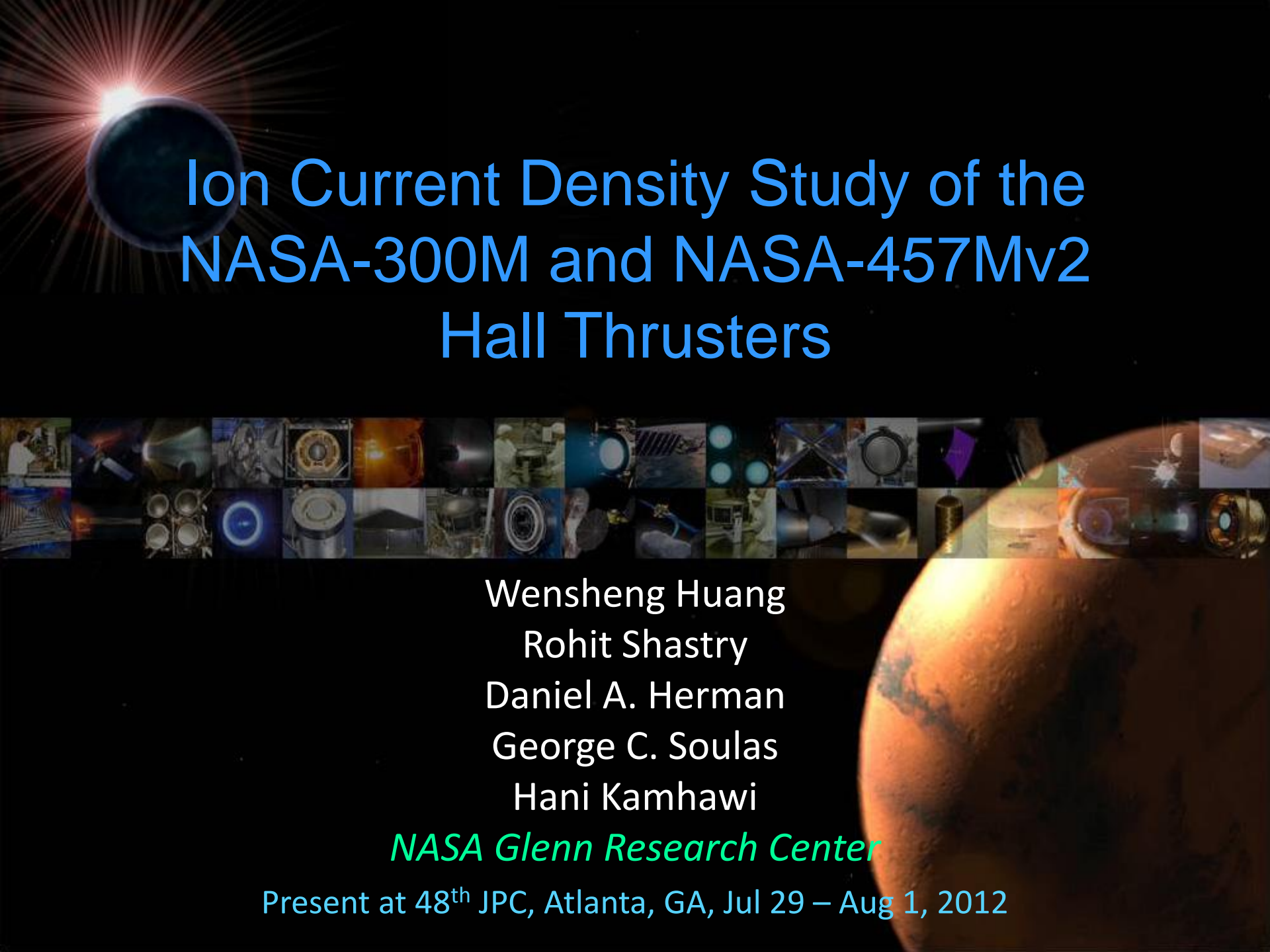


Title: Ion Current Density Study of the NASA-300M and NASA-457Mv2 Hall Thrusters

Abstract: NASA Glenn Research Center is developing a Hall thruster in the 15-50 kW range to support future NASA missions. As a part of the process, the performance and plume characteristics of the NASA-300M, a 20-kW Hall thruster, and the NASA-457Mv2, a 50-kW Hall thruster, were evaluated. The collected data will be used to improve the fidelity of the JPL modeling tool, Hall2De, which will then be used to aid the design of the 15-50 kW Hall thruster. This paper gives a detailed overview of the Faraday probe portion of the plume characterization study. The Faraday probe in this study is a near-field probe swept radially at many axial locations downstream of the thruster exit plane. Threshold-based integration limits with threshold values of $1/e$, $1/e^2$, and $1/e^3$ times the local peak current density are tried for the purpose of ion current integration and divergence angle calculation. The NASA-300M is operated at 7 conditions and the NASA-457Mv2 at 14 conditions. These conditions span discharge voltages of 200 to 500 V and discharge power of 10 to 50 kW. The ion current density profiles of the near-field plume originating from the discharge channel are discovered to strongly resemble Gaussian distributions. A novel analysis approach involving a form of ray tracing is used to determine an effective point of origin for the near-field plume. In the process of performing this analysis, definitive evidence is discovered that showed the near-field plume is bending towards the thruster centerline.



Ion Current Density Study of the NASA-300M and NASA-457Mv2 Hall Thrusters



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Present at 48th JPC, Atlanta, GA, Jul 29 – Aug 1, 2012

Introduction (1/2)

- In 2010, NASA Human Exploration Framework Team (HEFT) concluded 300-kW SEP system reduce heavy-lift launches needed for manned exploration of near Earth asteroid^[1]
- Will cluster 15- to 50-kW class Hall thrusters
- NASA GRC and JPL teamed up to study high power Hall thrusters
 - NASA-300M (20-kW)
 - NASA-457Mv2 (50-kW)
- The plan:
 - Step 1: Near-field/interior plume studies to validate Hall2De
 - Step 2: Use Hall2De to design long-life Hall thruster



Test lab thruster



Polish model



Design flight thruster

[1] http://www.nasa.gov/exploration/new_space_enterprise/home/heft_summary.html, Jan., 2011

Introduction (2/2)



- Near-field test completed, companion presentations:
 - Performance of 457Mv2: 2012-3940, Tues 10a, Regency VI
 - LP and emissive on 300M: 2012-4115, Tues 4p, Cortland
 - LP and emissive on 457Mv2: 2012-4196, Wed 10a, Cortland
- This presentation will focus on near-field ion current density measurement (Faraday probe) on the NASA-300M and NASA-457Mv2



- Introduction
- Experimental Setup
- Data Reduction
- Results
- Discussions on Near-field Plume Bending
- Future Works and Conclusion

NASA-300M and NASA-457Mv2



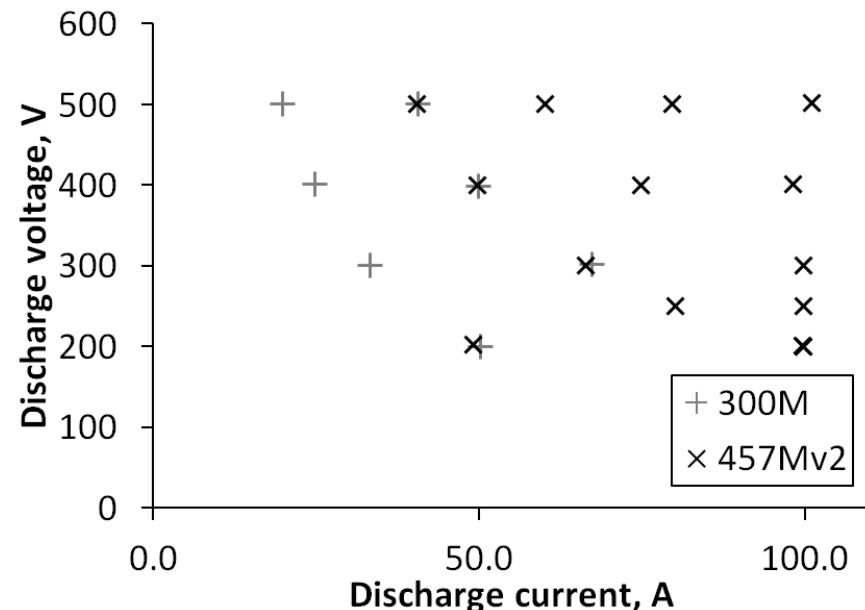
- 7 operating conditions on 300M; 14 on 457Mv2
 - Discharge voltage: 200 – 500 V
 - Discharge current: 20 – 100 A
 - Discharge power: 10 – 50 kW
- Lens-type magnetic field topology
- Centrally-mounted cathode (8% CFF)
- Xenon propellant
- 57-73% anode efficiency



NASA-300M



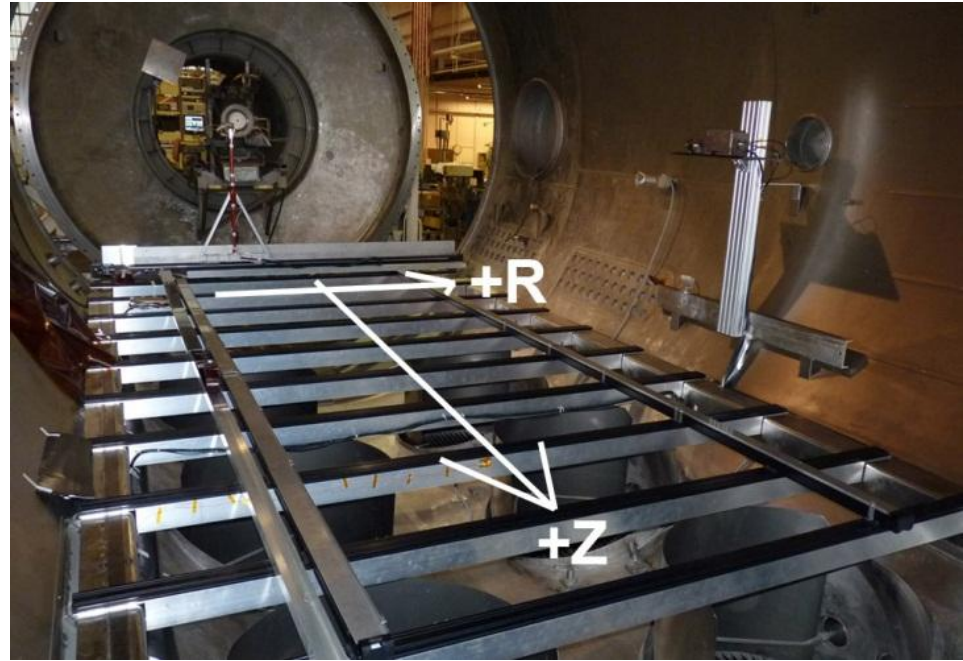
NASA-457Mv2



Setup: Facility and motion system



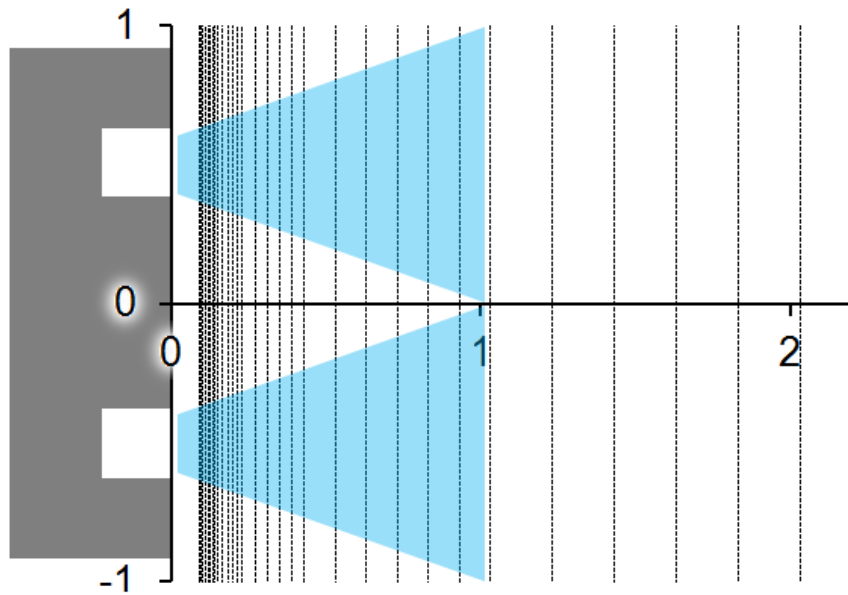
Mounted thruster



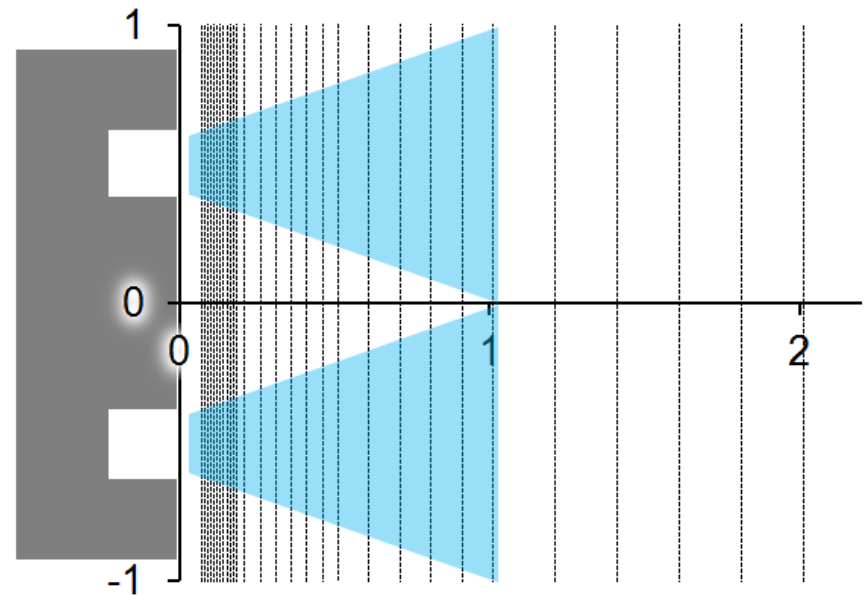
Motion stages and coordinate system

- Vacuum Facility 5 (VF5), $\varnothing 4.6$ m X 18.3 m
- Thruster on thrust stand, which is on end-cap
- Two-axis belt-driven motion system with fast radial stage
- Coordinate normalized by mean thruster diameter
 - R, norm. radial coordinate is 0 at thruster centerline
 - Z, norm. axial coordinate is 0 at thruster channel exit plane

Setup: Spatial resolution



Spatial resolution map for 300M



Spatial resolution map for 457Mv2

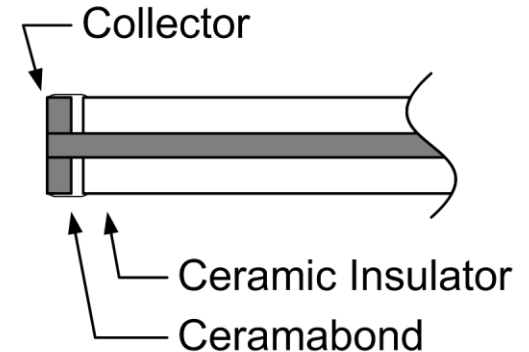
- Density of axial locations where radial sweeps are taken is densest near the thruster exit.

Setup: The Faraday probe

- Near-field Faraday probe is 1 of 4 probes in an array
- Molybdenum collector, ceramic body
- Ceramabond seal off the sides



Near-field Faraday probe (left) in probe array

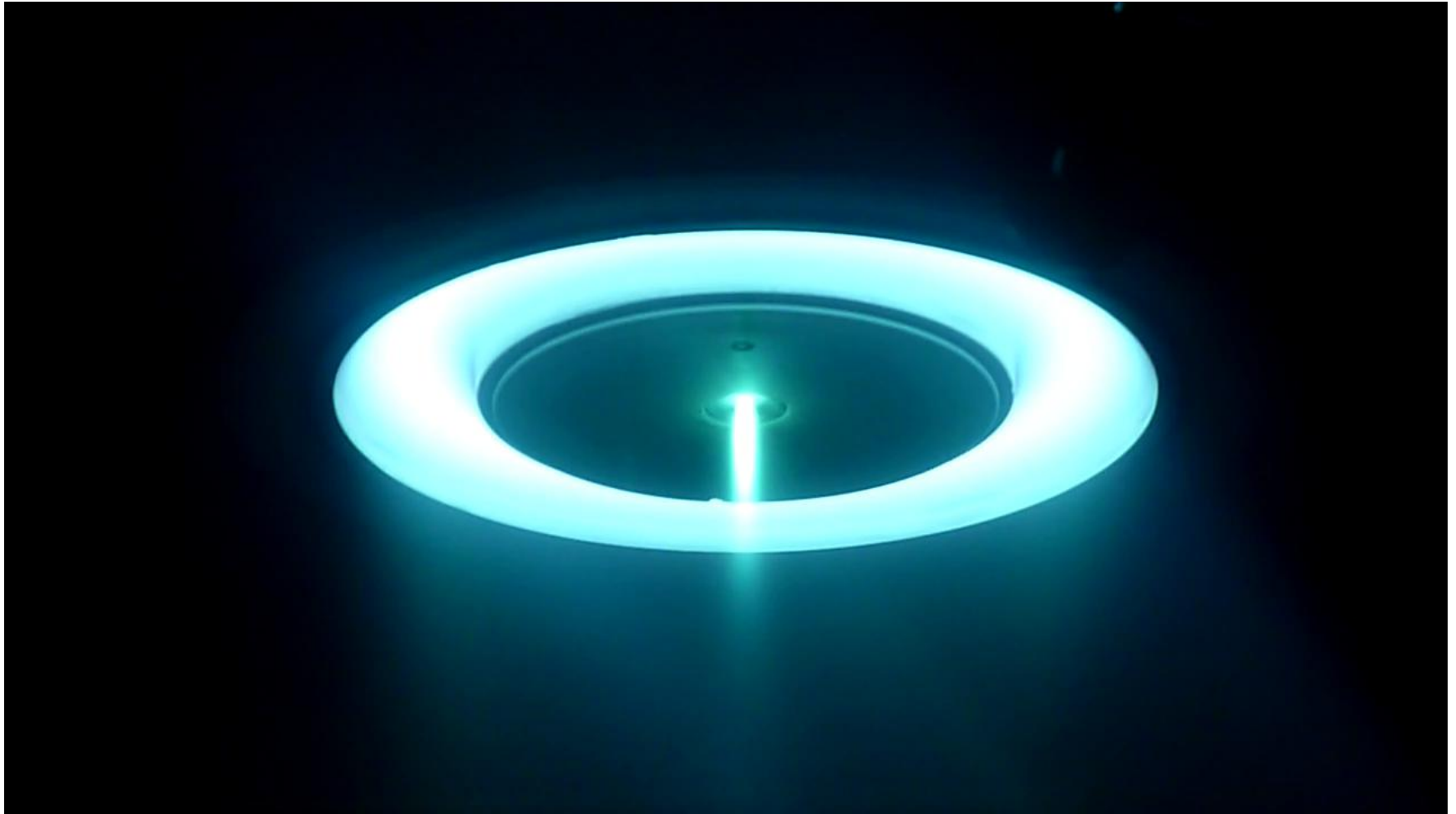


Probe diagram

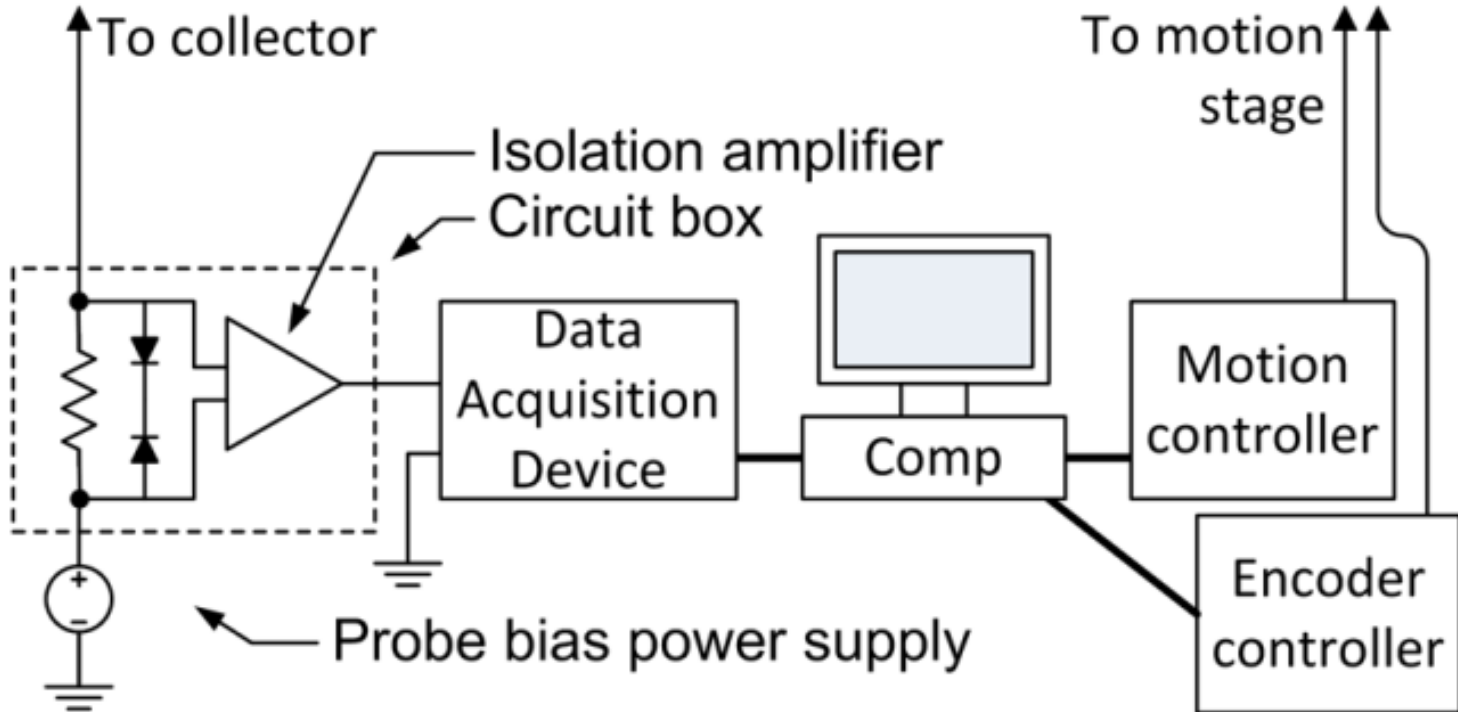
Setup: Faraday probe in plasma



***In this movie, Faraday probe is on the right, glowing light is emissive probe.**



Setup: Electronics



Data reduction: Divergence equation for radially-swept data



- Assumptions:
 - Plume is axisymmetric
 - Constant charge-state ratio
 - Constant mean particle velocity
- Charge-weighted divergence angle equation for polar sweep:

$$\langle \cos \delta \rangle_j = \frac{2\pi R^2 \int_0^{\pi/2} j(\theta) \cos \theta \sin \theta d\theta}{2\pi R^2 \int_0^{\pi/2} j(\theta) \sin \theta d\theta}$$

- Charge-weighted divergence angle equation for radial sweep:

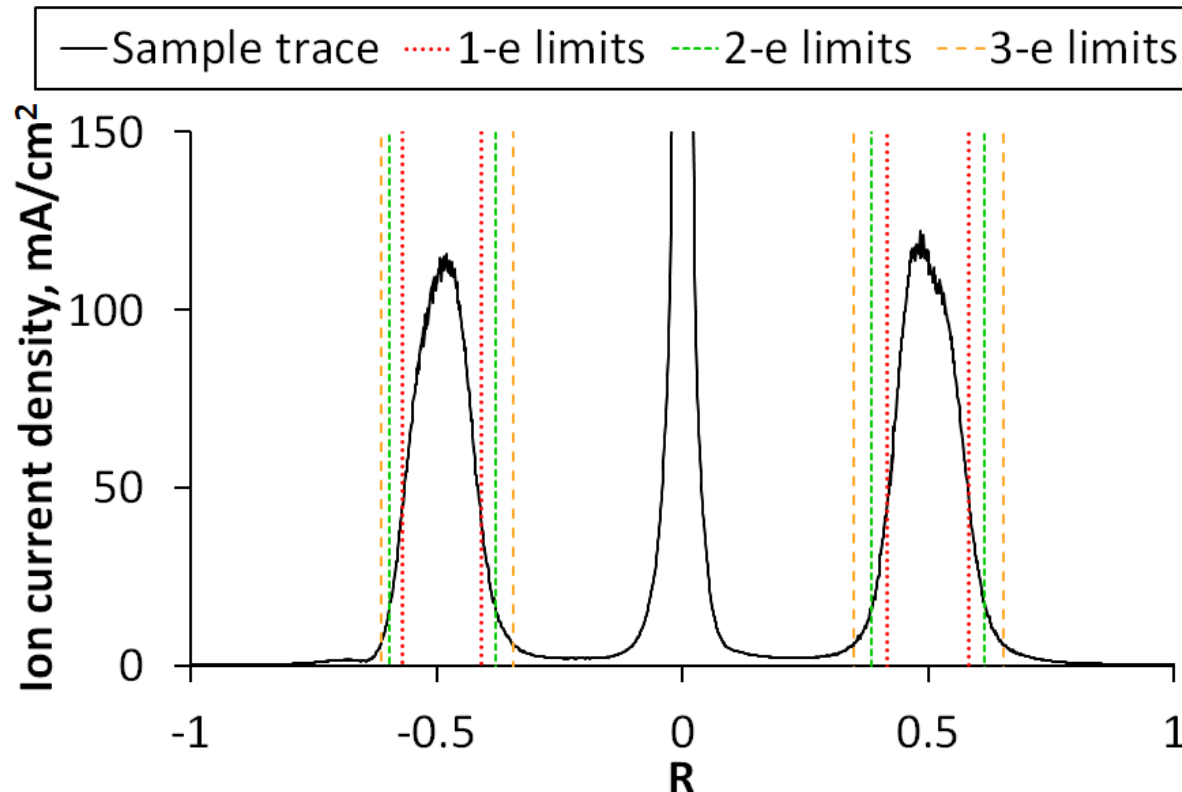
$$\langle \cos \delta \rangle_j = \frac{2\pi \int_0^\infty j_z(r) \cos \theta r dr}{2\pi \int_0^\infty j_z(r) r dr}, \quad \cos \theta = \frac{z_p}{\sqrt{r^2 + z_p^2}}$$

- Infinite boundary not physical, need to pick limits of integration



Sample trace and limits of integration (1/2)

- Tried threshold-based limits with 3 different threshold values:
 - “1-e” limits: $1/e$, or 36.8% of nearest channel-plume peak
 - “2-e” limits: $1/e^2$, or 13.5%
 - “3-e” limits: $1/e^3$, or 5.0%

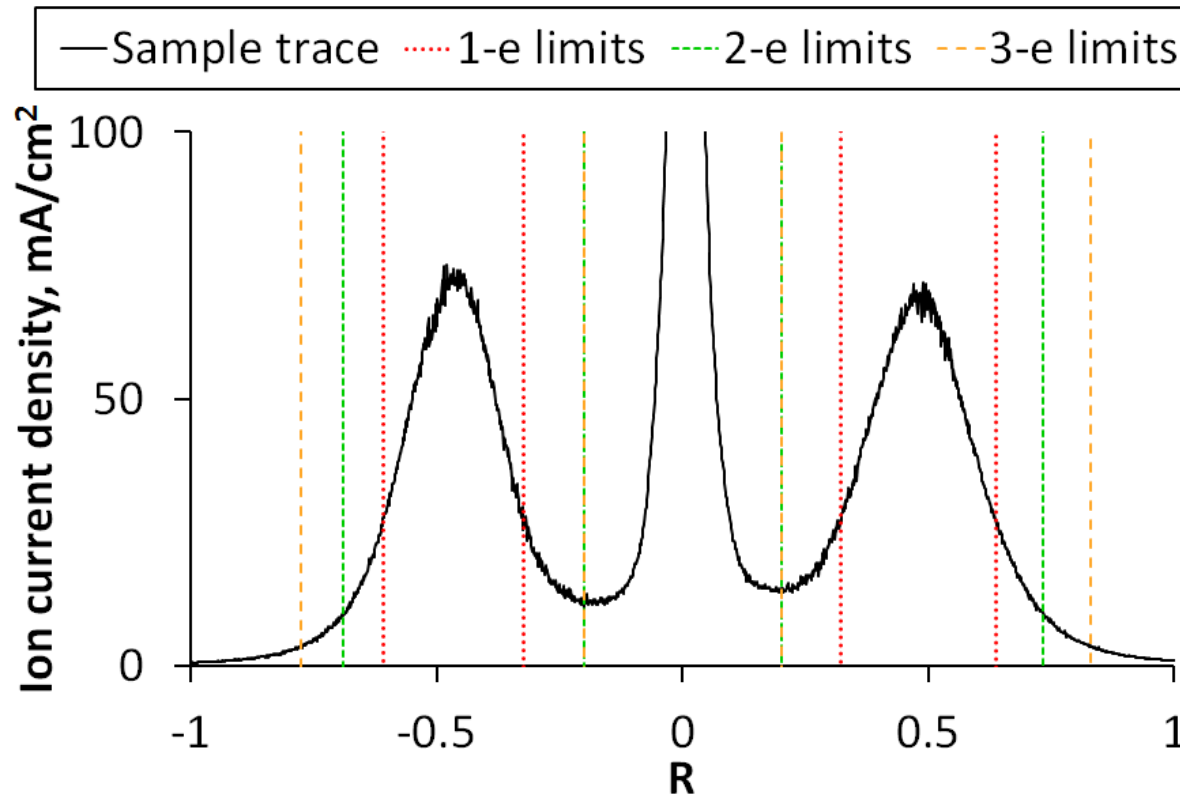


Ion current density profile plotted with limit locations (457Mv2, 300 V, 100 A, Z = 0.10)



Sample trace and limits of integration (2/2)

- On the “inner side”, when channel plume start interacting with cathode plume, use local minima
- When channel plume start interacting with the other channel plume, use thruster centerline

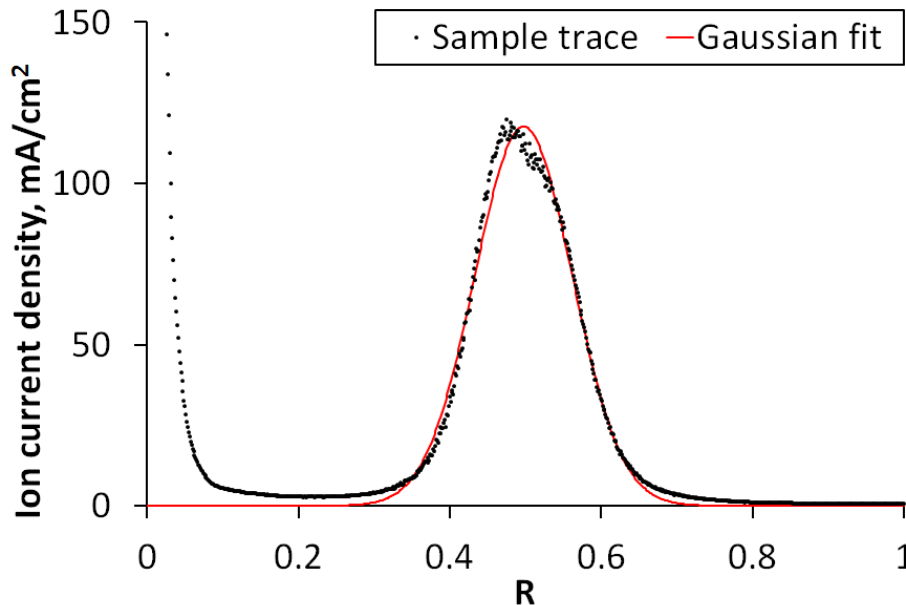


Ion current density profile plotted with limit locations (457Mv2, 300 V, 100 A, Z = 0.37)

Data reduction: Point of Origin for Divergence Calculations (1/2)



- To calculate divergence angle, a point of origin is needed
- Typically assume thruster center at exit plane for far-field data
- For this study, near-field plume (prior to plume interactions) strongly resemble Gaussian distributions
- Assumption: The near-field channel plume can be modeled as a **Gaussian beam originating from a single point**



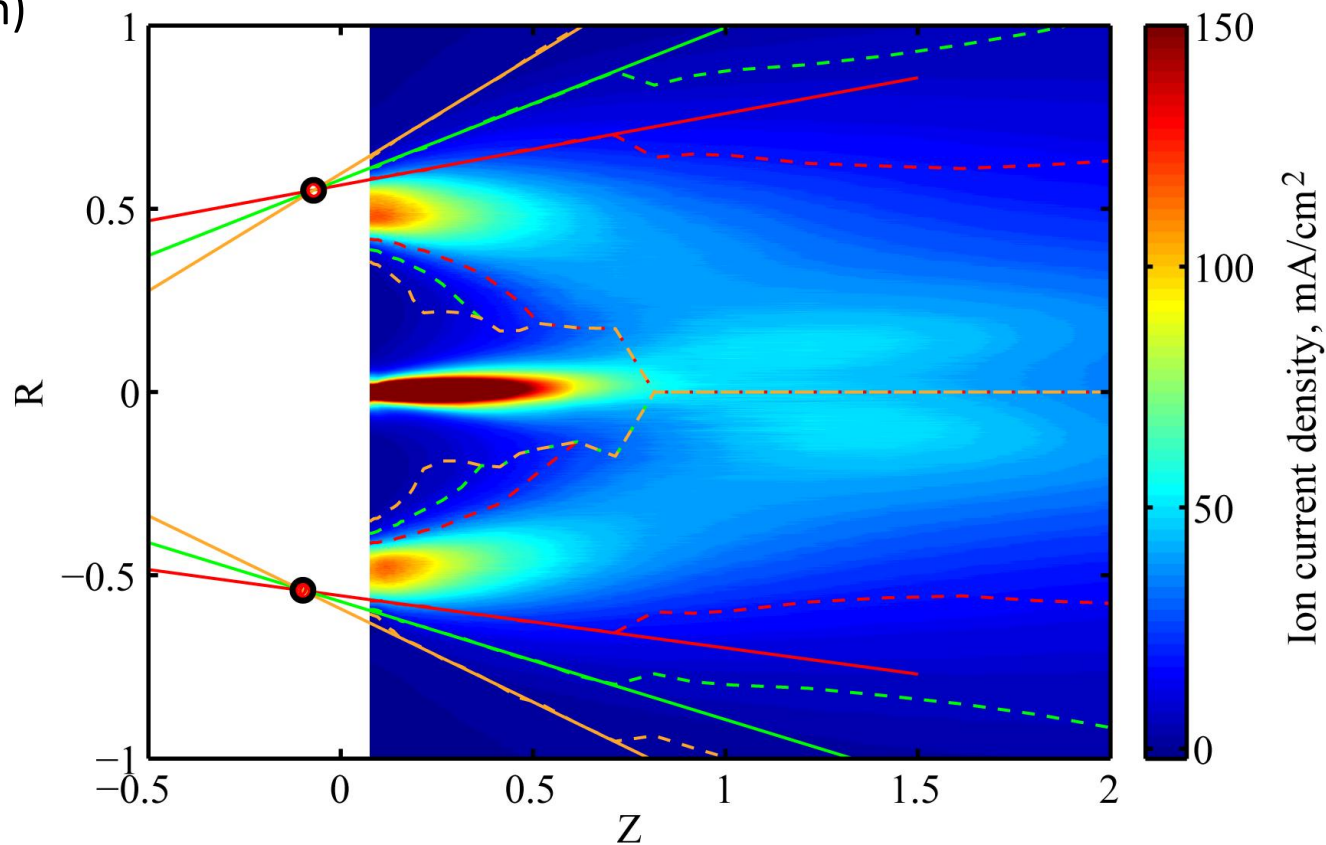
Gaussian fit to ion current density profile (457Mv2, 300 V, 100 A, Z = 0.12)

Data reduction: Point of Origin for Divergence Calculations (2/2)



- If assumption is true, the lines formed by the 1-e, 2-e, and 3-e limits will intersect at this point of origin
- Turns out the linear fit is only good for $0.2 < Z < 0.75$ ($0.2 < Z < 0.5$ for 200 and 250-V operation)

► Flooded contour, ion current density with data analysis overlaid (457Mv2, 300 V, 100 A)



Red line = 1-e

Green line = 2-e

Orange line = 3-e

Red circle = intersection between two of the solid lines

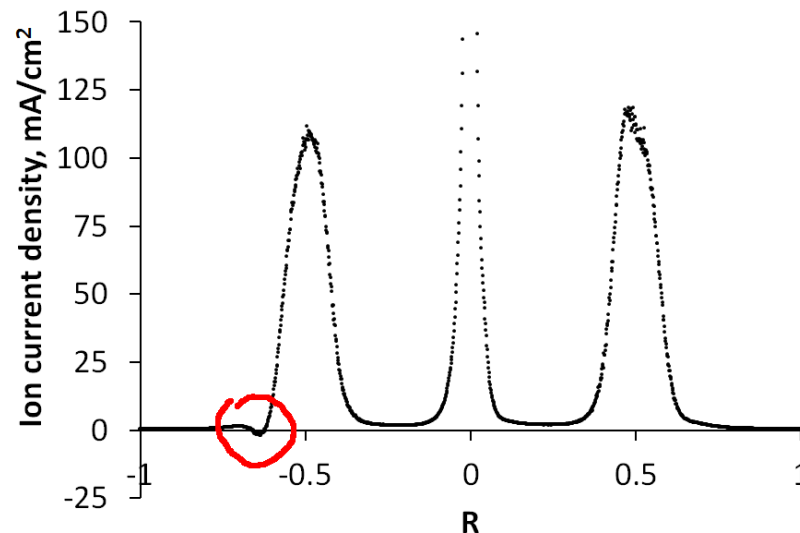
Black circle = average position of the three intersections

Data reduction: Uncertainty Analysis



- For each side of the thruster, total ion current is calculated using the full 1-e, 2-e, and 3-e limits; final result is averaged of two sides
- Divergence angle is calculated from the radial coordinate of the point of origin to the outer side ($|R| > 0.5$) integration limit; in other words, it is an “outer-side” divergence angle
- Total uncertainty in ion current density is +2%/-10% or $\pm 0.002 \text{ mA/cm}^2$, whichever is greater.
- Small region of ion current density profile found to dip below zero due to highly negative floating potential

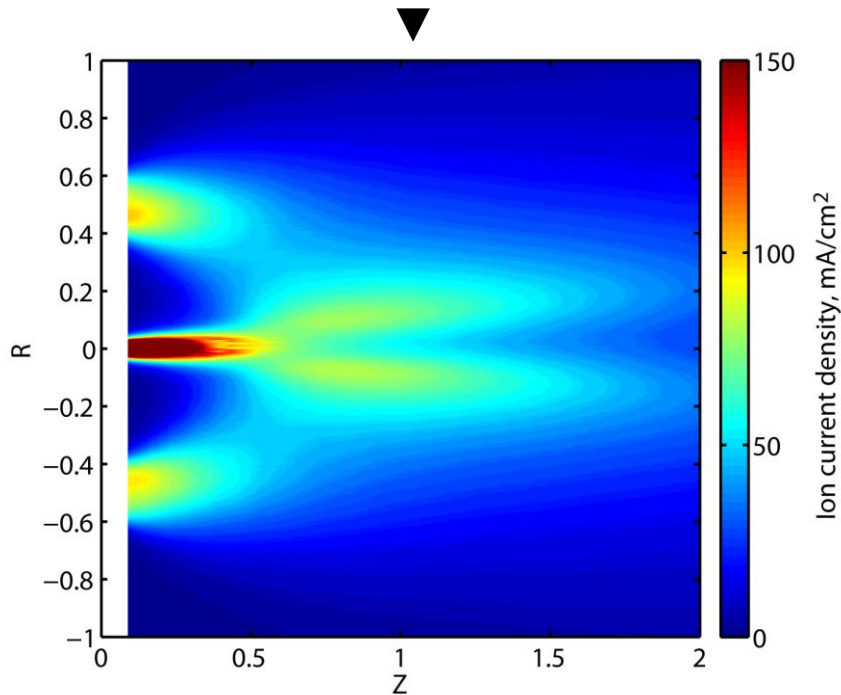
► Ion current density profile
(457Mv2, 300 V,
100 A, $Z = 0.08$)



Results: Ion current density contours
NASA-300M

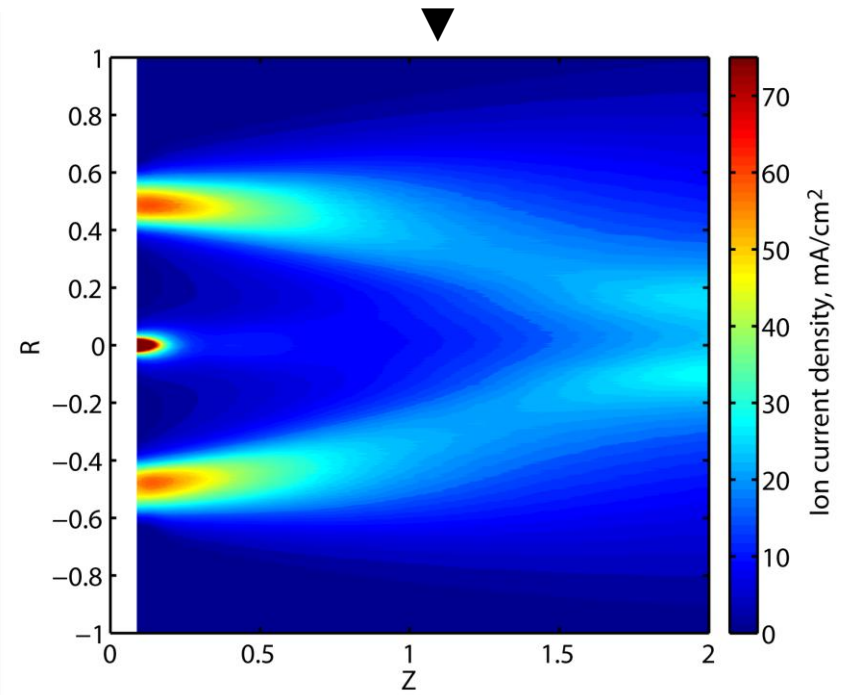
- Two types of near-field plume structure observed among 7 cond.
- 200 V, 50 A and 300 V, 67 A were Triceratops, rest were Trident

“Triceratops” (2/7)



Flooded contour (300M, 200 V, 50 A)

“Trident” (5/7)

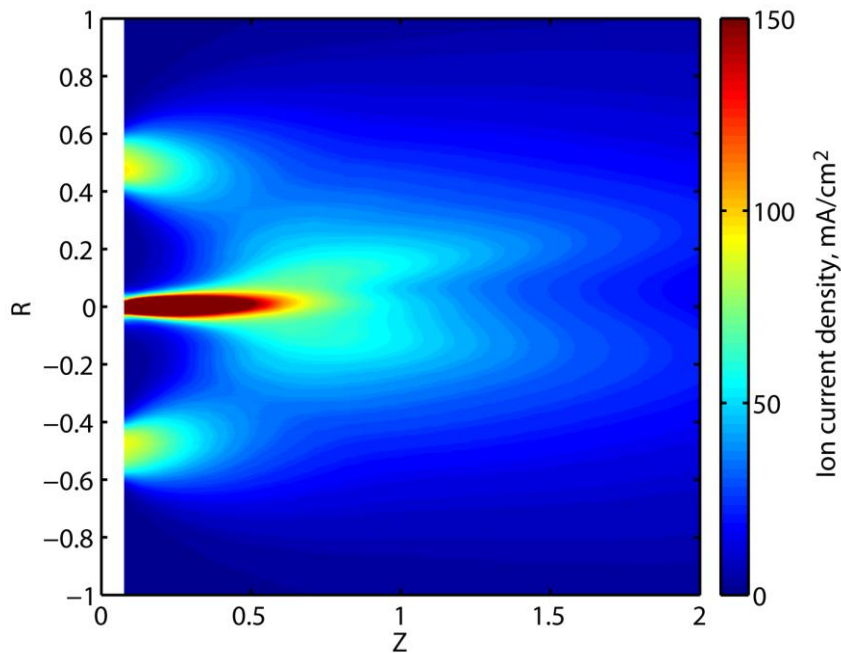


Flooded contour (300M, 500 V, 20 A)

Results: Ion current density contours
NASA-457Mv2

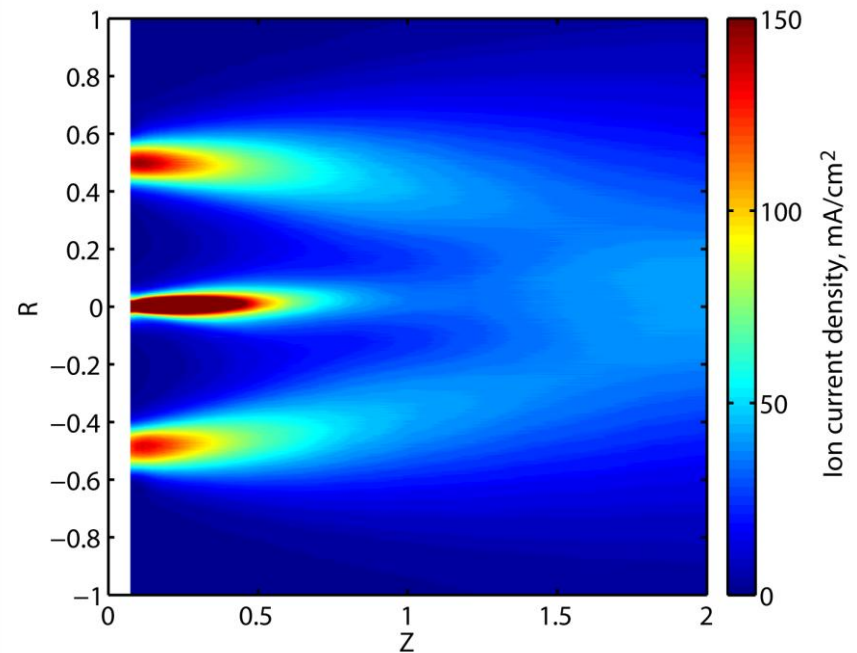
- Of 14 conditions, 4 were Triceratops, all 4 were low voltage (200-300 V) and high current (100 A)

“Triceratops” (4/14)



Flooded contour (457Mv2, 200 V, 100 A)

“Trident” (10/14)



Flooded contour (457Mv2, 500 V, 100 A)

Results: Total ion current and divergence angle



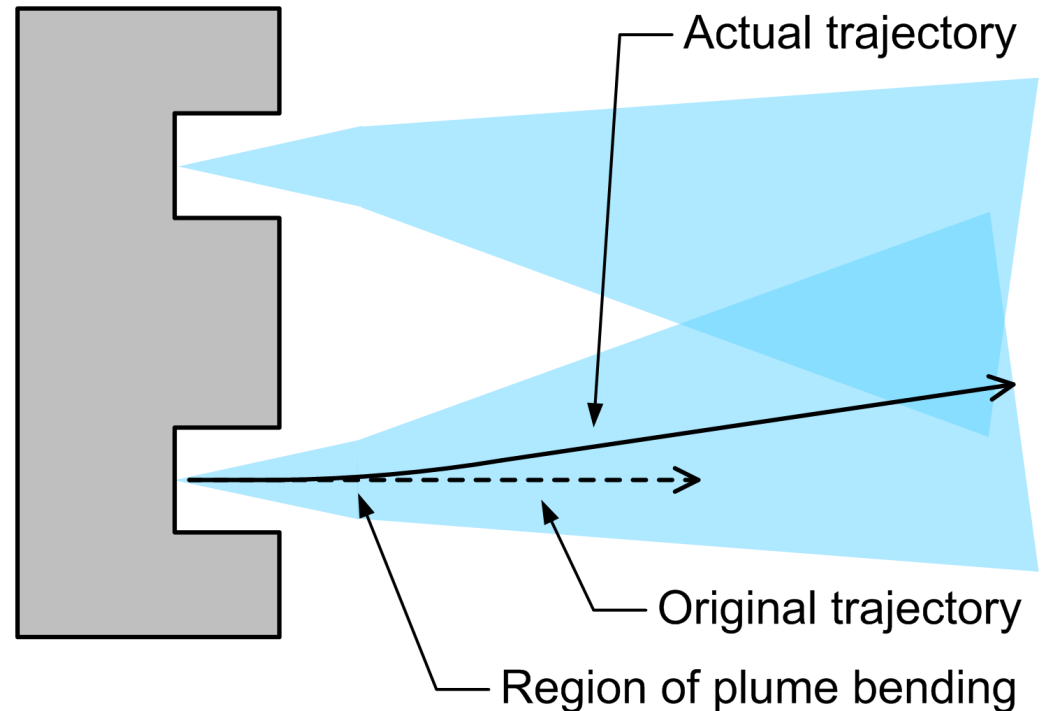
| Thruster | Discharge voltage, V | Discharge current, A | Anode mass flow rate, mg/s | Probe bias, V | Total ion current, A | | Outer-side divergence angle, deg. | |
|----------|----------------------|----------------------|----------------------------|---------------|----------------------|------------|-----------------------------------|------------|
| | | | | | 1-e limits | 2-e limits | 1-e limits | 2-e limits |
| 300M | 200 | 50.3 | 39.9 | -60 | 37.2 | 42.7 | 6.3 | 12.4 |
| | 300 | 33.3 | 32.3 | -60 | 22.6 | 27.6 | 1.9 | 4.7 |
| | 301 | 67.3 | 52.2 | -60 | 45.0 | 52.8 | 3.6 | 9.3 |
| | 401 | 24.9 | 25.2 | -60 | 17.2 | 20.9 | 2.0 | 4.9 |
| | 399 | 50.0 | 43.8 | -60 | 33.9 | 40.9 | 1.8 | 4.7 |
| | 501 | 19.9 | 20.7 | -60 | 14.4 | 17.1 | 2.9 | 5.7 |
| | 501 | 40.6 | 37.4 | -60 | 28.6 | 33.8 | 2.9 | 5.8 |
| 457Mv2 | 202 | 49.1 | 46.1 | -60 | 31.0 | 38.3 | 4.1 | 7.3 |
| | 200 | 99.8 | 77.8 | -60 | 71.0 | 82.1 | 8.1 | 14.9 |
| | 250 | 80.2 | 66.4 | -60 | 54.8 | 66.4 | 4.7 | 9.2 |
| | 250 | 99.8 | 76.7 | -60 | 66.1 | 78.7 | 4.8 | 10.2 |
| | 301 | 66.4 | 59.7 | -60 | 44.1 | 54.3 | 3.5 | 6.1 |
| | 300 | 99.8 | 79.5 | -60 | 72.9 | 86.4 | 5.2 | 9.7 |
| | 400 | 49.7 | 48.4 | -60 | 33.7 | 41.8 | 3.1 | 5.8 |
| | 400 | 74.8 | 65.9 | -60 | 51.9 | 63.1 | 3.5 | 5.7 |
| | 401 | 98.2 | 79.1 | -90 | 68.2 | 82.4 | 4.3 | 6.9 |
| | 501 | 40.5 | 38.8 | -80 | 28.9 | 34.7 | 4.0 | 6.9 |
| | 500 | 60.1 | 56.6 | -80 | 41.6 | 50.9 | 3.0 | 5.5 |
| | 501 | 79.7 | 69.0 | -80 | 56.7 | 67.9 | 3.7 | 6.4 |
| | 501 | 101.1 | 80.5 | -90 | 73.5 | 87.8 | 4.4 | 7.3 |

- Total ion current divide by discharge current for is 63-75% (1-e limits), and 78-87% (2-e limits)
- Average of outer-side div. angle is 4° and 8° for 1-e and 2-e limits, respectively.
- Typical far-field divergence angle is expected to be 15-25 °
- Points of origin were located axially near the anode and radially near the outer wall
- Why the discrepancy?

Discussions on Near-field Plume Bending (1/2)



- Hypothesis: **The near-field plume is bend slightly toward the thruster centerline after exiting the discharge channel**
- If true, can explain both the small outer-side divergence angle and the fact that the point of origin is found to be near the outer wall
- Given the straightness of the line form by the limits of integration at $Z > 0.2$, the bending likely happens at $Z < 0.2$



Discussions on Near-field Plume Bending (2/2)



- Could the plasma be residing near the outer wall and actually shoots out at an angle?
- Counter-argument:
 - Roughly symmetric field topology
 - Gaussian curve fit on data nearest the channel exit shows center of Gaussian is typically very close to the thruster centerline

Future Work



- Perform far-field Faraday probe measurements
- Find a way to analyze the inner-side of the near-field plume for divergence angle
- Calculate the angle by which the near-field plume is bent
- Model the near-field plume as simple Gaussian beams, and compare to measured contours
- Find the root cause of plume bending and control it if possible



- We have successfully collected near-field ion current density data for the NASA-300M and the NASA-457Mv2 for validating JPL Hall thruster model.
- We found “trident” and “triceratops” shaped plume structures.
- We used a novel ray-tracing technique to show the near-field plume can be modeled as Gaussian beams originating from a point and the point can be used calculate near-field plume divergence.
- The point of origin is, on the average, deep in the channel and near the outer channel wall.
- The outer-side plume divergence angle was 4-8° on the avg.
- We hypothesize the plume is bending toward the thruster centerline between the exit plane and $Z < 0.2$.

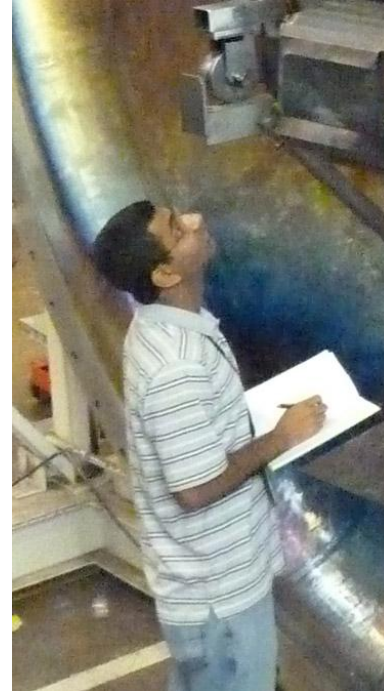
Thank Co-Authors



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George Soulas

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Questions

