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A TE-MODE ACCELERATOR : NEW ACCELERATION MECHANISM AND APPLICATION

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ABSTRACT

An accelerator is proposed in which charged particles are driven by a TE-mode instead of longitudinal fields or TM-mode waves used in conventional linear accelerators. The principle of the acceleration is based on "the V_pxB acceleration", or a dynamo force acceleration. A charged particle trapped in a transverse wave feels a constant electric field (Faraday induction field) and is accelerated when an appropriate magnetic field is externally applied in the direction perpendicular to the direction of wave propagation. A pair of dielectric plates is used to produce a slow TE mode. A particle simulation is performed to prove the principle of the mechanism. Discussions are given on several issues associated with the realization of the accelerator.

INTRODUCTION

A compact high-efficiency particle accelerator is required not only in the field of nuclear physics but also in the research of thermonuclear fusion as the driver for inertial fusion. We here present a concept of an accelerator based on a new mechanism of particle acceleration. A particle trapped in an electrostatic wave or in a TM-mode moves with the phase velocity V_p of the wave. If a static magnetic field B_0 is applied in the direction perpendicular to the wave vector k, the trapped particle feels a constant induction field (Faraday induction field) and is accelerated. For simplicity, we call the acceleration caused by this induction field "V_pxB acceleration". The V_pxB acceleration by electrostatic waves in plasmas was discussed by Sugihara-Midzuno[1] and Dawson et al.[2] and developed into the concept of Surfatron[3].

Recently Takeuchi et al.[4,5] showed that a transverse electromagnetic wave can trap charged particles and accelerate them by the V_pxB acceleration. In this paper we discuss the feasibility of an accelerator based on this new particle trapping.

We first introduce a two-dimensional waveguide in which a slow TE-mode wave is excited. The motion of trapped particles, trapping condition and equilibrium phase of trapped particles are discussed. A simulation which verifies the acceleration mechanism is also presented. Finally, several issues associated with the realization of the accelerator are also discussed.

MOTION OF A TEST CHARGE

A waveguide presented here is consisted of pairs of parallel dielectric materials and of conductors (Fig.1(a)). A schematic diagram of the system is illustrated in Fig.1(b). The required components E_x, B_y, and B_z are given by[5]

$$E_x=-E_0\cosh(\beta_0 y)\cos(kz-\omega t+\alpha) \tag{1a}$$

$$B_y=-(c/V_p)E_0\cosh(\beta_0 y)\cos(kz-\omega t+\alpha) \tag{1b}$$

$$B_z=(\beta_0/\kappa_0)E_0\sinh(\beta_0 y)\sin(kz-\omega t+\alpha) \tag{1c}$$

where β_0 and κ_0 are the wave numbers in the y and z-directions, respectively, and α is a phase angle.

The equation of motion for each velocity component of a test charge (electron) will be given by

$$md(\gamma v_x)/dt=-eE_x-(e/c)v_yB_z+(e/c)v_z(B_y+B_0) \tag{2a}$$

$$md(\gamma v_y)/dt=(e/c)v_xB_z \tag{2b}$$

$$md(\gamma v_z)/dt=-(e/c)v_x(B_y+B_0) \tag{2c}$$

where $\gamma=(1-v^2/c^2)^{-\frac{1}{2}}$. We deal with the motion in the wave frame and have the equation of motion in the forms

$$md(\Gamma V_x)/dT=(e/c)\gamma_pV_pB_0+(e/c)(V_zB_t-V_yB_z) \tag{3a}$$

$$md(\Gamma V_y)/dT=(e/c)V_xB_z \tag{3b}$$

$$md(\Gamma V_z)/dT=-(e/c)V_xB_t \tag{3c}$$

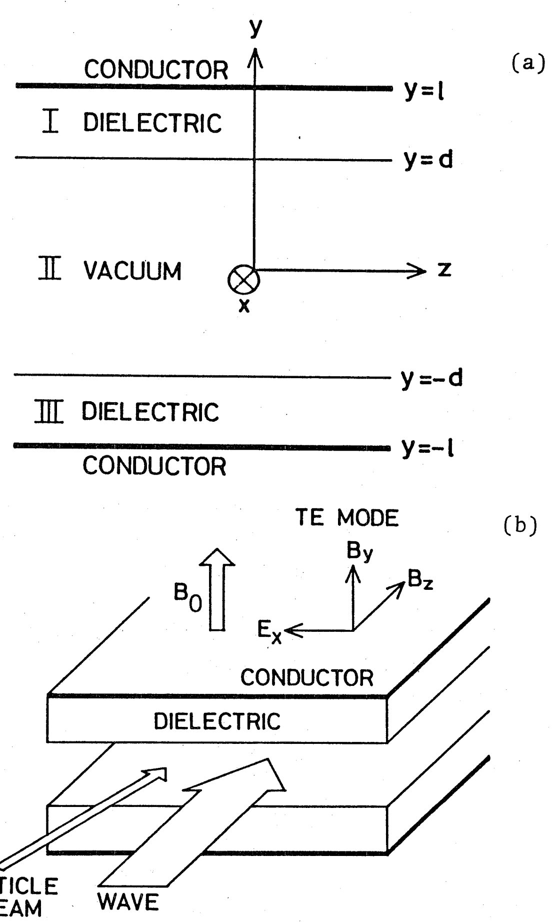

Fig.1 The waveguide and schematic diagram of the system.

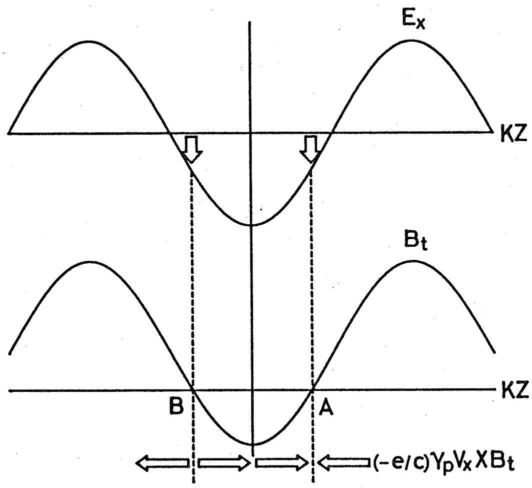

Fig.2 Mechanism of the trapping and acceleration by the slow TE wave.

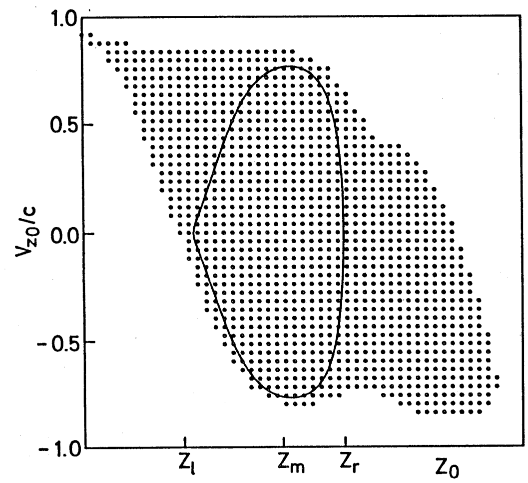

Fig.3 Trapping region in the phase space Z_0-V_{z0}.

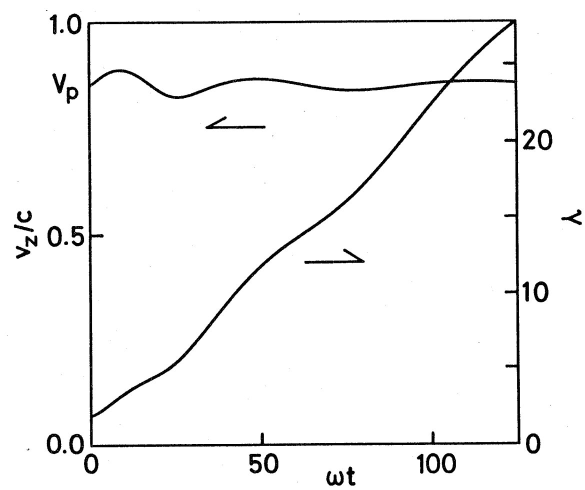

Fig.4 Time evolutions of the velocity v_z and γ.

where the capital letters V_x,V_y,V_z,T and Γ are those corresponding to the lower-case letters in (2a)-(2c) in the laboratory frame. The B_t is the y component of the total magnetic field in the wave frame, namely

$$B_t = \gamma_p^{-1} B_y + \gamma_p B_0. \qquad (4)$$

The field components B_y and B_z are equivalent to those in (1b) and (1c). The constant term $(e/c)\gamma_p V_p B_0$ in (3a) represents the induction field which accelerates the trapped particle and from which the terminology "V_pxB acceleration" is originated.

The motion along the Y axis, for a while, is assumed to be inhibited, i.e., Y=0 and V_y=0. We also assume that B_t in (4) becomes zero at some points as shown in Fig.2. This implies B_t having neutral points and is realized when

$$E_0 > \gamma_p (V_p/c) B_0. \qquad (5)$$

We note that a particle near a neutral point sees a constant electric field. Hence, the particle being around the point and moving with almost the same velocity as V_p experiences this constant field and is accelerated in the direction perpendicular to both directions of B_0 and of the wave propagation. Near the neutral point of A, the particle feels the restoring force equivalent to the Lorentz force $f_z=(-e/c)\gamma_p V_x x B_t$. As the velocity V_x increases with time, the force f_z becomes stronger and the particle is more tightly trapped in the neutral point of A. The above reason indicates that the trapped particle can never detrap from the neutral point and continues to be accelerated unlimitedly. These features can be shown analytically by reducing the equation of motion to an equation of anharmonic oscillator and by discussing the orbit of the particle (see Ref.4).

We have discussed the new acceleration in some quantitative fashon in Ref.4 and the result is displayed in Fig.3. The closed circles indicate the trapped particles. The particles inside the solid line are those which were initially in the potential well and the ones outside the line are those which were trapped as time elapses. The latter happens because the potential well becomes deeper as time passes. The positions Z_ℓ and Z_r are the points between which a merginally trapped particle bounces initially and Z_m indicates the potential minimum.

ENERGY GAIN OF THE TRAPPED PARTICLE

The energy gain of the trapped particle is obtained from the equation of motion (2a)-(2c) as

$$mc^2 d\gamma/dt = -ev_x E_x. \qquad (6)$$

Using the each field of (1) with y=0 and kz-ωt=0, and the velocity components $v_x \doteqdot (c^2-V_p^2)^{\frac{1}{2}} = c/\gamma_p$, $v_z \doteqdot V_p$ for the tightly trapped porticle we get the rate of energy gain from (6) in the forms

$$\Delta U/\Delta t = ec(\gamma_p^2-1)^{\frac{1}{2}} B_0 \qquad (7a)$$

$$\Delta U/\Delta z = e\gamma_p B_0 \qquad (7b)$$

$$\Delta U/\Delta x = e\gamma_p(\gamma_p^2-1)^{\frac{1}{2}} B_0 \qquad (7c)$$

where $\gamma_p B_0 = cE_0 \cos\alpha / \gamma_p V_p$ is used. In Fig.4, time evolutions of the velocity component v_z and γ in the laboratory frame are shown. The γ follows the prediction of (7), and the behavior of v_z indicates that the particle centers on Z=0.

The ratio of the acceleration length along x to z-directions is

$$\Delta x/\Delta z = (\gamma_p^2-1)^{-\frac{1}{2}}. \qquad (8)$$

Equation (8) implies that the particle orbit makes narrower angle with the propagation direction of the wave as γ_p becomes greater.

NUMERICAL SIMULATION

In order to check the physical mechanism of the TE-mode acceleration and the interaction between particles and the electromagnetic(EM) wave, a numerical simulation is performed by using a one-dimensional electromagnetic particle-in-cell(PIC) code.

In the real situation the slow mode of EM wave can be generated by using the dielectric material shown in Fig.1. For simplicity in the numerical analyses the slow mode of EM wave is realized by changing the dielectric constant in the Maxwell equation. In order to check the acceleration mechanism the artificial setting of the dielectric constant does not matter.

In the simulation the cyclic boundary condition is employed. Initially the number density of imposed electron beam is uniform in space. Figure 5 shows an example of numerical simulations. In this case the phase velocity of EM wave is 0.85c. The averaged particle velocity is 0.85c in the direction of wave propagation and 0.2c in its transverse direction. In the momentum space the particles are distributed following the Maxwell distribution function with the temperature of 5.4keV. The employed number density is in this case quite low so that any instability be avoided and so that the acceleration mechanism be demonstrated. Figure 5 presents that a part of introduced particles are trapped and accelerated by the EM wave clearly. The electric field of EM wave is 3.22×10^{5} (V/cm) and the wave length is 1 cm in this example. The applied static magnetic field has the strength of 132 (Gauss). Further investigation is now under way.

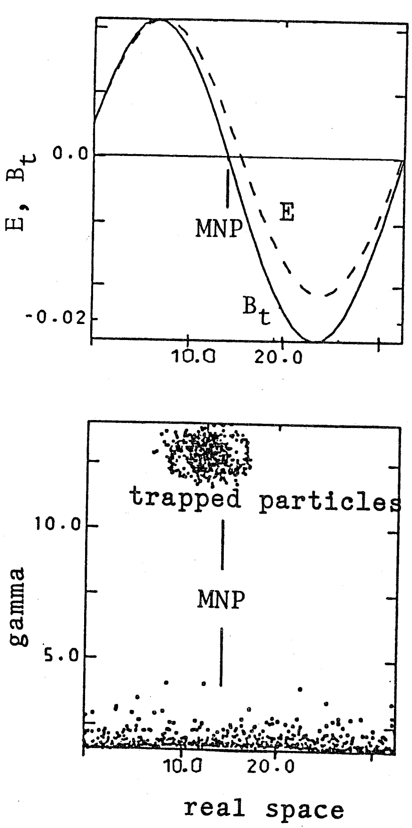

Fig.5 An example of particle simulations
Acceleration of trapped particles. The location of the magnetic neutral point is indicated by MNP.

DISCUSSION AND CONCLUSIONS

So far we have inhibited the motion along the y-axis. Due to the presence of B_z component the particle motion could become unstable. We can show, however, that the motion is stabilized by an introduction of an appropriate stabilization magnetic field. In an actual experiment or in an accelerator, the transition radiation or a polarization loss causes an energy loss of the particle. We, however, find that the loss can be disregarded if a wave with wavelength longer than 1μm is used.

An example of TE mode and parameters of the relevant waveguide are given in Table 1 by using parameters of the waveguide with $d=\ell/2=1.2$(cm), $\varepsilon_1=2.3$ and $\mu_1=1$. By the use of a certain pair of E_0 and the static field B_0 which satisfy the relation (5), the rate of the energy gain of an electron is also given in the same table.

Table 1

	injected EM wave	excited TE mode
wave length(cm)	$\lambda_0=3$	$\lambda=2.49$
wave number(cm^{-1})	$k_0=0.33$	$k=0.40$
frequency $f=\omega/2\pi$ (GHz)	f=10	f=10

$V_p/c=k_0/k=0.83$, $\gamma_p=1.80$, $\Delta x/\Delta z=0.67$

rate of energy gain	$\Delta U/\Delta z=0.54$ (GeV/m)
wave electric field	$E_0=10^7$ (V/cm)
static magnetic field	$B_0=10^4$ (Gauss)

An advantage of this scheme of acceleration is that we do not need the tuning of the phase velocity since once the particle is trapped it never detraps from the wave and continues to be accelerated indefinitely as long as the wave is sustained.

In conclusion, a TE-mode accelerator is proposed, the principle of which is based on $V_p \times B$ acceleration or a dynamo force acceleration. A slow TE mode which couples with the electrons is shown to be excited in a wavequide composed of a pair of dielectrics. When a static magnetic field is applied in the direction perpendicular to the wave vector k, the particles are trapped and accelerated in the direction perpendicular to both B_0 and k under the condition that $v_z=V_p$ and (5). Although the rate of acceleration is limited by the acceleration field which is, for example, 0.5 GV/m for a microwave of the wavelength 1cm, the acceleration is unlimited. By the use of a 2-3 km accelerator based on the present principle we may have tera-electron-volt electrons though there are very many problems left to be surmounted.

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