Resonant Wave-Particle Interactions in $\mathbf{v}_p \times \mathbf{B}$ Acceleration Scheme

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Experimental investigations on the resonant wave-particle interaction in the framework of both a $\mathbf{v}_p \times \mathbf{B}$ acceleration and a conventional resonance-absorption scheme have been performed by injecting electron beams into the wave-particle interaction region. In the $\mathbf{v}_p \times \mathbf{B}$ acceleration scheme, the particles can interact with the wave for a longer duration and the final particle energy reaches larger values (about 1.5 times) than those observed in the resonance absorption. A simple model based on the $\mathbf{v}_p \times \mathbf{B}$ acceleration scheme can interpret the results.

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Several new concepts for high-energy particle accelerators using plasma and related phenomena have been proposed.[1-8] One of these is a $\mathbf{v}_p \times \mathbf{B}$ accelerator[5] (also called a surfatron[3] or a cross-field accelerator[8]), where $\mathbf{v}_p$ is a wave phase velocity and $\mathbf{B}$ is a static magnetic field. In this scheme particles are accelerated along the wave front of a driver wave propagating perpendicularly to a static magnetic field. Theoretical[2,3,9] and experimental[5-8,10-13] investigations of the $\mathbf{v}_p \times \mathbf{B}$ acceleration phenomena have already been reported. The experimental results, however, were not fully controllable, because, in the experiments performed so far, only electrons of the background plasma, which have a velocity near the phase velocity of the excited plasma wave, were trapped and accelerated to high energy by the wave. Therefore, the number density of the trapped electrons and so the electron current flux could not be controlled. Furthermore, the initial velocity of the electrons trapped in the wave trough was not clearly identified because the phase velocity of the plasma wave was not very precisely determined. The wave-particle interaction, which is a key phenomenon of the present $\mathbf{v}_p \times \mathbf{B}$ acceleration mechanism, should be controlled very precisely for further understanding of the $\mathbf{v}_p \times \mathbf{B}$ phenomenon and its application to a high-energy particle accelerator.

In this paper, we present experimental results in which an electron beam with variable velocity and flux, produced from a small electron gun, is injected into a region of existing plasma wave, in order to show direct evidence of the wave-particle resonance interaction and particle acceleration. Specifically, the first demonstration of the acceleration of the injected electron beam by the $\mathbf{v}_p \times \mathbf{B}$ acceleration process is presented.

The experiments are performed in a cylindrical stainless-steel chamber with multidipole magnets on the outside of the chamber wall [Fig. 1(a)]. The argon plasma immersed in a weak magnetic field B (<11 G) is produced by pulse discharges (discharge duration of 3 msec and 10 Hz repetition). Typical plasma parameters are plasma density $n_e \lesssim 1\times10^{11}$ cm^{-3}, electron temperature $T_e \simeq 3$–5 eV, ion temperature $T_i \simeq T_e/10$, and density gradient scale length in the axial direction (z direction) $L_z \simeq 100$–150 cm and in the radial direction $L_r \simeq 100$–200 cm. Here, the static magnetic field is produced by a pair of saddle-shaped coils with diameter of about 60 cm. p-polarized microwaves with frequency 2.86 GHz, maximum power of 10 kW, and typical pulse width of 5 μsec are irradiated from the lower-density side through a

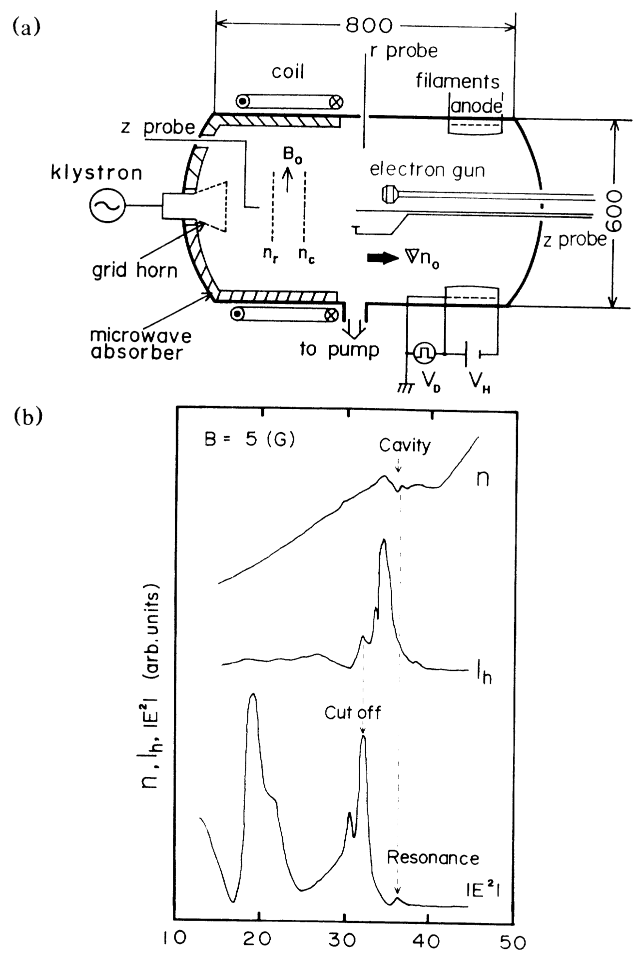

FIG. 1. (a) Experimental arrangement and (b) typical spatial profiles of electron density in steady state, n, high-energy electron emission, I_h, and absolute value of the rf electric-field pattern, E^2, vs the distance measured from the horn-antenna edge.

high-gain horn antenna. The typical rise time is about 50 nsec. An electron beam is injected into the interaction region from a small gun located at the higher-density side. The maximum energy available from this gun is 500 V at a beam current of 200 mA. The diagnostics include a tiny plate probe (1 mm×1 mm) for electron energy analysis and a cylindrical probe (0.5-mm diameter by 1.0-mm length) for measuring the field strength of the electron plasma wave. A reliable electron energy spectrum can be measured, with maximum energy up to about 400 eV in the present system, but the absolute strength of the wave field cannot be determined.

Before the electron beam is injected into the area where resonance absorption of the microwaves[14] occurs, we measure the damping length of the injected beam. As the particle mean free path in the present energy range is long enough (about 1 m), collisional damping of the beam is not important, and the defocusing effect resulting from the nonuniform electric field of the electron gun is dominant. The characteristic damping length $L_b = (d \ln n_b/dz)^{-1}$ of the electron beam is about 4.0 cm in the state without magnetic field, and the electron beam can be observed up to about 10 cm from the gun surface. Even in the state with magnetic field this length does not change essentially. When high-power microwaves are irradiated from the lower-density side, resonance absorption[14] occurs at the layer where the condition $\omega = \omega_{pe}$ is met, and density cavities are observed, such as shown in Fig. 1(b). Here, it should be noted that the plateau of the density profile in this figure is caused by the existence of the electron gun. When we apply a static magnetic field in order to effect the $\mathbf{v}_p \times \mathbf{B}$ acceleration scheme, a high-energy electron flux I_h (≥ 60 eV) in the direction of $(-e)\mathbf{v}_p \times \mathbf{B}$ (y direction) is observed, such as shown in Fig. 1(b).

As the first step, we have precisely measured the high-energy electron flux (≥ 60 eV) and its maximum energy as a function of the incident electron-beam energy. We confirmed beforehand that the energy of the electron beam is proportional to the acceleration voltage V_b. Figures 2(a) and 2(b) show the data observed in the case of no magnetic field, which corresponds to the case of resonance absorption. As the characteristic nature of the electron beam is controlled by the electron gun, particle trapping into the wave trough and particle accleration by the wave can be observed in a controlled manner. The high-energy electron flux I_h versus the beam accleration voltage is shown in Fig. 2(a), in which the open circles correspond to the accelerated high-energy component, and the solid ones to the incident beam itself. A resonantly larger flux is observed in the accelerated component with its peak at $V_b \simeq 150$ V. However, there is no clear peak on the incident beam component, as is expected. Here, the incident beam current I_b, and so the electron current flux, is kept constant at $I_b = 100$ mA. The energy spectrum of the accelerated electrons is measured at the same time. The maximum energy of the trapped component shown in Fig. 2(b) is about 200 eV regardless of the incident beam voltage, while the beam component shows the same energy as the acceleration voltage.

When a static magnetic field is applied, the $\mathbf{v}_p \times \mathbf{B}$ acceleration scheme is established and the high-energy electron flux, which is ejected in the direction of $(-e)\mathbf{v}_p \times \mathbf{B}$, increases more sharply at $V_b \simeq 150$ V, as shown by the open circles in Fig. 2(c). The interesting feature is that the maximum energy in this case increases up to about 330–350 eV, more than 2 times that of the incident beam energy of 150 eV [see Fig. 2(c)]. We can also see that the high-energy component has almost the same energy throughout the entire acceleration voltage range ($V_b \lesssim 400$ V), and the flux of the electron current becomes sharply larger at the resonance voltage of

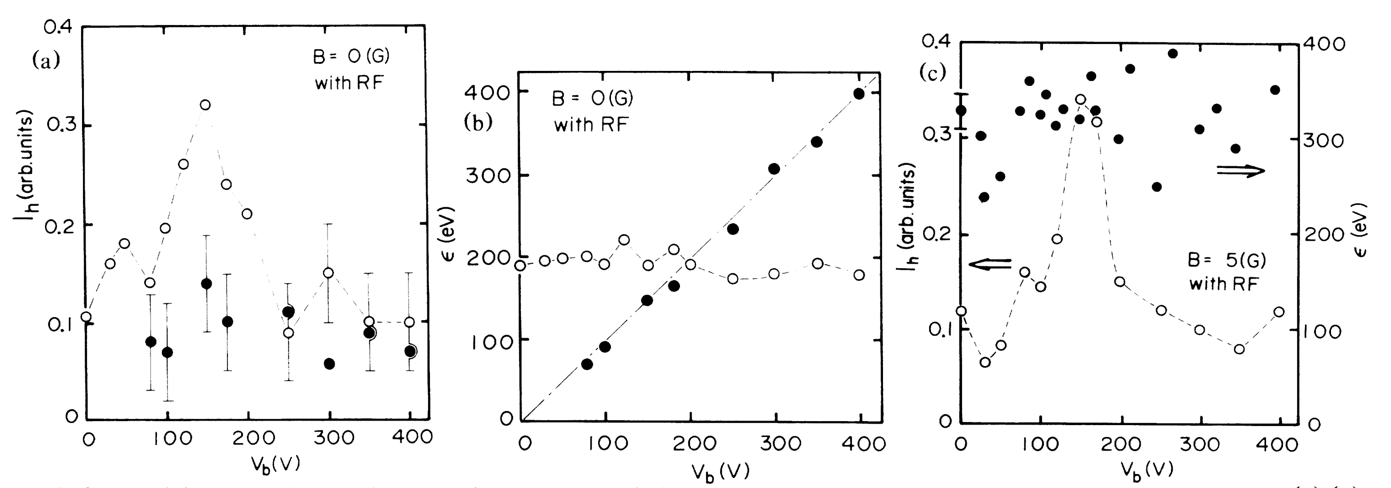

FIG. 2. High-energy electron flux I_h and the accelerated electron energy ϵ vs acceleration voltage V_b of electron beam. (a),(b) $B = 0$ G (resonance absorption), for the injected beam component (●) and the accelerated one (○). (c) The case $B = 5$ G ($\mathbf{v}_p \times \mathbf{B}$ scheme) for I_h (○) and ϵ (●).

$V_b \simeq 150$ V, the same as for the case without magnetic field. This is because at the resonance voltage more electrons with velocity equal to the wave phase velocity exist to be trapped by the wave trough and accelerated to high energy. Except at this velocity, only background electrons with velocity component near 150 V could be trapped and accelerated. The number of electrons in the latter case, however, is quite small in general because of the low electron temperature of the background plasma;[15] the maximum energy after acceleration would still be the same as that at the resonance voltage.

If the resonant increase of high-energy electron flux at $V_b \simeq 150$ V comes from the fact that the beam velocity equals the phase velocity of the electron plasma wave which is excited at the resonance layer, we can estimate the phase velocity of the wave from the following relation:

$$v_p = (2eV_b/m)^{1/2} = 7.3 \times 10^8 \text{ cm/sec},$$

for $V_b = 150$ V. This result is in reasonably good agreement with earlier ones obtained in the same machine by the interferometric method, $(3\text{-}6) \times 10^8$ cm/sec.[10,11]

When an electron plasma wave is excited at the resonance layer, it propagates down the density gradient for several centimeters with accompanying trapped electrons which are injected from the electron gun. If the wave propagates uniformly in space, the electrons once trapped in a wave trough are never released from it if no particle collision nor strong acceleration occurs, and, in principle, the particles are accelerated continuously for a long duration.

The resonance width ΔV_b in Fig. 2 could be determined by the width of the separatrix of the particle trajectory in phase space.[16] The particles existing inside of the separatrix are trapped to move with the wave, but those outside of the separatrix are never trapped and go through the wave. This fact is also suggested from the results shown in Figs. 3(a) and 3(b), where the high-energy electron flux is observed as a function of the beam voltages with the rf input power as a parameter. From these figures, the relation $\Delta V_b \propto \sqrt{P_0}$ is observed, as shown in Fig. 4. Therefore, the maximum amplitude of the wave potential may be $\Delta V_b/2$. As the wavelength λ_p is given as $\lambda_p = v_p/f_p = 0.26$ cm, the electric-field strength of the plasma wave is estimated to be $E_p \simeq \Delta V_b/\lambda_p \simeq 385$ V/cm for $\Delta V_b = 100$ V [see Fig. 3(a)], and the bounce frequency of the trapped electrons is $f_B = k/2\pi \times (e\Delta V_b/2m)^{1/2} \simeq 1.1$ GHz. The number density of the trapped electrons in the wave trough can be controlled by adjusting the acceleration voltage V_b to the phase velocity, and the number density is increased up to at least twice that of the initial state ($V_b = 0$) with the injection of an electron beam, as also seen in Fig. 2.

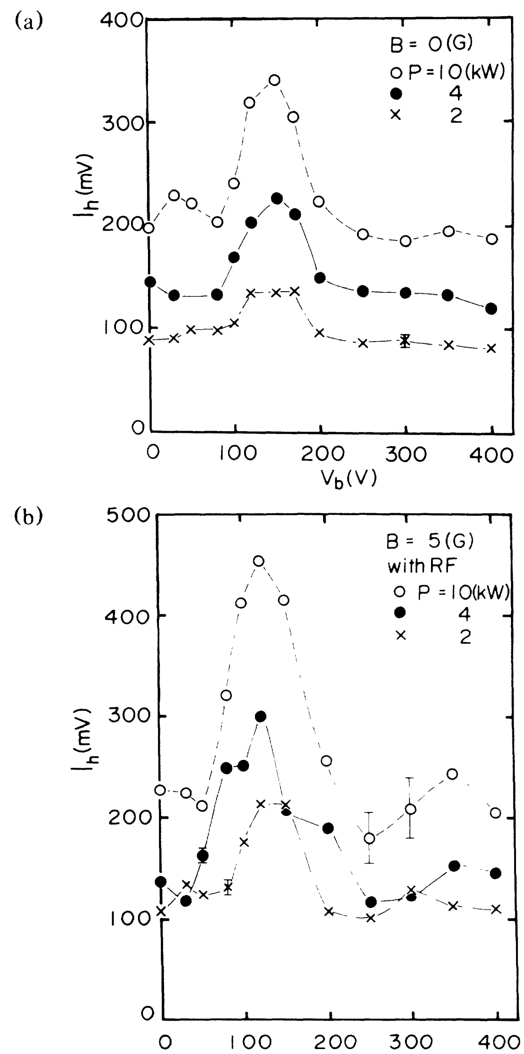

FIG. 3. High-energy electron flux vs the beam acceleration voltage as a function of the microwave irradiation power. (a) $B = 0$ G (resonance absorption) and (b) $B = 5$ G ($\mathbf{v}_p \times \mathbf{B}$ scheme).

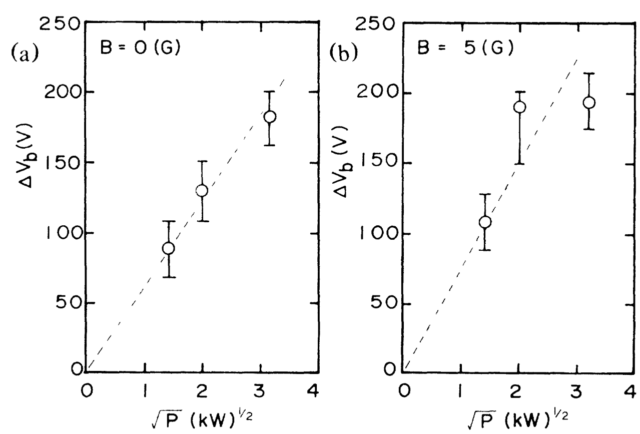

FIG. 4. The maximum width ΔV_b as a function of the square root of the irradiated rf power P, for (a) $B = 0$ G and (b) $B = 5$ G.

When there is no magnetic field in the steady state, electron acceleration by resonance absorption must be observed, and the electrons can gain energy from the wave within a quarter period of the oscillation. As the field strength of the wave is 385 V/cm and the bounce frequency is 1.1 GHz, the acceleration period is $\tau_a = 1/4f_B = 0.22$ nsec, and the maximum energy W_a of the trapped electrons reaches

$$W_a = W_0 + e\Delta V_b/2 = 200 \text{ eV},$$

where W_0 is the initial energy (=150 eV) accelerated by the gun. This result is in good agreement with the experimental results shown in Fig. 2(b).

In the $\mathbf{v}_p \times \mathbf{B}$ acceleration scheme with a static magnetic field, the electron plasma wave with trapped electrons can propagate across the magnetic field over an infinitely large space in the ideal case. The maximum acceleration time t_a, the maximum acceleration length L_a, and the maximum particle energy reached by this process $W_{a\,\max}$ are, as estimated from the $\mathbf{v}_p \times \mathbf{B}$ acceleration model,[6] $t_a = 118$ nsec, $L_a = 4.5$ m, and $W_{a\,\max} = 16.9$ keV, and $v_{y\,\max} = 7.7 \times 10^9$ cm/sec with $\Delta V_b = 100$ V. However, in the present machine, the spatially uniform region is restricted to about several centimeters ($< 10^3$-cm^3 volume), and the particles would be ejected from the wave after traveling this area. As a maximum energy of about 300 eV and $v_y = 1.0 \times 10^9$ cm/sec have been observed in the experiments, corresponding to acceleration period $\tau_a = 16.1$ nsec and $L_a = 8.3$ cm, intercepted electrons undergoing acceleration must have been observed. These results are consistent with the earlier ones.[10,11,13] If a uniform plasma of about 50^3-cm^3 volume could be produced and a large-amplitude electron plasma wave ($E_p \simeq 600$ V/cm), which propagates through this area, could be excited, we would expect high-energy electrons with $W_{a\,\max} = 13.5$ keV to be accelerated from an initial energy of 1.7 keV at $B = 9.5$ G. In order to obtain these results we are trying to excite a large-amplitude plasma wave within a microwave cavity filled with plasma.

In conclusion, we have experimentally investigated wave-particle interactions in the framework of both the $\mathbf{v}_p \times \mathbf{B}$ acceleration and the conventional acceleration scheme of resonance absorption, by injecting an electron beam into the wave-particle interaction region. In the $\mathbf{v}_p \times \mathbf{B}$ acceleration scheme, the electrons can interact with the wave for a longer duration and the final particle energy reaches much larger values than those observed in resonance absorption.

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