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Air Force Research Laboratory



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Electric Propulsion Test & Evaluation Methodologies for Plasma in the Environments of Space and Testing (EP TEMPEST)

***AFOSR T&E Program Review
13-17 April 2015***

Dr. Daniel L. Brown

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Aerospace Systems Directorate

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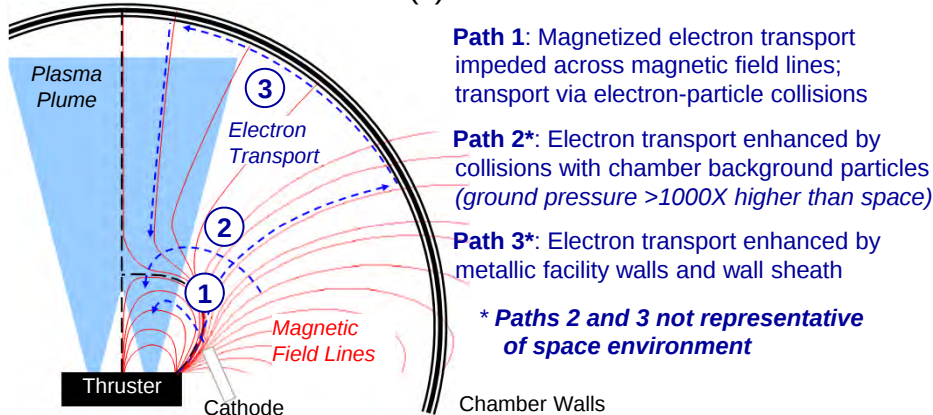
In-Space Electric Propulsion T&E for Plasma in the Space Environment

PI Dr. Daniel L. Brown AFRL/RQRS; TCTTA: Dr. Taylor Swanson AEDC

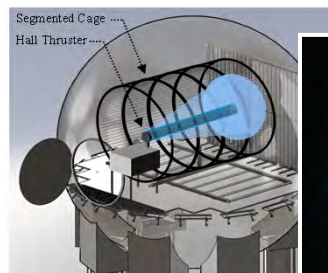


Hypothesis

Test chamber influences electron transport mechanism(s) from cathode to thruster anode



Cannot fully replicate space environment in ground T&E (higher pressure, metallic walls) → Impacts stability, performance, plume properties, life



LRIR Scientific Research



Transition Improved T&E Methods



PAYOFF - Pervasive Space Capability for Increased Payload

Purpose

Understand physics of ground vacuum chamber interactions on thruster plasma and electron dynamics in the exhaust plume

Determine cause of differences between ground T&E, computational simulations, and in-space operation

Approach

Study plume electron dynamics: Controlled chamber environment with advanced plasma diagnostics & high-speed imaging

Compare flight to ground T&E – Inform thruster operations on Class-D satellite (FalconSat-6, USAFA) for direct comparison with ground experiments → Unique V&V opportunity

Transition improved T&E methods to stakeholders

Scientific research & on-orbit data to advance T&E

Highlights

- Developed new T&E method to characterize thruster mode transitions and isolate pressure effects → transitioned to FalconSat-6, NASA, industry, and academia
- Correlated thruster plasma oscillations with transient ion flux impacting chamber surfaces → potential coupling mechanism
- Implemented advanced plasma probe system with high-speed imaging to study electron physics → unique AFRL capability

Stakeholders

- AEDC/TS, SMC/MC, AFRL/RQ, AFRL/RV and USAFA
- Industry, NASA



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Outline



- Technology Overview and Motivation
- Principles of Hall Thruster Operation and Facility Interactions
- T&E Lab Task Overview
- Facility Interaction Studies
 - High-Speed Imaging Results
 - Current-Voltage-Magnetic Field (I-V-B) Mapping
- Program Status and Transitions
- Summary and Conclusions



Electric Propulsion Mission Impact



Exploit Available On-Board Power for Enhanced In-Space Maneuverability

Technology Description

- Electric and magnetic fields to ionize and accelerate propellant to high velocity (>10,000 m/s)
- High efficiency, low propellant consumption
- Low thrust requires long firing time

Payoff

- Increase Delivered Payload to Orbit
- Rapid, Sustainable Repositioning and Station-keeping
- Smaller, Low-Cost Launch Vehicle
- Mission Enabling

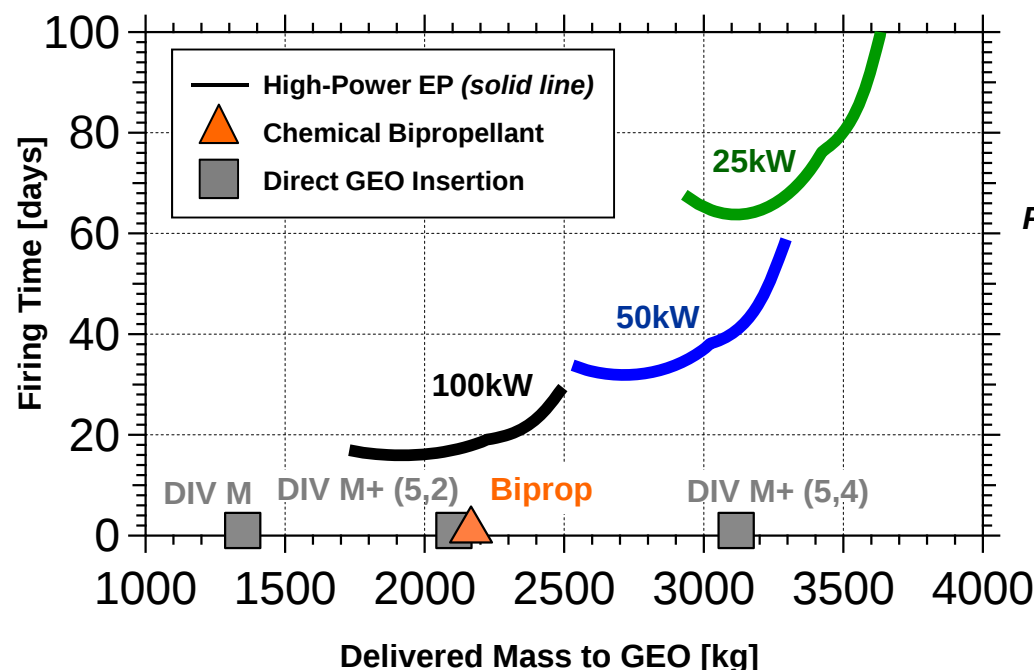
Mission Applications

- Advanced Extremely High Frequency (AEHF) Satellite Constellation
- Wideband Gap Filler (WGS)
- Commercial, NASA, others

Example: Improved GEO Payload Delivery

Delta IV Medium Launch Vehicle

$\Delta V \approx 5.8$ km/s, 4535 kg wet mass from GTO-GEO



Minimize Firing Time

High Payoff

Maximize Delivered Mass

High Payoff

Evolving Space Power Capabilities Driving Next Generation High-Power EP



The Big Picture



Motivation

Enhance Predictive T&E and M&S Capabilities for Space Operation and Satellite-Plume Interactions

Objectives

- Characterization of flight environment to support electric propulsion (EP) transition & integration to users
- In-space validation data for M&S and ground RDT&E
- Propulsion health monitoring

Technical Approach

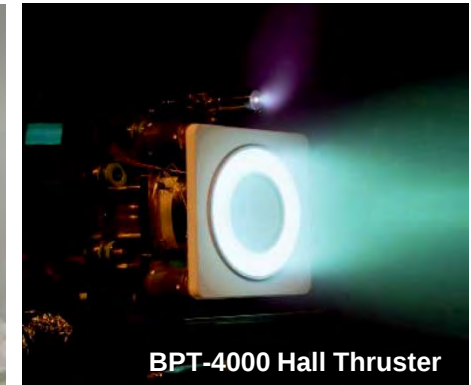
- Low-cost Size Weight and Power (SWAP) sensors
- Flight experiments
- In-house R&D on advanced diagnostics for EP systems

Challenges

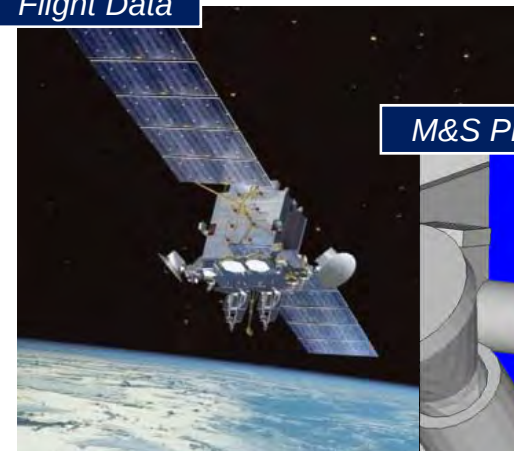
- Few opportunities for in-space measurements
- Cannot fully replicate space conditions in ground test environment
- Multi-scale / Multi-physics nature of problem

Coordination of Flight-M&S-Ground Experiments is Critical for EP Technology Infusion

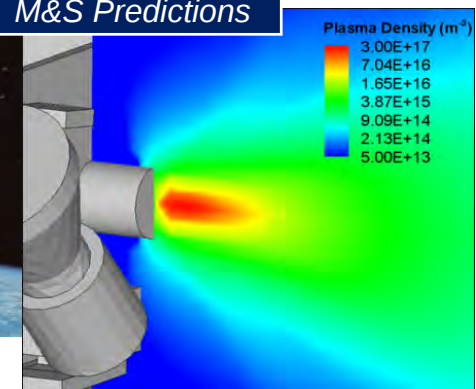
Ground Test



Flight Data



M&S Predictions

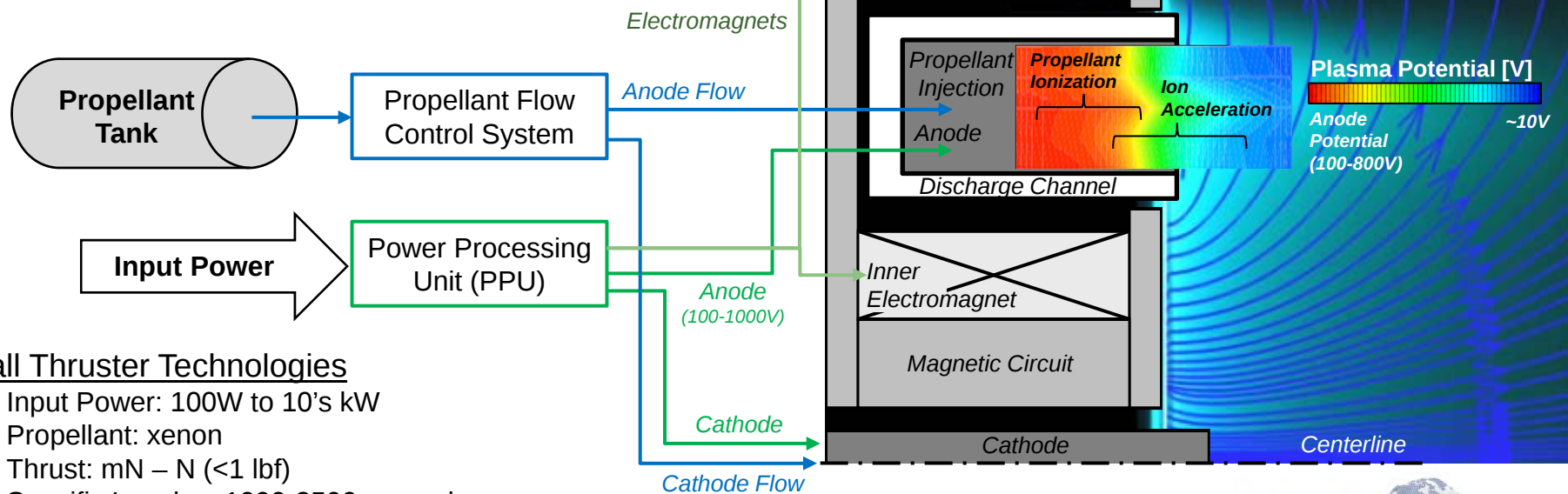
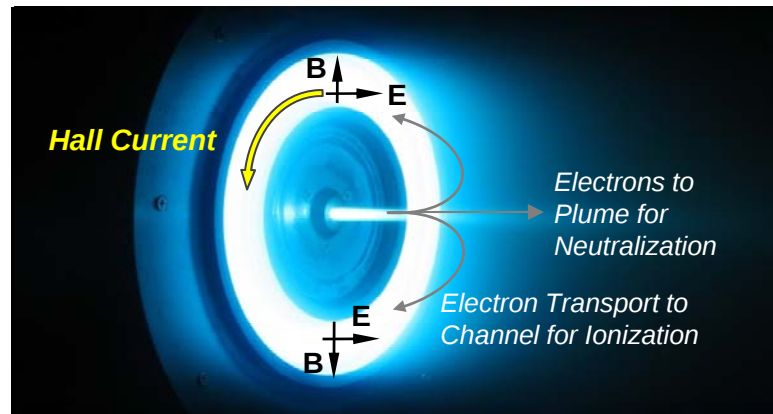


Images Courtesy of:
Ref. Fife, IEPC-2003-0136, 2003.
Ref. de Grys, AIAA-2003-4552, 2003.
Ref. AEHF Art, AEHF Homepage, www.lockheedmartin.com/





Principles of Hall Thruster Operation



Hall Thruster Technologies

Input Power: 100W to 10's kW

Propellant: xenon

Thrust: mN – N (<1 lbf)

Specific Impulse: 1000-3500 seconds

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Challenges of Hall Thruster RDT&E

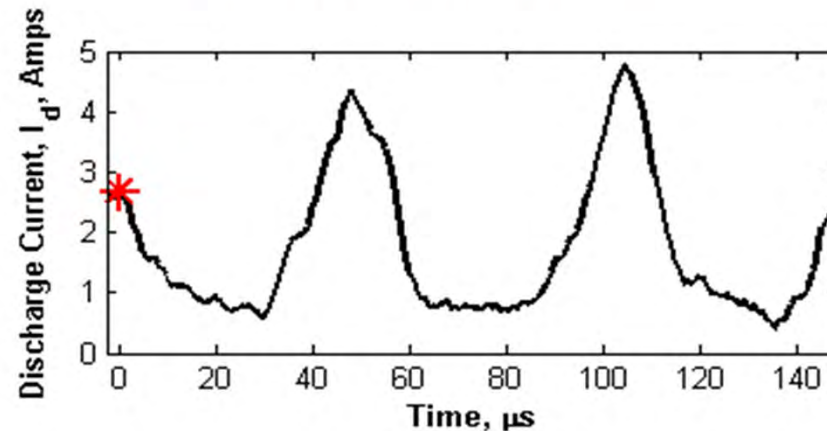
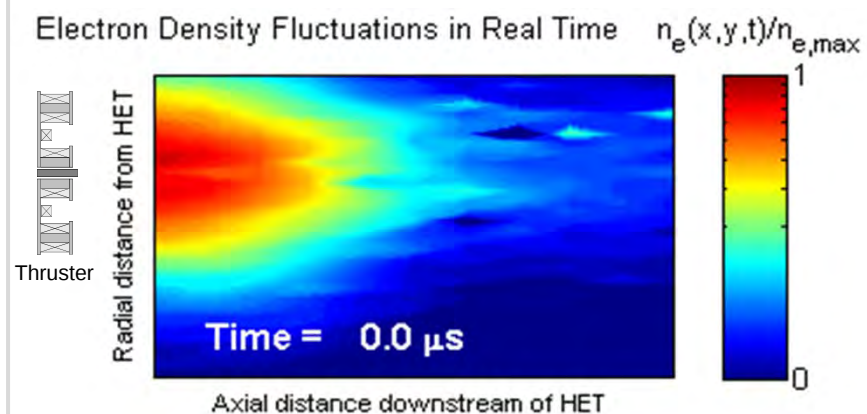
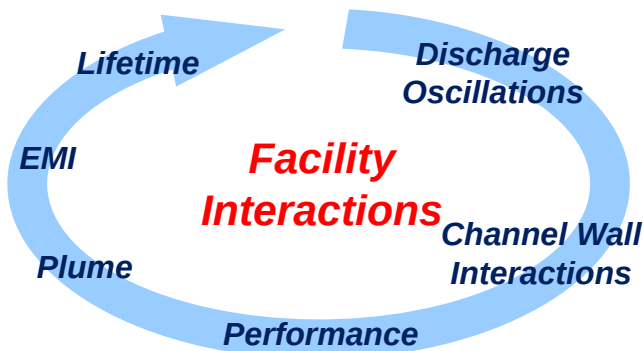
Multi-Scale / Multi-Physics Problem



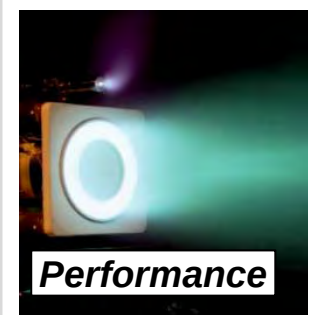
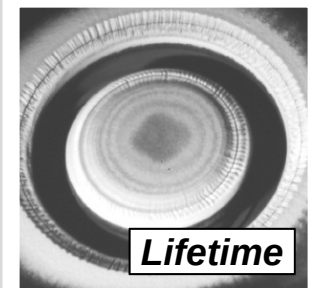
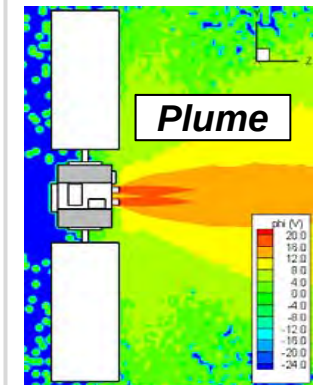
Multi-scale / Multi-physics Problem

- Particle Mass (5 Orders of Magnitude)
- Plasma Discharge (ns-ms, μ m-cm)
- S/C Plume Interactions (ms-hrs, cm-m)
- Mission Time-Scales (hours-years)

Complex Thruster Physics at Smallest Spatial/Temporal Scales Impact Macro-Level Characteristics



Ref. Lobbia, R. B., "A Time-Resolved Investigation of the Hall Thruster Breathing Mode," Ph.D. Dissertation, University of Michigan, Ann Arbor, MI, 2010.



Thruster Behavior is Complex $\rightarrow$ Further Complicated by Differences Between Ground Test and Space Environment

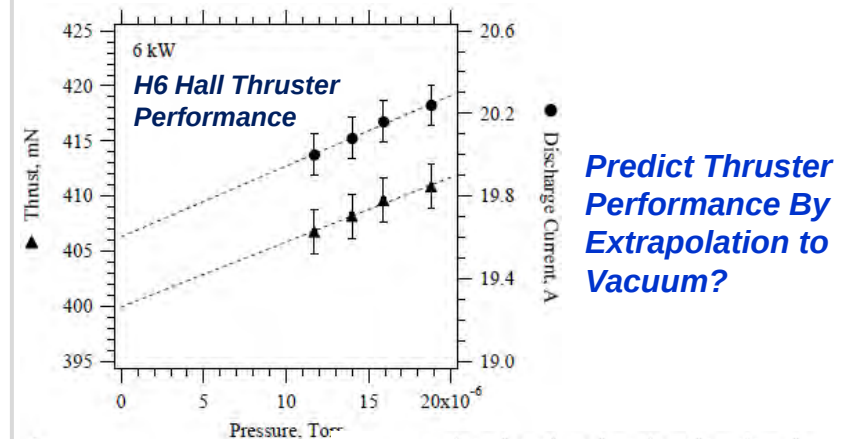


Hall Thruster Facility Effects

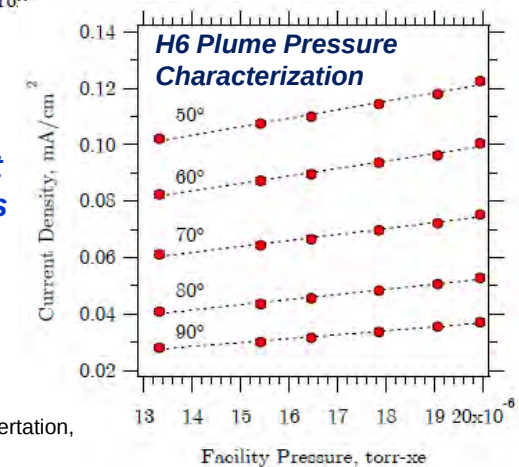


World-class EP RDT&E vacuum chambers cannot fully replicate on-orbit conditions

- Chamber pressure is many orders of magnitude higher than space → *artificial plume expansion and thruster ingestion of background particles (i.e. free propellant)*
- Presence of test chamber walls → *chamber material back-sputtering on thruster surfaces, chamber wall sheath may influence thruster-plasma “circuit”*



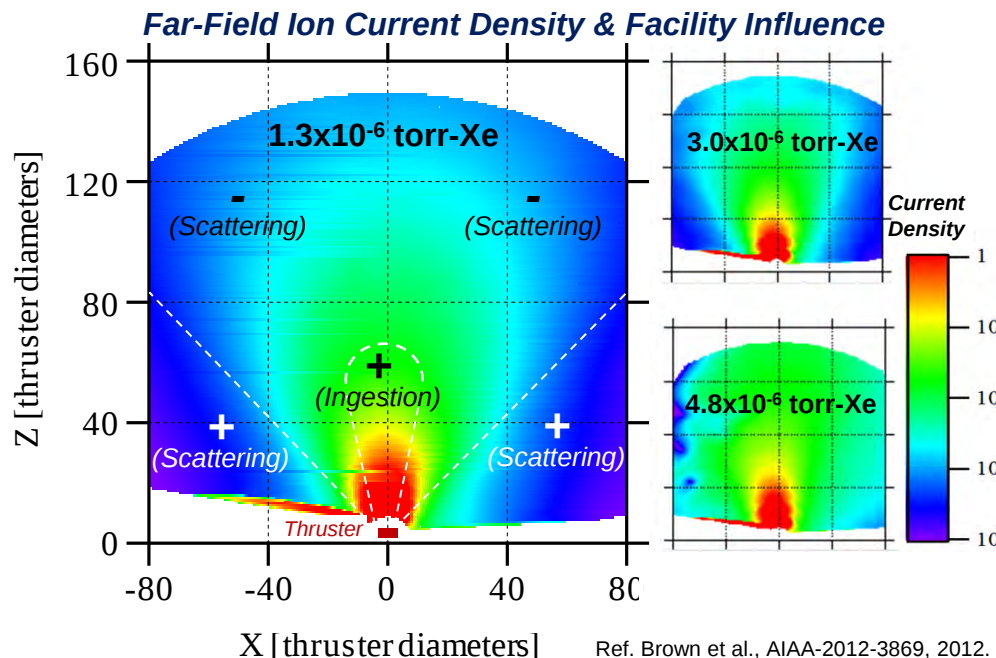
Predict Spacecraft Plume Interactions By Extrapolation to Vacuum?



Ref. Reid, B. M., Ph.D. Dissertation, U. of Michigan, 2009.

Facility Interactions are Unavoidable

**Effects on Plumes are Well-Characterized....
Thruster Interactions are More Complex**





Current T&E Approach



Signs of chamber effects on thruster performance, plume, and stability observed in U.S. since 1990s

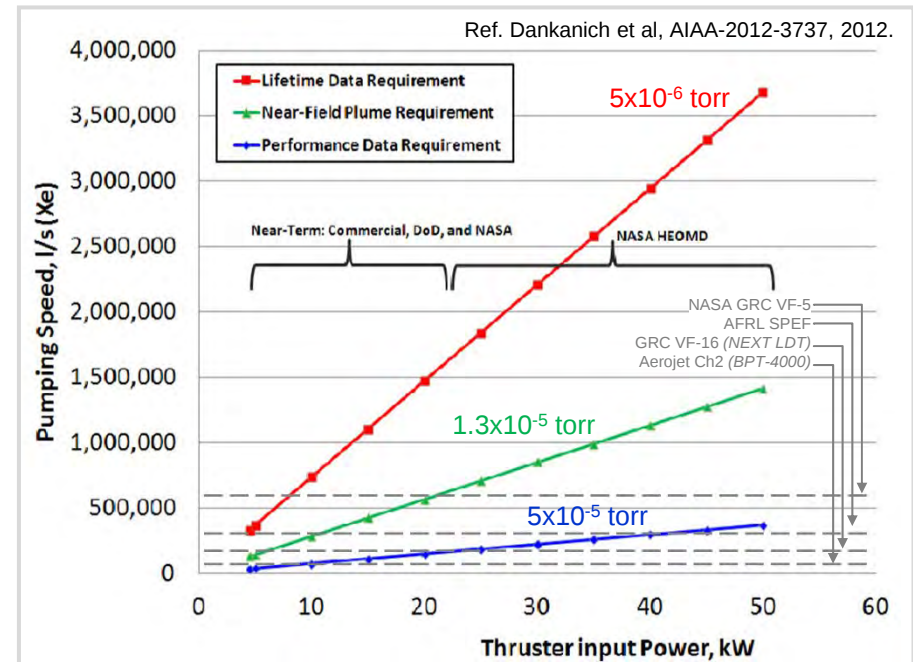
- RDT&E solution = Minimize chamber pressure
 - $<5 \times 10^{-5}$ torr for performance
 - $<1.3 \times 10^{-5}$ torr for plume measurements $<1.2\text{m}$
 - $<5 \times 10^{-6}$ torr residual for lifetime evaluation to maintain sputter return rate $<0.1\text{\AA/s}$
- Typically metallic chamber walls, low sputter surfaces

Conventional T&E methods unchanged in 20+ years

First flown on-orbit in 1972 (USSR); hundreds of SPT-100 Hall thrusters used successfully on commercial satellites

Modern designs are pushing operational envelope

- EP trending to higher power, higher performance, longer lifetime
 - Thruster power reaching limits of facility pumping for low pressure criterion
 - Longer lifetime requirements increase cost, extend qualification schedule
- Empirical designs based on ground data; limited data in space environment



Existing T&E Inconsistent with Modern Understanding of Hall Thruster Behavior and Facility Interactions

Critical to Minimize Risk and Mature New Capabilities



EP TEMPEST (Lab Task, FY14-FY16)

Program Goals and Objectives



Title: Electric Propulsion Test and Evaluation Methodologies for Plasma in the Environments of Space and Testing (EP TEMPEST)

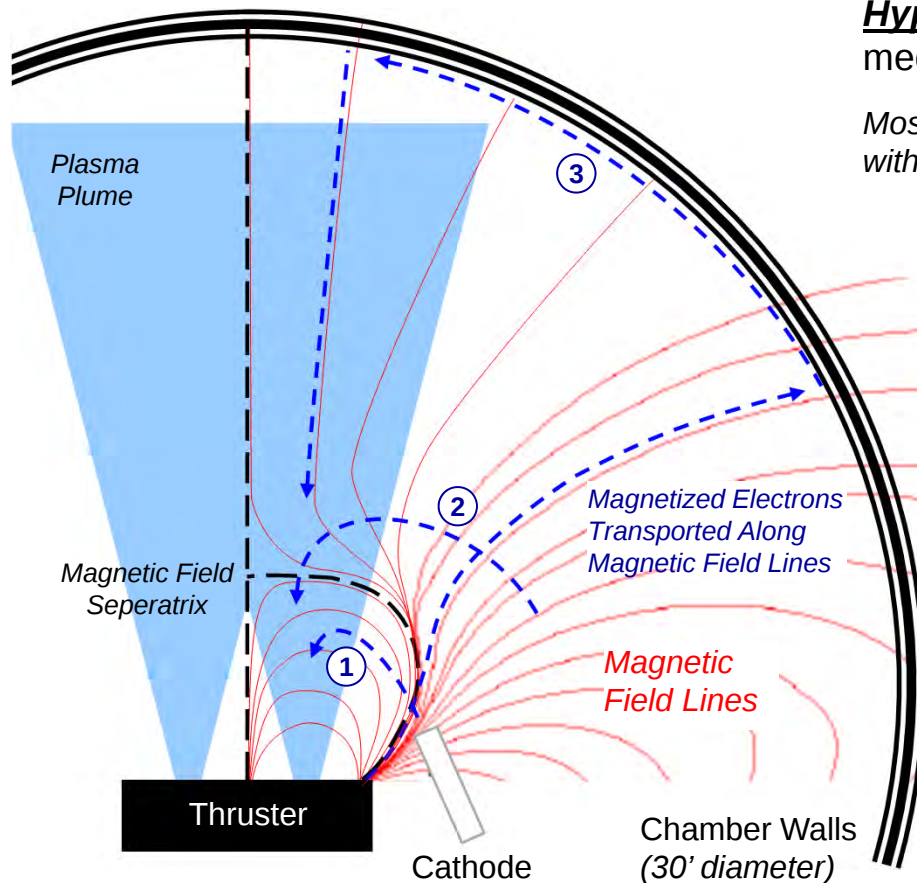
Goal: Investigate the impact of ground facility interactions on Hall thruster plasmadynamic behavior, with a goal to **innovate RDT&E methodologies that will enable accurate prediction of thruster stability and performance in the space environment.**

- Objective 1. **Investigate facility interactions** on Hall thruster plasma to understand the plasmadynamic processes and electron transport mechanisms driving differences in stability behavior between ground testing, computational simulations, and in-space operation.
- Objective 2. **Develop ground test methodologies** to predict in-space plasma stability and performance.
- Objective 3. **Validate test methodologies** through comparison of ground-based predictions with flight data from a low-power Hall thruster experiment on FalconSat-6.

Transition: Successful completion enables transition of EP T&E methodologies to Arnold Engineering Development Complex (AEDC), Space and Missile Systems Center (SMC), NASA, and industry



Hypothesis



Hypothesis: Test chamber influences electron transport mechanism(s) from cathode to thruster channel

Most theories/experiments/simulations focus on electron mobility within discharge channel

Path 1: Magnetized electron transport impeded across magnetic field lines; transport mechanism(s) not determined

Path 2*: Electron transport enhanced by collisions with chamber background particles (*ground pressure >1000X higher than space*)

Path 3*: Electron transport enhanced by metallic facility walls and wall sheath

*** Paths 2 and 3 not representative of space environment**

Cannot fully replicate space environment in ground T&E (higher pressure, metallic walls)

Impacts stability, performance, plume properties, life

ANALOGY → Think of path between cathode and anode as resistor network

- Increasing “resistance” in an area increases electric field in that area
- Ideally, all “resistance” occurs in thruster channel and minimal electrons travel to anode for ionization

Resistance (Mobility⁻¹) ~ $B^2/v \sim B^2/n_n$

where v = collision freq.

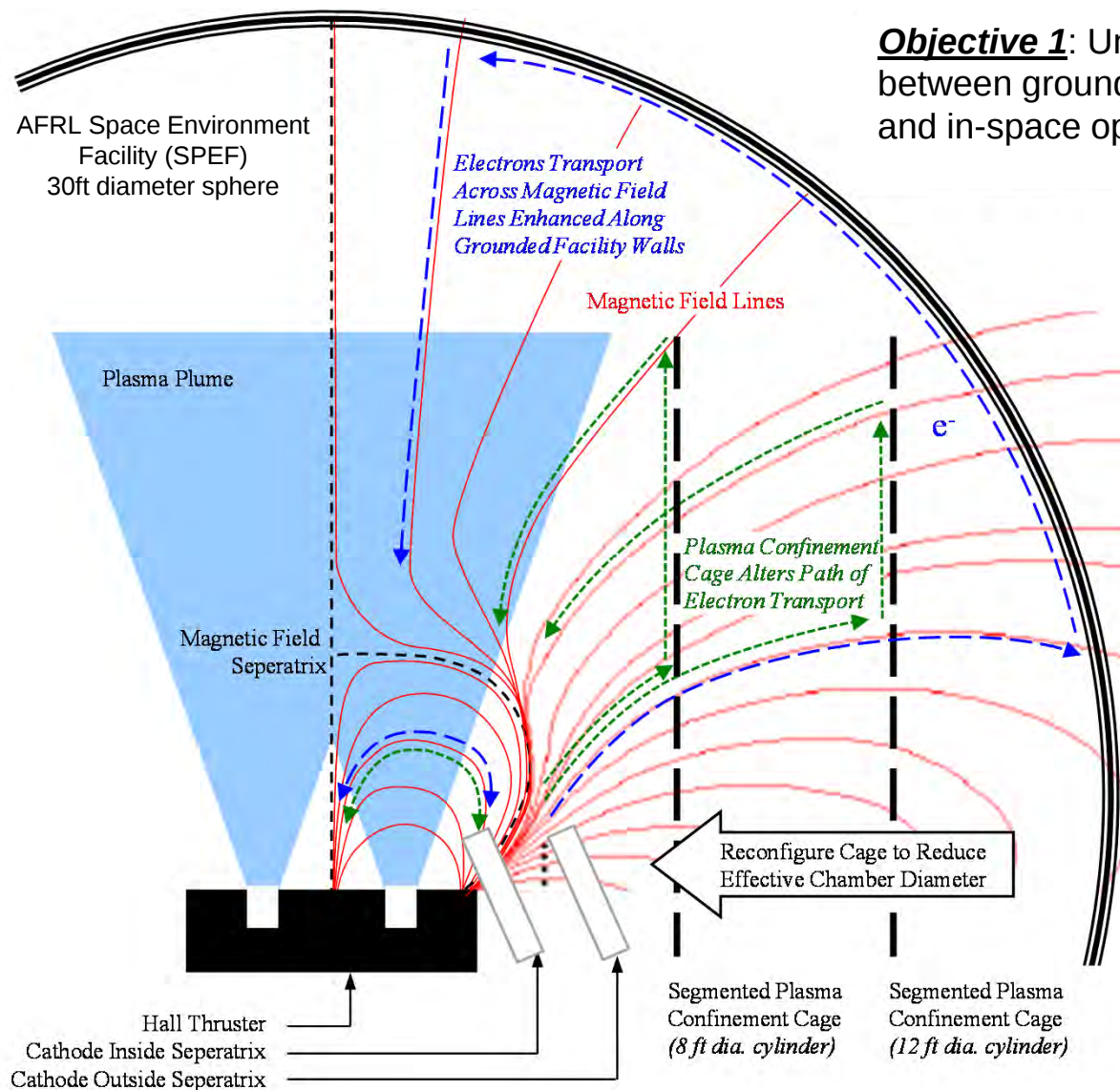
n_n = neutral density

B = Magnetic Field



Objective 1

Plume Electron Mobility and Facility Interaction Studies



Objective 1: Understand physics behind differences between ground testing, computational simulations, and in-space operation.

Understand electron mobility from cathode to channel

- Utilize state-of-the-art (SOTA) high-speed imaging and time-resolved diagnostics to study local plasma behavior
- Leverage studies of high frequency plasma behavior near channel exit (AFRL and U. of Michigan)

Systematic characterization and control of chamber environment (*wall sheaths, pressure*)

- Instrument plasma confinement cage and exposed surfaces to monitor path of current in plume
- Study with grounded, floating, and biased surfaces to evaluate differences between ground and space

Leverage AFRL M&S capabilities and AFOSR EP research efforts



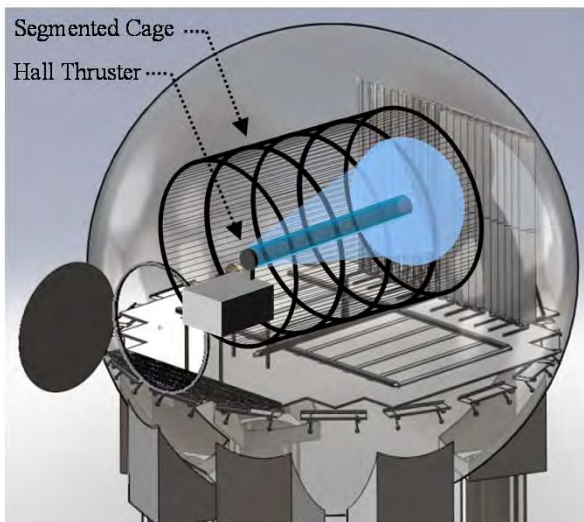
Objective 1

Facility Interaction Studies



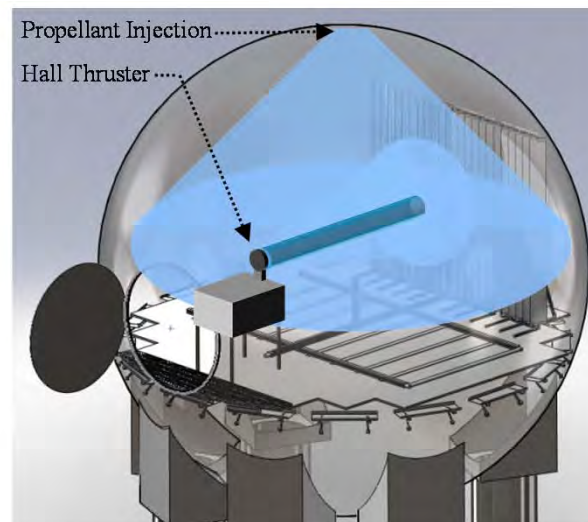
Key Question

How does vacuum chamber environment affect plume electron mobility, plasma oscillation behavior, and thruster operation?



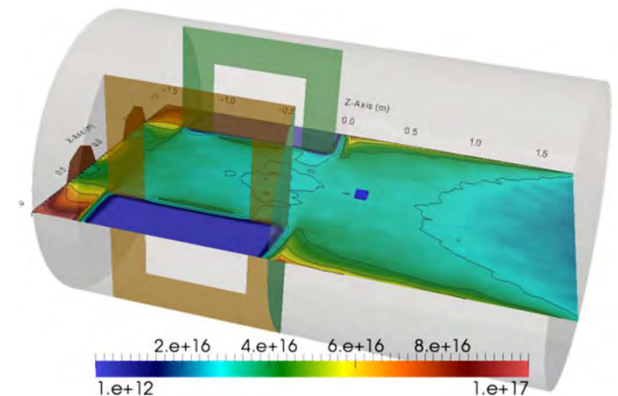
Plasma-Wall Interactions

- Instrument plasma confinement cage and exposed surfaces to monitor path of current and oscillations in facility
- Control grounded, floating, and biased surfaces to identify facility coupling and interactions that drive differences between ground and space



Background Pressure Effects

- Characterize chamber wall sheaths and background neutral particle distribution
- Evaluate thruster and plume from minimum pressure to accepted qualification pressure (1×10^{-5} torr) to estimate on-orbit behavior



Chamber Modeling and Simulation

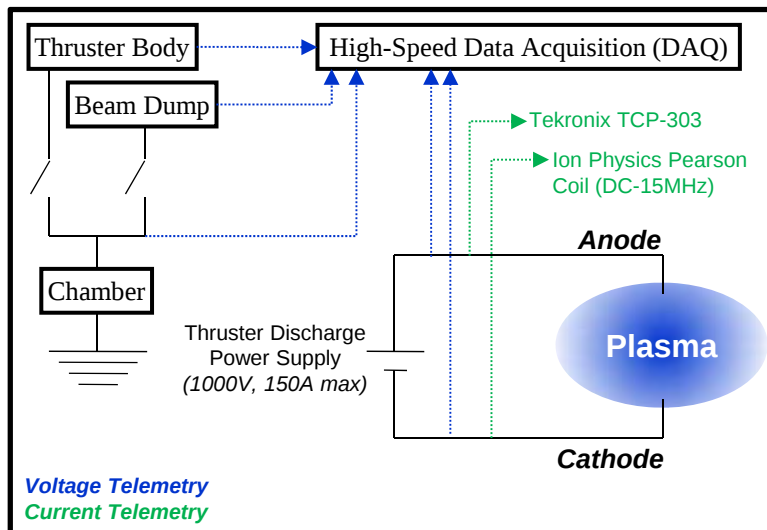
- Leverage existing in-house M&S capabilities to model plasma plume properties and wall sheaths
- Evaluate approaches to model thrusters in both ground chambers and space environment → identify the necessary validation data

Utilize Controlled Experiments of Chamber Environment to Study Electron Transport in Plume

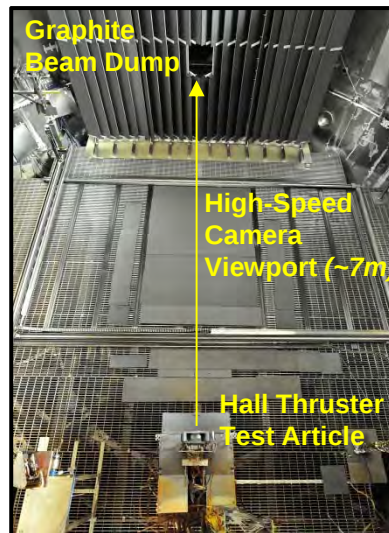


Objective 1: Facility Interaction Studies

Experimental Setup – High-Speed Image Analysis



Schematic of Thruster Electrical Configuration

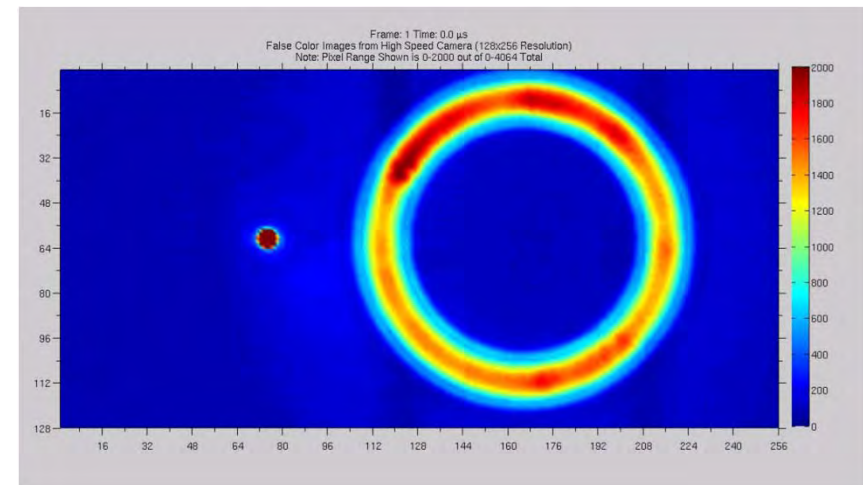


High-Speed Imaging

- Vision Research Phantom V2010, 341,463 frames/sec, 256x128 resolution, 12-bit depth
- Resolve up to 171 kHz Behavior
- Measurement duration 100,000 frames (~290 ms)
- Nikon ED AF Nikkor 80-200mm lens
- Located ~7m downstream of thruster, outside of chamber

Imaging correlated to time-resolved measurements of thruster discharge and facility

Fastest, Highest Resolution Images of a Hall Thruster To Date Enhances Study of Plasma-Facility



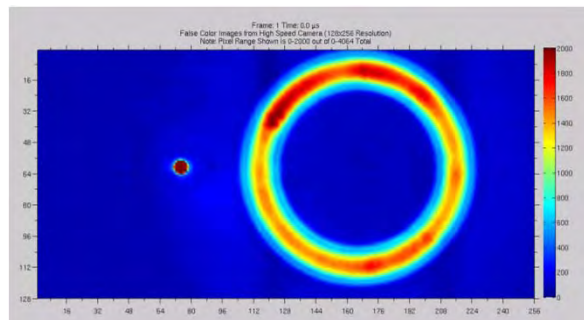
False Color Images from High-Speed Camera
(Pixel Range 0-2000 out of 0-4064)



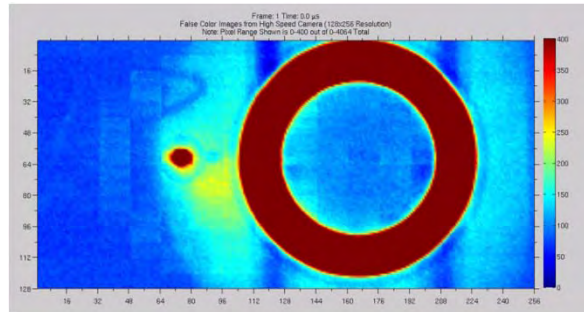


Objective 1: Facility Interaction Studies

Results – High-Speed Image Analysis (1/2)



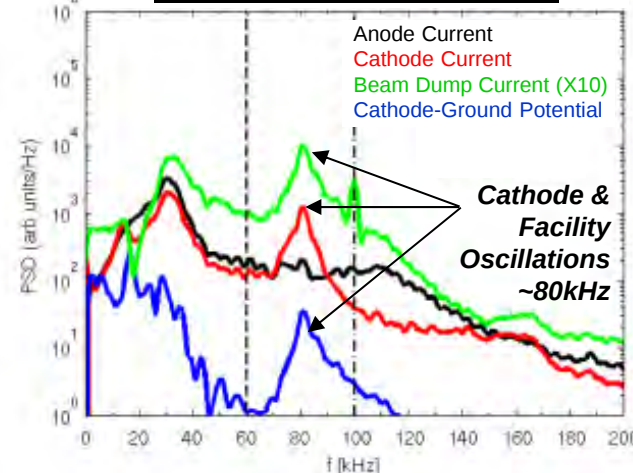
False Color Images from High-Speed Camera
Pixel Range 0-2000 (top) and 0-400 (bottom) out of 0-4064



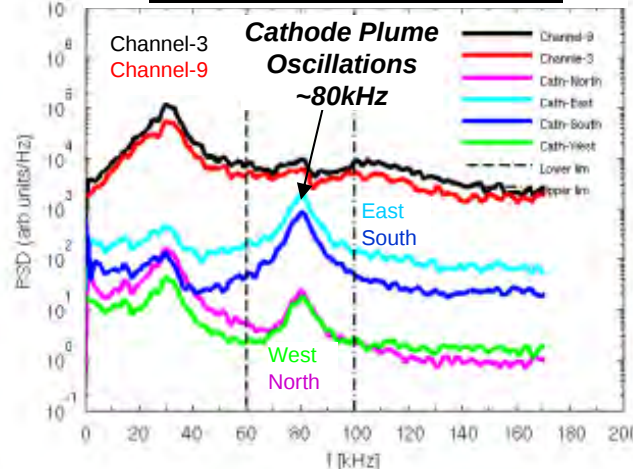
Observations

- Spokes rotate Counter-clockwise at 1783-1921 m/s
- Imaging shows local cathode “bursts” toward channel at ~80kHz
- Facility coupling indicated by 80kHz peak in cathode discharge current (red), beam dump current (blue), and cathode cathode to chamber ground potential (green)

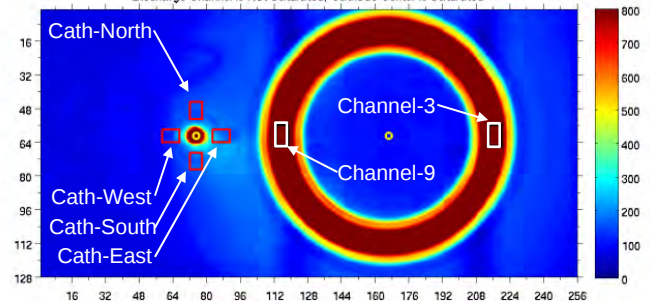
Current, Voltage Telemetry



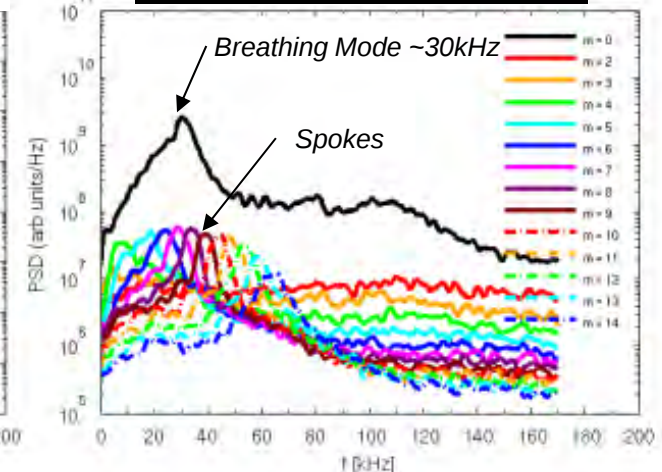
High-Speed Imaging - Axial



False Color Mean Image from High Speed Camera (128x256 Resolution)
Cathode Plume (Red) and Discharge Channel (Black) Locations Outlined
Cathode Center and Thruster Centerline (Yellow)
Note: Pixel Range Shown is 0-800 out of 0-4064 Total
Discharge Channel is Not Saturated, Cathode Center is Saturated



High-Speed Imaging - Spokes

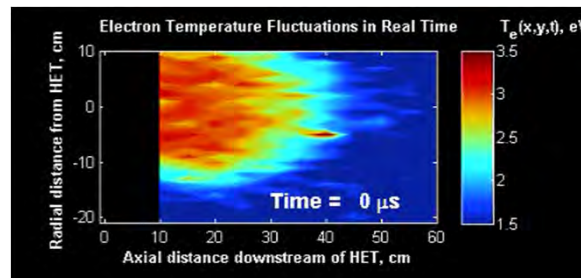
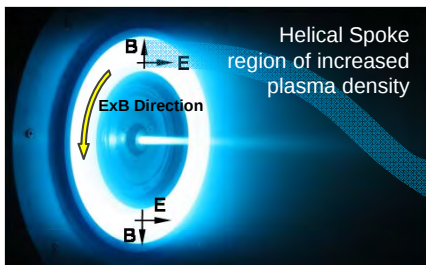
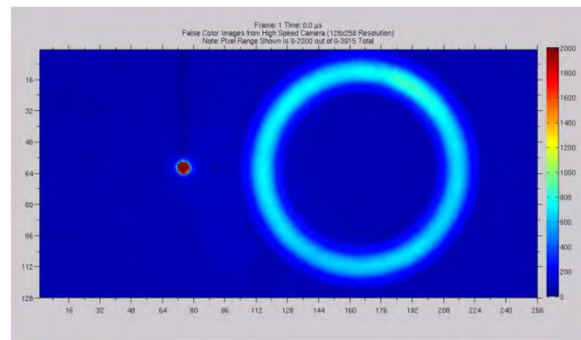
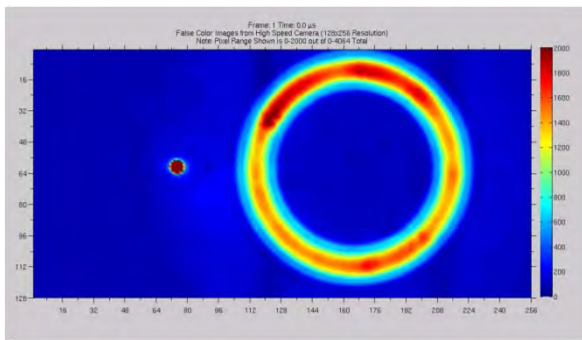


**Identified Facility Coupling Through Cathode Oscillations
Supports Plasma-Facility Interactions Through Electron Dynamics**

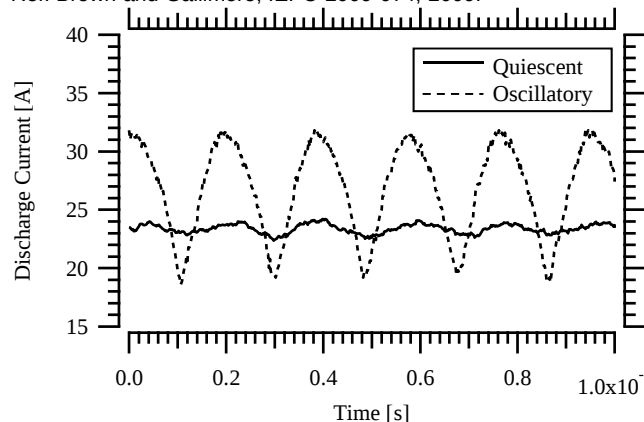


Objective 1: Facility Interaction Studies

Results – High-Speed Image Analysis (2/2)



Ref. Brown and Gallimore, IEPC-2009-074, 2009.



Ref. Lobbia, R. B., "A Time-Resolved Investigation of the Hall Thruster Breathing Mode," Ph.D. Dissertation, University of Michigan, Ann Arbor, MI, 2010.

Observations

- Identified multiple thruster oscillation behaviors
 1. Quiescent "local" mode with plasma spokes
 2. Oscillatory "global" mode with bursts of plasma
 3. Local cathode oscillations
 4. Past AFRL studies measured increased electron current from cathode in oscillatory mode
- Oscillations and thruster mode sensitive to discharge voltage, mass flow, B-field field, near-field neutral density (*i.e. pressure*)
- Organizing basic research collaboration with University of Michigan (UM) and Princeton Plasma Physics Laboratory (PPPL) to understand electron mobility physics and facility interactions → *AFOSR funding to universities (Birkan)*

**Electron Mobility Between Cathode and Thruster Channel
Hypothesized to Change with Plasma Oscillation Behavior
Investigate Coupling with Confinement Cage Experiments in FY16**



AFRL/RQ CSIRF Overview and Objectives



Motivation

Understand mechanisms of non-classical electron conductivity on Hall thruster stability and facility interactions

Objectives

- Investigate mechanisms of cross-field electron transport within near-field and discharge channel (i.e. channel near-wall conductivity and plasma turbulence)
- Determine relationship between electron transport internal and external to channel, with respect to thruster mode and background environment

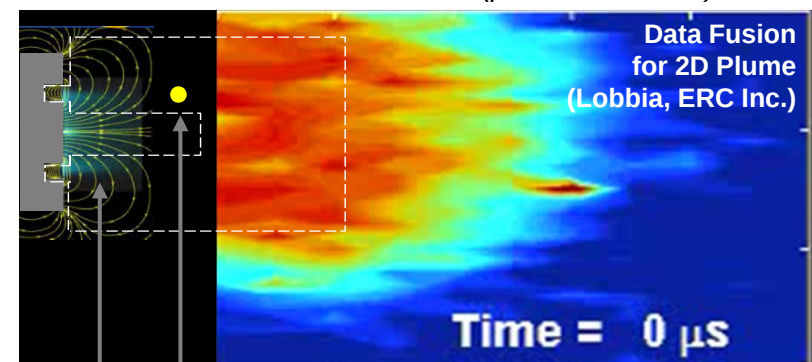
Payoffs

- Enhance understanding of thruster operating modes to support improved RDT&E methodologies and M&S
- Develop the first time-resolved validation dataset for Hall thruster plasma source models

CSIRF Complements LRIR Studies of Electron Transport from Cathode to Channel and Facility Interactions

AFRL/RQ Chief Scientist Innovation
Research Fund (CSIRF), FY14-FY15, \$50k

*Plume Measurements of Electron Density
Fluctuations (peak normalized)*



Ref. Lobbia, Ph.D. Dissertation, U. of Michigan, 2010

Existing Data

Point Measurement Correlated to
Discharge Oscillations and High-Speed
Imaging (Sekerak, U. Mich)

CSIRF

FIRST 2D Time-Resolved Plasma Measurements
of Near-field and Discharge Channel



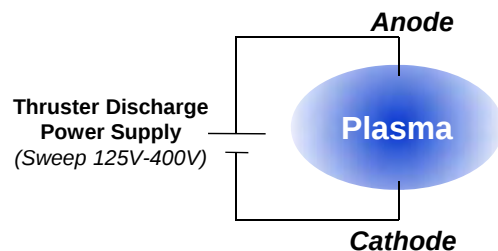
Objective 1: Facility Interaction Studies

Overview – Current-Voltage-Magnetic Field (I-V-B) Maps

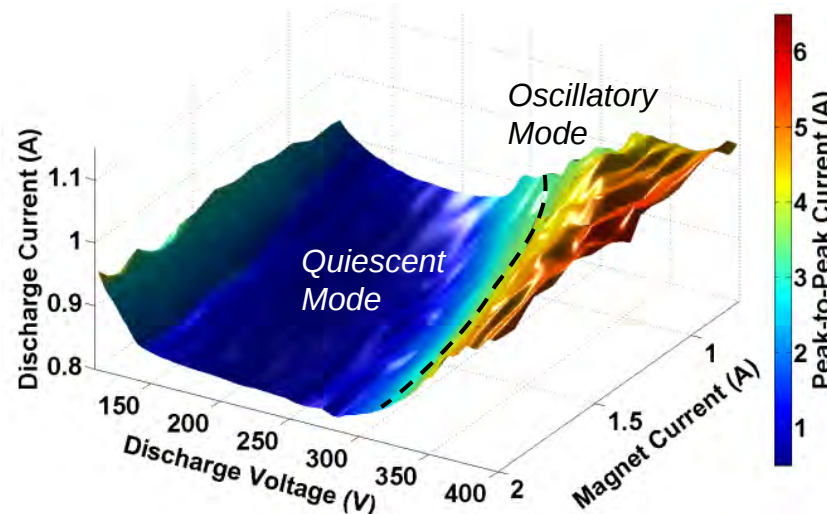
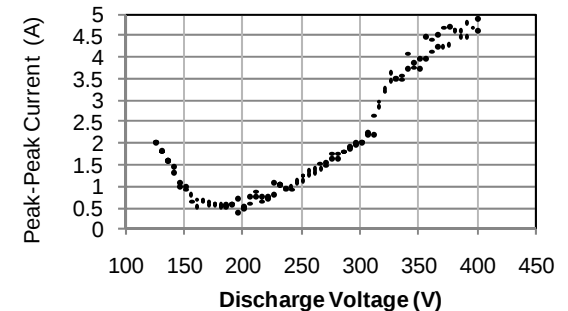
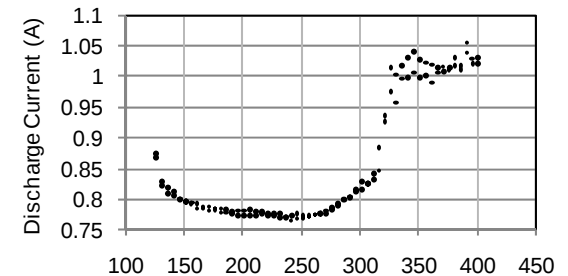
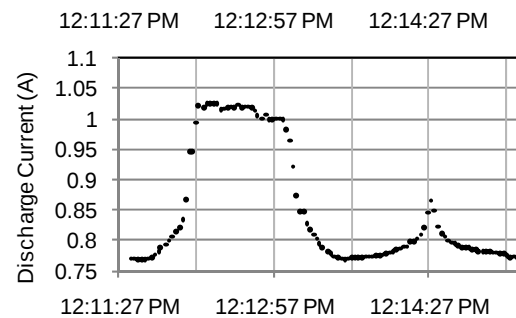
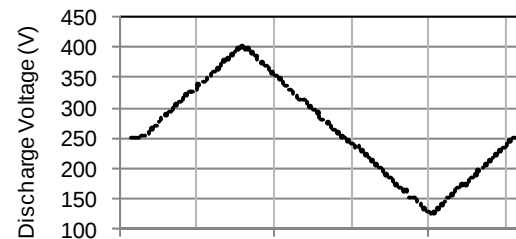


Developed experimental technique to rapidly map global thruster behavior and identify mode transitions

1. Set Thruster Input Parameters (mass flow, magnetic field)
2. Sweep voltage while measuring thruster current, oscillation telemetry
3. Evaluate sensitivity to changes in pressure and input parameters



Transitioned to USAF, NASA, and Industry



NEW RDT&E Methodology

Plot I-V-B map with color scale for telemetry (e.g. current oscillations) to assess global trends and facility interactions



Objective 1: Facility Interaction Studies

Results – I-V-B Maps

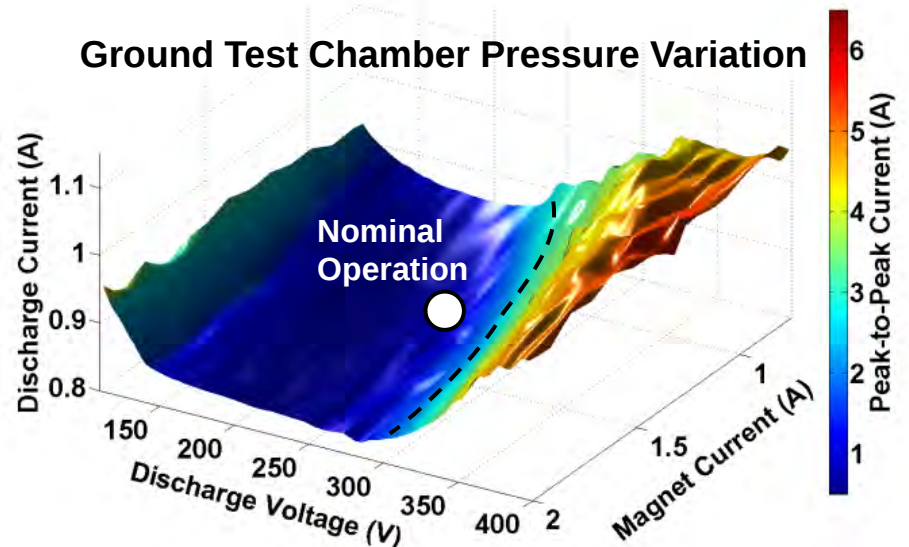
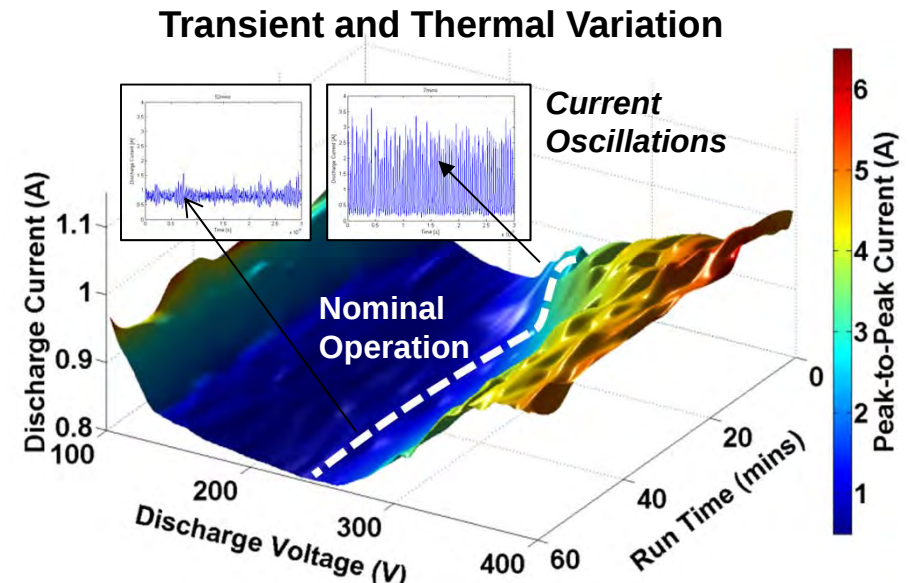
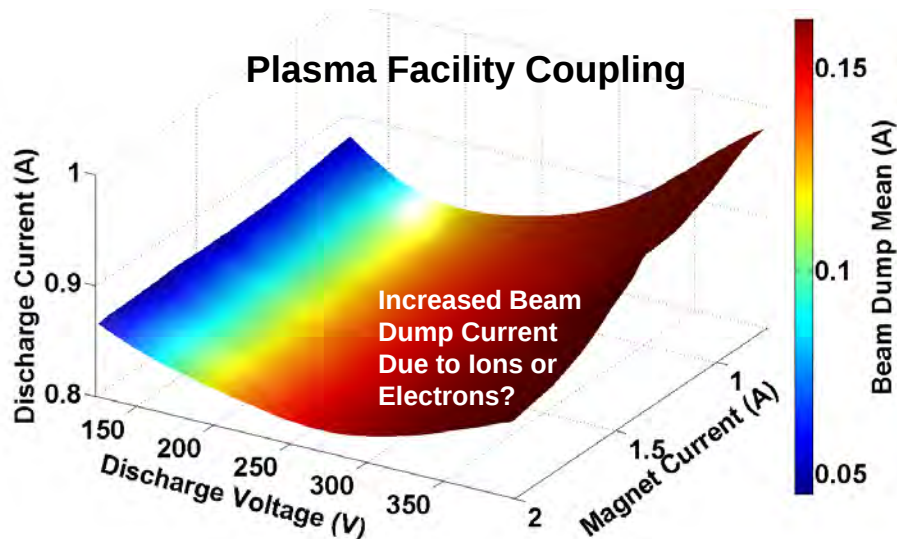


Key Technical Challenge

Cannot fully replicate space environment in ground T&E (*higher pressure, metallic walls*)

I-V-B maps support study of global trends, identify regions sensitive to mode transitions, and assess facility interactions

- Enables ability to characterize and isolate background pressure effects
- Informs short duration maneuvers (i.e. station-keeping)
- Shows sensitivity to thermal variation (i.e. sun)





Objective 2: Develop Ground T&E Methodologies

I-V-B Pressure Extrapolation to Space Conditions (1/3)

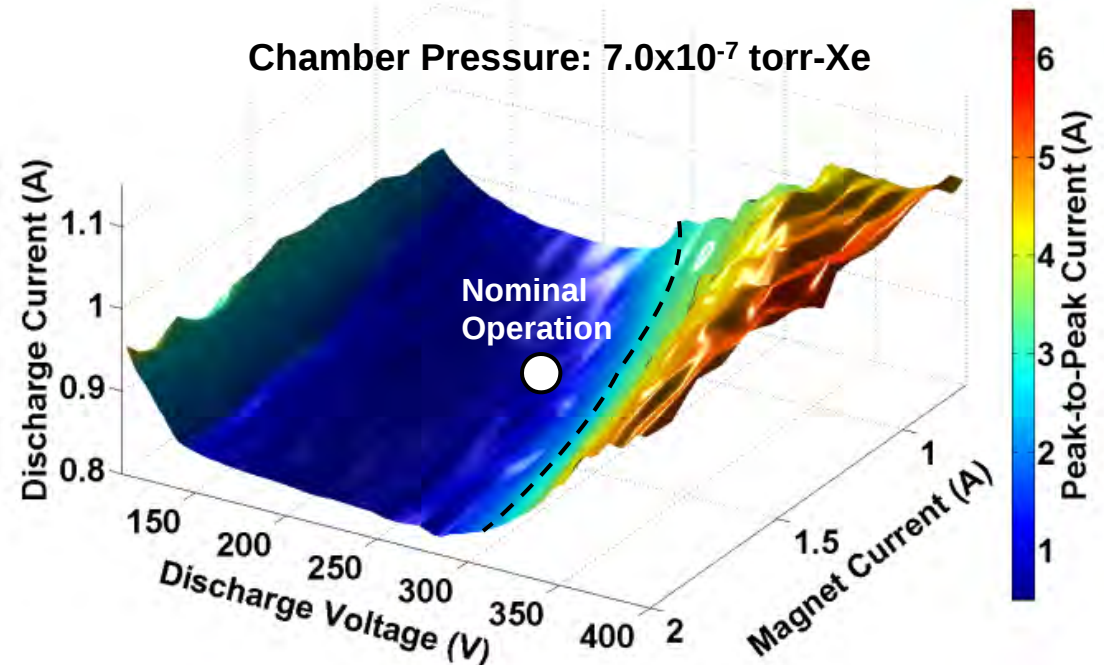


Develop ground test methodologies to predict in-space plasma stability and performance

- Pressure may reduce or exacerbate oscillations
- Pressure may influence thruster mode and mode transition region
- Past studies demonstrated peak performance near transition

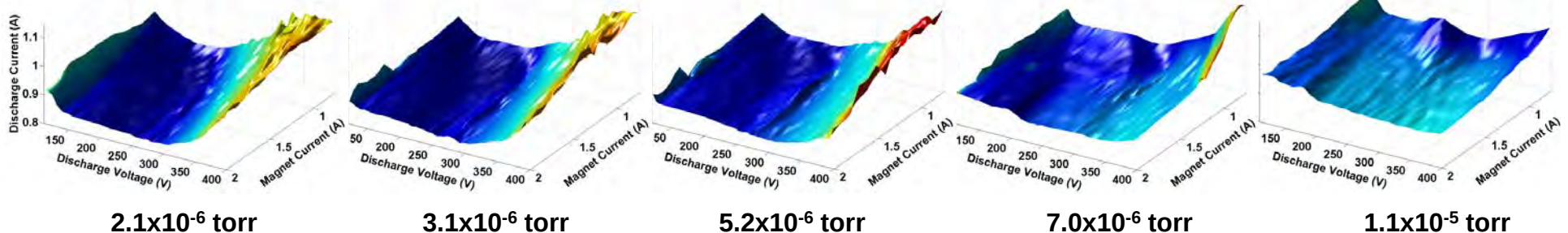
What is acceptable background pressure?

Can we extrapolate to zero pressure?



Increasing Background Pressure

Standard Qualification Pressure $\sim 2 \times 10^{-5}$ torr-Xe





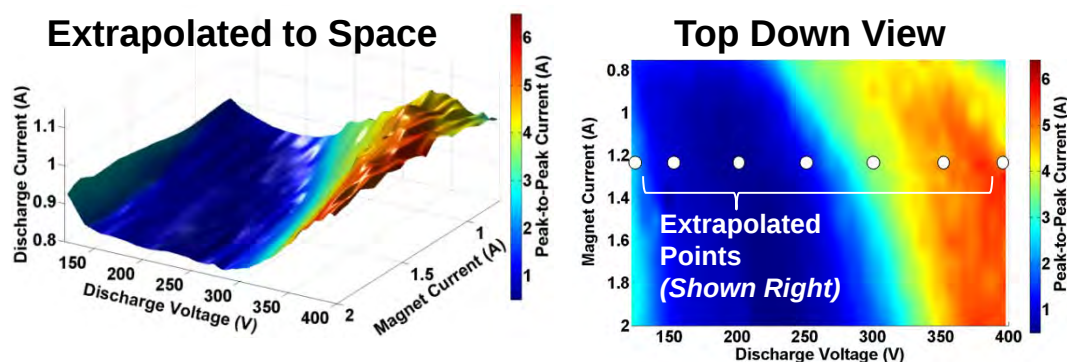
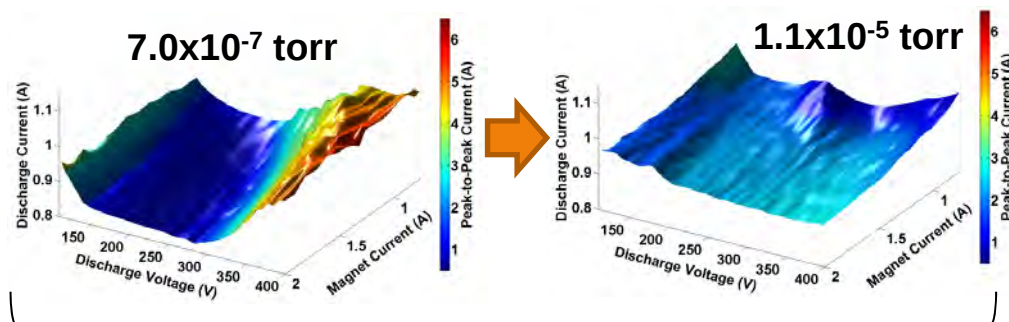
Objective 2: Develop Ground T&E Methodologies

I-V-B Pressure Extrapolation to Space Conditions (2/3)



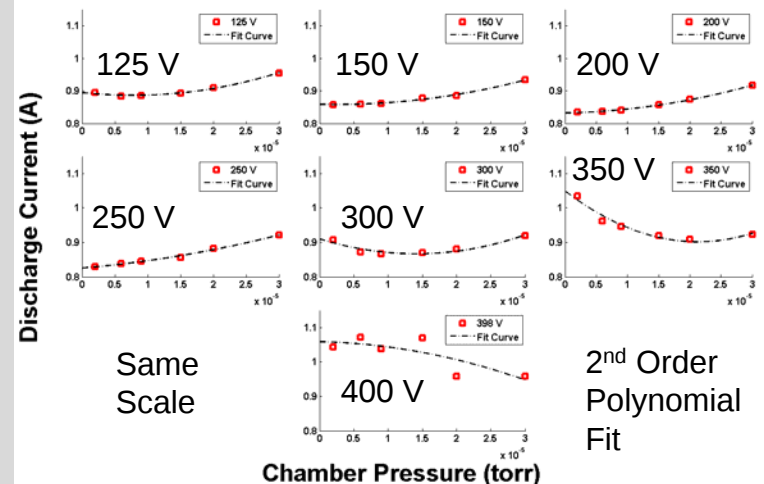
Preliminary assessment of extrapolation to zero pressure

- I-V-B characterization and oscillations at 6 pressures
- Extrapolate parameter (thruster current mean, peak-peak) to space pressure at each point in I-V-B map
- Does NOT account for metallic chamber walls

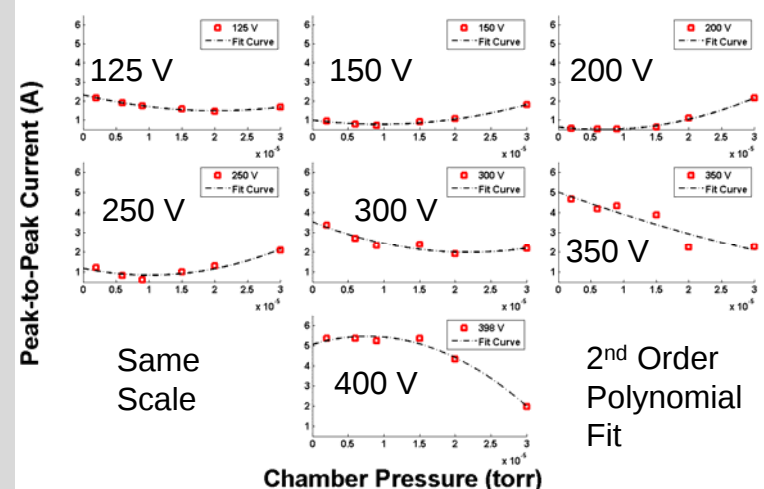


Detailed Pressure Characterization Shows Clear Trends to Vacuum → **POSITIVE SIGN**

Discharge Current Mean versus Pressure



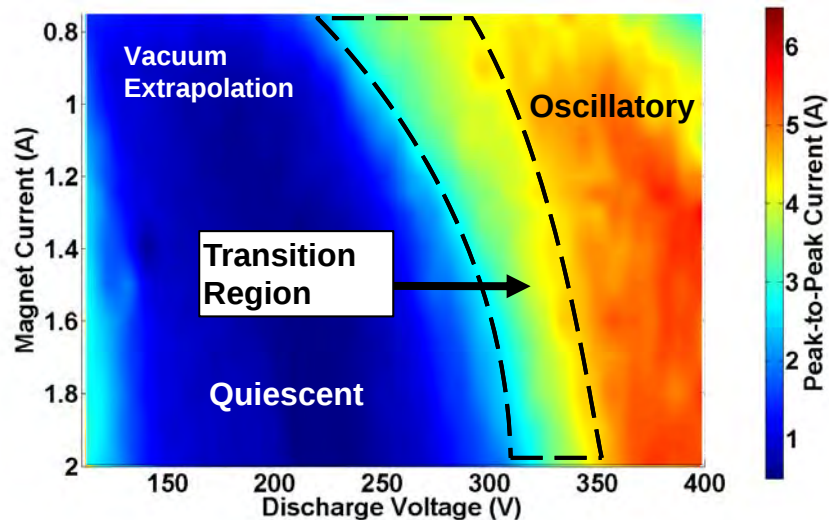
Discharge Current Peak-Peak versus Pressure



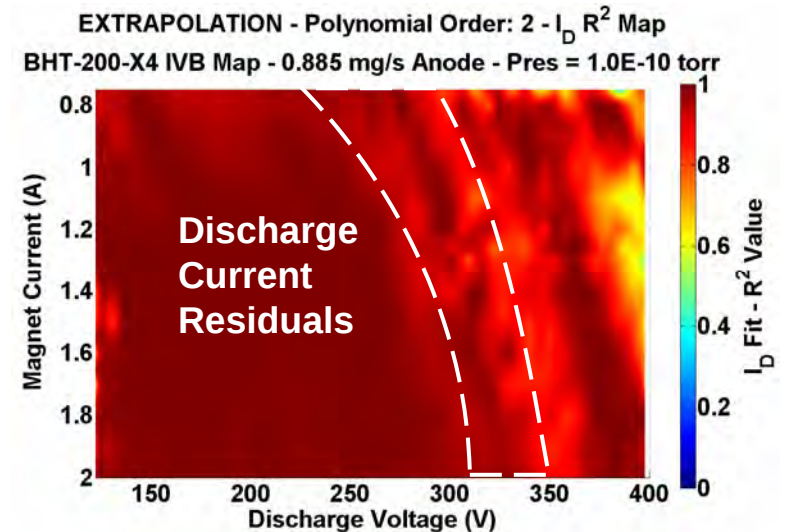


Objective 2: Develop Ground T&E Methodologies

I-V-B Pressure Extrapolation to Space Conditions (3/3)



Extrapolation Residuals



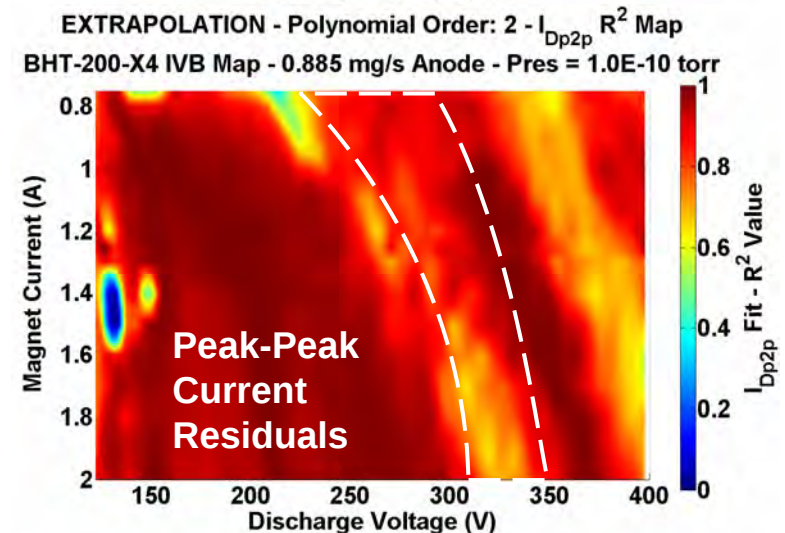
Data shows expected transition region in space pressure

- Transition region “narrows”
- Region of severe oscillations moves to lower voltage

Peak-peak current residuals may be leading indicator

Method requires further evaluation and development

- Evaluate across multiple thruster designs and facilities
- Assess with plasma confinement cage
- Compare space results to existing flight data





Objective 3: Validate Test Methodologies

Compare Ground Predictions to Space Operation

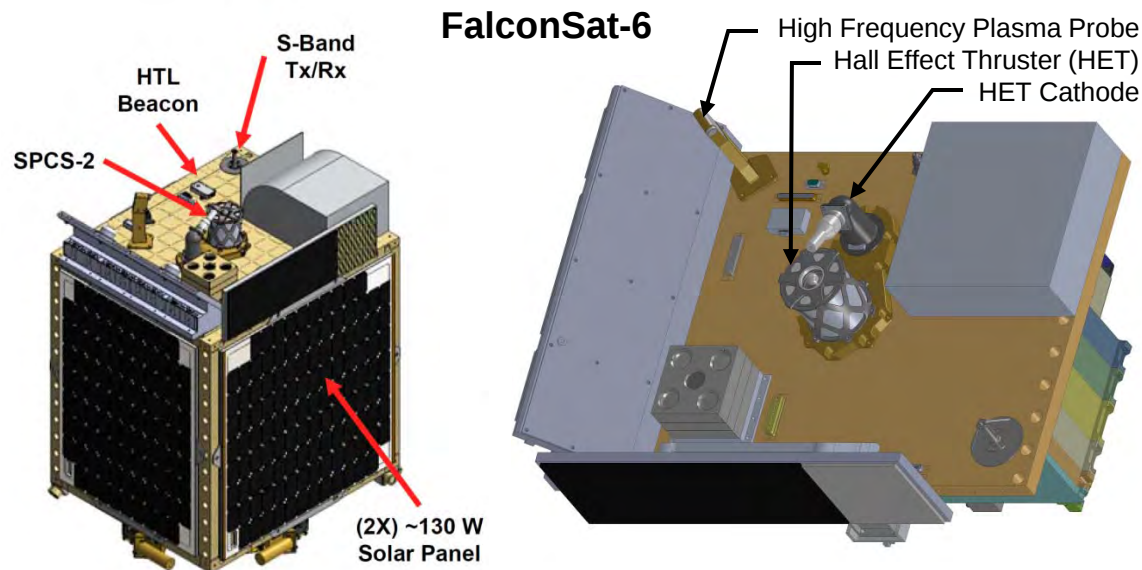


Key Question

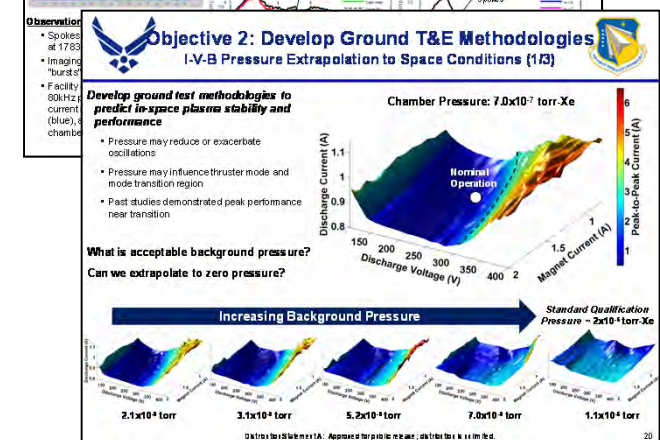
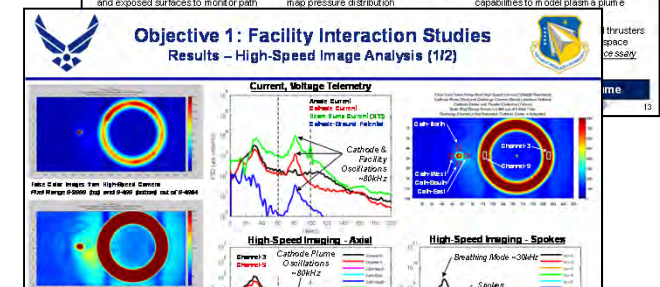
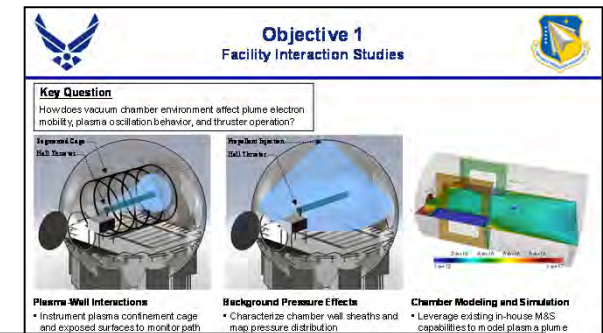
Do T&E methodologies accurately predict Hall thruster behavior in the space environment?

Approach: Compare T&E predictions with Hall thruster experiment on FalconSat-6

- Make predictions before launch (launch ready mid-FY15)
- Inform CONOPS of AFRL Space Plasma Characterization Source, Mark II (SPCS-2)
- Validate T&E with direct comparison of flight to ground measurements



Unique Opportunity to Directly Assess Ground vs Space Operation and Validate T&E Methodologies





Technology Transition and Program Status



- Transitioned I-V-B mapping techniques to USAF, NASA, and Industry
- Collaboration with AEDC through TCTTA Dr. Taylor Swanson
 - AEDC 12V chamber is world-class facility, with high pumping capability → taken out of mothball status in FY15
 - Incorporate newly developed EP diagnostic standards into new T&E capabilities
 - Transition T&E methods and AFRL M&S capabilities in FY16/17
- Coordinating AFOSR funded thruster plasma research w/ T&E lab task
 - U. of Michigan (UM) studies time-resolved plasma dynamics inside thruster channel
 - Princeton Plasma Physics Lab (PPPL) emphasizes theory of electron transport
- Formed working group with EP community devoted to *“understanding and mitigating facility effects in the testing and characterization of EP devices, and thereby supporting transition of EP technologies to flight”*
- Status of FalconSat-6 launch is uncertain; not expected to receive flight data by end of program in FY16



Summary and Conclusions



- Demonstrated plasma facility coupling through cathode oscillations
 - Supports hypothesis of facility interactions through electron dynamics → *additional research required*
 - Plasma confinement cage experiments are necessary to improve understanding, design and construction underway in FY15
- I-V-B methodology successfully demonstrated and transitioned for RDT&E
 - Identified global thruster trends and mode transitions
 - Enables extrapolation to zero pressure
 - Multiple transitions demonstrated utility for national space assets
- Successfully leveraging AF investments
 - AFOSR funding of plasma oscillations complements lab task
 - Informing FalconSat-6 predictions and exploiting unique opportunity for space validation
 - Research utilized for AFRL modeling activities and space predictions