Impact of Guard Scale Size on a Planar Langmuir Probe Ion Saturation Region

Jonas Rowan (rowanj2@my.erau.edu), Aroh Barjatya, Rob Clayton, Rachel Conway, Shantanab Debchoudhury, Nathan Graves, Henry Valentine
Embry-Riddle Aeronautical University, Daytona Beach, FL, United States

Embry-Riddle Aeronautical University
DAYTONA BEACH, FLORIDA

SAIL
Space and Atmospheric Instrumentation Lab
sail.erau.edu

Abstract

Langmuir probes have been widely used on rocket and satellite platforms, yet their accuracy is limited by assumptions about sensor geometry. Theory for planar or cylindrical probes assumes uniform electric fields like those caused by infinite surfaces. These are typically approximated by placing a "guard" electrode adjacent to the sensor and at the same potential to mitigate edge effects.

A Wide-Sweeping Langmuir Probe (WSLP) has been developed to investigate the current collection characteristics of several planar probes with varying guard-sensor area configurations in a laboratory with a new plasma source generating Low-Earth Orbit (LEO) like conditions (approximately ≤0.5eV, 10^{12} m^{-3}, with 4 km/s ion streaming velocity). The WSLP features a small form factor, easily programmable sweep rate and profile, and wide sweeping range of ±35V which make it ideal for investigation of current collection in both ion and electron saturation regions. This work presents the WSLP as a well as initial data from chamber tests with variety of probe geometries.

Background

Langmuir probes are among the simplest of plasma diagnostic instruments to build, and are therefore used on nearly all in-situ plasma measurement platforms.

Theory of Operation:
An electrode is exposed to a plasma and draws current from it based on the electrode's potential relative to that of the plasma. The current is collected by analog circuitry similar to figure 2 and then digitized [1].
The magnitude of the current is correlated with the plasma's ion and electron density and temperature, as well as electrode bias and probe geometry. A sweeping Langmuir probe (SLP) measures this current at many locations along a voltage range, from which a current-voltage (IV) curve can be constructed, as in figure 1.

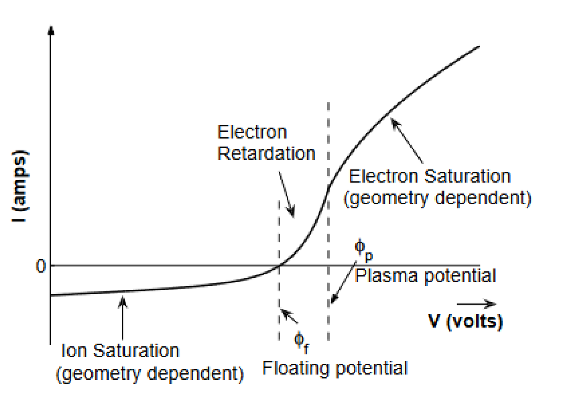

Figure 1: Langmuir Probe IV Curve

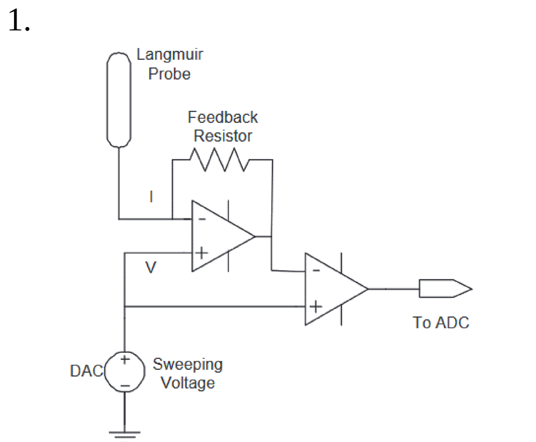

Figure 2: Langmuir Probe Electrometer circuit

Saturation Regimes:
Saturation regions exist where the bias magnitude is large enough to fully repel similar charges, e.g., the ion saturation region begins at the floating potential, V_f, where the probe is negative enough to repel thermal electron motion and establish a net current of zero between probe and plasma. The shape of this saturation region depends on the geometry of the plasma sheath, and hence the geometry of the probe: figure 3 shows the effect of various geometries on IV curve shape.

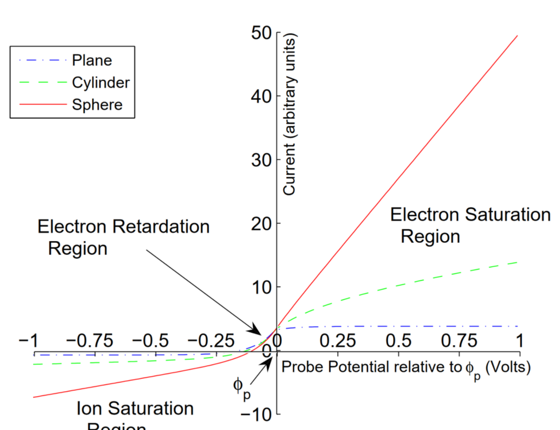

Figure 3: IV curves for varying geometries

On satellites, particularly small platforms like cubesats, Langmuir probes typically operate in the ion saturation region to avoid spacecraft charging. The ion currents can be calculated from the orbital motion-limited model (OML) with the equation below [1]. With an ideal planar probe (β = 0) the probe will collect the same ion current regardless of the bias applied. Even for small values of β from finite plates, the ram current is the dominant source, and thus makes measurements of absolute ion density easy.

$$I_i(V) = n_i e A \sqrt{\frac{k_B T_i}{2\pi m_i}} \left(1 + \frac{e(V - V_p)}{k_B T_i}\right)^{\beta} + I_{ram}, \quad \text{with} \quad \begin{array}{l} \beta = 0\text{, flat plate probe} \\ \beta = 1/2\text{, cylindrical probe} \\ \beta = 1\text{, spherical probe} \end{array}$$

Guarding:
Often, an equipotential guard electrode is placed adjacent to the sensing electrode to better approximate an infinite surface (and thus get as close to β = 0 as possible) by mitigating the end effects of the electric field. In the planar probe case, this is done by a ring around the sensor (see figures 5,6). The size of this guard should at least be the same scale as the sheath length, though an exact relationship has not been explored for planar probes.

Motivation:

Finding a guard scale size for planar probes that minimizes beta (maximizes IV curve flatness) would ease the analysis of future planar positive ion probes by letting collected current scale purely with plasma density, not bias voltage nor spacecraft charging.

Wide-Sweeping Langmuir Probe (WSLP)

The Wide-Sweeping Langmuir Probe (WSLP) was developed based on the SAIL rocket SLP design in order to characterize low density plasmas with a larger sweep range. For this experiment, the WSLP was configured with the following parameters:

- Sweep Range: –36V - +34V, ΔV=70mV
- Unity Gain channel: –11μA - +185μA, ±0.2μA
- High Gain channel: –1μA - +1μA, ±2nA
- 12.5Hz Sweep rate

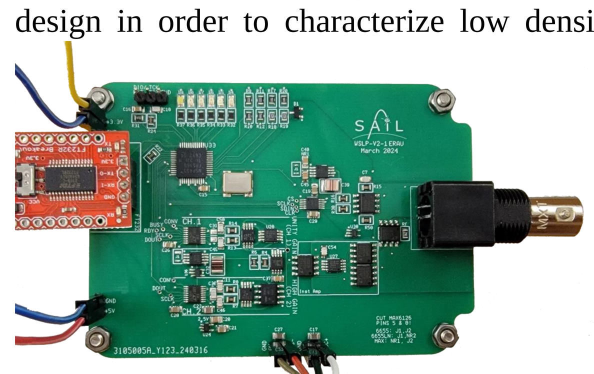
Figure 4: WSLP circuit board

Planar Probes

Planar probes were made from PCBs with exposed copper surface, based off of the LITTED design [3]. Dimensions of the exposed areas are in table 1. Exposed surfaces were plated with Electroless Nickel Immersion Gold (ENIG) coating. Plates were heated to remove some contamination effects, though only below 100°C to maintain structural integrity of the FR4 PCB.

Table 1: Planar Probe Dimensions

	Sensor Size			Guard Size			
Size	Width	Length	Area	Outer Width	Outer Length	Area	**Thickness**
Small	0.5	2.5	1.25	4	6	22.75	**1.75**
Medium	1	3	3	4	6	21	**1.5**
Large	2	4	8	4	6	16	**1**

All units in cm or cm², as appropriate

New plates were created with greater variation of guard thicknesses and made of Teflon to allow for better heating (>200°C), but arrived too late for testing (see figure 6).

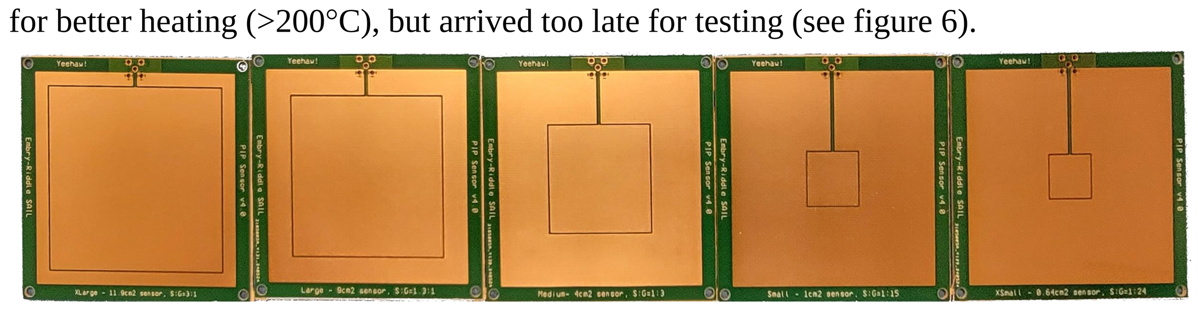
Figure 6: A set of new square plates with guard thicknesses from 1.7cm to 2mm

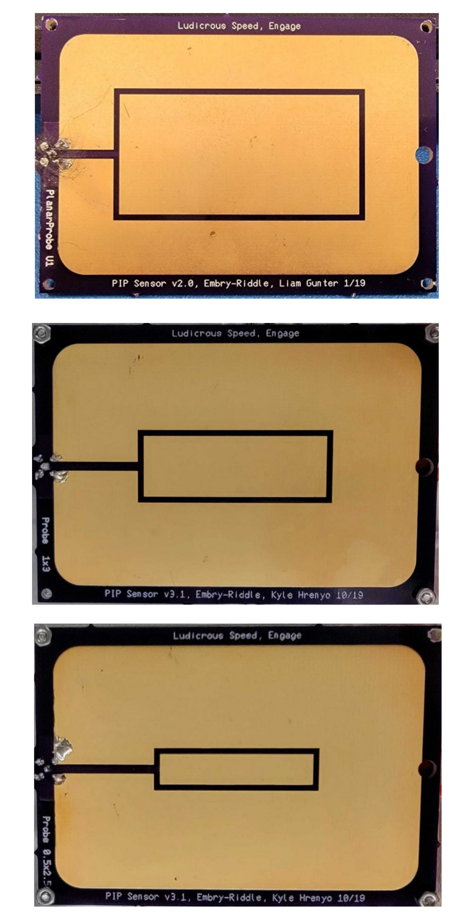
Figure 5: From top to bottom, the Large, Medium, and Small plates

SAIL Large Plasma Chamber Conditions

SAIL Large Plasma Chamber (LPC) is a 1m diameter, 2m length cylindrical vacuum chamber with a hot filament plasma source.

A magnetic filter was fit between source and chamber to reduce temperatures at low pressure and propel ions forward to simulate an ion ram beam at 4km/s. This has not been fully experimentally verified before these experiments.

The source conditions were kept constant throughout the trial: filaments heated to roughly 2100 K, and bias of 170V applied between them and chamber walls. Pressures range from 1.4e-5 Torr to 8e-5 Torr

$$\lambda_D \equiv \sqrt{\frac{(\epsilon_0 k_B T_e)}{n e^2}}$$

Table 2: Debye Lengths for approx. LEO conditions

N (m^{-3})	T (eV)	λ_D (cm)
1E+10	0.5	5.26
1E+10	1	7.43
1E+11	0.5	1.66
1E+11	1	2.35
1E+12	0.5	0.53
1E+12	1	0.74

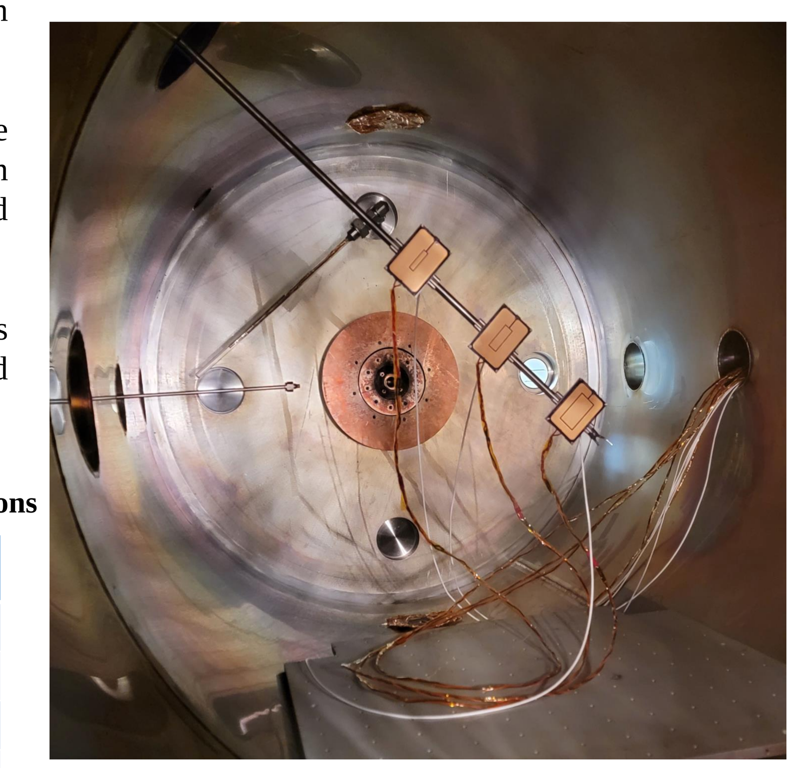
Figure 7: Image of three planar probes in the LPC, each spaced 8cm from each other

LPC Plasma Features

The "LEO" plasma produced by this source has not been fully quantified. Some features stand out from experimentation:

1. Ion ram dominates current collection below 3e-5 Torr
   The following plots show angles, where 0° is facing the source directly, and 180° is exactly in the shadow. By 4e-5 Torr, the sloped thermal component magnitude overtakes the flat ram ion contribution.

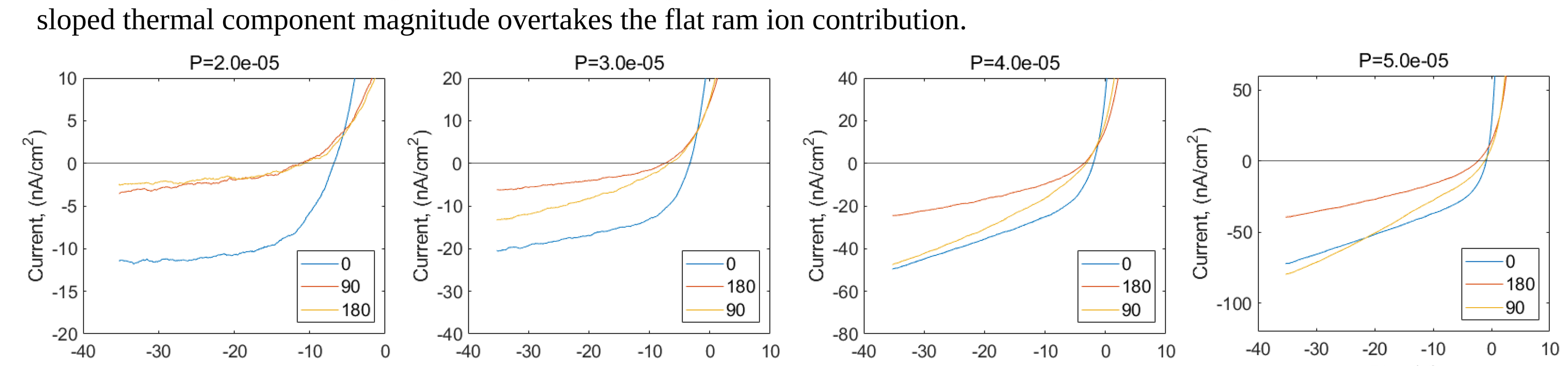

Figure 8: Ion Saturation curves for various low pressures, with each angle overlaid

2. Some weird, probably magnetic field, effects are definitely present: dI/dV should have a single peak at Vp around 3V. The steeper slope in the above 90° trials are also suspected to be a result of some magnetization.

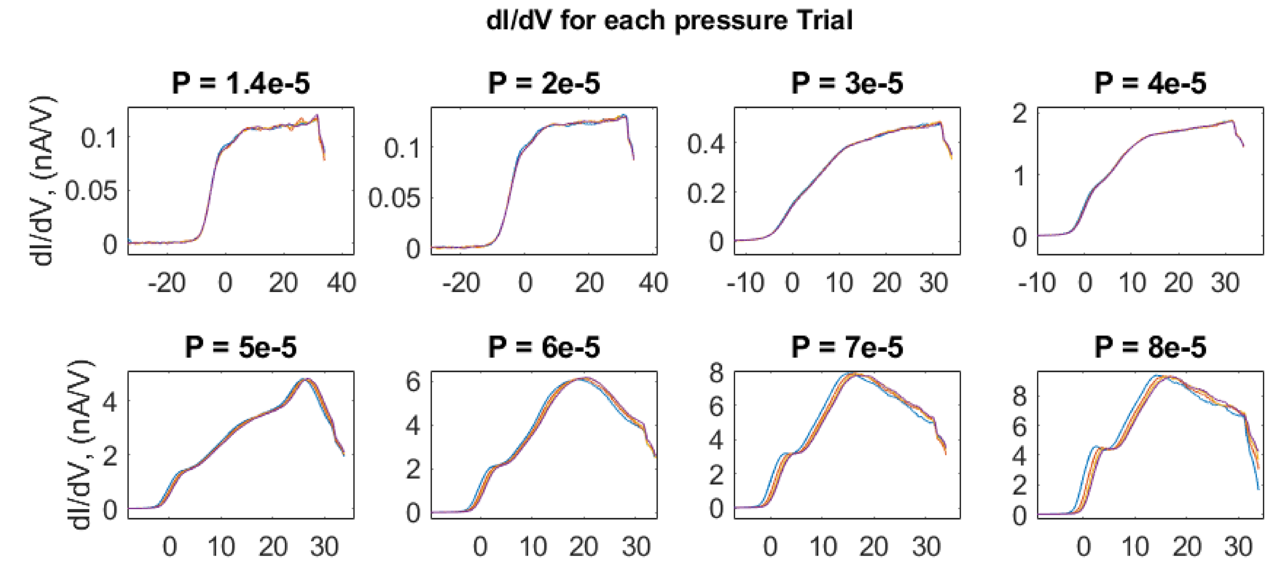

Figure 9: First derivatives of large plate IV curves, all upsweeps shown

Data Observations

Per unit area, the large plate consistently collects less current than the smaller plates

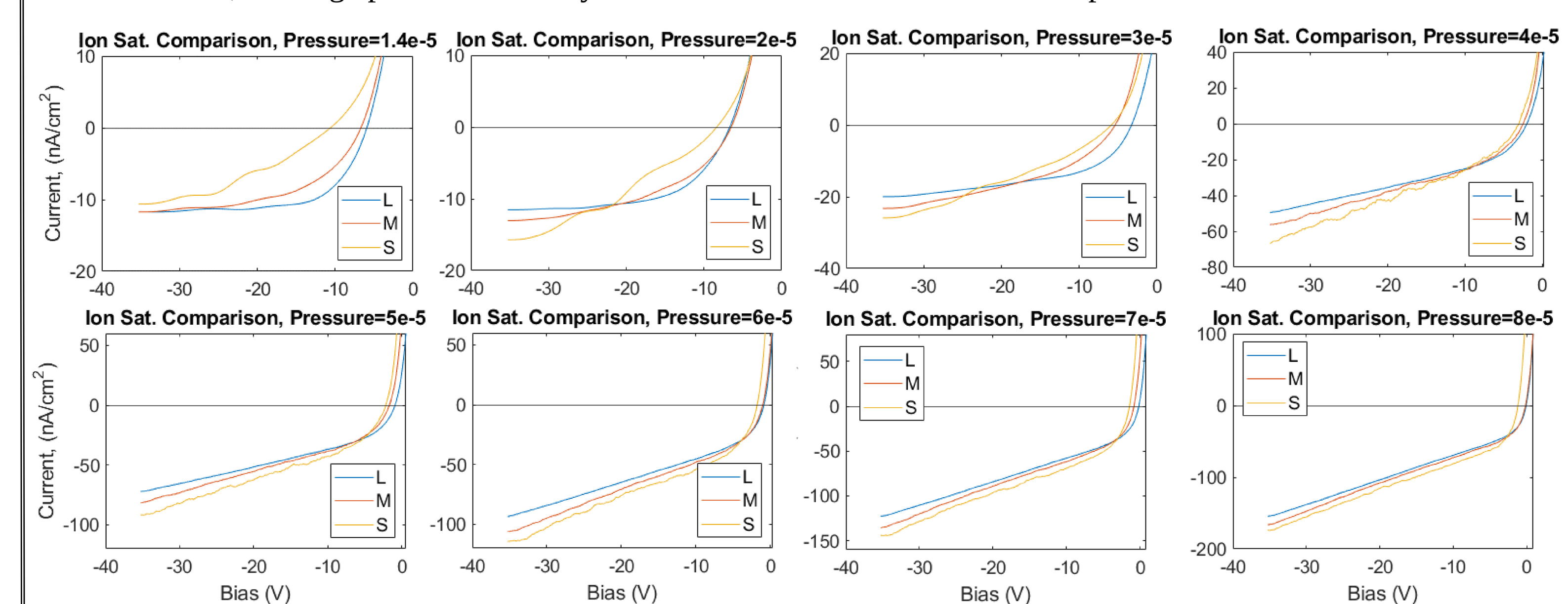

Figure 10: Ion Saturation regions for each pressure, each plate type overlaid

IV curves were fitted to OML theory to calculate Te and Ni; the results are located in tables 3 and 4 below. Derived β values were not all realistic. A large source of error here is that fits were made for pure argon plasma; but at these low pressures, at least 1.5μTorr of pressure was a result of air in the chamber, so at most 90% purity at lowest pressure. Thus, the ion current OML fitting will be a more involved procedure.

Table 3: Derived densities and temperatures from the Large plate

Pressure (Torr)	Ni (m^{-3})	Te (eV)	Vp	λ_D (cm)
1.4E-05	1.1E+11	1.9	2.2	3.19
2.0E-05	1.2E+11	2.2	2.9	3.21
3.0E-05	1.4E+11	2.4	6.4	3.09
4.0E-05	1.9E+11	1.9	5.2	2.36
5.0E-05	3.1E+11	1.5	5.0	1.63
6.0E-05	3.9E+11	1.2	4.1	1.32
7.0E-05	4.6E+11	1.1	4.6	1.17
8.0E-05	4.9E+11	1.1	4.5	1.11

Table 4: Derived densities and temperatures from the medium plate

Pressure (Torr)	Ni (m^{-3})	Te (eV)	Vp	λ_D (cm)
1.4E-05	7.6E+10	2.1	1.5	3.92
2.0E-05	6.9E+10	1.6	-0.8	3.55
3.0E-05	1.2E+11	2.6	4.6	3.47
4.0E-05	1.7E+11	1.6	2.4	2.27
5.0E-05	2.2E+11	1.4	2.5	1.86
6.0E-05	2.8E+11	1.5	3.5	1.71
7.0E-05	3.4E+11	1.4	3.3	1.49
8.0E-05	3.8E+11	1.1	2.6	1.28

Quantifying Flatness

A pseudo-beta value β_* was calculated to quantify the *flatness* of the ion saturation region in place of an OML β value from fitting, see equation to the right. Test voltages V_x were compared to -15V to show expected flatness in the realm of typical ion probe measurements.
<u>β_* equal to 0 means completely flat</u>

$$\beta_*(V_x) = \left|1 - \frac{I(V_f - 15V)}{I(V_f - 15V - \varphi)}\right|$$

Table 5: Large

Pressure	$\varphi = 5$	$\varphi = -5$
1.4E-5	0.022	0.031
2.0E-5	0.044	0.008
3.0E-5	0.091	0.099
4.0E-5	0.161	0.213
5.0E-5	0.164	0.209
6.0E-5	0.170	0.226
7.0E-5	0.177	0.255
8.0E-5	0.190	0.270

Table 6: Medium

Pressure	$\varphi = 5$	$\varphi = -5$
1.4E-5	0.011	0.010
2.0E-5	0.127	0.136
3.0E-5	0.075	0.196
4.0E-5	0.186	0.257
5.0E-5	0.166	0.225
6.0E-5	0.197	0.246
7.0E-5	0.187	0.298
8.0E-5	0.205	0.289

Table 7: Small

Pressure	$\varphi = 5$	$\varphi = -5$
1.4E-5	0.030	0.227
2.0E-5	0.078	0.246
3.0E-5	0.170	0.267
4.0E-5	0.196	0.277
5.0E-5	0.224	0.240
6.0E-5	0.215	0.267
7.0E-5	0.193	0.283
8.0E-5	0.203	0.360

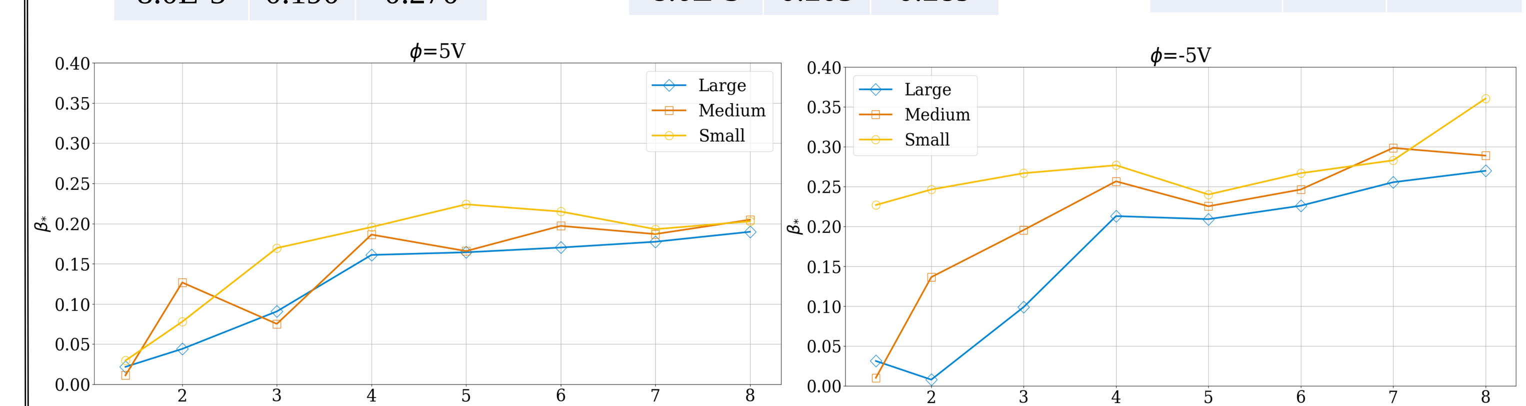

Figure 11: Pseudo-Beta plots for different comparison voltages

Takeaways & Future work

- Large plate with smaller guard performs better for all experiments conducted. The above data indicates that the Large plate, which is currently operational on LLITED CubeSats, is least impacted by +/-5V of spacecraft charging.
- With increasing pressures, and as the 'ram' streaming ion current decreases, all sensors show a larger beta. This needs to be re-assessed with full commissioning of the LEO Plasma Source.
- Work is planned with new plates—guard thicknesses will have more variation with respect to debye lengths and provide a fuller picture.

References

[1] A. Barjatya, "Langmuir Probe Measurements in the Ionosphere," Ph.D. dissertation, Utah State Univ., Logan, 2007.
[2] F. Chen, "Introduction," *Plasma Physics and Controlled Fusion*, 2nd ed. New York, NY, USA; Plenum Press, 1983, ch.1
3 L. Gunter, "Planar Ion Probe for Low-Latitude Ionosphere/Thermosphere Enhancements in Density Cubesat Mission," M.S. Thesis, Embry-Riddle Aeronautical Univ., Daytona Beach, FL, 2019.