NASA Glenn SmallSat/CubeSat Activities and Capabilities

International Cubesat Propulsion Workshop

George Washington University
Washington DC

August 1, 2018

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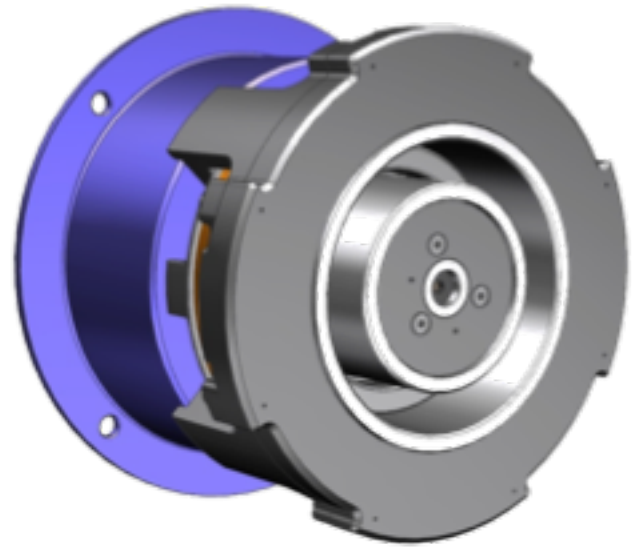
Presentation Outline

- On-going NASA GRC projects in the development of propulsion subsystems for cubesats and smallsats
- GRC capabilities for
  - Testing and characterization of third-party propulsion systems
  - Modeling and design analysis
  - Mission and system analysis
- Standards development for Class D missions

STMD Game Changing Development (GCD)
Sub-Kilowatt Electric Propulsion (SKEP)

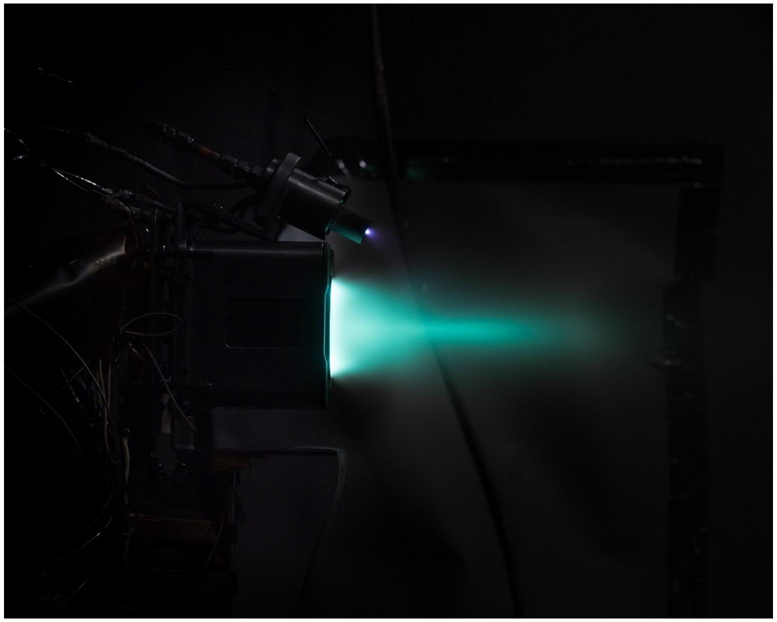
- Developing a long-life and high performance sub-kilowatt (~500 W) propulsion system appropriate for NASA exploration and science missions benefiting from low-cost ESPA-class (<500 kg) spacecraft.
- Lifetime and performance goals will be achieved by leveraging prior investments, including Center Innovation Funds (CIF), STMD Solar Electric Propulsion (SEP), Advanced In-Space Propulsion (AISP), Small Business Innovation Research (SBIR), Tipping Point, Announcement of Collaborative Opportunity (ACO), and investments in GRC infrastructure.
- Reliability shall be maximized and cost minimized by:
  - Minimizing number of throttle set-points (2)
  - Minimizing part count in propulsion system assembly
  - Maximize use of flight heritage components and assemblies
- Key technologies include:
  - Advanced Hall thruster magnetics
  - Centrally-mounted hollow cathode
  - GRC-pioneered hollow cathode assemblies such as the International Space Station Plasma Contactor Units
  - GRC robust propellant manifold assembly designs
  - Extensive in-house power processing unit development expertise



Key Performance Parameter	Goal
Total Impulse [MN-sec]	>1
Demonstrated Life Time [hours]	>10,000
On / Off Cycles	5,000
Propellant Throughput [kg] (Delta-V 300 kg Sat [km/s])	>90 (>5.3)
Integrated System Mass [kg]	<7

STMD Game Changing Development (GCD) - Advanced In-Space Propulsion (AISP)

- Development and demonstration of a 600W integrated Hall thruster iodine propulsion system (thruster, cathode, power processing unit, propellant storage, and feed system). The scope of work aimed to mature the critical propulsion system components and perform integrated system testing.
- Tasks aimed to address critical technology gaps and risks:
  - Scale up to higher power and increased propellant throughput
  - Evaluate engineering / material changes between xenon and iodine
  - Durability testing >1000 hrs for thruster and cathode
  - Iodine propellant flow control and metering
  - Material chemical interactions testing
- **Successfully performed 1,174 hour durability test**
  - Test concluded after 2nd load of propellant exhausted
  - Busek BHT-600-I Thruster (iodine fed)
    - Performed very similarly on iodine and xenon
    - Minor material compatibility issues, but easily resolvable
  - GRC heritage cathode (xenon fed)
    - SEM showed no observable iodine contamination or emitter degradation
  - GRC developed iodine storage and feed system
    - Very stable and reliable iodine delivery throughout test
    - No clogging or feed system component degradation
  - Laboratory power supplies
    - Busek developed 600W compact PPU not ready for implementation at time of durability test.



Reference paper: Benavides, Kamhawi, Mackey, Haag, and Costa, “Iodine Hall-effect Electric Propulsion System Research, Development and System Durability Demonstration, AIAA-2018-4422, AIAA JPC July 2018.

Space Technology Announcement of Collaborative Opportunity (ACO) - Busek 600W Hall Thruster Qualification Life Test

- ACO – focuses on advancing commercially-developed technologies that can benefit both commercial and government use of space
- Busek 600 W thruster wear test
  - BHT-600 Busek hall thruster, BHC-2500 cathode, and PPU
  - NASA GRC provided test facilities and test support
  - 5000 hour qualification life test
  - Retiring thruster lifetime testing will reduce cost for future customers
  - Testing window - June 2018 to June 2019

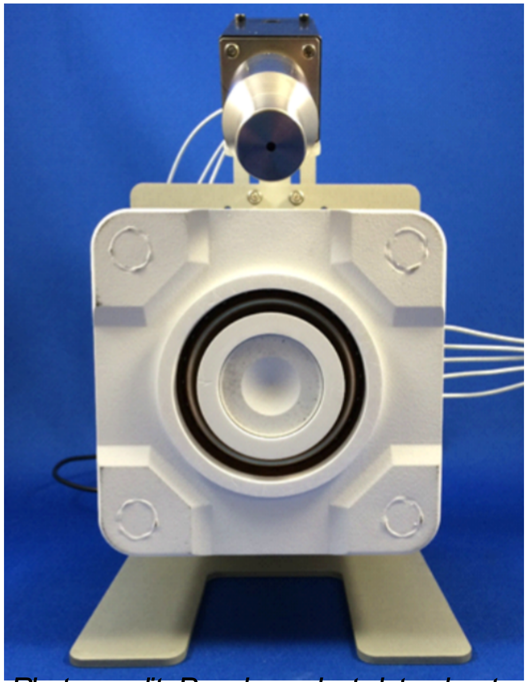
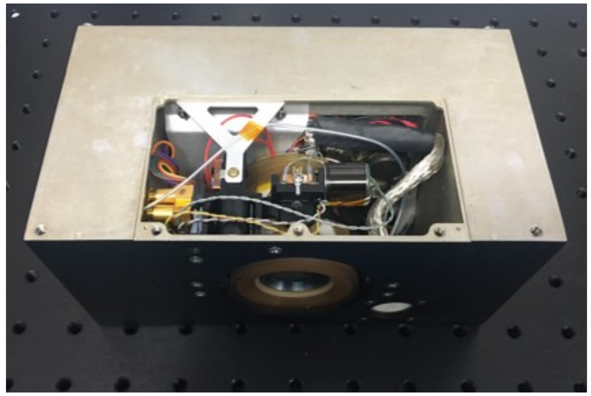


Photo credit: Busek product data sheet

BIT-3 and HEOMD AES Lunar IceCube

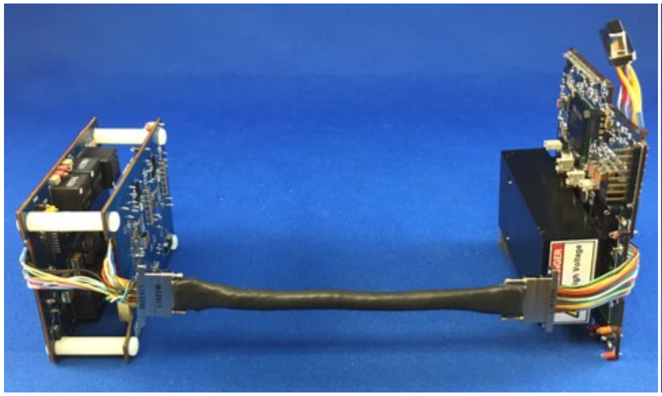
- Iodine-fueled BIT-3 RF ion propulsion system will be flying on Lunar IceCube and LunaH-Map (SLS EM-1 launch)
- BIT-3 is a complex EP system in a very tight package
  - Light weight, rad-tolerant PPU
  - Innovative iodine feed system w/ up to 1.5 kg propellant
  - 3cm gridded RF ion thruster and 1cm RF cathode
  - 2-axis gimbal with +/- 10º slew
- System undergoing integration and qualification testing now
  - Vibe by Mar 2018; Thermal-Vac by Apr 2018
- SBIR ph2-X recently awarded for extended life and integration testing
  - Test duration up to 4,000 hrs, start in Apr 2018
- BIT-3 flight hardware delivery to both flight missions is scheduled for CY18

BIT-3 System Characteristics	
Thrust	0.88 mN nom., 1.24 mN max.
Total Isp	1,870 sec nom., 2,640 sec max.
Input power	65 W nom., 80 W max.
Mass	1.5 kg dry / 3 kg wet
Volume	1.6 U
Delta-v	~2 km/s for 6U Cubesat

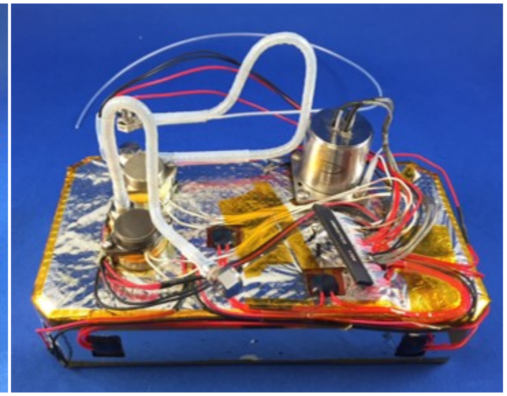


BIT-3 QM System (1.6U / 3kg Wet)

BIT-3 & Cathode at Max Power on Iodine



Power Processing Unit (500g)

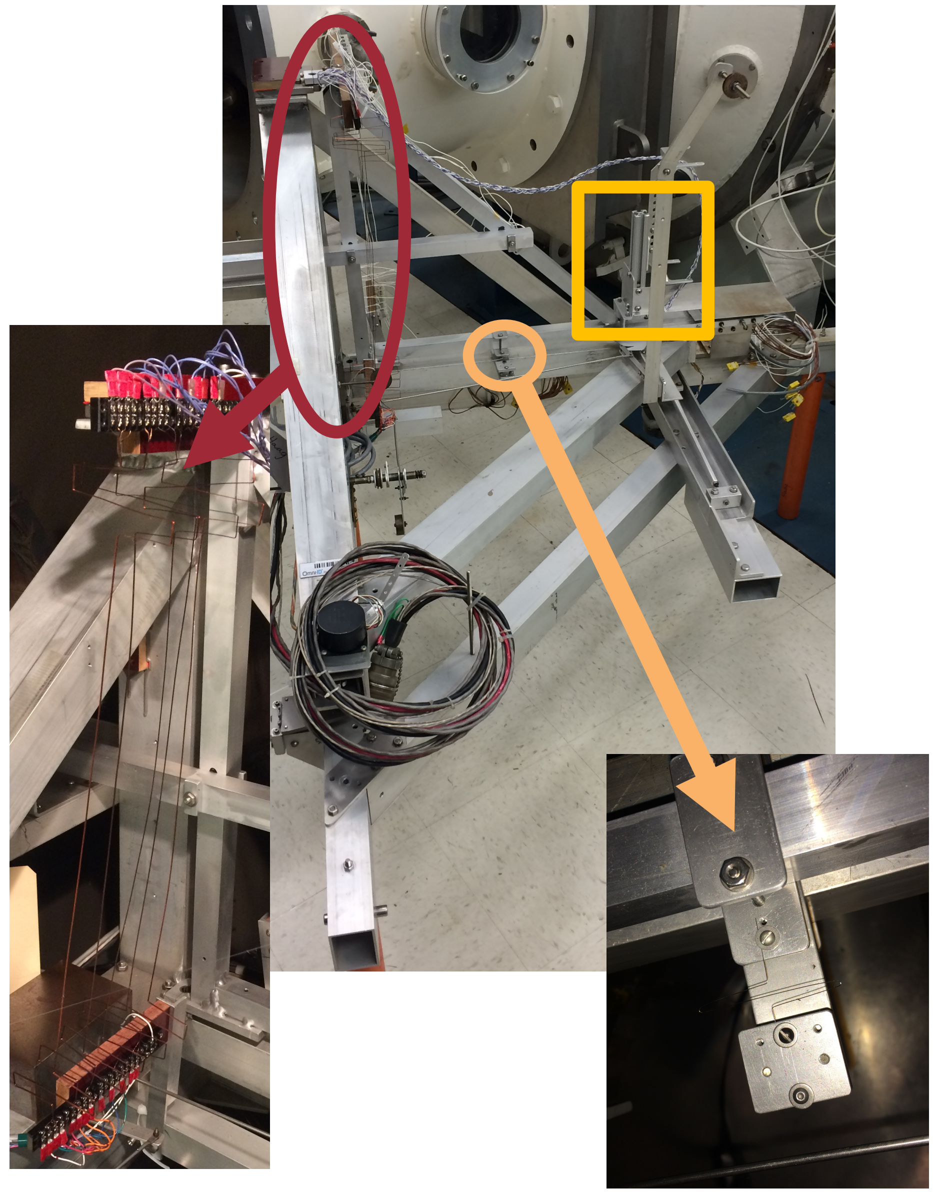


Iodine Feed System (450g Dry)

Lunar IceCube in Flight Configurations

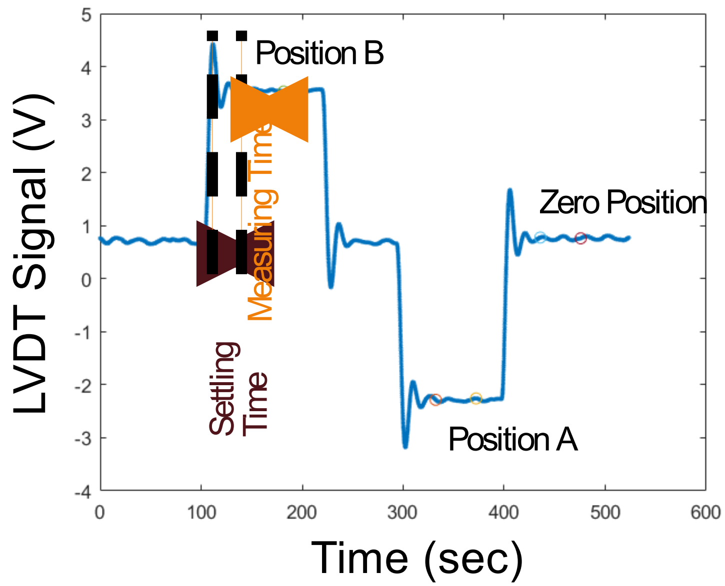
Torsional Thrust Stand

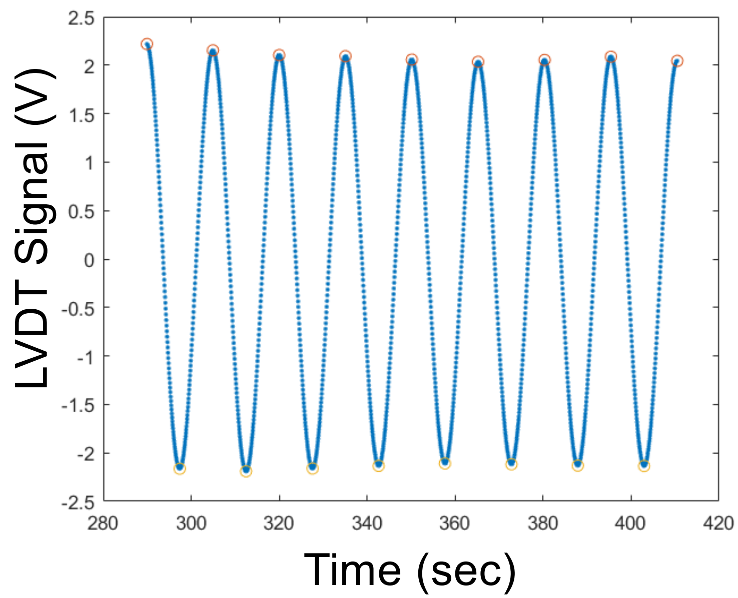
- Thruster can be mounted in the area indicated by the gold box. Calibration string to extend to the back, toward the photographer.
- Green circle shows electrical interface, terminal strip at top and bottom.
- Red circle shows tunable spring to control stand stiffness.
- Stand has pitch/roll control, LVDT displacement signal, damper coil, and calibration mechanism.



Torsional Thrust Stand: Example Calibration

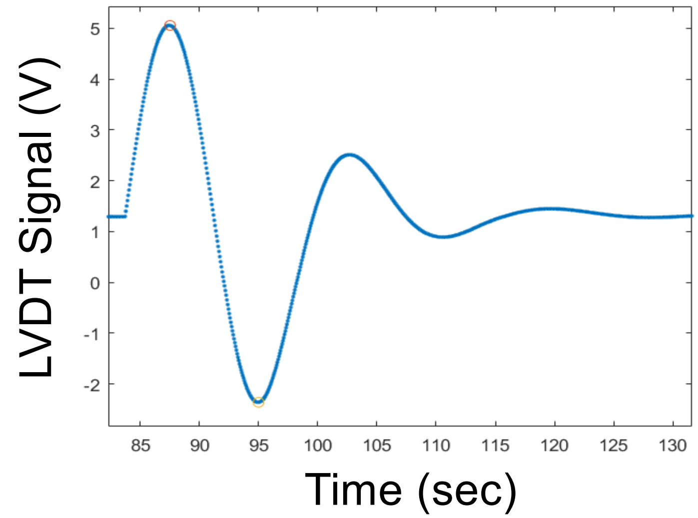
- Data to the right shows LVDT signal output while applying and removing known masses 'A' and 'B'.
- Example masses are 0.295g±0.007g (2.60 mN±0.06 mN)
- Natural frequency can be determined from cycling the stand in an "under-damped" configuration.
  - Natural frequency ~0.06 Hz.

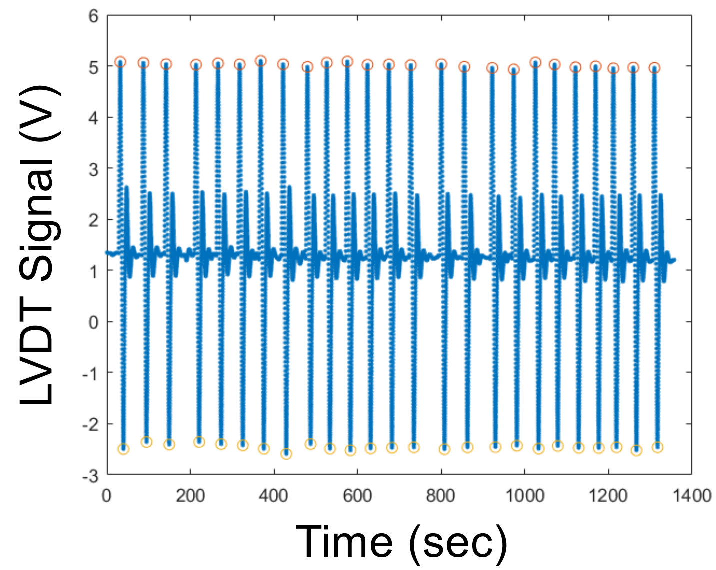




Torsional Thrust Stand: Example Impulse Bits

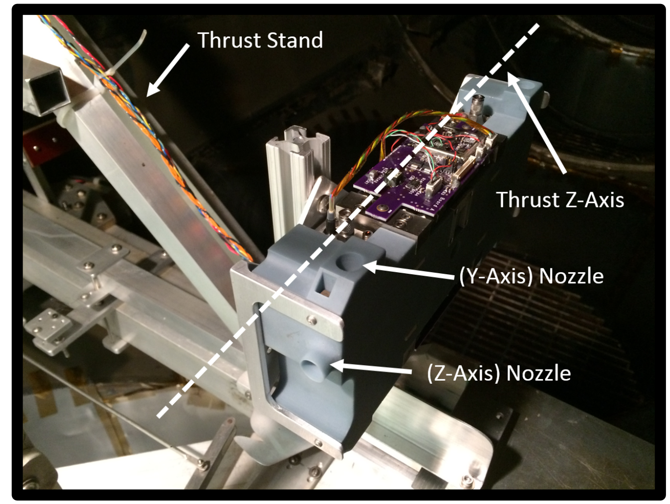
- Thrust stand can be operated in two modes with pulsed thrusters.
  - Measure single impulse bit
  - Measure “steady state” thrust
- Pulsed cold gas thruster example impulse bits shown to the right.
  - Top: single shot example, x-axis samples recorded, y-axis LVDT volts.
  - Bottom: example of 25 shots over ~30 minutes of testing. Same axes.
  - DAQ rate ~10 Hz.
  - Stiffness ~40 µN/V.

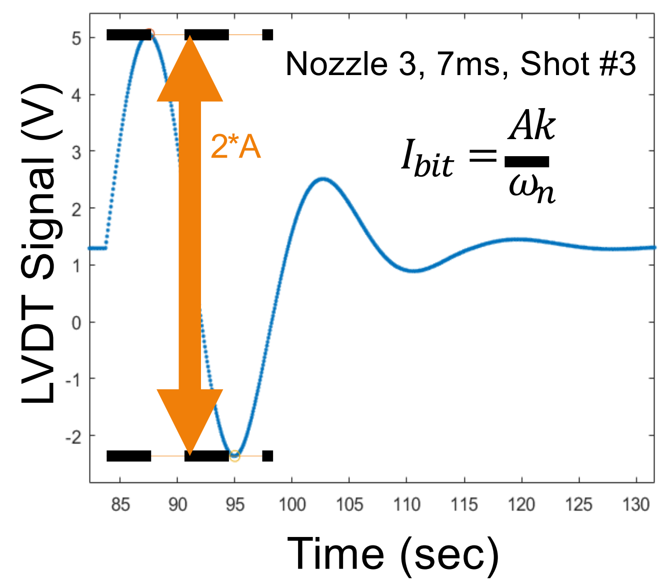




BioSentinel Thruster Performance Testing

- Cold gas propulsion system for the BioSentinel project.
  – 3D printed thruster developed by Georgia Tech with NASA Ames, tested at NASA Glenn Research Center.
- Testing consisted of firing one of seven nozzles along three principal directions: X-Axis, Y- Axis, and Z-Axis.
  – Firing times ranged from 3ms to 200ms.
  – Impulse bit, average thrust, and average propellant flow rate were determined.
- Impulse bit was estimated from shot amplitude (A), stand stiffness (k), and natural frequency (ω_n).
  – Measured impulse bits were 0.1 to 0.4 mN-s across hundreds of shots.
- Average thrust was estimated from impulse bit and shot firing time.
  – Measured average thrust was 40 to 70 mN.
- Average propellant flow rate was estimated from periodic mass of thruster.
  – Measured average flow rate was 0.2 to 0.4 g/s.





MIT Electrospray Thruster Performance Testing

- Massachusetts Institute of Technology (MIT) provided electrospray propulsion devices for thrust characterization tests at NASA GRC.
- Test campaign compared thrust measurements between MIT and GRC, validating thruster performance and thrust measurement techniques.
- Work conducted under contract funded by STMD Game Changing Development Program.

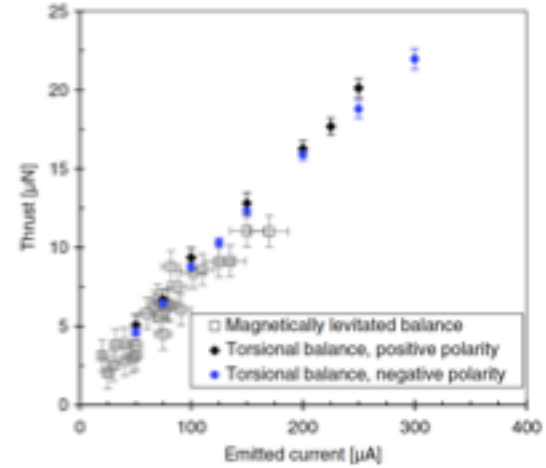
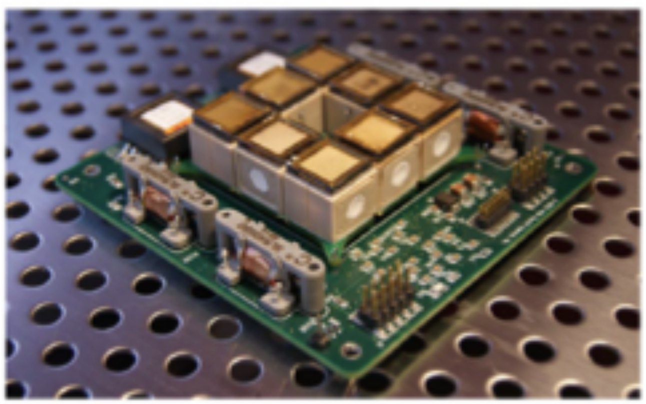
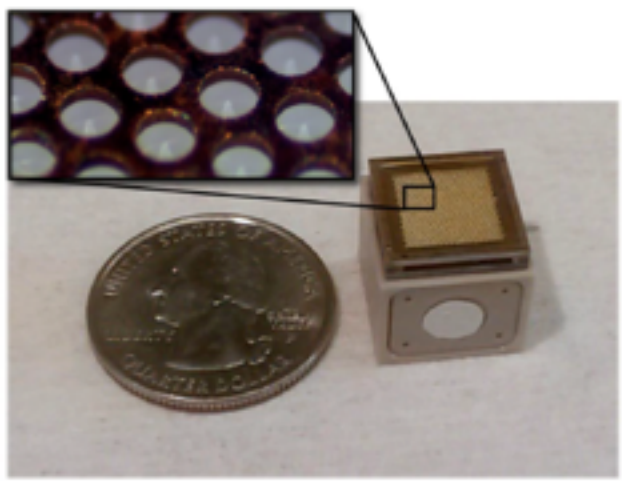


Fig. 14 Thrust as a function of emission current for two independent measurements performed at NASA GRC and MIT.





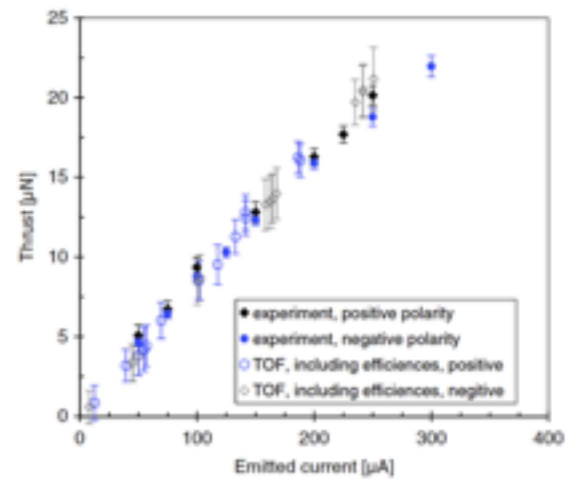


Fig. 16 Comparison of direct thrust measurements (GRC balance) to thrust derived from time-of-flight experiments, incorporating independently derived thruster efficiency.

Reference paper: Krejci, Mier-Hicks, Thomas, Haag, and Lozano, "Emission Characteristics of Passively Fed Electrospray Microthrusters with Propellant Reservoirs", AIAA Journal of Spacecraft and Rockets, Vol 54. No. 2, March-April 2017.

GRC EP Facilities

- GRC EP facilities located in EPL (Bldg 301) and the EPRB (Bldg 16). VF 2, 3, 5, 6, 7, 8, 11, 12 and 16 utilized for electric propulsion testing.
- VF 2, 3 and 8 are small diffusion pumped chambers for low power, lower fidelity experiments.
- VF 7 recently modified to perform iodine HET investigations.
- VF 11, 12, 16 are moderately sized, cryo-pumped chambers for higher pumping speed applications.
- VF 5 is large volume, high pumping speed chamber optimized for high fidelity EP experiments requiring low background pressure.
- VF 6 recently prepared for EP testing with installation of graphite shielding and EP specialized test equipment.
- Numerous other belljars are available for sub-component characterization, performance and life testing.
- Hardware buildup areas are located in both laboratories for assembly, integration and test activities.
- Dedicated class 100, 1000, 10K clean rooms and personnel certified in clean room and ESD operations
- Bonded storage for flight hardware

VF 5 – Dedicated EP Test-bed

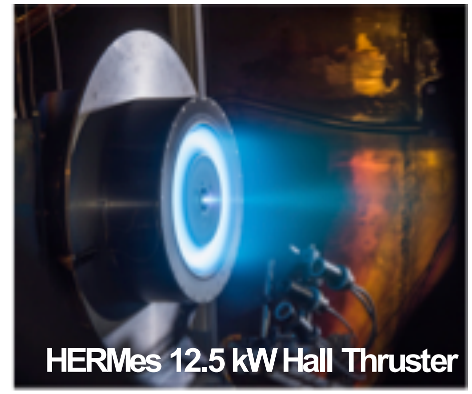
VF 7 – Iodine EP Facility

EPL Cleanroom HW Processing

Branch Mission and Functions

Electric Propulsion Systems Branch

- Performs research and technology development of electric propulsion components and sub-systems from concept through first flight
- Performs in-house design, analysis, fabrication and test of electric propulsion components and sub-systems
- Supports flight system integration of GRC developed propulsion systems onto S/C and performs sustaining engineering for on-orbit operations
- Develops and/or applies innovative design and analysis tools to the development and evaluation of electric propulsion devices
- Performs the technical functions required to execute procurement actions to select US industrial entities for flight system development and performs insight / oversight of development contracts
- Performs the systems engineering function for EP system development (thruster, gimbal, PPU, propellant feed system) including definition of requirements, test and verification plans, etc
- Conducts independent verifications up to and including flight qualification of EP components and systems for US industry and Government customers under SAA
- Provides electric propulsion discipline support for new mission designs and conceptual vehicle studies performed internally and externally
- The Chief implements Technical Authority as Discipline Lead Engineer for space propulsion engineering at GRC


HERMes 12.5 kW Hall Thruster


Annular GEN2 Ion Engine

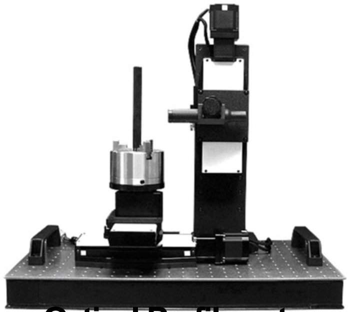

NEXT Thruster/PPU

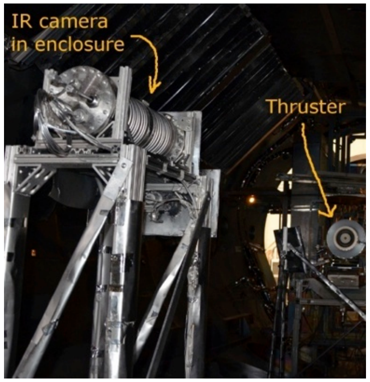
Capabilities

Electric Propulsion Systems Branch

- **Experimental Testing**
  - Extensive test infrastructure for thruster performance, plume, life and environmental characterization
  - Test infrastructure accommodates thruster power levels from < kilowatt to >100 kilowatts
  - Range of custom inverted pendulum and torsional thrust stands with measurements accuracy 1-2%
  - Custom IR thermal imaging system for high voltage, high-temperature, in-vacuum thermal characterizations
  - Langmuir & emissive probes for plasma temperature, density and potential. Faraday probes for ion current density. RPA for energy/charge. ExB for charged species. Rectilinear and polar motion systems for near & far field
  - Time resolved diagnostics for plasma oscillation characterization (advanced oscilloscope/spectrum analyzers, high-speed imaging system, high-speed Langmuir probes, and discharge chamber wall probes)
  - Non-intrusive optical emission spectometer for erosion characterization
  - Quartz crystal microbalance to measure back-sputter rate
  - Optical profilometer for erosion measurement of thruster components


High Power Thrust Stand


Optical Profilometer

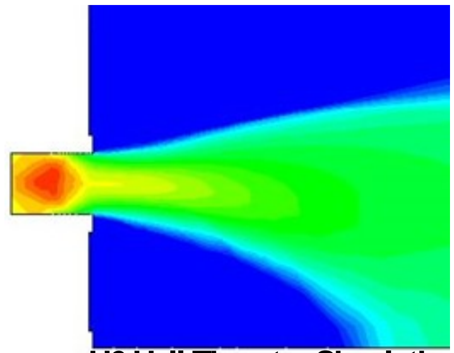


IR Thermal Imaging

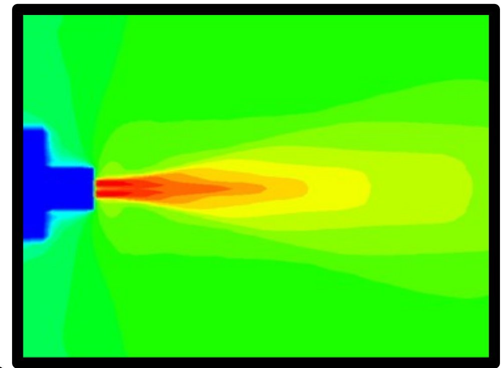
Capabilities cont.

Electric Propulsion Systems Branch

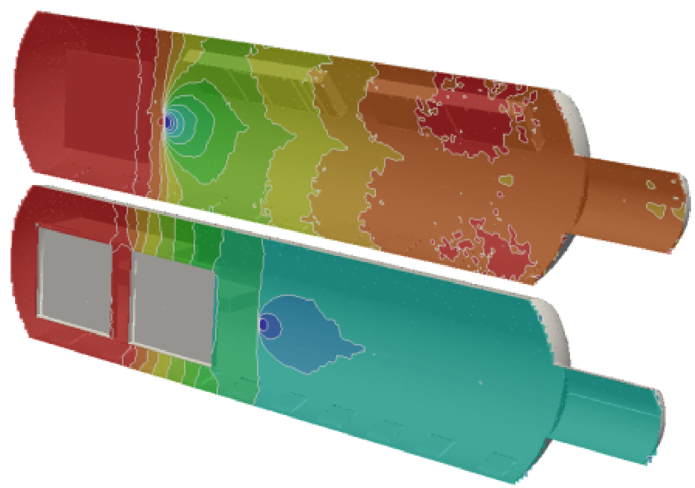
- **Modeling and Simulation**
  - Hall thruster modeling (Hall2De, HPHall)
    - Performance predictions
    - Erosion / lifetime calculations
    - Heat loads for thermal modeling
    - Inputs for plume modeling
  - Ion Optics Modeling
    - FFX – Hybrid 3-D code for optics performance & erosion
    - MICHELLE – Similar to FFX, but higher fidelity
    - CEX2D / CEX3D - Optics performance and erosion
  - Numerous in-house ion thruster codes
    - Plume modeling, neutral density modeling, facility back-sputtering, plasma codes for thermal inputs, etc
  - Electric propulsion plume simulations (Coliseum)
    - Spacecraft interactions
  - Magnetic field modeling (MagNet)
    - Hall thruster magnetic circuit design
  - Rarefied gas flow simulations (HAP)
    - Hall thruster manifold design and propellant flow uniformity
    - Ground vacuum chamber test facility background gas flows



H6 Hall Thruster Simulation



ISAT Plume Model



VF 5 Pumping Speed Simulation

Capabilities cont.

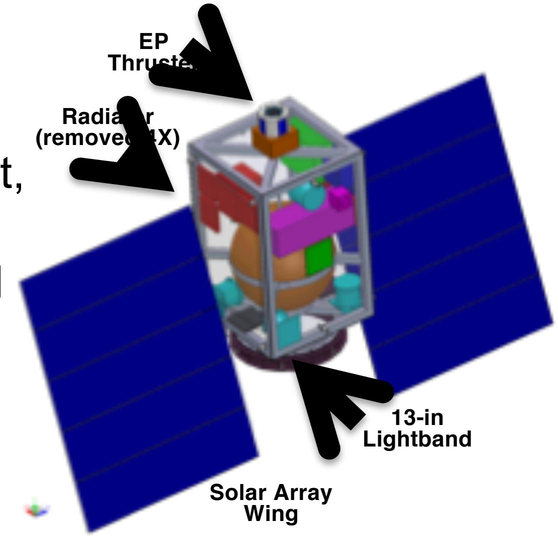
Electric Propulsion Systems Branch

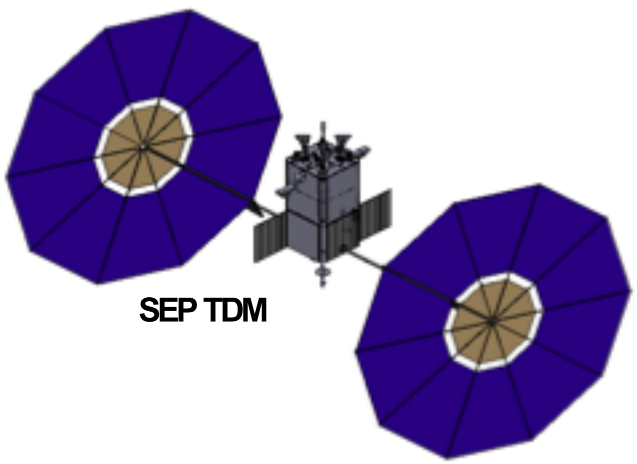
- **Electric Propulsion Hardware Design/Fabrication**
  - Workforce with physics based knowledge of electrothermal, electromagnetic and electrostatic EP devices
  - Current emphasis on electrostatic devices (HET and gridded ion) with modest level of activity in various small satellite propulsion system concepts
  - Gridded ion thrusters: Full design capability from concept to fabrication. Thruster sizing, magnetics, discharge chamber, optics and propellant manifold design and accompanying analysis. Sole manufacturing capability of >25 cm ion optics. Technology investment started in 1958. >24 separate designs and patents.
  - Hall thrusters: Equivalent to ion thruster design/fab capability. 7 separate NASA Hall thruster designs. 3 Patents.
  - Hollow cathodes: Full design capability from concept to flight hardware fabrication. Sole manufacturer of flight qualified cathode heaters for NSTAR/NEXT class ion engines. Sustaining engineering for on-orbit operations. 7 Patents
  - Power Electronics: PPU and laboratory power console design and interface definition.

Capabilities cont.

Electric Propulsion Systems Branch

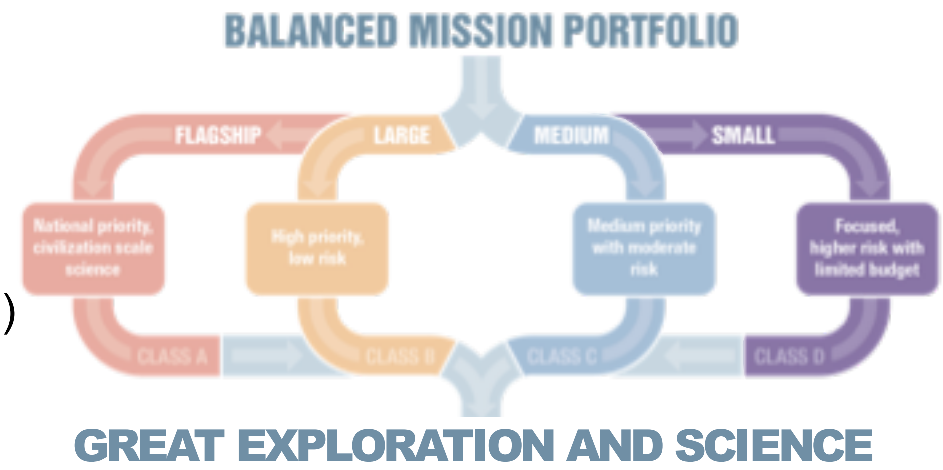
- **Electric Propulsion System Design**
  - Electric propulsion system design expertise for new mission concepts. Definition of architectures, performance, throughput, S/C to propulsion system interfaces, etc
  - Capability applicable to broad range maturity from conceptual vehicles (COMPASS) to flight systems (Discovery/New Frontiers/Flagship class missions)
  - Recent EP system designs include 14 SEP TDM concepts, multiple iterations of Micro SEPSAT, numerous CubeSat designs, numerous NEXT based Discovery/New Frontiers proposals, HiVHAc based architectures, Mars cargo, piloted SEP-Chem, etc.

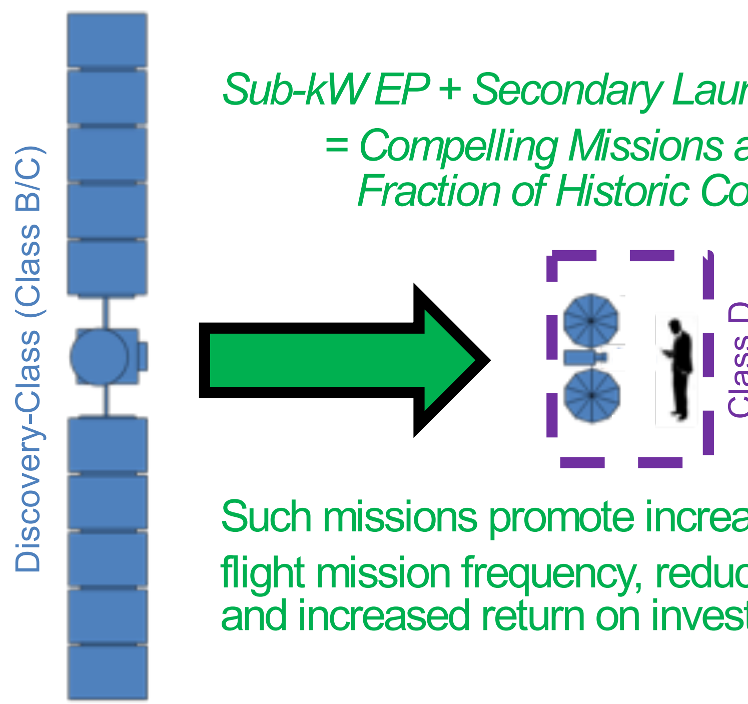




Class-D EP Qualification Best Practices

- Sub-kilowatt, long-life electric propulsion systems enable compelling cislunar and deep space NASA exploration and scientific missions.
- Misapplication of CubeSat development philosophy (i.e., very high-risk and expendable) is common among EP technology developers proposing to Class-D missions, which remain less risk-tolerant than missions such as:
  - Technology demonstration
  - Commercial mega-constellations
  - Educational design-build-test-fly
- NASA GRC is developing:
  - Recommended guidelines for EP flight qualification activities suitable for low-cost, higher-risk Class-D misisons
  - Best practices to avoid recurring issues and common pitfalls with EP flight qualification





Sub-kW EP + Secondary Launch
= Compelling Missions at Fraction of Historic Costs

Such missions promote increased flight mission frequency, reduced risk, and increased return on investment.

Summary

- There is an on-going and growing need to develop CubeSat propulsion for NASA missions and beyond.
- GRC has many capabilities for testing and characterizing propulsion systems.
  - Techniques were developed for high power devices but also applicable and available for cubesat devices.
- Importance of independent, third-party testing.
  - Verification of key performance parameters
  - Interface documentation
  - Operation documentation in users manuals
- Initiation of Standards for Class D missions

NASA