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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*

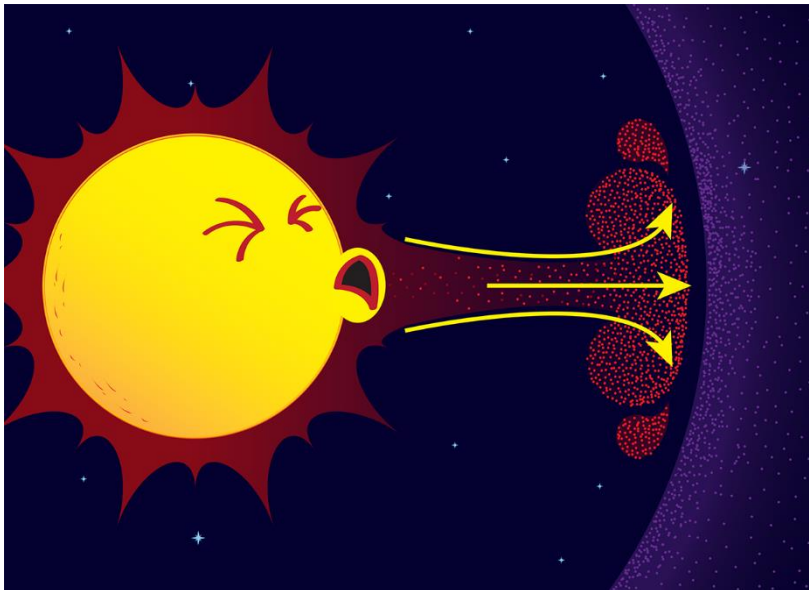


Image Credit: NASA (spaceplace.nasa.gov)



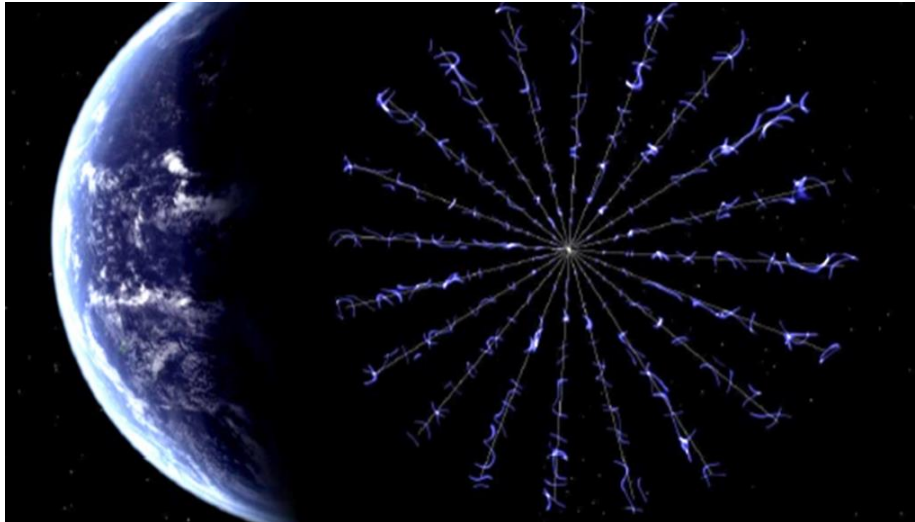
Image Credit: NASA (spaceplace.nasa.gov)

Objective

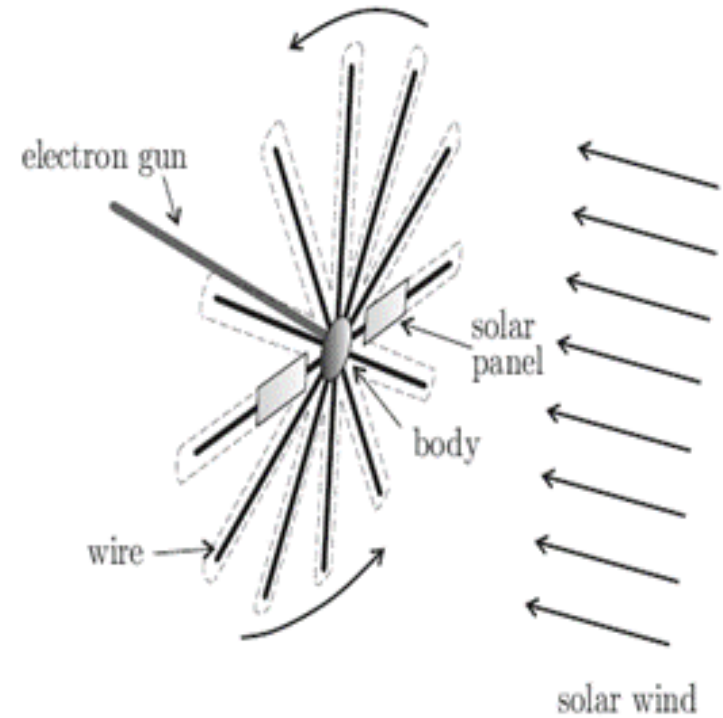
- Perform laboratory-scale plasma testing that can be extrapolated through modeling to solar wind scales
- Focus on ion interactions with positively biased bodies (cylindrical electrodes) that are surrogates for tethers



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)

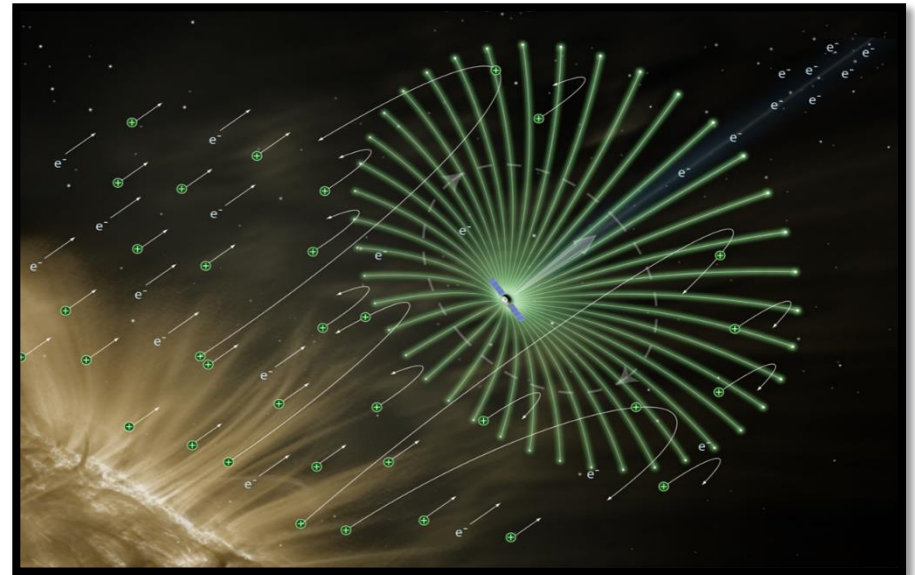


Image credit Alexandre Szames, Antigravite, Paris



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

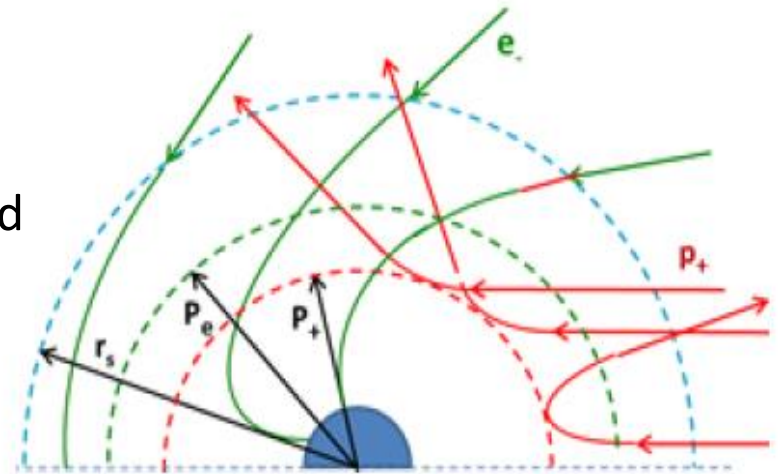
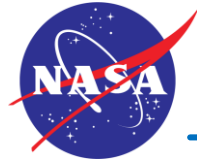
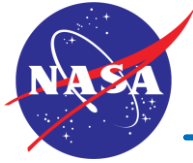


Image from NASA Innovative Advanced Concepts (NIAC) proposal: Heliopause Electrostatic Rapid Transit System (HERTS) Phase II April 27, 2015



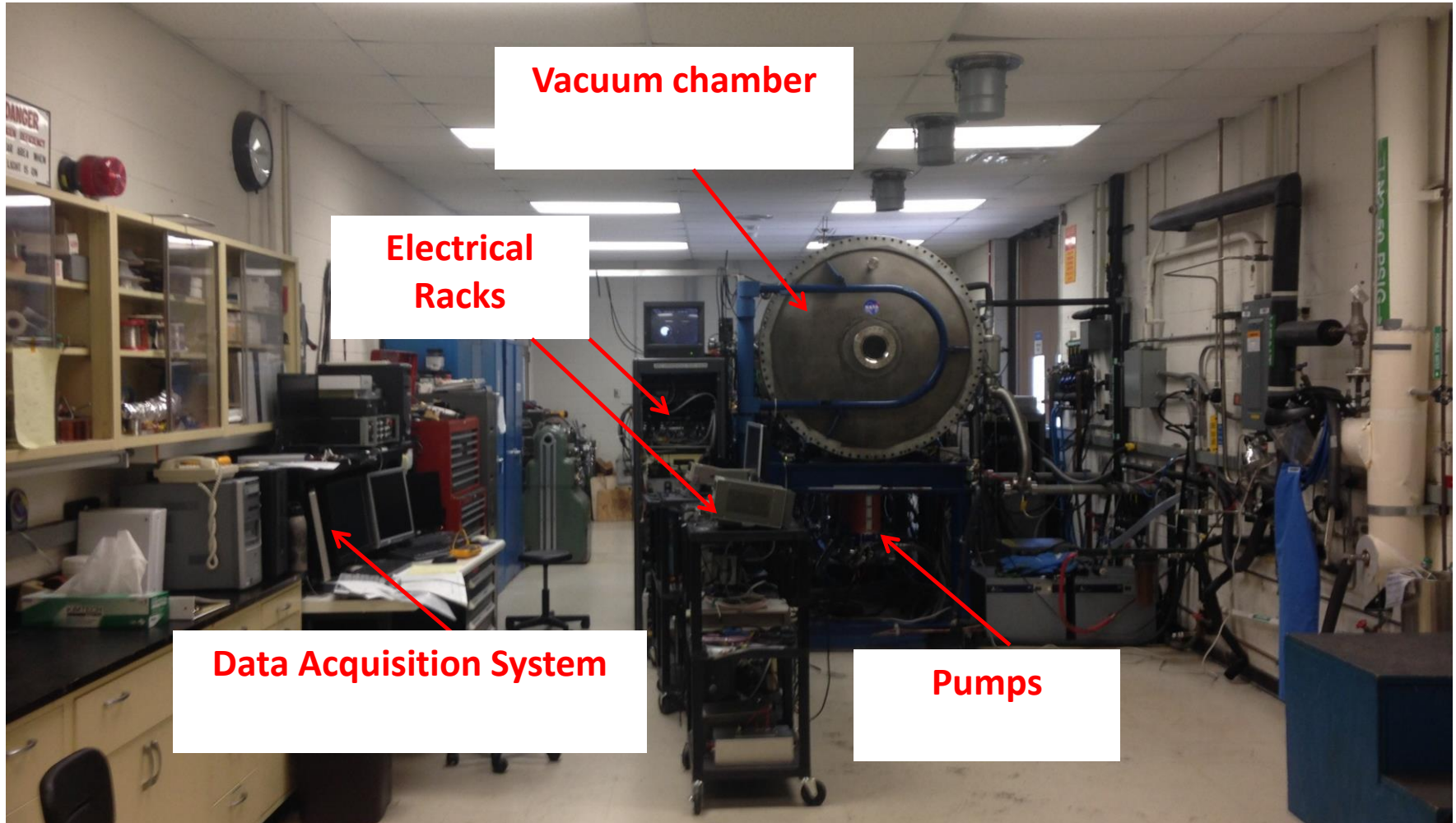
Scale Lengths of Interest

- ◆ Nominal solar wind
 - Proton speed is 400 – 450 km/s (~ 1000 eV)
 - Density $\sim 5/\text{cm}^3$
 - 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 $\sim 1 \times 10^6/\text{cm}^3$;
 - Electron temperature ~ 1 eV; Ion temperature $\ll 1$ eV
 - Debye length $< 1\text{cm}$;
 - Tether size ~ 1 mm so Debye length $>$ tether diameter
 - Tether bias \sim 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)

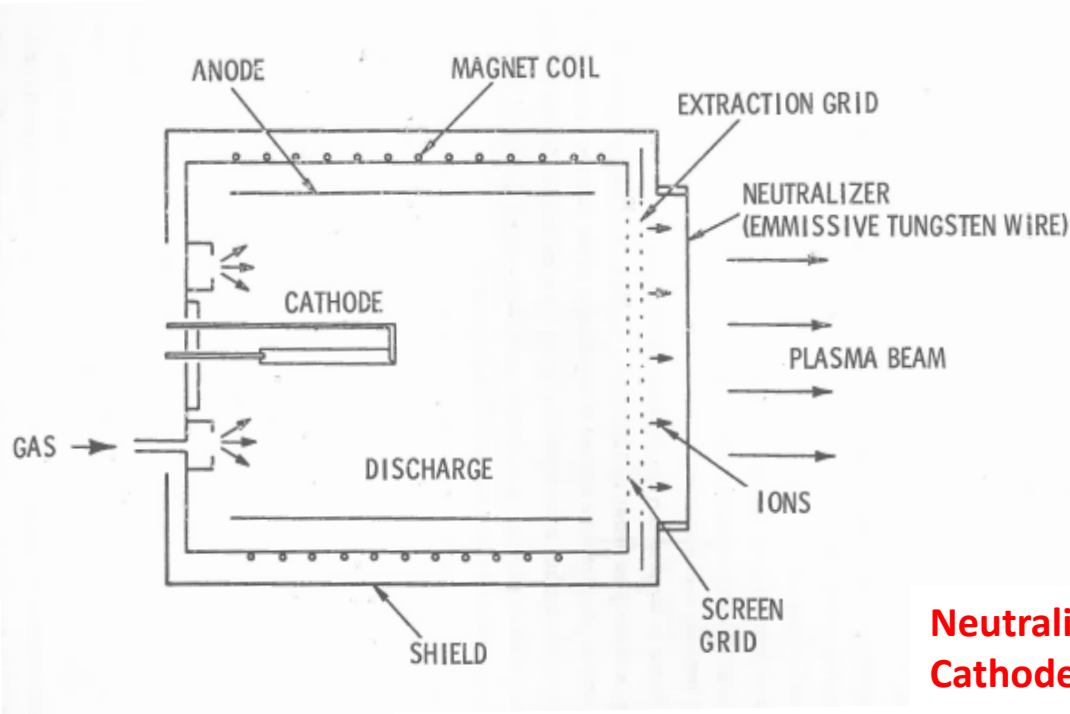
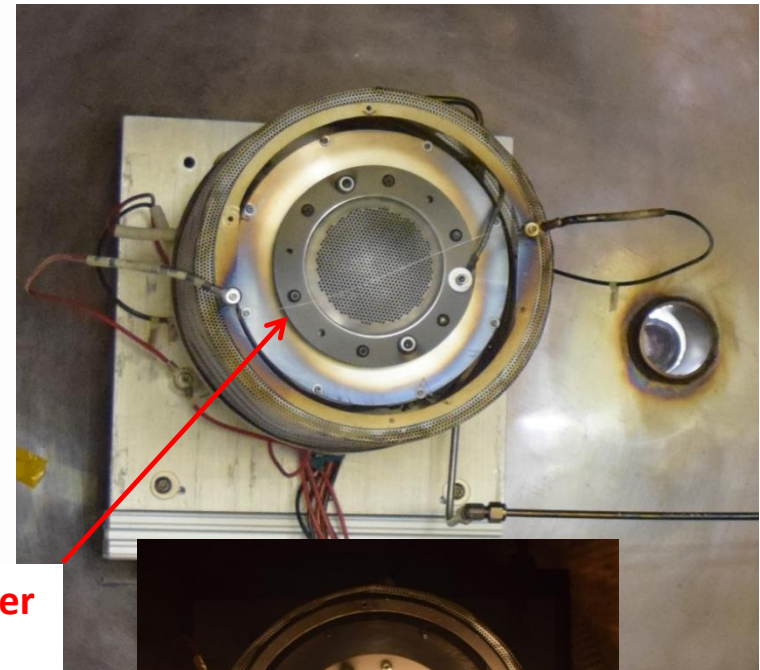
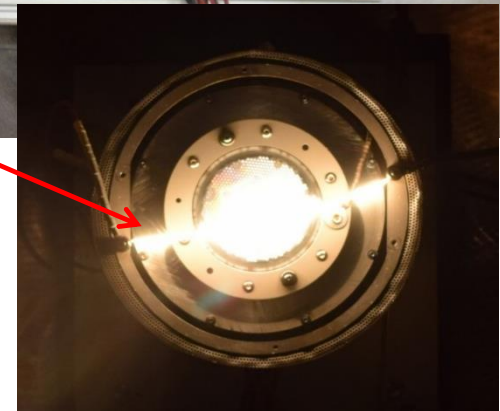


Figure from: N. H. Stone and W. K. Rehman, The simulation of ionospheric conditions for space vehicles, NASA TN-D-5894, 1970.

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

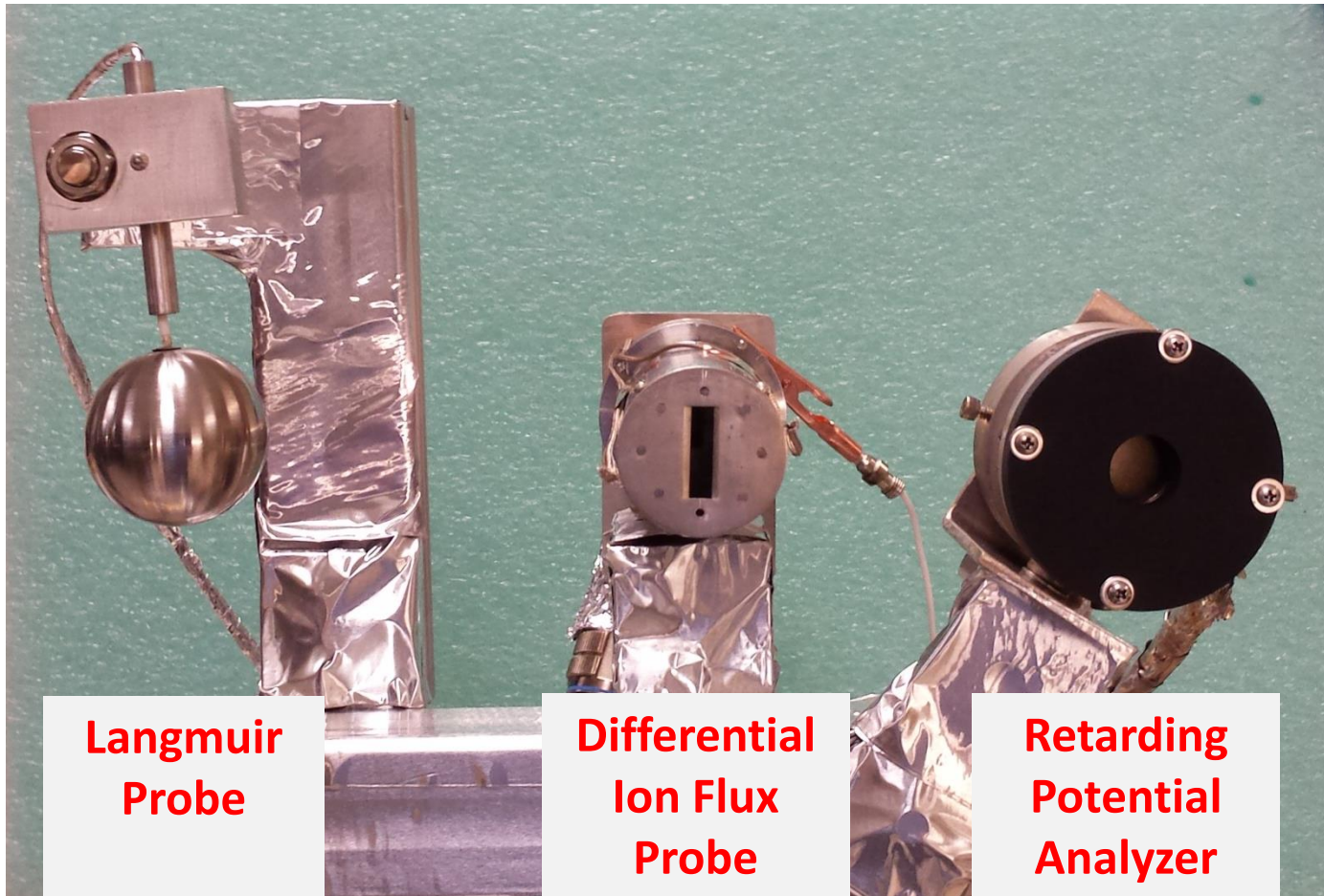


**Neutralizer
Cathode**





Probe Array



**Langmuir
Probe**

**Differential
Ion Flux
Probe**

**Retarding
Potential
Analyzer**

LP: Langmuir Probe

- electron temperature
- plasma space potential

DIFP:

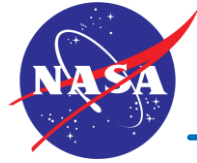
Differential Ion Flux Probe

- ion flow vector

RPA:

Retarding Potential Analyzer

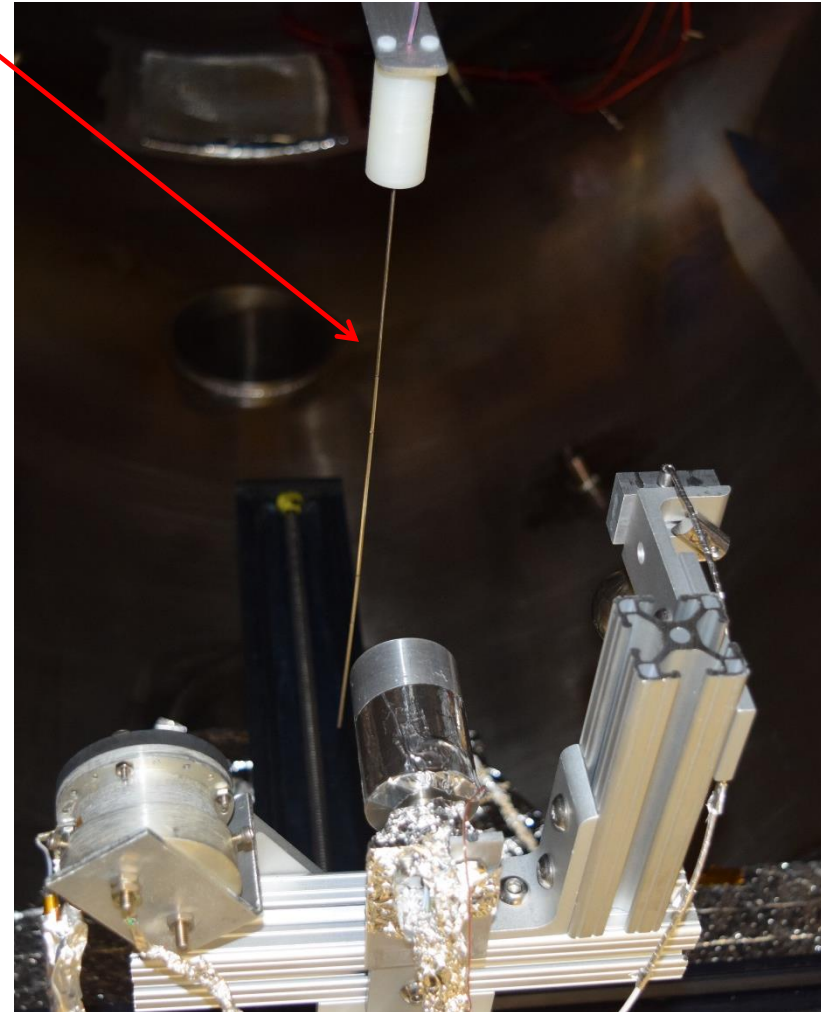
- ion flow energy
- plasma density



Test Body (Tether)

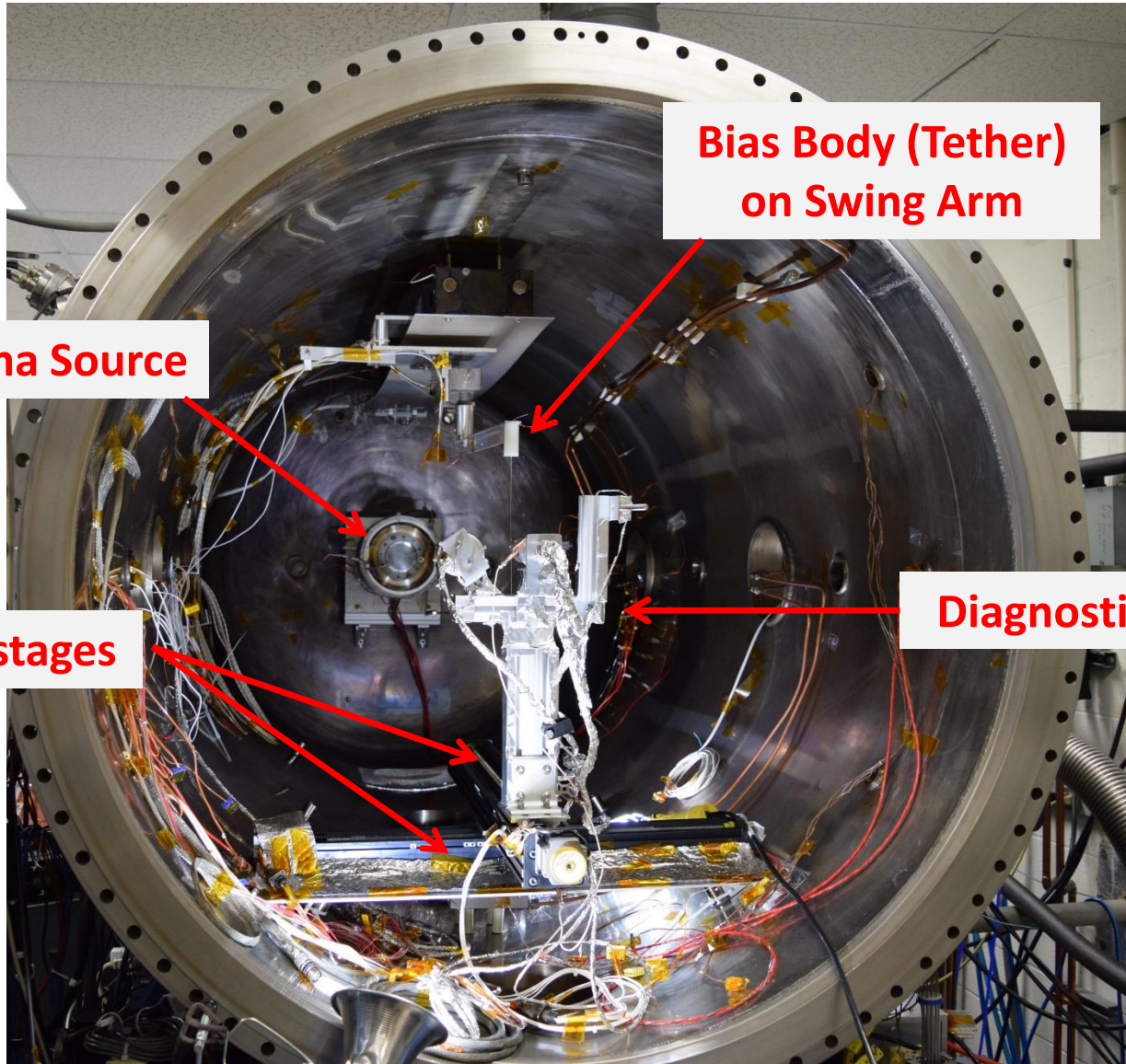
Test body (tether)

- 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 Source

**Bias Body (Tether)
on Swing Arm**

X,Y mapping stages

Diagnostic Probes



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 ($\mu\text{A}/\text{cm}^2$)	0.53	0.70
Electron Temperature	T_e (eV)	0.73	0.77
Plasma Density	n ($10^6/\text{cm}^3$)	1.47	1.4
Debye Length	λ_d (mm)	5.2	5.5

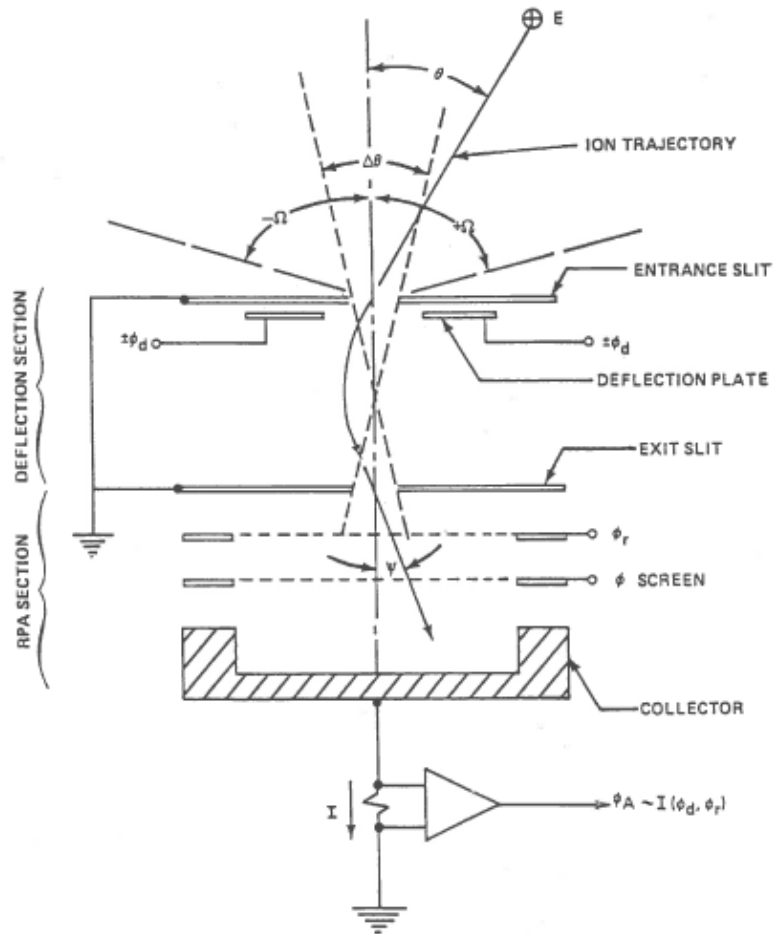
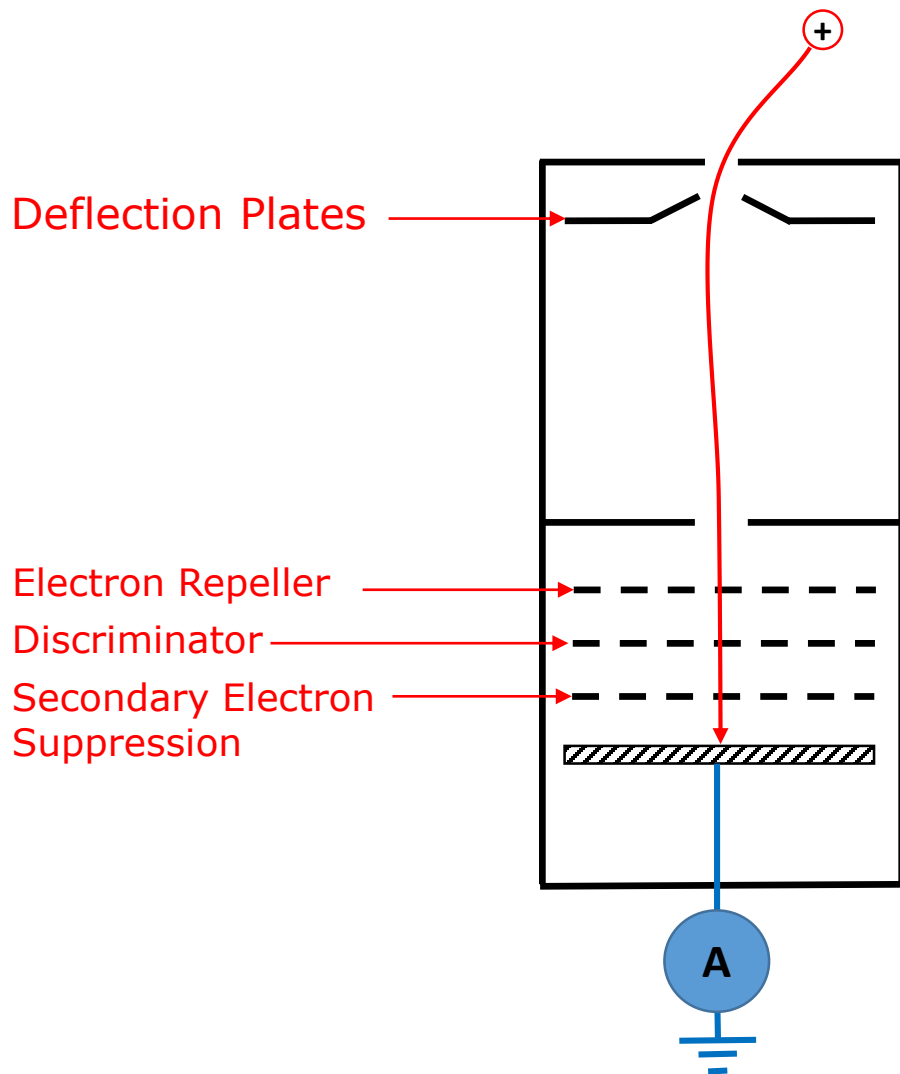
Cylindrical Vacuum Chamber Parameters

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

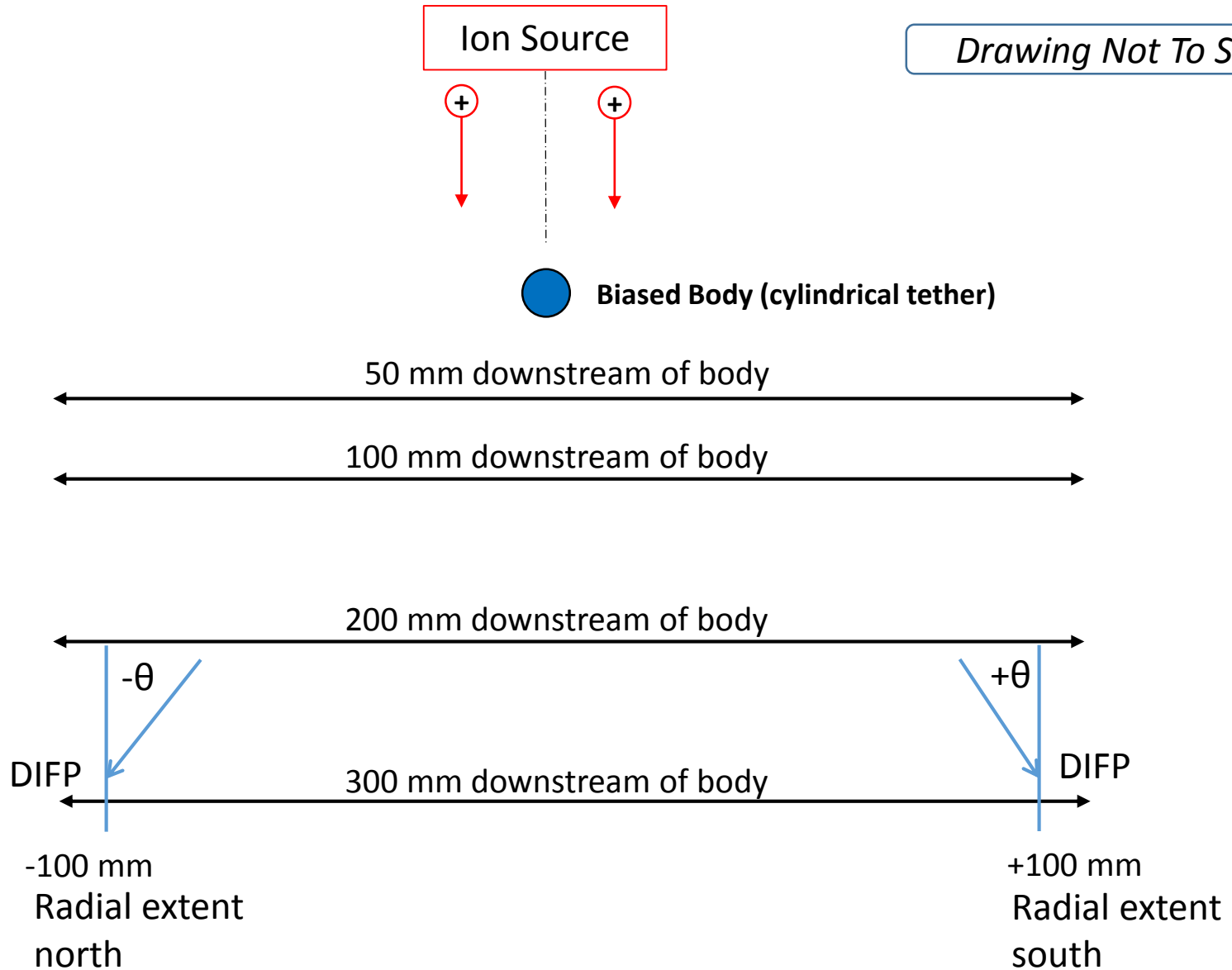
Top View through Instrument Mid-Plane



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



Top View: Measurement Locations

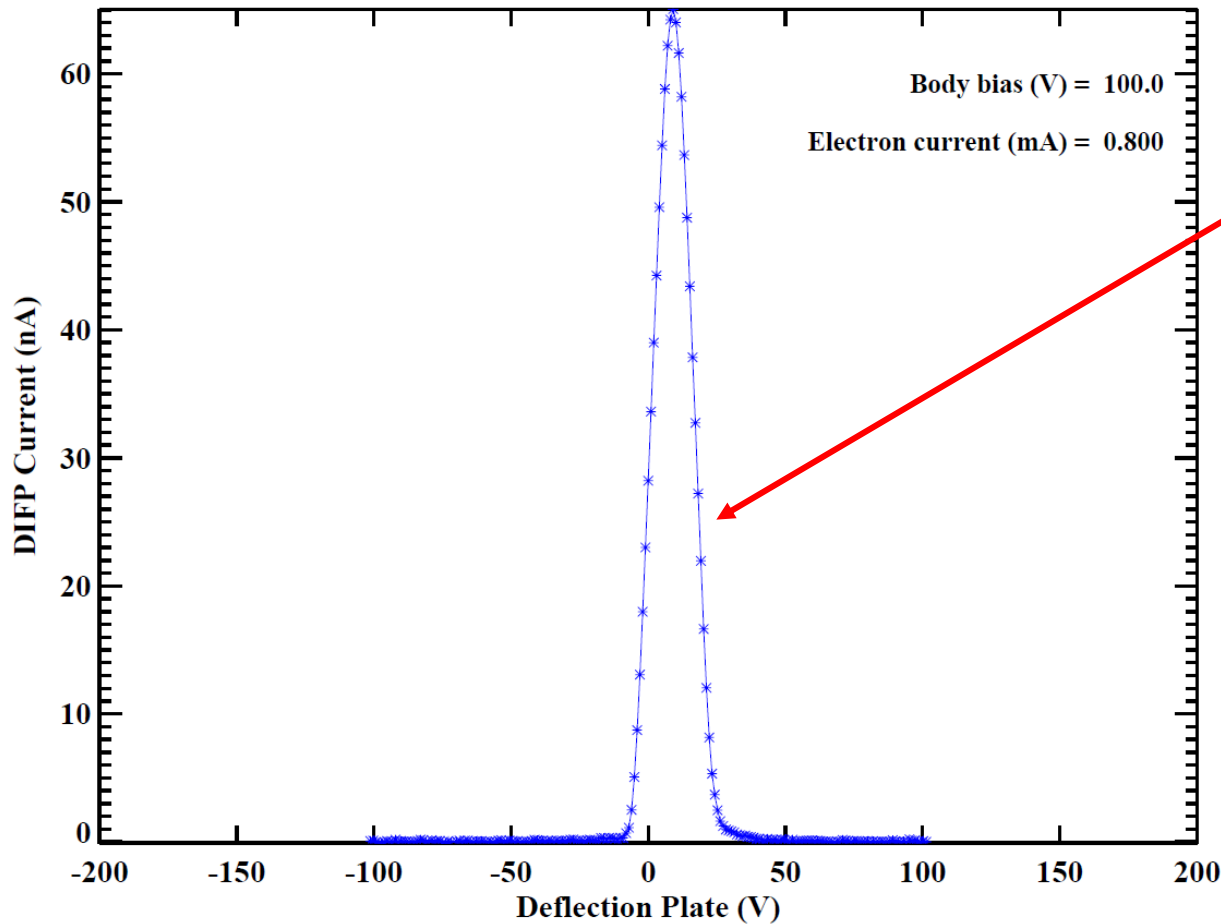




Typical DIFP Data

Collected ion current vs. Deflection Plate Voltage

111516145141; Radial (mm) = 100.0; Downstream (mm) = 100.0



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

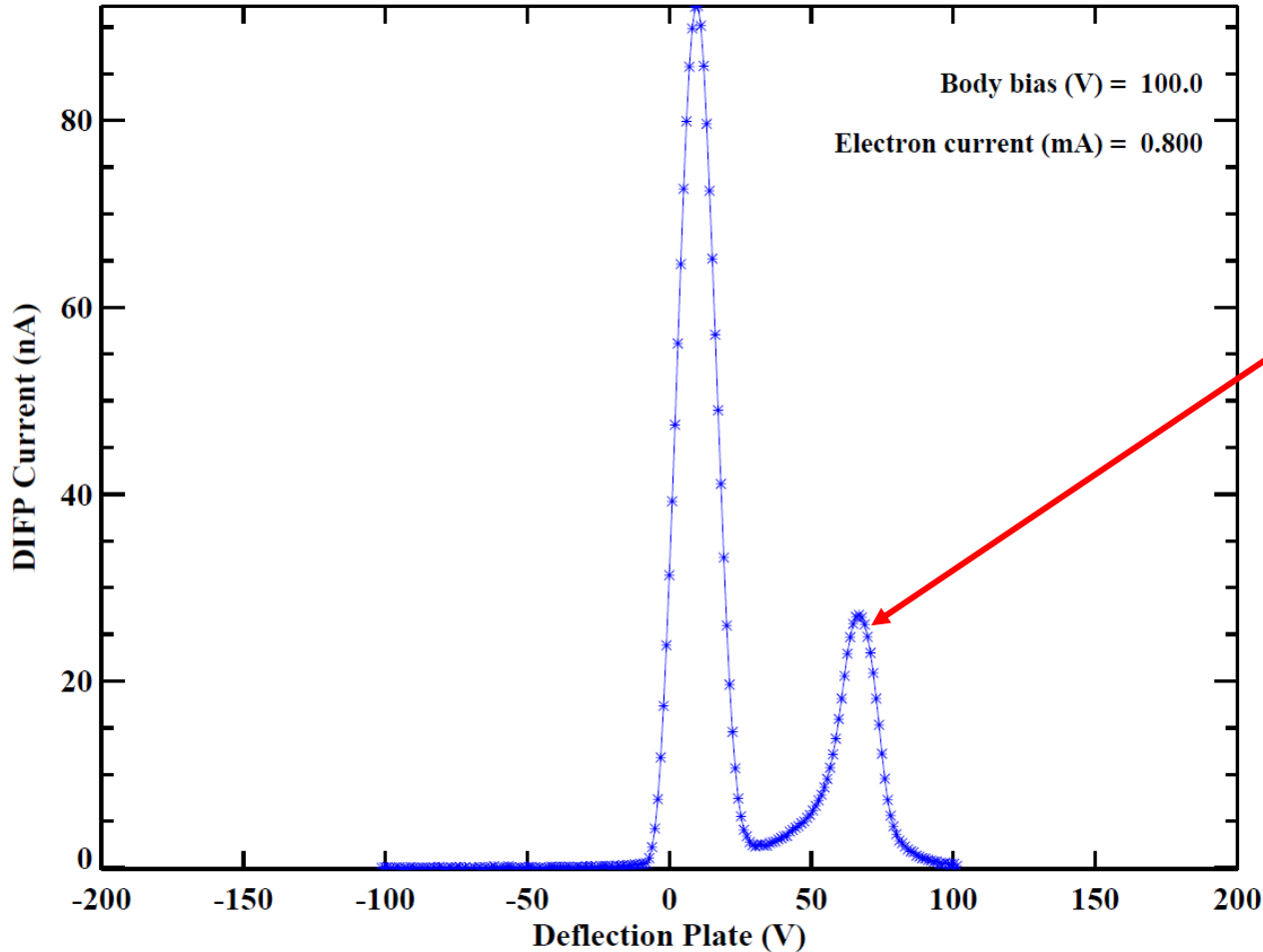
Deflection voltage is correlated to angle using a rotary stage in a separate calibration test



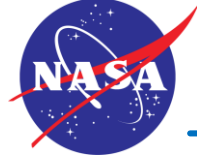
Typical DIFP Data

Collected ion current vs. Deflection Plate Voltage

111516144437; Radial (mm) = 40.0; Downstream (mm) = 100.0



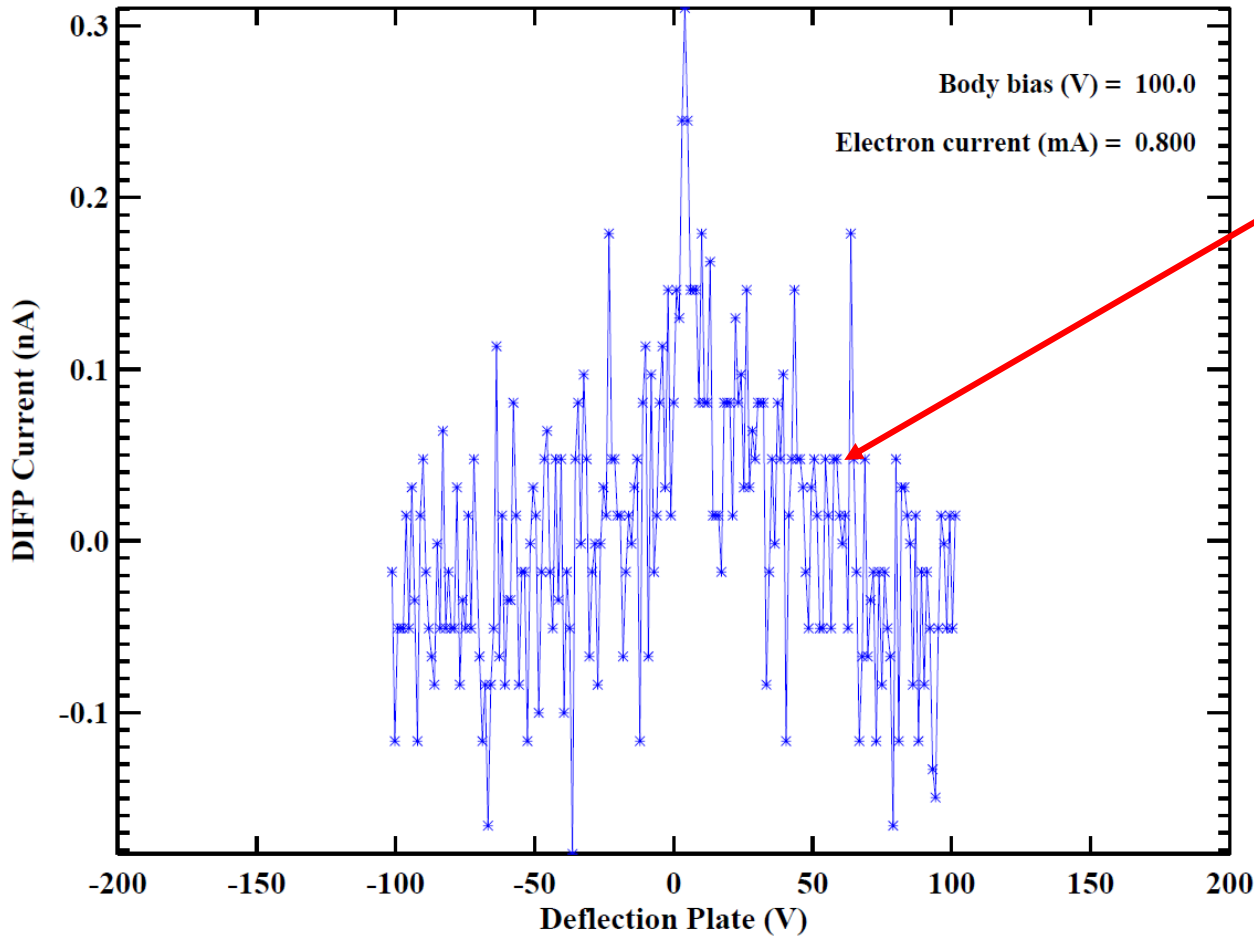
Second peak at high deflection voltage indicates particle trajectories with high angles relative to the ion flow axis



Typical DIFP Data

Collected ion current vs. Deflection Plate Voltage

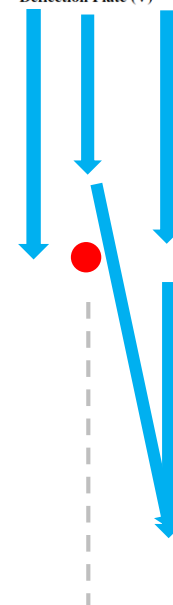
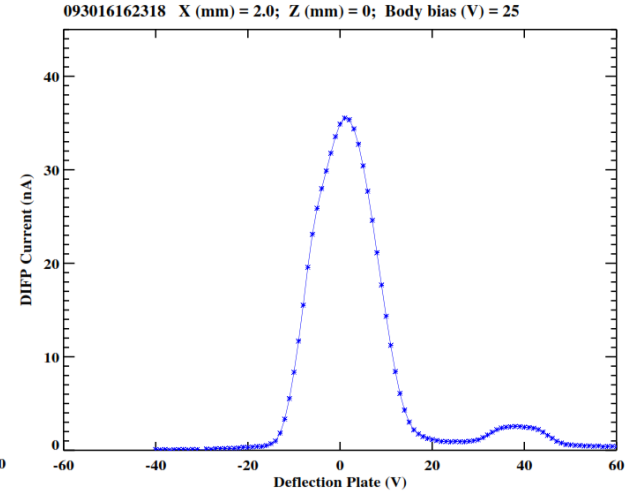
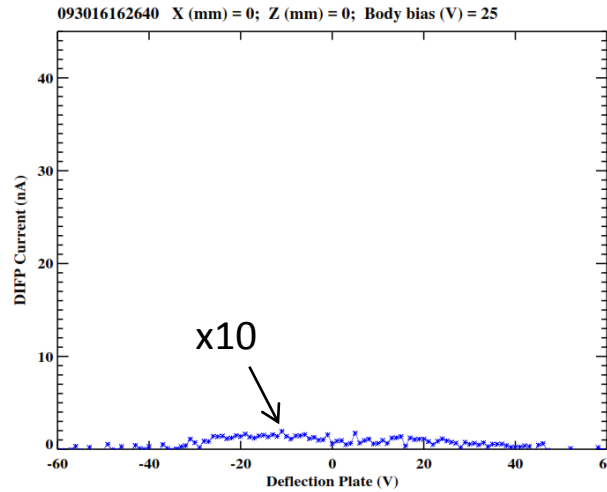
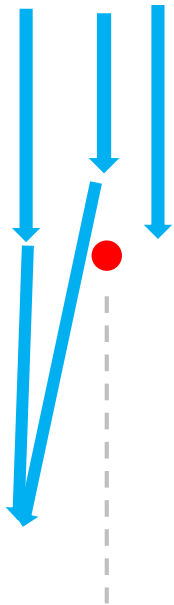
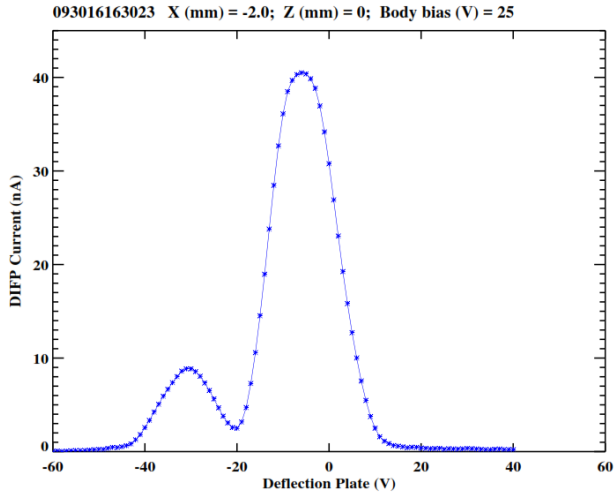
111516144030; Radial (mm) = 5.0; Downstream (mm) = 100.0

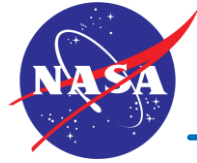


Low signal (noisy) indicates absence of particles – biased tether deflects particles around it leaving a void



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		

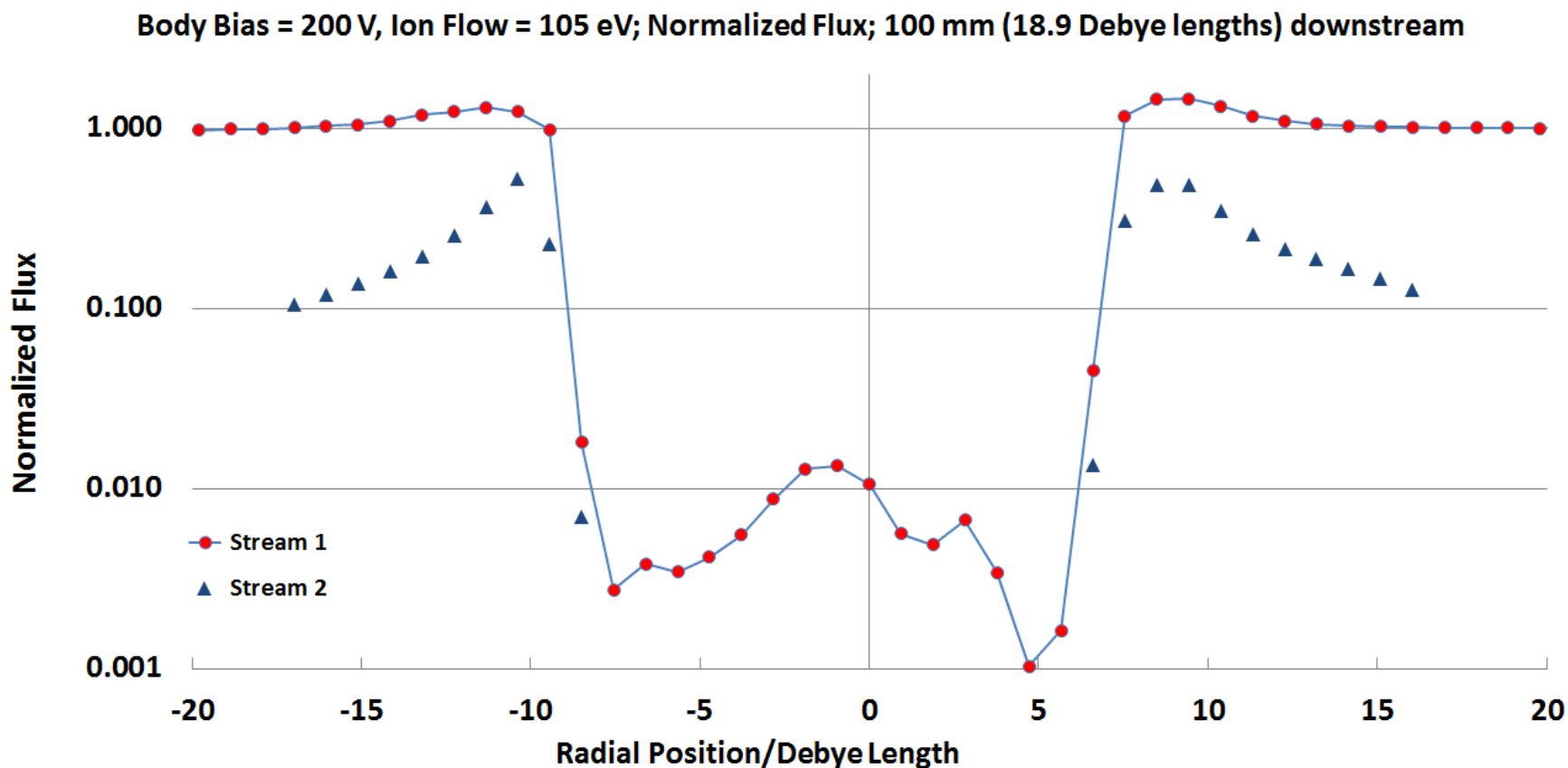
“X” indicates data set acquired

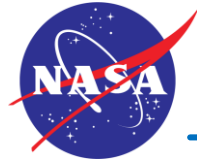


Flux vs. Radial Position

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

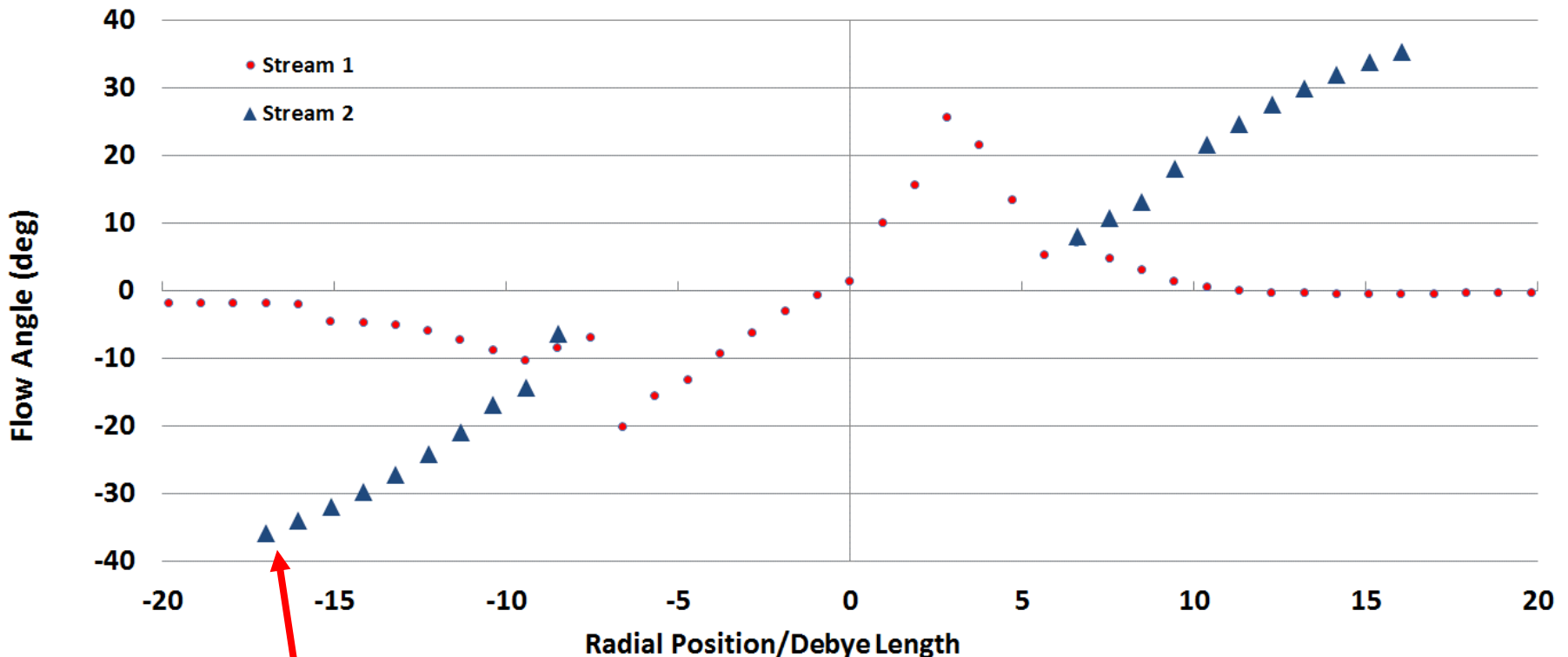




Flow Angle Summary

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

Body Bias = 200 V, Ion Flow = 105 eV; Flow Angle Profile; 100 mm (18.9 Debye lengths) downstream



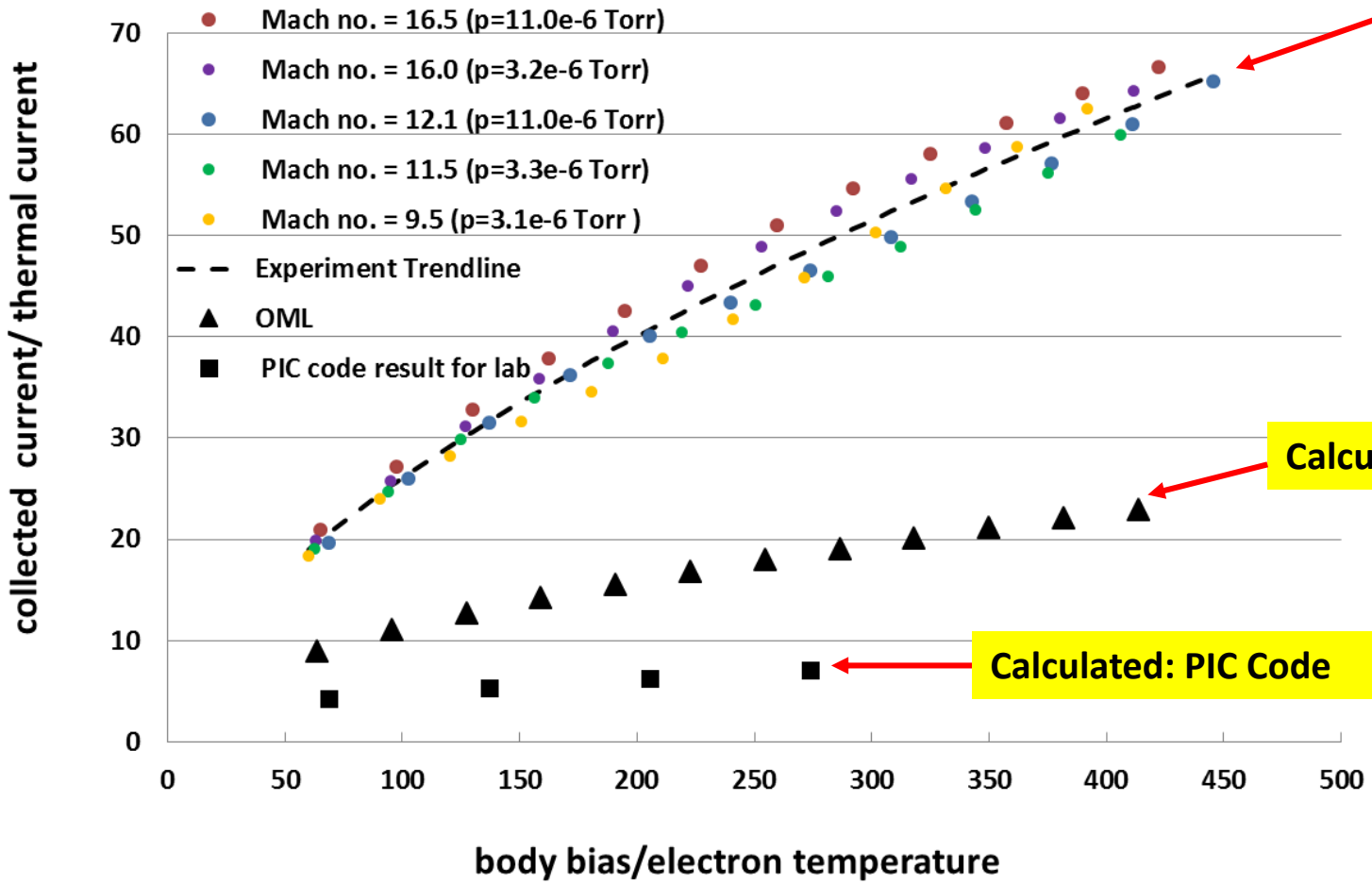
The plasma sheath around the tether scatters drifting ions into high angle trajectories measured downstream



Electron Current Collected by Test Body

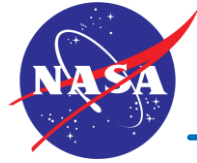
Lab Data: Mach Number & Neutral Pressure Varied

Normalized collected current - vs - normalized body bias



Calculated: OML Theory

Calculated: PIC Code



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