Filamentary double layers

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The properties of double layers produced in current filaments have been studied. The experiments were performed in a magnetized triple plasma device in which the diameter of the central plasma column could be varied. The scaling of the double layer potential drop $V_{\rm dl}$ with the parameter jd^2, where j is the current density in the double layer and d is the double layer thickness, was determined for several values of the current filament radius R_0. For relatively large values of R_0, the one-dimensional (Langmuir) scaling was obeyed, $V_{\rm dl} \sim (jd^2)^{2/3}$. When R_0 was decreased, a departure from the strictly one-dimensional scaling was observed, with $V_{\rm dl}$ becoming less and less dependent on the parameter jd^2.

I. INTRODUCTION

Electrostatic double layers have been studied in the laboratory for many years[1] and their importance in geophysical and astrophysical plasmas has been emphasized repeatedly by Alfvén[2] and others. The concept of "double layers" was introduced by Langmuir[3] in his classic paper on the interaction of electron and positive ion space charges in cathode sheaths. In this paper Langmuir presented a one-dimensional model for a strong double layer (initial velocities of the ions and electrons entering the double layer $<$ final velocity of ions and electrons accelerated through the double layer) which provided a relationship between the double layer potential $V_{\rm dl}$, the current density j, and thickness of the double layer. Borovsky[4] has shown that this Child–Langmuir law[5] is an excellent approximation to the magnetized warm plasma numerical solutions of Poisson's equation even for oblique double layers in which the electric field is directed at a finite angle to the magnetic field. One-dimensional potential structures have been produced in the laboratory in unmagnetized triple plasma devices[6,7] and two- and three-dimensional U-shaped double layers have been produced in triple plasma devices[8,9] with an axial magnetic field, in Q machines,[10,11] and in magnetized discharge devices.[12,13] Two-dimensional potential structures have also been inferred from *in situ* measurements in the Earth's auroral region.[14]

The purpose of this laboratory study was to investigate the formation of *filamentary double layers*,[15] i.e., double layers formed in thin current filaments. This is of some general astrophysical interest since currents in cosmic plasmas often tend to flow in thin filaments.[16] One specific question which this study addresses is the scaling between the double layer potential drop and its thickness, and how this relationship changes as the radius of the plasma column in which the double layer is embedded changes. As mentioned above, this scaling was first worked out by Langmuir for one-dimensional strong double layers who found that

$$V_{\rm dl} \sim (jd^2)^{2/3}, \tag{1}$$

where j is the current density through the double layer and d is its thickness, i.e., the separation between positive and negative charge layers. For a two- or three-dimensional double layer in a plasma with a radial extension R_0, one would expect that the relation (1) would continue to hold if the double layer thickness d were much smaller than R_0. However, for increasingly smaller current filaments it is reasonable to expect that this one-dimensional relationship would break down as R_0 is made smaller and smaller. In fact Carlqvist[15] argues that for $d \gg R_0$ the potential drop would become *independent* of d. His argument is based on the parallel plate capacitor analogy of the double layer. For two circular plates of radius R_0 carrying constant charge densities $+\sigma$ and $-\sigma$, respectively, the potential drop is directly proportional to d if $d \ll R_0$. As the separation becomes larger, the potential grows more slowly with d, and finally when $R_0 \ll d$, the potential drop becomes independent of d. A similar conclusion is obtained, if instead of using the capacitor analogy, we model the double layer as two electrodes immersed in a conducting medium. As in the case of the double layer, a potential difference exists between the electrodes because a current flows between them and $V = IR$, where R is the resistance between the electrodes. For small separations, d, between the electrodes, the resistance varies linearly with d, but for larger separations, R varies more slowly with d. For example, for two spherical electrodes of radius a immersed in an infinite, uniform conducting medium, the resistance between the two spheres is independent of their separation r in the limit $r \gg a$.[17] This model requires that the current remain constant (instead of the charge) as the voltage is varied. There is some laboratory evidence[9] that, at least under certain conditions, the current remains approximately constant as the voltage is increased after a certain voltage is reached.

Experimentally, the departure from the purely one-dimensional behavior in Eq. (1) would be evident in a reduced dependence of $V_{\rm dl}$ on the parameter jd^2, in other words Eq. (1) would be replaced by the equation

$$V_{\rm dl} \sim (jd^2)^m, \tag{2}$$

where the exponent m tends to smaller and smaller values as the configuration deviates from the one-dimensional case, i.e., as R_0 is made smaller. This paper describes an experiment designed to investigate this effect.

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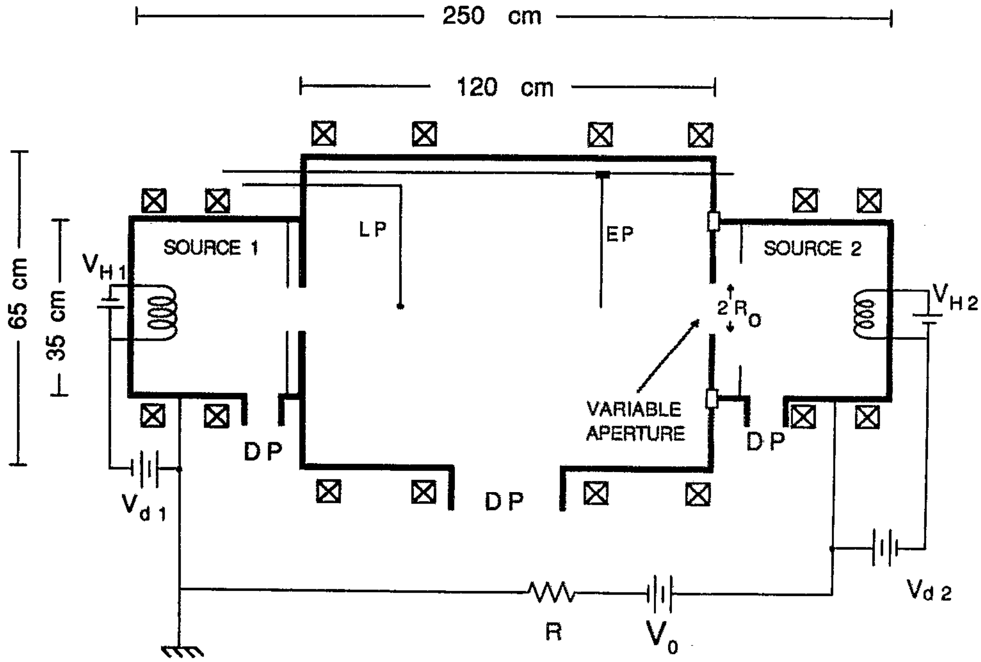

FIG. 1. Schematic diagram of the triple plasma device. Plasma is produced in the source chambers by discharges in argon. The double layers are formed in the central region by applying a bias, V_0, between the two sources.

In Sec. II the experimental setup and measurement techniques are described. Section III contains the experimental results and a discussion of their implications. A summary of the main points and the conclusions are collected in Sec. IV.

II. EXPERIMENTAL SETUP AND METHODS

The experiment was performed in a triple-plasma device consisting of a central chamber with coaxial plasma sources located on either side as shown schematically in Fig. 1. Plasmas were produced in the sources $S1$ and $S2$ by discharges in argon gas between thermionic tungsten filaments and the source chamber walls which contain rows of permanent magnets of alternating polarity to improve the plasma production efficiency. Typically the source chambers are operated with argon neutral pressures in the range of $3–5\times10^{-4}$ Torr, with discharge voltages $V_{d1}\approx V_{d2}\sim 50–60$ V, and discharge currents $I_{d1}\approx I_{d2}\sim 1$ A. The source chambers are separated from the central chamber by a set of 5 cm diameter apertures which together with the 36 cm diameter diffusion pump ensures that the pressure in the central chamber is at least ten times lower than in the source chambers. This differential pumping scheme is required to minimize the effects of ionization in the central chamber where the double layers are formed. Plasma from $S1$ and $S2$ diffuse through the apertures into the central chamber. The apertures determine the diameter of the plasma column which is confined radially by an axial magnetic field of 30 G in the central chamber. The plasma sources are electrically independent with $S1$ and the main chamber grounded and $S2$ floating. The potential of $S2$ relative to ground is controlled by the power supply V_0. When $S2$ is floating, the central plasma column is current-free, with a typical plasma densities $\approx 2\times10^{8}$ cm^{-3} and electron temperatures $T_e\approx 1–3$ eV.

The double layers are produced in the central chamber by lifting the potential of $S2$ relative to $S1$. The double layer appears as a transition region between the two plasmas of different space potential. The current drawn through the plasma column was $\sim$ few mA. The axial location of the double layer can be adjusted by varying the plasma densities in the sources. Typically, in this investigation, the double layers were positioned approximately 5–10 cm from the aperture in $S2$. The measurements of the double layer potential profiles were made using the floating potential of an emissive probe. To study the effect of varying plasma column diameter, an electrically floating iris was used as the aperture separating $S2$ from the central chamber. The iris diameter could be varied continuously in the range $0<R_0<1.75$ cm, and two additional fixed apertures were used with $R_0=2.25$ and 3.3 cm.

III. RESULTS AND DISCUSSION

The double layers that are produced when the bias voltage V_0 is applied between the two source plasmas have U-shaped equipotential contours. The diameter of these U-shaped potential structures is determined by the $S2$ aperture diameter. Figure 2 shows radial profiles of the emissive probe floating potential for three values of R_0. These profiles were taken at an axial position 4 cm from the $S2$ aperture for double layers that were positioned approximately 6 cm from the aperture.

Experimentally, we have two parameters that can be varied independently, the aperture radius R_0 and the bias

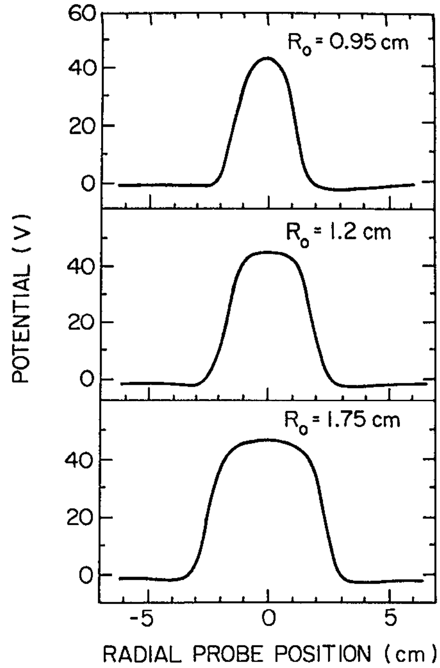

FIG. 2. Radial potential profiles taken 4 cm from the variable aperture for three values of the aperture radius R_0.

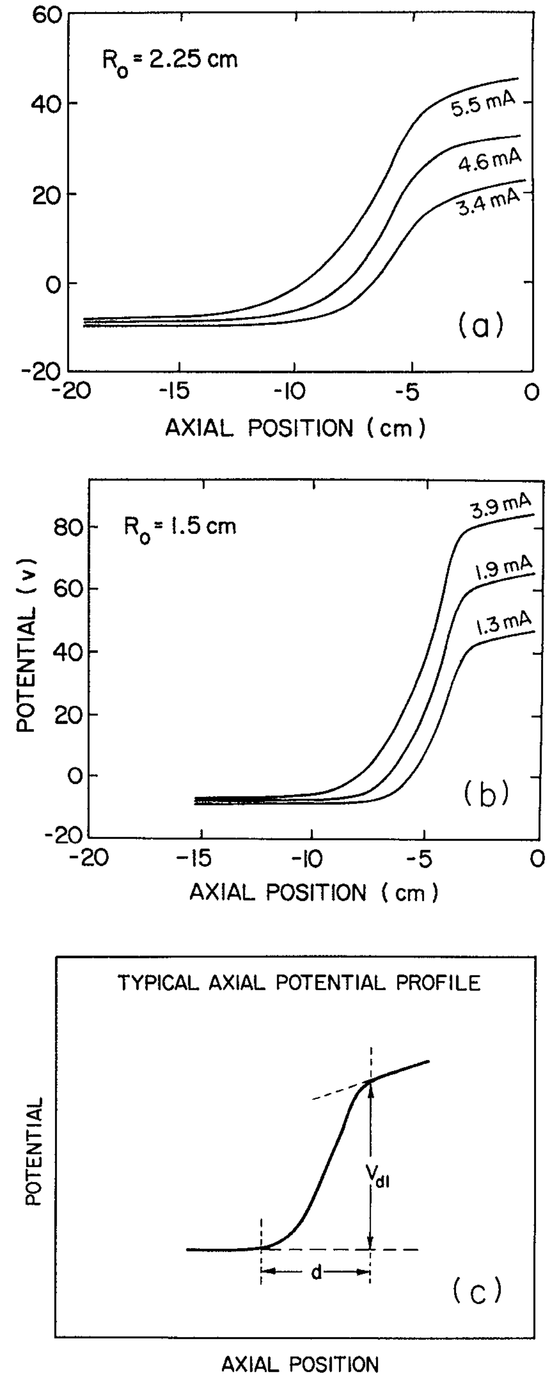

FIG. 3. Axial double layer potential profiles for (a) $R_0=2.25$ cm, and (b) $R_0=1.5$ cm. For each value of R_0, three profiles are shown corresponding to different V_0 values. The current I_0 in mA for each double layer profile is indicated. (c) A typical double layer potential profile showing how the measurements of V_{dl} and d were taken.

voltage V_0. The measurements consist of fixing R_0 and obtaining axial potential profiles for various values of V_0. The double layer potential V_{dl}, width d, and current I_0 increase with increasing V_0. Representative axial potential profiles for two values of R_0 are shown in Figs. 3(a) and 3(b). The double layer current values corresponding to each case are listed for each profile. The double layer potential V_{dl} and width d are measured using the procedure shown in Fig. 3(c). The axial positions used for measuring the thickness are positions where the slope of the potential profile is noticeably different than the slope of the potential profile in adjacent regions. The current density $j=I_0/\pi R_0^2$ is computed from the measured current and R_0 value.

Double layer characteristic plots (V_{dl} vs jd^2) for three values of R_0 are shown in Fig. 4. The value of the exponents m [see Eq. (2)] is then taken as the slope of each characteristic plot. A plot summarizing the results from several runs with various aperture settings is shown in Fig. 5. The values of m decrease as R_0 is decreased. For the larger R_0 values m approaches the value 2/3 as predicted in the one-dimensional analysis of Langmuir. To appreciate the result in Fig. 5, we show in Fig. 6 a plot of the actual measured double layer widths d vs R_0 for two representative values of V_0. First, we point out that for all values of R_0 employed, $d > R_0$, although the average value of d/R_0 decreases from about 5 to 2.5 as R_0 is increased to its maximum value. This means that even for the largest aperture size we were not, strictly speaking, in the one-dimensional regime defined by $d/R_0 \ll 1$. Nevertheless, the data of Fig. 5 seems to indicate that the scaling based on the one-dimensional analysis is appropriate for the largest aperture used. On the other hand, there is a clear deviation from the one-dimensional behavior as the aperture radius is reduced, showing that V_{dl} becomes less and less dependent on jd^2 for small R_0.

An attempt was made to investigate the scaling relationship for larger R_0 values than those shown in Figs. 5 and 6. However, with larger apertures it was not possible to maintain a sufficiently low neutral pressure in the central chamber so that the double layers that are formed are associated with ionization effects. Thus, the lowest value of

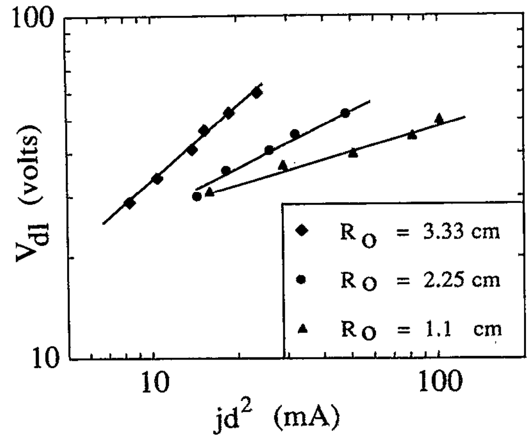

FIG. 4. Double layer characteristic plots, V_{dl} vs jd^2, for three values of R_0. These plots were constructed from data of the type shown in Figs. 3(a) and 3(b).

d/R_0 obtained represents an experimental limit not a physical limit. However, as a general comment, the double layers formed in the filamentary current channels tended to be more stable than those formed in the larger plasma columns. The double layers produced in the larger columns had larger fluctuations in their axial positions. These fluctuations were observed as a space potential oscillation on an emissive probe located near the center of the double layer.

IV. SUMMARY AND CONCLUSIONS

The formation of double layers in thin current channels of varying radius has been investigated. For several values of the channel radius, the relationship between the double layer potential drop, width, and current density has been determined. For the largest current channels this relationship seems to be consistent with the Langmuir result for one-dimensional (planar) double layers. For smaller current channels a departure from the planar case was observed, with the potential drop becoming less and less dependent on the current-width squared product (jd^2) as the filamentary case is approached.

Finally, these results appear to be in line with the suggestion of Carlqvist[15] that double layers should have optimum chances to form in filamentary current channels. This tentative conclusion is based on our observation that the double layers formed in the smaller diameter current channels were more stable than those formed in channels that more closely approximated the planar geometry.

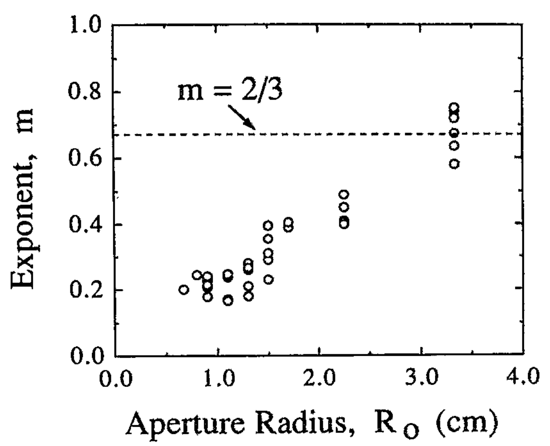

FIG. 5. Slopes, m, of the V_{dl} vs jd^2 plots as a function of R_0. The dotted line $m=2/3$ is the predicted value based on the one-dimensional strong double layer theory of Langmuir.

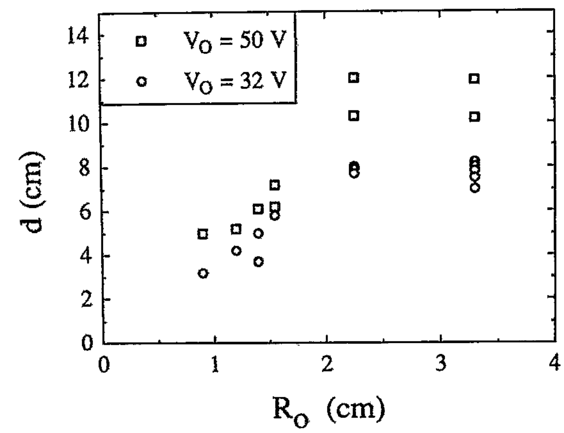

FIG. 6. Measured double layer widths, d, for two V_0 values as a function of R_0.

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