Design of an asymmetrically biased triple Langmuir probe and accompanying diagnostics tool

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Abstract A refined triple Langmuir probe design is described for use in a glow discharge device, which creates plasma by applying a large bias voltage across a neutral gas. The goal is to design a Langmuir probe which can measure the plasma temperature, density, and floating potential to within an order of magnitude while minimizing plasma perturbation. The probe functions in a plasma temperature range of 1-10 eV. First, an overview of the relevant theory is provided, followed by the design assumptions and a derivation of the working regime of the Langmuir probe. This working regime dictates the appropriate branch of Langmuir probe theory whose equations can be used to design the probe and extract the plasma electron temperature, density, and floating potential. Second, the probe's radius, length, and electrode spacing are derived using the applicable branch of Langmuir probe theory. The derived probe radius, length, and electrode spacing are 0.18 mm, 3 mm, and 55 mm, respectively. Third, an overview of the electrical design used to measure the triple probe voltages and currents is described. Finally, a discussion of the limitations and future work is provided, with methods listed to improve the specificity of the relevant theory and the accuracy of the probe measurements.

INTRODUCTION

Recent developments in fusion-based energy have increased the demand for plasma physics research at an undergraduate level. As such, Queen's University is interested in providing a plasma physics undergraduate lab to teach plasma physics in a hands-on environment. This will be done using the Queen's glow discharge device, a type of plasma generator that creates plasma by applying a bias voltage across a neutral gas (H Conrads & M Schmidt, 2000). This article describes the development of an asymmetrically biased triple Langmuir probe (Kozhevnikov et al., 2021). The probe is asymmetrically biased as each of the three probes are biased independently of one another. Langmuir probes are conducting structures inserted into a plasma and biased over a voltage range. The current draw of the probe is plotted as a function of input voltage, and properties of the plasma can be extracted from the resulting I-V curve (Figure 1). These properties include the plasma electron temperature, floating potential, and density (Chen, 2016).

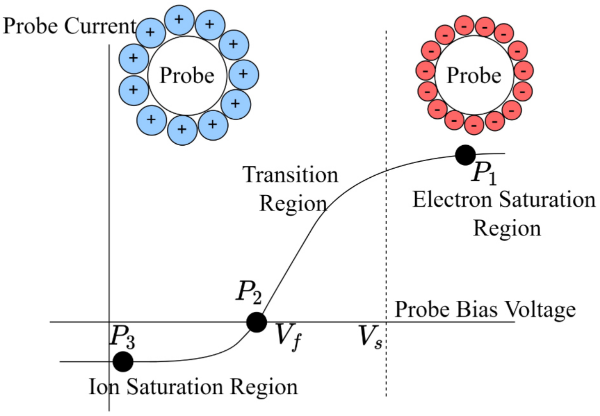

Figure 1 I-V curve showing the placement of the three data points. These three data points will be curve fit to recover the original I-V curve and the recovered I-V curve will be analyzed to extract the plasma temperature, density, and voltage

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Langmuir probes are not universal devices and should be designed with an understanding of the type of plasma they will be measuring (Chen, 2003). As such, this work aims to design a triple Langmuir probe suitable for use in the Queen's University glow discharge device. The advantage of a triple Langmuir probe is its measurement speed (Kozhevnikov et al., 2021). Traditional Langmuir probes must sweep across the voltage range to generate an I-V curve and extract the plasma parameters, whereas triple Langmuir probes measure three points on the I-V curve simultaneously, making them an essential measurement tool for high-speed fusion reactions (Biswas et al., 2015). While glow discharge devices operate in steady state and do not require instantaneous measurement, a triple probe will provide a useful learning tool for students to compare the measurement techniques for both steady state and transient plasmas, and will provide a tangible example of the compromises required to measure high-speed plasmas.

METHODS

Determination of the working regime

The first step in designing a Langmuir probe is to determine the working regime of the plasma, which dictates which branch of Langmuir probe theory is applicable (Hippler et al., 2008). The probe presented here is designed to work in the Queen's University glow discharge device. Steady state glow discharge devices are a type of plasma generator that apply a direct current voltage across a neutral gas to create a plasma (DeWit, 2021). Furthermore, a diagram of the triple probe design is presented in Figure 2.

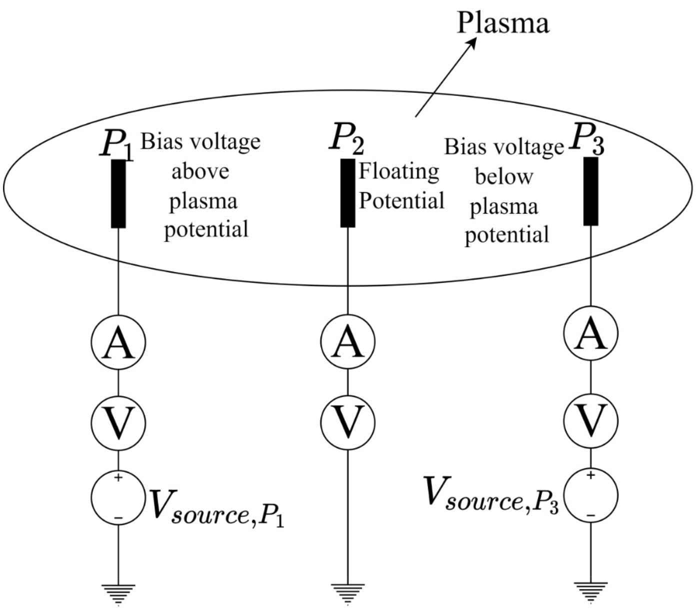


Figure 2 The triple probe design. The probe consists of three independent single probes for greater control over the acquisition of data.

When a biased Langmuir probe is inserted into plasma, a sheath of ions or electrons having a charge opposite to the probe bias forms around the probe, effectively shielding it from the bulk of the plasma. The length scale over which this shielding effect operates is known as the Debye length (Chen, 2016). The applicable branch of Langmuir theory depends on the geometric relationship between the probe radius r_p and the Debye length λ_D. The sheath is assumed to be negligible if,

$$\lambda_D \ll r_p \qquad (1)$$

(Chen, 2009, 2016; Lindner et al., 2023; Tichý et al., 1994). Edward DeWit, who worked previously on the Queen's glow discharge device, measured the Debye length λ_D $(5.7 \pm 0.7) \times 10^{-1}$ mm (DeWit, 2021). Thus, the sheath is negligible if,

$$r_{p,\min} \gg 5.7 \pm 0.7 \times 10^{-1}\ \mathrm{mm}, \qquad (2)$$

DeWit used a probe with a radius $r_{p,DeWit} = 0.16$ mm; however, they recommended reducing the probe radius because the larger probe surface area increased the voltage threshold required to enter the electron saturation region. This leads to the condition that the desired probe radius, $r_{p,desired}$, is constrained as follows:

$$r_{p,\mathrm{desired}} < r_{p,DeWit} < r_{p,\min}. \qquad (3)$$

Equation (1) cannot be satisfied under DeWit's recommendation, and thus sheath thickness must be considered in the design. Orbital Motion Limited (OML) theory applies to the thick sheath regime in a collision-less plasma and will be used to extract the plasma parameters (Tang & Luca Delzanno, 2014).

Design assumptions

The range of plasma potentials V_S experienced by the probe is constrained as:

$$0\ \mathrm{V} < V_s < 500\ \mathrm{V}, \qquad (4)$$

which constrains the maximum voltage at the anode of the glow discharge device. The range of voltage differences between the probe bias voltage V_b and plasma potential V_S is constrained as:

$$10\ V \leq |V_s - V_b| \leq 100\ \mathrm{V}. \qquad (5)$$

The upper bound of Equation (5) was set to ensure no electrical arcing and the lower bound was set to ensure reasonable resolution for the collected data. The electron temperature is constrained to be:

$$1\ eV \leq T \leq 10eV. \qquad (6)$$

It is also assumed that the plasma is collision-less, such that plasma is not colliding within the sheath (Sheridan & Goree, 1991).

Electrode geometry

Electrode geometry refers to a cylindrical electrode of length d and radius r_p. Equation (7) defines the ion and electron saturation currents of the probe:

$$I_{sat} = \frac{2er_pd}{n}\left(\frac{2e|V_s - V_b|}{m}\right)^{\frac{1}{2}}, \qquad (7)$$

where I_{sat} is the ion or electron saturation current, e is the fundamental charge, n is the plasma density, and m is the ion or electron mass, all other variables have been previously defined (Chen, 2016). The triple probe will consist of probes P_1,P_2, and P_3, which will be positively biased, unbiased, and negatively biased with respect to the plasma potential, respectively. Probes P_1 and

P_3 must draw currents above the electron and ion saturation currents, respectively. Drawing a current above the saturation current ensures a fully formed sheath and results in three distinct points for curve fitting (Figure 1).

Electrode spacing

Probe electrodes are separated such that their measurements are independent and no electrical arcing occurs between probes. The probes interact with one another if their sheaths overlap. Equations (8), (9), and (10) yield the sheath thickness s_f, s_-, and s_+ for voltages near the floating potential, at highly negative probe biases relative to the bulk plasma, and at highly positive probe biases relative to the bulk plasma, respectively (Hutchinson, 2002; Sun et al., 2022):

$$s_f \approx 1.02\lambda_D \left(\left(\frac{1}{2}\ln\left(\frac{m_p}{m_e}\right)\right)^{\frac{1}{2}} - \frac{1}{\sqrt{2}}\right)^{1/2} \left(\left(\frac{1}{2}\ln\left(\frac{m_p}{m_e}\right)\right)^{\frac{1}{2}} + \sqrt{2}\right) \tag{8}$$

$$s_- = 0.79\lambda_D \left(\frac{(e|V_s - V_b|)}{T}\right)^{\frac{3}{4}} \tag{9}$$

$$s_+ = 1.26\lambda_D \left(\frac{(e|V_s - V_b|)}{T}\right)^{\frac{3}{4}} \tag{10}$$

where $\frac{m_p}{m_e}$ represents the mass ratio for an electron-proton plasma and all other variables have been defined previously (Proton-Electron Mass Ratio, 2019). These equations will be used to calculate the probe sheath thicknesses and thus extract the electrode spacing.

RESULTS

Mechanical design

Using the plasma density of n ≈ (9 ± 2) x 10^{14} m^{-3} measured by DeWit and the constraints set by Equation (5) and (6), the probe geometry was calculated using Equation (7) (DeWit, 2021). The resulting probe has a radius of 0.18 mm and a length of 3 mm. Note that a standard wire gauge of AWG 27 ($\Phi \approx 0.36$ mm) was used for to simplify manufacturing.
Using Equations (8-10), the Debye length measured by DeWit, and the constraints set by Equations (5) and (6), the electrode spacing Δy was calculated to be 55 mm to allow for a factor of safety of 1.2 in the sheath thickness (DeWit, 2021). Note that the sheath lengths calculated from Equations (8) and (10) were summed to extract spacing as the floating probe will be centered between the biased probes, and Equation (10) yielded a larger sheath than Equation (9).

Electrical design

The chosen electrical design is shown in Figure 3. This circuit measures the current and voltage of the three probes and converts both the current and voltage measurements to 0-5V signals readable by an Arduino's GPIO pins. A low-pass filter was included to avoid aliasing above the Arduino GPIO Nyquist frequency of 5 kHz (Arduino, 2019; DeWit, 2021).

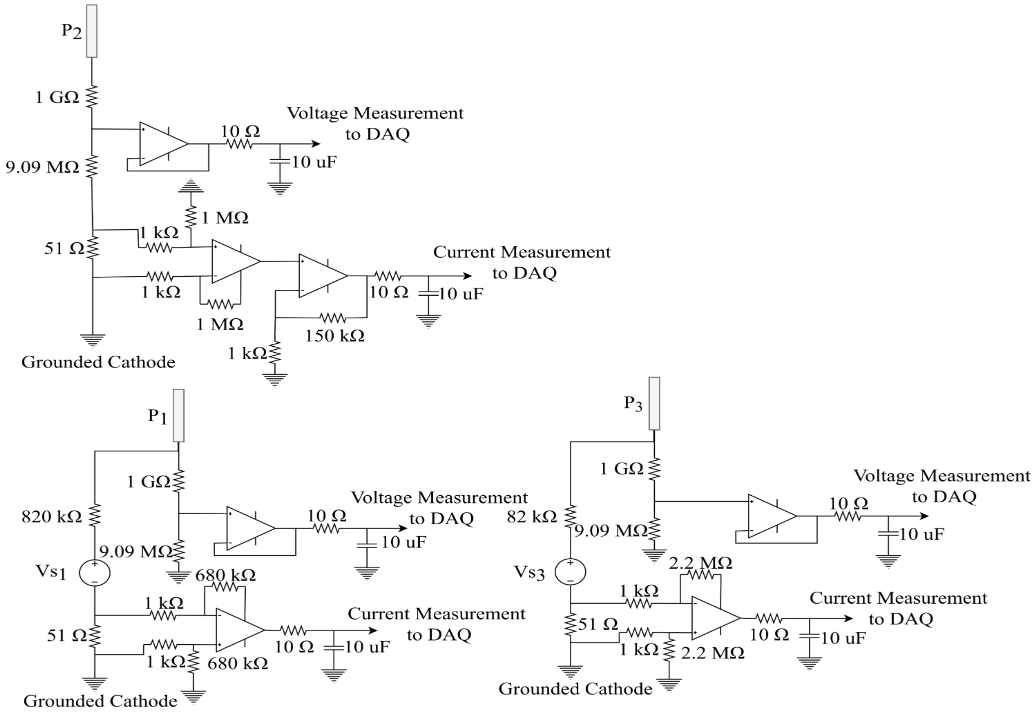


Figure 3 Circuit diagram for the triple probe. P_1 represents the positively biased probe, P_2 represents the floating probe, and P_3 represents the negatively biased probe. These biases are relative to the plasma potential. Each probe has two operational amplifiers which are used in conjunction with resistors to measure the voltage and current of each of the three probes. A current-limiting resistor was used for the three probes to control current influx from the plasma. Voltage dividers were used to attenuate the voltage measurements from the probes to the 0-5V range readable by an Arduino Uno's GPIO pins and extract the probe bias voltage. Current measurement resistors were used to convert the probe voltage into probe current such that it can be plotted on an I-V curve.

A python script utilizing the *PlasmaPy* module was written to extract the signals from the Arduino and re-convert them to the respective voltage and current measurements (*The PlasmaPy Project*, 2023). The I-V curve was extracted by curve fitting the three measured points using Equation (11),

$$I = I_0 + a\ln\left(a + (V - V_0) + \sqrt{1 + (V - V_0)^2}\right), \tag{11}$$

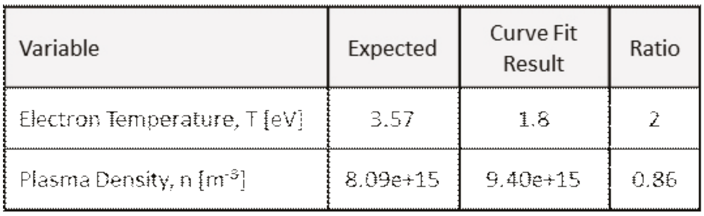
where I_0, V_0 are translation correction factors and a,b are curve fitting parameters. The plasma parameters were extracted using Equations (12-14).

$$T = \left[\frac{d(\ln I_e)}{dV_b}\right]^{-1} \tag{12}$$

$$n = \frac{I_{sat}}{2er_p d}\left(\frac{m}{2e|V_s - V_b|}\right)^{\frac{1}{2}} \tag{13}$$

$$V_s = V_f + \frac{T}{2e}\ln\left(\frac{2m_p}{m_e}\right) \tag{14}$$

The curve-fitting program was tested using publicly available data, and the results are shown in Table 1 (Pace, 2015). The program extracts plasma parameters within an order of magnitude of the data's reported results, as desired.



Variable	Expected	Curve Fit Result	Ratio
Electron Temperature, T [eV]	3.57	1.8	2
Plasma Density, n [m^{-3}]	8.09e+15	9.40e+15	0.86

Table 1 Algorithm test results. The program curve fits to Equation (11) and then uses the PlasmaPy python module to extract the plasma parameters from the I-V curve. This data is for a single swept Langmuir probe. Three points were chosen to be curve fit and processed in the analysis: one in the ion saturation region, one in the electron saturation region, and the floating potential point. The data was obtained from David Pace, the Deputy Director of the DIII-D National Fusion Facility, at General Atomics.

DISCUSSION

Limitations

DeWit measured collisions within the plasma sheath, however they are not considered in this paper and will need to be evaluated in future work (DeWit, 2021). This can be done by adding correction factors using Modified Talbot-Chou theory (Bose et al., 2017; Tichý et al., 1994). This theory corrects for the additional current draw due to charged particles colliding within the sheath. These collisions reduce the kinetic energy of incoming particles, which enables the probe to collect more particles and thus draw a greater current. Finally, the sensitivity of the signal conditioning circuit is limited for low voltage measurements. Testing should be conducted to see if this sensitivity is sufficient to repeatably measure the plasma parameters to within an order of magnitude of their true value. If this sensitivity is insufficient it is recommended to use instrumentation amplifiers in place of operational amplifiers as they provide better sensitivity for low voltage measurements.

Conclusions

The purpose of this research was to design a triple Langmuir probe to operate in the Queen's glow discharge device to educate plasma physics at an undergraduate level. The final design is a triple Langmuir probe comprised of two independently biased probes (P_1, P_3) and an unbiased probe (P_2). All probes are 0.18 mm in radius (r_p) and have an exposed electrode length of 3 mm (d). The probes are arranged in a vertical line, with the floating probe placed between the two biased probes. Vertical alignment was chosen because it is assumed that the radial variation of plasma parameters is negligible compared to the axial variation of plasma parameters. The probe electrode spacing is 55 mm (Δy). This spacing ensures the probe sheaths do not overlap, which could cause an electrical arc or introduce errors into the measurement of the plasma parameters. A signal conditioning circuit has also been designed to condition the high voltage signals from the probes to be read by an Arduino Uno. This circuit successfully conditions the high voltage probe signals to a 0-5V signal to be read by the Arduino. The diagnostics tool software has been written to communicate with the Arduino and extract the plasma parameters from the probe signals using equations derived from orbit motion limited (OML) theory.

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CONFLICT OF INTERESTS

The authors state no conflicts of interest.

REFERENCES

[1] Arduino. (2019, July 2). The Arduino analogRead() Function. Arduino Functions. https://www.arduino.cc/reference/en/language/functions/analog-io/analogread/

[2] Biswas, S., Chowdhury, S., Palivela, Y., & Pal, R. (2015). Effect of fast drifting electrons on electron temperature measurement with a triple Langmuir probe. Journal of Applied Physics, 118(6), 063302. https://doi.org/10.1063/1.4928404

[3] Bose, S., Kaur, M., Chattopadhyay, P. K., Ghosh, J., Saxena, Y. C., & Pal, R. (2017). Langmuir probe in collisionless and collisional plasma including dusty plasma. Journal of Plasma Physics, 83(2), 615830201. Cambridge Core. https://doi.org/10.1017/S0022377817000289

[4] Chen, F. F. (2003). Lecture Notes on Langmuir Probe Diagnostics. University of California, Los Angeles. http://www.seas.ucla.edu/~ffchen/Publs/Chen210R.pdf

[5] Chen, F. F. (2009). Langmuir probes in RF plasma: Surprising validity of OML theory. Plasma Sources Science and Technology, 18(3), 035012. https://doi.org/10.1088/0963-0252/18/3/035012

[6] Chen, F. F. (2016). Introduction to Plasma Physics and Controlled Fusion (2nd ed., Vol. 1). Springer International Publishing.

[7] DeWit, E. (2021). Measurements of a DC Gas Discharge [Master's Thesis, Queen's University]. https://qspace.library.queensu.ca/bitstream/handle/1974/28904/DeWit_Edward_B_202105_MASC.pdf?sequence=3

[8] H Conrads & M Schmidt. (2000). Plasma generation and plasma sources. Plasma Sources Science and Technology, 9(4), 441. https://doi.org/10.1088/0963-0252/9/4/301

[9] Hippler, R., Kersten, H., Schmidt, M., & Schoenbach, K. H. (2008). Low temperature plasmas. Eds R Hippler et al, Berlin: Wiley, 787.

[10] Hutchinson, I. H. (2002). Principles of Plasma Diagnostics (2nd ed.). Cambridge University Press; Cambridge Core. https://doi.org/10.1017/CBO9780511613630

[11] Kozhevnikov, V., Melnikov, A., & Khartov, S. (2021). Application of the triple Langmuir probe to study local plasma parameters in the radiofrequency discharge that is placed in an additional applied magnetostatic field. Physics of Plasmas, 28(3), 033502. https://doi.org/10.1063/5.0032306

[12] Lindner, J., Ross, U., Roddatis, V., & Jooss, Ch. (2023). Langmuir analysis of electron beam induced plasma in environmental TEM. Ultramicroscopy, 243, 113629. https://doi.org/10.1016/j.ultramic.2022.113629

[13] Pace, D. (2015). Swept langmuir probe test data. General Atomics. https://davidpace. com/wp-content/uploads/2015/11/sampleIV.csv

[14] Proton-electron mass ratio. (2019, May 20). National Institute of Standards and

Technology. https://physics.nist.gov/cgi-bin/cuu/Value?mpsme
[15] Sheridan, T. E., & Goree, J. (1991). Collisional plasma sheath model. Physics of Fluids B: Plasma Physics, 3(10), 2796–2804. https://doi.org/10.1063/1.859987
[16] Sun, G., Zhang, S., Sun, A., & Zhang, G. (2022). On the electron sheath theory and its applications in plasma–surface interactions. Plasma Science and Technology, 24(9), 095401. https://doi.org/10.1088/2058-6272/ac6aa7
[17] Tang, X.-Z., & Luca Delzanno, G. (2014). Orbital-motion-limited theory of dust charging and plasma response. Physics of Plasmas, 21(12), 123708.https://doi.org/10.1063/1.4904404
[18] The PlasmaPy Project. (2023, June 27). PlasmaPy. https://www.plasmapy.org/
[19] Tichý, M., Šícha, M., David, P., & David, T. (1994). A Collisional Model of the Positive Ion Collection by a Cylindrical Langmuir Probe. Contributions to Plasma Physics, 34(1), 59–68. https://doi.org/10.1002/ctpp.2150340108