INSTITUTE OF PLASMA PHYSICS

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RESEARCH REPORT

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New schemes are proposed for obtaining effective interaction between coherent electromagnetic wave and free electrons, both being traveling across the magnetic field. These schemes use the principle of the $V_p \times B$ acceleration of electrons originally observed in the plasma. Potential applications of the schemes are optical particle accelerators without using plasma.

The continued development of high energy particle accelerators demands the development of new physics field and technologies. Recently, laser accelerators are attracted to be future ultrahigh energy particle accelerators. One of them is proposed theoretically by Katsouleas and Dawson[1]. The idea is based on the relativistic version of the $v_p \times B$ acceleration[2,3] which is stated as that charged particles trapped by an electrostatic wave propagating across a static magnetic field B with a phase velocity v_p feel a DC electric field $v_p \times B/c$ and are suffered to a non-stochastic acceleration. Nishida et al[4-6] have proved the existence of the present acceleration in the microwave plasma interaction experiments.

In the present paper we wish to propose new schemes for realizing the $v_p \times B$ accelerator, by using no plasma system for producing the strong longitudinal waves. Before going to show the real accelerator schemes, it is convenient to discuss the $v_p \times B$ acceleration mechanism.

We consider a longitudinal plane wave $E = E_0 \sin(ky - \omega t)\hat{y}$ propagating perpendicularly to a uniform magnetic field $B = B_0\hat{z}$ (Fig.1). The case of oblique propagation has been discussed in Refs.7 and 8. The relativistic equation of motion for a particle of charge -e and rest mass m_0 is given as follows;

$$\frac{d(\gamma v_x)}{dt} = - \omega_c v_y \qquad (1)$$

$$\frac{d(\gamma v_y)}{dt} = \omega_c v_x - \frac{eE}{m_0}, \qquad (2)$$

where $\gamma^{-2} = 1 - (v_x{}^2 + v_y{}^2)/c^2$, and $\omega_c = eB_o/m_oc$ is the non-relativistic cyclotron frequency. Here, we assume $v_y = v_p$ is constant or the particle is deeply trapped, and $v_x = v_{xo}$ at the initial state and $v_z = 0$. By integrating eq.(1), one obtains

$$\gamma = -\omega_c t \frac{v_p}{v_x} + \gamma_o \frac{v_{xo}}{v_x}, \tag{3}$$

where $\gamma_o = \gamma(t=0)$. This shows that the particle trapped in the wave trough is accelerated in the negative x-direction.

The criterion for an initially, deeply trapped particle never to detrap is given as follows, after combining eqs.(1) and (2), and employing the conditon of $|\sin(ky - \omega t)| < 1$,

$$E_o/B_o > \gamma_p, \tag{4}$$

where $\gamma_p{}^{-2} = 1 - (v_p/c)^2$. The energy increment factor G is defined as follows;

$$G \equiv \varepsilon/\varepsilon_o = \frac{m_o\gamma c^2}{m_o\gamma_o c^2} = \frac{v_{xo}}{v_x} - \omega_c \frac{L}{\gamma_o v_x}, \tag{5}$$

where $L = v_p t$ is the acceleration length in the y-direction, v_{xo} and v_x have negative sign because of the particle being accelerated to $-x$ direction. Thus, G increases in proportion to the acceleration time and the magnetic field strength, although B_o has the limitation given by eq.(4). In order to obtain 10 GeV electrons from 0.1 GeV, for example, G must be larger than 100 times. As $\gamma_o = 195.4$ and for $\gamma_p = 1.155$, $B_o = 2.86$ kG, $E_o \geq 10^2$ (MV/m) and L = 100 m are necessary. If $E_o \simeq 10^3$ (MV/m) is available, $B_o = 28.6$ kG and L = 10 m are good enough for obtaining the same acceleration rate. These values may be available even in the present stage by using a powerful laser system.

It should be noted that in the conventional linac or a beat wave linac[9], the phase matching between waves and particles in acceleration is strictly hold, otherwise efficient acceleration cannot be expected. However, in the $v_p \times B$ acceleration scheme, the phase matching condition is not serious, because the particles are accelerated along the wave front.

For realizing the abovementioned acceleration, we wish to propose new two methods without using plasma. The first method is to use a grating for obtaining extended interaction of an electron beam moving along the grating surface with light beam incident also along the surface. Here, the electron beam propagates obliquely to the grating grooves and the light beam propagates parallel to the electron beam for producing strong electric field E_y over the grating grooves (Fig.2). The static magnetic field is applied perpendicularly to the grating surface as indicated in the figure. This scheme may somewhat be similar to that using the inverse Smith-Purcell effect[10], although there is no magnetic field in the latter system. In the present system, the beam interacts synchronously with the p-polarized wave which has the electric field be parallel to the grating surface; that is, an electron sees the same phase of the wave with the pitch of d. The synchronous condition is given

$$\cos\alpha = \frac{m\lambda}{d} - \frac{c}{v}, \tag{6}$$

where m = 1, 2, ..., d is the grating constant, $v = (v_x^2 + v_y^2)^{1/2}$, the velocity of the beam, λ is the free space wavelength of the light and α is the angle between the propagation direction of an electron beam and the y-axis. For obtaining an intense electromagnetic wave, we can expect to use laser light or strong microwave beam.

On the other hand, when the electron beam propagates faster than the phase velocity of the light wave, a net deceleration of the electron beam may occur to amplify the light with different frequencies from the original one, which may be emitted in the y-direction.

Another conventional scheme is suggested as shown in Fig.3. This is consisted of a filter type delay circuit used in the travelling wave tube, but the light beam propagates obliquely to the array of conductor fins or slots or a pair of gratings. The phase velocity of the spatial harmonics in the y-direction may be given as

$$v_y = (\omega/k_g) \cos \alpha = \omega D/(2\pi n + \phi) < c, \qquad (7)$$

where α is again the propagation angle measured from the y-direction, k_g is the wave vector in the wave guide, D is the pitch of the slot, ϕ is the phase lag of the wave traversing across a slot and n is an integer. Here, we can forget the effect of ω_c because of $\omega >> \omega_c$. In the present schemes the electric field can be intensified between the slots. By optimizing the phase velocity in the y-direction, we can expect efficient acceleration of the particle beam.

It should be recognized in the present schemes proposed here that light waves can interact with particles for a long time without losing phase matching conditions, because the particles in acceleration also travel along the light beam, but are accelerated in parallel to the wave front. With the aid of recent progress of powerful laser light or microwave source, such as the gyrotron, it should be possible to miniaturise linacs by using the $v_p \times B$ effect and the schemes proposed here.

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Figure captions

Fig.1. $V_p \times B$ acceleration scheme.

Fig.2. The grating type accelerator arrangement. (a) Polarized wave with an angle α from the y-axis propagates in parallel along the grating surface with grating constant d. Particles are accelerated along the wave propagation direction. The static magnetic field is applied perpendicularly to the grating surface. (b) Crossectional view of the arrangement in (a).

Fig.3. (a) Crossectional view of the wave guide type accelerator scheme. TM-mode wave propagates obliquely to the array of delay circuit fins. (b) Another arrangement of the delay circuit type accelerator. l is the depth of the slot.

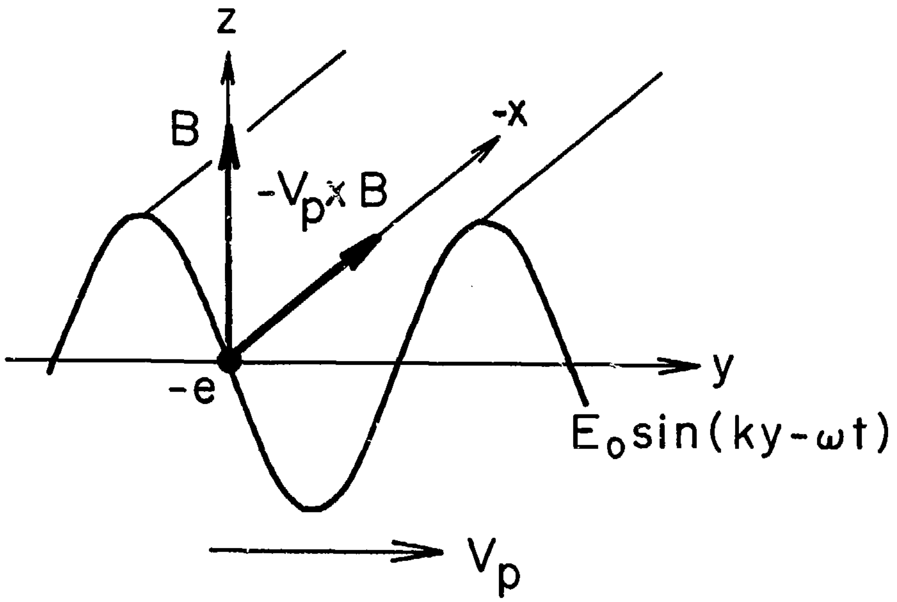

FIG. 1

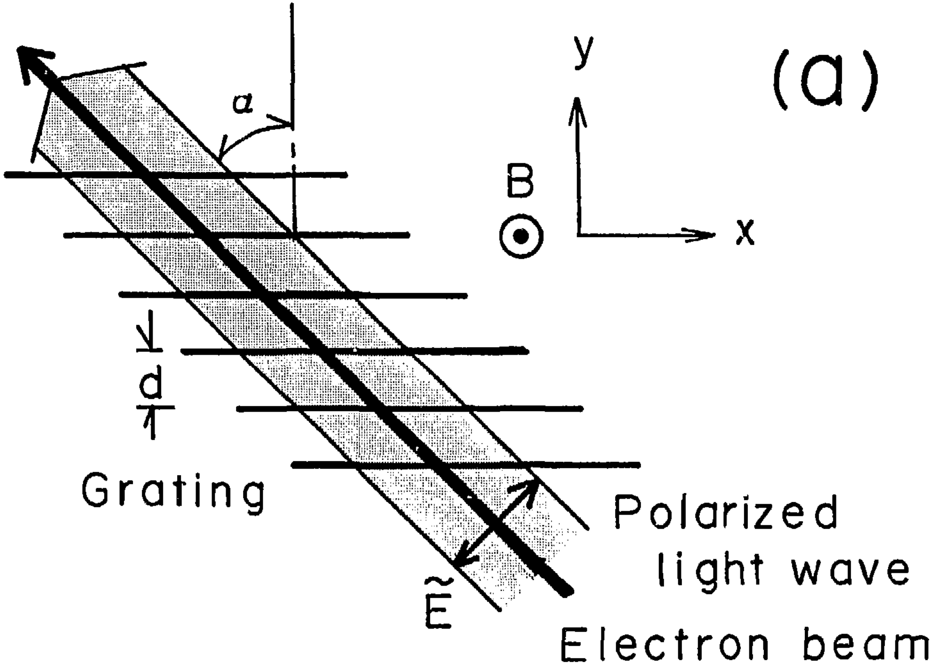

FIG. 2

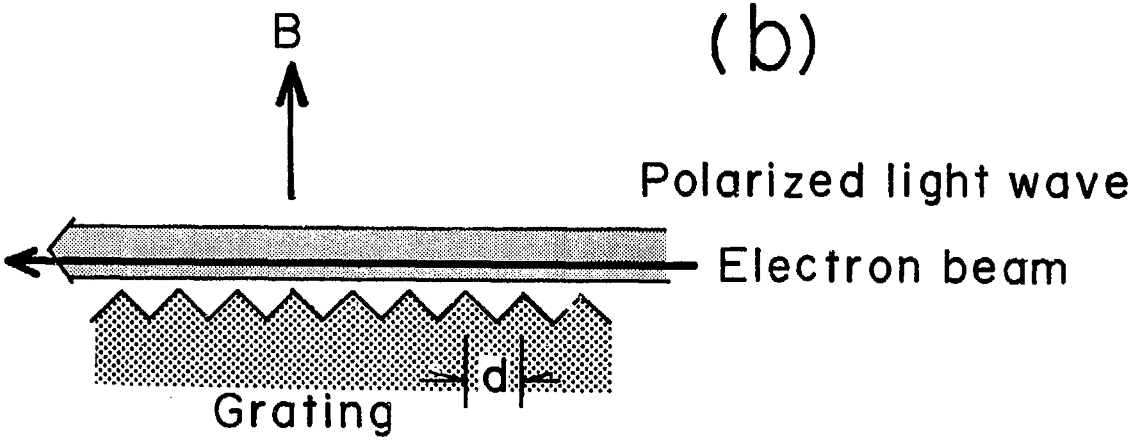

FIG. 2

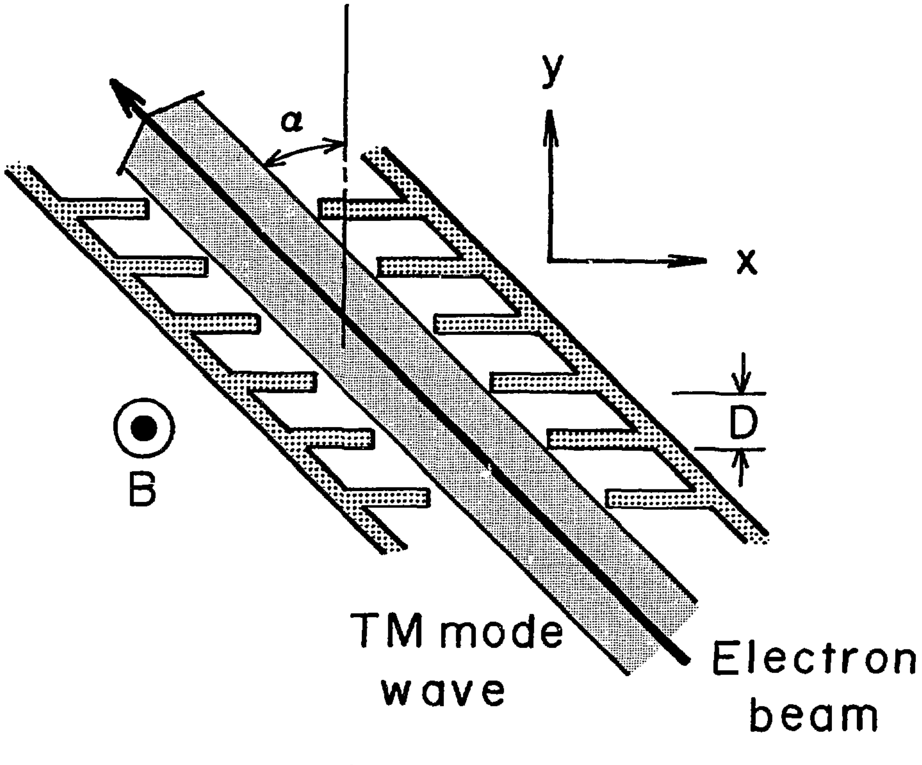

FIG. 3

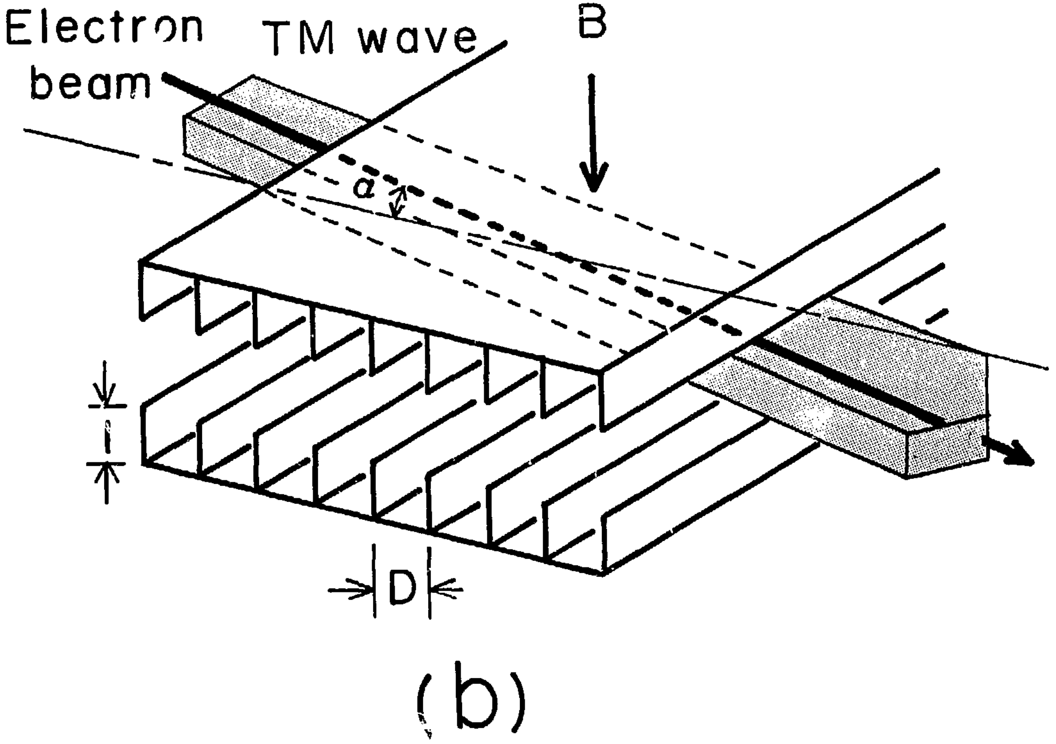

FIG. 3