Flight Development of Iodine BIT-3 RF Ion Propulsion System for SLS EM-1 CubeSats

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BUSEK
Space Propulsion and Systems

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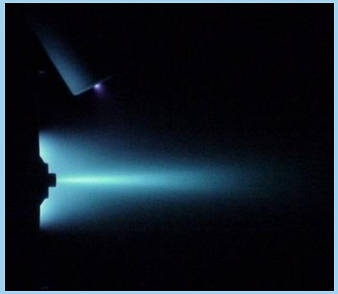
Busek Co. Inc.
A History of Innovation on Space Propulsion

Busek Co. Inc. was founded in 1985 and is an industrial leader in space system development

- Core expertise begins with electric propulsion (EP) that encompasses Hall effect thruster, ion thruster, pulsed plasma thruster, electrospray thruster, resistojet and arcjets
- Largest staff in industry world-wide dedicated to EP
- Proven methodology transitioning from R&D programs to deliverable flight hardware
- Over 20 flight and deliverable thrusters: all met or exceeded performance expectations & NASA/DoD standards
- All U.S. Hall thrusters flown to date (BHT-200 to BPT-4000) are based on Busek technology

Our key accomplishments include:

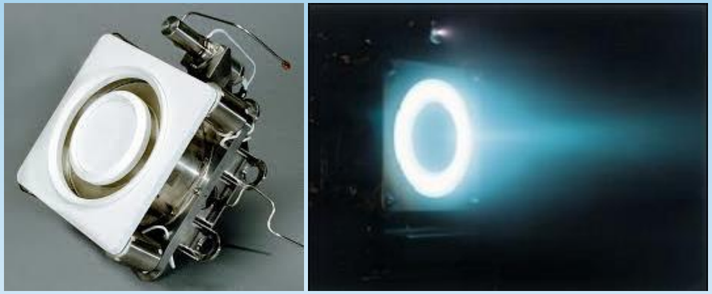
- ***All U.S. Hall thrusters flown are based on Busek technology***
- ***The first U.S. Hall thruster in space (TacSat-2, FalconSat-5)***
- ***The first micro pulsed plasma thruster in space (FalconSat-3)***
- ***The first flight qualified & operational electrospray thrusters in space (LISA Pathfinder ST-7)***



BHT-200

BHT-1500

Located in the Boston suburbs and employs 55 staff members (18 holds Masters/Ph.D.)



BPT-4000 (Licensed to Aerojet)

Propulsion Challenges for SLS EM-1 6U CubeSats

Most missions require lots of deltaV (>500 m/s), but SWaP is extremely limited

- Cold gas okay for ACS, but inadequate as primary propulsion
- 6U CubeSat form factor (shoe box shape) is unfavorable for any pressure vessel
- SOA solar array for 6U CubeSats generates <100W, a challenge for EP system (thruster & PPU) scaling
- Needs propulsive ACS to de-saturate reaction wheels → cold gas, multiplex, or gimbaling?

A short list of options…

Chemical

- "Green" monoprops such as AF-M315E or LMP-103S are the best chances from launch safety perspectives
- Large occupied volume for somewhat limited deltaV; relatively low Isp (210-235sec)
- Thermal soak-back problem often overlooked; insufficient radiator area on the spacecraft

Conventional EP

- Hall Effect thruster: scaling to <100W system is prohibitively inefficient
- Electrospray thruster: life concern for high deltaV missions (e.g. >4,000 hours) but technology is advancing
- DC gridded ion thruster: low-power system rare but possible (JPL's MiXI); Xe tank is a limiting factor
- Microwave ECR gridded ion thruster: low-power system exists (JAXA's µ1); microwave PS and Xe tank issues
- RF gridded ion thruster: scaling friendly (Busek's BIT-3); inherently compatible to solid-storable fuel like I_2

Unconventional EP

- Often focus on thruster head only with no associated subsystem development (feed system, electronics, etc)
- Too low TRL; "pie in the sky" kinds of performance number without accurate measurement verification

Iodine is a Game-Changing EP Propellant

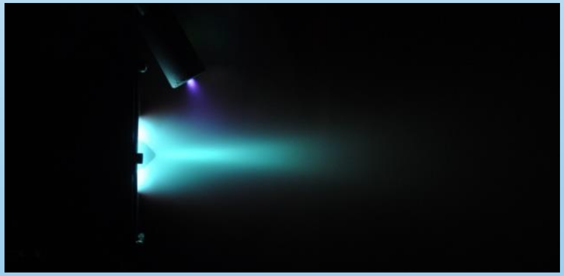
- Wanted: gases w/ heavy molecule & are easy to ionize – heavier ions produce more momentum change
- Mercury (atomic mass 200 g/mole) was used in 60s-70s but abandoned due to high toxicity
- Xenon (atomic mass 131 g/mole) is the current default EP propellant but it needs to be stored in high pressure (~2,000psi) and is very expensive (~$5k per kg)
- Iodine (atomic mass 127 g/mole, naturally dimers) has lots of potential & advantages and could be the future for EP
  - Stored as a solid that allows for lightweight and configurable tanks (not constrained to high pressure tanks shapes)
  - Simple to operate: sublimes with minimal heat input to form iodine vapor which is then fed to the EP device
  - Busek has shown with Hall thrusters that iodine provides almost identical performance as with xenon (for ion thrusters iodine may even surpass xenon if there proves to be significant I_2^+ heavy ions in the plume)
  - A "perfect" propellant for deep space CubeSat missions

Busek's Iodine Electric Propulsion Technologies

Busek Pioneered Practical Use of Iodine for EP, with IP Rights

- Iodine Hall Effect thruster BHT-200 (will fly on NASA's iSAT TDM in 2017)
- Demonstrated iodine HETs for up to 10kW
- Iodine related innovations (feed system, cathode, thruster) protected by U.S. patents

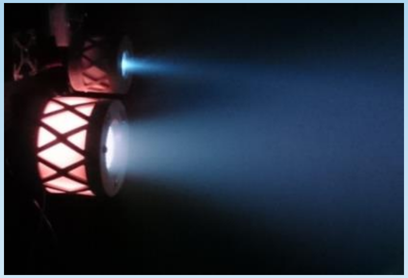

BHT-200, Flight Heritage Thruster Firing on Xe



BHT-200 Firing on I_2

Adaption of Iodine Technology by Busek's Miniature, High-Isp RF Ion Thrusters

- The BIT series thrusters (1-7cm sized) are inherently I_2 compatible
- The 3cm BIT-3 thruster is the world's 1st gridded ion thruster ever demonstrated with iodine
- Iodine BIT-3 system will be flying on "Lunar IceCube" and "LunaH-Map" 6U CubeSats on NASA's SLS EM-1

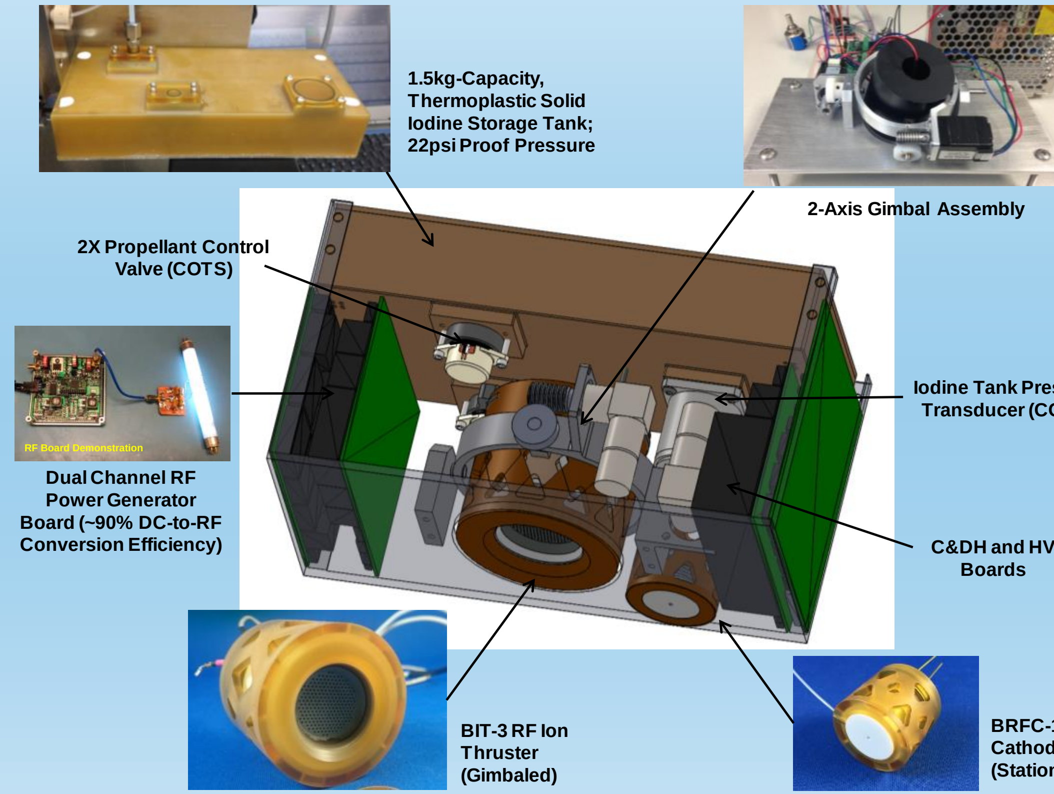



Prototype BIT-3 Thruster Firing on Xe

Prototype BIT-3 Thruster Firing on I_2

BIT-3 System Configuration

- Unprecedented performance per volume
  - 180x88x102mm system envelope
  - 3.0kg wet, 1.5kg propellant loading
  - 0.65-1.15mN thrust & 1200-2100sec Isp (55-75W throttleable system input)
  - >2km/s deltaV for 6U/14kg CubeSat
- 2-axis, ±10º gimbal integrated to thruster
  - No additional ACS thrusters needed for de-saturating reaction wheels
- Thermoplastic iodine tank
  - Lightweight, 22psi proof pressure verified (14.7psi MEOP)
  - I_2 vapor flow rate controlled tank heater with feedbacks from transducer, temp sensor and ion beam current
- Rad-tolerant, miniaturized PPU
  - 28-37V unregulated input, RS-485 comm
  - Designed for 55-75W power draw
  - SOA, 90% efficiency RF amplifiers
  - SOA, 85% efficiency 2kV converter
  - “Rad-Hard Fence” against 37MeV SEU



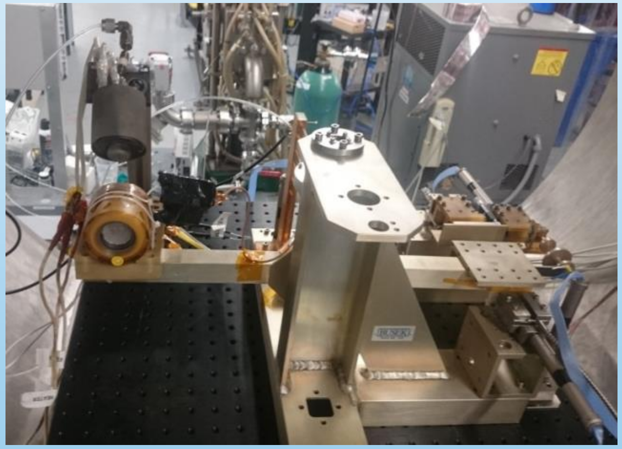
Conceptual Arrangement of BIT-3 Flight System

EM BIT-3 Thrust Measurement Results

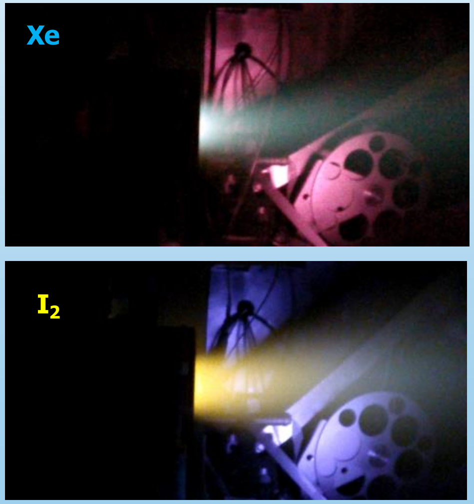
- EM thruster fired with a COTS cathode on a torsional thrust-stand with 10μN sensitivity
  - Torsional thrust balance is the only instrument capable of resolving 1mN level of thrust with confidence
  - Thrust calibration done with motorized weight drop (0.1g) in vacuum on a 0.002" nylon fishing line; accurate and consistent but has ± 10% uncertainty due to pump vibrations
- Thrust data obtained and baseline Xe performance confirmed
  - Xe data agree very well with theory

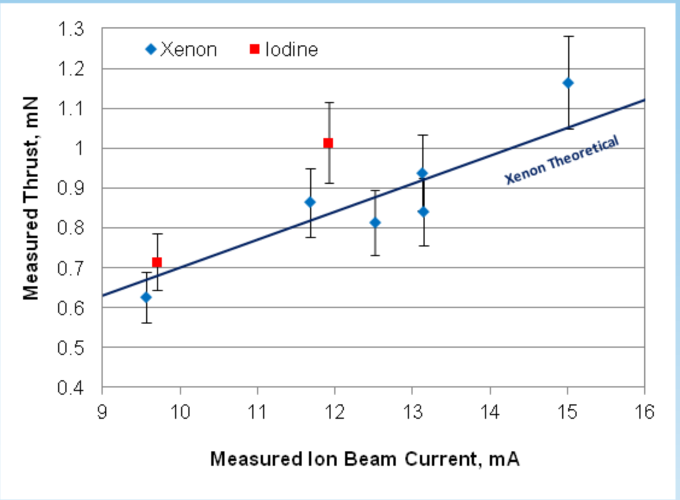
$$F_{predicted} = J_{beam}\sqrt{\frac{2m_i V_{screen}}{e}}$$

    which does not account for neutral thrust or beam divergence loss
  - More iodine thrust data pending, but possible that iodine can generate >10% thrust than xenon, suggesting significant (>20%) I_2^+ heavy ion presence in the beam



EM Thruster on Torsional Thrust Stand

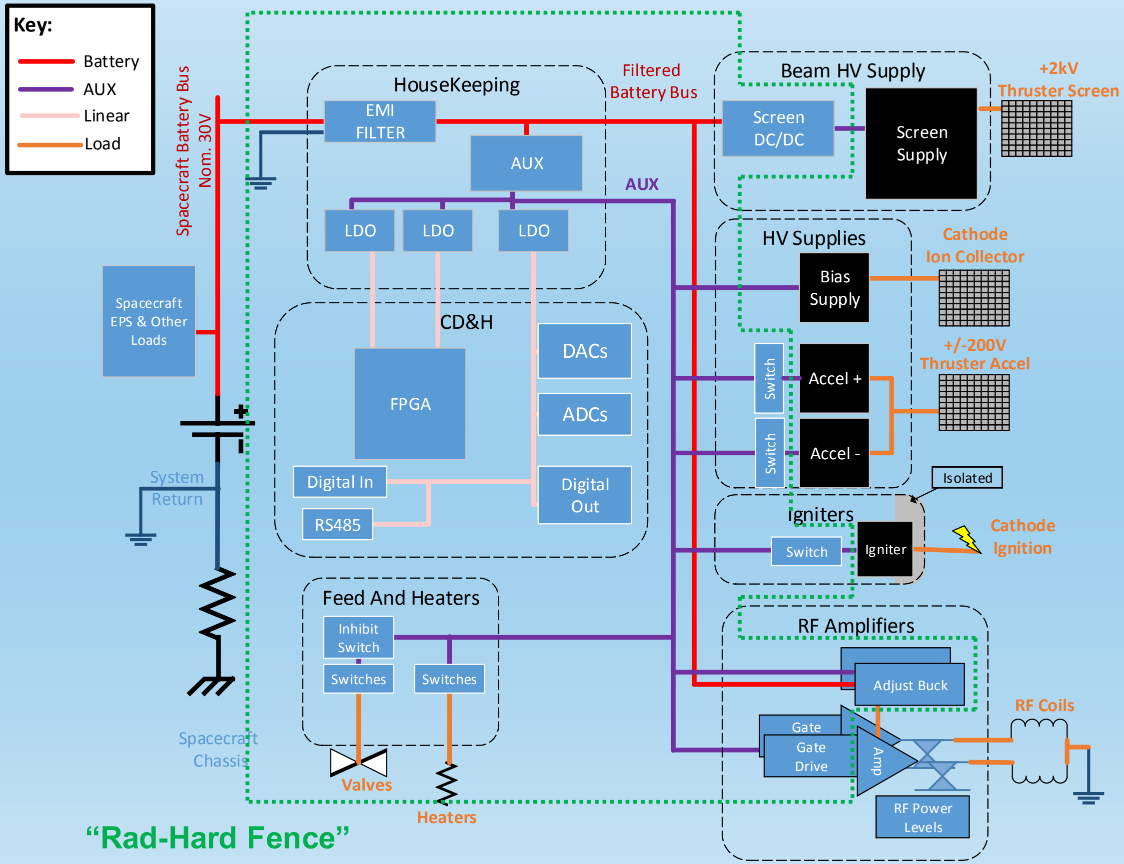




Thrust Stand Data to Date; 1800V at Fixed 48μg/s (0.5sccm Xe) Flow Rate

BIT-3 Power Processing Unit (PPU)

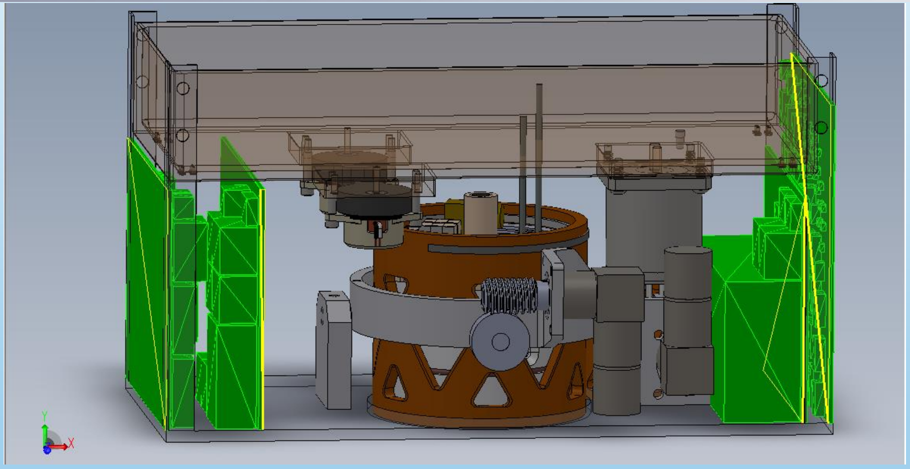
- Complex subsystem by nature
  - Process command & power from s/c bus
  - Includes various HV and RF converters to perform BIT-3 functions
  - Major challenge is to balance efficiency/volume/cost/rad-tolerance; there is no magic solution for all!
- Total Ionizing Dose (TID) management
  - ~10 kRad TID protection provided by 0.100” Al skin of spacecraft
  - TID not severe for intended missions beyond GEO; LRO measured <3 rad/yr in lunar orbit with similar shielding
- Single Event Effect (SEE) management
  - High energy particles can cause electronics latch-up and burnout
  - “Rad-Hard Fence” design provides assurance up to 37MeV where failure can cascade (e.g. housekeeping and CD&H)
  - Outside of “Rad-Hard Fence”, focus is on efficiency and volume while taking higher risks, but has safeguards like EEE-INST-02 de-rating and/or active current monitors for latch-up reset



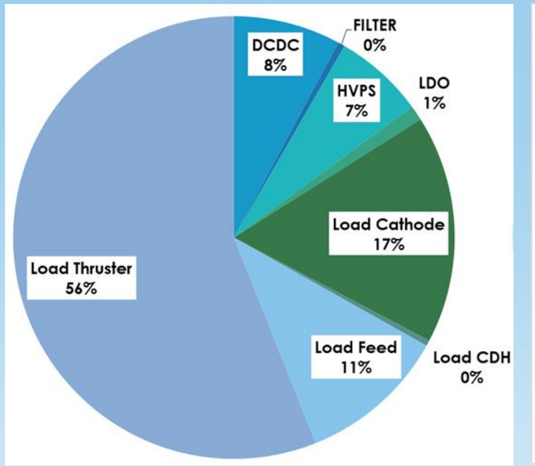
BIT-3 PPU Block Diagram

BIT-3 Power Processing Unit (PPU)

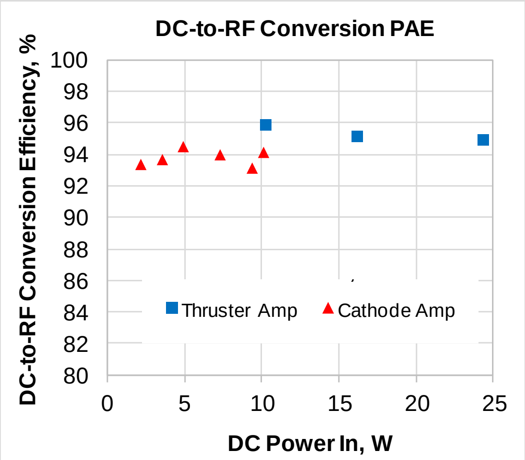
- Split PPU packaging design due to volume restriction
  - Separating out HV and RF boards which are the major power consumers
  - Eases thermal management
- System delivers 84% of input power to the loads
  - The "useful" loads are thruster, cathode and feed system
  - Minimized overhead power consumption by C&DH, filter, DC/DC converters
- SOA RF amplifier demonstrated
  - Achieved 93-96% Power Added Efficiency (PAE); large improvement from previous BIT-1 RF amp's 85% PAE
  - Thruster amp is slightly more efficient than cathode amp due to operating frequency difference
  - Taking into account gate drive loss and 95% efficient drain voltage regulator, the RF amp would have an overall efficiency of 90% (bus voltage in → stable RF power out), a remarkable result!
  - Breadboard design evolving into QM & FM



BIT-3 System's Split PPU Design (Highlighted in Green)



BIT-3 PPU Power Allocation



RF Amp Efficiencies

Summary

- BIT-3 RF ion thruster and BRFC-1 RF cathode neutralizer have been matured to EM status, leveraging prototype test results with I_2 propellant
- Actual Xe thrust measurement was obtained for EM thruster with proven 0.65-1.15mN thrust and 1200-2100sec total Isp; results agree very well with theoretical prediction
- I_2 thrust measurement ongoing, but early results indicate equal, if not more, thrust than Xe
- BIT-3 system design is well flushed out, including demonstration of SOA RF amplifiers at 90% efficiency
- BIT-3 system operates at 55-75W draw and can provide >2km/s deltaV to a 6U/14kg CubeSats; let's think about taking CubeSats to Mars, Europa or asteroids!
- Special thanks to the following sponsors of BIT-3 program:
  - Core R&D effort: NASA Small Spacecraft Technology Program (SSTP) of Space Technology Mission Directorate (STMD), via contract #NNX15CC90C
  - Lunar IceCube Mission (SLS EM-1): NASA Advanced Exploration Systems (AES) of the Human Exploration and Operations Mission Directorate (HEOMD), prime contractor Morehead State University
  - LunaH-Map Mission (SLS EM-1): NASA Science Mission Directorate (SMD), prime contractor Arizona State University