Electrospray Thruster Technology Development at NASA JPL

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ST7-DRS and LISA Pathfinder Teams, NASA JPL & GSFC, ESA & Airbus

Air Force Research Laboratory Electrospray Propulsion Workshop

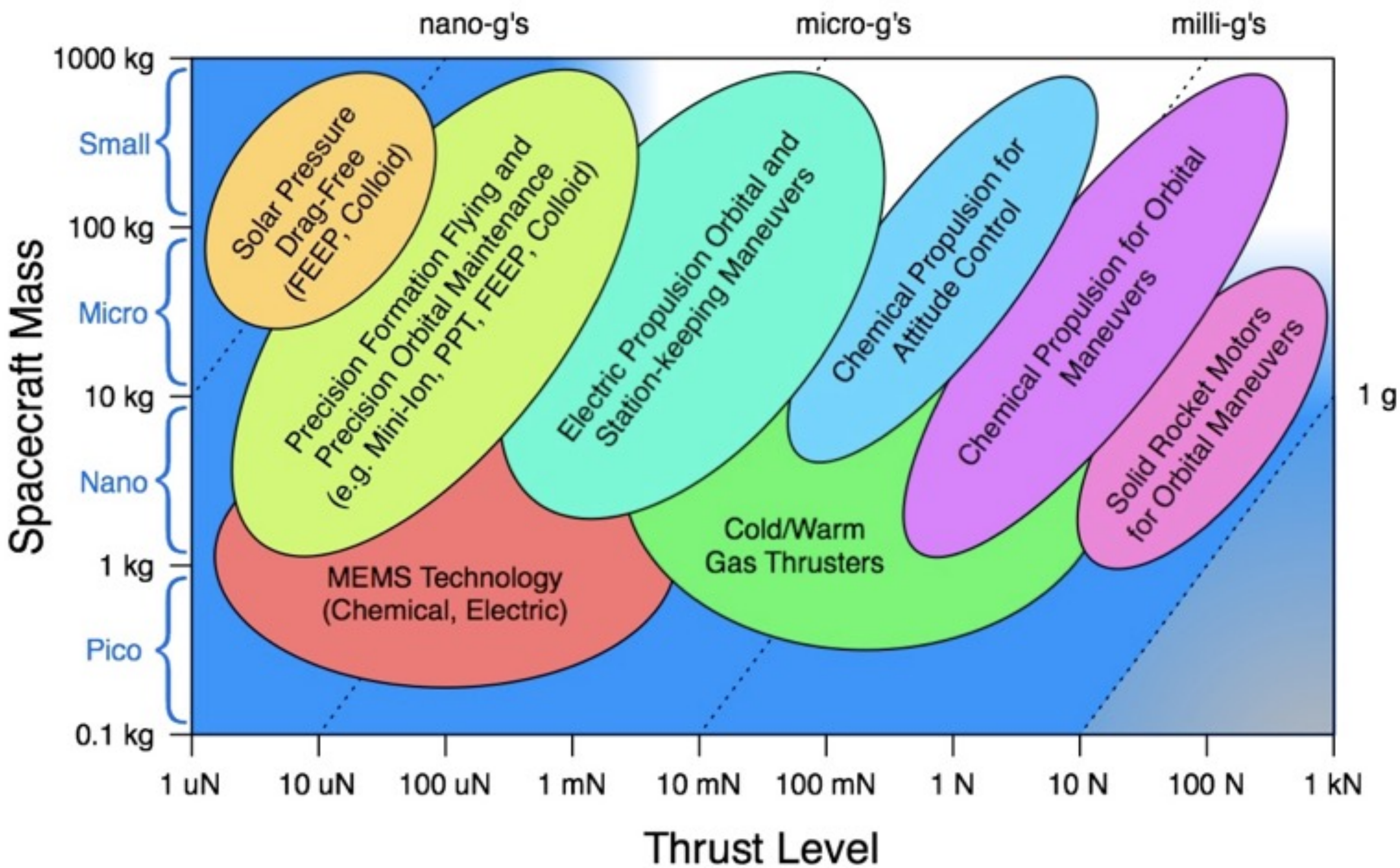
May 20 – May 22, 2019, Los Angeles Air Force Base

Jet Propulsion Laboratory

California Institute of Technology

Spacecraft and Propulsion Requirements and Capabilities

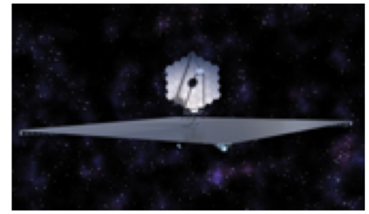
Micropropulsion Mission and Technology Space

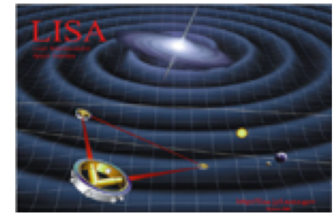


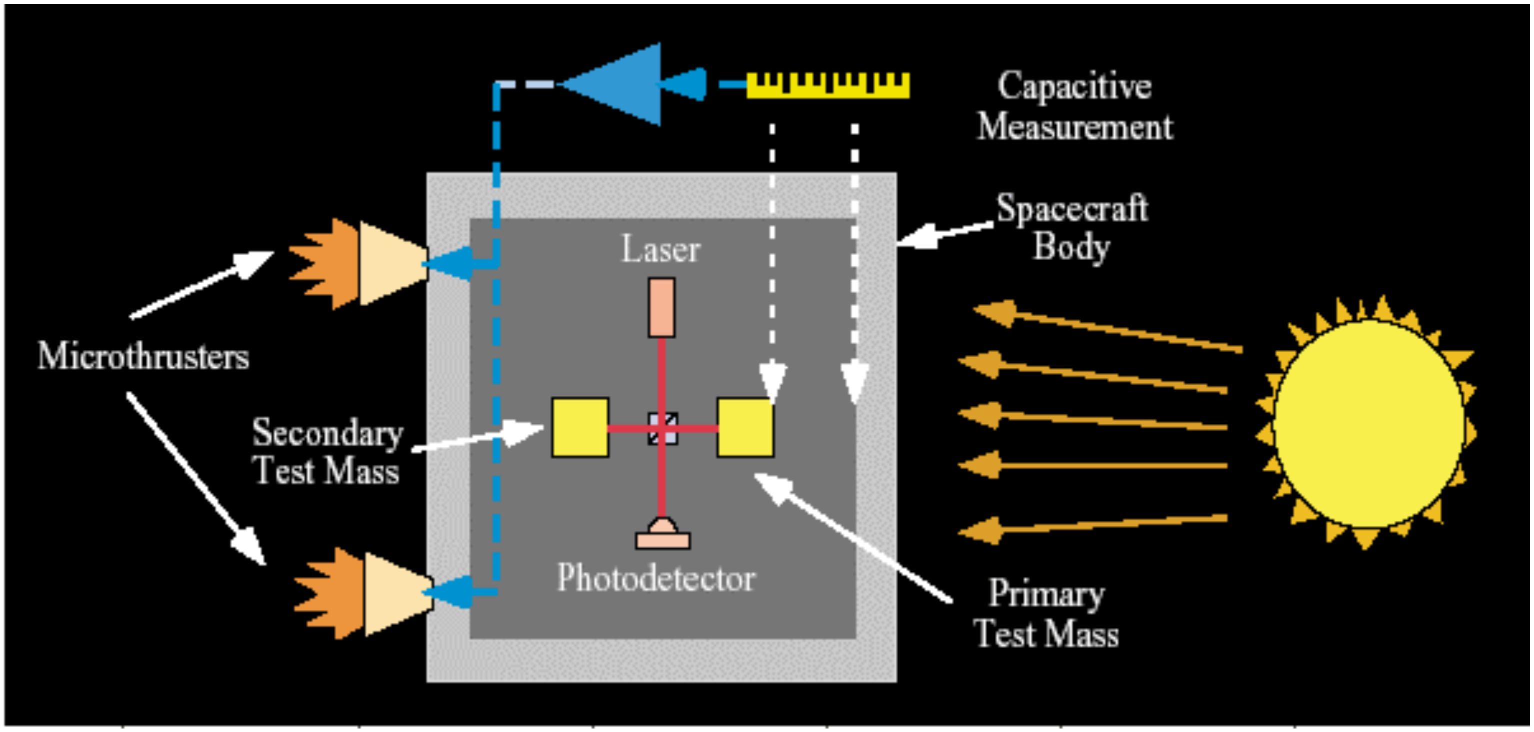
JPL Micropropulsion Activities

- Flight Missions
  - **LISA Pathfinder**, Space Technology 7
  - MARCO, Mars fly-by in support of InSight landing
  - **LISA,** ESA-Led Gravity Wave Observatory
- Mission Concept Development
  - HabEx, NASA-Led Exoplanet Observatory study for Decadal Survey
  - NASA Chief Engineer's Office study on replacing reaction wheels with precision microthrusters
  - "Small World" explorers (daughter-sats of interplanetary spacecraft)
  - Independent Small / CubeSats (e.g. Earth observer, Mars telecom relays, etc.)
- Microthruster Technology Development
  - **Precision Electrosprays - Colloid Microthrusters**
  - Microfabricated Electrospray Propulsion (MEP – C. Marrese)
  - Magnetically Shielded Miniature Hall Thruster (MaSMi – R. Conversano)
  - Small and "green" monopropellant microthrusters (JPL Chemical Propulsion Group - for orbit insertion / escape)
- Challenges
  - **Lifetime and reliability** (also cost, but not as much as for commercial applications)
  - System-level performance (total impulse / total mass; thrust / power)

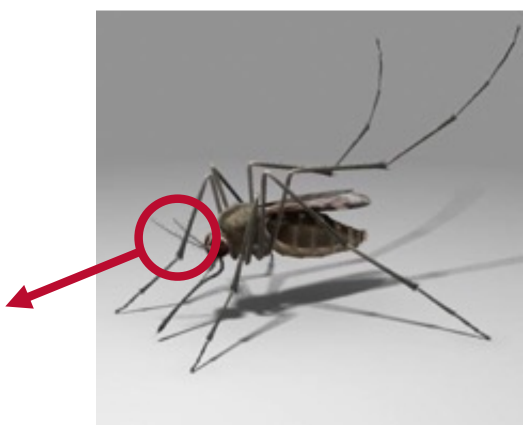
Drag-Free Spacecraft







~ 0.1 μN

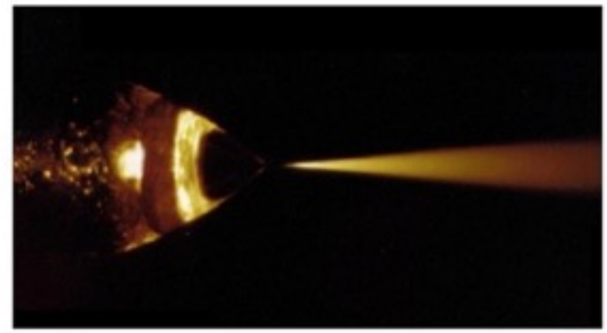


≈ 30 μN

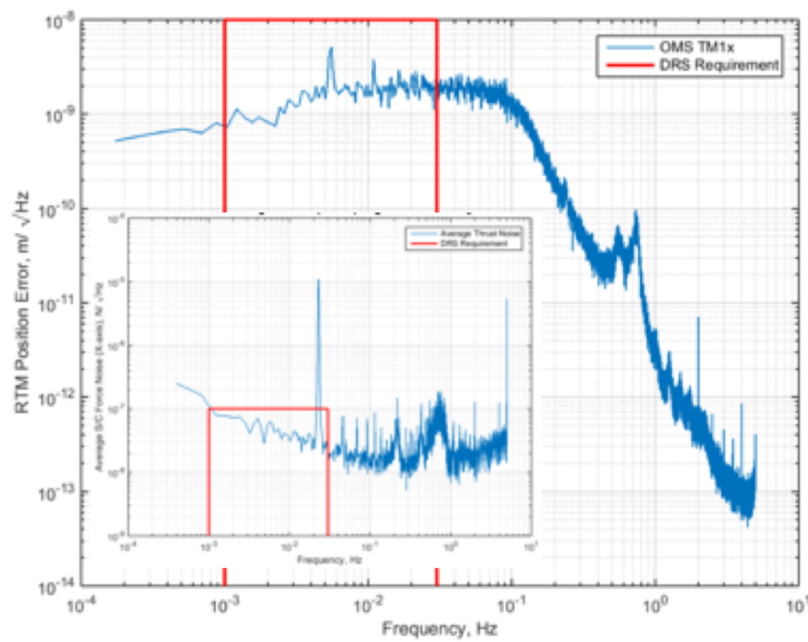
Colloid Thruster Electrospray Technology

- Colloid Thrusters emit charged droplets that are electrostatically accelerated to produce thrust

$$\text{Thrust} \propto I_B^{\,1.5} \cdot V_B^{\,0.5}$$



- Current and voltage are controlled independently by adjusting the flow rate and beam voltage
- Precise control of I_B (~ μA) and V_B (~ kV) facilitates the delivery of micronewton level thrust with better than 0.1 μN precision
- The exhaust beam is positively charged, well-defined (all charged particles), and neutralized by a cathode/electron source if needed



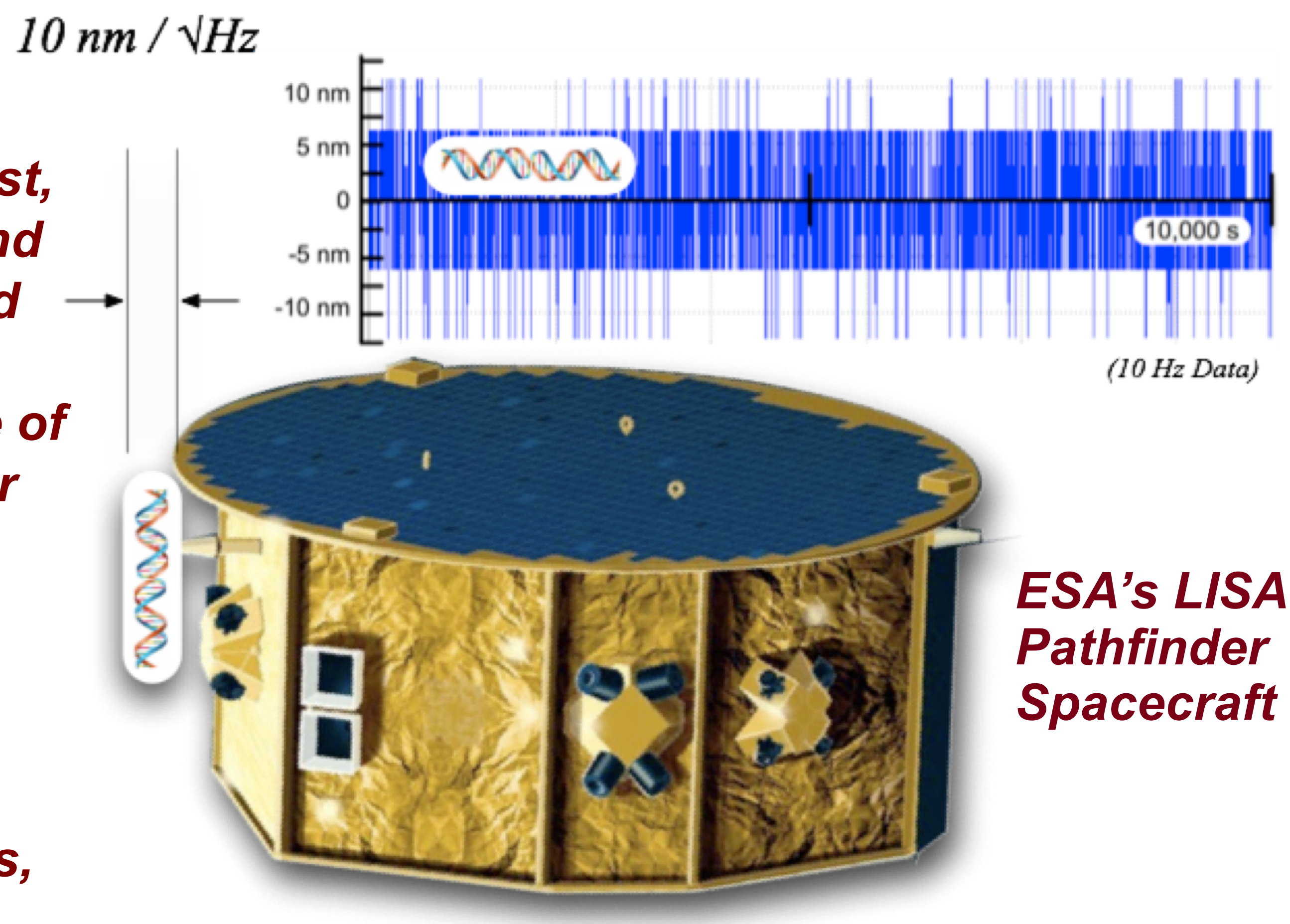
Why Colloid Microthrusters?

- **High Precision Performance and High Heritage**
  - Independent control of beam voltage and current leads to precise, low noise thrust
  - Ultimate performance and physics based thrust model has been validated on orbit
- **Low Propellant Mass and Volume**
  - Specific impulse (Isp – weight of propellant over total impulse) is >5x cold gas
  - Propellant is a liquid (1.53 kg/L) stored at 4 atm, only ~1 L / thruster for 6 years
- **Low, Steady Power**
  - Cluster of 4 thrusters on ST7 / LPF used ~20 W with only ~0.2 W dependent on thrust
  - Thrusters are thermally stable and have their own proportional controlled heater
- **Known Spacecraft Interactions**
  - Well defined and predictable exhaust plume (<35°) with no S/C charging concerns
  - No magnetic materials are required and mass distribution is predictable over time
- **Well Defined Interface**
  - Thrusters and electronics have a simple mechanical, power, and comm. interface
  - Tanks can be integrated with thruster assemblies or separated, as needed

Space Technology 7 – Disturbance Reduction System Precision Spacecraft Control Enables Gravitational Wave Measurement

ST7 has developed the lowest continuous thrust, precision propulsion and control system qualified for flight and the first confirmed performance of an electrospray thruster operating on orbit

Future applications include space-based gravitational wave and exoplanet observatories, large structure control, and formation flying



ESA's LISA Pathfinder Spacecraft

When DRS is active, S/C position noise is comparable to the diameter of a DNA Helix (2 nm)!

Space Technology 7 Disturbance Reduction System

BUSEK

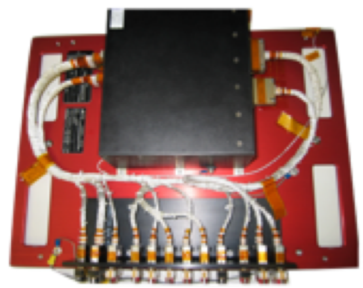
Colloid Micro-Newton Thrusters

Life-Test complete with 3,400 hrs. of operation

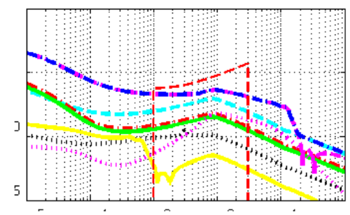
Passed all proto-flight qualification level testing

Broad Reach Engineering
Space Flight Hardware & Vehicle Design

Integrated Avionics Unit



Goddard
SPACE FLIGHT CENTER



Dynamic Control System

Drag-Free Control Software and Analysis

JPL

Project Management

Thruster Development

C&DH Software

Structures

Cabling/Harness

I&T and ATLO Support

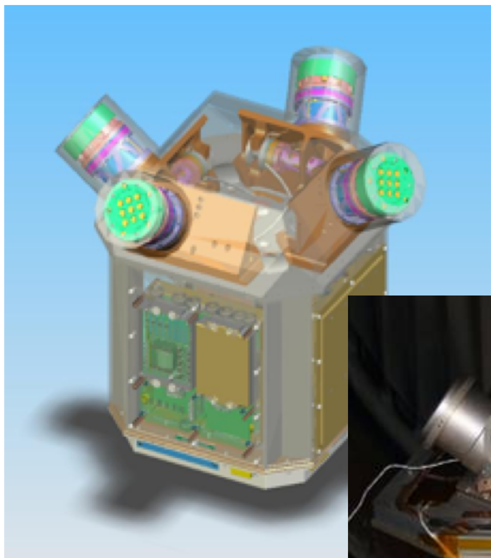
Operations

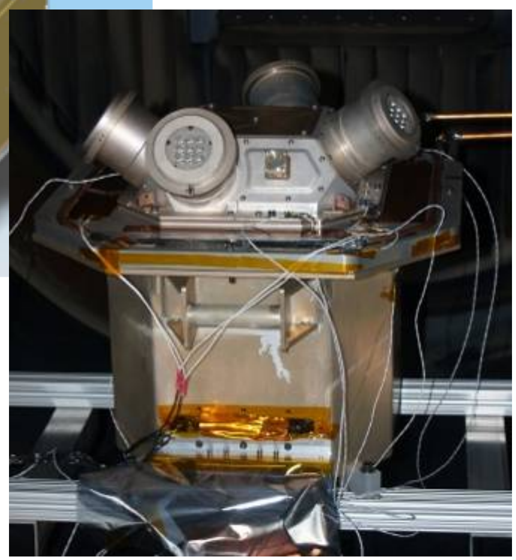
Instrument Delivery
June 20, 2008

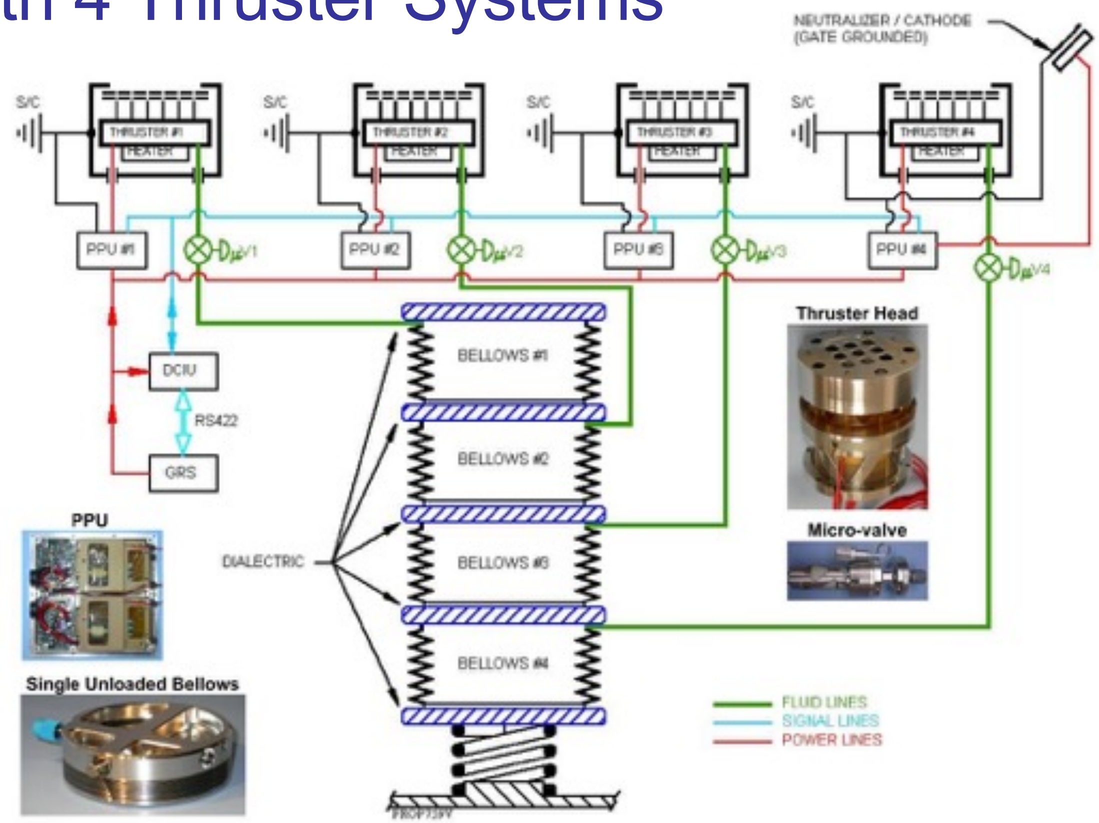
NASA esa AIRBUS DEFENCE & SPACE

ST7 Microthruster System Architecture

Cluster with 4 Thruster Systems







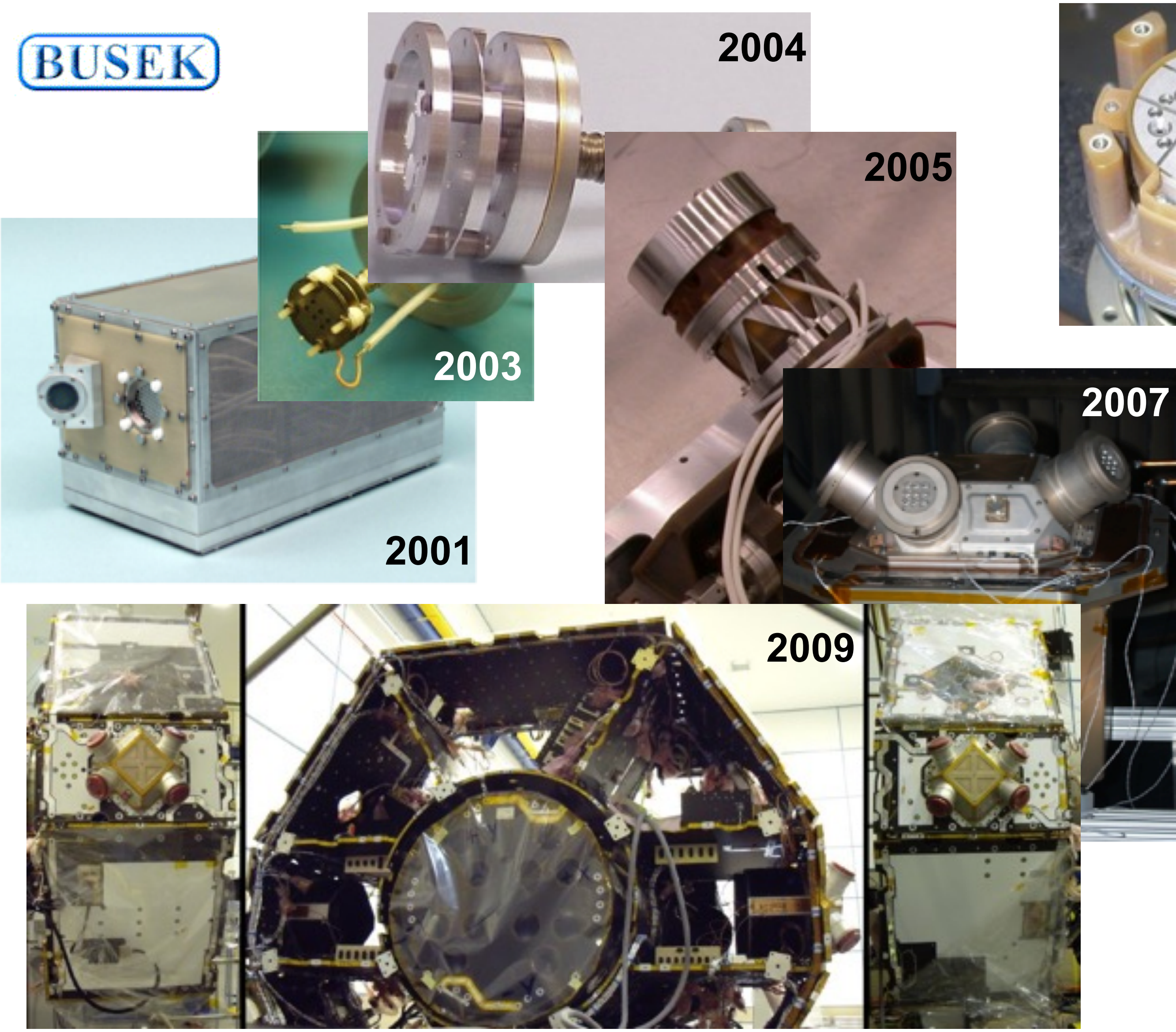
- ST7-DRS has 2 clusters with 4 thrusters per cluster
- All 8 thruster systems are identical
- There is one DCIU and neutralizer per cluster
- Thrust range: 5-30 μN from each thruster head

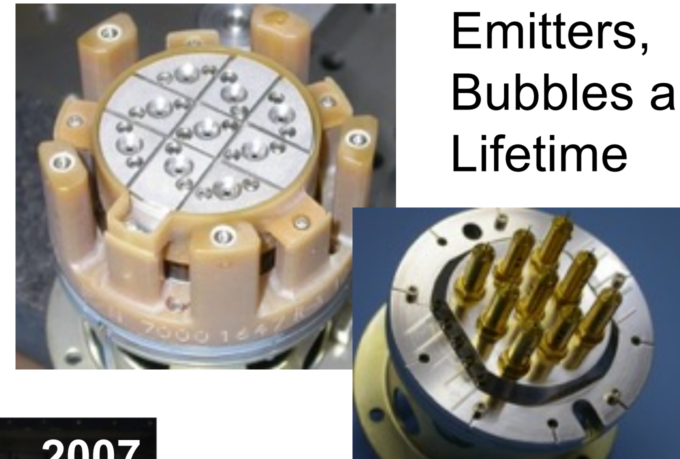
A single thruster system includes:

- Thruster Head (including heater)
- Microvalve (precision flow control)
- Bellows (propellant storage)
- PPU (high-voltage converters)

Challenges Going from SBIR to Flight Tech Demo

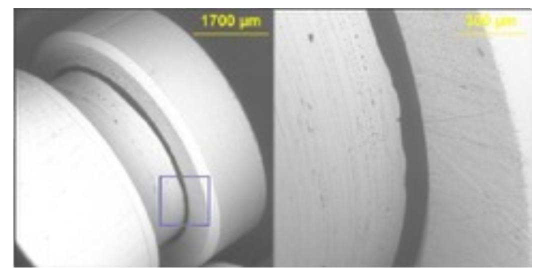
BUSEK

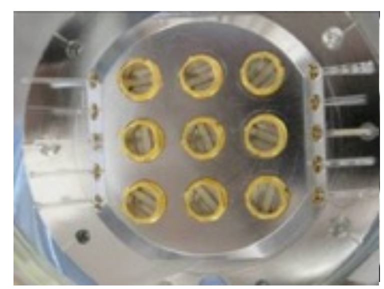




Emitters, Bubbles and Lifetime

Microvalve Manufacturing





Seals and Materials

LISA Pathfinder Launch!

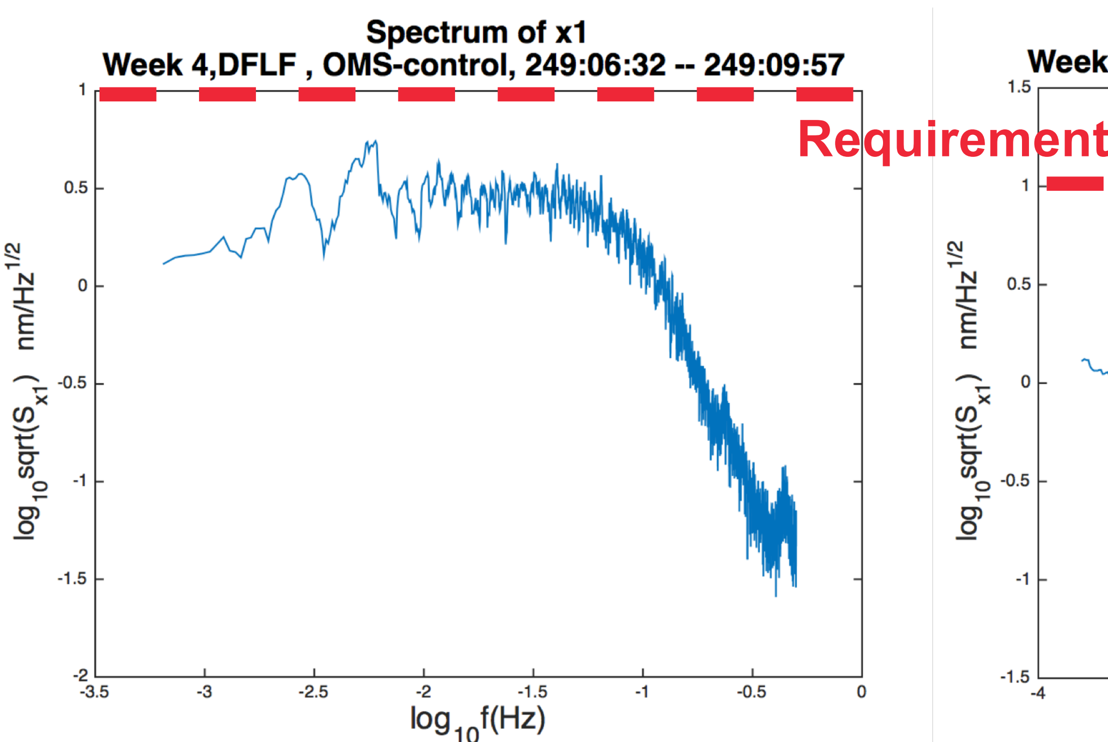
Launch from French Guiana December 3, 2015

Long duration storage of colloid thruster propellant (8 years in tanks) raised some concerns, but in the end a useful demonstration for future missions

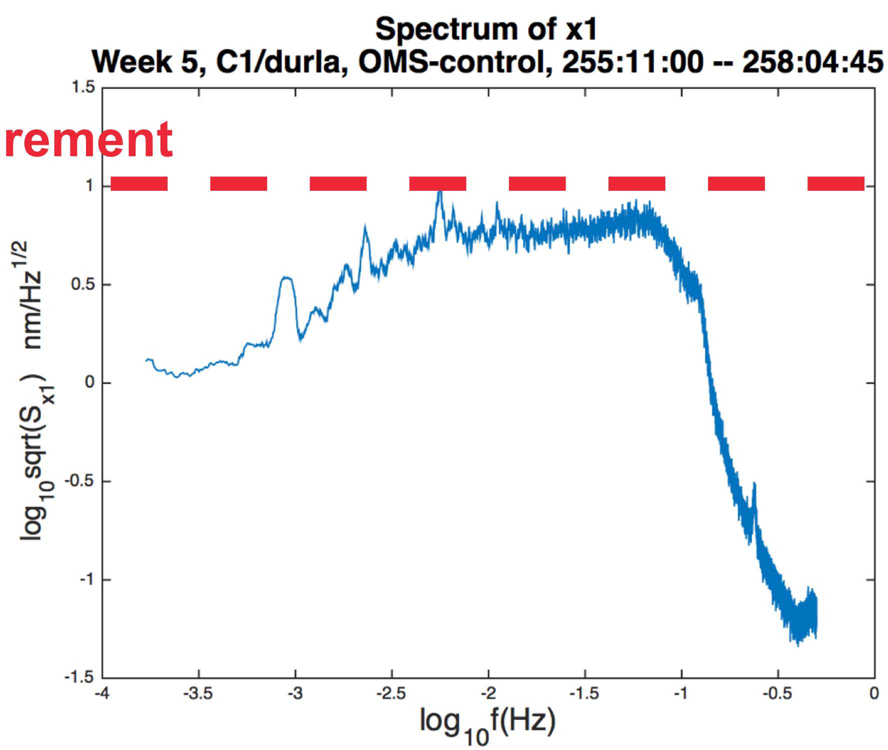
Results from Drag-Free Operation

Results Show Meeting L1 Requirement, <10 nm/√Hz position stability

Position Noise in Drag-Free Mode

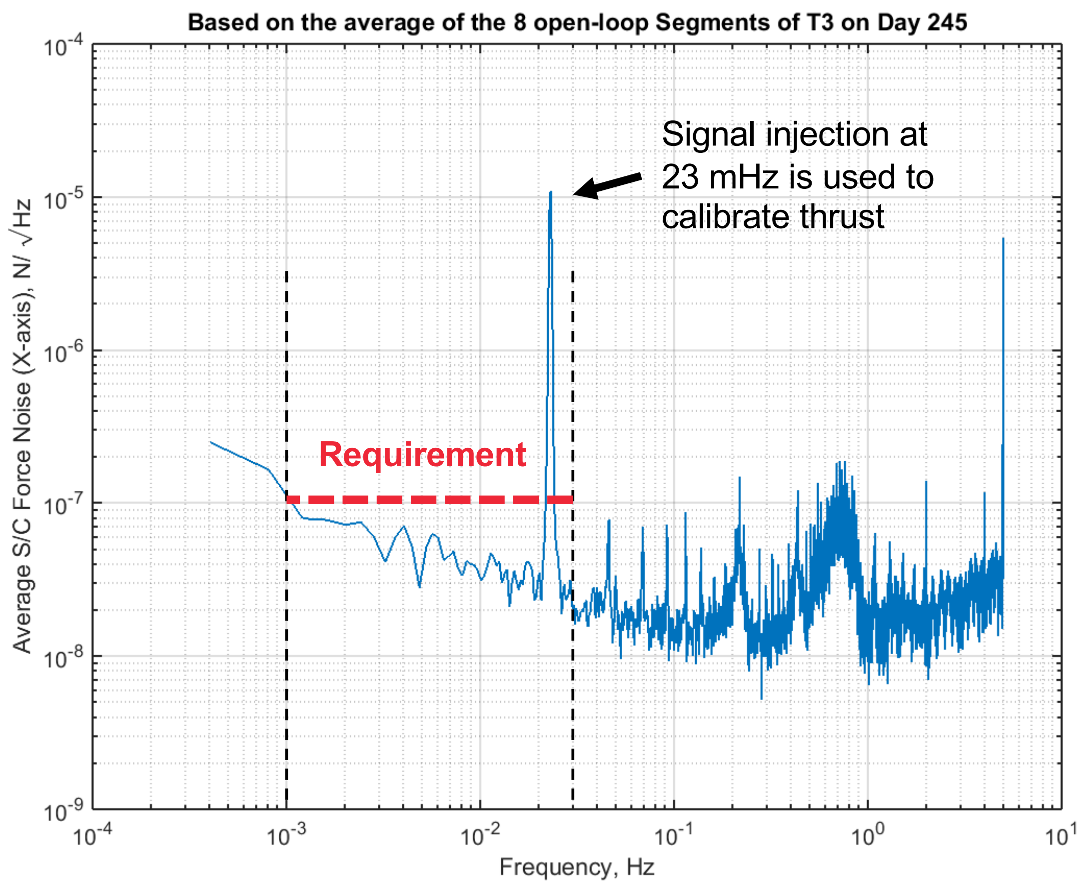


Position Noise in Science Mode



Thrust Noise Measurements

Results Show Meeting L1 Requirement, <0.1 μN/√Hz System-Level Thrust Noise



ST7-DRS Level 1 Requirements

Requirement	Full Success Criteria	Original Minimum Goals
Position control; 1-30 mHz	10 nm/√Hz	100 nm/√Hz
Drag-free sensor*	5 nm/√Hz	50 nm/√Hz
Propulsion system noise; 1-30 mHz	0.1 μN/√Hz	0.5 μN/√Hz

After successful commissioning, all L1 Requirements have been met

✓ 1. DRS shall demonstrate ability to control spacecraft position within 10 nm/√Hz on the sensitive axis over a frequency range of 1 mHz to 30 mHz
   – Derived from LISA requirement of necessary position noise along sensitive axis
   – Requires LTP position sensing noise to be ≤ 5 nm/√Hz

✓ 2. DRS shall demonstrate a spacecraft propulsion system with noise less than 0.1 μN/√Hz over a frequency range of 1 mHz to 30 mHz

✓ 3. DRS shall perform flight qualification of a Colloid Micro-Newton Thruster. DRS shall demonstrate a Colloid Micro-Newton Thruster in a space environment at any thrust level
   – Being a technology demonstration project, the majority of the challenge is to mature this technology to a point that it can be qualified for flight. **This will be 90% of the success for this project**. Due to the long storage and ATLO period of DRS, any in-flight operation of the thrusters is considered a success, even if the system is not operating completely as intended

✓ 4. The project shall document and archive design, fabrication, test and flight demonstration data relevant to the qualification and infusion of DRS systems into future missions requiring DRS technology

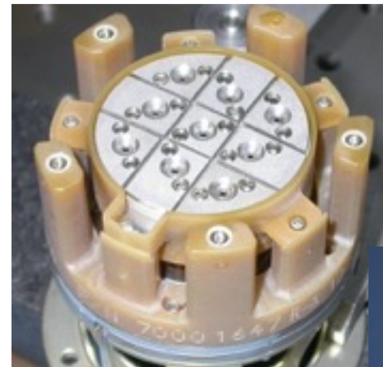
✓ **Minimum Mission Success:** DRS shall deliver a flight qualified Colloid Micro-Newton Thruster, producing any measurable thrust on-orbit, verified through analysis of telemetry.

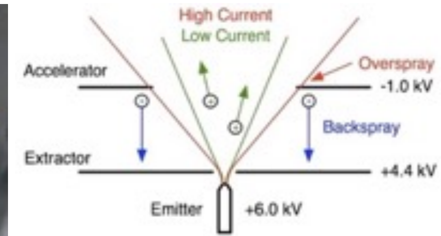
Plans for LISA, HabEx, and NASA Study

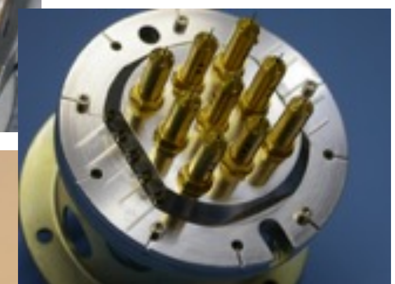
- LISA Microthruster Technology work is directly funded by NASA through Physics of the Cosmos Program – see following slides – and much of this work applies to HabEx as well
  - Focus is on demonstrating reliability and lifetime at TRL 6
  - Working with ESA and industrial partners on configuration studies
- HabEx needs additional work to identify thrust magnitude and thrust noise requirements at higher frequency
  - Might require an additional development beyond LISA, especially if the thrust level is higher with a higher frequency band, and likely continuing the LISA thruster lifetime test
  - HabEx has continued study funds to prepare for Decadal Survey, but no specific microthruster technology development funds yet
- Supporting a NASA Chief Engineer Office (CEO) study on replacing reaction wheels with microthrusters for fine pointing of the next-generation of space-based observatories

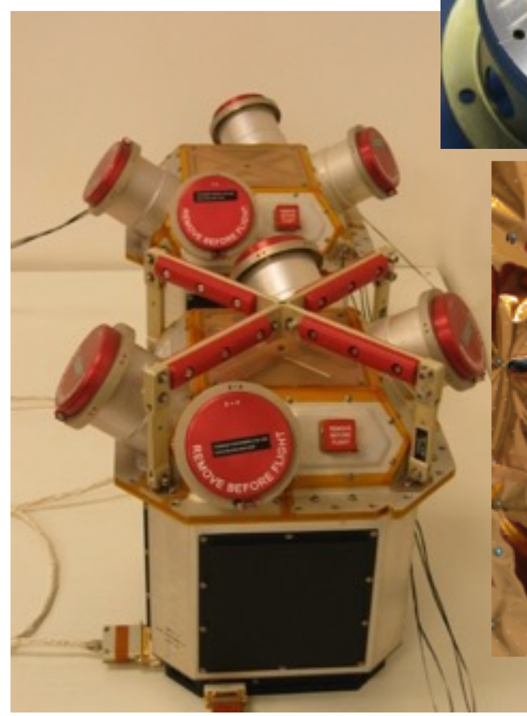
LISA Colloid Microthruster Technology Development

- Role in Flight System
  - Microthrusters are the actuator of the drag-free attitude control system (DFACS)
  - Performance was demonstrated on LISA Pathfinder (TRL 7), but new, lower TRL components and updates are required for increased reliability and lifetime on LISA
  - Key challenge is demonstrating lifetime
- Development Team
  - PDL: J. Ziemer (JPL)
  - Busek PI: N. Demmons (Busek Co.)
  - Modeling Lead: Prof. R. Wirz (UCLA)
  - Testing Lead: C. Marrese-Reading (JPL)
- Development Highlights
  - **Phase 1**: Updating ST7-DRS design with lessons learned, conducting trade studies, and initial modeling and test efforts - **DONE**
  - **Phase 2**: Component-level testing (TRL 5) starts in Oct 2019 through Dec 2020
  - **Phase 3**: System-level testing (TRL 6) goes from Jan 2021 to May 2023

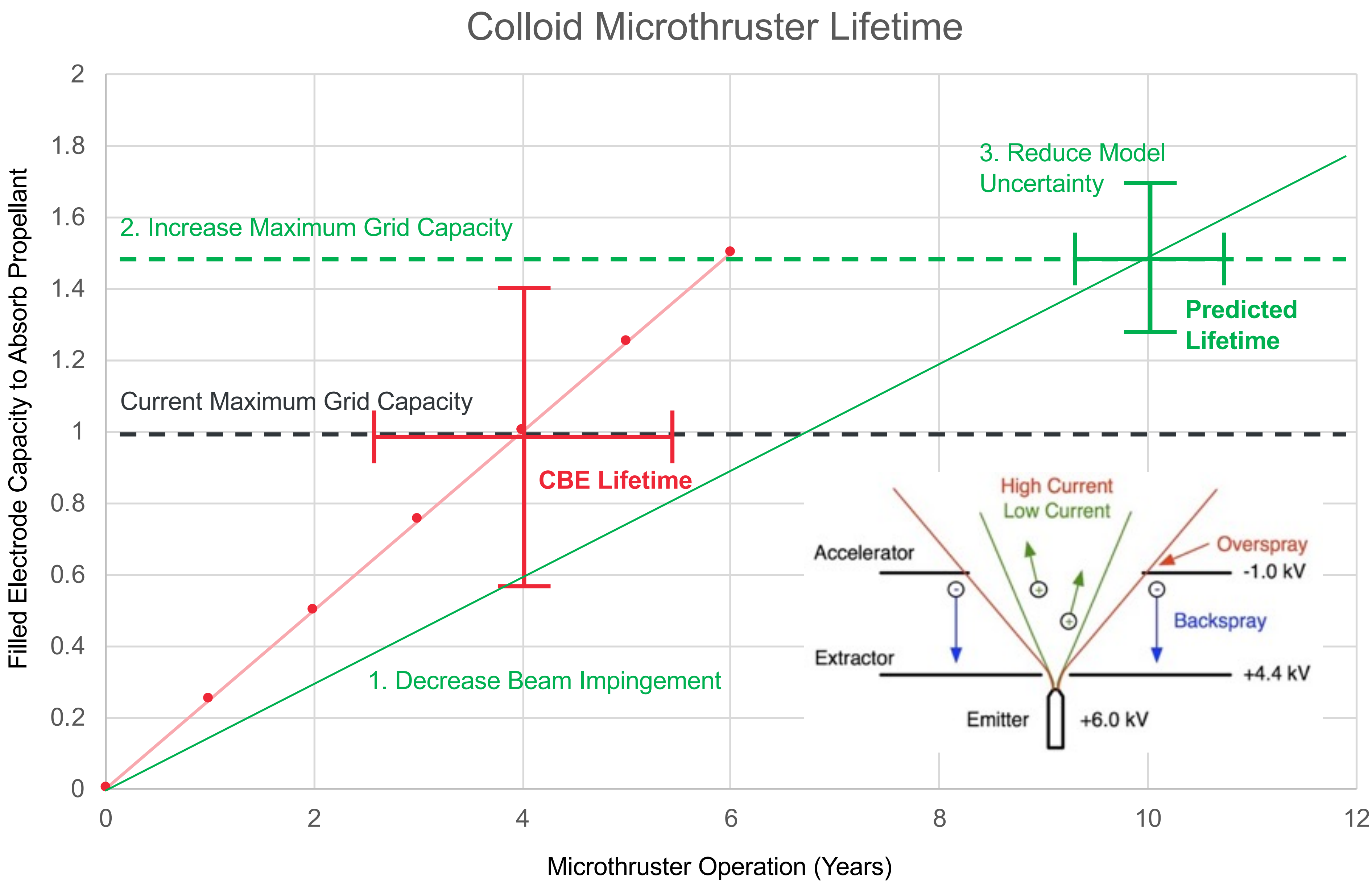




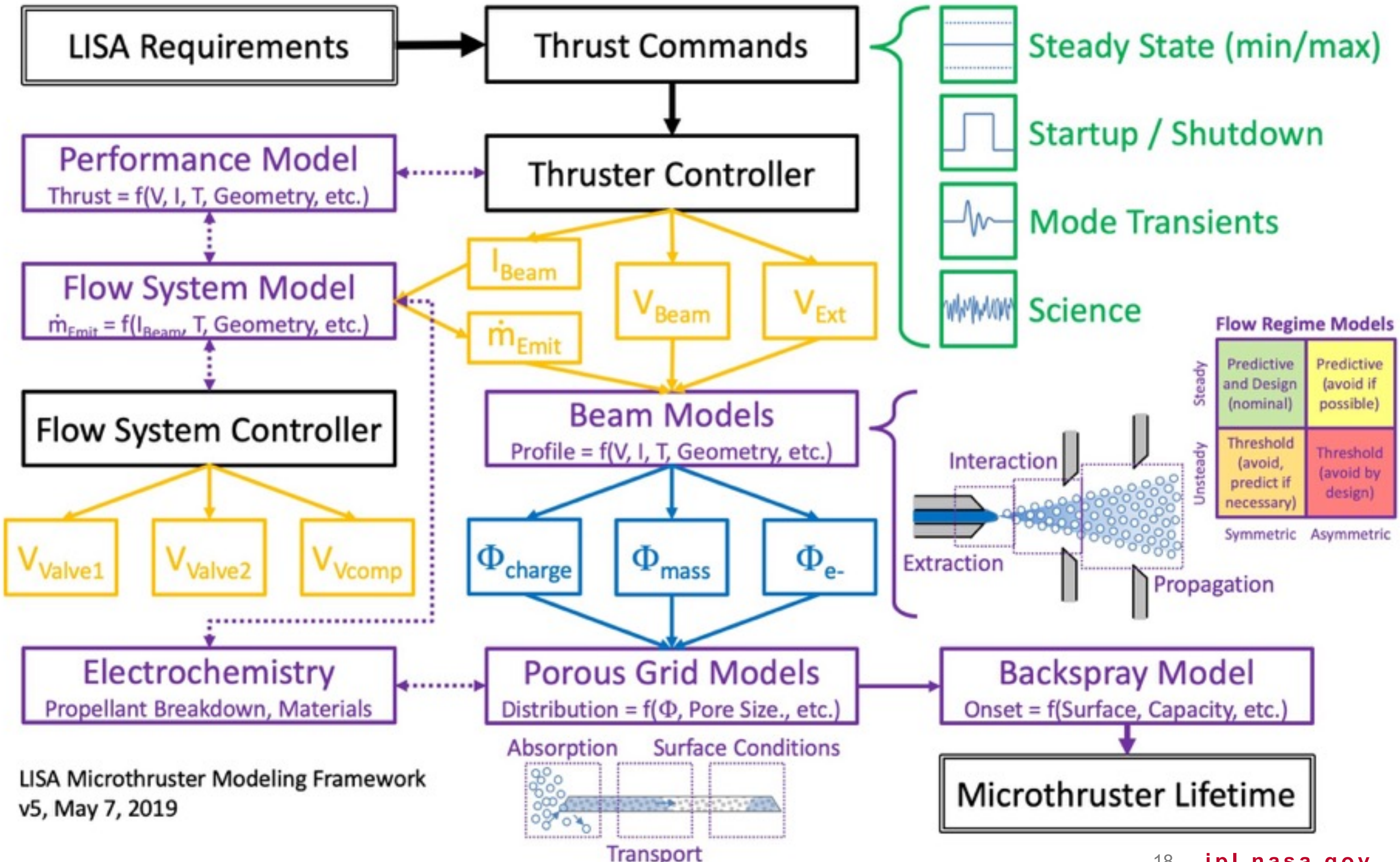




How to Improve Thruster Lifetime

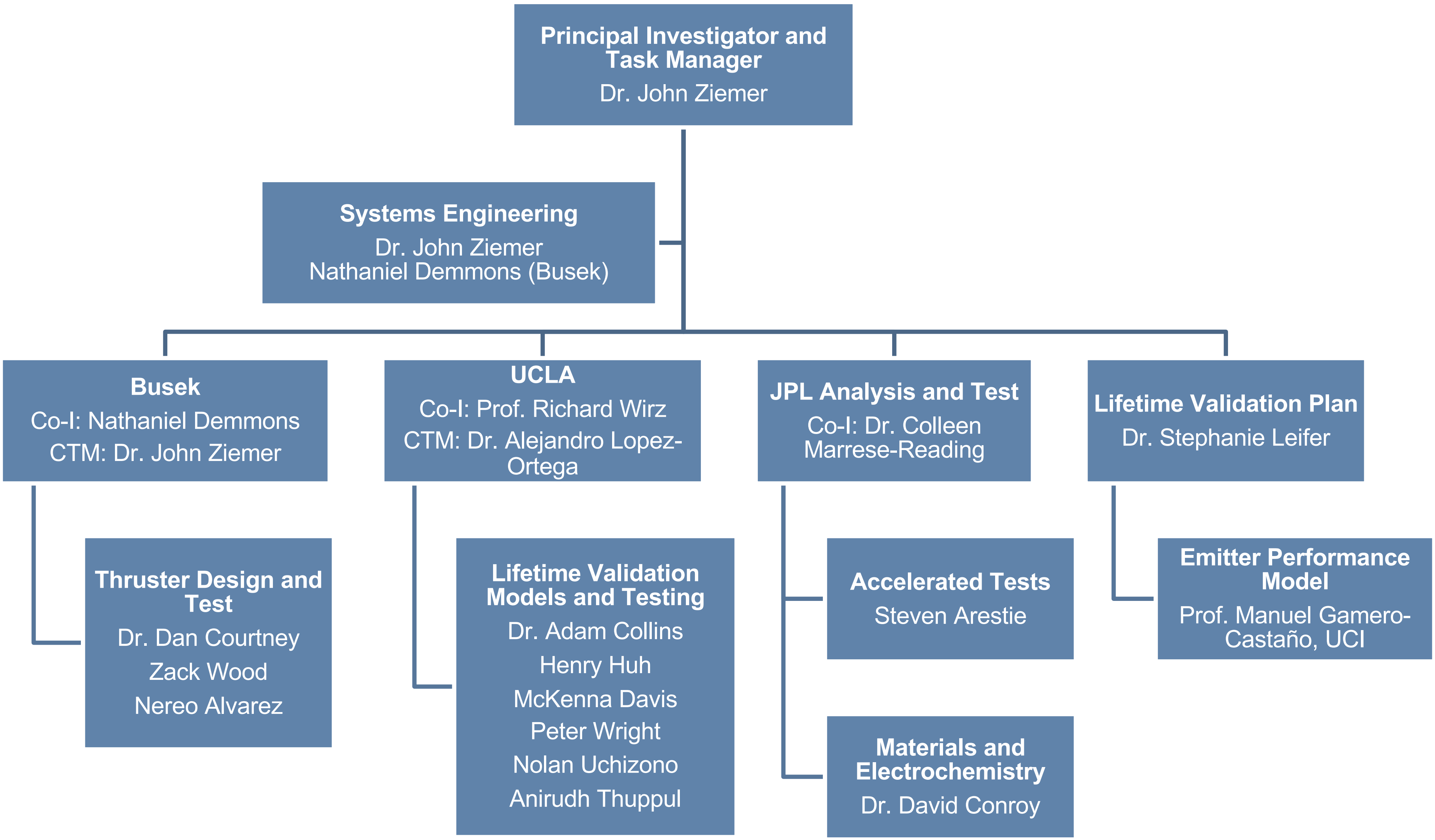


LISA Microthruster Modeling Framework

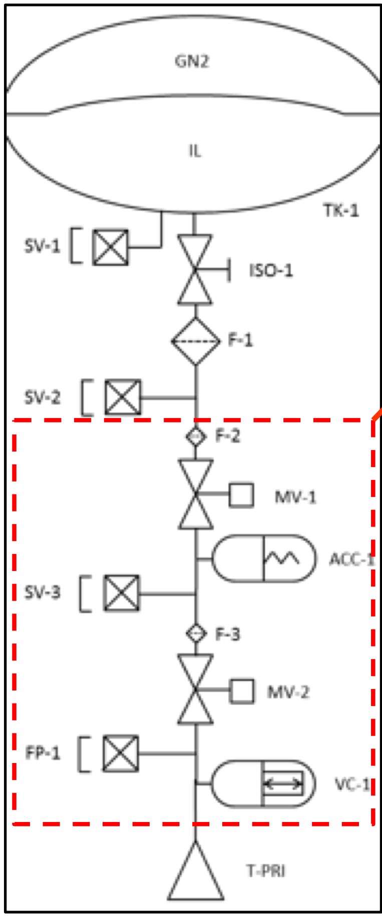


LISA Microthruster Modeling Framework
v5, May 7, 2019

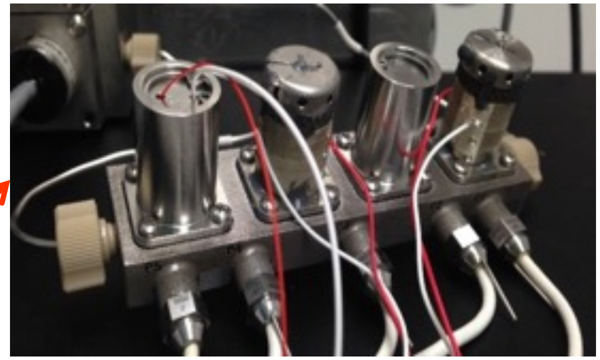
LISA Microthruster Organizational Chart



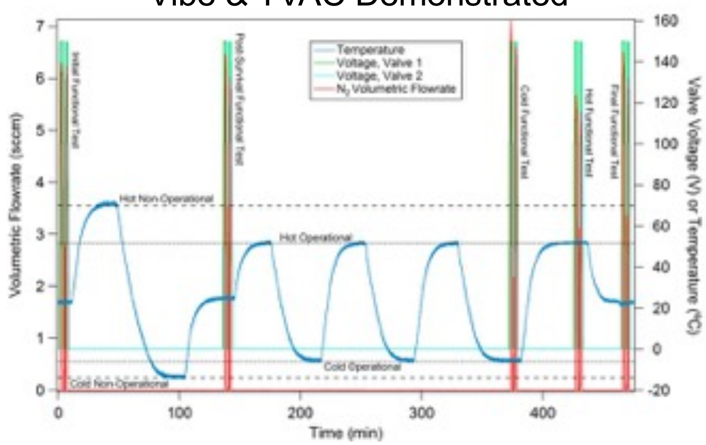
LISA Fully Redundant Propellant Flow Control Assembly



Integrated Series Redundant Valves



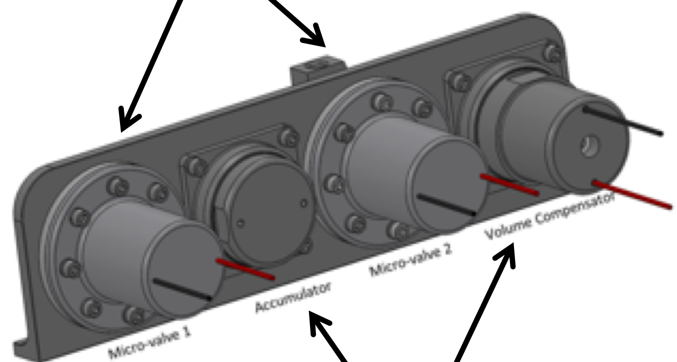
Vibe & TVAC Demonstrated



BUSEK

Series Redundant
Flow Control Valve

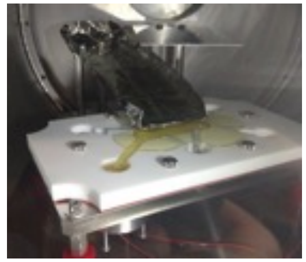
Updated Design



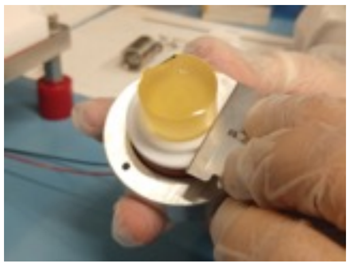
Propellant Thermal
Expansion/Contraction
Management

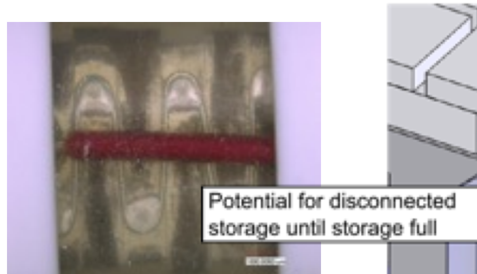
- Flow control assembly (two microvalves in series, an accumulator, and a volume compensator) has already been design, built, and tested in environments to reach TRL 5 as part of NASA SAT program in 2015

Ongoing Activities at Busek

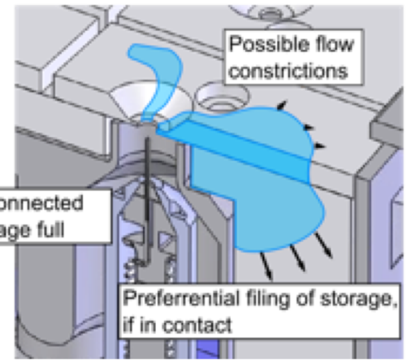


- Focused on breadboard component-level hardware design, build, and test
- Investigating lifetime limiting mechanisms

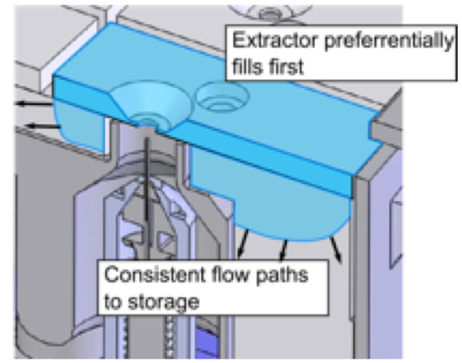


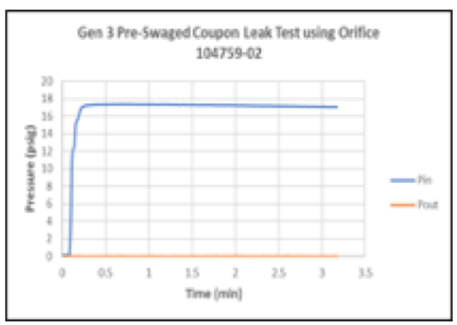


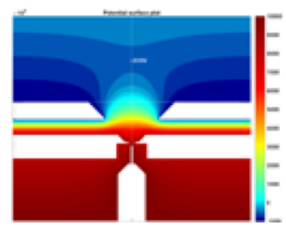
Pore Distribution 1

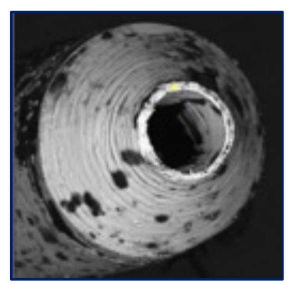


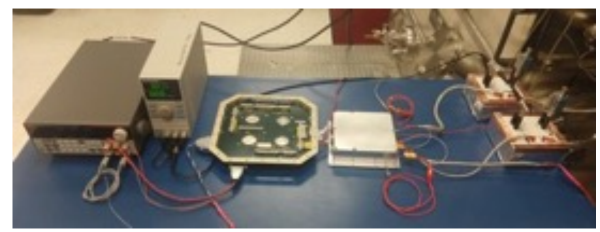
Pore Distribution 2

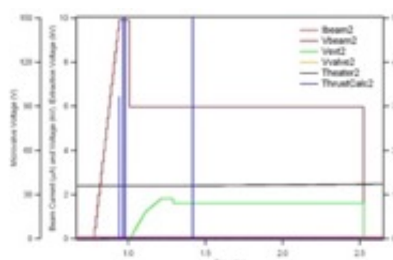


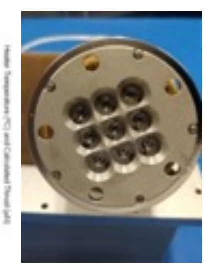




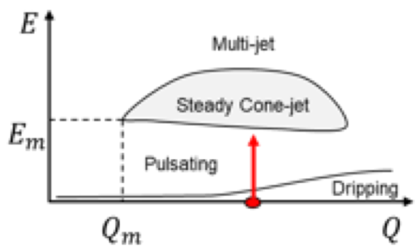


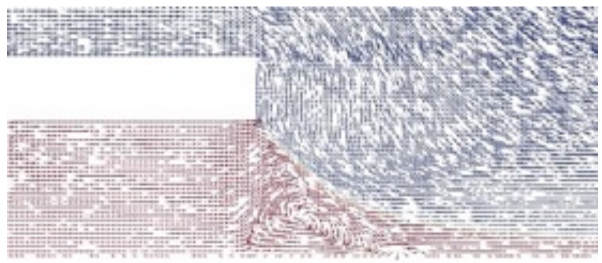




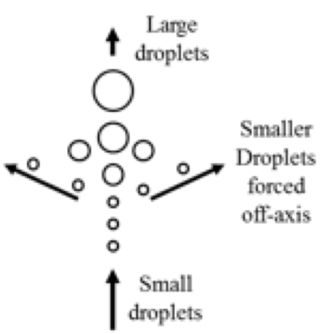


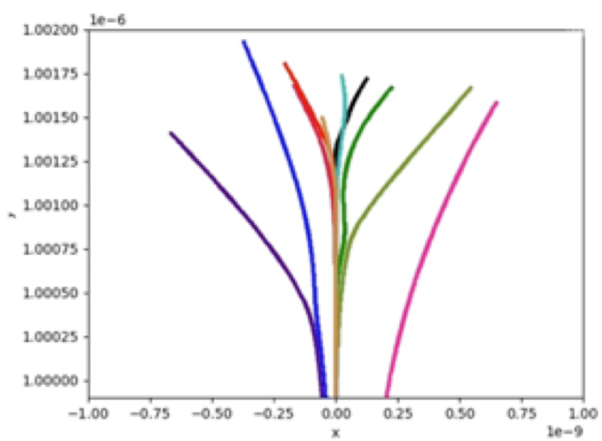
Ongoing Activities at UCLA

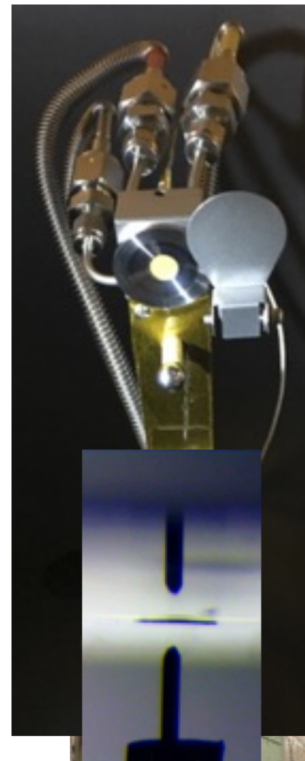


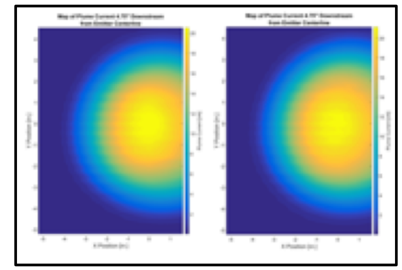


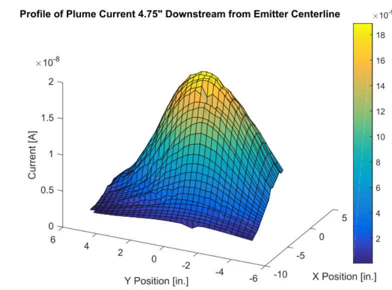
- Focused on emission stability, lifetime model development and validation

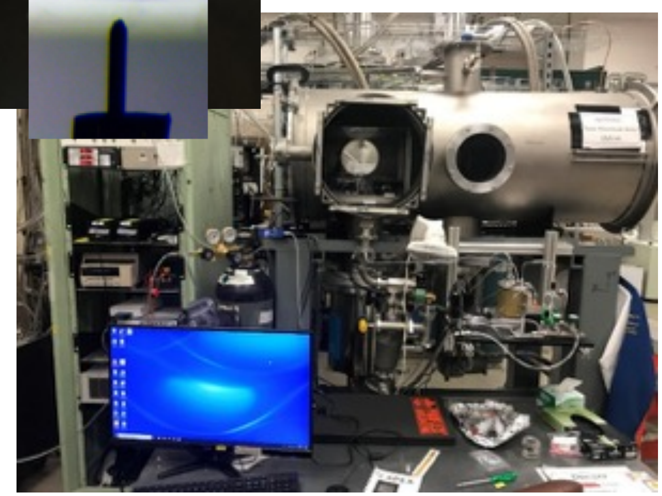




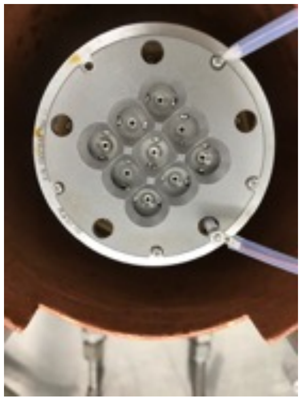




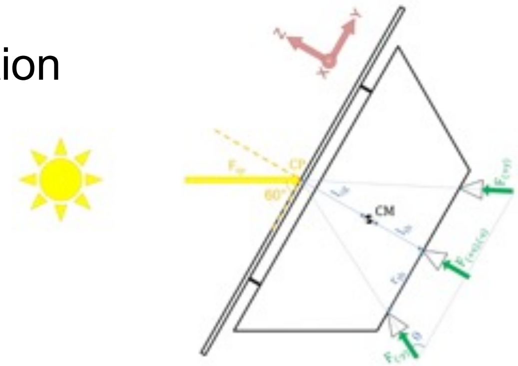


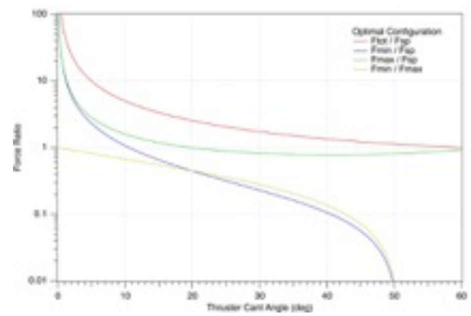


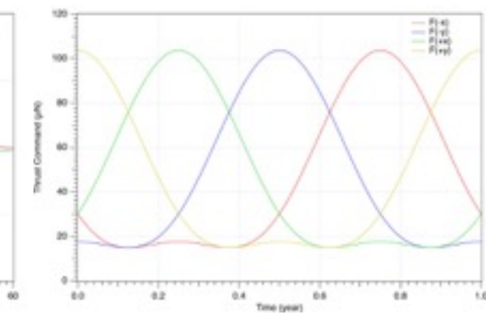
Ongoing Activities at JPL

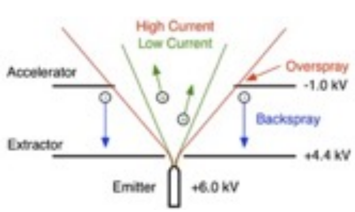


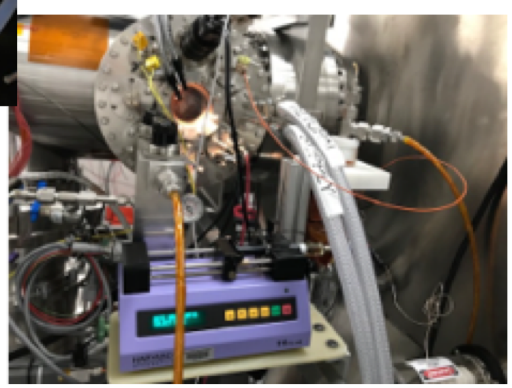
- Focused on system-level requirements, lifetime model validation and uncertainty quantification, and accelerated testing

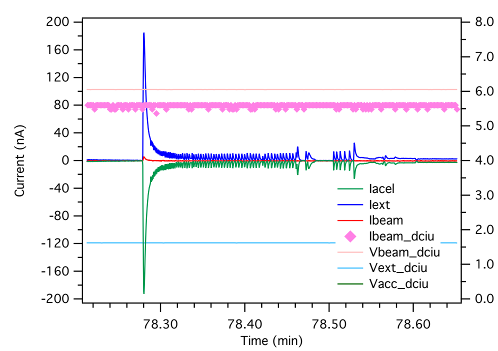


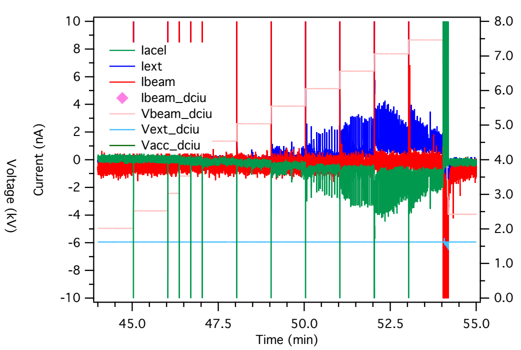












Summary

- NASA and JPL are developing precision electrospray propulsion technology for LISA
  - Great team across NASA, Industry, and Academia
  - Currently working for TRL 5 by Dec. 2020
  - Plans for TRL 6 by May 2023
- Focus is on understanding the fundamental physics of lifetime, developing models and validating them with hardware and test data
- Other NASA missions such as future in-space observatories can benefit from this work directly, as well as smaller spacecraft applications for efficient, low-mass, and high delta-V miniature / scalable systems

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