Evidence of Counter-Streaming Ions near the Inner Pole of the HERMeS Hall Thruster

AIAA-2019-3897

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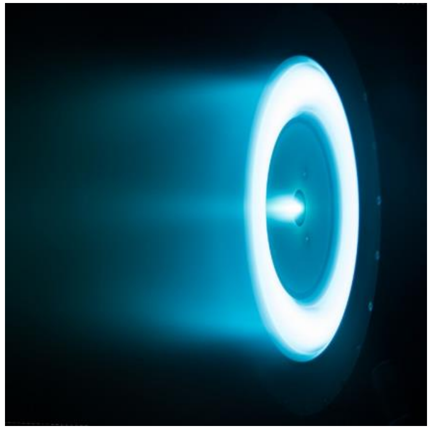
Outline

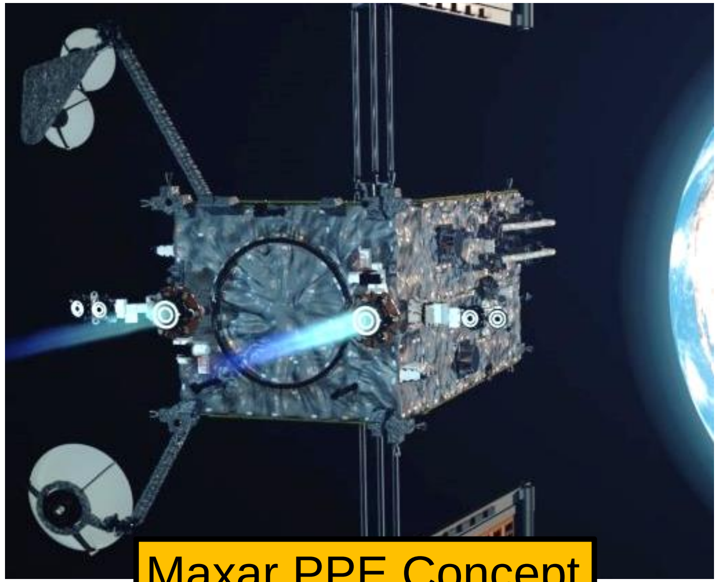
- Introduction
- Principles of LIF
- Experimental Setup
- Updated data analysis approach
- Results
  - Evidence of Counter-Streaming Ions near the Inner Front Pole
  - Implications for Pole Erosion and Comparison to Wear Measurements
  - Magnetic Field Strength Variation Study
  - Background Pressure Study
- Conclusion

Introduction

- A NASA GRC and JPL team developed a 12.5-kW, magnetically-shielded Hall thruster, called Hall Effect Rocket with Magnetic Shielding (HERMeS)
- Flight development continuing in the form of Aerojet Rocketdyne's Advanced Electric Propulsion System (AEPS)
- Candidate propulsion system for the Power and Propulsion Element (PPE), the first element of NASA's Gateway
- Completing risk reduction activities (using HERMeS) and transitioning to Engineering Test Unit (ETU) testing
- Developing a related Plasma Diagnostics Package (PDP)

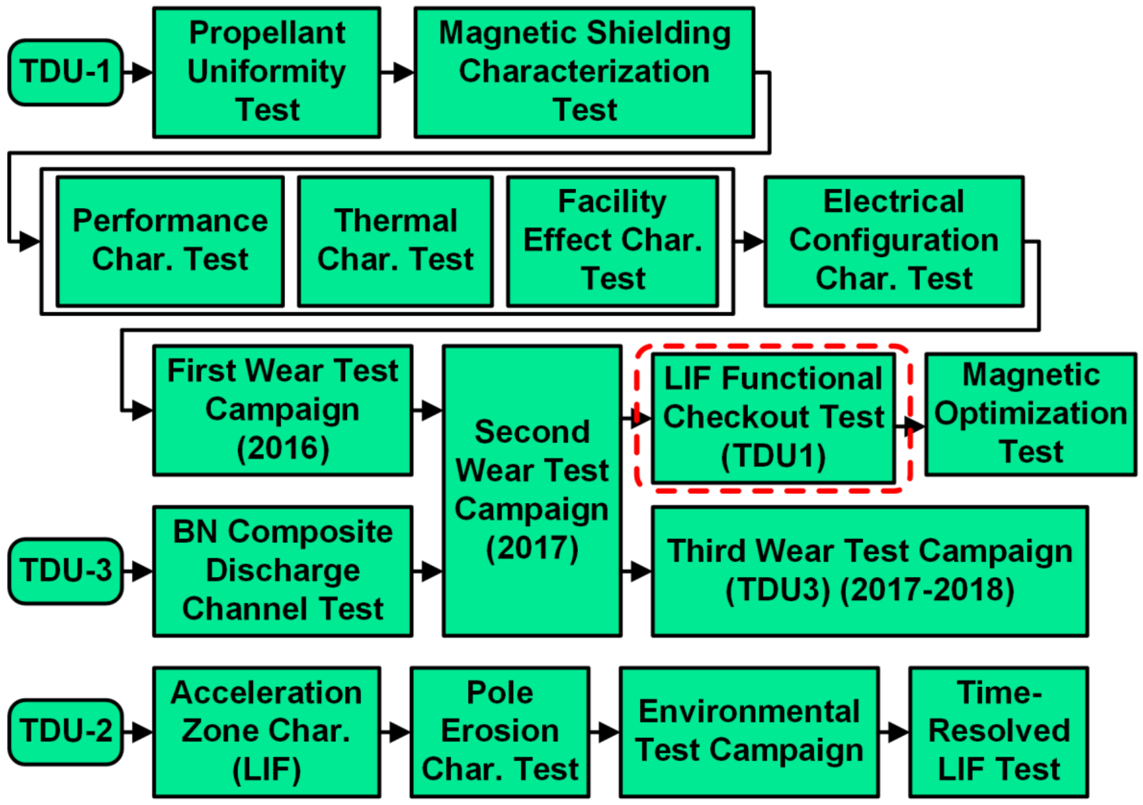


◄ HERMeS in operation



Maxar PPE Concept

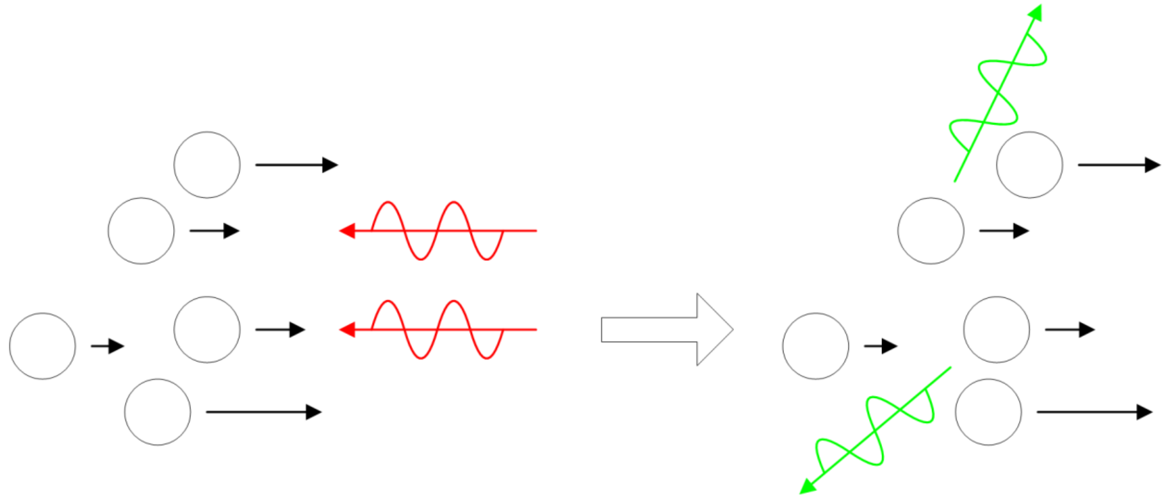
HERMeS Test Campaign Status

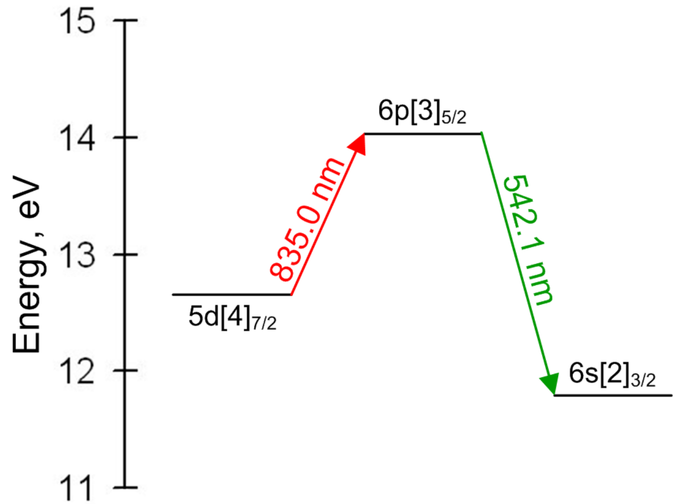


- Other JPC papers on PPE and AEPS
  - **Ticker**, PPE Status Update (AIAA-2019-3811, EP1, Mon morning)
  - **Frieman**, TDU Long Duration Wear Test (AIAA-2019-3895, EP4, Mon afternoon)
  - **Mackey**, TDU Erosion Uncertainty (AIAA-2019-3896, EP4, Mon afternoon)
  - **Lobbia**, Accelerated Backsputter Test (AIAA-2019-3898, EP4, Mon afternoon)

How does LIF work?

- Moving atoms absorb light at shifted frequency (Doppler effect)
- Collect emitted fluorescence while varying laser frequency to measure velocity distribution function (VDF)
- XE II 835.0 nm is easy to access with commercial diode laser
  - Metastable
  - Representative of bulk ion VDF
  - Fluoresce in green, 542.1 nm

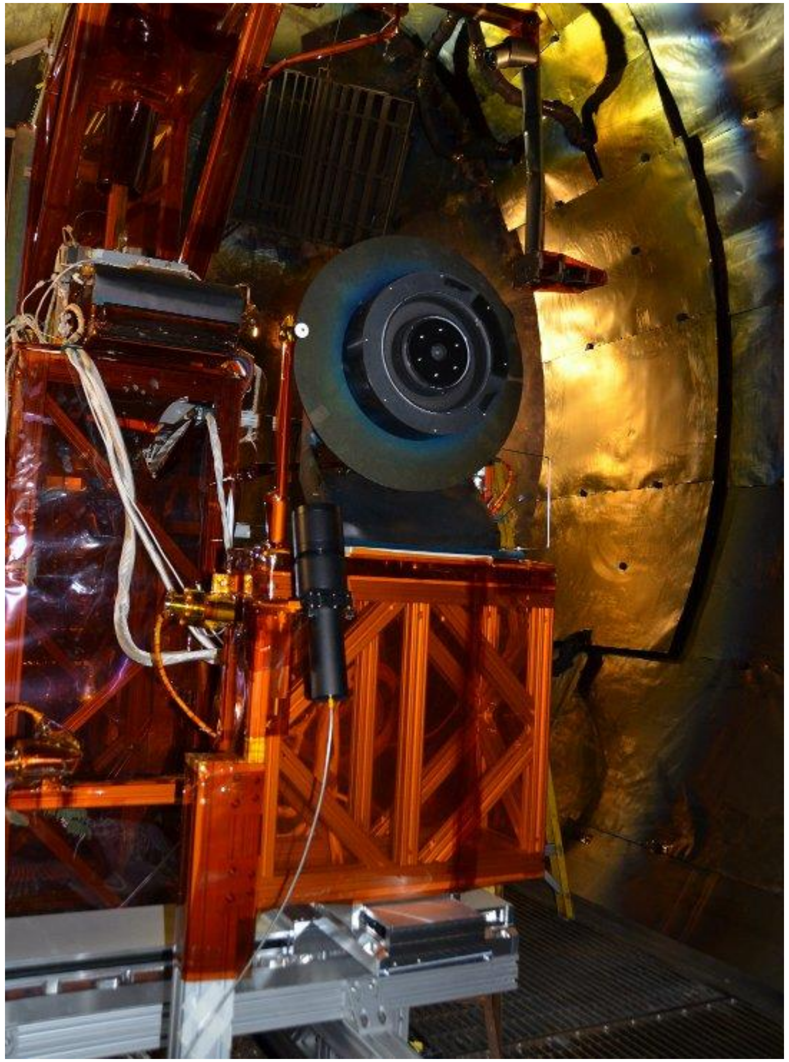




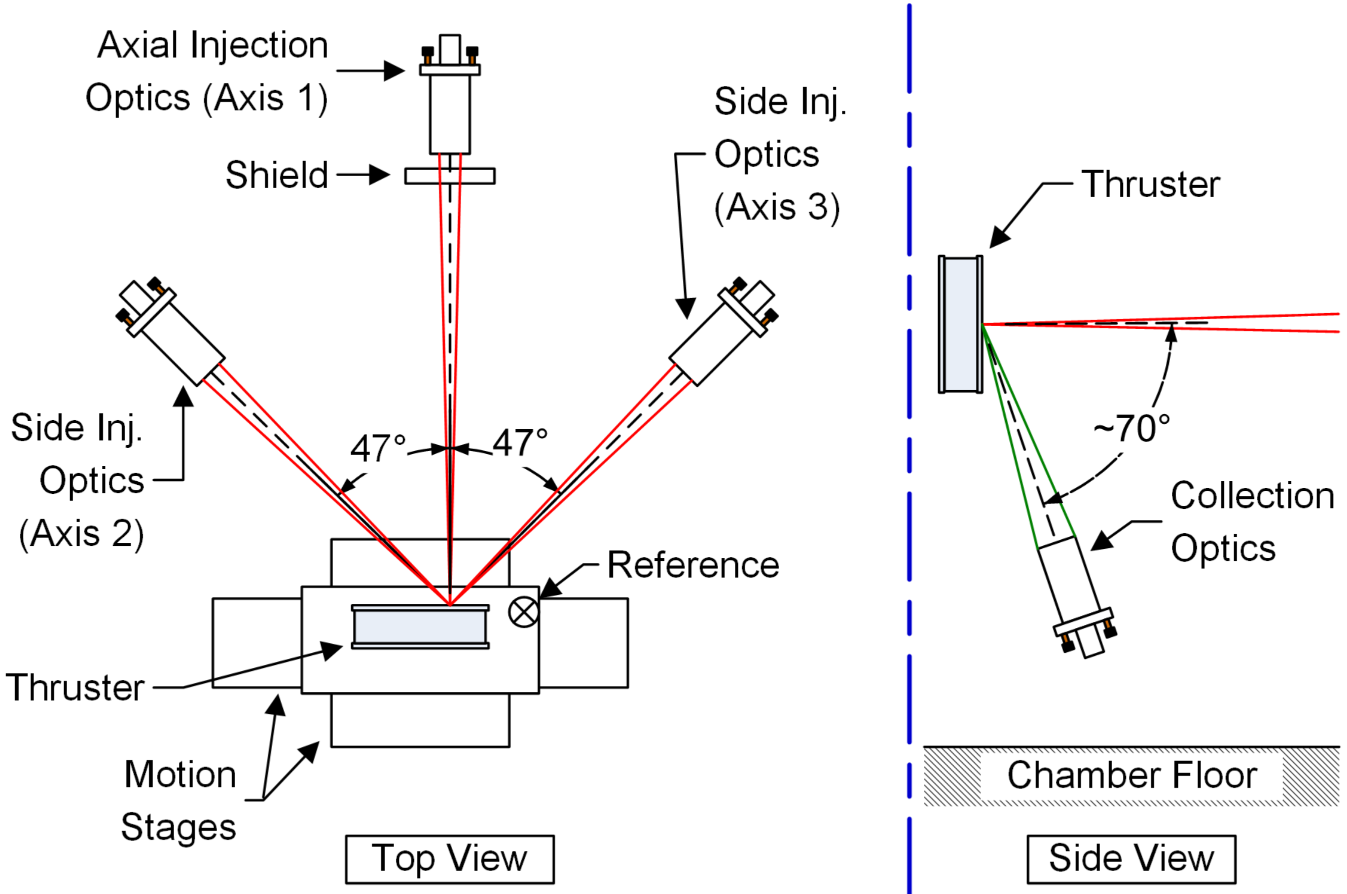
Experimental Setup – Test Article

- HERMeS TDU1
  - Throttle range from 0.6 to 12.5 kW, 2000 to 3000 sec
  - Magnetic shielding topology
  - Centrally mounted cathode, 7% cathode flow fraction
  - Cathode tied to thruster body
  - Test was in VF6, ~1.2e-5 Torr near thruster
- This presentation focus on these conditions:

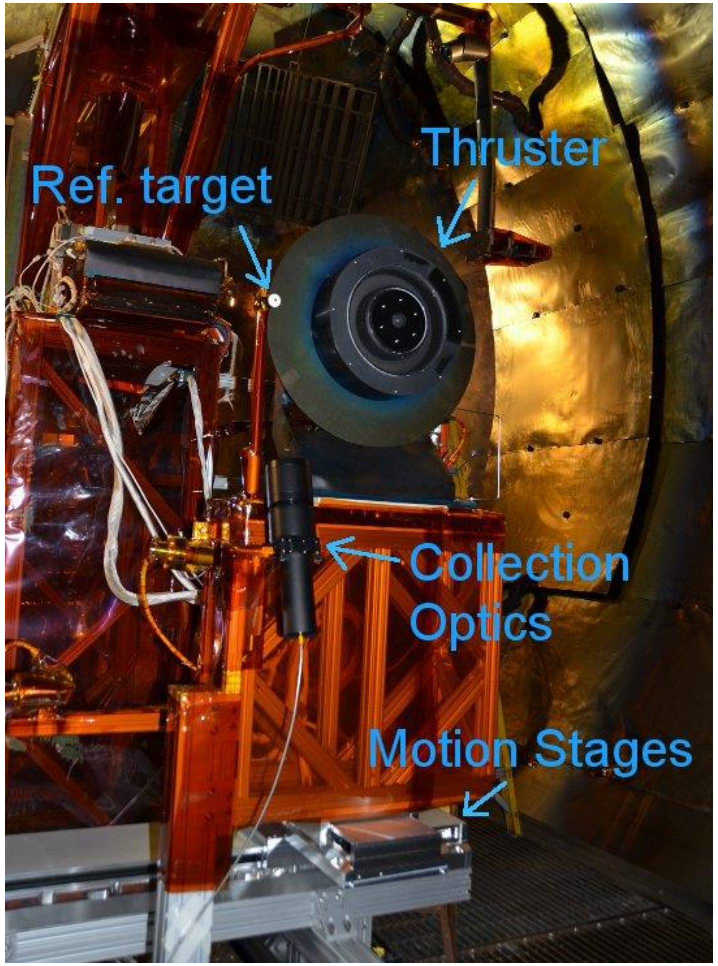
Label	Discharge voltage, V	Discharge power, kW
300-6.3	300	6.25
400-8.3	400	8.33
500-10.4	500	10.42
600-12.5	600	12.50



Experimental Setup – Vacuum Side Optics



(a) (b)



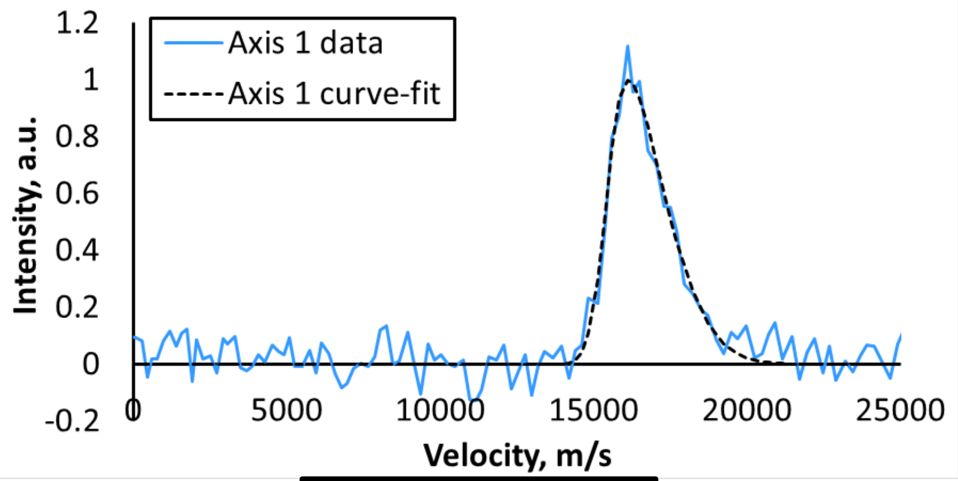
Additional setup info in AIAA-2018-4723

Data Analysis

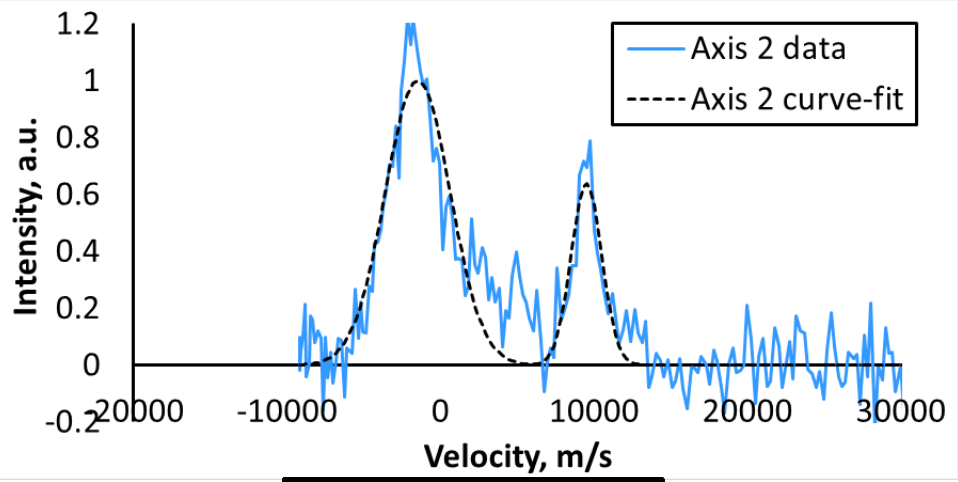
- Saturation study was performed, broadening no more than 10% on narrowest VDFs
- Data analysis steps:
  - Convert wavemeter and OG signal to velocity
  - Correct intensity by laser power variation
  - Apply curve-fits (Gaussian, skew-normal, two-Gaussian) with Zeeman effect
  - To correct for Zeeman effect, used mag sim data that has been confirmed by measurements and applied model from Huang's dissertation:

$$Split\ in\ MHz = 2.7273 * Mag\ strength\ in\ Gauss$$

- Spatial uncertainty: 0.5 mm
- Velocity uncertainty: $\pm$112 m/s typical ($\pm$600 m/s for noisiest scans)



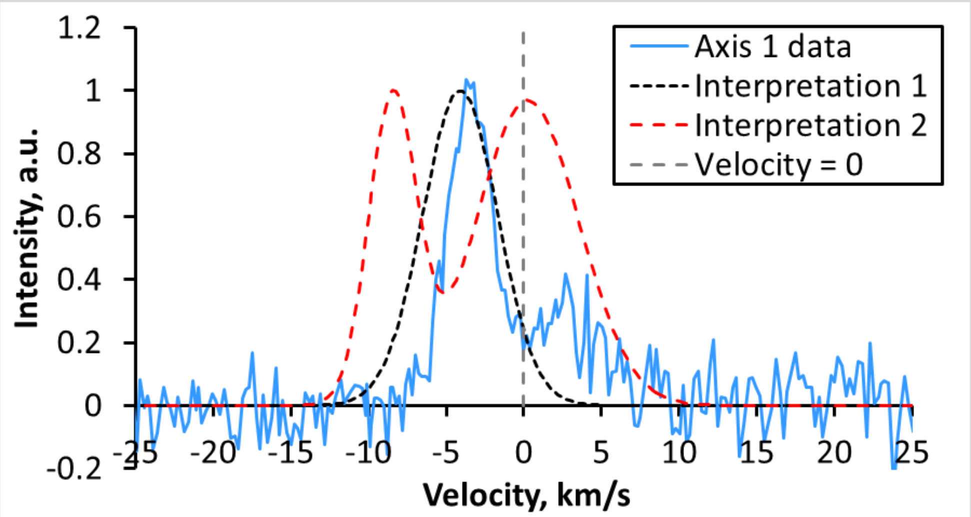
Skew-normal fit

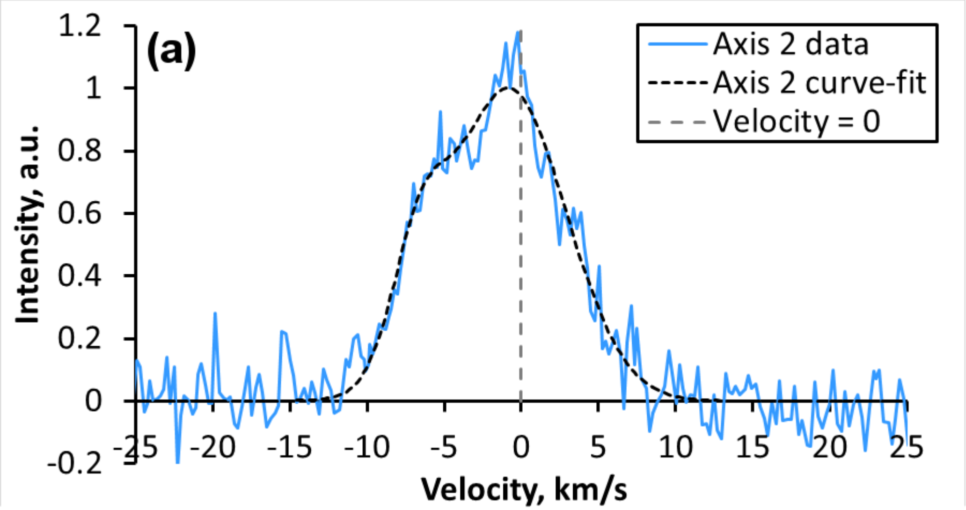


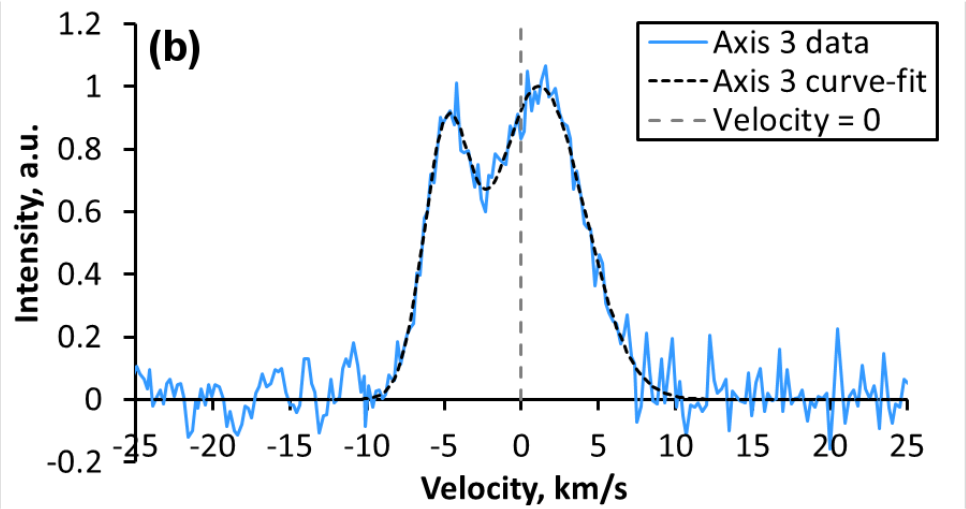
Two-Gaussian fit

Updated Data Interpretation

- Old analyses assumed two-peak structure near Inner Front Pole Cover (IFPC) were due to Zeeman effect; Zeeman effect correction showed that they are real ion populations
- When two axes have two peaks each, two different interpretations are possible
  - (1) Two streams of ions moving in opposite radial directions
  - (2) One stream directed at IFPC, other stream is stationary
- Comparing to axis 1 data across many studies and IFPC locations demonstrated that <u>interpretation 1 is correct (Two opposing streams)</u>

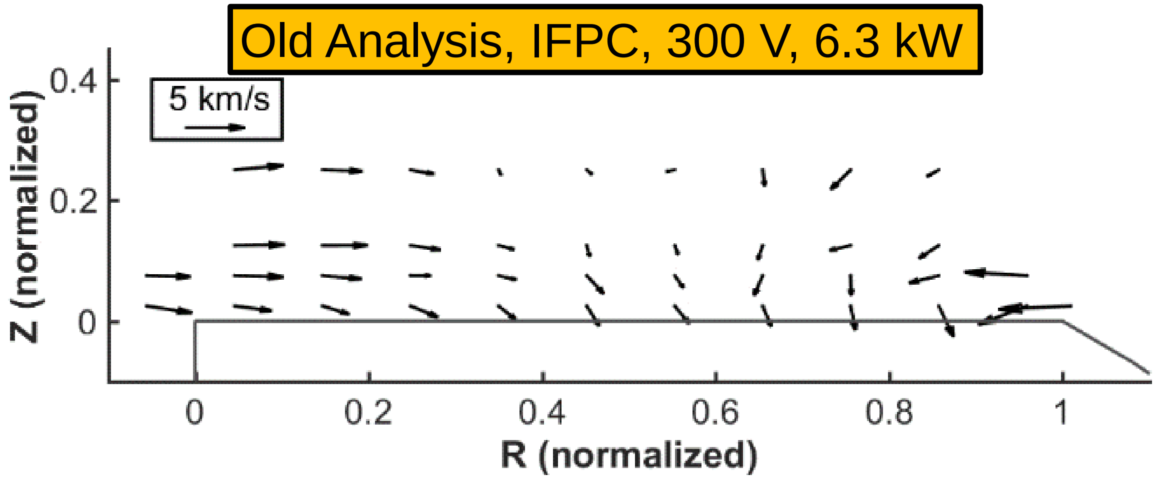


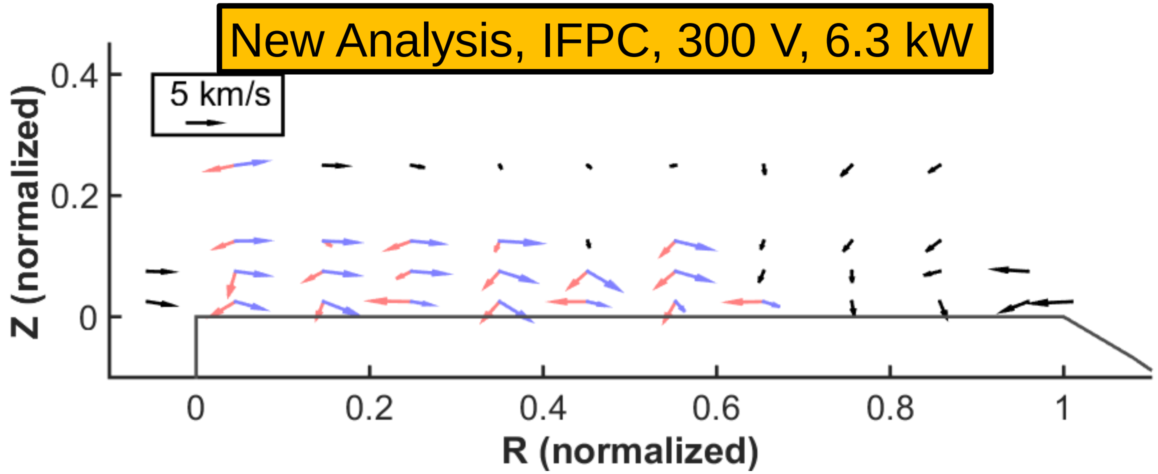


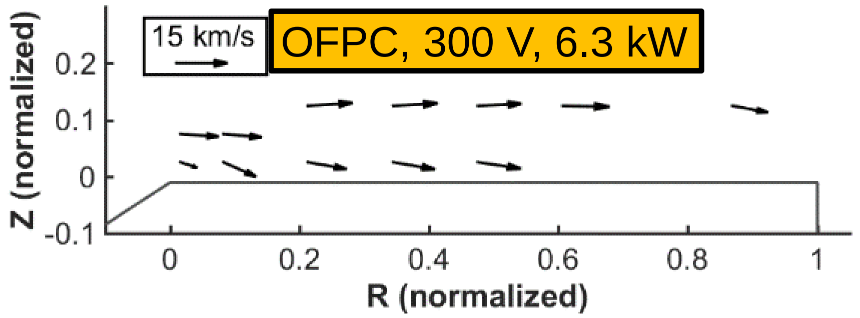


600 V, 12.5 kW, around radial middle of the IFPC

Evidence of Counter-Streaming Ions at IFPC



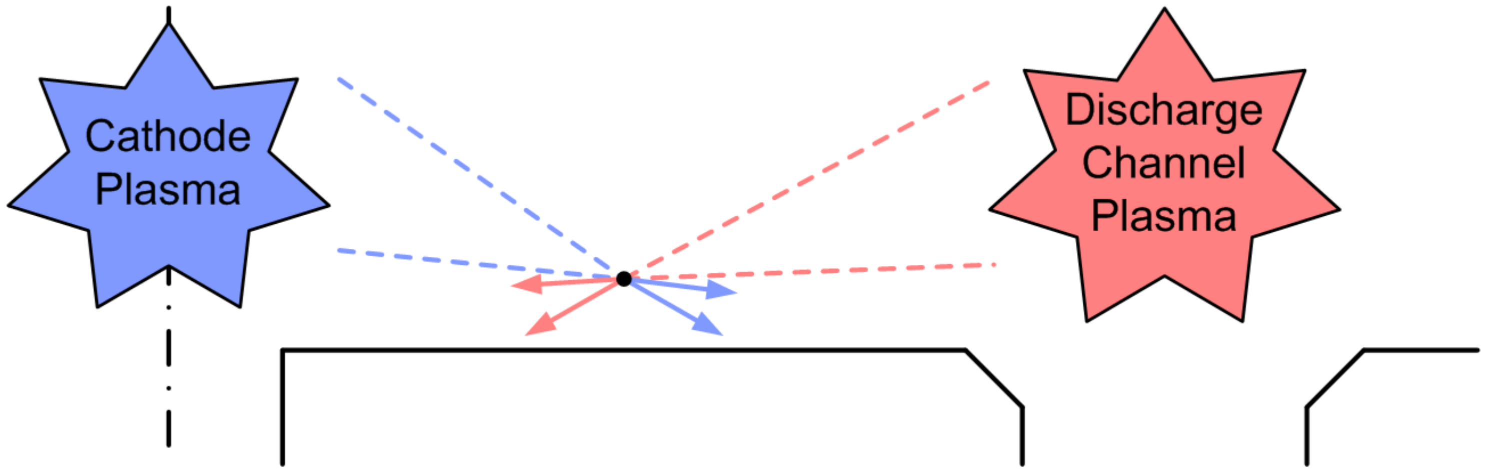




- Red vector: discharge channel stream
- Blue vector: cathode stream
- Vector turning seen in old analysis was actually a result of averaging two populations with varying density ratios
- New analysis show that <u>all ions were bombarding IFPC at large oblique angles</u>
- Ions arriving at IFPC undergo little interactions before hitting the pole cover (much like at OFPC)
  - Cannot develop electric field structure for turning ions on a conducting pole cover
  - Mean free path on the order of 100's to 1000's meters so not collisional

IFPC = Inner Front Pole Cover, OFPC = Outer Front Pole Cover

Source of Ions at IFPC



- Ions for the discharge channel stream (red) are most likely the low energy ions from the discharge channel previously reported (AIAA-2018-4723)
  - Charge exchange ions and partially accelerated ions (and partially accelerated CEX ions)
  - Azimuthal component of these ions are not negligible so R-Z plane data may underestimate the out-of-plane contribution to velocity and bombardment angle-of-incidence (AOI)
- Ions for the cathode stream (blue) are most likely from the cathode though there may some contributions from the other parts of the channel
  - There is also the central spike that is not well understood
- Existence of two ion populations was inferred in prior TDU simulations and experiments* and has been directly observed in this study

*Polk, et al., IEPC-2017-409; Lopez Ortega and Mikellides, AIAA-2018-4647; Lopez Ortega, et al., J. Applied Physics, vol. 125, pp. 033302, 2019.

Implications for Pole Cover Erosion

- Ions with high AOI are known to cause more erosion than ions at normal incidence
- Literature review shows 2.3 to 4.7 times higher erosion at high AOI than at normal incidence for Xenon on Carbon

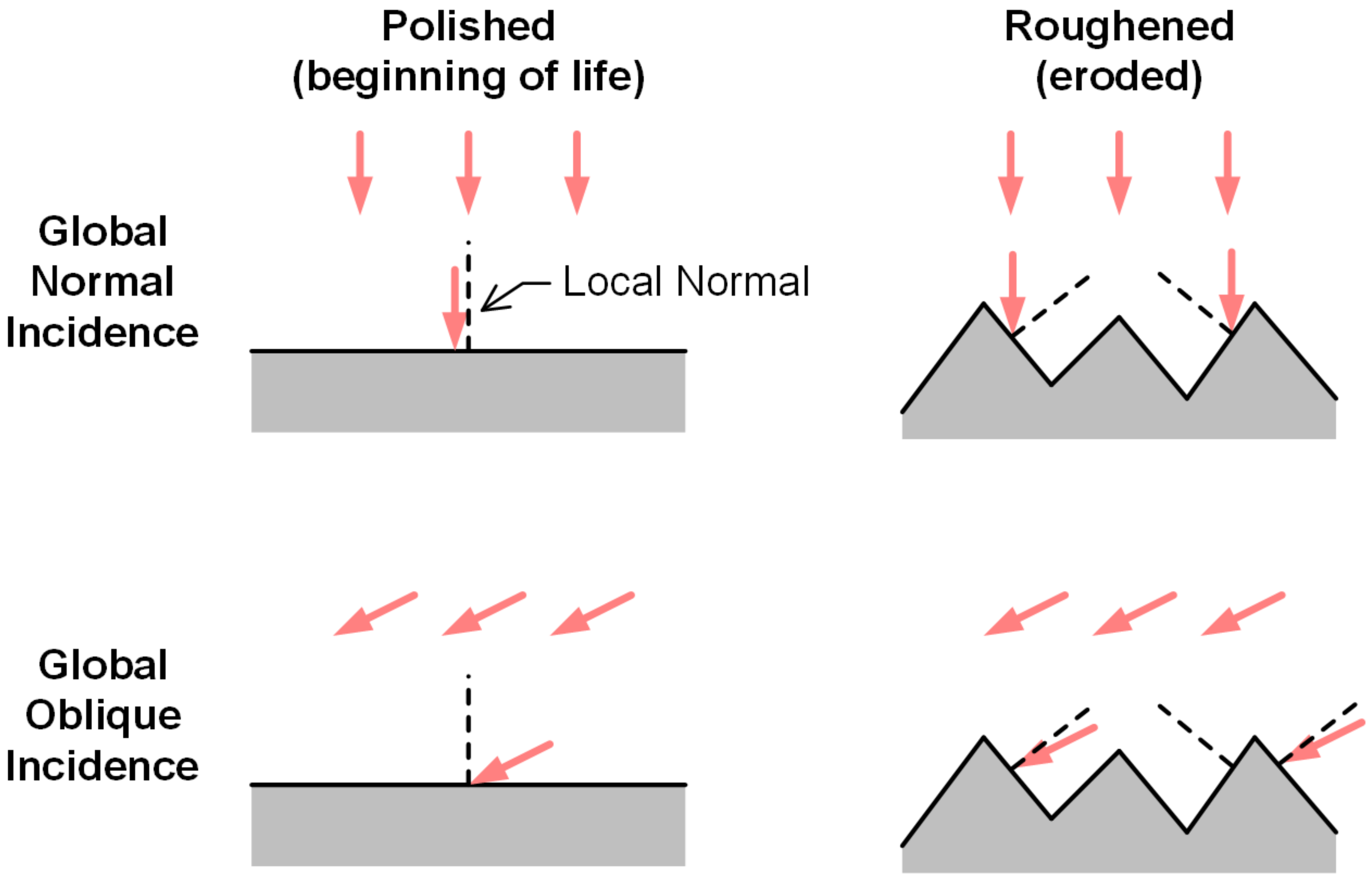
Graphite Type*	AOI = 0º	AOI = 70º
Pyrolytic	**0.011±0.005**	**0.110±0.022**
Isotropic	**0.024±0.010**	**0.048±0.018**

- Küstner, et al., did a study of deuterium-induced graphite erosion where surface roughness is controlled (part of data replicated in table)
  - Pyrolytic graphite can be polished, while isotropic is rough even after polished
  - Starting surface roughness of pyrolytic graphite samples were similar to polished pole covers whereas surface roughness of isotropic graphite samples were like eroded pole covers (roughness measurements show similar peak-to-peak values)
  - At normal incidence, roughened surface eroded faster than polished surface
  - At oblique incidence, roughened surface eroded slower than polished surface (though it always eroded faster than the normal incidence)

*Küstner, et al., Nuclear Instruments and Methods in Physics Research B, Vol 145, No 3, pp 320, 1998.

Physical Mechanism

- Top two graphs show how local AOI evolve as surface roughens for global normal incidence
- Bottom two graphs show the same for global oblique incidence
- Whereas the local AOI increased over time for global normal incidence, it decreased over time for global oblique incidence



Comparison to Wear Measurements

- During the first wear test campaign, IFPC aggregate erosion rate decreased by ~40% when comparing the 1000-hour test segment to the 250-hour test segment (which preceded the 1000-hour segment)*
- During the third wear test campaign, IFPC aggregate erosion rate decreased by ~20% when comparing measurements made at 1000 hour to those made at 620 hour for the same test segment**
- Reductions in erosion rate were larger than measurement uncertainties
- Aggregate erosion was calculated by measuring the difference in surface height between the start of the test segment and the time indicated
  - Change in aggregate erosion rate are generally less than change in instantaneous erosion rate
- Wear measurements supports the conclusion of the new LIF analyses: IFPC is being bombarded by ions with high oblique incidence (as opposed to largely normal incidence)

*Williams, G. J., et al., 35th IEPC, 2017-207.
**Frieman, J. D., et al., 2018 JPC, AIAA-2018-4645.

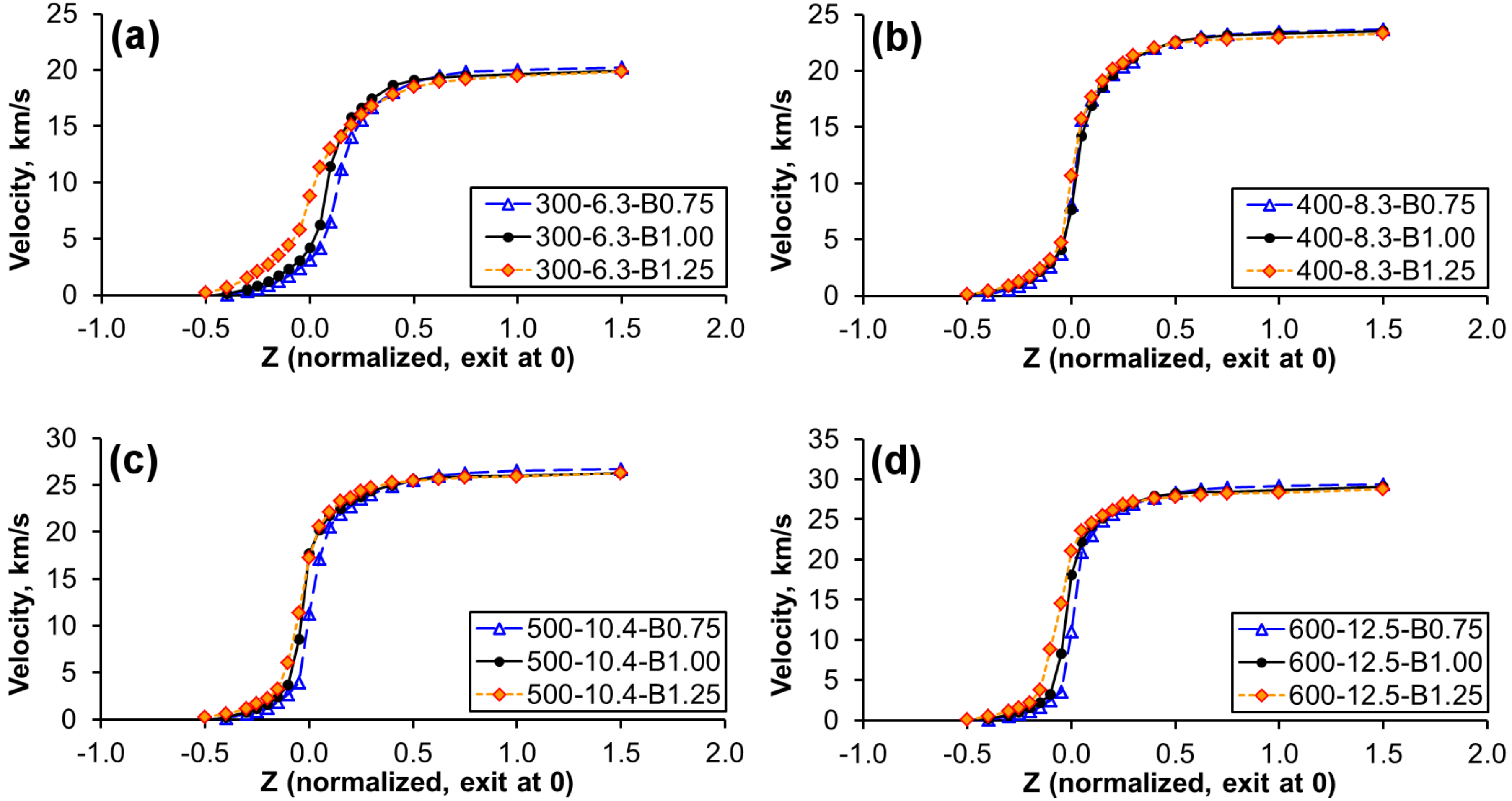
Outstanding Issues with the Evidence (1 of 2)

- The Küstner study was performed with deuterium ions, which could have chemically reacted in ways that xenon would not
  - Counter: Dependence of sputter yield on angles is well established for xenon on carbon, the Küstner study mainly provide guidance on the trends with different surface roughness and the underlying mechanisms
- The Küstner study did not report sputtering time and the study used 2 keV ions
  - Counter: Surface roughness measurement show good match in peak-to-peak values between the relevant TDU pole covers and the samples in the Küstner study

Outstanding Issues with the Evidence (2 of 2)

- Reported wear test erosion rates are aggregate rates and not instantaneous rates
  - Counter: Change in instantaneous rates should be larger than change in aggregate rates assuming monotonic change in rates
- LIF data were from TDU1 testing in VF6 while wear test data were from TDU1 and TDU3 testing in VF5
  - Performance and plasma data from TDU's were identical to within measurement uncertainties
  - Additional LIF testing in VF5 needed to resolve any potential differences due to facility effects

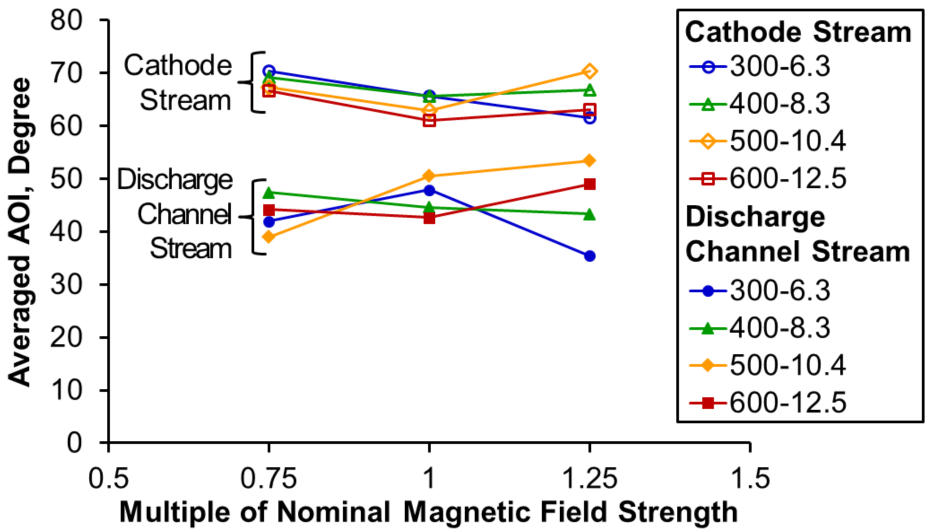
Magnetic Strength Variation Study: Discharge Channel Centerline Results

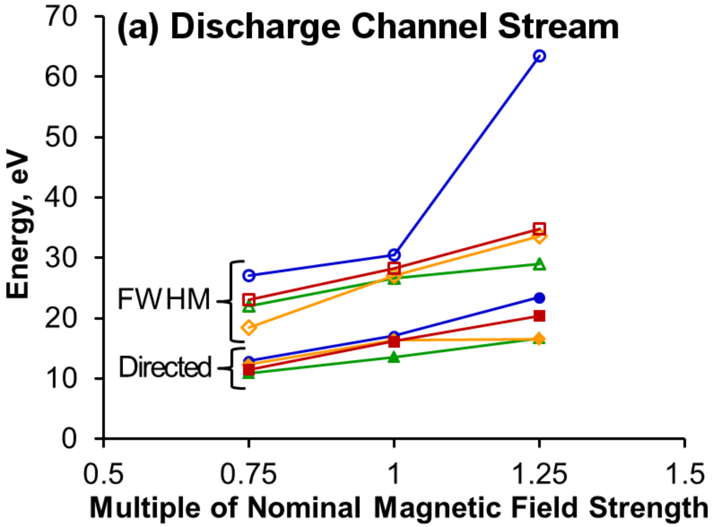


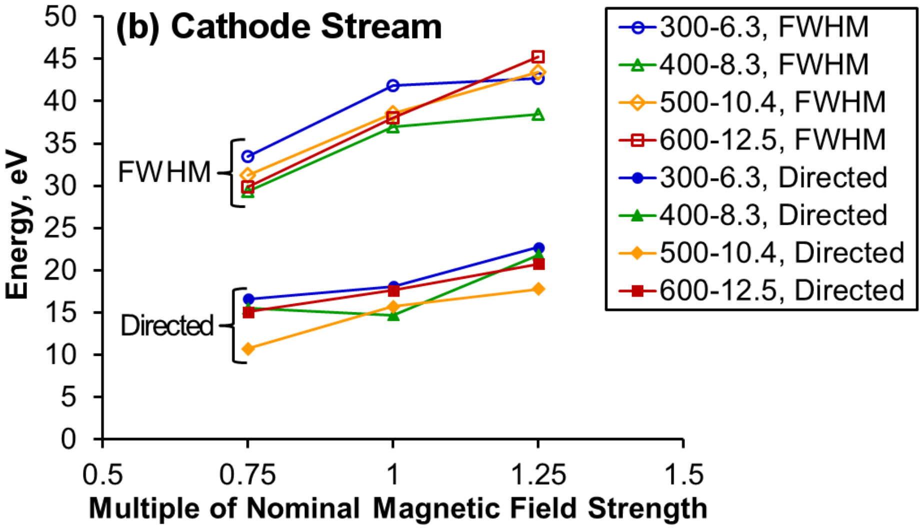
- Acceleration zone moves upstream as magnetic field strength increases

Magnetic Strength Variation Study: IFPC Results

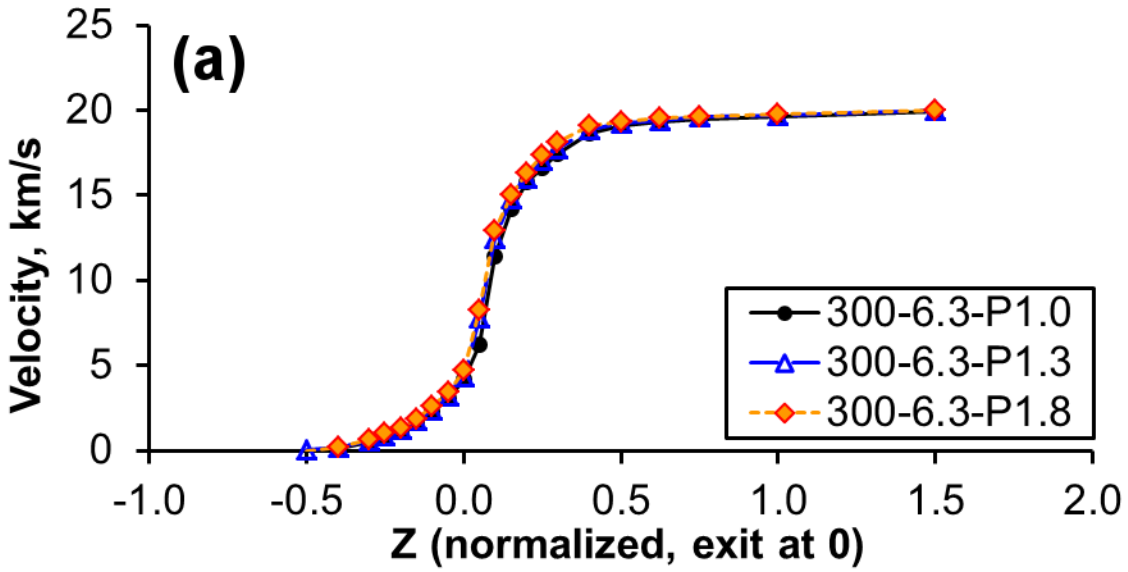
- Directed energy is low but high energy tail (50+ eV) exist because of wide energy distribution
  - High energy cathode ions (50+ eV) were previously observed in a TDU cathode test with mass spectrometry measurements (IEPC-2017-409)
- Ion energy (directed and FWHM) generally increase with magnetic field strength
- If ion density is about constant, erosion rate should increase with magnetic field strength; wear test measurements show this trend
- AOI is fairly constant with magnetic field strength
- Note also that the trends are very similar across different RFCs

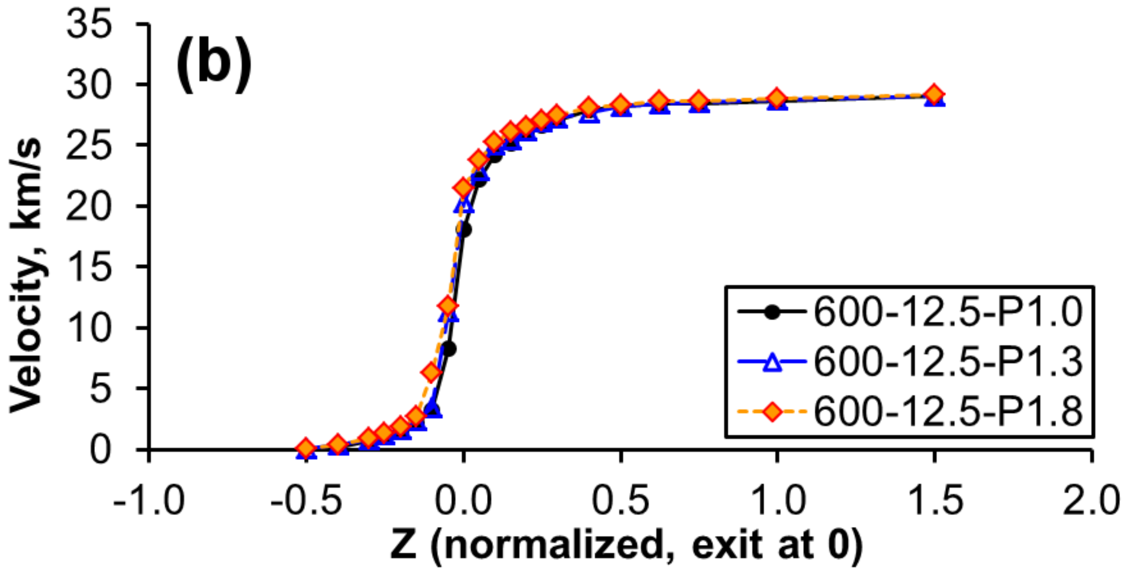






Background Pressure Study: Results

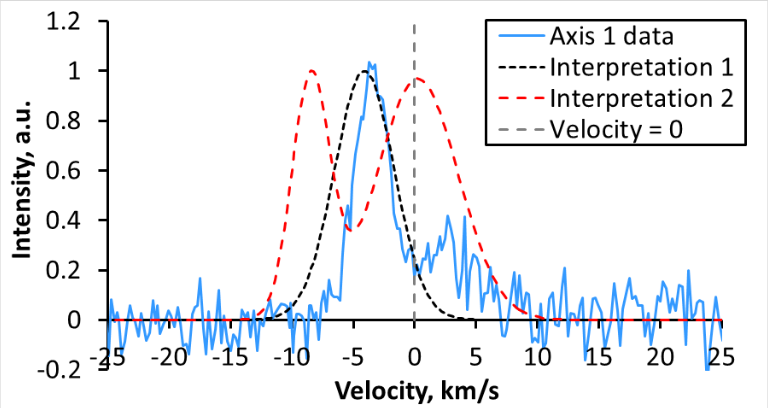


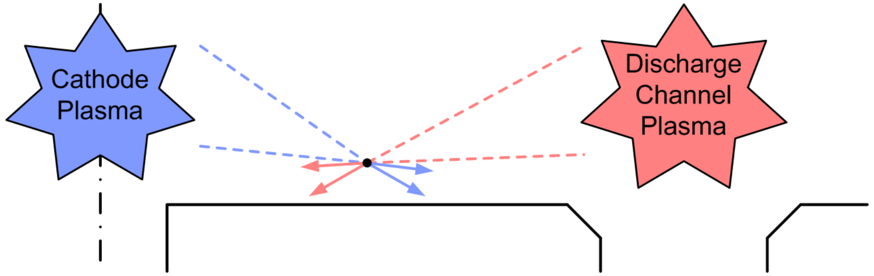


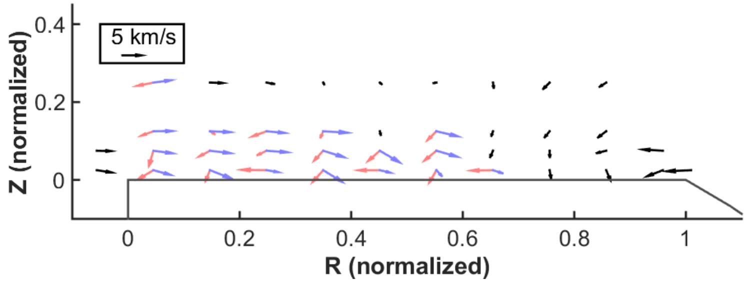
- Acceleration zone move slightly upstream with increasing background pressure over the tested range
- For averaged ion energies and AOI, variations were smaller than the measurement uncertainties over the tested range
  - See paper for actual values

Conclusion

- Performed updated analysis that correct for Zeeman Effect
- Discovered that IFPC was bombarded by two distinct populations of low-energy ions with high-energy (50+ eV) tail at oblique angles of incidence
  - Discharge channel and cathode streams
- Correlated LIF data trends to wear test trends
  - The fact that IFPC wear rate decreased over time supports the discovery that bombarding ions had oblique AOI
  - IFPC ion characteristics largely similar for different discharge voltage
  - Energy of ions bombarding poles increased with magnetic field strength; AOI did not vary noticeably
  - Variations with background pressure were negligible within the range of tested pressures







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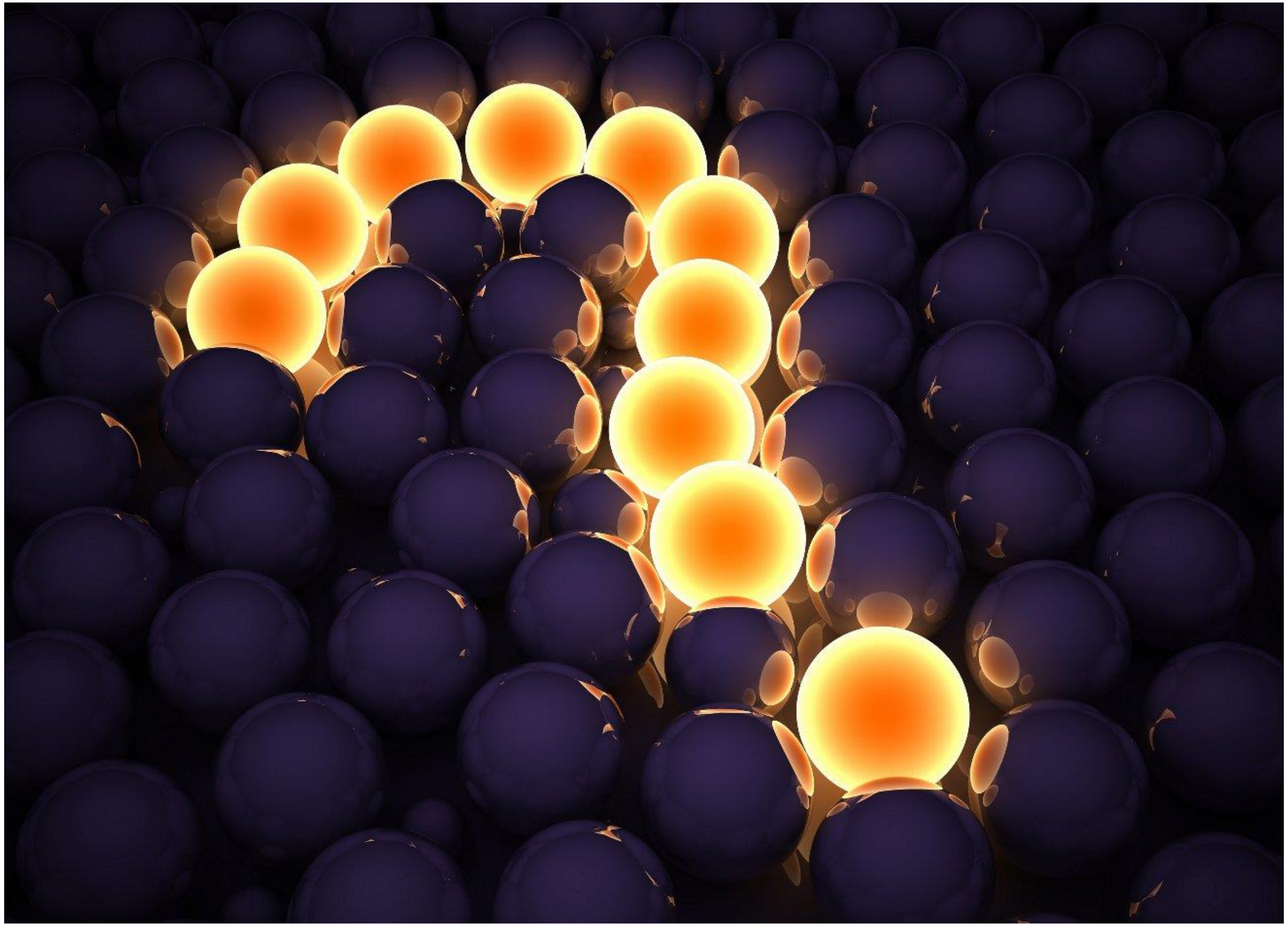
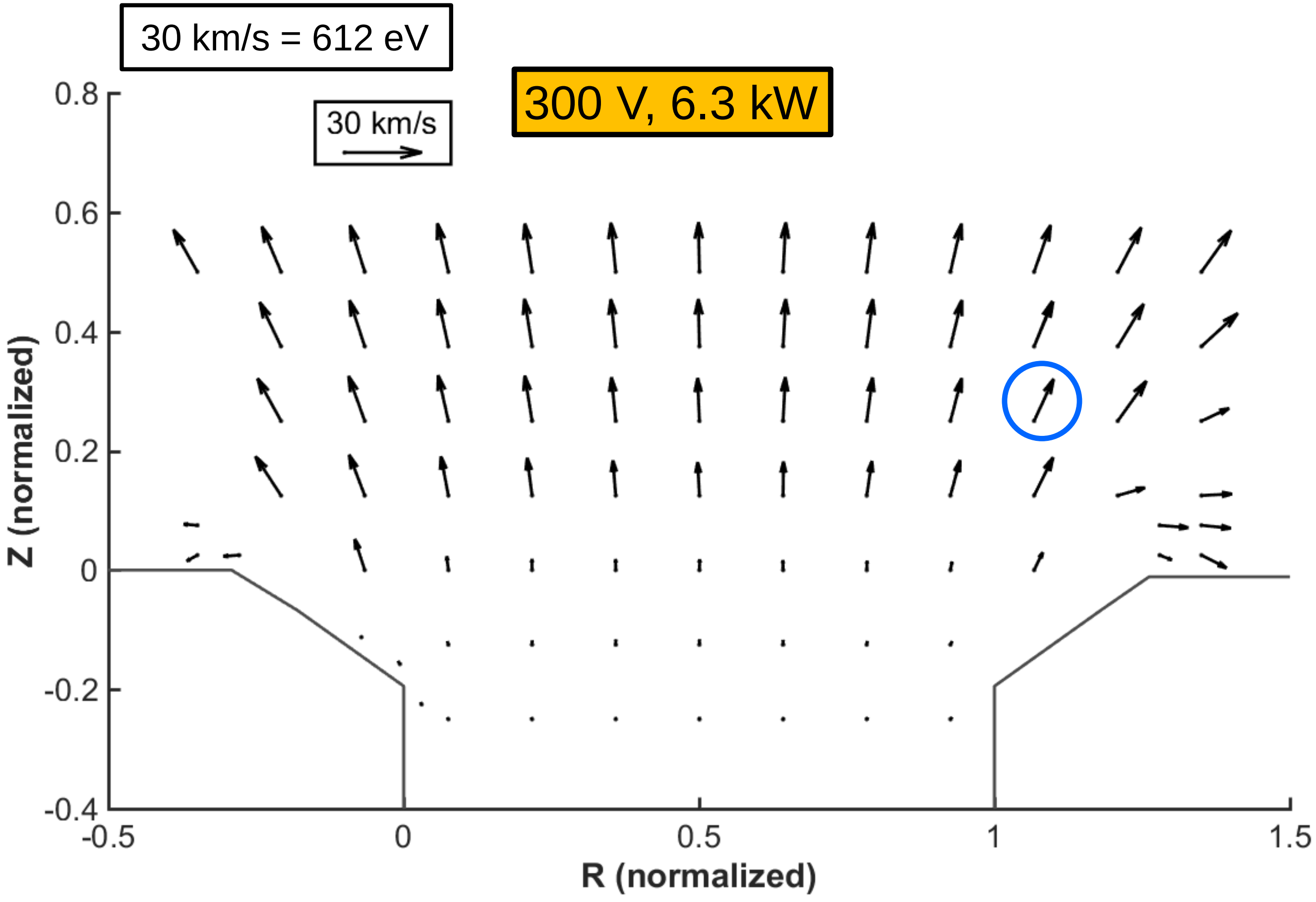
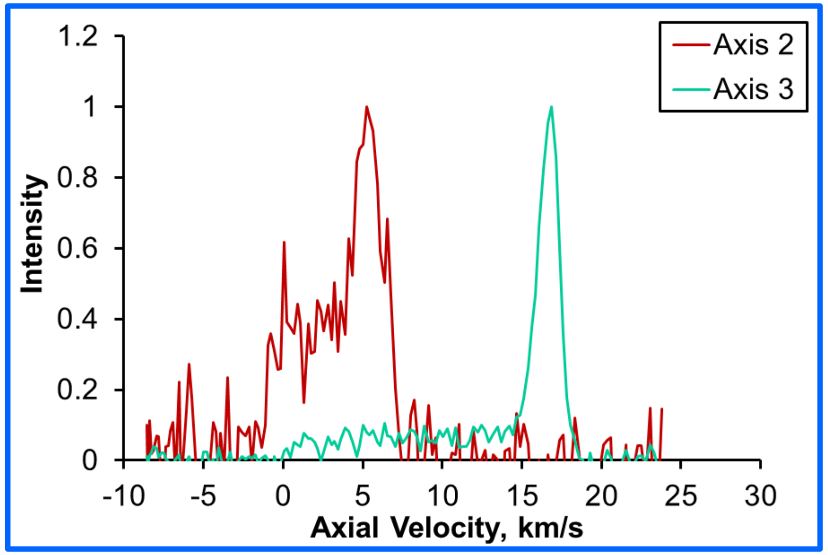
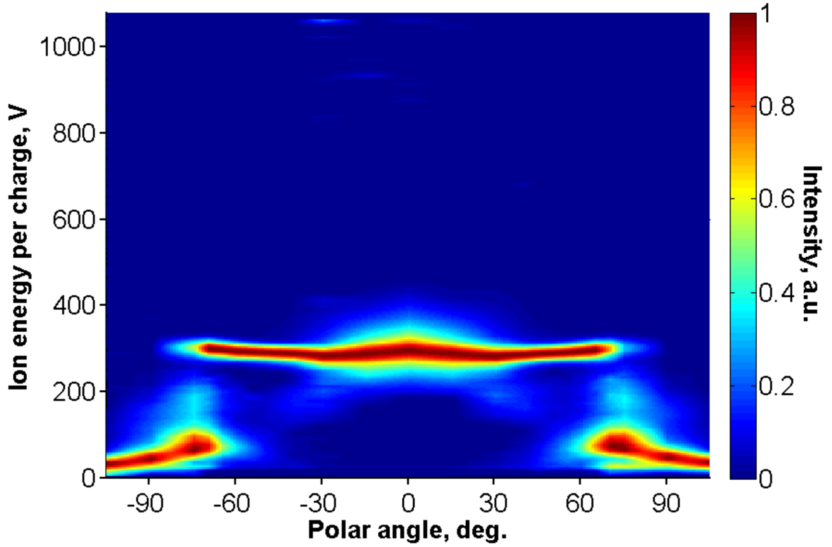


(Backup Slide) Results from AIAA-2018-4723: Discharge Channel Ion Velocity Vector: 300 V, 6.3 kW







(Backup Slide) Results from AIAA-2018-4723: Discharge Channel Ion Velocity Vector: 600 V, 12.5 kW