

A Comparison of Laboratory Experimental and Theoretical Results for Electrodynamic Tether Electron Collection Performance for Some Bare Tether Geometries

Keith R. P. Fuhrhop*

Northrop Grumman, Redondo Beach, CA., 90278

Éric Choinière†

Ottawa, ON, K1A 0Z4 Canada

and

Brian E. Gilchrist‡

University of Michigan, Ann Arbor, MI 48109

This paper presents the analysis of new measurements of electron current collection to porous tape probes in a high-speed flowing plasma, and a comparison to similar measurements with round cylinder, solid and slotted tape samples previously reported[§]. In these experiments, a Hall thruster was used to create a high-speed (~8 km/s) flowing unmagnetized plasma in a large 6-m × 9-m vacuum chamber. Experimental results of solid tape samples with widths spanning from 7.2 to 20.4 Debye lengths and slotted tapes with center-to-center line spacings spanning from 2.1 to 6.0 Debye lengths (gap widths from 1.3 to 3.6), were compared to measurements of holed tapes with hole diameters ranging from 1.4 to 9.4 Debye lengths. Several conclusions can be drawn from the analysis of the results in the regime tested: 1) Beyond a threshold bias potential probably close to the beam energy, holed tapes collect more current when oriented transverse (perpendicular) to the flow, just like solid and slotted tapes; 2) Holed tapes are more efficient electron collectors than both solid and slotted tapes in terms of collected electron current per unit area when oriented perpendicular to plasma flow. However, when oriented parallel to plasma flow, slotted tapes are more efficient than holed or solid tapes; and 3) When the tapes were oriented parallel to the flow, the electron current collected on holed tapes decreases with increasing hole size until a minimum is attained, beyond which it starts increasing again. The opposite effect occurred when the holed probes were oriented transverse to the flow, and a maximum efficiency was observed. We conclude that the holed tethers, which have better structural stability, also have the greatest mass equivalent electron current collection compared to that of solid and slotted tethers.

Nomenclature

A_p	= probe surface area [m ²]	e	= electric charge [C]
m_e	= mass of electron [kg]	n_e	= electron plasma density [particles/m ³]
I	= electron current collection [A]	T_e	= electron / ion Temperature [eV]
V_o	= potential of the conductive wire [V]	V_p	= ambient plasma potential [V]
λ_{De}	= Debye length [m]	μ_b	= beam fraction []

I. Background

BARE conductive tethers have been identified as being a useful mechanism for end-body collection in an electrodynamic tether system [1]. Plasma probe theory has been developed that explains the current collection behavior of such a probe in a non-flowing quasi-neutral plasma, assuming that the wire is small with respect to the Debye length [2]. This theory predicts that the current collection per unit area is maximized within this “orbital-motion-limited” regime.

NASA’s Propulsive Small Expendable Deployer System (ProSEDS) [3] was the first mission to employ the bare conductive tether technology. This particular mission was eventually cancelled [4], however designs for similar future

* Systems Engineer, Aerospace Systems, One Space Park / R5-2281B, AIAA Senior Member.

† Defense Research and Development Canada

‡ Full Professor, Electrical Engineering and Atmospheric, Oceanic and Space Sciences, 1301 Beal Ave. / 2240 EECS, AIAA Associate Fellow

§ ‘Porous’ tapes will be referred to as ‘holed’ tapes for the remainder of this paper.

missions have been developed. These proposed missions have designed a variety of tether geometries to be used as part of, or solely as the system anode. These designs address concerns of survivability to collisions with micro-meteoroids and space debris by using distributed or sparse geometries that span tens of Debye lengths, depending on plasma density and temperature [5].

The primary objective of this experiment is to further understand the differences and similarities behind how distributed or sparse geometries perform compared to that of thin cylindrical tether geometries within a high-speed flowing plasma. It is important to note that the mechanisms behind electron current collection within these various tether geometries for a flowing plasma have yet to be understood [6,8]. Some particular objectives that an electrodynamic tether design needs to account for are lifetime, minimum mass, minimum drag, and maximum current collection. The goal of this experimental work will be to contribute towards the understanding and knowledge base of this design.

As in Choinière et al [6], the orbital-motion limit (OML) will be used as a baseline when comparing the current collection results for various sample geometries and sizes. Recall that the theoretical expression for the OML electron current collected

by a thin cylinder is [2],[7]: $I = A_p n_e e \sqrt{\frac{eT_e}{2\pi m_e}} \frac{2}{\sqrt{\pi}} \sqrt{1 + \frac{V_0 - V_p}{T_e}}$. The electron density, mass, and temperature are defined as

n_e , m_e , and T_e . In addition, the potential with respect to the plasma is labeled, $V_0 - V_p$, and the probe surface area, A_p . This normalization allows one to directly compare our experimental results, which involve various tether geometries in a flowing plasma, against OML theory.

Previous experimental data [8],[18] indicated that a tape width of 6.9 Debye lengths would collect about 85%–90% of the electron current collected by an equal-area round cylinder, and that the perpendicular tape orientation, with respect to plasma flow, would consistently outperform the parallel orientation in terms of collected current varying percentages up to ~9%.

In this paper, we describe new results of a previous set of chamber tests [6] pertaining to the “holed tape” geometry with various hole sizes and spacings. The issue of end effects was addressed by adding guards to the tether samples, which are described below, and was discussed in Choiniere et al [16].

Sample	Description	Width (mm)	Hole Description
A	50% porosity, largest holes, offset matrix	2.89	Holes: Ø1.10 mm, spacing: 1.33 mm staggered
B	50% porosity, medium holes, offset matrix	2.89	Holes: Ø0.74 mm, spacing: 0.91 mm staggered
C	50% porosity, smallest holes, offset matrix	2.89	Holes: Ø0.56 mm, spacing: 0.69 mm staggered
E	Solid Tape	2.89	N/A
F	Slotted Tape	2.89	N/A

Table 1: Drawing an Description of the Guarded Tether Samples Shown Before Assembly, the Lengths Indicated in the Drawing are in mm (30-mm Probe, 60-mm Guards)

II. DESIGN AND ASSEMBLY OF GUARDED TAPE TETHER SAMPLES

The tether samples tested here, in addition to a thin cylindrical reference sample, included a solid tape sample, a slotted tape sample, and a holed tape sample with 3 separate hole diameters and spacings. The slotted sample and all three holed tape samples had approximately 50% porosity. Each of these samples had a length of about 3cm and was mounted with 2 6-cm guards. Details of the guard assemblies are given in [6]. Each tape sample was tested in two different orientations, parallel and perpendicular to the plasma flow, and, along with the reference sample, at three different distances from the hall thruster plasma source. Tungsten metal was used for all samples to ensure that they would endure the expected high temperatures that are caused by the collection of high-energy electrons at the samples’ surfaces. The diameter of the reference cylinder and widths of the solid and slotted tape samples are given in Table 2 in terms of the Langmuir- probe-determined local Debye length at the three chamber test positions.

Position	Ref. Cyl.	Solid Tape	Slotted Tape
75 cm	2.0	20.4	6.0
160 cm	1.1	11.0	3.2
300 cm	0.7	7.2	2.1

Table 2: Diameter of the Reference Cylinder, Width of the Solid Tape and Center-To-Center Line Spacing of the Slotted Tape, Expressed in Terms of Local Debye Length

Position	Hole size (diameter)			Hole Spacing (center to center)		
	Small	Medium	Large	Small	Medium	Large
75 cm	4.0	5.2	7.8	4.9	6.4	9.4
160 cm	2.1	2.8	4.2	2.6	3.5	5.1
300 cm	1.4	1.9	2.8	1.7	2.3	3.3

Table 3: Size and Center to Center Spacing of Holed Tapes at all Three Locations, Expressed in Terms of Local Debye Length

The three holed samples were designed with the same overall widths; this strategy allows us to directly compare the hole size of all three equivalent-porosity holed samples. In addition, the width of the holed tapes is equal to the width of the solid and slotted tapes, and their porosity is approximately the same as that of the slotted tape.

Figure 1 shows pictures of three of our tether sample assemblies: the reference cylinder, the wide solid tape, and the wide holed tape. The solid and holed samples are shown with both SHV connectors installed, while the reference cylinder sample is shown prior to the installation of the connectors.

III. VACUUM CHAMBER SETUP AND PLASMA SOURCE CHARACTERISTICS

The vacuum chamber tests were performed using the Large Vacuum Test Facility (LVTF), a 9-m by 6-m cylindrical stainless- steel-clad tank located within the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan, Ann Arbor. A 5 kW-class Hall thruster named “P5,” which was developed by the PEPL and the Air Force Research Laboratory; more detail is given by Haas *et al.* [9], was used as a plasma source. The specifics of the chamber setup and plasma diagnostics are described in depth by Choiniere *et al.* [6]

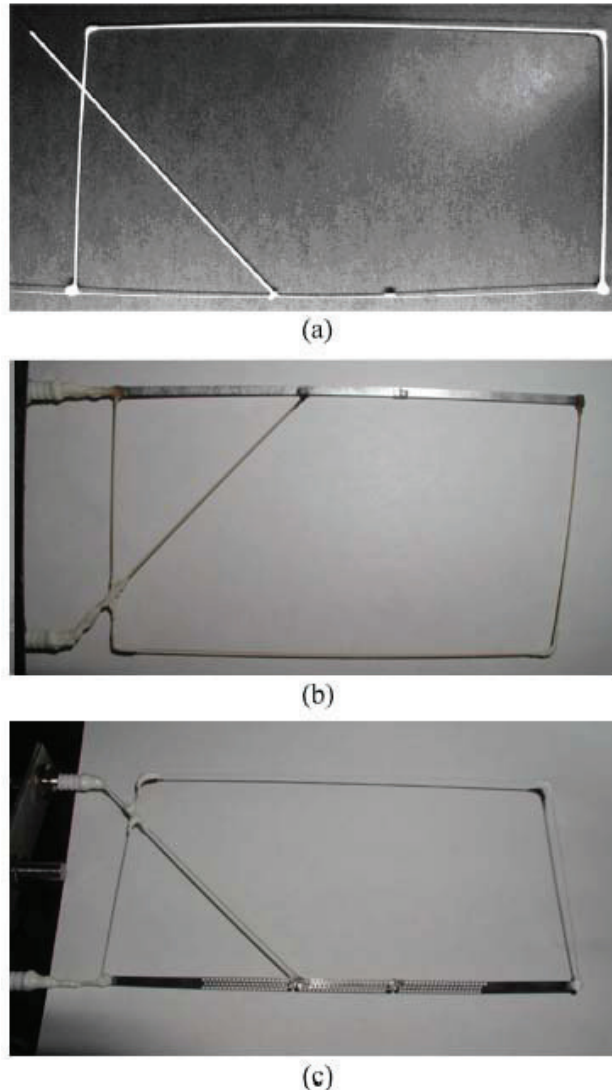


Figure 1: Pictures of three typical tether samples. (a) 0.28-mm diameter reference cylinder. (b) 2.89-mm-wide solid tape. (c) 2.89-mm-wide holed tape.

Plasma density and electron temperature were determined using a 4-cm long, vertically oriented (i.e., perpendicular to the flow) Langmuir Probe (LP) with a diameter of 0.28 mm (same diameter as our reference cylinder sample). All LP sweeps were performed using a Keithley 2410 source electrometer controlled via a custom LabVIEW script running on a personal computer. The plasma parameters, shown in Table 4, were extracted from the ion saturation (OML regime) and electron retardation regions of the $I-V$ characteristics of a LP oriented transverse to the direction of the flow. Density, temperature,

and Debye length estimates have about 8%, 5%, and 6.5% accuracy. In addition, using the Langmuir probe, the beam energy value was determined to be 25 eV. Using a particular procedure, the fraction of these flowing ions at each position could be calculated, as discussed in [6].

Position	n_e (m^{-3})	T_e (eV)	λ_{De} (mm)	μ_b
75 cm	4.95×10^{15}	1.8	0.14	95%
160 cm	1.37×10^{15}	1.72	0.26	53%
300 cm	0.51×10^{15}	1.47	0.40	32%

Table 4: Measured plasma parameters as a function of distance from the hall thruster. measurements were performed using the ion saturation and electron retardation data from a transverse Langmuir probe. The “beam fraction”, μ_b , indicates the fraction of all ions that are believed to be beam (high-speed) ions.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

Following a discussion of the error analysis, we describe and analyze results pertaining to the reference cylinder, the holed tapes, and then perform a comparison of the results obtained for solid, slotted, and holed tapes. All results are presented in the normalized form I_n vs. ϕ_o , where $I_n \equiv (I/I_{the})$ and $\phi_o \equiv ((V_0 - V_p)/T_e)$, consistent with the notation employed by Choinière *et al* [6]. The values used for the electron temperature, T_e , and the electron thermal current, I_{the} , are based on the Langmuir probe-measured electron temperature and plasma density. This normalization provides a means of evaluating the performance of various probes by comparing them to OML theory, as well as by comparing their current characteristics in terms of collected current per unit area. Note that the extent of the axis of the normalized voltage ϕ_o varies from one test position to another, due to differences in the electron temperatures (used in the normalization) measured at the three positions, and from variations in the applied voltage range.

A. Error Analysis

Before discussing experimental results, a brief error estimate is provided. Experimental errors resulted primarily from the repeatability of the experiment. Noise and sporadic phenomena such as arcing and current limiting effects were associated with many runs, which is why numerous runs were taken per probe. Additional errors associated with specified device tolerances and determination of probe area were also taken into consideration.

Multiple runs were conducted for which results differed slightly. The variations among these results were used to determine a measure of the “repeatability” error in measurements. The device tolerances and area calculation errors were added to this repeatability error.

Overall, the total errors remained under $\pm 1\%$ in most cases. The error increased up to $\pm 10\%$ in some cases when ϕ_o was less than 15, but then settled to slightly less than $\pm 1\%$. Particular cases such as the perpendicular and parallel medium holed sample at 160 cm had up to $\pm 3\%$. These errors are indicative of a sample that had runs that arced frequently, or did not have any runs with repeatable data.

B. Reference Cylinder – Analysis of Results

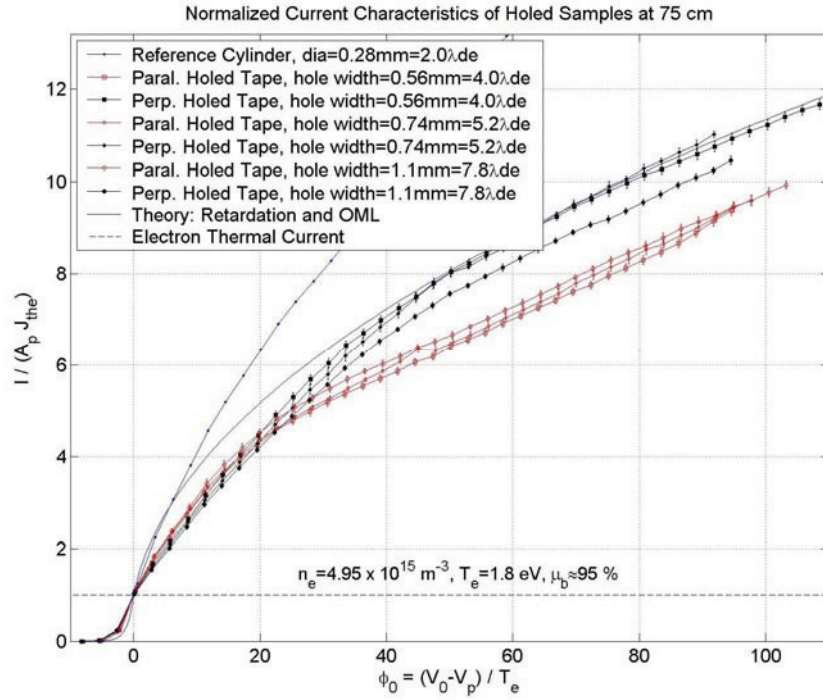
Figure 2 shows the normalized results for the reference cylinder at the three test distances from the plasma source (along with holed tape data). As pointed out in Choinière *et al* [6], the reference cylinder at 75 cm is seen to collect much more current than that predicted by OML theory, by as much as 40% at a bias of 100 T_e . This enhancement is seen to decrease as we move away from the thruster to 160 cm and 300 cm. In fact, there appears to be no enhancement at 300 cm, since the fraction of beam ions was also determined to fall off with distance (see Table 4) [6].

Through simulation, current collection by a Langmuir probe in a high-speed flowing plasma has been accurately described. It has been shown that in a flowing plasma, the wake side of a collecting cylinder possesses a deficiency of electrons, compared to that of the ambient density, while there is a surplus on the ram side. As a result, the sum of the electron current collected by the ram side and the wake side results in enhanced collection over that of OML collection in a non-flowing plasma [16] [17] [24].

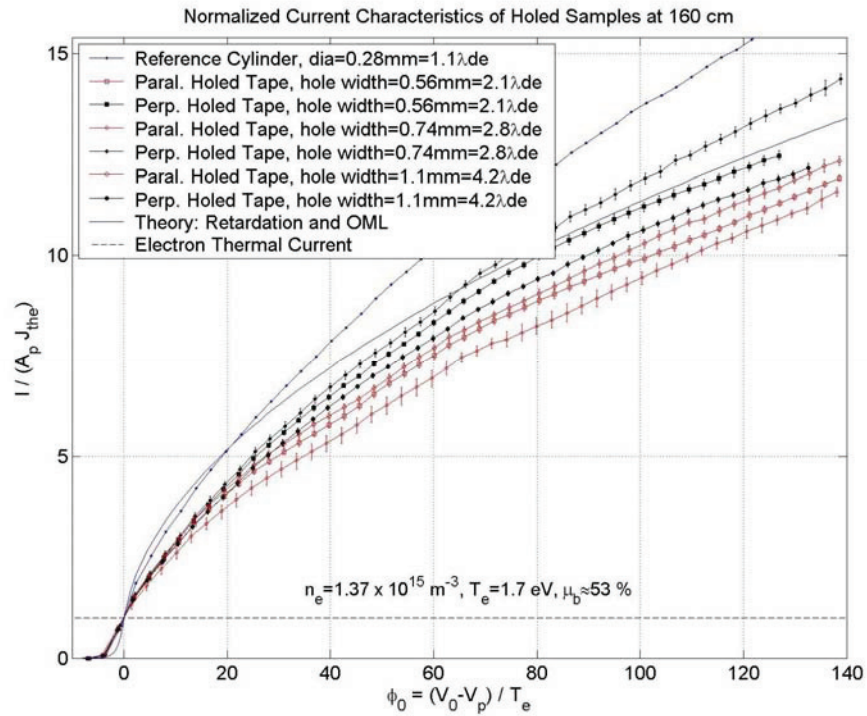
C. Holed Tapes – Observations and Analysis of Results

Figure 2 also presents results for all three holed tape samples at all three distances from the plasma source (75 cm, 160 cm, and 300 cm). The overall tape width, shown in terms of the Debye length, spans from 7.2 to 20.4 electron Debye lengths, while the radius of the holes on each tape ranges from 1.4 to 7.8, as shown in Table 2 and Table 3. It should be emphasized

that the overall widths of the holed tapes are the same as the medium solid tape width (2.89 mm) reported in [6]. We note that the quantitative comparisons among samples made in the remainder of this paper were all made at the highest recorded normalized potential points of the experiment. Three major observations are noted from these results.



(a)



(b)

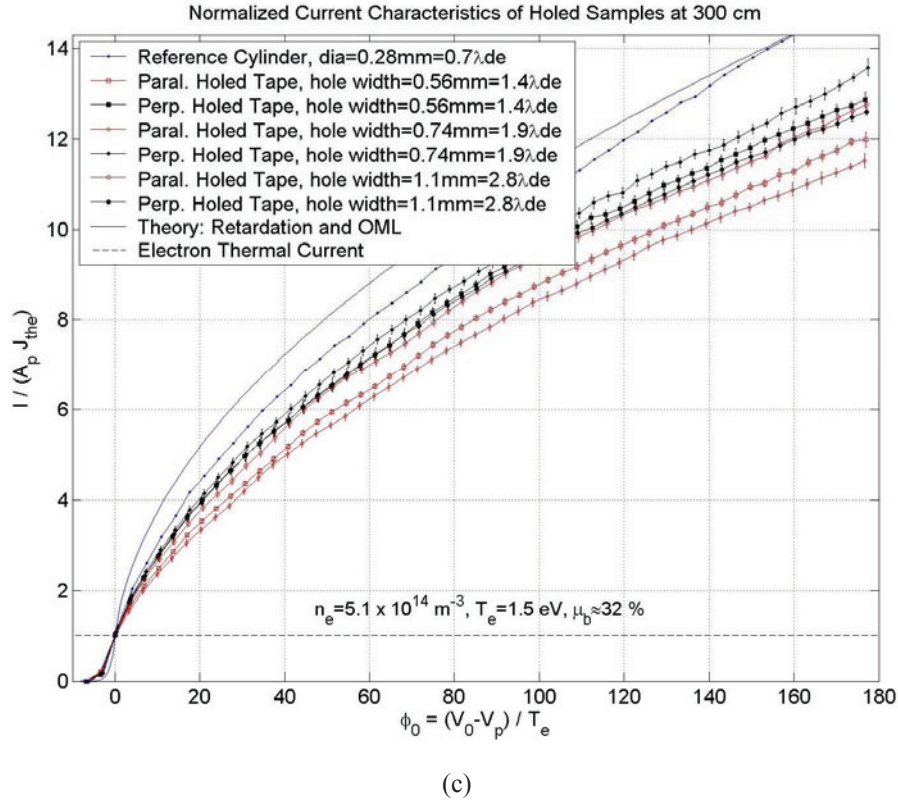


Figure 2: Plot the average run along with its associated tolerance for the (a) 75 cm, (b) 160 cm, and (c) 300 cm cases. The tolerances include device error as well as average run error.

- 1) At all three distances, all the holed tape samples collected more current when oriented perpendicular (transverse) rather than parallel to the flow. According to Figure 2, the most efficient perpendicular and parallel configuration per unit area are the medium hole and large holed configuration, respectively. The ratio of the most efficient perpendicular case to the best parallel case is 18.5%, 20.0% and 6.5% for the 75 cm, 160 cm and 300 cm distances, respectively.
- 2) For the perpendicular orientation at 75 cm, the medium- and small- holed tapes collect the most current per unit area, followed by the large holed tape. At 160 cm and 300 cm, however, where the density and high-speed fraction are lower, the medium-holed sample collected the most current per unit area. Collection on the most efficient hole size tape compared with the least efficient (always the large-holed case) is by 7.3%, 14.7% and 7.7% for the 75 cm, 160 cm and 300 cm, respectively. This may suggest the existence of an optimum hole size which maximizes current collection.
- 3) In the parallel orientation, an opposite observation can be made, i.e. an optimum hole size minimizes current collection. At 75 cm, the parallel medium-holed tape collects the least current on a per-area basis, followed by the small- and large-holed parallel tapes. At distances further from the source, the medium-holed tape became increasingly less efficient as compared to the most efficient large-holed sample, by 3.7%, 6.6% and 10.7% at 75 cm, 160 cm and 300 cm, respectively. This is another indication of the existence of an optimum hole size that minimizes current collection.

The observations concerning the comparative magnitudes of the collection orientations made above are similar to previous simulations and experimental results for slotted tapes explained by Choiniere et al. [6]. Similar to the reference probe, it has been shown that this phenomenon is likely due to the plasma sheath elongation on the wake side of flow [15], [16]. The parallel orientation for slotted tethers has much of the tape being shadowed in a region of reduced ambient density. Similarly, the perpendicular orientation for slotted tethers has the same total width of tape facing the ram direction. It can be inferred that this is the primary cause for the perpendicular oriented collection [25]. Holed tethers have more complex sheath structures due to the geometry differences, however both cases are 50% porous and the slotted spacing is approximately the small hole diameter. Since the holed tape is structurally comparable, similar reasoning can be applied for the holed case.

Also, as explained by Gilchrist et al., a “knee” appears in the current characteristics obtained with the parallel-oriented tapes beyond which the data points follow a $V^{0.5}$ slope [8]. This effect is very prominent in Figure 2a around a net bias ($V_0 - V_p$) $\cong 30T_e$, which is on the order of the ion beam energy [6]. It is also apparent at the 75-cm test position as the high-speed ion fraction was much higher.

The existence of a minimum current collection point in the parallel configuration is similar to previous experimental effects for slotted geometries [6]. The maximum collection point in the perpendicular orientation, however, appears to be unique to the holed tape cases. Both the maximum and minimum collection trends are discussed below.

Parallel Oriented Minimum Case:

Explanations to this phenomenon are likely due to shadowing affects as well as focusing affects. It has been shown in a non-flowing plasma that there exists a minimum collection point between two parallel conducting wires as the gap between them increases [17], [24]. This minimum point is due to unpopulated trajectories that connect the two wires, caused by the effects of the neighboring cylinder. This shadowing causes the trajectories to be emptied thereby reducing the density along their paths.

Simulations have been conducted for the parallel oriented slotted configuration in a flowing plasma, which details the current collection with respect to OML as the distance between the wires increase [25]. This same shadowing effect is observed for the front wire of this flowing case. On the wire in the wake of the first, a focusing effect can be observed. The ram side wire deflects the incoming plasma toward the wake side wire, thereby enhancing its current collection. The overall result implies that there exists a couple of minimum points as the gap spacing increases. Again, since the holed sizes are physically similar to the slotted sizes, the same overall trends are likely to occur.

Perpendicular Oriented Maximum Case:

Possible causes for the maximum points occurring are also likely the result of a combination of shadowing affects as well as focusing affects. As shown through previous simulation, the wake side of the perpendicularly oriented slotted tape in a flowing plasma also behaves similar to the shadowing encountered in the non-flowing case [25]. In addition, electron current collection on the wake side of this orientation is enhanced due to focusing. The incoming plasma is being deflected by the holed tape into a trajectory that results in the collection on the wake side. This collection enhancement exceeds that of the ram side collection. The overall result produces a few maximum collection points due to presently unexplained oscillations in the wake collection.

As the porosity of the collecting tape becomes much larger than 50%, the difficulty in maintaining a uniform pattern and a constant porosity becomes increasingly complicated. As a result, the distances between the holes will begin to impact the results, since they will not be uniform in all directions. Predicting the complex sheath interactions within such geometry is beyond the scope of existing current collection theories.

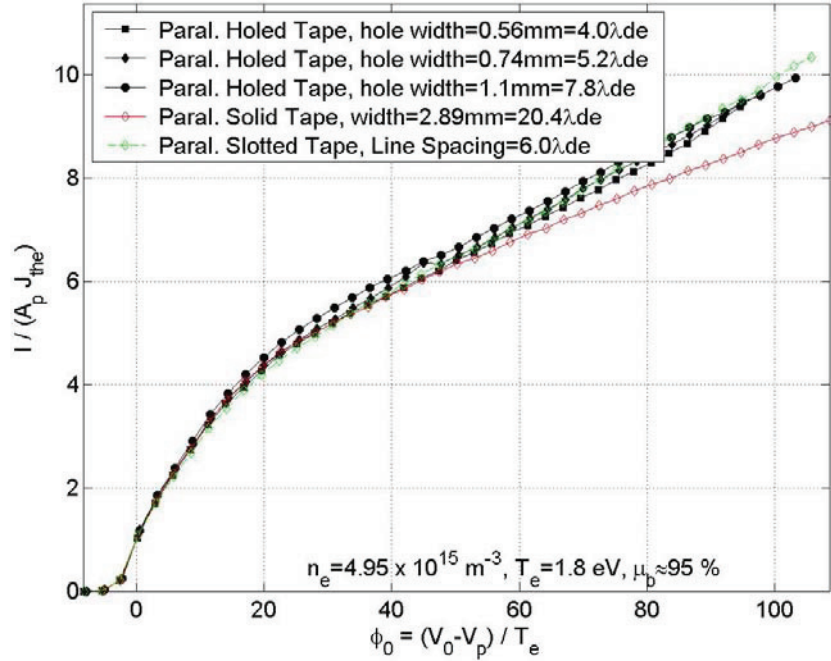
In order to further validate the predicted effects of the perpendicular and parallel orientations, experiments must be conducted that maintain the porosity of the tether at other hole sizes. For example, the small and large slotted samples were 28% and 75% porous, respectively. A possible test would be to design a uniform holed pattern that could maintain this porosity for various hole sizes as this experiment has done.

D. Comparison of the Holed, Slotted, and Solid Tapes

Figure 3, Figure 4, and Figure 5 display the same sets of results shown earlier, but with the holed, solid, and slotted tapes plotted on common graphs to facilitate their comparison. An important note is that the solid and slotted tape samples compared were the same width (2.89 mm) as the holed tape samples. The following is observed:

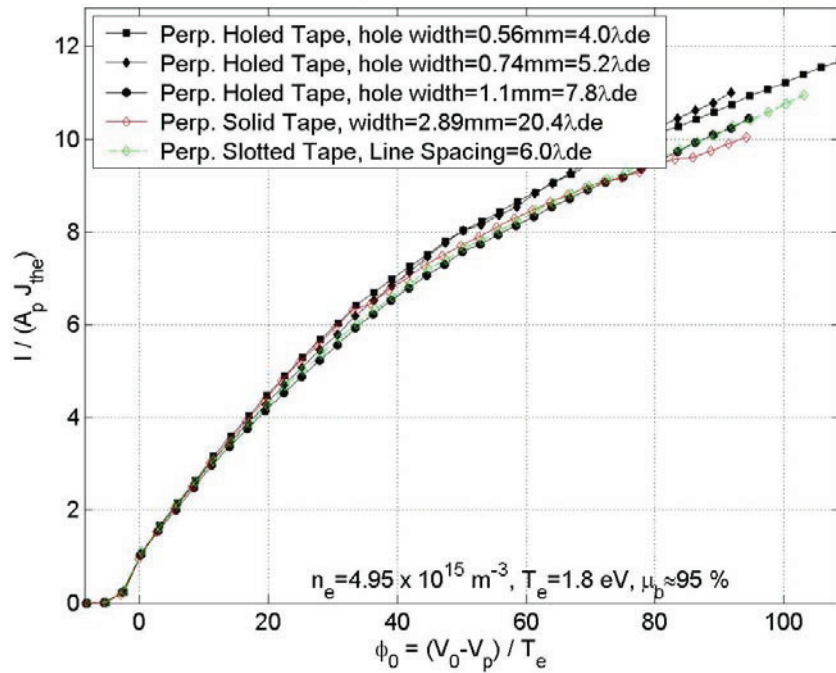
- 1) Despite the holed samples being more efficient per unit area, the absolute amount of current collected by the solid tape samples was higher than that collected by the holed tape samples. This can be seen compared to the holed and slotted tapes in Figure 6. This trend is expected, since the total surface area of the solid tape was slightly less than twice that of holed and slotted tapes.
- 2) The slotted and holed tape samples were more efficient on a per-area basis than their solid counterparts in both perpendicular and parallel configurations as seen in the figures. In addition, for all 3 hole sizes the holed samples were more efficient per unit area than their solid and slotted counterparts in the perpendicular orientations. Similarly, at all 3 distances, the slotted samples were more efficient per unit area than their solid and holed counterparts in the parallel orientations. This suggests that the sheath interactions, due to flow-induced sheath elongation, are greater with the holed probes at parallel configurations and for slotted probes at perpendicular configurations. The relationship between the slotted, solid, and holed tape probes along with the associated error for each probe is detailed in Table 5.

Normalized Characteristics of Parallel Holed Slotted and Solid Samples at 75 cm



(a)

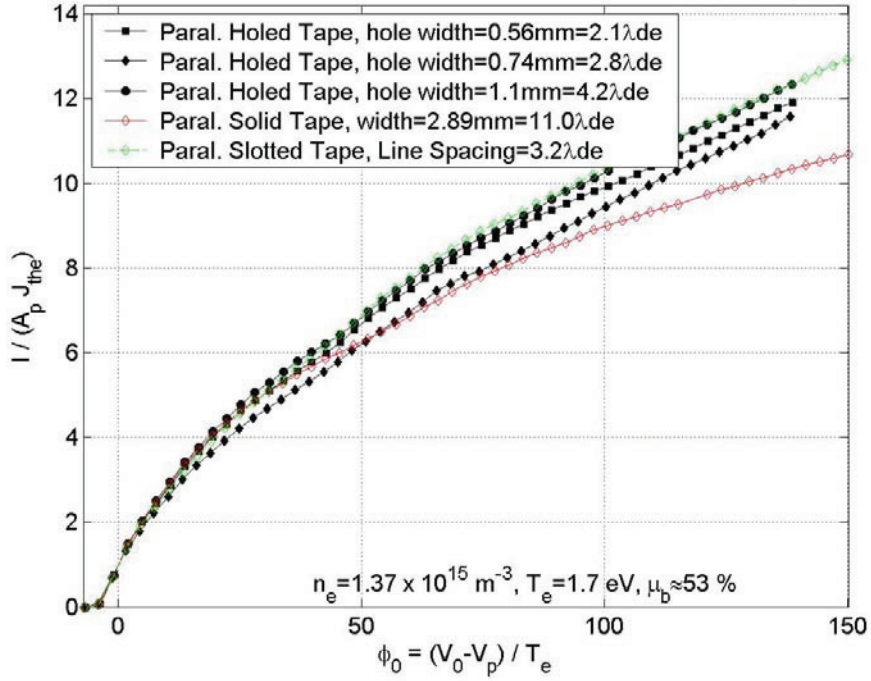
Normalized Characteristics of Perpendicular Holed Slotted and Solid Samples at 75 cm



(b)

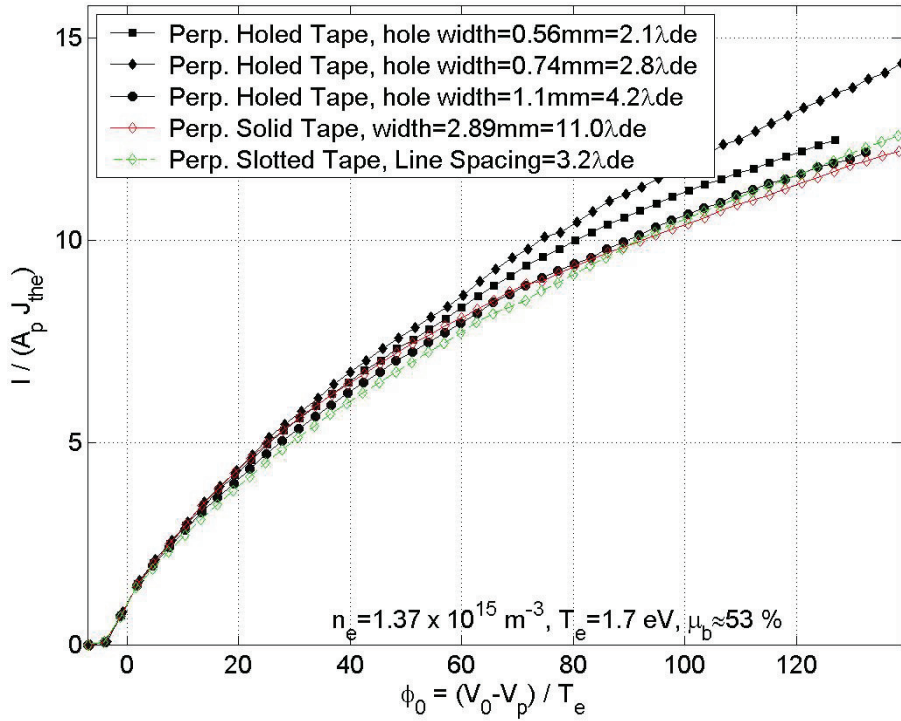
Figure 3: Comparison of the I - V characteristics of holed, solid, and slotted tapes at 75 cm. Upper and lower graphs are applicable to parallel and perpendicular tape orientations, respectively.

Normalized Characteristics of Parallel Holed Slotted and Solid Samples at 160 cm



(a)

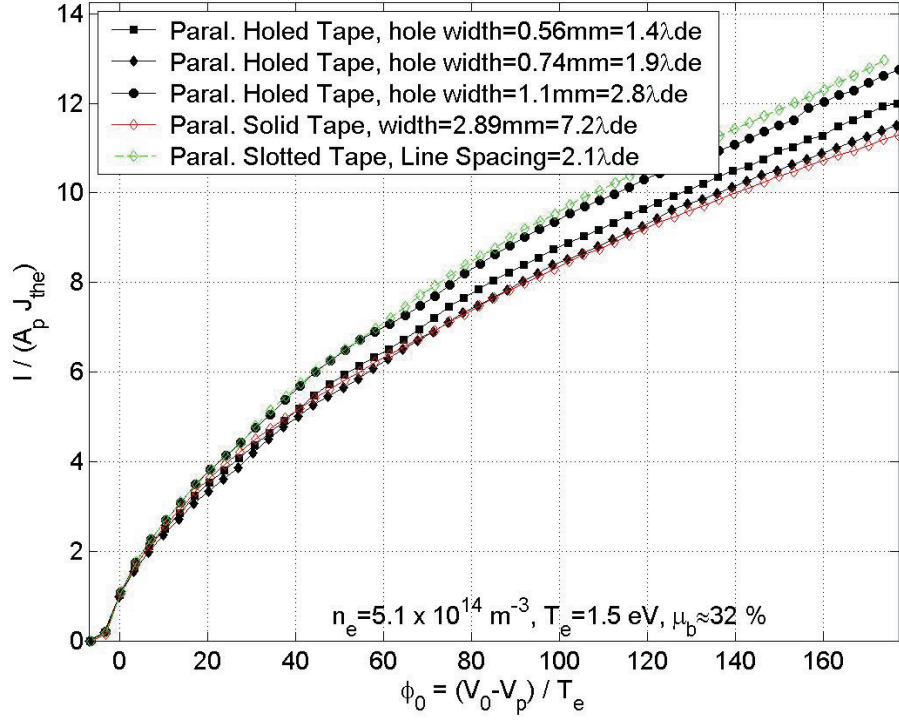
Normalized Characteristics of Perpendicular Holed Slotted and Solid Samples at 160 cm



(b)

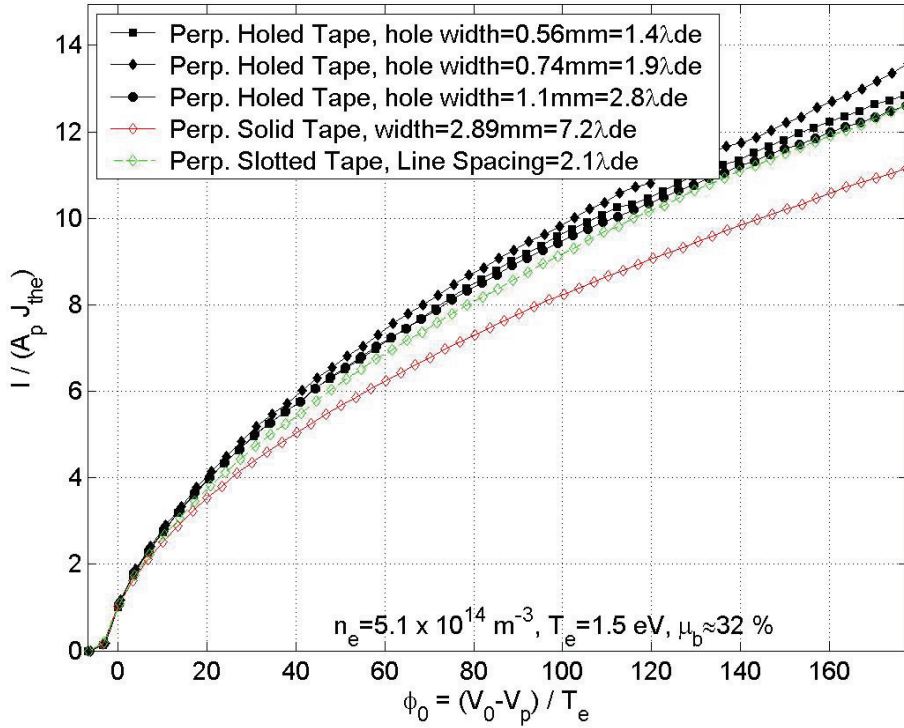
Figure 4: Comparison of the I - V characteristics of holed, solid, and slotted tapes at 160 cm. Upper and lower graphs are applicable to parallel and perpendicular tape orientations, respectively.

Normalized Characteristics of Parallel Holed Slotted and Solid Samples at 300 cm



(a)

Normalized Characteristics of Perpendicular Holed Slotted and Solid Samples at 300 cm



(b)

Figure 5: Comparison of the I - V characteristics of holed, solid, and slotted tapes at 300 cm. Upper and lower graphs are applicable to parallel and perpendicular tape orientations, respectively.

% Difference	75 cm Perp.	75 cm Par.	160 cm Perp.	160 cm Par.	300 cm Perp.	300 cm Par.
Best Hole / Slot	7.0	-0.8, in Noise	14.1	-0.1, in Noise	7.7	-2.7
Best Hole / Solid	11.1	10.8	16.5	19.4	21.8	11.7
% Error \pm	1.4	1.3	1.2	1.5	1.5	1.4

Table 5: Comparison of the percentage difference between the most efficient electron collection (per unit area) holed probe to a slotted or solid probe along with the percent error associated with that probe.

- 3) In both orientations, the large-holed tape samples were very similar to the slotted tape samples at all three distances. Two cases had less than 1% difference, which is in the noise of the experiment according to Table 5, except for the parallel oriented case at 300 cm (which had ~2.7% difference). The major difference between the large holed and slotted cases was that the large holed tape was often more efficient per unit area at lower bias potential values, and then eventually became equivalent starting above $(V_o - V_p) = 40-60 T_e$. Provided that the porosity remains the same, it appears that as the hole size increases in the holed samples, the closer the electron current collection would mimic the slotted samples. This holed sample structure physically resembles, and thus collects similar to the slotted sample because of the many thin lines for collection. More experimental investigation must be conducted to ascertain the cause of this phenomenon.

V. OPTIMIZING A BARE ELECTRODYNAMIC TETHER

Using holed tape tether technology has the potential to significantly reduce total tether mass compared to a solid tether while maintaining nearly the same electron collection. If hole diameter is small with respect to the thickness of the tether and Debye length, the trajectory of the attracted species has the possibility to be highly constrained and likely collected to the surface of the tether in passing through the hole. This geometry would likely collect similar to that of a solid tape. The difference would be that the total mass of the tether is reduced by the fraction of the porosity.

This trend is clearly shown in Figure 6 at the 75 cm distance. The total electron current collection grows, and becomes closer to the solid current collection as the holes get smaller. The results presented in this experiment are not sufficient to prove this phenomenon because hole size is still larger than a Debye length, but indicate a possible trend.

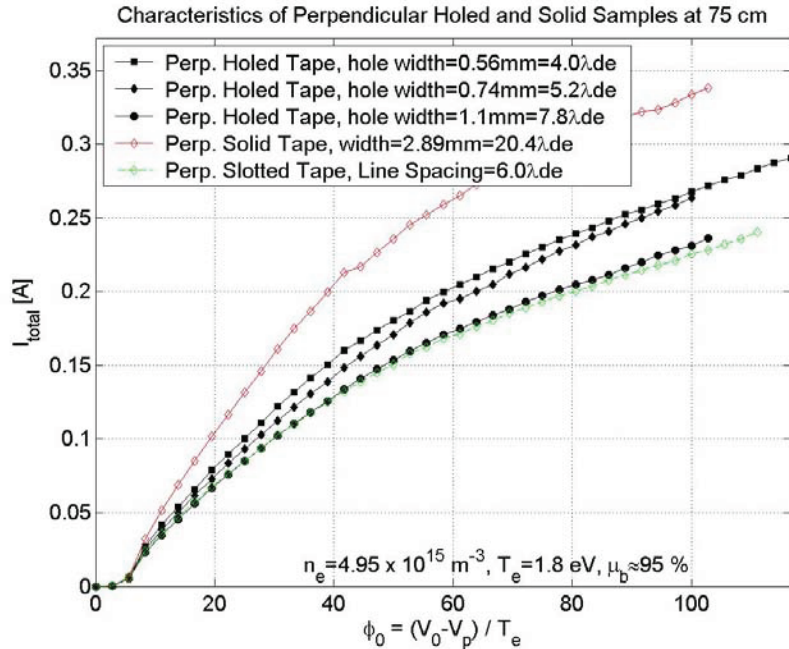


Figure 6: Absolute current collected from small, medium, and large size holes compared to the equivalent width solid tape at 75 cm distance.

VI. PRESENT STATUS AND CONCLUSION

Several conclusions can be drawn from the analysis of the results.

- 1) Beyond a threshold bias close to the beam energy, holed tapes collect more current when oriented transverse (perpendicular) to the flow rather than parallel, as also seen in Choinière et al. for slotted and solid tapes [6]. For the case involving the greatest plasma flow percentage, the 75 cm case, the most efficient perpendicular configuration (medium and small hole) was more efficient per unit area than the best parallel orientation (large hole) by 18.5%.
- 2) Holed tapes are more efficient than both solid and slotted tapes in terms of collected electron current per unit area when oriented perpendicular with respect to the plasma flow. In the perpendicular orientation, the most efficient holed tape (medium hole) is more efficient than the solid tape by 11.0% at the 75 cm position. These holed tapes became increasingly more efficient compared to the solid tapes at the more distant, less flowing, cases. Similarly, slotted tapes always appear to be equal to or slightly more efficient than holed or solid tapes when oriented parallel with respect to the plasma flow.
- 3) The electron current collection efficiency per unit area on holed tapes in the parallel orientation decreases with increasing hole size until a minimum is attained, beyond which it starts increasing again. This effect is in the noise at 75 cm, but distinctive at 160 cm and 300 cm. The opposite effect occurred when the holed probes were oriented transverse to the flow, where a maximum efficiency was obtained for a hole size somewhere between the small and large hole sizes tested.

Further experimentation is needed to more completely quantify the observed effects. In addition, larger and smaller width holed tapes should be tested in both the parallel and perpendicular orientations to verify the effects that have been displayed in this experiment. The porosity of the larger-width probes (as defined in [6]) designed should be 50% and 77% in order to mimic the approximate porosity of the slotted sample. Similarly, the smaller-width holed probes designed should be 50% and 31% porous. In addition, a probe could be made that would have larger holes than this experiment. This would verify the assumption made in item 3 of section D.

The results also indicate that alternative-geometry space tethers can potentially allow for efficient electron collection. The holed and slotted geometries have the advantage of collecting more current per unit area, thus reducing mass requirements. The holed tape has the further advantage of having better micrometeoroid impact resistance than the (strictly) slotted tape, allowing for a practical implementation in space tethers. Future improvements in 3-D sheath theory will improve tether design capability and ultimately allow for the combined maximization of electron collection and minimization of mass requirements.

Acknowledgements

The authors would like to thank Sven G. Bilén for his contribution to the experiment, and Alec. D. Gallimore for providing the test facilities at the Plasmadynamics and Electric Propulsion Laboratory. Keith Fuhrhop acknowledges support through the NASA GSRP from Marshall Space Flight Center under Contract NGT 8-52917.

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