Electric Propulsion Microthrusters for Spacecraft Precision Pointing and Attitude Control

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

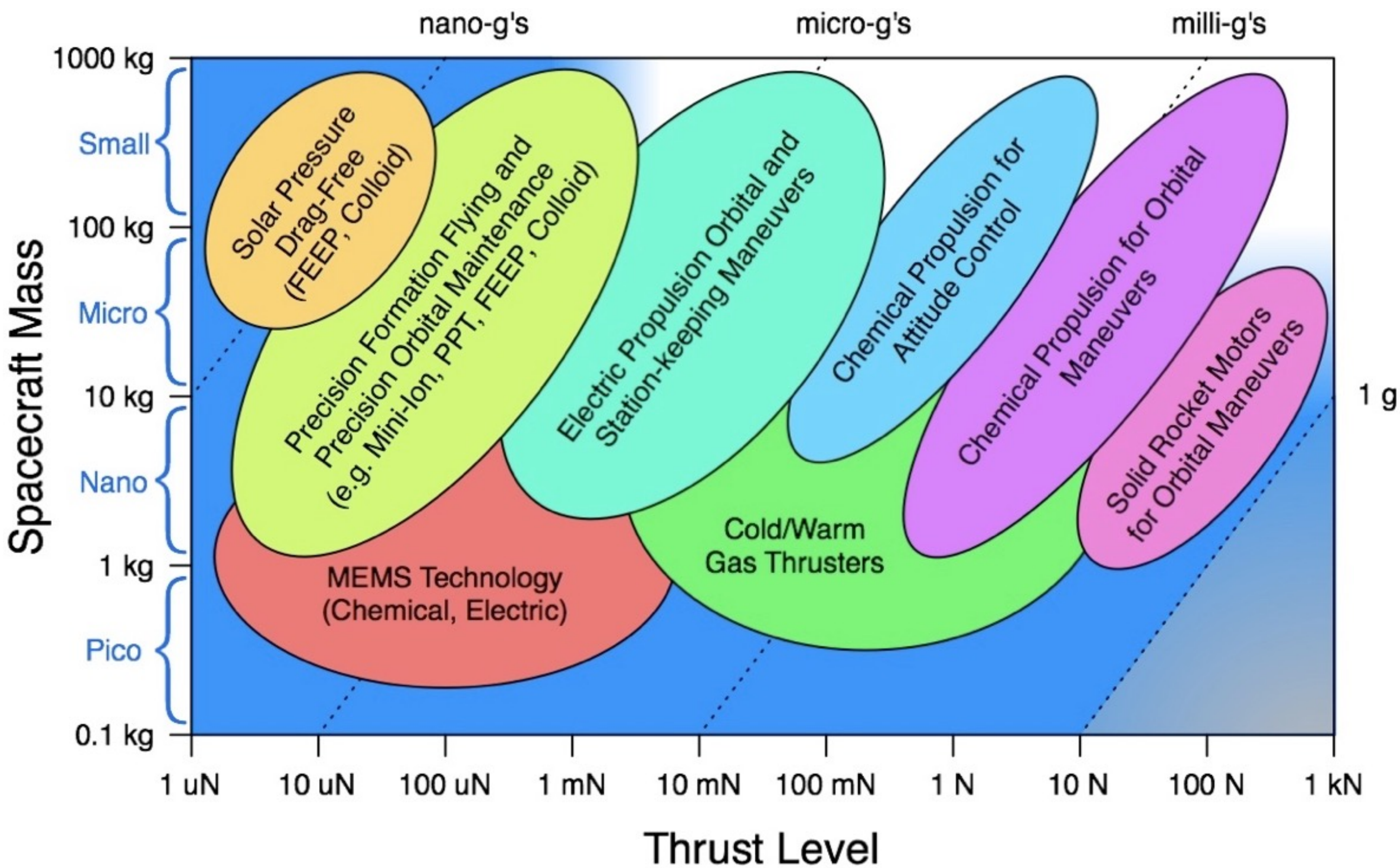
NASA Engineering & Safety Center (NESC) Academy Presentation

December 3, 2020, with Guidance, Navigation and Control Group

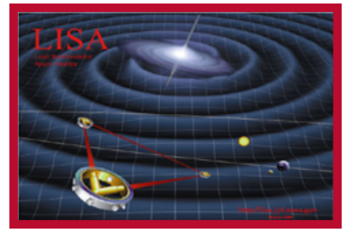
Jet Propulsion Laboratory
California Institute of Technology

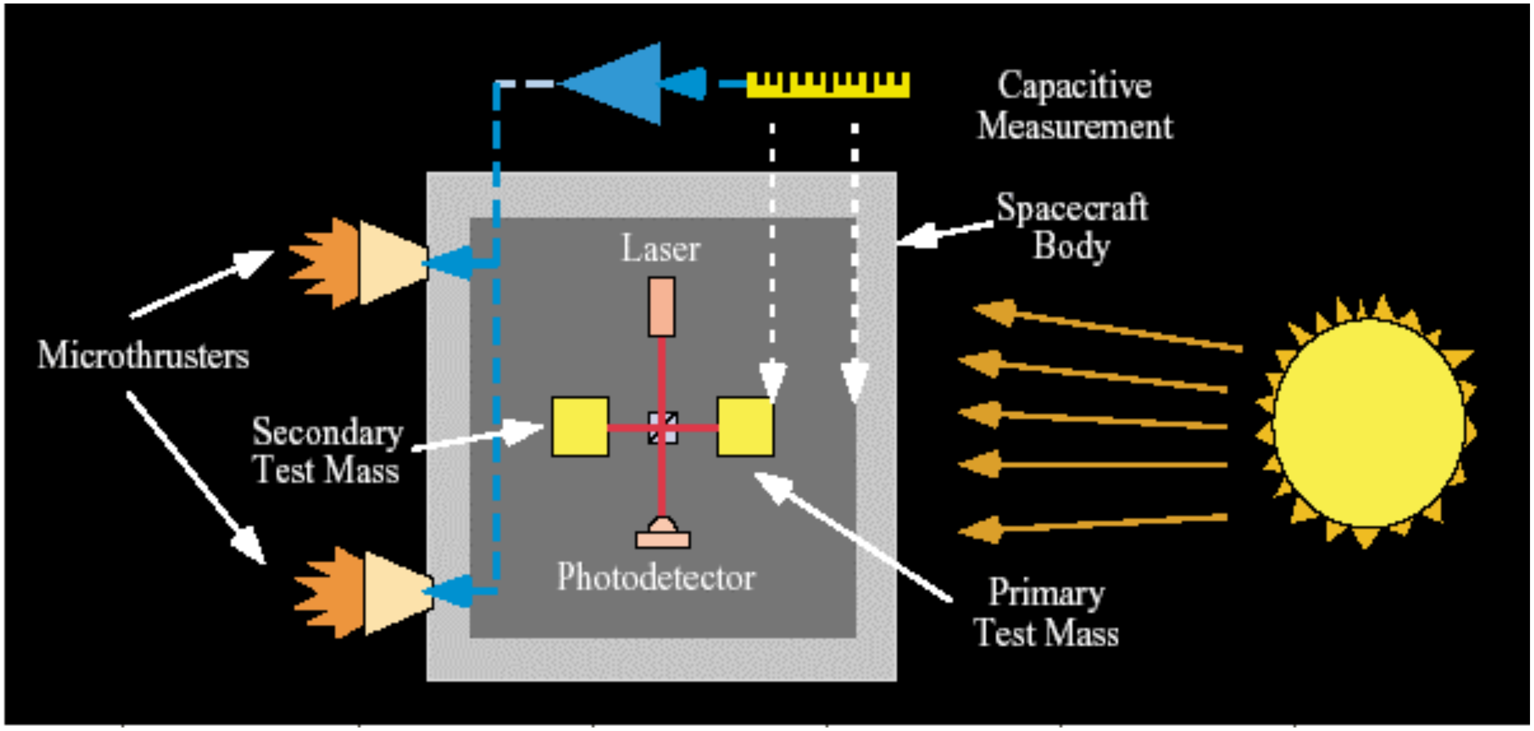
Spacecraft and Propulsion Requirements and Capabilities

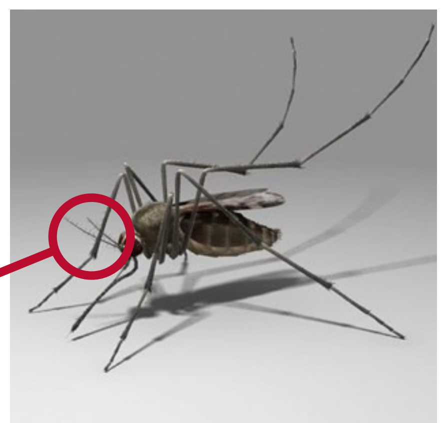
Micropropulsion Mission and Technology Space



Drag-Free Spacecraft



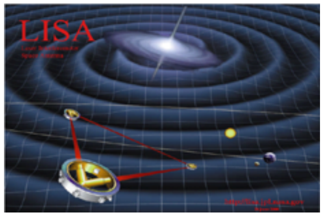


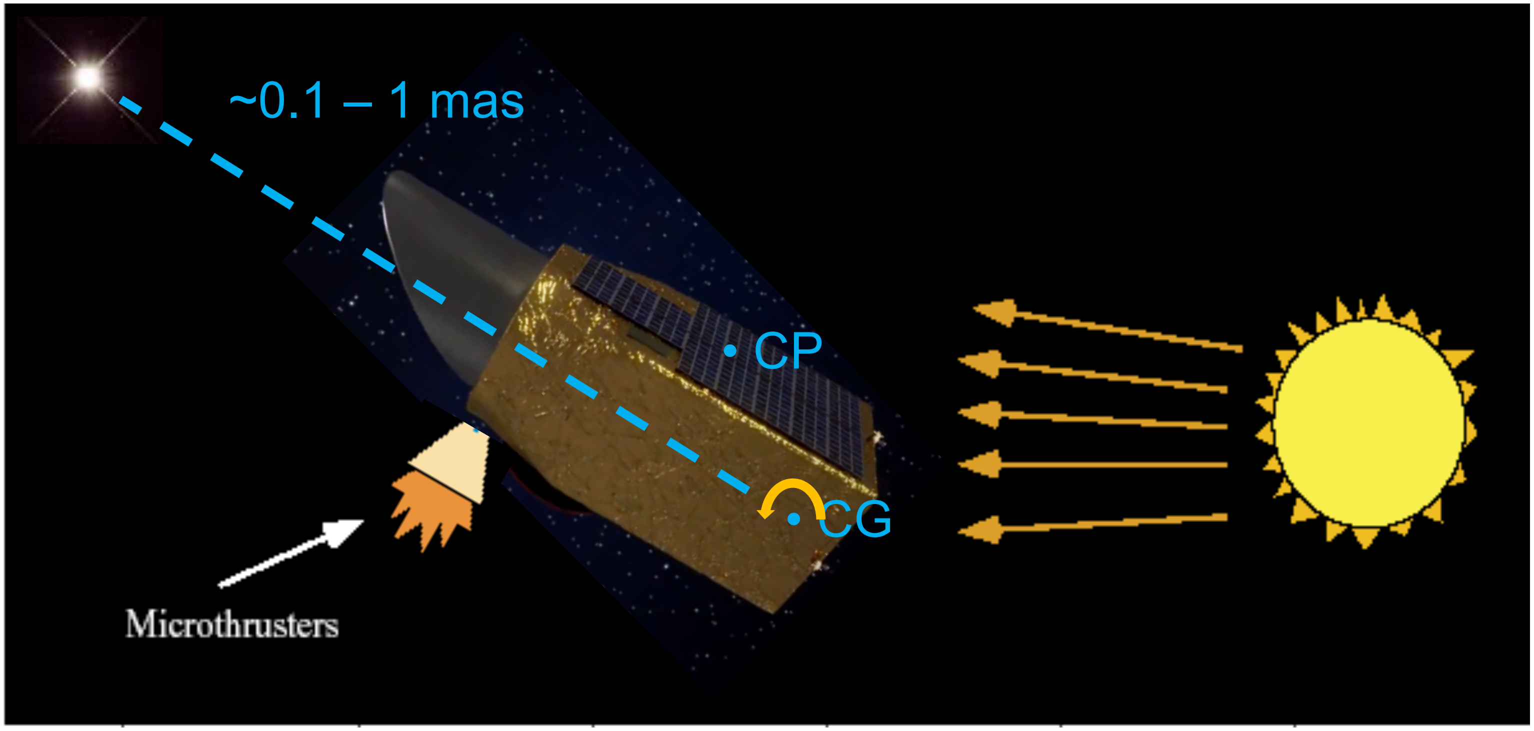


~ 0.1 µN

≈ 30 µN

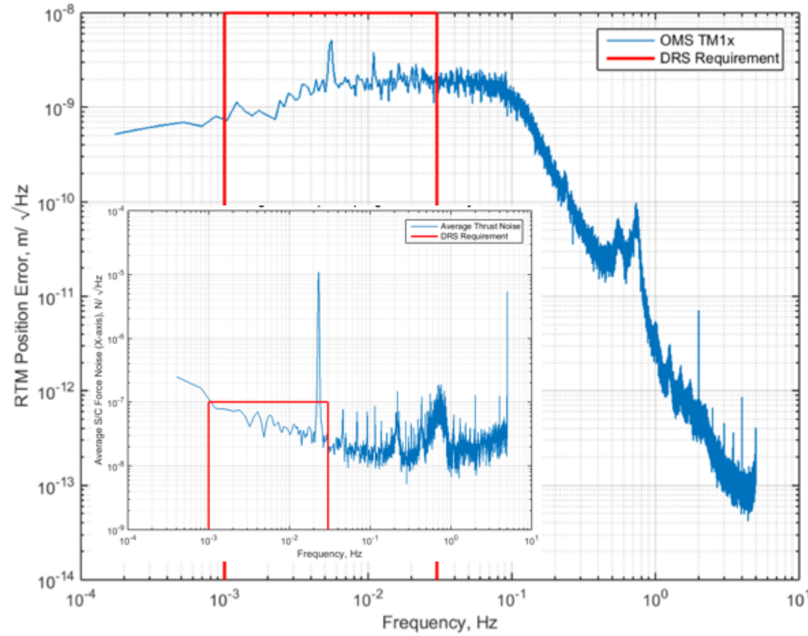
Fine Pointing Observatory

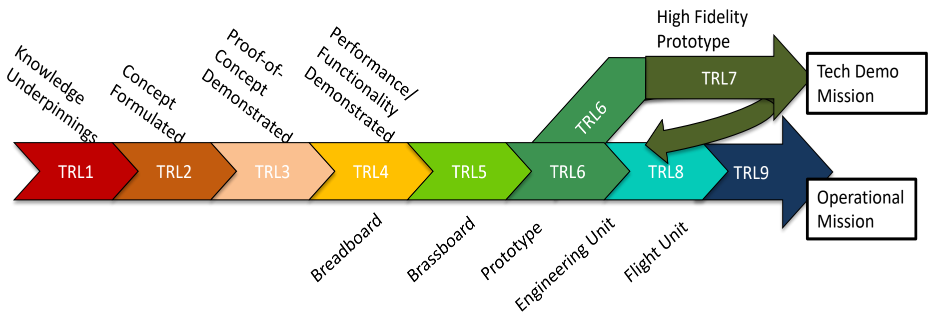


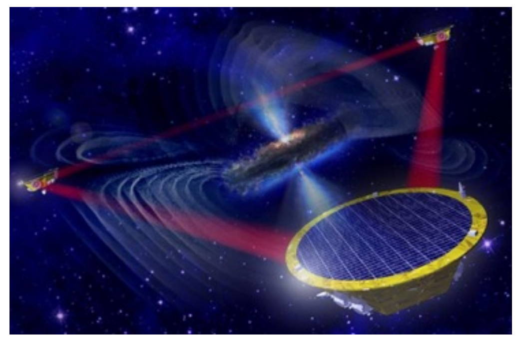


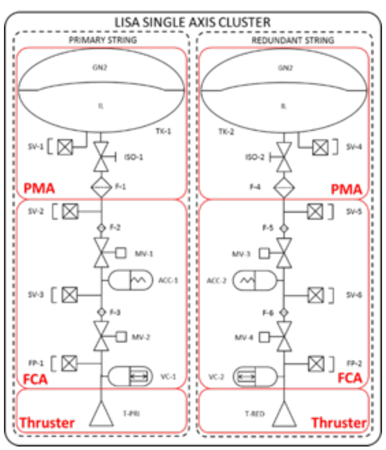
≈ 300 μN

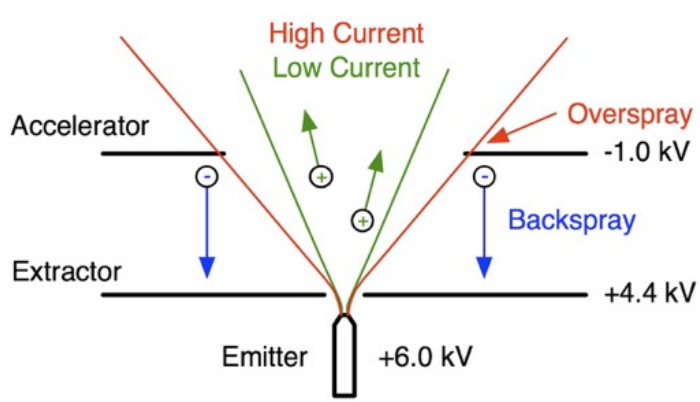
0.1 µN resolution => 0.00000001 kg on Earth











We need another order of magnitude

Lifetime

Understanding

Precision of ground validation

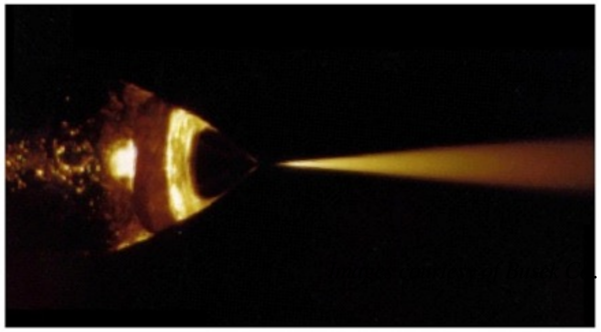
NASA Electric Micropropulsion Activities

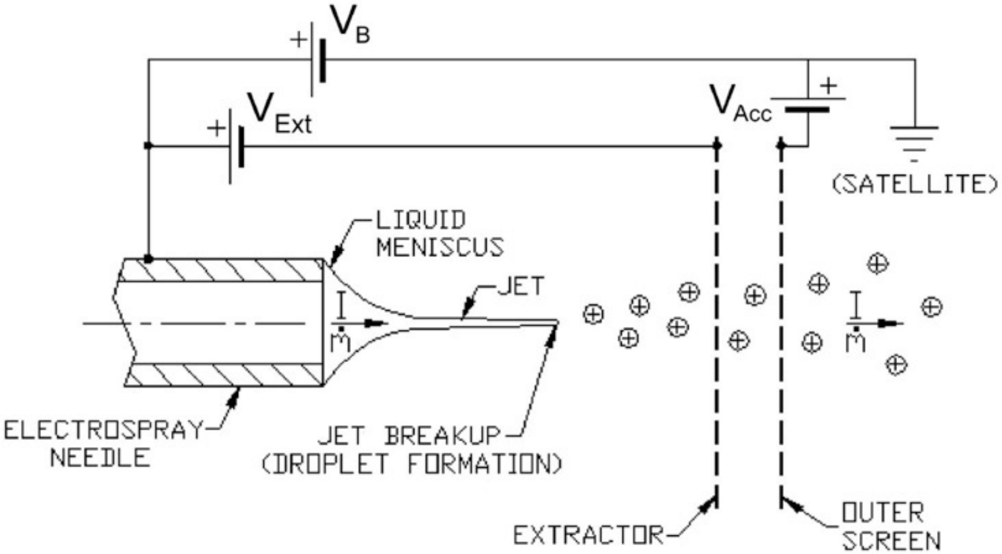
- Flight Missions
  - **LISA Pathfinder**, Space Technology 7
  - MARCO, Mars fly-by in support of InSight landing
  - Many micropropulsion technology demonstration projects coming soon!
  - **LISA,** ESA-Led Gravity Wave Observatory
- Mission Concept Development (ARC, GSFC, JPL)
  - **HabEx, NASA-Led Exoplanet Observatory study for Decadal Survey**
  - **NASA Engineering and Safety Center study on precision microthrusters for observatories**
  - "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 (JPL, Busek Co., Inc.)**
  - **Microfabricated Electrospray Propulsion (Accion, Busek, and JPL MEP – C. Marrese)**
  - Miniature Xenon Ion (MiXI) Thruster (UCLA – Prof. R. Wirz)
  - Magnetically Shielded Miniature Hall Thruster (MaSMi – R. Conversano)
  - Multiple Tipping Point (ExoTerra and Accion) and SBIR (Busek) activities (GRC – T. Liu)
- Challenges
  - **Lifetime and reliability** (also cost, but not as much as for commercial applications)
  - System-level performance (total impulse / total mass; thrust / power)

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

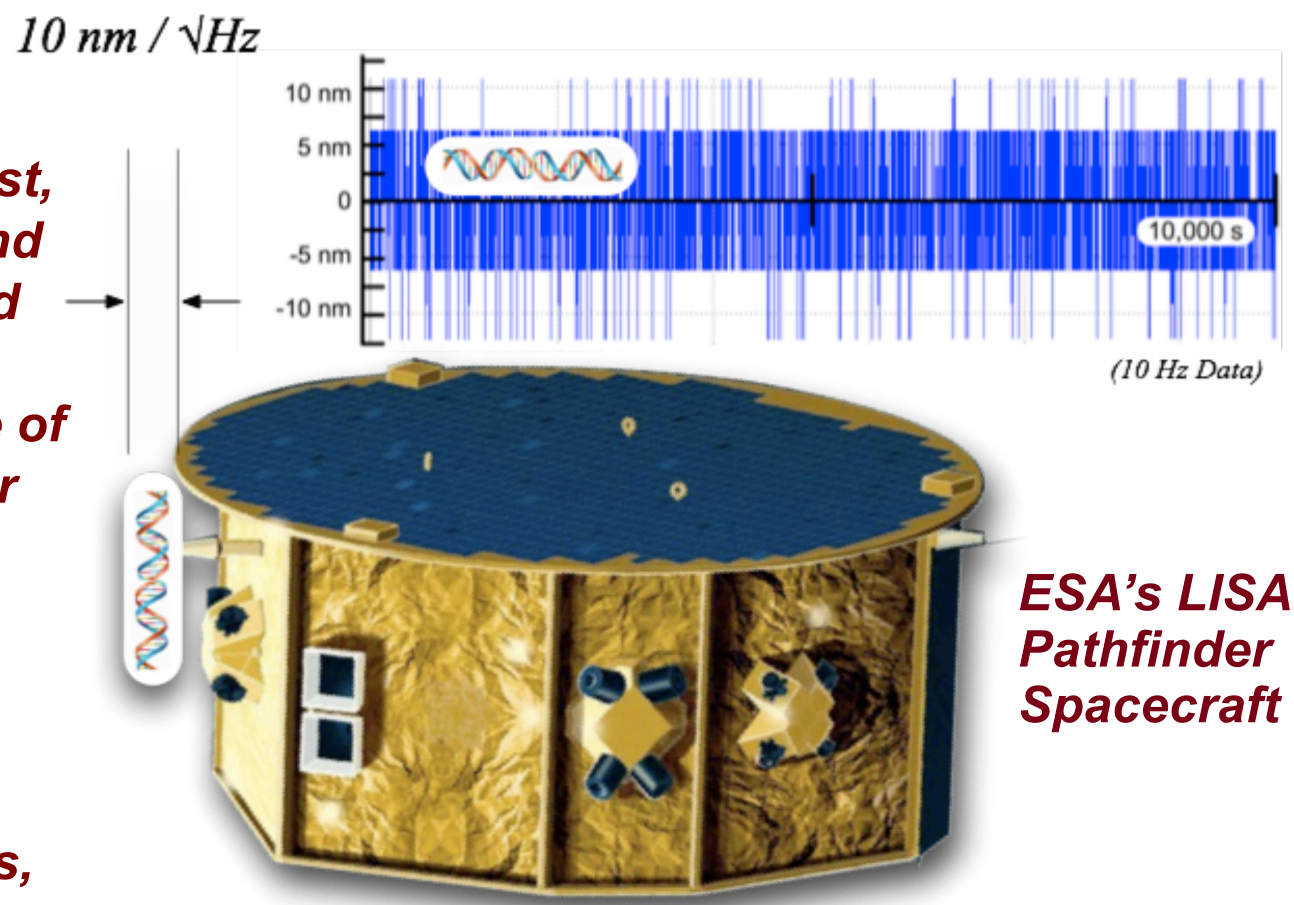
Why Colloid Microthrusters?

- **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

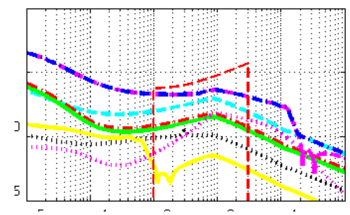
Life-Test complete with 3,400 hrs. of operation

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

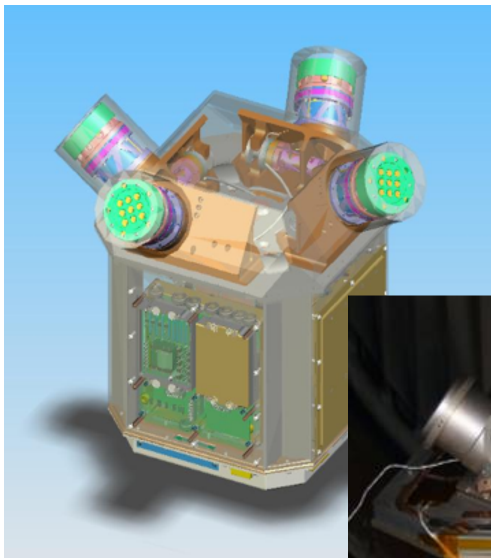
Operations

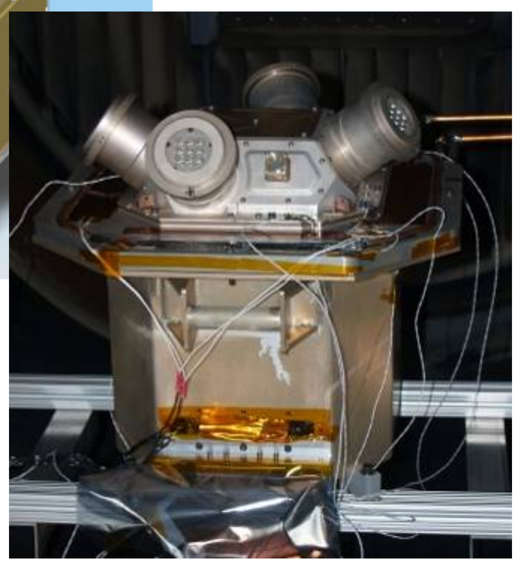
Instrument Delivery
June 20, 2008

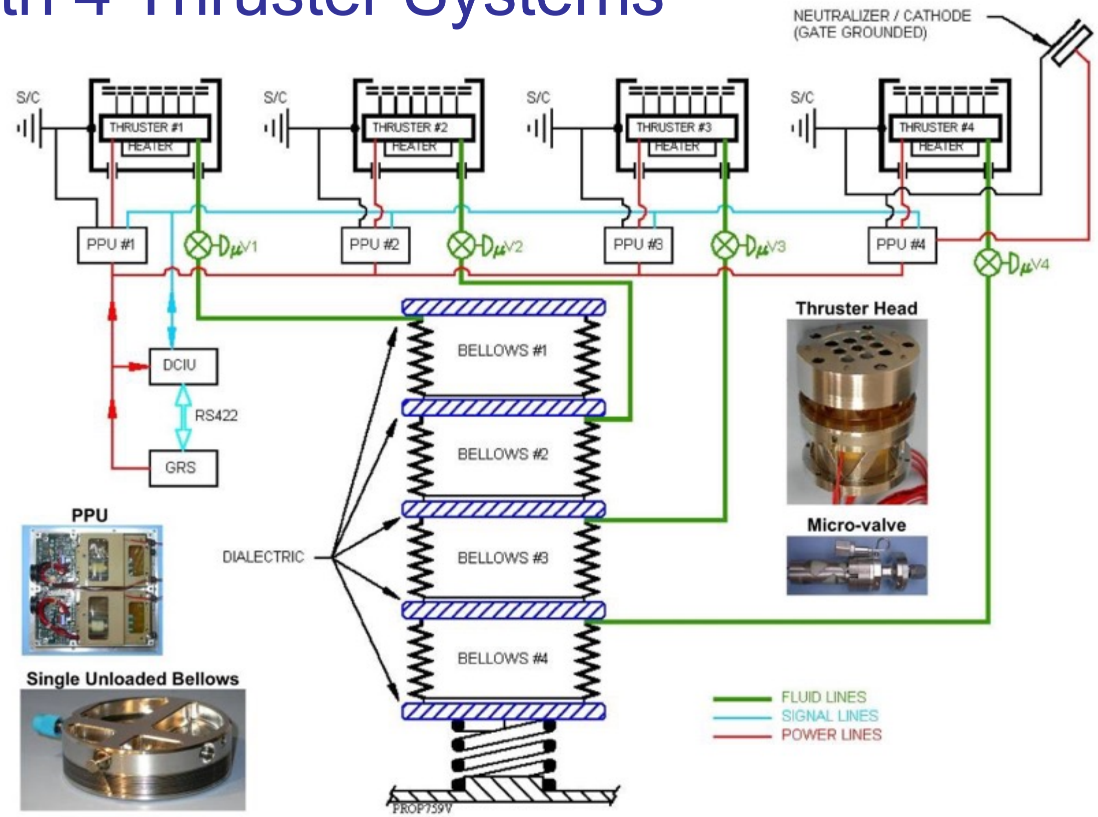
NASA esa AIRBUS DEFENCE & SPACE

ST7 Microthruster System Architecture

Cluster with 4 Thruster Systems







JPL
BUSEK

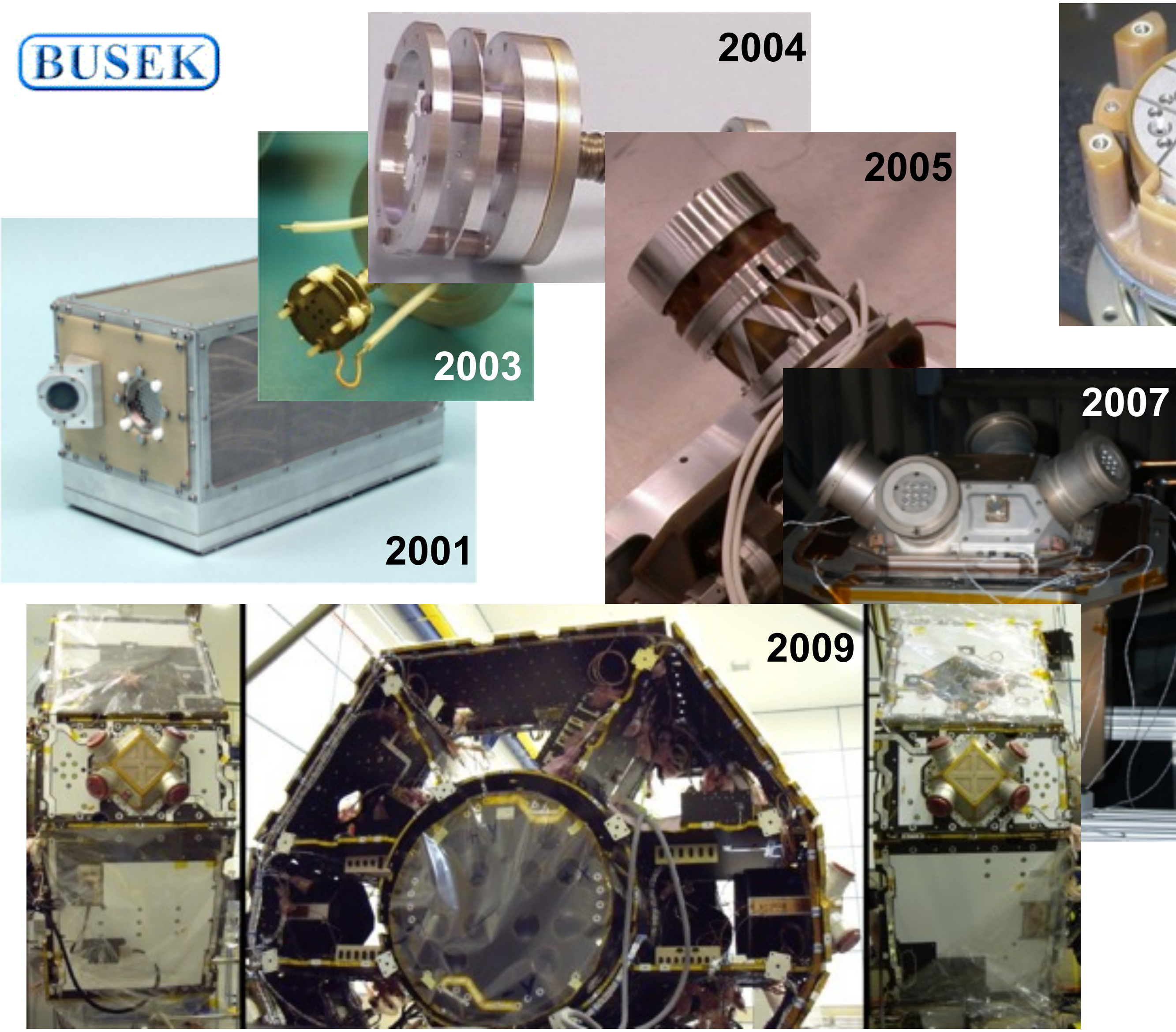
- ST7-DRS has 2 clusters with 4 thrusters per cluster
- All 8 thruster systems are identical
- There is one DCIU and neutralizer per cluster
- Thrust range: 5-30 μN from each thruster head

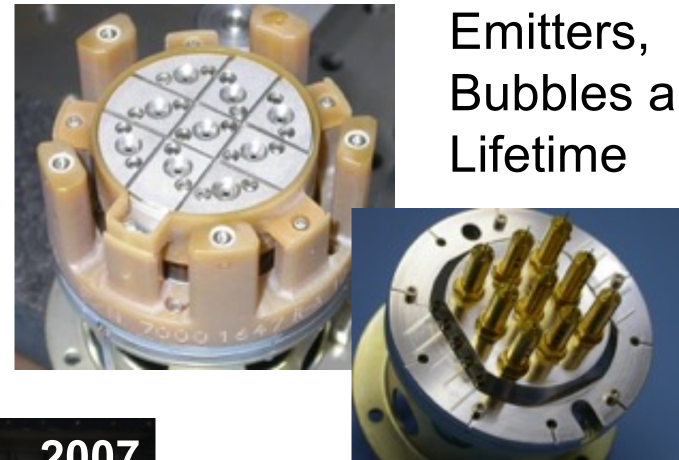
A single thruster system includes:

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

Challenges Going from SBIR to Flight Tech Demo

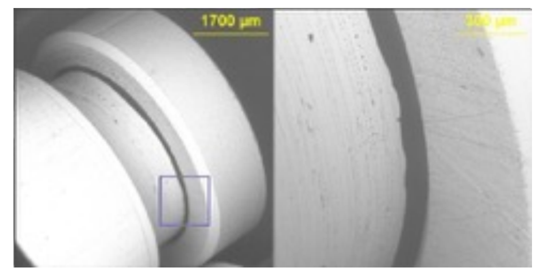
BUSEK

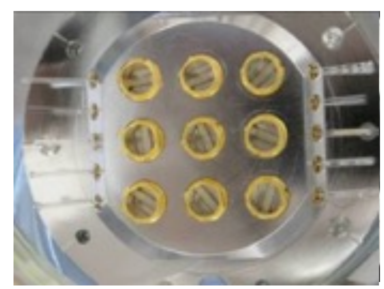




Emitters, Bubbles and Lifetime

Microvalve Manufacturing





Seals and Materials

LISA Pathfinder Launch!

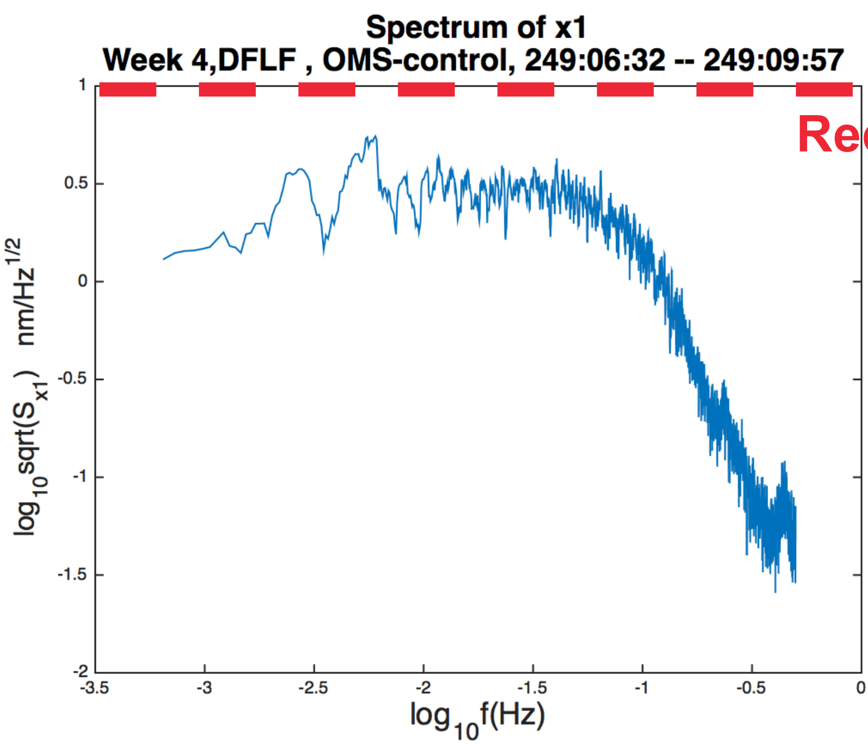
Launch from French Guiana December 3, 2015

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

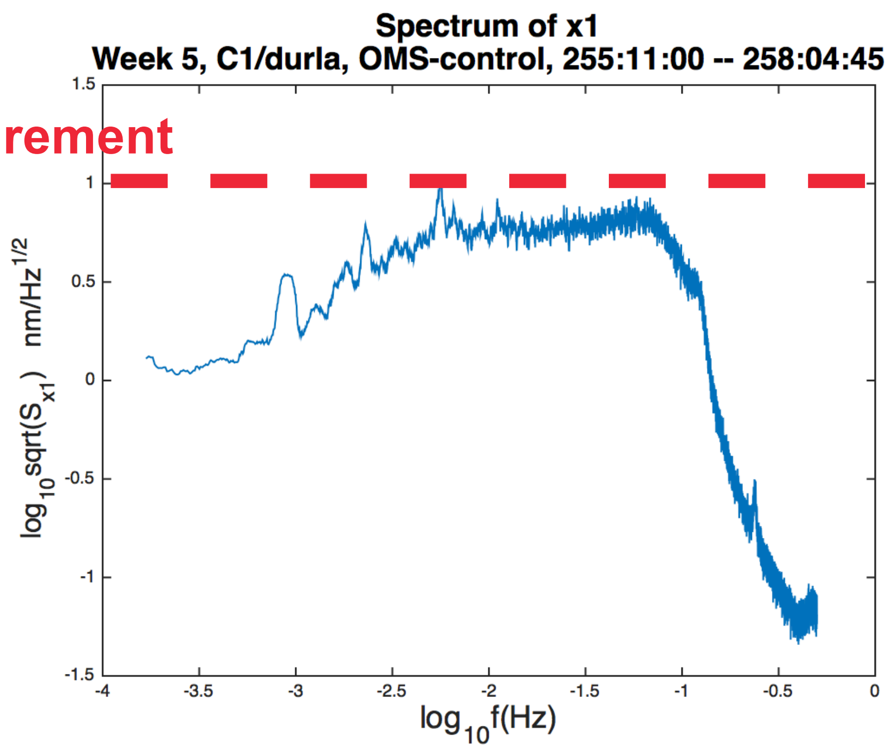
Results from Drag-Free Operation

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

Position Noise in Drag-Free Mode

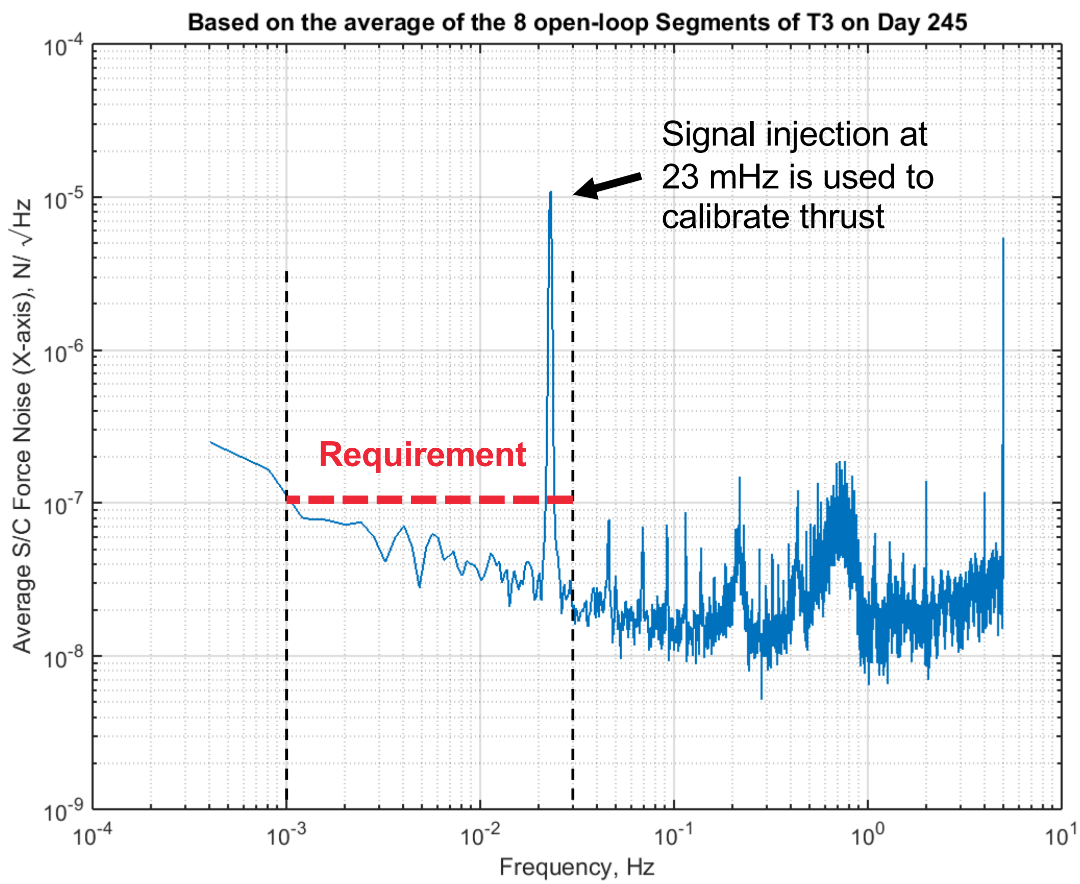


Position Noise in Science Mode



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.

Status of LISA, HabEx, and NASA Study

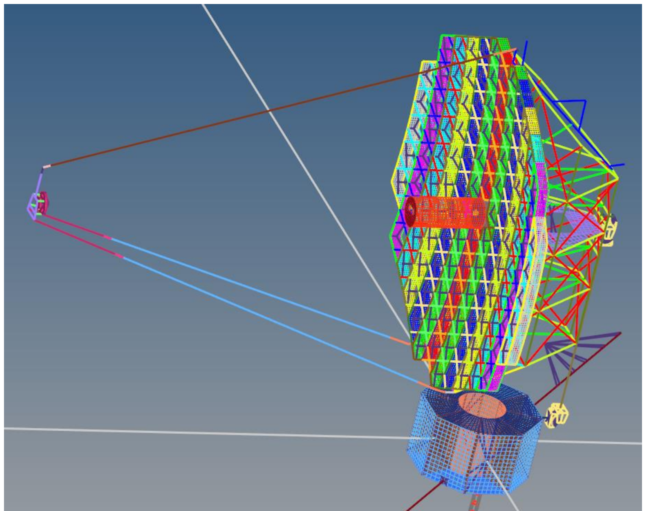
- NASA Engineering and Safety Center study on microthrusters for fine pointing of the next-generation of space-based observatories has been completed (NESC-RP-18-01375)

- 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 5
  - Working with ESA and industrial partners on configuration studies

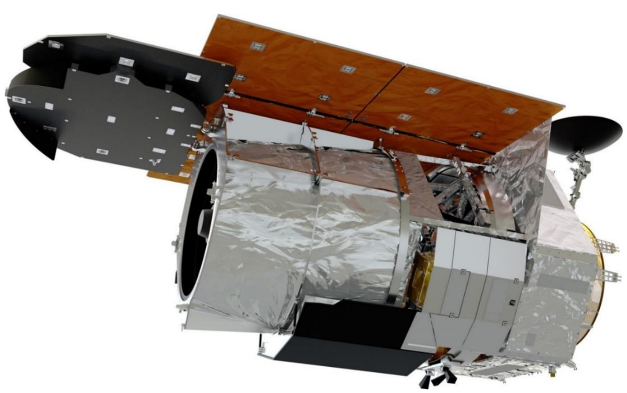
- HabEx has baselined Colloid Microthrusters, but needs additional work to finalize thrust magnitude and noise requirements
  - Might require an additional development beyond LISA, especially if the thrust level is higher with a higher frequency band
  - HabEx has continued study funds to prepare for Decadal Survey, but no specific microthruster technology development funds yet
  - This approach would also benefit LUVOIR, but has not been studied yet

Summary of NESC Study on Precision ACS (1)

See NESC-RP-18-01375; October 29, 2020



Observatory 1; ~35000 kg



Observatory 2; ~7500 kg

- NASA Engineering and Safety Center (NESC) Study led by Mr. Cornelius (Neil) J. Dennehy (GSFC) and Aron Wolf (JPL)
- Objective: assess the benefits of micro-thrusters for application on fine-pointing space observatory missions for fine pointing, in comparison to traditional architectures using reaction wheels alone.
- Study employed Aerospace Corp. for detailed simulations of two example observatories with a variety of cases including colloid and cold gas microthrusters along with reaction wheels
- Study found that microthrusters provided more than an order of magnitude improvement over SOA pointing (i.e. HST)

Summary of NESC Study on Precision ACS (2)

See NESC-RP-18-01375; October 29, 2020

Replacing reaction wheels with colloid or cold gas microthrusters dramatically improved pointing stability performance

Table 7.2-3. Pointing Stability Performance: Observatory 1 Cases

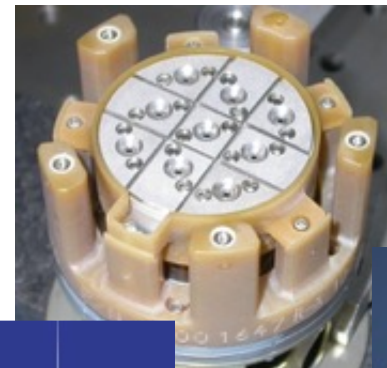
10s Sliding Window Angle Error RMS – 95%					
Case #	**Case**	**X-axis (mas)**	**Y-axis (mas)**	**Z-axis (mas)**	**RSS xyz (mas)**
1	Colloid micro-thrusters only	0.249	0.023	0.028	0.252
2	Wheels only	14.054	9.585	33.802	37.841
3	Cold gas micro-thrusters only	0.296	0.167	0.088	0.351

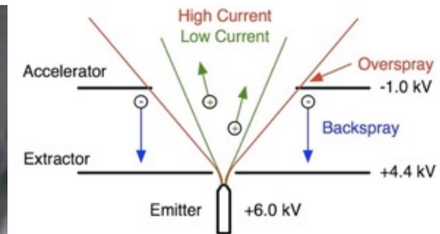
Table 7.2-1. Pointing Stability Performance: Observatory 2 Cases Without Isolator

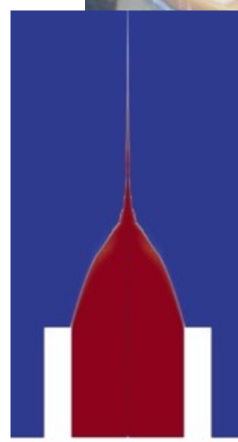
10s Sliding Window Angle Error RMS – 95%					
Case #	**Case**	**X-axis (mas)**	**Y-axis (mas)**	**Z-axis (mas)**	**RSS xyz (mas)**
8	Colloid micro-thrusters only	0.016	0.06	0.016	0.064
9	Wheels only	585.758	537.408	278.483	842.302
10	Cold gas micro-thrusters only	0.095	0.224	0.097	0.262

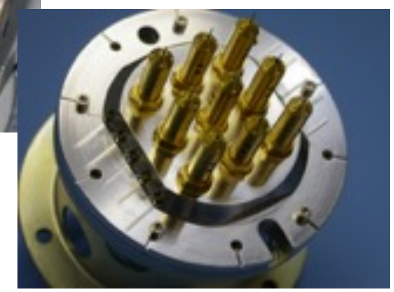
LISA Microthruster Technology Development Overview

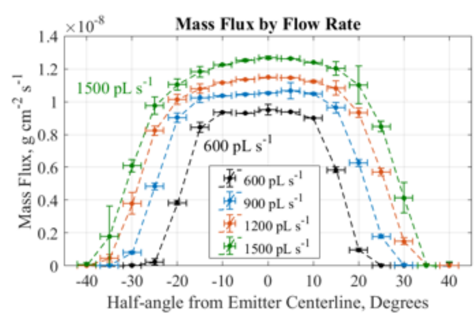
- **Role in Flight System**
  - Microthrusters are the actuator of the drag-free attitude control system (DFACS)
  - Performance was demonstrated on LISA Pathfinder (TRL 7), but new, lower TRL components and updates are required for increased reliability and lifetime on LISA
  - HabEx is also baselining colloid microthrusters for precision pointing of the observatory
  - **Key challenge is demonstrating lifetime**
- **Development Team**
  - *Product Delivery Lead: J. Ziemer (JPL)*
  - *Busek / HW Lead: 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 - **COMPLETE**
  - Phase 2: Component-level testing (TRL 5) starting Oct 2018 expected through Jan 2022
  - Phase 3: System-level testing (TRL 6) is on hold pending Decadal Survey recommendation











Microthruster Technology Development Objectives

P1, Yr 1, FY18

P2, Yrs 2-4, FY19-22

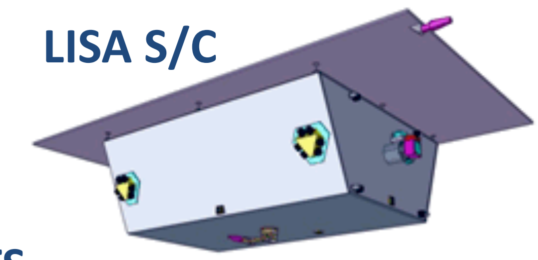
P3, Yrs 4-6, F22-24

1. Incorporate lessons learned from ST7-DRS and LPF, previous LISA, SBIR, and SAT thruster component development activities funded by NASA, as well as studies from the ESA-led industrial contracts to derive LISA colloid microthruster design guidelines and requirements.
2. Develop and validate models of colloid exhaust beam and interactions with electrodes to design thruster head to meet expected LISA thrust range and lifetime requirements.
3. Design, build, and test breadboard (BB) hardware (i.e. ST7 flight spares and EM units as well as SAT feed system), to validate models, component designs and procedures.
4. Develop colloid microthruster lifetime models and validate through accelerated and end-of-life (begin with thruster pre-conditioned to end-of-life conditions) testing.
5. Design, build, and test brassboard / demonstration model (DM) hardware (i.e. a full single-string thruster system including thruster head, feed system, and electronics), to meet LISA requirements and demonstrate TRL 5 at the thruster assembly level.
6. Start a long-duration lifetime demonstration using DM hardware, reaching at least 8000 hours of operation by the end of this project, allowing 50% of required lifetime by PDR (possibly in late 2022-24) and 100% of required lifetime by CDR.
7. Design, build, and test prototype model (PM) hardware (i.e. a full cluster of multiple string PM class thruster systems with flight-like materials and packaging) to meet LISA requirements and demonstrate TRL 6 at the full thruster cluster system level.
8. Deliver single PM thruster and PM cluster units used in all validation testing and the environmental test results for NASA and ESA review of potential contribution to LISA.

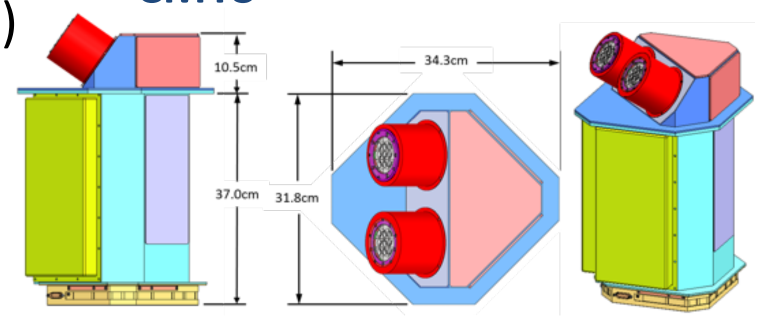
Microthruster Architecture Overview

- **Each spacecraft will have a micropropulsion system with multiple clusters of dual-string microthrusters that will be used for drag-free operation only**
- **Colloid Microthruster Subsystem (CMTS)**
  - Colloid Microthruster Assembly (CMTA)
    - Thruster Head Assembly (THA)
    - Flow Control Assembly (FCA)
    - Microthruster Structure
  - Propellant Management Assembly
  - Power & Control Electronics
  - Structure & Mechanical Assembly

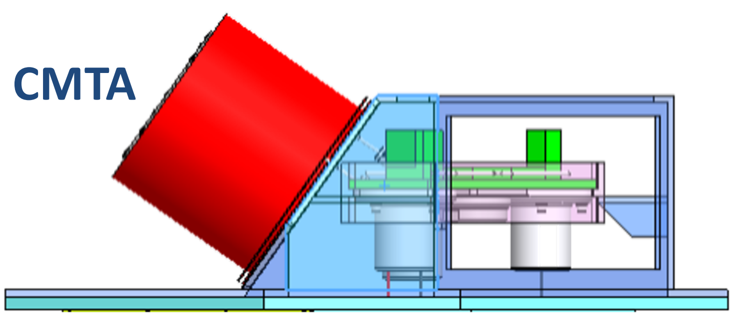
LISA S/C



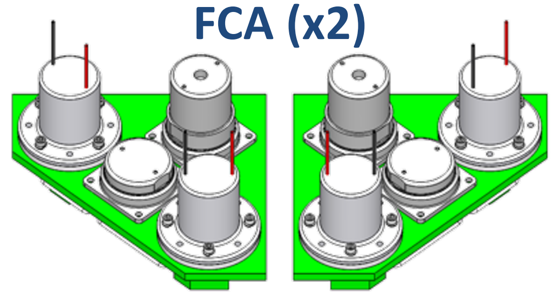
CMTS



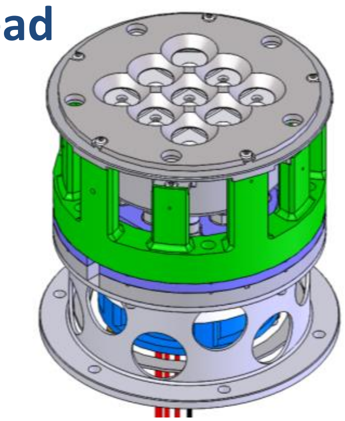
CMTA



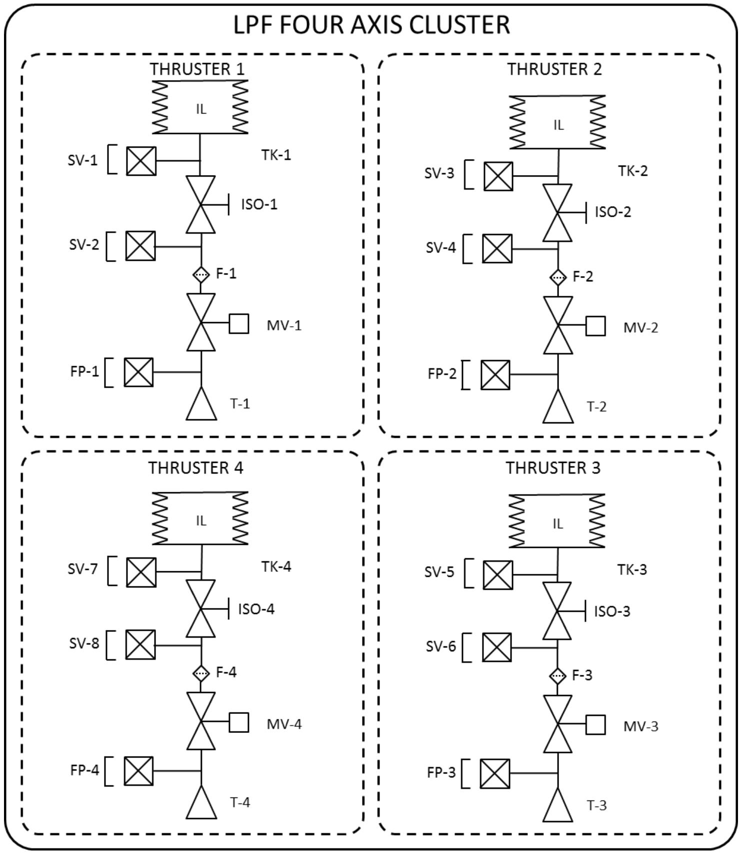
FCA (x2)



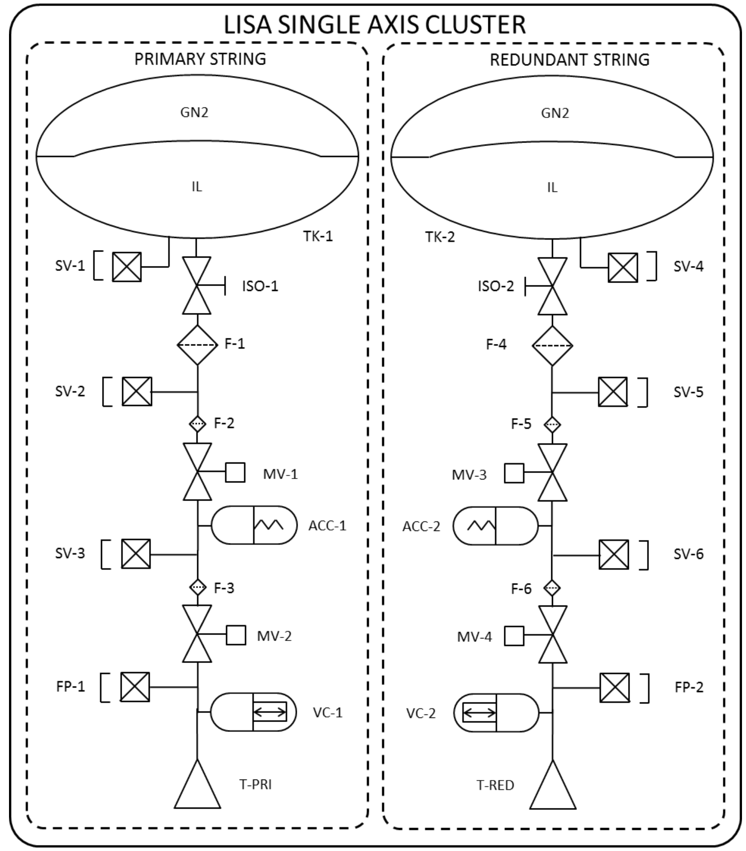
Thruster Head



LISA Requirements – Redundancy



Multiple Single Point Failures

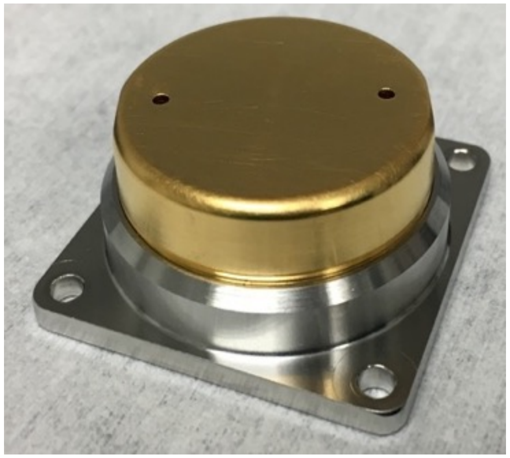


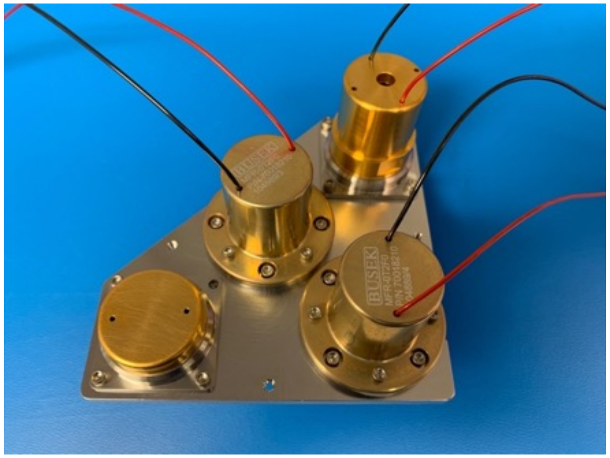
Full Redundant Approach

- **LISA requires bigger tanks and fully redundant stings and internal valves**
- **Tanks must be electrically isolated but can be placed in various orientations**
- **Colloid tanks will have a diaphragm and blow-down over the mission duration (BOL and EOL conditions on a metal diaphragm tank were demonstrated in SAT program)**

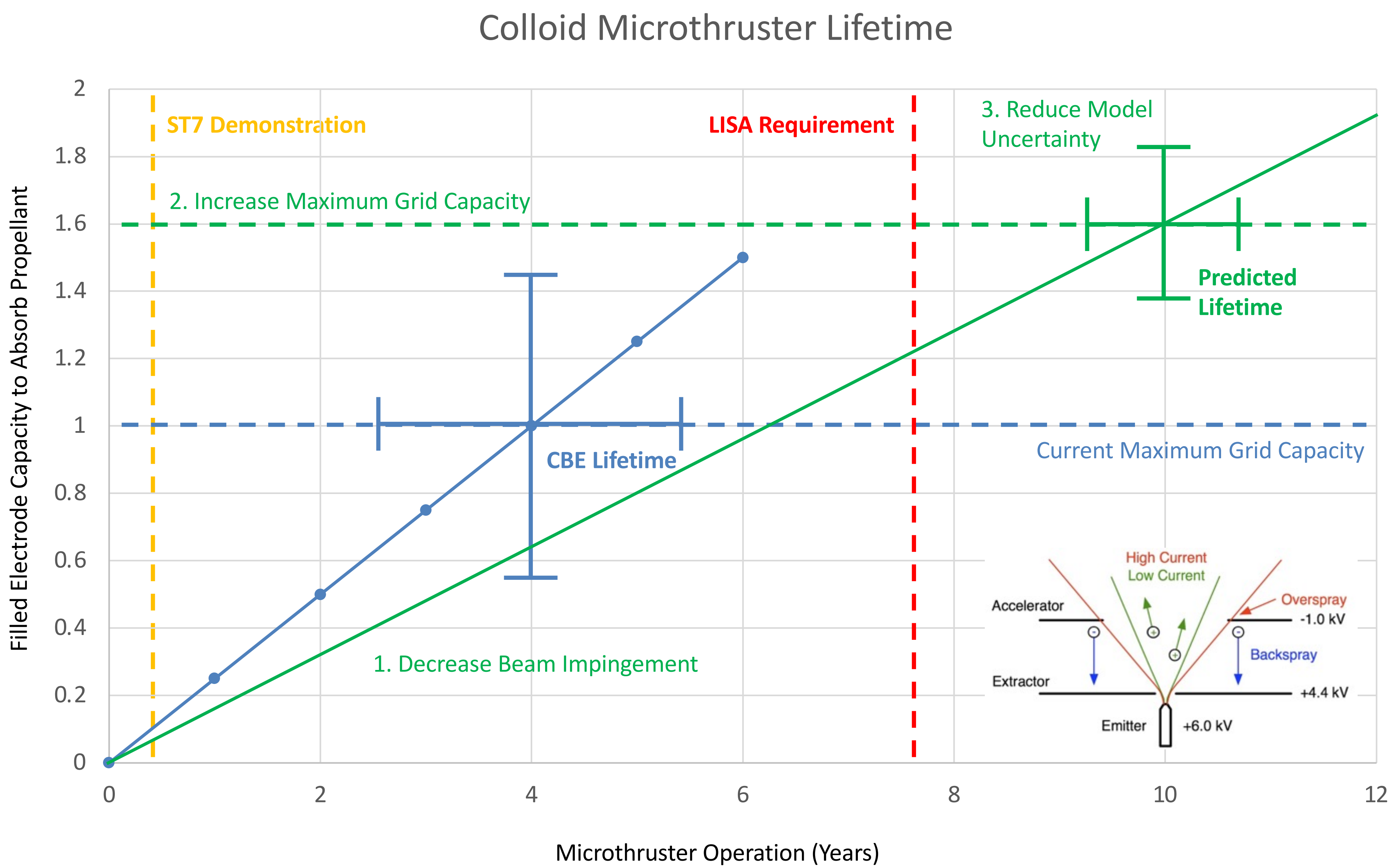
Progress on Hardware Development at Busek

- All new breadboard-level feed system components have passed through dynamic and thermal vacuum testing successfully using nitrogen for performance measurement
- Brassboard / Demonstration Model (DM) Flow control assembly (FCA) has been integrated together and has begun starting testing with propellant under vacuum
- Single-emitter tests are being used to examine lifetime sensitivity to alignment tolerances and electrode geometry





Increasing Thruster Lifetime



Quantification of Margins and Uncertainty

QMU Assessment

Model Credibility

Guidelines and Standards

- *NASA Modeling and Simulation Standard (7009)*
- *ASME, AIAA, DoE, DoD Publications*

Planning and Assessment

- *Predictive Capability Maturity Model*
- *Phenomena Identification and Ranking*

Heritage and Traceability

- *Model construction, CM and SQA*
- *Evidence management and traceability*

Prediction Uncertainty

Uncertainty Quantification

- *Numerical Errors*
- *Aleatory (Random) Variabilities*
- *Epistemic (Unknown) Variabilities*

Uncertainty Management

- *Integrated, Multiphysics Simulations*
- *High Fidelity Physics*

Model Verification and Validation

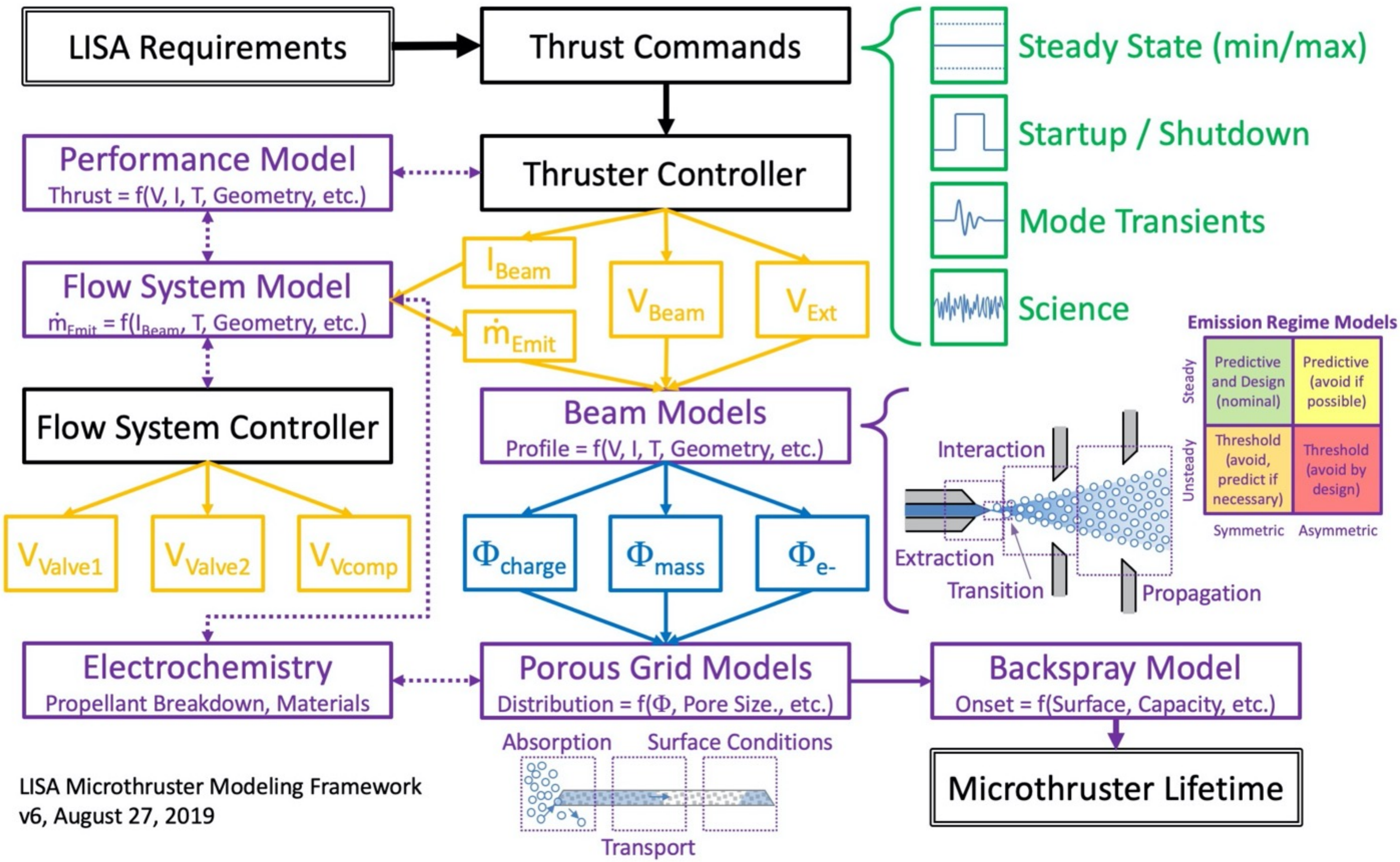
- *Test Selection and Design*
- *Parameter Calibration Tests*
- *Subsystem Acceptance Tests*

Tools

Model construction, heritage and traceability, uncertainty quantification, high fidelity models

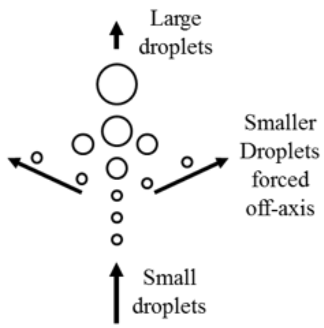
(Based on idea from K. Alvin, SNLA)

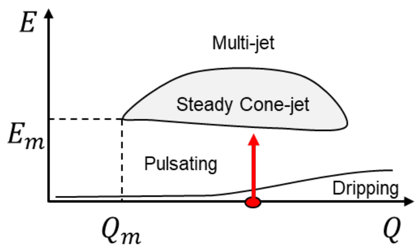
LISA Microthruster Modeling Framework

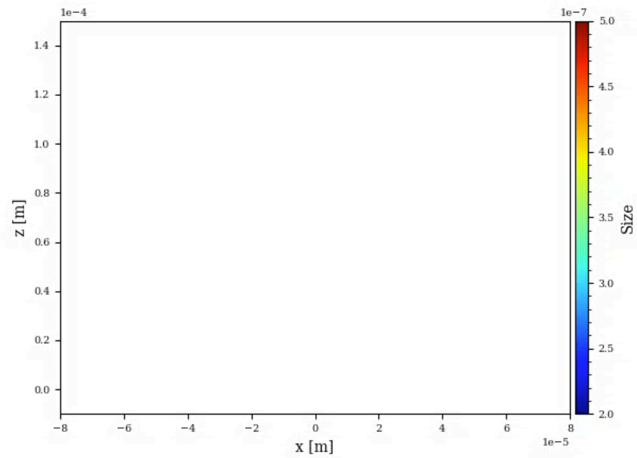


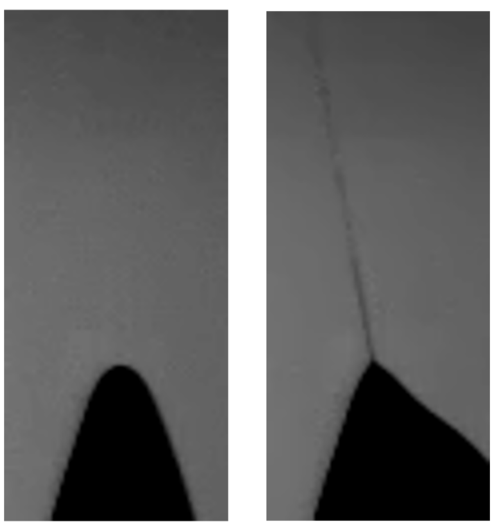
LISA Microthruster Modeling Framework
v6, August 27, 2019

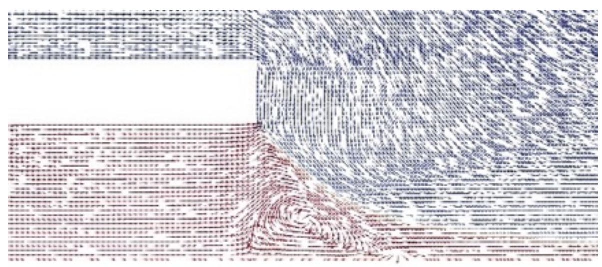
Ongoing Activities at UCLA



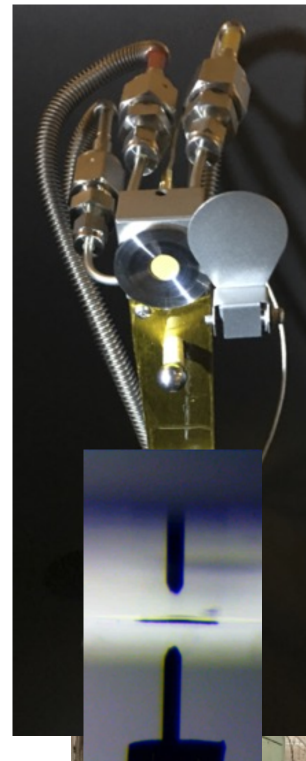


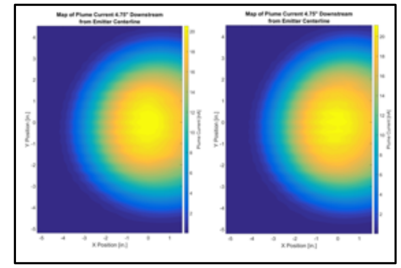


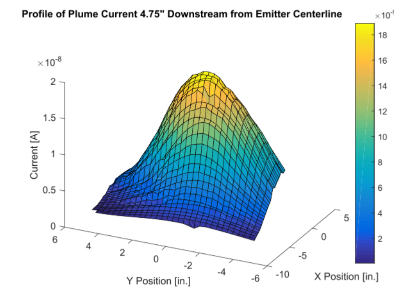


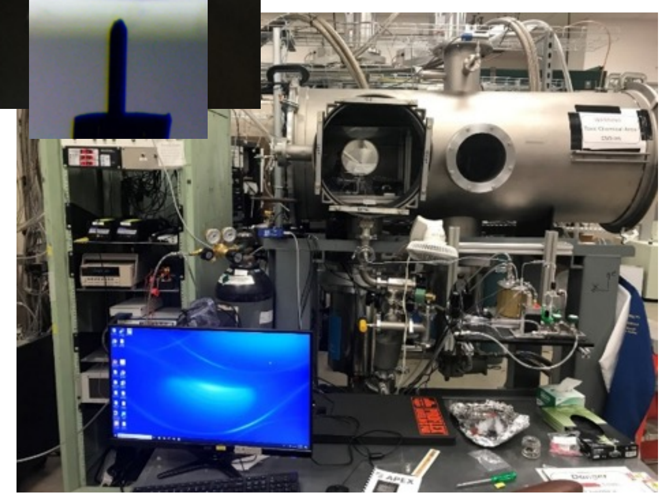


- **Focused on emission stability, lifetime model development verification and validation**

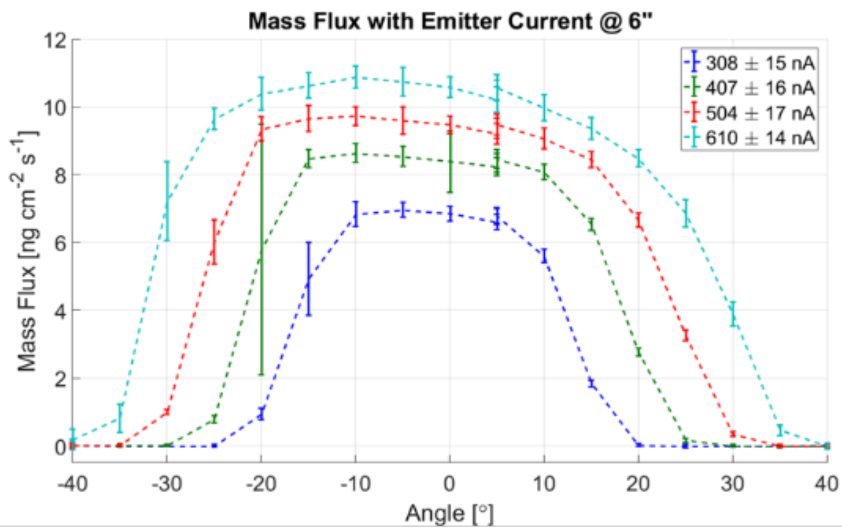


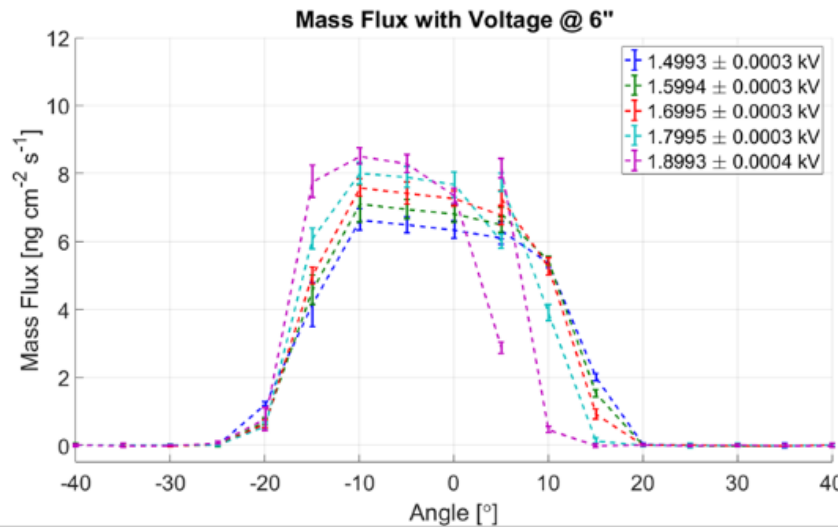


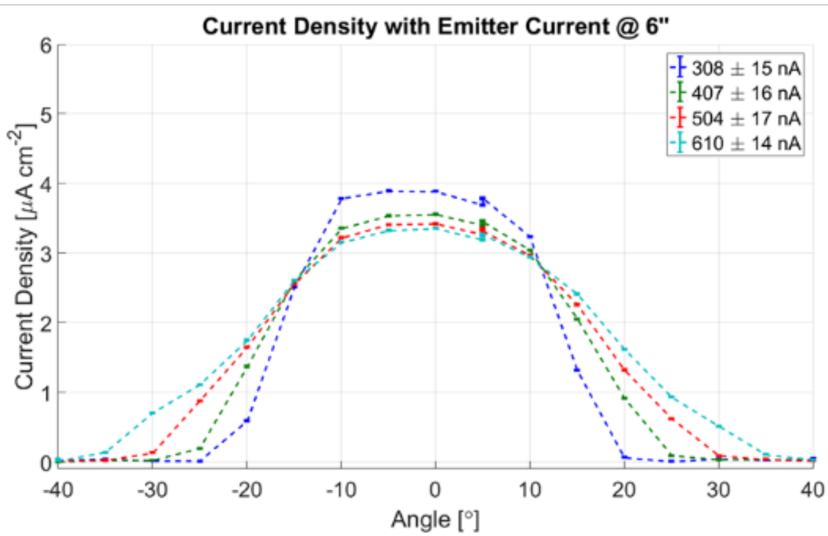


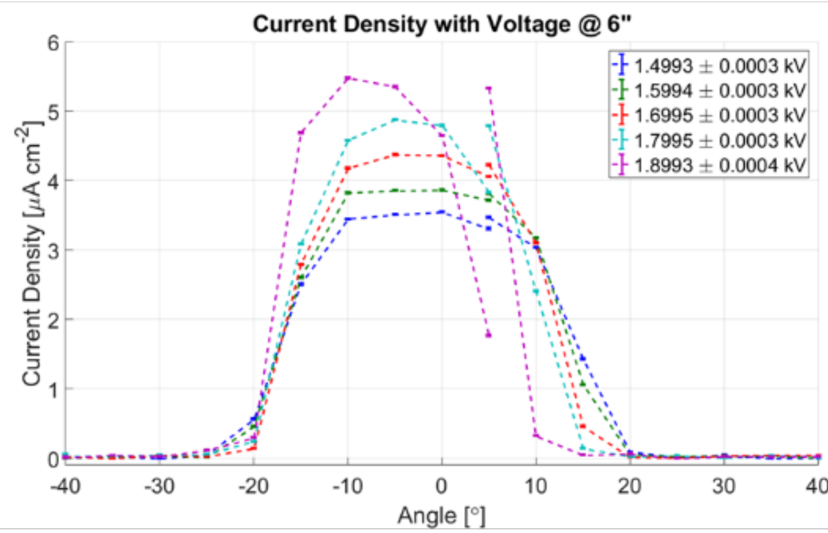


UCLA Experiments: Beam Profiles and Stability vs. Flow Rate and Extraction Voltage

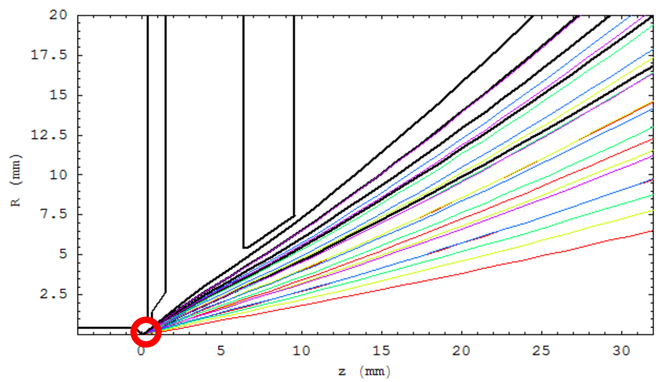


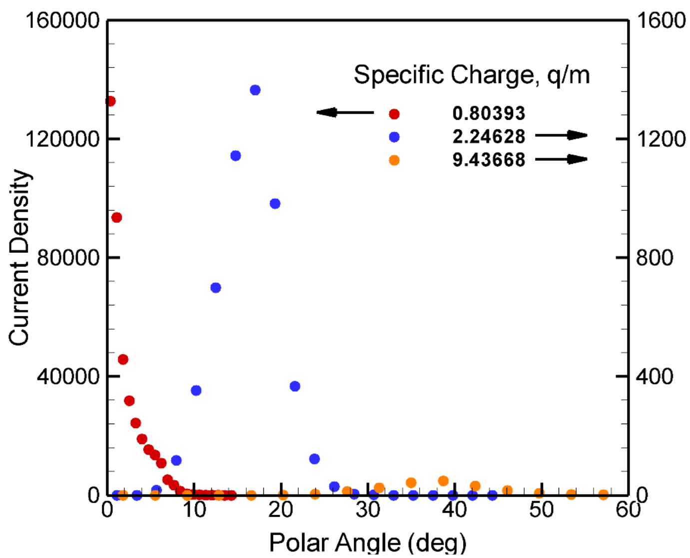


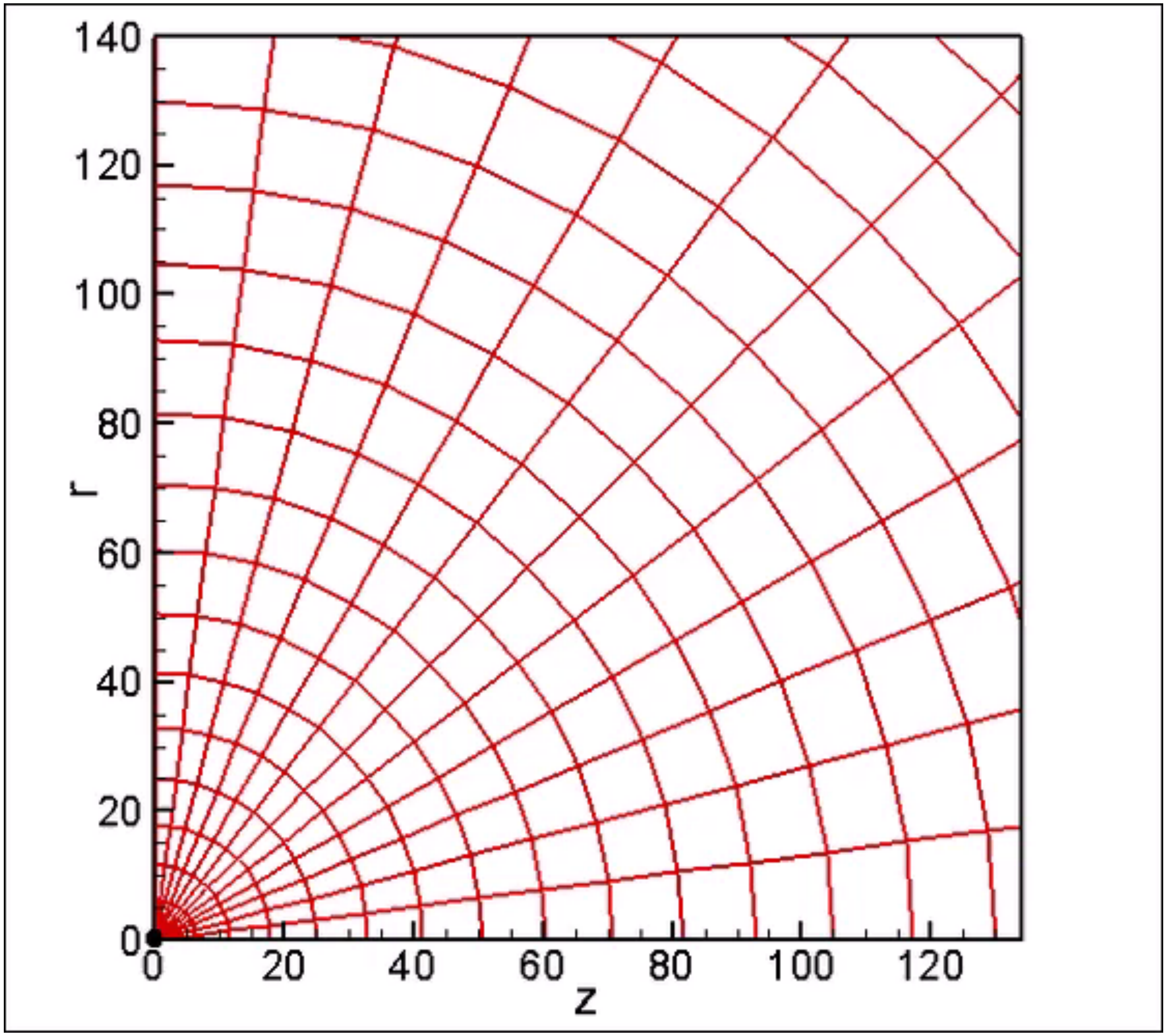




Simulation of 61511 droplets, varying Q/m





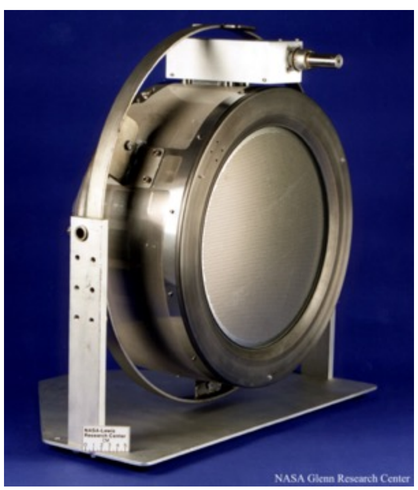


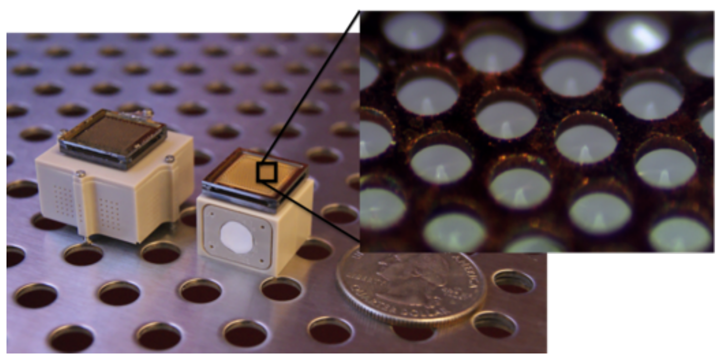
Summary for LISA / HabEx Colloid Microthruster Development

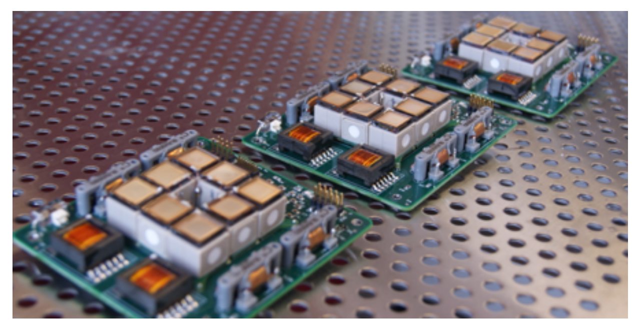
- LISA is updating the ST7 / LISA Pathfinder colloid microthruster technology to be more reliable and demonstrate the necessary lifetime for LISA and HabEx
- Lessons learned have been incorporated into design studies, breadboard components have been tested in relevant environments, and brassboard assemblies are being integrated together to reach TRL 5 by March 2022
- Lifetime estimation and prediction uses a modeling framework that includes performance, plume, and electrode models compiled together to be able to quantify margins and uncertainty using an established DOE / NASA process
- Model development is progressing well with a focus on V&V and establishing model credibility

Potential of Electrospray Thrusters

- In electrospray thrusters, all the emission takes place on micron scales
- This allows scaling to arrays with 100's of emitters per cm^2 and mN of thrust
- Electrosprays do not need to confine a plasma to generate ions efficiently (or have all those losses – no "blue glow")
- Recent and future electrospray development is focused on flying the modular "flat screens" of EP systems







(MIT iEPS Thruster System – NASA, MIT https://spacepropulsion.mit.edu/electrospray-thruster-engineering)

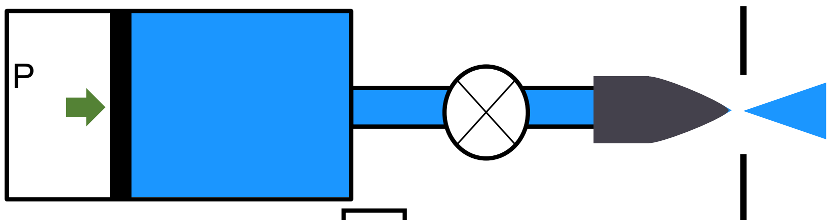
Electrospray Thruster Development at Busek

Busek Electrospray Families & Applications

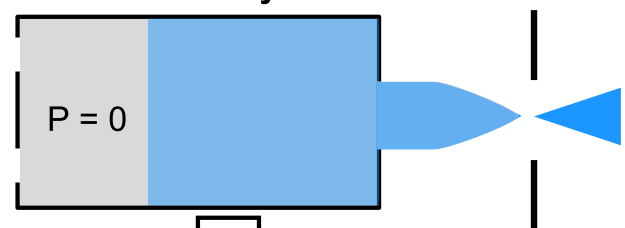
BUSEK Space Propulsion and Systems

Technology

Actively Fed



Passively Fed



Product Lines

Busek CMNT

Colloid Micro Newton Thruster

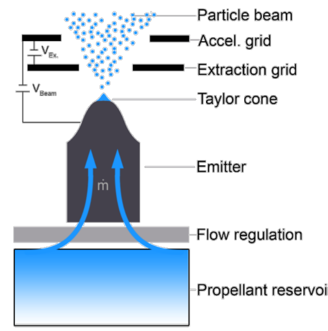
Capillary Emitters

Busek BET-100-A

Annular Thruster

High thrust variants

Busek BET-300-P



Applications

- LISA Full Mission: Gravity wave detection (~2034)
- Large observatory precision pointing
- Small sat precision formation flight and pointing
- Multi-Mode Propulsion (MMP)

Used with Permission from Busek Co., Inc. for Public Distribution

Busek CubeSat / SmallSat BET-300-P System

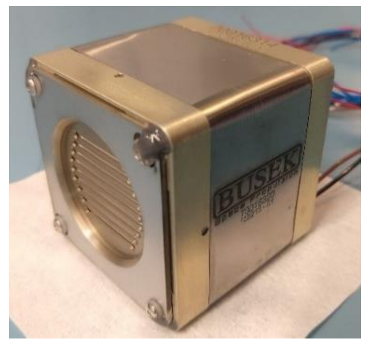
BUSEK Space Propulsion and Systems

BET-MAX

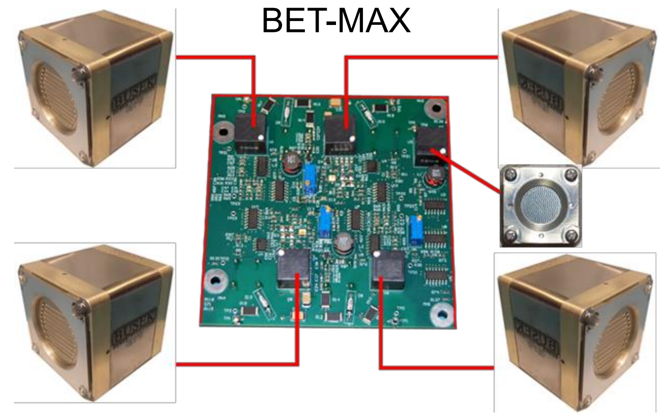
Busek Electrospray Thruster - MultiAxis

- ✓ 4X BET-300-P thruster heads w/ integral ~14g/ea propellant supply
  - ✓ Highly characterized thruster
  - ✓ Passed through environmental testing & life tests to propellant exhaustion
- ✓ Carbon Nanotube Field Emission Cathode (CNTFEC) neutralizer
  - ✓ Flight qualified and demonstrated on ESA LISA mission
  - ✓ New modifications to transition to low energy electrons suitable for balancing
- ✓ 1X electronics capable of controlling 4X thrusters and 1X cathode
  - ✓ Breadboard multi-axis PPU demonstrated
  - ✓ Presently designing, fabricating, & testing complete EM electronics
  - ✓ Firmware state machine already exists from prior CRP effort
  - ✓ Pending proto-flight build takes rad-hard hybrid design, critical components
  - ✓ For future full radiation hardened designs, most components have pathway to flight, minimal required part screenings

BET-300-P

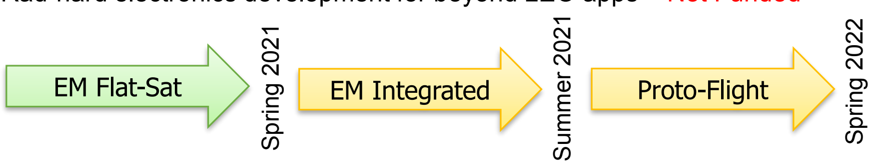


BET-MAX



Remaining Development to Flight

- ✓ Engineering Model flat sat / flight emulator testing & delivery - Funded
- ✓ Additional BET-300-P characterization vs. temperature – Funded
- ✓ BET-300-P integration of 2nd electrostatic grid for thrust modulation - Funded
- ✓ Investigations into next potential life limiting mechanisms beyond present propellant-loading limited design – Funded
- ✓ Engineering Model integrated testing – Funding Pending
- ✓ Proto-flight fabrication, acceptance testing, and delivery – Funding Pending
- ✓ Increased capacity or reloading for higher total impulse – NASA P2 not funded
- ✓ Rad-hard electronics development for beyond LEO apps – Not Funded



Key Performance Characteristics:

BET-300-P Performance	
Max Power	~3.5W
Nom (Max) Thrust	55µN (150µN)
Min Ibit	2µNs*
Thrust Noise	0.2µN*
Specific Impulse	~850s
Total Impulse	~91Ns (460hrs @ 55µN)
Dry Mass	141g
Dimensions	5cm x 5cm x 5cm

BET-MAX (4X BET-300-P Thrusters)	
Idle Power	~3W est.
Operational Power	12W nom. (25W max)
Max Thrust	150µN x 4
Communication	RS-485
Input Voltage	28V
Dry Mass	0.74
Wet Mass	0.80kg
Volume	~1.25U

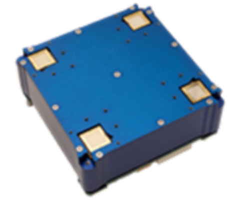
*Limited by present BET-MAX electronics, smaller impulse bits and resolutions demonstrated

ACCION SYSTEMS

(Used with Permission)

Accion Systems
529 Main Street
Suite 114
Boston, MA 02129-1125
POC: Courtney Oliver
Phone: (857) 770-1317
Email: courtneyo@accion-systems.com

TILE 2



Technology / Capability Overview:

Accion's Tiled Ionic Liquid Electrospray (TILE) propulsion system **provides safe, reliable, precise, modular and imperceptible propulsion with ultra-low SWAP-C;** and its compatibility with multi-mode propulsion increases space asset resiliency.

- Lower power phasing, orbit raising, and maintenance
- De-orbit capabilities and low-pressure tanks for minimal debris
- Precision maneuvers for proximity operations
- High efficiency thrust for orbit maintenance
- Low signature thrust (RF, heat and visible light)
- Systems can be aggregated for multiple degree of freedom control

Mission Benefits:

- **Extremely low SWaP will allow small CubeSats to meet FCC requirements for de-orbit and debris avoidance**
- Utilizes a safe, inert liquid propellant that is commercially available
- Low-cost design that can be mass produced in < 6 months
- Compact 0.5U design (includes propellant tanks) allows systems to be strategically dispersed on the satellite for specific mission needs
- High efficiency propulsion results in low RF, heat, and visible signature

Product Performance:

Performance Metric	Unit	TILE 2	Four Aggregated TILE 2s
Typical Total Impulse	N-sec	21	84
Max Thrust (axial)	mN	0.04	0.16
Specific Impulse	s	1,650	1,650
Dimensions	cm^3	461 (9.6 x 9.6 x 5)	1,843 (19.2x19.2x5)
Wet Mass	kg	0.48	1.92
Nom. Power (@ max thrust)	W	4	16
Standby Power	W	1.5	6
Operating Temperature Range	°C	10 to 50	
Survivable Temperature Range	°C	-20 to 60	

Space Heritage / Partners:

Current TRL: 6

- **Upcoming Deliveries and Flights:**

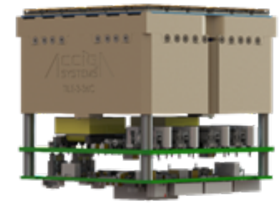
Customer / Program	#	Delivery Date	Satellite Manufacturer	Launch Provider	Launch Date
CubeSat STEM	1	Q1 '20	Irvine	TBD	TBD
University CubeSat	1	Q2 '20	MIT	SpaceX	Q2 '21
Commercial	1	Q1 '21	Astro Digital	SpaceX	Q2 '21
DoD	5	Q2 '21	DoD Selection	TBD	Q4 '21

- **Customers / Partners:**

(Used with Permission)

Accion Systems
529 Main Street
Suite 114
Boston, MA 02129-1125
POC: Courtney Oliver
Phone: (857) 770-1317
Email: courtneyo@accion-systems.com

TILE 3



Technology / Capability Overview:

Accion's Tiled Ionic Liquid Electrospray (TILE) propulsion system provides **safe, reliable, precise, modular and imperceptible propulsion with ultra-low SWAP-C;** and its compatibility with multi-mode propulsion increases space asset resiliency.

- Lower power phasing, orbit raising, and maintenance
- De-orbit capabilities and low-pressure tanks for minimal debris
- Precision maneuvers for proximity operations
- High efficiency thrust for orbit maintenance
- Low signature thrust (RF, heat, and visible light)
- Architectures supports multiple propellants, including ASCENT
- Systems can be aggregated for precision pointing

Mission Benefits:

- Scalable architecture - can be optimized for each satellite mission
- Utilizes a safe, inert liquid propellant that is commercially available
- Low-cost design that can be mass produced in < 6 months
- **Requires less than 50% of the power draw of other technologies allowing more power to be allocated to mission critical payloads**
- Compact 1U design (includes propellant tanks and power electronics) allows systems to be strategically dispersed on the satellite for specific mission needs

Product Performance:

Performance Metric	Unit	TILE 3	Four Aggregated TILE 3s
Typical Total Impulse	N-sec	755	3,020
Max Thrust (axial)	mN	0.45	1.8
Specific Impulse	s	1,650	1,650
Dimensions	cm^3	921.6 (9.6 x 9.6 x 10)	3,686 (19.2x19.2x10)
Wet Mass	kg	2	8
Nom. Power (@ max thrust)	W	20	80
Standby Power	W	1.5	6
Operating Temperature Range	°C	-10 to 60	
Survivable Temperature Range	°C	-20 to 70	

Space Heritage / Partners:

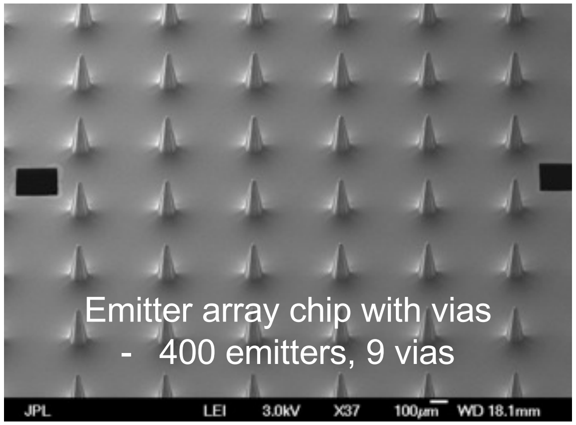
Current TRL: 5

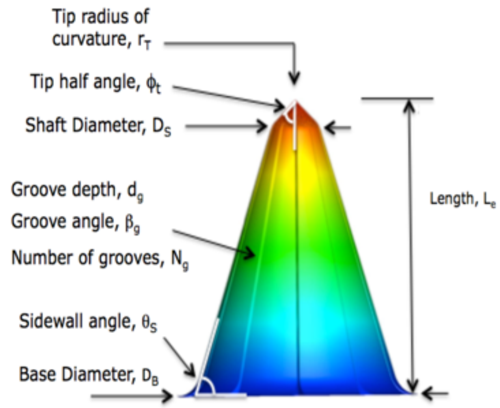
- **Upcoming Deliveries and Flights:**

Customer / Program	QTY	Delivery Date	Satellite Manufacturer	Launch Provider	Launch Date
DoD	1	Q2 '21	DoD Selection	TBD	Q4 '21
NASA	1	Q2 '21	NanoAvionics	SpaceX	Q3 '21
DoD	2	Q3 '21	TBD	TBD	TBD
Commercial	1	Q2 '21	Confidential		Q4 '21

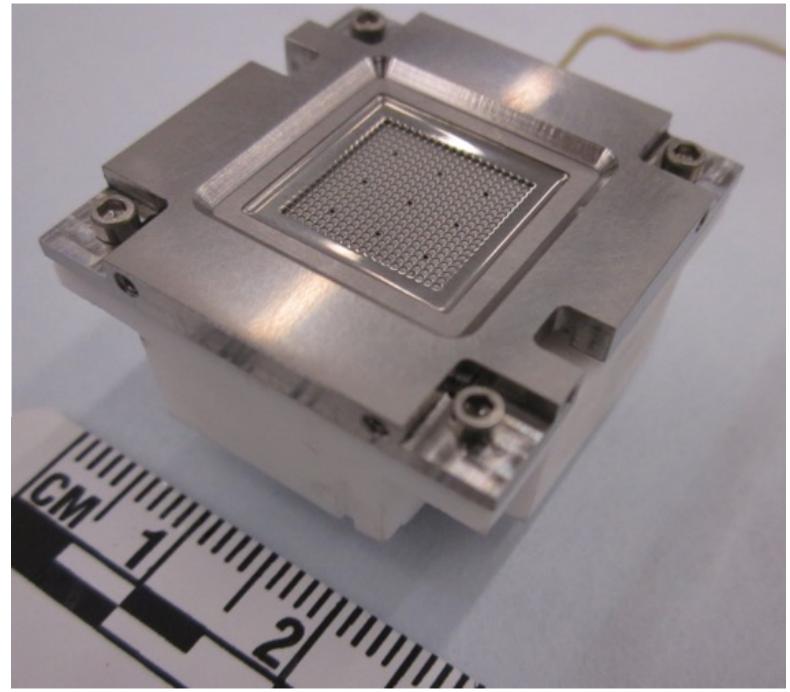
- **Customers / Partners:**

Microfabricated Electrospray Propulsion (MEP)





Parameter	Value
Emitter Voltage (volts)	1470
Extractor Voltage (volts)	-600
Emitter Array Current (microamperes)	1906
Extractor Current (microamperes)	32
Beam Power (Watts)	2.8
Heater Power (Watts)	0.74
Estimated Thrust (micronewtons)	>100
Estimated Specific Impulse (s)	>3100
Thruster Dry Mass (grams)	26
Thruster Volume (cm^3)	9



JPL MEP Thruster

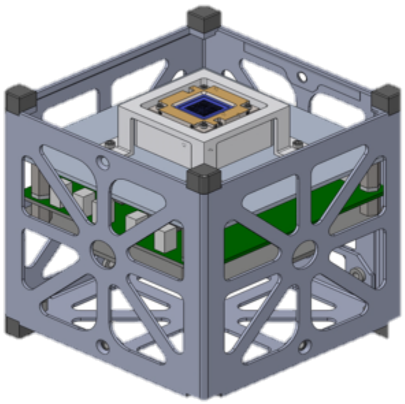
See C. Marrese-Reading, et al; JPC-2016

Primary Challenges:

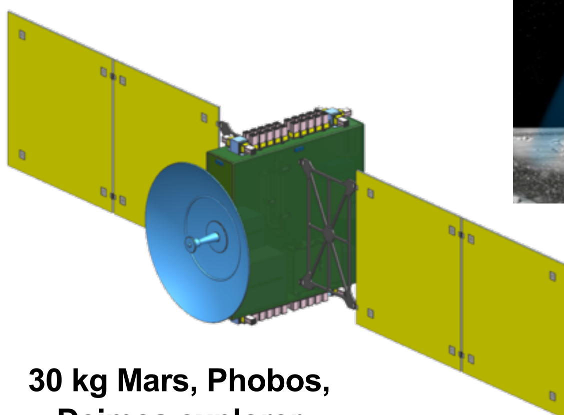
✓ Emitter chip/heater microfabrication with propellant loading
✓ Emitter array electrospray operation and testing (stable operation for 40 minutes at 100, 50 and 5 μN)
✓ Model development for emitter design requirements
✓ PMD loading, integration and operation
5. Thruster performance of 100-200 μN, 1500 – 3100 s, <100 g, <100 cm^3, >60% system efficiency with PPU (>88% thruster efficiency), ***200 hrs of continuous operation***

Applications for MEP

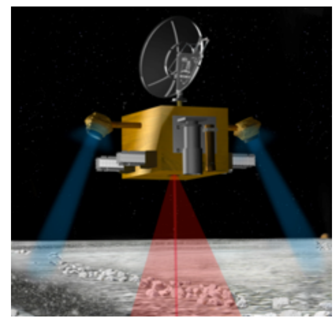
There are many potential large and small spacecraft applications for MEP thrusters at 100 μN and 1 mN:



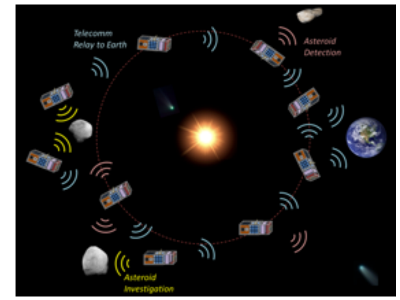
Single CubeSat thruster, PPU, DCIU design



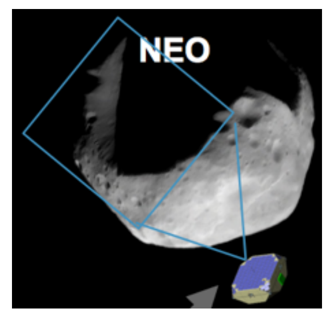
30 kg Mars, Phobos, Deimos explorer (J. Lang)



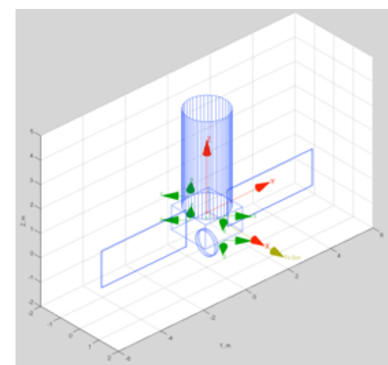
100 kg Saturn/Uranus Ring Observer/Interrogator (T. Spilker)



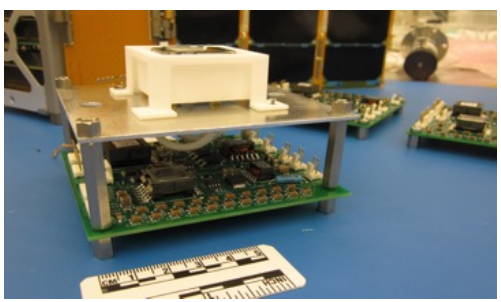
10 kg Interplanetary CubeSats, CubeSat swarms (D.Landau)



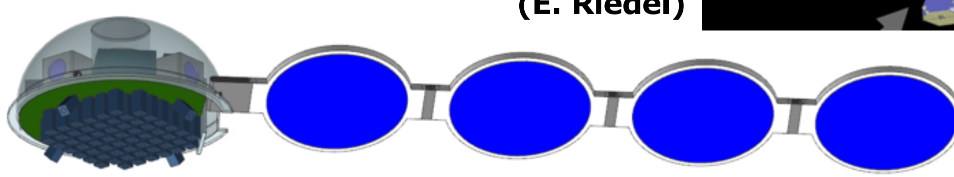
50 kg Micro Exo explorer to asteroids (E. Riedel)



2000 kg Exoplanet observatories with precision pointing (D. Scharf)



Thruster, thermal socket and PPU



12 kg Mars Sample Capsule Return (N. Strange)

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov