Abnormal Heating of Low-Energy Electrons in Low-Pressure Capacitively Coupled Discharges

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In low-pressure capacitively coupled plasmas, high-energy electrons are collisionlessly heated by large rf fields in the sheaths while low-energy electrons are confined in the bulk plasma by the ambipolar potential. Low-energy electrons are typically inefficiently heated due to their low collisionality and the weak rf electric field present in the bulk. It is shown, however, that as a result of the nonlinear interaction between the electron motion and the weak rf field present in the bulk, low-energy electrons can be efficiently heated. Electrons in the bulk that bounce inside the electrostatic potential well with a frequency equal to the rf excitation frequency are efficiently heated by the coherent interaction with the rf field. This resonant collisionless heating can be very efficient and manifest itself as a plateau in the electron energy probability function.

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Low-pressure capacitively coupled discharges have attracted attention for the last decades because of their interesting physics as well as their widespread applications [1]. Understanding the electron heating mechanisms in these discharges is therefore of major interest. At low-pressure, where the electron mean-free path is comparable to the system length, capacitively coupled discharges are maintained by collisionless (stochastic) heating [2,3]. On the other hand, at high pressure, the dominant heating is collisional (Ohmic). Godyak *et al.* [2] have measured concave electron energy probability functions (EEPFs) in low-pressure argon discharges. They attribute the formation of these EEPFs to a combined effect of stochastic heating and the Ramsauer effect. High-energy electrons capable of interacting with high electric fields in the sheaths gain energy collisionlessly while low-energy electrons are confined in the bulk plasma by the electrostatic potential. These low-energy electrons are weakly heated because the rf electric field in the bulk and the electron collision frequency are small.

An additional collisionless heating is also possible in bounded low-pressure discharges when the bounce frequency Ω_b of electrons in the electrostatic potential well is equal to the frequency ω of the driving rf field [4–10]. Under this bounce resonance condition, a local maximum of the plasma resistance has been observed in inductive coupled discharges [7]. Aliev *et al.* [5] have calculated the electron energy diffusion coefficient in bounded low-pressure capacitively coupled discharges accounting for the electron bounce heating. Their theoretical study based on the quasilinear theory, however, is not self-consistent and neglects backward influences caused by the perturbation of the EEPF on the electric field profile. Since, in capacitively coupled discharges, the changes in electron velocity caused by the rf field are in the same direction as the bounce motion, nonlinear effects should also be taken into account. Therefore, the bounce resonance heating needs to be studied as a nonlinear problem in a self-consistent way.

In this Letter, we report on the abnormal heating of low-energy electrons in low-pressure capacitively coupled discharges and show that low-energy electrons can be effectively heated collisionlessly even thought they do not interact with the sheath electric field. For this study, we have used an electrostatic particle-in-cell (PIC) simulation method coupled with a Monte Carlo collision model (MCC) [11]. The simulations are one-dimensional in space and three-dimensional in velocity. Argon discharges at 25 mTorr (3.3 Pa) were sustained between two parallel-plate electrodes that were separated by a gap distance L of 4 cm. At this pressure, the mean-free path of low-energy electrons ($\varepsilon < 2$ eV) is much larger than the system length L. The discharges were driven by a rf voltage source applied to the electrode positioned at $x = 0$ while the electrode at $x = L$ was grounded. In a first experiment, the amplitude of the voltage source was fixed at 40 V while its frequency was varied from 10 to 20 MHz. In a second experiment, the frequency was fixed at 13.56 MHz and the amplitude of the voltage source was varied from 40 to 200 V. In order to obtain meaningful results at steady state, several thousand rf cycles were simulated for each run. For simplicity, secondary electron emissions were not included in the simulation and Coulomb collisions were neglected because for the discharge conditions reported in this Letter the electron-electron collision frequency ($\sim 10^4$ s^{-1}) for low-energy electrons is much lower than the electron-neutral collision frequency ($\sim 10^6$ s^{-1}).

The EEPFs measured at the discharge center when the excitation frequency is 10, 13.56, and 20 MHz are shown in Fig. 1(a). The EEPFs at 10 and 20 MHz are bi-Maxwellian with a large low-energy electron population caused by the preferable collisionless heating of high-energy electrons and nonlocal electron kinetics. According to nonlocal electron kinetics, high-energy electrons can overcome the

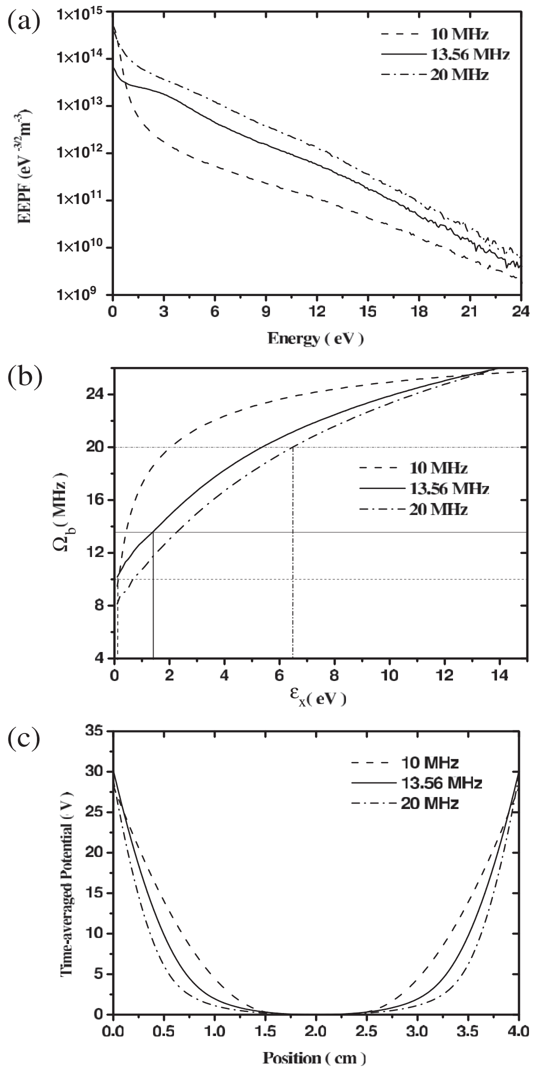

FIG. 1. Simulation results for three capacitively coupled discharges driven by a 40 V voltage source: (a) electron energy probability functions at the center of the discharge (b) electron bounce frequency as a function of x-directional energy (c) the spatial profiles of the time-averaged potential.

electrostatic potential well and interact with the oscillating sheaths. As a result of this interaction these electrons are strongly heated. On the other hand, low-energy electrons are trapped inside the electrostatic potential well and gain energy mainly through collisional heating. This heating, however, is usually weak due to the low collisionality of low-energy electrons and the weak electric fields present in the bulk. As a result, the electron energy distribution at low pressure is typically bi-Maxwellian, as shown for the 10 and 20 MHz cases in Fig. 1(a). For the 13.56 MHz case, however, a plateau in the low-energy region (1–3 eV) of the EEPF is observed [see Fig. 1(a)]. A similar structure has been measured in a capacitively coupled discharge when the operating pressure was decreased to 10 mTorr [10].

The formation of a plateau in the EEPF reflects the presence of a strong heating mechanism for electrons in the energy range where the plateau appears. For the 13.56 MHz case, the mechanism causing the plateau in the EEPF is the resonant (collisionless) heating of some low-energy electrons as they bounce in the electrostatic potential field with the same frequency as the excitation rf frequency, i.e., electron bounce resonance. The electron bounce frequencies in the self-consistent time-averaged electrostatic potential wells for the 10, 13.56, and 20 MHz cases are shown in Fig. 1(b) as a function of the electron energy ε_x. Although resonant electrons experience a potential well different from the time-averaged one, it turns out that for the conditions reported in this paper, the time-averaged potential well is a reasonable approximation. In fact, the difference of the bounce frequencies calculated with the time-averaged potential well (limit if $2\pi\Omega_b \ll \omega$) and the instantaneous potential wells (limit if $2\pi\Omega_b \gg \omega$) is less than 10%. As shown in Fig. 1(b), the energy of the electrons for which the bounce frequency is equal to 13.56 MHz coincides with the energy at which the plateau forms in the EEPF [Fig. 1(a)].

In a simplified model, the electric field in the plasma can be neglected and the sheath edges assumed to be infinite potential walls. In such scenario, the electron bounce resonant heating can be understood as follows: At low-pressure, where $\nu < \Omega_b$, electrons bounce against the oscillating potential walls completing more than one round trip before undergoing a collision. The electrons that satisfy the resonance condition ($2\pi\Omega_b \approx \omega$) interact coherently with the oscillating sheath fields. Therefore, these electrons can accumulate the energy kicks gained in subsequent interactions with the sheaths and diffuse in energy space towards higher energy, i.e., they are heated [4,5].

In the simplified model, all electrons can interact with the sheaths. In a real discharge, however, low-energy electrons are trapped inside the electrostatic potential well and cannot reach the peripheral regions where the rf field is large. Therefore, low-energy electrons can interact only with the small rf electric field that penetrates into the bulk [12] and are typically weakly heated. Low-energy electrons satisfying the bounce resonance condition, however, can be effectively heated by this small rf field. Figure 2 shows the kinetic energy ε_x of test particles as a function of time in three discharges driven at different frequencies. The test particles are collisionless electrons that move in the self-consistent field starting from the center of the discharge with an energy of 1 eV. After one bounce cycle, test electrons gain or lose energy depending on the phase between their motion and the rf field. It is shown in Fig. 2(b) that for the 13.56 MHz case, the kinetic energy of a test particle satisfying the bounce resonance condition has large excursions from its initial value with energy gains of ~0.5 eV per bounce. It should be noted that the initial energy of the electron is only 1 eV and therefore it is not sufficient to reach the strong fields in the oscillating sheaths. For the 10 and 20 MHz cases, however, the kinetic energy of the test particles has only small excursions

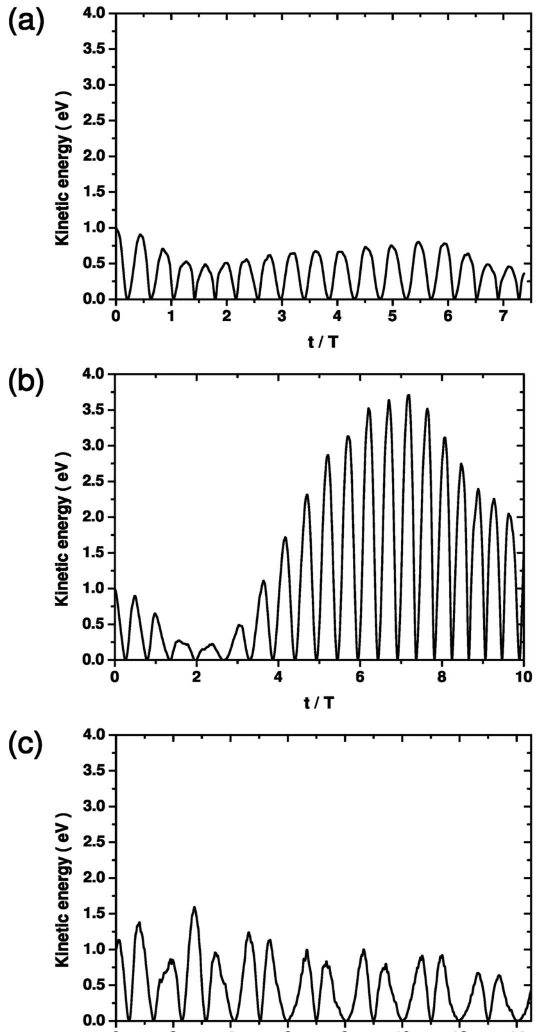

FIG. 2. Kinetic energy ε_x of collisionless test particles as a function of time for three capacitively coupled discharges driven by a 40 V voltage source: (a) 10, (b) 13.56, and (c) 20 MHz. Test particles are placed in the center of the discharge with an initial energy of 1 eV.

[Figs. 2(a) and 2(c)] indicating that bounce resonant heating is not significant.

In the simplified model, the bounce frequency Ω_b of an electron is given by $2L_{\mathrm{eff}}/v_x$, where v_x is the x-directional velocity of the electron and L_{eff} is the length of the bulk plasma. In a self-consistent calculation, however, the distance traveled by an electron in one bounce depends on its energy ε_x and therefore the bounce frequency is sensitive to the shape of the electrostatic potential. The potential profiles for discharges driven at 10, 13.56, and 20 MHz are shown in Fig. 1(c). As the frequency increases at a fixed rf voltage (40 V), the plasma density increases, the width of the bulk plasma becomes wider (sheaths shrink), and the electrostatic potential in the bulk flattens. As a result, the bounce frequency for a given electron energy decreases with increasing driving frequency [Fig. 1(b)]. For the 10 MHz case, the resonant energy is almost zero and the slope of the bounce frequency with respect to the electron energy near the resonant condition is much steeper than in the other two cases [Fig. 1(b)]. A large slope implies that resonant electrons are easily driven out of resonance even with small changes in energy and therefore it is not possible to have multiple coherent bounces. For this reason, no plateau is observed in the EEPF for the 10 MHz case. At 20 MHz, the bounce frequency equals the driving frequency for electrons with an energy ε_x of $\sim$6.5 eV [Fig. 1(b)]. Since the collision frequency ν of an electron in that energy range is larger than the driving frequency ($\nu_{6\ \mathrm{eV}} \sim 130$ MHz $\gg 20$ MHz), collisions prevent the otherwise resonant electron from having subsequent coherent energy kicks.

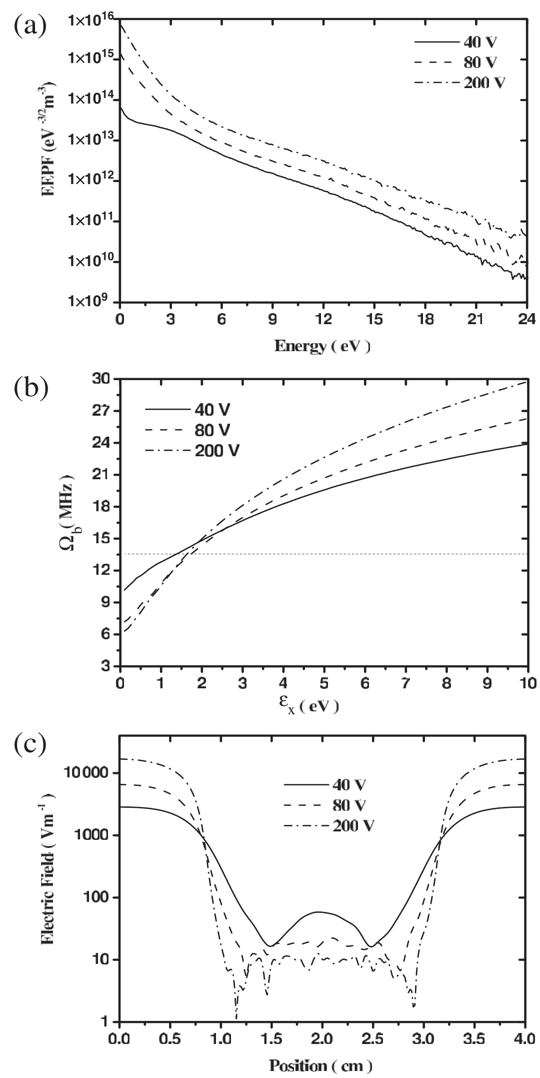

FIG. 3. Simulation results for three capacitively coupled discharges driven at 13.56 MHz: (a) electron energy probability functions at the center of the discharge, (b) electron bounce frequency as a function of x-directional energy, (c) the spatial profiles of rf electric field.

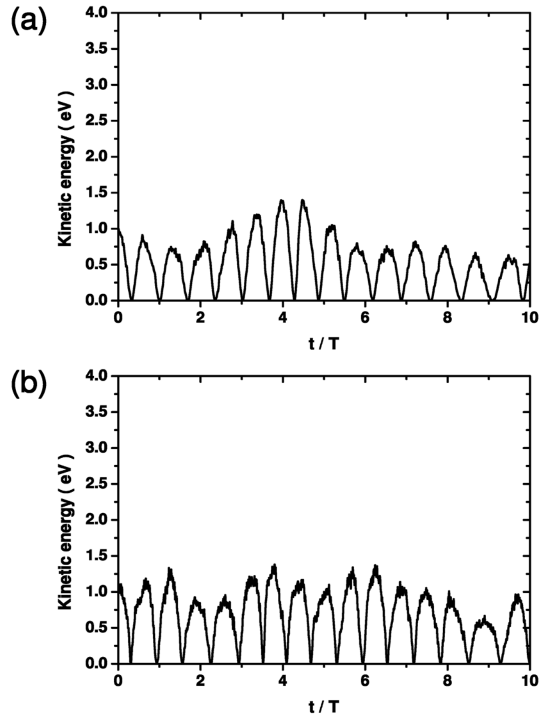

FIG. 4. Kinetic energy ε_x of collisionless test particles as a function of time for two capacitively coupled discharges driven at 13.56 MHz: (a) 80 V, (b) 200 V. Test particles are placed in the center of the discharge with an initial energy of 1 eV.

The EEPFs measured at the discharge center for discharges driven at 13.56 MHz with rf voltages of 40, 80, and 200 V are shown in Fig. 3(a). As the rf voltage increases, the plateau shown in the EEPF at 40 V disappears. The bounce frequency as a function of the electron energy ε_x is shown in Fig. 3(b) for the three discharges. The bounce frequency for low- and high-energy electrons decreases and increases, respectively, as the applied rf voltage is increased. The resonance energy, however, is almost the same ($\sim$ 1.6 eV) for the three discharges [Fig. 3(b)]. The spatial profiles of the rf electric field for the three discharges (40, 80, and 200 V) are shown in Fig. 3(c). The rf electric field is nonmonotonic at the bulk-sheath boundary [13] and is orders of magnitude smaller in the bulk than in the sheaths. As the rf voltage increases, the rf electric field in the bulk plasma decreases as a result of the nonlinear coupling between electric field, electron kinetics, and ambipolar diffusion [14]. Therefore, the kinetic energy gained by resonant electrons decreases with increasing rf voltages ($\Delta\varepsilon \propto E_o^2$, where E_o is the amplitude of the rf electric field in the bulk). As a result, at large rf voltages, the bounce resonance heating has no significant effect on the resulting EEPF [Fig. 3(a)]. For the 80 and 200 V cases, the kinetic energy of the test particles have only small excursions [Figs. 4(a) and 4(b)] indicating that bounce resonant heating is not significant.

In conclusion, we found a plateau in the low-energy portion of the electron energy probability function of a capacitively coupled argon discharge that reflects an efficient electron heating of low-energy electrons. This heating is explained in terms of the bounce resonant motion of low-energy electrons in the bulk plasma. Although these electrons cannot interact with the strong fields present in the sheaths, the weak rf electric field that leaks into the bulk plasma can effectively heat these electrons when the electron bounce frequency resonates with the rf excitation frequency $[2\pi\Omega_b(\varepsilon_x) \approx \omega]$. The energy of resonant electrons calculated in self-consistent electrostatic potentials that are obtained by means of PIC + MCC simulations agrees with the energy region where the plateau is observed in the EEPF. It is also shown that the resonant heating is disrupted when either collisions prevent subsequent coherent interactions with the electric field or the energy gained in one bounce period drives the electrons out of resonance.

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