Production of High Energy Electrons in Microwave Plasma

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High energy electrons are produced and play an important role such as radical particle production in microwave plasma. It was investigated how high energy electrons were produced through PIC-MCC simulations. The results show that the high energy electrons gain their energy when they pass the E-field of a resonantly excited electron plasma wave by a microwave around cut-off density, and the acquisition energy depends on the timing and their velocity of electrons entering into a resonant region.

Keywords: high energy electron, PIC-MCC, surface-wave plasma, microwave plasma

1 INTRODUCTION

Much attention has been paid to microwave plasma such as surface wave plasma (SWP) because of its high density and low electron temperature characteristic [1-10]. A resonant absorption model has been proposed as the mechanism of the high density and low temperature plasma sustainment of SWP [10]. The model says that the evanescent E-field of a microwave parallel to the density gradient would resonantly excite electron plasma waves at approximately the cut-off density. Then the efficient energy transfer from microwave to electron plasma waves would lead to high density because plasma density is approximately proportional to absorbed power by plasma. The enhanced E-field of the waves would subsequently produce high energy electrons, which will efficiently ionize neutral gas and produce a large amount of low temperature electrons, resulting in low average electron temperature. The transit time heating as the mechanism of high energy electron production was proposed by Alief et al [9]. High energy electrons were measured by Terebessy et al [8]. The stripe structure of electron distribution in Vx-X space and the limit of electron energy were obtained through the PIC-MCC simulation [10], but the reasons were not discussed in detail.

The aim of this study is to examine what determines the energy gain of electrons and how the upper limit of electron energy is defined.

2 SIMULATION MODEL

The 1D3V electrostatic PIC-MCC (xpdp1 [11]) is modified to include an evanescent oscillating E-field and employed for the present simulation, so that the code would treat acceleration of electrons by passing through an E-field of electron plasma waves. Since the xpdp1 is an electrostatic code, it cannot simulate electromagnetic waves. However, the E-field parallel to the density gradient of a microwave in highly dense plasma (beyond the cut-off density) may be approximated as decaying exponentially along gradient (say, along the x axis) and may be expressed [7, 12] as

$$E\left(x,t\right)=E_0\exp\left(-\alpha x\right)\sin\left(2\pi ft\right) \qquad (1).$$

The E_0, α, f are the amplitude, decay constant and frequency of the microwave, respectively (Table 1). We incorporate this E-field into xpdp1 as an external forcing term. Our 1D model describes the axis of a cylindrical SWP. The computational domain is bounded by two perfectly absorbing walls: the dielectric window at x = 0.00 m has floating potential, and the electrode at x = 0.02 m is grounded. The code includes the excitation, ionization, and elastic collision of electron-Ar, charge exchange, and ion-neutral scattering.

Table 1: Simulation parameters

Time step	5.0×10^{-13} [s]
Gas species, pressure	Ar, 0.01 [Torr]
Computational domain length and mesh size	0.02 [m] 1.0×10^{-5} [m]
Microwave frequency	2.45 [GHz]
Decay constant α and amplitude E_0	$1/(70\times10^{-3})$ [m^{-1}] 2.7×10^{3} [V/m]

A cell size is chosen so as to be sufficiently small to monitor a sheath and Debye length at cut-off density (43 μm). The number of superparticles in one cell is about 40. Computations were iterated until kinetic energy and the number of superparticles reached steady states.

3 RESULTS AND DISCUSSIONS

Figure 1 shows the electron density distribution. The electron velocity probability function is shown in Fig.2, which indicates that high velocity (energy) electrons are produced.

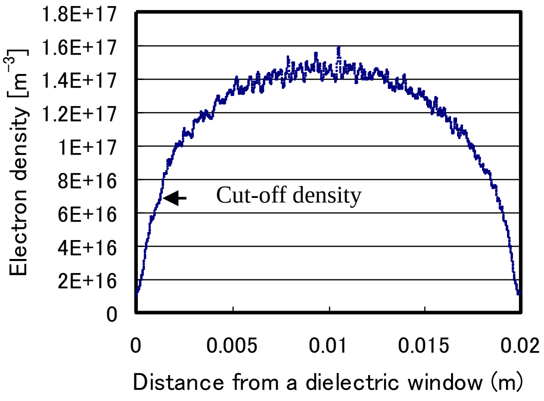


Fig.1: Electron density distribution

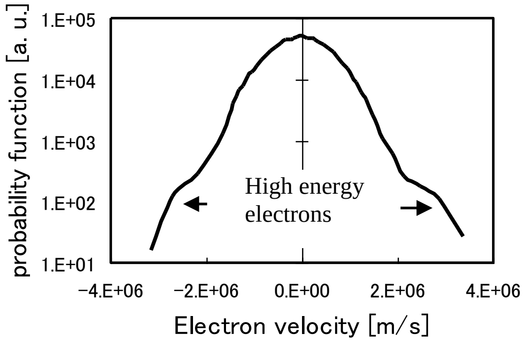


Fig.2: Electron velocity probability function

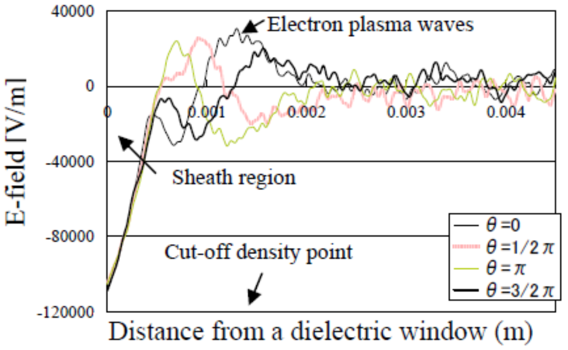


Fig.3: Electrostatic E-field distribution ($\theta = 0$) is the time when the amplitude of the electron plasma wave at cut-off density assumes a maximum value)

Electrostatic E-field distributions around the cut-off density are shown in Fig.3. One can see an electron wave is excited between the sheath edge and the cut-off density point. The $\theta = 0$ denotes the time when the amplitude of the electron plasma wave at cut-off density assumes a maximum value. Figure 4 indicates that electrons with nearly same incident velocity gains different energies if the values of the incident timing θ are different. So, the energy gain of electrons depends on their incident velocities and timings into a resonant region.

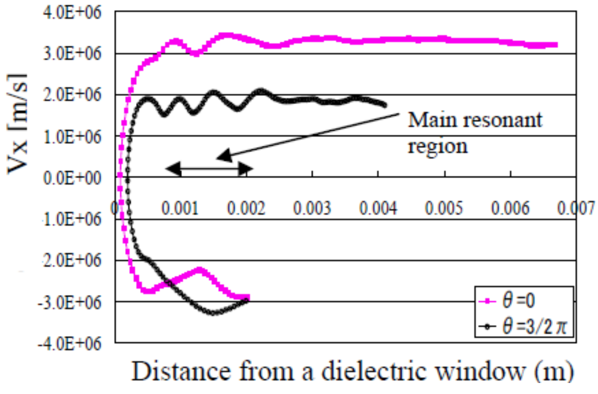


Fig.4: Electron trajectories with the nearly same incident velocity and the different incident timings

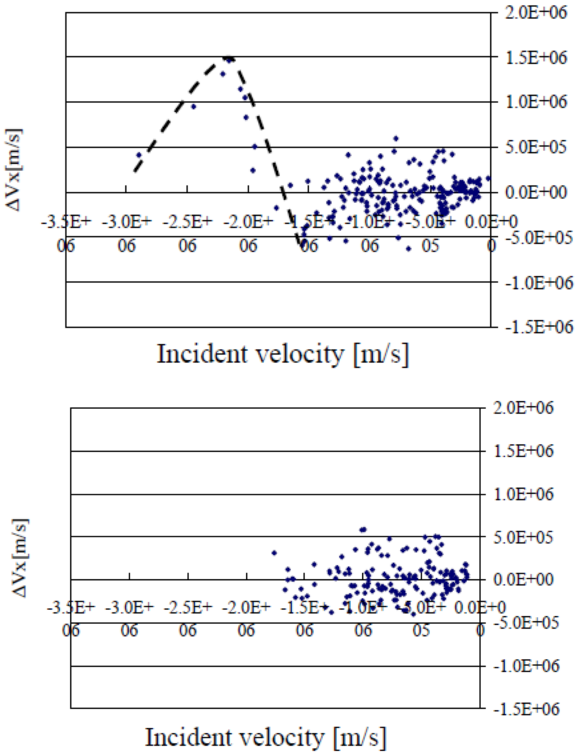
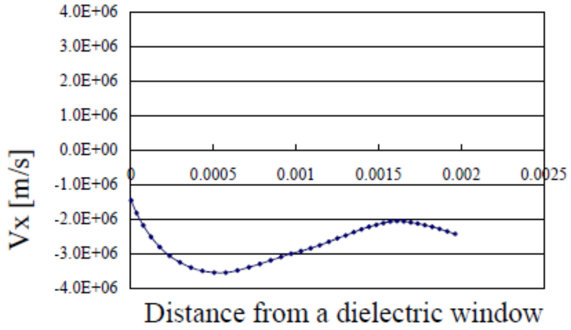
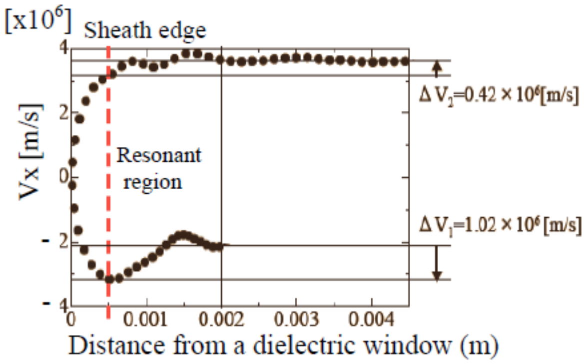


Fig.5: Dependence of the increase in an electron velocity, ΔV_x on the incident velocity into a resonant region at the different timings (for $\theta = 0$ top and $\theta = 1/2\pi$ bottom figure)

Figure 5 shows the typical examples of the dependence of the increase in an electron velocity after passing through a resonant region twice, ΔV_x on the incident velocity. For the incident timing $\theta = 0$, electrons with -3×10^6 m/s to -2×10^6 m/s are more efficiently accelerated, while for $\theta = 1/2\pi$ highly energetic electrons are not observed.



(a) Trajectory of a collided



(b) Trajectory of a reflected electron

Fig.6: Electron trajectories ($\Delta Vx = \Delta V_1 + \Delta V_2$)

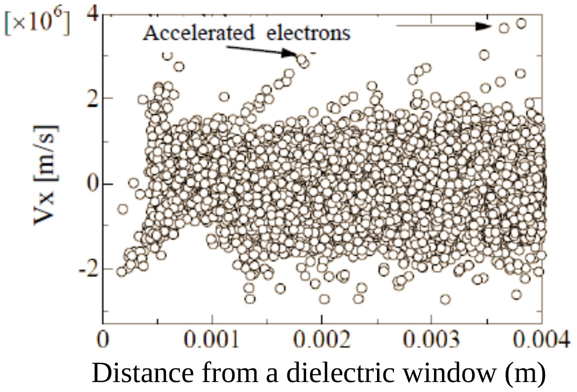


Fig. 7: Electron distribution in Vx-X space at the timing $\theta = 0$ (which is determined in Fig.3, Each circle represents an electron superparticle)

The electrons which are not repelled by sheath potential would collide with a dielectric window and disappear. An electron with about 37 eV (-3.6×10^6 m/s) collides with a dielectric window (see Fig. 6 (a)), on the other hand an electron with about 27 eV (-3.1×10^6 m/s) dose not collide, and it gains additional energy when passing through the resonant region again and its kinetic energy reaches about 37 eV (see Fig. 6 (b)). It means that some electrons may gain more energy than a limit energy determined by the sheath potential. Figure 7 shows the electron distribution in Vx-X space.

4 CONCLUSION

In a surface wave plasma (SWP) source, the evanescent microwave field in front of the dielectric window is shown to excite electron plasma waves, which in turn deliver kinetic energy to electrons bouncing off the sheath. The energy gain of electrons depends on the timing of electron entering into the resonant region of surface-wave plasma as well as their incident velocities. The maximum energy of the electrons would be determined by the limited value due to a sheath potential and an energy gain when passing through a resonant region again on the way back to bulk plasma.

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