First Experimental Measurements of the Plasma Potential throughout the Presheath and Sheath at a Boundary in a Weakly Collisional Plasma

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Experimental data obtained with emissive probes and Langmuir probes show that the plasma potential profile in the presheath scales as $-e\phi/T_e = \sqrt{(x_0 - x)/\lambda}$, consistent with ion flux conservation, and that the sheath consists of a transition region and an electron-free collisionless sheath with thicknesses scaling as $\lambda^{1/5}\lambda_D^{4/5}$ and $\lambda_D(e\phi/T_e)^{3/4}$, respectively, where λ is the ion-neutral collision length. Results support Rieman's presheath and transitional region model [Phys. Plasmas **4**, 4158 (1997)]. The potential drop over the presheath and transition sheath region were the order of T_e/e and $2T_e/3e$, respectively, increasing with increasing pressure.

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Determining the variation of the plasma potential and charged particle density near plasma boundaries is a task as old as the discipline of plasma physics [1]. Understanding the potential profiles is critical to achieving a basic understanding of confined plasmas and to improving plasma confinement and/or extraction of ions or electrons from laboratory, space, industrial, and fusion plasmas. Examples in weakly collisional plasmas include the following: ion anisotropy in plasma etching of semiconductors, ion flow out of accelerator sources and ion thrusters, ion saturation current to Langmuir probes, and plasma loss to divertors in fusion devices [2].

The most prominent feature of the boundary potential profile is the plasma sheath that normally forms at a plasma boundary to balance electron and ion loss flux [3]. Sheath electric fields are normally much stronger than bulk plasma electric fields. Light emission by energetic electron-produced atomic emission permits visual identification of sheaths in many systems. In collisionless and weakly collisional systems, sheath scale lengths depend on the Debye length λ_D and are normally much smaller than the plasma dimensions L. Plasmas are normally quasineutral in the bulk and non-neutral (positive ion rich) in the sheaths.

Over the last 75 years, the plasma/sheath problem has been modeled by many researchers using free fall theory [1], boundary layer theory [4], fluid theory [5–8], and kinetic theory [9]. The effects of charge exchange collisions [10] and ionization [11] on the presheath have also been investigated. Matching the plasma potential at the plasma/sheath [12] boundary leads to the conclusion that in collisionless and weakly collisional plasmas, ions must have a directed velocity into the sheath $\geq c_s \equiv \sqrt{(T_e + T_i)/m_i}$, where T_e and T_i are the electron and ion temperatures and m_i is the ion mass. The Bohm velocity c_s is finite even when $T_i = 0$. Although the plasma/sheath problem is critical to a basic understanding of confined plasmas, there has been almost no experimental verification of any of the theories. This paper presents the first experimental measurements that resolve the plasma potential from the bulk plasma to the wall near the boundary.

In dc plasmas, ion acceleration to the Bohm velocity is provided by the bulk plasma electric fields. When the bulk plasma scale length $\ell \gg \lambda_D$, it is convenient to describe the boundary by a sheath and a "Bohm presheath," a quasineutral region in which most of the ion acceleration takes place. Presheaths have been recognized since 1949 [12] and are thought to correspond to a variety of mechanisms. For example, in unmagnetized "collisionless" plasmas, they are associated with the plasma production mechanism and can be as large as half the size ($L/2$) of the confinement device [13]. In weakly collisional plasmas, if the ion-neutral collision length $\lambda \ll L/2$, the presheath length is found to be $\ell \approx \lambda$ [14]. When $\lambda_D \ll \lambda \ll L$ and assuming ion flux conservation in the presheath, Riemann [7] has shown most of the ion acceleration to the Bohm velocity, in systems with λ equal to a constant or proportional to the ion drift velocity, occurs in a presheath, in which plasma potential is given by

$$-\phi(x) = \frac{T_e}{e}\sqrt{\frac{x_0 - x}{\ell}} \tag{1}$$

with the sheath edge at $x = x_0$. He also argues that the sheath consists of a transition sheath, where the electron density is reduced from $n_e = n_i$ to $n_e \ll n_i$ with a scale length $\propto \lambda_D^{4/5}\lambda^{1/5}$ and an electric field of $\frac{T_e}{e\lambda^{3/5}\lambda_D^{2/5}}$. This connects to an electron-free sheath, where the electron density can be neglected, with a scale length of λ_D. Riemann identified the sheath edge as the location where the ion drift velocity $v_d = c_s$. He found good agreement of his analytic approximations with numerical solutions for $\frac{\lambda_D}{\lambda} \leq 10^{-2}$ assuming $T_i = 0$.

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TABLE I. Characteristic values of experimental parameters.

Pressure (mTorr)	Plasma density at sheath edge (10^7 cm^{-3})	Electron temperature (eV)	Collision length (cm)/ Debye length (cm)	Potential drop in the presheath (V)	Potential drop in the transition region (V)
1.0	6.5	0.5	3.0/0.07	0.55	0.4
0.8	5.0	0.7	4.6/0.09	0.65	0.45
0.65	2.9	0.8	6.5/0.12	0.75	0.5
0.48	0.9	1.4	7.0/0.29	1.3	0.9
0.3	0.36	2.3	11.0/0.6	1.75	1.7
0.44	0.65	2.0	7.0/0.40	1.6	1.4
0.44	2.1	2.4	7.0/0.25	2.0	1.7
0.44	4.9	2.2	7.0/0.16	1.9	1.2

In this paper, we present experimental measurements of plasma potential which resolve the structure of the presheath, the transition region of the sheath, and the electron-free region of the sheath. By operating with plasma densities the order of 10^7 cm^{-3}, $\frac{\lambda_D}{\lambda} \approx 0.02 \rightarrow 0.06$, and by varying neutral pressure, $0.2 < \frac{\lambda}{L} < 0.6$ (see Table I). Experiments were performed in multidipole argon plasma [15] (diameter = 19 cm, height = 33 cm). Electrons emitted from dc biased hot filaments produced the plasma. This configuration was chosen because of its low noise and flexibility. Presheath measurements were made on the axis of a flat 7.5 cm diameter stainless steel plate which was placed inside of the uniform plasma and located 10 cm from the chamber walls and 16 cm away from the chamber top. The plate was biased at −30 V with respect to the grounded walls. The density n and T_e were varied by changing the filament heating voltage V_H and bias voltage V_B. The plasma potential was determined with an emissive probe in the limit of zero emission [16] because this approach provides the best resolution of the plasma potential (as small as 0.2 V) and results in a minimum perturbation. Laser induced fluorescence measurements [17] of plasmas with densities $\approx 10^9$ cm^{-3} in the device found bulk plasma ion temperatures of approximately 0.04 eV and ion temperatures close to the plate = 0.1 eV, compared to $T_e \approx 1$ eV, so $T_i = 0$ is a reasonable approximation.

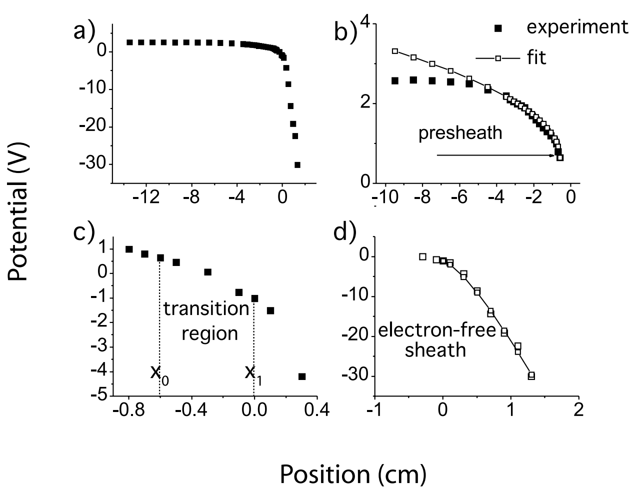

FIG. 1. Emissive probe potential measurements over all of the plasma (a), presheath (b), and transition region of the sheath (c), electron-free sheath (d), for 0.44 mTorr with a plasma electron density of 2.1×10^7 cm^{-3}. The lines show the fitted profiles.

Representative data for the plasma potential profile on the axis of the disk are given in Fig. 1(a) for an argon neutral pressure of 0.44 mTorr. The presheath and both sheath structures become apparent when examined on their separate scales as shown in Figs. 1(b)–1(d). The plasma potential scale is examined in more detail in Fig. 1(b). The majority of the plasma potential variation in the presheath was found to obey the asymptotic theory given in Eq. 1 by Riemann [7]. The fits found $\ell \approx 7$ cm. The fit deviates in the bulk plasma where the large-scale

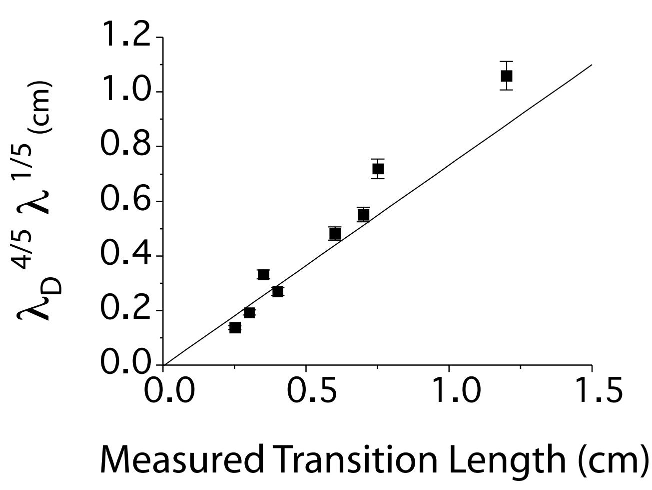

FIG. 2. The measured transition length vs Riemann's transition length.

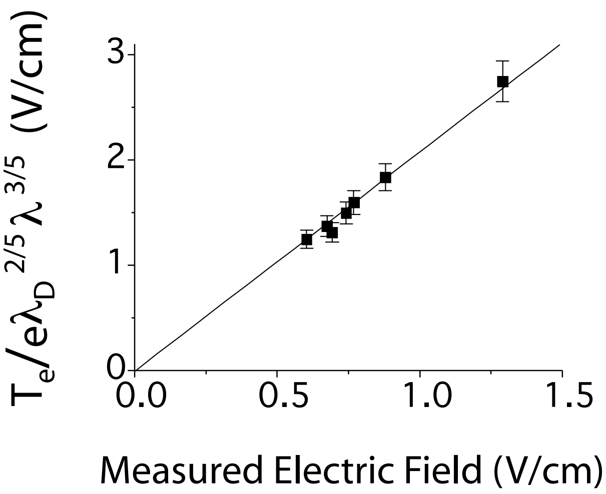

FIG. 3. The measured electric field vs Riemann's electric field in the transition region.

device geometry, ionization, and diffusion (not included in the model) determine the bulk plasma parameters. The potential was found to decrease by almost T_e/e over the presheath as shown in Fig. 1(b). Increases in neutral pressure p, were found to result in reduced presheath lengths $\ell \propto 1/p$, and ℓ was found to be approximately equal to λ [14], the ion-neutral collision length.

The transition region of the sheath is shown in Fig. 1(c), with an expanded x scale. Note that the potential drop is approximately $0.67T_e/e$. The electron-free sheath potential profile is given in Fig. 1(d) with an expanded horizontal scale. For $-\frac{e\phi}{T_e} \gg 1$, the electron-free sheath data were well fit by a collisionless "Child-Langmuir sheath" [18] for which

$$-\phi(x) = \left(\frac{3(x - x_1)}{\sqrt{2}\lambda_D}\right)^{4/3}\frac{T_e}{2e}, \tag{2}$$

where x_1 is the edge of the electron-free part of the sheath. After the presheath data and the electron-free sheath were fit, the remaining potential profile between them was identified as the transition region of the sheath.

In order to compare to the scaling predicted by Riemann, plasma parameters were varied by changing V_H, V_B, and neutral pressure (from 0.3–1.0 mTorr). The experimental transition lengths were fit with $\ell_m = \lambda^{0.2\pm\alpha}\lambda_D^{0.8\mp\alpha}$. Using this approach, a value of $\alpha = 0$ corresponds to Riemann's scaling $\ell_m = \lambda^{0.2}\lambda_D^{0.8}$ while a value of $\alpha = -0.2$ corresponds to scaling with λ_D, etc. The best fit was obtained with $\alpha = 0 \pm 0.05$. The measured data and Riemann transition sheath length data are shown in Fig. 2. These data show that the presheath and transition potential drops of approximately T_e/e and $2T_e/3e$, respectively, increase with increasing pressure.

The sheath electric field in the transition region was calculated from the potential drop over the transition region divided by the transition length. It was found to scale as predicted and to be twice the electric field $T_e/e\lambda^{3/5}\lambda_D^{2/5}$ predicted by Riemann, as can be seen from the comparison with the experimental electric field data shown in Fig. 3. Assuming λ is constant in the transition region of the sheath, the ion drift velocity equals c_s, and $E \approx 0$ at the presheath/sheath boundary, it follows [18] that

$$l_{sc} = 1.055\lambda^{1/5}\lambda_D^{4/5}(e\Phi/\mathrm{T}_e)^{3/5}. \tag{3}$$

As predicted by Riemann, the potential profile in a weakly collisional plasma has been found to consist of a parabolic presheath, followed by a sheath that consists of a collisional region, which begins quasineutral and ends ion rich, and a collisionless region where the electron density can be neglected.

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