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# A comparative study of emissive probe techniques for vacuum space potential measurements

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ABSTRACT

The major emissive probe techniques for the measurement of vacuum space potentials are compared to find the best emissive probe method in a vacuum. An overview of the inflection point method, the floating point method, and the vacuum current bias method is given, addressing how each method works in a vacuum. A comparison of the experimental data measured in a vacuum shows that the improved inflection point method has a best accuracy of 0.1 V in vacuum space potential measurements, while the original inflection point method can yield about half of a volt below the real space potential due to the inappropriate linear fitting in the method. Although the floating point method and the vacuum current bias method are convenient and rapid measurement techniques, the floating point method can only measure the vacuum potentials more than 1 V, and the space charge effect is not considered in the vacuum current bias method.

## 1. Introduction

A variety of electrical probes have become the major tool for obtaining the parameters of various plasmas since developed by Langmuir a century ago [1–7]. In all probes, emissive probes have been widely used for space potential measurements in low temperature plasmas [8–10], potential fluctuations [11–13], plasma sheaths [14–16], tokamaks [17–20], as well as vacuums [9,21–25]. Of the many existing emissive probe techniques, the methods which can be used to determine vacuum space potentials ($V_V$) include the inflection point method [8,9,21–26], the floating point method [9,24], and the vacuum current bias method [9,24,25]. These methods are based on different principles. The inflection point method measures the trend of the potential of the inflection point of the emissive probe *I-V* characteristics ($V_{ip}$) changing with the emission intensity, and finds the space potential at the limit of zero emission [8,21–24,26]. The floating point method measures the *I-V* characteristics under a condition of strong emission and takes the floating potential ($V_f$) where the emission current ($I_{emis}$) initiates as a direct measurement of vacuum potential [9,24]. On the other hand, the vacuum current bias method aims to bias the probe current and measure the probe voltage ($V_B$). When the $I_{emis}$ is equal to the fixed probe current ($I_B$) at $V_V$, the measured $V_B$ is the $V_V$ [9,24].

Although all these methods are based on different principles, they do not give the same results in $V_V$ measurements [24], and the accuracies of the methods have not been investigated in detail, especially the floating point method. In addition, with the realization of an automatic emissive probe apparatus which can automatically execute the conventionally cumbersome procedure of the inflection point method, the accuracy of the inflection point method in space potential measurements has been greatly improved [21,22]. Therefore, in order to preferably apply emissive probes to studies of complicated static electric field configuration and provide a reference for researchers in choosing an appropriate emissive probe method in different $V_V$ measurements, it is necessary to restudy and estimate the accuracies of the methods in $V_V$ measurements. In this paper, the comparative research of vacuum space potential measurements seeks to obtain the accuracies of the methods and present the advantage and disadvantage of the inflection point method, the floating point method, as well as the vacuum current bias method.

## 2. Emissive probe techniques used in vacuums

### 2.1. Inflection point method

The inflection point method was firstly developed by Smith et al. to minimize the space charge effects in measuring space potential [8,9].

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Generally, the inflection point method requires to find the relation between the potential of the inflection point of emissive probe *I-V* characteristic ($V_{ip}$) and the emission current ($I_{emis}$), linearly fit the $V_{ip} - I_{emis}$ experimental data and extrapolate to the limit $I_{emis} \to 0$ for obtaining the space potential [8,26,27].

The original inflection point (OIP) method is considered to have vast application in static electric field measurements [9,23]. The distribution of $V_V$ between two parallel plates was measured by Cho et al. to test the validity of the OIP method, showing a maximum uncertainty of ± 0.4 V [9,23]. However, the $V_V$ measurement accomplished by Cho et al. is not a good agreement with the calculated potentials, especially in the low potential approaching to zero [9,23]. On the other hand, the OIP method is not a rapid and convenient technique for space potential measurements due to its cumbersome manual execution [8,21–24,26]. In addition, the theoretical and experimental data show that the relation between $V_{ip}$ and $I_{emis}$ is not a good linear relation in space potential measurements [26,27].

According to the fact that $V_{ip}$ changes linearly with the probe filament heating current ($I_{ht}$) instead of $I_{emis}$, the improved inflection point (IIP) method is proposed by us to use linear extrapolation of the $V_{ip}$ vs $I_{ht}$ dependence to zero emission for the estimation of space potentials [21,22,27]. Due to the cumbersome procedure of the IIP method, an automatic emissive probe apparatus has been developed by us [21,22]. In the apparatus, the probe biasing circuit and the heating circuit are both controlled by the program through analog signals generated by a data acquisition (DAQ) card, and the probe bias voltage, probe current, as well as probe heating current are automatically acquired by the DAQ card through its analog input terminals [21,22]. After the acquisition of the experimental data, with the setting of linear fitting parameters in the program, the automatic apparatus can quickly give the space potential result [21,22], showing the convenient of the IIP method applied to the space potential distribution measurements. However, the rapid measurement of space potentials is still hard to be achieved by the IIP method.

### 2.2. Floating point method

In $V_V$ measurements, the floating point (FP) method is same to the zero current bias current because there are only electron emission currents when the bias of emissive probes ($V_B$) below $V_V$ [24]. As taking the floating potential ($V_f$) where $I_{emis}$ initiates as a direct measurement of potential, the FP method is thought to have the advantage in rapid and continuous measurements. Although the FP method is more convenient than other emissive probe techniques in $V_V$ measurements, it is not accurate enough for $V_V$ measurements [24]. As emissive probes only emit electrons in a vacuum, the $I_{emis}$ in a vacuum cannot quickly change with sudden decreases in $V_V$, and the FP method can not be used for negative potential measurements in a vacuum [24]. Furthermore, the FP method should be used under a strong emission as $V_f$ increases and approaches to $V_V$ with the increase of $I_{emis}$ in a vacuum (see the experimental emissive probe *I-V* curves shown in Ref. [23]), and the high temperature of emissive probes may cause ionization and change the measurement results [9,28].

### 2.3. Vacuum current bias method

The vacuum current bias (VCB) method was proposed by Diebold et al., which is very similar to the FP method [9,24]. This method needs to decide the fixed emission current ($I_B$) at the known $V_V$ firstly, and then set $I_{emis}$ of emissive probes and measure the voltage of probes ($V_B$). When the set $I_{emis}$ is equal to $I_B$, the measured $V_B$ is the accurate $V_V$ [9,24]. The advantage of the VCB method is that the probe in the VCB method responds more quickly than it in the FP method [24]. The VCB method is also capable for negative potentials measurements [24]. Unfortunately, the experimental and theoretical emissive probe curves show that the $I_{emis}$ at the real space potential is zero [23,29]. Although the $I_{emis}$ at the known $V_V$ is not zero under a strong emission condition where the VCB method used, it seem to be a result of space charge effects because the known $V_V$ is determined by the OIP method. Therefore, the greatest error of the VCB method is that it does not eliminate the space charge effects. In addition, emissive probes in the VCB method also need to be strongly heated which may cause uncertainty in the result [24].

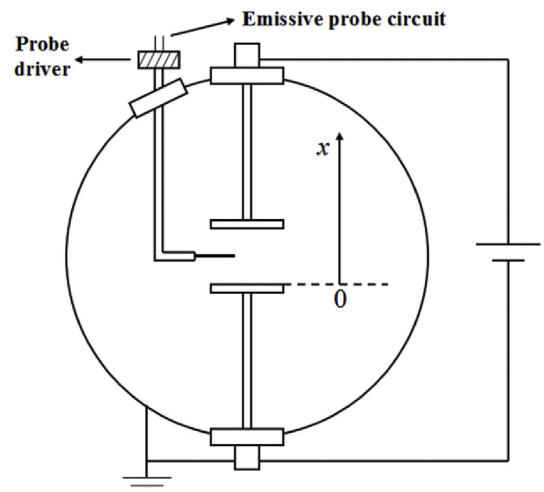

**Fig. 1.** Schematic of the experimental setup.

## 3. Experimental setup

The vacuum chamber used in the experiment of vacuum space potential measurements is cylindrical in shape with an inner diameter of 60 cm and depth of 80 cm, made of stainless steel [30]. As shown in Fig. 1, inside the chamber, we placed two stainless steel plates with diameter of 15 cm, in parallel, separated by 5 cm. The plates were cleaned by an ultrasonic cleaner with high purity alcohol (≥99.7%) and deionized water successively, avoiding the effect of the surface impurities on the results [23,24]. A potential difference supplied by an outside DC voltage source was applied between the two plates.

The emissive probe used in the experiment was a filament of pure tungsten wire of 20 μm in diameter and 5 mm in length, and was connected to the circuit of automatic emissive probe apparatus through ceramic-tube-covered conductive wires (tungsten wires of 0.2 mm in diameter), as shown in Fig. 2. The alumina tubes outside the conductive wires were 1 mm in diameter and about 10 cm in length. In the experiments, the emissive probe was parallel placed between the plates with about half length of the alumina tubes inside the plates, connected with a diver for moving the probe along the perpendicular center line, with a moving accuracy of 0.05 mm, as shown in Fig. 1.

Between the plates, the vacuum space potential measurement was respectively performed with the original inflection point method, the improved inflection point method, and the floating point method, as well as the vacuum current bias method. In all experiments, the chamber was exhausted to a pressure baseline of $1.6 \times 10^{-3}$ Pa as emissive probe diagnostic techniques are reliable in a collision-free vacuum (≤1.3 Pa) [31]. The DC voltage applied between the plates was randomly chosen to be 10.4 V, and the heating current step and the scanning bias step were respectively chosen to be 2 mA and 0.2 V.

For obtaining the emissive probe voltage, in the probe bias circuit, two resistors of 100 Ω were connected in series, and then connected with the probe filament in parallel. The midpoint between two resistors was the place where the probe potentials measured. As the filament impedance was only several ohms, the potential drop across the filament was small and negligible. In addition, the *I-V* characteristics of the emissive probe were measured point to point, from low potential to