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A Problem in the Interpretation of Tokamak Langmuir Probes when a Fast Electron Component is present

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ABSTRACT

In the edge plasma of magnetically confined devices such as tokamaks, the electron distribution is not necessarily Maxwellian, and may consist of a small number of electrons characterized by a hot temperature, T_{eh}, with the bulk of the electrons at a colder temperature, T_{ec}. In a strong magnetic field, there is no satisfactory theory for interpreting the IV characteristic above floating potential, and so usually only the high energy electrons in the distribution are used to deduce T_e. It is shown, that the value of T_e extracted from the Langmuir Probe characteristic in this way yields T_{eh}, unless the hot component is extremely small. Langmuir Probes therefore tend to overestimate T_e in magnetically confined devices. This effect may also be relevant to observations of (apparently) very low sheath heat transmission coefficients in tokamaks.

INTRODUCTION

Langmuir Probes are widely used to measure edge plasma conditions in tokamaks and other magnetic confinement devices [1-4]. In non-magnetic plasmas [5, 6] the entire probe characteristic between electron saturation current and ion saturation current collection can be used to measure T_e, and if the electron distribution is non-Maxwellian, the entire distribution can be obtained, in principle. In a magnetic plasma, the interpretation of the characteristic above floating potential, i.e., for net electron collection, remains problematical and often the practice is to use only the characteristic below floating potential [7, 8]. In this method only the high energy tail of the electron distribution is sampled and thus if the distribution is not that of a single Maxwellian, but is for example a 2-temperature one, then under certain circumstances, the cold component will be virtually unregistered, and its presence can be undetected by the probe. The conditions for this to occur are examined here, as well as some of the consequences. Methods of dealing with the problem are also considered.

The tokamak edge plasma under some circumstances may be characterized by an electron distribution, approximated as a 2-temperature one with a hot minority population, due to various causes, e.g., auxiliary heating methods used in the core plasma can create hot minority electrons in the edge. Transport conditions near the separatrix may cause the loss of some energetic electrons to the scrape-off layer, SOL. In a divertor tokamak, the classical conduction of electron heat along the SOL can result in a non-Maxwellian distribution of electrons near the target plate, even if the electron distribution near the periphery of the confined plasma is Maxwellian [9, 10]; unless the e-e mean free path is extremely short, the faster electrons at the mid-plane can reach the divertor collisionlessly, while the slower electrons in the distribution experience collisions and the drop in temperature along $\vec{B}$ associated with conductive heat transport.

A possible indication that fast electrons are present is a spatially localized drop in the probe floating potential sometimes recorded by Langmuir Probes located at or near a divertor plate, near the separatrix typically [11]. A sufficiently large population of hot electrons on a particular magnetic flux tube would increase the sheath voltage drop, i.e., the potential drop between the plasma in the flux tube and the floating probe. Provided the plasma potential itself was not greatly different between adjacent flux tubes, then such a localized population of fast electrons would manifest itself as a local negative dip in floating probe potential. There is generally no basis for the assumption that the plasma potential is constant from flux tube to flux tube, however, and so such an observation is not a guarantee of the presence of fast electrons. A separate measure of the local plasma potential would be valuable in this regard, but is not available from a Langmuir Probe characteristic when the analysis is limited to voltages below floating. Nor does the *absence* of a local negative dip in probe floating potential guarantee the *absence* of fast electrons since they may be present on all the flux tubes.

There is some experimental incidence that, at least under some circumstances, Langmuir Probes *do* yield a value of T_e which is not representative of the average electron energy, but a higher value. In ASDEX, a comparison has been made of T_e measured by a Langmuir Probe and by laser Thompson scattering, near the target plate [12]. In conditions of ohmic heating, the Langmuir Probe gave values of T_e about twice as high as the Thompson scattering. With neutral beam heating, and H-mode conditions, the Thompson scattering showed a non-Maxwellian distribution of electrons with a suprathermal component, $\lesssim$35eV, and with most of the electrons in the 1.5 - 4 eV range.

We thus consider the question of when the shape of the probe characteristic below floating potential gives the fast electron temperature, T_{ef}, the slow one, T_{es}, or some intermediate value. (Of course, the actual distribution may be more complicated than a two-Maxwellian one; here, however, we will assume the latter for purposes of simplicity.)

MODELLING

The analysis is based on that of an earlier, closely related paper [13]. For conditions of net electron collection, the net electron current to the probe is:

$$\begin{aligned} I_{net}^- &= (1-\sigma_s)\frac{1}{4} n_{eso}\, \bar{c}_{es} \exp(\psi) \\ &+ (1-\sigma_f)\frac{1}{4} n_{efo}\, \bar{c}_{ef} \exp(\psi/f_T) \end{aligned} \tag{1}$$

where $\sigma_{s,f}$ = secondary electron emission coefficients for the slow (fast) electrons; $\bar{c}_{es}$, $\bar{c}_{ef}$= $(8 kT_{es,ef}/\pi m_e)^{1/2}$; $\psi = eV/kT_{es}$; Z = 1 ions are assumed; $f_T \equiv T_{ef}/T_{es}$; $f_n \equiv n_{efo}/n_{eso}, f_i \equiv T_i/T_{es}$. The ion current is the saturation value:

$$I_{sat}^+ = \frac{1}{2} n_{io}\, c_s \tag{2}$$

where $n_{eso} + n_{efo} = n_{io}$ and the sound speed is:

$$c_s = [k(T_i + fT_{es})/m_i]^{1/2} \tag{3}$$

where $$f \approx f_T(1 + f_n)/(f_n + f_T) \tag{4}$$

Note that for cases of interest $f_n << 1$, $f_T >> 1$, $f \approx 1$ and the sound speed is dominated by the slow electrons. See [13] for further details. (Strictly, a value of f_n defined at the sheath edge, rather than at infinity, should be used in Eq. (4), but this has little effect on the conclusion that $f \approx 1$ at the sheath edge.)

From the foregoing equations one can construct the Langmuir Probe characteristic , that is, I vs. V, where $I = I_{sat}^{+} - I_{net}^{-}$. It is useful first to obtain the probe floating potential, V_{fl}, thus ψ_{fl}, i.e., the potential at which I = 0. This is given by the solution of:

$$\begin{aligned}(1-\sigma_s)\exp(\psi_{fl}) + (1-\sigma_f)f_T^{1/2}f_n\exp(\psi_{fl}/f_T) \\ = (1+f_i)^{1/2}\left(\frac{\pi m_e}{2m_i}\right)^{1/2}(1+f_n)\end{aligned} \tag{5}$$

Results for ψ_{fl} are given in Fig.1. Examples of I-V characteristics are given in Figs.2a, 2b, 2c, where I has been normalized by I_{sat}^{+} and the (normalized) floating potential has been subtracted from ψ. From an examination of Fig.2 it is evident that even relatively small fractions of fast electrons can totally dominate the probe characteristic (at least below floating potential, the only region considered). For example, for the case $(T_{ef}/T_{es}, T_i/T_{es}, \sigma_s, \sigma_f) = (10, 1, 0, 0)$ the presence of just 2% fast electrons by density would give a probe characteristic which could not, in practice, be distinguished from the characteristic which would result if 100% of the electrons were fast. Analysis of either characteristic would give $\approx T_{ef}$. As can also be seen from Fig.2, for a sufficiently small value of f_n the characteristic will be governed by the slow electrons and an analysis of the characteristic will yield the value of $\approx T_{es}$. For intermediate values of f_n, intermediate temperatures will be extracted from an analysis of the characteristic.

As to the effect of secondary electron emission: for sufficiently oblique angles between $\vec{B}$ and a surface, the emission is suppressed by recapture of the electron during its first Larmor orbit. Otherwise, for the example shown in Figs.2b, c, the value of $f_n \approx 2\%$, at which the fast component would dominate the inferred value of T_e, would change by a factor $(1 - \sigma_s)/(1 - \sigma_f)$, approximately.

It is useful to evaluate these two values of f_n: f_n^f, such that for $f_n \gtrsim f_n^f$, the characteristic will give $\approx T_{ef}$, f_n^s, such that for $f_n \gtrsim f_n^s$, the characteristic will give $\approx T_{es}$. These two values of f_n can be estimated as follows: if at floating potential the slow electron flux to the probe is less than a small fraction, taken here to be 1/5, of the fast flux, then the slow electron flux can be neglected for the entire characteristic below floating potential, and this gives f_n^f. One thus needs to solve Eq. (5) in conjunction with

$$(1-\sigma_s)\exp(\psi_{fl}) = \frac{1}{5}(1-\sigma_f)f_T{}^{1/2}f_n^f\exp(\psi_{fl}/f_T) \tag{6}$$

in order to eliminate ψ_{fl} and to obtain $f_n^f(f_T, f_i, \sigma_s, \sigma_f)$. A similar procedure with a factor 5 in place of 1/5 in Eq. (6) gives f_n^s. This elimination can be done graphically: in Fig.3, examples are given of ψ_{fl} from Eq. (6) for the fast assumption (factor 1/5 in Eq. (6)) and slow assumption (factor 5 in Eq. (6)) shown as dashed lines;where these interact the ψ_{fl}-line, one finds f_n^f, f_n^s, as indicated. For example, for $(T_{ef}/T_{es}, \sigma_s, \sigma_f) = (10^2, 0, 0)$ one finds f_n^f = 0.002, $f_n^s \approx 0.0007$, i.e., if $n_{ef}/n_{es} \gtrsim 0.002$ then analysis of the Langmuir characteristic will yield T_{ef}, while if $n_{ef}/n_{es} \lesssim 0.0007$, then the characteristic will yield T_{es}. Clearly, even a small component of fast electrons can dominate the Langmuir Probe characteristic — when only the part above floating potential is used to obtain T_e.

DISCUSSION

Except in highly collisional regimes, there is the possibility for non-Maxwellian electron distributions to arise, in which case the analysis of Langmuir Probe characteristics, using only the part above floating potential will yield only the characteristic energy, "temperature", of the high yield energy tail — which may be of extremely small number density relative to the total electron density.

In the "high recycling" regime of a divertor tokamak, large temperature gradients can develop between the upstream end, adjacent to the core plasma, and the target region [9], perhaps $T_e \sim 100$ eV at the upper end, ~5 eV at the target. The λ_{ee} collision length for the average electrons in the distribution is $\approx 10^{16} (T_e\,[eV])^2/n_e\,[m^{-3}]$, so if connection length $L_{||}$ = 50 m, say, then the average electrons at T_e = 100 eV will be collisional if $n_e > 2\times10^{18}$ m^{-3}, which is usually satisfied at the upper end. Unfortunately, the electrons in the high energy tail of the distribution are much less collisional — and they carry most of the heat; the heat flux is carried mainly by electrons with $v_{hot} \approx (3\text{-}5)\ \bar{v}_e$ [10]. The $\lambda_{ee}^{hot} \approx (v_{hot}/\bar{v}_e)^4 \lambda_{ee}$ and so, in order for these electrons to be collisional, one requires $n_e \gtrsim 5\times10^{20}$ m^{-3}, which is generally not satisfied at the upper end (although near the divertor λ_{ee} becomes much shorter, due to lower temperatures and higher densities). It is thus possible that the electron distribution at the target plate of a high recycling divertor will be substantially non-Maxwellian, with a small number of very fast electrons dominating (a) the heat flux, (b) the total potential drop across the sheath (thus the sputtering rate) — and (c) the Langmuir Probe characteristics above the floating potential.

This Langmuir Probe effect, of overestimating T_e, offers a possible explanation for the very low values for the sheath heat transmission coefficient γ reported on DIII-D [14] for some operating situations. The value of γ can be measured using:

$$\gamma = \frac{P}{kT_e\Gamma} \tag{7}$$

where P = power flux density onto the target

Γ = particle flux density onto the target

T_e = electron temperature at the target

On DIII-D each of the latter 3 quantities was measured: P from infra-red thermography, T_e and Γ from Langmuir Probes built into the target (Γ from I^+_{sat}). Sheath theory predicts values of $\gamma \approx 7$, for $T_e = T_i$, reducing to $\gamma \approx 5$ for $T_i << T_e$. Some of the DIII-D measured values were as low as ~2, however, which cannot be explained on the basis of conventional sheath theory. An attempt was made to explain and model the low values of γ on the basis of neutral collisions [14]. A recent and more quantitative re-working of this modelling approach [15] showed that the effect of neutral collisions is small.

An alternative explanation of measured low values of γ would be that suprathermal electrons are present as a high enough fraction of the total number to dominate the Langmuir Probe characteristic, but are not abundant enough to control the heat flux. The total heat flux (due to ions, fast electrons and slow electrons) is given in Fig. 4 of Ref. [13]. For example, for $T_{ef}/T_{es} = 10$, $n_{ef}/n_{es} = 10^{-2}$ one has $P \approx 21\ kT_{es}\ I_s^+ \approx 2.1\ kT_{ef}\ I_s^+$. For these parameters the Langmuir Probe characteristic will yield $\approx T_{ef}$. Thus one would conclude that $\gamma = 2.1$ from experimental measurements. For any larger values of n_{ef}/n_{es}, the fast electrons will still control the Langmuir Probe value of T_e, of course, but these fast electrons will also start to contribute significantly to P, which will raise γ as shown:

n_{ef}/n_{es}	γ
1	6.0
0.1	4.5
0.01	2.1

What can be done to confirm when the value of T_e given by a Langmuir Probe (which uses only data above the floating point) is representative of the majority of the electrons being sampled, and not just an unrepresentative high energy component? It may be possible to design a special kind of Langmuir probe — using a small collection element located immediately in front of a larger collecting element — to permit the use of the part of the characteristic (of the larger element) above floating to deduce T_e [16], however for a conventional single probe there is no evident solution to this problem.

Fortunately, the use of impurity spectroscopy in tokamak edge plasmas is a rapidly growing field, and this provides opportunities for confirming T_e-values measured by probes. Consider, as a simple example, the penetration of lithium neutrals into the plasma; lithium at velocity, 2000 m/s, $n_e = 10^{20}$ m^{-3} and 3 examples of electron distribution: (a) Maxwellian, T_e = 10 eV, (b) 2% of electrons with T_e = 10 eV, 98% at 2 eV, (c) Maxwellian, T_e = 2 eV. The penetration distance for the 3 cases: (a) 0.3 mm, (b) 3.4 mm, (c) 4.4 mm. Such differences should be observable. While a lithium source would require dedicated hardware, the naturally occurring impurities are also sensitive to the local values of T_e (also n_e) and the spatial distribution of the successive charge states can be interpreted, using codes such as DIVIMP [17], to yield T_e (with n_e given, say, by probes).

One can also use dedicated and separate diagnostic techniques such as laser Thompson scattering, which is now finding greater application in edge measurements on tokamaks. If one requires continual checking that all the probes are giving the bulk T_e, then it is clearly impractical — also pointless — to have Thompson scattering and probe measurements at all locations. If only infrequent checking is required, on the other hand, then this approach could be feasible, and would exploit the cost and simplicity advantages of built-in edge probes.

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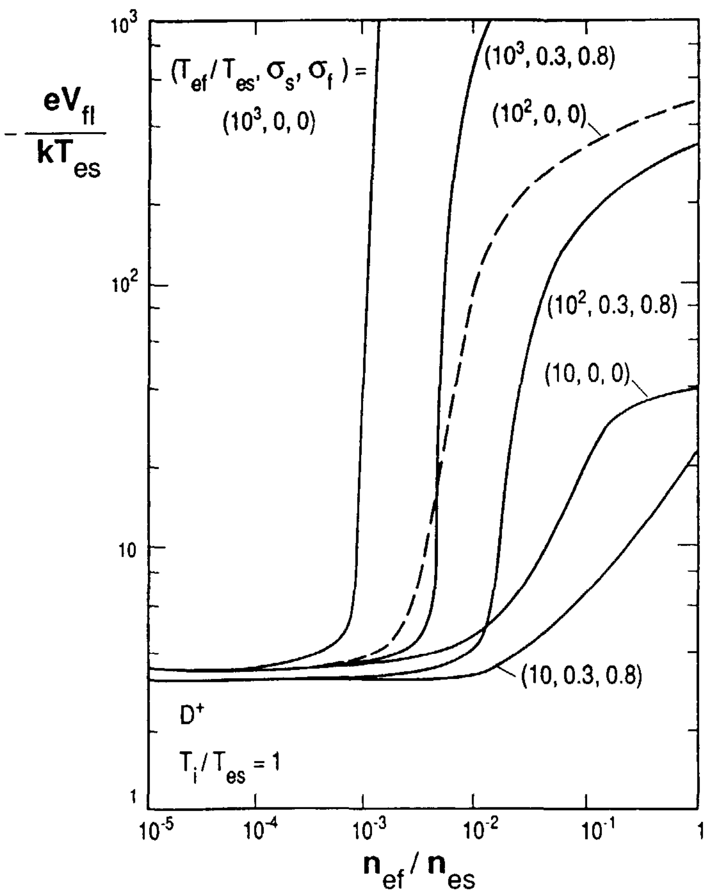

Fig.1: Examples of the probe floating potential, normalized to the slow electron temperature, T_{es}, as a function of the density ratio of fast/slow electrons, n_{ef}/n_{es}. D^+ ions. $T_i/T_{es} = 1$. Various values of fast/slow electron temperature T_{ef}/T_{es}, and for secondary electron emission coefficients for fast (slow) electron impact $\sigma_f(\sigma_s)$. From Ref. [13].

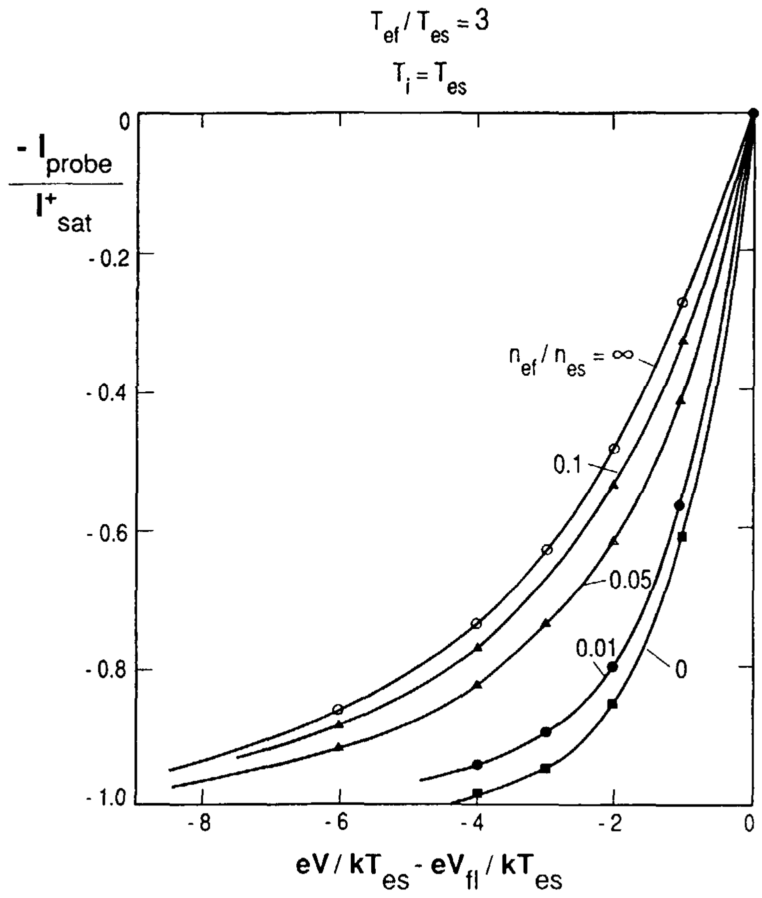

Fig.2a: The probe current density, normalized to the ion saturation current, below floating potential V_{fl} as a function of the probe potential V. Various values of the density of fast/flow electrons, n_{ef}/n_{es}. The case of D^+ ions, $T_{ef}/T_{es} = 3$, $T_i = T_{es}$, $\sigma_f = \sigma_s = 0$.

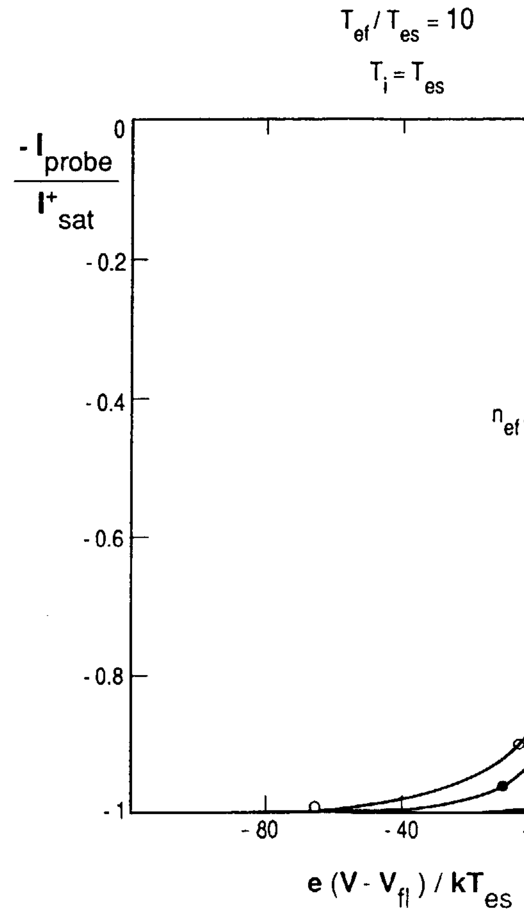

Fig.2b: As Fig.2a but T_{ef}/T_{es} = 10.

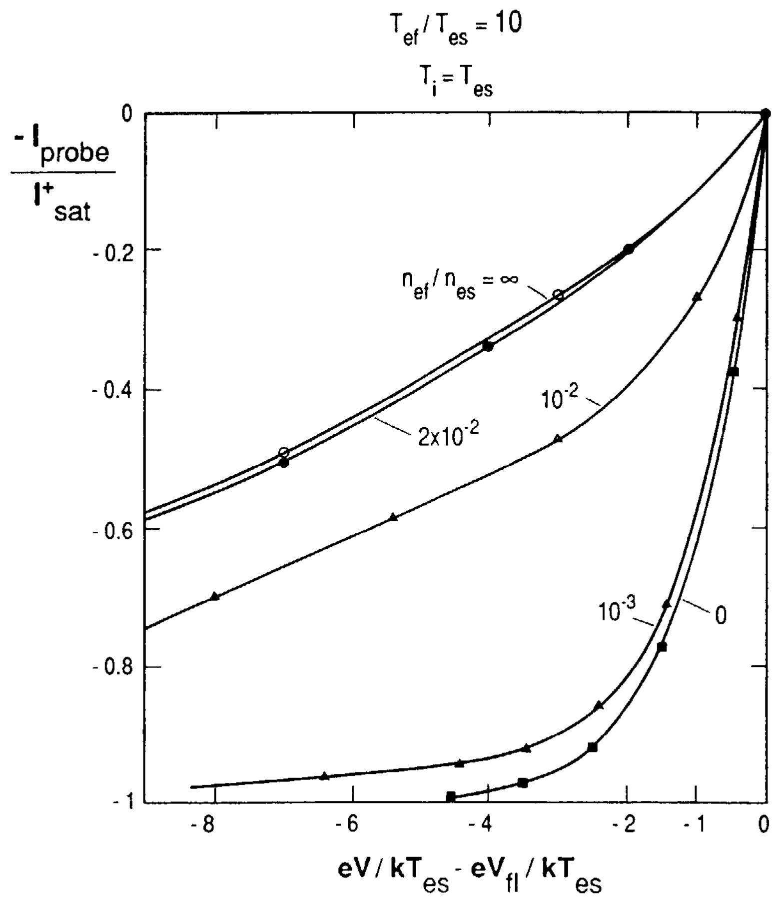

Fig.2c: As Fig.2b, expanded view near the floating potential.

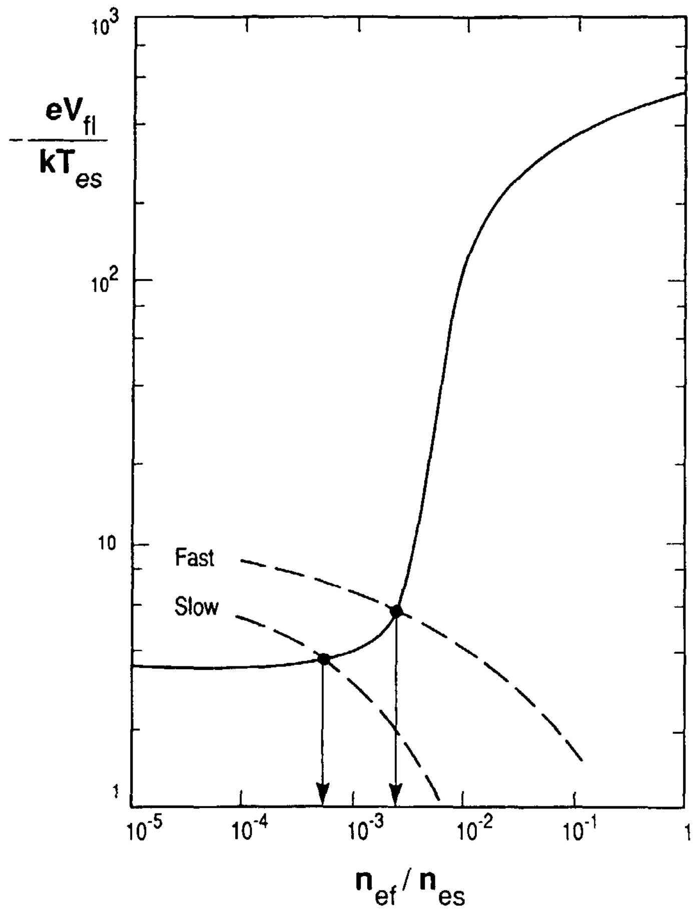

Fig.3: Graphical method of finding the values of n_{ef}/n_{es} above (below) which an analysis of the probe characteristic (using only data above floating potential) will yield an electron temperature value of $\approx T_{ef}$ ($\approx T_{es}$). For the case of D^+ ions, $T_i/T_s=1$, $T_{ef}/T_{es}=100$, $\sigma_f = \sigma_s = 0$. For intermediate values, $7\times10^{-4} \lesssim n_{ef}/n_{es} \lesssim 2\times10^{-3}$, the characteristic will not appear to be Maxwellian (above floating potential).