Experimental Observation of Slow Ion Acoustic Double Layers

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Laboratory results are presented to show the existence of a new type of double layer which has monotonic potential variations but can be triggered with an electron drift velocity less than the electron thermal velocity. These double layers are always found to evolve from virtual-cathode potential wells at the electron injection boundary, independent of the electron drift velocity. However, the amplitudes of these double layers are determined by the initial drift velocity of the injected electrons. Double layers with potential drops less than the ambient electron temperature are found to be unstable to ion-ion streaming instabilities and decay into ion acoustic double layers.

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Double layers are localized electric field regions in a plasma. Most studies[1,2] have indicated that a necessary condition for their formation is that the electron drift velocity v_D exceed the electron thermal velocity v_{te}. The only exception is found in the report of laboratory double layers with potential drops ϕ much greater than the ambient electron temperature T_e/e by Hollenstein, Guyot, and Weibel.[3] In that experiment, $v_D \approx 0.2 v_{te}$. On the other hand, numerical simulations[4] with $v_D < v_{te}$ have *only* found "ion acoustic" double layers and such double layers were recently found[5-7] in laboratory and space plasmas. These structures are potential steps with $\phi \lesssim T_e/e$ and are always preceded by negative potential pulses or dips. Perkins and Sun,[8] Stern,[8] and Schamel[9] have predicted yet one more class of double layers that requires little or no electron drift ($v_D < v_{te}$) and has $\phi \lesssim T_e/e$ as well as monotonic potential steps; i.e., they are not preceded by negative potential dips. These so-called "currentless"[8] or "slow ion acoustic"[9] double layers were found, analytically, to be associated with the slow ion acoustic mode, and are characterized by a counterstreaming-ion phase space.

In this paper, we present the first laboratory results which demonstrate the existence of this new class of double layers. We further show that the triggering mechanisms are very similar for double layers with $\phi > T_e/e$ and $\phi \lesssim T_e/e$. In each case, the double layers are found to evolve from a virtual-cathode–type potential well at the electron injection boundary. A similar type of evolution processes was previously observed for double layers with $\phi \gg T_e/e$ and an initial electron drift $v_D \gg v_{te}$ by Iizuka *et al.*[10] and by Leung, Wong, and Quons.[11] The growth of the potential well and the formation of the double layer in Ref. 10 were attributed to the Buneman-Pierce instabilities which required $v_D > v_{te}$. On the other hand, Leung, Wong, and Quons have proposed that the virtual-cathode potential wells were a result of the lack of neutralizing ions at the electron injection point.

However, the result reported here indicates a mechanism which is operative even when $v_D < v_{te}$. We show that the potential well which develops to limit the injected electron current and double-layer potential drop ϕ approximates the energy of the injected electrons; i.e., $\phi \approx (v_D/v_{te})^2 T_e/e$. We also show that when $\phi \lesssim T_e/e$, the monotonic double layer becomes unstable to ion-ion streaming instabilities and evolves into an acoustic-type double layer.

The experiments were performed in a triple-plasma device which has been described in detail elsewhere.[5] This device consists of two source plasmas bounding a target plasma. Plasma potential and density in the three plasmas can be varied separately. The source plasmas are created by filament discharge in argon (with an operating pressure $p_0 \lesssim 1\times10^{-4}$ Torr) with density $n_s \lesssim 10^9$ cm^{-3} and $T_e \approx 2$ eV. The boundary conditions for the present experiments are shown in Fig. 1. A steady-state target plasma with density $n_e \approx 10^7$ cm^{-3} was extracted from the high- (potential) side source through the two fine mesh grids d and e (each with 64% transparency). The resulting target plasma consisted of background electrons ($T_e \approx 2$ eV) and ions ($T_i \lesssim 0.3$ eV) at a uniform potential of $\phi_T \approx 3.0$ V. The low-side source electrons and ions were normally excluded from the target plasma by the potential barriers of grid b (biased at -30 V) and grid c (biased at $+12$ V), respectively.

At time $t=0$, grid b was switched to ground and the low-side source electrons were accelerated into the target plasma by the potential difference between ϕ_T and ground. The low-side source electrons entered the target

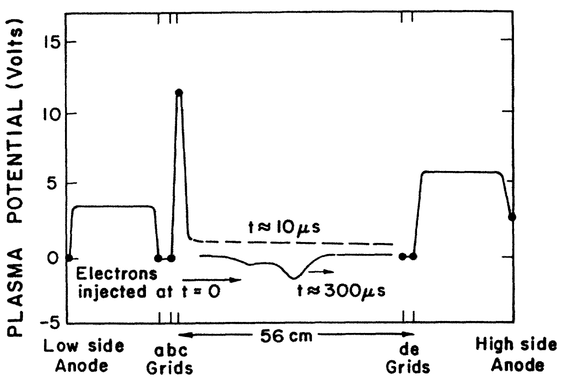

FIG. 1. Axial potential profile along the axis of the device. Grid b was switched from −30 V to ground at $t=0$.

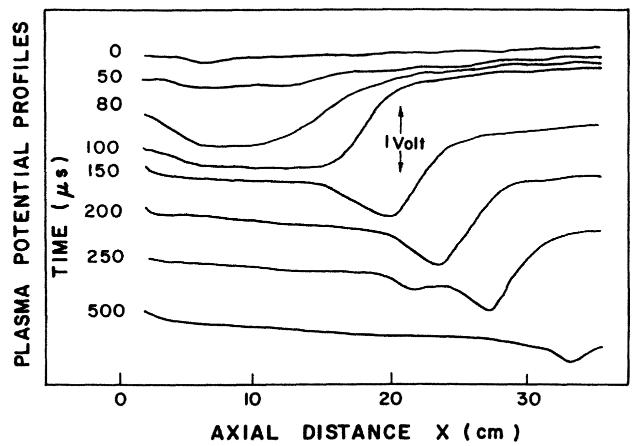

FIG. 2. Temporal evolution of the target-plasma potential profile when $v_D < v_{te}$. Each profile is displaced for clarity.

chamber as a half-Maxwellian distribution with a minimum drift energy $E_D = e\phi_T$. A portion of the left-going target-plasma electrons were also reflected by the potential barrier of grid b and became right-going electrons. As such, the average drift velocity of the low-potential-side electron distribution function depended on the density ratio of the drifting electrons and the thermal electrons. In the present experiment, the average drift velocity was found to be approximately equal to $(2eE_D/me)^{1/2}$, where m_e is the electron mass, or $v_D \approx (e\phi_T/T_e)^{1/2} v_{te}$. When the unneutralized electron stream entered the target plasma, the entire target-plasma potential was observed to decrease rapidly from 3.0 to 1.5 V in 10 μs. The temporal evolution of the target-plasma profiles, as obtained with an emissive probe with boxcar interferometer averaging techniques, is shown in Fig. 2. A potential well began to form near the low-side boundary at $t=50$ μs when $v_D \approx 0.7 v_{te}$. The slope of the potential drop began to steepen while the well grew in amplitude and in width. At $t > 75$ μs, a monotonic double layer with $\phi \approx 0.5 T_e/e$ formed and later evolved into one or more ion-hole-like[10] potential pulses. The potential profile at $t=150$ μs resembles an ion acoustic double layer.

The time history of the plasma potential (ϕ_L) at an axial distance of $x=10$ cm, the electron current flow to a single-sided Langmuir probe facing the potential source (I_{eH}), and the ion saturation current (I_{iL}) collected by a wire probe at $x=15$ cm are shown in Fig. 3 in order to illustrate the double-layer formation processes. At $t > 50$ μs when $\phi_T \approx 1$ V and $v_D \approx 0.7 v_{te}$, the potential well started to grow, corresponding to the abrupt decrease of ϕ_L. On the other hand, I_{eH} continued to increase as a result of the injected electron current until ϕ_L became negative at approximately 85 μs and I_{eH} decreased rapidly. As ϕ_L reached a minimum of −1.0 V, I_{eH} was observed to be reduced to almost the level at $t < 0$. ϕ_L subsequently became slightly positive and an intense low-frequency noise began to appear in I_{iL} which then corresponded to the evolution of the ion-hole-like pulse.

We interpret the data in Fig. 3 as follows: Electron injection from the low-side source created excess space charge at the injection boundary and a virtual-cathode–type potential well with amplitude ϕ_w was formed to limit the injected current. Since the potential well must become a potential barrier to the injected electrons in order to limit the current, $\phi_w \approx (v_D/v_{te})^2 T_e/e$. Since the potential drop of the double layer $\phi = \phi_w$, ϕ is approximately equal to $(v_D/v_{te})^2 T_e/e$. As shown in Fig. 3(c) and Fig. 1, the current I_{eH} was reduced to very small values as a result of the formation of the double

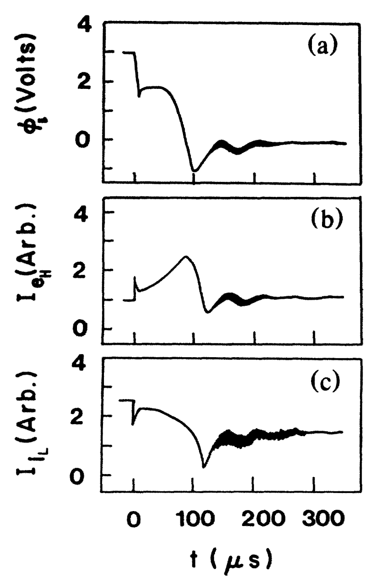

FIG. 3. Time history of (a) the target-plasma potential (ϕ_L) as measured by an emissive probe at 10 cm away from grid c, (b) the electron saturation current (I_{eH}) collected by a single-sided Langmuir probe facing the low-potential source, and (c) the ion saturation current (I_{iL}) collected by a wire probe at 15 cm away from the grid c.

layer. I_{eh} is related to the electron current flow from left to right across the double layer and can be written as

$$I_{eH} = eA(n_e v_{te} + n_{eD} v_D), \quad (1)$$

where A is the probe surface area, n_e is the background electron density, and n_{eD} is the density of the drifting electrons. From Figs. 2 and 3 it can be seen that the potential on the right-hand side of the double layer is always positive while the boundary grids d and e are grounded. Thus the electron flow from the high-potential source into the target chamber is not affected by the formation of the double layer. The current carried by the right-going electrons [i.e., the first term in Eq. (1)] should increase somewhat during the growth of the potential dip because of increased electron reflection back to the probe. However, this increase is offset by the shadowing effect of the probe on the left-going electrons. We conclude that the rapid decrease in I_{eH} during the double-layer formation comes entirely from the reduction in the current carried by the drifting electrons.

The growth of the potential well and the double-layer formation give rise to bursts of counterstreaming ions[10] which originate in the neighborhood of the potential well. These ions are suddenly accelerated down each side of the potential well with an average velocity

$$v_b < (2e\phi/T_e)^{1/2} c_s \quad (2)$$

which results in a counterstreaming-ion phase-space configuration at the double-layer front. Many numerical and experimental studies of ion acoustic shocks[12] and ion holes[13] show that the ion-ion two-stream region becomes unstable[12,13] when $v_b < c_s$ and evolves into one or more ion phase-space vortices. In particular, the experimental and theoretical work by Pecseli and Trulsen[13] have shown evolution processes of ion holes that are quite similar to our present observation. The evidence included the formation time scale of the order of $10 f_{pi}^{-1}$, the width of $(10-30)\lambda_D$, and the subsonic propagation velocity for the ion holes. Further evidence for this process was the onset of the intense low-frequency noise (a broad band below 100 kHz in I_{iL}) at the low-potential side of the double layer. The exact value of v_b could not be measured in this experiment because of the presence of such intense noise in the two-stream region. Saeki *et al.*[10] have studied the phase-space orbits of the ions in a time-increasing potential well experimentally and numerically. They have found that the sudden drop of the potential well produced counterstreaming ions with an average energy $E_b \approx 0.7 e\phi_{\max}$, where $\phi_{\max}$ is the maximum amplitude of the potential well. In the present experiment, $\phi_{\max} \lesssim 0.5 T_e/e$ or $v_b \lesssim 0.84 c_s$ with use of the results by Saeki *et al.*

We further confirmed our interpretation by increasing the target-plasma potential to $\phi_T = 4.0$ at $t < 0$ by increasing the anode bias and the high-side source density. After the injection of the low-side source electrons and the rapid initial drop in ϕ_T along the whole target plasma, ϕ_T settled to +3.0 V at $t \approx 10$ μs which results in $v_D > v_{te}$. As shown in Fig. 4, a potential well began to form and later evolved into a stable double layer with $\phi \approx 1.1 T_e/e$. The two-stream ion noise was not observed after the double-layer formation. The double layer was essentially stationary for $t > 800$ μs and did not break into ion-hole-like pulses. For this experiment we expect $v_b > c_s$; thus the double layer would be stable against ion-ion two-stream instabilities and the formation of ion phase-space vortices.

It appears that the formation of the virtual-cathode potential well is a result of the lack of neutralizing plasma ions at the electron injection boundary. As long as the injected electron density is sufficiently high, the potential well forms independently of v_D and is not associated with instabilities. In conclusion, our experiment has for the first time shown experimentally the evolution of a class of double layers which were formed to limit the injection of unneutralized electrons into a collisionless plasma. The current-limiting nature of these double layers, the measured properties of $e\phi/T_e \sim 1$, their propagation velocity of the order of the ion thermal velocity v_i

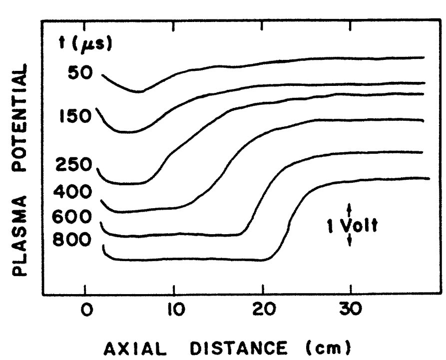

FIG. 4. Temporal evolution of the target-plasma potential profile when $v_D > v_{te}$ at $t \lesssim 10$ μs.

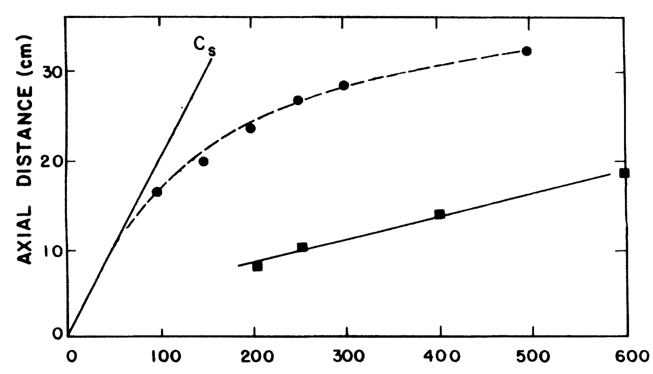

FIG. 5. The trajectories of the ion hole (circles) and the slow ion acoustic double layer (squares).

(see Fig. 5), and the inferred small drift velocity v_D associated them with the "currentless"[8] or "slow ion acoustic"[9] double layers that have been previously predicted. The small double-layer velocity (the order of v_i) introduces an asymmetry in the counterstreaming-ion phase space. Schamel has demonstrated[9] that such an asymmetry combined with Boltzmann electrons is consistent with the existence of such double layers. These results may explain why steady-state double layers were always found with $\phi > T_e/e$ and an initial electron drift velocity $v_D > v_{te}$ in laboratory experiments, while only transient ion-acoustic-type double layers with $\phi \lesssim T_e/e$ have been found when $v_D \lesssim v_{te}$.

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[1]L. P. Block, Cosmic Electrodyn. **3**, 349 (1972).

[2]B. H. Quon and A. Y. Wong, Phys. Rev. Lett. **37**, 1393 (1976).

[3]Ch. Hollenstein, M. Guyot, and E. S. Weibel, Phys. Rev. Lett. **45**, 2100 (1980).

[4]T. Sato and H. Okuda, Phys. Rev. Lett. **44**, 740 (1980).

[5]C. Chan, M. H. Cho, N. Hershkowitz, and T. Intrator, Phys. Rev. Lett. **52**, 1782 (1984).

[6]A. N. Sekar and Y. C. Saxena, Plasma Phys. Controlled Fusion **27**, 181 (1985).

[7]M. Temerin, K. Arny, W. Lotko, and F. S. Mozer, Phys. Rev. Lett. **48**, 1175 (1982).

[8]F. W. Perkins and Y. C. Sun, Phys. Rev. Lett. **46**, 115 (1981); D. Stern, J. Geophys. Res. **86**, 5839 (1981).

[9]K. Y. Kim, Phys. Lett. **97A**, 45 (1983); H. Schamel, Z. Naturforsch. **39a**, 1170–1183 (1983).

[10]S. Iizuka, K. Saeki, N. Sato, and Y. Hatta, Phys. Rev. Lett. **43**, 1404 (1979); K. Saeki, S. Iizuka, and N. Sato, Phys. Rev. Lett. **45**, 1853 (1980).

[11]P. Leung, A. Y. Wong, and B. H. Quon, Phys. Fluids **23**, 992 (1980); N. Singh and R. W. Schunk, Phys. Fluids **26**, 2781 (1983).

[12]R. J. Mason, Phys. Rev. Lett. **15**, 1162 (1972); P. H. Sakanaka, Phys. Fluids **15**, 1323 (1972).

[13]H. L. Pecseli and J. Trulsen, Phys. Rev. Lett. **48**, 1355 (1982); H. L. Pecseli, R. J. Armstrong, and J. Trulsen, Phys. Lett. **81A**, 386 (1981).