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

**Briefing Charts**

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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

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

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

PAYOFF - Pervasive Space Capability for Increased Payload

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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

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

- Maximize Delivered Mass
- Minimize Firing Time

High Payoff
Evolving Space Power Capabilities Driving Next Generation High-Power EP
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
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

Power Processing Unit (PPU)
- Input Power
- Anode Flow
- Cathode Flow
- Outer Electromagnet
- Inner Electromagnet
- Magnetic Circuit
- Plasma Potential [V]
  - Anode Potential (100-800V)
  - ~10V

Electromagnets
- Electron Transport to Channel for Ionization
- Electrons to Plume for Neutralization
- Hall Current

Propellant Flow Control System
- Propellant Tank
- Anode Potential (100-1000V)

Magnetic Field Lines
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

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

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

$1.3 \times 10^{-6}$ torr-Xe

$3.0 \times 10^{-6}$ torr-Xe

$4.8 \times 10^{-6}$ torr-Xe

Predict Thruster Performance By Extrapolation to Vacuum?

Predict Spacecraft Plume Interactions By Extrapolation to Vacuum?


Facility Interactions are Unavoidable

Effects on Plumes are Well-Characterized…. Thruster Interactions are More Complex
Signs of chamber effects on thruster performance, plume, and stability observed in U.S. since 1990s

- RDT&E solution = Minimize chamber pressure
  - <5x10^{-5} torr for performance
  - <1.3x10^{-5} torr for plume measurements <1.2m
  - <5x10^{-6} torr residual for lifetime evaluation to maintain sputter return rate <$0.1\text{Å/s}$
- 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
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 plasmodynamic 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 plasmodynamic 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*

**Resistance (Mobility⁻¹)~ B²/v~B²/nₙ**

where  

- \( v = \text{collision freq.} \)
- \( nₙ = \text{neutral density} \)
- \( B = \text{Magnetic Field} \)

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
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
**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 ($1 \times 10^{-5}$ 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

**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
Objective 1: Facility Interaction Studies
Results – High-Speed Image Analysis (1/2)

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)

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)

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
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
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

**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

Transitioned to USAF, NASA, and Industry

Distribution Statement A: Approved for public release; distribution is unlimited.
**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)

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**Objective 1: Facility Interaction Studies**

**Results – I-V-B Maps**

**Plasma Facility Coupling**

- Increased Beam Dump Current Due to Ions or Electrons?

**Ground Test Chamber Pressure Variation**

- Nominal Operation

**Transient and Thermal Variation**

- Current Oscillations

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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?

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

Nominal Operation

Discharge Current (A)

Peak-to-Peak Current (A)

Discharge Voltage (V)

Magnet Current (A)

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
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

![Graphs showing Discharge Current Mean versus Pressure](image)

![Graphs showing Discharge Current Peak-Peak versus Pressure](image)

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

![Diagram of FalconSat-6](image)

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