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ELECTRON ACCELERATION BY AN ELECTROMAGNETIC WAVE WITH A STATIC MAGNETIC FIELD

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Abstract A new mechanism is presented for high-energy electron acceleration 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.

INTRODUCTION

A number of mechanisms have been proposed for high-energy particle acceleration[1-3]. In this paper we present a new mechanism for a high-energy electron acceleration by an EM wave. An EM wave traveling across a static magnetic field accelerates high-energy electrons. 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. In addition, a pulse EM wave whose profile is Gaussian, is also disscussed for a realistic acceleration.

ACCELERATION MECHANISM

Figure 1 presents this mechanism for high-energy electron acceleration by an EM wave with a static magnetic field. A plane EM wave propagates at the speed of light 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.

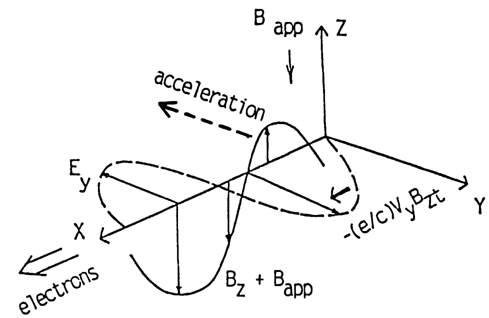

FIGURE 1 A mechanism of high-energy electron acceleration by a plane EM wave with a weak static magnetic field in free space. In the acceleration region indicated in the figure, electrons can be accelerated in -y direction by an electric component.

If the system has no static magnetic field, an oscillating electron motion may be expected and the electron cannot absorb the EM-wave energy. This comes from the symmetry of the EM wave in space. Our idea is to remove this symmetry by applying a static magnetic field B_{app}. The electron equation of motion and the energy equation are as follows:

$$dP_x/dt=-ev_y(B_z+B_{app})/c, \quad (1)$$
$$dP_y/dt=F_y=-e[(1-v_x/c)B_z-v_xB_{app}/c] \quad (2)$$
$$d(mc^2\gamma)/dt=-eE_yv_y \quad (3)$$

Here $E_y=B_z=A\sin[k(x-ct)]$ and A is the amplitude of the EM wave. The speed of v_y in Eq. (3) is determined by Eq. (2). The force in the y direction is proportional to the factor of $(1-v_x/c)B_z-v_x/cB_{app}$. We can choose an estimation value of B_{app} so that in the region of $\pi<k(x-ct)<0$ this factor becomes quite small, that is,

$$B_{app}/A=-(1-v_x/c)/(v_x/c) \quad (4)$$

and the electron trajectory is not influenced significantly, although B_z changes in the above sin function. In the remaining half-wave of $2\pi<k(x-ct)<\pi$, that is, the acceleration phase, the force F_y enhanced to be $-e[(1-v_x/c)|B_z|+v_x|B_{app}|/c]$ and the electron is accelerated in the -y direction. In addition, the electron feels the force of $-ev_y(B_z+B_{app})/c= +e |v_y(B_z+B_{app})|/c$ 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. Consequently the electron can be accelerated efficiently by the EM wave.

NUMERICAL ANALYSES

First, a single particle analysis is performed in the fixed fields in order to demonstrate this mechanism. In this case, the linearly polarized 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 $0.1xE_0$, $E_0=1.02x10^7/L$ 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 B_{app} for this specified parameter set. 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. (4), we can estimate that B_{app} is about -0.02A, which corresponds well to the optimal value employed in this numerical integral.

We also perform the 1.5-dimensional(x,v_x and v_y) particle-in-cell(PIC) simulation[1,2]. 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 $n_0=2.18x10^8/L^2 cm^{-3}$. The electrons are distributed uniformly $0<x<20$ and follow the Maxwell distribution with the temperature of 1.0keV at t=0. The optimal B_{app} is slightly different from the value employed in the above analysis because of the finitude of the EM wave, and -0.025xA in this case. As the boundary condition, the perfect conductors are set at x=0 and 1024.

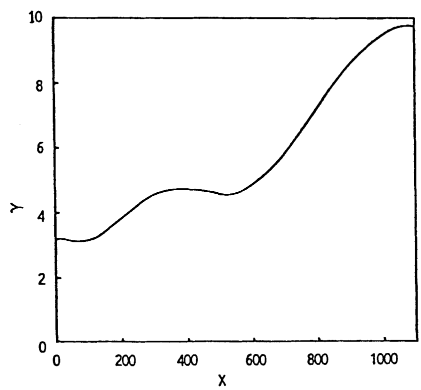

FIGURE 2 Electron energy versus x. After passing through one wavelength of an EM wave, the electron absorbs the wave energy.

Figure 3 represents the relativistic factor versus the real space x. Figure 3 clearly shows the acceleration and scattering of electrons in our system. Some of the electrons absorb energy up to $6.82xmc^2$. This maximum energy is less than that obtained in the former analysis(see Fig.2). This difference comes from the finitude of the EM wave.

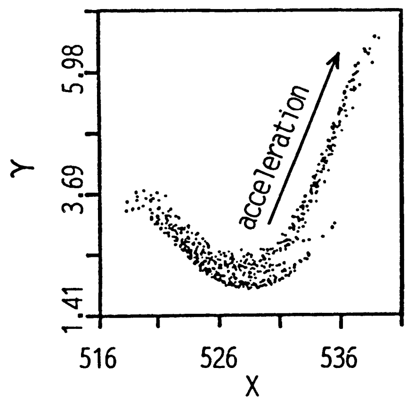

FIGURE 3 Particle simulation results for a high-energy electron acceleration by an EM wave with a weak static field(B_{app}). shows the relativistic factor versus x.

ELECTRON ACCELERATION BY GAUSSIAN PULSE

In order to apply this mechanism to a realistic acceleration of electron, 1.5-dimensional numerical single-particle analyses are performed for the electron acceleration by the Gaussian pulse as shown in Fig. 4(a). The Gaussian pulse employed is

$$A\exp((x-ct)^2/2M^2)\sin(x-ct). \qquad (5)$$

Figure 4(b) presents the relativistic factor versus wave coordinate. This result shows that our mechanism is applicable for a realistic acceleration. In this example $M=L/2$, $A=1.64\times10^6/L$ volt/cm, L is the wavelength in cm, x coordinate is normalized by L/32. Figure 4(b) shows that electron can be accelerated well by a realistic Gaussian pulse.

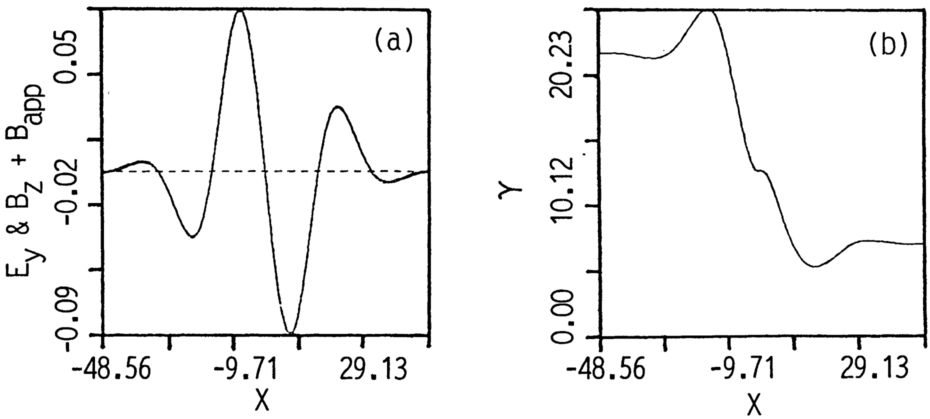

FIGURE 4 (a) Gaussian pulse, (b) The relativistic fuctor versus x in the wave coordinate. V_x=0.9454C & V_y=0.2939C at time=0.

CONCLUSIONS

In this paper, we proposed a new mechanism for high-energy electron acceleration by an EM wave traveling across a weak static magnetic field, and demonstrated its viability and effectiveness by numerical analyses and particle simulations.

REFERENCES

1. S. Kawata, A. Manabe, T. Yabe, S. Takeuchi, K. Sakai and R. Sugihara, Jpn. J. Appl. Phys., 27, 163 (1988) and references therein.
2. S. Kawata, A. Manabe and S. Takeuchi, Jpn. J. Appl. Phys., 28, L704 (1989).
3. W. Werner and H Hora, Laser and Particle Beams, 7, 315 (1989).