the doubly excited level populations.

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Formation of Potential Double Layers in Plasmas*

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Large localized potential double layers, $e\varphi \gg kT_e$, are observed to develop from a solitary E-field structure in a plasma traversed by electron drifts, $v_d \simeq v_e$. Strong electron and ion accelerations occur across the layers. At large electron drift velocities ($v_d > 3v_e$), layers are unstable to large ion fluctuations with $\delta n/n$ approaching unity.

The existence of intense localized dc electric fields, potential double layers, has been the subject of many investigations in connection with intense beam injections[1] and in the ionospheric formation of auroral substorms.[2] We wish to present experimental evidence on the formation and stability of such potential layers in a bounded low-density plasma ($n \sim 10^8$ cm^{-3}) traversed by electron drifts, $v_d \approx v_e$ [$v_e = (kT_e/m)^{1/2} \sim 0.8\times10^8$ cm/sec]. Coherent potential perturbations initially excited by electron-ion drift instability[3,4] are observed to transform into stationary potential jumps[5] which exist self-consistently with the interpenetrating plasma streams and reflected ions and electrons.

The experiments were performed in the University of California at Los Angeles double-plasma beam system[6,7] which consists of two electrically isolated stainless-steel cylinders separated by two closely spaced tungsten grids (with 200×200 fine mesh). Plasmas are produced by bombardments of neutral gas (Argon, $P_0 \sim 10^{-4}$ Torr) with electrons from a set of hot filaments in the source chamber. The plasma potentials can be varied by applying an appropriate voltage bias between the two chambers to produce plasma flows. Three distinct regimes of operations can be accomplished, as shown in Fig. 1. *Regime I:* Slow electron-ion drifts [$0.3v_e > v_d > v_s$, where $v_e = (kT_e/m)^{1/2}$ and $v_s = (kT_e/M)^{1/2}$ are the electron thermal and ion acoustic speeds, respectively]. Plasma fluctuations identified as the current-driven ion acoustic instabilities were observed to grow spatially and become saturated at $\delta n/n \lesssim 10\%$ by an electron trapping process. Small amplitude waves were found[6] to develop into large-amplitude

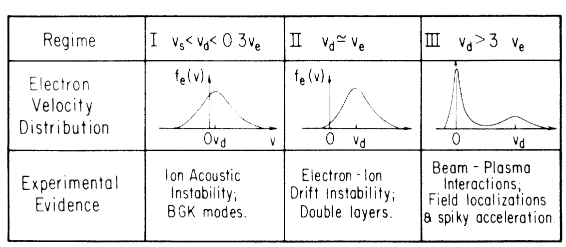

FIG. 1. The three regimes of plasma interactions observed with use of the double-plasma beam system.

undamped Bernstein-Greene-Kruskal (BGK) modes[8] with trapped electrons. *Regime II:* Large electron drifts ($v_d \simeq v_e$). A stable potential double layer with an overall potential jump of $\Delta\varphi \sim 3-15$ V and a gradient length 3–5 cm ($20-30\lambda_D$) develops via a two-stream instability to be discussed below. *Regime III:* Beam-plasma flows in which "bump-on-tail" electron distributions with beam velocities $v_d \approx 3-10 v_e$ can drive electron plasma waves to large amplitude. Ion waves of $\delta n/n < 10\%$ are excited parametrically and effective beam thermalization has been observed in this regime by intense localized high-frequency field.[7] The dynamic behavior of plasmas in Regime II is linked to Regimes I and III, during the spatial and temporal evolution of the electron distribution.

The existence of potential double layers in Regime II was verified by measurements of the plasma potential using Langmuir probes and electron-beam diagnostics. The potential profile measured is shown in Fig. 2, together with the phase-space representaions of electron and ion distributions obtained by probes and energy analyzers (with use of lock-in differentiation or computer analysis). In Fig. 2(b), drifting electrons are acceleated by the layer in the forward direction, forming an energetic electron beam downstream, similar to the distribution in Regime III. The beam is subsequently thermalized via beam-plasma interactions[7] in a downstream region 5–10 cm beyond the layer, producing hot electrons moving in both ($\pm x$) directions. Electons moving backward along $-x$ direction are reflected. Ions are accelerated and reflected [Fig. 2(c)] in directions opposite to the electrons except in one respect: Those ions moving in $-x$ direction are accelerated by the layer but are reflected by the grounded grid (positive with respect to the plasma potential) in front of the source chamber. Counter-streaming ion beams are formed in the low-potential side of the layer and are found to be essential for the existence of the layer. For example, no layer was formed when the grid is left floating or biased at a negative potential with respect to the source plasma. The energy gains by the electrons and ions across the layer compare well (within 10%) with the total potential jump, as shown by the energy of the beams. The reflection of ions and hot electrons on opposite sides of the potential layer gives rise to two charge sheets at their reflection points such that the potential jump can be described by the spatial charge distribution using Poisson's equation. Our experimental data appear to support the theoretical picture[9] of a double layer which exists self-consistently with reflected particles.

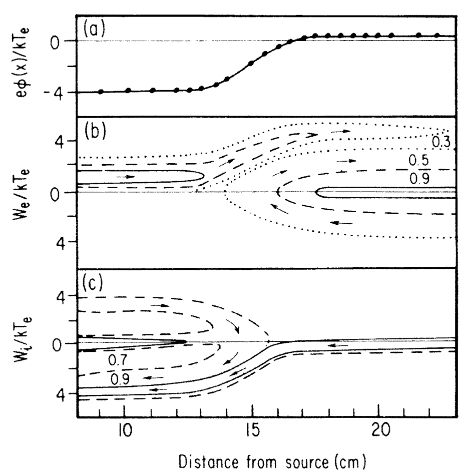

FIG. 2. (a) plots of steady-state plasma potentials, (b) the phase-space representations of the electron velocity distribution, and (c) ion velocity distribution function. Velocities are plotted in energy scales of $W_{e,i}/kT_e$, where $W_{e,i} = \frac{1}{2}m_{e,i}v^2$ for electrons and ions, respectively. Numbers indicated the normalized height of the distribution functions.

The temporal evolution of the potential double layer was studied by pulsing the electron drift on and off, through the control of the potential difference between source and target chambers. The electric field in the layer was directly measured using a probing electron beam located in the center region of the target plasma (15 cm from the source). The beam deflection caused by axial electric fields in the direction of electron drift are observed on a screen and detected by a split-plate detector with a high-gain difference amplifier. The calibrated measurements in Fig. 3 show a threshold ($v_d \simeq 1.0 v_e$) at which a solitary E-field structure was detected at ~ 80 μsec after the electron drift is turned on, indicating a speed of $v \sim 2\times10^5$ cm sec^{-1}, which is close to the ion acoustic speed. This propagating speed increases with the electron drift to 10^6 cm sec^{-1} at $v_d \simeq 1.5 v_e$ and a steady state $E \approx 4$ V/cm was established after the passage of the solitary structure (50 μsec). The E-field in both the traveling solitary structure and the subsequent steady-state layer is always pointing in a direction opposite to the electron drift. For $v_d \simeq 1.5 v_e$ the spatial potential profile was measured at successive stages of the temporal evolution by sampling the electron distribution, $f \simeq f_0 \exp\{-e[\varphi_\infty - \varphi_{\text{probe}}]/kT_e\}$, at a

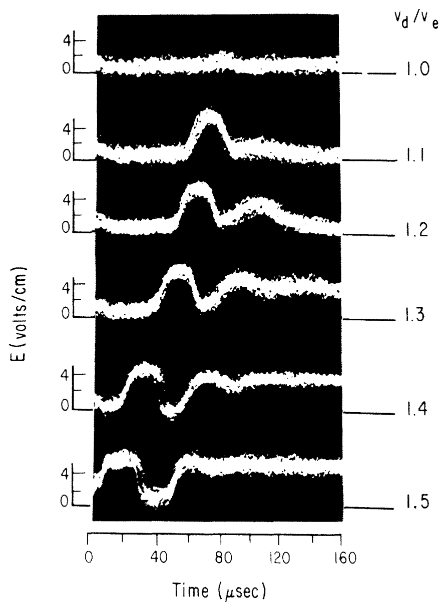

FIG. 3. Electric fields measured by deflections of a probing beam located at the center of the device (15 cm from the source). Positive E is pointed in the opposite direction of the electron drift. Signals shown are detected by a split-plate detector with a high-gain difference amplifier which subtracts noises picked up by each individual plate.

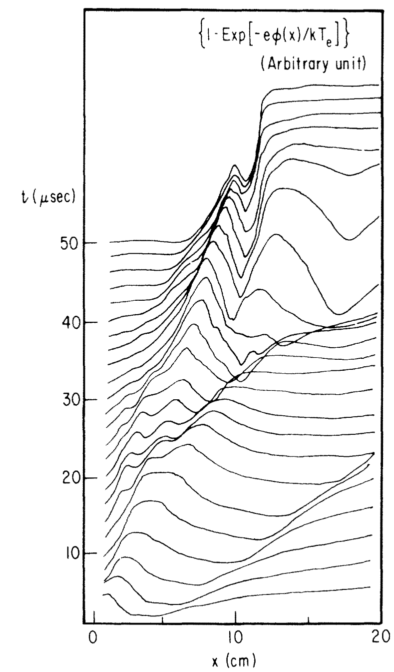

FIG. 4. Representation of plasma potential profile in time sequences $0<t\lesssim 50$ μsec, showing the transformation of moving potential perturbations into a stationary potential double layer for $v_d \simeq 1.5v_e$.

fixed probe potential φ_{probe}, and plotting

$$[f_0 \exp(e\varphi_{\text{probe}}/kT_e) - f]/f_0 \exp(e\varphi_{\text{probe}}/kT_e) \simeq 1 - \exp[-e\varphi(x)/kT_e],$$

as shown in Fig. 4. This representation[10] shows the spatial potential profile and amplifies the spatial potential variation by the exponential function. Figure 4 demonstrates that (1) at earlier times (10–20 μsec) a potential perturbation was excited to propagate in the drift direction at a speed 10^6 cm sec^{-1}; (2) the perturbation grows in amplitude to $e\varphi/kT_e \gtrsim 1$ and evolves into moving potential steps which are the spatial description of the same solitary E-field structure observed in time (20–30 μsec) by the electron-beam deflection in Fig. 3; and (3) after the passage of the leading pulse (40–60 μsec), ions are accelerated to stream in the direction opposite to the perturbation, such that the trailing pulses appear to slow down in the laboratory frame; and the dc potential double layer develops and remains essentially stationary in later times. Thus both the electric field and the potential profile reveal the formation of a stationary potential double layer from moving solitary-field structure in time of 30–60 μsec, a time corresponding to 5–10 ion plasma periods, $(f_{\text{pi}})^{-1}$.

Stable double layers are formed in the plasma with good stable characteristics over a range of drift velocities, $v_e \lesssim v_d \lesssim 3v_e$. Large ion fluctuations ($\delta n/n \lesssim 50\%$) can be excited in the low-potential side of a stable layer. However, at higher drifts ($v_d > 3v_e$), the layer breaks up into intense field spikes ($E_{\max} \gtrsim 10$ V/cm) and large-amplitude ion fluctuations[11] ($\delta n/n \approx 1$ and $\omega \approx 0.1\omega_p$) are observed. These greatly enhanced fluctuations associated with unstable double layers may present a new type of plasma turbulence and deserve further investigation.

In conclusion, the foregoing experiments have demonstrated unambiguously the existence of a stationary potential double layer. Solitary E-field structures initially excited by the potential changes at the source reflect ions to form counterstreaming ion distribution necessary for the establishment of the double layer. The potential double layer is essentially the transformation of the solitary E structure from the moving frame into a stationary frame. At higher drifts the layer is unstable because of large electron-ion counter-streaming at the layer.

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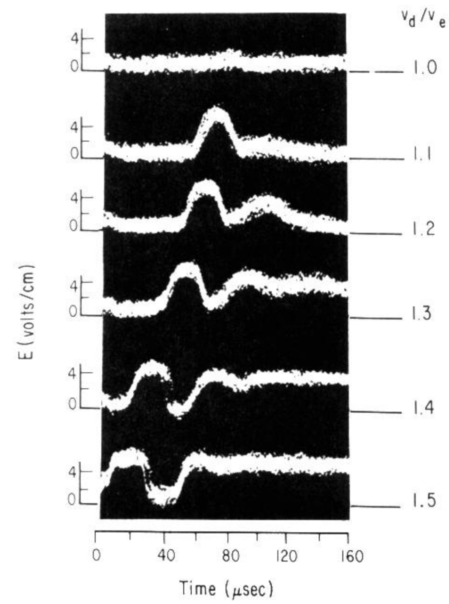

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