JET-P(95)21

# Determination of $T_e$ from a Langmuir Probe in a Magnetic Field by Directly Measuring the Probe's Sheath Drop using a Pin-plate Probe

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Preprint of a paper to be submitted for publication in
Plasma Physics and Controlled Fusion

## ABSTRACT

In principle, it is not possible to interpret a Langmuir probe in a strong magnetic field since the modelling of non-ambipolar cross-field transport is uncertain. In some circumstances the portion of the probe I-V characteristic below floating potential may not be contaminated by magnetic field effects, and it can be possible to extract $n_e$ and $T_e$ from such data; unfortunately, it is not known with any certainty when this situation holds. By using a special probe with a small collecting element (Pin) just in front of the principal collecting element (Plate) it is possible to correct for the influence of the magnetic field, and to use simple single-probe theory to extract $n_e$ and $T_e$. The uncertain influence of the non-ambipolar cross-field transport is entirely circumvented. Using such a probe it is possible to also use the part of the I-V characteristic above floating potential; thus, if the electron distribution is non-Maxwellian, that can be measured.

## INTRODUCTION

In the absence of a magnetic field, it is relatively straightforward to use all of a Langmuir I-V characteristic below the plasma potential, taken to be $V = 0$ here, see Fig.1, in order to deduce information about the electron velocity/energy distribution [1]. If the distribution is Maxwellian then a value of $T_e$ is extracted which is based on information from the entire distribution (or at least, the distribution of the electrons which were moving toward the probe; directional probes can then be used to deduce any anisotropies [1]). If the distribution is non-Maxwellian, then by double-differentiating the I-V characteristic — the Druyvesteyn Method — the actual electron distribution can be deduced [1]; again, however, the entire I-V characteristic has to be used if the complete distribution is sought.

At least since the work of Bohm [2], using Langmuir probes in a strong magnetic field, it has been known that (at least) the electron-collection part of the I-V characteristic is substantially distorted by the $\vec{B}$ field. The most obvious evidence that the B-field has strongly influenced the I-V characteristic is that the ratio of electron-to-ion saturation currents, $I_{sat}^{-}/I_{sat}^{+}$, which is found to be $\approx(m_i/m_e)^{1/2}$ experimentally when $B = 0$, in accord with simple probe theory, becomes smaller for $B \neq 0$. Bohm found reductions from the hydrogenic value of about 50, down to ~10 [2]. In tokamaks similar values have been reported [3, 4], and more recently values as low as unity [4] and even below unity [5].

Bohm [2] hypothesized that the effect of $\vec{B}$ on the I-V characteristic was through disturbance to the electron collection, with the ion collection still being essentially as for $B = 0$, i.e., $I_{sat}^{+} \approx e n_{e\infty} c_s$, with $c_s \approx (k(T_e + T_i)/m_i)^{1/2}$ the ion acoustic speed, and $n_{e\infty}$ the far distant, undisturbed density [1]. He modelled the electron collection on the basis of very slow cross-field transport into the magnetic flux tube subtended by the probe, together with rapid transport along $\vec{B}$ to the probe, Fig.2. Thus the probe "collection" or "disturbance" length is long and narrow. The shape of the probe itself is not very important, only its cross-sectional area, perpendicular to $\bar{B}$ being relevant.

In Bohm's model, the drawing of net electron current by the probe caused the plasma density in the flux tube, just in front of the probe $n_{pse}$ ("probe sheath edge"), to be depressed relative to its undisturbed value at infinity, $n_{e_\infty}$, because of cross-field and parallel-field electrical resistance. The cross-field and parallel-field potential "drops" (positive increments, in fact) required to attract the electrons, repelled the ions which Bohm assumed then adopted a Boltzmann factor relationship between the ion (thus plasma) density and the electrostatic potential, i.e., $n \propto \exp(eV/kT_i)$ — thus giving the above-mentioned density depression. Since the electron current density to the probe is proportional to the plasma density in the probe flux tube, just in front of the probe, $n_{pse}$, such currents are thus reduced compared with the $B = 0$ case.

## THE BASIC PROBLEM

Since Bohm's work a number of elaborations and changes have been made by other workers to the original formulation of the theory for probes in a magnetic field [6-9]. Despite all the changes the basic problem remains essentially the same:

(a) The voltage change applied to the probe, when $B \neq 0$, does not appear in its entirety across the probe's sheath — as is the case for (small) probes in $B = 0$ plasmas — but is "consumed" by various plasma and/or sheath resistances elsewhere in the probe circuit. Thus the principal assumption required for application of single-probe theory is not satisfied; the *circuit* I-V characteristic is not identical with the probe *sheath* I-V characteristic. Thus, one cannot extract $T_e$ from the circuit I-V characteristic using traditional single-probe theory.

(b) While, in principle, one can model the other plasma and/or sheath resistance in the circuit — which would then permit, in effect, the identification of the probe-sheath resistance — such modelling requires knowledge of non-ambipolar cross-field transport mechanisms, which are, in fact, poorly understood.

The problem is further discussed in conjunction with Fig.3, which represents the circuit for a single probe in a magnetic plasma. The collection element of the probe is biased relative to the major edge structures of the tokamak, i.e., the limiters or divertor targets — and possibly the probe housing surrounding the probe collection element also. In the following we discuss each of the circuit resistances shown in Fig.3:

(a) The probe sheath resistance, $R_{sheath}^{probe}$: Ideally this would be the only resistance in the circuit and would be given by the nonlinear I-V sheath relation:

$$I = I_{sat}^{+}[1 - \exp(e(V - V_{fl})/kT_e)] \text{ for } V < 0 \tag{1}$$

where $V_{fl}$ is the probe floating potential at which I = 0. Note that Eq. (1) implicitly assumes that the plasma potential in the flux tube just in front of the probe, $V_{ppse}$ (the "plasma potential at the probe sheath edge") is at $V_{ppse} = 0$. This, however, is the crux of the problem; when the other resistances, as shown in Fig.3, are non-zero, then $V_{ppse} \neq 0$ when finite currents are drawn. We thus do not know the value of the voltage drop across the probe sheath, $\Delta V_s^p$:

$$\Delta V_s^p \equiv V - V_{ppse} \tag{2}$$

In fact, it is $\Delta V_s^p$ which we need in Eq. (1), not V. This information is not available using a conventional single probe, however.

(b) The return sheath resistance, $R_{sheath}^{return}$: Of course, the probe circuit has to be completed through some other sheath bounding the plasma. This applies to all plasmas regardless of whether B = 0 or ≠ 0. Strictly speaking, $R_{sheath}^{return}$ is therefore also always present in the probe circuit, and there is no such thing as a single probe. Single probe theory, however, can be an excellent approximation if the collection area of the return sheath is much larger than that of the probe sheath. This is commonly the situation with B = 0 plasmas. This was Bohm's implicit assumption also for B ≠ 0 plasmas, and those works building directly on Bohm's [6-9]. Whether or not this assumption is valid for a B≠ 0 plasma depends on the relative rates of parallel to cross-field transport (which may differ for electrons and ions): if perpendicular transport is extremely slow, relative to parallel transport, then the probe's collection tube will reach all the way to the "opposite surface", and the return sheath collection area will be of approximately the same area as the probe collection area. Thus the probe will act approximately like a double probe [10, 11]. If the "opposite surface" is infinitely distant, then the return sheath will be on the solid surface adjacent to the collecting element of the probe, e.g., the housing of the probe or the limiter/divertor target surface for flush-mounted probes. This, of course, requires some cross-field transport. The area of the return sheath will be very small if cross-field transport is enormously slower than parallel transport, and so the return sheath area may be of the same size as the probe sheath, or smaller. Again, one would expect to see a probe circuit I-V characteristic something like that of an (asymmetric) double probe — with the probe sheath area larger or smaller than the return sheath area.

(c) The cross-field resistance $R_\perp$: Generally, there will be cross-field transport, and an associated resistance — quite possibly nonlinear, and differing for net electron and ion collection.

(d) Parallel resistance $R_{||}$: Generally the parallel flow of current encounters some resistance due, for example, to neutral friction. Bohm, etc. [2, 6-9] also included e-i friction, although this may not be correctly included [10].

One aspect of the problem is that it is not known whether the non-ambipolar cross-field transport is anomalous or not. One could make the hypothesis which Bohm and other (non-probe) studies [12, 13, 23] have made, that cross-field flux densities are driven by cross-field density and potential gradients:

$$\Gamma_{\perp}^{e,i} = -D_{\perp}^{e,i} \frac{dn}{dx_{\perp}} + \mu_{\perp}^{e,i} enE_{\perp} \tag{3}$$

where $D_{\perp}^{e,i}$ are the diffusion coefficients and $\mu_{\perp}^{e,i}$ are the mobility coefficients. Bohm went so far as to assume that the Einstein relation was also satisfied for these cross-field coefficients, i.e.,
$D/\mu = kT/e$ and thus that $\mu$ is anomalous. Other researchers have calculated $\mu_{\perp}$ by assuming a balance between the $j_{\perp}B$ force and neutral friction or viscosity [10, 11, 24, 25]. The cross-field transport coefficients for heat, particles and momentum ($\chi_{\perp}$, $D_{\perp}$, $\eta_{\perp}$) can still not be calculated from first principles but are anomalous. There is little experimental information on non-ambipolar cross-field transport to indicate whether it is anomalous or not. The most useful information on this question is biased divertor/limiter experiments [13-15, 23]. The Tokamak de Varennes results [23] do confirm some aspects of classical/neoclassical theories [24, 25], but not others; the magnitude of the cross-field mobility may be anomalously high. The 2-D codes used to model drifts in the edge often contain an anomalous cross-field conductivity term [26] owing to such uncertainties. In fact, we do not know that non-ambipolar cross-field fluxes are driven by cross-field potential and density gradients; other gradients and other factors may be involved; even if n and V gradients are involved we do not know if the fluxes are linearly proportional to these gradients and we do not know the proportionality constants, nor how to relate those constants to each other. Non-ambipolar cross-field transport may be due to magnetic fluctuations.

It appears therefore not to be possible to calculate $R_{\perp}$ with reliability at this time. Our inability to model non-ambipolar cross-field transport also prevents us from calculating $R_{sheath}^{return}$ and $R_{||}$:

(a) $R_{sheath}^{return}$: As already mentioned, the area of the return sheath, and thus its resistance, is governed by the relative rates of parallel-to-perpendicular transport.

(b) $R_{||}$: Whether the circuit extends to a far surface, or closes (cross-field) to adjacent ones, depends on the relative rates of parallel-to-perpendicular transport.

In a tokamak environment, a number of other complicating effects further prevent a reliable modelling of the circuit:

(a) Magnetic shear: In a magnetic field which is straight and constant (invariably the assumption in probe modelling) the magnetic flux tube subtended by the probe remains constant in cross-sectional shape and area. In the tokamak edge neither of these are true. In particular the magnetic shear can cause enormous distortions of the cross-sectional shape of the probe's flux tube — especially as it passes near the X-point of a divertor configuration. This can cause the probe's flux tube to become so "smeared out", as projected in the poloidal plane for example, that the cross-field thickness of the tube can become smaller than the electron Larmor radius. At that point, presumably the flux tube should be treated as being effectively coupled to an "infinite plasma". In any case, further major complications and uncertainties clearly attend the modelling of the probe circuit due to magnetic shear.

(b) Cross-field E×B flows: Generally the edge is characterized by poloidal/parallel and radial electric fields and thus radial and poloidal E×B flows. It is unlikely that such flows are divergence-free, even in the absence of a probe; in the presence of a probe, with n depressed in the probe's flux tube, such E×B flows are certain to not be divergence-free. Thus these flows constitute sources/sinks on the probe's flux tube and complicate the problem further.

In light of the foregoing it is evident that reliable modelling of all of the circuit elements, $R_{sheath}^{return}$, $R_{\perp}$, $R_{\parallel}$, is not possible. Thus, it is not possible — at least in principle — to know $\Delta V_s^p$, Eq. (2), as is needed if one is to be able to extract a meaningful value of $T_e$ from the circuit I-V characteristic. It is important to emphasize "not possible *in principle*" here since this is only *strictly* true: it *may happen* that $R_{sheath}^{probe} >> R_{sheath}^{return}$, $R_{\perp}$, $R_{\parallel}$ — and then the circuit I-V characteristic is identical to the probe sheath I-V characteristic. For some time it has been hoped — although traditionally without solid proof — that this is indeed the case for $V < V_{fl}$, i.e., for net ion collection. Thus, the practice on many tokamaks has been to extract $T_e$ just using the portion of the characteristic below floating [16, 17]. Even if the magnetic field has no significant effect on this part of the characteristic, this practice encounters a potentially serious problem: one is only sampling the high energy tail of the distribution, and so if the electrons are non-Maxwellian one can extract an unrepresentative (typically too high) value of $T_e$ [18]. Here, however, we are concerned about the more fundamental question of whether the magnetic field is non-disturbing for *any* part of the characteristic, even below floating. The strict answer, as discussed above, is "no". As will be discussed next, however, it appears that this can be a fairly "safe" part of the characteristic in some circumstances.

## EXPERIMENTAL EVIDENCE THAT LANGMUIR PROBES CAN BE RELIABLE IN THE PRESENCE OF STRONG MAGNETIC FIELDS

The last section will have struck too pessimistic a note if the implication is taken that Langmuir probes cannot yield reliable values of $n_e$ and $T_e$ when used in a strong magnetic field. Comparisons have been made between Langmuir probes and other plasma measuring techniques such as Laser Thompson Scattering [19] and other methods [20] — which showed, for the examples reported, that agreement can often be to within a factor of 2.

What the last section does indicate is that, *in principle*, the extraction of $T_e$ is problematical — and that, unfortunately, we do not know when these problems will arise.

A further piece of experimental evidence that, at least the portion of I-V characteristic below floating, can be free of disturbing influences by the magnetic field (thus yielding at least a high energy tail value of $T_e$) — is provided by Pin-Plate Probe experiments performed on the DITE tokamak [21, 22], Fig. 4. The Plate element was 5×10 mm$^2$ in area, the Pin, 1 mm diameter, 5 mm long, placed 2 mm in front of the plate, i.e., just outside the plate sheath (although such a separation may be marginal, and a somewhat larger one is to be preferred). The Pin was floated and thus $V_{fl}^{pin}$ gave the potential of the plasma just in front of the plate, i.e., $V_{ppse}$ (actually $V_{fl}^{pin}$ differs from $V_{ppse}$ by the Pin sheath drop but this is assumed to be a constant).

Figure 5, reproduced from [20] shows in (a) the I-V characteristic of the Plate circuit, $I^{plate}$ vs. $V^{plate}$, (b) $V_{fl}^{pin}$ as a function of $V^{plate}$, (c) $I_{sat+}^{pin}$ as a function of $V^{plate}$ (the measurements in (b) and (c) were carried out in successive discharges). The I-V characteristic of Fig.5a was processed in the usual way, i.e., fit by Eq. (1) using data for $V^{plate} < V_{fl}^{plate}$ only; this yielded a value of $T_e$ = 5.5 eV ± 0.4 eV. For variations of $V^{plate} < V_{fl}^{plate}$ it can be seen, Fig.5b, that $V_{fl}^{pin}$ changed very little. Thus — at least for these operating conditions and for this part of the characteristic — no significant voltage drop existed in the probe circuit of the sort mentioned earlier, i.e., evidently $R_{sheath}^{probe} >> R_{sheath}^{return}$, $R_\perp$, $R_\parallel$ here. Thus, the value of $T_e$ extracted using the data for $V^{plate} < V_{fl}^{plate}$ only, should give $T_e$ correctly (or at least the high energy tail value correctly). This, then, constitutes *direct* proof — the first such, evidently — that, at least under some circumstances, the standard assumptions about single probe behaviour can, in fact, be satisfied.

One may note, by contrast, that for $V^{plate} > V_{fl}^{plate}$, that $V_{fl}^{pin}$ showed very large changes in the local plasma just in front of the plate probe, i.e., $V_{ppse}$ — thus confirming that the standard single-probe assumptions are *not* satisfied here. In this part of the characteristic evidently $R_{sheath}^{return}$, $R_\perp$ and/or $R_\parallel$ have become significant compared with $R_{sheath}^{probe}$ for the Plate. Thus, this part of the Plate I-V characteristic cannot be (directly) used to extract information on $T_e$. This situation corresponds to the "standard" one in tokamak Langmuir probe work, where one relies on the part of the I-V characteristic below floating to give $T_e$, while one avoids using data above floating [16, 17]. We do not know, unfortunately, if this situation holds generally.

It is to be noted that Fig.5c is also important: this indicates whether or not the density just in front of the probe, $n_{pse}$ ("probe sheath edge"), varies with $V^{plate}$. If this density varies, then another of the basic assumptions of single probe theory is violated, since a constant density is assumed. Given that $R^{return}_{sheath}$, $R_{\perp}$ and $R_{\parallel}$ may be significant compared with $R^{probe}_{sheath}$, it is not at all assured that $n_{pse}$ will stay constant as $V^{plate}$ is varied. As can be seen from Fig. 5c, $I^{pin}_{sat+}$, thus $n_{pse}$, *is* approximately constant for $V^{plate} < V^{plate}_{fl}$ — for this case. One may also note that for $V^{plate} > V^{plate}_{fl}$, it is not.

## PROPOSED USE OF A PIN-PLATE PROBE TO EXTRACT VALUES OF $T_e$ IN THE PRESENCE OF A STRONG MAGNETIC FIELD

It can therefore be proposed that, whenever one wishes to confirm that the value of $T_e$ extracted from a Langmuir probe characteristic is reliable (in the sense of not being directly contaminated by the magnetic field; the problem that the electron distribution may not be Maxwellian is a separate issue [18] — although see below) — then a Pin-Plate Probe be deployed.

If the characteristics of the Pin and Plate appear approximately as in Fig.5 then one will be justified in using the "standard" interpretation method of employing the Plate I-V characteristic below $V^{plate}_{fl}$ to extract a (tail) value of $T_e$. Note that the interpretation — at least a direct, uncorrected application of the single probe theory — requires that *both* the conditions are met:

(a) $V^{pin}_{fl} \approx$ constant as $V^{plate}$ varies (as Fig.5b).

(b) $I^{pin}_{sat+} \approx$ constant as $V^{plate}$ varies (as Fig.5c).

What if these latter two conditions are *not* met? This does not prevent the extraction of a (tail) value of $T_e$: one only needs to *allow* for these variations. This is done as follows:

(a) If $V^{pin}_{fl}$ varies with $V^{plate}$, then one uses $\Delta V^{p}_{s}$, Eq. (2), in Eq. (1) rather than $V^{plate}$. One takes $\Delta V^{p}_{s}$ to be:

$$\Delta V^{p}_{s} = V^{plate} - V^{pin}_{fl} + \text{constant}$$

where the constant represents the value of the Pin sheath floating voltage drop. Since one only needs the *slope* of the log I vs. V plot to extract $T_e$, the value of this constant has no effect.

(b) If $I^{pin}_{sat+}$ varies with $V^{plate}$ then one may assume that $I^{plate}_{sat+}$ varies in the same way (since both vary as $n_{pse}$). This is then allowed for in Eq. (1), i.e., the dependence of $I^{+}_{sat}$ on $V^{plate}$ is allowed for.

What about the Plate characteristic *above* $V_{fl}^{plate}$? This can also be used, following precisely the same prescription as just outlined. The results, using the data from Fig.5, are shown in Fig.6. Since $I_{sat+}^{pin}$ does not vary that much for the first 10 volts or so above $V_{fl}^{plate}$, the $n_{pse}$-correction has not been made here, and the only correction is to plot the probe current vs. $\Delta V_s^p$ rather than $V^{plate}$. As can be seen from Fig.6, this pulls the points onto a straight line (on the log plot), and gives a value of $T_e$ = 4.6 eV, which is quite close to the value obtained just using the data below $I_{sat+}^{pin}$ alone, Fig.5, ~5.5 eV. One should note that in Fig.6 the $\Delta V_s^p$ values were used not just above $V_{fl}^{plate}$ (thus pulling the data points to the left), but also below $V_{fl}^{plate}$ (which, here, pulled the points, slightly, to the right).

Thus a Pin-Plate Probe can be used to extract information about the electron distribution over a wider energy range, than just the high energy tail. Evidently, in the example of Fig.5, the electron distribution was approximately Maxwellian — at least down to the lowest energy sampled. Assuming that the plasma potential is at 3 $kT_e/e$ above $V_{fl}^{plate}$, and that $T_e$ = 4.6 eV, the implied plasma potential is at +11.8 volts. As can be seen from Fig. 6, the plot vs. $\Delta V_s^p$ remains Maxwellian to within a few volts of this value. Thus, for this example, almost the entire velocity distribution of the electrons has been sampled, and is confirmed to satisfy a single Maxwellian. In other circumstances, non-Maxwellian electrons could be present. In that case, use of the I-V characteristic above $V_{fl}^{plate}$ could be used to obtain quantitative information about the electron energy distribution — free of contaminating effects of the magnetic field.

It is to be noted that one is not, necessarily, able to sample the electron distribution right down to zero electron energy. The data of Fig.5 were taken with the probe located in the Scrape-Off Layer, SOL, of the DITE tokamak, 4 cm outside the Last Closed Flux Surface, LCFS, defined by the limiters, and the probe faced a limiter just 4 m away. In this geometry, the probe disturbance length [17] almost certainly extended to the limiter (one cannot know for sure, for the reasons given in Sec. 2), and so the probe acted, partially, as an asymmetric double probe, with the $R_{sheath}^{return}$ on the "opposite", i.e., limiter, surface being the second probe. Thus, the electron distribution can only be sampled down to a minimum value such that the electron current to the probe equals the ion saturation current through the Return Sheath.

This brings one to the matter of explaining — at least qualitatively — why the electron current saturates (at values less than the B = 0 case of $\approx(m_i/m_e)^{1/2}$). As mentioned, for some cases — as the Fig.5 data — it is probably due to the probe acting, partially, as an asymmetric double probe. In other circumstances the $R_{sheath}^{return}$ may not be important, but $R_\perp$ may be controlling. Then, in order to repel all the ions from the probe's flux tube, the cross-field potential drop will have to attain some (saturated) value; while we do not know how to relate the cross-field potential drop to the cross-field density drop with any confidence (as mentioned, Bohm assumed the coupling was via the Boltzmann relation, $n \propto \exp(eV/kT_i)$ and also assumed the Einstein relation between $D_\perp^e$ and $\mu_\perp^e$, but we do not know if these assumptions are valid) — it may well be that they are related in some monotonic way. In that case, the cross-field density drop — associated with the total repelling of ions from the probe's flux tube — will also saturate. Thus, one will have some saturated value of $n_{pse} < n_{e_\infty}$ for total ion rejection, hence a saturated value of $I^{e}_{sat}$. In this case one would expect that if one included the $n_{pse}$-correction to $I^{plate}_{sat+}$ (taken from the variation of $I^{pin}_{sat+}$ with $V^{plate}$, e.g., Fig. 5c), one could sample the *entire* electron distribution all the way down to zero energy. (Of course, if $R_\perp = 0$, and if $n_{pse}$ is free to rise *above* $n_{e\infty}$, as a result of biasing, then there would be no electron saturation.)

Examination of Figs.5b and 5c indicate that this is almost certainly a case where $R^{return}_{sheath}$ is as important as $R_\perp$: at the value of $V^{plate}$ where $I^{plate}$ has already reached $I^{plate}_{sat-}$, the value of $I^{pin}_{sat+}$ has only decreased by ~30% from its value for $V^{plate} < V^{plate}_{fl}$. Thus, in this case, $I^{pin}_{sat-}$ would appear to be due to asymmetric double probe $R^{return}_{sheath}$) behaviour, rather than "pure" $R_\perp$-limitation and $n_{pse}$-reduction. Given the close proximity of the probe to the limiter for this case, 4 m, this is not surprising.

Recently, ratios of $I^{e}_{sat}/I^{i}_{sat}$ have been reported of order unity, and even smaller [4, 5]. As discussed, this can be explained — at least qualitatively — by either a $R^{return}_{sheath}$ or a $R_\perp$ effect (in the latter case, it may be that totally repelling of ions requires, for some reason, larger drops in $n_{pse}$ than total repelling of electrons). In such cases one would expect the contaminating effect of the magnetic field to extend even into the part of the I-V characteristic below floating potential. Thus the type of corrections made possible by the use of a Pin-Plate Probe would be required for the entire characteristic.

In the absence of a Pin-Plate Probe it is probably a reasonable assumption that the portion of the I-V characteristic below floating will yield a (high energy tail) value of $T_e$, free from contamination by the magnetic field, when $I^{e}_{sat} >> I^{i}_{sat}$ — which is fortunately a fairly common situation.

## CONCLUSIONS

The interpretation of a single Langmuir probe in a strong magnetic field is, in principle, not possible since we do not know very well how to model non-ambipolar cross-field transport. Furthermore, divergence of E×B drifts, and distortions of the probe's flux tube due to magnetic shear make a full analysis still more intractable. It may be that the portion of the I-V characteristic below floating potential can be interpreted using Single Probe theory to extract a (high energy tail) value of $T_e$, free of contamination by the magnetic field — but there is no way to know for certain when this is the case. The only measurements available from a Single Probe are the I-V characteristics of the *circuit*, which is not identical with the I-V characteristic of the probe *sheath* — owing to the presence of other resistances, $R^{return}_{sheath}$, $R_\perp$, $R_\parallel$ in the probe circuit. The theory for Single Probe analysis only applies to the probe sheath I-V characteristic.

By locating a small Langmuir probe (Pin), directly in front of the principal Langmuir probe (Plate) (but more than a sheath thickness away) one can *directly* measure the plasma potential and plasma density just in front of the probe, thus avoiding the uncertainties of non-ambipolar cross-field transport, divergent E×B fields and magnetic shear. This additional information is sufficient to give the probe sheath I-V characteristic *directly*, and to provide a value of $T_e$ which is not contaminated by the magnetic field. In this way it is also possible to sample much more of the electron distribution than is the case if analysis is restricted to $V^{plate} < V_{fl}^{plate}$, and if the distribution is non-Maxwellian, the actual distribution can be measured.

It would be valuable to carry out more extensive experimental tests of Pin-Plate Probes, over a wider range of operating conditions, to confirm whether the picture presented here is a general one. It will be useful to develop designs which are consistent with the nearly-flush-mounted operation required in high power tokamaks.

## ACKNOWLEDGEMENTS

The author wishes to thank A. Chankin, K. Günther, G. F. Matthews and R. A. Pitts for helpful discussions. Support by the Canadian Fusion Fuels Technology Project is acknowledged.

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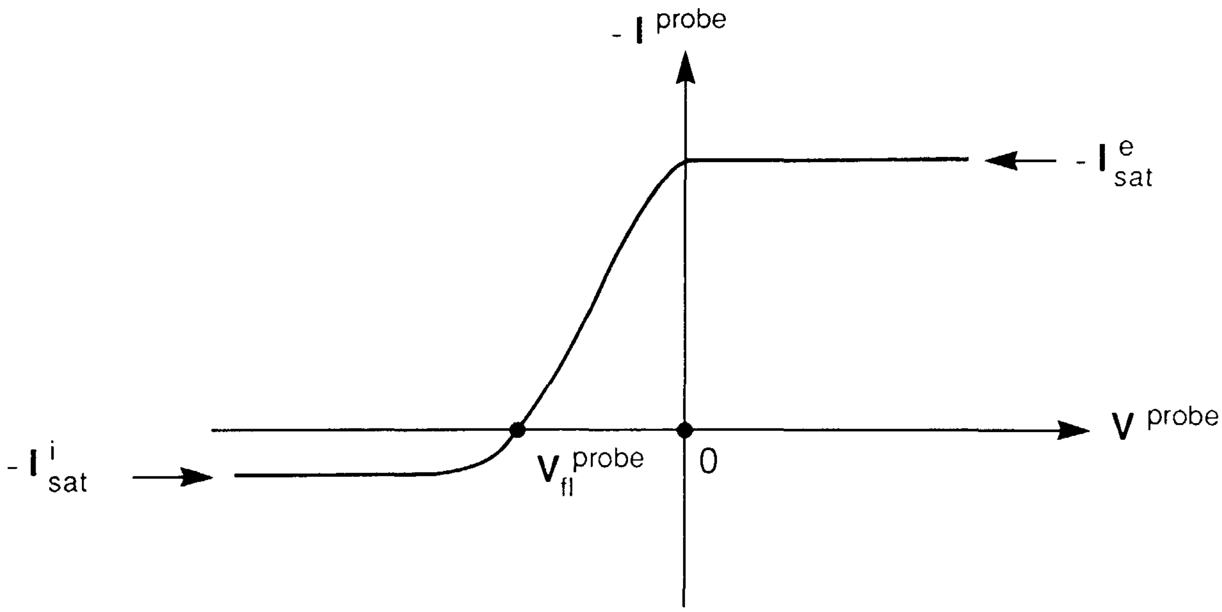


*Fig.1: A schematic of a single Langmuir probe characteristic. Idealized. The "saturated" electron and ion currents are not always so well-defined. By definition, here, V = 0 gives the plasma potential. In the simplest probe models, it is assumed that the ion part of the total current equals $I_{sat}$ for $V^{probe} < 0$, while going to zero for $V^{probe} > 0$.*

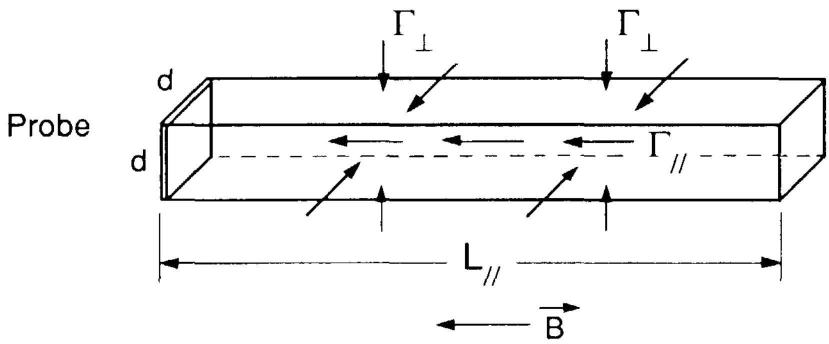


*Fig.2: Schematic of the probe's collection flux tube, for a strong magnetic field. $L_{||} >> d$.*

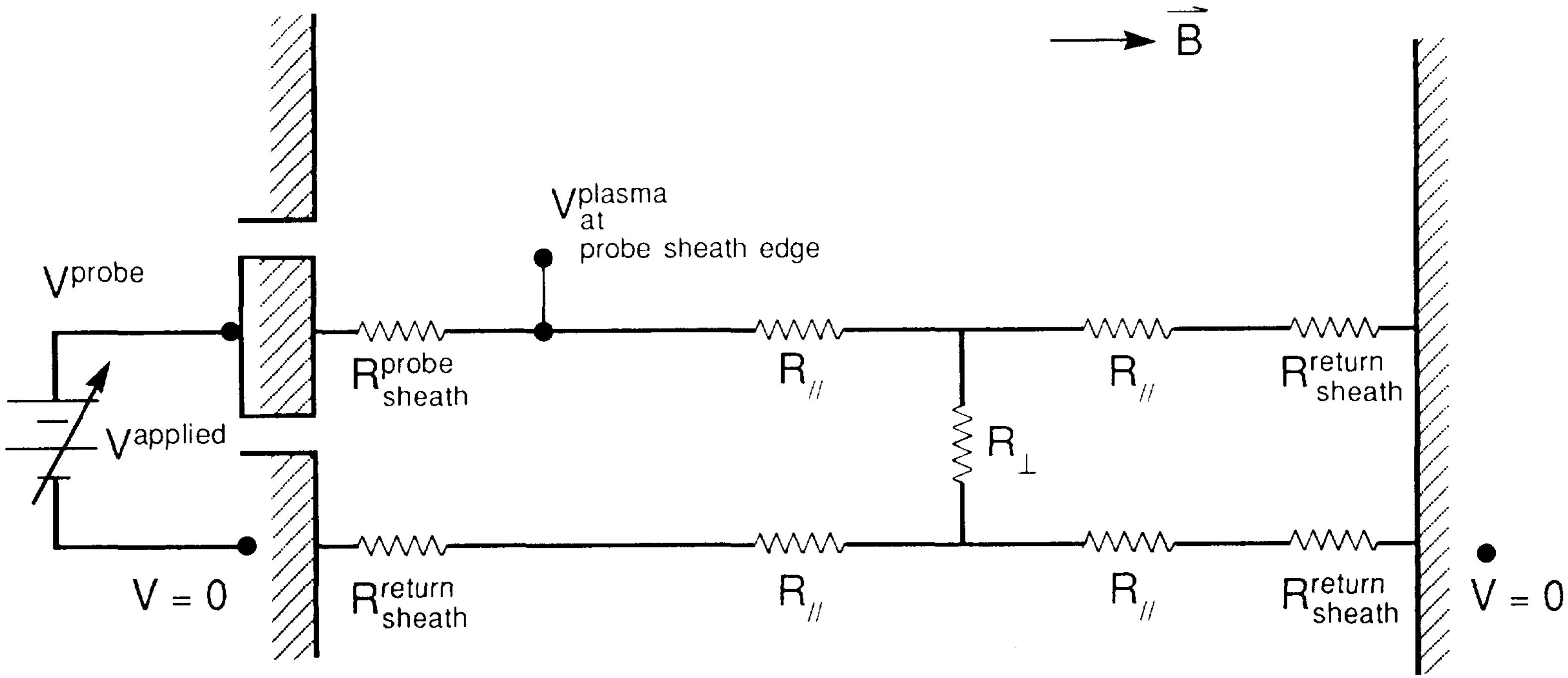


*Fig.3: Schematic of the plasma and sheath resistances in the circuit for a single Langmuir probe. See text.*

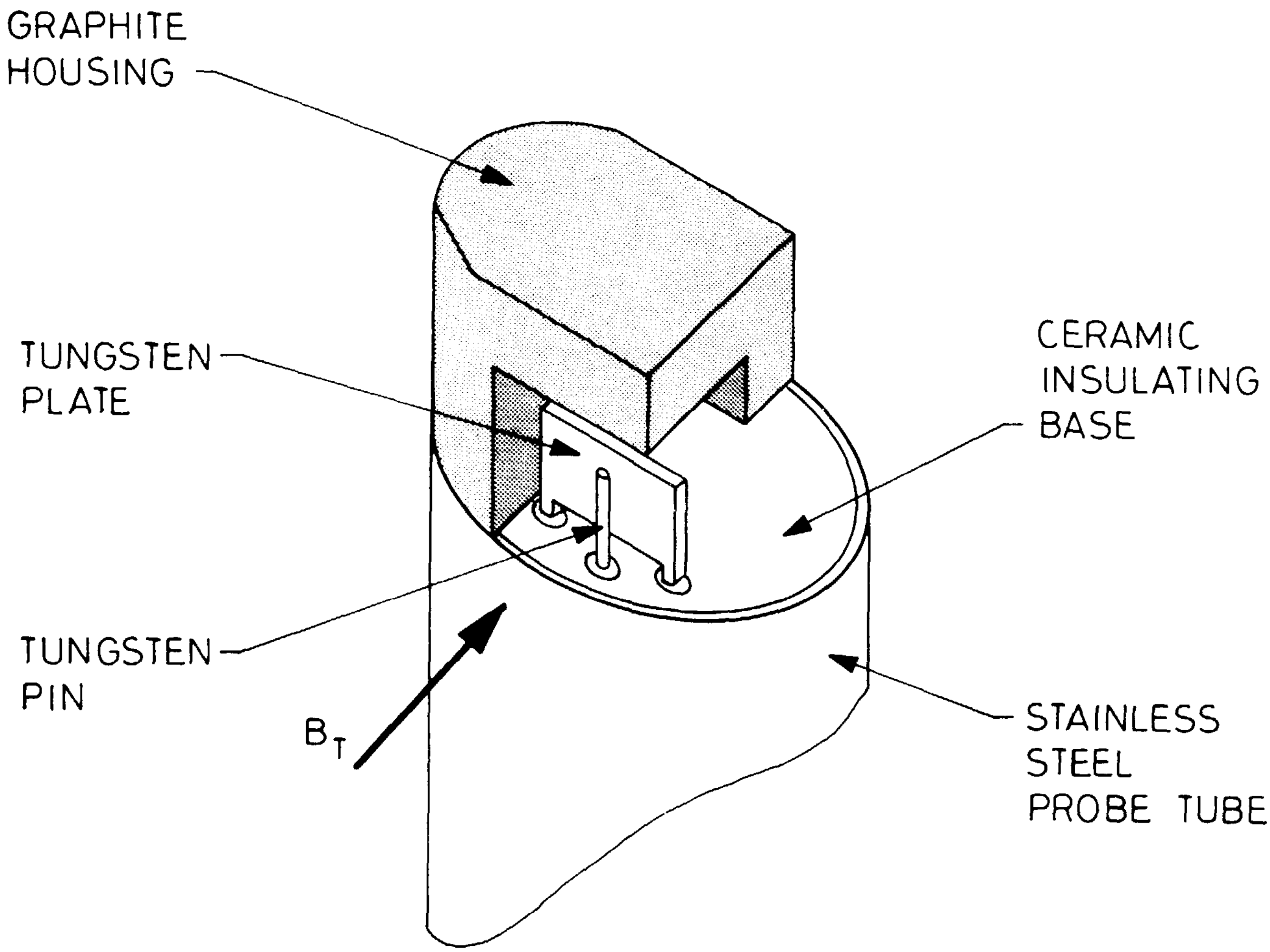


*Fig.4: Cutaway isometric of the Pin-Plate Probe head [20].*

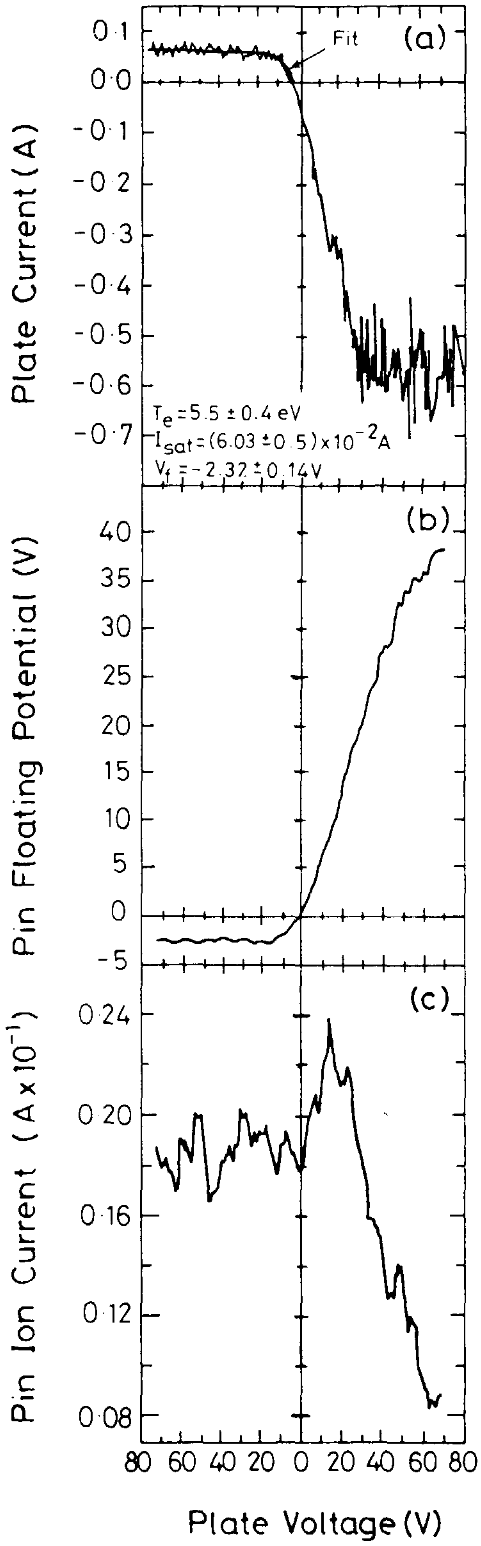


*Fig.5a: For the Pin-Plate Probe operated in the DITE tokamak [20]. The plot of $I^{plate}$ vs. $V^{plate}$.*

*Fig.5b: As Fig. 5a, but $V^{pin}_{floating}$ vs. $V^{plate}$.*

*Fig.5c: As Fig. 5a, but $I^{pin}_{sat+}$ vs. $V^{plate}$ (results in Figs. 5b and 5c taken in separate, but similar, discharges).*

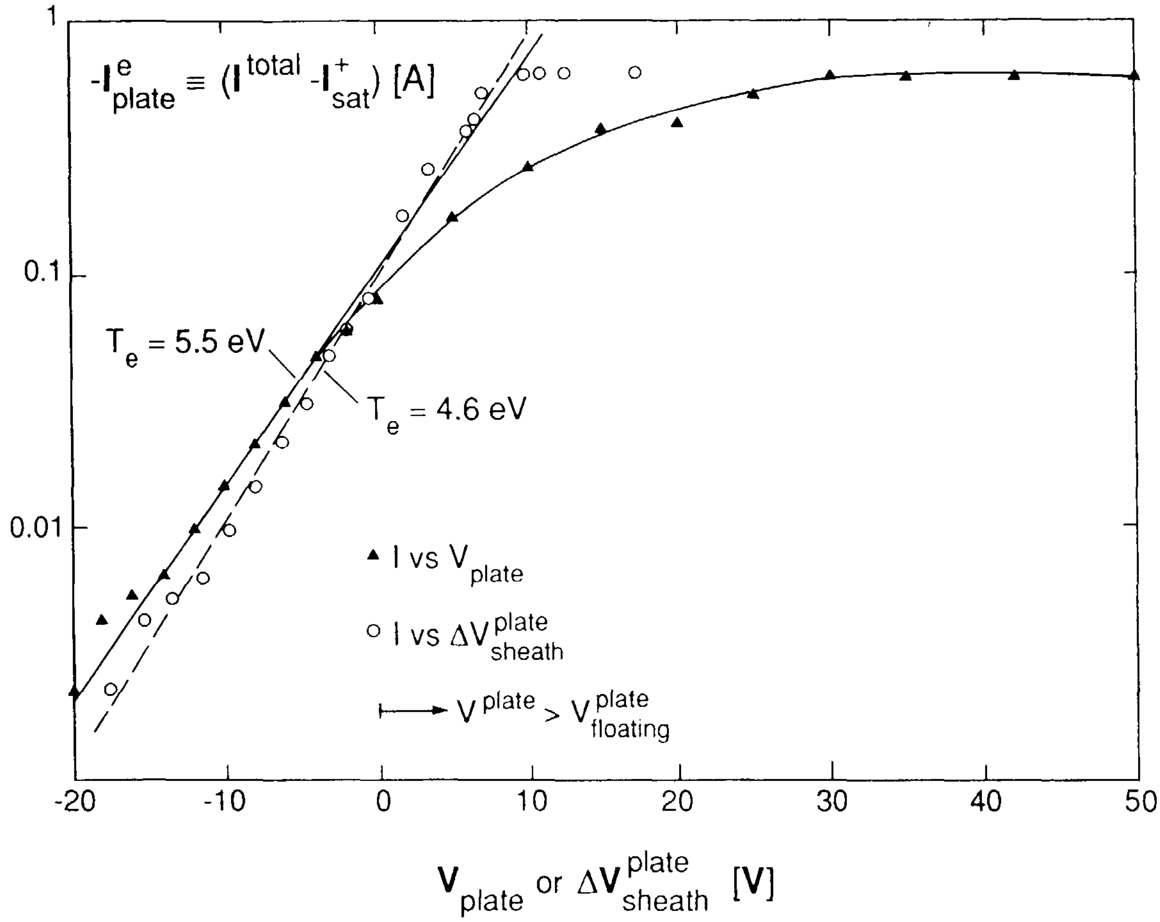


*Fig.6: The data from Figs. 5a and 5b were combined to give the values of the potential drop across the plate sheath, $\Delta V_s^p = V^{plate} - V_{fl}^{pin}$. The plot of $I^{plate}$ vs. $V^{plate}$ for $V > V_{fl}^{plate}$ does not give a well-defined electron temperature but the plot of $I^{plate}$ vs. $\Delta V_s^p$ does give a well-defined value of $T_e$ = 4.6 eV, which is close to the value obtained using only data for $V^{plate} < V_{fl}^{plate}$, namely 5.5 eV. Note also, that the plot vs. $\Delta V_s^p$ reveals that the electron distribution is well described, in this example, by a Maxwellian over almost the entire velocity range.*