

Diagnostic of plasma streams from ion thrusters for space propulsion using emissive probes

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Abstract.

The emissive probes are employed for the determination of the local plasma potential of plasma streams produced by ion thrusters. Its operation basically relies on electron collection and emission and are less sensitive to the ion motion than collecting probes. The diagnostic using emissive probes is reviewed with emphasis in low density plasmas. Our results support the conclusion that potential structures around the probe, as virtual cathodes, would be responsible for the operation of emissive probes in low density plasmas.

1. Introduction

The next generation of satellites will make use of the recent developments in space propulsion using high energy plasma streams. The advantages of electric propulsion (EP) for long term missions rely on combined reasons of economy and practical interest. These systems produce ion streams with exhaust velocities of tens of kilometers per second, much higher than conventional propulsion systems using reactive chemicals as propellants. This fact leads to high values of the specific impulse that results in relevant weight savings over traditional propulsion systems [1]. In addition, the EP engines are powered by electric the solar panels and are propelled by chemically inert gases (usually Xenon) of easy stowage. Therefore, the EP offers considerable advantages for in orbit station keeping of geostationary satellites, deep space missions or planetary probes [1].

These propulsive systems need of long term endurance experiments and intensive laboratory testing in order to determine their performances, as well as their actual levels of thrust. In particular, the mapping of the electric potential spatial profile of the low density plasma stream (also denominated *plasma plume*) [1] is of the paramount importance. The electric fields driving the plasma stream collimate the dispersion of the plasma exhaust stream and therefore modulate the effective thrust imparted by the ion engine. Additionally, large angle dispersion of the plasma plume would affect the operation of nearby satellite payloads by the undesired bombardment of ions from the plasma thruster exhaust [1].

The electric probes allow pointwise measurements of the plasma parameters and are well suited for this space mapping [2]. The collecting Langmuir (CLP) and emissive (EMP) probes are currently used for the determination of the plasma density and electric potential spatial



profiles. They are made of plasma exposed metallic conductors that collect ions and electrons for different electric bias potentials. The plasma parameters are later evaluated from these voltage current (IV) characteristic curves of CLP and EMPs [2]. These calculations assume isotropic energy distributions for ions and electrons and involve physical models for the charge collection processes from the plasma.

However, in the plasma streams of ion thrusters the ions have important drift velocities with respect to the probe at rest and these conditions are not always fulfilled. The physical size of the probes also introduces plasma wakes downstream that are not considered in most CLP current collection models. Consequently, most classical models for CLPs are less applicable in plasma flows except in the limit of low relative ion drift velocities.

On the contrary, emissive probes are less sensitive to the ion motion because its operation basically relies on the electron collection and emission processes [2, 3, 4]. As the Fig. (1) shows the probe emits a thermionic electron current which is retained for bias voltages V_p over the plasma potential $V_p > V_{sp}$ or emitted to the plasma otherwise. The local value of the plasma potential is determined by the abrupt change in the probe current produced by the transition between the electron collection and emission. The contribution of ions in low density plasmas could be usually neglected. This local measurement makes EMPs suitable for the plasma potential mapping of plasma streams [2, 3, 4].

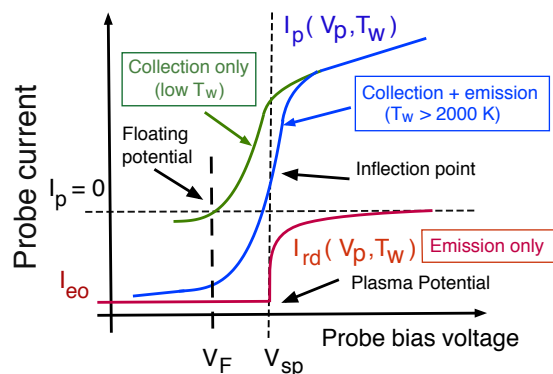


Figure 1. Scheme of two idealized IV curves $I_p(V_p, T_w)$ of an emissive probe and the thermionic emission current $I_{rd}(V_p, T_w)$ as a function of the probe bias potential.

Nevertheless, despite the success of this plasma diagnostic its theoretical support still remains incomplete [4, 5, 6]. In the operation of EMPs the plasma results inevitably perturbed by the electron thermionic emission and we will discuss its extent for the case of low density plasmas. In this case the measurements using the denominated *inflection point* method [3, 4], corresponding to low emission thermionic currents are difficult because of the poor signal to noise ratio as the Fig. (2) shows. On the opposite limit, the larger thermionic currents involved in the so called *floating point* method [5, 7, 8] might result in the strong perturbation of the nearby plasma.

However, the experimental data in this *strong emission* regime of EMP suggest the development of plasma potential structures around the probe [9, 12, 13, 14] that could be responsible for the partial trapping of the emitted electrons [5]. We conjecture that such electron confinement would limit the plasma perturbation extent and explains the reliable measurements of V_{sp} using the floating potential of EMPs.

2. The operation of the emissive Langmuir probes

The original concept of the EMP could be traced back to Irving Langmuir and the Refs. [4, 7] are comprehensive reviews of this experimental technique. The EMPs are essentially intended to measure the local plasma potential and also the electron temperature according to some authors [15]. They are usually made up of a electrically conductive thermionic electron emitter heated

up to high temperatures, such as a loop of a thin tungsten wire [5, 6] or a LaB₆ crystal [8]. This latter is exposed to the plasma and for the temperature T_w emits a thermionic electron current density is given by Richardson-Dushman expression,

$$J_{rd}(T_w) = C T_w^2 \exp\left(-\frac{e W_f}{k_B T_w}\right) \quad (1)$$

where C is a constant and W_f the work function of the material [16]. In our particular case [5], the probes are made of a tungsten wire with diameter $d = 0.8$ mm heated up by a DC current. The wire temperature T_w is related to the heating current I_H through the following phenomenological expression,

$$T_w = T_o + P_1 \left(\frac{I_H}{d^{3/2}}\right)^{P_2} \quad (2)$$

Here d is the diameter of the wire in centimeters, $P_1 = 29.50$ K, $P_2 = 0.59$ are constants and $T_o = 204.35$ K [17, 18].

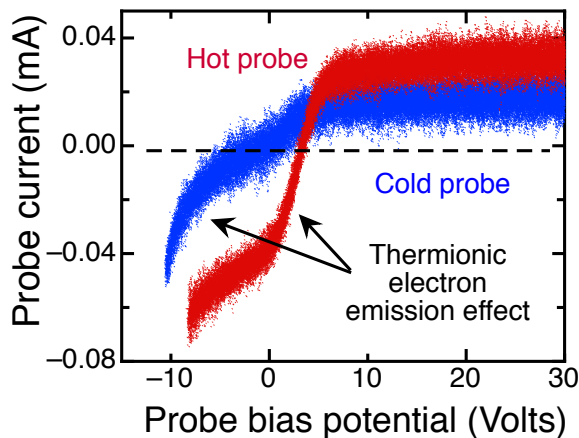


Figure 2. The current voltage characteristic curves of an emissive probe for two temperatures T_w in the low thermionic emission mode.

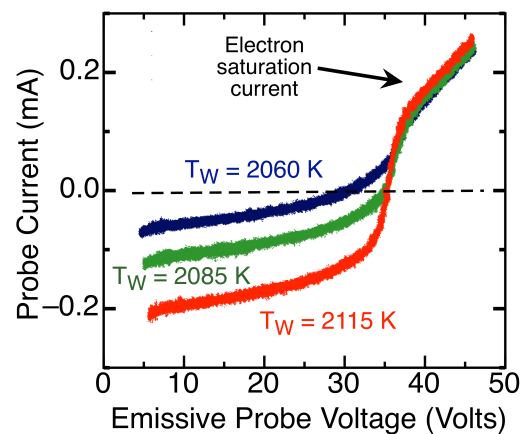


Figure 3. The current voltage characteristic curves of an emissive probe of in the large thermionic emission mode.

In the scheme of Fig. (1) the vertical dotted line denotes the value of the plasma potential V_{sp} and the horizontal dashed line indicates the current $I_p(V_F, T_w) = 0$ corresponding to the floating potential $V_F(T_w)$. The red curve for the thermionic electron emission current has a steplike characteristic where the maximum negative emitted electron current $I_{eo}(T_w)$ takes place for $V_p \ll V_{sp}$ because all thermionic electrons are rejected towards the plasma. On the contrary, the emission current $I_{rd}(V_p, T_w) \simeq 0$ for $V_p \gg V_{sp}$ when the electrons cannot leave the probe surface.

Two idealized IV curves $I_p(V_p, T_w)$ are also represented in Fig. (1) to illustrate the EMP operation principle. For low probe temperatures T_w the thermionic electron current $I_{eo}(T_w) \simeq 0$ (green curve) could be neglected and this cold EMP collects a current from the plasma $I_p(V_p, T_w) \simeq I_p(V_p)$ essentially as a CLP. When $V_p < V_F$ the probe drains the small ion saturation current and $I_p(V_p, T_w)$ increases for $V_p > V_F$, and for bias voltages over the knee corresponding to V_{sp} the probe current saturates.

The blue IV characteristic curve $I_p(V_p, T_w)$ for a hot EMP in Fig. (1) results from the combined effects of the thermionic electron emission and charge collection from the plasma. The electron emission current $I_{rd}(V_p, T_w)$ introduces a sharp jump located close to the plasma

potential and the magnitude of this steep change depends of the probe temperature T_w through the Eq. (1).

The typical IV curves of two different emissive probes operating in low and large thermionic emission modes are represented in Figs. (2) and (3) whereas the details of these experiments are discussed in Ref. [5]. For cold probe temperatures the small surface of the emissive probe collects low currents that give rise to a poor signal to noise ratio. The effect of the electron thermionic emission is also observed in Fig. (2) by the small shift between the two curves when the probe temperature is slightly increased.

In order to obtain the characteristic curve of Fig. (3) the probe temperature needs to be substantially raised over the values of Fig. (2) and $I_p(V_p, T_w)$ increments by more than an order of magnitude. The probe temperature dependent step produced by the emission current $I_{eo}(T_w)$ of Fig. (1) that gives rise to the difference between Figs. (2) and (3) also depends of additional factors, such as the length of the wire or the cleanliness of the metal surface. Our probes need to be typically heated up to $T_w > 2000$ K to obtain appreciable electron emission currents as those of Fig. (3).

The arrows in the scheme of Fig. (1) indicate relevant points such as those related to the *inflection point* and the *floating potential* methods that are currently employed to determine V_{sp} from the IV characteristics curve of EMPs. As the probe temperature increases, the growing emission currents $I_{rd}(V_p, T_w)$ added to the cold probe characteristic produce steeper $I_p(V_p, T_w)$ curves close to the plasma potential. This is observed in the curves of Fig. (3) where the temperature dependent floating potential $V_F(T_w)$ approaches the plasma potential and $V_F(T_w) \simeq V_{sp}$ when the probe is hot enough. Additionally, the emission current introduces a change in the slope of $I_p(V_p, T_w)$ that would be observed in the curves of Figs. (2) and (3). The corresponding *inflection point* also moves close to $V_F(T_w)$ as the probe temperature increases.

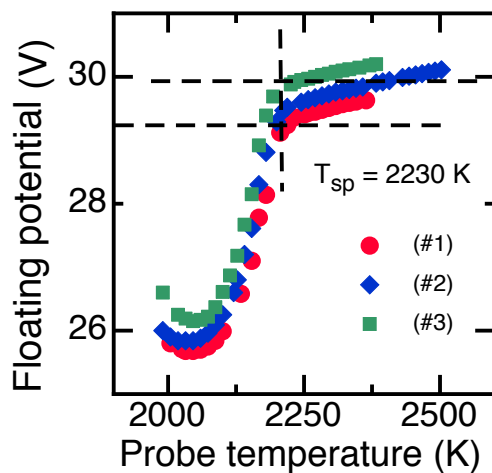


Figure 4. Three sets of measurements of the floating potential of the emissive probe as a function of the probe temperature T_w .

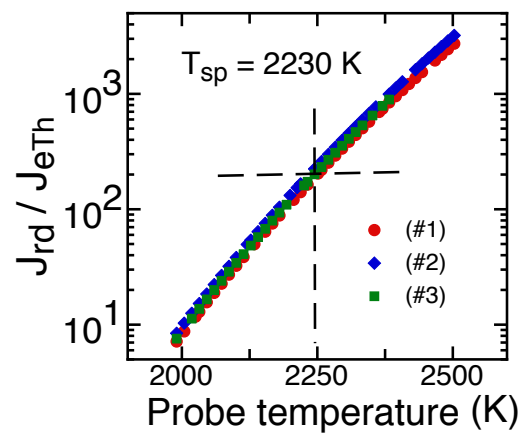


Figure 5. The ratio between the thermionic $J_{rd}(T_w)$ and the plasma thermal electron J_{eTh} current densities for the experimental data of Fig. 4.

The *inflection point* method [3, 4] requires a low thermionic electron current which minimizes the perturbation introduced in the plasma by the EMP operation. The value of probe current $I_i(T_w) = I_p(V_i, T_w)$ corresponding to the inflection point bias voltage $V_i(T_w)$ is found by derivation of the IV curves of Figs. (2) and (3) with respect to V_p [3, 4]. The maximum corresponds to $V_i(T_w)$ and these values are represented against the ratios $I_i(T_w)/I_{eTh}$ where I_{eTh} is the plasma electron thermal current. The plasma potential V_{sp} is calculated by experimental

data fitting in the limit of low thermionic electron emission [3, 4].

This identification of such inflection point with the plasma potential is essentially qualitative but constitutes a good approximation for V_{sp} [3] as suggests the scheme of Fig. (1). The main drawback of this method in low density plasmas relies in the derivation of the $I_p(V_p, T_w)$ of noisy IV curves, as those of Figs. (2) and (3) with respect to the bias potential V_p .

Alternatively, the plasma potential could be also determined by the *floating point* method by the saturation observed in Fig. (4) when representing $V_F(T_w)$ against T_w (or equivalently, the heating current I_H) [5, 6, 7, 8]. For probe bias potentials $V_p \leq V_{sp}$ in a Maxwellian plasma the electron current density to the emissive probe is [8],

$$J_p(V_p, T_w, T_e) = J_{ce}(V_p, T_e) - J_{rd}(T_w) - J_{ci}(V_p) \quad (3)$$

where $J_{ci}(V_p)$ is the current density of attracted ions and $J_{rd}(T_w)$ given by Eq. (1) corresponds to the population of repelled thermionic electrons. The contribution $J_{ce}(V_p, T_e)$ of the Maxwellian plasma electrons is,

$$J_{ce}(V_p, T_e) = J_{eTh} \exp\left(\frac{e(V_p - V_{sp})}{k_B T_e}\right) \quad (4)$$

and when the probe is biased to the floating potential $J_p(V_F, T_w, T_e) = 0$ and we obtain,

$$V_F - V_{sp} = \frac{k_B T_e}{e} \ln\left(\frac{J_{rd}(T_w) + J_{ci}}{J_{eTh}}\right) \quad (5)$$

Therefore, as the probe temperature T_w increases the thermionic electron emission grows and when $J_{rd}(T_w) \simeq J_{eTh}$ we obtain $V_F \simeq V_{sp}$. The small contribution of the attracted ion current $J_{ci} \ll J_{eTh}$ is usually neglected [5, 7, 8] in low density plasmas.

The Eq. (5) is derived under the assumption of a Maxwellian energy distribution for the plasma electrons. More complex distributions such as bi-Maxwellian have been observed in a number of situations such as plasma double layers [10], divertor plasmas in tokamaks [11], etc. In these situations, the plasma parameters could then be obtained by using new methods that have been recently reported [11].

3. Discussion

The measurements of the floating potential as a function of the temperature T_w are easy to implement. The Eq. (2) allows us to estimate the temperature of the emissive probe that constitutes the key physical parameter to evaluate the thermionic electron emission current density of Eq. (1). This permits to asses both the Eq. (5) and the magnitude of the plasma perturbation by the EMP electron emission.

This latter is small for low T_w (typically below 2100 K) and in this regime the Fig. (4) shows that the emissive probe basically acts as a CLP, where the floating potential remains independent of the probe temperature. The values of $V_F(T_w)$ increases with T_w when the thermionic electron emission grows in Fig. (4) as well as in Figs. (2) and (3). Finally, the curve saturates in Fig. (4) for the temperature T_{sp} where $V_F(T_{sp}) \simeq V_{sp}$. This basic response of the EMP has been reported by a number of authors and provides values of the plasma potential with reasonable accuracy in different plasmas [5, 6, 7, 8].

In Fig. (5) are represented the ratios $R = J_{rd}(T_w)/J_{eTh}(T_e)$ between the emitted thermionic current density of Eq. (1) and the electron thermal random current of the plasma $J_{eTh}(T_e)$ for the experimental data of Fig. (4). Because of the low plasma densities ($n_e \sim 0.1 - 8 \times 10^8 \text{ cm}^{-3}$) and electron temperatures ($T_e \sim 1\text{-}2 \text{ eV}$) the electron emission currents are between one and two orders of magnitude higher than $J_{eTh}(T_e)$ within this probe temperature range [5]. Therefore the excessive probe heating results in large thermionic electron emission currents that perturb

the surrounding plasma. Nevertheless, the cross check of the EMP against the measurements with collecting probes indicates that the knee of Fig. (5) corresponds to the actual value of the plasma potential [5, 19].

Additionally, the Eq. (5) also would provide the electron temperature by the experimental data fitting of $V_F(T_w)$ as the Fig. (6) shows. The electron temperatures calculated from the slopes m of the experimental data of Figs.(4) and (5) are usually give higher values than those obtained by other methods.

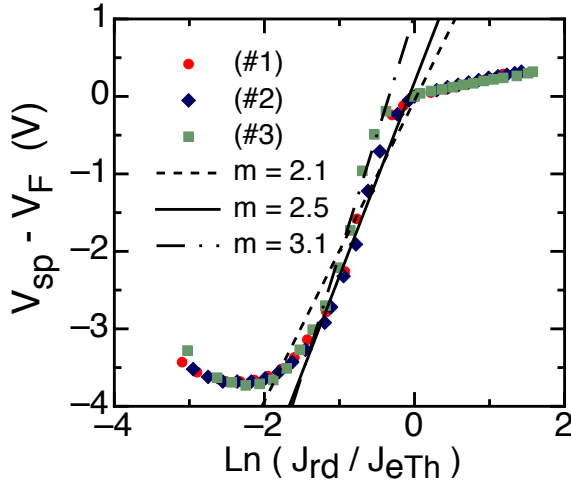


Figure 6. The fitting of the experimental data experimental data of Fig. (4) to Eq. (5) to evaluate the electron temperature using their slopes m .

4. Conclusions

The previous experimental evidences point out that the simple model for $V_p \leq V_{sp}$ that gives rise to Eq. (5) is questionable for EMP operating in low density plasmas. In accordance to Fig. (5) we conclude that the Eq. (5) is not satisfied because of the large values of the ratios $J_{rd}(T_w)/J_{eTh}(T_e)$. This is also the case for the electron temperature fitting of Fig. (6) which deviates from the values of T_e provided by other plasma diagnostics.

These results only involve the electrons emission and collection processes and are weakly dependent of the ion motion which is neglected in the previous derivation of Eq. (5). The classical model of Eq. (5) only considers that the thermionic and the plasma electron groups contributes to the probe current for $V_p \leq V_{sp}$. In order to explain the experimental findings discussed before, additional electron populations would be close to the surface of the EMP that also contribute to the probe current [5].

The physical origin of this third electron group would be the development of a plasma potential structure around the EMP. In low density plasmas the large thermionic emission currents would modify the classical plasma sheath around the probe. These structures, also denominated *virtual cathodes*, might develop a plasma potential minimum that could trap and/or return a fraction of the emitted electrons by the EMP [12, 13, 14]. We conjecture that, despite the large ratios of $J_{rd}(T_w)/J_{eTh}(T_e)$, this electron confinement would limit the extent of the EMP perturbation in the nearby plasma and explains the reliable values of V_{sp} in low density plasmas.

In order to evidence the role of this third electron group the previous model for $V_p \leq V_{sp}$ based only on the emitted and plasma electron groups was refined in Ref. [5]. An additional electron group at the surface of the probe approximated by a Maxwellian distribution with an effective temperature. This parameter allows to fit the slopes of Fig. (6) and this result suggests that different electron groups are present at the surface of the electron emitting EMP. The consideration of a Maxwellian electron group is only regarded as an approximation and does not

preclude other electron energy distribution functions for this electron group that might provide similar results.

This *floating point* method is more invasive than the *inflection point* discussed before which involves lower thermionic electron emission currents. However, in low density plasmas the noisy IV curves as those of Fig. (2) force the experimenters to operate the EMP in the high electron emission regime. The basis of the EMP operation in this latter case should be revised using more involved models than Eq. (5) to account for the different electron groups.

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