# NASA's Evolutionary Xenon Thruster (NEXT) Long-Duration Test as of 736 kg of Propellant Throughput

**Abstract**: The NASA's Evolutionary Xenon Thruster (NEXT) program is developing the next-generation solar-electric ion propulsion system with significant enhancements beyond the state-of-the-art NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) ion propulsion system to provide future NASA science missions with enhanced mission capabilities. A Long-Duration Test (LDT) was initiated in June 2005 to validate the thruster service life modeling and to qualify the thruster propellant throughput capability. The thruster has set electric propulsion records for the longest operating duration, highest propellant throughput, and most total impulse demonstrated. At the time of this publication, the NEXT LDT has surpassed 42,100 h of operation, processed more than 736 kg of xenon propellant, and demonstrated greater than 28.1 MN·s total impulse.

Thruster performance has been steady with negligible degradation. The NEXT thruster design has mitigated several lifetime limiting mechanisms encountered in the NSTAR design, including the NSTAR first failure mode, thereby drastically improving thruster capabilities. Component erosion rates and the progression of the predicted life-limiting erosion mechanism for the thruster compare favorably to pretest predictions based upon semi-empirical ion thruster models used in the thruster service life assessment. Service life model validation has been accomplished by the NEXT LDT. Assuming full-power operation until test article failure, the models and extrapolated erosion data predict penetration of the accelerator grid grooves after more than 45,000 hours of operation while processing over 800 kg of xenon propellant. Thruster failure due to degradation of the accelerator grid structural integrity is expected after groove penetration.

# NASA's Evolutionary Xenon Thruster (NEXT) Long-Duration Test as of 736 kg of Propellant Throughput

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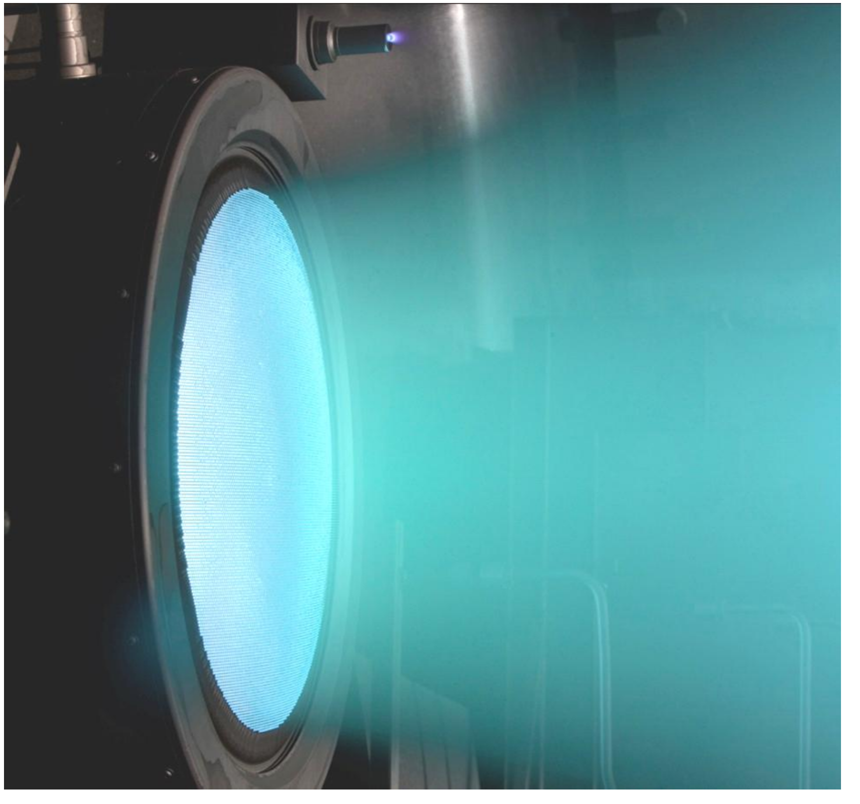
# Outline

- Purpose of the Work
- NEXT LDT Status and Throttling Plan
- Performance Data
- Erosion Images and Data
- Summary and Questions

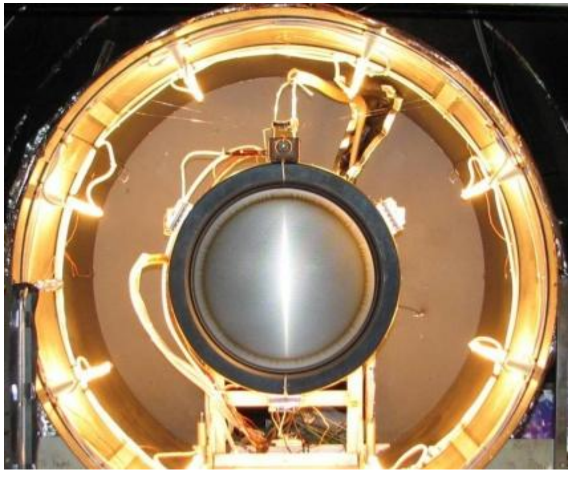


Photograph of NEXT EM3 thruster operating at full-power

# NASA's Evolutionary Xenon Thruster (NEXT)

- The NEXT project is advancing the capability of ion propulsion offering mission enhancement with broad mission applicability
- NEXT is a significant enhancement beyond state-of-the-art (NSTAR)
  - Higher-power, higher-thrust, higher-specific-impulse
  - Wider throttling range, higher thruster service life capability
- Evolutionary design allows us to take advantage of 58,000 hours of NSTAR operating time and lessons learned
  - Address NSTAR issues and failure modes
- Key ion propulsion system hardware has advanced to a high state of maturity

**NEXT is ready for first flight mission opportunities**


Prototype-Model NEXT thruster during thermal vacuum testing at JPL

# Purpose of the NEXT Long-Duration Test (LDT)

- Initiated as part of a comprehensive thruster service life assessment utilizing testing and modeling analyses
  - NEXT 2,000 h EM thruster wear test
  - NEXT thruster service life model development
  - NEXT PM1R thruster and propellant management system wear test
  - NEXT Long-Duration Test (LDT)

- LDT goals:
  - √ Qualify the NEXT thruster propellant throughput capability to an initial value of 450 kg
  - √ Validate thruster service life models
  - √ Characterize thruster performance over test duration
  - √ Measure critical thruster component erosion rates
  - √ Identify unknown life-limiting mechanisms

- LDT objective to demonstrate 450 kg was redefined after completion in December 2009 to test-to-failure of the thruster

# LDT Operating Conditions

- The 5 extended operating time conditions are numbered below in order based upon NEXT LDT throttling profile
- Thruster performance periodically assessed for 11 operating conditions covering the entire NEXT throttle table (shown in red)
  - There are a total of 40 discrete operating conditions in the NEXT technology development throttle table

| | | Beam Voltage | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1800 | 1567 | 1396 | 1179 | 1021 | 936 | 850 | 679 | 650 | 400 | 300 | 275 |
| Beam Current | 3.52 | 1 | | | 2 | | | | | | | | |
| | 3.10 | | | | | | | | | | | | |
| | 2.70 | | | | | | | | | | | | |
| | 2.35 | | | | | | | | | | | | |
| | 2.00 | | | | | | | | | | | | |
| | 1.60 | | | | | | | | | | | | |
| | 1.20 | 5 | | | | | | | 3 | | | | |
| | 1.00 | | | | | | | | | | | | 4 |

Table illustrating the NEXT throttle table consisting of 40 operating conditions.

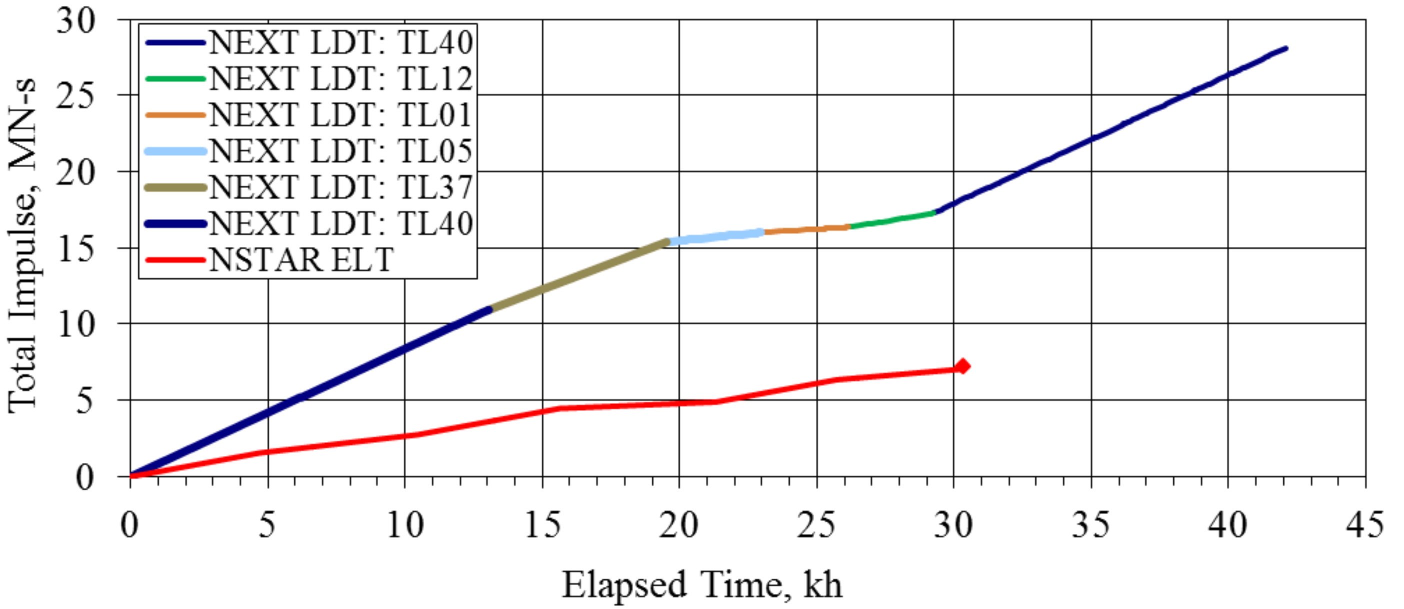
# NEXT LDT Throttling Profile

| Throttle Level | Input Power, kW | Operating Condition | Duration, kh | Segment Throughput, kg | Segment Total Impulse, N·sec | Segment End Date |
|---|---|---|---|---|---|---|
| TL40 | 6.9 | 3.52A, 1800V | 13.0 | 264.7 | $1.09 \times 10^7$ | 11/17/2007 |
| TL37 | 4.7 | 3.52A, 1179V | 6.5 | 132.6 | $4.45 \times 10^6$ | 12/23/2008 |
| TL05 | 1.1 | 1.20A, 679V | 3.4 | 26.7 | $6.30 \times 10^5$ | 6/24/2009 |
| TL01 | 0.5 | 1.00A, 275V | 3.2 | 23.4 | $3.39 \times 10^5$ | 12/15/2009 |
| TL12 | 2.4 | 1.20A, 1800V | 3.1 | 24.5 | $9.11 \times 10^5$ | 5/5/2010 |
| | | Totals | 29.2 | 471.9 | $1.73 \times 10^7$ | |

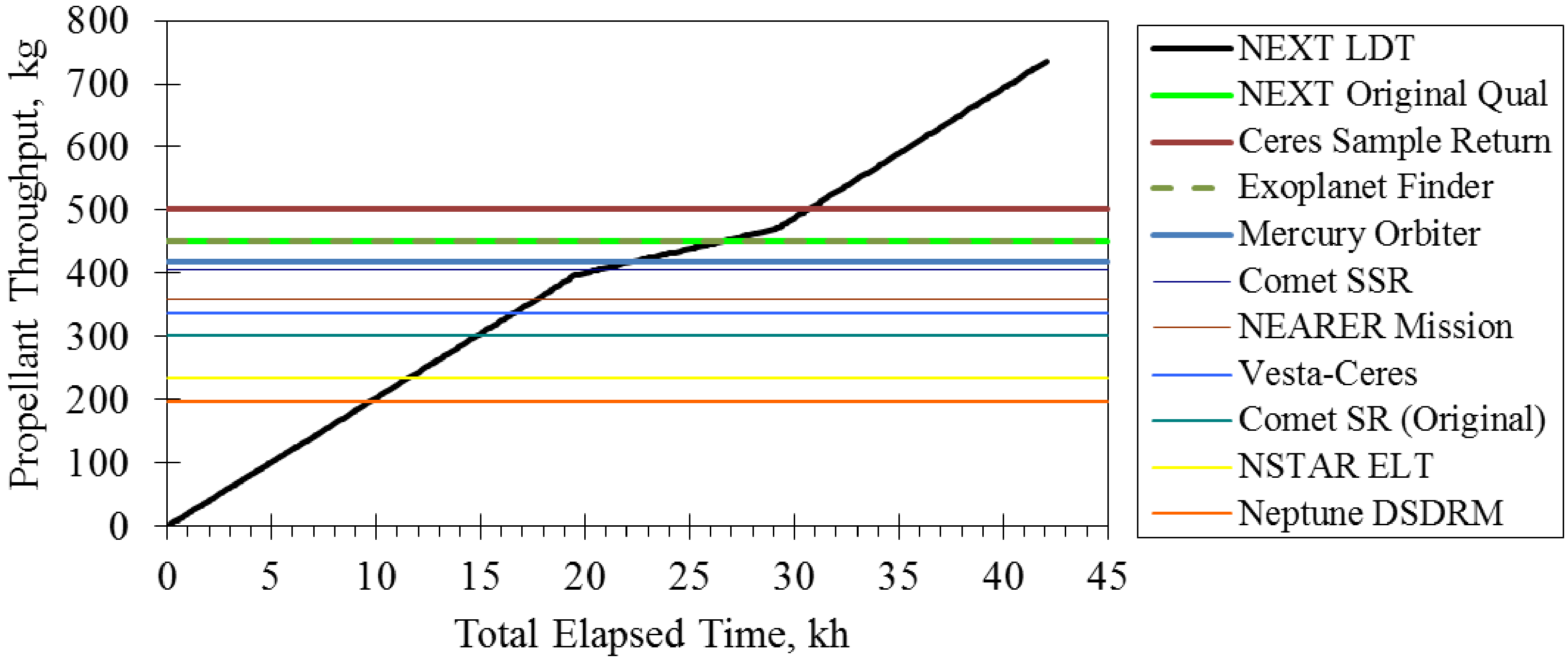
- Throttle the engine in a mission-like profile
  - Throttle down in power consistent with outbound mission profile
  - Thruster has been throttled back to full-power after profile completed consistent with inner solar system flyby or sample return trajectory profiles
- Extended operations at throttle table extremes
- Characterize critical component erosion for model validation at worst-case operating conditions
- Since completion, thruster has been operated at full-power (TL40)

# NEXT LDT Status

- Test article is a flight-like engineering-model thruster
  - Prototype Model (PM) ion optics and graphite discharge cathode keeper
- As of 7/20/2012
  - 42,100 hrs of high-voltage operation : ***Record electric propulsion thruster***
  - 736 kg of xenon processed: ***Record electric propulsion thruster***
  - 28.1 MN-sec demonstrated: ***Record electric propulsion thruster***
- ***Thruster operating at full power until test completion***



# LDT Propellant Throughput

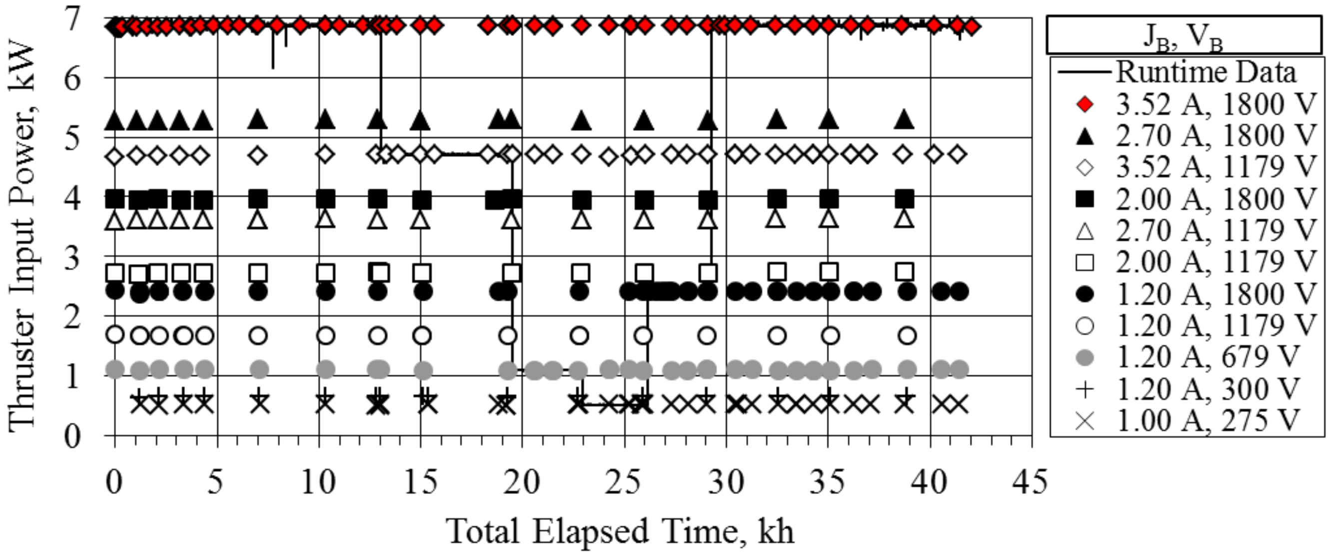



- **NEXT LDT Demo'd (Current): 736 kg**

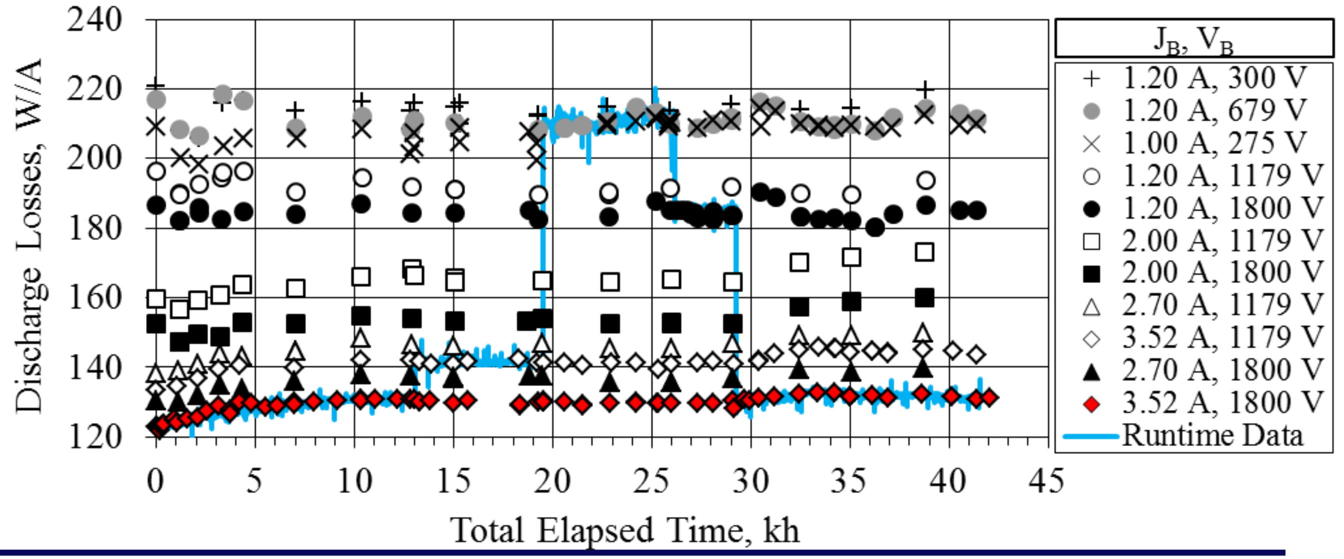
- Ceres Sample Return: 503 kg
- **NEXT LDT Qualified (Current): 491 kg**
- NEXT Qual. Requirement (Original): 450 kg
- Exoplanet Finder: 450 kg
- Mercury Orbiter: 418 kg
- Comet Sample Return: 405 kg
- NEARER Mission: 360 kg
- Vesta-Ceres Rendezvous: 338 kg
- Comet Sample Return (Original): 301 kg
- NSTAR ELT: 235 kg
- Neptune DSDRM: 197 kg
- NSTAR DS-1: 73 kg

# Thruster Performance Parameters

- Minimal increase in input power and discharge losses after 736 kg Xe processed
  - Maximum 30 W increase in input power (at high power) compared to BOL
  - NEXT discharge loss increase a maximum 10 W/A compared to 22 W/A for NSTAR

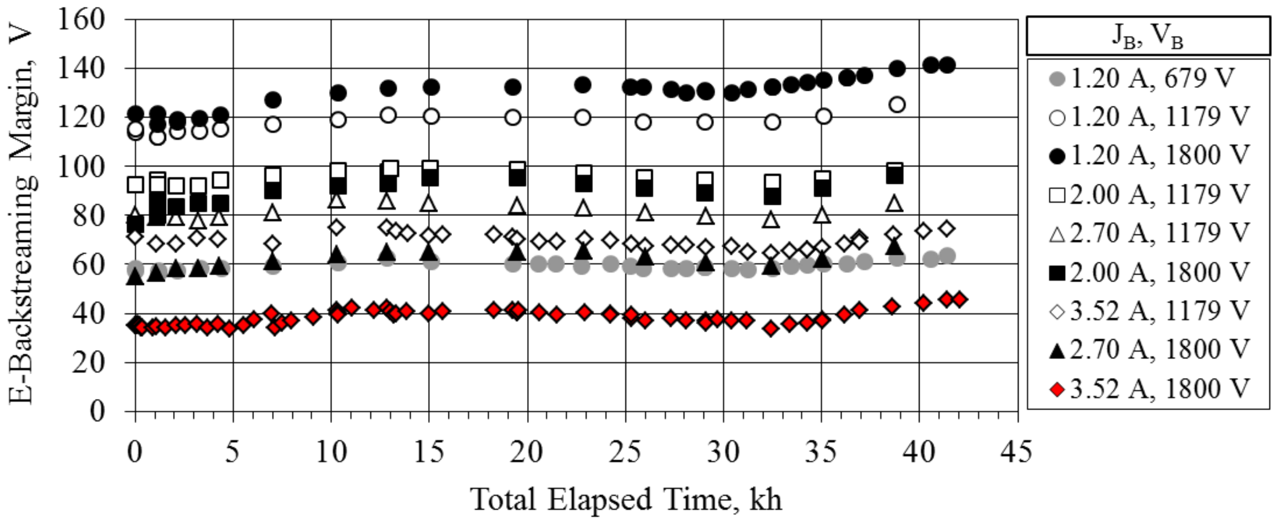


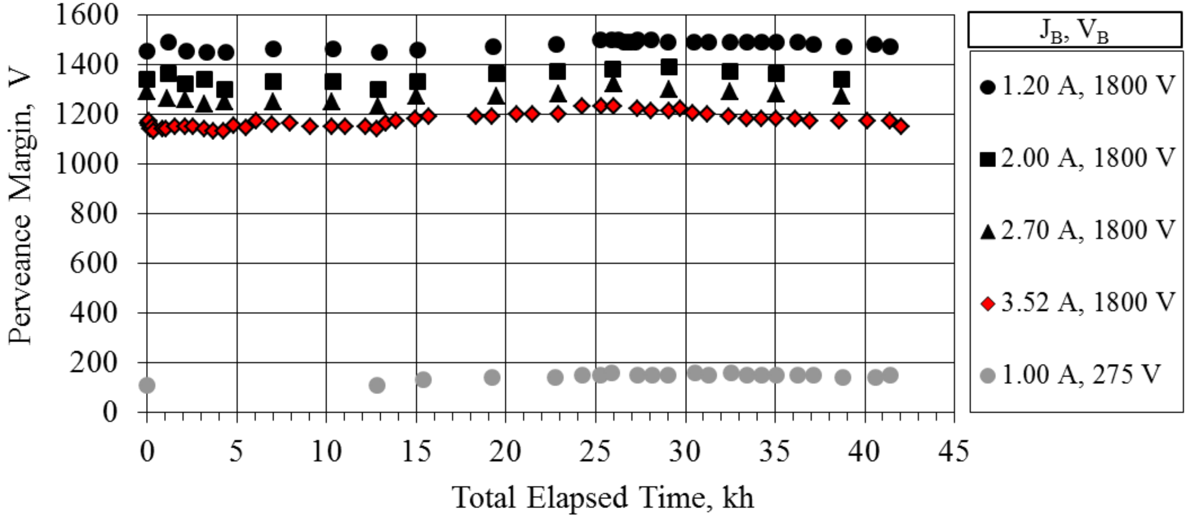

- Constant thrust, Isp, and thrust efficiency
  - Minor variations resulting from neutralizer flow rate changes



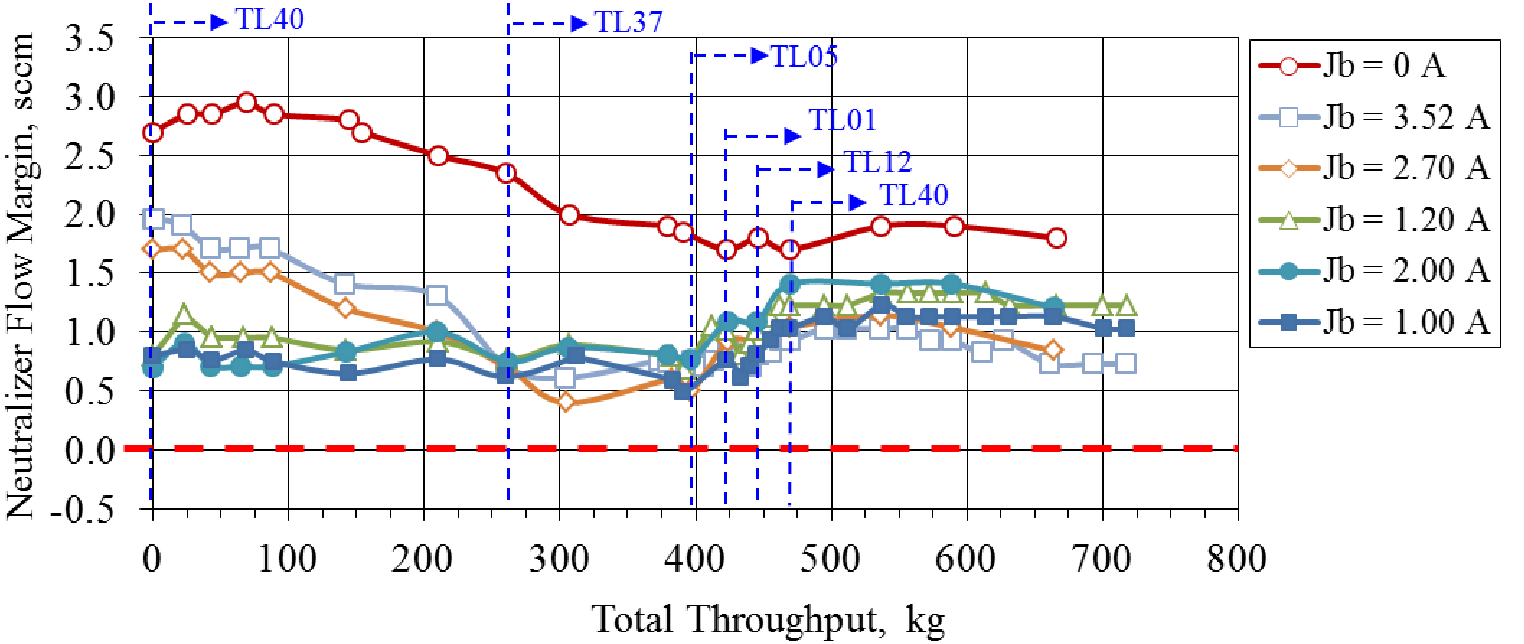
# Ion Optics' Performance Parameters

- Slight electron backstreaming margin increase during full-power run segments
  - Speculated due to back-sputtered carbon deposits within accelerator apertures
  - Supported by negligible change in accelerator aperture cusp erosion and minor downstream chamfer erosion
  - NSTAR first failure mode was electron backstreaming margin decrease to zero
- No change in perveance margin
  - Slight changes due to accelerator aperture chamfering



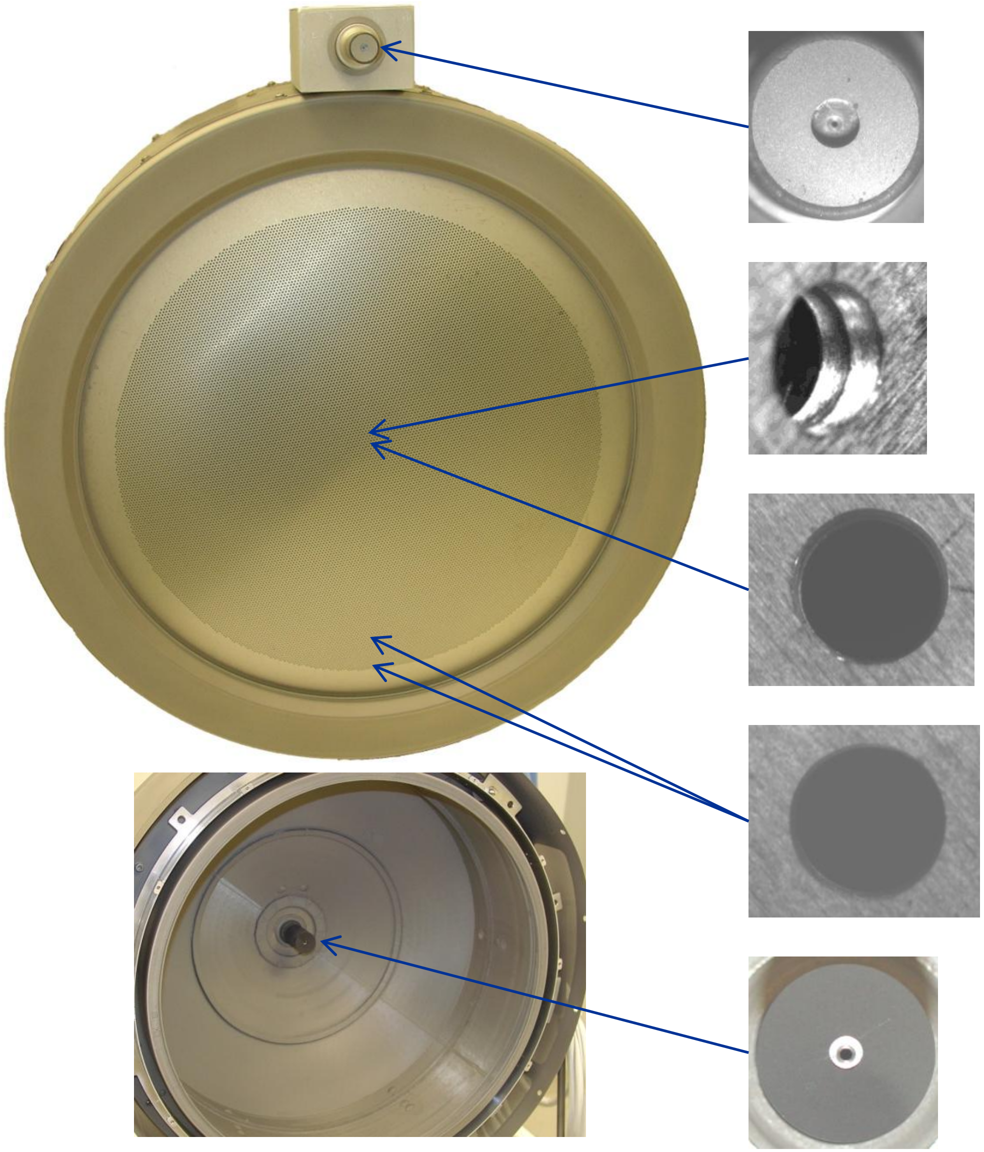



# Neutralizer Performance



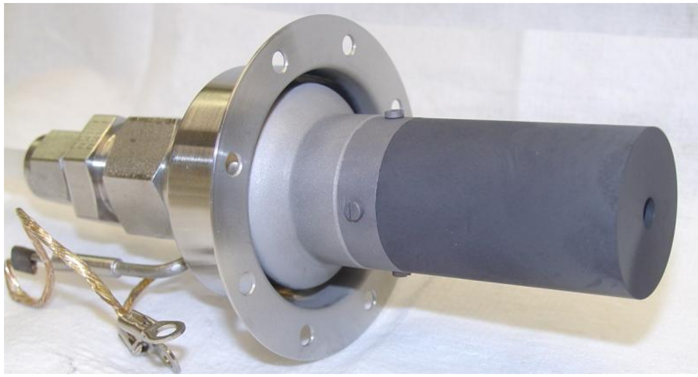

- Loss of neutralizer flow margin (IEPC-2009-154) addressed via:
  - NEXT PM neutralizer design change to increase BOL flow margin at low emission currents
  - Modified NEXT technology development throttle table to ensure adequate margin with thruster operating time
    - Neutralizer flow set points increase as a function of propellant throughput
- ***Maintain minimum 0.4 sccm neutralizer flow margin***

# In-Situ Erosion Diagnostics

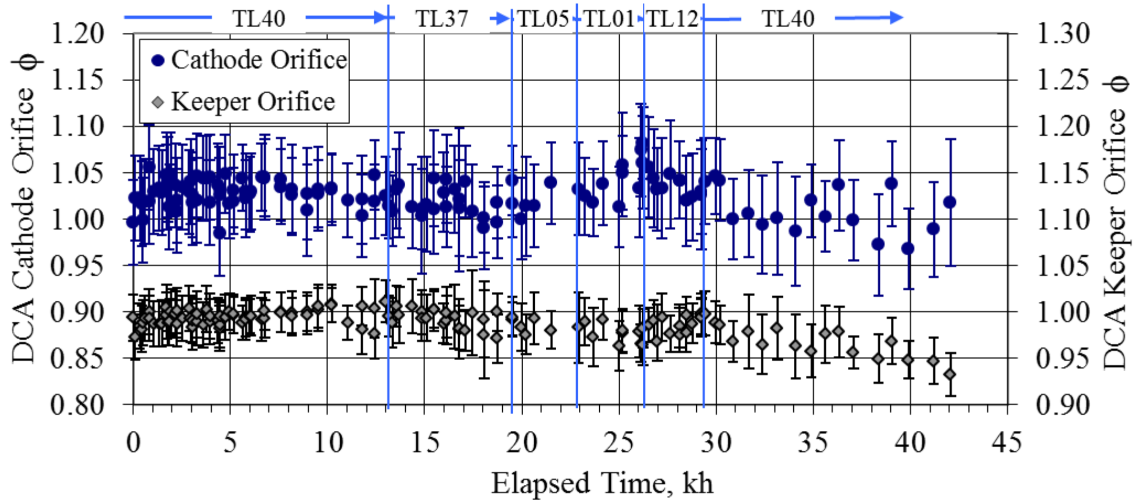


- Neutralizer cathode assembly
  - Concern of orifice erosion or clogging and keeper erosion due to ion impingement
- Cold ion optics’ grid-gap at center
  - Concern of changing grid-gap contributing to electron backstreaming
- Accelerator grid center radius aperture cusp and downstream chamfer diameters
  - Concern of aperture enlargement due to charge-exchange ion impingement
- Accelerator grid outer radii apertures cusp and downstream chamfer diameters
  - Concern of aperture enlargement due to charge-exchange ion erosion and direct impingement due to beamlet over-focusing
- Discharge cathode assembly
  - Concern of orifice erosion and keeper erosion due to discharge plasma

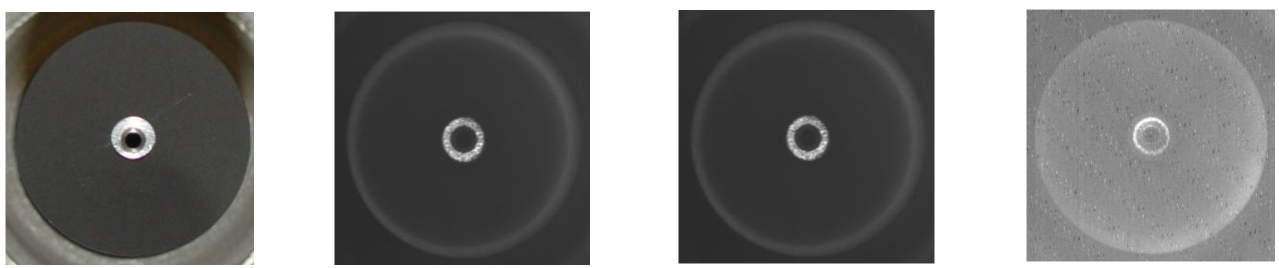
# In-Situ Erosion Diagnostic - Discharge Cathode



NEXT EM3 beginning-of-life discharge cathode assembly with graphite keeper electrode

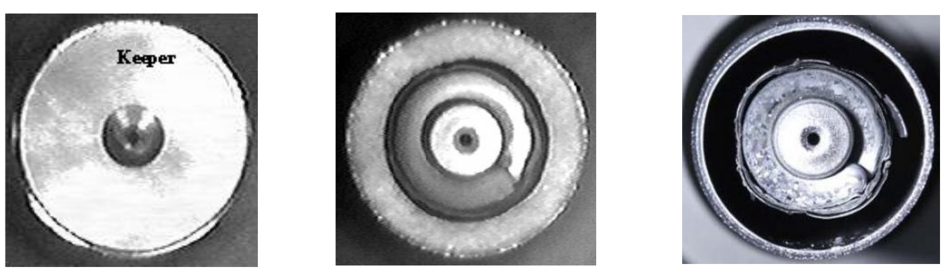



NEXT



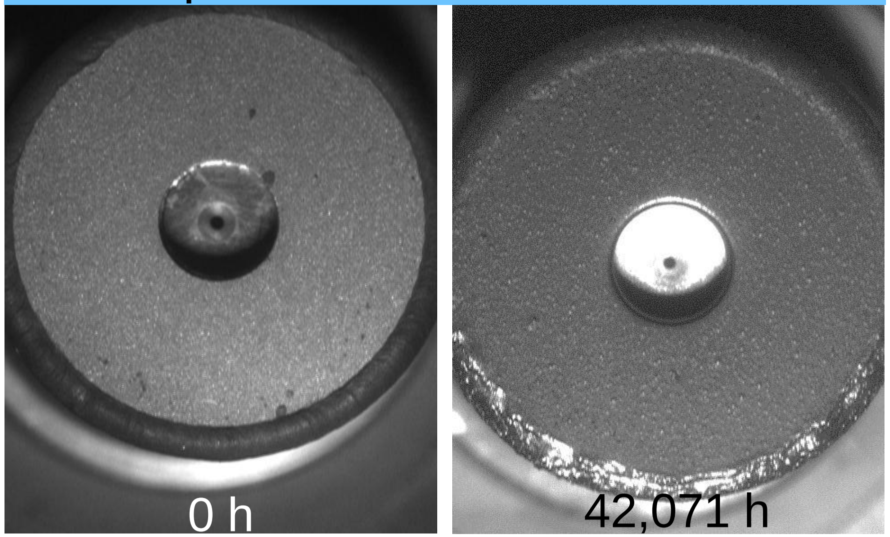
0 kg → 150 kg → 235 kg → 736 kg

NSTAR

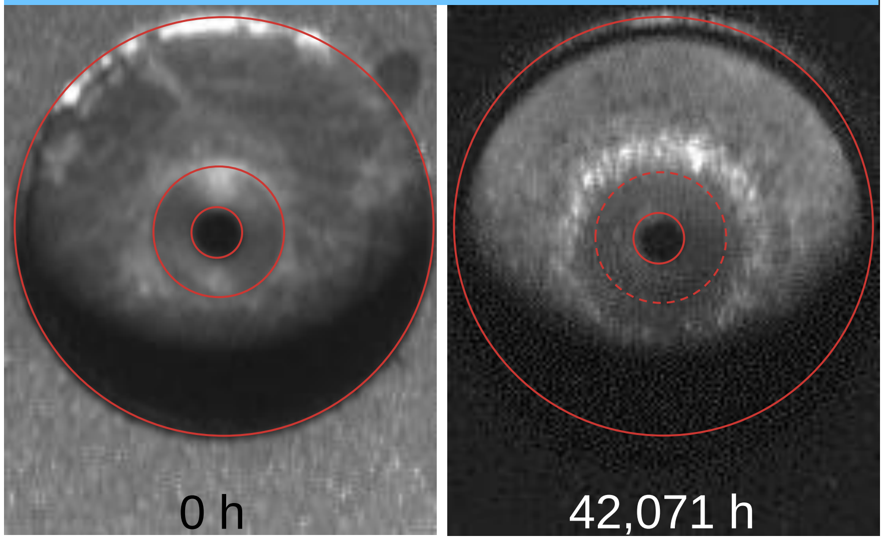


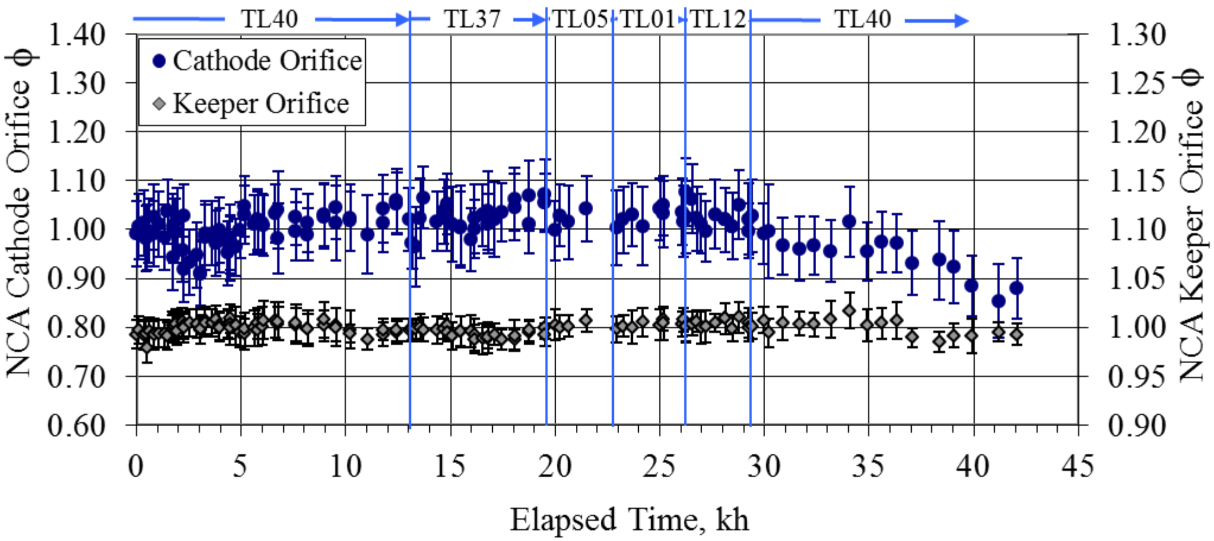
# In-Situ Erosion Diagnostic – Neutralizer Cathode

## Keeper Inner/Outer Diameters



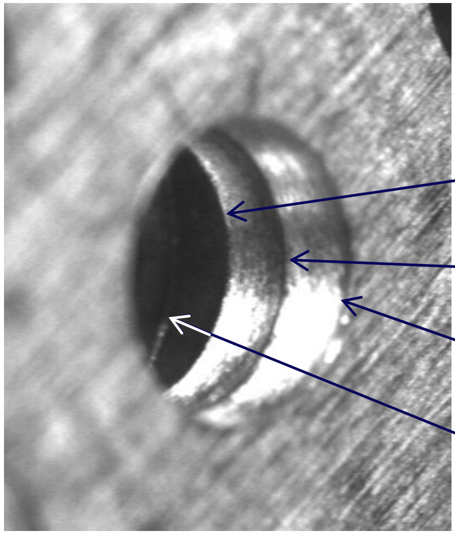

## Cathode Orifice Diameter




- No cathode orifice minimum increase/decrease
  - Clogging observed during NSTAR ELT at low current
  - Orifice channel erosion predicted and modeled
    - AIAA-2009-5196
- No keeper orifice erosion
- No keeper outer diameter erosion due to ion beam impingement

# In-Situ Erosion Diagnostic – Cold Grid Gap



Centerline Accelerator Grid Aperture (at 45°)

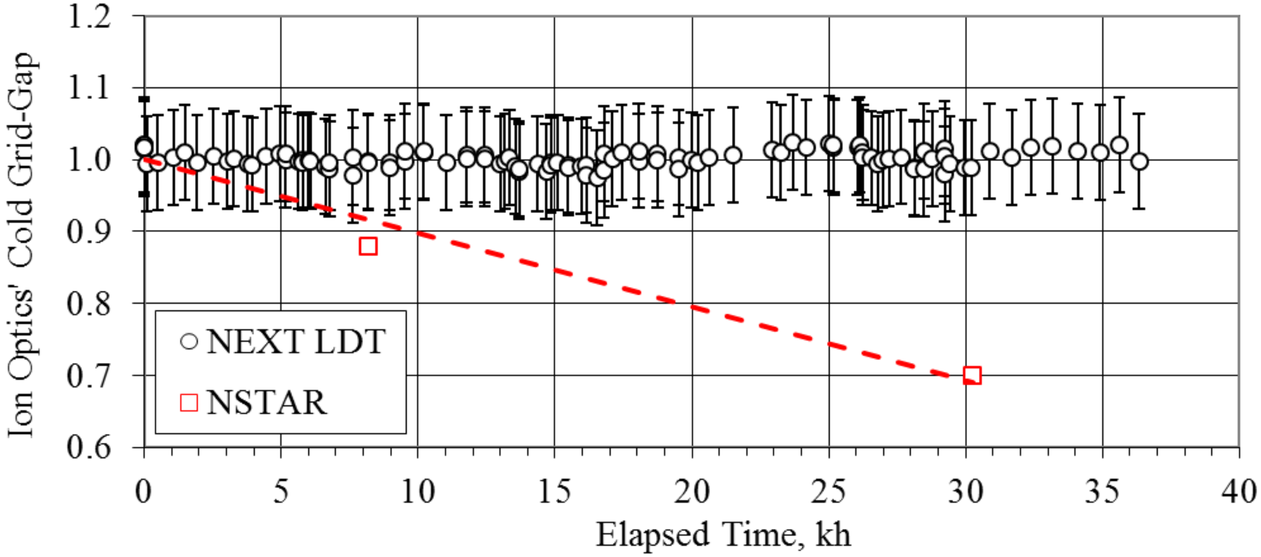
– Upstream Edge

– Cusp

– Downstream Edge

Screen Grid Downstream Edge

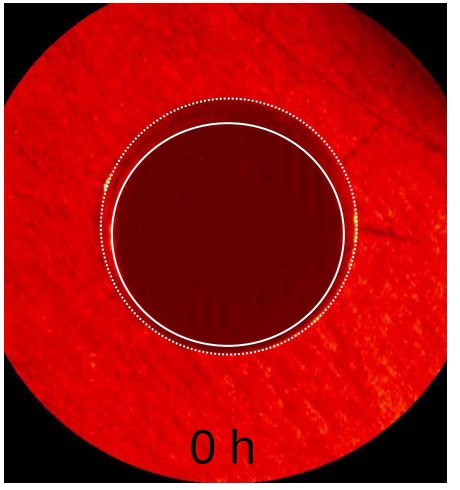
0 h

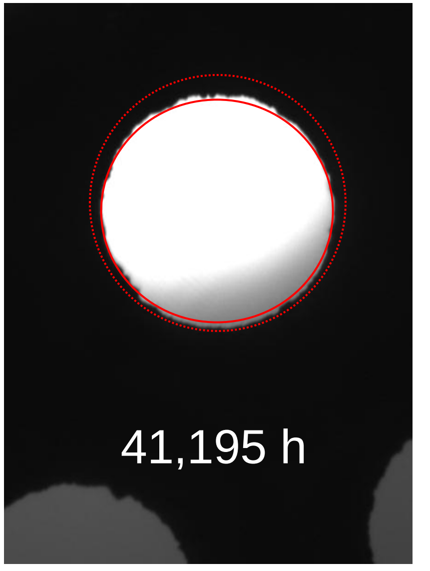


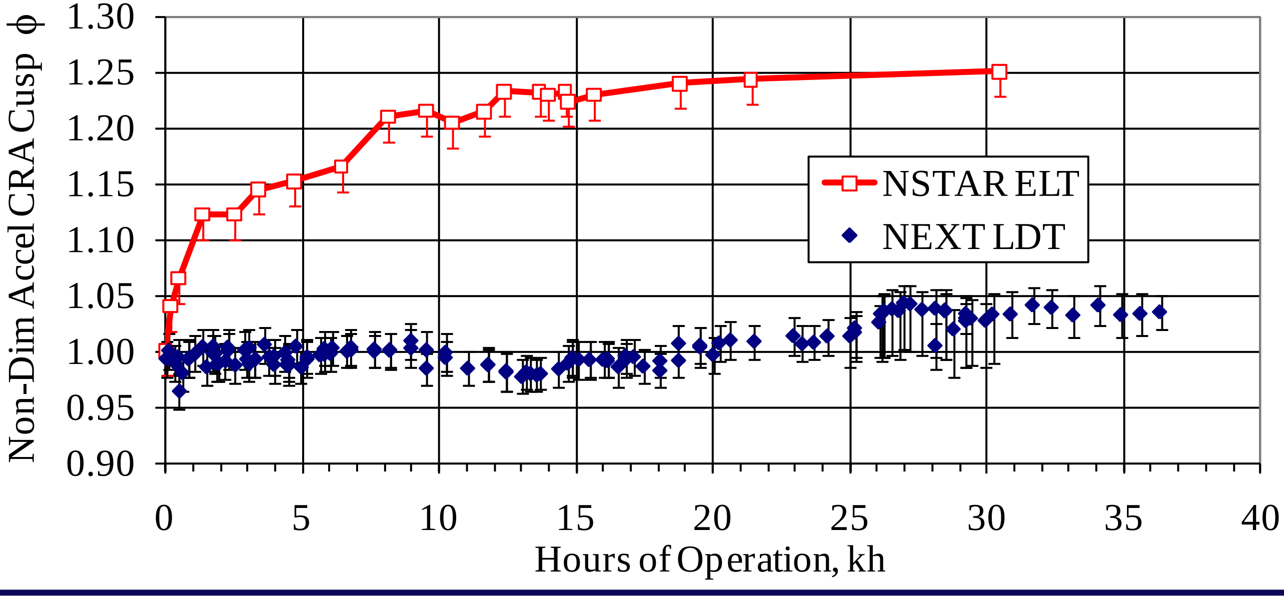

- No observed change in cold grid gap for NEXT PM optics
- NSTAR wear test data indicated increase in grid gap
  - Thermally induced stresses in mounting scheme
  - Contributed to NSTAR first failure

# In-Situ Erosion Diagnostic – Accel. Center Aperture

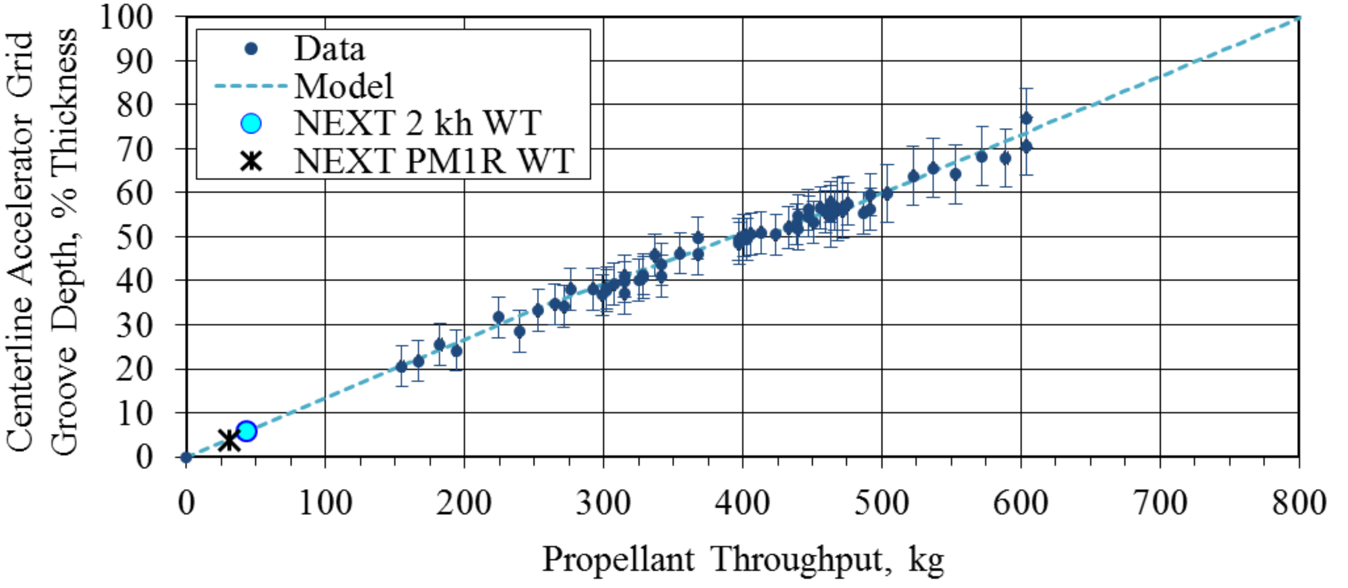
- Pit and groove formation
- Buildup of back-sputtered material between pit-groove hexagonal pattern and aperture
- Negligible cusp erosion
  - Improved NEXT beam flatness vs. NSTAR
- Approximate 15% increase in down-stream orifice diameter



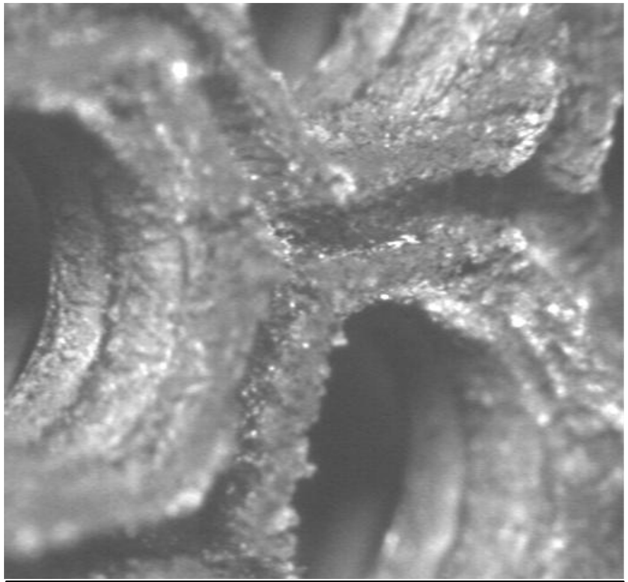



# In-Situ Erosion Diagnostic – Groove Depth

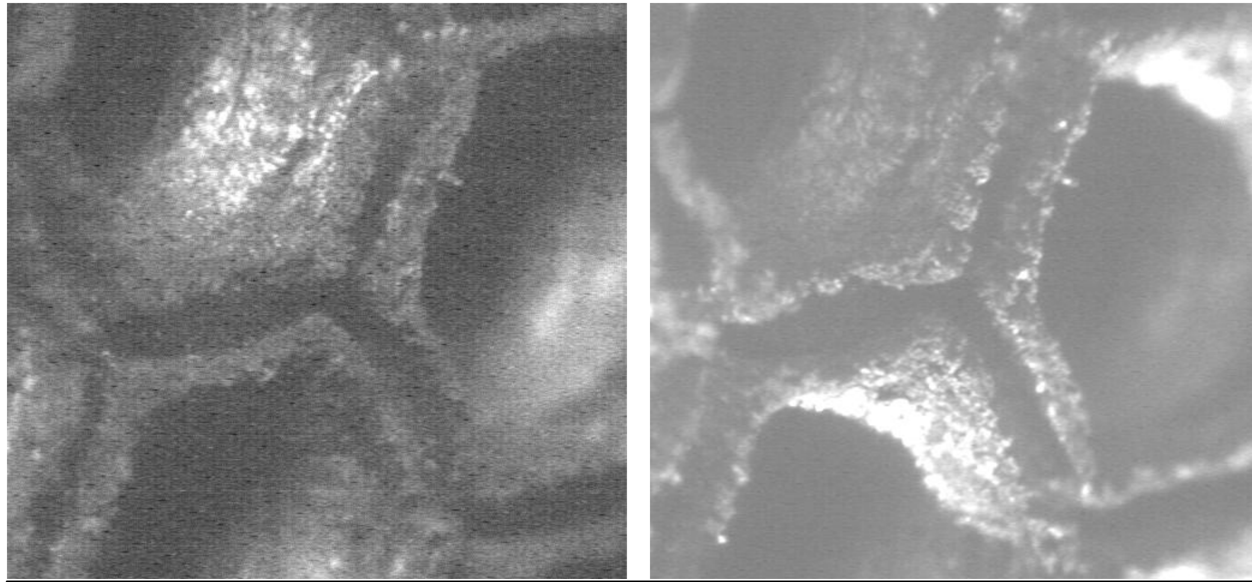



- Model predicted groove depth data for full-power operation (6.9 kW) segment #1 give minimum thruster service life (exclusively at TL40)
  - Groove wear through after 36 kh (≥750 kg xenon throughput)
- Validated groove erosion modeling
  - All other operating conditions have predicted lifetimes in excess of full-power
- Model predicts groove penetration for LDT assuming continued full-power operation (TL40) after 45 kh (≥800 kg xenon throughput)

# Groove Depth Measurement Status



Pit & Groove Depth Image – 30,204 h



Pit & Groove Depth – 36,434 h: image (left) and with external lighting (right)

- The pit and groove measurement is no longer possible due to lack of illumination of the bottom of the deep grooves
  - Last measurement was obtained at 35,618 hours
- Attempts to illuminate the grooves externally have been unsuccessful
  - Only 4 facility view ports are available for external lighting
    - The 2 at the end of the tank are blocked by the cameras and mounting mast
    - One side port is obstructed by the camera mounting mast during imaging
    - The other side port illuminated from a near glancing angle to the accelerator grid resulting in lack of illumination inside the pits and grooves (see right image above)

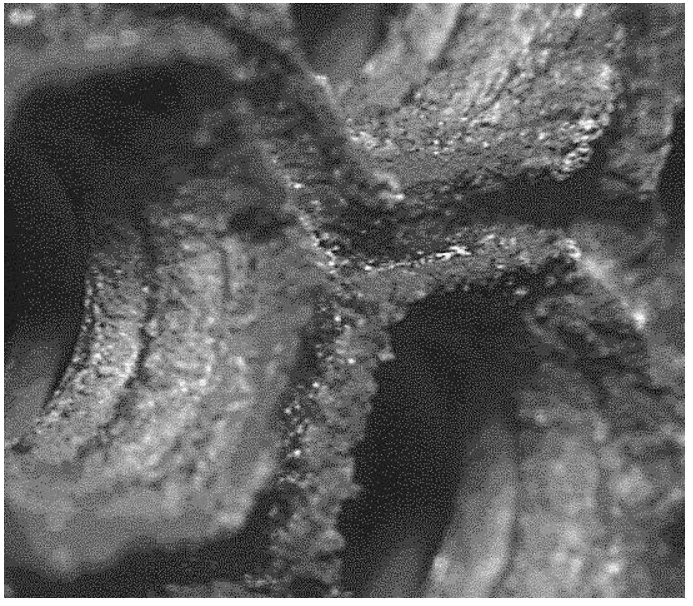
# NEXT LDT Thruster – Performance Summary

- NEXT LDT setting records for an electric propulsion thruster demo
  - Most accumulated hours of operation
  - Highest total impulse
  - Highest total propellant throughput
- ***NEXT LDT surpassed the qualification throughput (450 kg) in CY09***
  - One of the main objectives of the LDT accomplished
  - Objective redefined to test to failure (estimated ≥800 kg throughput)
- Negligible change in thruster performance parameters
  - Thrust, specific impulse, and thrust efficiency constant
  - Increase in discharge losses (10W/A at full-power) consistent with prediction
  - Slight increase in thruster input power (30 W maximum)
- Ion optics behavior unchanged – NSTAR first failure mode mitigated
  - Negligible change in electron backstreaming and perveance margins
- Loss of neutralizer flow margin has been addressed
  - NEXT PM thruster neutralizer design change to increase margin at low $J_b$
  - NEXT throttle table updated to ensure adequate margin over thruster lifetime

# NEXT LDT Thruster – Erosion Summary

- Discharge keeper erosion alleviated by graphite keeper
- NSTAR First-Failure mode (electron backstreaming) mitigated by NEXT
  - Improved beam flatness and constant cold grid-gap
- NEXT First-Failure mode progressing at model-predicted rates
  - NEXT predicted first failure mode is accelerator grid structural failure following groove penetration resulting from charge-exchange ion impingement
  - Service life assessment groove progression model validated
  - Indicates NEXT minimum thruster service life >750 kg throughput
    - Full-power has highest groove wear rate with time
    - Consistent with pretest service life assessment, i.e. 700 - 800 kg
- Plan to continue full-power operation until end of test
  - Predict groove penetration after 45 kh (≥800 kg)
    - Given testing duty cycle, groove penetration predicted in January 2013

# Thruster Failure Update



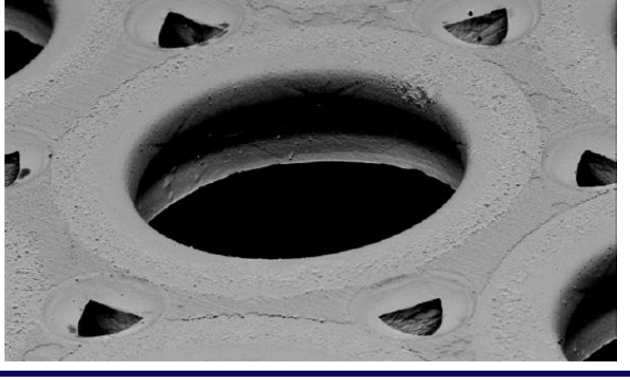
- Uncertainty in determining the depth of pits by direct measurement
  - Images appear to show centerline grooves have nearly constant depth along length so the pits are at least as deep as the grooves
  - When last measurements attempted, pit depths were ~85% of the groove depth

- Erosion through of both the pits and grooves will result in structural failure of the accelerator grid
- Predict groove penetration for LDT profile after 45 kh (≥800 kg)
  - If pits are same depth as groove, structural failure after ≥800 kg
  - If pit depth is 85% of the groove depth then the grid might not structurally fail until after 52 kh (≥940 kg)
- **NEXT LDT test article failure prediction: 48.5 ± 3.5 kh of operation (870 ± 70 kg of xenon propellant throughput)**

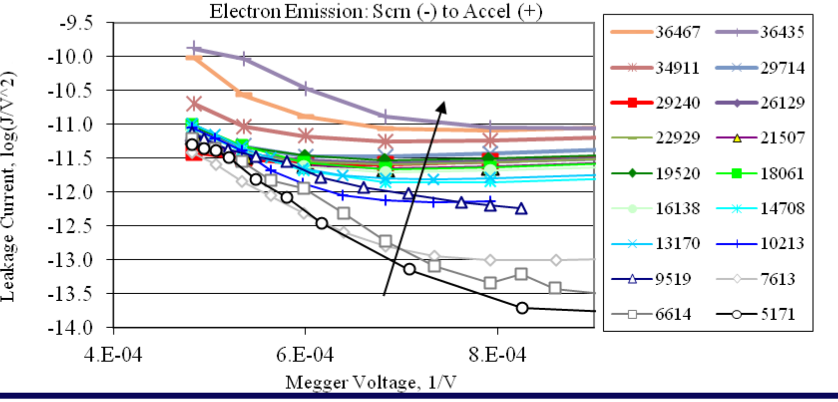
# NEXT LDT Thruster Failure Behavior Data

- Increasing frequency of data collection that might capture the penetration of pits and/or grooves and subsequent changes in thruster telemetry and performance prior to failure
  - Increase frequency of backlight center radius aperture images (every 350 hours of operation) to directly measure pit and/or groove penetration
  - Obtain full-power electron backstreaming and perveance measurements every 350 hours to try to capture changes in the operating ion optics' grid-gap as the accelerator grid structural integrity is compromised
  - Obtain Fowler-Nordheim electron emission characteristics for both grids every 750 hours in order to try to capture potential increased intra-grid deposition resulting from pit and/or groove penetration and subsequent undercutting resulting in deposits between the grids

**NSTAR ELT Pit Undercutting**



Fowler-Nordheim Characteristic



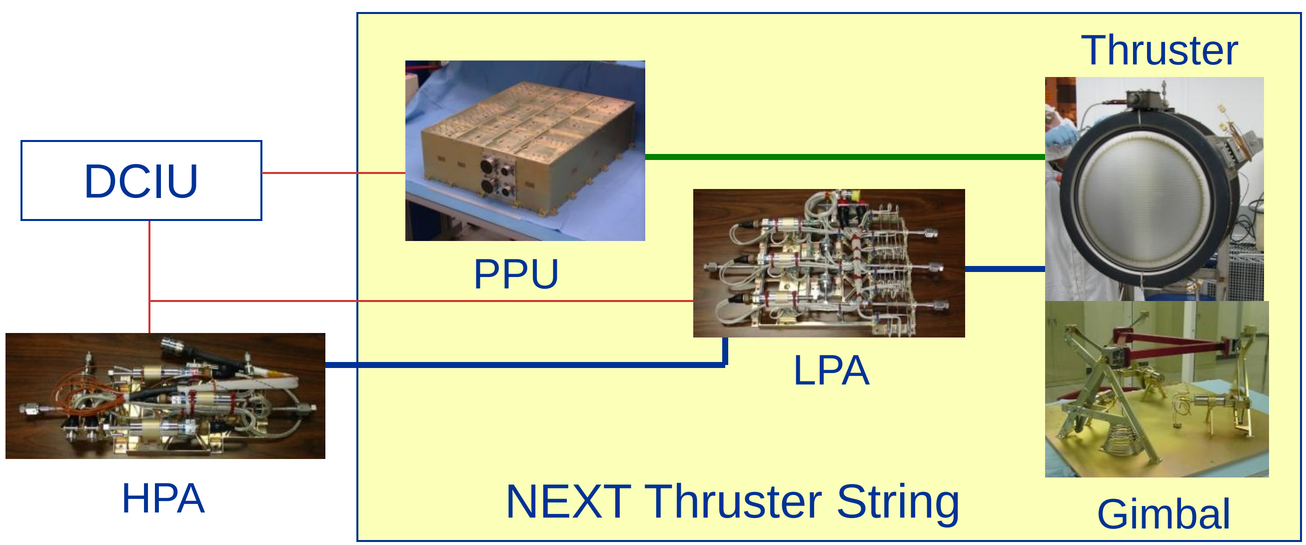
# Questions?

# NEXT – Performance Benefits vs. NSTAR

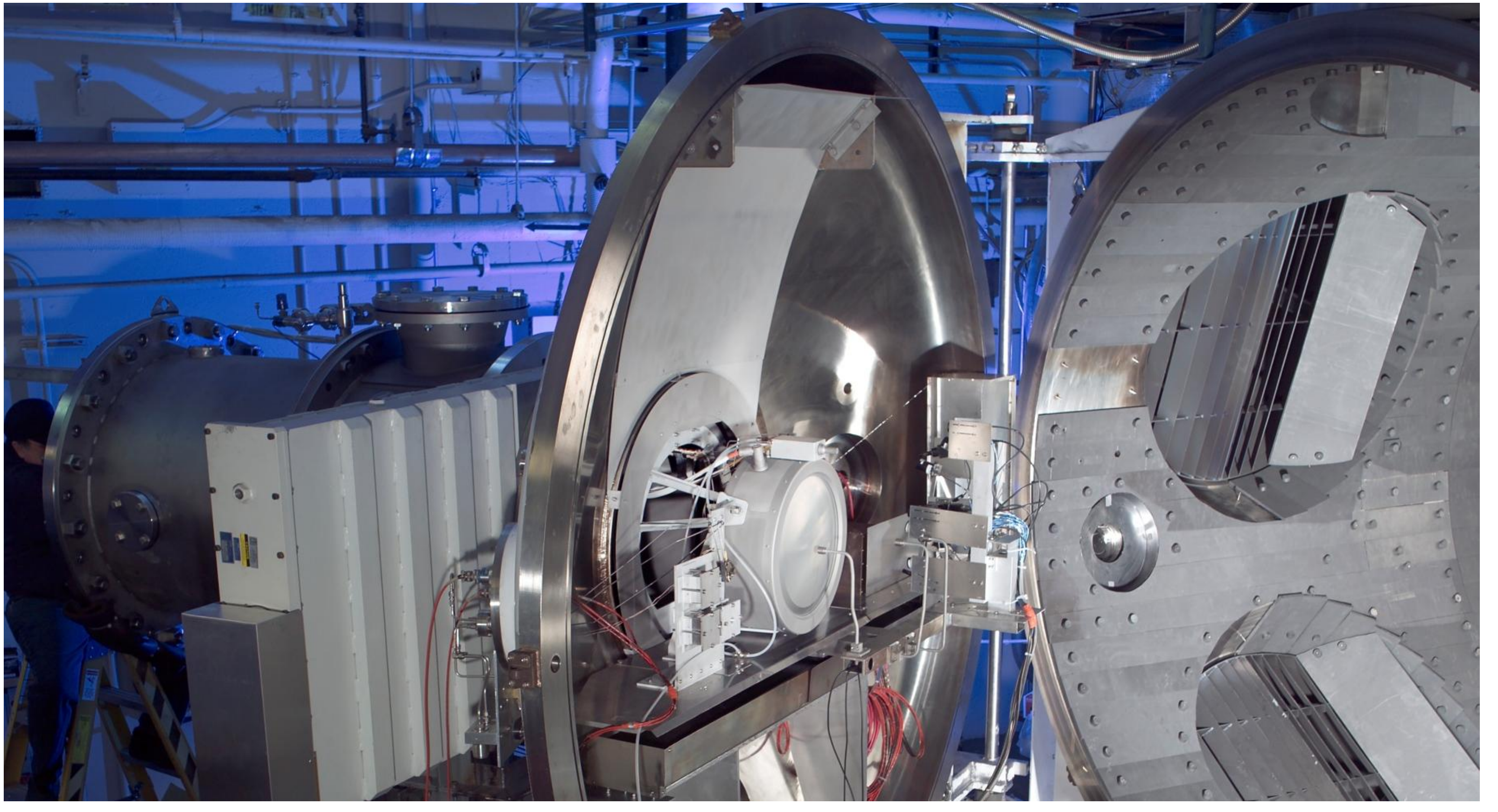
- Thruster rated xenon throughput
  - >500 kg (analysis-based) vs. 150 kg for NSTAR state-of-art
  - Accomplish low power, high $\Delta V$ missions (Dawn-like) with fewer thrusters
- Power/thrust capability
  - 6.9 kW vs. 2.3 kW maximum power to the thruster
  - 236 mN vs. 91 mN maximum thrust
  - Accomplish power-driven missions (Outer-planet) with fewer thrusters
- Thruster specific impulse
  - 4170 s vs. 3120 s
  - Reduces spacecraft propellant mass, providing more payload
- System throttle range
  - 11.9-to-1 PPU input power range vs. 4.9-to-1
  - Allows single thruster string use over a broad range of solar distances

# The NEXT System

- NEXT Ion Propulsion System Integration Test Completed with highest fidelity hardware developed
  - Prototype-model ion thruster
  - Flight-like propellant management system configured to operate up to three thrusters simultaneously
  - Thermally-compliant engineering-model power processing unit
  - Digital control and interface unit software to command and record telemetry from all NEXT ion propulsion subsystem elements



# Test Support Hardware – Vacuum Facility



- VF-16 at NASA GRC (2.7 m diameter x 8 m long)
  - 10 cryogenic pumps provide ≥ 180,000 L/s xenon pumping speed
  - Full-power operating pressures of $2.5 \times 10^{-6}$ Torr
  - All surfaces downstream of thruster lined with 1.2 cm graphite paneling
  - NEXT LDT began June 5, 2005

# Throttle Points of Interest for Life Assessment

- 3.52 A, 1800 V
  - First Failure Mode: Groove Wear Through (36 kh estimated)
  - Worst Case Pit and Groove Total Hours
  - Worst Case Pit and Groove Throughput
    - For all conditions with $P_{Input}$>0.5 kW
- 3.52 A, 1179 V
  - First Failure Mode: Groove Wear Through (42 kh estimated)
  - Worst Case Center Hole Barrel Erosion
    - Uncertainty in estimating electron backstreaming margin reduction
  - Highest Ratio of DCA Emission Current to discharge cathode flow rate
    - May have contributed to anomalous DCA erosion during NSTAR ELT
- 1.20 A, 1800 V
  - First Failure Mode: Groove Wear Through (200 kh estimated)
  - Worst Case Outer Aperture Erosion
- 1.00 A, 275 V
  - First Failure Mode: Groove Wear Through (45 kh estimated)
  - Worst Case Pit and Groove Throughput

# Throttle Table Points of Interest

Highest Groove Erosion (Input Power > 0.5 kW)

Highest CRA Barrel Erosion
Highest Ratio $J_e/m_c$

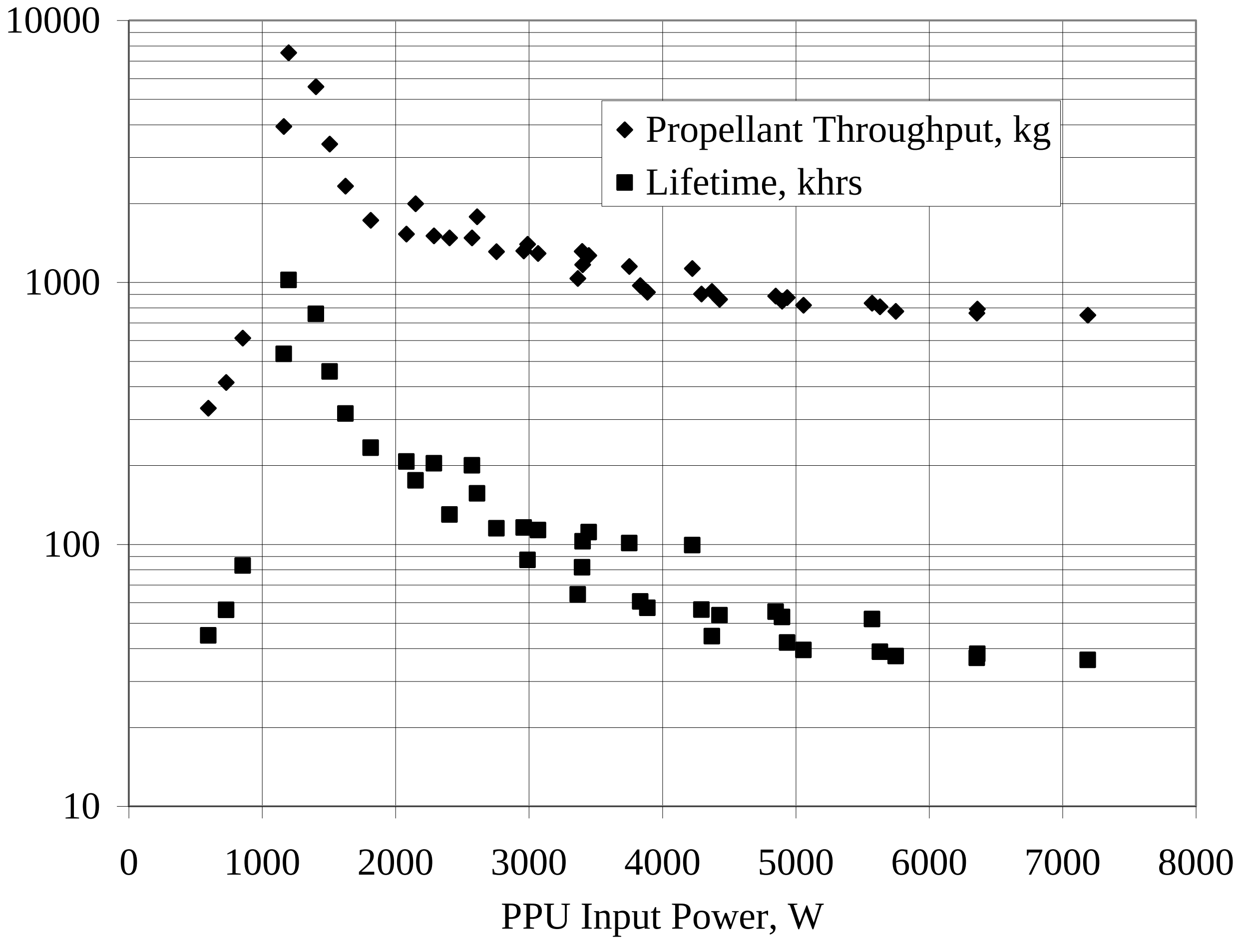
| Beam Current \ Beam Voltage | 1800 | 1567 | 1396 | 1179 | 1021 | 936 | 850 | 679 | 650 | 400 | 300 | 275 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.52 | 36 kh | | | 42 kh | | | | | | | | |
| 3.1 | | | | | | | | | | | | |
| 2.7 | | | | | | | | | | | | |
| 2.35 | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | |
| 1.6 | | | | | | | | | | | | |
| 1.2 | 200 kh | | | | | | | | | | | |
| 1 | | | | | | | | | | | | 45 kh |

Highest ORA "Ear" Erosion

Highest Groove Erosion (based on throughput)

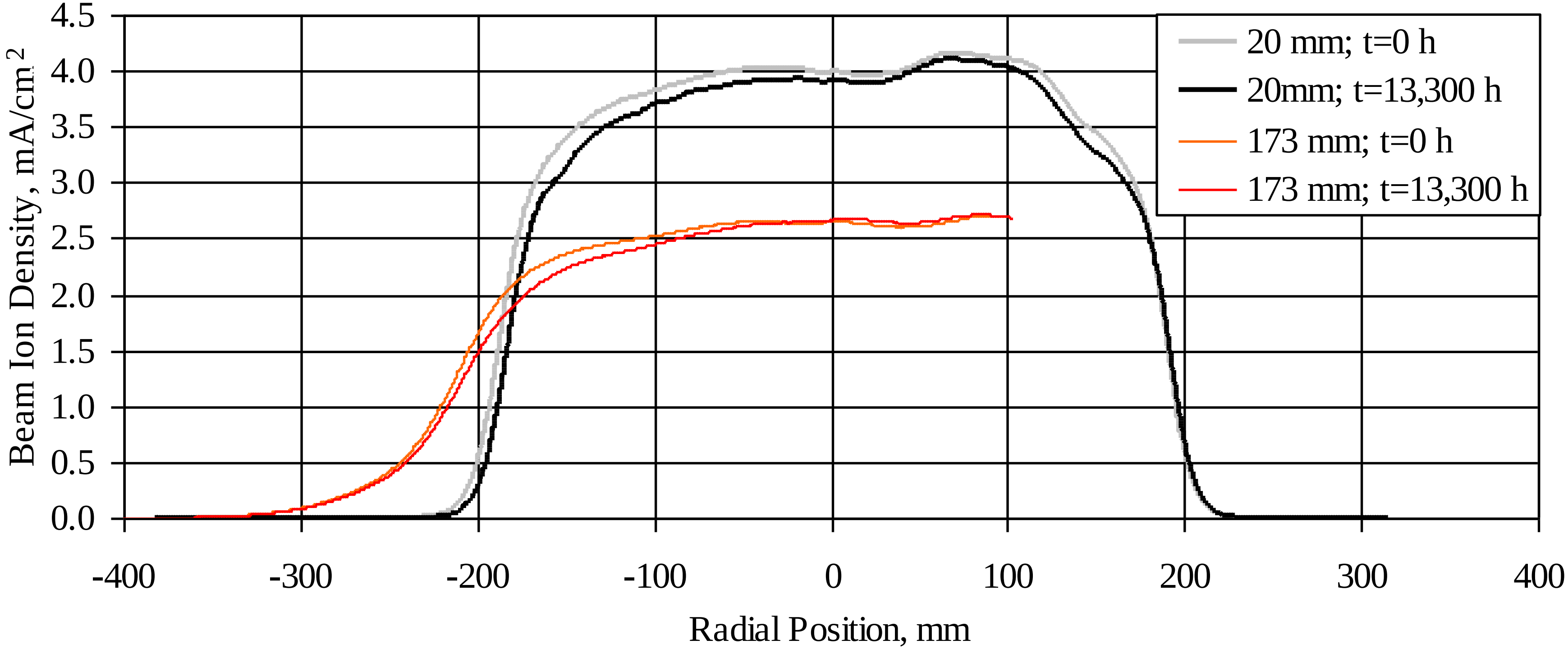
- For all operating conditions groove wear through is expected to be the first failure mode (>36,000 h of operation expected)
  - Should operate at other conditions of interest to:
    - Reduce risk of alternate wear mechanisms causing degradation and possible failure
    - Improve service life and thruster performance modeling capability

# Structural Failure from Pit and Groove Erosion




- Primary failure mode predicted over the throttling range to be structural failure of the accelerator grid from groove penetration

# Thruster Beam Profiles




| Comparison of beginning of test with 8,000-hr: | 0 h | 8000 h | 13000 h |
|---|---|---|---|
| • Integrated beam current: | 4.015A | 3.878 A | 3. 719 A |
| • Error in measured current vs. measured: | 14% | 10% | 6% |
| • Peak beam current: | 4.16 mA | 4.17 mA | 4.12 mA |
| • Beam flatness: | 0.831 | 0.831 | 0.841 |
| • Divergence: | 24.54 | 25.34 | 25.67 |
| • Ft: | 0.976 | 0.976 | 0.974 |