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Ion-Acoustic Double Layers

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It is found, by means of numerical simulations, that an ion-acoustic instability ($v_d < v_{te}$) results in the formation of double layers in a sufficiently long system. Anomalous resistivity generated by the ion-acoustic instability causes the buildup of a dc potential which in turn accelerates electrons further to enhance the original instability leading to the formation of double layers.

Anomalous resistivity and double layers have long been important subjects in both laboratory and space plasmas.[1-5] Because of the highly nonlinear aspect of double layers, existing theories deal only with the steady-state solutions.[1,2] In order for double layers to be a reality, however, one must prove that they can be reached from a realistic initial condition. Computer simulation is the most powerful tool to study this dynamical process. The necessary condition for the formation of double layers obtained from the previous simulations,[3,4] the steady-state theory,[1] and laboratory experiments[5,6] is that the electron drift velocity exceed the electron thermal velocity ($v_d > v_{te}$), or double layers are a result of two-stream (Buneman) instability.

There are, however, observations[7] which support the existence of double layers (electrostatic shocks) along the auroral field lines where the electron drift speed is much less than the electron thermal speed. The low-intensity field-aligned current may be able to excite electrostatic ion-cyclotron waves or ion-acoustic waves, but cannot excite two-stream instability.[8]

In this Letter we show that, contrary to the earlier conclusion, double layers can be formed even if the electron drift speed is less than the electron thermal speed. This is proved by means of extensive one-dimensional particle simulations to be discussed. The underlying physical picture for this new process is the following: Suppose the system under consideration is sufficiently long. Then, no matter how small, the anomalous resistivity may be caused by an ion-acoustic instability, and the dc potential buildup associated with the localized resistivity in the system becomes large enough to accelerate electrons further. The acceleration in turn should enhance the original instability so that the anomalous resistivity and dc potential are further enhanced by a bootstrap action. Therefore, a new stage of the instability will take place which would not happen in a short system where little effective acceleration occurs.

In order to study this process in detail, we have performed one-dimensional particle simulations with the system length $L = 1024\lambda_D$, $512\lambda_D$, and $256\lambda_D$, and $128\lambda_D$ where λ_D is the initial electron Debye length which is equal to computational mesh size. Initially the density is uniform and the electron velocity distribution is assumed to be a drifting Maxwellian. $T_e/T_i = 20$, $M_i/M_e = 100$, and v_d (electron drift speed) $= 0.6v_{te}$. A smaller drift speed at $v_d = 0.3v_{te}$ and $L = 1024\lambda_D$ is also tried with the other parameters remaining the same. Periodic boundary conditions are used throughout the calculations. No external potential is applied across the system.

Figure 1 shows the results of $L = 1024\lambda_D$ and $v_d = 0.6v_{te}$ for the electron and ion phase-space distributions, Figs. 1(a) and 1(b), the electron and ion density profiles in real space, 1(c) and 1(d), and the potential profile, 1(e), at $t\omega_{pe} = 960$ when the localized structure (double layer) has fully developed. In Fig. 1(e), a large potential jump comparable to the thermal energy, $e\Delta\varphi/T_e \approx 1$, can be seen across the double layer. Along with the potential jump, large density discon-

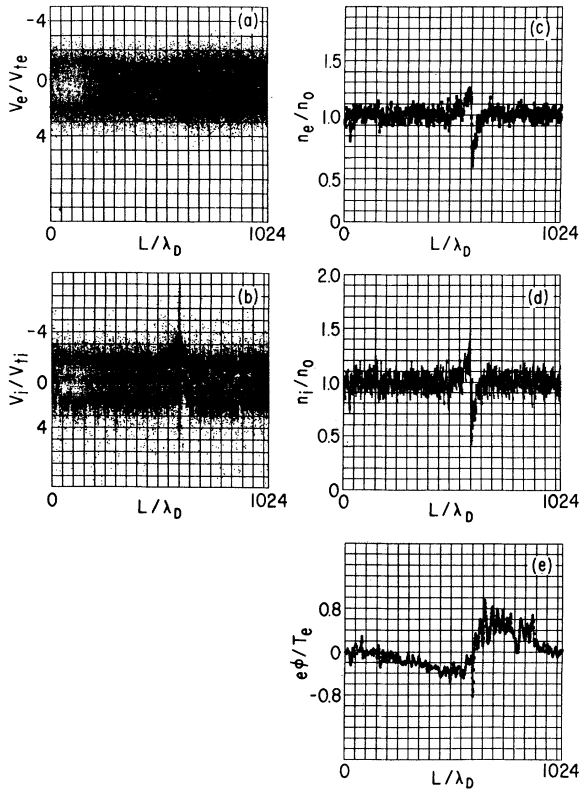

FIG. 1. Results of simulations using $L = 1024\lambda_D$ and $v_d/v_{te} = 0.6$ for (a) the electron phase space, (b) ion phase space, (c) electron density profile, (d) ion density profile, and (e) the potential profile at $t\omega_{pe} = 960$ (averaged over one plasma period). $n_0\lambda_D = 100$.

tinuities, $\delta n/n_0 \sim 1$, are generated for both electrons and ions. Furthermore, electron and ion densities are considerably compressed in the upstream region of the electron flow and are rarified in the downstream region. In a narrow transition layer, where a strong negative potential spike exists, large spikes in both the electron and ion densities are found. The phase-space plots shown in Figs. 1(a) and 1(b) indicate that ions are considerably decelerated in the potential double layer while electrons are accelerated. From these observations it is clear that a double layer can be formed through the ion-acoustic instability.

It is interesting to observe a conspicuous leading oscillatory structure in the downstream region of the potential profile.[9] The wavelength of the structure roughly corresponds to that of the most unstable ion-acoustic wave ($k\lambda_D \approx 0.2$).

Shown in Fig. 2 are the time evolution of the

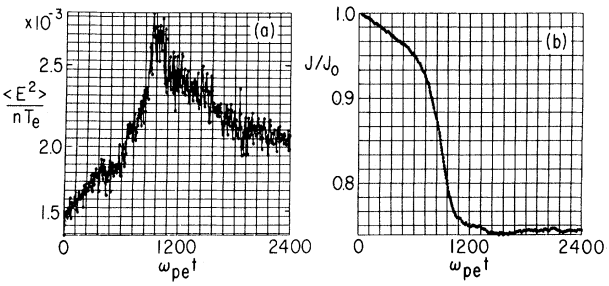

FIG. 2. Time evolution of (a) the wave energy and (b) the electric current for the same run as in Fig. 1 (plotted are the values averaged during five plasma periods). $L = 1024\lambda_D$ and $v_d/v_{te} = 0.6$. Note that the wave energy associated with the acoustic instability saturates at $t = 500\omega_{pe}^{-1}$ beyond which it grows explosively with a much faster growth rate.

wave energy, 2(a), and the electron current, 2(b), for the same run. In the early stage of wave evolution ($t\omega_{pe} = 0$–500) the total field energy increases almost linearly and the current relaxes slowly at roughly a constant rate, which indicates the generation of a small but finite anomalous resistivity associated with the ion-acoustic instability. The magnitude of this resistivity, η_a, is given by $\eta_a/\eta_0 \approx 5\times10^{-5}$ where $\eta_0 = 4\pi/\omega_{pe}$.[10] A drastic reduction of the current, and hence a sudden enhancement of the anomalous resistivity, takes place at about $t\omega_{pe} \approx 600$. The enhanced anomalous resistivity becomes more than ten times larger than the "acoustic" resistivity, $\eta_a/\eta_0 \approx 6\times10^{-4}$. At this stage, an explosive increase of the wave energy takes place resulting in the formation of the double layer by a bootstrap action. Frequency spectrum measurements at the double layers reveal the growth of new modes at a much faster rate when the double layer is formed. The frequency of this new instability is much smaller than the initial ion-acoustic instability, and is observed only at the location where the double layer exits. The drastic changes suddenly cease at $t\omega_{pe} \approx 1000$, the anomalous resistivity is completely shut off, and the resistivity drops to almost zero, that is, less than the classical value.

When the system length is shortened, the strength of double layers is reduced. Shown in Fig. 3 are the ion density and the potential profiles for $L = 512\lambda_D$ and $v_d = 0.6_{te}$ at $t\omega_{pe} = 1432$ when a double layer is at its peak. In comparison of the present result with that of the present result with that of the previous case, double-layer struc-

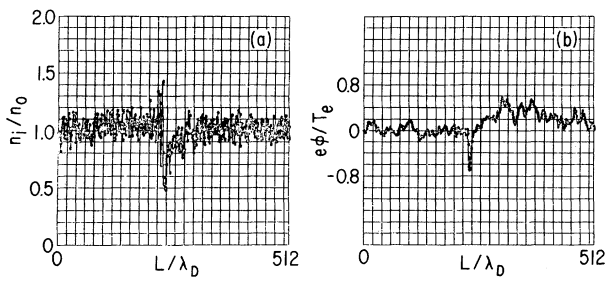

FIG. 3. Results of simulations using $L = 512\lambda_D$ and $v_d/v_{te} = 0.6$ for (a) the ion density profile and (b) the potential profile, at $t\omega_{pe} = 1432$. $n_0\lambda_D = 100$.

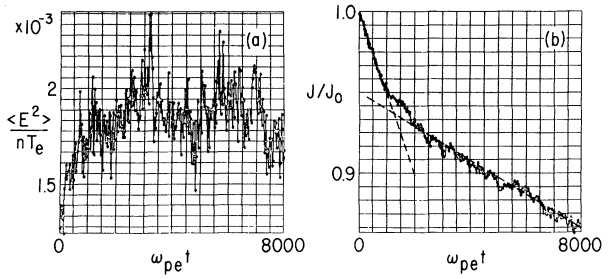

FIG. 4. Time evolution of (a) the wave energy and (b) the electric current for $L = 128\lambda_D$, $v_d/v_{te} = 0.6$, and $n_0\lambda_D = 100$.

tures are very similar to each other except for the potential jump $\Delta\varphi$ across the double layer which is now reduced to about one half of the previous value, i.e., $e\Delta\varphi/T_e \approx 0.5$. The "enhanced" anomalous resistivity reached, however, is almost the same value as that for $L = 1024\lambda_D$, i.e., $\eta_a/\eta_0 \approx 6\times10^{-4}$. When the system is further reduced to $L = 256\lambda_D$, it is found that the formation of double layers is marginal and the jump in potential is small. This indicates that $L = 256\lambda_D$ must be the marginal system length L_c for the case of $v_d = 0.6v_{te}$.

When the system length is reduced to $L = 128\lambda_D$, no double layers are formed, consistent with the previous simulations.[3,4,11] This is because, for these simulations, the system length was too short and the resultant acceleration of electrons associated with the anomalous resistivity was not large enough to form a double layer for the case of $v_d < v_{te}$.

Figure 4 shows the time evolutions of the wave energy, 4(a), and the current, 4(b). In the period of exponential growth ($t\omega_{pe} = 0$–800) nearly constant slowing down of the current is observed, which indicates the existence of the anomalous resistivity associated with the ion-acoustic instability. The resistivity is nearly equal to that of the previous case, i.e., $\eta_a/\eta_0 \approx 5\times10^{-5}$.

No indication of "enhanced" anomalous resistivity or a "burst" of ion-acoustic waves is observed in this case and, hence, no double layers. After $t\omega_{pe} \approx 1000$, the wave growth stopped and correspondingly, the anomalous resistivity disappeared and the classical resistivity η_c due to particle collision was observed. The classical resistivity turns out to be $\eta_c/\eta_0 \approx 10^{-5}$ for this case.[12] From these results we may conclude that double layers are generated when the system is long enough and they become stronger as the system length becomes longer.

Let us consider the mechanism underlying the formation of double layers in the regime of the ion-acoustic instability. The dc potential $\Delta\varphi$ across the region of localized resistivity may be given by $\Delta\varphi \sim l\eta J$ where η is the resistivity generated by the ion acoustic waves, J is the current density, and the length l is observed to be comparable to the system length L. During the phase of acoustic instability $\eta_a/\eta_0 \approx 5\times10^{-5}$ and J is approximately given by its initial value, i.e., J_0 where $J_0 = n_0 e v_d$ (n_0 is the average electron density), and hence the potential buildup across the system is $e\varphi_c/T_e \approx 3\times10^{-5}\, L/\lambda_D$. The critical length L_c for the formation of double layers for $v_d = 0.6v_{te}$ was found roughly $L_c \approx 256\lambda_D$ through our simulations, so that the critical potential φ_c turns out roughly $e\varphi_c/T_e \approx 10^{-2}$. Note that this value is smaller by two orders of magnitude than that given by a steady-state theory.[3] Now associated with the dc potential is the acceleration of the electrons. When the energy gain for the electrons from the dc potential becomes large enough, the instability is bootstrapped leading to the formation of a double layer. We observe that a necessary condition for ion-acoustic double layers is approximately given by

$$L\eta_a J > \varphi_w, \tag{1}$$

where φ_w is the wave potential associated with the acoustic instability.

The condition given by Eq. (1) assumed that the anomalous resistivity associated with the acoustic instability persists by the time a double layer is formed. We have seen in Fig. 4, however, that the anomalous resistivity reduces to much smaller classical resistivity after the acoustic instability saturates and the potential buildup will be much smaller. For such a case, a sufficient ac-

celeration of the electrons must take place before the ion-acoustic instability saturates. This latter condition gives $T_c \equiv L_c/v_d < T_s$ where T_s is the time for the ion-acoustic instability to saturate. In fact, this requirement is satisfied for the simulations using $L = 1024\lambda_D$ and $512\lambda_D$.

To check this point we have performed another simulation with $v_d = 0.3v_{te}$ and $L = 1024\lambda_D$. The result has shown the presence of acoustic anomalous resistivity ($\eta_a/\eta_0 = 3.8\times10^{-5}$) until $t\omega_{pe} \approx 750$ but after the saturation of the instability, it reduced to the classical value ($\eta_c/\eta_0 = 1.3\times10^{-5}$) and no double layers were formed. Using $v_d = 0.3v_{te}$ and $L = 1024\lambda_D$ we find $T_c \approx 3300\omega_{pe}^{-1}$. At this time, the acoustic instability has saturated and no more anomalous resistivity is present and therefore $T_c < T_s$ is not satisfied.

While periodic boundary conditions are used for the simulations reported here, we believe they are not important for a sufficiently long system, since the electrons had no chance to return before the double layer was formed. In support of this, two more simulations were carried out with and without the use of the periodic boundary conditions with the system length of 4096 Debye lengths. The results indicate that formation of double layers for both cases are similar to each other. It appears, however, that the use of periodic boundary condition will shorten the lifetime of double layers by mixing the upstream electrons with the downstream electrons.

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Internal Energy of Heterogeneous Reaction Products: Nitrogen-Atom Recombination on Iron

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Electron-beam–induced fluorescence has been used to measure the vibrational energy of nitrogen molecules desorbing from a polycrystalline iron surface, following atomic permeation and recombination on the iron surface. The vibrational temperature of the desorbing nitrogen is found to be significantly greater than the temperature of the iron surface, indicating that a fraction of the nitrogen-atom recombination energy remains with the desorbing nitrogen molecule as internal excitation.

Characterization of the reaction dynamics in heterogeneous systems requires a knowledge of the energy state of the heterogeneous reaction products. Ideally, one would like to know the translational- and internal-energy–state distribution, as well as the spatial distribution of desorbing product species. This energy and angular information can be very useful in describing the detailed dynamics of reactions taking place on solid surfaces. Some effort has been made to obtain angular distributions of heterogeneous reaction products.[1] In addition, the translational