National Aeronautics and Space Administration

# End-of-test Performance and Wear Characterization of NASA's Evolutionary Xenon Thruster (NEXT) Long-Duration Test

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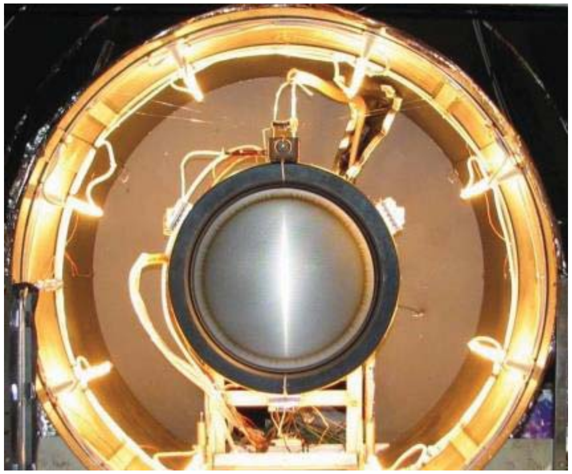
# Presentation Outline

- Overview and Status Update
- Diagnostics Repair Summary
- Ion Current Density Profiles
- Component Performance and Wear
    - Discharge Chamber/Cathode
    - Neutralizer Cathode
    - Ion Optics Assembly
- Characterization of Facility Effects
    - Measured Facility Backsputter Rates
    - Prediction of Accelerator Grid Current at Zero Pressure
- Summary

# NASA's Evolutionary Xenon Thruster

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



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 both testing and modeling analyses, comprised of:
  - NEXT 2,000 h EM thruster wear test
  - NEXT thruster service life model development
  - NEXT PM1R thruster and propellant management system wear test
  - NEXT LDT
- Goals of the NEXT LDT
  - Qualify the NEXT thruster propellant throughput capability to an initial value of 450 kg
  - Validate the thruster service life models
  - Characterize thruster performance over test duration
  - Measure critical thruster component erosion rates
  - Identify unknown life-limiting mechanisms
- Objective to demonstrate 450 kg throughput redefined after completion in December 2009 to test-to-failure of thruster or voluntary test termination

# NEXT LDT Throttling Profile

| Throttle Segment | Operating Condition ($J_B$, $V_B$) | Input Power, kW | Segment Duration, kh | End of Segment Date |
|---|---|---|---|---|
| 1 | 3.52 A, 1800 V | 6.9 | 13.0 | 11/17/2007 |
| 2 | 3.52 A, 1179 V | 4.7 | 6.5 | 12/23/2008 |
| 3 | 1.20 A, 679 V | 1.1 | 3.4 | 06/24/2009 |
| 4 | 1.00 A, 275 V | 0.5 | 3.2 | 12/15/2009 |
| 5 | 1.20 A, 1800 V | 2.4 | 3.1 | 05/05/2010 |
| 6 | 3.52 A, 1800 V | 6.9 | 21.9 | 02/28/2014 |

- Throttled the thruster in a mission-representative profile
- Extended operation at throttle table extremes
  - Characterized critical component erosion rates for model validation at worst-case operating conditions
- Since profile completion, thruster was operated at full power (6.9 kW)

# NEXT LDT Status Update

- Decision was made in April 2013 to voluntarily terminate the NEXT LDT
- A comprehensive post-test performance characterization was completed across the entire NEXT throttle table (40 conditions)
- The main facility was vented to atmosphere in order to repair diagnostics that had failed over the course of the test
  - Thruster was retracted into a separate port, isolated and kept under hard vacuum during repair process
- Using full suite of diagnostics, a comprehensive end-of-test performance characterization was completed across the entire NEXT throttle table
  - These data are the subject of this presentation
- Thruster was vented to atmosphere in April 2014 and post-test inspection is underway
- At the end of the test, the NEXT LDT:
  - accumulated 51,184 hour of high-voltage operation
  - processed 918 kg of xenon
  - delivered 35.5 MN-s of total impulse

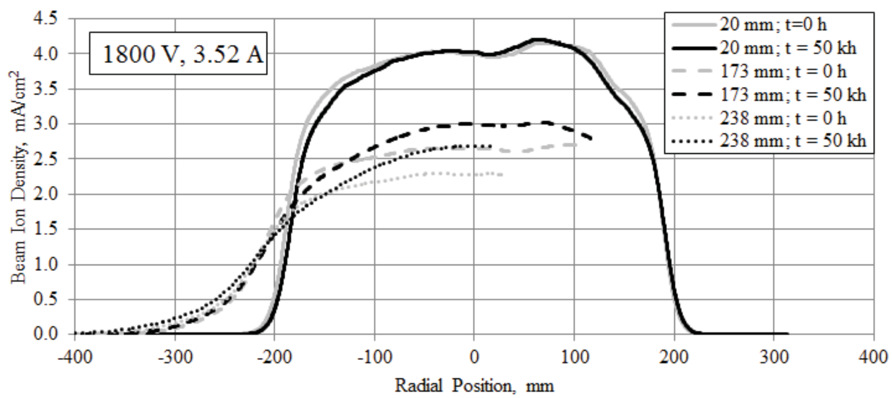
# Diagnostics Repair Summary

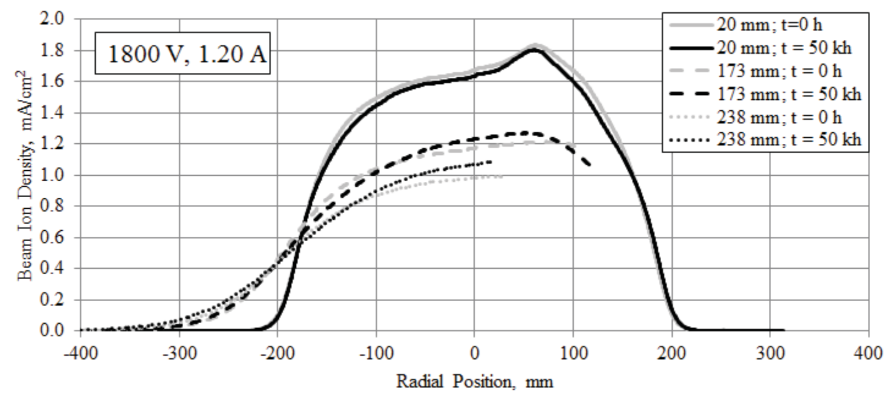
- Quartz crystal microbalance had failed after ~12.5 kh
  - Inspection revealed both crystals had shattered – crystals were replaced and QCM shutter was removed
- Staggered planar probes showed signs of shorting to ground, with permanent short observed at ~ 14 kh
  - Inspection revealed deposition on insulator between collector and guard ring, as well as coaxial cable short – cable was replaced and insulators cleaned

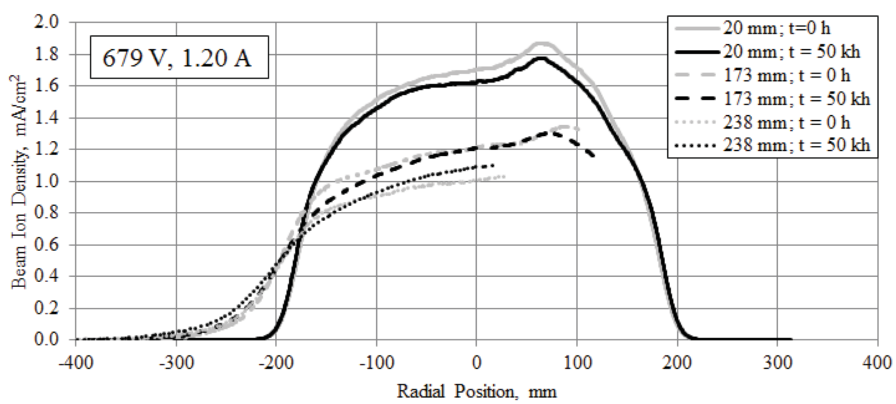
- Internal ionization gauge failed after ~ 6.5 kh
  - Inspection revealed probe clamp had failed, grounding probe grid – probe replaced with high-accuracy ionization gauge
- LED lighting for in-situ cameras degraded significantly between 30 – 40 kh
  - Inspection revealed damage to plastic diffusers – lights and/or diffusers were replaced
- Viewports on facility with backsputtered deposition were replaced
- An additional auxiliary flow line was placed at the chamber mid-length to facilitate pressure variation studies on thruster telemetry and performance

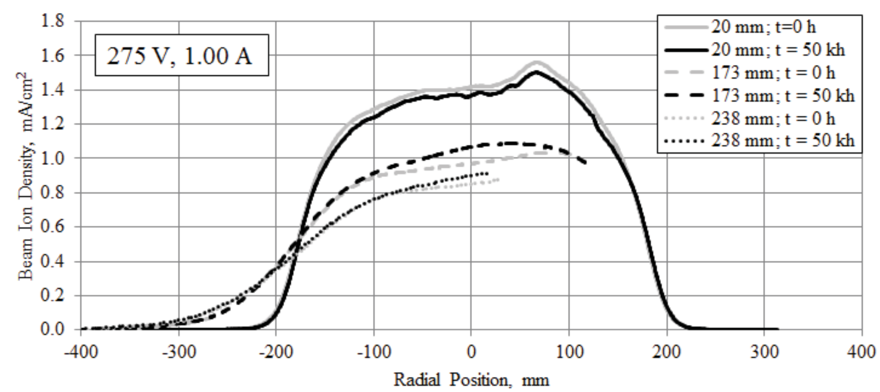
# Ion Current Density Profiles

- Comparison of pre-test and end-of-test profiles indicate only minor changes to profiles 20 mm downstream of optics
- More significant changes observed at 173 and 238 mm, the cause of which is still being investigated
- Calculated properties, such as divergence angle, showed little change between 13 and 50 kh



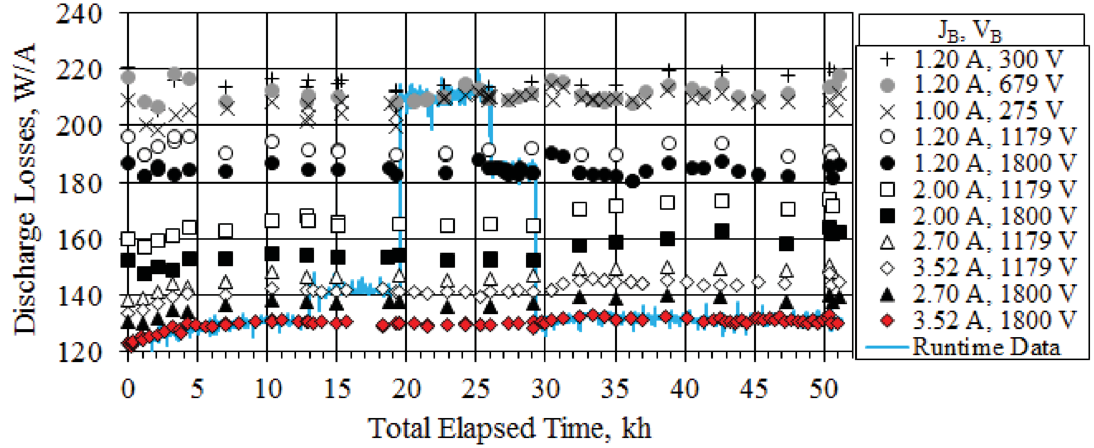



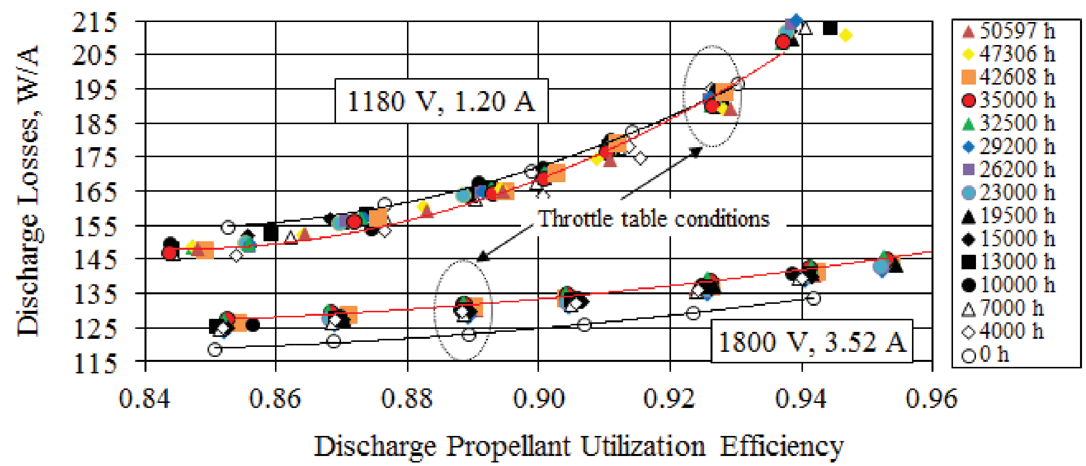



# Discharge Chamber Performance

- Modest increases in discharge losses (≤ 8% across throttle table), primarily occurring in the first 10 kh of operation
- Increase primarily attributed to observed accelerator grid aperture chamfering, causing a drop in neutral density within the discharge chamber
- Negligible changes in discharge performance due to diagnostic repair process
- Discharge characteristics shift up (within first 10 kh) with no shape change, corresponding to rise is discharge losses and no magnetic circuit degradation



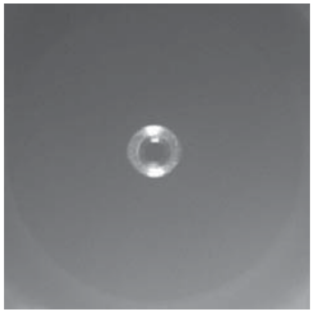



# Discharge Cathode Erosion

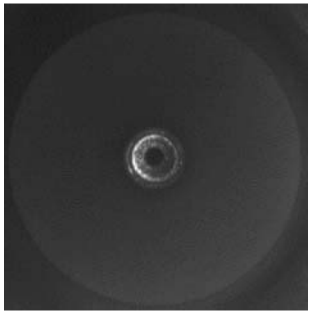
- In-situ camera images of NEXT discharge cathode assembly indicate minimal change (< 5%) in cathode orifice diameter
- Decreasing trend in keeper orifice diameter over last 10-15 kh found to be likely due to camera lighting degradation – repaired lighting confirms minimal change (< 5%)
- Change in cathode orifice chamfer diameter confirmed at ~20-25% increase over 51 kh
  - Post-test inspection is needed to confirm dimension and determine overall shape of chamfer
- Change to graphite keeper material has resulted in intact electrode even after 51 kh – excessive keeper erosion observed in NSTAR has been mitigated

NSTAR DCA @ 0 h

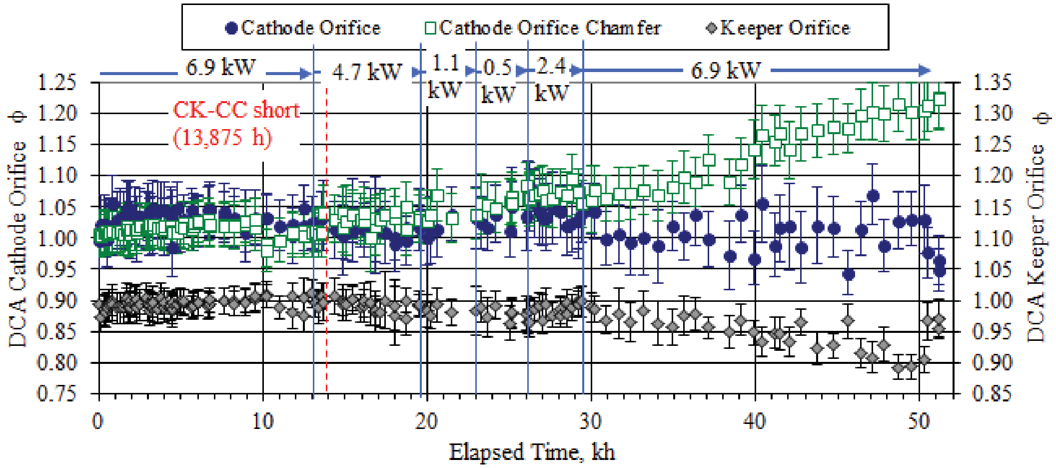
NSTAR DCA @ 30,352 h



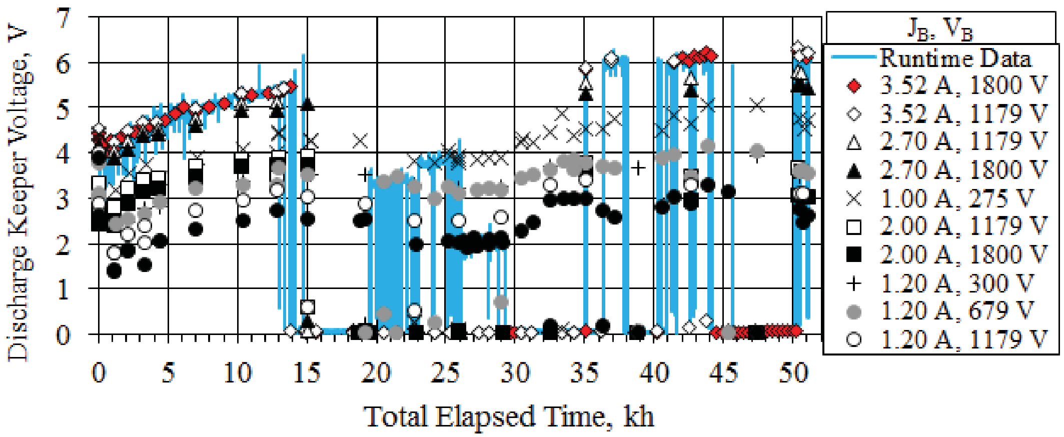
NEXT DCA @ 0 h

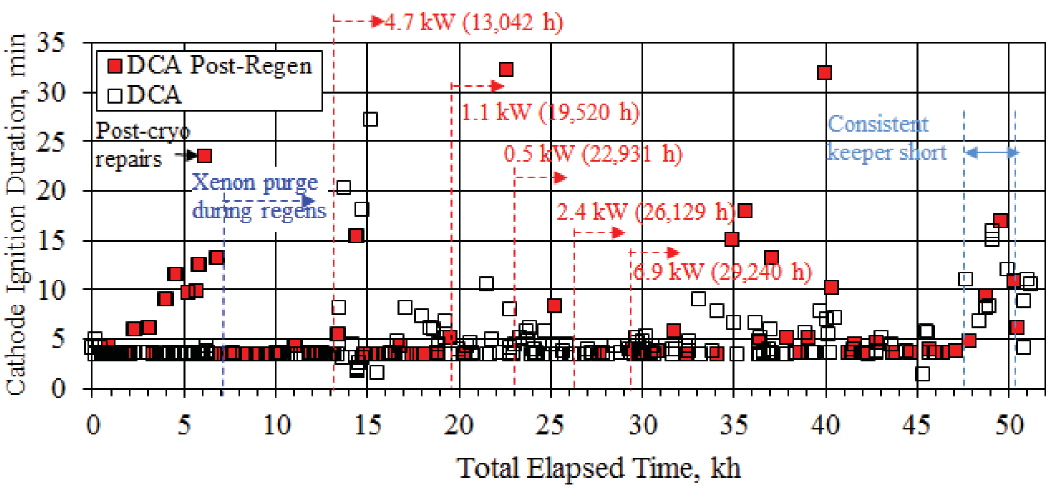


NEXT DCA @ 51,184 h



# Discharge Cathode Keeper Short

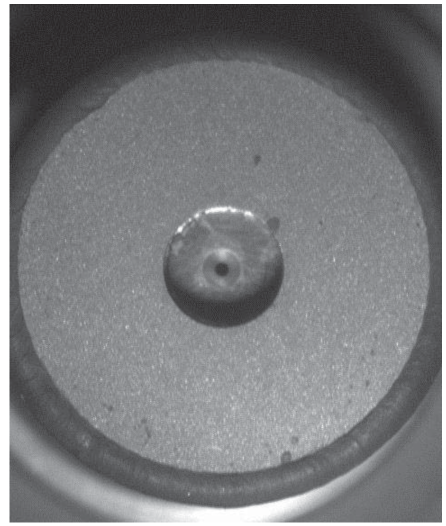


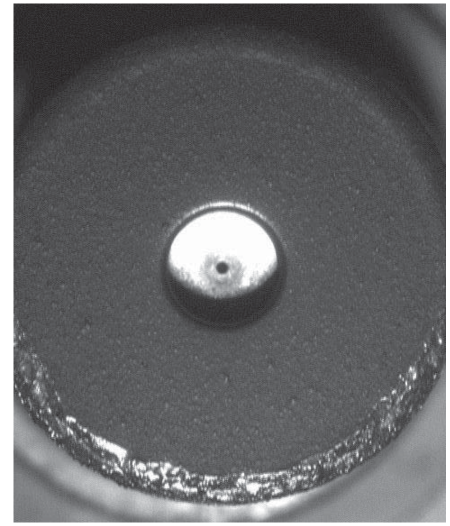

- Thermally-induced shorting has been observed between discharge cathode and keeper since ~ 14 kh
- Development of consistent short at ~ 48 kh, and its subsequent removal at ~ 50 kh, likely a result of anomalous pressure excursions (to ~ 300 mTorr) during facility regenerations
- This short has resulted in ignition times in excess of 10 minutes
- Determination of the root cause of this short is a critical task of the post-test inspection and analysis
- Methods to mitigate this issue and eliminate extended duration ignitions are actively being investigated

# Neutralizer Cathode Erosion

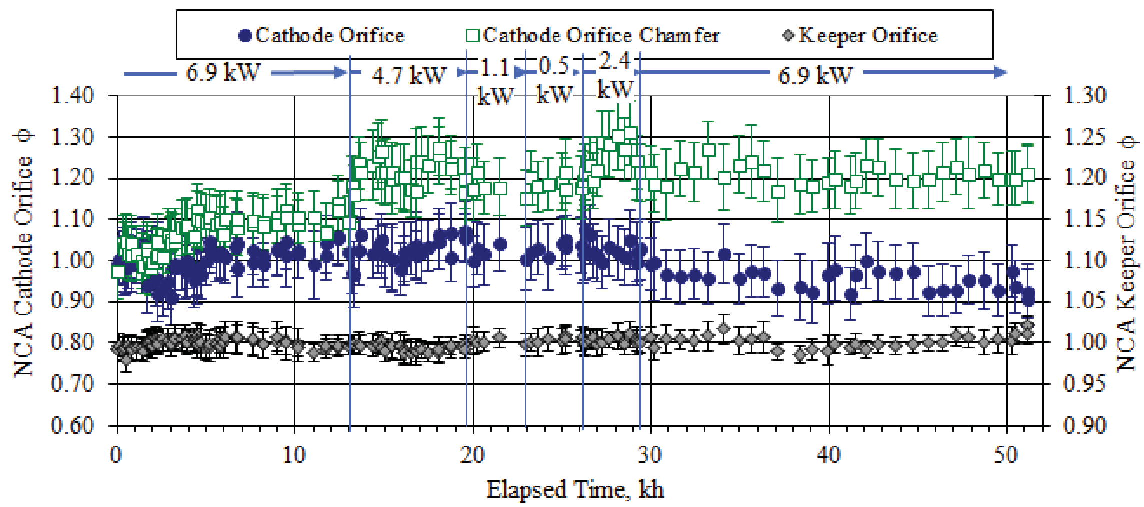
- Minimal cathode and keeper orifice diameter changes (<5%) over 51 kh of operation
- No observed clogging of neutralizer orifice despite 9.7 kh of operation at low power conditions
- Observed increase of 20% in cathode orifice chamfer
    - Dimension and overall shape needs to be measured in post-test analysis
- Performance degradation of neutralizer presently attributed to change in orifice geometry – needs to be measured in post-test inspection
    - In-situ camera can only measure minimum orifice diameter in profile



NEXT NCA @ 0 h

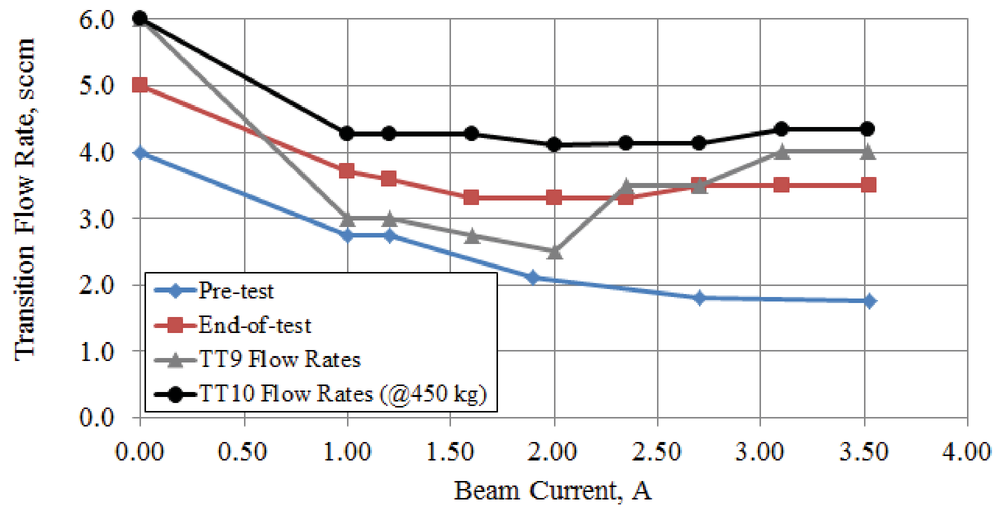


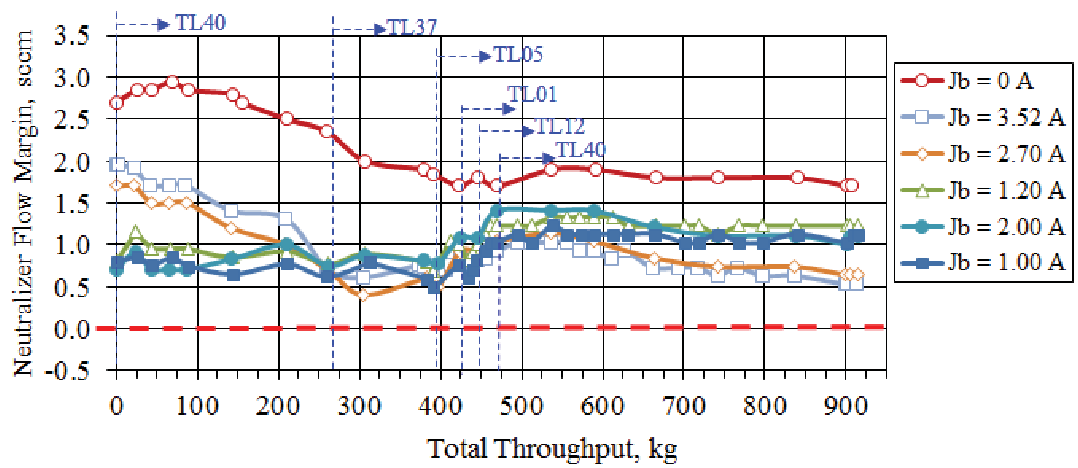
NEXT NCA @ 51,184 h



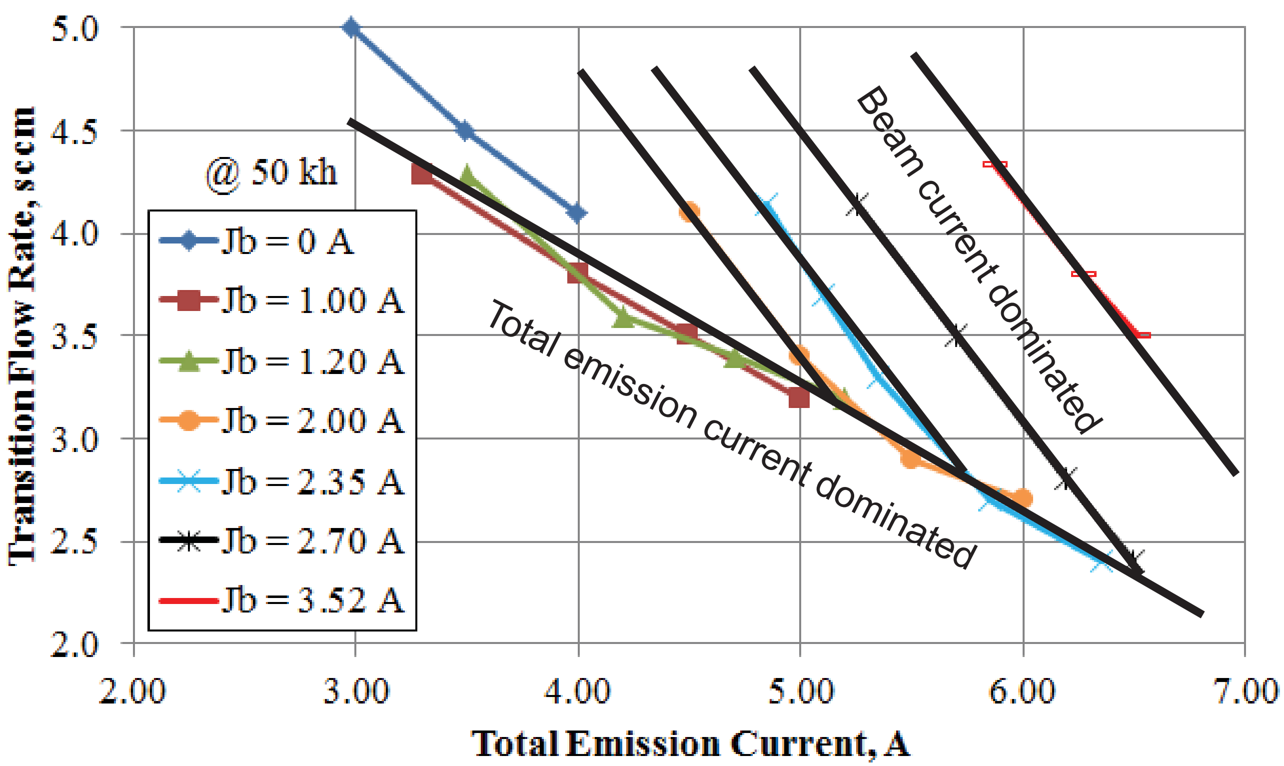
# Neutralizer Flow Margin from Plume Mode

- Loss of flow margin observed, primarily during operation at $J_B$ = 3.52 A during first 20 kh
- Inability to prevent transition to plume mode using TT9 flow rates, resulting in updated throttle table (TT10) which increases neutralizer flow rate with throughput to maintain flow margin
- TT10 maintains a minimum of 0.4 sccm margin over course of test across all beam currents
- Negligible changes in neutralizer performance after ~ 650 kg throughput
- Changes made to PM neutralizer in order to increase margin at lower beam currents where loss of margin was greatest
- TT10 results in loss of total efficiency due to increase in flow rate – what about modulating neutralizer keeper current?



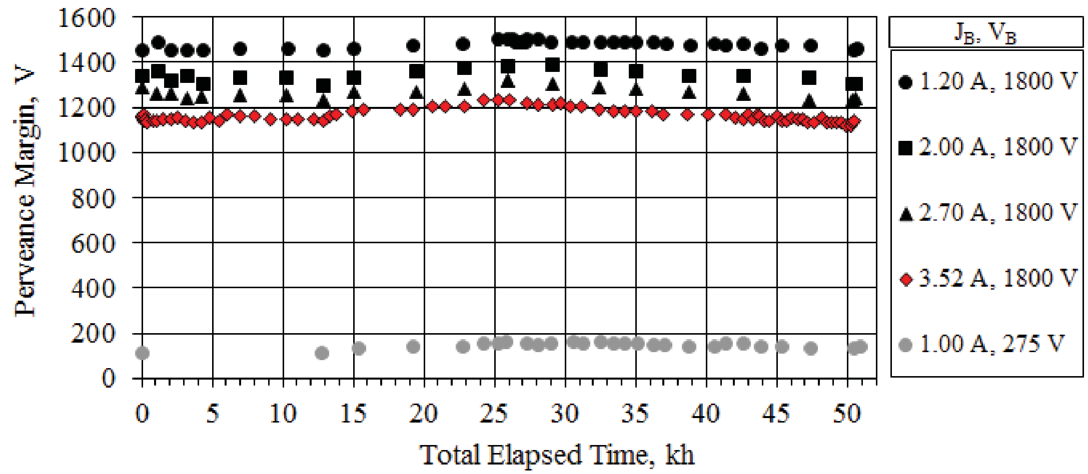
# Neutralizer Keeper Current Modulation

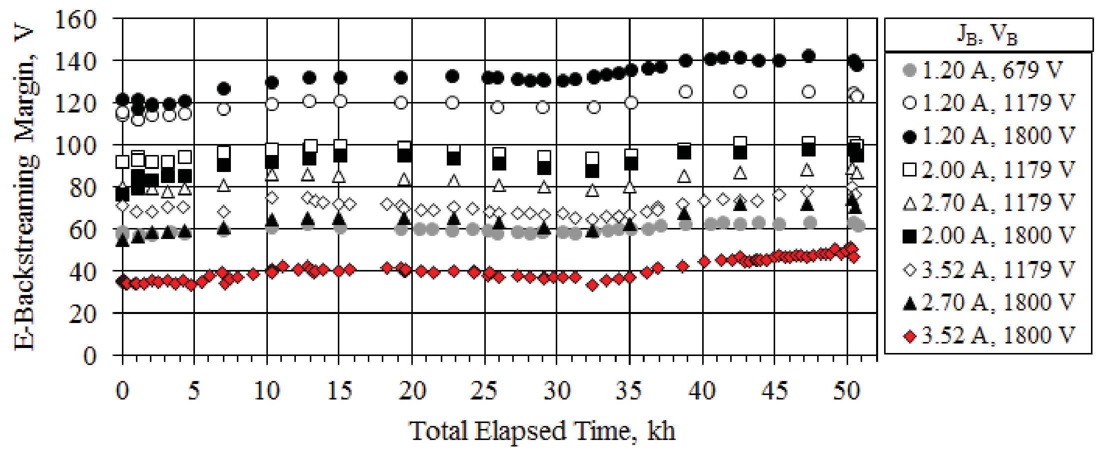



- Two distinct behaviors present
  - Total emission current dominated – for $J_B/(J_B + J_{NK}) \leq 0.4$
  - Beam current dominated – for $J_B/(J_B + J_{NK}) \geq 0.4$
- BOL flow rates cannot be used to maintain spot mode over lifetime without increasing $J_{NK}$ above 4.0 A

# Ion Optics Performance

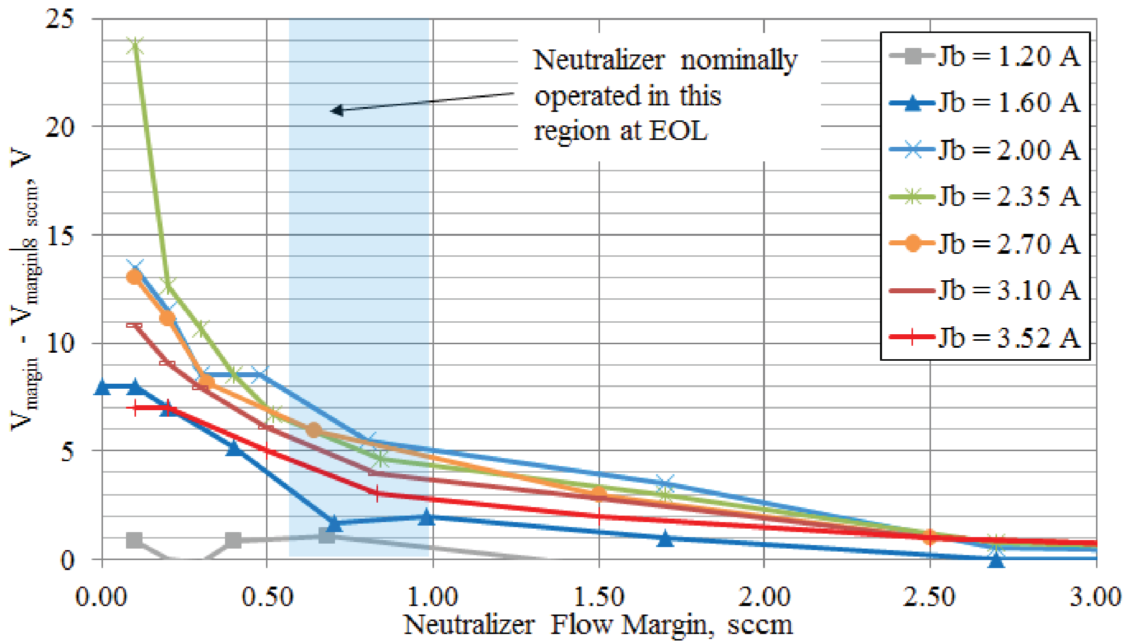
- No large changes in perveance margin or electron backstreaming margin over course of test
- Slight increase in perveance margin at beginning of test attributed to downstream chamfering of accelerator grid apertures, similar to NSTAR ELT
  - Decrease observed after 29.2 kh due to backsputtered carbon partially filling in eroded sites
- Slight increases in electron backstreaming margin observed during extended operation at full power (6-13 V)
  - Could be due to increase in accelerator grid thickness due to backsputtered carbon as well as slight deposits within accelerator aperture barrels
  - Changes to near-field plasma properties due to varying neutralizer flow margin could also be a factor



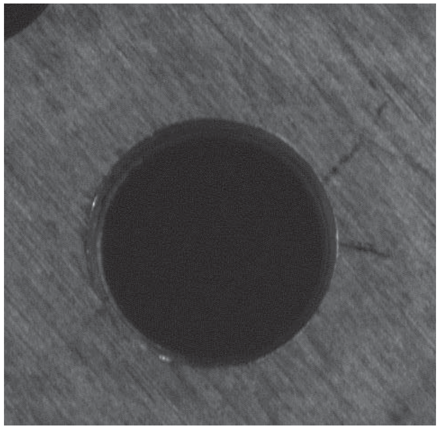
# Effect of Neutralizer Flow Margin on EB Margin

- Inspection of NEXT LDT data indicates a correlation between neutralizer flow margin and electron backstreaming margin
- Electron backstreaming margin measurements taken as a function of neutralizer flow margin indicate large increases in EB margin as plume mode is approached
- Variation in flow margin during extended operation at full power indicates that this effect may only contribute ~ 3 V change in EB margin, and thus can only partially explain observed changes
- Regardless of cause, changes in EB margin are minor and not expected to change significantly in flight

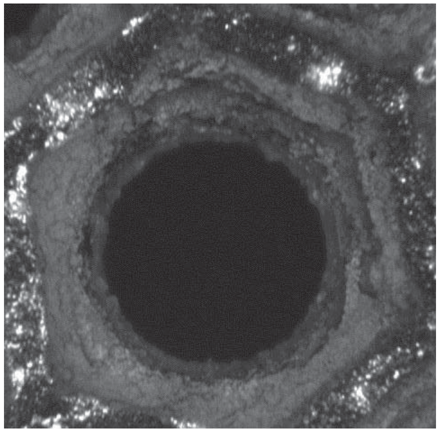


# Accelerator Grid Erosion – Center Radius Aperture

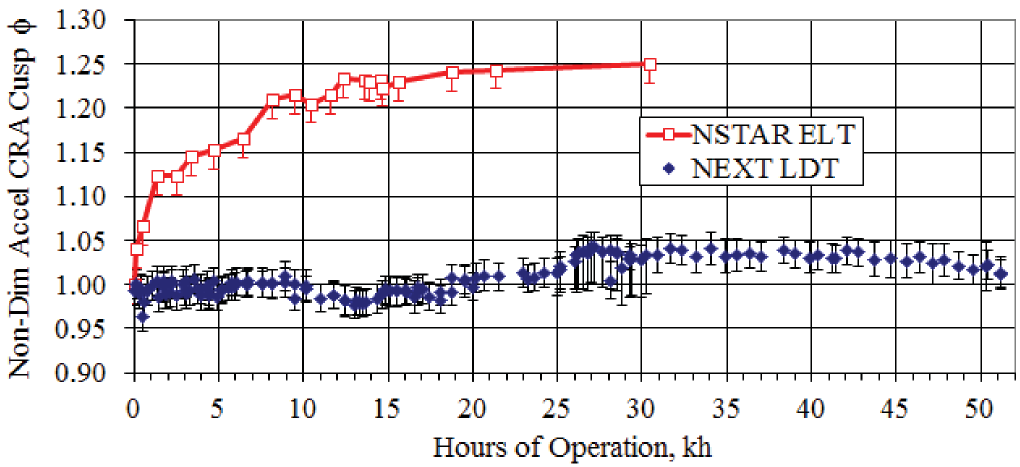
- Negligible change (< 5%) in CRA cusp diameter over course of test
  - Partially responsible for no observed decrease in electron backstreaming margin
- Enlargement of accelerator apertures led to inability to prevent electron backstreaming at full power during NSTAR ELT (first failure mode of NSTAR)
- Downstream chamfering and pit-and-groove erosion also observed in final in-situ image of NEXT CRA



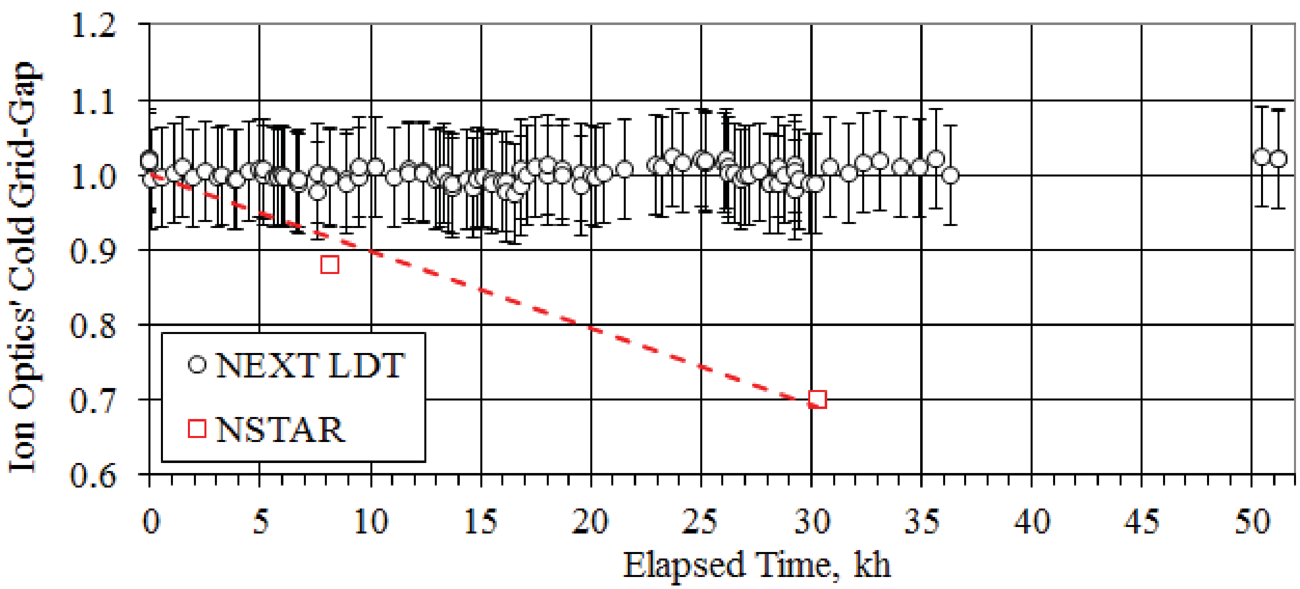
NEXT CRA @ 0 h



NEXT CRA @ 51,184 h



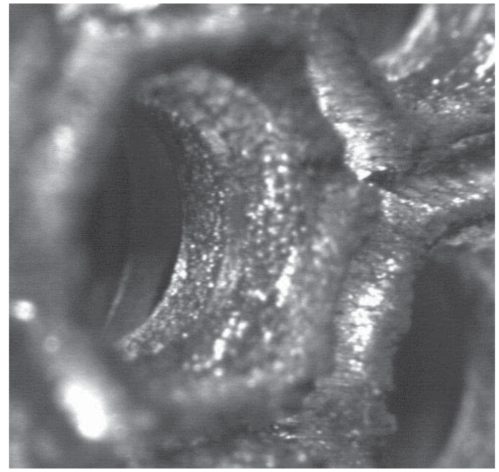
# Ion Optics Cold Grid Gap



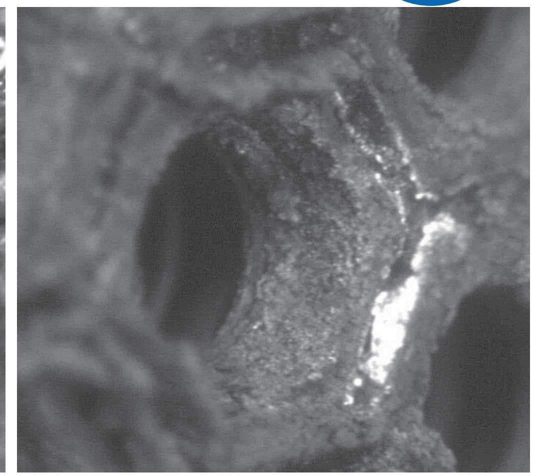

- Decrease in ion optics cold grip gap partially responsible for first failure mode of NSTAR
- Measured grid gap not available during 36-50 kh due to in-situ lighting degradation
  - Diagnostic repair allowed confirmation that cold grid gap has not changed over course of test
- Lack of change in grid gap and aperture cusp diameter has mitigated first failure mode observed during NSTAR ELT
- Presently first failure mode is expected to be penetration of pit-and-groove pattern through accelerator grid, causing loss of structural integrity of optics

# Status Update on Pit-and-Groove Erosion

- Groove depth measurements taken from 7.6 kh to 35.6 kh
  - Could not be obtained afterwards due to lighting degradation and groove shadowing
- Repair and augmentation of in-situ lighting allowed imaging of pit-and-groove pattern after 50 kh



NEXT @ 19,520 h



NEXT @ 50,453 h

- Pit and groove pattern is irregular around the aperture and varies from aperture to aperture
  - Three-dimensional, random nature of pattern indicates that cause cannot be modeled with simple modeling tools
- Presence of carbon deposits within pit-and-groove pattern, which was confirmed during initial inspection of the optics at atmosphere
- Detailed examination of thruster images indicate center of accelerator grid began to slowly change appearance ~ 36 kh – change could be caused by carbon deposits forming within pit-and-groove pattern
- Sectioning of grid and determination of final groove depth is critical to assessing first-failure mode and when carbon buildup began occurring

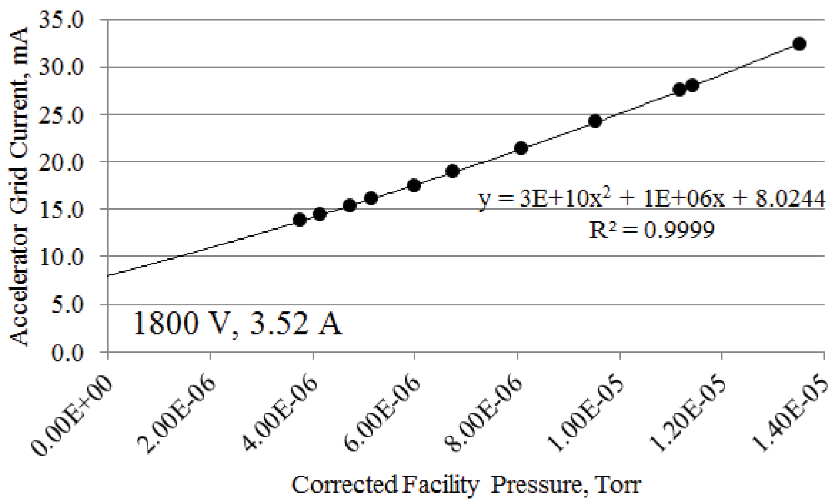
# Measured Facility Backsputter Rates

- Repaired QCM allowed for measurement of backsputter rates at end-of-test
- Measurements were taken for extended duration (> 12 hours) at 5 conditions in LDT throttling profile to obtain high-fidelity values
- Measurement at full power in excellent agreement with value obtained at the beginning of the test, indicating that the backsputter rate did not change significantly over the course of test
- Using measured backsputter rates, total film thickness is estimated to be ~ 109 µm

| Operating Condition ($J_B$, $V_B$) | Input Power, kW | Backsputter Rate, µm/khr |
|---|---|---|
| 3.52 A, 1800 V | 6.9 | 2.8 |
| 3.52 A, 1179 V | 4.7 | 1.2 |
| 1.20 A, 679 V | 1.1 | 0.2 |
| 1.00 A, 275 V | 0.5 | 0.1 |
| 1.20 A, 1800 V | 2.4 | 1.0 |

# Predicted Accelerator Grid Current at Zero Pressure

- Measuring telemetry at various facility background pressures allows extrapolation of values to zero-pressure, flight-like conditions
- Extrapolation was performed using linear and quadratic fit, and beam current was held constant by varying discharge current and main mass flow rate (all yielded similar results)
- Results indicate accelerator current is 35-75% higher during ground operation compared to zero-pressure conditions
- Modeling will need to be performed to determine impact on demonstrated lifetime on ground compared to flight




| Operating Condition ($J_B$, $V_B$) | $J_{A,facility}$, mA | $J_{A,0}$, mA | $J_{A,facility}/J_{A,0}$ |
|---|---|---|---|
| 3.52 A, 1800 V | 14.0 | 8.0 | 1.75 |
| 3.52 A, 1179 V | 14.6 | 8.9 | 1.64 |
| 1.20 A, 679 V | 2.4 | 1.6 | 1.50 |
| 1.00 A, 275 V | 2.3 | 1.7 | 1.35 |
| 1.20 A, 1800 V | 3.9 | 2.6 | 1.50 |

# Summary

- The NEXT LDT has successfully completed or exceeded all of its goals that were defined at the beginning of the test in 2005
- As part of the voluntary test termination process, a comprehensive end-of-test performance and wear characterization was made after repairing numerous diagnostics that had failed over the course of the test
- These results have confirmed many of the trends observed over the course of test, including:
  - Steady performance with minimal degradation
  - Mitigation of the first-failure mode of NSTAR through negligible aperture enlargement and change in ion optics grid gap
  - Mitigation of excessive keeper erosion
- The first failure mode of NEXT is expected to be loss of structural integrity of the ion optics due to penetration of the pit-and-groove pattern through the accelerator grid
  - Observation of carbon deposits within the pattern at 50 kh necessitates a final groove depth measurement in atmosphere to assess status of the first failure in ground testing
- NEXT LDT test article has been vented to atmosphere and post-test inspections are presently underway

NASA