Electron Acceleration by Oscillating Electric Field

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A unique experimental system with collisionless electrons has been developed to investigate wave-particle interaction and/or particle acceleration in turbulence. In the system, electrons are injected from a tip of electron source along a magnetic field in a region between two electrostatic potentials. Some of the electrons trapped in the potentials are accelerated and other electrons are decelerated by oscillating electric field localized at the electrostatic potential with larger magnitude. The accelerated electrons were observed as a current into a disk electrode placed outside the steady electrostatic potential with lower magnitude. The results show that the escaping electrons' current was the superposition of (1) current enhanced at some discrete frequencies of the oscillating electric field and (2) current continuously increased with increasing the frequency of the oscillating electric field.

Keywords: electron acceleration, stochastic acceleration, wave-particle interaction, bounce motion

The problem of the resonance was removed by terminating the transmission line in the characteristic impedance of 50 Ω in the present experiment.

1. Introduction

Cosmic ray particles with extremely high energy range between $10^8$ eV and $10^{21}$ eV have been observed [1] and a power law distribution in the medium energy range has been explained by a diffusive shock acceleration model at supernova. The model is based on Fermi acceleration, the original of which was the acceleration by particle scattering against moving magnetic inhomogeneities [2].

In laboratory plasmas, Fermi acceleration has been investigated in relation to wave-particle interactions or interactions between electric field and electrons from the wave viewpoint [3, 4, 5] and from the particle viewpoint [6, 7, 8]. Subsequently, the experiment of electron heating has been performed in an electron trap, where oscillating electric fields interacted with bouncing electrons [9]. Similar work was reported in the past in an after glow plasma as a model experiment of the transit time heating based on Fermi acceleration [10]. In these experiments, electrons were thermalized due to frequent electron collisions.

In the present experiment, electrons were injected along magnetic field from a tip of electron source and trapped between two electrostatic potentials [11, 12], which were apart by a distance of $L \simeq 30$ cm. Since the trapped electron density was approximately $1 \times 10^7$ cm$^{-3}$ under a back ground pressure of $p \lesssim 10^{-4}$ Pa, the electron was able to move back and forth approximately $10^4$ times between the two electrostatic potentials and the collisionless condition was satisfied [12]. Then, by applying an oscillating electric field to one of the electrostatic potentials, the electron acceleration related to the resonance of the electron bounce motion was observed and that related to stochastic nature was also observed. These results are different from the previous results [11, 12] due to the resonance of the transmission line for the oscillating electric field.
A signal was terminated in the characteristic impedance $R_G = 50 \, \Omega$ and passed through the capacitance of $C_G = 0.1 \, \mu F$ to the plug electrode (A) so that the problem of the resonance of the transmission line was removed. In the experiment, the amplitude of the RF signal, $V_{RF}$, was varied up to $10 \, V$. The amplitude of the potential oscillation at the reflection point of the electron with an energy of $E$ can be estimated by

$$V_{\text{reflect}} \approx V_{RF} \frac{E}{(eV_A)} ,$$

since the oscillating potential profile at the electrode (A) always keeps a similar shape, where $e$ is the elementary charge. For example, $V_{\text{reflect}} \approx 3.75 \, V$ for an electron with the injection energy of $E = -eV_E = 30 \, eV$ when $V_{RF} = 10 \, V$ and $V_A = -80 \, V$.

In the system, some of the electrons between the two electrostatic potentials (A) and (B) are accelerated or decelerated when the electrons are reflected at the electrostatic potential (A) with the oscillating electric field. The electrons reached sufficiently high energy by successive acceleration can escape from the electrostatic potential (B), the magnitude of which is less than that of the electrostatic potential (A), i.e., $|V_B| < |V_A|$. Then, the escaping electrons are detected as a current of $I_C$ by the collector placed farther right of the plug electrode (B), as shown in Fig. 1 (a), and the increase of the kinetic energy of the escaping electrons from its initial kinetic energy is easily evaluated by

$$\Delta K \geq -e(V_B - V_E) .$$

3. Results

Figure 2(a) shows the current $I_C$, due to the escaping electrons through the electrostatic potential (B), as a function of time $t$ when the frequency $f_A$ of the oscillating electric field was swept between 1 and $50 \, MHz$, which is represented by a sweep voltage $V_{\text{sweep}}$ as a function of time $t$ in Fig. 2(b) under the condition of $V_A = -80 \, V$, $V_B = -60 \, V$, $V_E = -30 \, V$, and $V_{RF} \approx 7.5 \, V$. Figure 3 shows the relationship between the current $I_C$ and the frequency $f_A$, which is obtained from Figs. 2(a) and (b). In Fig. 3, four peaks of $I_C$ can be easily found and their frequencies are approximately 39.5, 42.6, 44.9, and 47.2 MHz. Besides the peak with the lowest frequency of 39.5 MHz, the difference between the two adjacent frequencies is approximately 2.2 MHz, which agrees with the bounce frequency of an electron with a kinetic energy of $\sim 4.8 \, eV$. Since the density of the electron cloud between the two electrostatic potentials was estimated to be approximately $1 \times 10^7 \, cm^{-3}$ and the space potential on the axis of the central electrode to be approximately $-25 \, V$, the value of $\sim 4.8 \, eV$ may be considered as the initial kinetic energy $K_0$ of the electrons from the electron emitter: $K_0 \sim 4.8 \, eV$. In fact, the difference of the adjacent peak frequencies was inversely proportional to the axial length $L$ of the two electrostatic potentials. In that case, the gain of the kinetic energy of the escaping electron can be estimated as

$$A = \frac{\Delta K}{K_0} \approx 6.3 .$$

If we see Fig. 3 carefully, then, we find that the base of $I_C$ continuously increases with increasing $f_A$ for $f_A \lesssim 40 \, MHz$. So, we may say that the current $I_C$ is composed of (1) current enhanced at some discrete frequencies of the oscillating electric field and (2) current continuously increased with increasing the frequency of the oscillating electric field.

By the variation of $V_{RF}$, the relationship between $I_C$ and $f_A$ varies, as shown in Fig. 4, where the upper, middle, and lower curves represent the cases of $V_{RF} = 10, 7.5, \text{ and } 5 \, V$, respectively, under the condition of $V_A = -80 \, V$, $V_B = -60 \, V$, and $V_E = -30 \, V$. This figure shows that the magnitude of $I_C$ increases with increasing $V_{RF}$: and the discretely enhanced current of the type (1) is clearer for the case of the smaller $V_{RF}$ and the continuously increasing current of the type (2) is clearer for the case of the larger $V_{RF}$.

The relationships between $I_C$ and $f_A$ for various values of $V_B$ are also shown in Fig. 5 under the condition of $V_A = -80 \, V$, $V_E = -30 \, V$, and $V_{RF} = 7.5 \, V$. Here, the upper, middle, and lower curves represent
The cases of $V_B = -40$, $-50$, and $-60$ V, respectively. From the figure, we can see that the magnitude of $I_C$ decreases with increasing $|V_B|$; and the discretely enhanced current of the type (1) is clearer for the case of the larger $|V_B|$ and the continuous increasing current of the type (2) is clearer for the case of the smaller $|V_B|$.

Figure 6 shows the relationship between $I_C$ and $f_A$ under the condition of $V_A = -80$ V, $V_B = -40$ V, $V_E = -30$ V, and $\tilde{V}_{RF} = 10$ V. From the discussion of Figs. 4 and 5, it is considered that the continuous increasing current of the type (2) appears clear in Fig. 6. In fact, the base of $I_C$ becomes large and the ratio of the magnitude of the peak and that of the base for $f_A \gtrsim 40$ MHz is $\lesssim 1.3$, which is smaller than the ratio of $\gtrsim 2.5$ in the case of $V_A = -80$ V, $V_B = -60$ V, $V_E = -30$ V, and $\tilde{V}_{RF} = 7.5$ V (Fig. 3). In the frequency range of $f_A < 40$ MHz of Fig. 6, some peaks of $I_C$ appear and the ratios of the magnitude of the peaks and that of the base are relatively large ($> 2$), although the rate of the electron acceleration is very small and $I_C$ was not observed in the case of $V_A = -80$ V, $V_B = -60$ V, $V_E = -30$ V, and $\tilde{V}_{RF} = 7.5$ V (Fig. 3). Thus, with the fact that the difference of the frequencies of the adjacent peaks was inversely proportional to $L$, we see that the electron acceleration rate increased around the frequencies with the peaked $I_C$ due to the resonance of the elec-
Fig. 6 Relationship between $I_C$ and $f_A$ under the condition of $V_A = -80$ V, $V_B = -40$ V, $V_E = -30$ V, and $V_{RF} = 10$ V.

The experiments with the oscillating electric field with different two or three frequencies have been performed to investigate particle acceleration in turbulence.