

CROSS-FIELD ACCELERATION BY ELECTROMAGNETIC WAVE

Shigeo Kawata, Atsushi Manabe and Hiroaki Watanabe
 Department of Electrical Engineering, Faculty of Engineering,
 Nagaoka University of Technology, Nagaoka 940-21, Japan

A new mechanism is presented for high-energy electron acceleration from an electron beam by an electromagnetic(EM) wave with a static magnetic(B) field. Numerical analyses and simulations show that this mechanism works well for high-energy-electron acceleration. Typically the magnitude of the static B field is significantly small compared with the amplitude of the EM wave. The optimal magnitude of the static B field is also discussed.

INTRODUCTION

A number of mechanisms have been proposed for high-energy particle acceleration[1-17]. Previously, it was shown that a slow electromagnetic (EM) wave could trap and accelerate charged particles[15-17]. However, a slow EM wave is essential but is not yet established definitely. In this paper, we present a new mechanism for a high-energy electron acceleration by EM wave propagation at the speed of light(c). In this mechanism, an EM wave traveling across a static magnetic field produces high-energy electrons from an electron beam. The magnitude of the static magnetic field is surprisingly small compared with the amplitude of the EM wave. The optimal magnitude of this static magnetic field is also discussed.

ACCELERATION BY AN ELECTROMAGNETIC WAVE WITH
 A STATIC MAGNETIC FIELD

Figure 1 shows the proposed mechanism for the high-energy electron production from an electron beam by an EM wave with a static magnetic field. A plane EM wave propagates at the speed of light, c, in the +x direction. The magnetic component of the wave is in the x-z plane and the electric one is in the x-y plane.

An electron's speed is less than c. Therefore the EM wave propagating with c catches up with the electron and leaves it behind. If the system has no static magnetic field, an oscillating electron motion may be expected. When an EM wave passes through an electron by the half wavelength, the electron can absorb the wave energy. But in the remaining half-wavelength, the electron loses its energy. Finally, the electron cannot absorb the EM-wave energy. This fact comes from the symmetry of the EM wave in space.

Our idea is to remove this symmetry by applying a static magnetic field Bapp. Therefore, the applied static magnetic field has an important role in the high-energy electron production system shown in Fig.1. The electron equation of motion and the energy equation are $dP_x/dt = -e\beta_y(B_z + B_{app})$, $dP_y/dt = F_y = -e[E_y - \beta_x(B_z + B_{app})] = -e[(1 - \beta_x)B_z - \beta_x B_{app}]$ and $d(mc^2\gamma)/dt = -eE_y V_y$. Here $\beta_x = V_x/c$, $\beta_y = V_y/c$, $E_y = B_z \sin[k(x-ct)]$ and A is the amplitude of the EM wave. From the energy electron acceleration, because E_y is specified by the incoming EM wave. V_y is determined by the y component of the above equation of motion. The force in the y direction is proportional to the factor of $(1 - \beta_x)B_z - \beta_x B_{app}$. We can choose an appropriate value of Bapp so that in the region of $\pi < k(x-ct) < 2\pi$ this factor becomes quite small, that is,

$$B_{app}/A = -(1 - \beta_x)/\beta_x \quad (1)$$

and the electron trajectory is not influenced significantly, although B_z changes in the above sin function. If there is no Bapp and β_x is exactly 1, then the EM wave has no effect on the electron trajectory. In fact, β_x is less than 1 and $(1 - 3\beta_x)B_z$

is not zero. In our system, $(1 - 3\beta_x)B_z$ is almost compensated in the region of $\pi < k(x-ct) < 2\pi$ by adding Bapp. In the remaining half-wave of $2\pi < k(x-ct) < 3\pi$, known as the acceleration phase, the force F_y enhanced to be $-e[(1 - \beta_x)|B_z| + \beta_x|B_{app}|]$ and the electron is accelerated in the -y direction. Therefore the electron has the velocity of V_y and can absorb the wave energy. In addition, the electron feels the force of $-e\beta_y(B_z + B_{app}) = +e|\beta_y(B_z + B_{app})|$ in the +x direction, so the relative velocity between the EM wave and the electron becomes small in the acceleration phase. Thus the electron stays longer in the acceleration phase, that is, $2\pi < k(x-ct) < 3\pi$, than in the phase of $\pi < k(x-ct) < 2\pi$. Consequently the electron can be accelerated efficiently by the EM wave.

First, a single particle analysis is performed in the fixed fields in order to demonstrate this mechanism. In this case, the EM wave is infinitely continuous in the x direction. Figure 2 shows electron energy versus the x coordinate. In this case, the initial electron velocity is 0.95c in the x direction and the electron has no V_y initially. In this example, the amplitude of the EM wave is $0.1 \times E_0$, $E_0 = 1.02 \times 10^7 / L$ volt/cm, L is the wavelength in cm, the space x coordinate is normalized by L/20 and $-B_{app}/A = 0.018$ which is the optimal value of Bapp for this specified parameter set. As described above, the electron velocity V_x changes during the acceleration. The numerical integral of the relativistic equation of motion shows that the averaged V_x becomes about 0.98c in the acceleration phase in this case. By using this value of V_x and eq.(1), we can estimate that Bapp is about -0.02A, which corresponds well to the optimal value employed in this numerical integral. Figure 3 shows the time sequences of x and $-E_y V_y$ in proportion to the time derivative of the electron energy. In the figure, time is normalized by a factor of $L/(20c)$. From Fig.3, we find that the electron obtains its energy mainly in the acceleration region as mentioned above. Figure 4 presents the optimal Bapp versus the initial electron velocity $V_x(t=0)$ for various EM wave amplitudes. The optimal value depends on EM wave amplitude A and also on V_x in the acceleration phase shown in eq.(1). Estimation of the averaged value of V_x in the acceleration phase is not so simple. As described above, this averaged value of V_x is different from the initial $V_x(t=0)$ and changes depending on the EM-wave amplitude A. Figure 4 shows this fact: when the amplitude A becomes larger, the average V_x in the acceleration phase approaches c and so |Bapp| becomes smaller.

In order to ascertain the effect of the finitude of the incoming EM wave in the x space on high-energy electron production, we perform the 1.5-dimensional (x, V_x and V_y) particle-in-cell(PIC) simulation[17,18]. The relativistic equation of motion and the Maxwell equations are solved in the program self-consistently. In the simulation, the model employed is nearly the same as that used in the above analysis, however there is a difference in the finitude of the EM wave in the x space. At the start of $t=0$, the incoming EM wave exists infinitely only when $x < 0$. The EM wave then propagates in the +x region and catches up with electrons traveling with the velocity of $V_x(t=0) = +0.95c$. The wavelength L covers 20 space meshes. The x coordinate is normalized by L/20. The total mesh number is 1024. The initial number density of the electron beam is $n_0 = 2.18 \times 10^8 / L^2 \text{ cm}^{-3}$. The electrons are distributed uniformly $0 < x < 20$ and follow the Maxwell distribution

with the temperature of 1.0keV in the momentum space at $t=0$. Each mesh has 100 numerical super-particles. Other normalization factors and parameter values are also the same as those employed above, except for B_{app} . The optimal B_{app} is slightly different from the value employed in the above analysis because of the finitude of the EM wave, and $-0.025 \times A$ in this case. As the boundary condition, the perfect conductors are set at $x=0$ and 1024.

Figure 5 shows the simulation results. Figure 5(a) represents the relativistic factor versus the real space x and Fig.5(b) the electric E_y and magnetic B_{zt} fields. Figure 5 clearly shows the acceleration and scattering of electrons in our system. Some of the electrons absorb energy up to

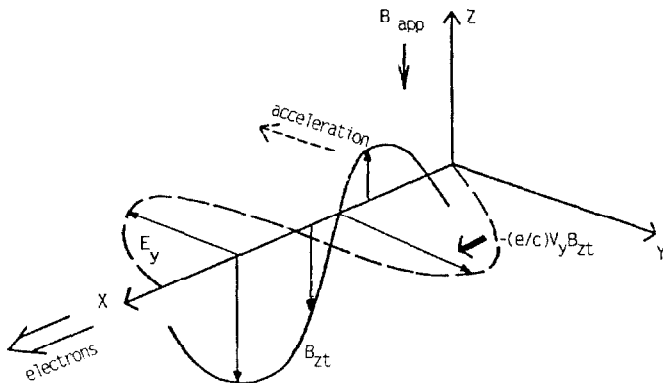


Fig.1. A mechanism of high-energy electron production by a plane EM wave with a weak static magnetic field in free space. An electron beam propagates parallel to an EM wave. In the acceleration region indicated in the figure, electrons can be accelerated by an electric component in the $-y$ direction. In the other half-wavelength, electrons experience almost no force and pass through freely.

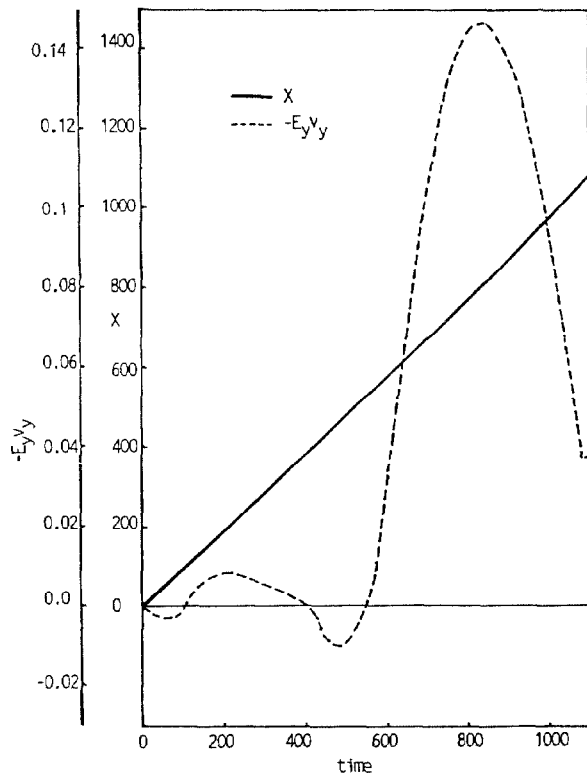


Fig.3. Time derivative of electron energy versus time. Electron absorbs the wave energy mainly in the acceleration region shown in Fig.1.

$6.82 \times mc^2$, which corresponds to $\gamma=6.82$. This maximum γ is less than that obtained in the former analysis (see Fig.2). This difference comes from the finitude of the EM wave: the head of the EM wave is slightly modified from a perfect sinusoidal shape by the finitude of the EM wave in order to satisfy the Maxwell equations. Because the EM wave at $t=0$ only exists when $x < 0$ and the wave head has to be continuous in space, the wave shape is different from the sinusoidal one employed in the former analyses to obtain the results in Figs.2-4. This simulation result reconfirms that high-energy electrons can be produced efficiently by an EM wave with a static magnetic field in this mechanism.

The maximal electron energy obtained from the EM wave depends on several parameters. One of them is the number density of the electron beam. If the number density is too high, i.e., the electron-energy density is comparable to or greater than that of the EM wave energy, the maximum γ becomes less than 6.82 in the above case. The absolute value of the final electron energy also depends quite heavily on the intensity of the incoming EM wave.

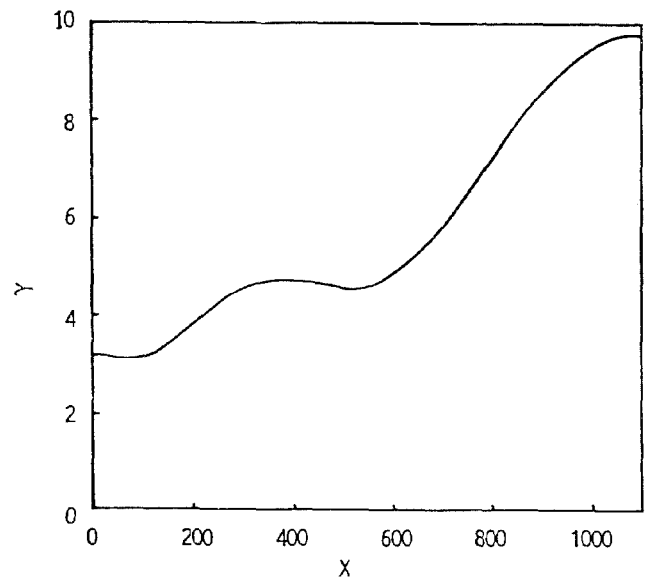


Fig.2. Electron energy versus x . After passing through one wavelength of an EM wave, the electron absorbs the wave energy.

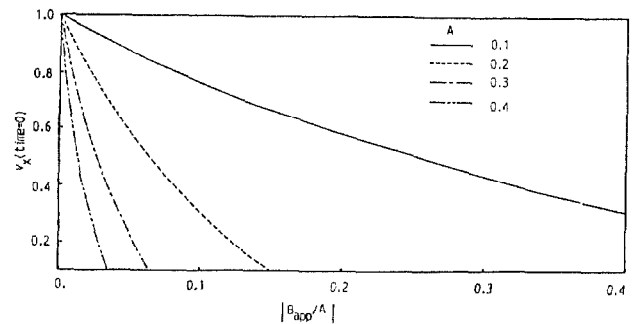


Fig.4. The optimal value of the applied static magnetic field for the maximum acceleration versus the electron initial velocity for various amplitudes (A) of the EM wave. The amplitude A is normalized by $1.02 \times 10^7 / L$ volt/cm and L is the wavelength in cm.

CONCLUSION

In this paper, we proposed a new mechanism for high-energy electron production from an electron beam by an EM wave traveling across a weak static magnetic field, and demonstrated its viability and effectiveness by numerical analyses and particle simulations. This mechanism can be seen in any systems or situations in which a pure electron beam and an EM wave with a static magnetic field interact.

time = 560

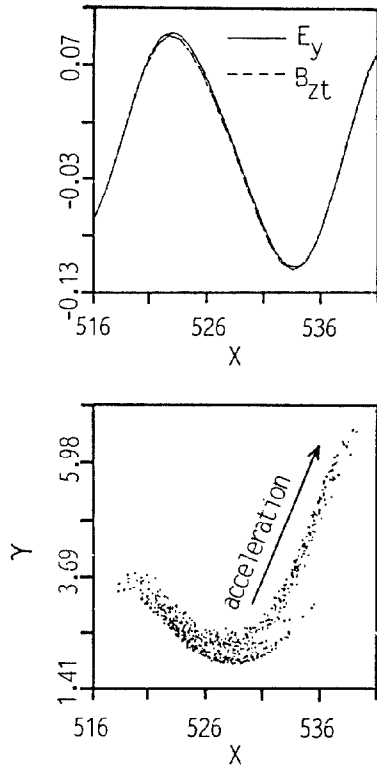


Fig.5. Particle simulation results for a high-energy electron production by an EM wave accompanying a weak static magnetic field. This simulation result clearly shows the production of the high-energy electrons. Figure 5(a) shows the relativistic factor

One example application may be in a particle accelerator. If the initial electron energy is rather high, i.e., the electron is relativistic initially, the electron trajectory may not be much affected by the acceleration and only the electron mass increases. Thus we may control the electron trajectory and our proposed mechanism may be applicable to the particle accelerator. Another application might be found in laser fusion. The hot electrons and the magnetic field produced by the laser-target interaction may couple with the laser.

REFERENCES

- [1] IEEE Trans. Plasma Sci. PS-15(1987)No.2.
- [2] American Inst. Phys. Conf. Proc. No.130(1985).
- [3] T. Tajima and J.M. Dawson: Phys. Rev. Lett. 43(1979)267.
- [4] P. Chen, J.M. Dawson, R.W. Huff and T. Katsouleas: Phys. Rev. Lett. 54(1985)693.
- [5] K. Mizuno, S. Ono and O. Shimoe: Nature 253(1975)184.
- [6] K. Mizuno, J. Pae, T. Nozokido and K. Huruya: Nature 328(1987)45.
- [7] N.M. Kroll, P.L. Morton and M.N. Rosenbluth: IEEE J. Quantum Electron. QE-17m(1981)1436.
- [8] S. Sprangle and C.M. Tang: IEEE Trans. Nucl. Sci. NS-28(1981)3340.
- [9] A. Loeb and L. Friedland: Phys. Rev. A33(1986)1832.
- [10] A. Loeb, L. Friedland and S. Eliezer: Phys. Rev. A35(1987)1692.
- [11] R. Sugihara, S. Takeuchi, K. Sakai and M. Matsumoto: Phys. Rev. Lett. 52(1984)1500.
- [12] Y. Nishida, M. Yoshizumi and R. Sugihara: Phys. Fluids 28 (1985)1574.
- [13] F.F. Chen: Univ. of California, Los Angeles, Report PPG-1107(1987).
- [14] T. Katsouleas and J.M. Dawson: Phys. Rev. Lett. 51(1983)392.
- [15] S. Takeuchi, K. Sakai, M. Matsumoto and R. Sugihara: Phys. Lett. A122(1987)257.
- [16] S. Takeuchi, K. Sakai, M. Matsumoto and R. Sugihara: IEEE Trans. Plasma Sci. PS-15(1987)251.
- [17] S. Kawata, A. Manabe, T. Yabe, S. Takeuchi, K. Sakai and R. Sugihara: Jpn. J. Appl. Phys. 27(1988)163.
- [18] A. B. Langdon and B. F. Lasinski: Meth. Comp. Phys. 16(1976)327.