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Air Force Research Laboratory

Electric Propulsion Test & Evaluation Methodologies for Plasma in the Environments of Space and Testing

(EP TEMPEST)

AFOSR T&E Program Review
11-15 April 2016

Dr. Sasha A. MacDonald

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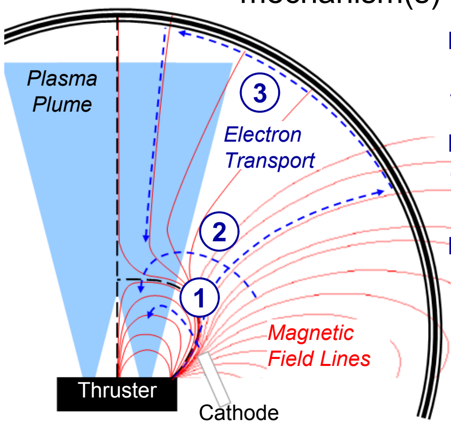
Integrity ★ Service ★ Excellence

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

PI Dr. Natalia A. MacDonald AFRL/RQRS; TCTTA: Dr. Taylor Swanson AEDC

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



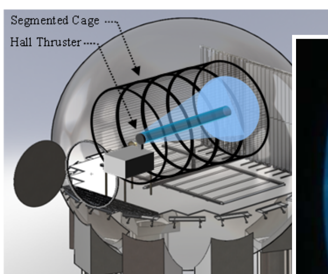
Path 1: Magnetized electron transport impeded across magnetic field lines; transport via electron-particle collisions

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, thruster lifetime



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

Transition improved T&E methods to stakeholders

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

Highlights

- Utilized new T&E methods to characterize thruster mode transitions during FalconSat-6 ground test campaign. Results used to predict on-orbit operation. → *Unique V&V opportunity*
- Designed and built plasma confinement cage in vacuum test facility to directly measure influence of chamber surfaces on electron transport and thruster plasma oscillations. → *potential coupling mechanism*

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
- Development of T&E Methodologies
  - Current-Voltage-Magnetic Field (I-V-B) Mapping
- Facility Interaction Studies
  - Background Pressure
  - Plasma Wall Interactions
- Program Status and Transitions
- Next Steps
- Summary and Conclusions

Electric Propulsion (EP) Mission Impact

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

EP Technology Description

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

Payoff

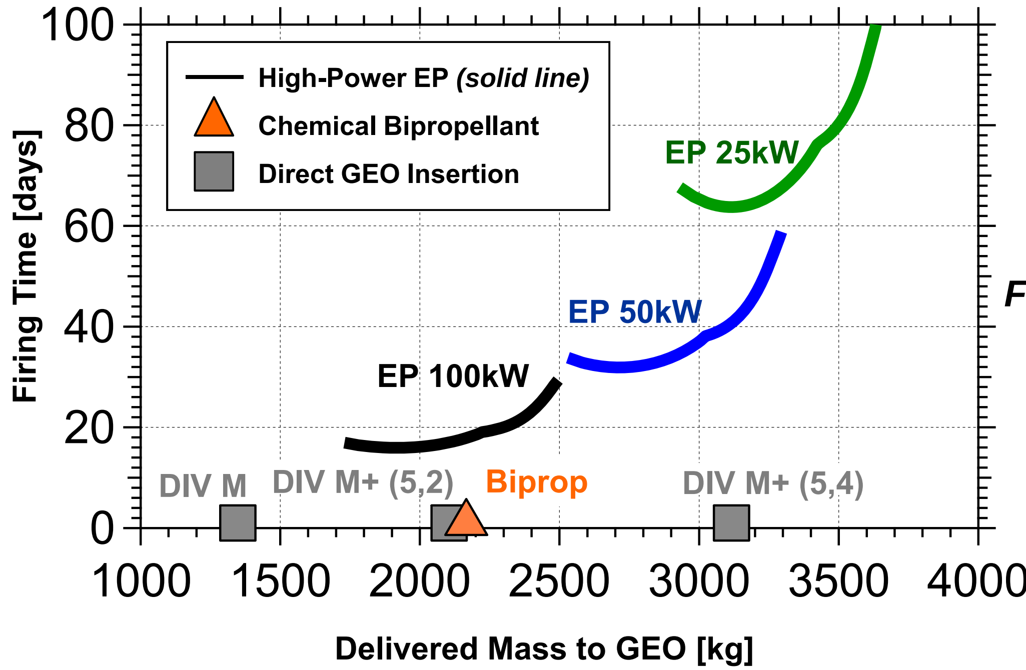
- Increase Delivered Payload to Orbit
- Rapid, Sustainable Repositioning and Station-keeping
- Smaller, Low-Cost Launch Vehicle and Dual Launch
- Mission Enabling

Mission Applications

- Advanced Extremely High Frequency (AEHF) Satellites
- Wideband Global Satcom (WGS)
- Commercial, NASA, others

Example: GEO Payload Delivery

Delta IV Medium Launch Vehicle
ΔV≈5.8 km/s, 4535 kg wet mass from GTO-GEO



Minimize Firing Time

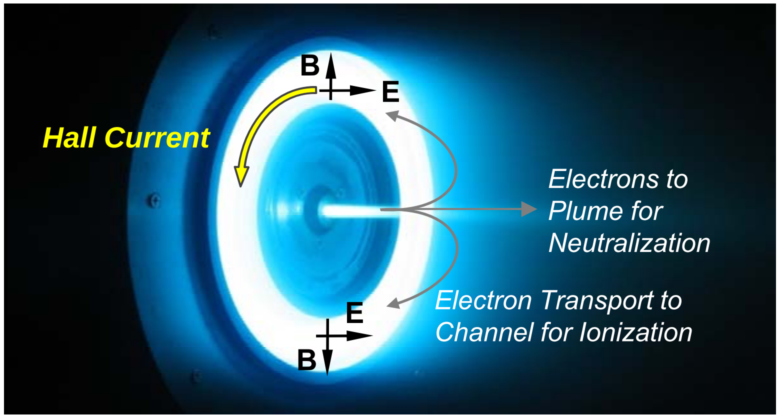
High Payoff

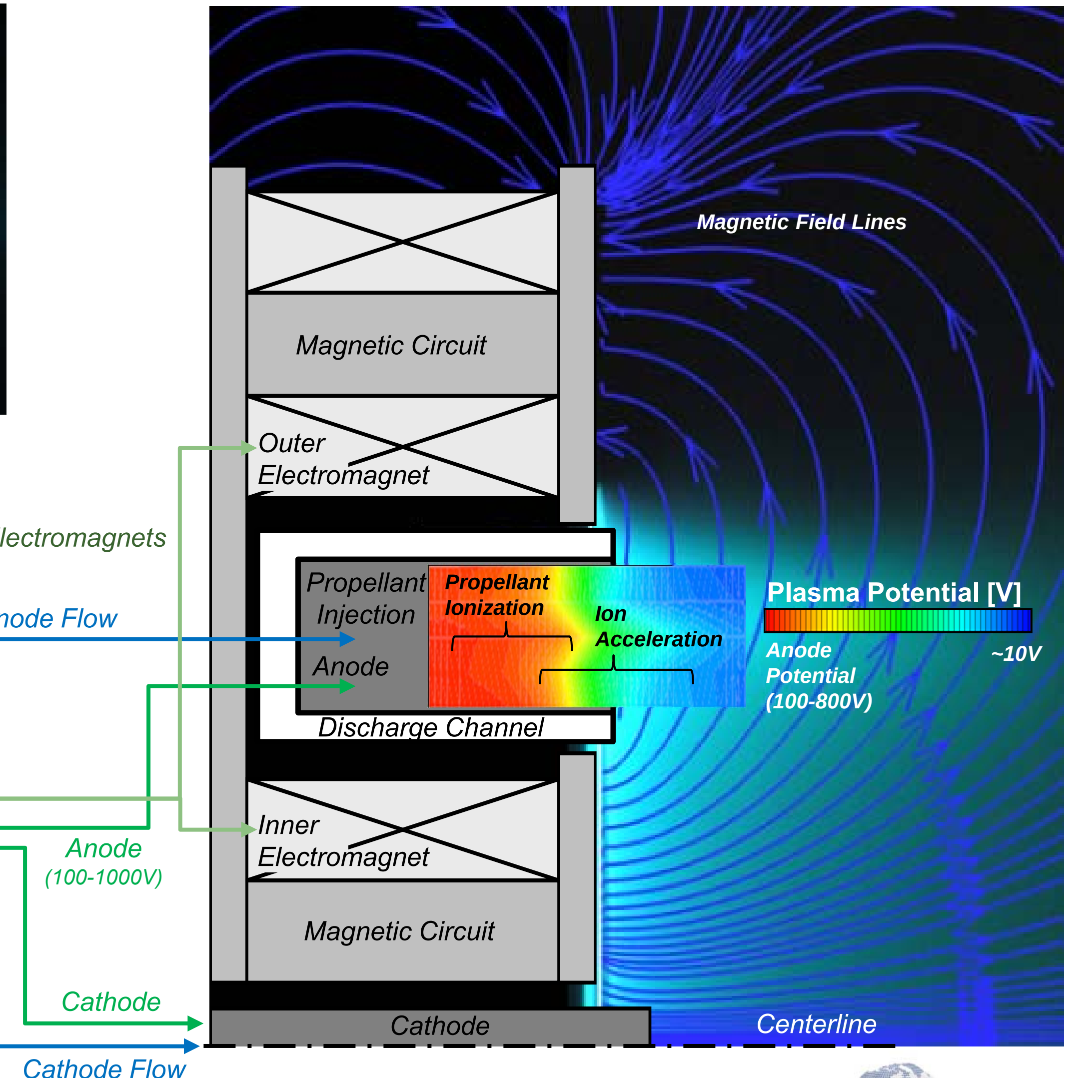
Maximize Delivered Mass

High Payoff

Evolving Space Power Capabilities Driving Next Generation High-Power EP

Principles of Hall Thruster Operation





<u>Hall Thruster Technologies</u>

Input Power: 100W to 10's kW
Propellant: xenon
Thrust: mN – N (<1 lbf)
Specific Impulse: 1000-3500 seconds

AFRL Objective

Motivation

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

Objectives

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

Technical Approach

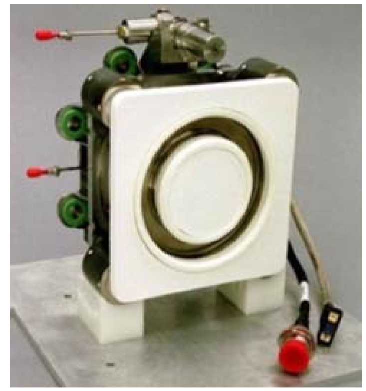
- Low-cost Size Weight and Power (SWAP) sensors
- Flight experiments
- In-house R&D on advanced diagnostics for EP systems

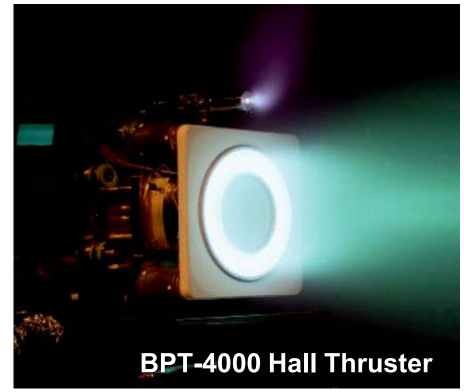
Challenges

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

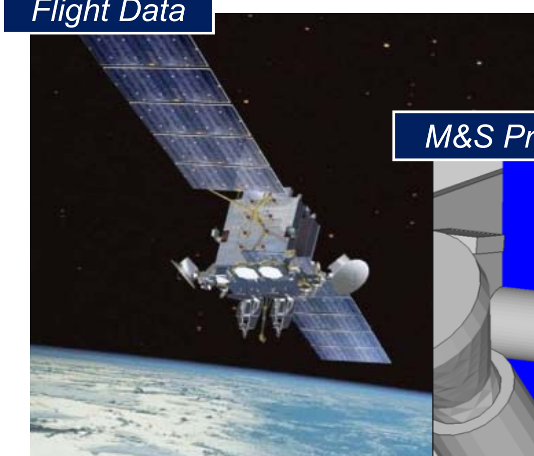
Coordination of Flight–M&S-Ground Experiments is Critical for EP Technology Infusion

Ground Test

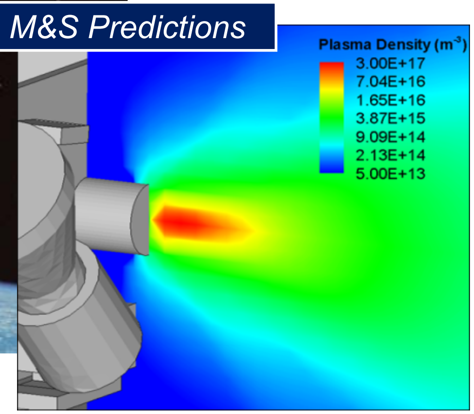




Flight Data



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/

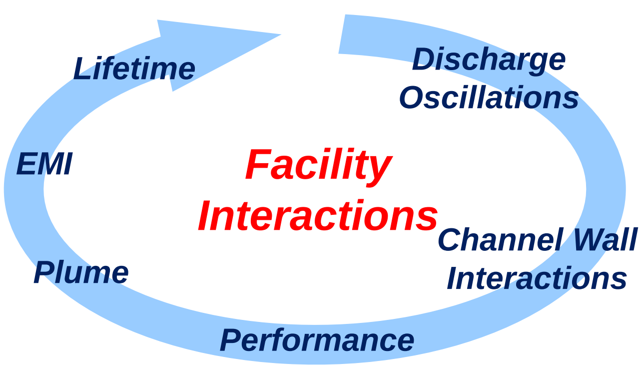
Challenges of Hall Thruster RDT&E

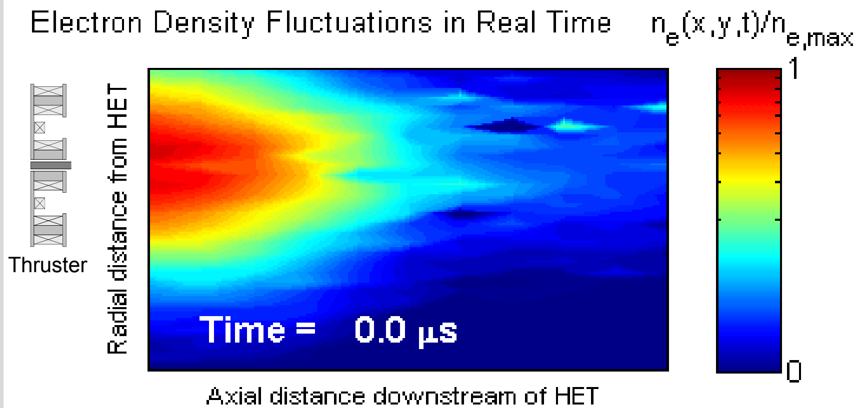
Multi-Scale / Multi-Physics Problem

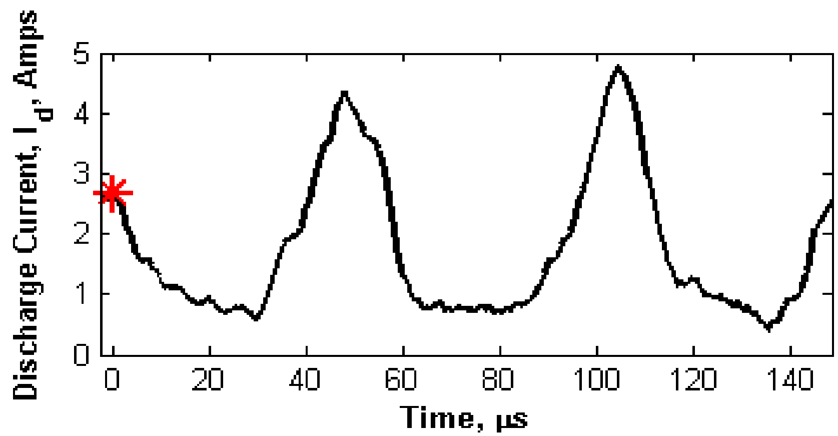
Multi-scale / Multi-physics Problem

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

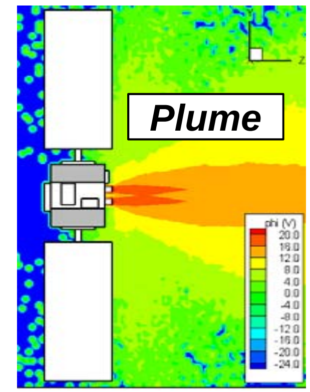
Complex Thruster Physics at Smallest Spatial/Temporal Scales Impact Macro-Level Characteristics

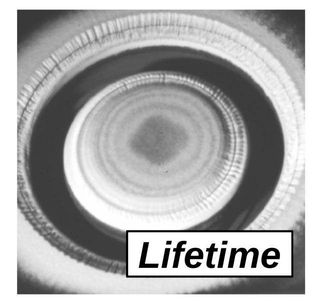


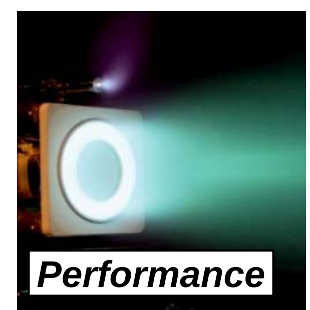




Ref. Lobbia, R. B., "A Time-Resolved Investigation of the Hall Thruster Breathing Mode," Ph.D. Dissertation, University of Michigan, Ann Arbor, MI, 2010.







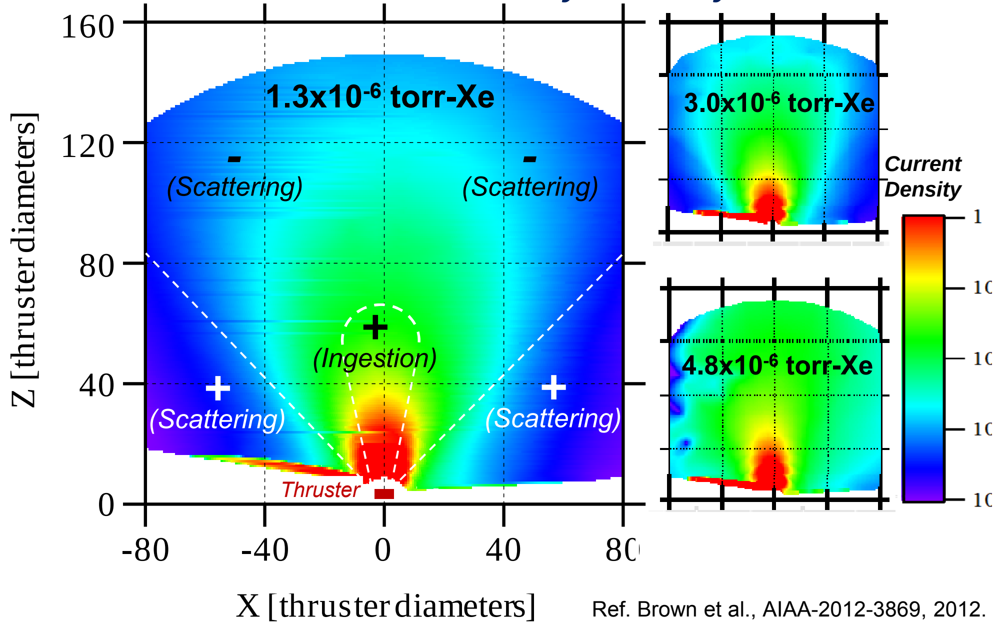
Thruster Behavior is Complex → *Further Complicated by Differences Between Ground Test and Space Environment*

Hall Thruster Facility Effects

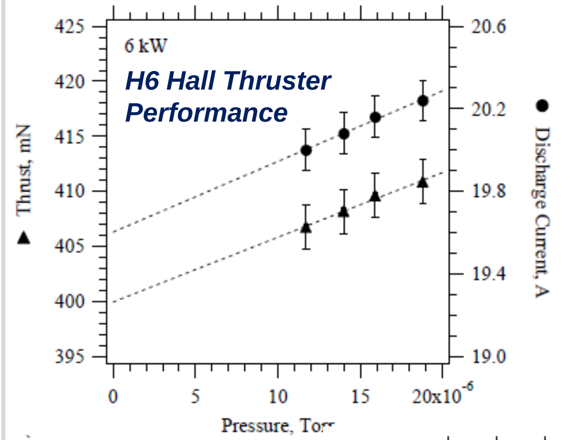
World-class EP RDT&E vacuum chambers cannot fully replicate on-orbit conditions

- 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"*

Far-Field Ion Current Density & Facility Influence

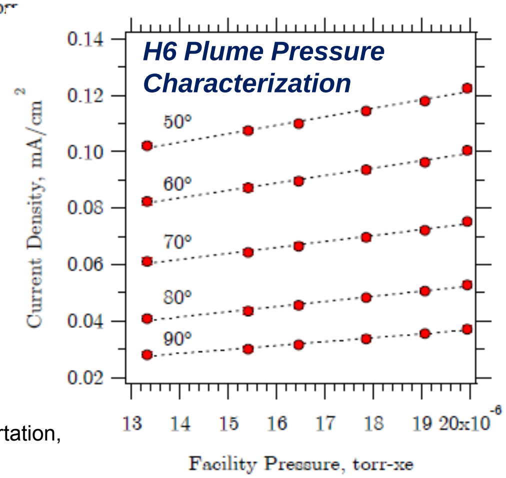


Ref. Brown et al., AIAA-2012-3869, 2012.



Predict Thruster Performance By Extrapolation to Vacuum?

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

Hall thrusters first flown in 1972 (USSR); 100's successfully used on commercial satellites

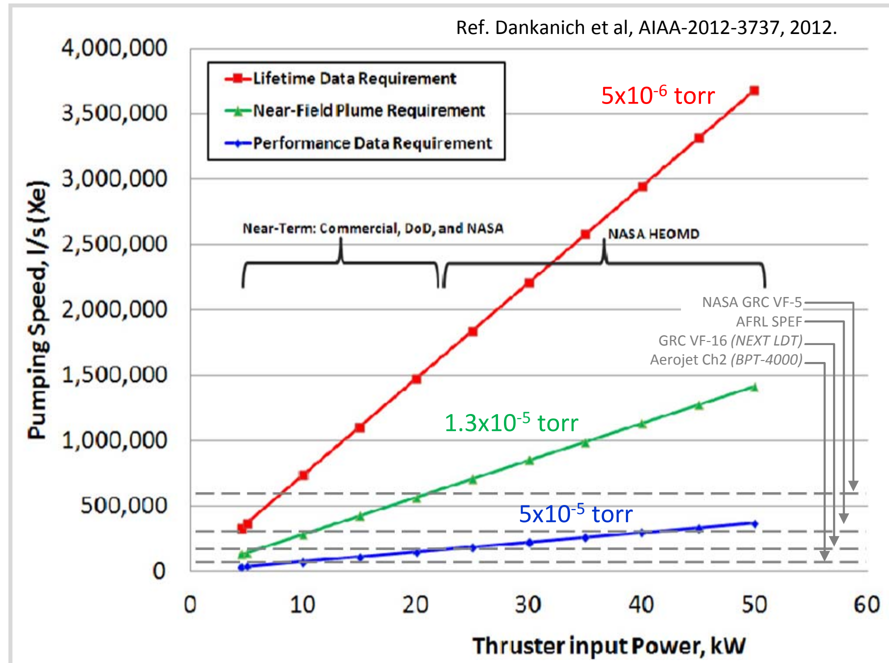
Signs of chamber effects on thruster performance, plume, and stability observed in U.S. since 1990s

Conventional T&E unchanged in 20+ years

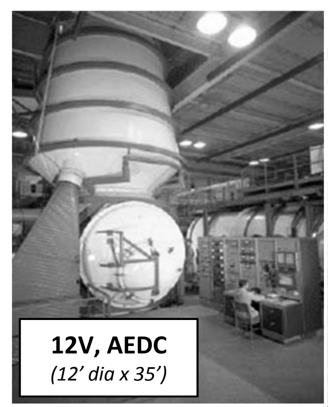
- RDT&E solution based on analysis; minimize pressure
  - $<5\times10^{-5}$ torr for performance
  - $<1.3\times10^{-5}$ torr for plume measurements <1.2m
  - $<5\times10^{-6}$ torr residual for lifetime evaluation to maintain sputter return rate <0.1Å/s

Modern designs are pushing operational envelope

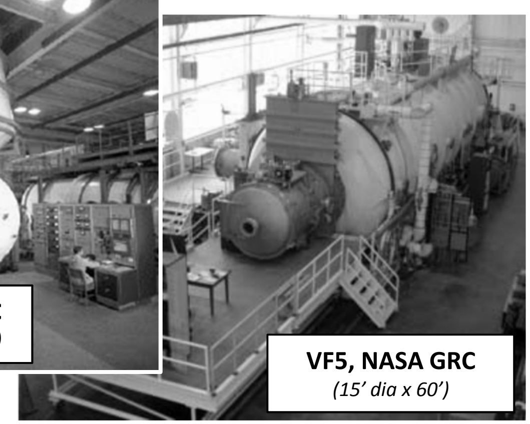
- EP trending to higher power, longer lifetime
- Empirical designs based on ground data; limited data in space environment



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



12V, AEDC
(12' dia x 35')



VF5, NASA GRC
(15' dia x 60')

AFOSR Lab Task, FY14-FY16

Program Goals and Objectives

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***.

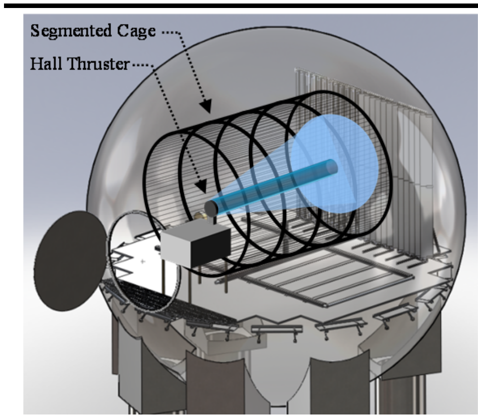
Objective 1. **Investigate facility interactions** on Hall thruster plasma to understand the mechanisms driving differences in stability behavior between ground testing, simulations, and in space

Objective 2. **Develop test methodologies** to predict in-space plasma stability and performance.

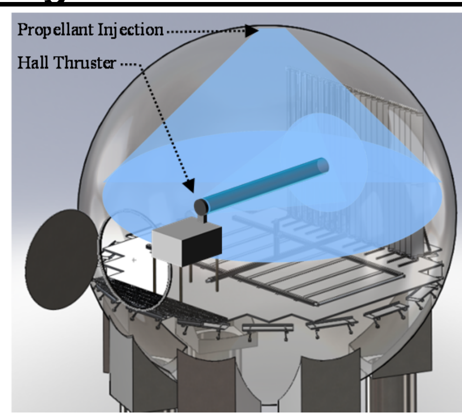
Objective 3. **Validate test methodologies** through comparison of ground-based predictions with flight data from a low-power Hall thruster experiment on FalconSat-6.

Transition: Transition to AEDC, SMC, NASA, Industry

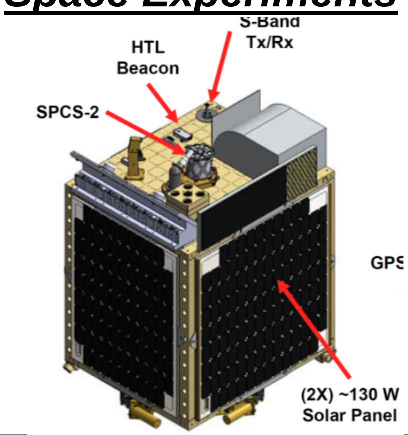
Plasma-Wall Interactions



Background Pressure Effects

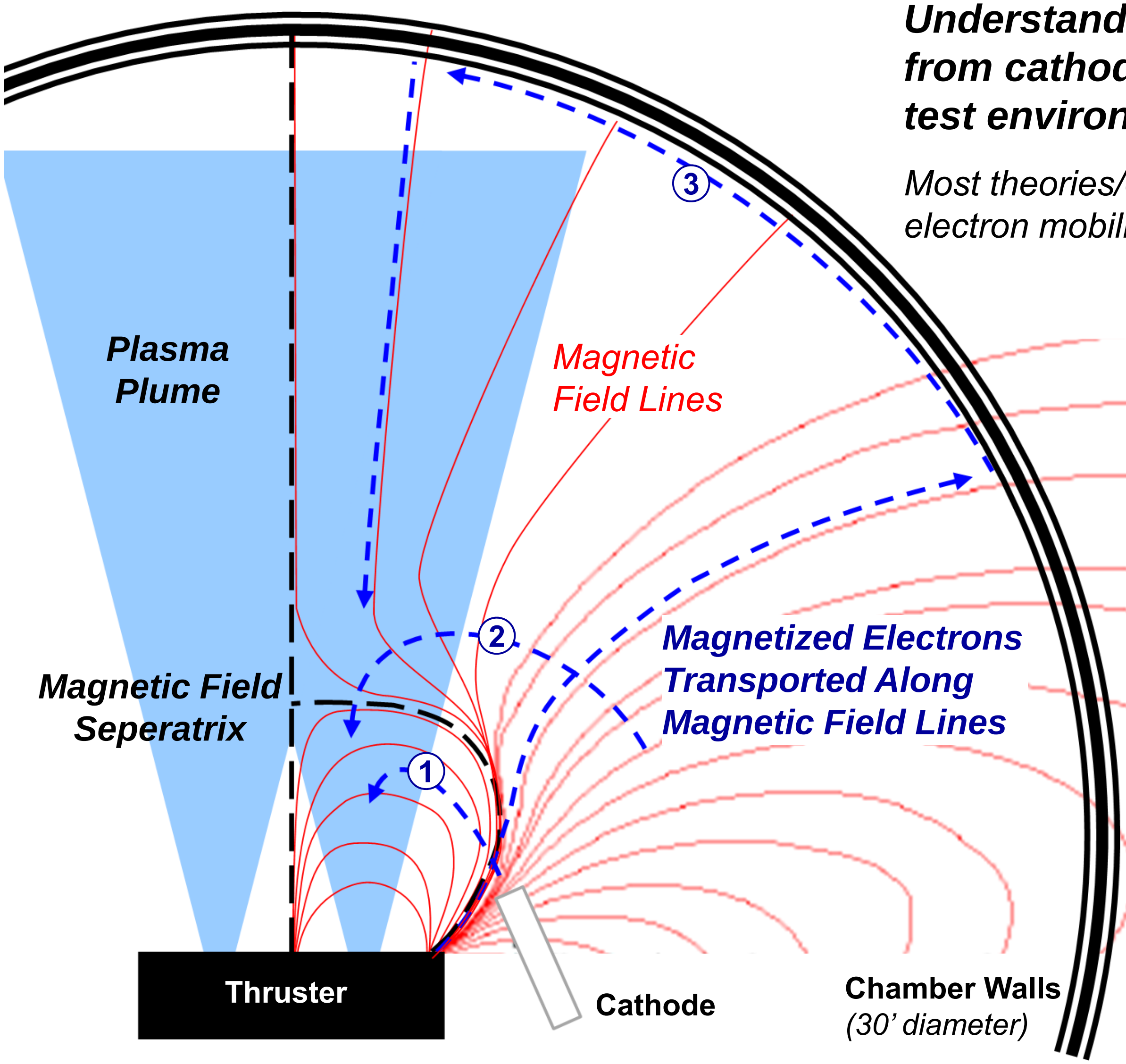


Space Experiments



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

Approach



Understand electron transport mechanisms from cathode to thruster channel in ground test environment and space

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

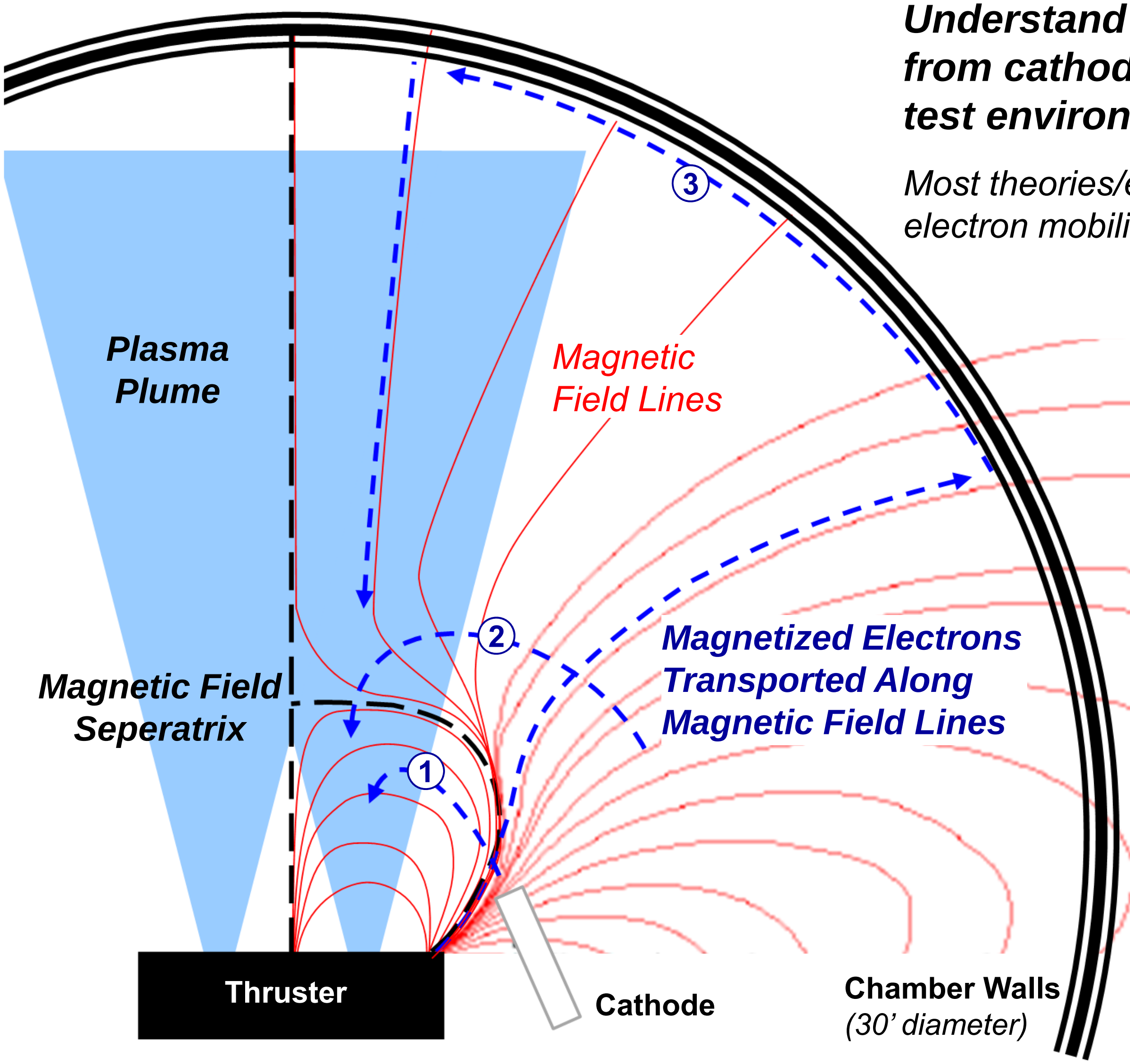
Path 1: Magnetized electron transport impeded across magnetic field lines; ***transport mechanism(s) not determined***

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***

Approach



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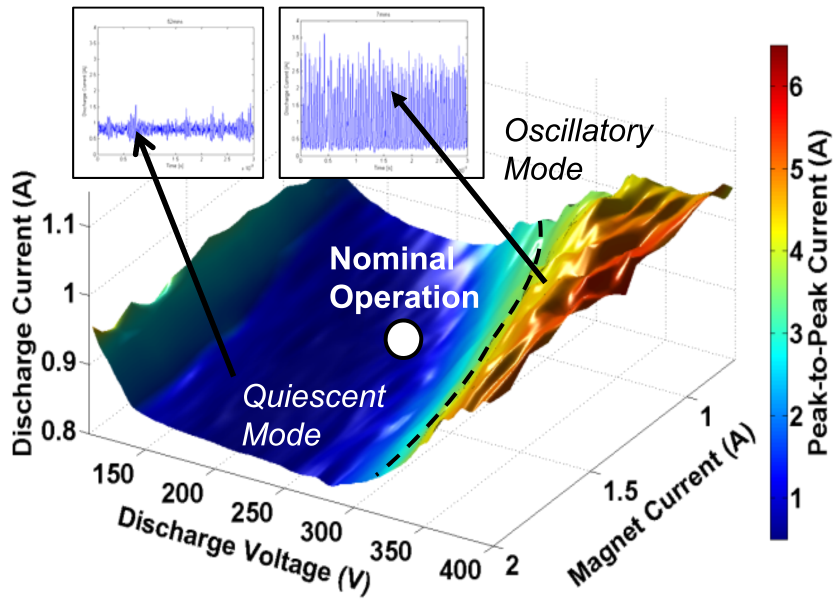
Development of Ground T&E Methods
I-V-B Pressure Extrapolation to Space Conditions

- ***I-V-B Mapping Technique***
  - Set Thruster Input Parameters *(mass flow, magnetic field)*
  - Sweep voltage while measuring thruster current, oscillation telemetry
  - Evaluate sensitivity to changes in pressure and input parameters
- ***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
  - Extrapolate to zero pressure to emulate on-orbit conditions
- ***Observations***
  - Pressure may reduce or exacerbate oscillations
  - Pressure may influence thruster mode and mode transition region
  - Past studies demonstrated peak performance near transition, reduced T/P and efficiency in oscillatory mode

Chamber Pressure: 7.0x10^{-7} torr-Xe



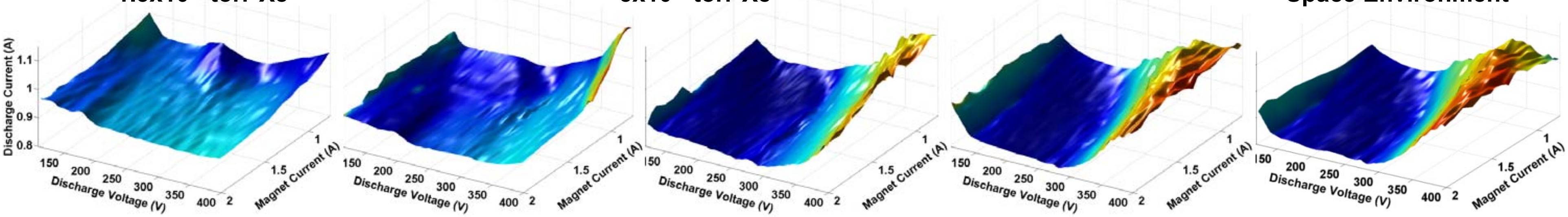
Standard Qualification Pressure
~ 2x10^{-5} torr-Xe

Extrapolating to zero pressure

Near-Field Plume Measurements
<1.3x10^{-5} torr-Xe

Lifetime Evaluation
<5x10^{-6} torr-Xe

Extrapolation to Space Environment



1.1x10^{-5} torr | **7.0x10^{-6} torr** | **3.1x10^{-6} torr** | **7.0x10^{-7} torr** | **GEO, <1x10^{-10} torr**

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I-V-B Pressure Extrapolation to Space Conditions

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✓ Transitioned to USAF, NASA, and Industry

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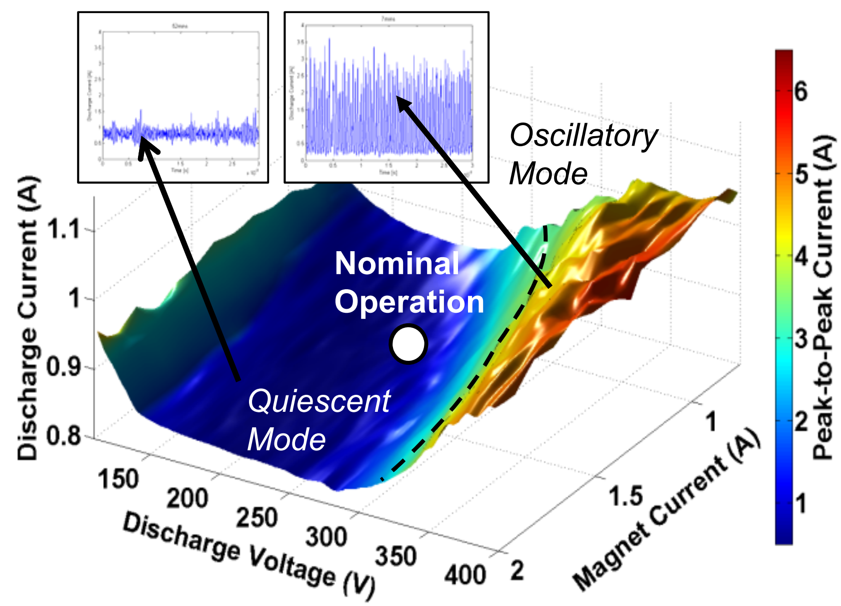

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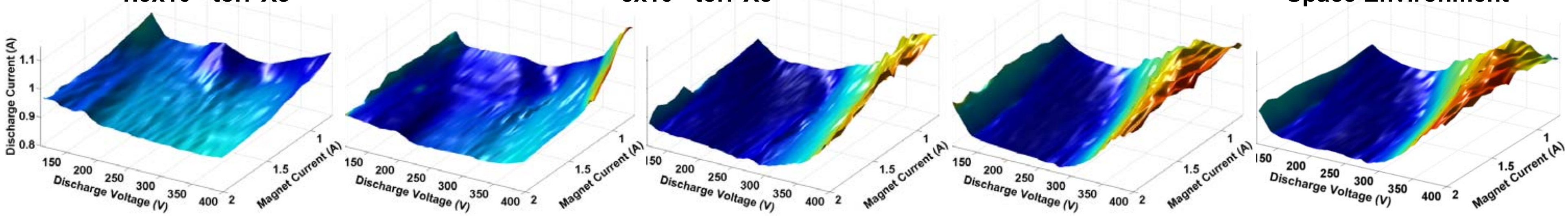

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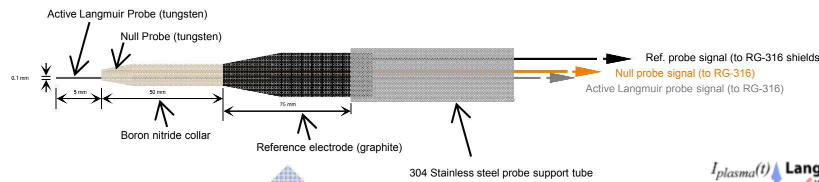
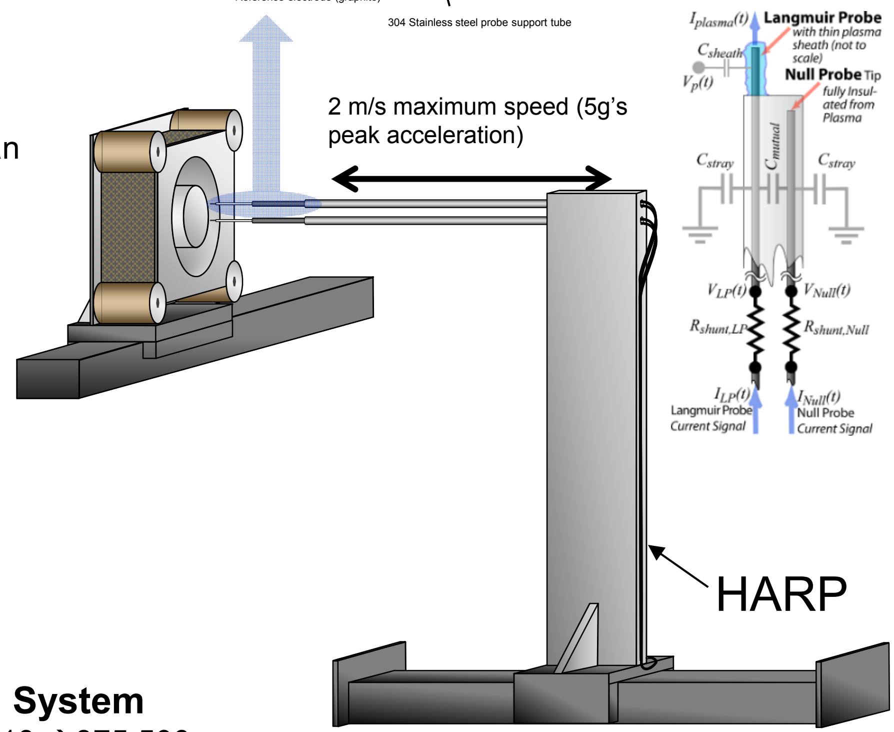
Facility Interaction Studies: Background Pressure

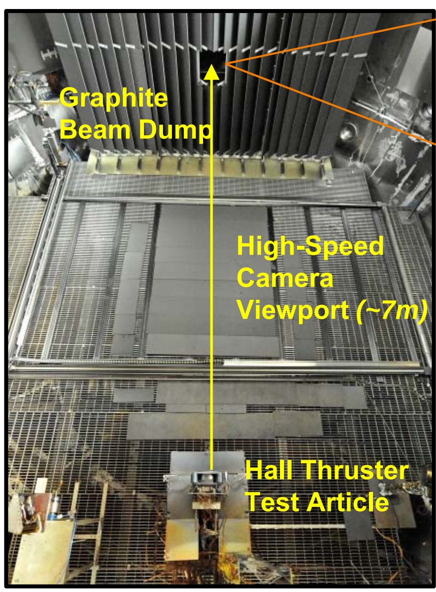
High-speed Plasma Imaging & Probe Diagnostics

Dual Langmuir Probe (HDLP)

- Advanced high-speed Langmuir probe capable of direct time-resolved plasma measurements
  - 1 µs resolution of most plasma properties
  - Electron density and temperature
  - Plasma potential
  - Electron energy distribution function (EEDF)
- Developed (2008) in collaboration with the University of Michigan
- HARP (High-speed Axially Reciprocating Probe) system allows for interrogation of internal discharge plasma



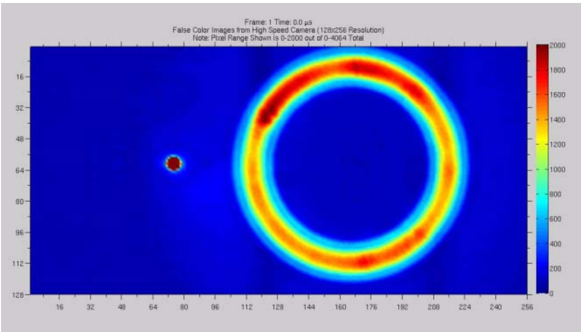


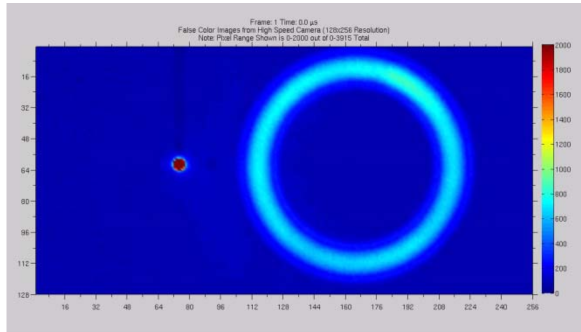


High-speed Plasma Imaging System

- Vision Research Phantom V2010 →375,500 frames/sec 256x128 12-bit, ISO100,000
- Demonstrated Xe & Ar line-filtered 2 µs imaging
  - Collisional radiative theory/models → qualitative plasma images → time-resolved 2-D electron temperature & density

Facility Interaction Studies: Background Pressure
Results – High-Speed Image Analysis



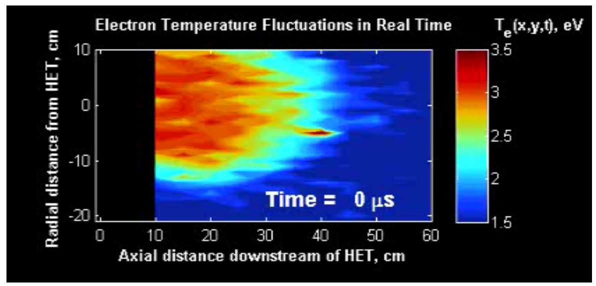


Thruster oscillation behaviors

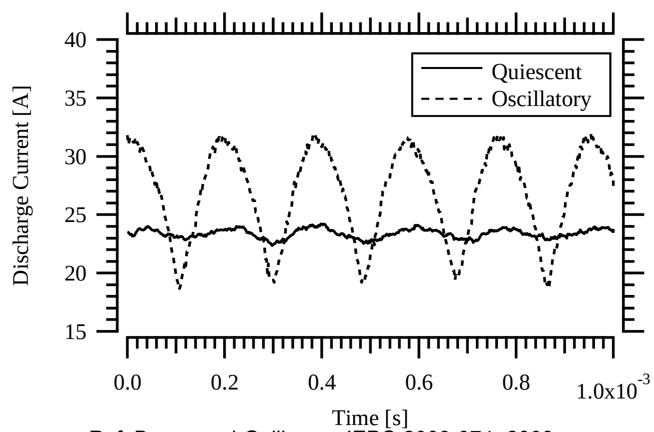
- Quiescent "local" mode with plasma spokes rotating at 1783-1921 m/s
- Oscillatory "global" mode with bursts of plasma, ~30 kHz breathing mode
- Local cathode "bursts" toward channel at ~80kHz

➢ ***Hypothesis: Electron mobility between cathode and thruster channel change with plasma oscillation behavior***

Coupling Investigated with Confinement Cage Experiments

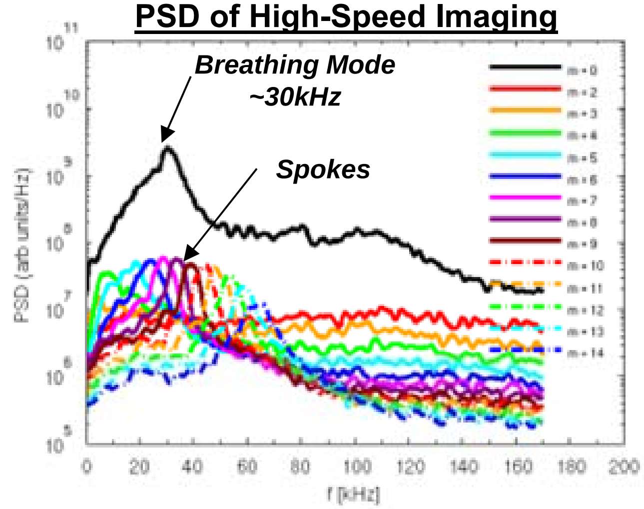


Lobbia, R. B., Ph.D. Dissertation, U of Michigan, 2010.

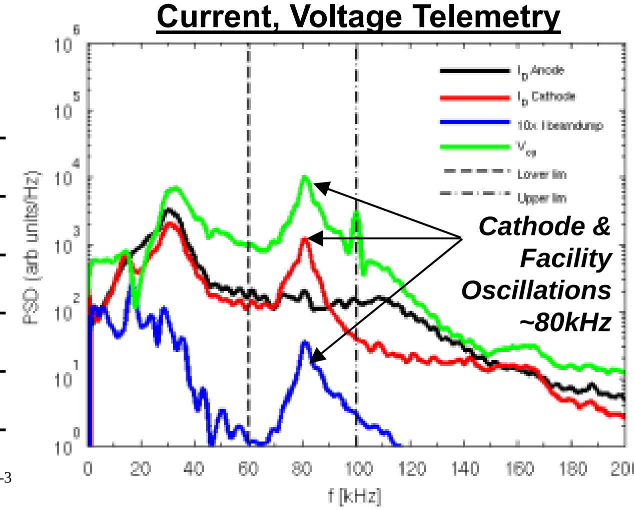


Ref. Brown and Gallimore, IEPC-2009-074, 2009.

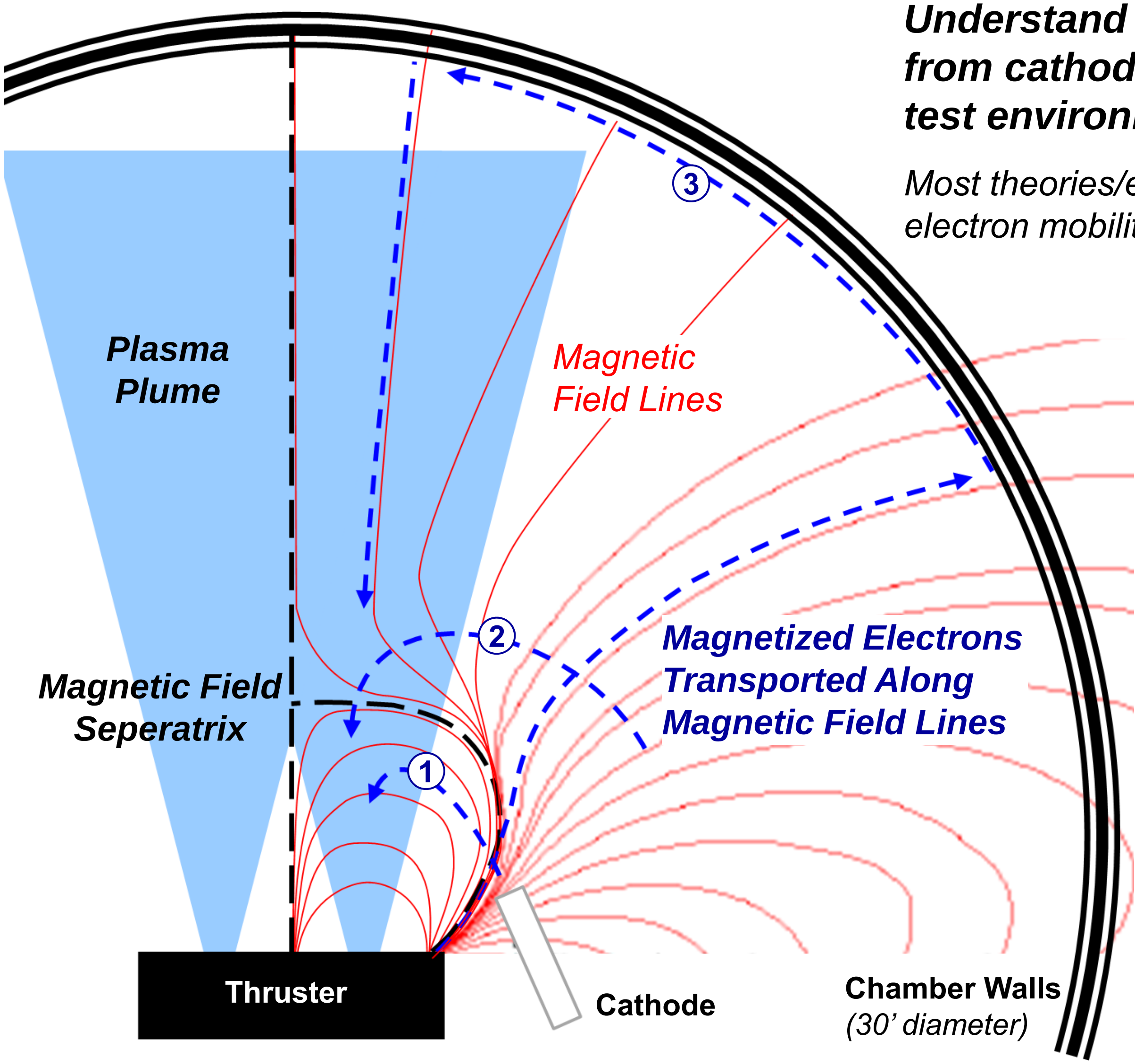
PSD of High-Speed Imaging



Current, Voltage Telemetry



Approach



Understand electron transport mechanisms from cathode to thruster channel in ground test environment and space

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

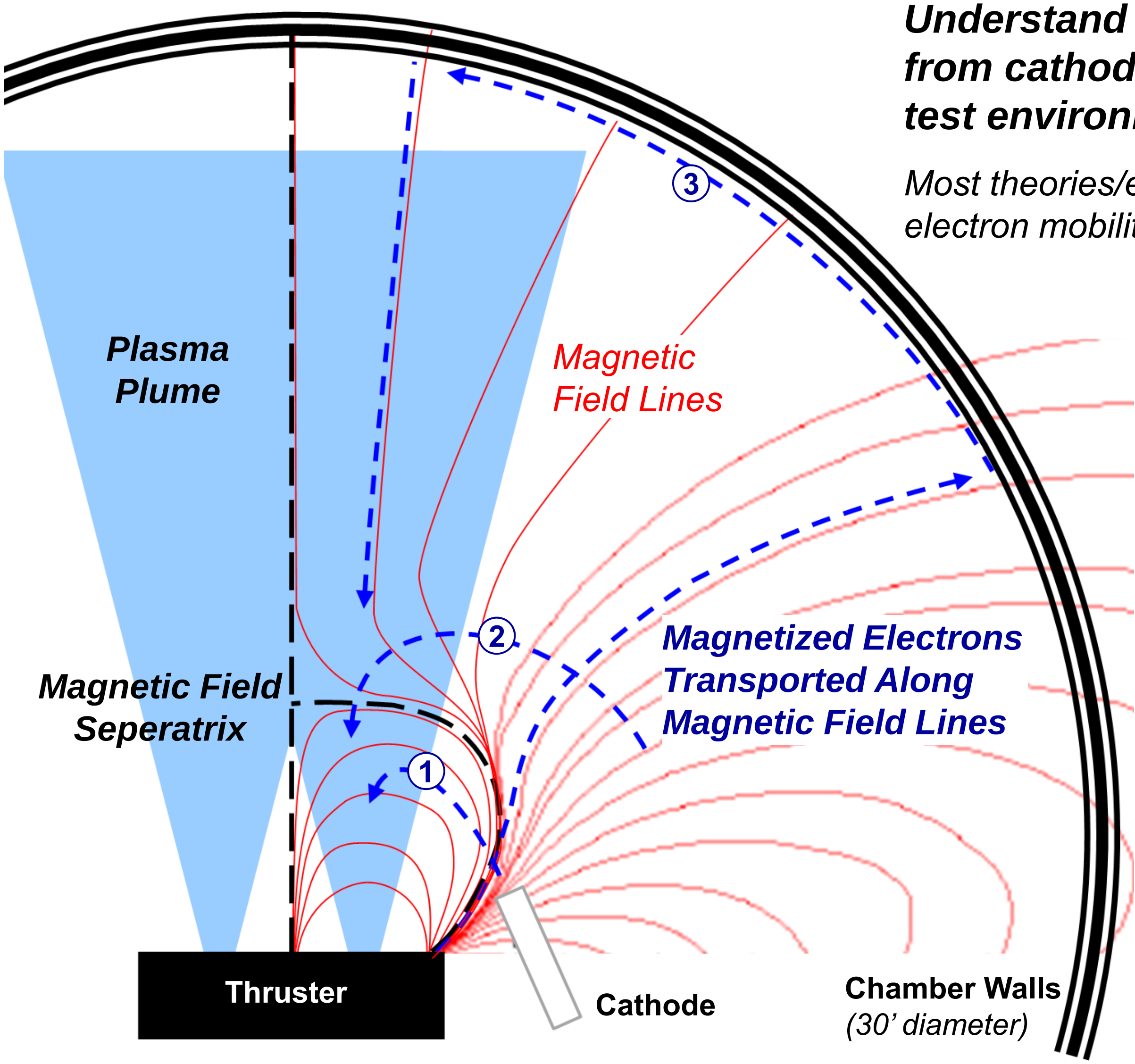
Path 1: Magnetized electron transport impeded across magnetic field lines; ***transport mechanism(s) not determined***

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***

Approach



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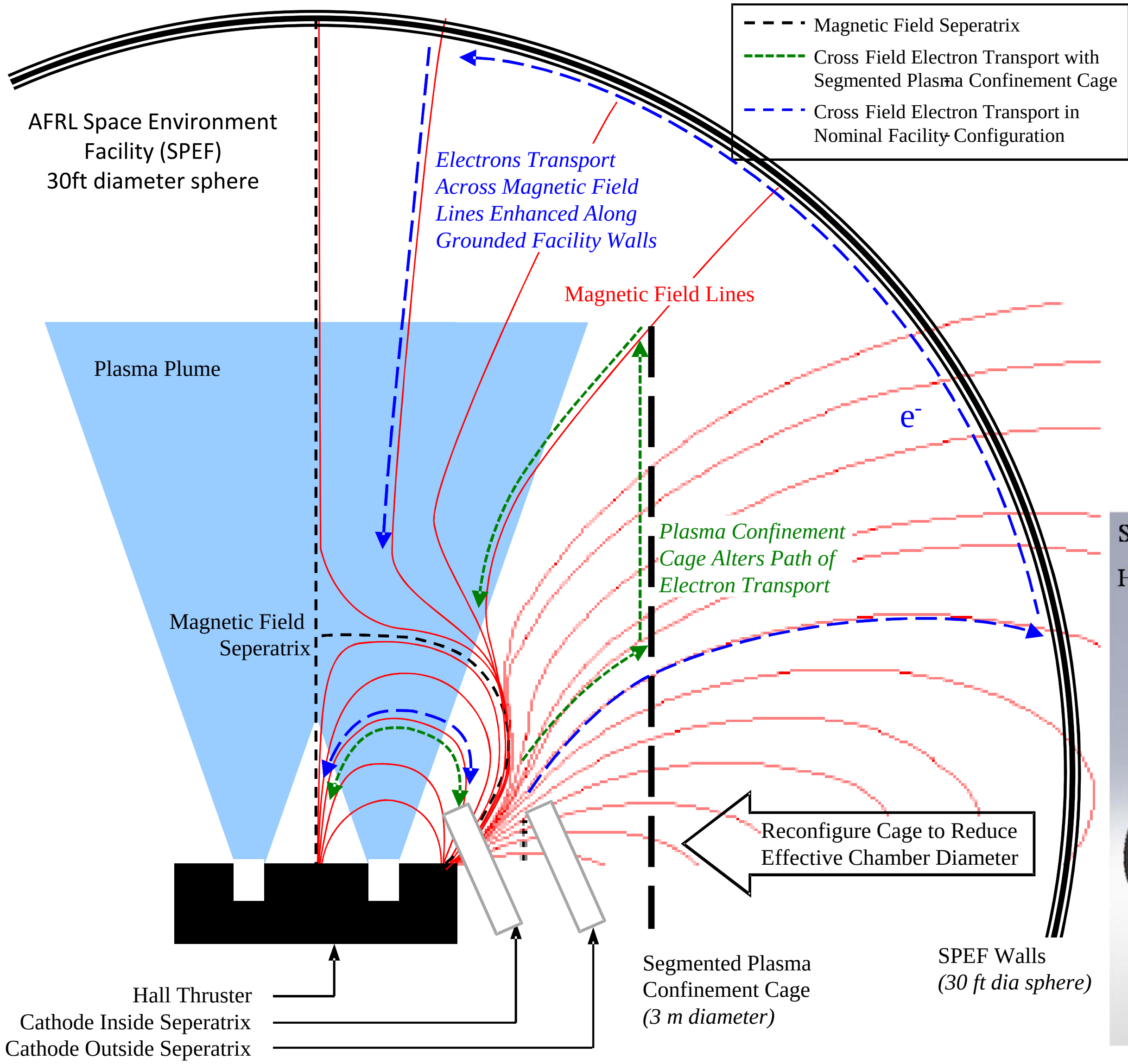
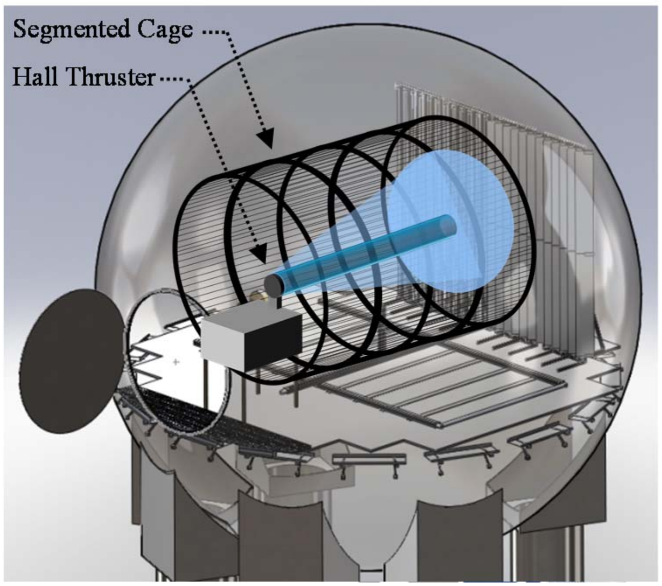
Facility Interaction Studies: Plasma Wall Interactions

Plume Electron Transport



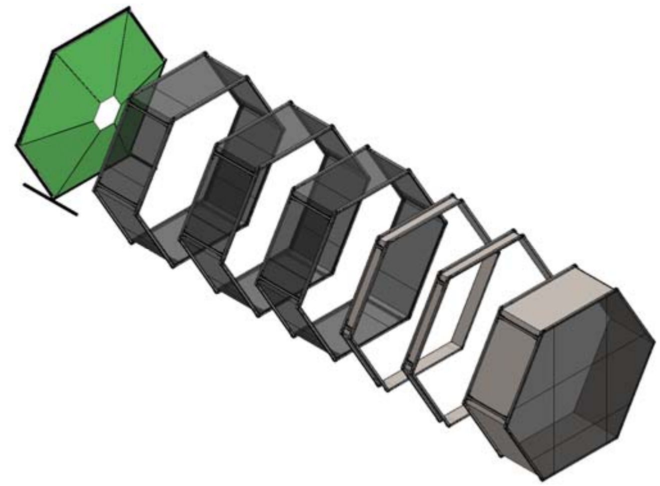
1. Utilize state-of-the-art (SOTA) high-speed imaging and time-resolved diagnostics to study local plasma behavior
2. Control chamber environment with plasma confinement cage to monitor path of current in plume and conductive surfaces
3. Leverage AFRL M&S capabilities and AFOSR EP research efforts

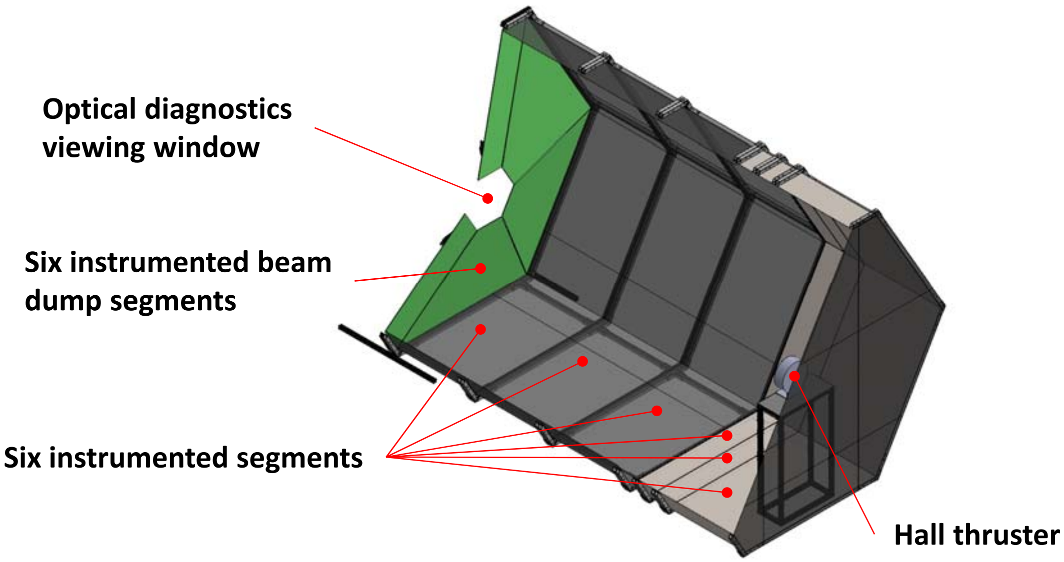


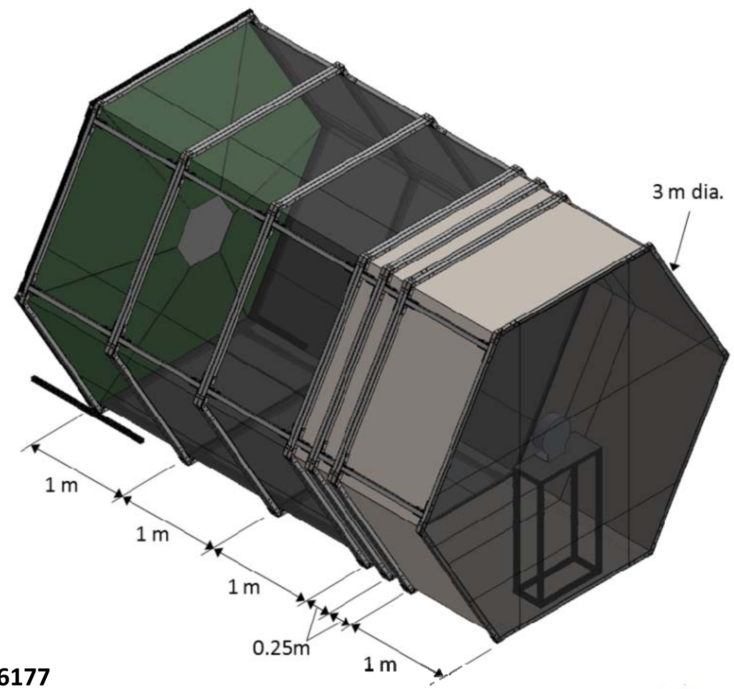
Facility Interaction Studies: Plasma Wall Interactions

Confinement Cage Design

- **Six isolated segments**
  - Instrumented to monitor the path of current and oscillations in the facility along internal surfaces
  - 50-100 channels of 1 MHz simultaneously acquired data
- **Capability to control grounded, biased, and floating surfaces**
  - Identify facility interactions responsible for differences between ground T&E and space
- **Characterize chamber wall sheaths and map neutral distribution as a function of pressure**



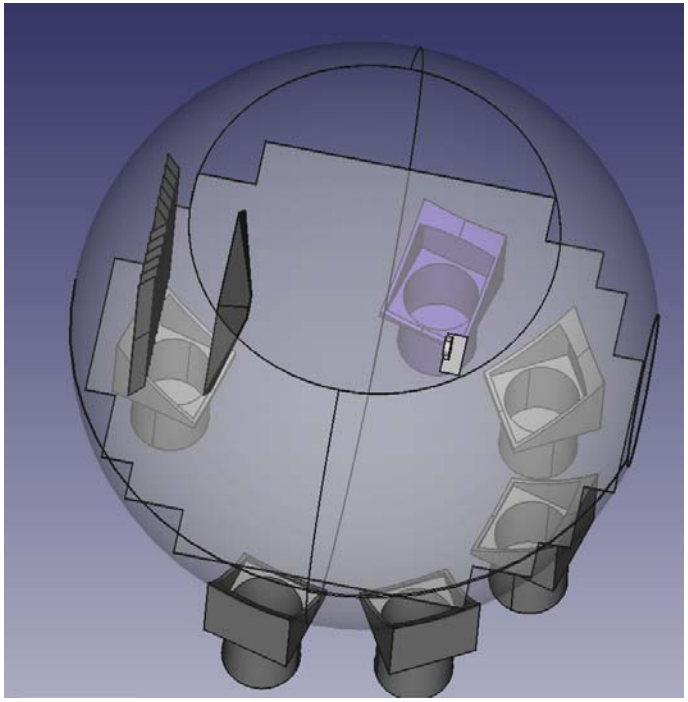


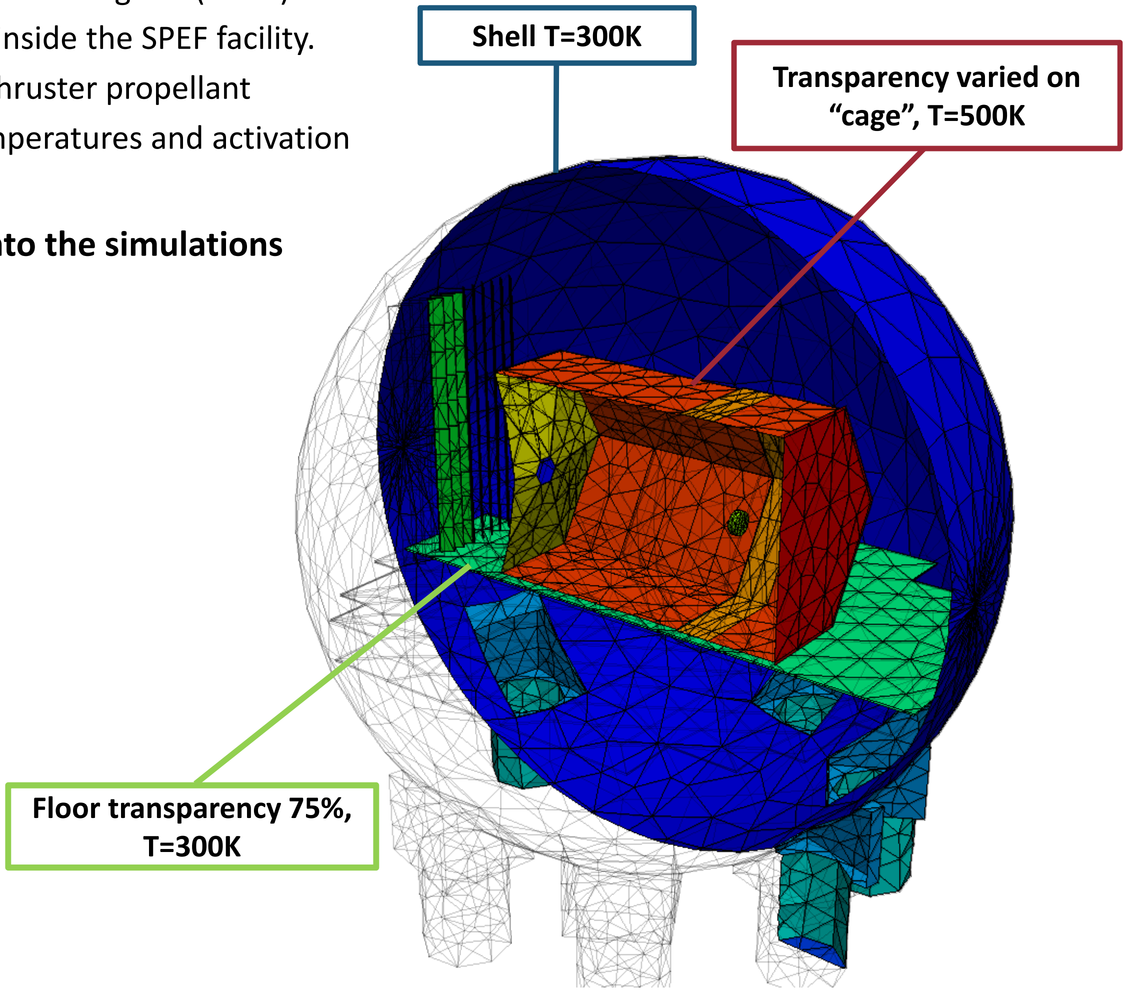


Facility Interaction Studies: Plasma Wall Interactions
Confinement Cage Modeling (1/2)

- **SPEF vacuum chamber modeled using Contamination Transport Simulation Program (CTSP)**
  - Developed by developed by Particle In Cell Consulting LLC (PIC-C).
  - Temporally and spatially resolved pressures inside the SPEF facility.
  - Gas sources: material outgassing, leaks, EP thruster propellant
  - Sinks: vacuum pumps w/defined surface temperatures and activation energies to compute residence time).

➢ **Does NOT incorporate any plasma solvers into the simulations**

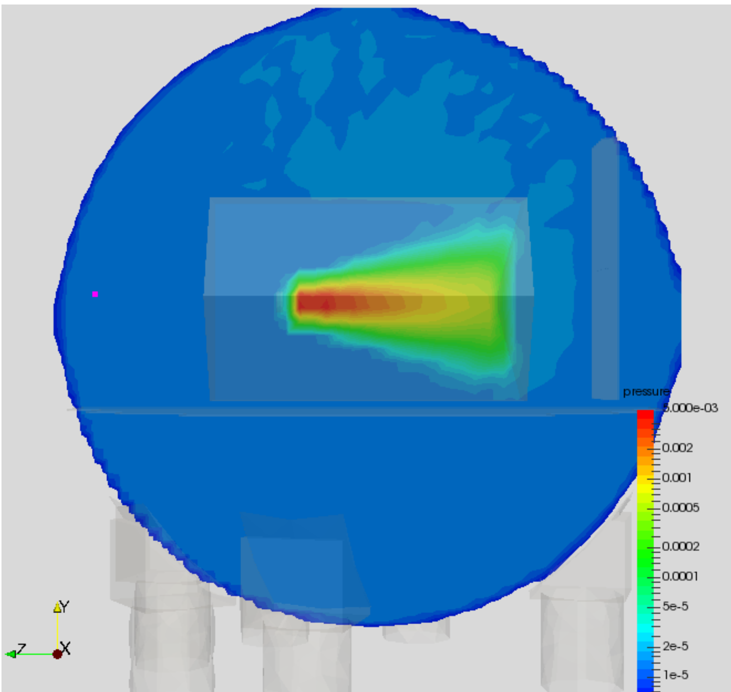




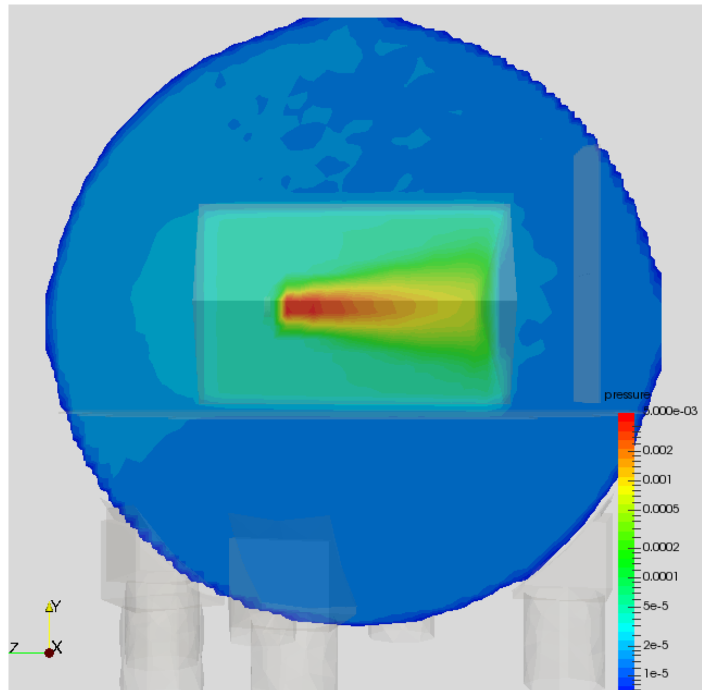
Facility Interaction Studies: Plasma Wall Interactions

Confinement Cage Modeling (2/2)

- **Gas flow representative of model thruster**
  - e.g. 16mg/s total flow → 15mg/s at 15km/s and (ions), 1mg/s at 100 m/s (neutrals)
- **Pressure achievable at steady state informs choice of mesh**
  - Solid walls → lower pumping speed → higher steady state pressure
  - Too high of pressure → inhibits IVB/P extrapolation to space conditions, dampens out oscillatory modes
  - Ideal mesh size meets pressure requirements, maximizes ability to measure current pathways



40% mesh



Solid cage with 40% mesh in back

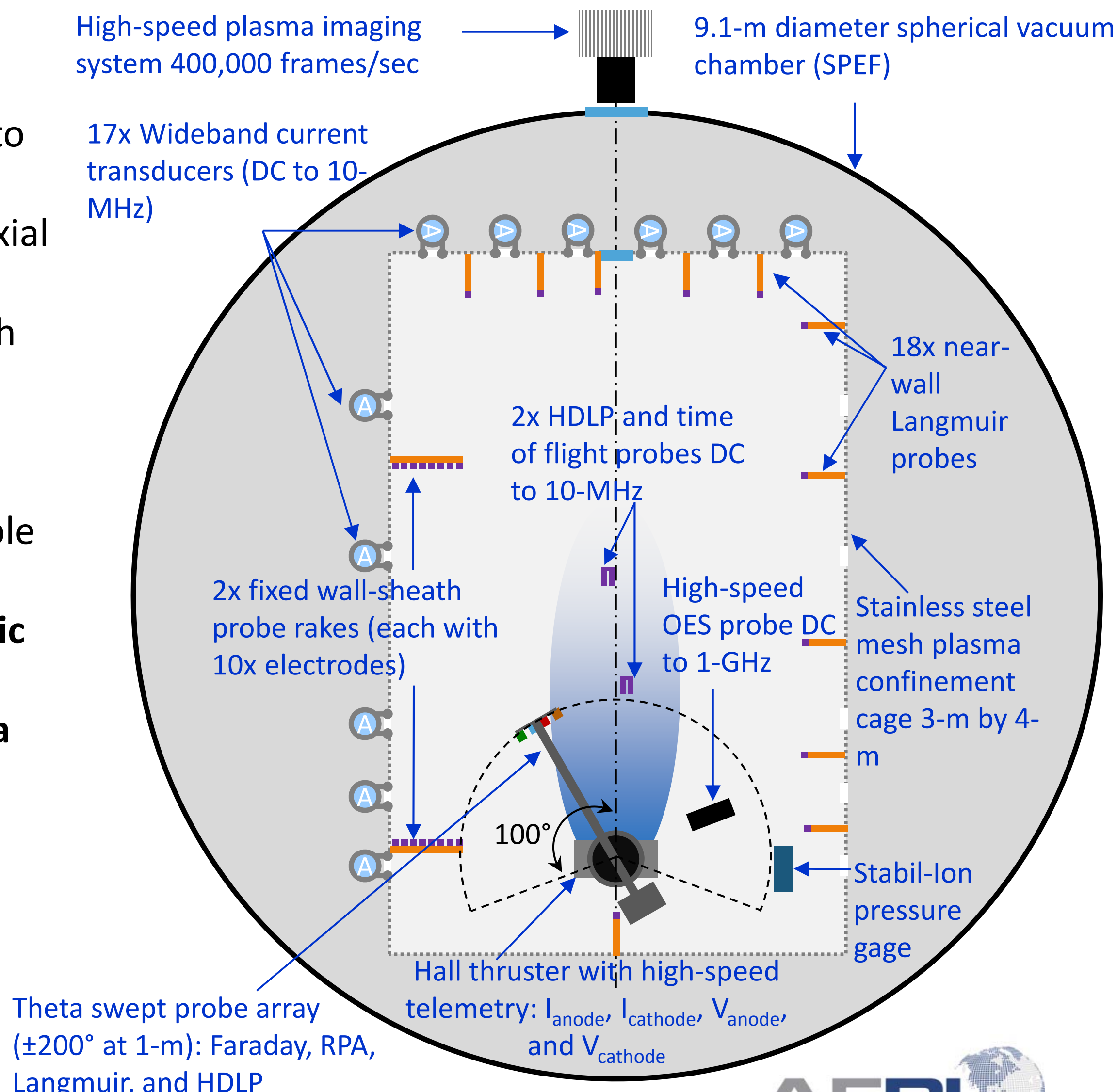
Facility Interaction Studies: Plasma Wall Interactions
Test Instrumentation

Test Instrumentation

- **Plasma confinement cage**
  - Plasma electrostatically confined to cage; all ion paths baffled
  - 18 discrete sections to measure axial and azimuthal current flows
  - Near-wall Langmuir probe for each section
  - 2 wall-sheath probe rakes
  - Internal graphite beam dump
  - Quartz viewport into cage to enable high-speed plasma imaging
- **5x high-speed (DC-10 MHz) electrostatic and optical plasma probes**
- **42x time-averaged electrostatic plasma sensors (Langmuir, RPA, Faraday)**

Data Acquisition

- **24 channels of 200 MHz 16-bit DAQ**
- **100 channels of 2 MHz 16-bit DAQ**

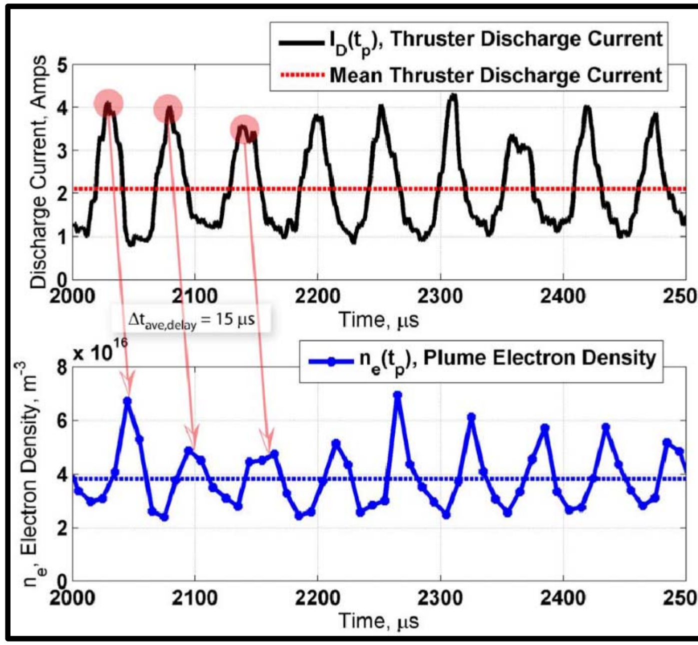


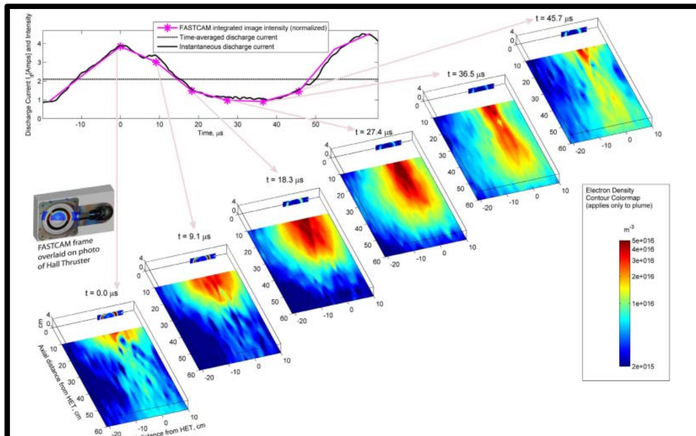
Facility Interaction Studies: Plasma Wall Interactions

Anticipated Results

- **Time-resolved measurements of ion and electron current fluxes**
  - **Resolve fraction of discharge current that is comprised of electron current from the cathode**
    - **Cathode inside the seperatrix →less susceptible to facility effects/coupling**
  - **Increased electron current → primary loss mechanism in plasma discharge**
    - **Indicates change of global electron mobility in the plume**
    - **Identifies facility influences on transport mechanisms, how these mechanisms change with thruster stability**
  - **Identify transient wall surface particle fluxes**
    - **Characterize wall-thruster coupled plasma-dynamics & transport processes**
- **Time-resolved measurements of plasma properties**
  - **Faraday, RPA, Langmuir and HDLP**
    - **Electron density and temperature**
    - **Plasma potential**
    - **Ion & Electron energy distribution functions (IEDF & EEDF)**
  - **OES, High-speed Camera**
    - **Electron density and temperature**

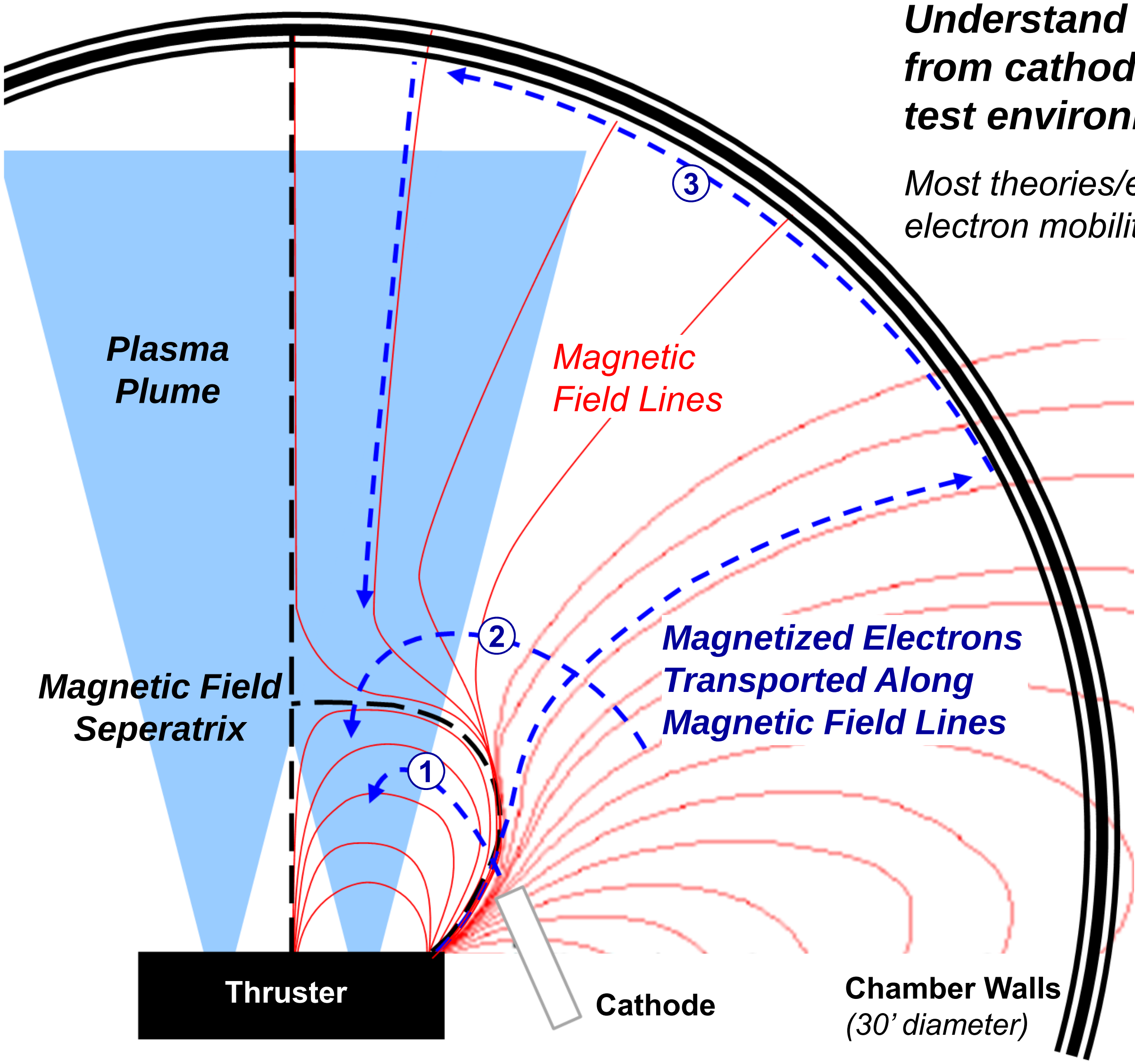
➢ **Critical inputs for M&S**





Multi-signal spatio-temporal data fusion correlation methods that shall be applied to collected confinement cage signals. (from: Lobbia, R. and Gallimore, A., Information Fusion 2009, 12th International Conf. on, pp. 678-685, 2009).

Program Status (1/2)



Understand electron transport mechanisms from cathode to thruster channel in ground test environment and space

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

Path 1: Magnetized electron transport impeded across magnetic field lines; ***transport mechanism(s) not determined*** — **Follow-On Effort**

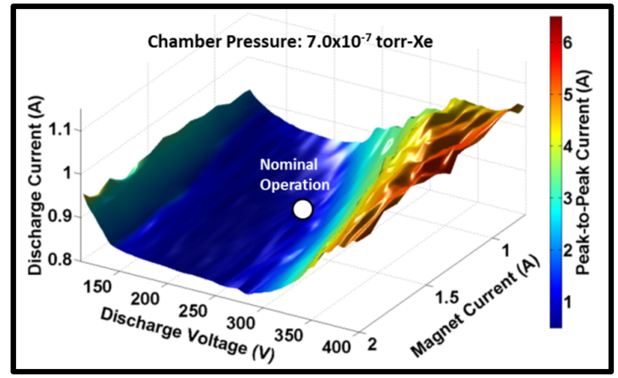
Path 2*: Electron transport enhanced by collisions with chamber background particles *(ground pressure >1* — **✓ Completed 2014/15**

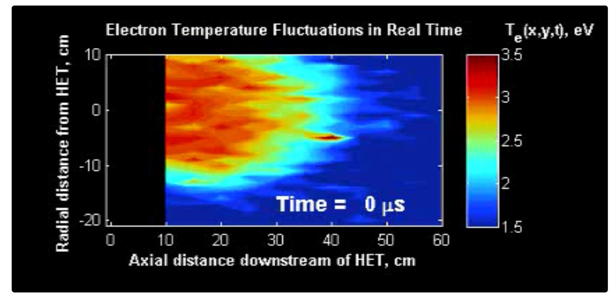
Path 3*: Electron transport enhanced by metallic facility walls and wall sheath — **✓ Completed by Oct 2016**

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

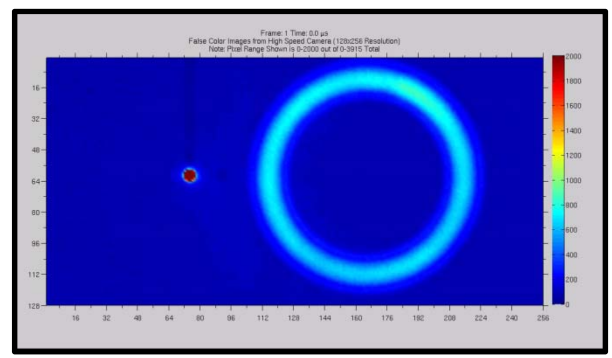
Program Status (2/2)

- **FY 14/15: Development of test methodologies**
  - Developed IVB, IVP mapping T&E approach
  - Demo high speed probe and FASTCAM diagnostics
- **Oct 2015 – Jan 2016: FalconSat-6 spacecraft testing**
  - Fixed probe Hall thruster plume mapping: RPA, ExB, LPs, HDLP, FASTCAM
  - Limited "IVB/P" mapping
- **Mar– May 2016: Hall thruster testing in confinement cage**
  - Evaluate thruster performance and plume characteristics from minimum facility pressure to maximum accepted qualification pressure to estimate on-orbit behavior
  - IVB/P, stability mapping
  - High-speed plasma diagnostics, FASTCAM
  - Cage-panel leakage-current transient measurements
  - Beam dump biasing
- **September 15, 2016: FalconSat-6 Launch**





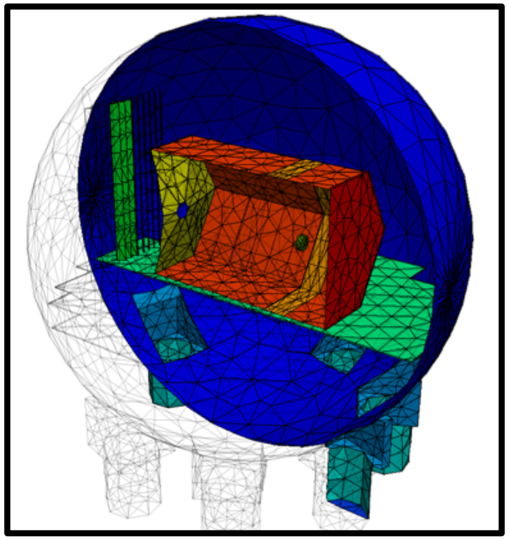
Ref. Lobbia, R. B., Ph.D. Dissertation, University of Michigan, Ann Arbor, MI, 2010.



Next Steps

Objectives of an EP TEMPEST Follow-On Effort

1. **Develop an Electron Mobility Diagnostic (EMD) to measure the cross-field transport of electrons in the discharge of a Hall thruster**
   - **Leverage in-house M&S capabilities to model probe characteristics to enable extraction of accurate electron mobility values from measured electron energy distribution functions (EEDFs)**
2. **Incorporate electron mobility measurements into vacuum chamber facility models in the SM/MURF framework**
   - **Better understand the impact of background pressure and metallic chamber walls on the plasmadynamic processes and electron transport mechanisms driving differences in stability behavior**
3. **Use integrated thruster and facility models to inform modification of AFRL's SPace Environment Facility (SPEF) to better emulate the space environment**
4. **Validate test methodologies and facility improvements through comparison of ground-based predictions with flight data FalconSat-6**
5. **Transition validated methodologies and test capabilities to AEDC, NASA and industry partners**



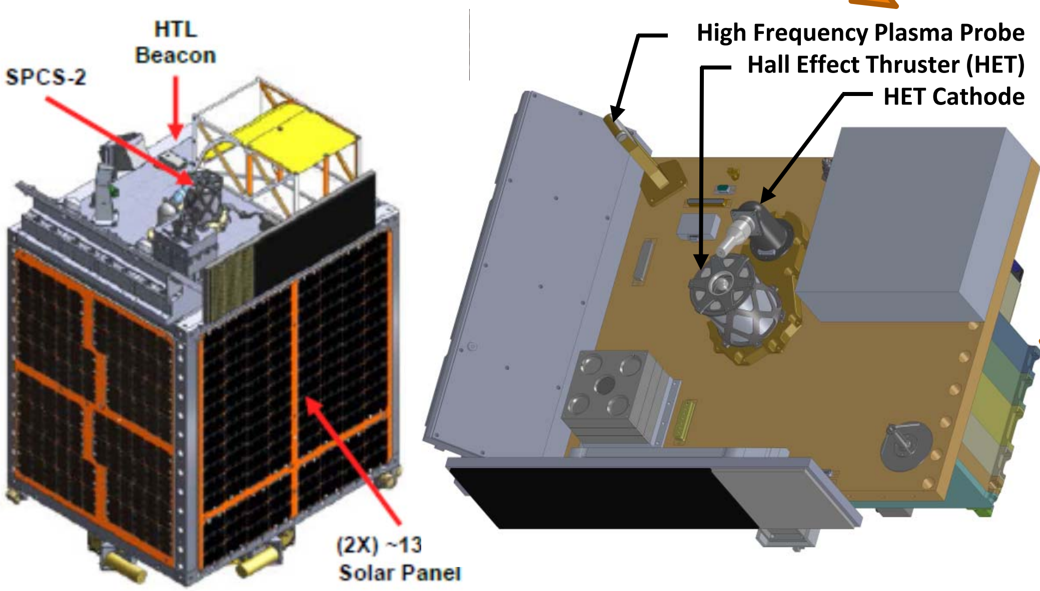
Validation of T&E Methodologies
Compare Ground Predictions to Space Operation

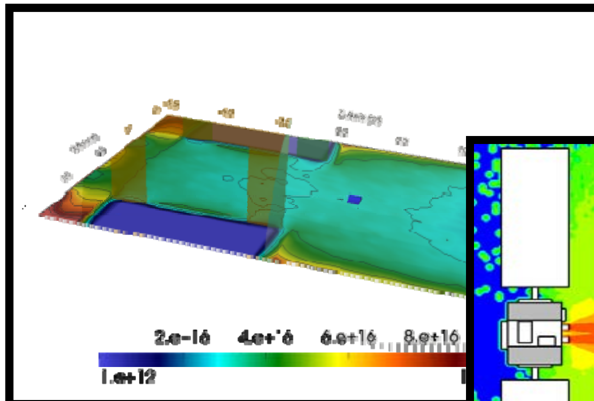
FalconSat-6 (Launch in Late 2016)

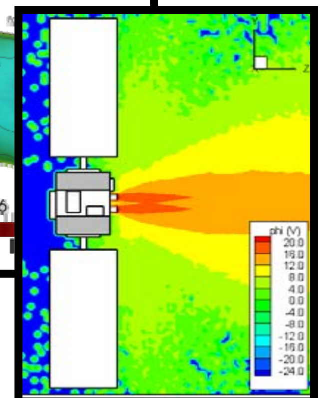
Unique Opportunity to Directly Assess Ground vs Space Operation and Validate T&E Methodologies

1. **Develop predictions based on experiments and models prior to launch**
2. Inform propulsion CONOPS for AFRL Space Plasma Characterization Source, Mark II (SPCS-2) on FalconSat-6
3. Validate methods with direct comparison of flight data to predictions

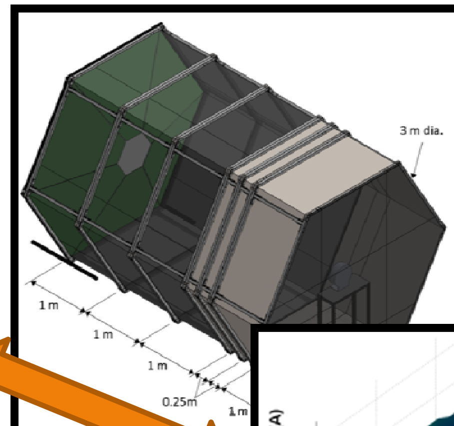
FalconSat-6



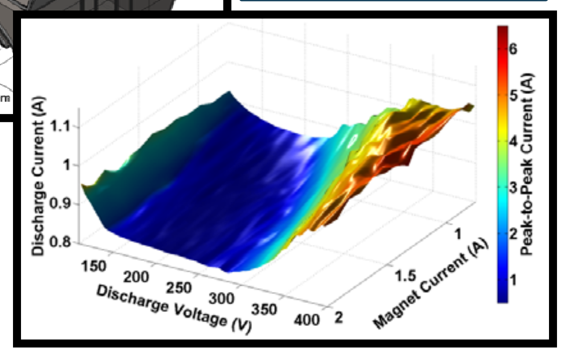




M&S in ground vs space environment



Facility interaction studies, new T&E methods



Technology Transition Status

- **Transitioned I-V-B mapping techniques to USAF, NASA, and Industry**
- **Received SMC/MCA Endorsement for 6.1 EP T&E Research**
- **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
  - Plan to incorporate newly developed EP diagnostic standards into transition
  - Transition T&E methods and AFRL M&S capabilities in FY16/17
- **Coordinating AFOSR funded thruster plasma research and M&S efforts 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 and coherent plasma structures
  - Lab Task: "Laser Plasma Interactions (LPI)," PM: Jason Marshal (AFOSR), PI: David Bilyeu (AFRL/RQRS)
- **Continued participation in EP working group devoted to *"understanding and mitigating facility effects in the testing and characterization of EP devices, and thereby supporting transition of EP technologies to flight"***
  - Anomalous electron transport workshop (JPL, August 2015)
  - Plasma transport workshop (Joint Propulsion Conference, July 2016)

Summary and Conclusions

- **I-V-B methodology successfully demonstrated and transitioned**
  - Identified global thruster trends and mode transitions
  - Enables extrapolation to zero pressure
  - Multiple transitions demonstrated utility for national space assets
- **Plasma wall interaction study is ongoing**
  - Confinement cage built and instrumented
  - Identify current paths that enhance electron transport across magnetic field lines
- **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
- ***Follow on proposal submitted***
  - *Addresses direct measurement of electron mobility*
  - *Coordinated effort with M&S to investigate physics behind "mode-hopping"*
  - *Successful completion will inform T&E facility modifications to better emulate space environment*

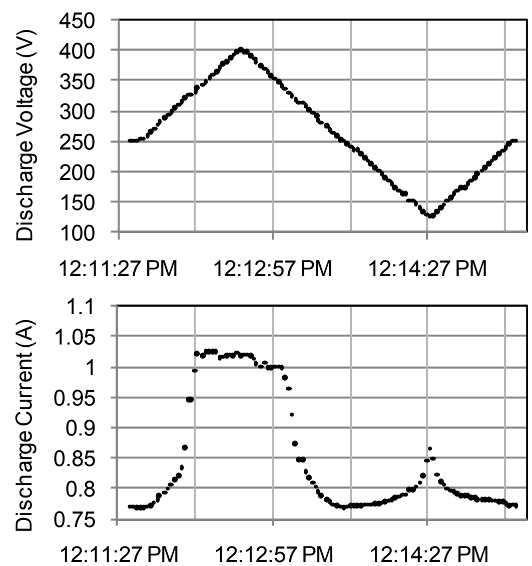
Questions?

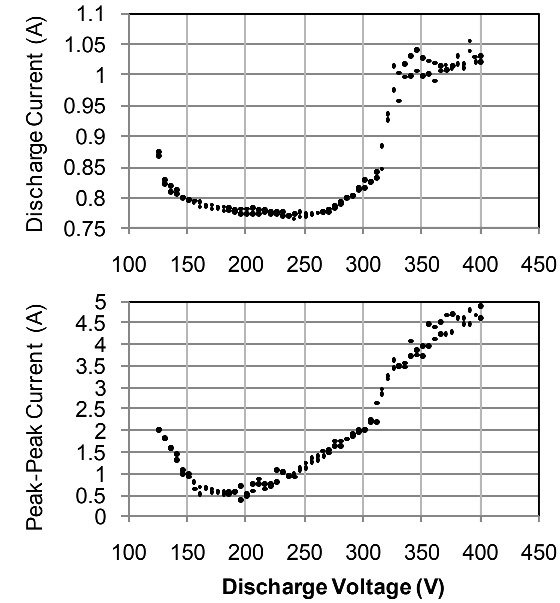
Facility Interaction Studies: Background Pressure

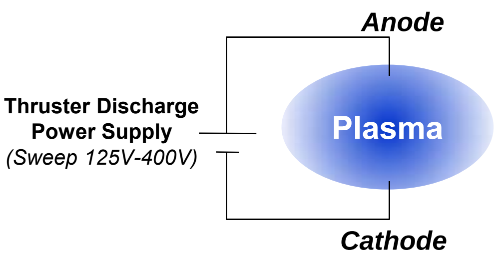
Current-Voltage-Magnetic Field (I-V-B) Maps

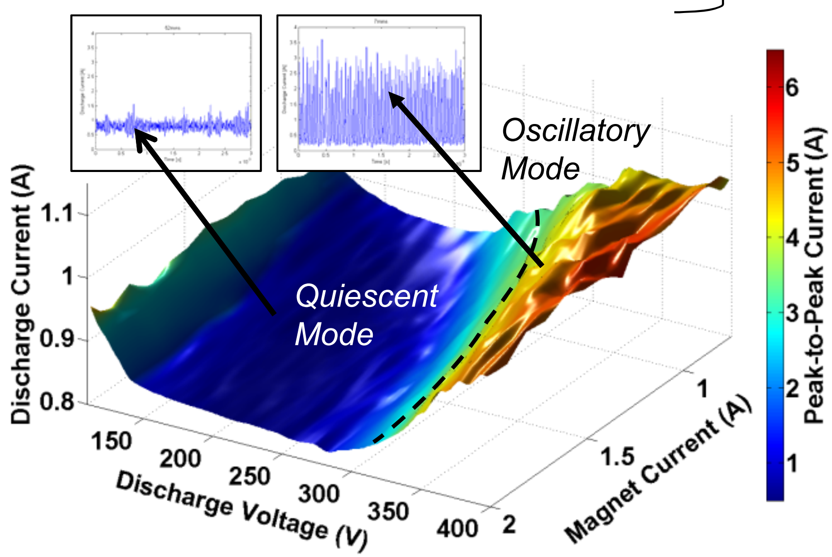
Rapidly map global thruster behavior and identify mode transitions

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

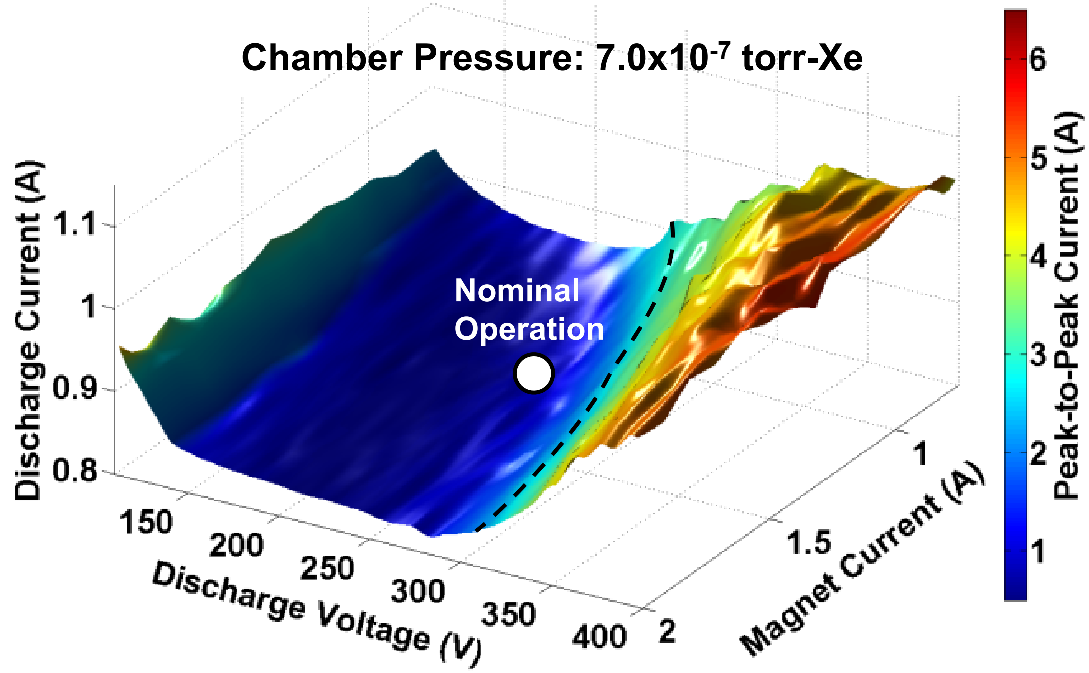
Plot I-V-B map with color scale for telemetry (e.g. current oscillations) to assess global trends and facility interactions

Development of Ground T&E Methods

I-V-B Pressure Extrapolation to Space Conditions (1/2)

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

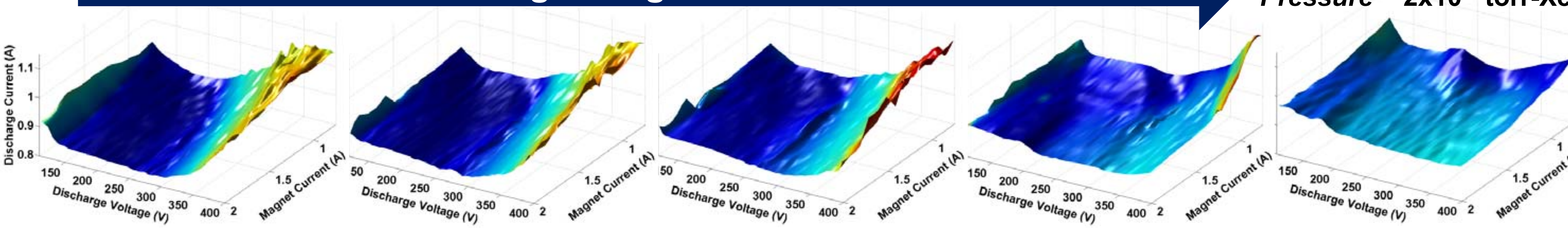


What is acceptable background pressure?

Can we extrapolate to zero pressure?

Increasing Background Pressure

Standard Qualification Pressure ~ 2x10^{-5} torr-Xe



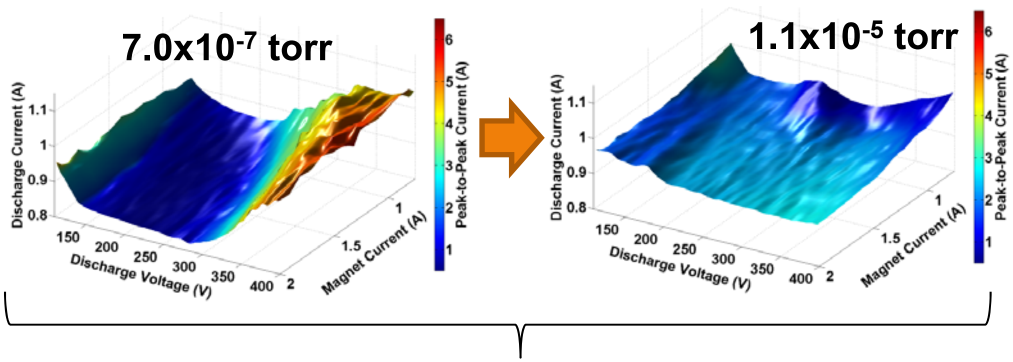
2.1x10^{-6} torr | **3.1x10^{-6} torr** | **5.2x10^{-6} torr** | **7.0x10^{-6} torr** | **1.1x10^{-5} torr**

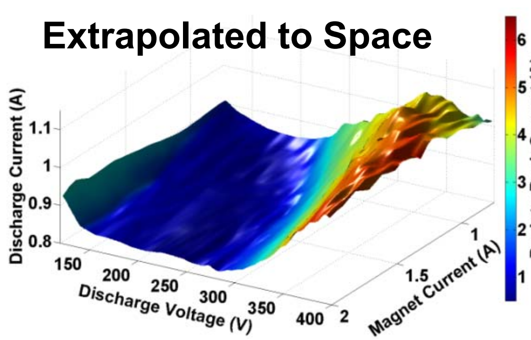
Development of Ground T&E Methods

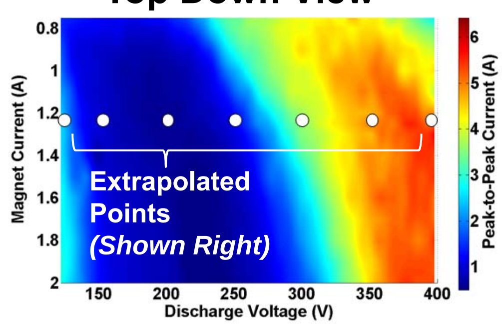
I-V-B Pressure Extrapolation to Space Conditions (2/2)

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**

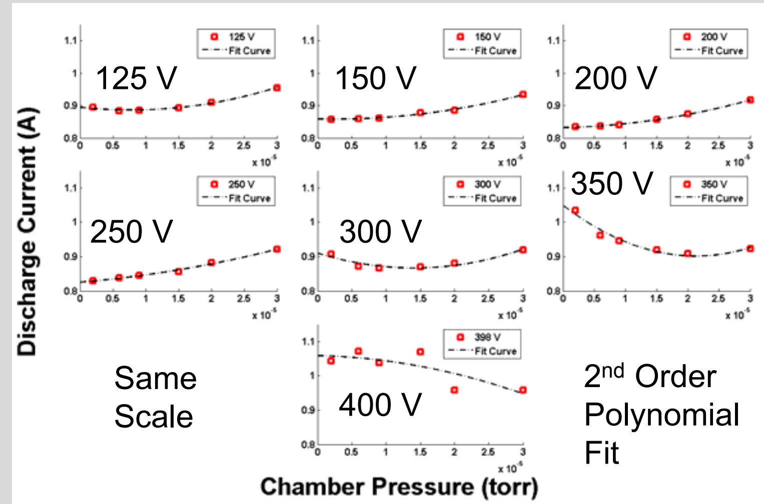






Detailed Pressure Characterization Shows Clear Trends to Vacuum → POSITIVE SIGN

Discharge Current Mean versus Pressure



Discharge Current Peak-Peak versus Pressure