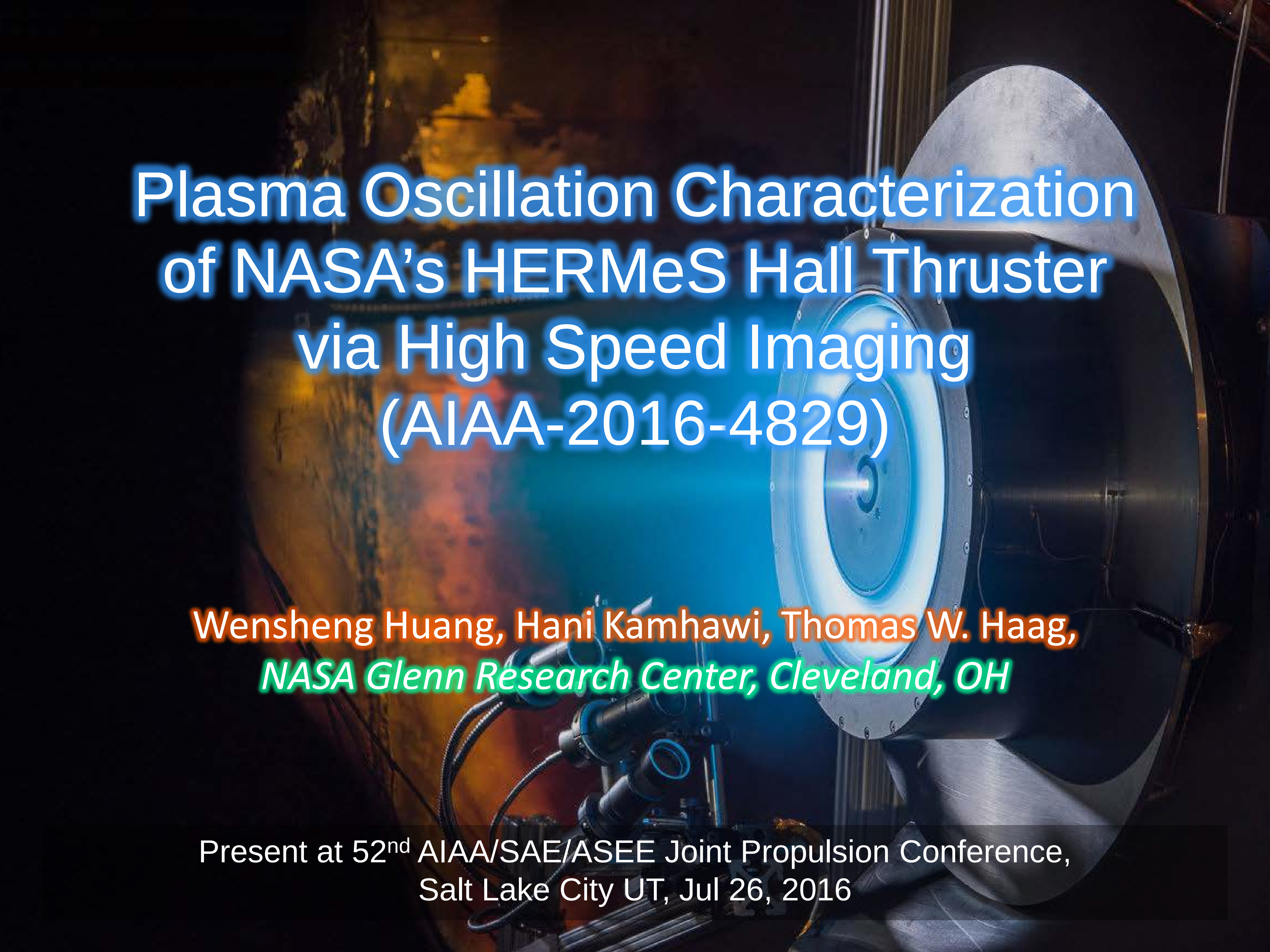


Plasma Oscillation Characterization of NASA's HERMeS Hall Thruster via High Speed Imaging (AIAA-2016-4829)

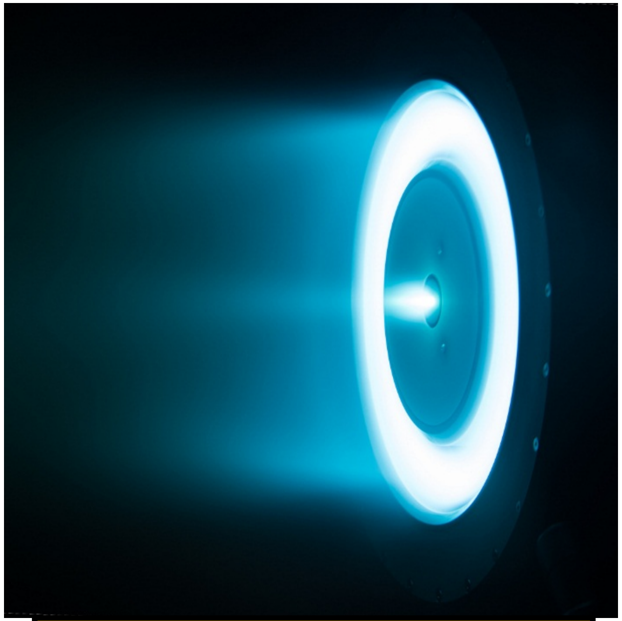
Wensheng Huang, Hani Kamhawi, Thomas W. Haag,

NASA Glenn Research Center, Cleveland, OH

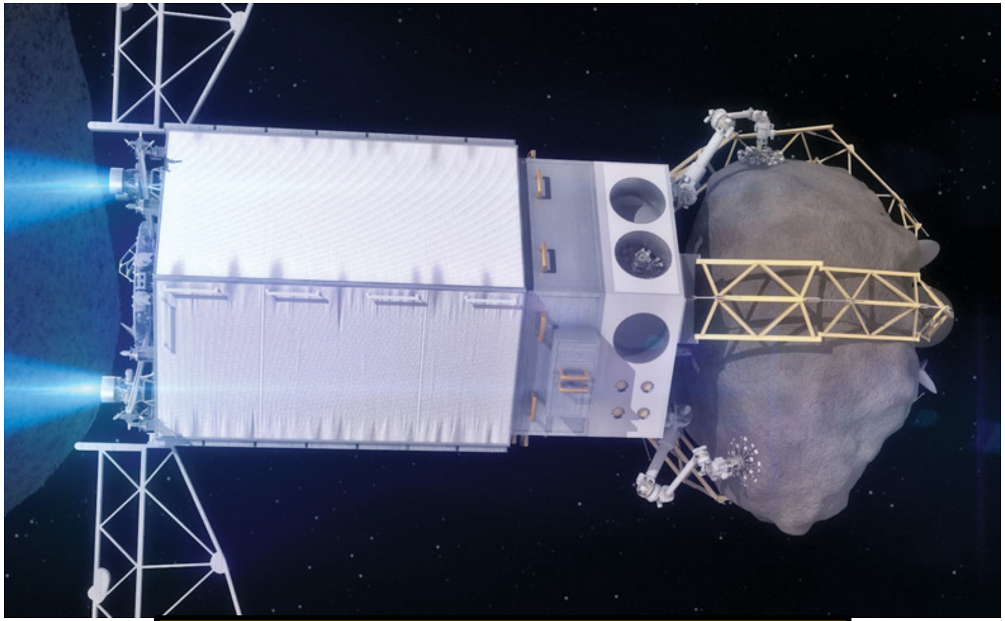
Present at 52nd AIAA/SAE/ASEE Joint Propulsion Conference,
Salt Lake City UT, Jul 26, 2016

Introduction

- A NASA GRC and JPL team is developing a 12.5-kW, magnetically-shielded Hall thruster, called Hall Effect Rocket with Magnetic Shielding (HERMeS)
- Mission concepts utilizing HERMeS Technology Demonstration Unit (TDU) include Solar Electric Propulsion (SEP) Technology Demonstration Mission (TDM), a concept of which is the Asteroid Redirect Robotic Mission (ARRM)
- This presentation is about three high-speed camera (HSC) studies during the Performance and Facility Effect Characterization Tests

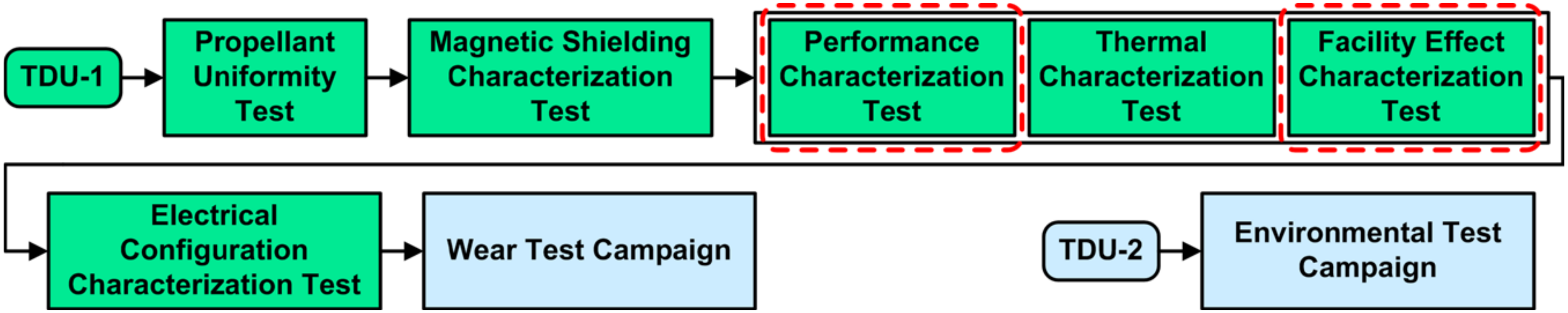


HERMeS TDU1 in operation



Notional Asteroid Redirect Vehicle

HERMeS Test Campaign Status

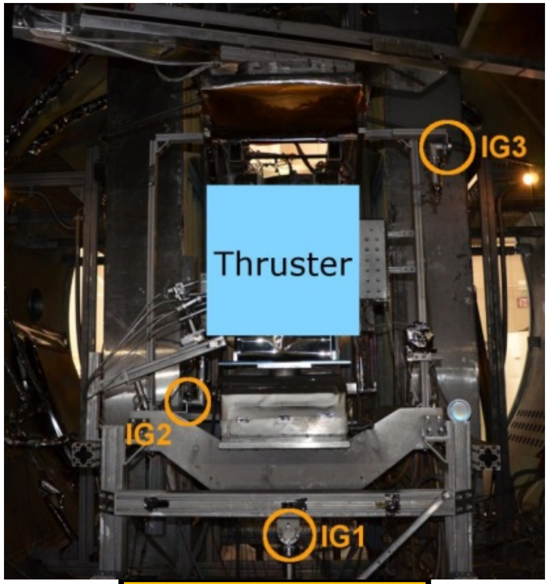


- Completed the following tests on TDU-1:
  - Propellant uniformity test (JANNAF-2015-3926, JANNAF-2015-3884)
  - Magnetic shielding characterization test (AIAA-2015-3919)
  - Performance characterization test (IEPC-2015-007)
  - Thermal characterization test (AIAA-2015-3920)
  - Facility effect characterization test (IEPC-2015-007, AIAA-2016-4828)
  - Electrical configuration characterization test (AIAA-2016-5027)
- Additional overview found in AIAA-2016-4824, 4825, 4826
- **Magnetic field strength variation study**
  - Determine nominal magnetic coil settings and field strength margins
- **Background pressure effect study**
  - Determine maximum background pressure for future testing
- **Cathode flow fraction study**
  - Determine cathode flow fraction (CFF) margins

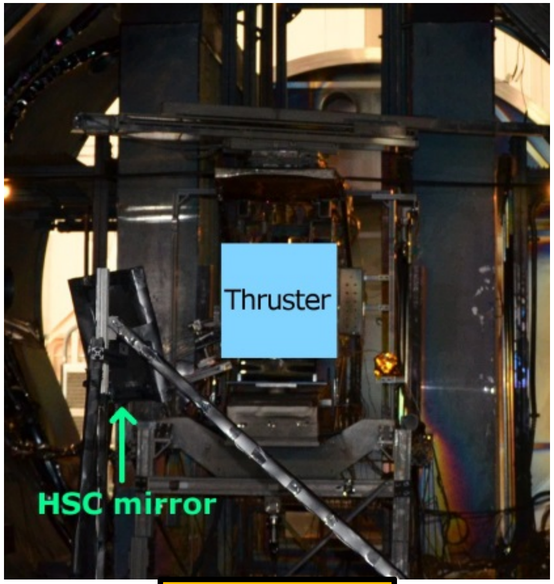
Test Setup: Test Article

- HERMeS TDU1 is a 12.5-kW, 3000 sec, magnetically-shielded Hall thruster
  - Demonstrated throttling from 0.6 to 12.5 kW, 2000 to 3000 sec
  - Magnetic shielding topology maintained throughout, magnetic field strength measured by peak radial magnetic field strength on channel centerline
  - Nominal magnetic field strength set for best performance while maintaining a reasonable margin against oscillation mode transition
  - Nominal 7% CFF
- 3 ion gauges near thruster
  - IG 2 & 3 are reference

Label	Discharge voltage, V	Discharge power, kW
300-4.7	300	4.7
300-9.4	300	9.4
400-12.5	400	12.5
500-12.5	500	12.5
600-12.5	600	12.5
700-12.5	700	12.5
800-9.7	800	9.7
800-12.5	800	12.5



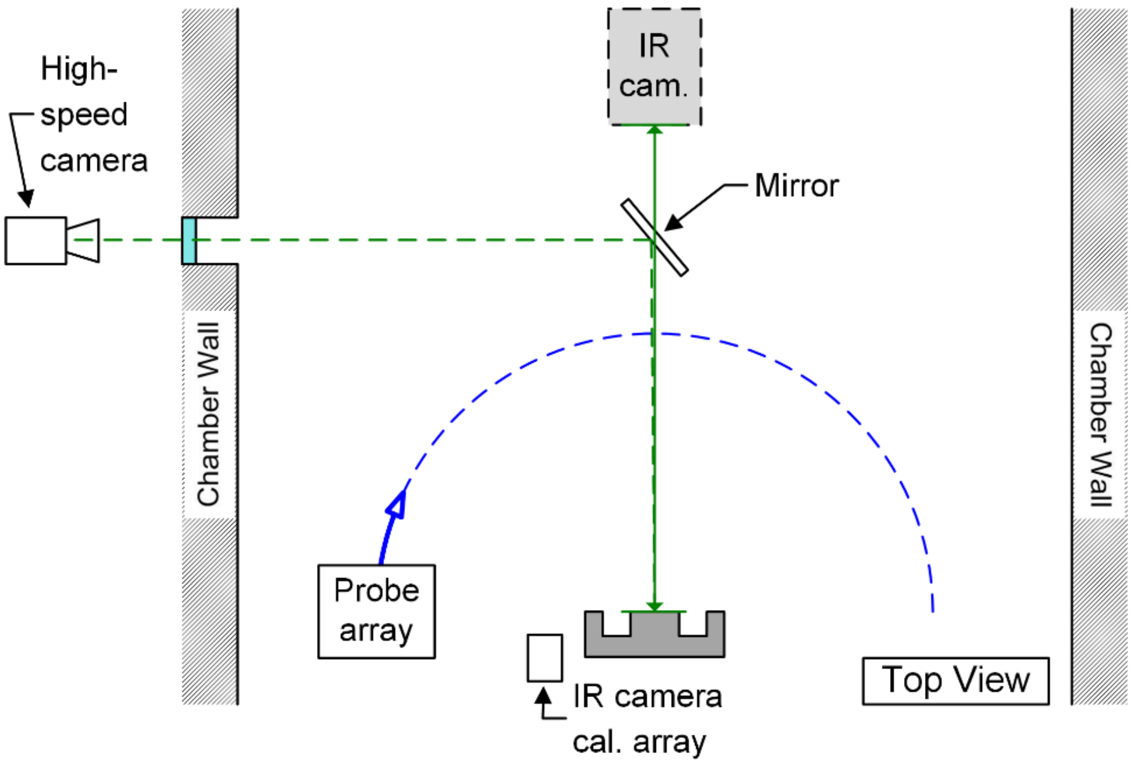
HERMeS TDU1



HSC mirror

Test Setup: Facility and Diagnostic

- GRC Vacuum Facility 5
  - Lowest pressure achieved by thruster: 3.0×10^{-6} to 6.3×10^{-6} Torr
- High-speed camera (HSC) views thruster through a mirror close to the firing axis
- Three current probes, one of which is electrically downstream of the electrical filter and upstream of the thruster
  - Current probe power spectra match HSC 1D power spectra

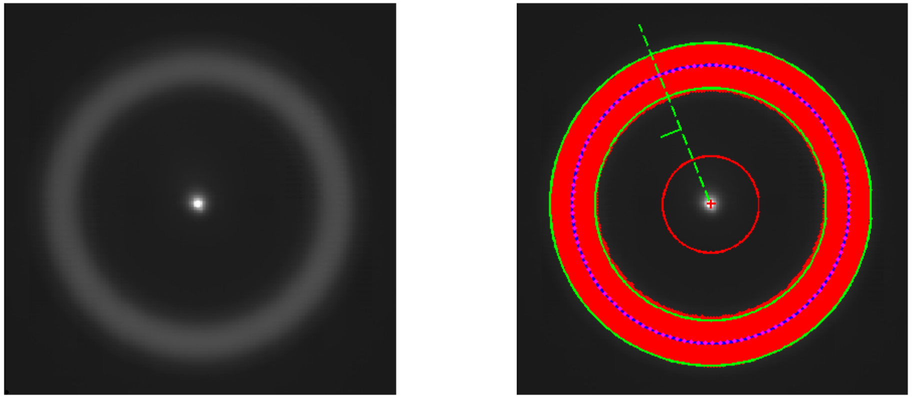


Test Procedure

- **Magnetic field strength variation study**
  - Background pressure set to lowest achievable
  - Cathode flow fraction set to 7%
  - Mass flow rate fixed at nominal
  - Magnetic field strength was varied
    - Reported strength normalized by maximum tested value
- **Background pressure effect study**
  - Magnetic field strength set to nominal
  - Cathode flow fraction set to 7%
  - Background pressure varied between lowest to 5 times lowest
    - Auxiliary Xe flow inject far downstream
  - Mass flow adjusted to maintain constant discharge power
- **Cathode flow fraction study**
  - Magnetic field strength set to nominal
  - Background pressure set to lowest achievable
  - Anode mass flow rate set to nominal
  - CFF varied from 4% to 9%

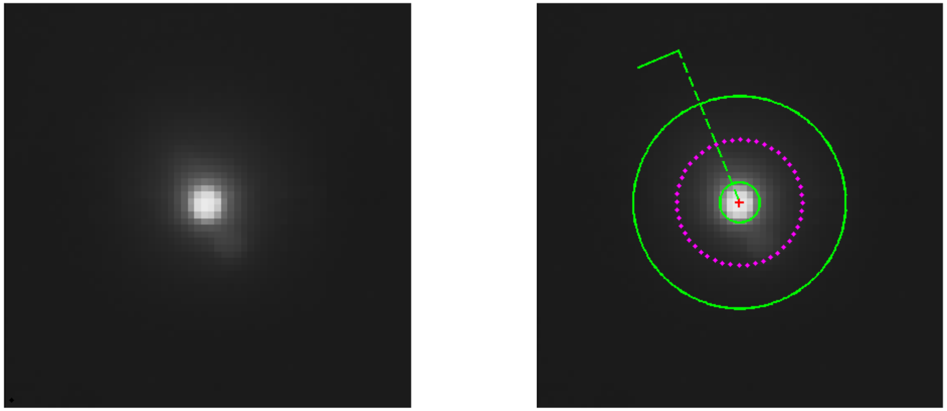
Data Reduction

- Thruster video capture discharge channel and cathode
  - Cathode excluded from analysis
- Cathode video capture only cathode
- Analysis steps:
  1. Create average image
  2. Define interrogation zones
  3. Apply spatial calibration and create 120 azimuthal bins
     - 48 bins for cathode video
  4. Create probability distribution function (PDF) plots
  5. Perform Fourier transform
  6. Plot results against control variables



Average image   Detection zone

Analysis of thruster video

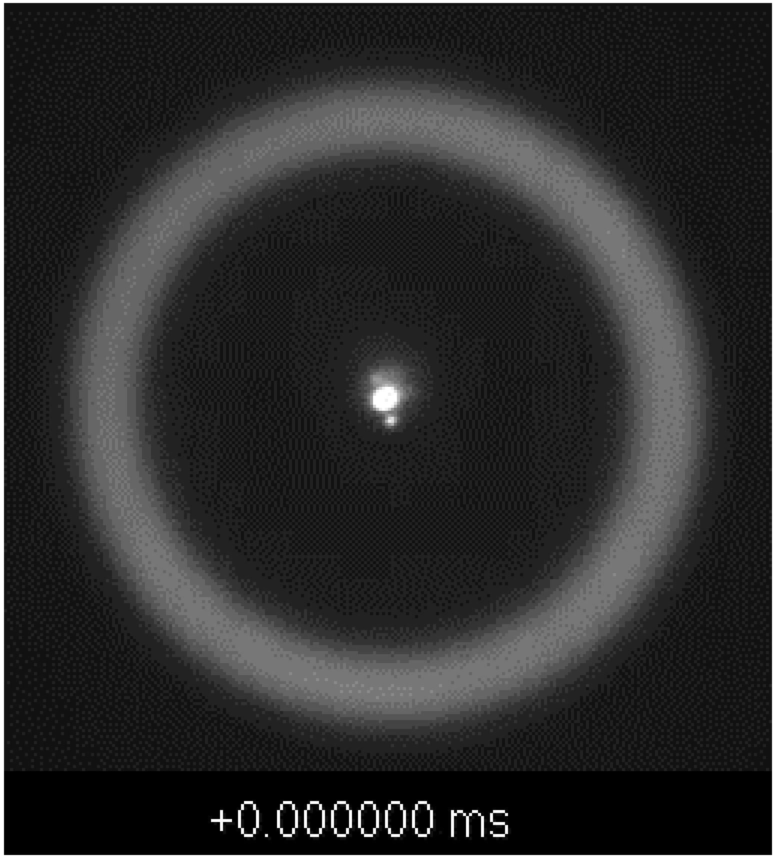


Average image   Detection zone

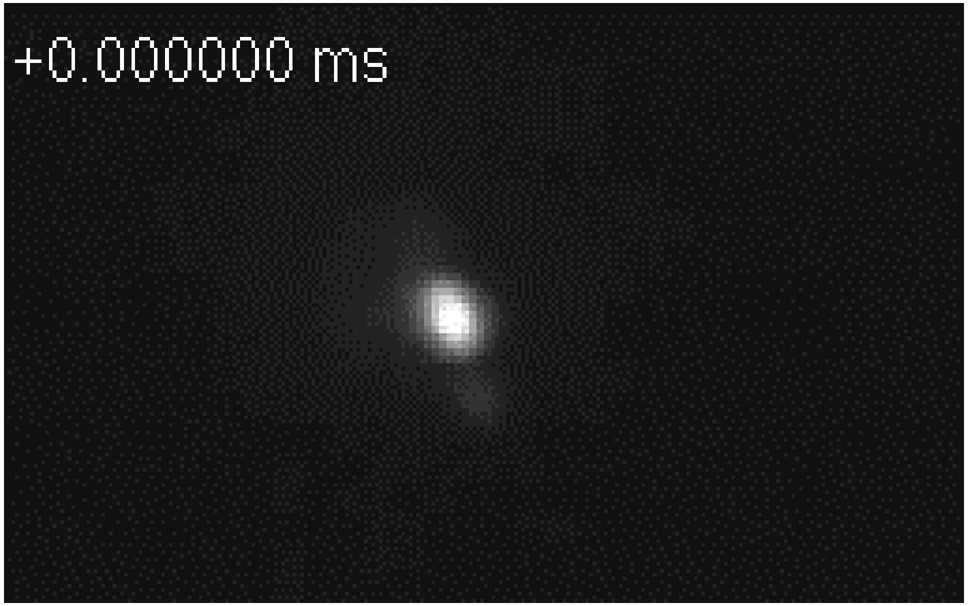
Analysis of cathode video

General Results

- Observed mostly global oscillation in discharge channel
  - Exception: spokes at 300 V, 4.7 kW, high magnetic field strength
- Gradient-driven mode observed at cathode



Thruster Video

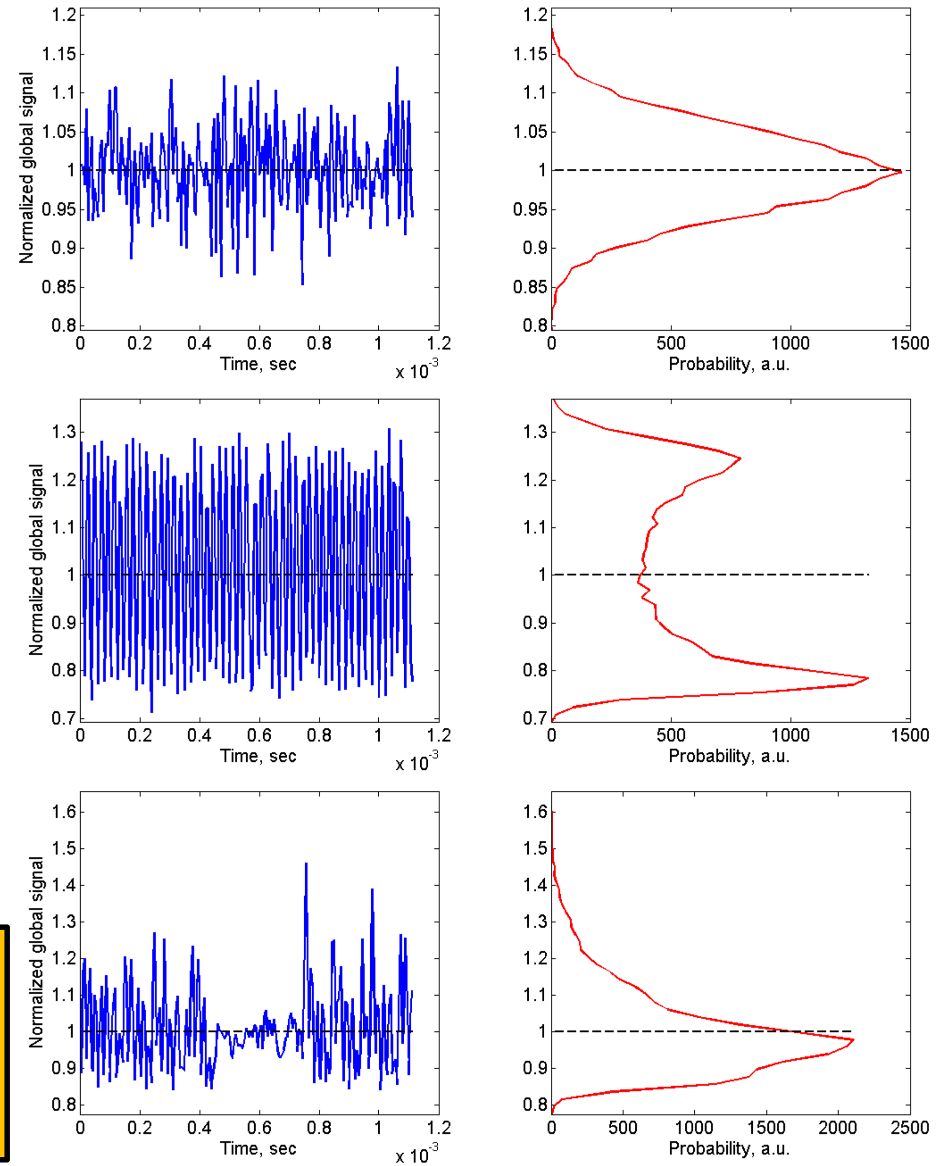


Cathode Video

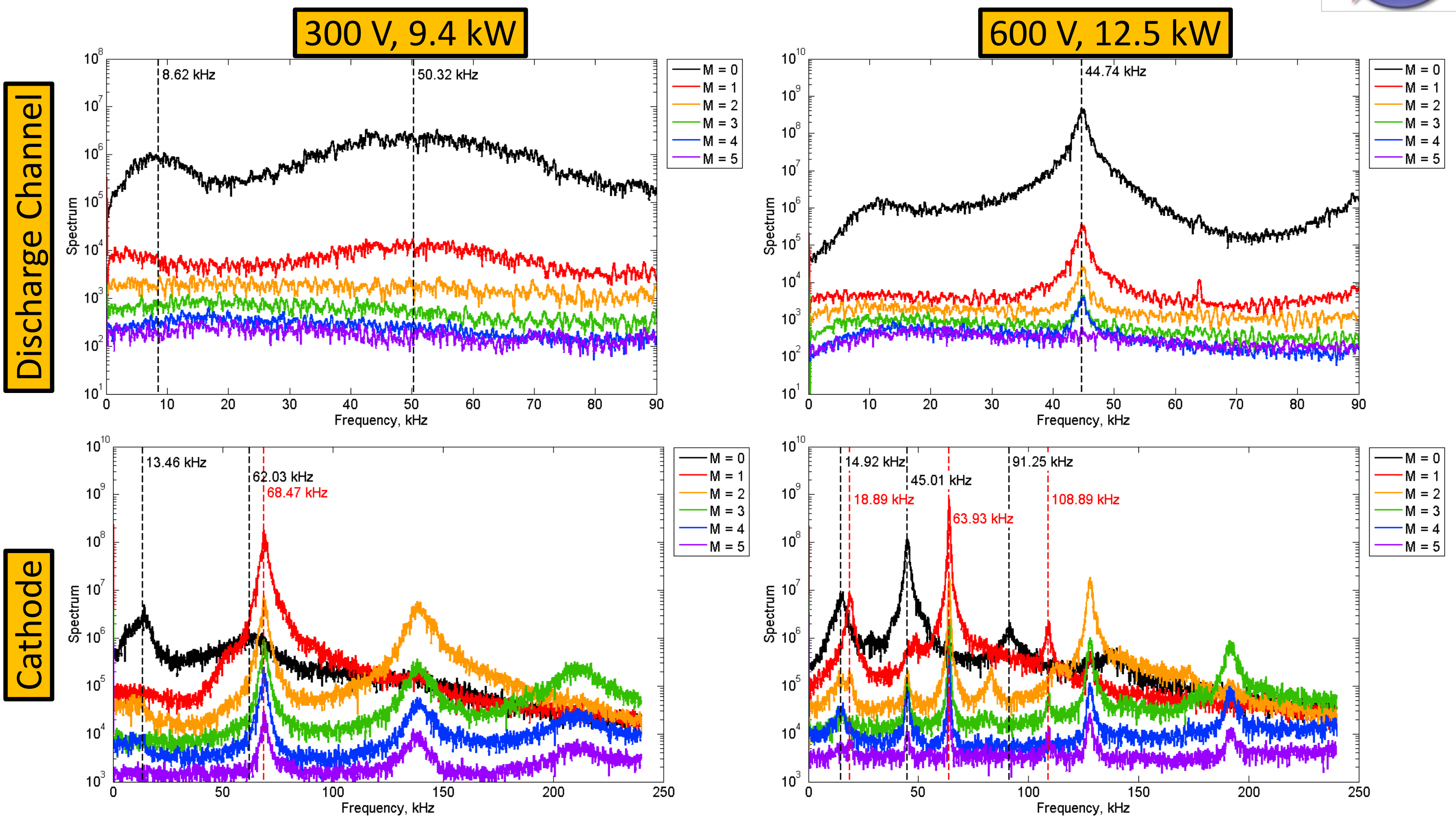
Oscillation Characteristics – PDF

- Binned data into light intensity PDFs to provide an additional way of characterizing oscillation modes
- PDFs for cathode video mostly matched PDFs for thruster video
  - Exception: when sinusoidal PDF found in discharge channel, cathode PDF tended to be skewed

▶ Examples of
Gaussian PDF (top)
Sinusoidal PDF (middle)
Skewed PDF (bottom)



Oscillation Characteristics – Power Spectra



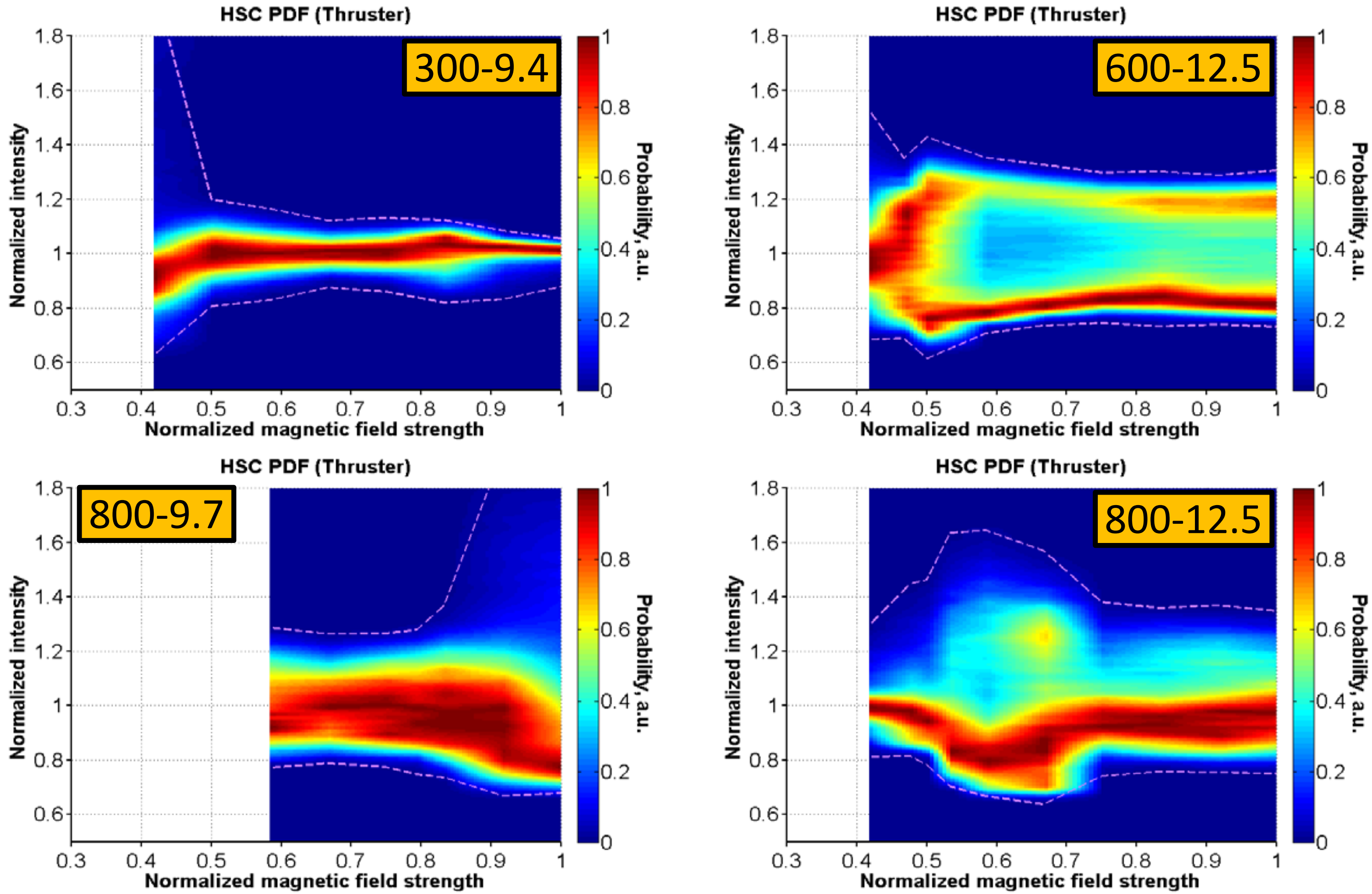
- Discharge channel: low and high frequency global oscillation
- Cathode: m = 0 similar to discharge channel;
  m = 1 show gradient-driven mode

Cross Correlation Study

	Gaussian	Skewed	Sinusoid
Low freq. only	10%	21%	2%
High freq. only	13%	3%	21%
Low and high freq.	10%	15%	5%

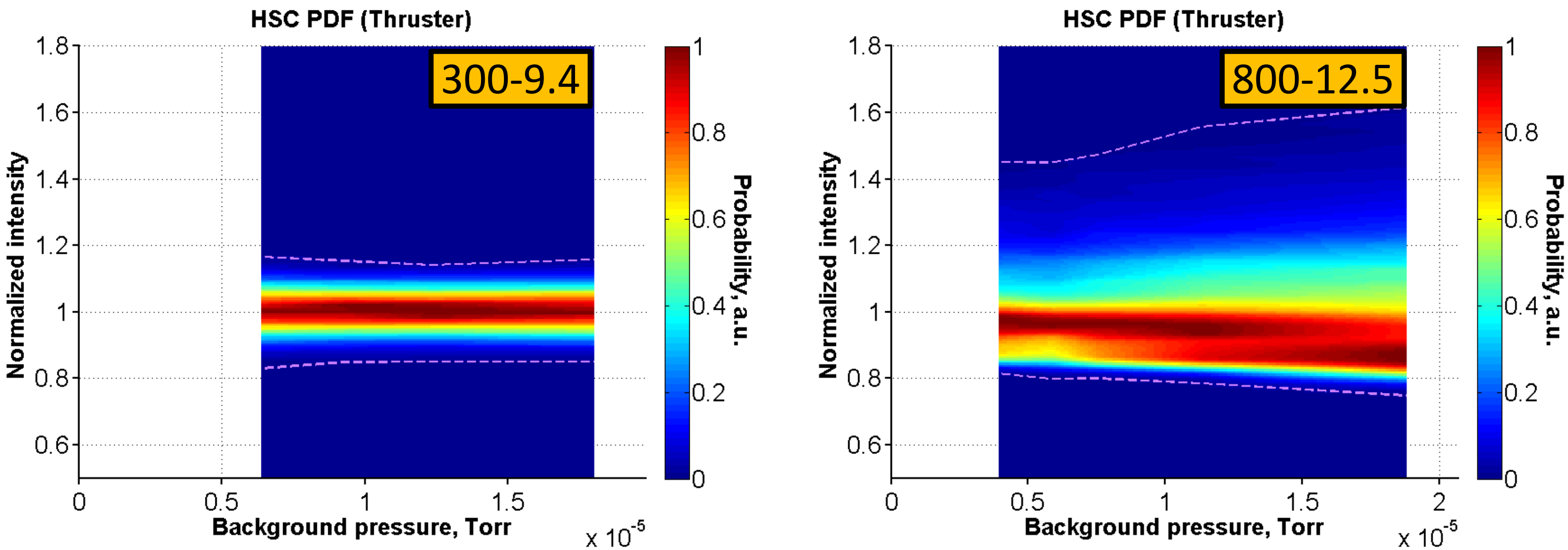
- Cross correlate to identify links between frequency and PDFs; help identify modes present
  - Sinusoidal PDFs ↔ high frequency oscillation; generally does not co-exist with low frequency modes
  - Skewed PDFs ↔ low frequency oscillation; can co-exit with high frequency modes
  - Both low and high frequency Gaussian modes were present
- Low frequency Gaussian and Skewed modes likely associated with breathing mode
  - Powerful damping (wall contact and turbulence) based on random processes → Gaussian-like distributions
- High frequency Sinusoidal mode may be unique to magnetic-shielding and/or central mounting of cathode
  - Reduced wall contact → reduced damping → enabled harmonic oscillation
- High frequency Gaussian mode may be related to breathing mode or high frequency Sinusoidal mode (need further investigation)

Magnetic Field Strength Variation Study



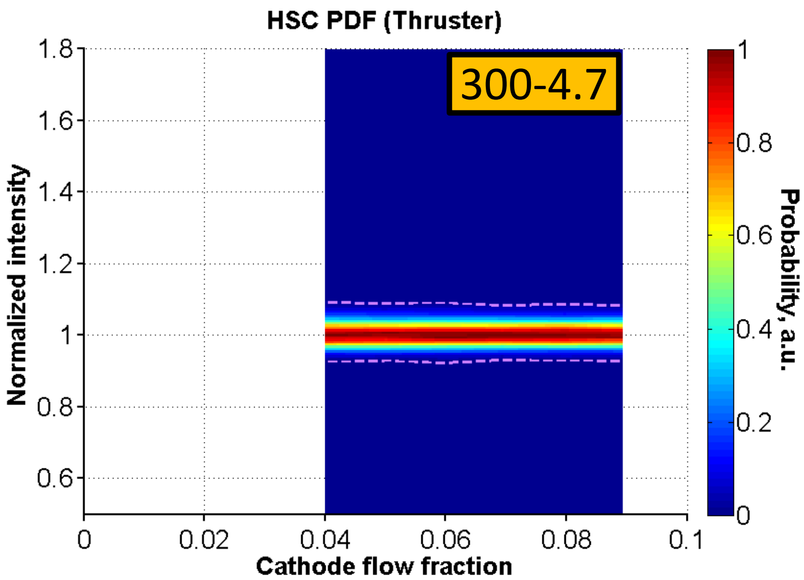
- Oscillation type and amplitude mostly constant over large range of field strength
- Moderate changes in frequency
  - Low freq.: 50% decrease in frequency with magnetic field strength
  - High freq.: increase and decrease observed, up to 50% change

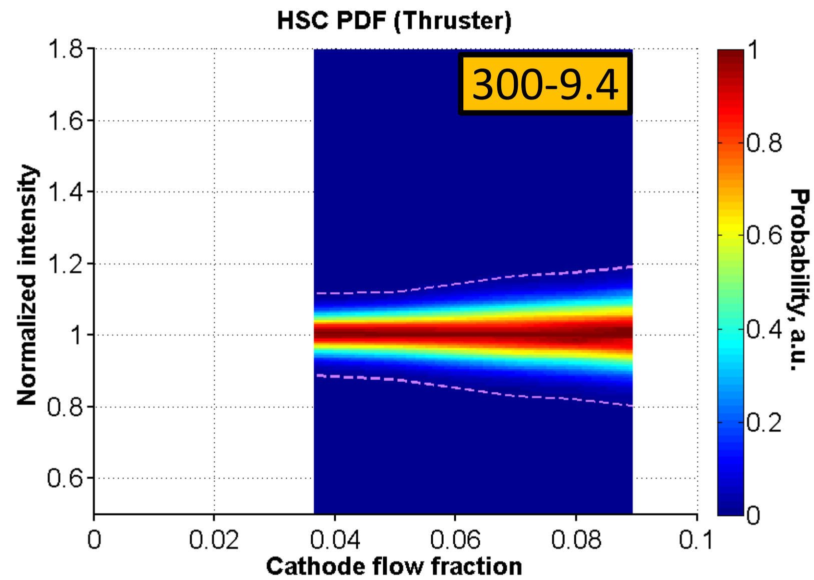
Background Pressure Effect Study



- Oscillation type and amplitude mostly constant over tested range of background pressure (up to 5 times lowest achieved)
  - Exception: 800-12.5 show widening PDF with increasing pressure
- Relatively small change in frequencies over tested range
  - Low freq.: 0-15% increase in frequency with pressure
  - High freq.: 10% decrease to 30% increase in frequency with pressure

Cathode Flow Fraction Study





- Oscillation type and amplitude mostly constant over tested range of CFF (4-9%, nominal 7%)
  - Exception: 300-9.4 show increasing amplitude with CFF
- Negligible change in frequencies for discharge channel
- Up to 25% decrease in frequency for cathode gradient-driven mode

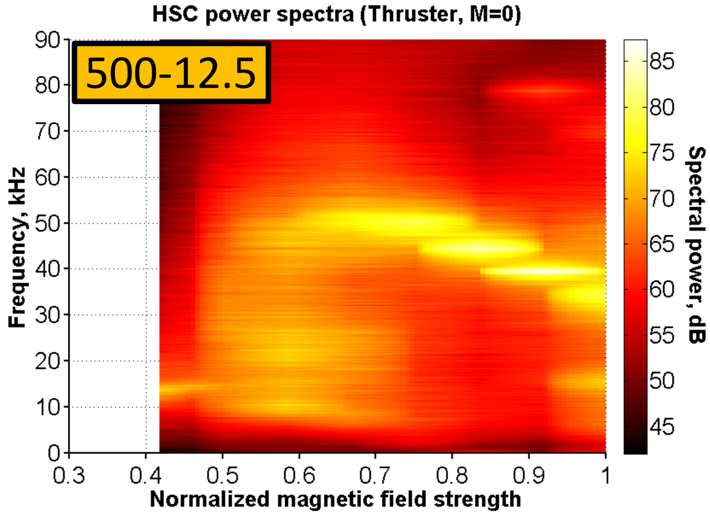
Trends for Specific Modes

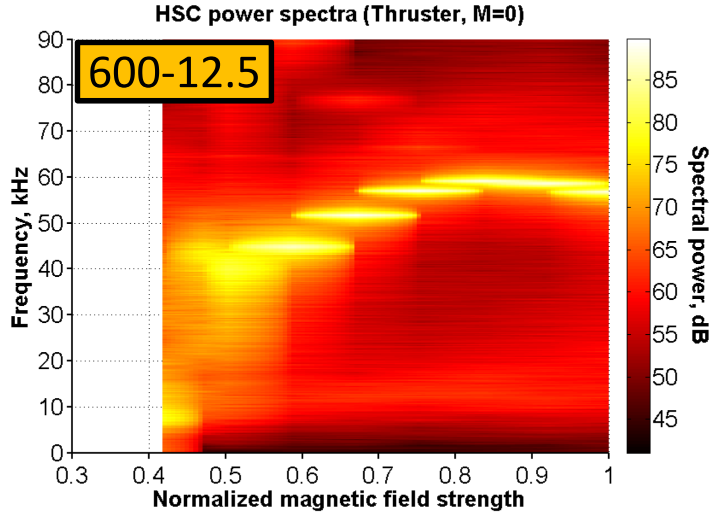
Mode	Trend with increasing magnetic field strength	Trend with increasing background pressure	Trend with increasing cathode flow fraction
Breathing	Low V_d: ω decreased High V_d: when present, ω constant or increased	Low V_d: ω slightly increased High V_d: ω mostly constant	Constant
Cathode Gradient-Driven	Low V_d: ω increased High V_d: ω constant	Constant	ω decreased
High-Freq. Sinusoidal	High V_d only; ω decreased for 500-12.5; ω increased then plateaued for 600-12.5 and 700-12.5	ω increased for 600-12.5; ω slightly decreased for 700-12.5	No example

- Breathing mode
  - Magnetic field ↑ → Ionization zone length ↑ → frequency ↓
  - Background pressure ↑ → Discharge recede into channel → frequency ↑
  - Constant with CFF, cathode neutrals far from discharge channel
- Cathode gradient-driven mode (match predictions by Jorns and Hofer*)
  - Magnetic field ↑ → frequency ↑
  - Constant with background pressure, centrally mounted cathode not sensitive to background pressure?
  - CFF ↑ → e-N collision frequency ↑ → local Te ↓ → frequency ↓

*Jorns and Hofer, Physics of Plasmas, Vol. 21, No. 5, p. 053512, 2014

The High-Frequency Sinusoidal Mode



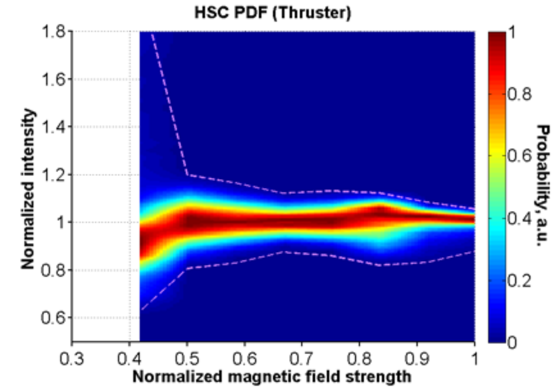


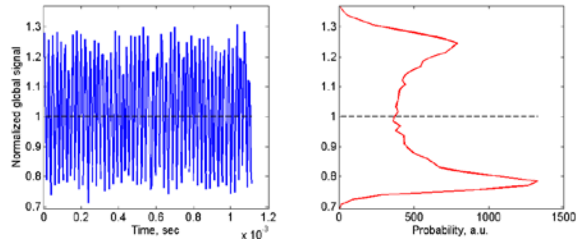
- High-frequency sinusoidal mode
  - Exhibited complex behavior with magnetic field, frequency appears to maximize at different magnetic field strength for different V_d
  - Exhibited conflicting trend with background pressure for the two test cases
  - Hypothesis 1: Excited by cathode gradient-driven mode
    - Frequencies and trends do not match
  - Hypothesis 2: A form of breathing mode
    - Different trends, especially with magnetic field; different PDFs
  - May be a new mode unique to magnetic shielding and/or central cathode
    - Reduced wall contact → reduced damping → enabled harmonic oscillation
  - Also may have simply gone unnoticed in Hall thrusters until now

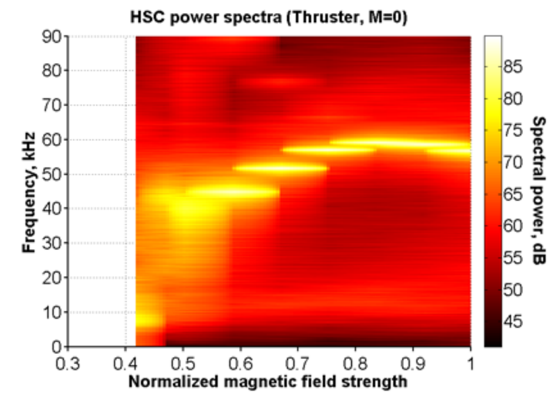
Conclusion

- Performed three high-speed camera studies
  - Magnetic field study showed large regions of stable operation
  - Background pressure study showed small and manageable variations
  - Cathode flow fraction study showed excellent margins on cathode flow rate

- Trends in breathing and gradient-driven modes in excellent agreement with theories
- New high-frequency sinusoidal mode discovered that does not match known modes
  - May be unique to magnetic shielding and/or central cathode
  - May also have been present in prior work but not been identified







Acknowledgment

- We thank,
  - NASA Space Technology Mission Directorate Solar Electric Propulsion Technology Demonstration Mission project for funding this work,
  - Daniel A. Herman and Richard R. Hofer for leading the effort,
  - The entire SEP TDM HERMeS team for work on the thruster,
  - Kevin L. Blake, George P. Jacynycz, Thomas A. Ralys, and Terrell J. Jensen for the fabrication and assembly of the test setup, and operation of the vacuum facility.

Question?

Backup chart –
Power spectra showing breathing mode