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Flowing Plasma Interaction with an Electric Sail Tether Element

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Introduction

Motivation

Contribute to the NASA Innovative Advanced Concepts Phase II development of the:

Heliopause Electrostatic Rapid Transit System HERTS

- *Solar Wind Electric Sail Propulsion to Interstellar space*

Image Credit: NASA (spaceplace.nasa.gov)

Objective

Perform laboratory-scale plasma testing that can be extrapolated through modeling to solar wind scales

- Focus on ion interactions with positively biased bodies (cylindrical electrodes) that are surrogates for tethers

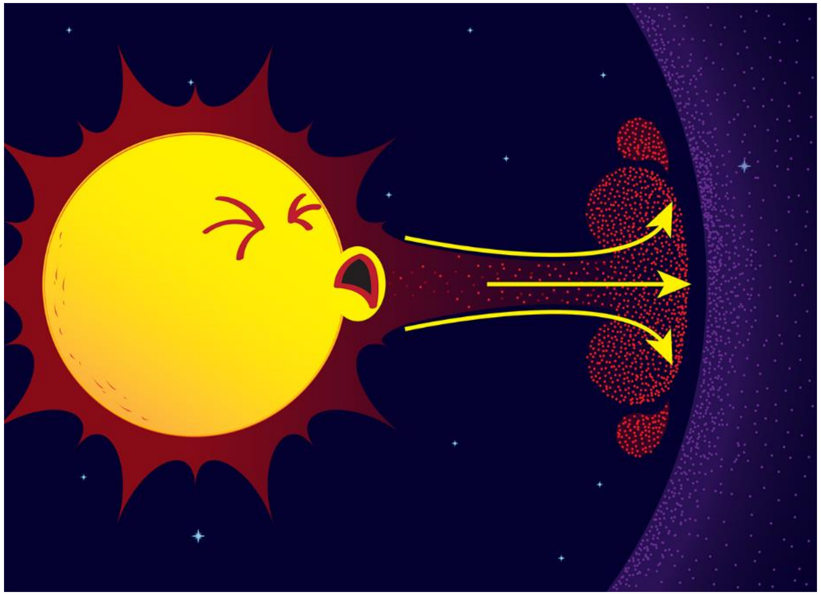
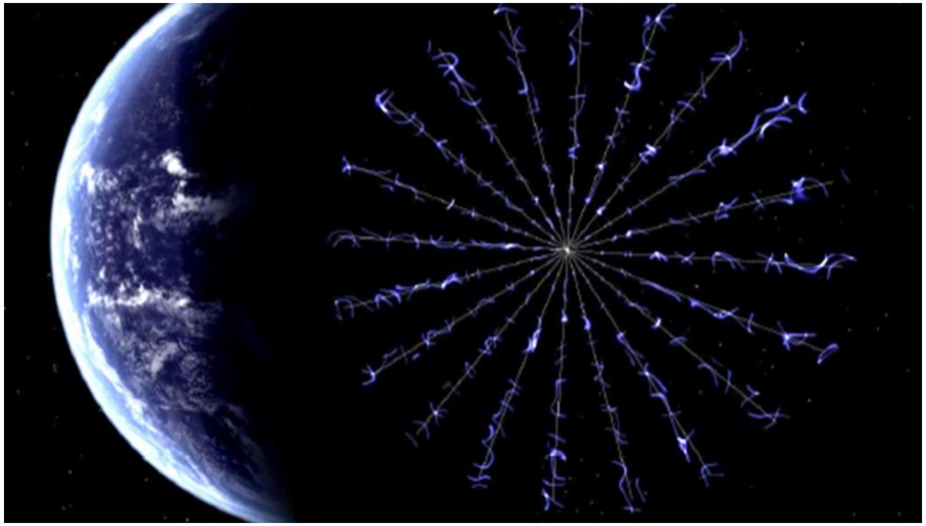
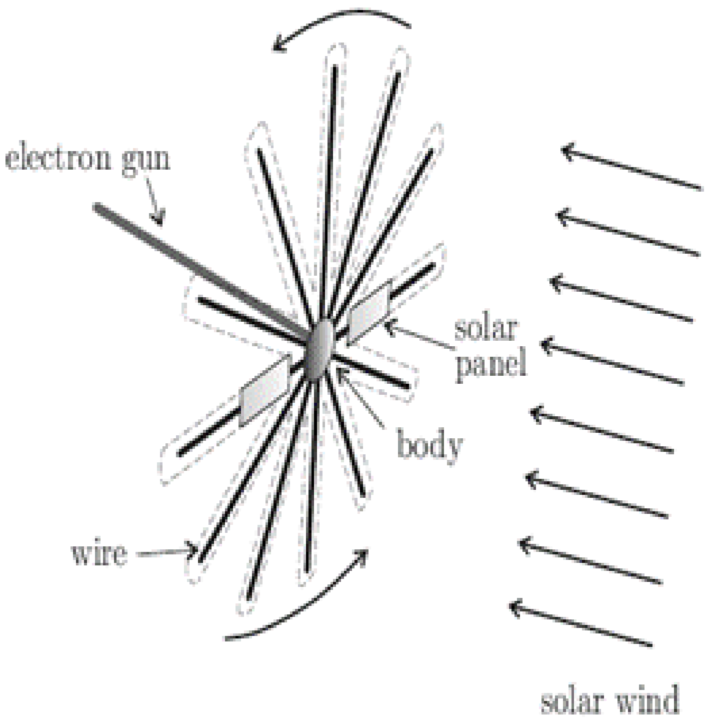


Image Credit: NASA (spaceplace.nasa.gov)

E-Sail Concept





- An Electric Sail or E-Sail propulsion system is designed to harness the solar wind proton energy by repelling the protons
- A high voltage (kV) bias is applied to multiple tether wires extending radially outward from the spacecraft body
- A plasma sheath will form around each tether wire to create an enhanced interaction region to maximize the proton momentum exchange
- To maintain the high voltage bias on each tether requires emitting collected electrons via an electron gun on the spacecraft

Electric Sail History and Benefits

- The electric solar wind sail, or electric sail for short, is a propulsion system invented in 2006 by Dr. Pekka Janhunen (Finish Meteorological Institute)
- The electric field surrounding each wire extends ~ 10 meters into the surrounding plasma and gradually expands as the distance from the sun increases (tether wire is <0.1 mm dia.)
- Electric sail acceleration extends deep into the solar system (6 times further than a solar sail)
- Has the potential to fly payloads out of the ecliptic and into non-Keplerian orbits, place payloads in a retrograde solar orbit, missions to terrestrial planets and asteroids, and position instruments for off-Lagrange point space weather observation
- Offers ultimate velocities that could allow a mission to the heliopause in 15 years (within a research scientists' career)

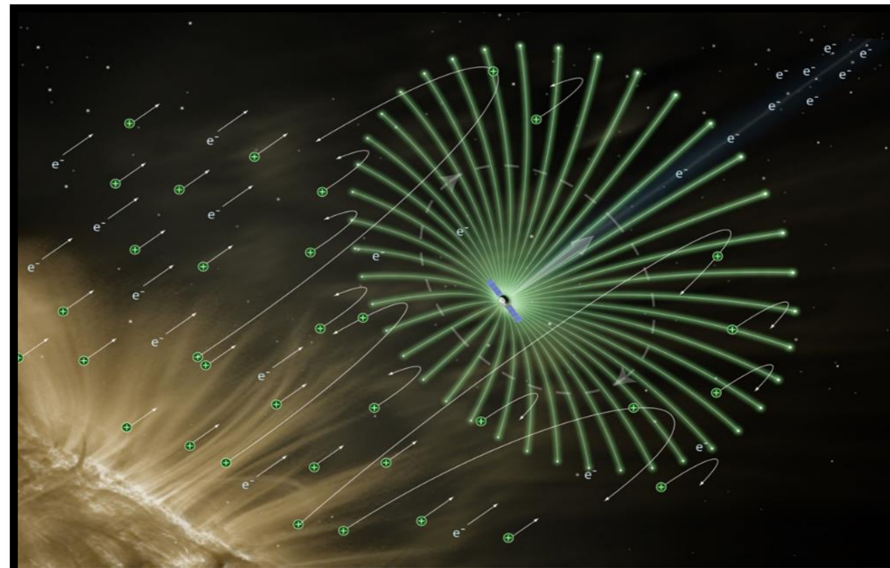


Image credit Alexandre Szames, Antigravite, Paris

Project Description

- In 2015 NIAC Funded a Phase II Research Effort
  - Heliopause Electrostatic Rapid Transit System (HERTS)
  - Effort to emphasize measuring the deflection of ions on a positively biased tether
    - Propulsive thrust is determined by the ion deflection
    - Sheath size is critical to maximizing interaction area
    - Are Orbital Motion Limited (OML) sheath estimates conservative?
  - Determine the amount of electrons collected by a positively biased tether
    - A power system driver
    - Electron gun design driver
  - Develop a Particle In Cell model to extend the ground based measurement to space
  - Benchmark Model with ground based experiments

Focus of this talk is on the laboratory measurements of ion deflection and electron collection

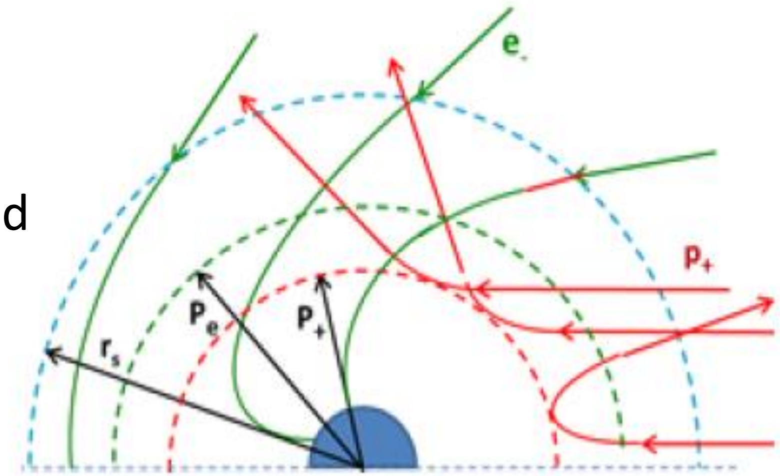


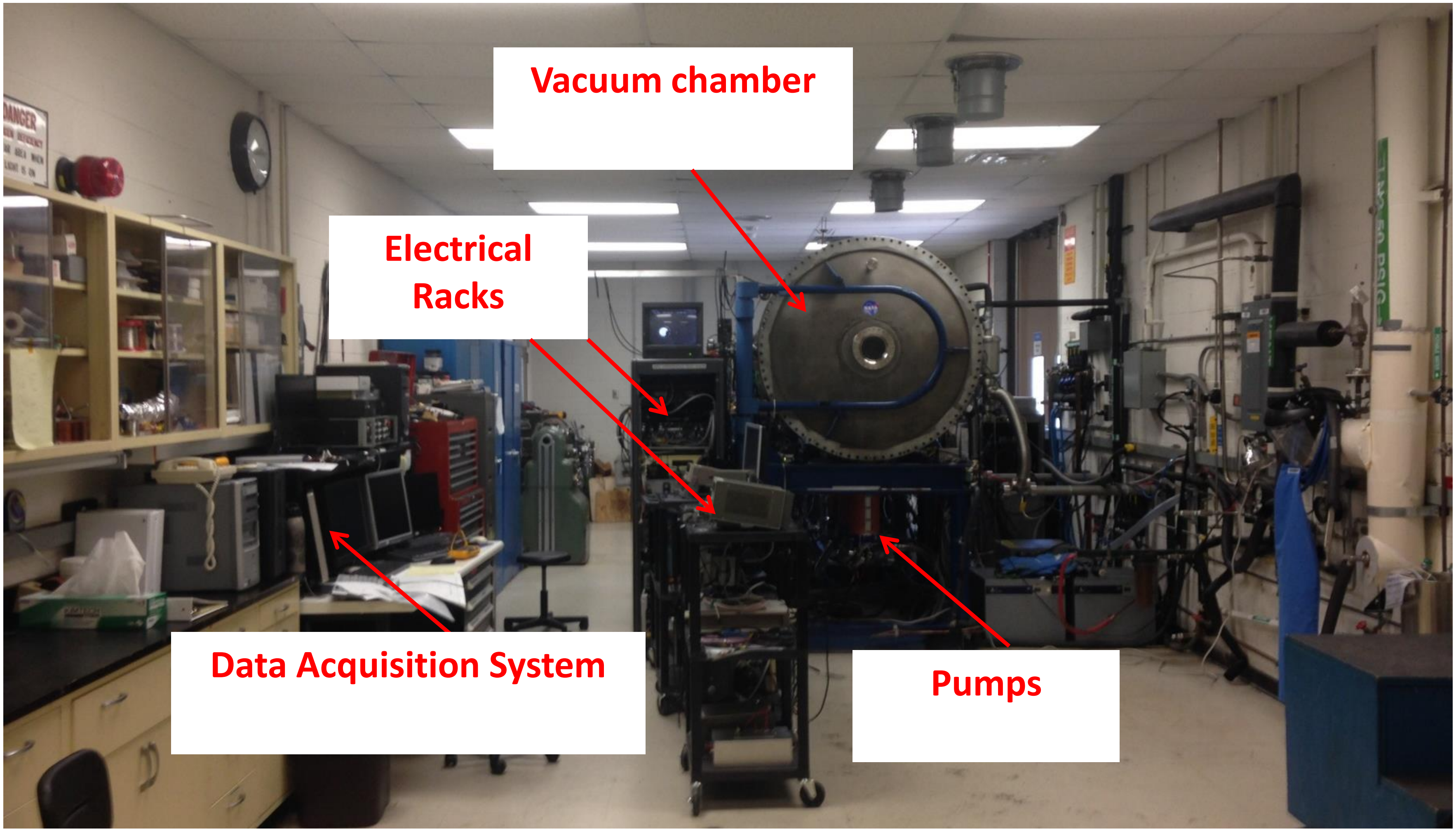
Image from NASA Innovative Advanced Concepts (NIAC) proposal: Heliopause Electrostatic Rapid Transit System (HERTS) Phase II April 27, 2015

Scale Lengths of Interest

- Nominal solar wind
  - Proton speed is 400 – 450 km/s (~ 1000 eV)
  - Density ~ 5/cm^3
  - Core electron temperature ~ 15 eV, ion temperature ~ 12 eV
  - Debye length ~ 10 m
- Chamber size for lab experiment must be many Debye lengths in diameter
  - Size required is too large for quantitative reproduction of solar wind Debye length
- Use low energy plasma analog (qualitative scaling to reproduce physical process)
  - Ion drift energy ~ 100 eV
  - Density ~ 1x10^6/cm^3;
  - Electron temperature ~ 1 eV; Ion temperature << 1 eV
  - Debye length < 1cm;
  - Tether size ~ 1 mm so Debye length > tether diameter
  - Tether bias ~ ion drift energy

Plasma Experiment Facility

NASA Marshall Space Flight Center – Huntsville, Alabama, USA



Experiment Facility – Ion Source

Schematic of Kaufman Ion Source (Side View Cross-section)

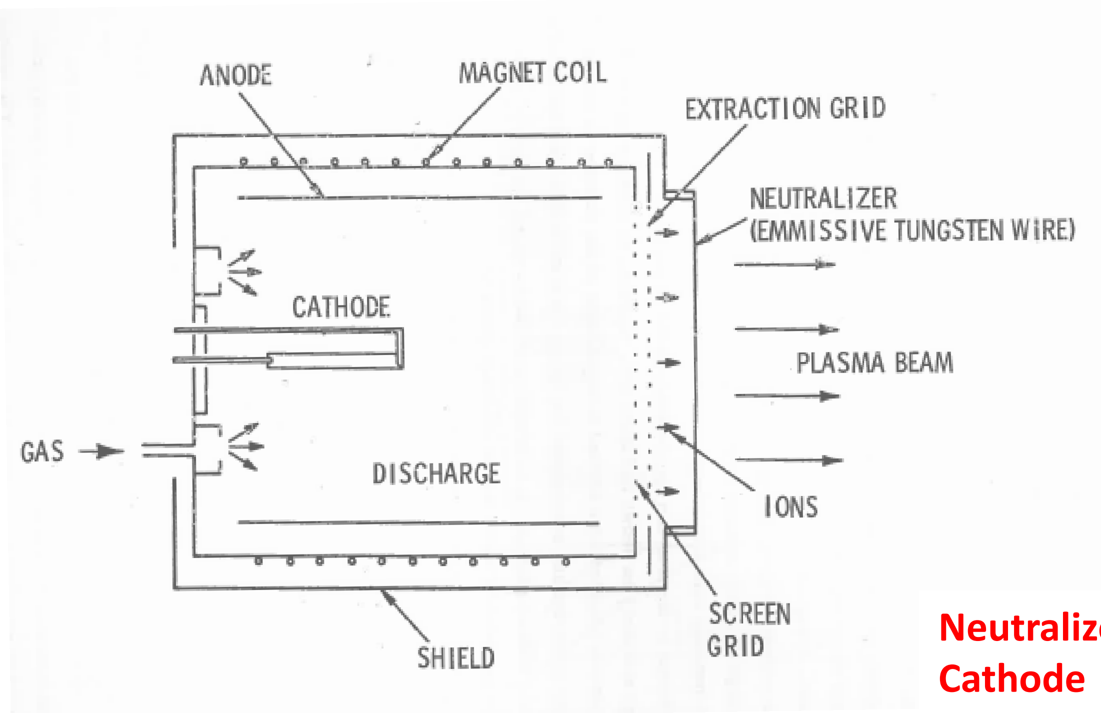
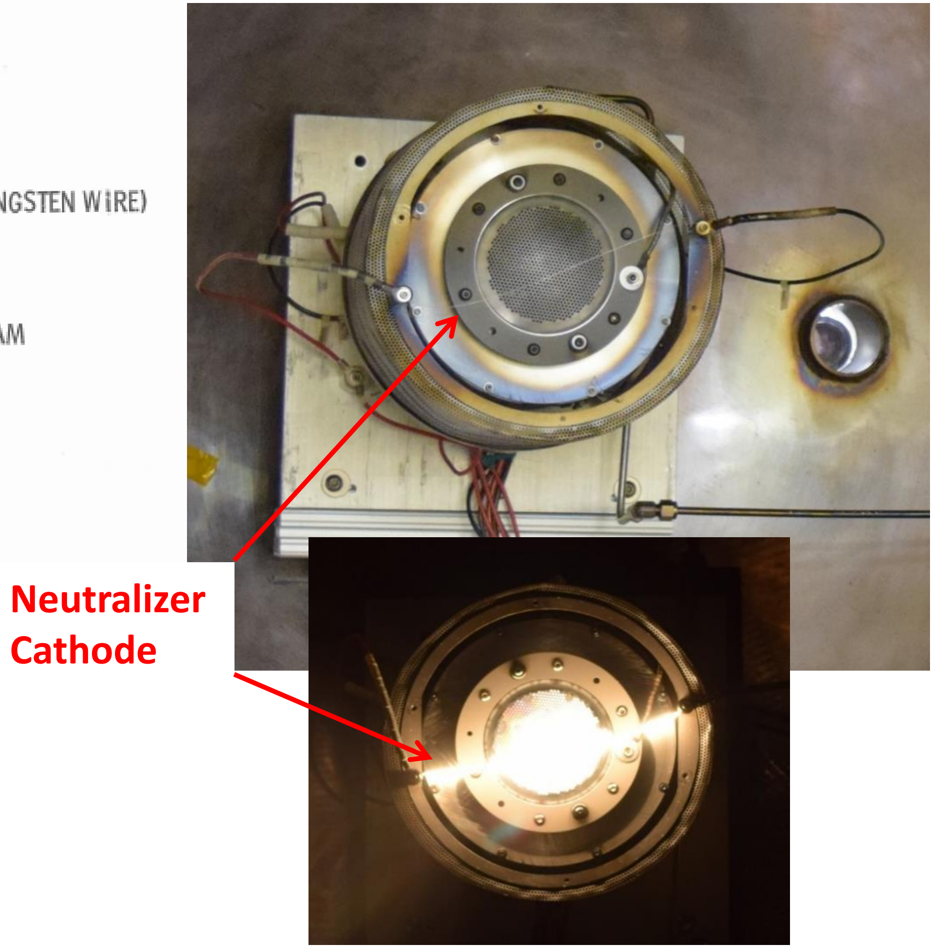
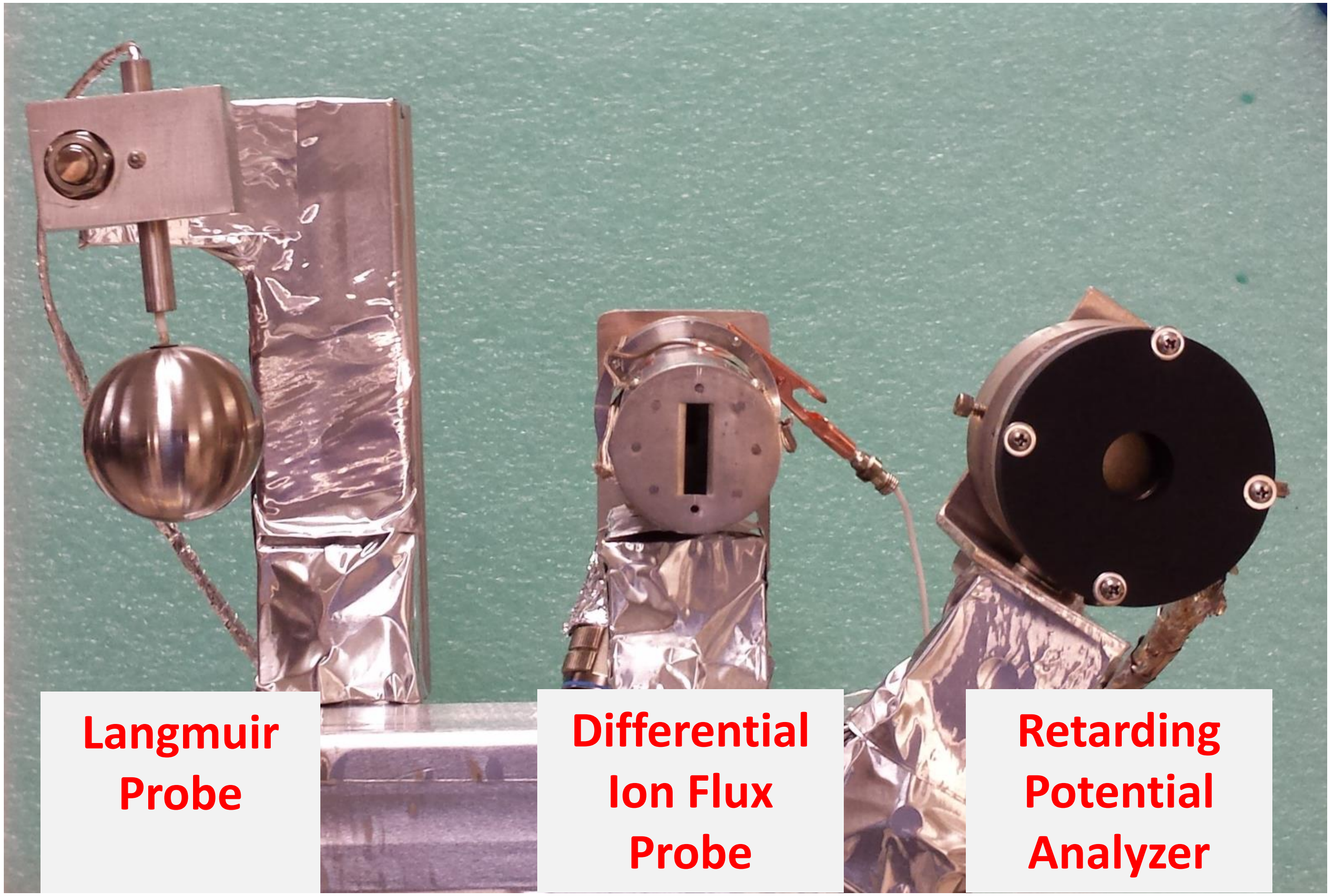


Figure from: N. H. Stone and W. K. Rehman, The simulation of ionospheric conditions for space vehicles, NASA TN-D-5894, 1970.

Picture of Kaufman Source (End View of Grids & Neutralizer)



Probe Array

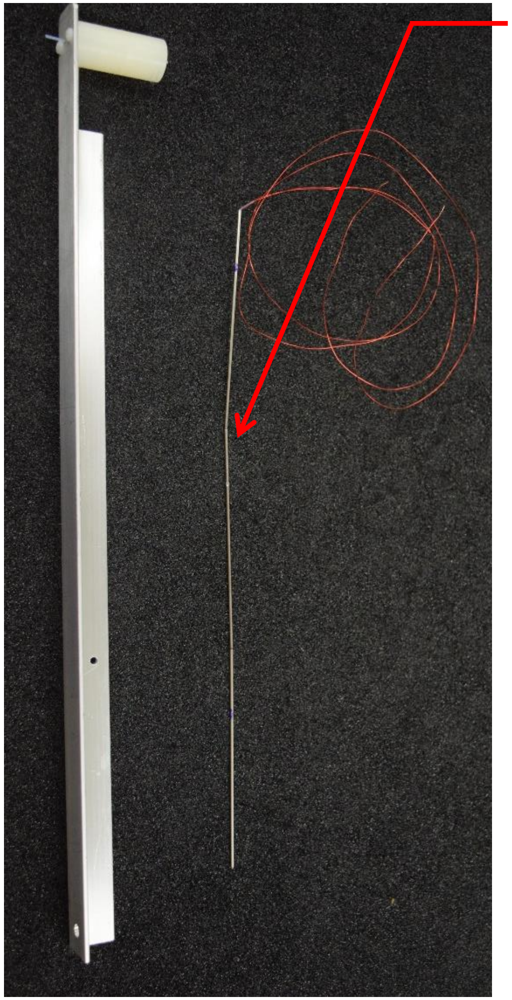


LP: Langmuir Probe
- electron temperature
- plasma space potential

DIFP:
Differential Ion Flux Probe
- ion flow vector

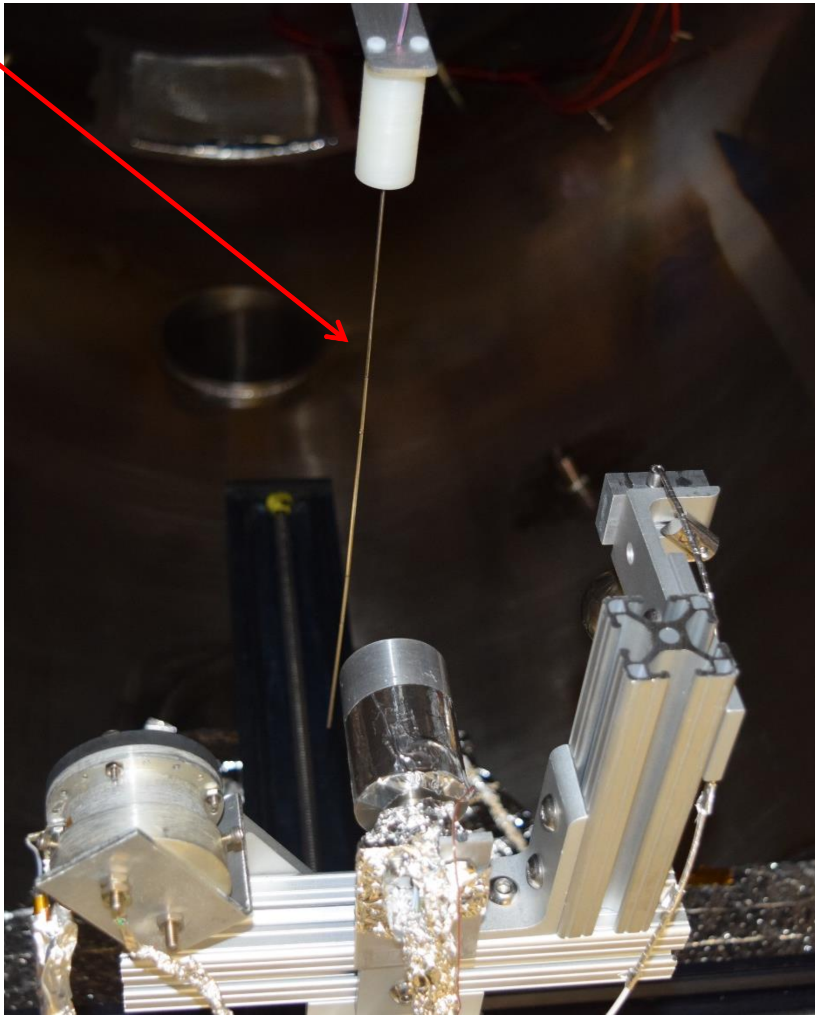
RPA:
Retarding Potential Analyzer
- ion flow energy
- plasma density

Test Body (Tether)

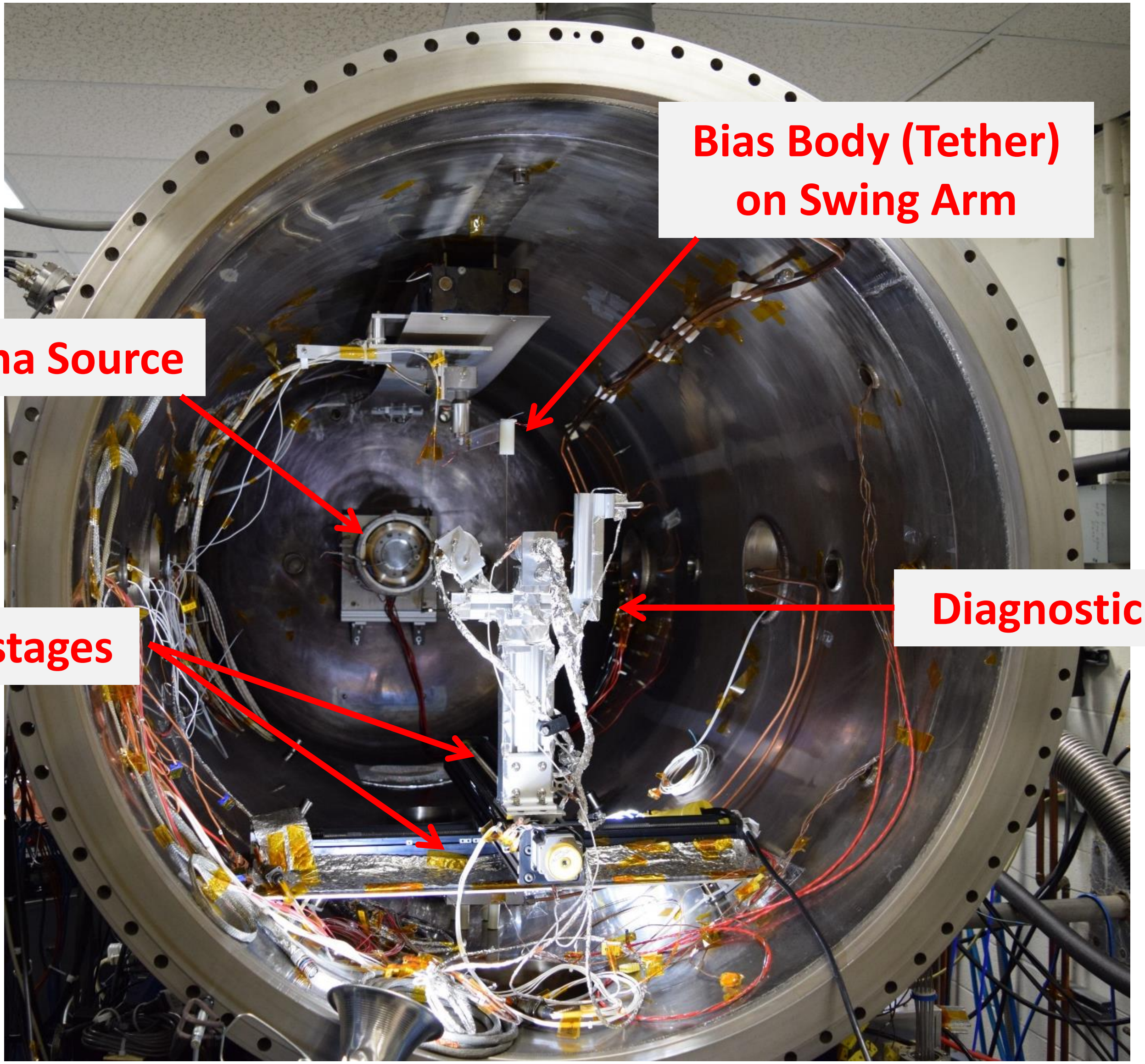


Test body (tether)

- **3 segment**
- **Stainless steel cylinder**
- **Guarded design**
  - **All sections biased, only center section can collect current**
  - **Reduces end effects**
- **1.85 mm diameter**
- **Top guard length = 9.7 cm**
- **Center collector length = 13.2 cm**
- **Bottom guard length = 12.8 cm**



Plasma Test Chamber (Downstream End)



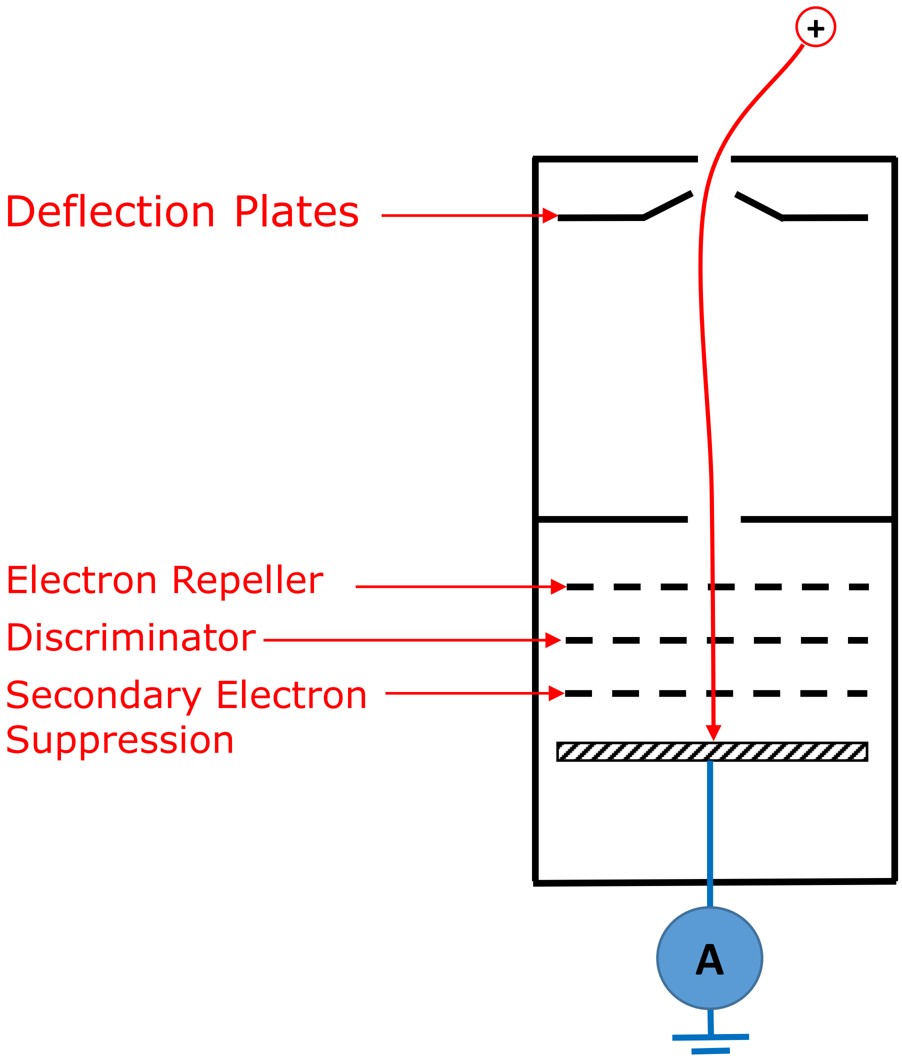
Plasma Properties and Scale Lengths

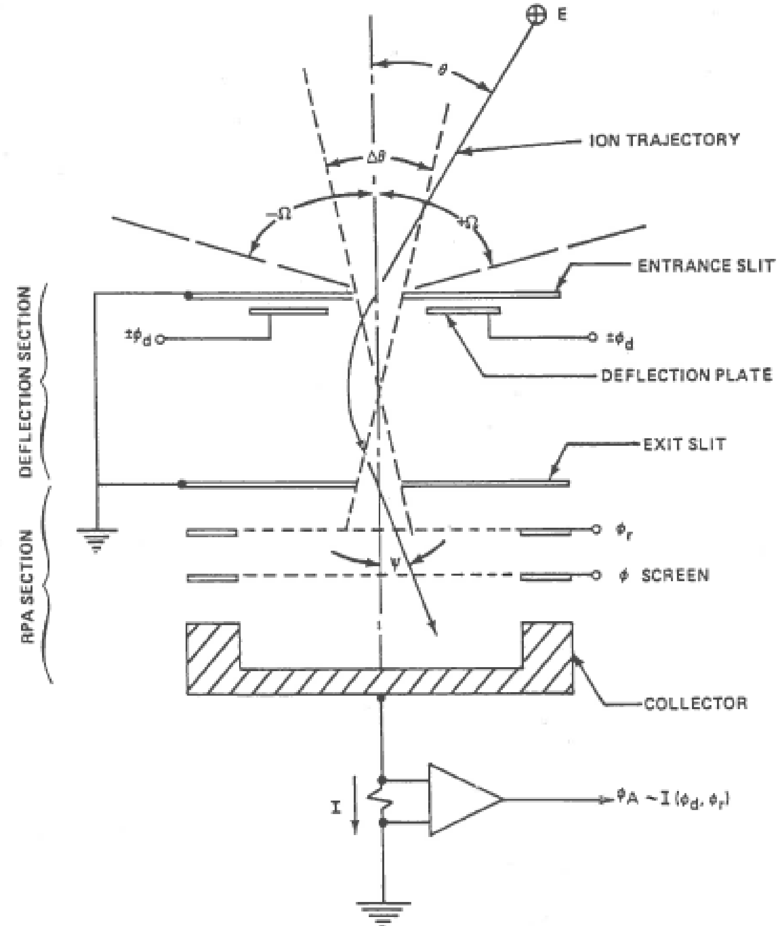
Typical Argon Plasma Parameters			
Property	**Parameter (Units)**	**100 eV Nominal**	**200 eV Nominal**
Ion Drift Energy	E (eV)	105	203
Ion Current Density	J (μA/cm^2)	0.53	0.70
Electron Temperature	Te (eV)	0.73	0.77
Plasma Density	n (10^6/cm^3)	1.47	1.4
Debye Length	λd (mm)	5.2	5.5

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

DIFP schematic

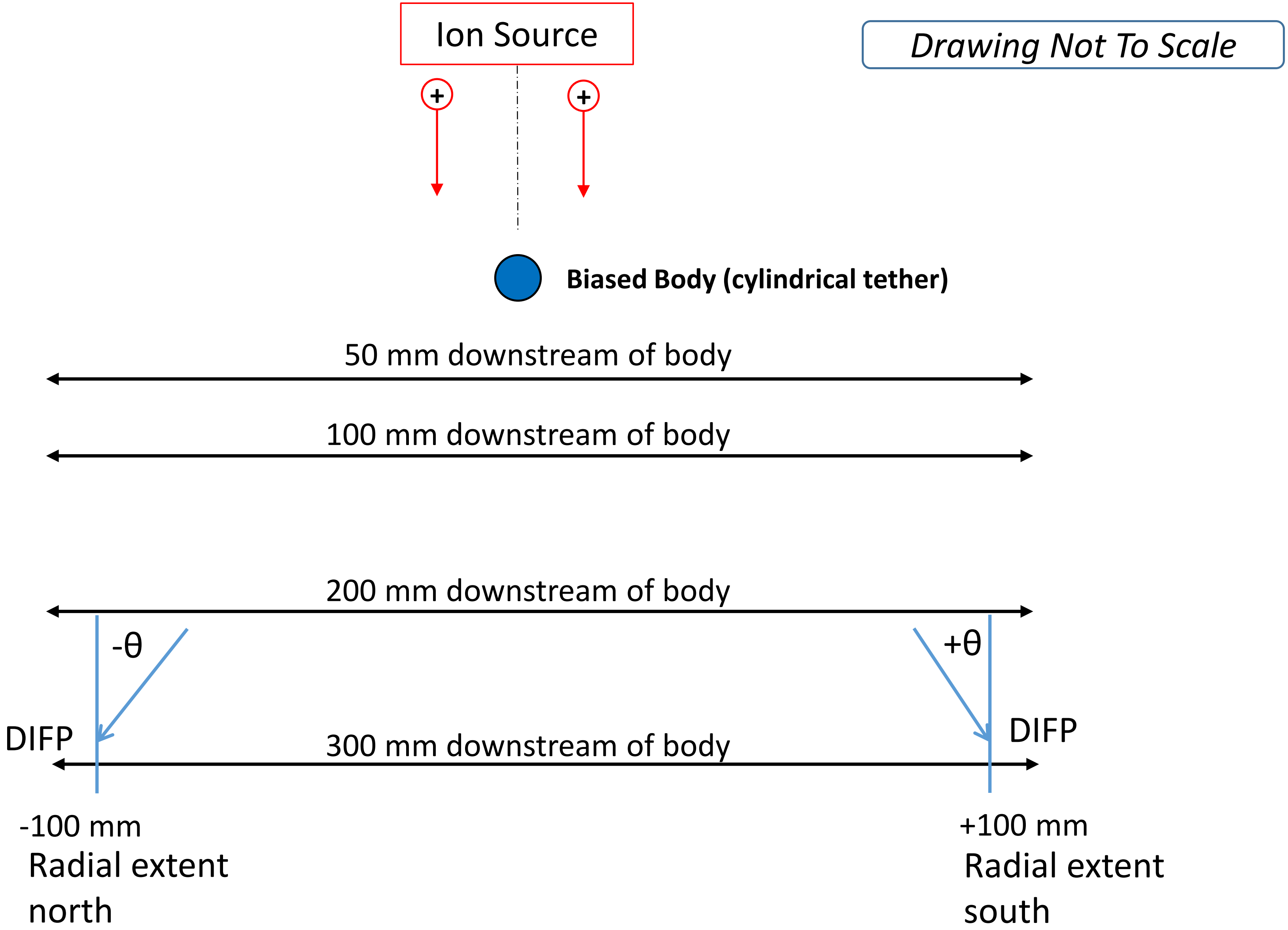
Top View through Instrument Mid-Plane





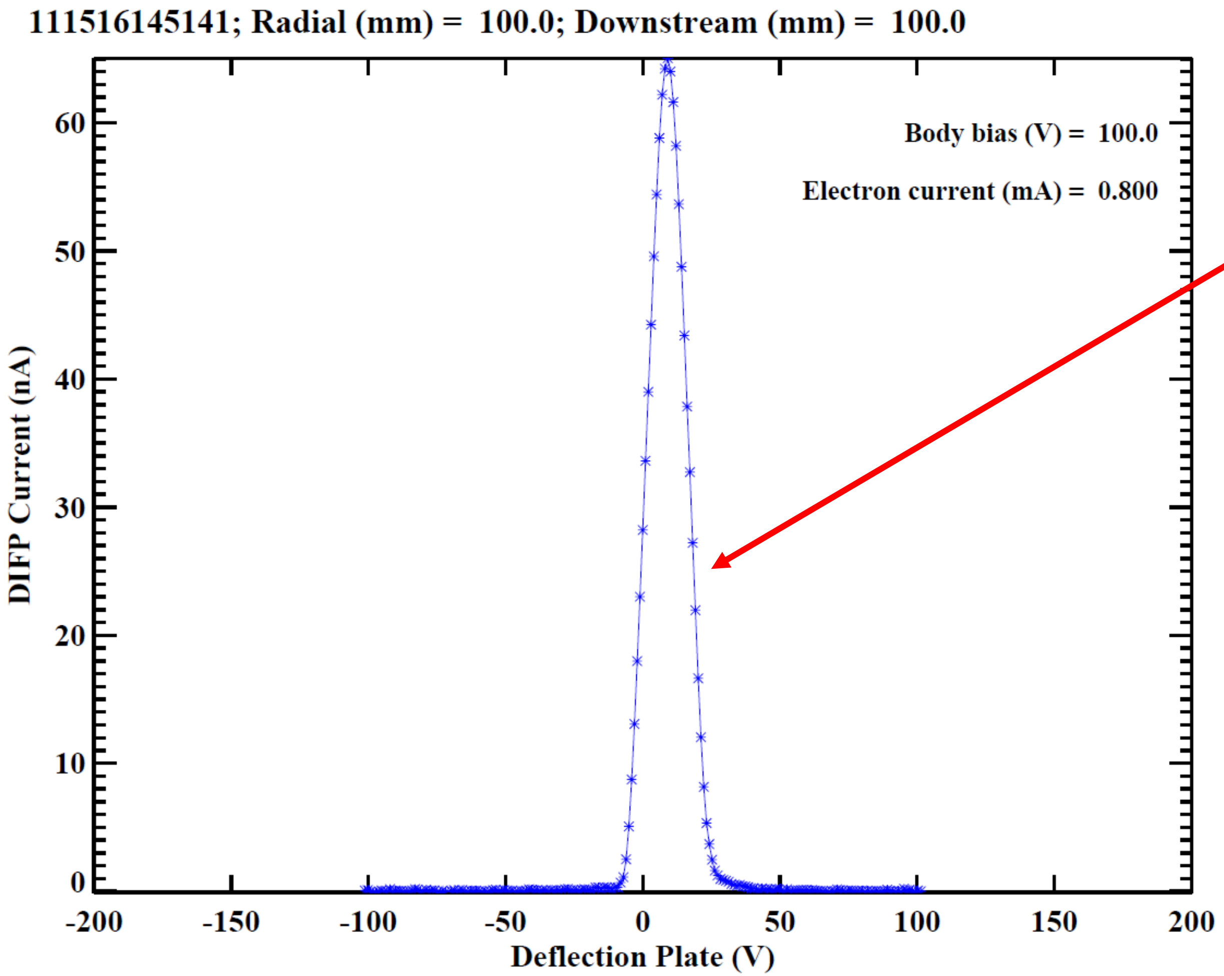
N. H. Stone, Technique for measuring the differential ion flux vector, *Rev. Sci. Instrum.*, *48*, 1458, 1977.

Top View: Measurement Locations



Typical DIFP Data

Collected ion current vs. Deflection Plate Voltage

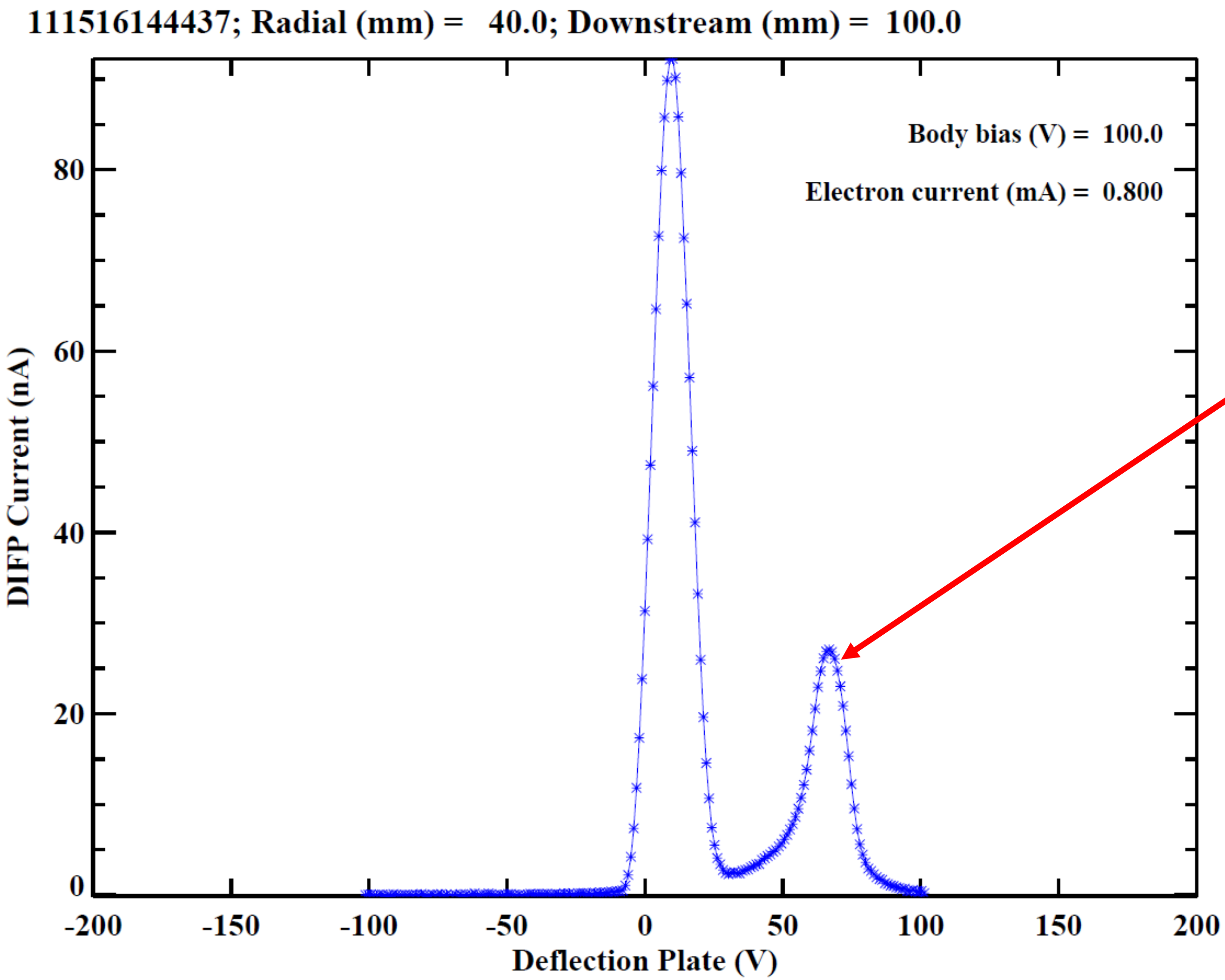


Typical Gaussian data set. Very little deflection plate voltage implies small angle for the ion beam, i.e. undisturbed flow region

Deflection voltage is correlated to angle using a rotary stage in a separate calibration test

Typical DIFP Data

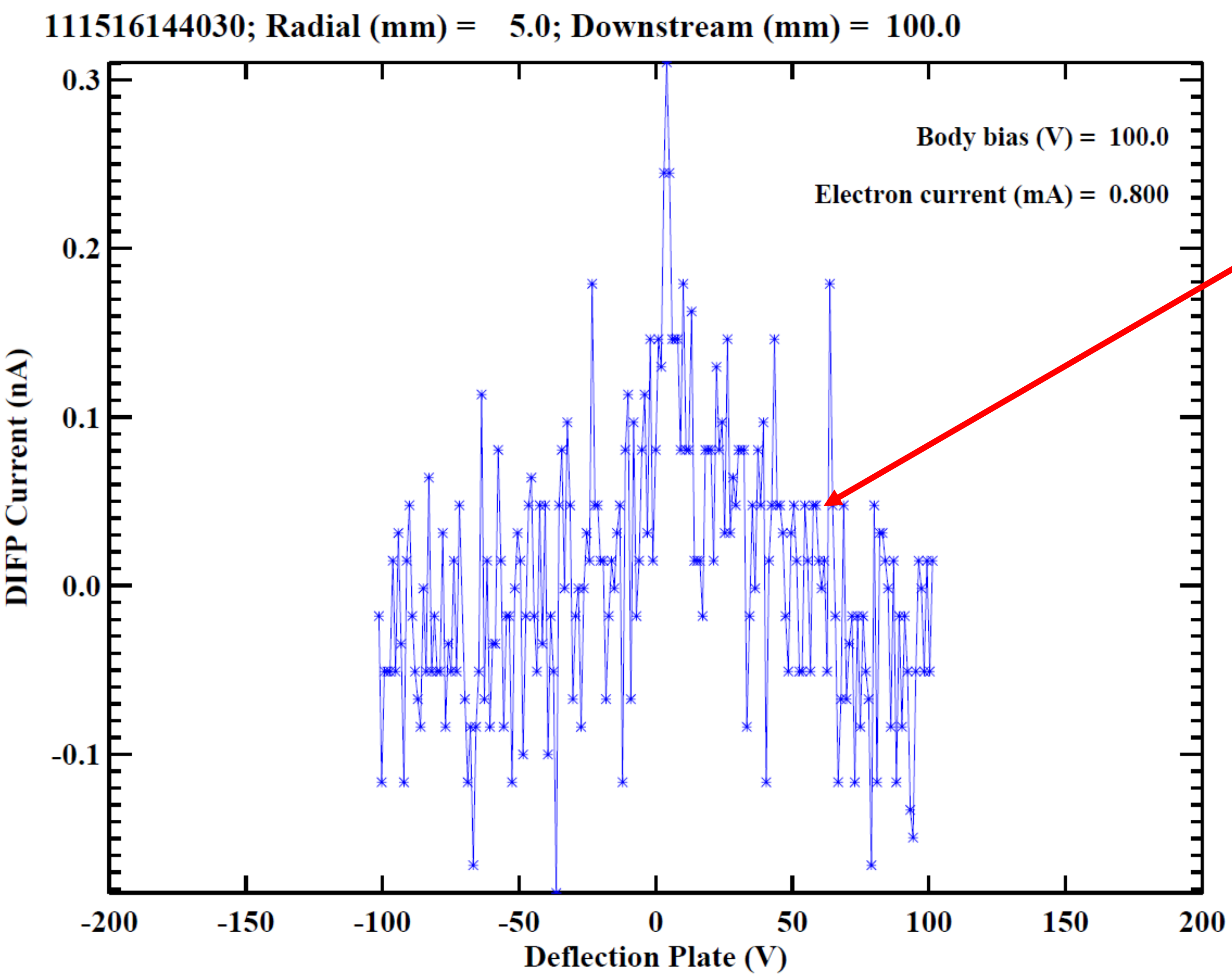
Collected ion current vs. Deflection Plate Voltage



Second peak at high deflection voltage indicates particle trajectories with high angles relative to the ion flow axis

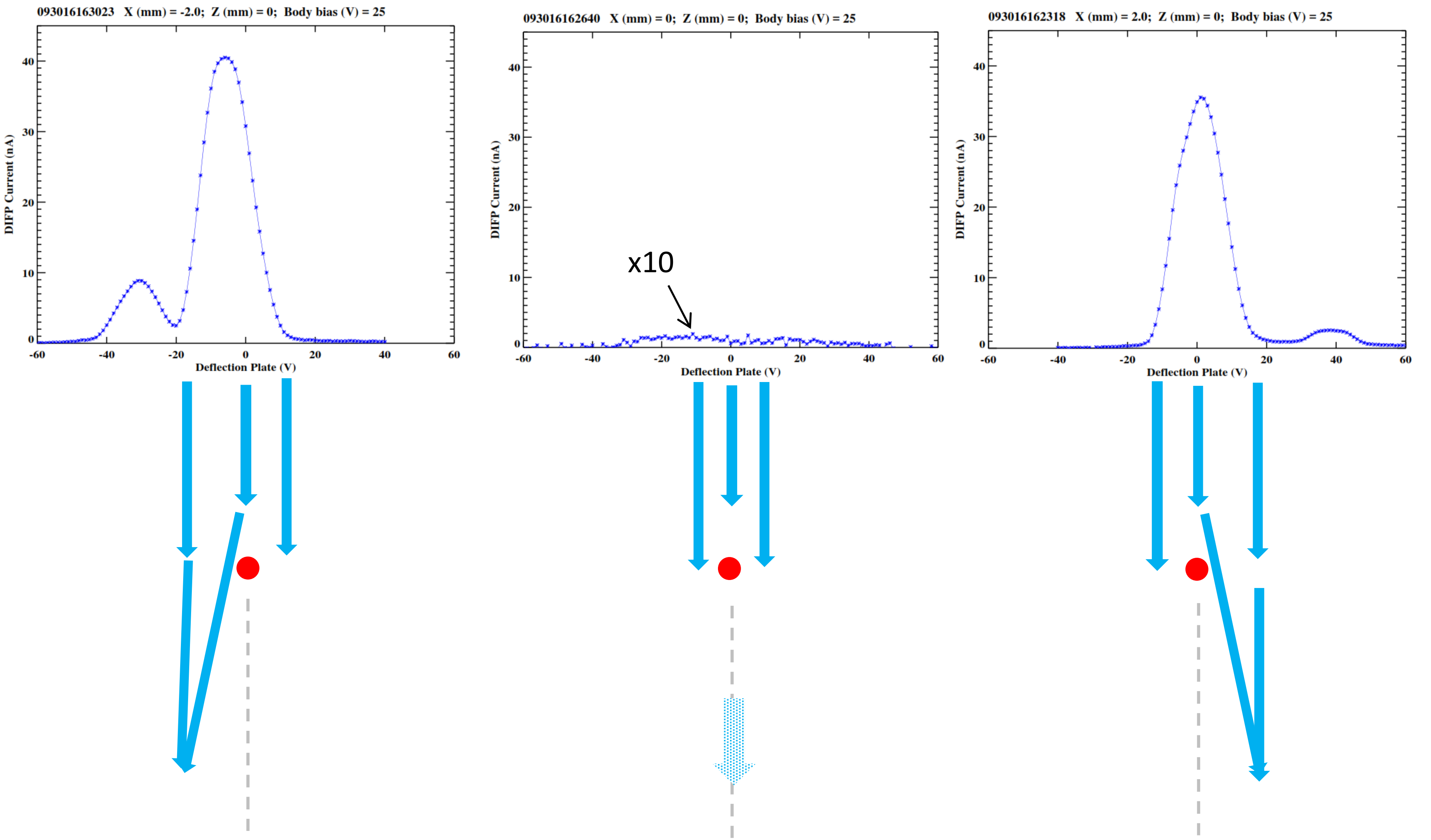
Typical DIFP Data

Collected ion current vs. Deflection Plate Voltage



Low signal (noisy) indicates absence of particles – biased tether deflects particles around it leaving a void

Interpretation of DIFP Data



Test Matrix

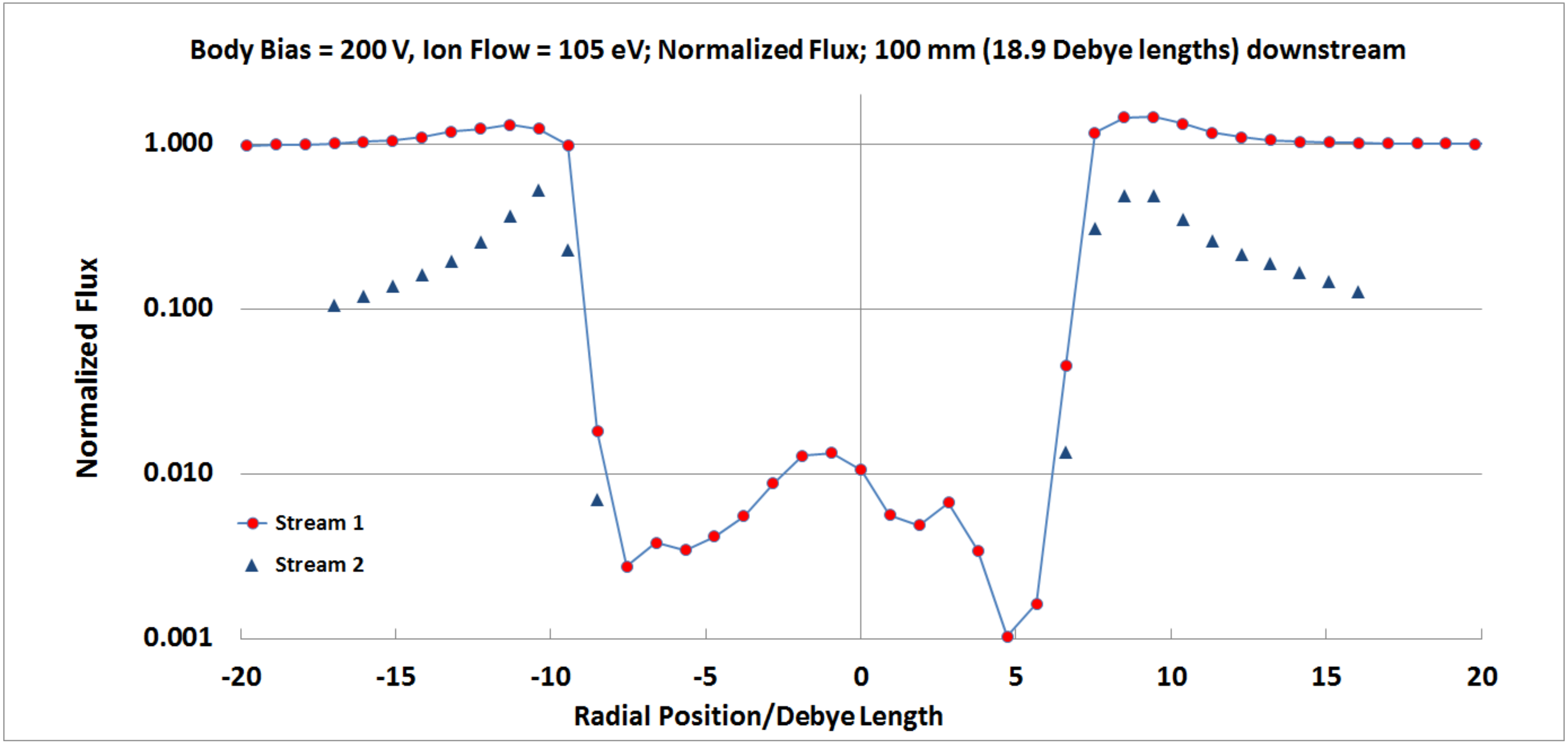
	77 eV flow	105 eV flow					200 eV flow	
	Body Bias (V)	Body Bias (V)					Body Bias (V)	
Downstream position (mm)	200	50	100	150	200	300	150	300
50	X	X	X	X	X		X	
100	X	X	X	X	X	X	X	X
200			X		X	X		
300			X		X	X		

“X” indicates data set acquired

Flux vs. Radial Position

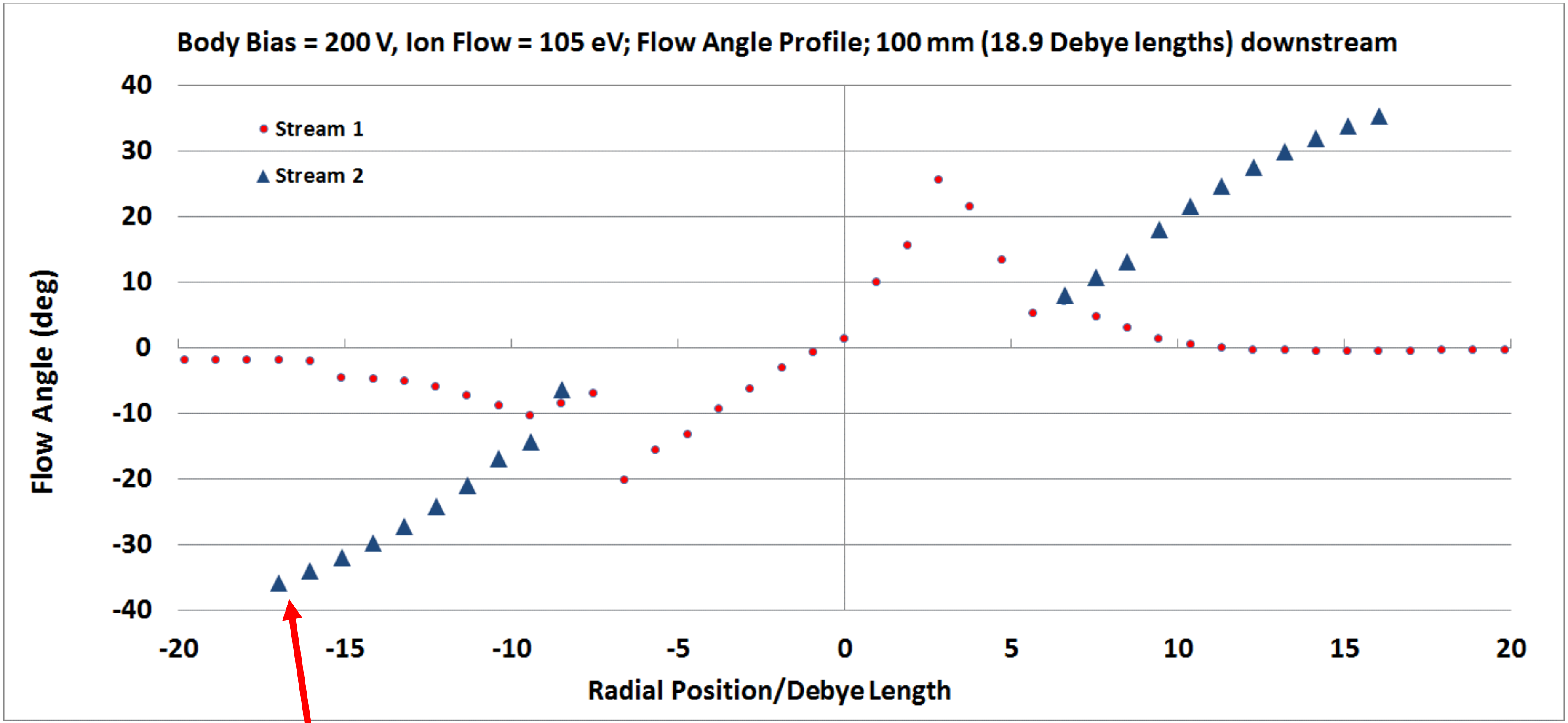
200 V Bias Body "Tether" located at 0 Radial Position

The plasma sheath around the tether deflects and repels ions creating a low flux region (void) downstream



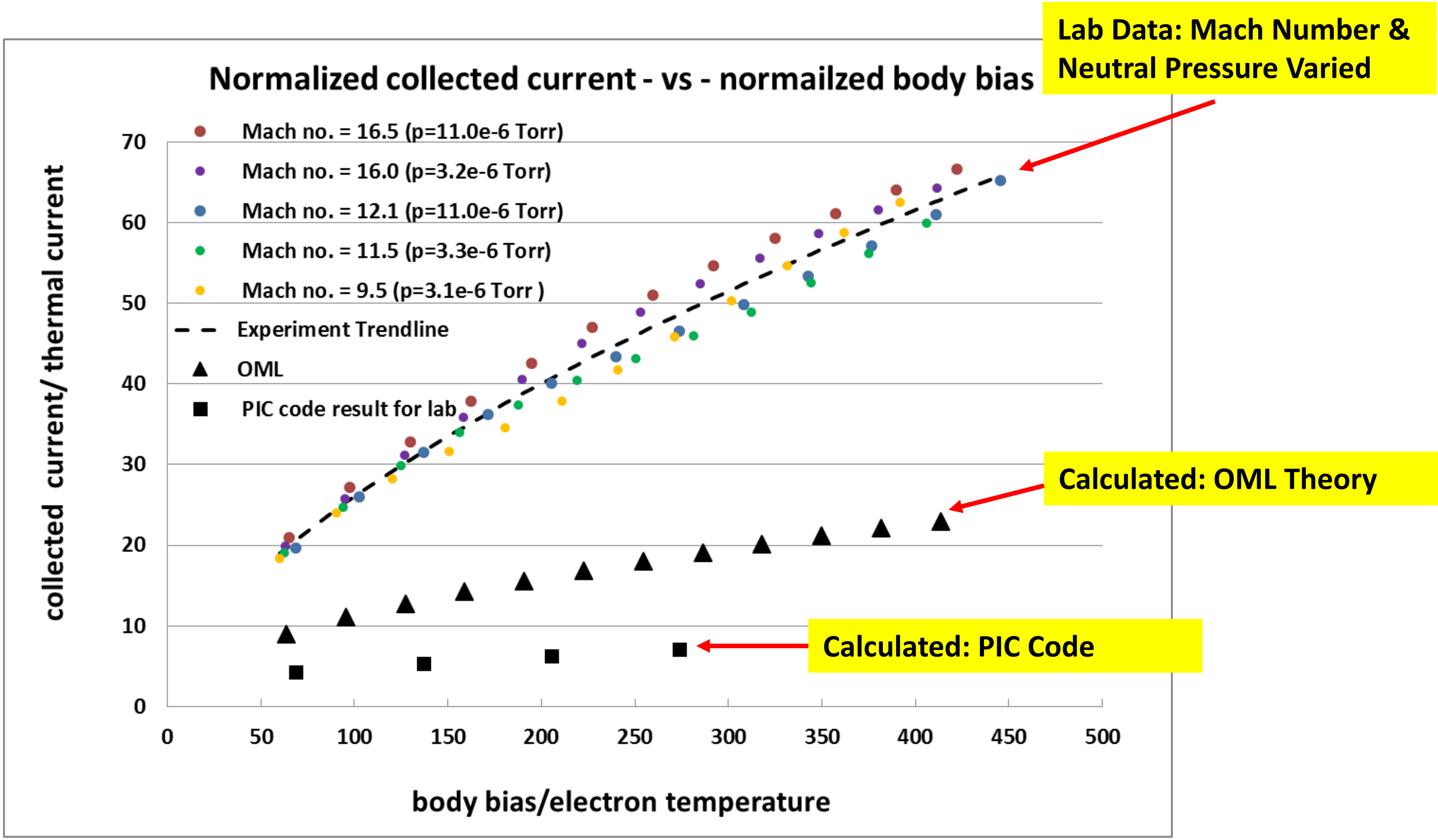
Flow Angle Summary

200 V Bias Body "Tether" located at 0 Radial Position



The plasma sheath around the tether scatters drifting ions into high angle trajectories measured downstream

Electron Current Collected by Test Body



Summary

- Motivated by work on the Heliopause Electrostatic Rapid Transit System (HERTS) project, a set of tests was conducted to answer fundamental questions about the interaction of a drifting plasma with a positively biased body (tether)
  - HERTS propulsion was based on an Electric Sail concept that relies on biased tethers
- A Kaufman ion source was operated in a parameter space designed to allow relative scaling to solar wind and Electric Sail dimensions/conditions
- A cylindrical biased body (tether) was created that could be inserted into the drifting plasma from the ion source
- Applying a diagnostic known as a Differential Flux Ion Probe (DIFP) ion trajectories downstream of the biased body (tether) could be measured
  - Analysis of the DIFP data allows mapping of interactions between drifting ions and the sheath around the biased body (tether)
  - Results show ion deflection and repulsion by the tether sheath
- Measurements of electron collection by the biased body (tether) immersed in the drifting plasma have also been made
  - Compared to some calculated values, the laboratory test levels are high
- The laboratory data will ultimately be used to anchor a Particle In Cell code used to scale to full size Electric Sail systems operating in the solar wind