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How to cite:

Franklin, R. N. (2002). You cannot patch active plasma and collisionless sheath. IEEE Transactions on Plasma Science, 30(1) pp. 352–356.

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Version: [\[not recorded\]](#)

Link(s) to article on publisher's website:

<http://dx.doi.org/doi:10.1109/TPS.2002.1003879>

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# You Cannot *Patch* Active Plasma and Collisionless Sheath

Raoul N. Franklin

**Abstract**—The fluid equations for the plasma-sheath are examined over the range of collisionality from collisionless to fully collisional. The method of “patching” plasma to sheath is examined critically in comparison with matched asymptotic approximations and solutions computed without approximation. It is concluded that it is necessary to include a transition layer in order to smoothly join plasma and collisionless sheath—and then the Bohm Criterion applies. When the sheath is collisional, the orderings are different and there is no transitional layer but equally there is no collisionally modified Bohm Criterion. Nevertheless, a method is given for calculating the ion flux to the wall under conditions where the sheath is collisional.

**Index Terms**—Bohm Criterion, matched asymptotic approximations, plasma sheaths.

## Nomenclature

$C_s$	Ion sound speed.
$c_{Bm}$	Modified Bohm speed.
$e$	Electron charge.
$E$	Electric field.
$E_p$	Electric field at the patching point.
$E_s$	Electric field at the sheath edge.
$k$	Boltzmann’s constant.
$L$	Plasma transverse dimension.
$M$	Ion mass.
$n_i$	Ion density.
$n_e$	Electron density.
$n_{e0}$	Electron density at center.
$n_s$	Plasma density at the sheath edge.
$N$	Normalized charged particle density.
$r_p$	Probe radius.
$T_e$	Electron temperature.
$U$	Normalized ion speed.
$v_i$	Ion speed.
$v_e$	Electron speed.
$v_{is}$	Ion speed at the sheath edge.
$V$	Electrostatic potential.
$x$	Spatial coordinate.
$X$	Normalized spatial coordinate.
$Y$	Normalized spatial coordinate.
$Z$	Ionization rate.
$\phi$	Normalized potential.
$\eta$	Normalized potential, measured relative to the plasma edge.

$\lambda_D$	Electron Debye length.
$\lambda_{D0}$	Electron Debye length at center.
$\nu_i$	Ion collision frequency.
$\lambda_{Ds}$	Electron Debye length at sheath edge.
$\lambda_i$	Ion mean free path.

## I. INTRODUCTION

IN AN EFFORT to simplify consideration of the plasma-wall boundary region, Godyak and Sternberg [1] proposed that the plasma (quasi-neutral) solution and the sheath (zero generation) solution be joined at a point where the electric field had a specified value, namely  $kT_e/e\lambda_D$ , where  $T_e$  is the electron temperature and  $\lambda_D$  the local Debye length.

There is no doubt that in the plasma-sheath the electric field passes through this value as it increases monotonically from virtually zero deep within the plasma to several times  $kT_e/e\lambda_D$ —even when the wall is only at floating potential.

The purpose of this note is to examine critically the patching process and the developments of it, because that process denies the existence of the region that is necessary to join plasma and collisionless sheath smoothly. Such a region was the natural result of the analyses of the probe-plasma situation given by Lam [2], [3], and for the plasma-wall sheath by Franklin and Ockendon [4]. The analyses referred to, involved the use of the method of matched asymptotic approximations which had by then transformed the field of fluid mechanics and gas dynamics [5]. Its use in plasma physics has been less intensive, but the list of references [2]–[4], [6]–[25], [33], [34], shows that it has been applied in a variety of situations with a significant increase in recent years.

We will keep our considerations here confined to the basics of the problem because part of the difficulty in assimilating the technique into the natural “armoury” of plasma physicists has been its apparent mathematical complexity. This contrasts with the situation in fluid mechanics where in the latter half of last century it was the “playground” of applied mathematicians.

## II. BASIC EQUATIONS

We will work essentially in the collisionless fluid approximation, as did Godyak and Sternberg, when the relevant equations are for charged particle generation and loss in the volume in one dimension

$$\frac{d}{dx}(n_i v_i) = \frac{d}{dx}(n_e v_e) \quad (1)$$

$$= Zn_e. \quad (2)$$

Manuscript received March 15, 2001; revised November 27, 2001.

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Publisher Item Identifier S 0093-3813(02)02458-X.

The collisionless ion fluid momentum equation is

$$v_i \frac{dv_i}{dx} + \frac{Zn_e}{n_i} v_i = \frac{e}{M} \frac{dV}{dx}. \quad (3)$$

While the electrons obey a Boltzmann relation

$$n_e = n_{e0} \exp\left(\frac{eV}{kT_e}\right). \quad (4)$$

Normalizing these equations with  $N = n_i/n_{e0} = n_e/n_{e0}$ ,  $U = v_i/c_s$ ,  $X = xZ/c_s$  where  $c_s^2 = kT_e/M$  leads to equations for the plasma

$$\frac{dX}{dU} = \frac{1-U^2}{1+U^2}, N = \frac{1}{1+U^2} = \exp(-\phi)$$

where  $\phi = -eV/kT_e$ . The equations are singular (i.e., they have infinite spatial derivatives) at the point where  $U = 1$ .

From these, one can determine parameters where the field attains the value suggested for patching viz.  $kT_e/e\lambda_{Ds}$ . Writing  $U = 1 - u$  where  $u$  is small compared to 1, one readily finds that  $u = (\lambda_{Ds}/L) \cdot (ZL/c_s)$  where  $x = L$  at the plasma boundary and  $ZL/c_s = \pi/2 - 1$  [26, p. 28]. Normally,  $\lambda_{Ds}/L \sim 10^{-3}$  in gas discharge plasmas and, thus, the ion speed is very close to the Bohm speed  $c_s$  and the point in question is less than a Debye length from the singular point.

Now the sheath solution can be written as

$$\frac{d^2\eta}{dY^2} = (1+2\eta)^{-1/2} - \exp(-\eta) \quad (5)$$

where  $\eta$  is the normalized potential relative to the singular point and  $Y = -x/\lambda_{Ds}$  where  $\lambda_{Ds}$  is the Debye length corresponding to  $n_{es} = n_{e0}/2$ .  $d^2\eta/dY^2 \rightarrow 0$  as  $\eta \rightarrow 0$ . Equation (5) can readily be integrated to give

$$\frac{1}{2} \left( \frac{d\eta}{dY} \right)^2 = (1+2\eta)^{1/2} - 2 + \exp(-\eta). \quad (6)$$

Thus, we can find the value of  $\eta$  where  $d\eta/dY$  has the requisite value for patching. It is very close to 2.4 (2.4031), and thus we are confronted with a serious dilemma. Continuity of electric field requires a major discontinuity in potential and consequent discontinuities in both electron and ion densities as well as ion speed. The ion flux is virtually continuous, but that is because there is next to no charged particle generation in the sheath.

If one avoids the discontinuities in potential and electron density by redefining the reference potential, one is still left with a discontinuity in ion density and ion speed, and this is intimately linked with the fact that while the field is continuous its spatial derivative is not.

Thus, we see that it is not possible to join plasma and sheath smoothly by "cutting and pasting." The reason for this lies in the structure of the equations being approximated to by considering only the plasma solution and the sheath solution.

Fig. 1 shows both solutions for the electron and ion densities and the smooth joining found both by matched asymptotic approximations and by computation of the full plasma-sheath equations. Fig. 2 concentrates on potential and electric field and shows again all three solutions for the electric field expressed in Debye lengths based on the plasma edge density  $n_s = n_0/2$  as a function of the potential. The field where the transition layer

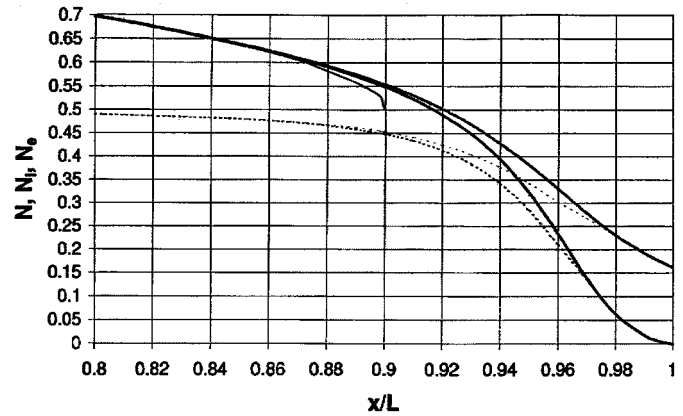


Fig. 1. The regions near the wall for a plane collisionless plasma and collisionless sheath for the case where  $\lambda_{D0}/L = 0.7071 \times 10^{-2}$ ,  $\lambda_{D0}$  is the central Debye length and  $L$  the plasma dimension. The fine line is the plasma solution ( $N$ ) ending at the singular point. The dotted lines are the ion ( $N_i$ ) and electron ( $N_e$ ) densities corresponding to the collisionless sheath solution. The full lines are the computed solutions for the densities. They are indistinguishable from the asymptotic solutions in the interval 0.87-0.97.

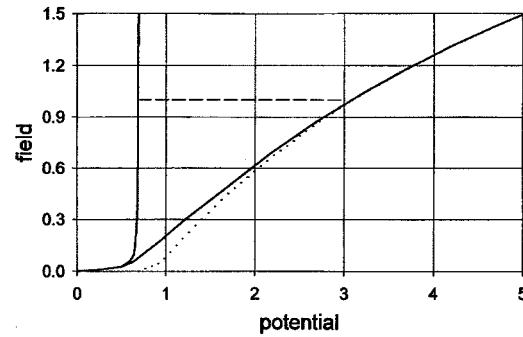


Fig. 2. The variation of electric field  $E$  in units of  $kT_e/e\lambda_{Ds}$  as a function of the potential in units of  $kT_e/e$  again for  $\lambda_{D0}/L = 0.7071 \times 10^{-2}$ . The fine lines correspond to (a) the plasma solution which is singular where  $\phi = \ln 2 = 0.693$ , and (b) the collisionless sheath solution which has  $\psi = 0$  where  $\phi = 0.693$ . The full line is the asymptotic/computed solution joining them smoothly. The dotted line corresponds to patching where  $E = kT_e/\lambda_{Ds}$ .

breaks away from the plasma solution agrees with Riemann's estimate [15] of  $(\lambda_{Ds}/L)^{3/5} = 0.0631$  and where it joins the collisionless space charge sheath is  $\sim 1$ .

The need for and the purpose of, the transition layer is clear and the claim of Godyak and Sternberg that patching leads to a smooth joining of plasma and sheath is seen to be false. A particular conclusion from the representation in Fig. 2 is the importance of the transition layer in the growth of the electric field and the electrostatic potential.

The *disjunction* between "plasma" and "sheath" is made manifest.

What patching does is effectively to remove the transition layer that is necessary to join plasma and sheath smoothly. This is not surprising because Godyak and Sternberg in their approach explicitly rejected the concept of a transition layer. In their words "Several attempts have been made to remove these discontinuities by introducing a transition layer. Here we avoid considerations of transition layers by an appropriate choice of boundary condition at the plasma-sheath interface." They were mistaken in their assertion that there were discontinuities as can be seen from the curves giving the full solutions in Figs. 1 and

2. Discontinuities arise only from limiting consideration to the plasma solutions and sheath solutions alone, as they did.

### III. CONCEPT OF A COLLISIONALLY MODIFIED BOHM CRITERION

They then went on to propose the concept of a collisionally modified Bohm Criterion suggesting that it was given by

$$c_{Bm} = c_s \left( 1 + \frac{\pi \lambda_{Ds}}{2 \lambda_i} \right)^{-1/2} \quad (7)$$

at the patching point and this has been taken up elsewhere [27] and become part of the “received wisdom.”

When the sheath is collisional, Blank [28] showed that there is a smooth joining of active plasma and space charge sheath without the need to introduce a transitional layer and the ion speed in the sheath is much less than the Bohm speed. However, the claim by Godyak and Sternberg that there is a collisionally modified Bohm speed  $c_{Bm}$  cannot be sustained. The significance of the Bohm speed as a Criterion derives from the disjunction between plasma and collisionless sheath and the transition layer is the region where the ion speed passes through the sonic or Bohm speed. Thus, there is no characteristic speed when there is no transition layer.

At the point within the sheath where the field reaches the value  $kT_e/e\lambda_{Ds}$  the ion speed is given by

$$\frac{Mv_i^2}{\lambda_i} = cE = \frac{kT_e}{\lambda_{Ds}}$$

or

$$v_i = c_s \left( \frac{\lambda_i}{\lambda_{Ds}} \right)^{1/2}$$

which apart from a numerical factor is (7) above when  $\lambda_i \ll \lambda_{Ds}$ , but since the sheath joins the plasma smoothly under collisional conditions this point has not the same physical significance.

We conclude that there is no such thing as a collisionally modified Bohm Criterion. That this is so has now been comprehensively demonstrated by computational solutions of the full plasma-sheath equations [29], [30].

The thought that the Bohm Criterion might be modified by collisions was an idea that needed to be explored (see Valentini [31] and Riemann’s refutation [15]). However, the time has now come to recognize that it was a “blind alley” and move on.

For a number of years, it seemed that the Bohm Criterion was a relation that held only in the limiting case where  $\lambda_i/L \rightarrow 0$ . However, it is now clear that its region of validity extends to points where the ion mean free path must be compared with both  $\lambda_{D0}$  and  $L$ . It is still valid when  $\lambda_i < L$  and  $\lambda_{D0} < \lambda_i$ , but not if  $\lambda_i < \lambda_{D0}$  and the limit to its validity is given approximately by  $\lambda_i = \lambda_{D0}^{4/5} L^{1/5}$  [22], [29], [30], [32]. The theoretical and experimental evidence is now in place.

The reasoning behind Godyak and Sternberg’s choice of  $E_p = kT_e/e\lambda_{Ds}$  for the field value at which to patch plasma and sheath lay in the fact that for a collisionless sheath the potential across the sheath is of the order of  $kT_e/e$  and its length of the order of  $\lambda_{Ds}$ . However, Blank [28] showed that for

the constant collision frequency for momentum transfer model that the collisional sheath has dimension  $L^{1/3}\lambda_{D0}^{2/3}$  where  $\lambda_{D0}$  is the central Debye length and the plasma solution varies linearly near the wall. This was consistent with earlier work [33], [34] which considered the sheath around an electrostatic probe of radius  $r_p$  and found that such a collisional sheath had dimensions  $r_p^{1/3}\lambda_D^{2/3}$ . Thus the field  $E_s$  at the sheath edge is

$$E_s = - \left( \frac{dV}{dx} \right)_s = - \frac{kT_e}{e} \frac{1}{n_s} \left( \frac{dn}{dx} \right)_s = \frac{kT_e}{e} \frac{\pi}{2} L^{-1/3} \lambda_{D0}^{-2/3}$$

and the local Debye length

$$\lambda_{Ds} = \lambda_{D0} \left( \frac{n_0}{n_s} \right)^{1/2} = \lambda_{D0} \left( \frac{L}{\lambda_{D0}} \right)^{1/3} \left( \frac{2}{\pi} \right)^{1/2}$$

so that

$$E_p = \frac{kT_e}{e} \left( \frac{\pi}{2} \right)^{1/2} L^{-1/3} \lambda_{D0}^{-2/3}$$

and, thus, the field at entry to the sheath  $E_s = E_p(\pi/2)^{1/2}$  or  $E_p \sim E_s$ . However, from the equation of motion we have

$$Mv_{is}v_i = cE_s = kT_e \frac{\pi}{2} L^{-1/3} \lambda_{D0}^{-2/3}$$

or

$$v_{is} = \frac{c_s^2}{v_i} \frac{\pi}{2} \left( \frac{\lambda_{D0}}{L} \right)^{1/3} \frac{1}{\lambda_{D0}}$$

giving

$$\frac{v_{is}}{c_s} = \left( \frac{\pi}{2} \right)^{3/2} \frac{\lambda_i}{\lambda_{Ds}} \quad (8)$$

with  $\lambda_i = c_s/v_i$ .

The corresponding matched asymptotic approximation treatment with a constant mean free path has been given recently [25]. The collisional sheath thickness has dimension  $L^{1/5}\lambda_{D0}^{4/5}$  and the plasma density varies parabolically near the wall. Following the same reasoning as previously, we again find that  $E_s \sim E_p$  but the ion equation of motion gives

$$\frac{v_{is}^2}{c_s^2} \sim \frac{\lambda_i}{\lambda_{D0}} \left( \frac{\lambda_{D0}}{L} \right)^{1/5} \sim \frac{\lambda_i}{\lambda_{Ds}} \quad (9)$$

Thus, (8) and (9) may be compared with (7) above and show that the ion speed at “entry” to a collisional sheath is in both models related to  $\lambda_i/\lambda_{Ds}$  but this does not imply that there is a modified Bohm Criterion. What it does mean is that the ion flux to the wall can be calculated using such expressions provided that they are coupled with an appropriate value of the ion density. This assertion can be demonstrated using the relevant plasma equations because in the sheath there is no generation and the ion flux is constant.

The fact that when both plasma and sheath are collisional the ion equation of motion is the same in plasma and sheath is what ensures that plasma and sheath join smoothly. Thus, patching under those circumstances introduces minimal discontinuity of the variables provided that they are defined locally. Indeed there is no difference between the two, except that patching occurs at an apparently arbitrary point. So far as the local Debye length is

concerned, this means knowing how the electron density varies in the plasma solution near the wall and the scale length of the sheath.

However, stating that the ions are moving in equilibrium with the local electric field does not amount to a modified Bohm Criterion. The criterion and the transition layer were necessary for a collisionless sheath to join smoothly to a plasma (collisional or collisionless) and the criterion fails once the ion collision length becomes less than the scale of the transition layer (and the layer no longer exists). For this reason there is no criterion when the outer layer(s) are sufficiently collisional.

The ion speed at the patching point for the collisionless space charge sheath is much greater ( $\sim 2.4096$  times) than the Bohm speed, but is given by the expressions (8), (9) above when the sheath is collisional and a smooth variation occurs in the range  $\lambda_i \sim \lambda_{Ds}$  but (7) does not describe that transition.

The only physical quantity that has a finite nonzero value at the “plasma edge” and, therefore, through the space charge sheath is the ion flux and that can be simply calculated from the plasma solution. Since

$$n_e = n_{e0} \exp \frac{eV}{kT_e} = n_{e0} \cos \frac{\pi x}{2L}$$

$$\frac{e}{kT_e} \frac{dV}{dx} = \frac{-\pi \sin \frac{\pi x}{2L}}{2L \cos \frac{\pi x}{2L}}$$

but

$$MV_i v_i = -e \frac{dV}{dx}$$

therefore

$$n_i v_i \rightarrow \frac{kT_e}{M} \frac{\pi}{2L} \frac{n_{e0}}{v_i} = n_{e0} \frac{\pi \lambda}{2L} c_s$$

as  $x \rightarrow L$  and this is precisely the value given by a convoluted calculation determining self consistently the ion density and speed at the point where the field is given by

$$eE = \frac{kT_e}{\lambda_{Ds}}.$$

#### IV. CONCLUSION

Thus, we conclude that this patching point introduced by Godyak and Sternberg has no significance when the sheath is collisionless, but corresponds approximately to the beginning of the space charge collisional sheath at high pressures. Then, patching is not appropriate since plasma and sheath join smoothly.

The Bohm Criterion derives from the requirements on (3) and its integral as clearly shown in Franklin and Ockendon [4]. The collisional space charge sheath joins the plasma solution smoothly without there being an additional requirement on the ion speed, and thus the introduction of the concept of a collisionally modified Bohm criterion was misguided.

#### REFERENCES

[1] V. A. Godyak and N. Sternberg, “Smooth plasma-sheath transition in a hydrodynamic model,” *IEEE Trans. Plasma Sci.*, vol. 18, pp. 159–168, Feb. 1990.

[2] S. H. Lam, “Unified theory for the Langmuir probe in a collisionless plasma,” *Phys. Fluids*, vol. 8, pp. 73–87, 1965.

[3] —, “Theory of Langmuir probes at moderate pressures,” in *Proc. 8th Int. Conf. on Phenomena in Ionized Gases*, Vienna, Austria, 1967, pp. 545–568.

[4] R. N. Franklin and J. R. Ockendon, “Asymptotic matching of plasma and sheath in an active low pressure discharge,” *J. Plasma Phys.*, vol. 4, pp. 371–385, 1970.

[5] M. van Dyke, *Perturbation Methods in Fluid Mechanics*. New York: Academic, 1964.

[6] K.-U. Riemann, Ph.D. dissertation, University Bochum, Westfalen, Germany, 1977.

[7] M. S. Benilov, “Electrode region of a weakly ionized plasma in chemical equilibrium,” *Fluid Dyn.*, vol. 17, pp. 117–127, 1982.

[8] —, “Theory of a spherical electric probe in a weakly ionized plasma at rest,” *Fluid Dyn.*, vol. 17, pp. 773–779, 1982.

[9] —, “The perturbed region of a weakly ionized plasma near a cold electrode,” *Fluid Dyn.*, vol. 18, pp. 226–234, 1983.

[10] P. G. Daniels and R. N. Franklin, “The positive column in electronegative gases—A boundary layer approach,” *J. Phys. D, Appl. Phys.*, vol. 22, pp. 780–785, 1989.

[11] P. G. Daniels, R. N. Franklin, and J. Snell, “The contracted positive column in electronegative gases,” *J. Phys. D, Appl. Phys.*, vol. 23, pp. 823–831, 1990.

[12] K.-U. Riemann, “The Bohm criterion and sheath formation,” *J. Phys. D, Appl. Phys.*, vol. 24, pp. 493–518, 1991.

[13] R. N. Franklin, P. G. Daniels, and J. Snell, “Characteristics of electric discharges in the halogens: The recombination-dominated positive column,” *J. Phys. D, Appl. Phys.*, vol. 26, pp. 1638–1649, 1993.

[14] K.-U. Riemann, “The Bohm criterion and boundary conditions for a multi component system,” *IEEE Trans. Plasma Sci.*, vol. 23, pp. 709–716, Apr. 1995.

[15] —, “The influence of collisions on the plasma sheath transition,” *Phys. Plasmas*, vol. 4, pp. 4158–4166, 1997.

[16] M. Thornhill and P. V. Desai, “Asymptotically matched sheath and presheath in a dense plasma,” *J. Plasma Phys.*, vol. 59, pp. 505–536, 1998.

[17] —, “Asymptotic solutions for a symmetric plasma under ionization nonequilibrium,” *J. Appl. Phys.*, vol. 86, pp. 4792–4798, 1999.

[18] V. Baritello, F. Porcelli, and F. Subba, “Plasma-wall boundary layers,” *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 60, pp. 4733–4742, 1999.

[19] M. S. Benilov and R. N. Franklin, “Joining sheath to plasma in electronegative gases at low pressures using matched asymptotic approximations,” *J. Plasma Phys.*, vol. 62, pp. 541–559, 1999.

[20] M. S. Benilov, “Theory of plasma-wall transition with account of variable ion temperature,” *Phys. Plasmas*, vol. 7, pp. 135–143, 2000.

[21] —, “Boundary conditions for the child-langmuir sheath model,” *IEEE Trans. Plasma Sci.*, vol. 28, pp. 2207–2213, Dec. 2000.

[22] K.-U. Riemann, “Theory of the plasma-sheath transition,” *J. Tech. Phys.*, vol. 41, pp. 89–121, 2000.

[23] M. S. Benilov and P. K. Shukla, “Bohm criterion for a plasma composed of electrons and positive dust grains,” *Phys. Rev. E, Stat. Phys. Plasmas. Fluids. Relat. Interdiscip. Top.*, vol. 63, pp. 016401–016410, 2000.

[24] M. S. Benilov, “Collision dominated to collisionless electron-free space charge sheath in a plasma with variable ion temperature,” *Phys. Plasmas*, vol. 7, pp. 4403–4411, 2000.

[25] M. S. Benilov and R. N. Franklin, “Asymptotic theory of a collision-dominated space charge sheath with a velocity-dependent ion mobility,” *J. Plasma Phys.*, to be published.

[26] R. N. Franklin, *Plasma Phenomena in Gas Discharges*. Oxford, U.K.: OUP, 1976.

[27] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*. New York: Wiley, 1994.

[28] J. L. Blank, “Collision-dominated positive column of a weakly ionized gas,” *Phys. Fluids*, vol. 11, pp. 1686–1698, 1968.

[29] R. N. Franklin and J. Snell, “The transition from collisionless to collisional active plasma in the fluid model and the relevance of the Bohm criterion to sheath formation,” *Phys. Plasmas*, vol. 7, pp. 3077–3083, 2000.

[30] —, “The plasma-sheath transition with a constant mean free path model and the applicability of the Bohm criterion,” *Phys. Plasmas*, vol. 8, pp. 643–647, 2001.

[31] H.-B. Valentini, “Bohm criterion for the collisional sheath,” *Phys. Plasmas*, vol. 3, pp. 1459–1461, 1996.

- [32] N. Hershkowitz and L. Oskuz, "Experimental test of Riemann and Godyak presheath/sheath transition and sheath electric field scaling," in *Proc. 15th ESCAMPIG*, Lillafüred, Hungary, Aug. 26–30, 2000, pp. 474–475.
- [33] C. H. Su and S. H. Lam, "Continuum theory of spherical electrostatic probes," *Phys. Fluids*, vol. 6, pp. 1479–1491, 1963.
- [34] I. M. Cohen, "Asymptotic theory of spherical electrostatic probes in a slightly-ionized collision-dominated gas," *Phys. Fluids*, vol. 6, pp. 1492–1499, 1963.



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