Electron Linear Accelerator using Phased TE Electromagnetic Wave Beams

Y. Nishida, N. Yugami, and K. Otsuka

Department of Electrical and Electronic Engineering
Ustunomiya University,
Ustunomiya, Tochigi 321, Japan

Abstract

The motion of charged particles in a multi-electromagnetic wave-beam syatem (Multi-EM Beam) with static magnetic field has been investigated numerically, showing the particle trapping and acceleration. This system consists of a lot of plane electromagnetic-wave beams propagating in parallel each other, but each beam is successively delayed of its phase from the one to the other, making an apparent wave propagating obliquely to the original EM beams. When the static magnetic field is applied in parallel with the fluctuating magnetic field, the charged particles are trapped to be accelerated stably. For realizing the present scheme, a simple new system which consists of many mirrors but uses one EM beam is proposed.

Introduction

Recently much interest has arisen in plasma based high energy particle accelerator schemes.[1] The V_pxB plasma based accelerator[2] is one of such scheme, where V_p is the phase velocity of the electron plasma wave. This scheme, however, needs high field, large amplitude plasma wave to be excited. For this purpose, the plasma wake-field[3] can be employed. The V_pxB electron linear accelerator[4] is another trend, which uses no plasma, but depends on the same scheme originally found in the plasma.[2] In this scheme, the slow-wave sturucture is employed for making a driver wave of the TM mode. The laser light has strong field intensity, but it cannot be used for the accelerator field as it is, because of the transverse wave.

The V_pxB linear accelerator[4] has shown efficient acceleration of electrons, in which charged particles are accelerated along the wave front, perpendicular to the direction of the wave propagation. When an electromagnetic wave (EM wave) is used for a driver in the accelerator, it is difficult to realize the interaction of charged particles with the wave without any structure such as a slow wave structure, because the EM wave is a transverse mode propagating with a velocity of light in free space. For overcoming this demand, a multi-electromagnetic wave-beam system (Multi-EM Beam), has been proposed.[5,6] This system consists of a lot of plane electromagnetic-wave beams propagating in parallel each other, but each beam is successively delayed of its phase from the one to the other. If we look over a part of the same phase, it seems that another apparent wave propagates obliquely with a phase velocity $V_p= c\cdot\cos\theta < c$, where θ is an angle between the propagation direction of two waves, the real transverse wave and the apparent mode. In the slower wave, the charged particles could be trapped in the wave trough for strong interaction.

We have investigated numerically the motion of charged particles in this system and obtained that the charged particles are really trapped and accelerated stably into high energy.

Theory

We consider a multi-beam system consisting of electromagnetic wave-beams (multi-EM-beam system) as schematically shown in Fig.1, in which each beam propagates in parallel in the z direction. The phase of each beam is slightly delayed with an amount of α from beam to beam.

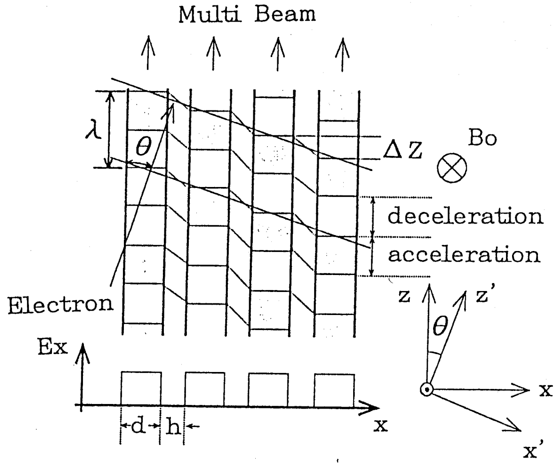

Fig.1. Schematic description of multi-electromagnetic wave beam system.

The equations of motion for an electron in such a scheme are written in the components:

$$m_0 \frac{d(\gamma v_x)}{dt} = e\{E_x - v_z(B_y + B_0)\},$$
$$m_0 \frac{d(\gamma v_y)}{dt} = 0, \qquad (1)$$
$$m_0 \frac{d(\gamma v_z)}{dt} = e v_x(B_y + B_0).$$

As the electric field E_x is changing sinusoidally, a half cycle of the wave corresponds to the acceleration phase (in the +x direction) for the electron and another half cycle to the deceleration phase. The following inequality must be satisfied for particle trapping.

$$\frac{B_y}{B_0} > \frac{\gamma_p^2}{2} = \frac{1}{2\sin^2\theta}, \qquad (2)$$

where, $\gamma_p= \{1-V_p^2/c^2\}^{-1/2}=1/\sin\theta$.

If the electron is assumed to pass by only the acceleration phase successively from beam to beam, the continuous acceleration of electron can be accomplished. For this purpose, the following condition on the beam width must be satisfied,

$$d+h < \frac{\lambda}{2}\frac{1}{\tan\theta} = \frac{\lambda}{2}\frac{1}{(\gamma_p^2 - 1)^{1/2}}. \qquad (3)$$

This expression shows that the beam width can be determined only by the phase velocity Vp with a constant wave length (or a wave frequency).

The multi-beam system could be assumed to have the shape expressed in Eq.(4), which is a Gaussian distribution in space.

$$E_x = E_{x0}\exp[- w\cdot\sin^2\{\frac{\pi}{d}(x + \frac{d}{2})\}]\times \sin(kz - \omega t). \qquad (4)$$

3. Numerical calculations and results

(a) *The case with rectangular beam*

At first we have performed calculations with rectangular shaped beams (w=0). The typical example of the results are shown in Fig.2 (a) and (b), which show the variation of electron energy as a function of the time. The parameter of Fig.2(a) is the beam width d, and that of Fig.2(b) is the static magnetic field B_0. Other parameters are kept constant: E_x = 210(kV/m), B_y = 7(G), $V_p = v_0$ = 0.99c (γ_p= 7.1), and f = 30(GHz). The static magnetic field B_0 in Fig.2(a) is B_0 = 0.25 (G) which is below the critical value of trapping electrons of B_c = 0.27(G) calculated from Eq.(2). The beam width condition also has a restriction as is given by $d+h < 3.5\lambda$. Initially all the electrons are located at z_0 = 0. Figure 2(a) shows the results, in which the trapping condition is satisfied and in Fig.2(b) the restriction on the beam width is satisfied. When the condition for the beam width is not satisfied, the electron can be accelerated continuously up to the time when the electrons come into the deceleration phase. When the static magnetic field B_0 is larger than the value for the particle trapping, the electron energy can increase in early stage of the acceleration, but as the time passes by, the electron is detrapped from the wave trough and its energy does not increase anymore as seen in Fig.2(b).

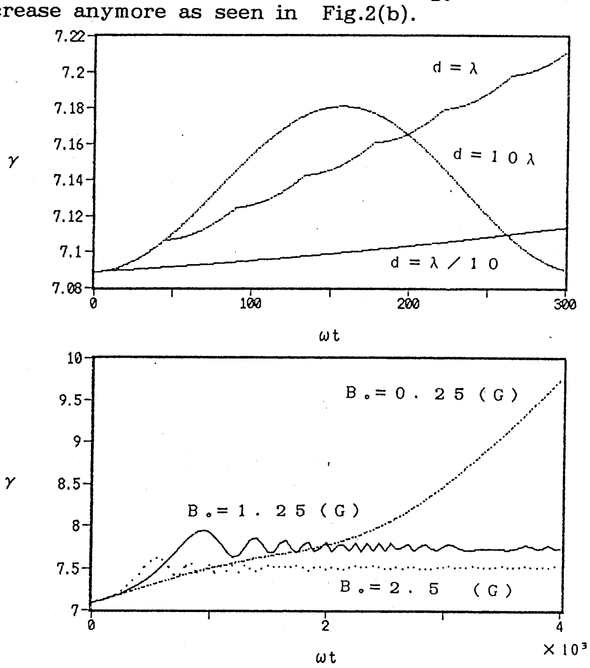

Fig.2. Electron energy as a function of the acceleration time. (a) EM beam width is a parameter. B_0 = 0.25 (G). (b) Static magnetic field strength B_0 is a parameter. d = h = λ/2. Here, the critical value for particle trapping is B_c = 0.27 (G), E_x = 210 (kV/m), V_p/c = 0.99 (γ_p = 7.1), and f= 30 (GHz).

Figure 3 shows the phase space display of the electron energy as a parameter of time variation. The abscissa is the phase in a wave length of the EM-beam propagating to the z direction with a speed of light. Initially all the electrons are injected uniformly in a phase space with a velocity $|v| = V_p$. Other parameters are E_x = 210(kV/m), B_y = 7(G), f = 30 (GHz), d = λ, h $\geq$ 0, and $v_0 = V_p$ = 0.9c (γ_p = 2.3). The critical value, B_c, for electron trapping is B_c = 0.27(G), and the condition for a beam width is $d+h < 3.5\lambda$. It is clear from the figure that almost all the electrons are bunched to be accelerated, resulting in the particle energy increment. The bunching point is moving to be delayed from the wave phase. This is because that the phase in the abscissa is fixed to the EM-beam frame which is propagating with the speed of light, and so the electron is delayed from the wave beam to be taken over into the next neighbouring wave, where the wave phase is the accelerating phase.

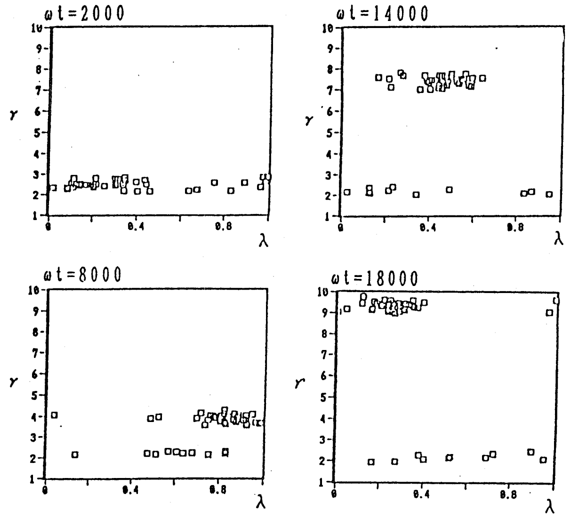

Fig.3. Electron energy distribution in a phase space. E_x = 210 kV/m, B_0 = 0.25 G, V_p/c = 0.9 (γ_p = 2.3), d = λ, and h = 0.

(b) *The case of Gaussian beam*

When the cross section of the electromagnetic wave beam has the Gaussian distribution described in Eq.(4), the situation of the particle acceleration could change. The typical results of numerical calculation are shown in Fig.4 under the condition that the particles are trapped well within a wave trough. Here, the cross section of the beam shape changes depending on the w values in Eq.(4). When 400 electrons are injected uniformly into the whole phase-space ($0 \leq kZ \leq 2\pi$, $-0.1 \leq V_z/c \leq 0.1$), the electrons are bunched to be accelerated into high energy as seen in Fig.4(a)-(b). However, the bunching strength seems to be weak compared with the previous case, still electron energy increases quite clearly.

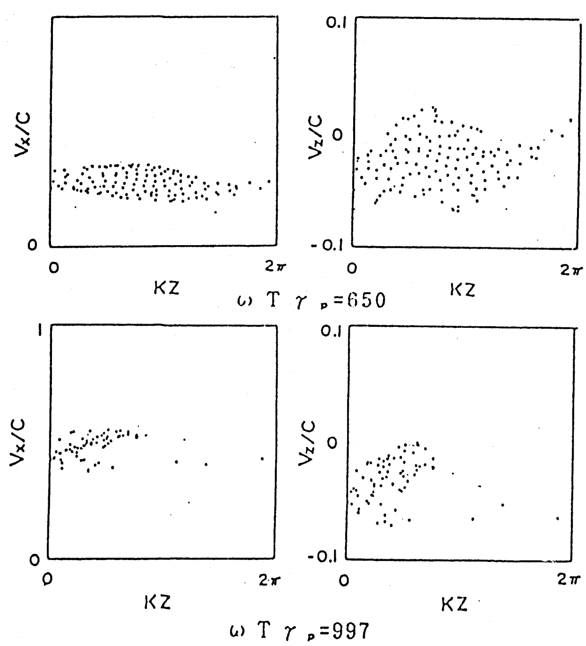

Fig.4. Electron distribution in the phase space in the limit of d -> 0. (a)V_x/c vs. KZ, and (b)V_z/c vs. KZ. E_x = 900 (kV/m), B_0 = 5 (G), θ = 24.9°. V_p/c = 0.9 (γ_p = 2.3), and f = 30 (GHz). The critical value for a particle trapping is B_c = 11.3 (G).

4. Discussion

In the numerical calculations we have obtained enough acceleration of electrons in the multi-EM-beam system, even if each beam is a transverse wave. In order to understand the underlying mechanism more precisely, we have tried to obtain an effective potential in a wave frame propagating along the z' axis (see Fig.1).

From the equation of motion Eq.(1), after the integration over T, one obtains

$$\frac{d^2Z}{d\tau^2} = -\frac{dU(Z)}{dZ} + F(\tau), \qquad (5)$$

where

$$F(\tau) = \Gamma(\tau)\omega_c V_p \tan\theta \frac{1}{\gamma_p}\frac{B_y}{B_o}\sin(KZ)$$

$$- \omega_c^2\gamma_p^2 V_p \Gamma(\tau)\tau\{1 - \frac{1}{\gamma_p^2}\frac{B_y}{B_o}\sin(KZ)\},$$

$$U(Z) = \frac{\omega_c^2\gamma_p^2}{2}[W(Z)^2 - 2\{W(Z) - \frac{W_o}{\omega_c\omega_p}\}W(Z),$$

with $W_0 = \Gamma_0 V_{x0} + \omega_c\gamma_p V_p T_o$. Equation (5) shows that the charged particles are moving in the equivalent potential U(Z), but that the existing of the function $F(\tau)$ exhibits to prevent the particle entrance into the next wave phase, because the potential becomes higher. When the trapping condition Eq.(2) is satisfied, the potential well exists at certain phase, and most of the particles are trapped within this well. Some others, however, cannot be trapped there depending on their initial phases.

If the trapping condition is not satisfied, the potential U(Z) has no well and the particle trapping necessary for enough acceleration does not occur. The well in the equivalent potential corresponds to the magnetic neutral point where the attractive force appears to bunch particles. The hill also corresponds to the magnetic neutral point but almost out of phase from the well, and the repulsive force appears.

In the present system the most attractive merit is to use no slow wave structure such as necessary for the V_pxB linear accelerator using TM mode.[4] In order to realize the electron linear accelerator by using the present system, the quite precise adjustment is required for EM-beam handling. The Multi EM-beam accelerator should have many beams and satisfy several conditions such as (1) each beam should be slightly and precisely phased, (2) all EM-beams are in parallel at least in the acceleration area, and (3) the beam width has also restriction given by Eq.(3). These conditions are not so difficult to realize with the present technology, if we could use the laser beams or short wave length microwave beams. An example of one realistic alignment for the electron linear accelerator is shown schematically in Fig.5, in which one rf beam source makes multi-beam system for acceleration and the wave energy could be used efficiently until the wave depletion becomes seriously important.

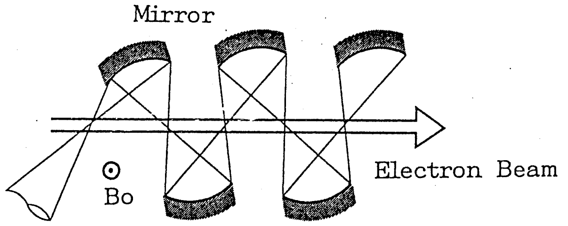

Fig.5. Schematic structure of a realistic linear accelerator concept.1: electron beam, 2: focussing mirrors, and 3: laser beam.

The energy increment, therefore, can be expressed as follows;

$$\frac{d\gamma}{dt} = \omega(\gamma_p^2 - 1)^{1/2}, \quad (\text{for } t >> c/V_p\omega_c)$$

$$\frac{d\gamma}{dx} = \frac{\omega_c}{c}\gamma_p(\gamma_p^2 - 1)^{1/2}, \qquad (6)$$

$$\frac{d\gamma}{dz} = \frac{\omega_c}{c}\gamma_p.$$

We can see from Eq.(6) that the energy increment depends on the wave phase velocity and the static magnetic field strength, and also see that the particles can be accelerated more effectively in the x direction by the amount of γ_p (>>1) compared with the wave propagation direction (z direction).

Conclusion

We have discussed the trapping and acceleration of electrons in a new system: multi-electromagnetic wave beam system. In this system, we can use the transverse-wave with a phase velocity equal to the light speed c. By operating the phase shift between each EM beam, the effective slow wave structure for the electrons can be realized. Adding the static magnetic field B_0 in parallel with the wave field B_y, which is perpendicular to the wave propagation direction, the V_pxB acceleration mechanism can be constructed. The acceleration mechanism has been analyzed by introducing the equivalent potential which shows the bunching and trapping of electrons. For realizing the present multi-EM-beam mode accelerator, the system with multi-mirrors but using single coherent EM wave beam is proposed.

Acknowledgement

The authors are greatly appreciated Prof. R.Sugihara and Dr. S.Takeuchi for their vivid discussions. A part of the present works are supported by the Grant-in-Aide from the Ministry of Education, Science and Culture, Japan.

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