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Influence of plasma flow on the floating potential and an ensuing novel technique for measuring parallel flows

S. Jachmich[1], H. Van Goubergen[2] and R. Weynants[1]

1 *Laboratoire de Physique des Plasmas — Laboratorium voor Plasmafysica, Association Euratom – Belgian State", Ecole Royale Militaire — Koninklijke Militaire School, B–1000 Brussels, Belgium, Partner in the Trilateral Euregio Cluster*

2 *Department of Applied Physics, Ghent University, Rozier 44, B-9000 Gent, Belgium*

1. Introduction

The knowledge of the electric field is an important key towards the understanding of transport mechanisms in tokamak plasmas. Lacking more sophisticated diagnostics such as heavy ion beam probes, electrical probes are still frequently used to infer it from a determination of the plasma potential V_{pp}. The voltage difference arising between the probe tip and a reference probe, normally the enclosing wall of the device, is defined as the floating potential V_{fl} . Provided that the reference electrode is large enough not to limit the current flowing through the probing tip, the Langmuir probe will act as a single probe and the floating potential V_{fl} is related to the plasma potential V_{pp} is via the sheath drop [1] such that

$$V_{fl} = V_{pp} - T_e \ln (I_{es}/I_{is}) , \tag{1}$$

with I_{es} and I_{is} as electron and ion saturation current respectively. The logarithm in Eq. (1) is typically about 2-3, depending on the model used for the calculation of I_{es} and I_{is}. Whereas it is not the aim of this paper to enter the discussion on the correct value of this factor, we would like to point out that extra terms have to be added on the right hand side if a plasma flow is present. The calculations are carried out for a toroidal device but can easily be extended to other magnetic field configurations. The analytical study will be cross-checked with experimental results from the TEXTOR–94 tokamak. Finally a new scheme to measure parallel Mach numbers will be demonstrated.

2. Theory and experimental comparison

Let us first consider a probe tip consisting of two plane collectors, with an insulator in between, which are at equal potential due to the connection in point A as shown in Fig. 1b. Each collector has its own single probe I(V)-characteristic: $I_k=-I_{is,k}+I_{es} \exp((V_{pr}-V_{pp})/T_e)$, with $k=d,u$. The probe voltage V_{pr} is the potential difference between the probe tip and the ground. The quantities related to the collector facing the plasma flow downstream are denoted by "d", the other upstream side by "u". The electron saturation current I_{es} is assumed to be the same for both probes. The total current through the probe $I_u + I_d$ must by definition be zero if the probe is at floating potential. A straight-forward calculation then yields that, for this set-up, the floating potential is

$$V_{fl} = V_{pp} - T_e \ln\left(\frac{2I_{es}}{I_{is,u} + I_{is,d}}\right) . \tag{2}$$

In reference [2] an expression is derived for the up- and downstream ion saturation current collected by a probe in the presence of a flow, which can be approximated as (c_u, c_d $\approx$1):

$$I_{is,{}^u_d} = I_{is,0} \sin\alpha \exp\left(\pm M_{\|,\infty} \mp M_\perp \cot\alpha\right) \quad , \tag{3}$$

with $M_{\|,\infty}$ as the parallel flow Mach number and $M_\perp$ the perpendicular one. By using Eq. (3) we find an expression for the changes of the floating potential due to an existing plasma flow:

$$V_{fl} = V_{pp} - T_e \ln\left(\frac{I_{es,0}}{I_{is,0}}\right) + T_e \ln\left(\cosh(M_{\|,\infty} - M_\perp \cot\alpha)\right) \quad . \tag{4}$$

By merging the two sides of the probe of Fig. 1b one obtains a single probe with a rectangular tip. If α=90°, the logarithm in the last term is always positive and will not be larger than 0.4, which is the value corresponding to the maximal parallel Mach number $M_{\|,\infty}$=1. In case of a plasma at rest ($M_{\|,\infty}$=0), Eq. (1) is retrieved. In the case of a cylindrical probe tip, whose main axis is aligned radial (see Fig. 1a), one has to integrate the sum of the ion saturation current over the range 0°<α<180°. The floating potential then becomes

$$V_{fl} = V_{pp} - T_e \ln\left(\frac{I_{es,0}}{I_{is,0}}\right) + T_e \ln\left(\tfrac{1}{2}\int_0^\pi \sin\alpha \cosh(M_{\|,\infty} - M_\perp \cot\alpha)\, d\alpha\right) \quad . \tag{5}$$

The contours in Fig. 2 show the numerical result of the logarithm in the third term for given parallel and perpendicular Mach numbers. The additional perpendicular flow further diminishes the T_e – correction. At the most this will be reduced by a factor of 2.

Equations (4-5) show that a parallel flow will diminish the contribution of the electron temperature correction to the plasma potential for a single probe. In many applications, where the floating potential is used to determine the electric field, the derivatives of the parallel Mach number profile and electron temperature profile are a magnitude of order smaller than that of the potential profile. The flow dependence gives an additional argument to neglect the electron temperature contribution and to use directly the derivative of the floating potential as a measure for the radial electric field.

To test the above formalism experimentally a probe with two physically separated, but electrically connected plane collectors has been inserted into the plasma edge in TEXTOR-94. This asymmetric double probe behaves like a "divided" single probe. During the flat top phase of an ohmic discharge the probe was rotated with a frequency of 1 Hz around a axis aligned along the radial direction to establish the various contributions of perpendicular and parallel plasma flow (see Figure 1b). The data clearly show changes of the floating potential with the inclination angle α (Fig. 3), as predicted by Eq. (4). A Taylor-expansion to second order, which is valid for small $M_\perp$, allows us to compare the theoretical function with the experimental data:

$$V_{fl} \approx V_{pp} - T_e \ln\left(\frac{I_{es,0}}{I_{is,0}}\right) + \tfrac{1}{2} T_e \left(M_{\|,\infty} - M_\perp \cot\alpha\right)^2 \quad . \tag{6}$$

The red solid lines in figure 3 show the results of the least-square fits according to Eq. (6). Each cycle is fitted for angles 10°<α<170°. The fit-results agree rather well with the data, clearly following the temporal trend as the inclination angle changes. The blue circles indicate times when α=90°. The observed changes with time of the floating potential is attributed to changes in the edge profiles.

3. A novel method to measure Mach numbers

The effect of the parallel plasma flow on the floating potential can also be used to determine the parallel Mach number by means of a split probe of the type of Fg. 1c. Her the floating potential of two opposite plates is measured separately, and their difference $\Delta V_{fl}=(V_{fl,u}-V_{fl,d})$ can, using Eq. (3) for α=90°, be related to the Mach number as

$$M_{||,\infty} = \Delta V_{fl} / 2T_e \quad . \tag{7}$$

This technique has been applied in polarisation discharges [3], where large radial electric fields are induced to set-up high poloidal flows. In these discharges also the parallel flow changes in the presence of electrical fields. Figure 4a shows that the floating potentials are indeed different on both sides. Using this difference and Eq. (7) then yields the red curve of Fig. 4b as a first measurement of $M_{||,\infty}$. The blue curve is based on the ratio of ion-saturation currents, from which $M_{||,\infty}$ can be calculated by using the relation $M_{||,\infty} = 0.43 \ln(I_{is,u}/I_{is,d})$ (see [2], and note that our approximate Eq. (3) yields 0.5 as the proportionality factor). The agreement is excellent. An advantage of the method here proposed is that the time resolution is not limited by the sweeping frequency of the probe voltage, which is needed to retrieve the up- and downside ion saturation current. The agreement of both methods provides a further confirmation of the reliability of the presented model.

4. Summary and Conclusions

The effect of streaming plasma on the floating potential of a Langmuir probe has been studied. Our findings show that the floating potential changes in the presence of flows. Theory predicts that the contribution of the sheath drop to the plasma potential will be diminished by the flow. The overall effect for typical Mach numbers of 0.5 will not be larger than 20%, which is in an acceptable range. As in all cases the flow will decrease the importance of the sheath drop in the traditional Eq. (1) and as furthermore T_e–gradients are rather modest in many experimental studies, our findings give support to the practice of neglecting the sheath drop altogether and calculating the electric field simply as the derivative of the floating potential.

The reliability of the model has been proven experimentally by a rotating double-plate probe. For such probe configuration the floating potential must accommodate the asymmetry between the I(V)-characteristic of the two sides. The observed change of the floating potential as a function of rotation angle could be explained by the relative change in the contribution of the parallel and perpendicular plasma flows. It was also shown that the difference in the floating potential for an up- and downstream collecting plate can be used to determine the parallel Mach number. The remarkable agreement with the common method, where $M_{||,\infty}$ is deduced from the ion saturation current ratio, substantiates the role of the floating potential as a key quantity to other plasma parameters.

References

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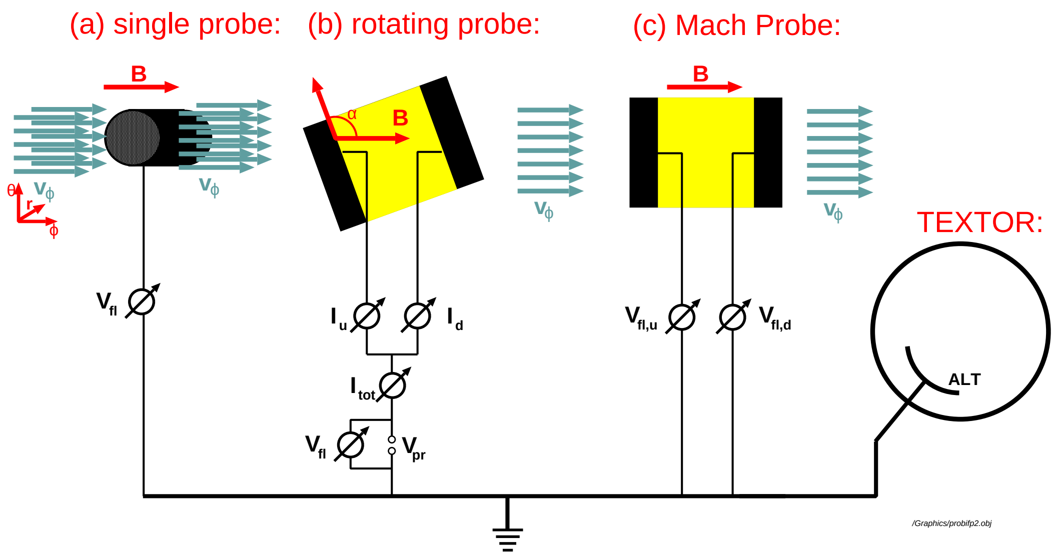

Figure 1: Schematic view of (a) single probe, (b) splitted rotating probe, (c) Mach probe

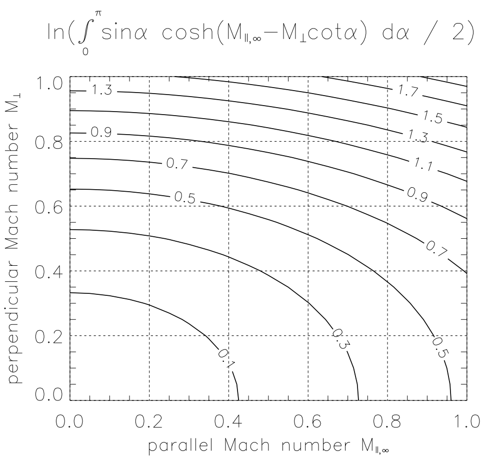

Figure 2: Contour plot of logarithm in Eq. (5) for given parallel and perp. Mach numbers.

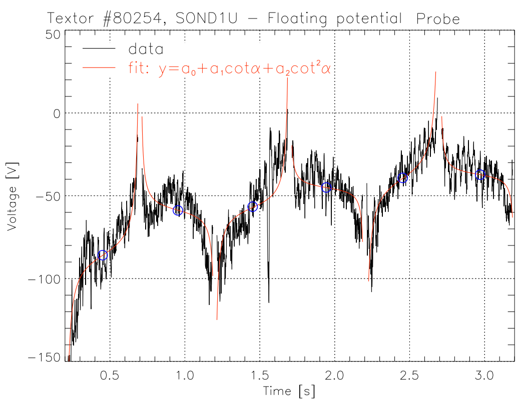

Figure 3: Voltage signal of rotating probe in ohmic plasma. The open circles indicate times for α =90°.

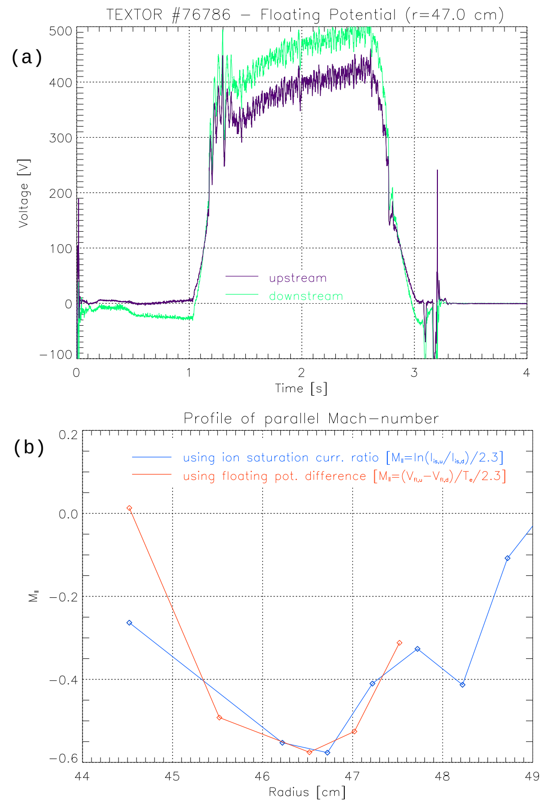

Figure 4: Time traces of (a) floating potentials of the up- and downstream collectors and the resultting parallel Mach number profile in a polarisation discharge.