The adverse effect of perpendicular ion drift flow on cylindrical triple probe electron temperature measurements

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The cylindrical triple probe method is an attractive technique for measuring electron temperatures ($T_e$) and electron number densities ($n_e$) in a variety of plasmas sources. In practice, however, the cylindrical triple probe can be sensitive to sources of error that affect all Langmuir probe techniques. In particular, the presence of an ion drift velocity component that is perpendicular to the probe axis has been known to result in erroneous measurements of $n_e$. Less obvious, however, is that ion flow perpendicular to the probe has a significant effect on the indicated $T_e$. The purpose of this note is to make researchers aware of such an effect and to demonstrate a technique which can mitigate it. The approach taken to investigate this phenomenon was to make $T_e$ measurements in the plume of a 20 kW magnetoplasmadynamic thruster with the probe oriented at several angles with respect to the local ion flow.

I. INTRODUCTION

The triple probe method of Chen and Sekiguchi1 is a convenient and accurate technique for measuring the electron temperature ($T_e$) and number density ($n_e$) of a plasma. A triple probe, shown schematically in Fig. 1, consists of three separate electrodes that are electrically configured to eliminate the need for a voltage sweep. This allows for the instantaneous measurements of both $T_e$ and $n_e$ by measuring the voltage between the floating electrode and electrode 1 of Fig. 1 ($V_{d1}$) and the probe current, $I$. This measurement capability can be exploited with a probe positioning mechanism to obtain $T_e$ and $n_e$ profiles by sweeping the probe through the plasma.

The ion saturation current is independent of potential when the applied voltage, $V_{d2}$, is such that $\exp(eV_{d2}/kT_e)>1$, the area of the electrodes are equal, and the electrons are Maxwellian. Under these conditions, the following expression for $T_e$ can be derived:1

$$\frac{kT_e}{e} = \frac{V_{d2}}{\ln 2} \tag{1}$$

where $k$ is the Boltzmann constant and $e$ is the elementary charge. The electron number density can be calculated from the measured electron temperature and the triple probe current, which is equal to the ion saturation current of electrode 3. Since no voltage sweep between electrodes is necessary, with a fixed voltage between electrodes 1 and 3 ($V_{d3}$), $T_e$($t$) can be obtained from $V_{d2}$($t$) with Eq. (1), and $n_e$($t$) from $T_e$ and $I(t)$ using an appropriate ion saturation current model. Note that the instantaneous floating and plasma potential can also be measured with the triple probe.2

When the ion saturation current is a function of the electrode potential, the determination of $T_e$ depends on many more parameters, such as the ion–ion collision frequency, electron gyroradius, and the ion flow velocity perpendicular to the triple probe electrodes. It was the purpose of this work to investigate the influence of perpendicular ion flow on cylindrical triple probe measurements of $T_e$.

II. EXPERIMENTAL APPARATUS

The plasma source for this experiment was a 20 kW steady-state magnetoplasmadynamic (MPD) thruster that used argon as the propellant. The thruster (cf. Fig. 2) has a 2% thoriated tungsten cathode (0.64 cm o.d.) and a flared radiation cooled anode made of graphite with an outer diameter of 10 cm and an inner diameter of 3.5 cm at the exit plane. The thruster was operating typically at discharge currents between 500 and 800 A, at mass flow rates between 6 and 12 mg/s, and with terminal voltages between 15 and 25 V. The thruster was operated in a 6.4-m-long by 1.5-m-diam vacuum tank that is pumped by a 1.2-m-diam oil diffusion pump backed by a Roots blower. Tank pressure was maintained to less than $2 \times 10^{-4}$ Torr during thruster operation.

Probe positioning was achieved by attaching the triple probe to the end of a pendulum arm that was swept through the plume of the MPD thruster. The stepper motor used to rotate the arm has its axis located 34 cm radially from the thruster axis (cf. Fig. 2) and swept the arm through the plume at a rate of 21 cm/s azimuthally. To study the effect of plasma flow, a small servomotor was used to vary the angle between the probe axis and the thruster axis (cf. Fig. 2). As is shown in the figure, the probe support was configured in a U shape such that the axis of probe rotation is located at the midpoint of the
three electrodes. The first 90° bend in the 3-mm-diam alu-
mina tubing probe support is located 3 cm downstream
of the axis of rotation.

The triple probe consisted of three tungsten wires con-
figured in a three-in-line fashion within a plane parallel
to the pendulum arm axis. The probe dimensions were
chosen as a compromise between negligible end effects and sheath
interactions, and good spatial resolution [spacing = 1 mm, probe
radius ($r_p$) = 0.12 mm, and electrode length ($L$)
= 5 mm]. A Kepco 100 V, 1 A power supply was used to
supply $V_{d3}$, and two Tektronix AM501 operational amplifiers
were used to measure $V_{d2}$ and the voltage from the shunt (a 50 Ω thin film resistor). In all experiments, $V_{d3}$
was set to 14 V. Probe data was collected by a Nicolet 320
digital oscilloscope and transferred to a personal computer
for processing. Since contamination of the probe electrode
surface is known to seriously affect triple probe measure-
ments,3 the triple probe used in this study was cleaned via ion bombardment for a few minutes before
each test run by flooding the vacuum chamber with argon
and maintaining a glow discharge between the probe elec-
trodes and the thruster anode. More details associated with
the experimental apparatus can be found in Refs. 3 and 4.

![FIG. 1. Schematic of the triple probe.](image)

![FIG. 2. Thruster and servomotor configuration.](image)

**III. RESULTS AND DISCUSSION**

It is well documented that supersonic ion flow perpen-
dicular to a cylindrical probe increases the ion current
significantly.5–7 This is because ions are not only collected
by diffusion but also from convection due to the ion drift
velocity. Typical ion flow velocities, $U_i$, in MPD thruster
plumes correspond to speed ratios, $\mathcal{S}_r (U_i / \sqrt{2kT/M_i})$, be-
tween 1 and 10.8,9 Thus, for these experiments the indi-
cated electron number density was observed to be strongly
dependent on ion flow conditions (direction and magni-
tude), as expected.3 Less obvious, however, is the fact that
ion flow perpendicular to the probe artificially increases
the indicated electron temperature. In theory, even if more
ions are collected at each electrode due to ion drift, if the
ion collection process is independent of potential, an
assumption made in the derivation of Eq. (1), this effect
should cancel out in the determination of the electron
temperature. However, as is seen in Fig. 3, this is not the case.
Plotted is $V_{d2}$ taken 2.9 cm downstream of the thruster exit
plane [cf. Eq. (1)] versus radius from the thruster center
line with the probe axis at angles of 0°, 30°, 60°, and 90°
with respect to the thruster axis of symmetry. As the figure
shows, the orientation of the probe with respect to the ion
flow vector has a significant impact on the indicated elec-
tron temperature.

In self-field MPD thrusters, the ion flow velocity can
be estimated to reasonable accuracy (~50%) by the fol-
lowing equation:10

$$U_i = \frac{\mu I_i}{4\pi m_i} \left[ \ln \left( \frac{r_a}{r_c} \right) + \frac{1}{2} \right],$$

(2)

where $\mu$ is the permeability of free space, $I_i$ is the thruster
current, $m_i$ is the propellant mass flow rate, and $r_a$ and $r_c$
are the anode and cathode radii, respectively. Using this
equation, assuming $T_e \approx T_i$, which is appropriate for MPD
thruster plumes, the value of the perpendicular component
of the speed ratio, $\mathcal{S}_r (\approx U_i / \sqrt{2kT/M_i})$, is approxi-
mately $\sim 2 \sin \theta$, where $\theta$ is the angle between the probe
axis and the local flow vector.

![FIG. 3. Output of the triple probe at various angles with respect to the thruster axis ($V_{d2}$). The probe swept through a plane that was 2.9 cm
downstream of the thruster exit plane ($J_i=450$ A, $\dot{n}_e=8$ mg/s).](image)
In regions of the plume where the triple probe is aligned with the local ion flow vector, it may be possible to use Laframboise's exact calculations of the ion saturation current to a cylindrical electrode\(^1\) to determine \(T_e\) and \(n_e\) if certain conditions exist in the plasma. Typical ratios involving the electron Debye length \((\lambda_D)\), ion–ion mean free path \((\lambda_{ii})\), electron–ion mean free path \((\lambda_{ei})\), ion gyroradius \((r_{Li})\), electron gyroradius \((r_{Le})\), and electron drift velocity \((V_e)\) are \(r_{Li}/\lambda_{ii} > 10, \lambda_{ei}/r_{Le} > 300, \lambda_{ei}/r_{Li} > 200, r_{Le}/r_{Li} > 10^4, r_{Le}/r_{Li} > 50,\) and \(U_e/V_e < 1\), where \(V_ax\) is the electron thermal velocity—indicate that Laframboise’s model is applicable. Note that the Larmor radii and electron drift velocities were derived from magnetic field measurements made throughout the plume.\(^4\)

In addition to validating the applicability of Laframboise’s model, the values of the ratios above suggest that the effects of collisions, magnetic fields, electron drift velocity perpendicular to the probe, sheath interactions, and end effects on the triple probe measurements of Fig. 3 are negligible. Plasma stagnation near the electrodes is expected to be insignificant since the support structure diameter is about one-tenth the size of the local mean free path. Finally, gradient length scales for variations in \(T_e, n_e\), and plasma potential are all sufficiently large as to eliminate gradient effects as a cause for the behavior shown in Fig. 3. Therefore, by the process of elimination, the cause of the effect seen in Fig. 3 is due to ion flow perpendicular to the triple probe axis.

Similar results were obtained in a study with a multimegawatt, quasisteady MPD thruster\(^2\) where plasma densities were two orders of magnitude larger than those in the 20 kW device at similar exhaust velocities.\(^3\) In fact, measurements in the high power MPD thruster suggest that the triple probe is even more sensitive to flow angle at higher number densities \((r_{Li}/\lambda_{ei} > 100)\).

To interpret this behavior, the results of Godard and Laframboise (see Fig. 5 of Ref. 7) can be used. These results are considered approximate because of their symmetric sheath assumption, and are expected to be accurate for the following conditions: \(r_{Li}/\lambda_{ei} < 1\), or \((S_{Li})^{1/3} \chi > 1\), or \((S_{Le})^{1/3} \chi < 1\) where \(\chi\) is defined as the dimensionless probe potential \((eV/kT_e)\). Although none of these conditions are satisfied in this study or in MPD thruster plumes in general, Godard and Laframboise’s calculations do explain qualitatively the results of Fig. 3. Godard and Laframboise show that as \(S_{Li}\) increases, the ion current becomes a stronger function of \(\chi\), which can lead to the measurement of artificially large electron temperatures.\(^12\) However, the amount of error in measuring \(T_e\) predicted by Godard and Laframboise from this effect appears to be significantly less than that seen in Fig. 3. The origin of this discrepancy may be the assumption of a symmetric sheath in their analysis and the fact that their study is not accurate for plasma conditions that were present in these experiments. This assumption also neglects wake effects which may alter the functional dependence of the ion saturation current on the electrode potential. This effect is expected to become more pronounced as the number density of the flowing plasma is increased, a trend that is observed in experiments with high power MPD thrusters.

Therefore, rigorous ion current calculations which account for asymmetric sheaths are needed to resolve this issue. Until such models are developed, however, the one method that currently exists to compensate for \(T_e\) and \(n_e\) measurement error due to perpendicular ion velocity components is to align the cylindrical triple probe with the ion flow vector.\(^6\) Accurate profiles of \(n_e\) and \(T_e\) can be obtained by successively sweeping the triple probe through the plume at different angles with respect to the thruster axis, selecting only data at each radial location from the angle corresponding to minimum probe current. Figures 4 and 5 show radial profiles of \(T_e\) and \(n_e\), respectively, obtained by this method. The probe was rotated to six different angles with respect to the thruster axis \((0°, 10°, 20°, 30°, 40°,\) and \(50°)\) on successive sweeps through the plume. The estimated uncertainty in these measurements is \(\approx 10\%\) for \(T_e\) and \(\approx 60\%\) for \(n_e\), both of which are due primarily to unknown \(T_i\). Note, this technique may also be used for obtaining flow angle information in the plume.\(^8\)

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