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PUMPING POTENTIAL WELLS

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ABSTRACT

Nonmonotonic plasma potential structures are a common feature of many double layers and sheaths. Steady state plasma potential wells separating regions having different plasma potentials are often found in laboratory experiments. In order to exist, all such structures must find a solution to a common problem. Ions created by charge exchange or ionization in the region of the potential well are electrostatically confined and tend to accumulate and fill up the potential well. The increase in positive charge should eliminate the well. Nevertheless, steady state structures are found in which the wells do not fill up. This means that it is important to take into account processes which "pump" ions from the well. As examples of ion pumping of plasma wells, we consider potential dips in front of a positively biased electron collecting anode in a relatively cold, low density, multidipole plasma. Pumping is provided by ion leaks from the edges of the potential dip or by oscillating the applied potential. In the former case the two-dimensional character of the problem is shown to be important.

I. INTRODUCTION

A variety of experimental measurements of double layer and double layer related phenomena have demonstrated the presence of steady state plasma potential dips, at least in one dimension. Experiments range from glow discharge plasmas (Biborosch et al., 1984), to unmagnetized collisionless laboratory plasmas (Leung et al., 1980), to Q machine experiments (Sato et al., 1981), to fusion experiments (Hershkowitz, 1984). The general problem with all such structures is the question — what prevents the dip from filling up with ions either by charge exchange or by some kind of scattering? This problem has been identified as a key issue in maintaining "thermal barriers" in tandem mirrors (Baldwin and Logan, 1979) for which several techniques have been proposed for "pumping" out trapped ions. The only technique so far tested has been "neutral beam pumping" (Inutake et al., 1985; Grubb et al., 1984) — they use charge exchange of trapped ions on energetic neutral beams injected into the thermal barriers.

Although a dip may be present in one-dimensional data, it is not immediately apparent that ions are electrostatically confined in the dip in the perpendicular dimensions. Many structures have been found to have only minima in the potential in one dimension, while, in the other dimension the potential might be a relative maximum. In this case ions are not confined, pumping is not an issue, and potential variations in the perpendicular dimension can dominate the self-consistent solution to the problem. It is clear that the double layer is the wrong structure upon which to concentrate. This paper considers the problem of pumping steady state and slowly time varying potential dips in a multidipole laboratory plasma.

Representative double layers with dip structures that have been previously reported are shown in Figures 1 through 4. The data in Figure 1 (Coakley et al., 1978) were obtained in a triple plasma device for which $T_i = 0.2$ eV. The various steady state structures were obtained by varying the bias on a boundary grid on the low potential

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side. Note that potential dips as deep as 5 V, equal to 25 T_i/e, were achieved. For these data the pumping mechanism was later identified to be ion leaks in the perpendicular dimension. Another example is a discharge tube double layer shown in Figure 2 (Maciel and Allen, 1984). Examination of the associated radial potential profile also showed that the potential minimum was a relative maximum in the perpendicular dimension and that ions could again leak out.

While the first two examples are ones for which the ions can easily leak out, the data shown in Figure 3 (Suzuki et al., 1984) give a different situation. In that case a double layer was found at a B field minimum in a magnetized plasma. Ions trapped in the dip had to cross the magnetic field. In addition it was also found that the dip was an absolute minimum in potential in the radial direction. As the neutral pressure was incresed to 7×10^{-6} from 10^{-7} Torr, the dip was substantially reduced and eventually disappeared (as seen in Figure 4) (Suzuki et al., 1984). The pumping mechanism of this dip is not yet understood, but it is possible that instabilities provided wave energy which energized the trapped ions or that trapped ions were lost to the diagnostic used to determine the dips presence.

II. EXPERIMENTAL RESULTS

Consider the potential near a positively biased plate (Forest and Hershkowitz, 1986). A copper plate, radius = 3 cm, coated with a ceramic insulator on the back side and support, was introduced into an argon plasma with plasma density $n = 10^8$ cm^{-3} and electron temperature $T_e = 3.5$ eV. The plate was biased to +20 V and the chamber walls were grounded. The plasma was produced in a conventional multidipole device (Leung et al., 1975).

The plasma potential measured with an emissive probe along the axis of the plate is given in Figure 5. Note that a potential dip equal to $\Delta\phi \approx 1.7$ V is found a distance d_{MIN} from the plate and that the potential far from the plate is only 3 V compared to the plate bias potential of 20 V.

We have also achieved a similar result (Wang et al., 1986) by looking at the potential on the axis of a set of parallel plates mounted in the same device. One was grounded and one biased to an oscillating potential at 100 kHz whose amplitude was approximately 12 V. The resulting plasma potential profiles at the maximum and minimum part of the cycle are shown in Figure 6. Note that once again a potential dip is also apparent in front of the positively biased electrode. In this case the backs of the plates were not insulated. The data shown in Figure 6 were taken using a new technique based on differentiated time-averaged emissive probe I-V characteristics which has been described elsewhere (Wang et al., 1986).

We can separate the interpretation of the results shown in Figures 5 and 6 into two issues. The first is the dip characteristics and the second is the question of why the dip does not fill in. Figure 7a shows that the size of the potential dip in Figure 5 scales linearly with electron temperature and is approximately equal to $T_e/2$. In Figure 7b it is also shown that the dip separation d_{MIN} from the plate decreases as the plasma density is increased. In Figure 8 we compare the dip separation to the predictions of the Child-Langmuir law and show that there is good agreement. This indicates that the self-consistent potential is established to make the electron loss from the plasma consistent with space charge limited emission as only electrons from the plasma are present near the front of the plate.

The question of why the dip does not fill in requires a look at the two-dimensional equipotential contours for a somewhat different case (shown in Figure 9) which also exhibits a dip (labeled 16). For that particular case, contours are apparent (indicated by $+4 \rightarrow +14$) which are negative with respect to the potential dip. These were identified as being associated with a fingerprint on the plate. These suggest that the presence of an insulator on the surface could provide the necessary ion leaks. A careful examination of the contours near a cleaned plate is given in Figure 10. The potential dip is still present. Note that the dip contours terminate on the edges of the plate at the insulator which coats the back of the plate. The pumping is clearly provided by these leaks. Note also that the contours are quite one-dimensional near the center of the plate and that the radius of the plate is equal to approximately 30 Debye lengths.

We investigated the spatial profile near the plate as a function of neutral pressure and found that the dip is reduced as the neutral pressure increased (as shown in Figure 11). This can be understood as the leaks out of the end of the dips not being able to keep up with the charge exchange filling of the dip.

We believe that ion pumping is a necessary condition for the presence of the dip. We can test this conjecture by removing the pumping from the system. For the static case, we removed the source of the pumping, i.e., the insulator from the back of the plate. This resulted in a very different plasma potential axial profile shown in Figure 12. These data correspond to the same conditions as those shown in Figure 5. The only difference is that the insulator on the back of the plates was not present for the data in Figure 12 but was present for the data in Figure 5. It is apparent that when pumping is not present, the plasma potential is everywhere more positive than the plate. This means that the self-consistent solution that the plasma finds is determined by the coating on the back of the plate, 30 Debye lengths from the center of the plate. This result strongly suggests that double layer potential profiles may be determined by the presence of, for example, an insulating boundary on the edge of the device. We demonstrated that the insulator must be in a location where it can pump the dip by removing the insulator from the plate while still locating it within the plasma volume. In this case the plasma potential also remained more positive than the plate.

The data shown in Figure 7 indicate that a similar potential dip can also occur in front of a capacitor plate during the part of the cycle that it is biased positively. However, in that case there is no problem with trapped ions because such ions empty out during the part of each cycle when the plate is negatively biased.

III. SUMMARY

We have shown that a plasma potential dip can exist in front of positively biased plates because of "ion pumping" of trapped ions from the dip. The dips were located in front of a steady state positively biased plate and also when the maximum positive bias was applied during an oscillating potential. Pumping was achieved by providing ion leaks, i.e., decreasing potential contours leading far from the structure that is usually measured, and indicates that boundary conditions far from the axes of experimental devices may play key roles in determining measured structures. A similar plasma potential structure was found when an oscillating potential was applied to a plate and no insulator was present. In that case ions were emptied from the dip by the time varying potential.

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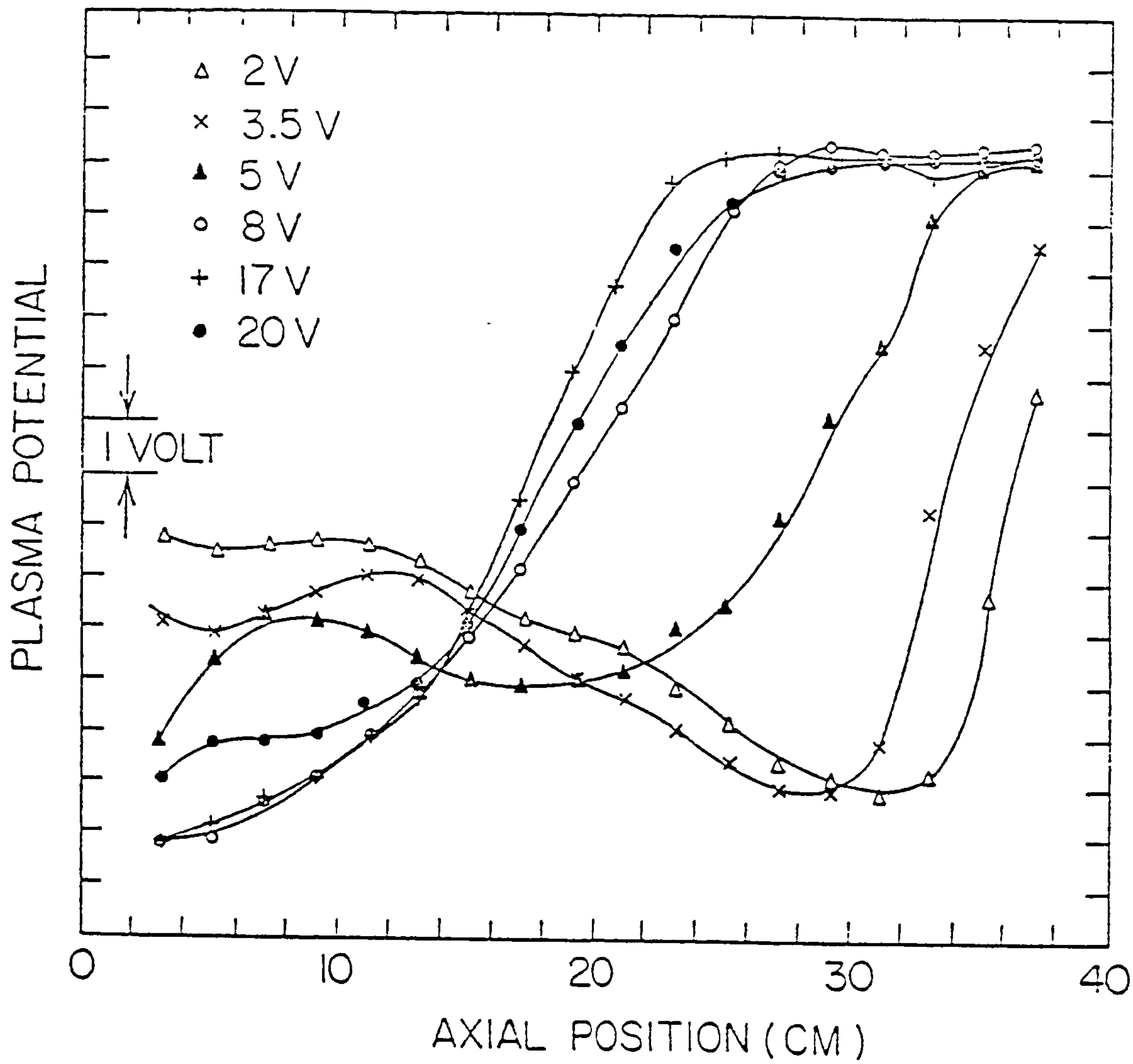

Figure 1. Stationary double layers showing potential dips on the low potential side. Axial potential profiles are given as a function of the bias of a grid on the low potential boundary. Multidipole double layers are apparent for bias voltages of 2-5 V. A bias voltage of 18 V was applied across the two source chambers.

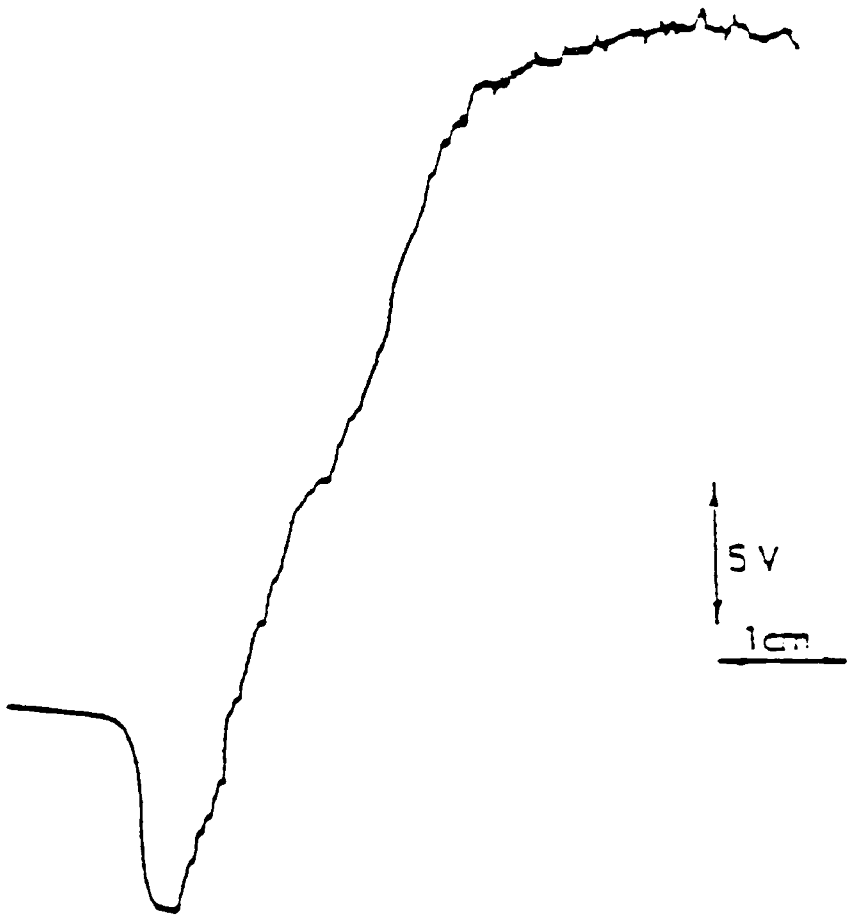

Figure 2. Triple layer axial potential profile obtained in a low pressure Hg arc discharge. This solution was identified to depend only on the boundary conditions; i.e., it was found to be a BGK solution.

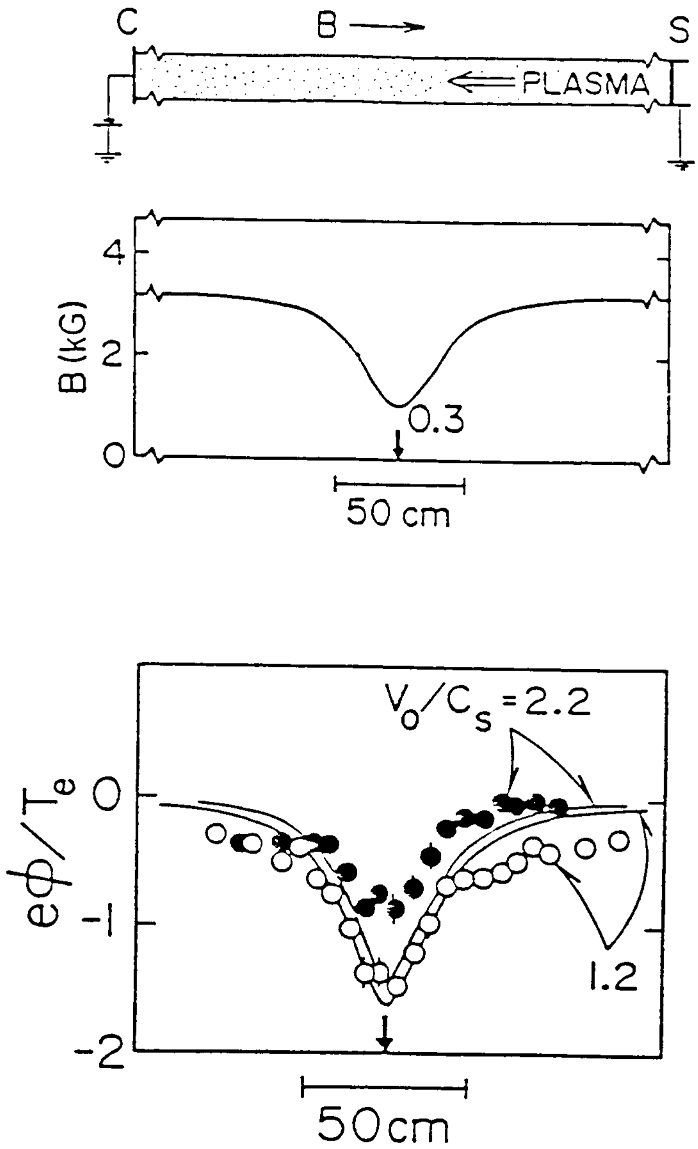

Figure 3. Schematic of the Q machine setup used by Suzuki et al. (1984) and the corresponding axial magnetic field profile. The axial potential profiles corresponding to two ion flow speeds are also shown.

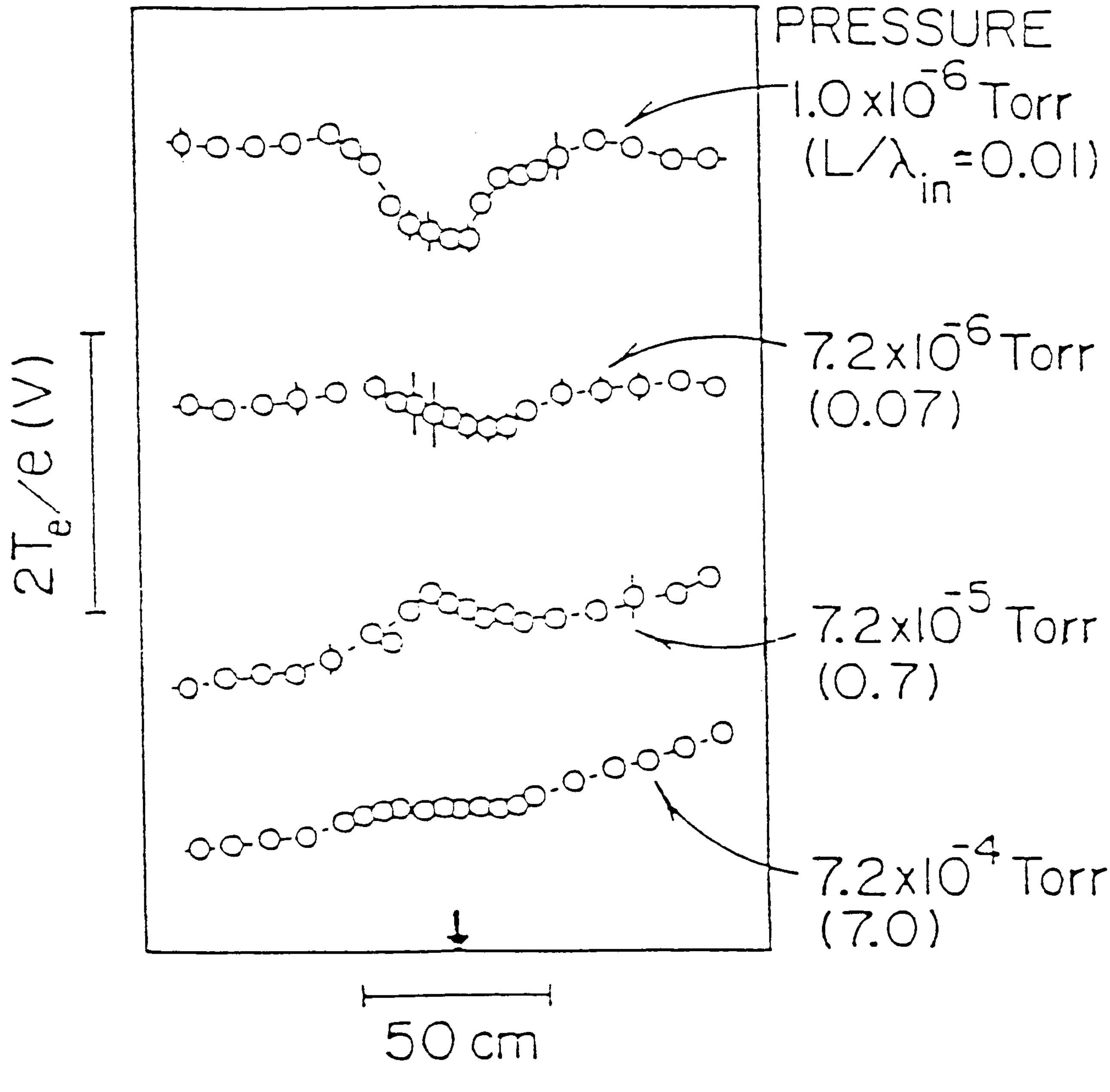

Figure 4. Axial potential profiles as a function of neutral gas pressure in the magnetic well (R_m = 0.3).

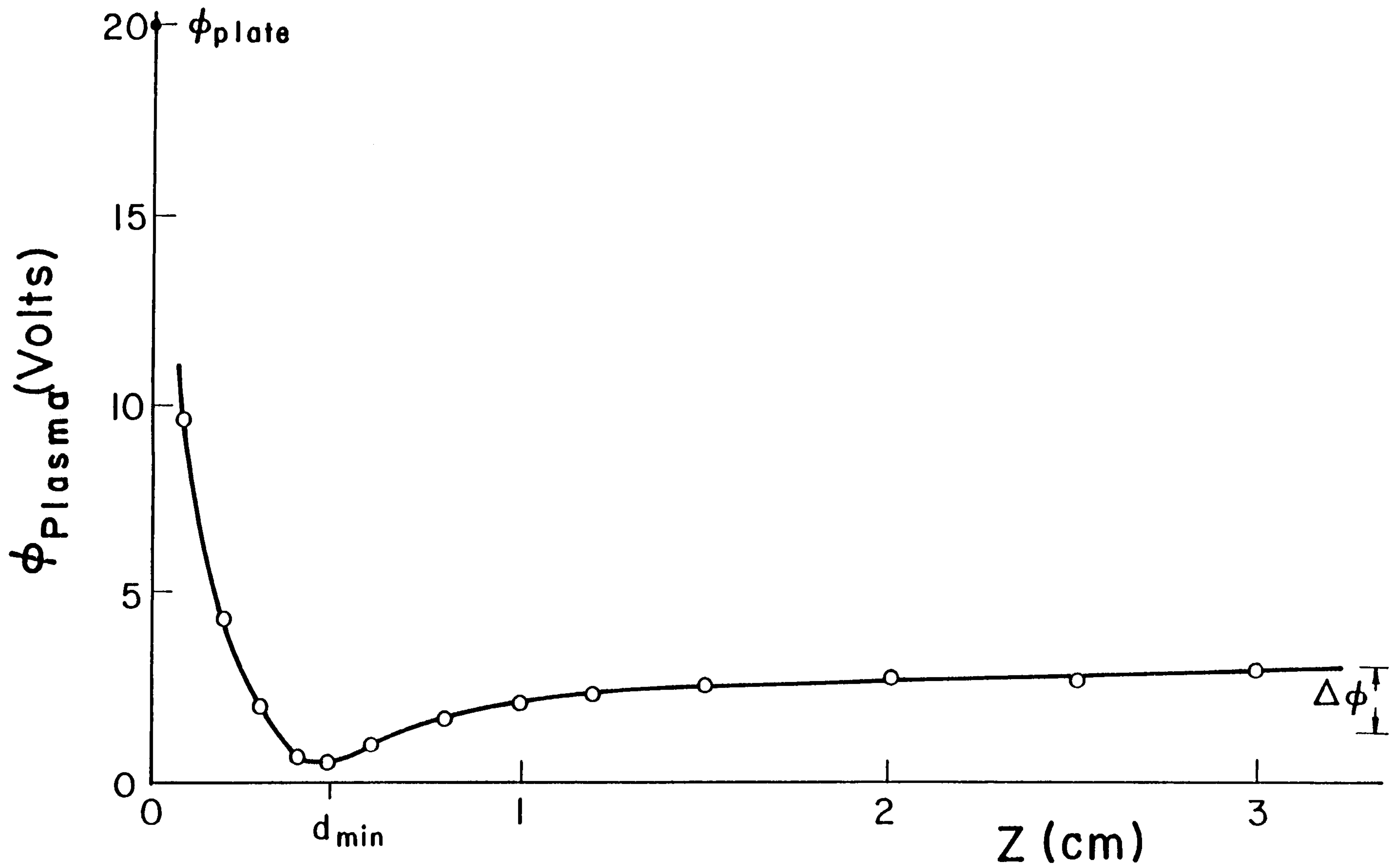

Figure 5. The plasma potential, measured with an emissive probe on-axis of a circular plate biased at +20 V. The electron temperature was measured to be T_e = 3.5 eV.

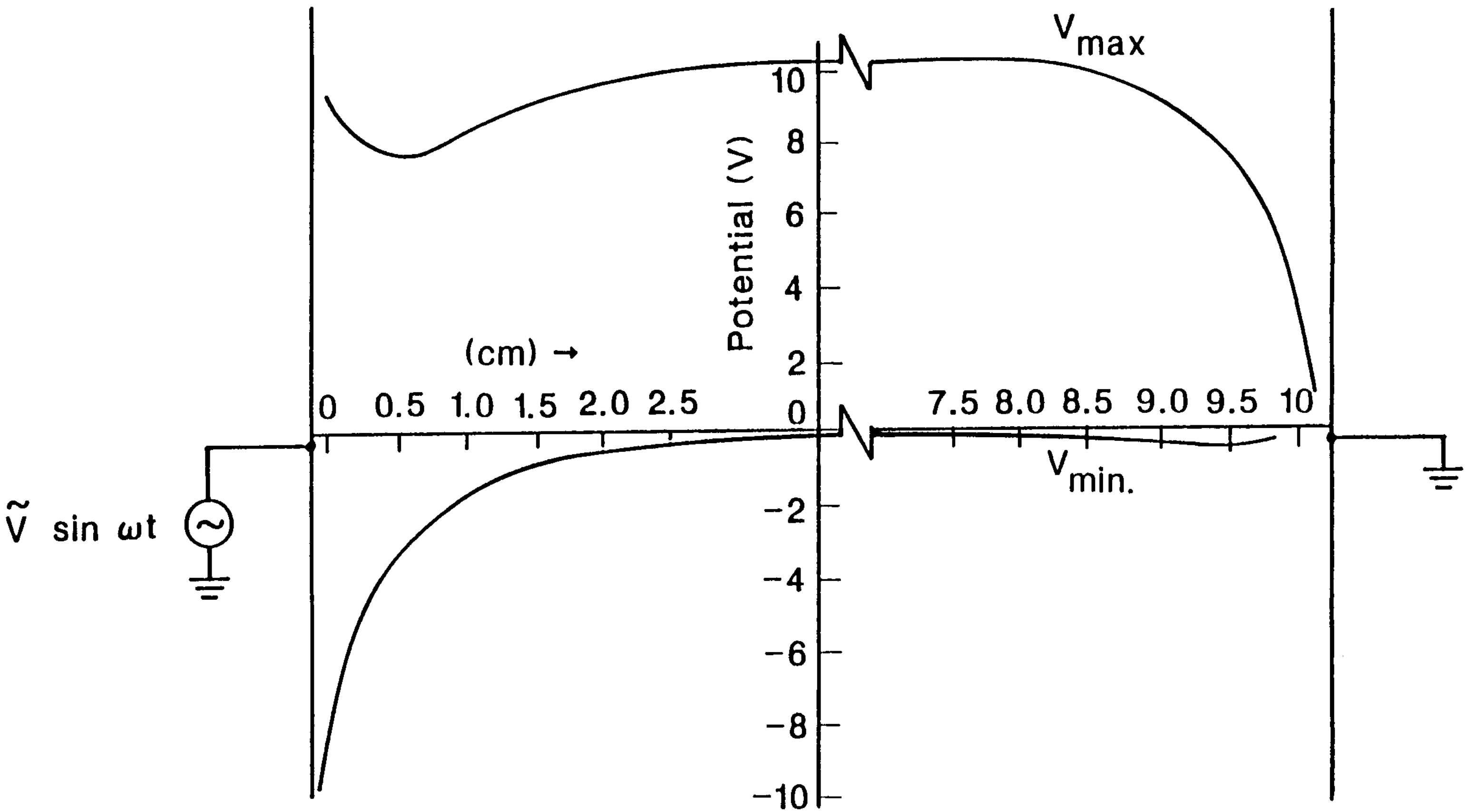

Figure 6. The maximum and minimum potential profiles between two parallel plates; a 100 kHz potential was applied between the plates. Data were obtained using emissive probes and a time-averaging method.

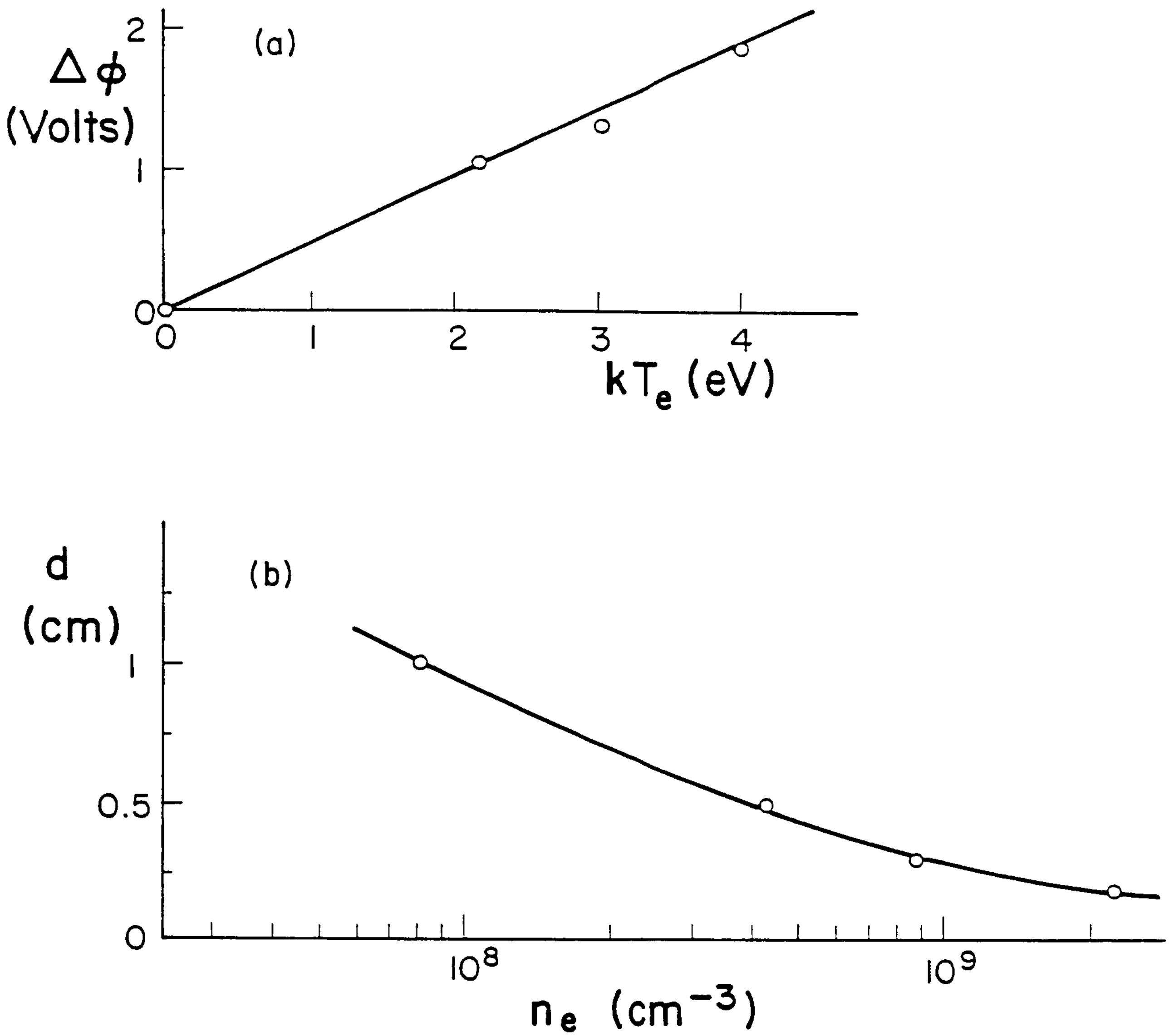

Figure 7. (a) The potential difference Δφ between the plasma and the inflection point of the dip, as a function of electron temperature. A straight line is drawn through the data. (b) The penetration of the dip (d) as a function of plassma density. A smooth curve is drawn through the data.

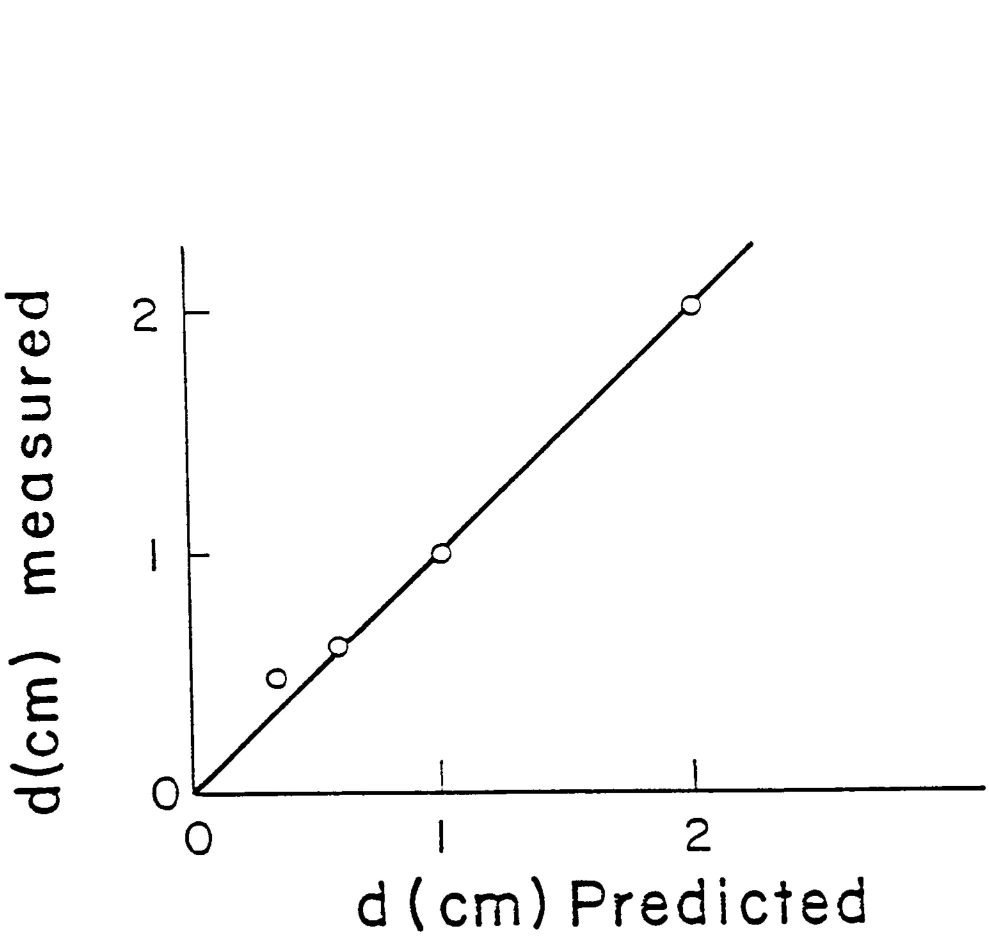

Figure 8. A comparison between measured values of d_{min} and values predicted by using space charge limited electron flow to the plate.

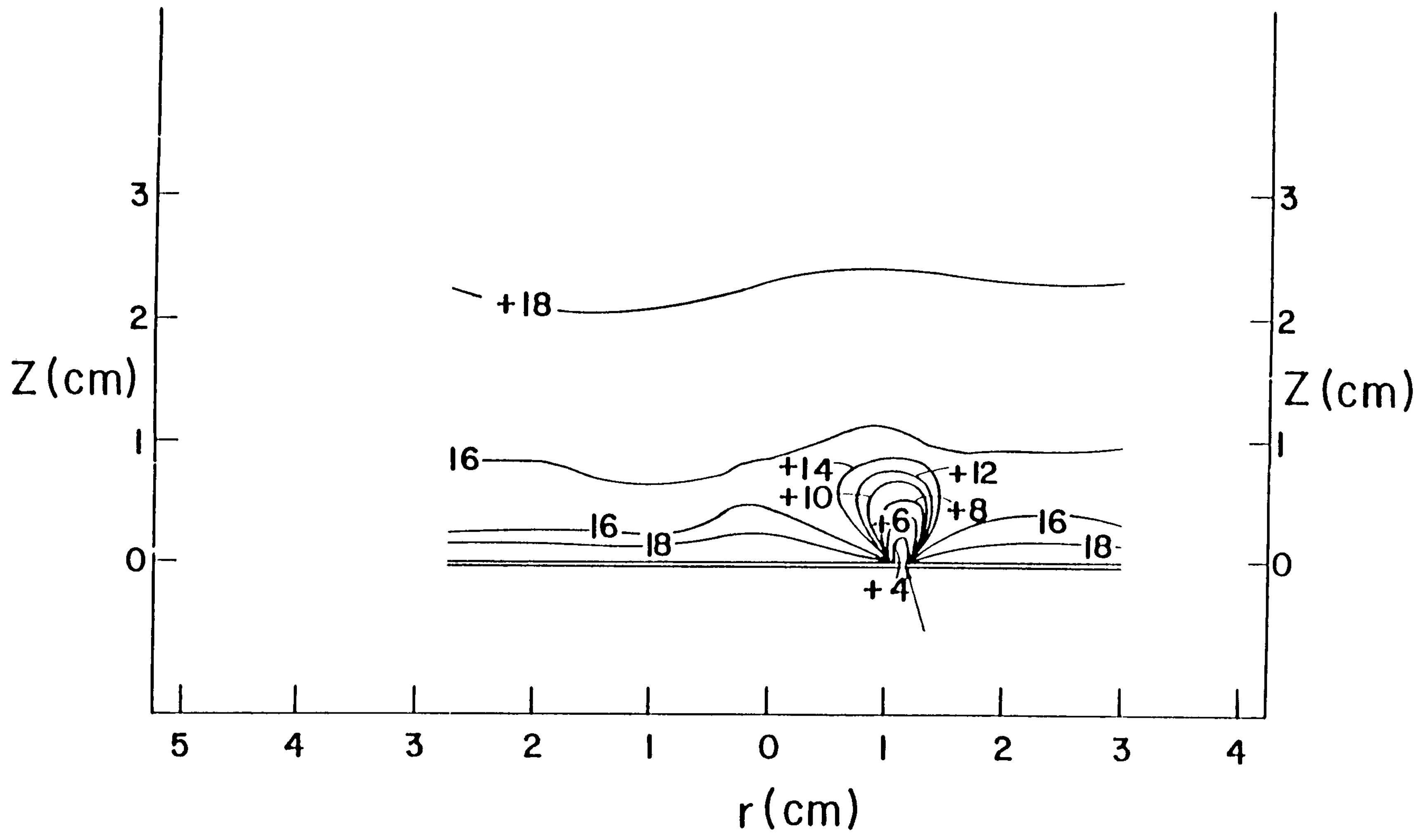

Figure 9. The equipotential contours near a circular brass plate (r = 3.5 cm, 2 mm thick). Note the contours near a grease fingerprint (labeled by the arrow). The plate is in the center of the multidipole soup pot device, 10 cm from one end.

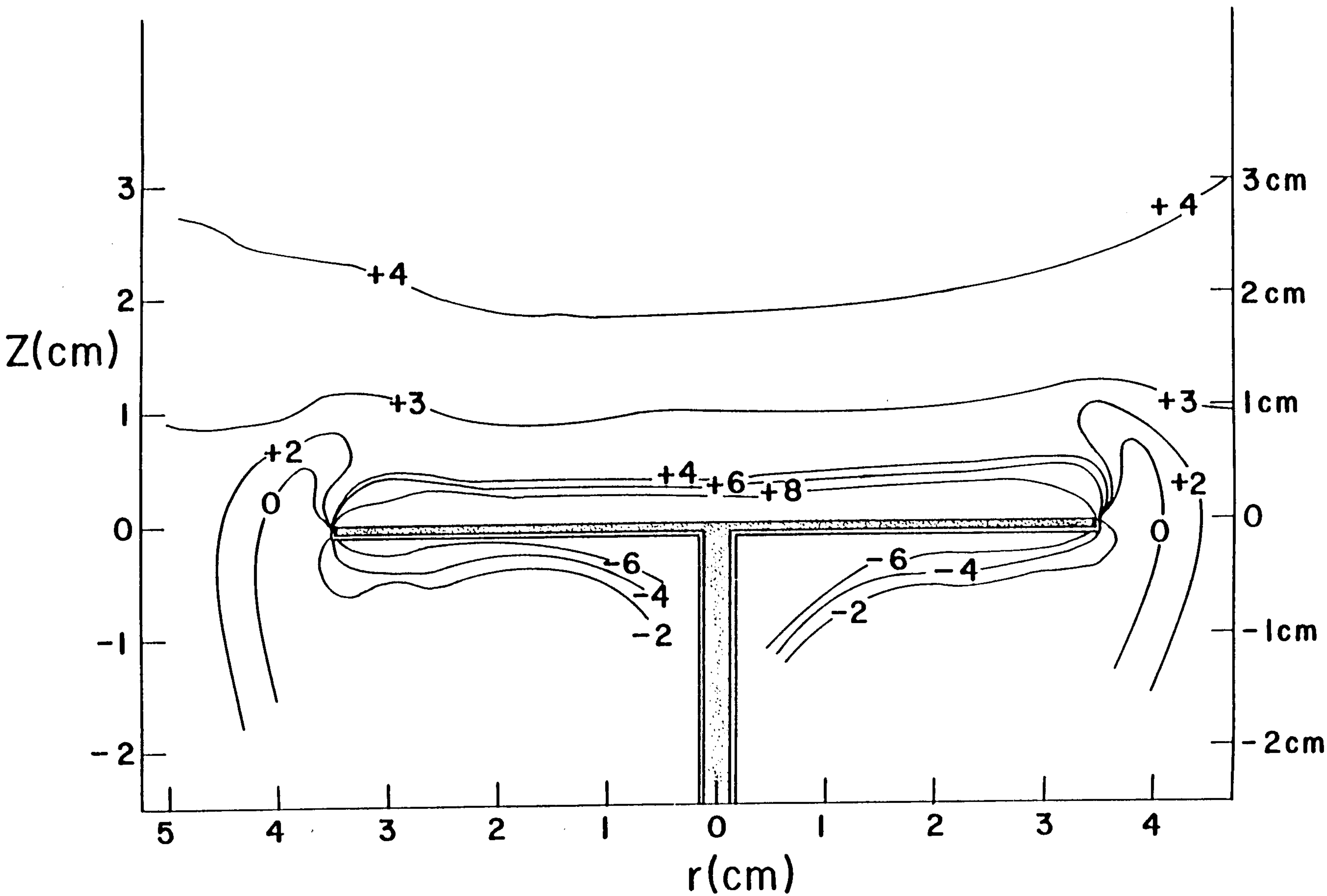

Figure 10. The equipotential contours near a clean plate. The back of the plate, the edges of the plate, and the support are covered with ceramic.

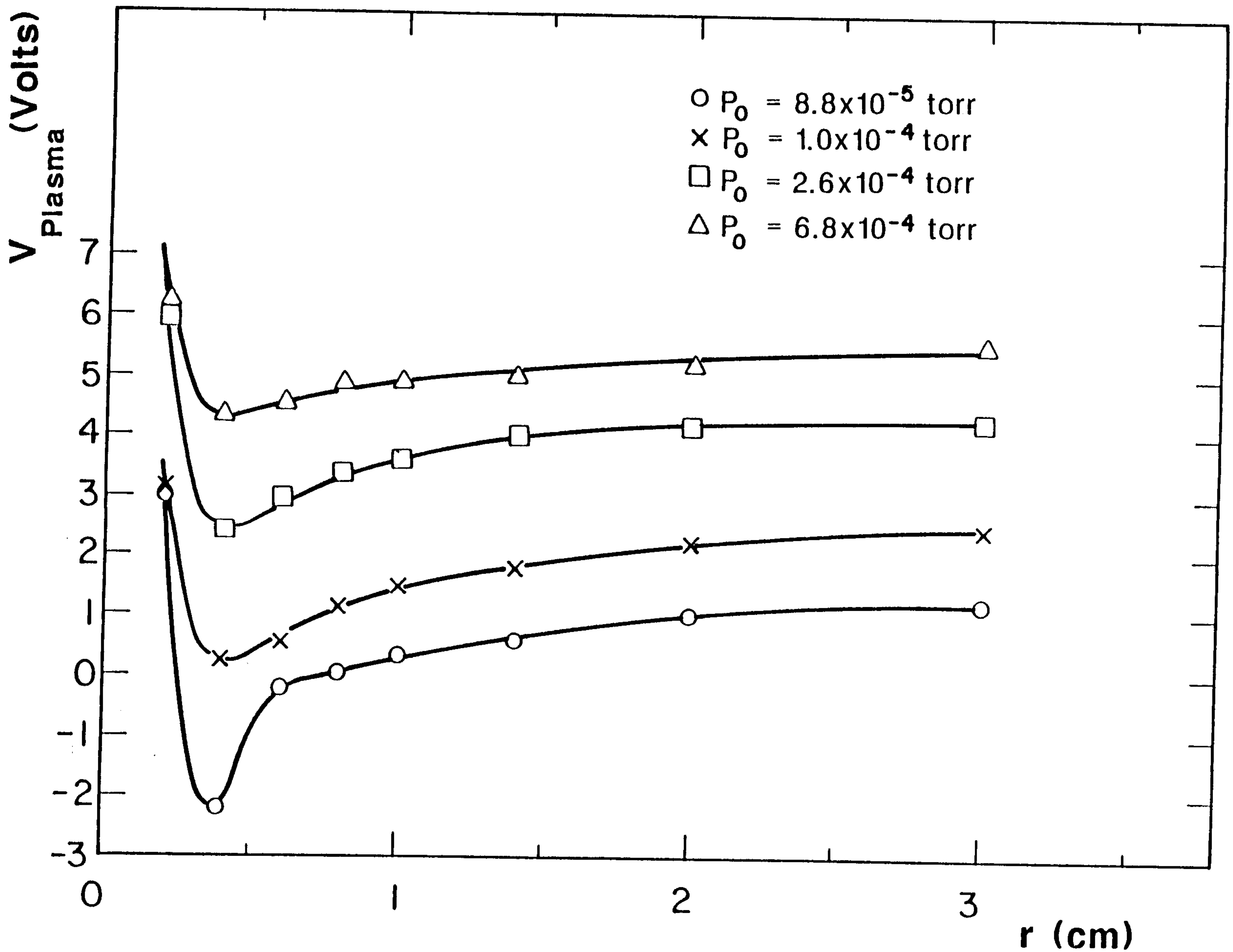

Figure 11. Axial potential profiles, near the positively biased disc, at several neutral pressures. As the neutral pressure is increased, the size of the dip $\Delta\phi$ is seen to be reduced.

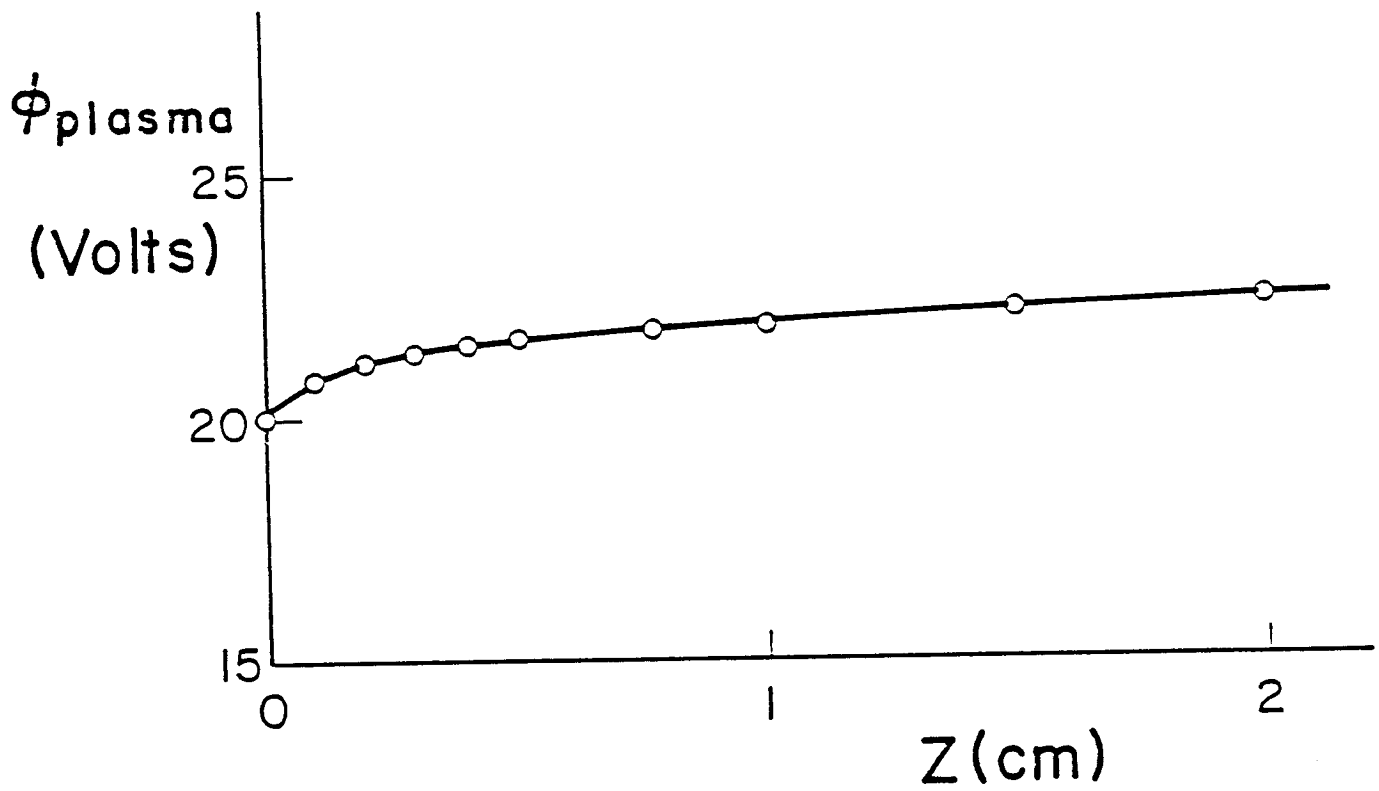

Figure 12. The plasma potential measured on the axis of the plate with ceramic removed from the back.