Electron Linear Accelerator based on $V_p \times B$ Acceleration Mechanism using Disk – Loaded Slow Wave Structure

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Abstract

The mechanism of $V_p \times B$ acceleration, which has been demonstrated by using a square shaped slow wave structure, [1-3] higher acceeleration rate compared with a conventional electron linear accelerator. In the present experiments a disk – loaded slow wave structure is employed for demonstrating this mechanism. The incident electron beam velocity is about 0.43c (corresponding to 50 keV). The energy increment of the electron is proportional to the square of the applied magnetic field until the paarticle trapping condition breaks, in reasonable agreements with the theory.

Introduction

Recent particle accelerators require a tremendously large appratus in order to obtain fully accelerated high - energy particles. The particle accelerators demand new acceleration principles that can create a high field gradient . Several new acceleration shemes, specifically using plasma, including a plasma wake field accelerator (PWFA), a plasma beat wave accelerator (PBWA) and a $V_p \times B$ accelerator, have been proposed.[4-11]

In this paper, we report experimental results on the electron linear accelerator based on new type particle acceleration scheme, which is called the $V_p \times B$ acceleration scheme, or the Cross Field Accelerator (CFA). The $V_p \times B$ acceleration phenomena have been observed in the experiments of microwave - plasma interaction for the first time. [10] In this scheme a static magnetic field is applied vertically to the wave propagating direction and the particles are accelerated continiously along the wave front at constant phase with respect to the wave, until the trapping condition breaks. In this scheme, the driver wave should be a longitudinal mode, but the transverse wave could also be employed.

Theory of $V_p \times B$ Acceleration

We consider the motion of a charged particle in the laboratory frame of reference(Fig.1). The static magnetic field is applied in the x direction. An electromagnetic field propagates in the z direction. The present electromagnetic wave is TM mode, which has a longitudinal component of the wave electric field.

The motion of charged particle can be written in the frame moving with a phase velocity v_p (wave frame).

$$m_0 \frac{d(\Gamma V_y)}{dT} = qB_0\gamma_p(V_z + v_p), \tag{1}$$

$$m_0 \frac{d(\Gamma V_z)}{dT} = qE_0 \sin(KZ) - qB_0\gamma_p V_y, \tag{2}$$

where the capital letters denote the values measured in the wave frame and $\Gamma = (1 - V^2/c^2)^{-1/2}$, $V^2 \equiv V_z^2 + V_y^2$, $K = k/\gamma_p$, and $\gamma_p = (1 - v_p^2/c^2)^{-1/2}$.
In eq.(2),if

$$E_0 > \gamma_p B_0 V_y \tag{3}$$

is satisfied, the particles are kept accelerating. This is the trapping condition of the particle in the $V_p \times B$ acceleration scheme.
The total energy of the electron γ is written as

$$\gamma(y) = \gamma_p \left[1 + \frac{\omega_c v_p \gamma_p}{c^2} y\right], \tag{4}$$

or

$$\gamma(z) = \gamma_p \left[1 + \frac{\omega_c^2}{c^2} z^2\right]^{1/2}. \tag{5}$$

The increment of γ in y and z direction are

$$\frac{d\gamma}{dy} = \frac{\omega_c v_p \gamma_p^2}{c^2}, \tag{6}$$

$$\frac{d\gamma}{dz} = \gamma \frac{\omega_c^2}{c^2} z \left[1 + \frac{\omega_c^2}{c^2} z^2\right]^{-1/2} \approx \gamma_p \frac{\omega_c}{c}. \tag{7}$$

Thus, in the limit $v_p \to c$, the increment in the y direction is γ_p times larger than in the z direction, i.e. the $V_p \times B$ acceleration has larger degree of acceleration compared with the conventional acceleration scheme.

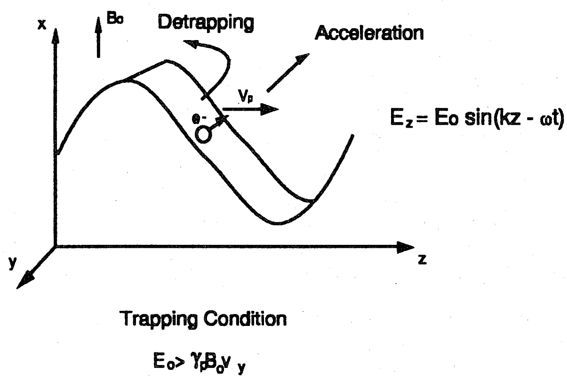

Figure 1

Experimental Apparatus

Figure 2 shows the experimental apparatus. The electron gun for the electron beam injection has a maximum energy of 100 keV with a maximum beam current of 1.5mA. The accelerated electrons through the accelerator are analyzed by the electron energy analyzer, and are detected by an MCP(micro channel plate) detector.

The RF source is a magnetron of 2.45 GHz with a typical pulse width of 10 μsec in repetition of 10 Hz. The maximum power is 10 kW. A vertical magnetic field in the x directions is produced by a pair of saddle - shaped coils. The maximum strength of the applied static magnetic field is 10 Gauss. The present experimental apparatus can be operated as a conventional linear accelerator, when no magnetic field is applied. Therefore, we can easily demonstrate both the $V_p \times B$ acceleration and the conventional linear accelerator.

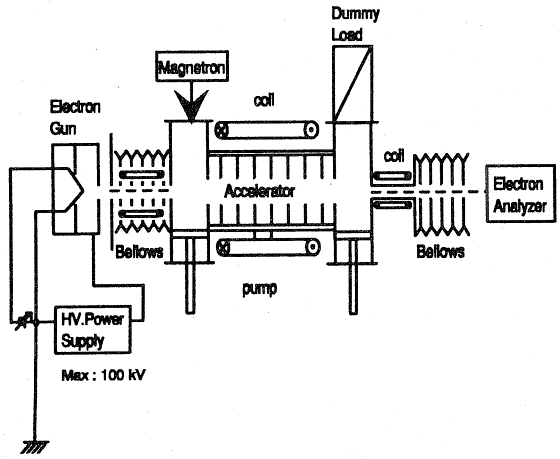

Figure 2

Experimental Results

Figure 3 shows the energy increment as a function of the incident electron energy varied from 10 to 60 keV. Symbol ◇ , □ , and ○ denote the results when the applied magnetic field is 0, 0.33, and 0.5 Gauss, respectivily. Three acceleration regions appeared. Typical examples of the observed energy spectrum with the change of the applied magnetic field are shown in Fig.4 , where the incident beam energy is 42 keV. At $B = 0$, the accelerator operates again as the conventional electron accelerator. Until $B = 1.1$ G , the electron energy corresponding to the peak flux indicated by an arrow increases. For further increase after $B = 1.1G$, the decrease of electron energy was observed. This shows that the magnetic field strength $B = 1.1$ G is a critical value for the trapping condition. Detailed discussion will be presented later on Fig.5 shows the relation between the applied magnetic field and the energy increment $\Delta\varepsilon$. Where the incident electron beam energy is 42 keV in Fig.5 . Solid line represents that $\Delta\varepsilon'$ which is proportional to B^2 . This dependence will be discussed in the next section.

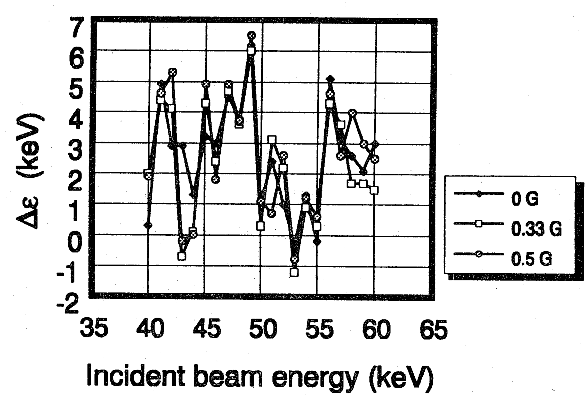

Figure 3

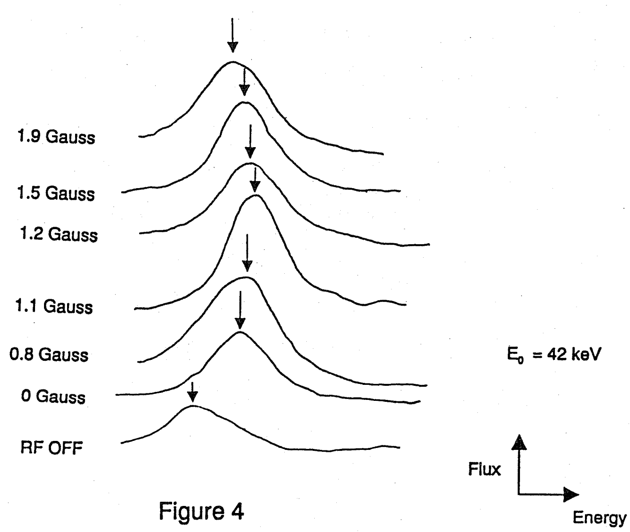

Figure 4

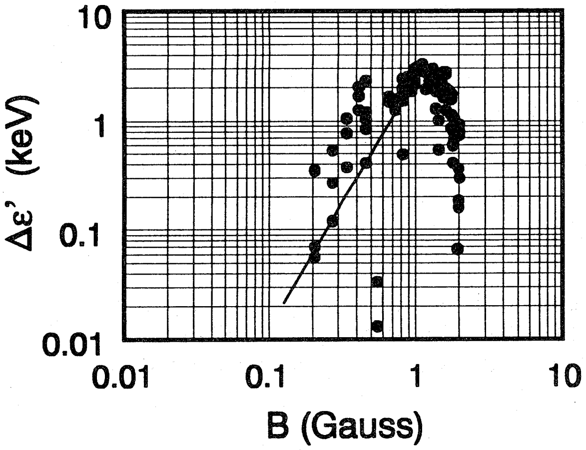

Figure 5

Discussion

In eq.(5), $\gamma(z)$ expresses the total energy of the electron. The energy gain($\Delta\gamma = \gamma(z) - \gamma_p$) is given by

$$\Delta\gamma = \frac{\gamma_p}{2}\left(\frac{\omega_c z}{c}\right)^2. \tag{8}$$

Therefore, we obtain

$$\Delta\varepsilon' = \Delta\gamma mc^2 = \frac{\gamma_p}{2m}(eB_0 z)^2 \propto B_0^2. \tag{9}$$

This equation shows that $\Delta\varepsilon'$ is proportional to B^2. The experimental results are in fairly good agreements with the theory.

We consider the trapping time of electrons. If t_d is the time when the electron is detrapped from the wave trough, we have

$$\omega_c t_d = \frac{1}{\delta}\sqrt{1-\delta^2} - \cos^{-1}\delta + kz(0) - \frac{kv_x(0)}{\omega_c} \tag{10}$$

where $\delta = \omega_c^2/\omega_b^2 \ll 1$, $\omega_c = qB/m$, and $\omega_b^2 = qEk/m$. In the experiment, we assume that $z(0) = 0$, $v_y(0) = 0$, at $t = 0$, then we obtain,

$$\omega_c t_d = \frac{1}{\delta}\sqrt{1-\delta^2} - \cos^{-1}\delta. \tag{11}$$

Since $\delta \ll 1$, we have

$$\omega_c t_d = \frac{1}{\delta} \tag{12}$$

$$t_d = \frac{kmE}{q\omega_c b^2} = \frac{mE}{qcB^2} = 1.90\frac{E(kV/m)}{B^2(Gauss)}(ns) \tag{13}$$

Table 1. The parameters of the experimental results and t_d

E (kV/m)	B (Gauss)	t_d (ns)	τ (ns)	B_d (Gauss)
3.2	1.1	4.95	4.18	1.21

Inserting experimental values, the caluculated t_d , τ , B_d are listed in table 1. Symbole τ represents the time when the electron travels through the accelerator with the incident velocity. Where τ is the transit time of electrons with an initial velocity, E is the electric field in the accelerator, and B_d is a value of magnetic field for $t_d = \tau$. The table 1 shows $t_d \simeq \tau$ and $B \simeq B_d$. Thus, the experimental results can be compared with the theory.

Conclusion

The $V_p \times B$ acceleration scheme are demonstrated in a disk - loaded electron linear accelerator. The energy gain ($\Delta\varepsilon'$) for $V_p \times B$ acceleration is proportional to B^2, and is in fairly good agreement with the theory. When the incident beam energy is 42 keV, the electron is detrapped from the wave trough at B = 1.1 (Gauss), and showing the coincidence with the theoretical value.

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