Fluctuation studies using combined Mach/triple probe

W. M. Solomon[a)] and M. G. Shats
Plasma Research Laboratory, Research School of Physical Sciences and Engineering, Australian National University, Canberra ACT 0200, Australia

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A probe consisting of two poloidally separated triple probes and a Mach probe (TMT probe) has been designed and installed on the H-1 heliac to study fluctuations. Mach probes are shown to be sensitive to the fluctuations in the electron density, electron and ion temperatures, and ion drift velocity. If the ion Larmor radius is much larger than the characteristic probe dimension, then the Mach probe is insensitive to the magnetic field. When the Mach probe is oriented such that the two tips are separated radially, it becomes sensitive to the radial velocity of the ions. A model has been devised to allow the above mentioned time-resolved plasma parameters to be reconstructed from the data obtained using the TMT probe. One of the important results of these studies is that ion temperature fluctuations cannot be neglected.
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I. INTRODUCTION

For finite ion temperature T_i, the ion saturation current measured by a single probe has a functional dependence on T_i, $I_s \sim n\sqrt{T_e+T_i}$. When analyzing ion saturation currents for fluctuation studies, it is usual to neglect fluctuations in the ion temperature $\tilde{T}_i$. Indeed the electron temperature $\tilde{T}_e$ is often neglected as well. In the H-1 heliac,[1] T_i is significantly higher than the T_e.[2] Given this, it is natural to expect that $\tilde{T}_i$ might contribute significantly to the measured saturation currents. An immediate consequence of this may be that both the amplitude and the phase of the density fluctuations $\tilde{n}$ are incorrectly inferred from I_s.

To assess the importance of temperature fluctuations, the two saturation currents of a Mach probe were analyzed. Mach (or paddle) probes are often used to provide information about plasma flow velocities. Mach probes are attractive from an experimental point of view because of their design simplicity.[3] A Mach probe typically consists of two identical collectors separated by an insulator. Both collectors are negatively biased into the ion saturation current. It is known that the ion saturation current is dependent on the velocity at which the ions stream towards the probe. Therefore, if the plasma drifts with some velocity perpendicular to the axis of the probe, then the two probe tips will collect ions arriving with different velocities and therefore measure different currents.

We take the time average of the two ion saturation currents, $\langle I_s^+\rangle$ and $\langle I_s^-\rangle$, where ''+'' and ''-'' refer to currents ''upstream'' and ''downstream,'' respectively, and refer to them as the ''dc'' currents. For any finite ion drift velocity, the ratio of these two dc currents, $R=\langle I_s^+\rangle/\langle I_s^-\rangle$ will be greater than one. This dc asymmetry is used to estimate the ion drift velocity in the plasma.

However, in addition to this asymmetry in the time-averaged ion saturation currents, an asymmetry in the fluctuating components of the ion saturation currents is also observed. The ratio of the root-mean-square (rms) values of the fluctuating components of the ion saturation currents is quite different to that of the average components. If $I_s^{\pm}=\overline{I_s^{\pm}}+\tilde{I}_s^{\pm}$, where $\overline{I_s^{\pm}}$ represents the dc currents and $\tilde{I}_s^{\pm}$ the fluctuating currents, then in general

$$\frac{\overline{I_s^+}}{\overline{I_s^-}} \neq \frac{\mathrm{rms}(\tilde{I}_s^+)}{\mathrm{rms}(\tilde{I}_s^-)}. \tag{1}$$

If fluctuations in I_s were due primarily to density fluctuations $\tilde{n}$ as is usually assumed, then the two ratios would be equal. Temperature fluctuations must be significant to allow this effect. We shall proceed with the understanding that all parameters (namely density n, electron and ion temperatures T_e and T_i, and drift velocity V_d) and their fluctuations all contribute to this effect. By adopting the approach that *all* fluctuations are significant, it is our goal to extract information about *all* the fluctuating components.

In Sec. II, a revision of the Bohm theory suitable for Mach probe saturation currents with finite T_i is presented. In Sec. III, the composite Mach-triple (TMT) probe is described and its application in unravelling the fluctuating components of the ion saturation currents is explored.

II. THE MODEL

In the case where the characteristic probe dimension r_p is less than the ion Larmor radius ρ_i, the Mach probe is referred to as ''unmagnetized.'' The use of unmagnetized Mach probe theory is justified experimentally as described in Refs. 2 and 4. The theoretical model proposed by Hudis and Lidsky[5] is the most widely used in unmagnetized plasmas. However, it is only applicable for the case $T_i<T_e$. This condition is not satisfied in H-1.[2] Laframboise[6] presented numerical solutions for this case; however, for later discussions we seek an analytic solution for the ion saturation currents of the Mach probe.

[a)]Electronic mail: Wayne.Solomon@anu.edu.au

We shall follow the derivation of the Bohm current, but allow for finite T_i. Consider ions at the edge of the sheath approaching the Mach probe in the one-dimensional case. A negative potential ϕ, extends outward from the center of the probe and vanishes at infinity. Ions arrive at the probe sheath with a velocity equal to that of the ion acoustic velocity, namely $c_s=\sqrt{q(T_e+T_i)/m_i}$, where temperatures are measured in electron volts, q is the ion charge and m_i the ion mass. Ions far from the probe have an initial velocity made up as the vector sum of their thermal velocity V_{ti}, and their drift velocity V_d. We are only interested in ions in this region whose net velocity is directed towards the probe, since these are the ones that will be accelerated through the presheath potential to the required sheath entrance velocity. If we assume that the axis of the Mach probe is oriented such that it is perpendicular to the drift velocity, then we can show that the average velocity of ions (that are travelling towards the probe) is

$$\langle (u_x^+)^2\rangle = V_d^2+V_{ti}^2+\frac{2V_{ri}V_d\sqrt{1-N^2}}{\pi-\arccos(N)},$$

$$\langle (u_x^-)^2\rangle = V_d^2+V_{ri}^2-\frac{2V_{ti}V_d\sqrt{1-N^2}}{\arccos(N)}, \tag{2}$$

where $N=V_d/V_{ti}$. For $N\leqslant 0.4$ we may approximate these equations by

$$\langle (u_x^\pm)^2\rangle = V_{ti}^2\pm\frac{4V_{ri}V_d}{\pi}. \tag{3}$$

We may now write an equation based on conservation of energy

$$\tfrac{1}{2}m\langle (u_x^\pm)^2\rangle = \tfrac{1}{2}mc_s^2+q\phi_s^\pm, \tag{4}$$

which will allow for the potential at the sheath edge to be determined. This can then be used to calculate the electron density, assuming it follows a simple Boltzmann relation, $n_s^\pm=n_\infty \exp(\phi_s^\pm/T_e)$, where n_∞ is the density far from the probe. Finally, the ion saturation currents can be calculated as

$$I_s^\pm = qAc_s n_s^\pm. \tag{5}$$

Using Eq. (5) we can readily determine an expression relating the ratio of the two ion saturation currents, $R=I_s^+/I_s^-$, to the drift velocity

$$V_d=\frac{\pi q T_e \ln(R)}{4mV_{ti}}. \tag{6}$$

Since the Mach probe is unmagnetized, we can orient the probe radially. That is, the tips of the Mach probe are oriented such that they are separated radially and are therefore subject to radial drifts. Since we are now dealing with radial velocities, we replace our nomenclature for the drift velocity V_d with V_r.

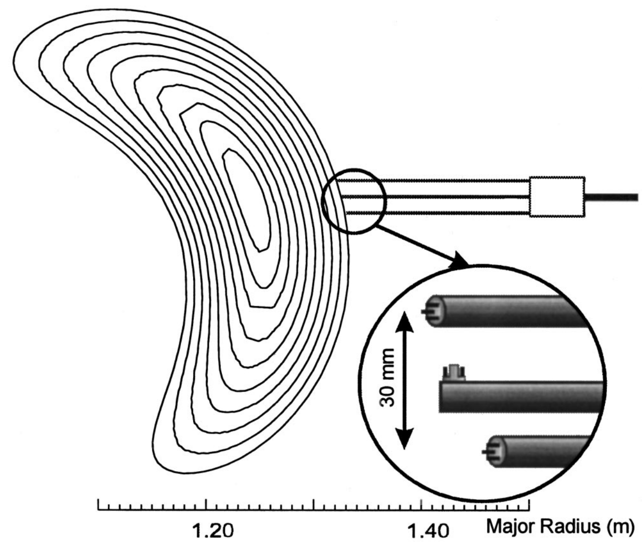

FIG. 1. Schematic of the TMT probe. The tips of all three probes lie on the same flux surface. The central probe (Mach) is aligned to be sensitive to the radial flow. The inset shows an enlarged view of the probe tips.

III. THE COMPOSITE MACH-TRIPLE PROBE FOR FLUCTUATION STUDIES

Equation (6) immediately highlights that although the Mach probe is sensitive to the four plasma parameters mentioned, namely n_e, T_e, T_i, and V_r, it cannot determine them all. To determine T_i, one should know T_e and V_r. Time-resolved electron temperature can be obtained using a triple probe.[7] The procedure of determining V_r is described below.

We use three poloidally separated probes: two triple probes, equally spaced on either side of the Mach probe, as per Fig. 1. The two collectors of the Mach probe are made of tungsten wire (0.7 mm diameter). They are 3 mm apart and are separated by a ceramic insulator in between as illustrated by the inset in Fig. 1. The probe tips are 1.5 mm long. The triple probes are similarly constructed from the same 0.7 mm diameter tungsten, exposed by 2 mm from the ceramic. The three probes are arranged with the Mach probe midway between the two triple probes. The tips of all three probes are positioned on the same flux surface. The poloidal separation of the two triple probes is $\Delta y = 30$ mm. Such poloidal separation ensures unambiguous determination of the phase shifts of the low mode number (and low wave number) fluctuations. We refer to this probe as triple–Mach–triple (TMT) later in this letter.

The flowchart in Fig. 2 shows the algorithm by which the time-resolved signals can be unravelled. The second row of boxes in the diagram represents the raw digitized signals from the TMT probe. The tips measuring saturation currents $I_{s\,\mathrm{(in)}}$ and $I_{s\,\mathrm{(out)}}$ are labeled with ''in'' and ''out'' to refer to their radial positions in the plasma. The third row shows the parameters readily inferred from the triple probes. The plasma potential ϕ_p is determined as $\phi_p=\phi_f+CT_e$, where ϕ_f is the floating potential and C is a constant that depends on the plasma discharge gas. Since the tips of the triple probes are aligned poloidally, the two plasma potentials give

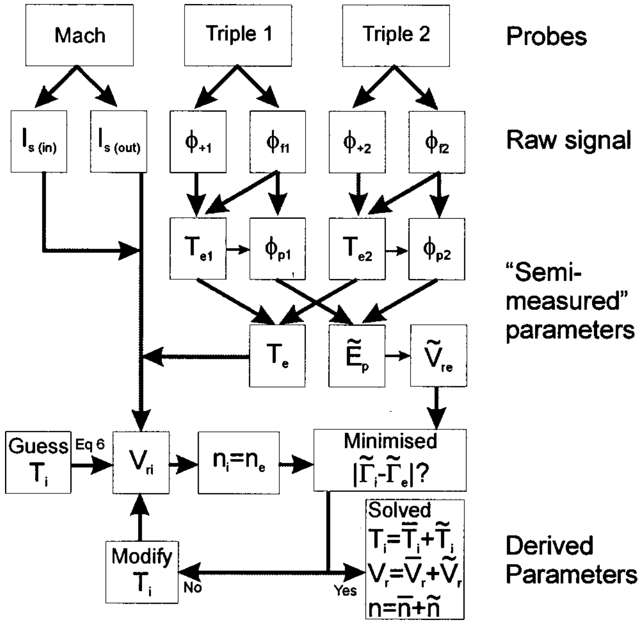

FIG. 2. Flowchart showing the algorithm of extracting the time-resolved signals of electron and ion temperature, electron and ion radial velocity, and density from the TMT probe.

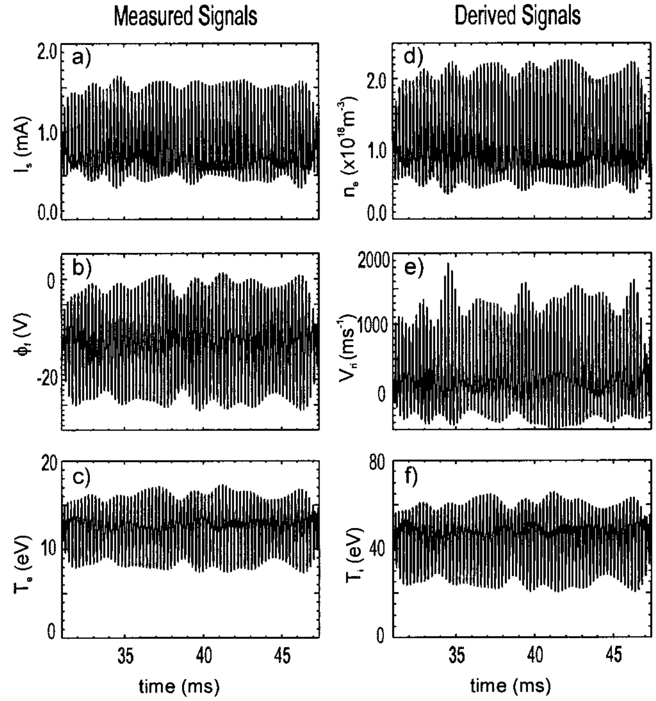

FIG. 3. Signals from the TMT probe at radial position $r/a \sim 0.4$. Measured signals: ion saturation current (a), floating potential (b), and electron temperature (c). Derived signals from the algorithm: electron density (d), radial ion velocity (e), and ion temperature (f).

a measure for the fluctuating poloidal electric field $\tilde{E}_p = (\phi_{p2} - \phi_{p1})/\Delta y$ as shown on the fourth row. This in turn gives $\tilde{V}_{re} = \tilde{E}_p/B$ for ***electrons***. It is important to stress this, since previous measurements with the poloidal Mach probe[2] indicated that the poloidal ion drift velocity is considerably smaller than the corresponding $V_{E\times B}$ velocity for electrons. Therefore, we shall not assume *a priori* that $\tilde{V}_{re} = \tilde{V}_{ri}$. However, to relate the two velocities we use the condition of ambipolarity of the fluctuation driven particle fluxes

$$\tilde{\Gamma}_i = \tilde{\Gamma}_e, \tag{7}$$

where $\tilde{\Gamma}_i = \langle \tilde{n}\tilde{V}_{ri}\rangle$ and $\tilde{\Gamma}_e = \langle \tilde{n}\tilde{V}_{re}\rangle$ and angular brackets denote time averages. This gives us an additional condition for relating $\tilde{V}_{re}$ and $\tilde{V}_{ri}$. Even if $\tilde{V}_{re} \neq \tilde{V}_{ri}$ the two fluxes can be equal if their phases with respect to $\tilde{n}$ are different.

The electron temperature at the Mach probe is deduced from the two triple probes. Since the two triple probes are separated by a distance less than the poloidal fluctuations correlation length, the two measured temperatures can be phase shifted to estimate the electron temperature at the position of the Mach probe.

The remaining two rows describe the iterative technique used to unravel the fluctuations from the saturation currents measured by the Mach probe. An initial guess of T_i is provided as an input to the system. Then we can determine V_{ri} from Eq. (6). The density n can then be determined from either part of Eq. (5). We iterate our estimate of T_i by invoking the condition of ambipolarity of the fluctuation driven fluxes [Eq. (7)]. That is, we proceed by minimizing $|\langle \tilde{n}\tilde{V}_{ri}\rangle - \langle \tilde{n}\tilde{V}_{re}\rangle|$. Thus, by using such a scheme, we can extract fully time-resolved signals of the four plasma parameters, density, ion and electron radial velocity, and ion and electron temperatures.

The described algorithm has been applied to the signals obtained using the TMT probe on H-1. Measurements have been taken with the TMT probe in the low confinement mode plasma conditions described in Ref. 8. The plasma fluctuations are dominated by highly coherent, low frequency ($f \sim 5$ kHz and its harmonics) pressure-gradient-driven resistive magnetohydrodynamic modes. Figures 3(a) and 3(b) show a sample of the measured signals from the TMT probe during a plasma pulse at $r/a \sim 0.4$. This radial position approximately corresponds to the maximum in the density fluctuation level. The plasma is produced with 60 kW of 7 MHz rf power at magnetic field approximately 0.09 T. The six raw signals from the TMT probe readily provide the electron temperature Fig. 3(c) and plasma potential. These signals are the input to the model, and using the iteration described by the last two rows of Fig. 2, a set of converging solutions has been found. The output signals are shown in Figs. 3(d)–3(f). At this radial position, we find the ion temperature to be around 40 eV, and across the plasma the profile seems to be quite flat. This estimate of the T_i and its profile agrees well with first measurements in H-1 using the retarding field energy analyzer[2] and confirmed by spectroscopic measurements.[9] The ion temperature fluctuations are found to be of the order $\tilde{T}_i/\overline{T_i} \sim 35\%$. This is comparable to fluctuations in the other plasma parameters: $\tilde{T}_e/\overline{T_e} \sim 30\%$, $\tilde{n}/\overline{n} \sim 35\%$.

In summary, the technique described in the article allows localized simultaneous measurements of the fundamental plasma parameters, namely electron density, electron temperature, and ion temperature using a combination of two triple probes and a radial Mach probe.

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