Langmuir Probe Test Plan

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Overview of relevant Langmuir probe theory

The Langmuir probe is one of the most versatile tools used for plasma diagnostics and provides valuable information on key plasma parameters, including ion and electron saturation currents, temperatures, densities and plasma potential. The probe is most commonly operated using a single electrode but more electrodes can be added for operation in double, triple and quadruple probe configurations, each providing different insights into plasma parameters. A single electrode is used for basic measurements of plasma density and potential. Double probes are designed to minimise the perturbations to plasma potential and are often used in fluctuating plasmas. Triple probes extend this concept, allowing for simultaneous measurements of electron temperature and density with improved accuracy. Quad probes can further analyse ion currents and are especially useful for distinguishing between different plasma regions. The choice of configuration depends on the desired resolution and the plasma parameters of interest. This probe is especially useful in the context of ongoing work on the AQUAHET to experimentally characterise the behaviour and properties of oxygen plasma plumes. The overall aim of these experiments is to attempt to validate existing numerical code especially in the anode region, in-channel and near field regions. This will help inform future iterations of PlasmaSim code and more in-depth experimental characterisation using the Langmuir probe.

Testing scope

This test plan outlines an initial series of diagnostics experiments to demonstrate a proof-of-concept working of Langmuir probes constructed using limited materials. The experiments aim to generate an IV trace by sweeping from low bias voltages (-30V) to high bias voltages (+50V) and vice versa to obtain experimental data on electron density and temperature at in-channel and near field locations relative to the AQUAHET thruster. Primary diagnostic methods include testing a Langmuir probe in single probe mode with tungsten electrodes and stainless steel electrodes of different diameters and comparing their operation based on the IV trace generated. This initial series of tests will help inform future iterations of Langmuir probe construction, especially if different probe geometries are needed for different locations along the plasma stream.

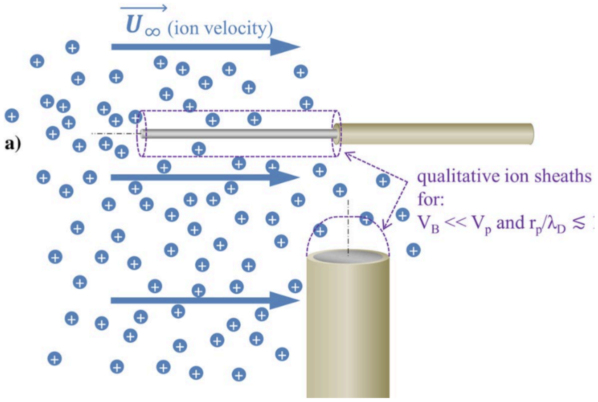

Figure 1: Alignment of cylindrical and planar probes in plasma field (Lobbia, 2017)

Construction guidelines

Recommended practice suggests using refractory materials such as tungsten, tantalum or graphite but these have been extensively tested in xenon and krypton thrusters, the properties of which have been well established. Since there is very limited experimental data available on oxygen plasmas for comparison, stainless steel electrodes were deemed suitable and accessible for construction to address potential oxidation issues. The performance of the stainless steel probe will be compared with a probe constructed using tungsten filament. Two different filament diameters will be tested (0.1 mm and ~1 mm), one to be used in the in-channel region and the other to be used in the far field.

Sheath approximations are critical in interpreting Langmuir probe data. A thin sheath approximation applies when the sheath thickness is much smaller than the probe's characteristic dimension, allowing one to neglect the effect of sheath expansion on the measurements. Conversely, a thick sheath approximation is used when the sheath extends significantly, requiring corrections for the sheath's influence on the collected current. The transitional sheath falls between these extremes, necessitating a more detailed analysis. Important limits include the probe length-to-radius ratio, which should be large to ensure one-dimensional sheath expansion, and electrode spacing in multi-probe configurations, which must be sufficient to prevent interference between adjacent sheaths while being close enough to accurately measure local plasma properties.

Construction methodology

- Handle probe construction using gloves at all times to limit oils from skin being absorbed into probe materials. This also helps lower the time for outgassing in the vacuum chamber since contaminants with unknown composition take a longer time to outgas.

- Cut the alumina tube into 10 cm lengths using a diamond blade for rough cutting. The rough side will contain the wire extensions and will be sealed with tape. Future working versions of the probe will have an aluminium encasing around this portion and sealed with Ceramabond or another adhesive.
- Extend the wires through the bores in the alumina tube, making sure to leave an extended length trailing from the rough end of the alumina in case the wires get displaced.
- Solder each of the trailing wires to a terminal block. These will be connected to longer wires that provide a connection to electrical feedthroughs.

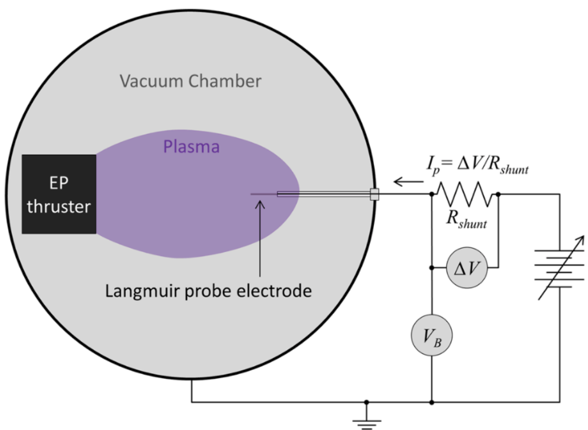

Figure 2: Proposed high-level configuration of cylindrical Langmuir probe biased to voltage V_B drawing current I_P (Lobbia, 2017)

Table 1: Overview of material dimensions used to construct proof-of-concept Langmuir probes

Probe	**Electrode material and dimensions**	**Alumina bore sizes (4 bores each)**	**Electrode lengths (extending out of alumina)**	**Anticipated region of use**
1	0.1mm tungsten	2.5 mm OD, 0.5 mm ID	10 mm	Anode region, in-channel region
2	1mm tungsten	6 mm OD, 1.3 mm ID	30 mm	Near field, far field regions
3	0.1mm stainless	2.5 mm OD, 0.5	10 mm	Anode region,

	steel	mm ID		in-channel region
4	0.8mm stainless steel	6 mm OD, 1.3 mm ID	30 mm	Near field, far field regions

Test plan

To obtain a plasma I-V characteristic:

- Vary probe bias (V_B) with respect to ground to collect electron current
- Ion saturation current ($I_{i,sat}$).
- Electron saturation current ($I_{e,sat}$) → occurs when $V_B = V_p$
- Floating potential (V_f)
- Plasma potential (V_p)
- Expected n_e and T_e values were taken from published PlasmaSim code

Table 2: Test matrix for initial tests

Probe type	**Location relative to HET**	**Bias voltage range**	**Propellant**	**Expected n_e**	**Expected T_e**
Tungsten single probe	In-channel	-30V to +50 V	Oxygen	10e19	5-8 eV
Tungsten single probe	In-channel	+50V to -30 V	Oxygen	10e19	5-8 eV
SS single probe	In-channel	-30V to +50V	Oxygen	10e19	5-8 eV
SS single probe	In-channel	+50V to -30V	Oxygen	10e19	5-8 eV
Tungsten single probe	Near field	-30V to +50V	Oxygen	10e17	3-5 eV
Tungsten single probe	Near field	+50V to -30V	Oxygen	10e17	3-5 eV
SS single probe	Near field	-30V to +50V	Oxygen	10e17	3-5 eV
SS single probe	Near field	+50V to -30V	Oxygen	10e17	3-5 eV

Testing variables

- Assume the thruster power will be kept constant as measurements are being taken
- The independent variables are the location of the probe relative to the thruster and the type of probe being used to make the measurements. In-channel measurements will be taken starting from the anode and remaining within the channel up until the channel exit. Near field measurements correspond to data points taken at s a point X mm away from the channel exit.
- We currently aim to operate LP in single probe configuration but this could be extended to double, triple and quad configurations in the future to make full use of the 4 electrodes on the probe. This may require additional circuit elements to do so.
- We aim to operate the AQUAHET using two propellant types: oxygen and water vapour (will be tested depending on time). We anticipate the oxygen propellant to give us more reliable data since we have experienced issues with operating using water vapour.
- Mass flow rate through the anode will most likely be kept constant. A more thorough test plan might incorporate the effect of varying mass flow rate through the anode.
- Keep vacuum pressure constant.
- Operate the AQUAHET at low power (~200-500 W)

Testing protocols

- Take IV traces using two voltage sweeps: one from negative to positive bias and another from positive to negative bias
- Take a trace three times for each location and compare the average trace with the individual trace.
- Record data in 5V increments using an excel spreadsheet.
- Identify the shape of the trace and whether the ion saturation, electron saturation and ionisation regions are present or if the shape is not what is expected.

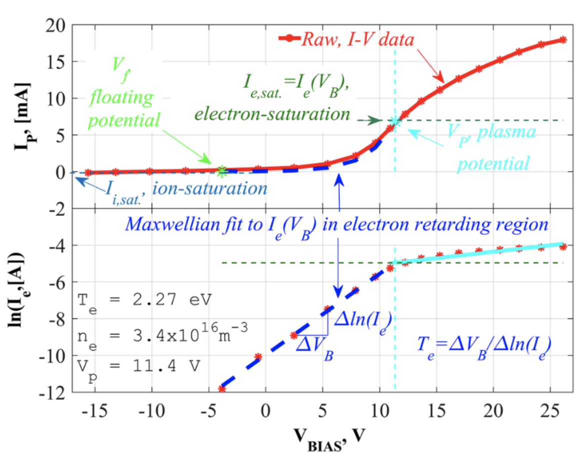

Figure 3: Example of expected characteristic I-V curve showing key regions that help determine key plasma parameters (Lobbia, 2017)

Langmuir Probe Testing Equipment Checklist

- *Measurement Instruments*: Ensure availability of multimeters, oscilloscopes, and other necessary diagnostics tools.
- *Source Meter Use*: Set up a source meter for operating the Quad Langmuir Probe (QLP) in a single probe configuration to streamline the wiring process.
- *Vacuum Chamber Feedthroughs*: Inspect and confirm the functionality of feedthroughs for electrical and signal connections into the vacuum chamber.
- *Electrical Connections*: Arrange for a standard electrical feedthrough that allows connections to exposed wire ends; set up terminal blocks for secure connections on both vacuum and air sides.
- *In-Channel Measurements*: Prepare to affix the probe to the thruster using tape or a suitable adhesive method for direct in-channel readings.
- *Near-Field Probe Positioning*: Develop a strategy for securing probes at a predetermined distance (X mm) from the channel exit, considering the use of retort stands or clamps for stable placement.

Calibration steps

Thruster Calibration (Before Inserting Probe):
This step gives a brief overview of the main considerations when calibrating the thruster before operation.

- Baseline Testing: Run the thruster without the probe inserted to establish a performance baseline. Measure and record thrust, power, and specific impulse values.
- Control Parameters: Confirm that all control settings (such as power supply voltages and currents) are correctly adjusted to match the intended operating conditions.
- Diagnostics Check: Verify that all diagnostic tools (thermocouples, pressure sensors, mass flowmeters) are functioning correctly and are calibrated.

Probe Cleaning Procedure for Vacuum Chamber Use:
The purpose of this step in the procedure is to eliminate any potential sources of outgassing that could interfere with vacuum chamber operations or plasma measurements. Some considerations to include are:

- Conduct a vacuum bake-out, where the probe is placed in a vacuum oven at an elevated temperature if the material tolerances allow. This process helps to release and evacuate any trapped gases or vapours from the probe materials.
- Throughout the cleaning and installation process, handle the probe with cleanroom gloves to prevent oils from hands from causing new contaminants that could outgas.

Potential future work

- After testing the probe for a single probe configuration, alter the electrical circuits as needed for double, triple and quad probe configurations.
- Build and test more probe configurations (using different wire diameters and adhesives) to measure different parts of the plasma plume and iteratively determine the best performing probe configuration. Compare these results with published data on Langmuir probe testing
- Build a fast-acting translational probe stage to quickly move the probe in and out of the plasma if needed.
- Develop a planar probe for far field measurements to characterise the plasma closer to the wall of the vacuum chamber.

References

Here are some of the papers I read in detail to gather adequate information to inform this test plan.

Lobbia, R. B., and Beal, B. E., "Recommended Practice for Use of Langmuir Probes in Electric Propulsion Testing," Journal of Propulsion and Power, Vol. 33, No. 3, May–June 2017, pp. 566–581. Doi: 10.2514/1.B35531

- Very detailed guidelines on relevant plasma physics and probe construction for single, double and triple Langmuir probes
- Provides information on what a characteristic I-V curve should look like and which regions are important in determining important parameters (plasma potential, electron saturation current, floating potential)

Gatsonis, N. A., Byrne, L. T., Zwahlen, J. C., Pencil, E. J., and Kamhawi, H., "Current-Mode Triple and Quadruple Langmuir Probe Methods With Applications to Flowing Pulsed Plasmas," IEEE Transactions on Plasma Science, Vol. 32, No. 5, October 2004, pp. 2118-2129.

- More specific information on triple and quad Langmuir probes with a focus on deriving the more complex mathematical equations before moving onto an experimental setup
- Mainly used this paper to get a brief understanding of quad Langmuir probes since we want to build up to using this in the lab, very complicated to go into more depth

Nakagawa, T., Yamamoto, N., Komurasaki, K., and Arakawa, Y., "Experimental Investigation of a Hall Thruster Using Oxygen as the Propellant," Proceedings of the Japan Society for Aeronautics and Astronautics, Vol. 51, No. 598, 2003, pp. 606–612.

- Provided information on expected electron temperature ranges for an oxygen HET operating at a similar power range (1 kW) to the AQUAHET, uses discharge voltage
- Mainly focuses on measuring thrust, Isp and propellant utilisation efficiency with not as much focus on specific plasma parameters

Tejeda, J. M., and Knoll, A., "A Water Electrolysis Hall Effect Thruster Computational Model with Radiofrequency Excitation," Paper presented at the 37th International Electric Propulsion Conference, Massachusetts Institute of Technology, Cambridge, MA, USA, June 19–23, 2022.

- Extensively references PlasmaSim results for the WET-HET and compares them with the experimental data from the 2022 campaign
- PlasmaSim provided a general trend of varying electron temperature and density as a function of channel length, the main parameter mentioned was discharge power

Azevedo, E. R., Jones-Tett, K., Larsen, H., Reeve, S., Longhi, E., et al., "Sizing and Preliminary Design of a 2-kW Water Propelled Hall Effect Thruster," Paper presented at the 37th International Electric Propulsion Conference, Massachusetts Institute of Technology, Cambridge, MA, USA, June 19–23, 2022.

- Presents experimental results for an early prototype of the AQUAHET and uses PlasmaSim code to decide the most important parameters for thruster geometry (channel length, diameter and width)
- Also includes experimental measurements of thrust, Isp and anode efficiency with both oxygen and water vapour propellants

Williams, J., "A Simple, Inexpensive, Langmuir Probe Experiment," 2014, [Online]. Available: https://advlabs.aapt.org/items/detail.cfm?ID=14050. [Accessed: Aug. 1, 2023].

- An accessible paper that gives details on how to conduct a simple proof-of-concept experiment using Langmuir probes
- Used this paper as a starting point to determine what specific equipment might be needed for vacuum chamber testing

Mazouffre, S., "Electric Propulsion for Satellites and Spacecraft: Established Technologies and Novel Approaches," Plasma Sources Science and Technology Journal, Vol. 25, No. 3, 2016, pp. 033002-1–033002-27. DOI:10.1088/0963-0252/25/3/033002

- An overview paper that summarises relevant EP technologies, provides details on HET geometry and operation
- Compares different propellants and their performance in EP devices