Flowing Plasma Interaction with an Electric Sail Tether Element

Todd Schneider[1], Jason Vaughn[1], Kenneth Wright[2], Allen Andersen[3], and Nobie Stone[4]

[1]NASA, Marshall Space Flight Center, Huntsville, 35812 USA (e-mail: todd.schneider@nasa.gov)
[2]Universities Space Research Association, Huntsville, 35805 USA
[3]Utah State University, Logan, 84322, USA
[3]NeXolve Corp., Huntsville 35806, USA

I. Introduction

Harnessing the power of the solar wind, an Electric Sail, or E-sail, is a relatively new concept that promises to deliver high speed propellant-less propulsion. The electric sail is an invention made in 2006 at the Kumpula Space Centre in Finland by Pekka Janhunen [Janhunen and Sandroos, 2007]. At its core, an electric sail utilizes multiple positively biased tethers which exchange momentum with solar wind protons via the repelling electric field established around each tether, in other words, by reflecting the solar wind protons. Recognizing the solar wind is a plasma, the effective repelling area of each tether is increased significantly by the formation a plasma sheath around each tether. Fig. 1 shows schematically a spacecraft employing an electric sail. The positive voltage bias (> 10kV) applied to each tether naturally results in electron collection. Therefore, the electric sail concept necessarily includes an electron source (electron gun) to return collected electrons to space and maintain the positive bias of the tether system.

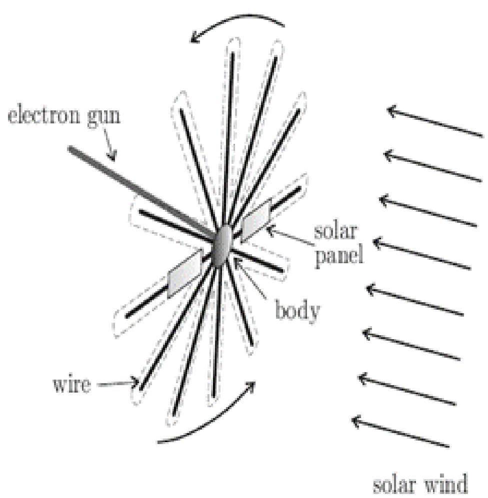

Figure 1. Schematic diagram of an Electric Sail [Mengali, et al., 2008]

Following Janhunen's introduction and development of the electric sail concept, additional work by the Finnish team and others suggested that missions employing electric sails could realize fast trip times to the outer planets and even the edge of the solar system [Janhunen 2008; Quarta and Mengali, 2010]. Interested by such exploration opportunities, the Advanced Concepts Team at NASA's Marshall Space Flight Center (MSFC) began investigating the prospects of using an electric sail to travel to the edge of the solar system (the heliopause). In 2014, they received an award from the NASA Innovative Advanced Concepts (NIAC) program to investigate the feasibility of an electric sail mission they developed called the Heliopause Electrostatic Rapid Transit System (HERTS). The HERTS Phase I study concluded an E-sail mission to the heliopause could be completed within 15 years, which is much faster than any other existing propulsion system could deliver.

While the HERTS Phase I study of an electric sail mission to the heliopause showed good overall feasibility, some technical challenges remained to be addressed. In 2015, the NIAC program provided resources for a Phase II study with the objective of having the HERTS team investigate some of the key challenges identified in the first study. One of those challenges was: "Lack of a reliable model for solar wind proton and electron interactions with the highly biased wires" [Wiegmann, 2015]. To address this problem, the HERTS team chose to conduct laboratory testing that could be used to anchor a Particle-In-Cell (PIC) model capable of reliably extrapolating to solar wind scales. The focus of this paper is the initial results of that laboratory investigation.

II. Testing Framework

Essential to the operation of an electric sail is the formation of a large plasma sheath around the very small diameter positively biased tether wires. Recall, sheath formation is a fundamental property of plasmas which naturally organize to screen out unbalanced electric fields. The characteristic screening distance is known as the Debye length. As seen in equation (1), the Debye length is a function of the plasma density and electron temperature.

$$Debye\ \ Length = \lambda_D = \sqrt{\frac{\varepsilon_0\ kT_e}{q^2\ n_0}} \tag{1}$$

Where ε_0 is the permittivity of free space, k is Boltzmann's constant, T_e is the electron temperature, q is the electron charge, and n_0 is the plasma density. In general, the size, or thickness, of a plasma sheath is said to be a few Debye lengths.

Table I was created during the test formulation phase to help provide a framework for the laboratory test setup. The test conditions were optimized for scaling where possible, with primary focus on Debye length. It was determined the Debye length of the laboratory plasma:

- Should be much larger than the tether diameter
- Should be much smaller than the plasma test chamber diameter (to avoid wall effects)

The overall test objective, was, for a given set of relevant plasma conditions, measure the extent of the sheath around a biased tether element, and map the deflection of ion trajectories caused by the sheath. Then feed this data into a model capable of extrapolating to E-sail mission scales.

TABLE I. COMPARISON OF PARAMETERS: E-SAIL AND LABORATORY

	Parameter	Value	Comment
E-Sail Mission	Proton Speed	400 - 450 km/s	~1000 eV
	Density	~5/cm^3	
	Electron Temp.	~12 eV	
	Ion Temp.	~10 eV	
	Debye Length	~10 m	
	Tether Diameter	~7.5x10^{-5} m	~75 microns
	Tether Bias (+)	>10 kV	
Laboratory Low Energy Analog	Ion Speed	~19 - 38 km/s	~80 - 300 eV
	Density	~1x10^6/cm^3	
	Electron Temp.	< 1eV	
	Ion Temp.	<< 1eV	
	Debye Length	< 1 cm	>> Tether Dia.
	Tether Diameter	~1mm	
	Tether Bias (+)	100 - 300 V	> Ion Energy

III. TEST SETUP

The Space Environmental Effects Team at NASA's Marshall Space Flight Center was selected to execute the HERTS laboratory investigation, in part, because of their existing operational array of plasma sources, high vacuum test chambers, and diagnostic sensors.

A. *Plasma Source*

The test team evaluated multiple source options in the context of fitting in the framework described above and, in general, providing a quasi-neutral plasma with drifting ions. Ultimately, a broad-beam gridded ion source, or Kaufman source, was selected. This type of source offers control of the ion drift energy using the accelerating grids. The Kaufman source also provides low energy electrons via its neutralizer cathode. Fig. 2 is a picture of the Kaufman plasma source used in the test. Table II provides typical plasma parameters generated by the source. All testing was conducted with an Argon plasma. While the Kaufman source is capable of operating with Hydrogen gas, the production of molecular Hydrogen ions (H_2^+) along with protons complicates the plasma dynamics and analysis.

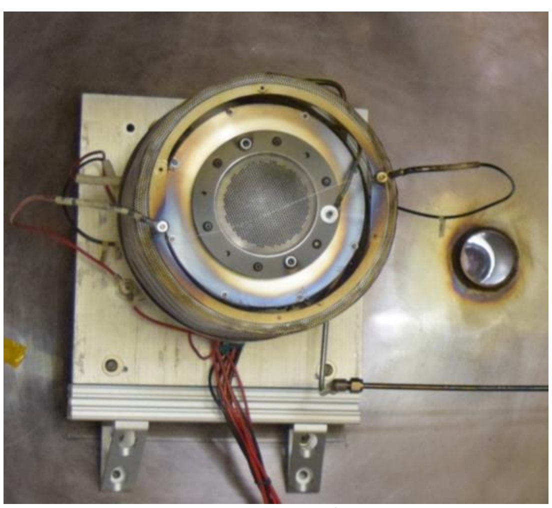

Figure 2. Gridded plasma source (Kaufman type) with neutralizer cathode

TABLE II. TYPICAL PLASMA PARAMETERS

Typical Argon Plasma Parameters			
Property	**Parameter (Units)**	**100 eV Nominal**	**200 eV Nominal**
Ion Drift Energy	E (eV)	105	203
Ion Current Density	J (μA/cm^2)	0.53	0.70
Electron Temperature	Te (eV)	0.73	0.77
Plasma Density	n (10^6/cm^3)	1.47	1.4
Debye Length	λd (mm)	5.2	5.5

B. *Diagnostic Sensors*

Three diagnostic probes were used throughout the test campaign. A spherical Langmuir Probe (LP) measured the plasma electron temperature, plasma density, and plasma potential. The gridded Retarding Potential Analyzer (RPA) provided ion energy and flux. The Differential Ion Flux Probe (DIFP) provided ion trajectory information [Stone, 1977]. All of the probes were mounted together as a movable array. Fig. 3 shows the probe arrangement.

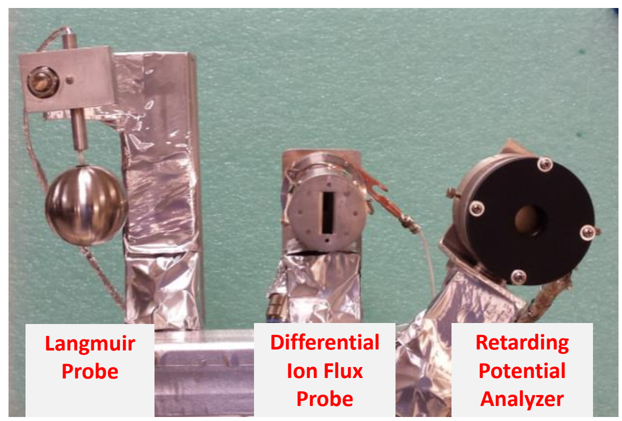

Figure 3. Plasma diagnostic probe array

The LP and RPA are common diagnostic probes for making plasma measurements, however the DIFP is a unique instrument, and given its important role in the testing, merits further description. A cross-section schematic of the DIFP is shown in Fig. 4.

The DIFP uses electrostatic deflection to steer ions into a collector where they are measured as current. The level 1 output of the DIFP is current versus deflector voltage. By calibrating the DIFP at known angles, the product of the DIFP can be transformed into flux versus angle, i.e. the trajectory of ions beam can be determined. As conceived by Stone, the DIFP instrument can yield ion angle and energy information. Since a dedicated RPA was part of the instrument array, the energy measurement feature of the DIFP was not employed for the test campaign.

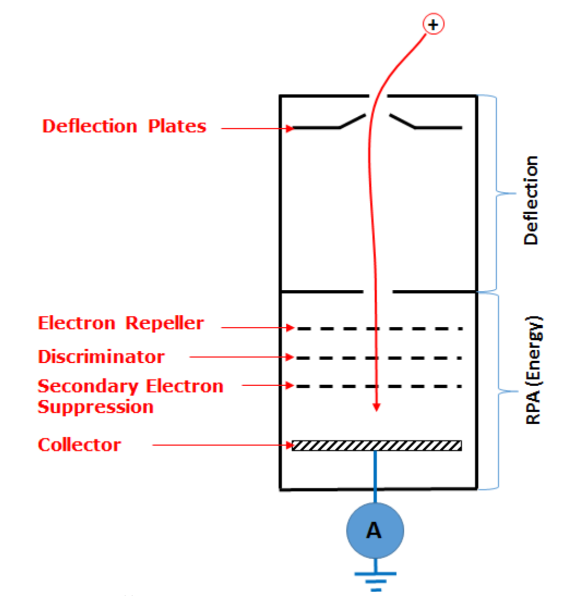

Figure 4. Differential Ion Flux Probe (DIFP) schematic (top view at mid-plane)

C. *Tether Element (Biased Body)*

For a full scale electric sail, the tethers are tens of kilometers in length, and only tens of microns in diameter. Constructing a tether element that would fit inside the test chamber, as well as remain straight and fixed in a precise location, necessitated the creation of a custom test article instead of using a small piece of actual tether material. Fig. 5 shows a picture of the tether element (also called the biased body) on the laboratory bench. The layout of the stainless steel tether element is shown in Table III. To minimize end effects, a guarded design was employed for the tether element. The tether element assembly is mounted to a swing arm that allows the tether element to be moved out of the ion flow without breaking vacuum.

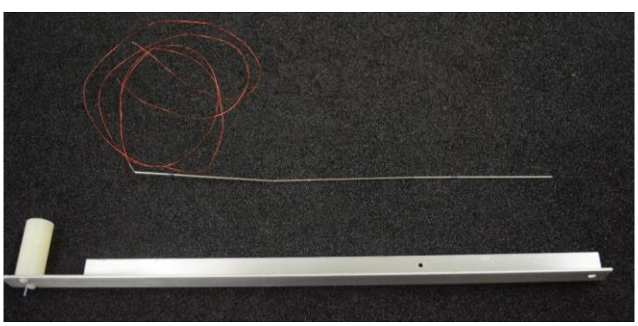

Figure 5. Stainless steel cylindrical tether element (top) and swing-arm support (bottom)

TABLE III. TETHER ELEMENT LAYOUT

Diameter	Section	Length	Role
1.85 mm	Top	9.7 cm	Guard (biased; no collection)
	Middle	13.2 cm	Primary Element
	Bottom	12.8 cm	Guard (biased; no collection)

D. *Vacuum Chamber*

The vacuum chamber was selected for the test based on three primary factors: 1) Its overall large size; 2) The high pumping speed of the vacuum system; and 3) The 2D motorized translation system in place. Key parameters of the vacuum chamber are shown in Table IV. Fig. 6 shows the vacuum chamber interior layout.

TABLE IV. VACUUM CHAMBER PARAMETERS

Cylindrical Vacuum Chamber Parameters		
Property	**Parameter (Units)**	**Typical**
Chamber Length	L (m)	2.7
Chamber Diameter	D (m)	1.2
Base Vacuum Pressure	P (Torr)	3.0E-07
"Source On" Pressure	P1 (Torr)	6.0E-06
Source to Tether Dist.	L1 (m)	1.0

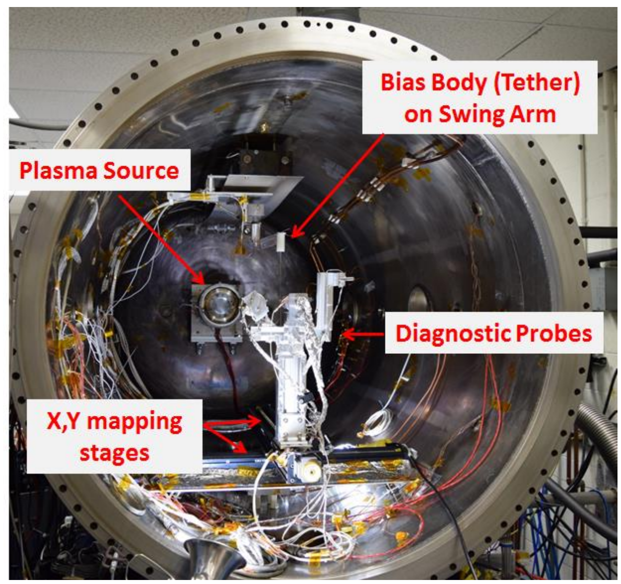

Figure 6. End view of vacuum test chamber

E. *Overall Arrangement*

The main components that make up the test system are arranged along the mid-plane of the chamber: The ion source is located at the far east end; approximately 1 m downstream of the ion source is the tether element suspended vertically; and up to 300 mm downstream from the tether element is the probe array. The probe array is mounted to a 2D motor-driven translation stage that allows the probes to travel between 50 mm and 300 mm downstream of the tether element and +/- 100 mm along the chamber radius.

IV. ION DEFLECTION AND PLASMA SHEATH MEASUREMENTS

To develop a picture of the sheath thickness around the cylindrical tether element, and to verify the change in ion trajectories as they encounter the positively biased tether element, the DIFP is moved systematically along a range of downstream and radial locations. At each location, DIFP data such as shown in Fig. 7 is acquired (Ion Current vs. Deflection

Voltage). The plot in Fig. 7 contains two peaks and represents the situation where a +100 V bias is applied to the tether element (causing 100 eV ions to be deflected or repelled). The tall peak occurs at low deflection plate voltage, which represents ions entering the DIFP at small angles. The short peak, however, occurs at a high deflection plate voltage, which means ions with high angle trajectories are present in the flow.

DIFP data sets gathered downstream from a positively biased tether element are always compared to freestream data where there is no bias on the tether element or the tether element is completely removed from the flow. Such comparisons show definitively the presence of a plasma sheath when there is a positive bias on the tether element, and show ions are deflected by the sheath into large angle trajectories.

Analyzing a set of DIFP data taken at multiple radial locations downstream of a positively biased tether element provides clear evidence the plasma sheath reflects ions that are flowing directly into the center of the sheath, and deflects ions that flow near the sheath edge. Fig. 8 shows the extent of the plasma sheath around a +200 V tether element as 105 eV ions drift into it. Both the small angle (stream 1) and large angle (stream 2) beams are impacted by the presence of the sheath. A low flux region (void) is created downstream of the sheath as the stream 1 particles are reflected and stream 2 particles are scattered into large angles. Data sets such as those plotted in Fig. 9 help quantify the flow angles of particles scattered by the

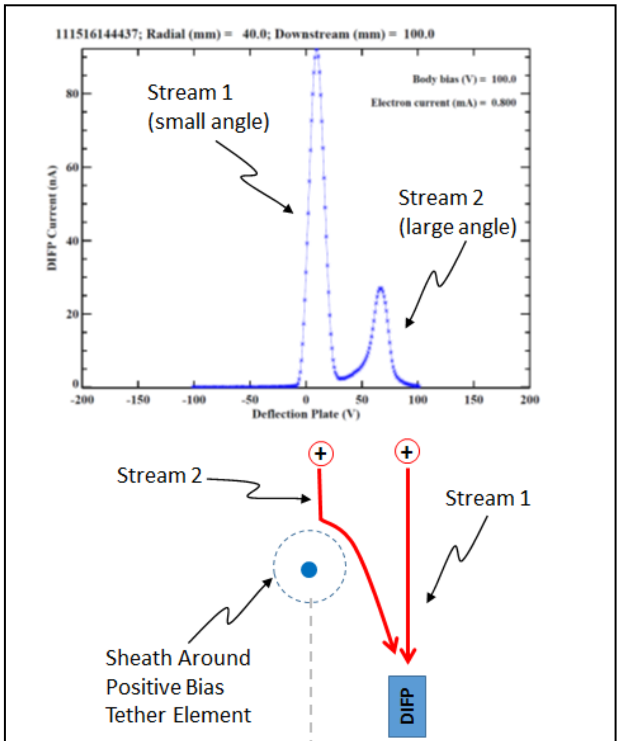

Figure 7. Top: Typical DIFP data (Current vs. Deflection Plate voltage); Bottom: Schematic diagram correlated to data plot

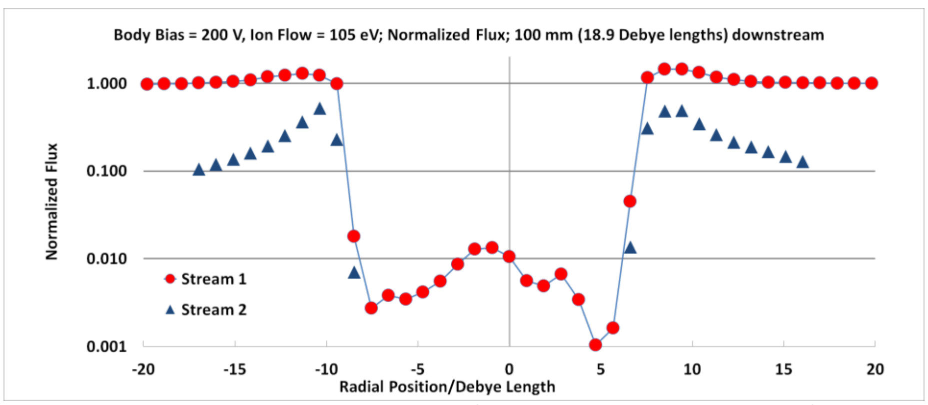

Figure 8. Normalized flux vs. Radial Position measured 100 mm downstream of the tether element (+200 V). The low flux region indicates the sheath around the tether is deflecting incoming particles – resulting in a void downstream of the tether element

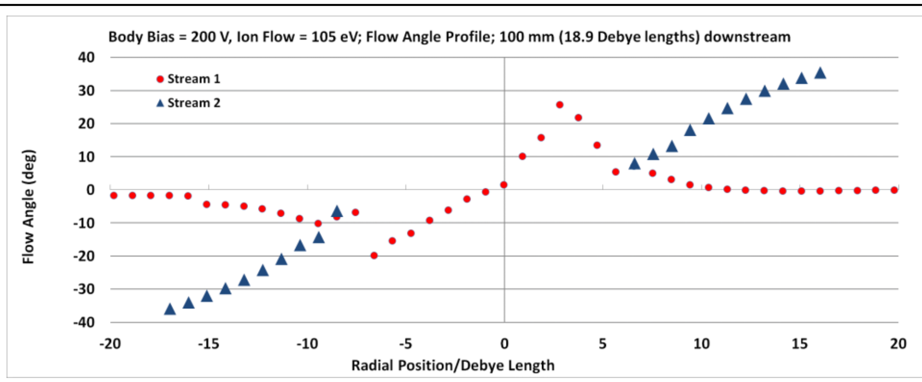

Figure 9. Flow angle vs. Radial Position measured 100 mm downstream of the tether element (+200 V). The sheath around the cylindrical tether element is deflecting/scattering ions into large angles with respect to the undisturbed flow. The extent of the sheath influence is ~14 Debye lengths (~74 mm)

tether element sheath. Fig. 9 represents just one downstream position, when flow angle data from other downstream positions is added, a comprehensive picture of the sheath can be constructed and compared to computer models.

V. Electron Current Collection

An important operational parameter for electric sails is the electron current collection that occurs as a result of the high voltage positive bias on each tether. The amount of electron collection will drive the total power required for the high voltage power supply and the emission requirements of the electron gun on the spacecraft. Therefore, throughout the test campaign to characterize the sheath effects associated with the positively biased tether element, current collection measurements were made. A summary of the electron current measurements is provided in Fig. 10. The data in Fig. 10 cover a wide range of plasma conditions, tether bias voltages, and neutral pressures. The Mach numbers represent the ratio of ion drift speed to the ion sound speed. (Recall, ion sound speed is a function of electron temperature.) Interestingly, despite the wide range of conditions studied, the laboratory data tend to follow a common trend. Comparison of the laboratory electron collection data to the first generation Particle-In-Cell (PIC) code showed a significant under prediction by the code. The agreement is expected to improve as details of the plasma sheath in the PIC code are refined with data from DIFP measurements.

VI. Summary

Electric sails are a relatively new concept for providing high speed propellant-less propulsion. Employing multiple tethers biased to high positive voltage levels (kV), electric sails are designed to gain momentum from the solar wind by repelling solar wind protons. To maximize the area of the sail that interacts with the solar wind, electric sails rely on the formation of a large plasma sheath around each small diameter tether. Motivated by interest in advancing the development of electric sails, a set of laboratory tests has been conducted to study the interaction of a drifting plasma with a sheath formed around a small diameter tether element biased at positive voltages. The laboratory test setup was created with Debye length scaling in mind to offer a path to extrapolate (via modeling) to full scale electric sail missions. Using an instrument known as a Differential Ion Flux Probe (DIFP) the interaction between a positively biased tether element and a drifting plasma has been measured for several scenarios. Clear evidence of the tether element sheath deflecting ions has been obtained. Maps of the flow angle downstream from the tether element have been made and they show the influence of the plasma sheath. Finally, electron current collection measurements have been made for a wide range of plasma conditions and tether element bias voltages. The electron collection data will have an impact on electric sail power requirements, as high voltage power supplies and electron guns will have to be sized to accommodate the electron currents collected by each tether.

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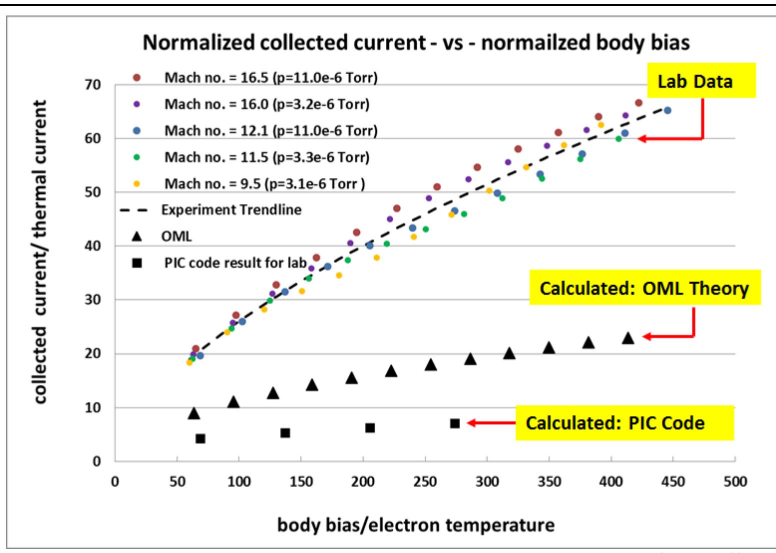

Figure 10. Tether element electron collection summary. The lab data remains grouped together, despite significant differences in ion speed (Mach number) and chamber neutral pressure. The Particle-In-Cell code was a first generation run with limits on the sheath scaling and resolution.