight along the x coordinate because of the relativistic speed of the electron.

We also perform a simple analytical estimation for the final γ, the optimal $E_{\rm app}$, and the optimal β_{y0}. By integrating the equation of motion in the y direction, first we find the optimal $E_{\rm app}$ with the condition that v_y should be zero at $k(ct-x)=\pi$ as described above:

$$E_{\rm app}=\frac{E_{y0}\lambda}{\pi c\tau'}+\frac{mc\gamma_0\beta_{y0}}{e\tau'}\equiv\frac{E'_{\rm app0}}{\tau'}\,. \tag{1}$$

Here τ' is the time at $k(ct-x)=\pi$. In order to find the final γ we integrate the energy equation by introducing an effective β_{xe}, which is defined by $\int_0^t(1-\beta_x)dt'=(1-\beta_{xe})t$:[19]

$$\gamma^2\simeq\frac{e^2E_{y0}E_{\rm app}}{\pi m^2c^2}\frac{\lambda\tau}{c(1-\beta_{xe})}-\frac{2eE_{\rm app}}{mc}\left(\gamma_0\beta_{y0}+\frac{eE_{y0}\lambda}{2\pi mc^2}\right)\tau+\frac{e^2E_{\rm app}^2}{m^2c^2}\tau^2+\gamma_0^2\,. \tag{2}$$

Here τ is the time at $k(ct-x)=2\pi$ and can be estimated by $\lambda/c(1-\beta_{xe})$. When we assume $\tau'=\tau/2$ and use Eq. (1), only the first term depends upon τ. Assuming

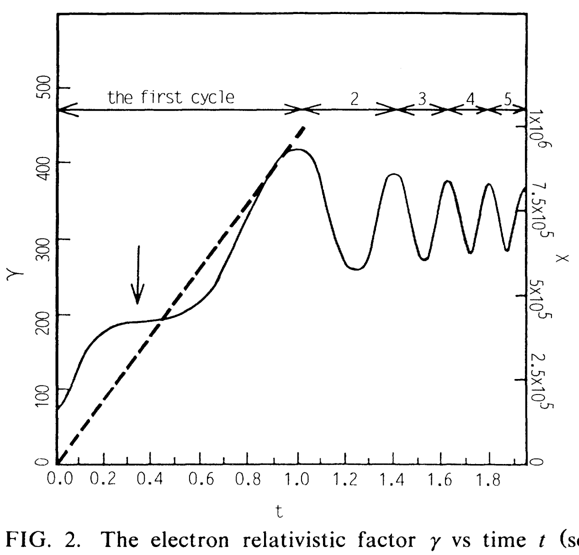

FIG. 2. The electron relativistic factor γ vs time t (solid line) from a numerical single-particle analysis. The electron initial speed is $0.9999c$. An arrow shows the time at which the EM wave passes through the electron by a half wavelength. After the first period, indicated in the upper part in the figure, γ oscillates because of the continuous wave field. However, the electron does not couple so well with the wave field after the first period. Therefore the lowest γ is rather high compared with the initial γ_0 after the first period. This figure suggests letting the electrons leave the wave field after the acceleration. The dashed line shows x (x coordinate of the electron) vs t.

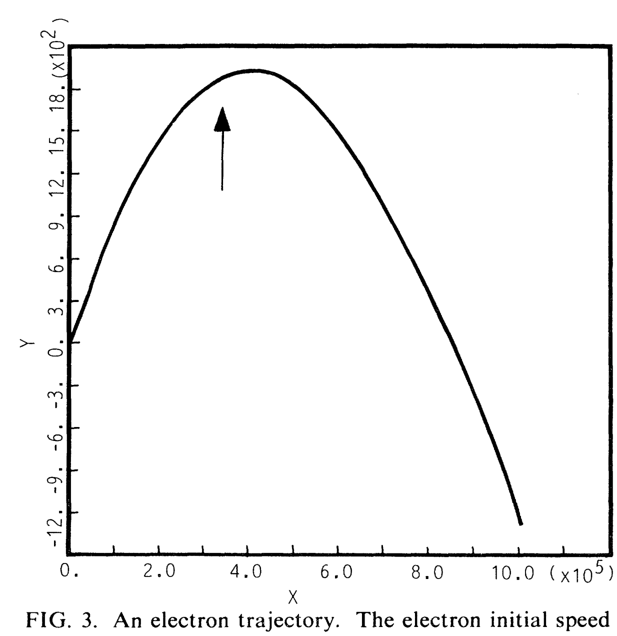

FIG. 3. An electron trajectory. The electron initial speed is $0.9999c$. It should be noted that the electron trajectory does not bend much and is rather straight along the x coordinate because of the relativistic speed of the electron. An arrow shows the time at which the EM wave passes through the electron by a half wavelength.

further $\beta_{xe} \simeq \beta_x$, that is, the final value at $k(ct-x)=2\pi$, and using the relation $1/(1-\beta_x) \simeq 2\gamma^2/(1+\gamma^2\beta_y^2)$, we obtain the following expression:

$$\gamma^2 \simeq \frac{\eta^2 - 2\eta(\gamma_0\beta_{y0} + \alpha/2) + \gamma_0^2}{1-(4\gamma_0\beta_{y0}\alpha + 4\alpha^2)/[1+(\gamma_0\beta_{y0}+2\alpha)^2]} . \quad (3)$$

Here $\alpha = e\lambda E_{y0}/\pi mc^2$ and $\eta = 2eE'_{\text{app}0}/mc$. In deriving (3) we also use the relation $\gamma\beta_y = -\gamma_0\beta_{y0} - 2\alpha$, which is derived from the equation of motion in the y direction with $\tau' = \tau/2$ in a similar way to the integration deriving Eq. (1). In addition, the condition $d\gamma/d\beta_{y0} = 0$ leads to the expression for the optimal β_{y0}, when $\gamma_0 \gg \alpha$, $\gamma_0 \gg 1$, and $\beta_{y0} \ll 1$: $\beta_{y0} \simeq [(1+\alpha^2)^{1/2} - \alpha]/\gamma_0^2$.[20]

Figure 4 shows γ versus the amplitude factor A of the EM wave; the solid line and the dashed line are obtained by single-particle computations for $v_0 = 0.999c$ and $0.99c$, respectively. Circles besides these lines are obtained by the relation (2) and Eq. (1) with $\tau' = \tau/2$, and by the use of the numerical values for τ and β_{y0} obtained by the single-particle computations for $v_0 = 0.999c$ and $0.99c$. In Fig. 4 the crosses show γ estimated by the relation (3) with the expression for the optimal β_{y0}. This figure shows that the analytical estimation can reproduce the general tendency of the numerical results, though there is some discrepancy between the numerical value and the analytical one by the relation (3). We believe that the expressions derived above present the scaling laws for this mechanism.

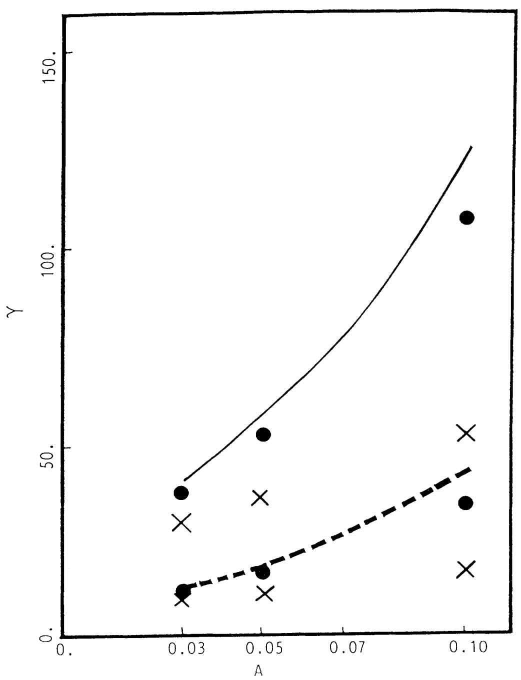

FIG. 4. The final electron relativistic factor γ vs the amplitude factor A of the EM wave. Solid and dashed lines are obtained by results of single-particle computations for $v_0 = 0.999c$ and $v_0 = 0.99c$, respectively. Circles besides these lines are obtained by the relation (2) and Eq. (1) with the assumption $\tau' = \tau/2$, and by the use of the values of τ and β_{y0} obtained by the numerical computations. The values for τ and β_{y0} employed are as follows: For $A = 0.1$, $\tau = 9980$ and $\beta_{y0} = 0.105$ for $v_0 = 0.99c$, and $\tau = 1.01 \times 10^5$ and $\beta_{y0} = 0.0335$ for $v_0 = 0.999c$. For $A = 0.05$, $\tau = 4340$ and $\beta_{y0} = 0.155$ for $v_0 = 0.99c$, and $\tau = 4.31 \times 10^4$ and $\beta_{y0} = 0.0497$ for $v_0 = 0.999c$. For $A = 0.03$, $\tau = 3130$ and $\beta_{y0} = 0.181$ for $v_0 = 0.99c$, and $\tau = 3.01 \times 10^4$ and $\beta_{y0} = 0.0581$ for $v_0 = 0.999c$. The normalization factor for τ is $\lambda/32c$. In addition, crosses show the results by the relation (3).

A 1.5-dimensional (x, v_x, v_y) particle[21] (PIC) simulation is also performed with the following initial and boundary conditions: The averaged electron speed is $0.95c$, the averaged incident angle with respect to the x axis is 13.83°, which is the optimal one obtained by the above single-particle analysis, the electron temperature is 100 keV, the electron number density is $7.96 \times 10^6/\lambda^2$ cm^{-3}, the amplitude factor A of the EM wave is 0.1, $E_{\text{app}}/E_{y0} = 2.23 \times 10^{-2}$, which is also optimal, and we take a cyclic boundary condition in the x direction. Figure 5 presents an electron map in x-y space and shows that some electrons are accelerated well by this mechanism; the γ for electrons accelerated is about 18, which coincides well with the value of 18.28 obtained from the single-particle analysis presented above. In addition, 22.5% of the electrons are accelerated beyond $\gamma = 17.6$ in this case. This simulation result also confirms that the mechanism proposed in this paper works well.

The essential physics involved in the present mechanism is as follows.

(1) The applied field breaks the symmetry of the laser field in space and time. This idea provides a rather high acceleration gradient, that is, possibly about 1 GeV/m or more, depending on the laser power, though this is a one-kick acceleration. This acceleration mechanism

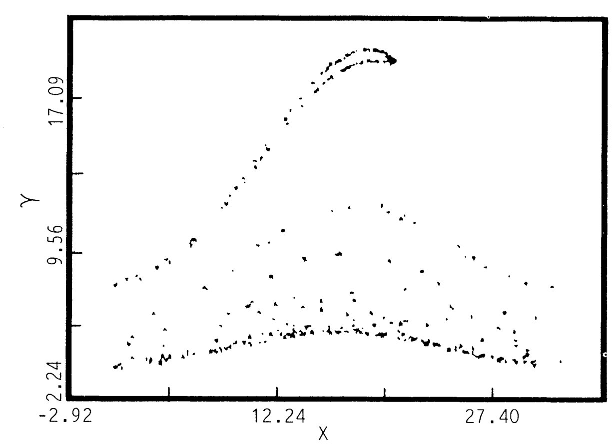

FIG. 5. A particle map by a particle (PIC) simulation in a space of the final electron relativistic factor γ vs x, which is normalized by $\lambda/32$.

might be called inverse-bremsstrahlung electron acceleration, because of its configuration, that is, the applied static electric field and the absorption of the EM wave energy by a particle.

(2) The interaction time between electron and laser is also essential for efficient acceleration and, because of $F_x > 0$, becomes long in this system, compared with $\lambda/c \times(1-\beta_{x0})$ which is the roughly estimated interaction time evaluated by the initial v_{x0}. This means that the slight increase in v_x is important.

Another characteristic feature of this system is the simplicity: neither a plasma nor any structure is needed. The system only requires a high-power laser, a weak static electric field, and a preaccelerated electron in a vacuum. Another important feature is that the trajectory does not bend much and is rather straight along the x coordinate because of the relativistic speed of the electron, as shown in Fig. 3.

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[1]IEEE Trans. Plasma Sci. **15**, No. 2 (1987), edited by T. Katsouleas.

[2]*Proceedings of the Second Workshop on Laser Acceleration of Particles, Los Angeles, California, 1985,* edited by C. Joshi and T. Katsouleas, AIP Conf. Proc. No. 130 (American Institute of Physics, New York, 1985).

[3]T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).

[4]P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, Phys. Rev. Lett. **54**, 693 (1985).

[5]K. Mizuno, S. Ono, and O. Shimoe, Nature (London) **253**, 184 (1975).

[6]K. Mizuno, J. Pae, T. Nozokido, and K. Huruya, Nature (London) **328**, 45 (1987).

[7]N. M. Kroll, P. L. Morton, and M. N. Rosenbluth, IEEE J. Quantum Electron. **17**, 1436 (1981).

[8]S. Sprangle and C. M. Tang, IEEE Trans. Nucl. Sci. **28**, 3340 (1981).

[9]A. Loeb and L. Friedland, Phys. Rev. A **33**, 1828 (1986).

[10]A. Loeb, L. Friedland, and S. Eliezer, Phys. Rev. A **35**, 1692 (1987).

[11]R. Sugihara, S. Takeuchi, K. Sakai, and M. Matsumoto, Phys. Rev. Lett. **52**, 1500 (1984).

[12]Y. Nishida, M. Yoshizumi, and R. Sugihara, Phys. Fluids **28**, 1574 (1985).

[13]T. Katsouleas and J. M. Dawson, Phys. Rev. Lett. **51**, 392 (1983).

[14]S. Takeuchi, K. Sakai, M. Matsumoto, and R. Sugihara, IEEE Trans. Plasma Sci. **15**, 251 (1987).

[15]V. V. Apollonov, A. I. Artem'ev, Yu. L. Kalachev, A. M. Pronkhorov, and M. V. Fedorov, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 77 (1988) [JETP Lett. **47**, 91 (1988)].

[16]S. Kawata, A. Manabe, and S. Takeuchi, Jpn. J. Appl. Phys. **28**, L704 (1989).

[17]S. Kawata, H. Watanabe, A. Manabe, and H. Kuroda, Jpn. J. Appl. Phys. **29**, L179 (1990).

[18]Without $E_{\rm app}$ an electron can be accelerated only during a half period. With the same initial conditions of $A=0.1$ and $v_0=0.9999c$ an electron can be accelerated up to $\gamma=2.66\gamma_0$ with an incident angle of 0.477°, which is the optimal value for this case.

[19]This treatment is based on the numerical result that x is nearly proportional to t (see the dashed line in Fig. 2). The factor $\int(1-\beta_x)dt$ appears in $E_y=E_{y0}\sin(\omega t-kx)$, in which $\omega t-kx=kc(t-x/c)=kc\int(1-\beta_x)dt$.

[20]After simple algebra, $d\gamma/d\beta_{y0}=0$ gives the equation $\beta_{y0}^4+a_1\beta_{y0}^2+a_2\beta_{y0}+a_3=0$, where $a_1=2(1-4\alpha^2-\gamma_0^2)/\gamma_0^2$, $a_2=4\alpha\times(2-2\alpha^2-\gamma_0^2)/\gamma_0^3$, and $a_3=(2-1/\gamma_0^2+8\alpha^2)/\gamma_0^2$. When $\gamma_0\gg\alpha$, $\gamma_0\gg 1$, and $\beta_{y0}\ll 1$, this equation reduces to $\beta_{y0}^2+(2\alpha/\gamma_0)\beta_{y0}-1/\gamma_0^2=0$.

[21]A. B. Langdon and B. F. Lasinski, Methods Comput. Phys. **16**, 327 (1976).