A resistively heated CeB$_6$ emissive probe

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The plasma potential, $V_p$, is a key quantity in experimental plasma physics. Its spatial gradients directly yield the electrostatic field present. Emissive probes operating under space-charge limited emission conditions float close to $V_p$ even under time-varying conditions. Throughout their long history in plasma physics, they have mostly been constructed with resistively heated tungsten filament's. In high density plasmas ($>10^{12}$ cm$^{-3}$), hexaboride emitters are required because tungsten filaments cannot be heated to sufficient emission without component failure. A resistively heated emissive probe with a cerium hexaboride, CeB$_6$, emitter has been developed to work in plasma densities up to $10^{13}$ cm$^{-3}$. To show functionality, three spatial profiles of $V_p$ are compared using the emissive probe, a cold floating probe, and a swept probe inside a plasma containing regions with and without current. The swept probe and emissive probe agree well across the profile while the floating cold probe fails in the current carrying region. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4921838]

I. INTRODUCTION

The reliable measurement of the plasma potential, $V_p$, is necessary to characterize the electrostatic fields in plasmas. In 1923, Irving Langmuir proposed two methods of measuring $V_p$ using electron collecting or emitting probes.\(^1\) Since then, the voltage-swept Langmuir probe and emissive probe have become mainstays in plasma physics. The collecting probe method presents various theoretical and practical limitations when measuring $V_p$, especially in the presence of rapid fluctuations of plasma parameters.\(^2,3\) This article presents the design of an emissive probe using CeB$_6$, which in floating configuration can effectively operate under such conditions.

The primary limitation of plasma potential measurements using swept probes is the speed with which the probe voltage can be swept relative to the time variation of parameters. In cases where variations are too fast or performing a voltage sweep is impractical, the floating potential, $V_f$, of the probe is occasionally used as a proxy for $V_p$ with the assumption that $V_f$ tracks $V_p$. The difference between $V_f$ and $V_p$ is then characterized by the formula

$$V_p = V_f + \alpha \frac{T_e}{e},$$

where $T_e$ is the temperature of the electron fluid and $\alpha$ is a parameter characterizing the probe sheath. The parameter $\alpha$ has theoretical values ($\alpha \sim 2-4$) for a cold probe in a Maxwellian plasma depending on the sheath geometry, the presence of a magnetic field, and the ion mass.\(^2,3\) It can be calculated from an appropriate model or experimentally determined for each probe using a calibration measurement, i.e., a swept probe measurement. The sheath also has a capacitive effect on the measurement of time dependent phenomena due to the slower response to ions during negative potential swings than to electrons during positive swings. The ability of a hot probe to emit electrons substantially changes the sheath characteristics.\(^4\) In the limit of large emission, the floating potential of the emissive probe has the same relation between $V_p$ and $T_e$ as in Eq. (1). The factor $\alpha$ can be determined using a variety of models which result in $\alpha \sim 1.5$–8 Hobbs and Wesson determined the potential drop across the sheath of a planar emitting surface using a fluid model to be $1.02 T_e$.\(^3\) Ye and Takamura developed an analytic model taking space charge effects into account that resulted in $\alpha = 0.99$ for a Helium plasma.\(^6\) The kinetic models of Schwager and Sheehan\(^7,8\) also predict order unity $T_e$ corrections to floating emissive probes. For more detailed descriptions of these models, the reader is referred to Refs. 5–8. These models do not include the effects of magnetic fields, which modify the effective emission and collection areas of a probe. This should only become problematic for wire emissive probes oriented parallel to the magnetic field.\(^9\) The efficacy of the different methods of measuring $V_p$ using emissive probes in various plasma parameter regimes has been extensively studied\(^9,10\) and the reader is referred to those and similar studies for a discussion of the differences in the methods. These models all agree that the emissive probe tracks the plasma potential more closely than a cold probe by reducing the dependence of the sheath drop on local plasma parameters.

Until recently, most emissive probes comprised resistively heated filaments of thoriated tungsten wire (e.g., Refs. 11 and 12). The basic design requirement of an emissive probe is that it emit an electron current comparable to the particular plasma’s electron saturation current, $I_{sat}$, at a structurally safe temperature determined approximately from the Richardson-Dushman equation

$$J = AT^2 e^{-\phi/k_BT},$$

where $J$ is the emitted current density, $A$ is the Richardson constant, $T$ is the material temperature in Kelvin, $\phi$ is the material work function in eV, and $k_B$ is Boltzmann’s constant.

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In a $2 \times 10^{12} \text{cm}^{-3}$, 1 eV plasma, $I_{\text{ex}} \sim 19 \text{A/cm}^2$, a tungsten probe with Richardson constant 74 A/K$^2$ cm$^2$ and a work function of 4.55 eV would need to operate at $\sim 3000 \text{K}$ to emit a comparable current.\(^\text{13}\) At this temperature, the tungsten filament is prone to breaking. On the other hand, cerium hexaboride, CeB$_6$, with a Richardson constant of 3.6 A/K$^2$ cm$^2$ and a work function of 2.59 eV, would need to operate at a temperature of $\sim 2200 \text{K}$.\(^\text{14}\) At this temperature, CeB$_6$ is mechanically stable and is thus a more suitable emitter for high density plasmas. Lanthanum hexaboride, LaB$_6$, has a similar emissivity to CeB$_6$, which has long been known,\(^\text{14–16}\) and has been successfully exploited for plasma sources.\(^\text{17}\) Additionally, an emissive probe has been developed that uses a high power laser to heat a LaB$_6$ emitter.\(^\text{18,19}\) In contrast, the probe reported herein is resistively heated using simple, cheap components and was designed to attach to readily available, motorized probe drives.

During development, sintered pieces of both LaB$_6$ and CeB$_6$ were considered—sintered hexaborides having the benefit of being more economical than their single-crystal forms. LaB$_6$ and CeB$_6$ have comparable work functions, and LaB$_6$ has a higher accepted Richardson constant.\(^\text{14}\) However, the accuracy of the Richardson-Dushman equation is highly dependent on the reproducibility of materials.\(^\text{20}\) Thus, it is not worthwhile to distinguish the two very similar materials on this basis alone, where the sintering process induces enough variability to question the value of the distinction. The choice of sintered CeB$_6$ as the emitter material was dictated by longevity at emission temperatures. From initial tests, which trend to agree with published studies of evaporation rates,\(^\text{21}\) CeB$_6$ was found to maintain its structural integrity longer than LaB$_6$.

To the authors’ knowledge, no hexaboride has been implemented in a resistively heated probe configuration that can operate in $>10^{12}$ cm$^{-3}$ plasmas. The probe presented here provides a simple, low-cost measurement of the plasma potential with good spatial resolution—especially advantageous where optical access for laser power delivery is limited. It is hoped that this article and its suggestions for design improvements will benefit other experimentalists who need to adapt it to their own constraints. Benchmarking of the emissive probe was conducted at the Basic Plasma Science Facility (BaPSF) at UCLA in the upgraded Large Plasma Device (LAPD).\(^\text{22}\)

II. EXPERIMENTAL DEVICE

The LAPD is a turnkey plasma source dedicated to basic physics. Its vacuum vessel is 1 m in diameter and 20 m long. The vacuum chamber is surrounded by electromagnets that produce an axial magnetic field of up to 3.5 kG (0.35 T). For these experiments, the field was set to 1 kG (0.1 T) and the chamber is filled with a mixture of H$_2$ and He gases with partial pressures of $9 \times 10^{-6}$ and $4.5 \times 10^{-5}$ Torr (1.2 and 6 mPa), respectively. A BaO-coated nickel cathode paired with a semi-transparent mesh anode 51 cm away is located on one end of the device. A 10 ms discharge with a 1 Hz repetition rate creates a quiescent, zero-current plasma column outside the cathode-anode source region, hereinafter called the BaO plasma, with typical parameters of $n_e \sim 10^{12}$ cm$^{-3}$, $T_e \sim 4$–8 eV, and a diameter of $\sim 40$ cm. A 20 cm $\times$ 20 cm LaB$_6$ cathode has recently been installed in the opposite end of the machine with its anode’s location variable along the machine axis. In addition, a 10 cm diameter LaB$_6$ cathode with a dedicated anode has been developed for insertion at variable locations along the LAPD axis.\(^\text{23}\) The LaB$_6$ cathodes operate simultaneously with the BaO cathode and can produce plasmas with $n_e \sim 10^{13}$ cm$^{-3}$ and $T_e \sim$ 8–12 eV.

Figure 1 shows a schematic of the experimental setup that was used in benchmarking the emissive probe. A 10 cm diameter LaB$_6$ cathode was located 11 m away from and facing the BaO cathode. The LaB$_6$ discharge started 5 ms after the BaO discharge and lasted 5 ms, at which point both discharges were stopped. The different cathode sizes created a spatially non-uniform, current-carrying plasma column, hereinafter called the LaB$_6$ plasma, embedded within the BaO plasma. The pressure gradient at the interface between the magnetized LaB$_6$ and BaO plasmas generates an electrostatic field for comparison of emissive probe measurements to those of cold floating probes and swept probes.

In addition to providing measurements of the fundamental plasma parameters, $T_e$, $n_e$, and $V_p$, the I-V curves of oppositely directed planar probes (A $\sim 1$ mm$^2$) provided qualitative electron distribution functions, $f(x,v_z)$. Figure 2 shows $f(x,v_z)$ taken from 500 $\mu$s sweeps starting 2 ms after the start of the LaB$_6$ discharge. The contours are of constant phase-space density clearly showing the increase in density and the presence of a population of non-Maxwellian electrons carrying current in the LaB$_6$ plasma. Figure 2 also clearly shows that distribution functions containing high-energy electron tails are confined to approximately the diameter of the 10 cm LaB$_6$ cathode at this axial location along the machine.

III. CONSTRUCTION OF THE CeB$_6$ PROBE

The assembled emissive probe is shown in Fig. 3(a), and a cut-away view is shown in Fig. 3(b). The CeB$_6$ emitter is held in place by carbon tweezers composed of two class
FIG. 2. Electron energy distribution function, $f(x, v_z)$, 1.6 m from the LaB$_6$ cathode. The left side of the $f(x, v_z)$ is facing the BaO cathode, and the right side is facing the LaB$_6$ cathode. There is a visible high-energy tail facing the LaB$_6$ cathode. Adjacent contours are separated by powers of $e^{1/2}$ in arbitrary units.

three levers (fulcrum-force-load). The fulcrum is a piece of alumina resting between the levers on the left side of the carbon in Fig. 3(b). A hand-tightened steel screw that slips through holes in the bases of the levers [Figs. 3(b) and 3(c)] provides the torque to hold the CeB$_6$ in place. The screw is electrically isolated from one of the levers by an alumina collar. To facilitate a stable electrical contact between the carbon and the emitter, a triangular groove is carved into the end of the tweezers, and the base of the CeB$_6$ emitter is then shaped into a right rectangular prism to fit therein (see inset Fig. 3(a)). The tip of the emitter in contact with the plasma is cylindrical with a length of $\sim 0.76$ mm and a radius less than 0.56 mm. Power is delivered to this assembly via high current AWG 10 wires along the probe shaft. Nickel lugs are used to fasten the wires to the carbon levers using the same steel screw that provides the gripping force on the emitter.

Between the lugs and the emitter, the carbon levers are shaped to bow outwards to avoid an electrical short from bending of the carbon under the torque of the lever. Near the tip, the carbon bows back inward to make contact with the emitter. The tip of the carbon tweezers and the emitter base is covered by a high-temperature AX05 Boron Nitride (BN) cap. The cap contains a hole through which only the emitter tip protrudes. A piece of Rescor™ 310M silica foam slip-fits over the BN cap. The foam serves the dual purpose of insulating the carbon levers from the plasma and acting as a thermal barrier between the CeB$_6$ tip and the clamping assembly. The silica foam is clamped into place by set screws located in the BN foam holder. The tweezer clamping mechanism is insulated by the BN housing. A BN washer and the foam holder clamp the base of the carbon tweezers to prevent them from translating due to thermal expansion of the heater components. The BN washer, BN housing, and BN foam holder are held in place by two 0-80 threaded rods that screw into the aluminum (Al) cone seen in Fig. 3(b). The Al cone secures the assembly to the probe shaft.

IV. OPERATION OF THE PROBE

A circuit diagram of the heating and measurement circuits is shown in Fig. 4. Heating of the CeB$_6$ is accomplished using a 150 kHz power inverter, transformer-coupled to drive the necessary current in the floating probe circuit. This frequency was chosen to reduce the transformer size so as to minimize the capacitive load on the leads connected to the probe tip; however, the inductive impedance of the probe’s leads requires a bridge rectifier to ensure efficient power delivery to

FIG. 3. (a) A photo of the assembled probe. The inset photo is a magnified view of the uncovered CeB$_6$ tip showing the carbon clamp. (b) Cutaway schematic of the probe. (c) 90° rotated close-up of the clamping assembly.
FIG. 4. Heating and measurement circuits for the emissive probe. The sweeping circuitry shown in the dashed-line box is disconnected during floating measurements.

the emitter. The transformer consists of 8 Fair-rite brand type 77 E42/15 ferrite cores, with a 5-turn primary and a single-turn copper strap as the secondary. When taking measurements, the heater circuit is shut off for the duration of the plasma discharge to prevent signal contamination by the inverter’s RF output.

With the emitter tip located in the region of highest plasma density, the input power is incrementally increased while obtaining I-V curves using the sweeping circuitry (dashed box, Fig. 4). After each increase in power, the probe tip is allowed to equilibrate its emission for at least 30 s. If the probe had been exposed to air or other contaminants for extended periods of time or is undergoing its first heating phase, extra time is required to condition the surface. Surface contaminant removal was observable during initial heating of the probe (power <100 W) in increases of the emission current over a few minutes at a fixed power and voltage bias. Once the operating point is established, the sweeping circuitry is disconnected.

Figure 5 shows I-V curves averaged over 60 shots for six different heater powers. Heater power refers to the DC power delivered to the probe. At full power (curve 6), the typical current through the probe tip was around 18 A. As the heater power increases, the emission current climbs. The slope of the I-V curve near \( I = 0 \) increases with heater power and shifts the floating potential higher towards the plasma potential (curves 2-4). The steepening of the curve near the floating potential eventually saturates and is accompanied by a change in the temperature limited region of the curve at large negative biases (curves 5 and 6). This saturation in the floating potential occurs due to space charge limitations and is the primary indicator that emission is sufficient under the given plasma conditions.

FIG. 5. I-V curves at constant plasma density for several heater powers.

Another way to see the space charge limited behavior clearly is through emission I-V curves under different plasma conditions at a fixed heater power. Emission is calculated by subtracting from the emission curves \( I_{esat} \) at full power divided by the ratio of \( I_{esat} \) to ion saturation current, \( I_{isat} \), with no input power to account for modification of the probe’s surface area. Figure 6 shows the curves for 5 different densities after accounting for this generally small correction. Because \( V_p \), \( n_e \), and \( T_e \) all change from one curve to another, the voltage sweeps have been aligned such that emission begins at the same voltage, \( V_{em} \). Under the assumption of temperature limited operation, i.e., insufficient thermionic emission, the emission I-V trace would rise sharply for initially decreasing voltage and plateau for large biases. The steadily increasing emission for large bias and the monotonic increase in emission (–50%) with increasing electron density are directly indicative of space-charge limited operation.

A feature to note in Fig. 5 is the increase in \( I_{esat} \) with heating power. A partial contribution to this effect has been observed previously in other emissive probes where it was attributed to surface conditioning.\(^{12}\) In this case, an additional and potentially dominant contribution is from sliding of the
boron nitride cap relative to the exposed CeB₆ emitter due to differences in thermal expansion of components. This alters the exposed area for electrons to be collected from and emitted into the plasma. The carbon tweezers are fixed relative to the shaft by the BN housing shown in Fig. 3(c) to help minimize this effect. Typical indicators of sufficient emission are the ratio of emission to electron collection current or saturation of the floating potential which are independent of or at most weakly dependent on probe area. Thus, the change in the electron saturation current with power is not expected to alter the quality of the measurements made by the probe.

V. BENCHMARKING THE EMISSIVE PROBE

The emissive probe in floating configuration was benchmarked against standard measures of \( V_p \) with cold probes. A double-sided Langmuir probe (\( A \sim 2 \text{ mm}^2 \)) provided floating measurements, \( V_{fj} \), and swept measurements. The swept plasma potential, \( V_{p,sw} \), was taken from the location of the knee on a semi-log plot of the probe’s I-V curves which comprised 500 \( \mu \text{s} \)-long voltage sweeps averaged over 30 shots. Benchmarking data were taken every 0.5 cm over a span of 30 cm across the plasma column, in a plane 1.6 m downstream of the LaB₆ cathode. The density was \( n_e \sim 1.2 \times 10^{12} \text{ cm}^{-3} \) within the BaO plasma and peaked at \( 6.6 \times 10^{12} \text{ cm}^{-3} \) within the LaB₆ plasma. For \( V_{fj} \) and the emissive probe floating potential, \( V_{ep} \), 10 shots were averaged at each location. Figure 7(a) shows the profiles of the three potential measurements. The profiles exhibit the same qualitative behavior with respect to 3 distinct regions. These regions are the lower density BaO plasma (\( x < -3 \text{ cm} \), \( x > 6 \text{ cm} \)), the current-carrying LaB₆ plasma (\( -1 < x < 4 \text{ cm} \)), and the transition region between them where the density gradient is largest. The potential profiles are flat in the BaO plasma with a depression in the LaB₆ plasma. Total changes in potential amount to \( -11 \text{ V}, -20 \text{ V}, \) and \( -32 \text{ V} \) for \( V_{p,sw}, V_{ep}, \) and \( V_{fj} \), respectively, with the bulk of the decrease occurring within the transition region. The drops in floating potentials are different because of the presence of a temperature gradient and its effect on the probes’ sheaths according to Eq. (1).

Figure 7(b) shows the profile of \( T_e \) across the plasma as measured by the swept Langmuir probe. The profile is the average of 5 temperature profiles measured during stable operation of the LaB₆ plasma and are smoothed over 5 points using a boxcar average. As can be seen from the figure, \( T_e \) in the BaO plasma is about 6 eV, and in the LaB₆ plasma, \( T_e \) peaks at 12 eV. These values are substituted into Eq. (1) along with appropriate values for \( \alpha \) to calculate the corrected plasma potential.

Figure 7(c) shows the calculated plasma potentials of the emissive and cold floating probes, \( V_{p,ep} \) and \( V_{p,fj} \). \( V_{p,sw} \) is also shown for comparison, though it remains unchanged from Fig. 7(a). For cold floating probes, \( \alpha \) is theoretically related to \( I_{esat} \) and \( I_{sat} \) via \( \alpha \approx \ln I_{esat}/I_{sat} \). In the LAPD, with a helium plasma and equal ion and electron probe collection areas, \( \alpha \approx 4 \). However, in this experiment, \( I_{esat} \) and \( I_{sat} \) were directly measured, and \( \alpha \) was found to be around \( 2.06 \pm 0.17 \), in poor agreement with the idealized model. For the emissive probe, \( \alpha = 1 \) was used.

As can be seen from Fig. 7(c), the potential from the emissive probe, \( V_{p,ep} \), compares well with that from the swept measurement, \( V_{p,sw} \). The main discrepancy lies in the left transition region where \( V_{p,sw} \) is higher than \( V_{p,ep} \). In this region, density fluctuations and drift waves due to the density gradient can move the measured location of the knee of the I-V curve. This density aliasing is partially reflected in the asymmetry between the transition regions in the \( V_{p,sw} \) profile. The large averaging of the sweeps was meant to reduce this particular effect on the swept data, but it was unavoidable in the transition region. Note that this is not an issue for the floating measurements; \( V_{p,ep} \) and \( V_{p,fj} \) largely agree even as the probes enter the transition region from the BaO. Only in the

FIG. 7. (a) \( V_{p,sw} (-\cdot-), V_{ep} (-\cdot-), \) and \( V_{fj} (-\cdot-) \) profiles, (b) \( T_e \) profile, and (c) calculated \( V_{p,ep} \) and \( V_{p,fj} \) profiles using Eq. (1). Boundaries of BaO, LaB₆, and transition region (T) shown for clarity.
center of the LaB$_6$, where the density fluctuations subside and the bulk of the current and non-Maxwellian electrons exist, do $V_{p,e}$ and $V_{p,f}$ disagree. This is not surprising owing to the sensitivity of a non-emitting surface to particle flows. Both cold and emissive probes adjust their potential to neutralize currents, but the deviation from the plasma potential will be more for the cold probe to reflect the surplus of fast particles. This behavior is not properly accounted for by the use of Eq. (1) for a cold probe. Where no large gradients, currents, or non-Maxwellian populations exist in the BaO plasma, all three measurements spatially track the plasma potential.

VI. DISCUSSION

Though the benchmarking was done in a relatively stationary plasma with only low frequency perturbations, the primary benefit of the floating emissive probe is its high frequency response. Sheath response times of an emissive probe are on the order of electron transit times, which in the benchmarked plasmas are less than a nanosecond. Thus, the frequency response of the measurement is limited mostly by the stray capacitance of the wiring. For the circuit used in Fig. 4, the frequency response was measured to be flat up to about 10 MHz using a signal generator and an external resistance that approximated the connection resistance of the probe to the plasma. This response is particularly useful for studies of phenomena occurring faster than the ion cyclotron period in magnetic fields in excess of 1 kG (0.1 T).

Bousselin et al. recently noted that density fluctuations can modulate the sheath drop in floating emissive probe measurements. They measured this effect as a function of probe emission starting from no emission. In this study, the amplitude of the measured fluctuation signal dropped markedly as the probe was heated, which would seem to corroborate their findings. The mechanism of their density aliasing, however, was the independence of probe emission on the local plasma density. The probe described here can quite readily modulate the sheath drop in floating emissive probe measurements. They measured this effect as a function of input power, but at 200 W the probe’s components failed first and the tip was replaced rather than re-used.

It is hypothesized that several material improvements could be made that would most readily increase the functional lifetime of the probe as well as lead to a reduction in its perturbative size. Molded alumina housing components and cap might allow reduced size and evacuation issues associated with the use of BN. A different choice in tweezers materials would also make a significant improvement in the probe lifetime. The alternative material would have to be strong enough to maintain its shape under thermal and mechanical stress and also not disrupt the boride structure of the emitter—precluding the use of most refractory metals, although this can be somewhat mitigated by first carbonizing the CeB$_6$ contact area. Finally, wiring with a higher melting point might serve better than copper, although efficacy of power delivery could be somewhat reduced by the increased resistance. Furthermore, copper’s relatively low melting point makes it necessary to have long, thin tweezers to prevent heat conduction. Wiring that can survive at 1500 C or more, carry 20 A, and not introduce deleterious capacitance to the circuit would allow for a much simpler and smaller tweezer design.

VII. CONCLUSION

In conclusion, the design of a resistively heated, relatively simple, and inexpensive emissive probe has been presented as well as its ability to measure the plasma potential in high density ($n_e \sim 10^{13}$ cm$^{-3}$) plasmas. Measurements of plasma potential using the emissive probe and the usual swept Langmuir probe technique produce similar spatial profiles. In contrast, the simple floating potential of a cold probe has a substantial defect in a current-carrying plasma with non-Maxwellian electrons. In repeatable, pulsed experiments with small temperature gradients, the emissive probe is capable of mm-scale resolution of the electrostatic fields with better frequency response and fidelity than a cold probe. The described probe can operate continuously for days under the conditions useful for diagnostic measurements. Once it
has reached the end of its functional lifetime, it only requires reconditioning or replacement of easily machined pieces. With suggested material improvements, the authors expect functionality might be extended to higher densities or for longer periods of time, making it valuable to the diagnostic arsenal of high density plasma physics.

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