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To cite this version:

HAL Id: hal-01290319
https://hal.archives-ouvertes.fr/hal-01290319
Submitted on 9 Mar 2017
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Article in Review of Scientific Instruments · February 2000
DOI: 10.1063/1.1150234

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Continuous heatable Langmuir probe for flowing afterglow measurements

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(Received 16 June 1999; accepted for publication 28 September 1999)

A heatable Langmuir probe consisting of a continuous dc-heating-current loop of tungsten wire is presented. This technique is efficient to keep the probe surface clean for flowing afterglow measurements. In our experimental conditions, the perturbations on the electron density determination can be considered as very small. The measurement of the well-known rate for the dissociative recombination of $O_2^+$ shows that the gas surrounding the probe is not heated for estimated probe temperature up to 700 K. © 2000 American Institute of Physics.

[S0034-6748(00)01501-X]

I. INTRODUCTION

The Langmuir probe can be considered as a classical diagnostic tool for use in the determination of plasma parameters. The standard technique is to insert a small electrode into the plasma and to polarize it, electrically. The analysis of the current–voltage characteristic allows one to determine electron density, electron temperature and in certain circumstances, the electron energy distribution.

The flowing afterglow Langmuir probe-mass spectrometer (FALP-MS) apparatus in our laboratory employs this method in order to measure room temperature rate coefficients of ion-molecule reactions, electron attachment, and dissociative recombination for ions and molecules of astronomical interest.1–3 Contamination of the probe surface can lead to an erroneous determination of the plasma parameters due to a distortion of the probe characteristic.4 By polarizing the probe negatively or positively to a large potential, ion or electron bombardment can remove the contamination layer.5,6 This method is efficient however, only if the time scale for recontamination is large compared with the time needed to acquire the probe characteristic. In the case of plasma containing hydrocarbon ions, which we have used for dissociative recombination measurements, we observed that this condition is not always respected. To eliminate such contamination in Q machines, a continuous indirect heating of the Langmuir probe is found to be efficient.7,8 To keep the probe surface clean during the FALP-MS measurements, a continuous direct heating of the Langmuir probe has been provided by using a dc-heating-current loop of tungsten wire.

We present here the design and operating characteristics of this continuously heated probe. The perturbations due to this system are discussed and the measurement of the well-known rate for the dissociative recombination of $O_2^+$ shows that the electron density determination is not perturbed and that the gas surrounding the probe is not heated.

II. LANGMUIR PROBE DESIGN AND THE OPERATING SYSTEM

Figure 1 shows the probe design we used for our investigations and Fig. 2 summarizes the heating and data acquisition system. The following method gives some ideas about temperature of the W wire versus the heating current ($I_h$). From the slope of the $V_s-I_h$ characteristic (where $V_s$ is the heating voltage applied to the wire), we obtain the ratio $R/R_0=g(I_h)$ (where $R$ is the resistance value of the wire when $I_h$ passes through it and $R_0$ is the value for $I_h=0$ A, i.e., at room temperature). We made the hypothesis that temperature is the same all along the W wire, and, in this case, the estimated temperature $T_w$ consists of the lower limit of the probe temperature. The resistivity $\rho$ of tungsten versus temperature is well known and, considering the dilatation phenomenon be small (i.e., $p/\rho_0=R/R_0$), it is easy to obtain the curve $T_w=h(I_h)$ (see Fig. 3).

III. DISCUSSION ABOUT PERTURBATIONS DUE TO THE CONTINUOUSLY HEATED PROBE

Due to the heating current, we have to take into account a voltage existing between the extremities of the probe (length $l$): if we call $V_{s0}$ the probe voltage at $x=0$ (located in the middle of the probe), we have to consider that the voltage at $x=\pm l/2$ is $V_{s0}\pm \Delta V$. Two consequences have been considered:

(a) When no heating current exists (i.e., $\pm \Delta V=0$) and when the electron density is to be measured, the characteristic curve $V_s-I_e$ is usually analyzed in the region (so-called accelerating region under orbital-motion-limited current conditions) where $V_s>\sqrt{V_p+10kT_e/q}$, with $V_p$ being the plasma potential, $q$ the electron charge, $T_e$ electron temperature, and $k$ the Boltzmann constant. In the case of the continuously heated probe, analysis of the characteristic curve must be made on the region where

$$V_s-\Delta V>\sqrt{V_p+10kT_e/q}.$$  

Under typical experimental conditions (probe radius $r_s=1.25\times10^{-3}$ cm, $T=700$ K, $\rho(T=700$ K) = 16.09

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$\mu\Omega \text{ cm, } I_h = 130 \text{ mA, } l = 0.4 \text{ cm, } T_e = 300 \text{ K}$, $\Delta V$ is estimated to be $\equiv 0.09 \text{ V}$ (or $\equiv 3.5kT_e/q$).

(b) When the W wire is heating (i.e., $\Delta V \neq 0\text{ V}$), errors in the electron density determination have to be estimated. If we consider that the Langmuir probe can be represented by the sum of elementary cylindrical probes of length $d\ell$ (such as $\sum d\ell = l$) centered at the position $x$, the elementary electronic current $d\ell_i$ collected at $x$ is

$$d\ell_i = \frac{kT_e}{V_0} n_e d\ell A^1$$

Accurate values of the electron density are obtained from the slope of the linear plots of $I_s^2$ versus $V_s$. Under our experimental conditions, linearity is still verified in the range from $V_p = 50$ to $100kT_e/q$. In this case, Eq. (1) is always respected. In the more unfavorable case (i.e., $\Delta V = 3.5kT_e/q$ and $V_s = 50kT_e/q$), the perturbation can be estimated and considered as insignificant,

$$\frac{(\Delta V(x))^2}{V_0} + \frac{(kT_e)^2}{qV_0} \equiv 0.5\%.$$ (4)

IV. IS THE PLASMA HEATED? DISSOCIATIVE RECOMBINATION OF $O_2^+$ AS A TEST

If the medium surrounding the probe is heated, the plasma parameters can be perturbed. Measurement of the $O_2^+$...
dissociative recombination rate coefficient $\alpha(O_2^+)$ is a good test to show if in fact the plasma is perturbed since it has been well established that $\alpha = 1.95 \times 10^{-7}$ cm$^3$ s$^{-1}$ at 300 K and is found to vary as $T^{-0.7}$.9

The FALP-MS experimental apparatus has been described in detail before10 and only a brief description is given here (Fig. 4). The technique is an extension of the conventional FALP technique11 that is supplemented by a movable mass spectrometer and allowed us to ensure that the reactions (8), (9), (10) were completed and that only $O_2^+$ ions were present.

Neglecting diffusion loss, one can write down the equation giving the change in the electron density $n_e$ as a function of distance, $z$, along the flow tube, thus

$$\frac{1}{n_e(z)} = -\frac{\alpha}{\nu_p} z + \frac{1}{n_e(z=0)}.$$

The plot of $1/n_e(z)$ against $z$ allows us to determine $\alpha$ (knowing the value of the flow velocity $\nu_p$).

Table I shows the measured $\alpha(O_2^+)$ versus the estimated temperature $T_w$ (up to 690 K) of the heated W wire (estimated with the method described above). All values are very similar and in agreement with a rate coefficient at $T = 300$ K, and we can consider that in this range of temperature no perturbation due to the heated probe occurs.