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Interpretation and implementation of an ion sensitive probe as a plasma potential diagnostic^{a)}

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An ion sensitive probe (ISP) is developed as a robust diagnostic for measuring plasma potentials (Φ_p) in magnetized plasmas. The ISP relies on the large difference between the ion and electron gyroradii ($\rho_i/\rho_e \sim 60$) to reduce the electron collection at a collector recessed behind a separately biased wall distance $\sim \rho_i$. We develop a new ISP method to measure the plasma potential that is independent of the precise position and shape of the collector. Φ_p is found as the wall potential when charged current to the probe collector vanishes during the voltage sweep. The plasma potentials obtained from the ISP match Φ_p measured with an emissive probe over a wide range of plasma conditions in a small magnetized plasma. © 2010 American Institute of Physics.

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I. INTRODUCTION

The electrostatic plasma potential (Φ_p) is one of the most fundamental plasma parameters in magnetic fusion. There are several probes capable of measuring the plasma potential in tokamaks and the most widely used is the Langmuir probe.¹ However, Langmuir probes do not directly measure Φ_p : the plasma potential is inferred from other plasma parameters: the electron temperature (T_e), the ion and electron saturation currents (I_{SAT} and I_{e-SAT} , respectively), and the floating potential (V_f).¹

The most common method to measure the plasma potential directly is using an electron emissive probe.² The attractiveness of the emissive probe is the ease of interpretation: the probe begins to float at $\sim \Phi_p$ (within $1 T_e/e$, where e is the elementary charge)³ when operated in the high emission regime.² The disadvantages of the emissive probe are its filament fragility and the limit on the maximum attainable electron emission due to the melting of the filament. As a result, emissive probes operate in plasmas with densities typically below 10^{18} m^{-3} .

It is also possible to determine Φ_p with a retarding field energy analyzer (RFEA).⁴ However, the RFEA design is complex; multiple biased (and fragile) grids are necessary. The analyzer is also more perturbing to plasma than other probes. The body of the RFEA protrudes several millimeter into plasma past the analyzer's entrance slit.

It has been proposed^{5,6} to use the large difference between the electron and ion gyroradii (ρ_e and ρ_i , respectively) in magnetized plasmas to measure ion properties and Φ_p directly. Standard theory demands that the collector be precisely positioned a distance $h \approx \rho_i$ behind a wall to reduce the

electron collection to meet the $I_{e-SAT}=I_{SAT}$ criterion. The ion motion is assumed to be demagnetized and space-charge effects are ignored. At this point the collector is assumed to float at Φ_p . Different variations of the original Katsumata design^{5,6} are the ion sensitive probe (ISP),⁷⁻⁹ the plug probe,¹⁰ the tunnel probe,¹¹ the ball-pen probe,¹² and the baffle probe.¹³ We will use the ISP acronym to refer to this type of probe throughout the paper.

The purpose of our study is to explore the validity of the accepted ISP theory of operation to determine Φ_p . Additionally, we would like to develop a technique that is insensitive to the exact positioning of the collector by examining the current collection as a function of the wall potential. Ultimately, we want to design and implement a robust, long-lived probe suitable for the plasma potential measurements in the scrape-off layer (SOL) plasmas of Alcator C-Mod tokamak, where densities commonly exceed 10^{18} m^{-3} , which makes the emissive probe unsuitable.

II. EXPERIMENTAL APPARATUS

The ISP was studied in a magnetized rf plasma, DIONISOS.¹⁴ The magnetic field was a constant $B = 0.04 \text{ T}$ and the working gas was argon at a neutral gas pressure $P_{Ar} = 0.26 \text{ Pa}$. The rf source was a 3 kW Apex 3013 rf generator from Advanced Energy and the rf power was coupled to the plasma via a Nagoya III antenna¹⁵ through a matching network. The plasma density range was $\sim 10^{16} - 10^{18} \text{ m}^{-3}$. The diameter of the extracted plasma column was $\sim 5 \text{ cm}$. The electron temperature range was 7–15 eV, implying that $\rho_e \sim 0.2 \text{ mm}$.

The main components of the ISP (Fig. 1) were (1) a circular stainless steel “collector,” diameter $d_{COLL} = 4.69 \text{ mm}$; (2) a cylindrical stainless steel “wall,” inner diameter $ID_{WALL} = 6 \text{ mm}$ and outer diameter $OD_{WALL} = 6.8 \text{ mm}$; and (3) cylindrical alumina shield, $ID_{SHIELD} = 6.8 \text{ mm}$ and $OD_{SHIELD} = 11.3 \text{ mm}$. The collector and the

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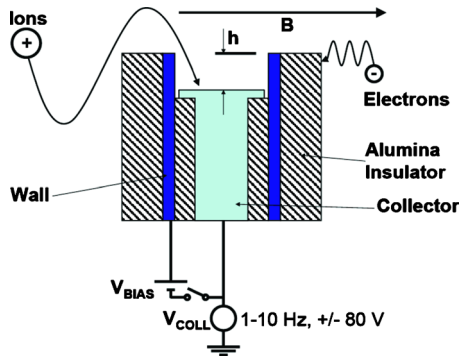


FIG. 1. (Color online) A schematic of the ISP. h =recess height; solid-conductor, hashed-insulator, and cylindrical symmetry.

wall were biased using a bipolar power supply. The wall (V_{WALL}) and the collector (V_{COLL}) potentials were either swept together at the same frequency ($f=1-10$ Hz, triangular waveform, $V_{\text{SWEEP}}=\pm 80$ V) with a constant relative bias between them ($V_{\text{BIAS}}=V_{\text{WALL}}-V_{\text{COLL}}$) or the wall voltage was held fixed and only the collector was swept. The probe entrance was positioned at the center of the plasma column with the collector surface aligned parallel to the magnetic field. The collector recess distance h was varied between 0 and 10 mm.

The plasma potential in the DIONISOS plasma was independently measured with a hot emissive probe at the same location and plasma conditions as the ISP measurements. The emissive probe was a U-shaped loop of thoriated tungsten wire ~ 1 cm long and $125 \mu\text{m}$ in diameter. The filament was heated by passing a dc current (I_{dc}) through it. The emissive probe was operated in the hot emission regime.² When the floating potential of the probe stopped changing as a function of I_{dc} (typically, $I_{\text{dc}} > 2$ A), then $V_{\text{F}} \sim \Phi_{\text{P}}$ (within $1 T_{\text{e}}/e$).

III. EXPERIMENTAL RESULTS AND DISCUSSION

The plasma potential can be determined by examining a current-voltage (I-V) characteristic of the probe collector as a function of the wall (not the collector) potential. In the simplest picture, no ion is electrostatically allowed to enter the probe volume once the wall potential is raised above the plasma potential; therefore, Φ_{P} can be determined as the wall potential at which the collected current vanishes. Figure 2 shows two typical I-V curves where the wall and the collector were both swept simultaneously with a constant bias ($V_{\text{BIAS}}=V_{\text{WALL}}-V_{\text{COLL}}$) between them. The I-V characteristic of the wall was constant and similar to a regular Langmuir probe trace with $I_{\text{SAT}}=0.007$ A $\ll I_{\text{e-SAT}}=0.21$ A and $T_{\text{e}}=7$ eV. The plasma potential, determined by the emissive probe, was ~ 15 V. The collector current remains in the ion collection regime at all times when the bias voltage is positive ($V_{\text{WALL}} > V_{\text{COLLECTOR}}$) by 5–10 V. The current drops to zero once the wall potential is raised above the plasma potential. If the bias voltage is negative ($V_{\text{WALL}} < V_{\text{COLLECTOR}}$), one often measures substantial electron current for $V_{\text{WALL}} < \Phi_{\text{P}}$, but which also goes to zero when $V_{\text{WALL}} > \Phi_{\text{P}}$. Using this technique, we verified Φ_{P} measurements against emissive probe results in DIONISOS

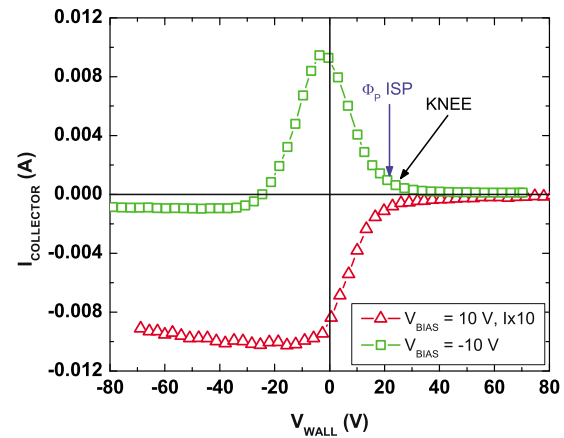


FIG. 2. (Color online) ISP collector current as a function of the wall potential for two cases: $V_{\text{WALL}} > V_{\text{COLLECTOR}}$ (triangles) and $V_{\text{WALL}} < V_{\text{COLLECTOR}}$ (squares). $P_{\text{rf}}=1600$ W and $h=-5$ mm.

over a wide range of densities and plasma regimes (Fig. 3). Note that the hot emissive probe does not float at exactly the plasma potential; however, its V_{F} is typically within $\sim 1 T_{\text{e}}/e$ depending on the plasma density and temperature.^{3,16} The main source of error in the ISP measurements is due to the uncertainty of the “knee” location in the collected current in the vicinity of $V_{\text{WALL}}=\Phi_{\text{P}}$. The width of the knee is typically ~ 5 V, meaning that the plasma potential measurements between the two probes are in good agreement. We further examine the ion and electron saturation currents on the probe collector at fixed wall voltages. Figure 4 shows several I-V curves at four different constant wall voltages: $V_{\text{WALL}}=-20, -10, +10,$ and $+25$ V. We observed that both the ion and electron saturation currents drop to zero once the wall voltage exceeds the plasma potential, consistent with the results in Fig. 2. The disappearance of the collector current is independent of the shape of the collector; the same results were obtained with a conical, ball-penlike collector.¹² The plasma potential measured with the ISP is also insensitive to the exact recess distance of the collector, unlike the standard ISP theory where the collector must be precisely positioned at $h \sim 2$ mm to balance the electron and ion saturation currents.⁶ Note that the maximum measured electron current far exceeds the current expected from a

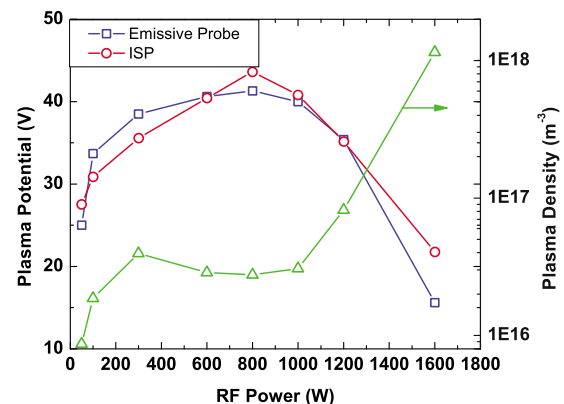


FIG. 3. (Color online) Comparison of plasma potential measurements between ISP and emissive probe in DIONISOS as a function of rf power. Plasma density is also plotted.

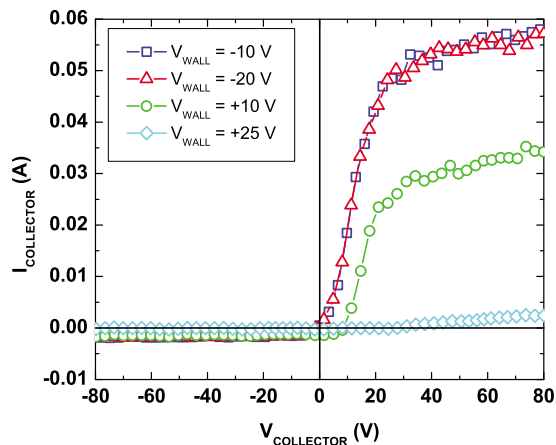


FIG. 4. (Color online) ISP collector current as a function of the collector potential at four different constant wall potentials. $P_{rf}=1600$ W and $h=-5$ mm.

simple gyromotion of the electrons; the recess distance of the collector is tens of ρ_e 's and yet the electron current remains much greater than the ion current. It is sometimes speculated in the literature that the source of the electrons at the collector surface is due to the secondary electron emission from the wall.¹⁷ However, our results show that the electron collection disappears for $V_{WALL} \geq \Phi_P$ and $I_{WALL} = I_{e-SAT}$, implying that the source of the electrons is not secondary emissions from the wall.

The ion collection curve for the case of $V_{BIAS}=10$ V (Fig. 2) can also provide us with additional information on the perpendicular ion temperature. An exponential fit to the decaying part of the curve, similar to the technique used to estimate the electron temperature with Langmuir probes,¹ gives us $T_{i,\perp} \sim 10$ eV. The high $T_{i,\perp}$ in helicon argon plasmas was reported elsewhere,^{18,19} where the authors used laser induced fluorescence to measure the ion temperature. The authors reported $T_{i,\perp}$ in excess of 1 eV, depending on the magnetic field, the rf power, and the frequency of the rf source.

The high (>1 mA) measured collector current in the ISP appears to exceed the maximum allowed space-charge limited current if only ions exist in the probe volume.^{20,21} A simple one-dimensional estimate of the Child–Langmuir current carried by singly charged argon ions between a potential difference of 40 V, over a distance of 5 mm, and collected over a circular electrode of 5 mm in diameter gives $I_{COLLECTOR} \sim 1.7 \mu A$, which is three orders of magnitude lower than the measured current. The Child–Langmuir current limit is enhanced by treating the problem in two dimensions and by considering the nonzero velocity of the ions;^{22,23} however, the total enhancement in $I_{COLLECTOR}$ due to these effects is still less than one order of magnitude. It seems necessary to involve electrons in the probe volume,

perhaps by $E \times B$ drift, to explain the results. This also places in question $T_{i,\perp}$ measurements; however, Φ_P results appear robust.

IV. CONCLUSION

The ISP appears to be a viable, robust, and long-lived alternative to the emissive probe as a plasma potential diagnostic in magnetized high density plasmas. We developed a new method to measure the plasma potential with the ISP that is independent of the precise position and shape of the collector: the plasma potential is equal to the wall potential when charge current on the probe collector vanishes. The ISP measurements show good agreement with emissive probe results over a wide range of densities and regimes in DIONISOS.

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