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Interaction of Electrons with an Oscillating Potential

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Abstract

A model experiment of Fermi acceleration was performed in a trap, where electrons moved between an oscillating potential and a fixed potential along a magnetic field. In the trap some of the electrons were accelerated until they went over the fixed potential. We have observed such electrons at specific frequencies of the oscillating potential. A numerical study relates this resonance behavior to the stochastic acceleration of electrons confined in the oscillating wall and the fixed wall.

Keywords:

fermi acceleration, electron acceleration, oscillating potential, resonance, fermi map

1. Introduction

Extremely high-energy particles have been known to exist in space [1]. Fermi acceleration has been considered as one of the candidates of the acceleration mechanism and has attracted many researchers from the beginning of the plasma physics. Interactions between particles and fields are primarily important and were experimentally studied in an electron trap [2], where electron heating was observed by oscillating an end potential or two end potentials under the collisional regime. In the present study, a similar electron trap with the previous work has been used under the collisionless regime. The most distinct observation was that the amount of accelerated electrons was enhanced at specific frequencies of an oscillating end potential. This resonant behavior of the electron acceleration has been investigated further by the numerical study.

2. Experiment

2.1 Experimental Method

The electron trap consisting of seven ring electrodes with 30 mm in length and 30 mm in diameter, which is schematically shown in Fig. 1(a), was placed in a vacuum chamber with the base pressure of about 2×10^{-3} Pa. Figure 1(b) shows the potential profile as a function of z along the axis of the trap by a solid line. The left potential wall was formed by the bias –50 V applied to the leftmost ring electrode and was modulated by a sinusoidal signal with the amplitude of 3 V. Thereby we call the left potential wall 'an oscillating potential'. The right potential wall was formed by the bias –10 V applied to the rightmost ring electrode. Note that all the other electrodes were grounded and the height of the right potential wall $\phi_B = -6$ V was about 60 percent of the bias voltage to the rightmost ring electrodes. We call this potential wall 'a barrier potential' since its height determines the energy of escaping electrons along the magnetic field. The escaping electrons were collected by a disk electrode placed outside of the rightmost electrode and were detected as current I. The electrons injected from the electron source at the center (see Fig. 1(a)) moved back and forth between the oscillating potential and the barrier potential to form an electron cloud with a column shape. The electron density was about 2×10^7 cm^{-3} and the electron temperature about 2 eV. The column radius of about 2 mm was almost as large as Debye length but much larger than the electron Larmor radius of 0.12 mm for the magnetic field of 400 G. For

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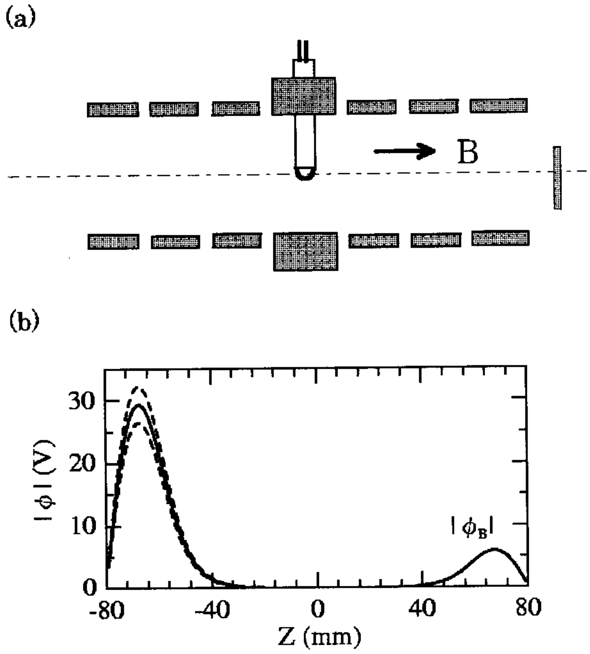

Fig.1 (a) Experimental setup and (b) axial potential distribution along the axis.

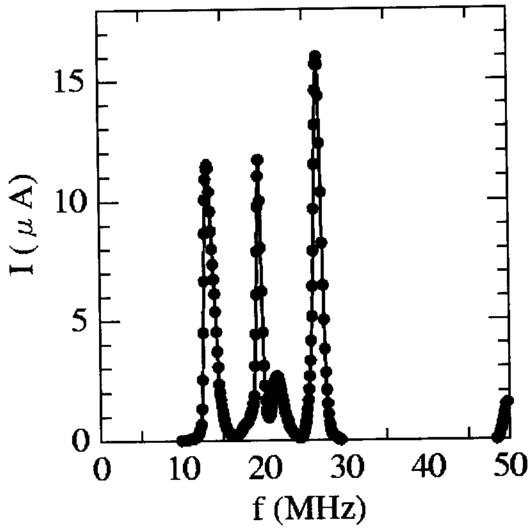

Fig.2 Current due to escaping electrons as a function of frequency of the oscillating potential for $\phi_B = -6$ V and $B = 446$ G.

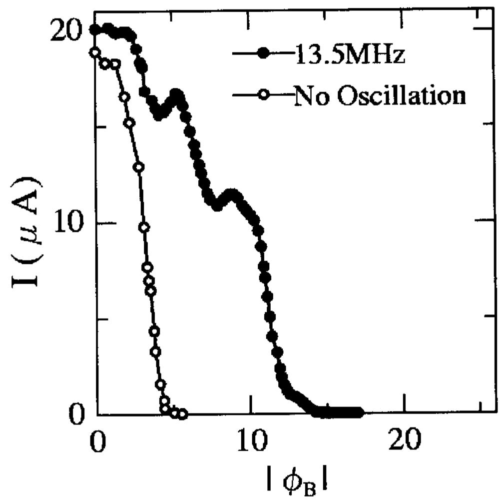

Fig. 3 Current due to escaping electrons as a function of the barrier potential $|\phi_B|$ for $B = 256$ G.

the energy of the injected electrons of 2 eV, the bounce frequency between the oscillating potential and the barrier potential was about 3 MHz.

2.2 Experimental Results

Relation between the frequency of the oscillating potential f and the current due to the escaping electrons I is shown in Fig. 2. The current I is shown to be enhanced at specific frequencies. This phenomenon indicates a resonance effect between the electron bounce frequency and the frequency of the oscillating potential for the electron acceleration. In Fig. 3, closed circles depict the relation of the current I with the barrier potential $|\phi_B|$ when there was the modulation of the left potential wall with the frequency 13.5 MHz, while open circles depict the relation when there was no modulation. The modulated frequency 13.5 MHz corresponds to the lowest resonance frequency as represented in Fig. 2. It is clear that the electron energy increased up to about 17 eV from 5 eV by the oscillating potential. The derivative $dI/d|\phi_B|$ is proportional to the energy distribution function if we assume that the electron energy increases monotonically, that is, $f(E) \propto -dI/d|\phi_B|$. The presence of the regions with $dI/d|\phi_B| > 0$ suggests that some electrons decrease energy near the top of the barrier potential $|\phi_B|$.

3. Numerical Study

3.1 Mapping

To understand our experimental observation, we applied the standard mapping [3]

$$u_{i+1} = |u_i + \sin \theta_i| \qquad (1)$$

and

$$\theta_{i+1} = \theta_i + 2\pi M / u_{i+1} \qquad (2)$$

where u_i, normalized by $2a\omega$ (a and ω are the maximum displacement and the frequency of the oscillating wall, respectively), is a velocity of the particle before the i-th collision, θ_i is a i-th phase of the oscillating potential wall, and M $(= L/2\pi a)$ is the normalized distance between an oscillating potential wall and a fixed barrier. The distance between the oscillating potential wall and the fixed barrier L is assumed to be much larger than the amplitude of the oscillating wall a. A phase space of the particles is shown in Fig. 4 for M = 20 and u_0 = 11.5 which corresponds to $E_{\rm in}$ (initial energy of electrons) = 6 eV for parameters of $a = 8.0 \times 10^{-4}$ m and $\omega/2\pi$ = 12.6 MHz. It is seen that some of the electrons are accelerated beyond 10 eV and that the unoccupied island develops in the range of about 6 eV to about 11 eV in Fig. 4(a). Figure 4(b) shows the corresponding energy distribution of the particles. It is seen that the particles near the boundary of the island change energy rapidly and the number of particles with that region, or $f(E)$ with the correspomding energy, is small.

3.2 Numerical Analysis

We now set a limited potential at the fixed barrier to compare with the experimental measurements. A lifetime of an electron is defined as a time when the electron escapes from the fixed barrier. The escaping electron has an energy $E_{\rm out}$ which is equal to $e|\phi_{\rm B}|$. The lifetimes of the electrons are recorded each time and the current I was estimated from the sum of the inverse of the electron lifetimes. Figure 5 shows the current I as a function of the frequency f of the oscillating potential wall. The resonant features are clearly shown as observed in the experiment, although some discrepancies are present including the first peak around 5 MHz appeared in the numerical analysis. The current obtained in the range of high frequency above 35 MHz increases with frequency, because the model is not applicable to the frequency that the velocity of the oscillating potential wall becomes faster than electrons. Such a fast movement of the wall invalidates the mapping equations we used for our numerical analysis. The resonant frequencies are found to be given by the equation:

$$f \simeq \frac{(2n-1)}{2}\left(\frac{f_{\rm in}+f_{\rm out}}{2}\right) \quad (n = 1,2,3...), \qquad (3)$$

where

$$f_{\rm in} = 1/(2L)\sqrt{2E_{\rm in}/m}$$

and

$$f_{\rm out} = 1/(2L)\sqrt{2E_{\rm in}/m}. \qquad (4)$$

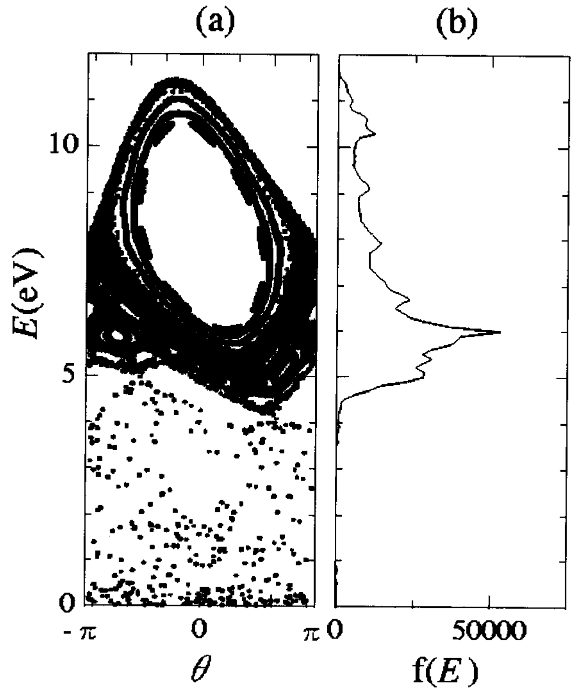

Fig. 4 (a) Phase space and (b) energy distribution of the particles for $E_{\rm in}$ = 6 eV and M = 20.

4. Conclusion

We have carried out the model experiment of Fermi acceleration and our numerical analysis clarified some of the features of stochastic acceleration observed in the experiment. It is found that there was the resonance between accelerated electrons and the oscillating potential.

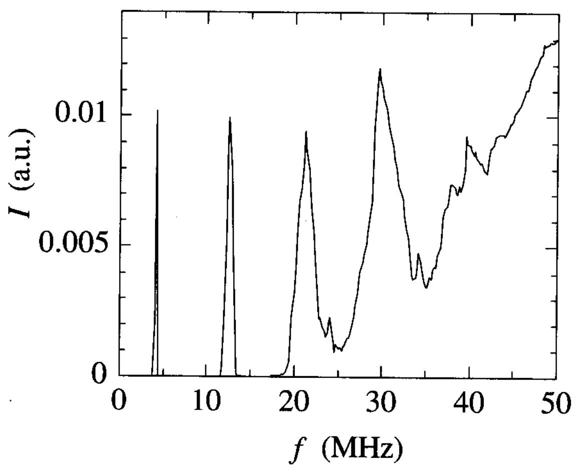

Fig. 5 Current due to escaping electrons as a function of frequency of the oscillating potential wall f for $E_{\rm in}$ = 6 eV, $E_{\rm out}$ = 10 eV, $a = 8.0 \times 10^{-4}$ m, and L = 0.1 m.

Acknowledgements

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