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# A LABORATORY INVESTIGATION OF POTENTIAL DOUBLE LAYERS

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## ABSTRACT

In a triple plasma device, the injection of electron current from the source chamber to the target chamber causes the formation of a potential double layer. At a low current density, the space charge of the injected current produces a virtual cathode-type potential double layer. This double layer is stable, and various wave instabilities are observed to associate with this double layer. As the current density is increased, the double layer becomes unstable, and a moving double layer results. As the current density is increased further, the enhanced ionization causes the neutralization of the space charge of the electron beam, and the "beam plasma discharge" is ignited.

## I. INTRODUCTION

The importance of potential double layers in astrophysical phenomena is well known (Alfvén, 1958). Theoretical work on potential double layers has indicated that wave instabilities may be responsible for the formation of potential double layers. However, different theoretical models have predicted different instabilities in order for a double layer to form. These instabilities include ion-acoustic (Sato and Okuda, 1980), ion hole (Schamel and Bujarbarua, 1983), Langmuir turbulence (Levine and Crawford, 1978), and Buneman (Iuzuka et al., 1979) instabilities. This paper presents experimental measurements of the characteristics of instabilities associated with a potential double layer. The double layers were produced in a conventional triple plasma device by the injection of an electron current from the source chamber to the target chamber. Different types of wave turbulences were observed to be associated with a stable double layer. Despite the presence of these wave instabilities, the virtual cathode-type mechanism (Leung et al., 1980) associated with the space charge of the injection electron current was found to be the single most important mechanism responsible for the double layer formation. Experimental data on the transition of the double layer phenomenon into the beam plasma discharge phenomenon (Bernstein et al., 1978) will also be discussed. This transition was due to the transition from space charge-limited electron current flow to source temperature-limited electron current flow. This transition further illustrates the importance of space charge effects in the stability and formation of potential double layers.

Part II of this paper describes the experimental setup, part III presents the measurements of wave instabilities associated with a stable double layer, part IV discusses the transition of a stable double layer into the beam plasma discharge phenomenon, and part V is the conclusion.

## II. EXPERIMENTAL SETUP

The experiments were performed in a modified triple plasma device. The details of this setup have been described elsewhere (Leung et al., 1980). In most of the experiments, the system was operated as a double plasma device. The diagnostics consist of a two-sided Langmuir probe and an emissive probe, both mounted on the same

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probe shaft. This permits measurements of plasma potential and plasma electron distribution function simultaneously. An electron gun (5-9 keV, 100 nA) is available for electric field measurements. This gun provides a non-perturbative diagnostic to verify the existence of a double layer. The ion dynamics are measured by an electrostatic energy analyzer.

A shielded RF probe is used to measure the unstable wave spectrum. Wavelength measurements are made by two probe correlational methods. In this series of experiments, the frequency of unstable waves ranges from 50 kHz to 100 MHz.

## III. RESULTS

A steady state double layer is produced by operating the system in a double plasma device configuration. The potential profile and the grid biases are shown in Figure 1. The plasma parameters associated with this double layer are shown in Figure 2. In the high potential side, the electron distribution function is in the form of a bump-on-tail distribution. In the low potential region, the electron distribution function is a modified drifting Maxwellian. In the low potential region, counterstreaming ion beams are present; whereas, in the high potential region, only thermal ions are present. These particle distributions are very important for the understanding of a potential double layer since they are responsible for both the self-consistent potential profile and the wave instabilities.

The typical frequency spectrum associated with a stable double layer is shown in Figure 3. The frequency spectrum can be divided into two regions: (1) the high frequency spectrum around the electron plasma frequency and (2) the low frequency spectrum in the vicinity of the ion plasma frequency. The unstable waves at $\omega_{pe}$ only have significant amplitude at the high potential side. This is because the bump-on-tail electron distribution on the high potential side excites beam plasma instabilities. The cross-spectral intensity obtained by a two-probe correlation method is shown in Figure 4a. The value of the wavelength derived from this interferometer trace indicates that the waves propagate at approximately the same velocity as the electron beam that is present in the high potential region. Consequently, the waves are excited by the beam-plasma (Schmidt, 1979) instabilities.

The waves around the ion plasma frequency range from 0.1 $\omega_{pi}$ to 3 $\omega_{pi}$, where $\omega_{pi}$ is the ion plasma frequency. The amplitudes of these waves are significant only in the low potential region. Figure 4b shows a typical cross-spectral density function obtained by the two-probe correlation measurement technique. The dispersion relationship of these low frequency waves is shown in Figure 5. The data displayed in Figure 5 show that the phase velocity of most waves is faster than $V_b$, where $V_b$ is the ion beam velocity associated with the stable double layer. Due to their fast phase velocity and the fact that the unstable waves are present above the ion plasma frequency, the waves cannot be excited by the ion-beam plasma instabilities.

A theoretical model was developed to interpret the dispersion relationship shown in Figure 5. The details of this model are discussed in a previous publication (Leung, 1980). The model indicates that the waves around the ion plasma frequency are excited by a modified Buneman-type (Buneman, 1959) instability. The main interaction mechanism is operating between the drifting electrons and the ion beam that is propagating at the same velocity as the electron drift. In the stationary frame of the ion beam, the excited waves have Buneman-type properties. The observed dispersion relationship is just the Buneman dispersion relationship after a transformation from the stationary frame of the ion beam to the stationary frame of the laboratory. The drifting electrons should also interact with the ion beam that propagates in the opposite direction; however, the resulting unstable waves will be subjected to strong Landau damping. This is because the phase velocity of this unstable wave in the laboratory frame will be very close to the velocity of the preceding (rightward in Figure 2) ion beam. Consequently, this mode was not observed in the measurements. The theoretical model discussed in Leung (1980) predicts a very high growth rate. In our measurements, the growth of the Buneman-type waves was not observed. This could be due to the fact that the high growth rate caused the waves to saturate near the grid.

## IV. TRANSITION OF A STABLE DOUBLE LAYER INTO THE BEAM PLASMA DISCHARGE

The current that flows from the source to the target region can be increased by increasing the grid bias. As the grid bias is increased, the potential drop across the double layer also increases. This trend continues until the potential drop reaches 14 V, which is approximately the first ionization potential of argon. Beyond this point, a sudden increase in the grid bias causes an abrupt increase in the current; and, at the same time, the double layer potential profile collapses (Fig. 6). The plasma density in the target chamber increases by more than an order of magnitude and the "beam plasma discharge" (Bernstein et al., 1978) is excited. The ignition of the beam plasma discharge (BPD) phenomenon is characterized by abrupt increases in the following plasma parameters: (1) optical emission, (2) plasma density, (3) plasma current (Fig. 7), and (4) wave turbulence (Fig. 8).

It should be noted that before the ignition of BPD, the double layer becomes unstable, and large amplitude potential fluctuations are observed. Figure 9a shows the fluctuations in the local electric field as measured by the diagnostic electron beam. The electric field fluctuates at a frequency of approximately 1 kHz. Figure 9b shows the signal detected by the Langmuir probe. The fluctuation in the probe current was due to the change in local plasma potential induced by the moving double layer. The temporal change in potential profile was obtained by performing a time sampling of the emissive probe trace. Figure 10 shows the time development of the potential profile. In this figure, $t = 0$ is chosen arbitrarily. The data show that the double layer is no longer stable but is moving toward the end of the chamber, i.e., away from the source. The velocity of propagation varies, but under most conditions it is faster than the ion-acoustic speed. The data presented in Figure 10 indicate the significance of the space charge of the electron current in double layer formation. At $t = 150$ μs, the normalized potential of the low potential region has a value of 2, and the amount of electron current that can flow from source chamber to target chamber is very large (Figs. 11a,b). At $t = 200$ μs, the normalized potential has a value of 6, the flow of current from source to target is severely limited, and the potential double layer is not well defined. The cycle for the formation and disappearance of a potential double layer repeats itself. This is responsible for the observed fluctuation in the potential profile. A detailed model (Leung et al., 1980) on double layer formation has been discussed elsewhere and will not be discussed in this article.

Referring again to Figure 10, at $t = 150$ μs, the current limitation by the space charge effect is at its minimum. If the absolute potential of the low potential region is further reduced, the current flow is significantly increased (Figs. 11a,b). This increase in current increases the rate of ionization in the high potential region. The increase in the ion fluxes further reduces the space charge in the low potential region, and eventually the space charge limitation of the electron current flow is eliminated. The uninhibited flow of current leads to the ignition of the beam plasma discharge.

It should be noted that the transition from double layer (DL) to BPD is not a reversible process. By lowering the bias, the BPD will not transform back to a DL immediately. A DL is formed only when the bias voltage is lowered to a value such that the ionization cross-section is substantially reduced.

The injection of electron current from the source to the target chamber is very similar to the injection of an electron beam from a rocket to the ionosphere. BPD has been observed in several rocket experiments (Hallinan et al., 1978). In some of the beam injection experiments, large amplitude fluctuations (Winckler, 1980) in the electron return current and in the optical emission were also observed. This type of fluctuation could be due to the excitation of moving double layer-type potential structures in the ionosphere. The space shuttle and the future Space Station, with its diverse sophisticated diagnostic instruments, should be able to provide a test bed for beam-excited double layer structures in the ionosphere.

## V. CONCLUSIONS

This paper has discussed the instabilities associated with a stable double layer. The unstable wave spectrum around the electron plasma frequency is due to the excitation of the beam plasma instabilities by the electron beam that is present in the high potential region. The unstable waves around the ion plasma frequency are due to the excitation of the Buneman-type waves by the electron current.

The data in our experiments show that as the grid bias is increased, there is a transition from a stable double layer to a moving double layer, followed by the ignition of beam plasma discharge. This transition shows that the space charge of the injected electron current plays a very important role in double layer formation. The role of instabilities is not evident in our experimental measurements. Since wave instabilities are always associated with double layers, their role in modifying the characteristics of DLs is undeniable and should be further investigated.

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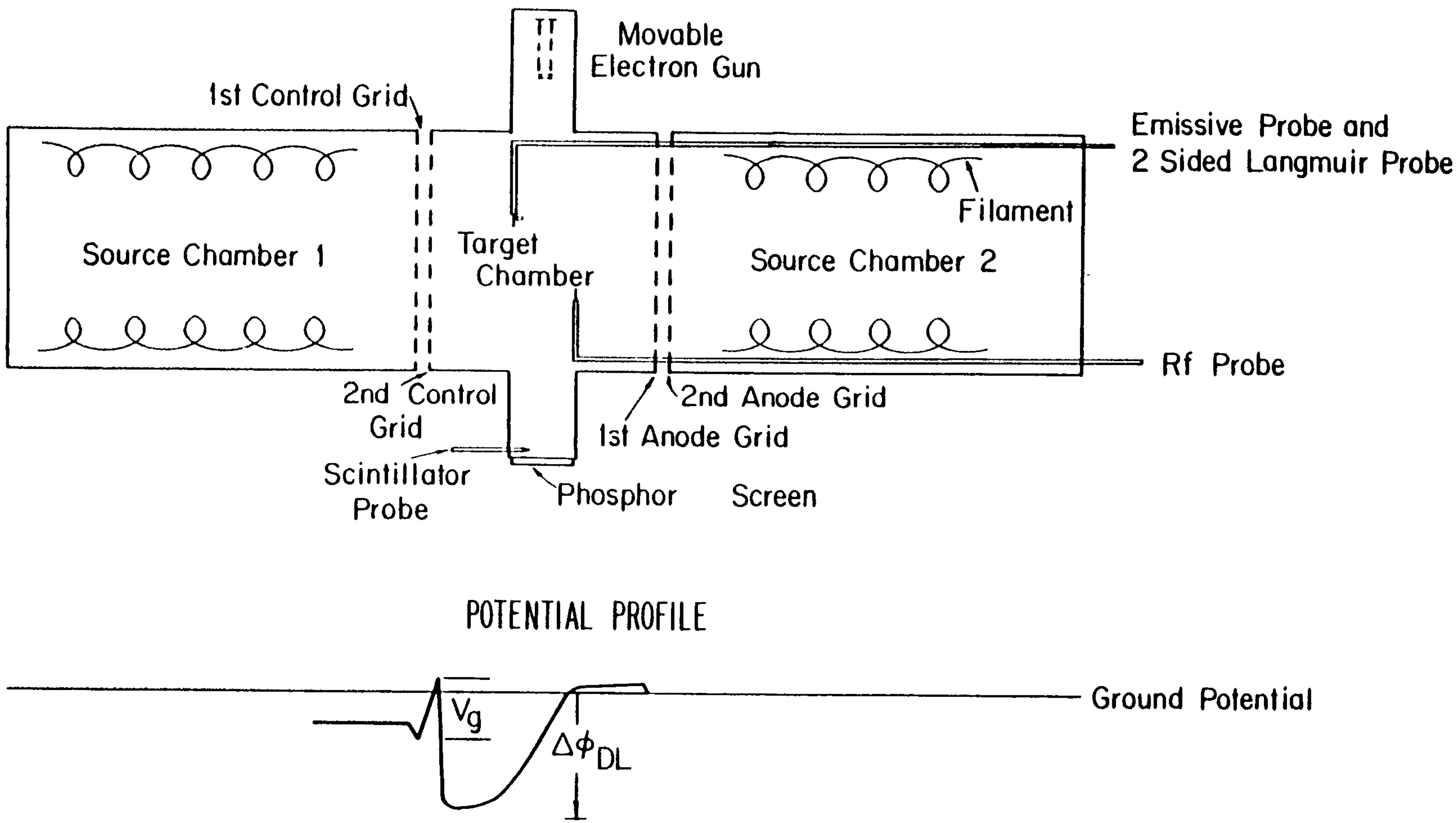


Figure 1. Schematics of the triple plasma device.

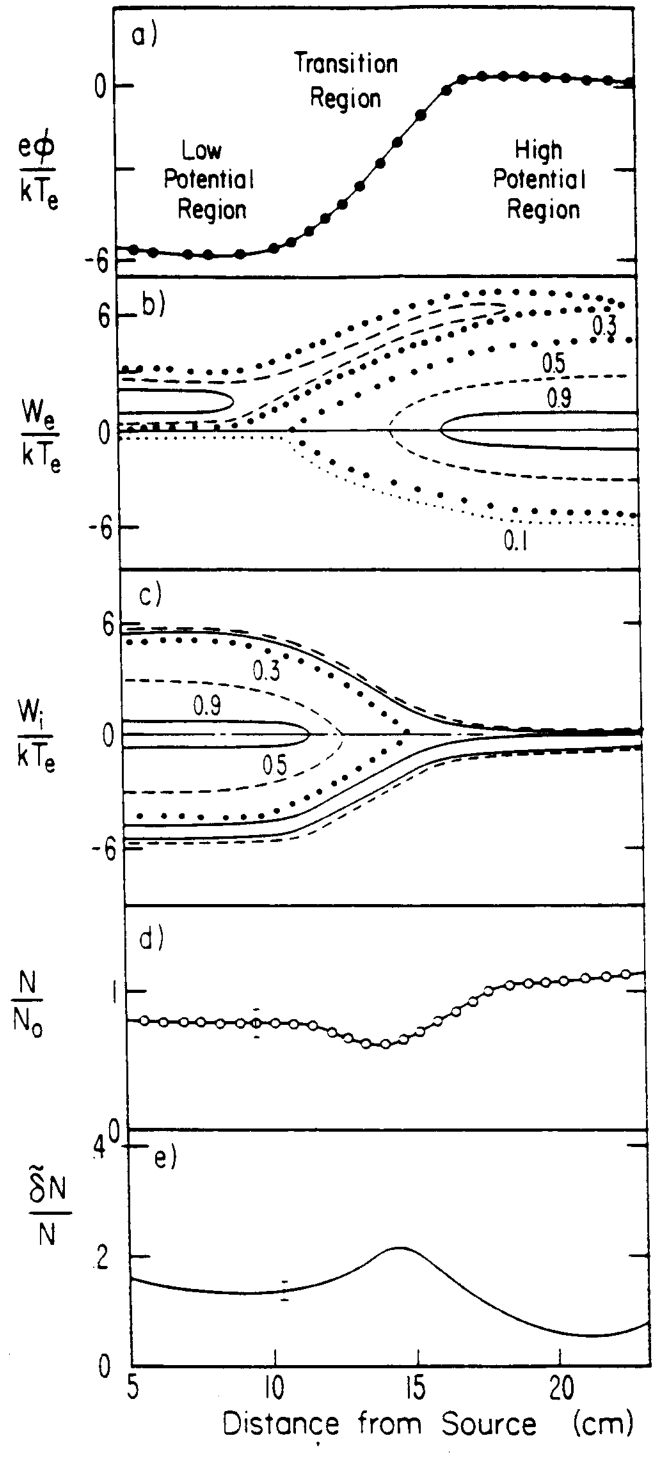


Figure 2. The plasma parameters associated with a potential stable double layer. The plasma parameters are normalized with respect to electron temperature $T_e$ and the electron density at the high potential side. (a) Plasma potential profile. (b) One-dimensional phase-space representation of electron distribution, $W_e = 1/2\, m_e v^2$, where $W_e$ is the normalized electron energy. The numbers on the curves indicate the normalized height of the distribution function. The negative values of $W_e/kT_e$ represent velocity in the opposite direction, (c) Phase representation of the ion distribution function, $W_i = 1/2\, M_i v^2$. (d) Relative electron density. N is the spatial density in the target region. (e) Relative peak-to-peak density fluctuation.

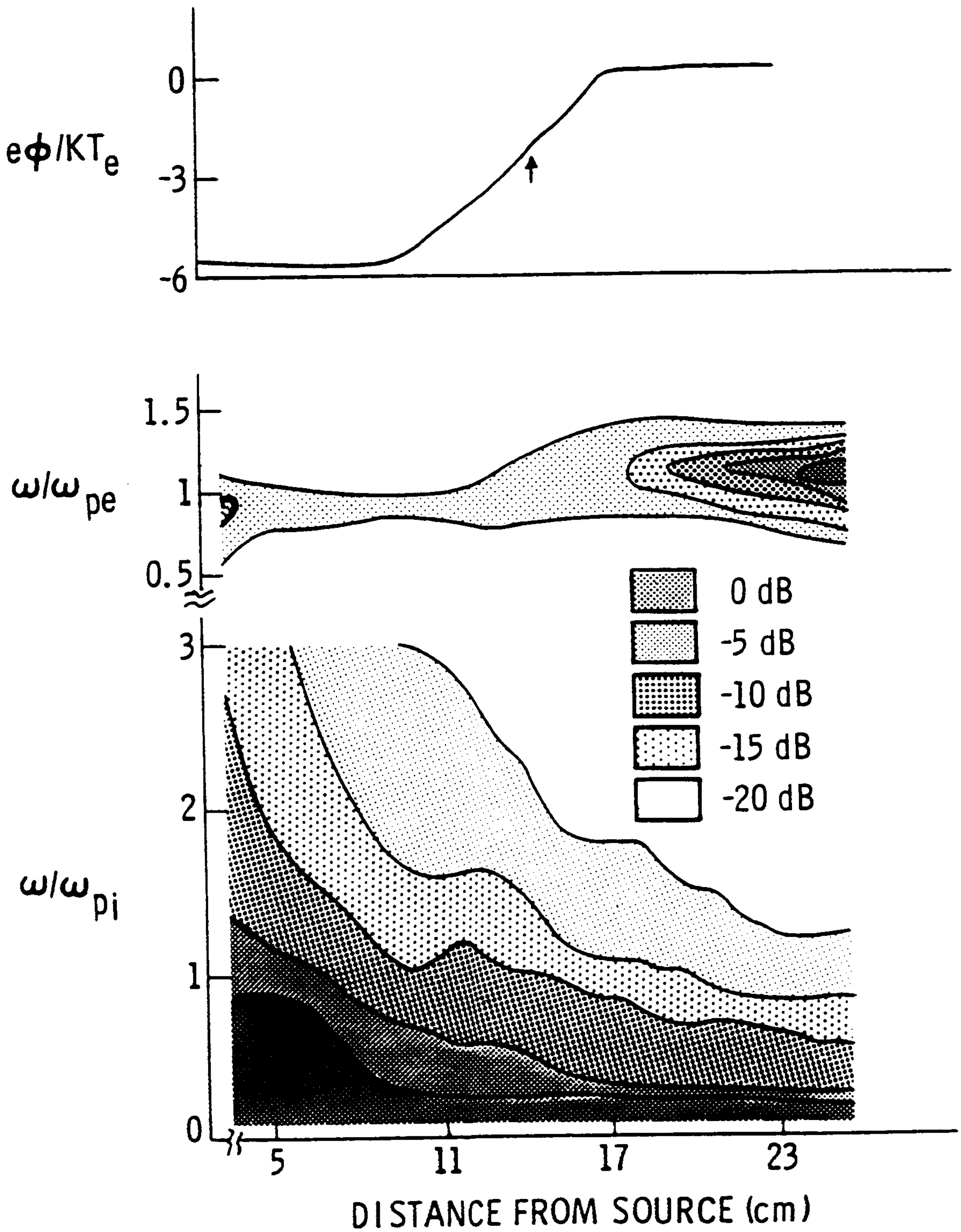


Figure 3. The power spectrum of unstable waves associated with a stable double layer, showing the power level of different frequencies present at different points along the potential profile (top). The power levels are divided into five arbitrary levels. The frequencies of unstable waves are normalized to electron plasma frequency ($\omega_{pe}$) and ion plasma frequency ($\omega_{pi}$).

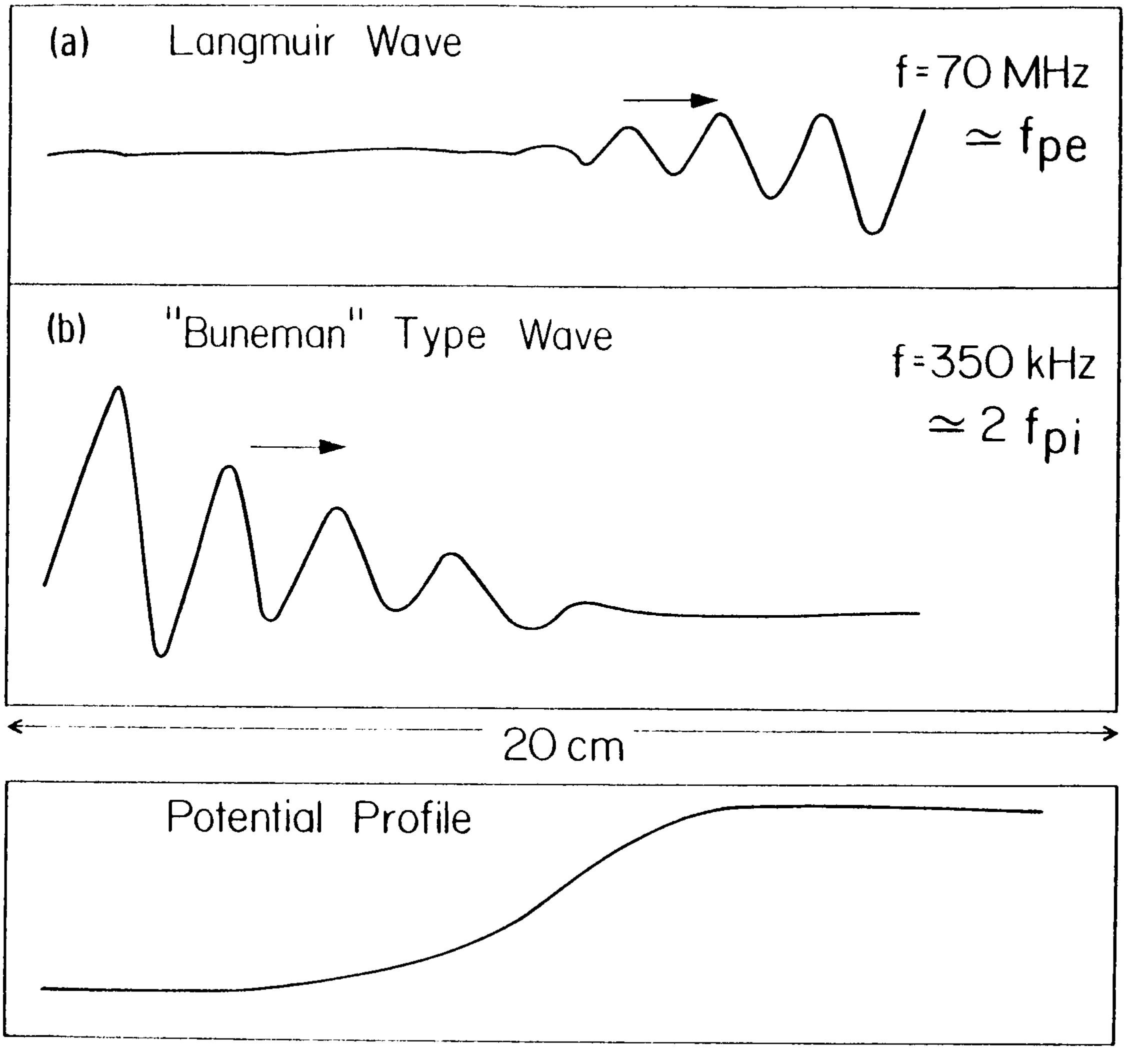


Figure 4. The cross power spectral density of the Langmuir wave and Buneman-type waves. The potential profile is also shown here for reference.

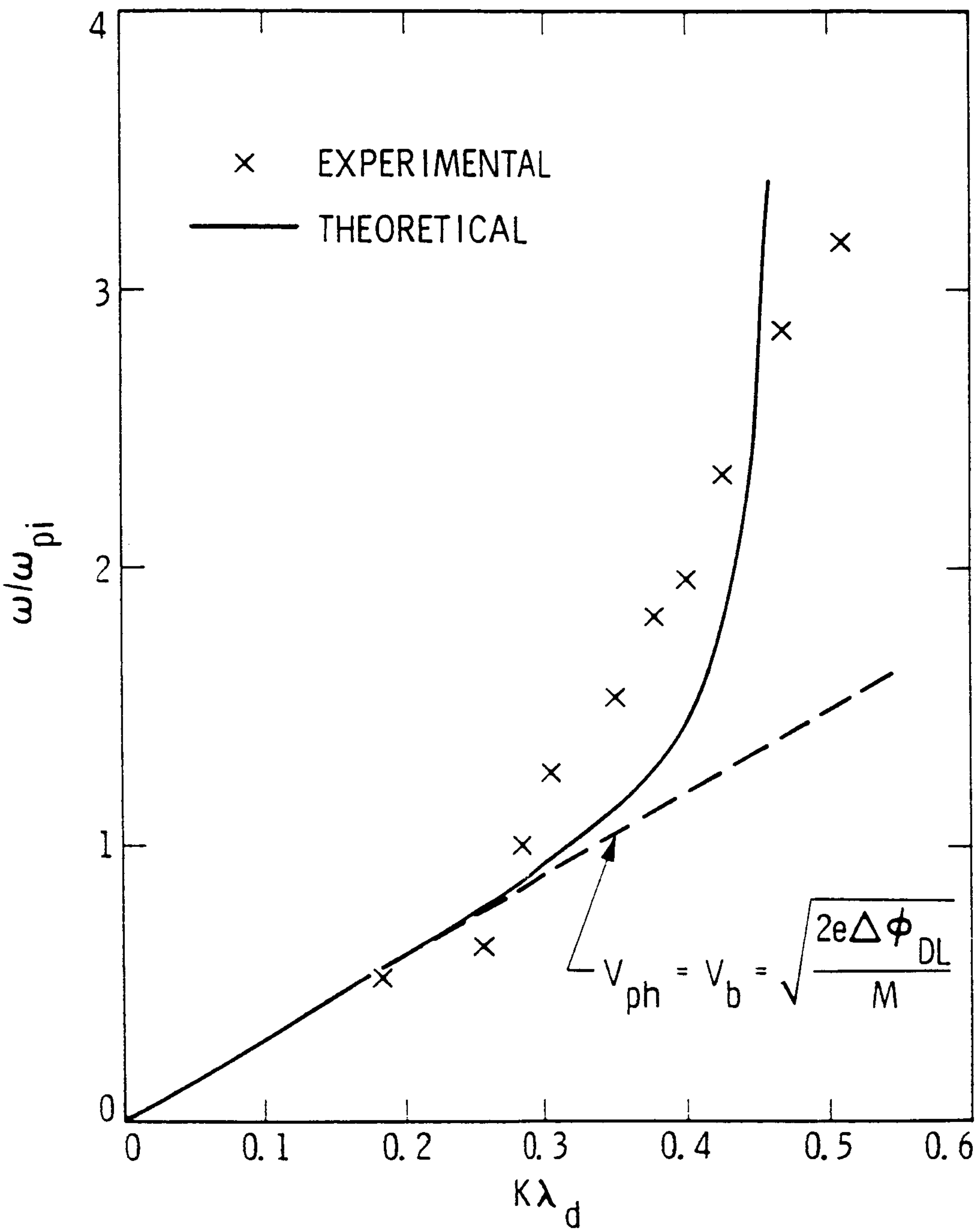


Figure 5. The dispersion relationship of the Buneman-type wave: x represents the experimental data, and the solid line is the theoretical dispersion relationship.

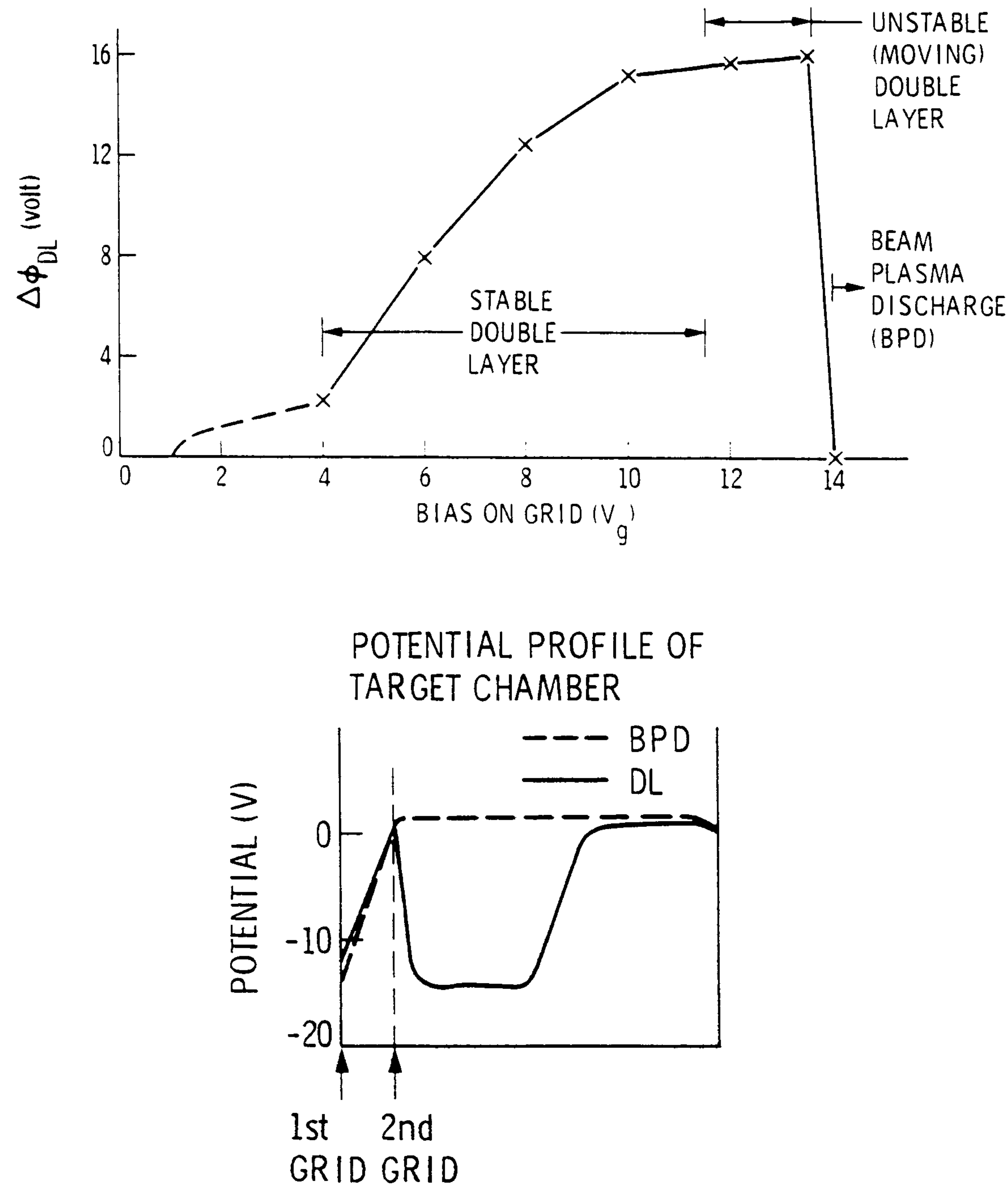


Figure 6. The change in potential drop of the double layer as the grid bias is increased. The beam plasma discharge is ignited when the grid bias exceeds 13 V. The potential profile of the target chamber before and after the ignition of the BPD is shown in the lower diagram.

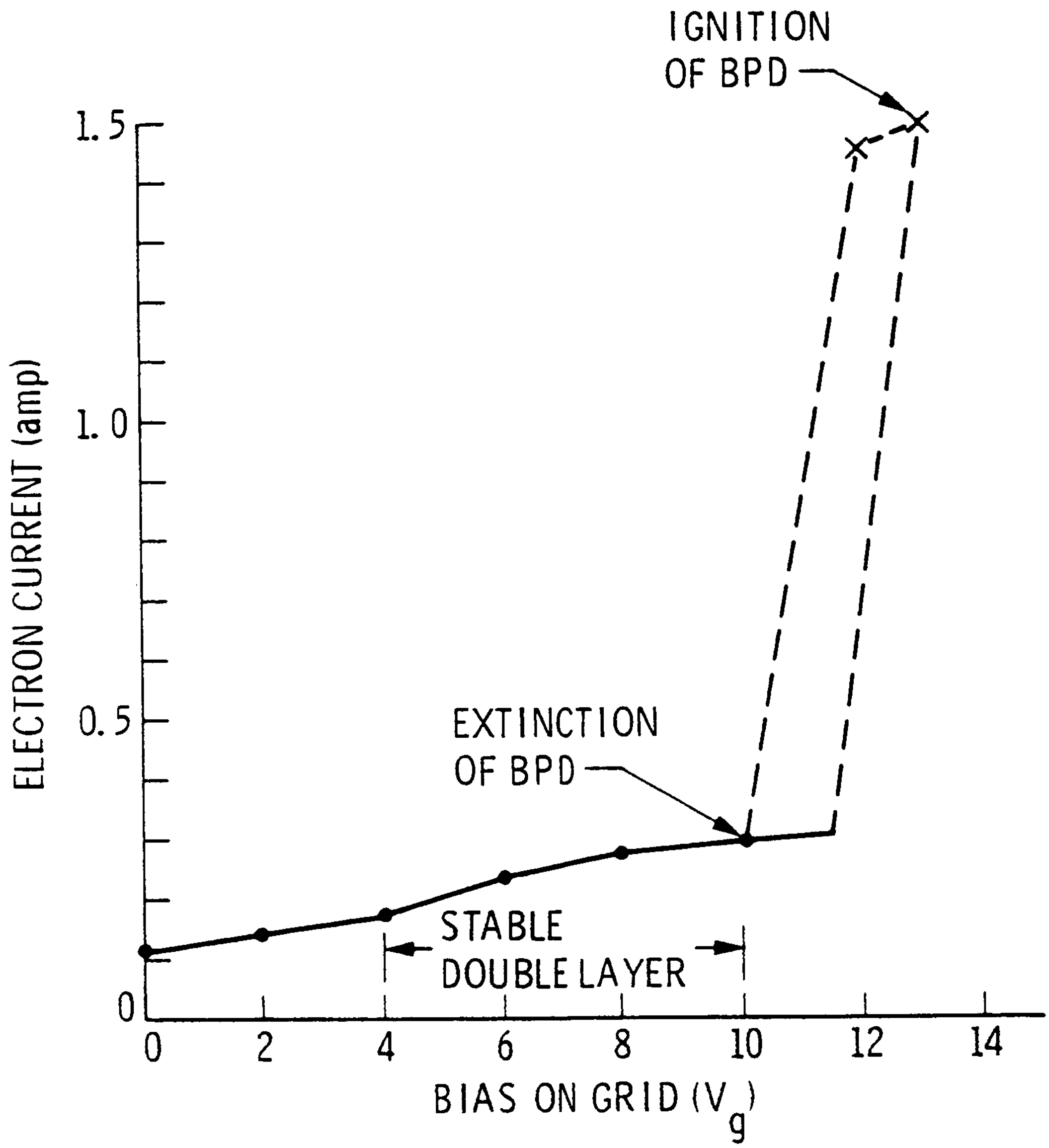


Figure 7. The injected electron current as a function of the grid bias showing the ignition of the BPD.

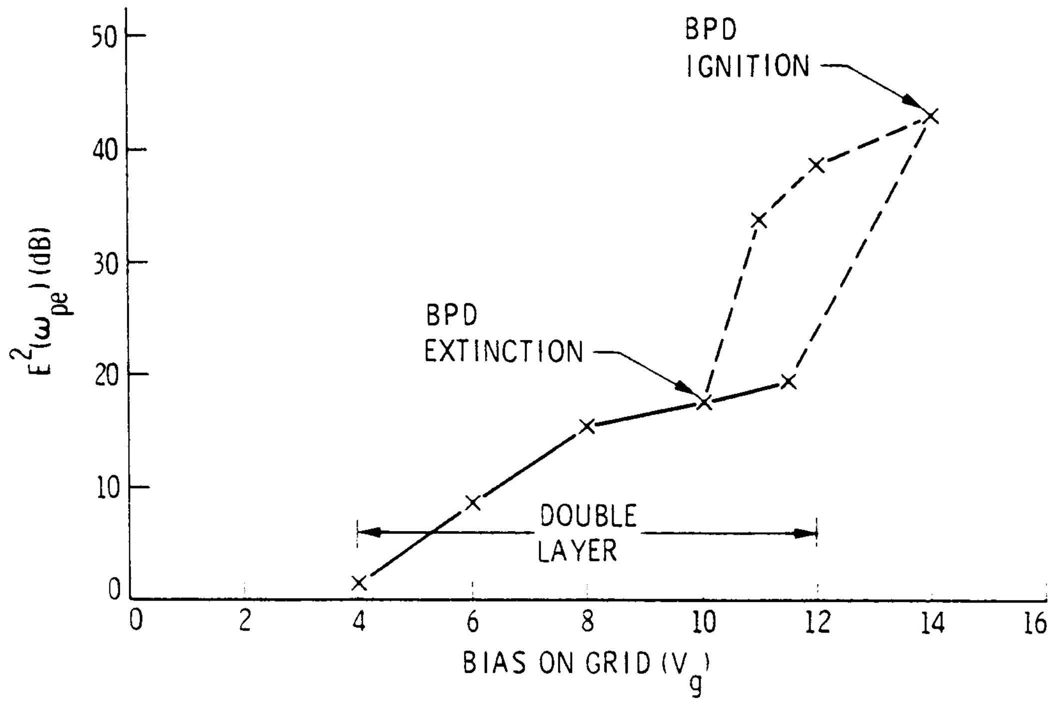


Figure 8. The wave turbulence level as a function of grid bias showing the igniton of BPD. When the BPD is ignited, the electron distribution function is a bump-on-tail distribution.

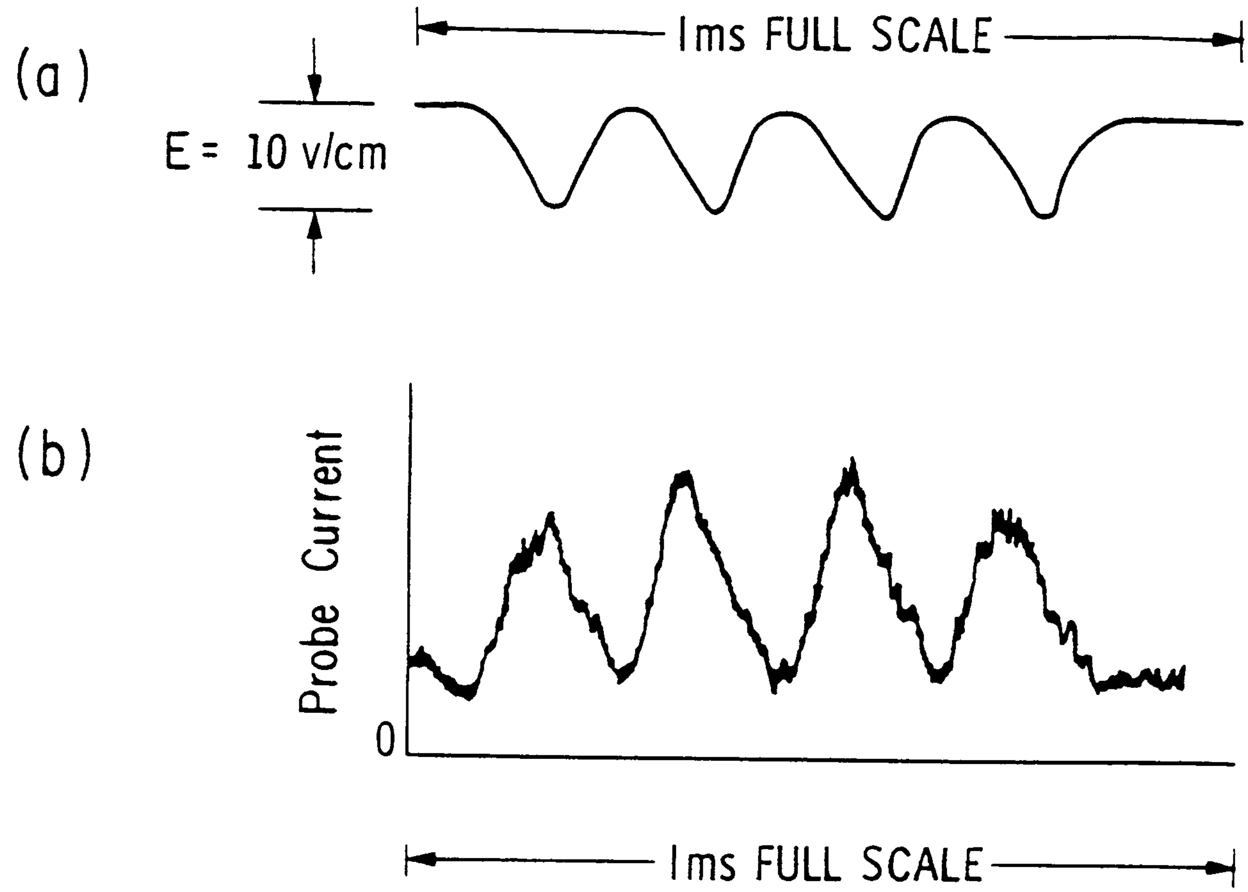


Figure 9. The top trace (a) shows the fluctuation in the local electric field as measured by the diagnostic electron beam. The fluctuation is due to the motion of the double layer. The corresponding fluctuation in the Langmuir probe current is shown in the bottom trace (b).

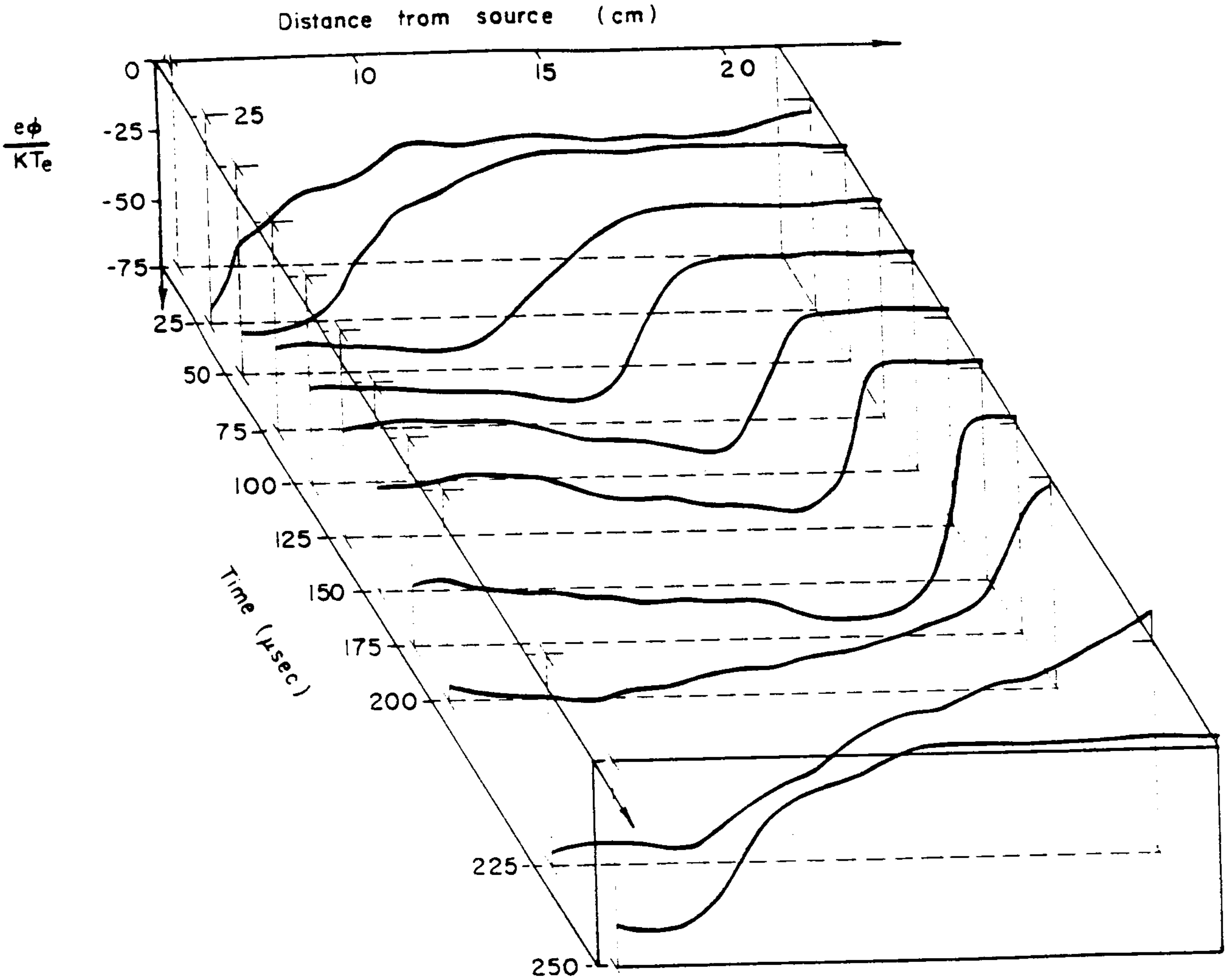


Figure 10. Time development of moving double layers.

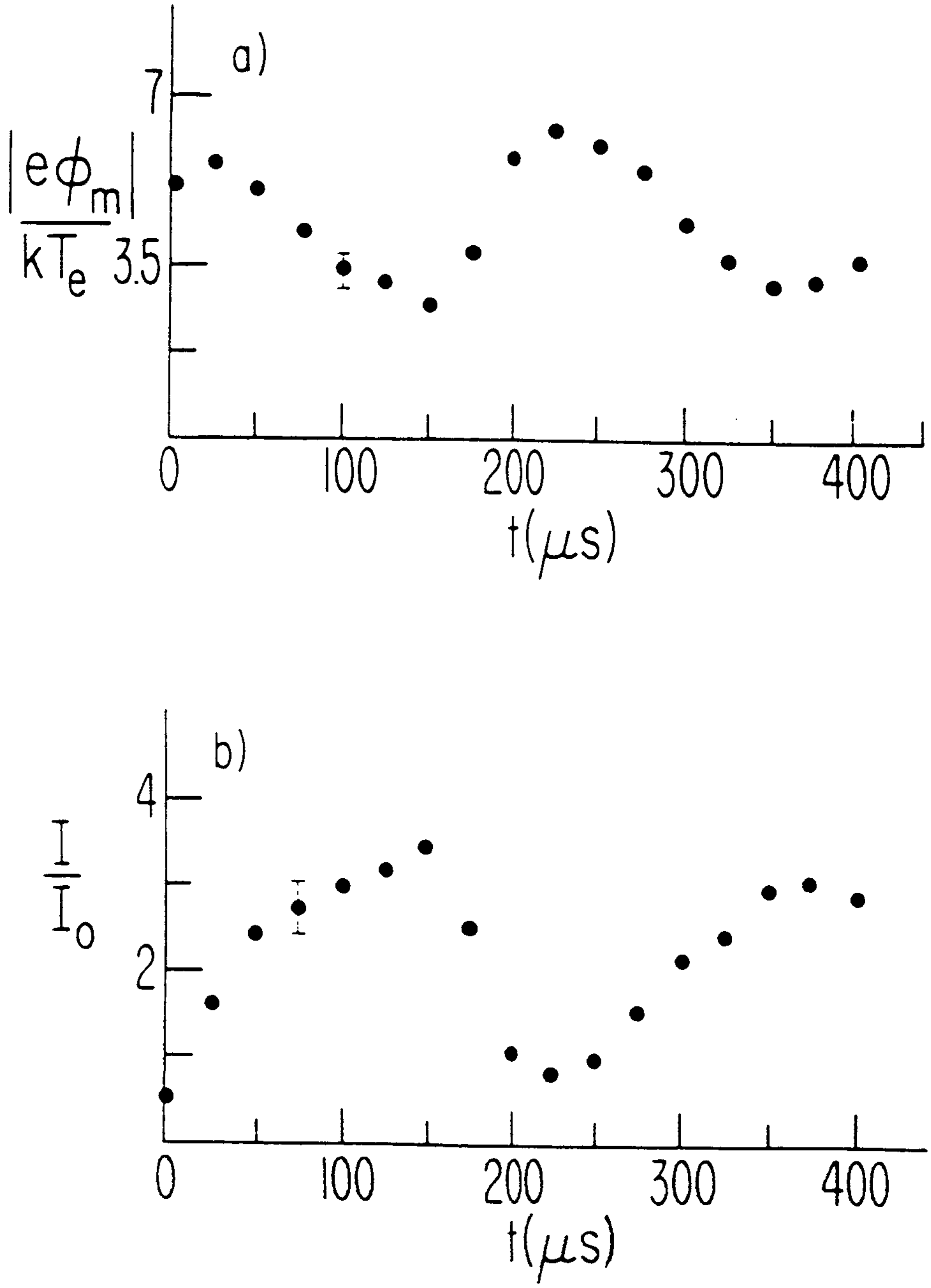


Figure 11. The two important parameters that control the moving double layers: (a) the potential of the low potential region and (b) the injection current as a function of time.