

NEXT Ion Propulsion System Risk Mitigation Tests in Support of the Double Asteroid Redirection Test Mission

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Outline

- Background
 - DART mission
 - NEXT development
- Test Objectives
- Experimental Results
- Summary

Background: DART Mission

- Demonstrate kinetic impactor deflection of a representative threat asteroid
- A controlled impact experiment to increase confidence of kinetic impact predictions and improve understanding of asteroid physical properties and high speed collisions
- Binary target allows measurement of deflection by ground-based observatories
- The primary launch period extends from 22 July to 11 August 2021
- Spacecraft impact in Sept./Oct. 2022, optimized to achieve the impact geometry requirements



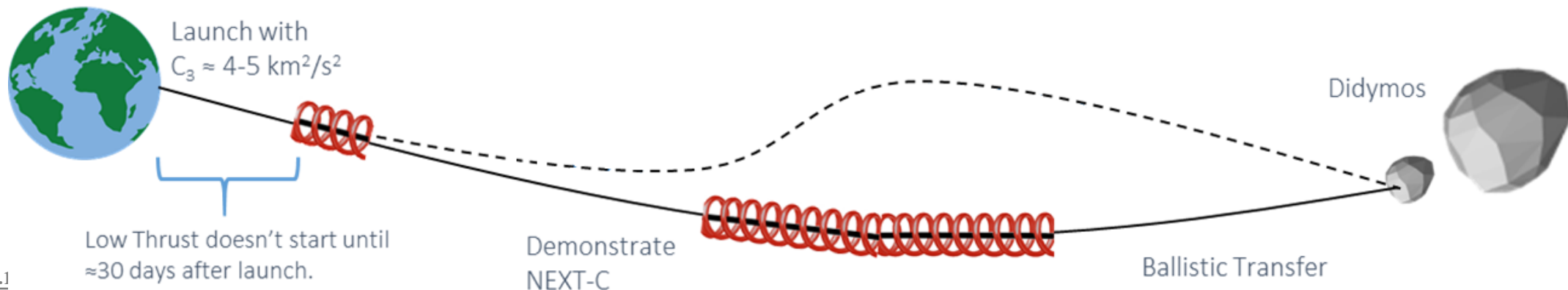
The DART target (the moon of 65803 Didymos) is a realistic-sized asteroid of the most common NEO composition

Background: NEXT Ion Propulsion System

- NEXT began as a technology development program in 2002
 - the thruster was deemed to be at TRL 6 and the PPU at TRL 4/5 at end of Phase II development program
- Following Phase II program, NASA partnered with Aerojet Rocketdyne and subcontractor Zin Technologies to build two flight thrusters and PPUs in an effort to commercialize the technology (NEXT-Commercial Project)
 - address known issues with PPU design
 - make design changes to make system more commercializable while maintaining validity of prior testing (e.g. 51 khr life test)
- NEXT IPS utilized on the DART mission, investigated for other future potential missions

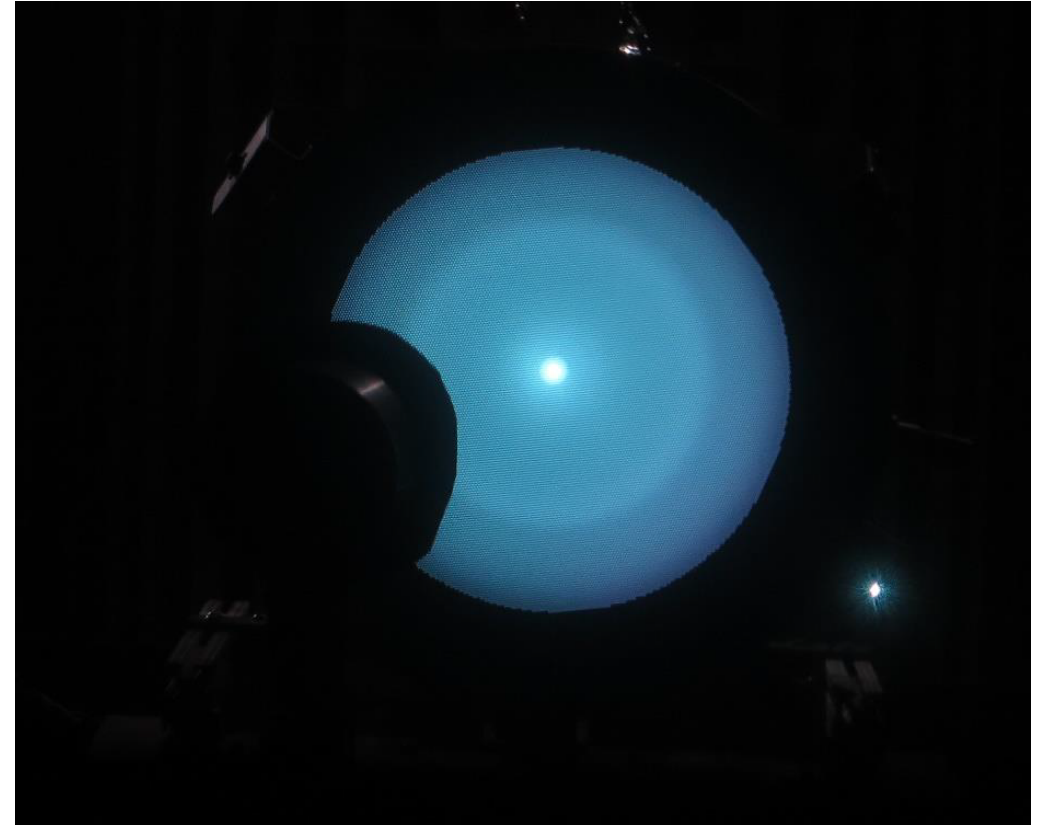
NEXT Use on DART Mission

- DART mission will use NEXT for TCMs and then exercise it using several “neutral burns”
 - the burn has the objective of demonstrating NEXT-C without risking the ballistic impact
 - NEXT will be operated for a total of ~ 1400 hours
- The neutral burns are achieved by pointing DART’s +X axis to the Sun and rotating about the Sun-line with a 12 hour period
 - Over the full period, the induced orbit change integrates to nearly zero change in velocity
 - Fixes spacecraft geometry (solar arrays locked)
 - Gives consistent low-gain-antenna gain to Earth
 - Given its constant attitude state, it requires little propellant for attitude control
- At any point, if NEXT-C thruster is turned off, the original impact conditions can be recovered for < 3.5 m/s with a TCM



Overview: Risk Mitigation Testing

- **Objectives:** Conduct Risk Mitigation Testing in support of implementation of NEXT for DART to validate the proposed DART NEXT system configuration and concept of operations
- **Hardware:** NEXT engineering model thruster hardware with laboratory power supplies and mass flow controllers
- **Venue:** All testing conducted at Aerospace Corporation (EP2). TAC under contract with NASA for testing as both the test venue, and executing organization with respect to plume diagnostics



Risk Mitigation Tests and Goals

Test	Overview	Goals
1.1: Mission Specific Throttle Levels	A. Sensitivity-Analyses: Evaluate NEXT thruster sensitivity at DART TL28, and other selected power levels. Involves dynamic control of individual NEXT thruster input parameters, documenting thruster response and operating margins.	Provide data for defining flight XFS flow control requirements, and for the DDU Beam-Current Regulation Algorithm
	B. Steady-State Performance: Evaluate the NEXT thruster performance at DTL28, and other selected power levels	Verify thruster performance against that documented in NASA's NEXT Throttle Table. Characterize plume expansion, and the presence of energetic high-angle ions which may be of relevance to spacecraft integration.
	C. Life & Erosion: Evaluate the NEXT thruster erosion signatures at DTL28 and other selected power levels. Primary emphasis at DTL28.	Document in-situ erosion and deposition measurements
1.0: Start-Up Sequence	Define, demonstrate, verify, and evaluate the Start-Up sequence for DART at DTL28, and other selected intermediate power levels, over a range of anticipated DART initial thermal conditions. Testing will document associated start-up transients. Measurements of the Thrust Vector and Thrust Vector Stability during the startup transient will be documented.	Provide data for defining flight XFS flow control requirements and commands, and PPU commands and sequences. Provide data for gimbal control.
1.2: Mission Specific Profiles	Define, demonstrate, verify, and evaluate the Beam Current Regulation Algorithm, and the Throttling Algorithm for DART	The Beam Current Regulation Algorithm parameters will be defined and demonstrated, and the Throttling Algorithm will be defined and demonstrated, consistent with the DART Concept-of-Operations (CONOPS) and thrust control requirements

Test Description

- **Sensitivity-Analyses –**
 - Examine the thruster performance and life implications of the XFS flow control requirements – and the viability of relaxing these [$\pm 3\%$ of run value on all lines]. Also examine parameters associated with the Beam-Current Regulation Algorithm
 - Configuration included Scanning ExB instrument used to measure Charge-State (for thrust correction, and life assessment), and Mini-Planar Probe (MPP) used to measure ion beam current at the grid face
 - Thruster electrical data, and plume measurements characterized at 15-flow conditions for DART TL28 (3 MAIN; 5 DCA), as well as throttle levels DTL29, DETL2.7A, DETL2.7B
- **Steady-State Performance –**
 - Evaluate the NEXT thruster performance at DTL28, and other selected power levels. Characterize plume expansion (beam divergence). Document presence of energetic high-angle ions. Assess thruster performance against that documented in NASA's NEXT Throttle Table 11.1. Document NEXT plume at the specified throttle levels with sufficient fidelity and spatial extent to provide validation data for modeling/simulation of the thruster plume. Generate sufficient data to develop a DART-specific Throttle Table
 - Configuration included a total of 6 probes on 3 different motion control systems – One pair of probes (Faraday and RPA) in the near-field to interrogate Energetic ions out to extreme angles; Two pairs of probes, in the Mid-field (1.8 m) and Far-field (2.8 m) to document the plume expanse to yield beam divergence
 - Thruster electrical data, and plume measurements characterized at 15-flow conditions for DART TL28, as well as power throttling from TL29-TL28

Test Description Cont.

- **Life & Erosion –**

- Evaluate the NEXT thruster erosion signatures at DTL28 and other selected power levels using Laser-induced fluorescence (LIF) Spectroscopy. Document in-situ erosion and deposition measurements. Verify and refine: (1) knowledge of thruster surface erosion rates; (2) thruster eroded-product deposition rates; and (3) thruster life time projections, at the proposed DART flight throttle levels
- Configuration included LIF system, Quartz-Crystal Micro-Balances (QCMs), and Witness Plates
- Thruster electrical data, and erosion & deposition data documented over a range of discharge flow conditions at DTL28, NCA flow rates, and at DTL29 and DETL2.7A

- **Start-Up Sequence –**

- Define and evaluate a Start-Up sequence for DART at DTL28 consistent with the mission CONOPS
- Document associated start-up transients. Measure Thrust Vector and Thrust Vector Stability during the startup transient.
- Configuration included 20-Element TVM Probe Array
- Thruster electrical data, and thruster beam-centroid documented during start-up transient, through thermal equilibrium at DTL28

Risk Reduction Test Matrix

- All tests conducted at a beam current of 2.70 A at three different beam voltages
- Mass flow rate ranges: Main +/- 3%; Cathode +/-6%; Neutralizer Cathode +/-6%

	V_{bpps} V												
I_b , A	1800	1567	1396	1179	1021	936	850	700	679	650	400	300	275
3.52	TL40	TL39	TL38	TL37	ETL3.52A	ETL3.52B	ETL3.52C	ETL3.52D					
3.10	TL36	TL35	TL34	TL33	ETL3.1A	ETL3.1B	ETL3.1C	ETL3.1D	ETL3.1E				
2.70	TL32	TL31	TL30	TL29	TL28	ETL2.7A	ETL2.7B	ETL2.7C	ETL2.7D	ETL2.7E			
2.35	TL27	TL26	TL25	TL24	TL23	ETL2.35A	ETL2.35B	ETL2.35C	ETL2.35D	ETL2.35E			
2.00	TL22	TL21	TL20	TL19	TL18	ETL2.0A	ETL2.0B	ETL2.0C	ETL2.0D	ETL2.0E			
1.60	TL17	TL16	TL15	TL14	TL13	ETL1.6A	ETL1.6B	ETL1.6C	ETL1.6D	ETL1.6E	ETL1.6F		
1.20	TL12	TL11	TL10	TL09	TL08	TL07	TL06		TL05	TL04	TL03	TL02	
1.00													TL01

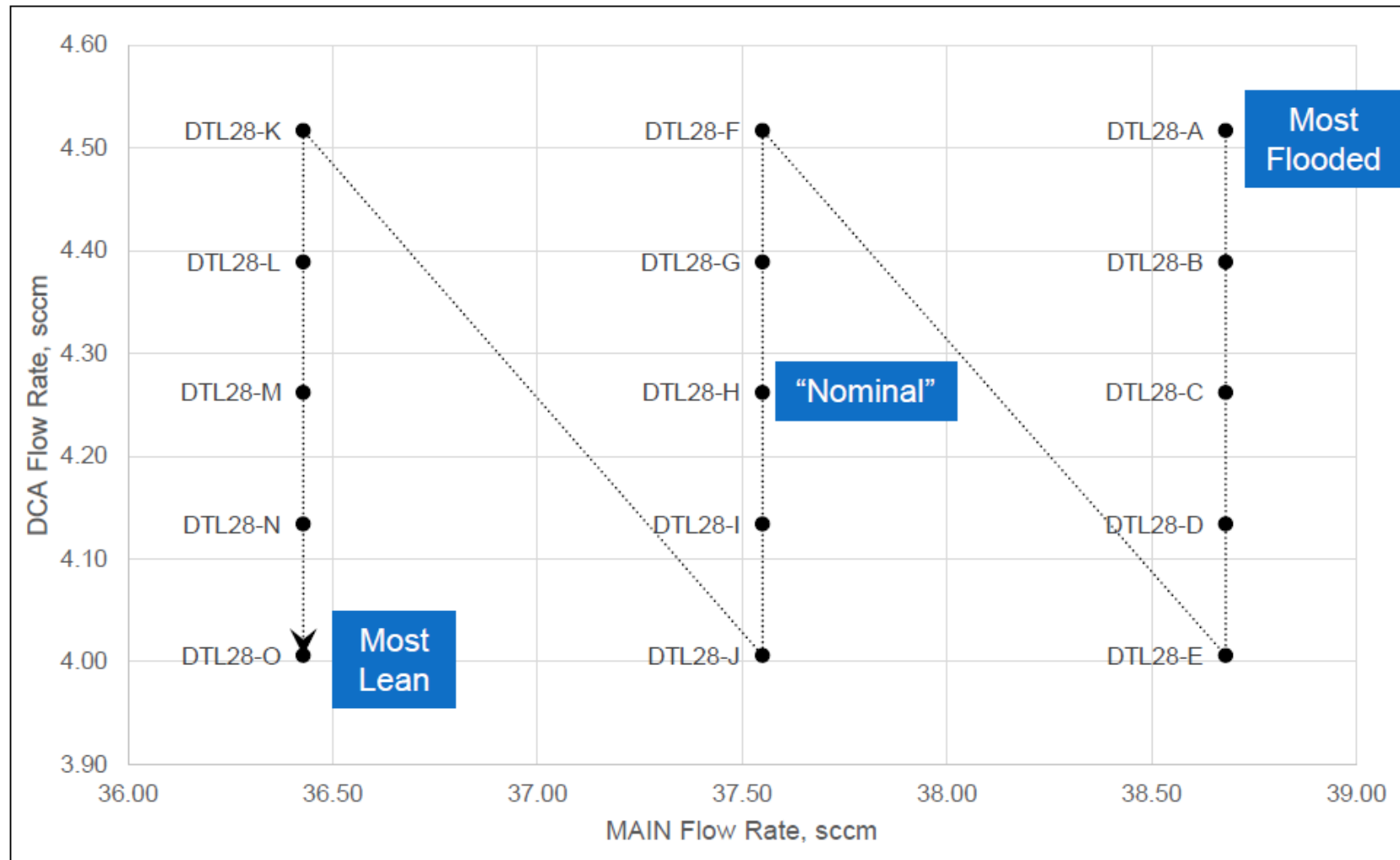
DART Flight Sequences Investigated During Test

1. Cathode Conditioning: Procedure that is used to prepare thruster cathodes for operation after exposure to contaminating environments.
2. Discharge: Procedure for igniting the neutralizer cathode and then the discharge cathode.
3. Throttle: Procedure for igniting the thruster discharge, applying high voltage to the ion optics, and ramping the discharge current to achieve the set-point beam current.
4. Beam Current Regulation: Actively controls the beam current (thrust) during steady-state operation.
5. Power Throttling: Procedure for transitioning the engine to the desired throttle level during steady-state operation.
6. Shut Down: Procedure for removing input power and propellant flow from an operating thruster.

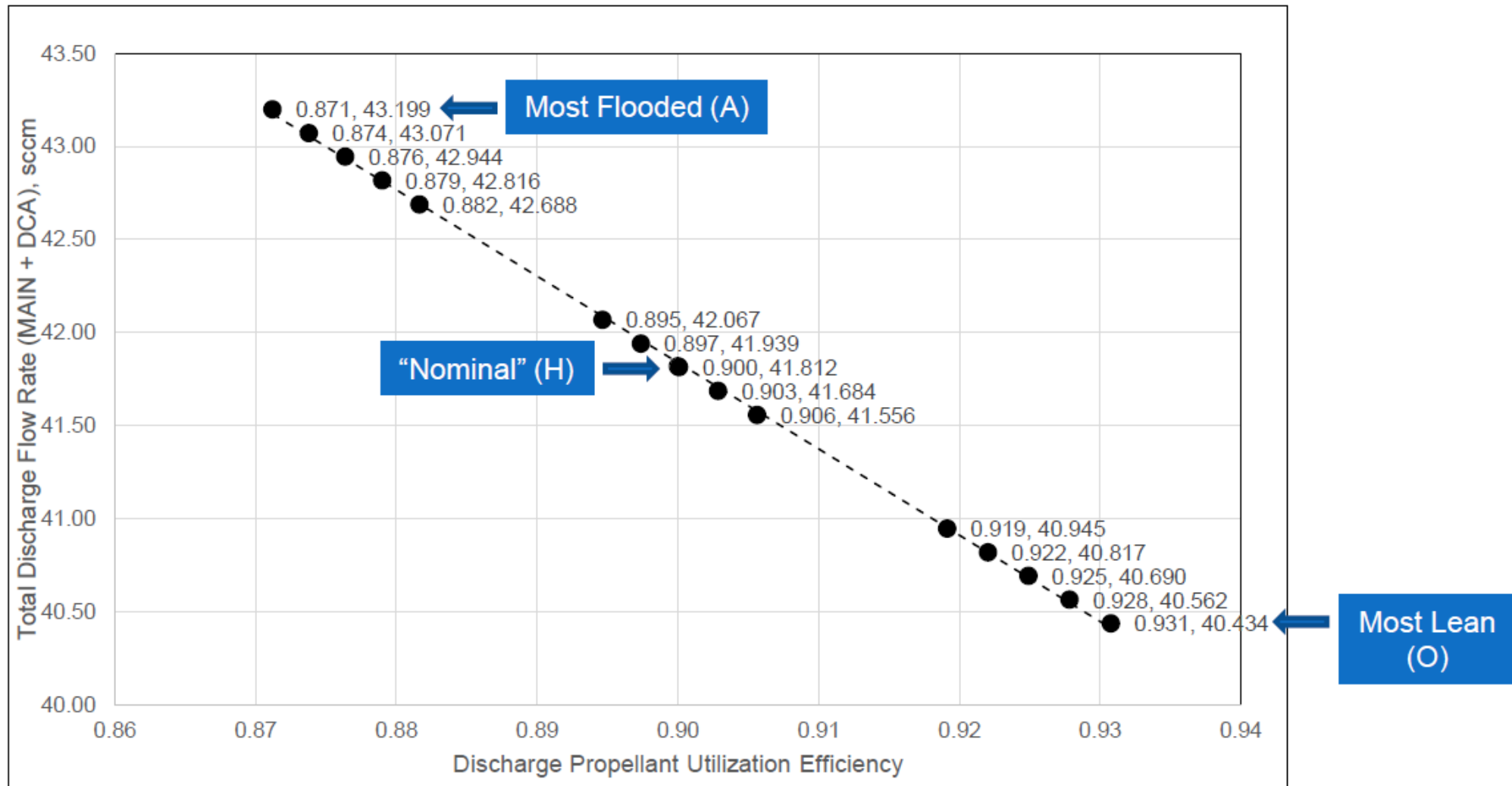
Test Results

- The following slides describe:
 - ❖ Sensitivity Analysis: thruster performance
 - ❖ Thrust correction factors
 - ❖ Laser induced fluorescence results
 - ❖ Thrust vector (inferred from beam centroid measurements)

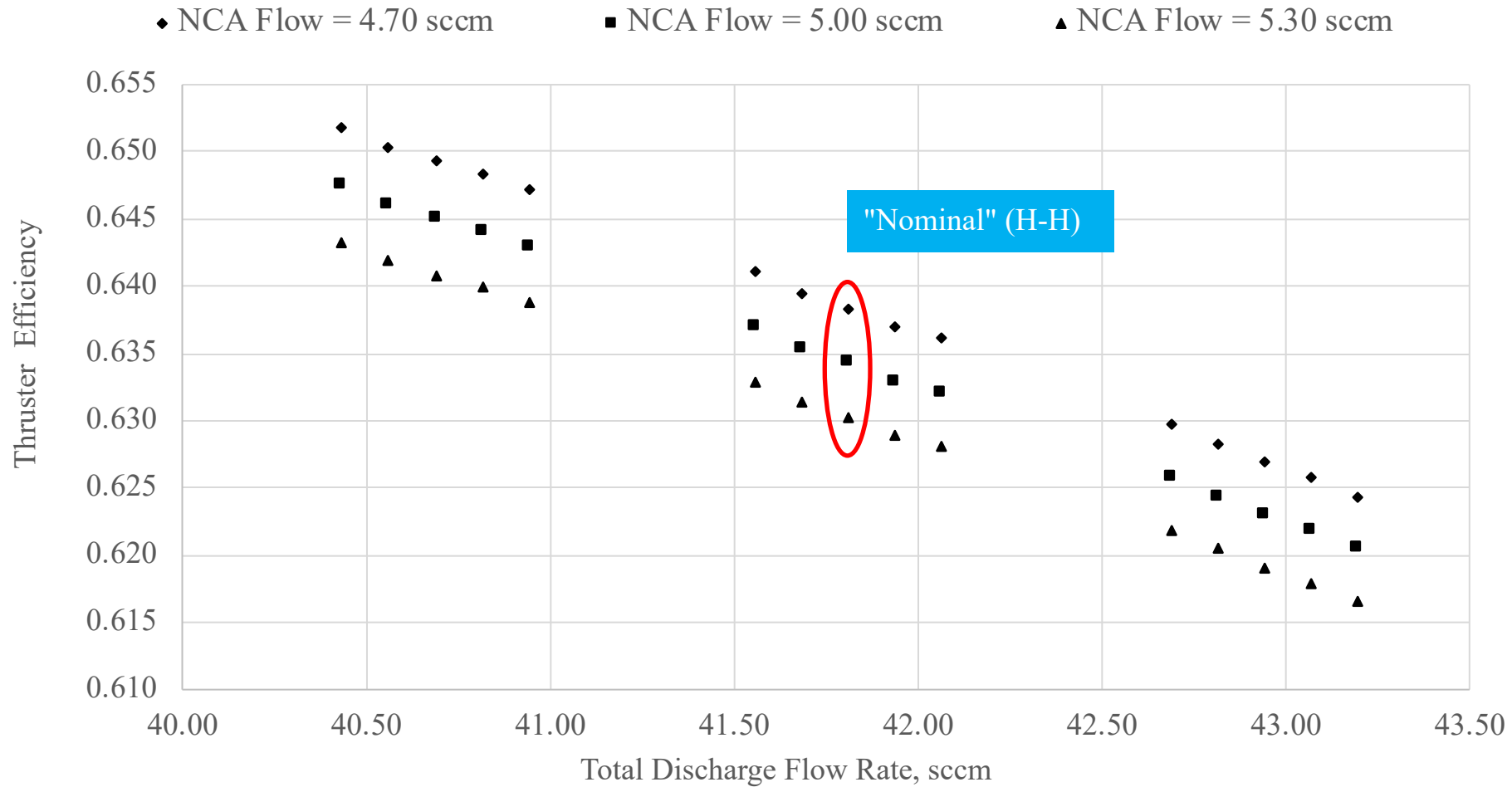
Sensitivity Analysis: Flow Rates Investigated



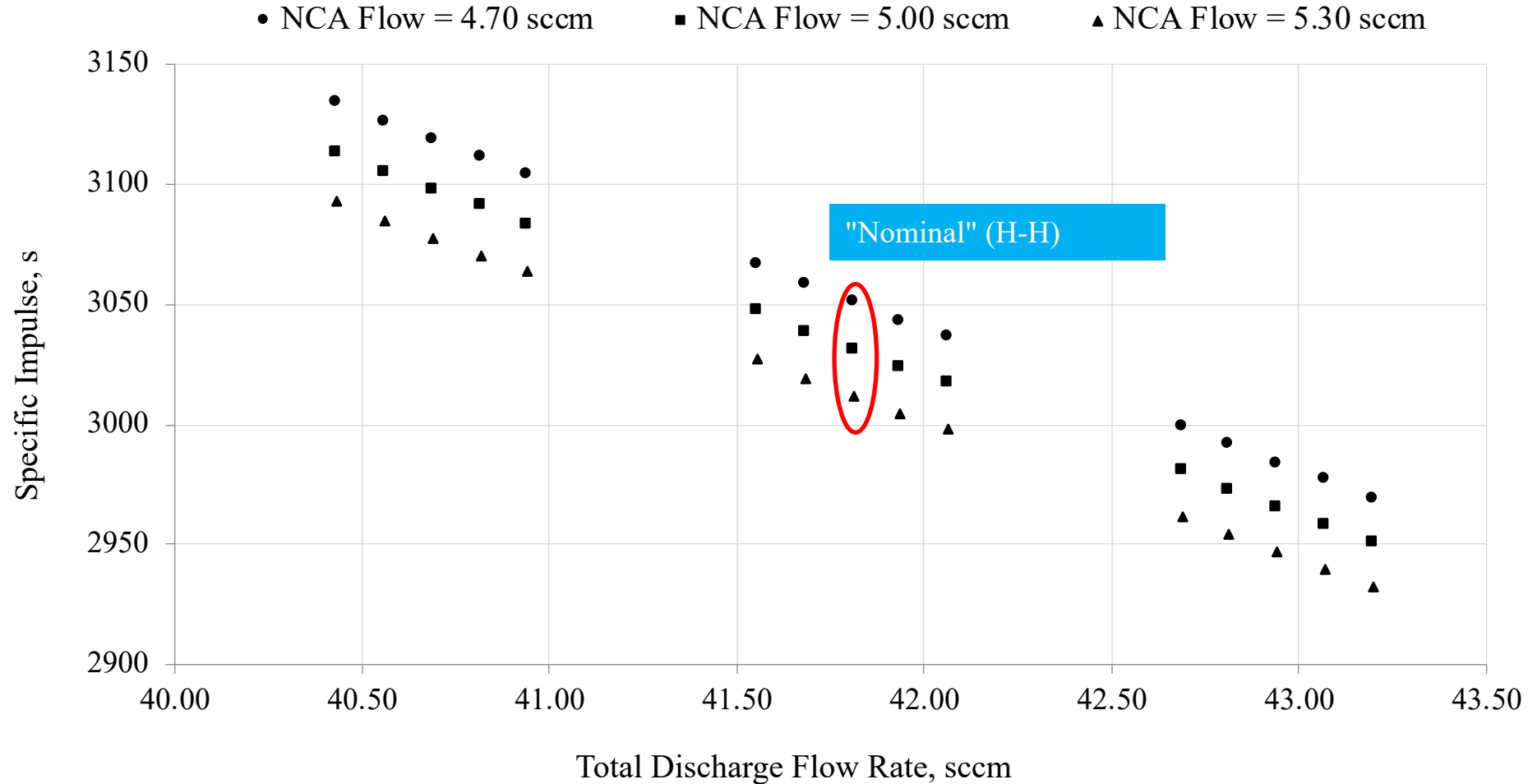
Sensitivity Analyses Results: Propellant Utilization Efficiency



Steady State Performance: Thruster Efficiency

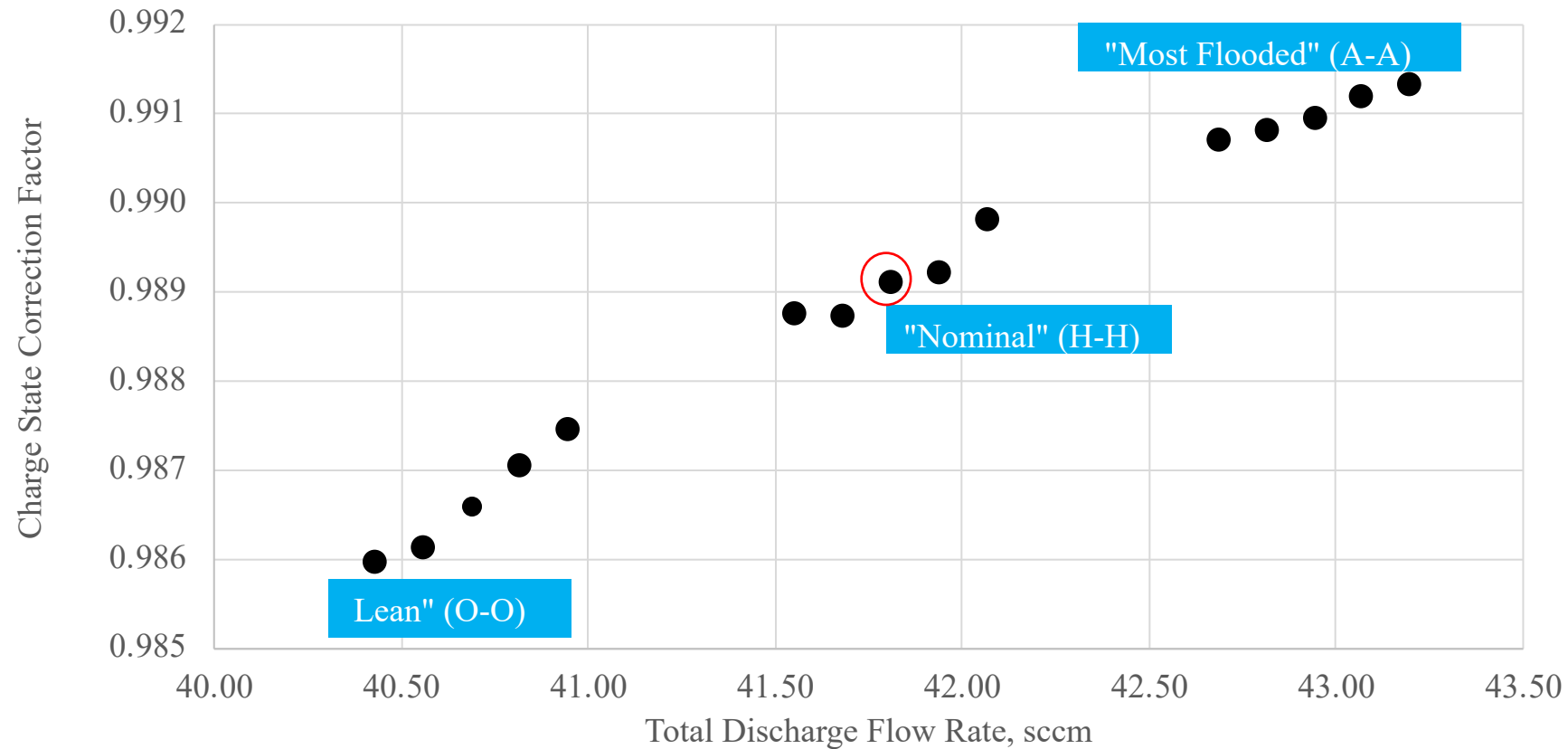


Steady State Performance: Specific Impulse



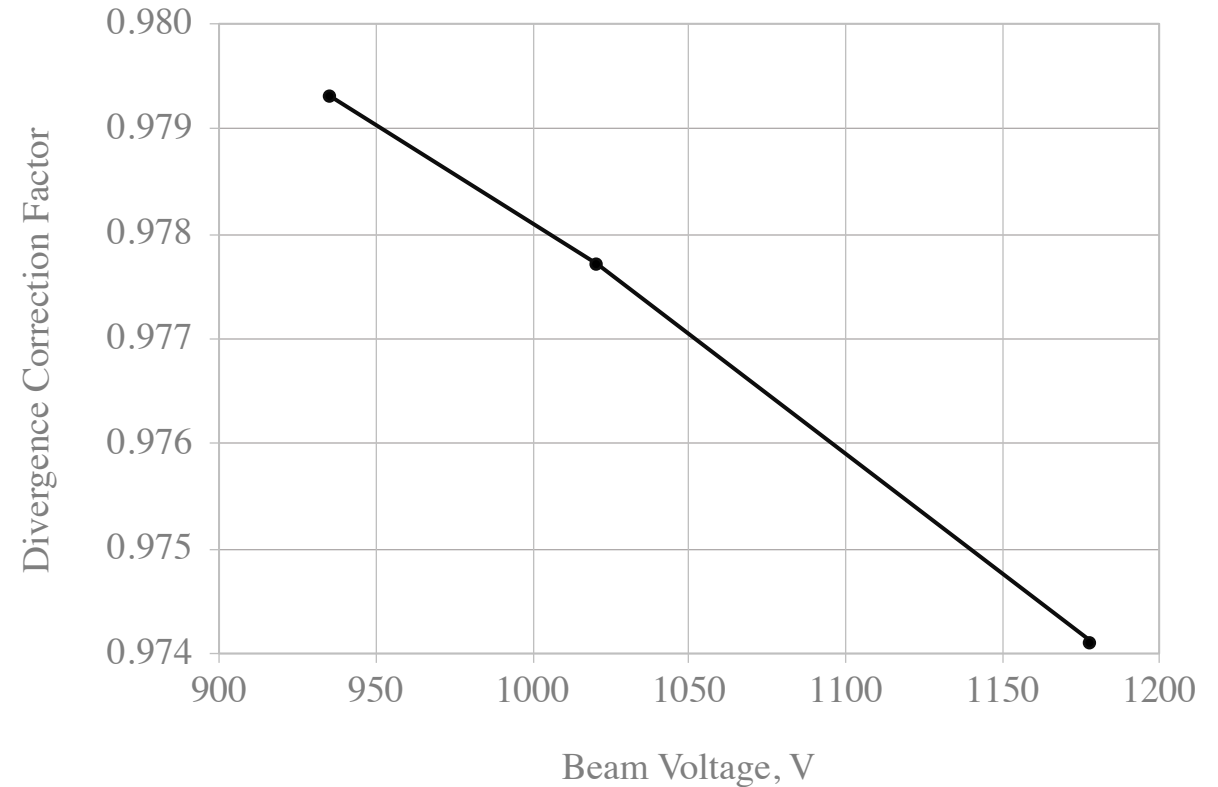
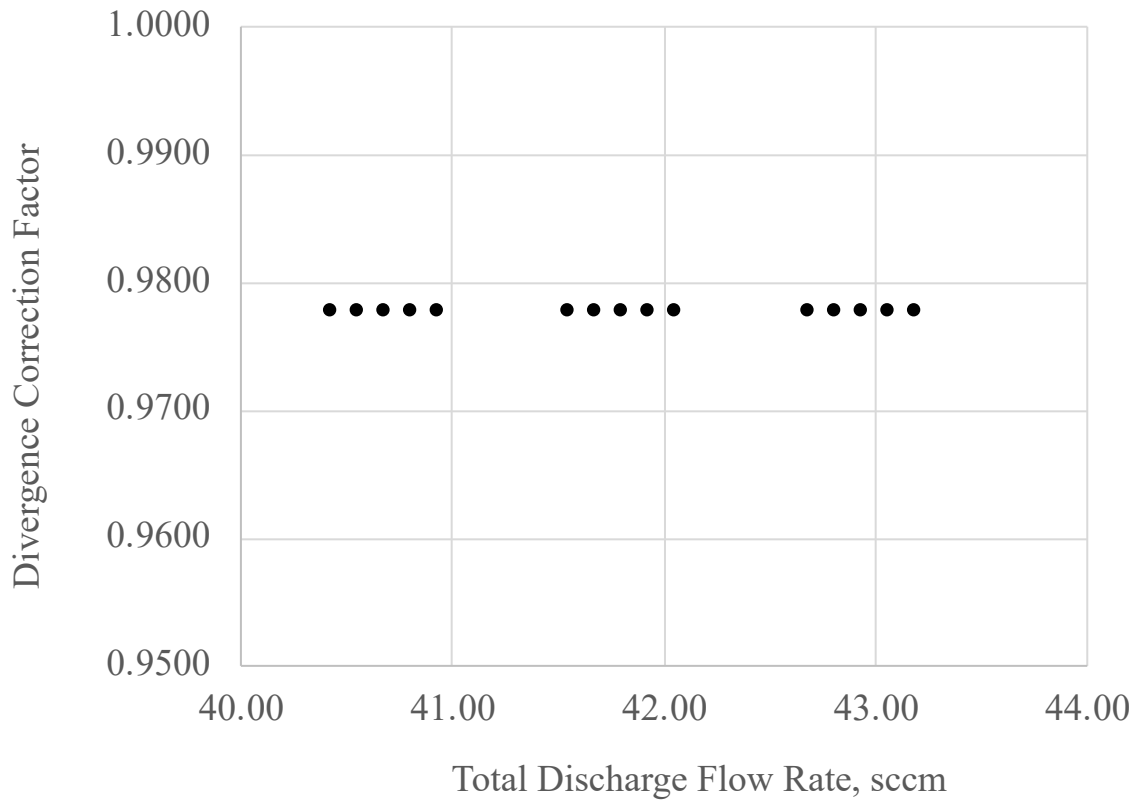
Charge State Correction Factor (α)

- Related to thruster efficiency and erosion of cathode potential surfaces
- Followed expected trends, within acceptable bounds for all conditions tested



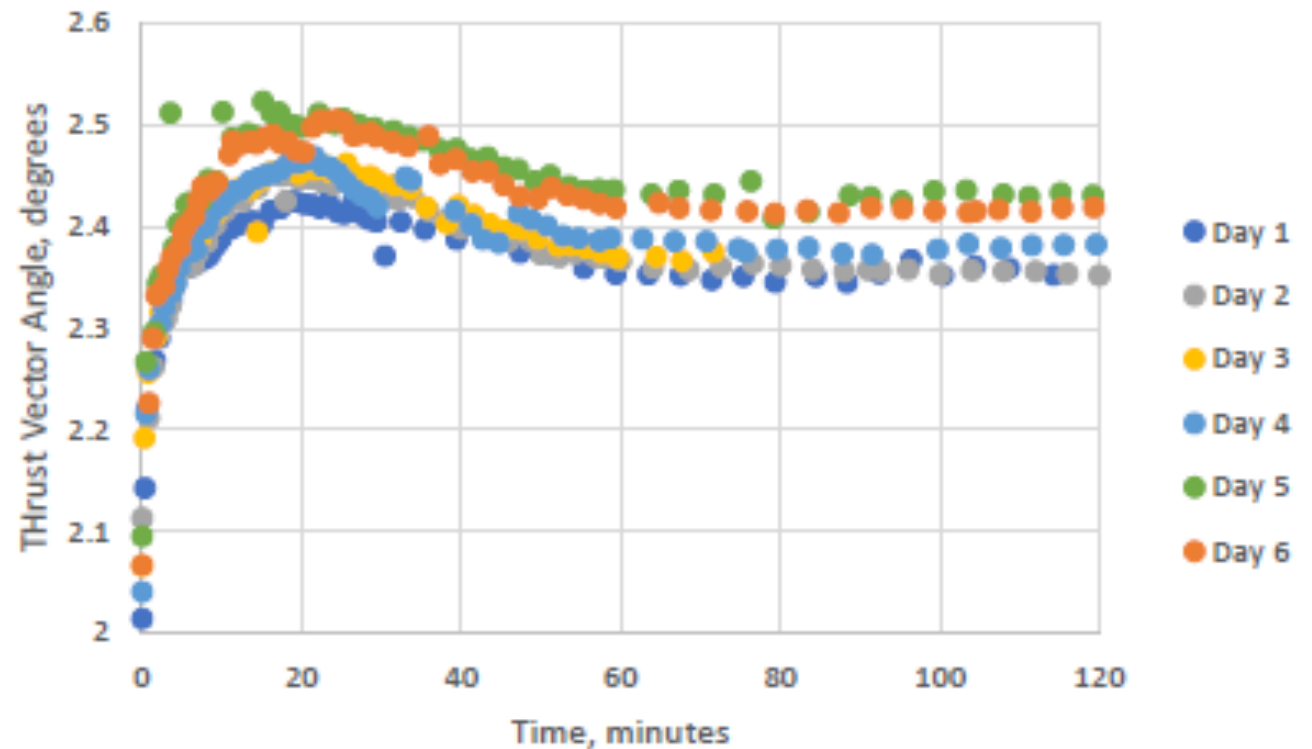
Divergence Correction Factor (β)

- Related to thruster efficiency the potential erosion of spacecraft surfaces
- β decreases with beam voltage, invariant with changes in flow for a given beam voltage



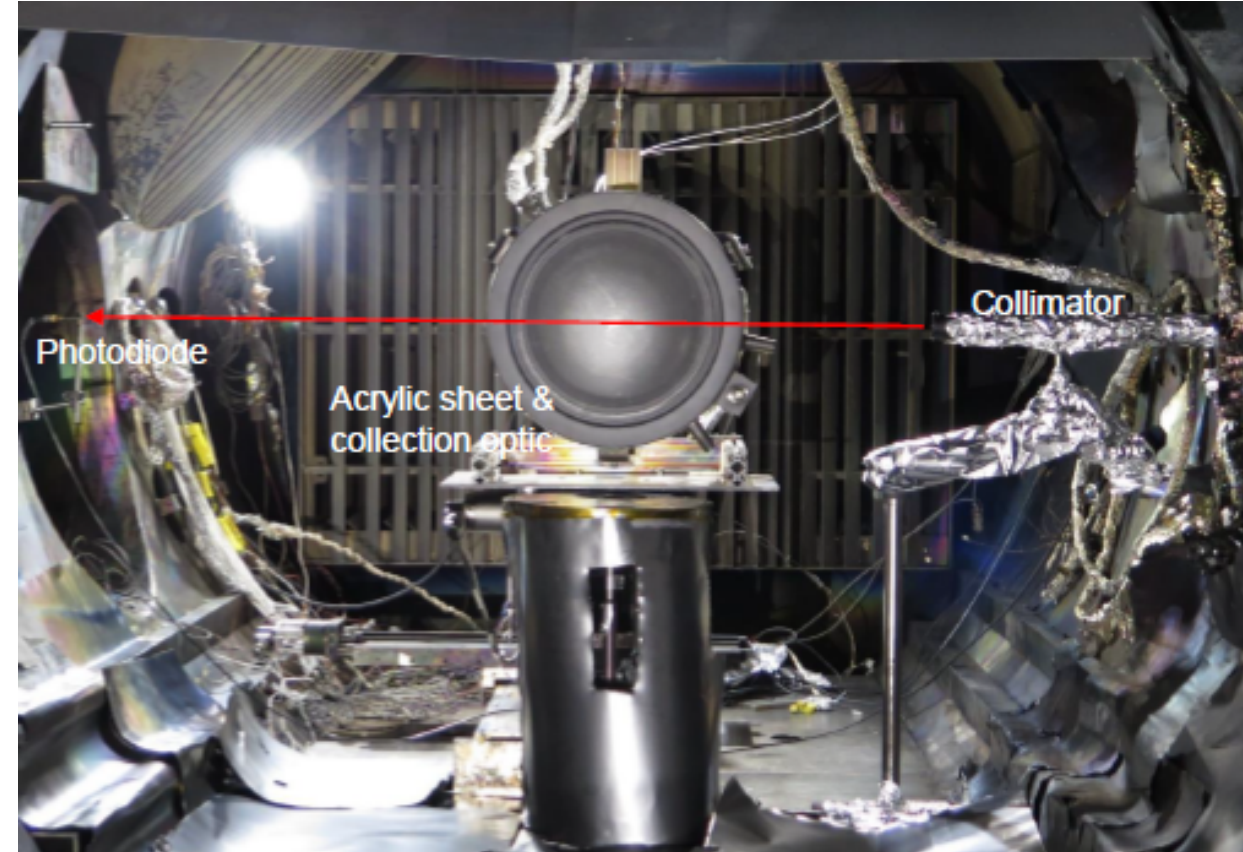
Thrust Vector Measurements

- Array of 20 planar probes located 1 m downstream of engine used to characterize beam centroid during thruster start-ups
- Thrust vector at DART conditions highly dependent on grid clocking
 - grid clocking is significant, but not sole source of thrust vector drift
- Thrust vector migration highly repeatable for a given thruster configuration
 - initial transient possibly due to thermal grid effects, negligible drift over extended durations
- Thrust vector magnitude and start-up trends consistent with ion engine literature



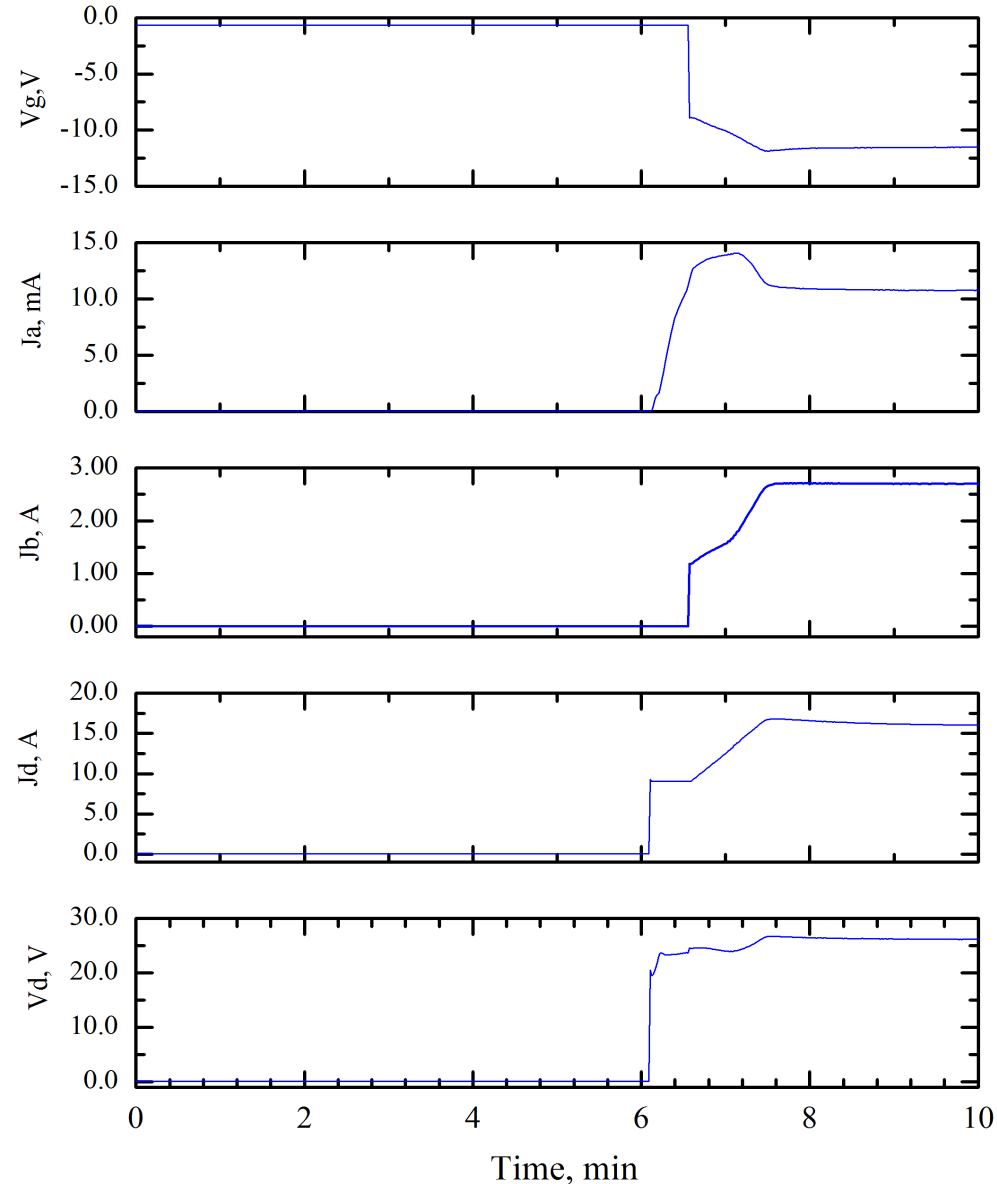
Erosion Measurement Results

- QCM measurements and witness plates indicate higher grid material efflux than previous measurements documented on the NEXT thruster. The measurements indicate aperture barrel erosion is the dominant mechanism, which may be expected over the first ~1000 hours of operation;
- Changes in measured efflux accurately tracked the expected with variation in discharge flow rates: lean conditions yield reduced erosion, while flooded conditions increase erosion ;
- Worst-Case QCM analyses indicate $\ll 1 \times 10^{-11}$ gm/(cm²-s) Mo mass deposition rates behind the exit plane of the thruster;
- No anomalous erosion rates were found at any grid position or throttle level with LIF or QCM measurements, and there is substantial grid lifetime margin for the DART mission.



Algorithm Results

- Multiple start-ups performed from cold (-30 C) to ambient with no anomalous behavior or issues
- Repeatedly demonstrated off to full power in less than 8.0 min, J_b controlled to within 1% during steady-state operation
- All parameters of interest within acceptable bounds during start-up sequences:
 - **Discharge voltage** (V_d): related to erosion of cathode-potential surfaces
 - **Discharge current** (J_d): controls beam current
 - **Beam current** (J_b): thrust directly proportional to beam current
 - **Accelerator current** (J_a): related to erosion of accelerator grid
 - **Coupling voltage** (V_g): related to thruster performance



Summary

- Sensitivity-Analyses, Steady-State Performance, and Life & Erosion tests at DART Mission Specific Throttle Levels were successfully completed:
 - NEXT thruster operations compatibility (performance, life, and stability) with the proposed DART XFS flow control approach was demonstrated;
 - Refined thruster performance values were documented at DART anticipated throttle conditions;
 - The NEXT thruster plume was documented with sufficient fidelity and spatial extent to provide validation data for modeling/simulation of the thruster plume
- Definition and Assessment of a Flight Sequences for DART was successfully concluded:
 - A baseline Start-Up script was defined and repeatedly demonstrated from ambient (-30 C) to full-power for DART, yielding full-thrust operation in less than 8.0 minutes
 - Beam current regulation algorithm controlled beam current (thrust) to within 1%
 - All thruster parameters were conducive to long-life operation during automated sequences