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Electron Acceleration by TE wave based on $V_p \times B$ Acceleration

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abstract

To demonstrate the $Vp \times B$ acceleration mechanism using TE wave in vacuum we have designed a slow wave structure with a dielectric material. This mechanism predicted the electron acceleration by transverse electromagnetic wave by applying external magnetic field to break a symmetry of the fluctuating magnetic field of the wave. Magnetic neutral point is formed along the wave propagating direction and charged particles are bunched there. The electromagnetic waves need to have a phase velocity less than a speed of light to interact with electrons. The phase velocity in a slow wave we designed with dielectric materials has been measured to indicate the phase velocity of 0.43c and the dielectric constant can be estimated to be 6.3 at 2.45 GHz.

Introdution

Recent interests of charged particle accelerators are focused on generating a much higher acceleration gradient than the present conventional accelerators which have typical acceleration gradient of about 10 – 20 MeV/m. In the last decade some of new acceleration schemes specifically using a plasma, including a plasma wake field accelerator (PWFA), a plasma beat wave accelerator (PBWA) and a $v_p\times$B accelerator (or a surfatron), have been proposed.[1–10] In addition to them, a possibility of the charged particle acceleration using a transverse electric field added with a weak external static magnetic field in parallel to the wave magnetic field has also been discussed.[11] Some of the experimental results based on the above mentioned schemes have shown to give a higher acceleration gradient than the conventional methods has, and within next three years, the acceleration gradient for electrons or positrons, could achieve more than 1 GeV/m gradient or 1 GeV within 10 m accelerator. The new schemes using plasma can be expected to generate much higher electric field for acceleration, but it is also easy to pick up some difficulties of controlling plasma parameters for adjusting the appropriate conditions for the accelerator. The $v_p\times$B acceleration phenomena have been observed in the experiments of microwave-plasma interaction for the first time. In this scheme a static magnetic field is applied vertically to the wave propagation direction and the particles are accelerated continuously along the wave front at constant phase with respect to the wave, until the trapping condition breaks. This condition can be determined by the strength of the wave electric field, the wave phase velocity and the applied static magnetic field as far as the longitudinal wave exists.[6] In this mechanism the existence of the plasma is not necessarily essential, therefore the charged particle could be accelerated even in vacuum and the experimental results have been reported.[8,9]

This mechanism can be applied to the electron acceleration by the TE (Transverse Electric) wave that propagates in vacuum. The static magnetic field is applied in parallel to the magnetic field of the electromagnetic wave and makes a trapping position in the phase space by breaking the symmetry of the fields.

In this paper the theory of the $V_p \times B$ mechanism of the electron acceleration using TE wave in vacuum and the experimental results that generate the slow wave using dielectric materials are described.

Theory

We consider the $V_p \times B$ acceleration mechanism using TE wave as schematically shown in Fig. 1, in which the electromagnetic wave propagates in the z direction. Then the x component of the electric field of the wave E_x and the y component of the magnetic wave B_y can be represented as follows;

$$E_x = E_{x0}\sin(kz - \omega t),$$
$$B_y = B_{y0}\sin(kz - \omega t),$$

To realize the $V_p \times B$ mechanism, a static magnetic field B_0

whose strength is less than the maximum amplitude of the magnetic field B_{y0} is applied in the y direction. The resultant magnetic field is

$$B = B_y + B_0 = B_{y0}\sin(kz - \omega t) + B_0$$

Two magnetic neutral points, which are defined as the point where the value of the magnetic field is zero, is formed along the z direction. At these points, although there are no magnetic fields, there exits the electric field.

Next we consider a particle motion around the magnetic neutral points that are denoted as A and B in Figure 1 (b). There are two points at which the direction of the force changes. The particles near the point A feel the Lorentz force as the restoring force, while the repulsive force near the point B. Thus, the particles bunch toward the point A, called the trapping point.

II. Experiments

The EM waves need to propagate with the phase velocity as same as the electron velocity to interact efficiently with the electron. To generate such an electromagnetic wave, the slow wave structure using dielectric materials was chosen. Figure 2 shows the schematic view of the slow wave structure. The accelerator is 50 cm in length and the dielectric is 25 mm in thick. The selected material was Folsterite that has the dielectric constant 7.0 at 1 MHz. The upper dielectrics can move in the y direction to change the phase velocity. The EM wave propagates between the dielectrics in the z direction with the phase velocity less than c, the speed of light. The phase velocity of the wave is mainly determined by the thickness of the materials, their separation and the wave frequency. Although the phase velocity is predicted by the theory, we measured it at first because of the lack of the data of the dielectric constant in higher frequency region.

Experimental setup for measuring the phase velocity is shown in Fig. 3. The EM wave with the frequency 2.45 GHz that is emitted from the standard oscillator, is divided into two directions. One is led into the accelerator and is absorbed by the dummy load at the end of the accelerator. The electric field in the slow wave structure is measured by the probe that can scan in the z direction. The signal obtained by it has the phase difference with respect to the original signal. Other EM wave is mixed up with the signal from the probe. The mixed signal has a higher and a lower frequency component. The low pass filter (LPF) can eliminate the higher signal. The resultant data drawn on an $x - y$ chart describes the wave length in the accelerator. The phase velocity is obtained as follow;

$$V_p = \omega / k'.$$

Experimental data is shown in Fig. 4. The horizontal axis shows the thickness of the dielectric material normalized by the half of their separation and the vertical axis represents the phase velocity normalized by c. The solid line is calculated from the theory indicating the dielectric constant at the frequency 2.45 GHz of $\varepsilon_s = 6.3$.

Conclusion

We have constracted the dielectric wave guide to demonstrate the $V_p \times B$ acceleration mechanism using the transverse electric wave in vacuum. Preliminary experiments which measured the phase velocity of the wave have been carried out. The results show the velocity is $0.43c$ and the dielectric constant of the material is estimated to be 6.3. In the acceleration experiments the formation of the $V_p \times B$ acceleration mechanism and the electron accelerations are predicted.

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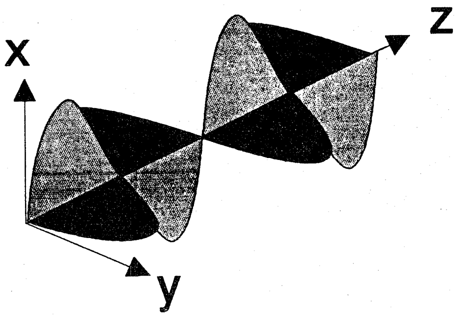

FIG.1(a)

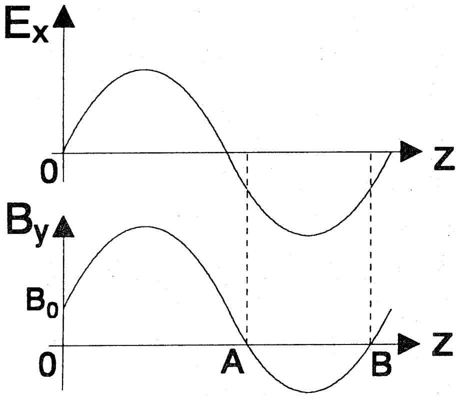

FIG.1(b)

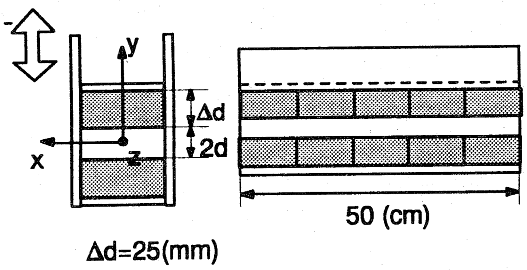

FIG.2

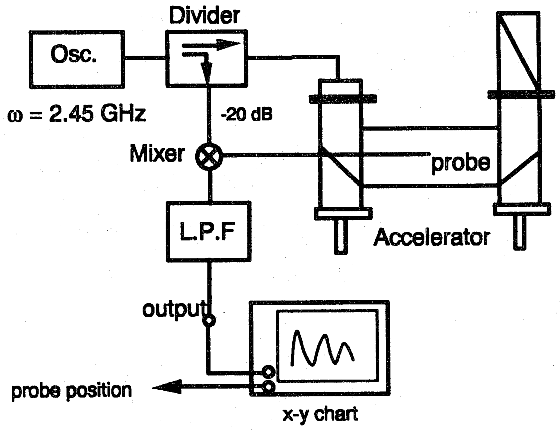

FIG. 3

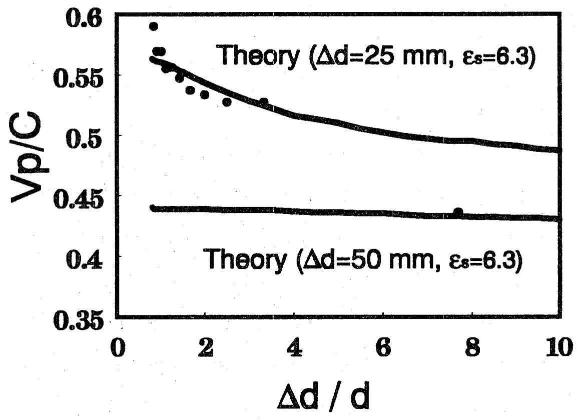

FIG. 4