Post-test Inspection of NASA's Evolutionary Xenon Thruster Long Duration Test Hardware: Ion Optics

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Introduction

- NEXT Long Duration Test (LDT) conducted as part of service life verification approach
- LDT thruster operated from June 2005 to February 2014, after which test was voluntarily terminated
  - 918 kg propellant throughput
  - 51,184 h operation
  - 35.5 MN·s
- LDT thruster vented to atmosphere April 2014 for inspection
  - Ion optics inspection nearly completed
  - Paper presents ion optics results to date

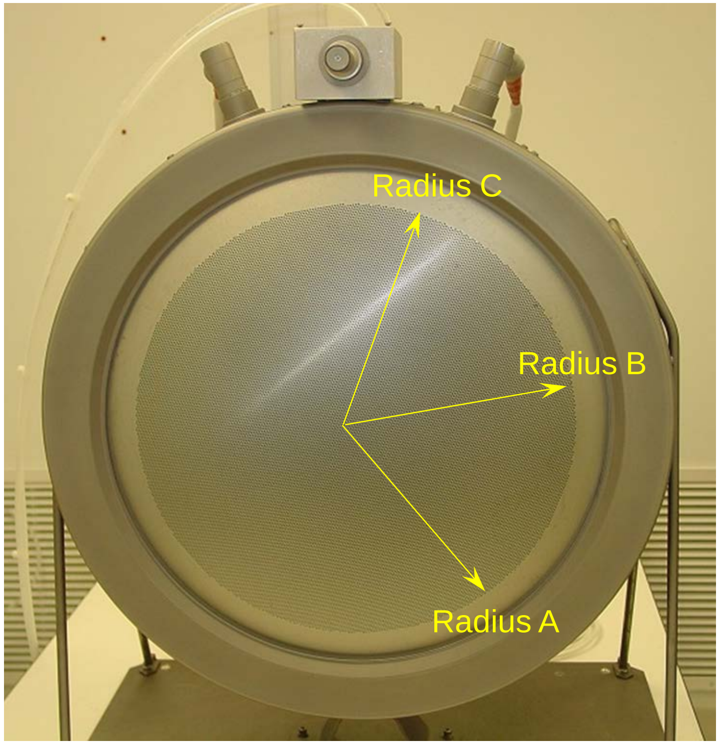
Operating Condition	Segment Duration, h	Post-Segment Duration, h
3.52 A, 1800 V	13,042	13,042
3.52 A, 1179 V	6,478	19,520
1.20 A, 679 V	3,411	22,931
1.00 A, 275 V	3,198	26,129
1.20 A, 1800 V	3,111	29,240
3.52 A, 1800 V	21,944	51,184

Optics Inspection Objectives & Plan

- Measure wear of & deposition on critical surfaces to verify & update service life models
  - Screen grid wear of upstream surface
  - Accelerator grid wear of downstream surface & aperture walls
  - Deposition on both grids (potential source for grid short)
- Verify in situ erosion measurements
  - Grid aperture diameters, center cold grid gap, groove depth
- Resolve thruster-related issues encountered during test
  - Impedance degradation, unanticipated performance trends, sources of rogue holes, and differences between models & observed erosion
- Verify design changes made prior to LDT had desired impacts
  - Grid masking, accelerator aperture diameter increase & control, compensation change
- Identify any unanticipated thruster life-limiting phenomena

Test Hardware

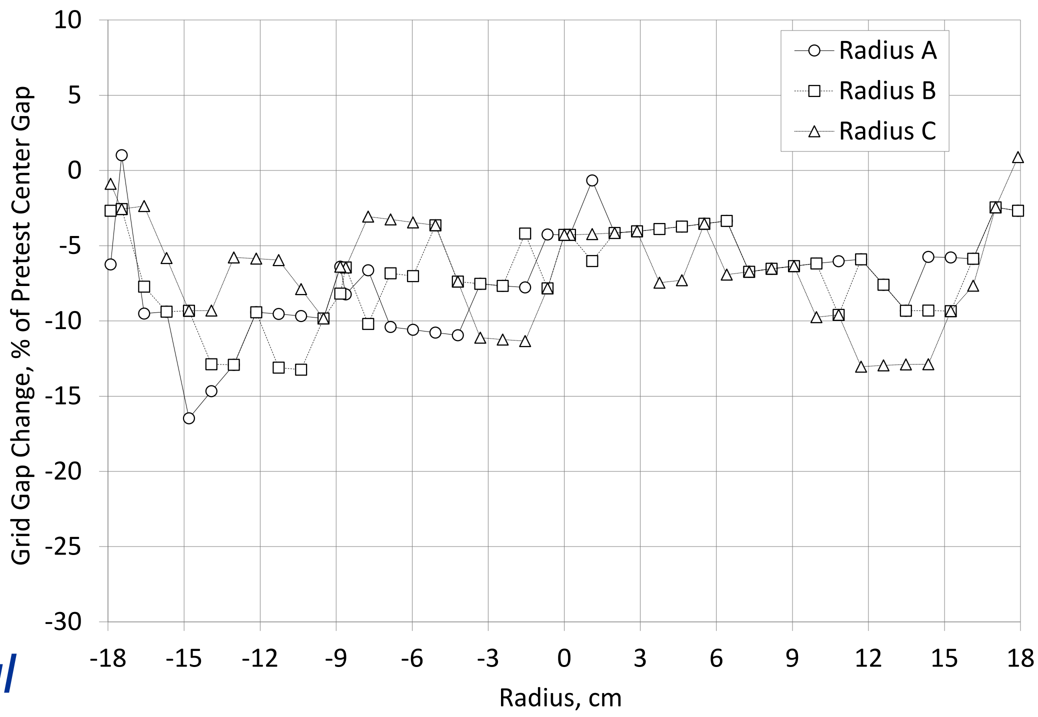
- EM3 thruster
  - Much of design & design approach evolved from NSTAR
  - Prototype model ion optics utilized
    - Manufactured by Aerojet
    - Two grid, convex electrodes
- PM optics design includes:
  - 36 cm beam extraction diameter for reduced outer aperture erosion
  - Improved manufacturing of electrodes for tighter aperture tolerances & reduced cusp profile
  - Improved mounting design that reduced stresses for gap stabilization
- Comparisons with NSTAR electrodes
  - NEXT screen grid aperture diameters, center-to-center hole spacing, & thickness are same
  - NEXT accelerator grid aperture diameters & thickness are 11% & 50% larger, respectively
  - NEXT cold grid gap 8% larger at center
  - NSTAR beam extraction diameter 28.4 cm



Cold Grid Gap

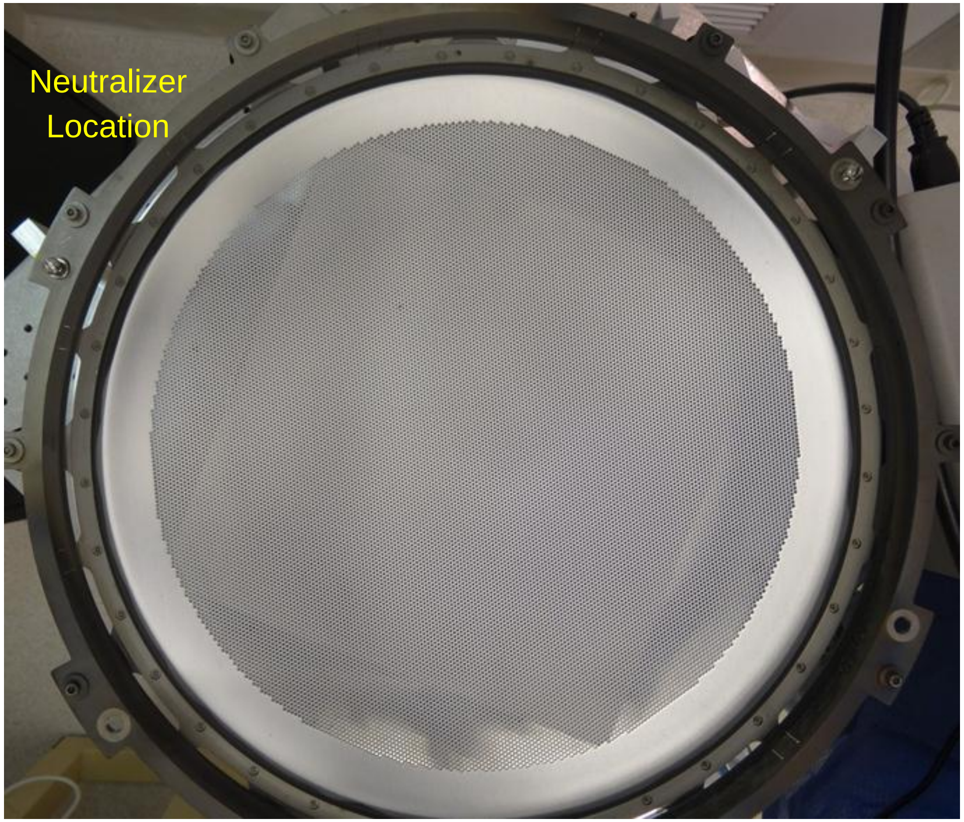
Cold Grid Gap

- Post-test cold grid gap
  - Measured with gages
  - Corrected for downstream screen surface deposition
- Change in cold grid gap (% pretest center gap):
  - Center = -4%
  - Average = -7%
  - NSTAR ELT = -30%
- *Efforts to stabilize NEXT cold grid gap were largely successful*
- In situ diagnostic (center cold grid gap) correlates with post-test measurement within uncertainties



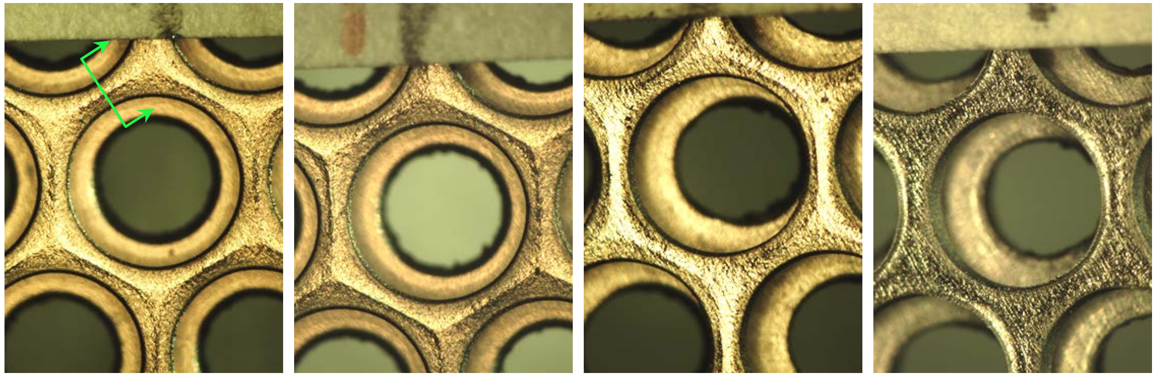
Screen Grid

Screen Grid Overall Condition

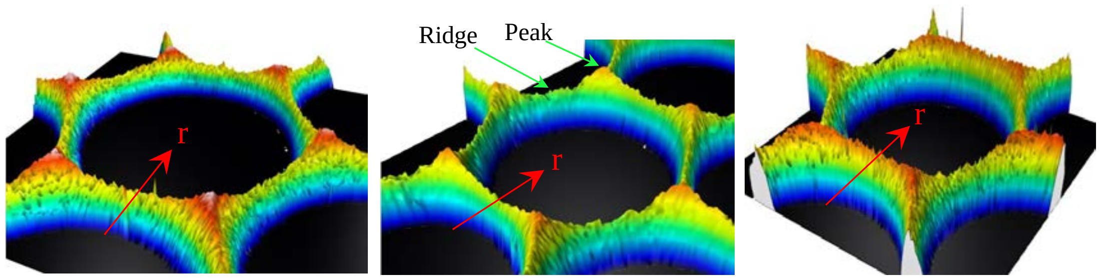


- Net erosion of upstream screen grid surface

Screen Grid Upstream Erosion



r = 0 cm   r = 2.0 cm   r = 9.1 cm   r = 15.2 cm



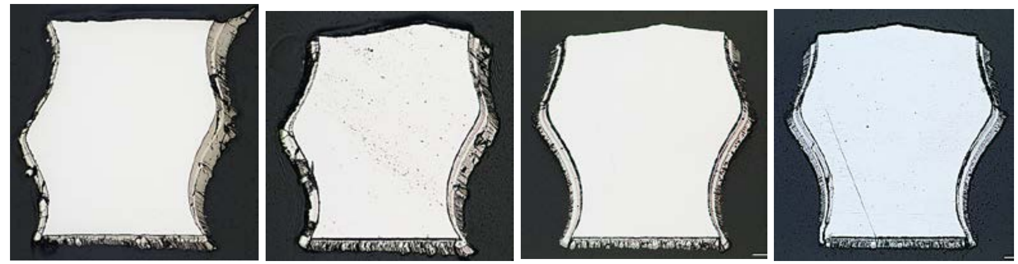
r = 2.2 cm   r = 4.0 cm   r = 6.9 cm

- Upstream grid exhibited chamfered erosion pattern
  - Pronounced near grid center, faded away with increasing radius
  - *Very similar to NSTAR ELT erosion pattern*

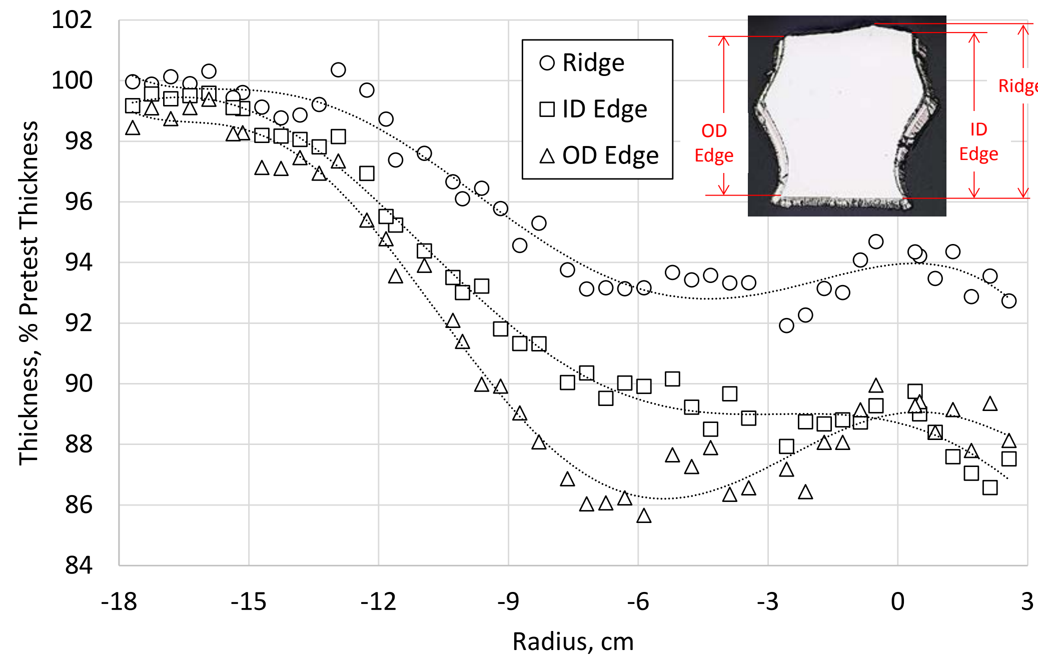
- Worst case screen webbing erosion was close to center of a ridge for screen grid service life assessment

Screen Grid Thickness

- Webbing cross-sectioned
  - Radius B selected because along probe path & highest j_b
  - Photomicrographs show eroded pattern & deposition
- Minimum screen grid thickness was 86% of pretest (off-center)
- *Screen grid has substantial service life remaining*

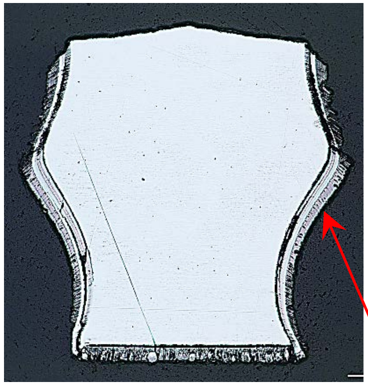


r = -15.9 cm   r = -9.2 cm   r = -2.1 cm   r = 0.4 cm

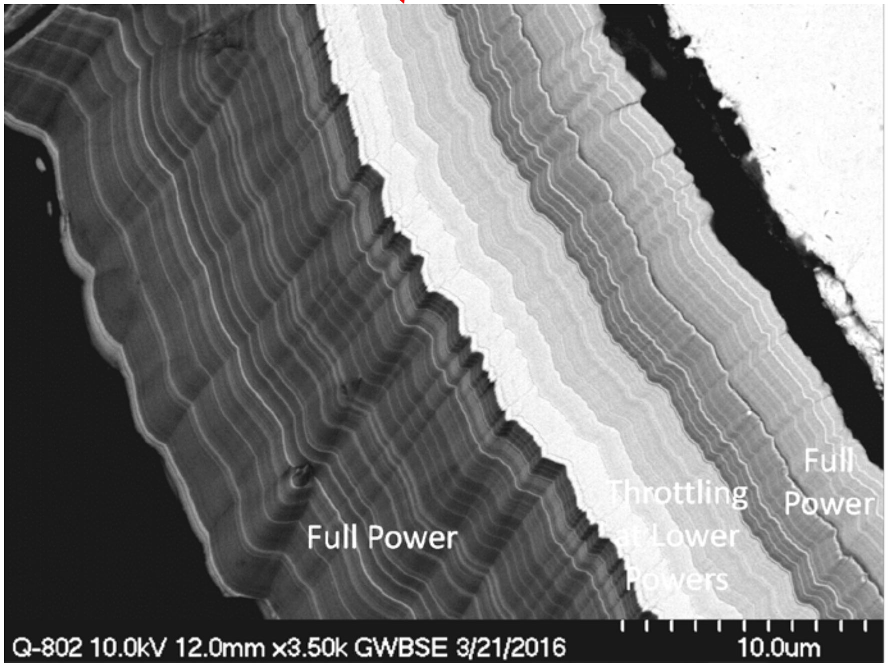


Screen Grid Deposition

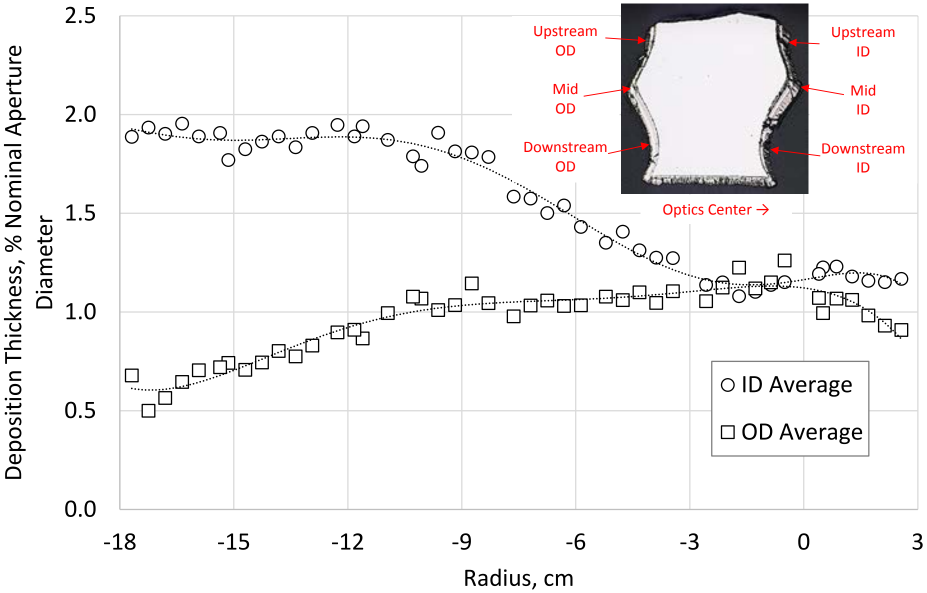
- Deposition on aperture walls & downstream surface
- Deposition composed of grid material & C with trace O & trapped Xe
  - Grid material from accelerator aperture erosion
  - C likely back-sputtered
- Backscattered electron image shows:
  - Broad discolored bands, likely from operation at different throttled levels
  - Whitish lines, likely from perveance measurements

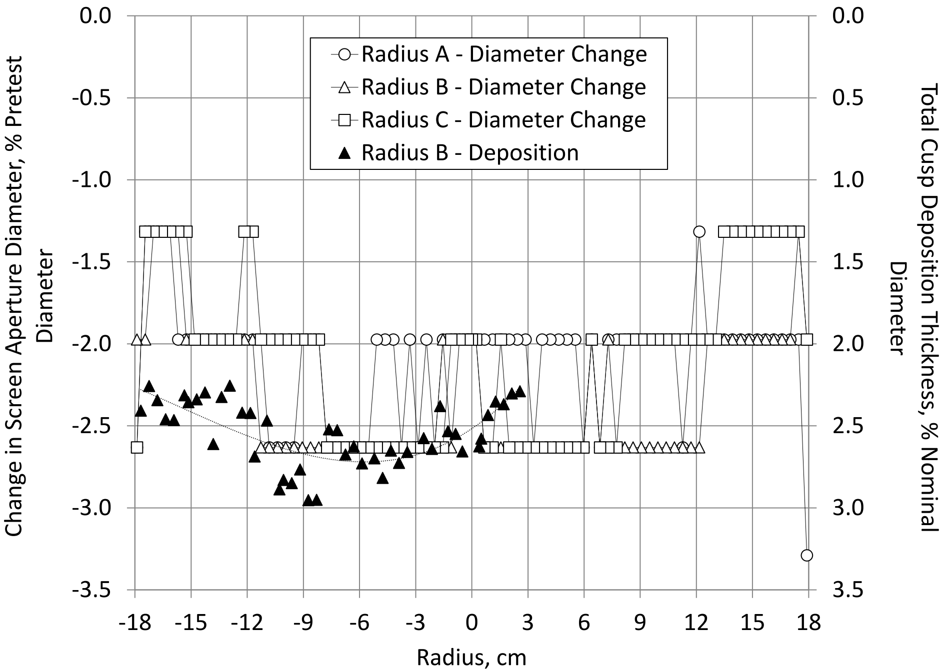


r = 0.4 cm



Screen Grid Aperture Wall Deposition

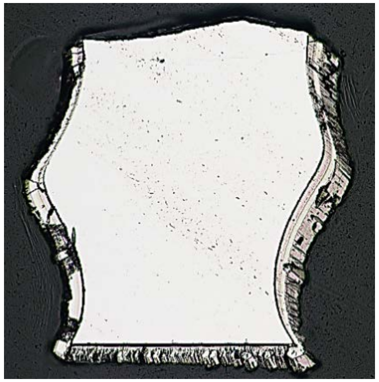




- Aperture wall deposition was thicker on webbing surface closest to grid center at large radii, which increased with radius
  - Due to non-uniform accelerator wall erosion
- Deposition led to average 2.2% decrease in screen aperture diameters
  - Reduces open area by 4.4% & *likely contributed to reduced screen grid ion transparencies during test*

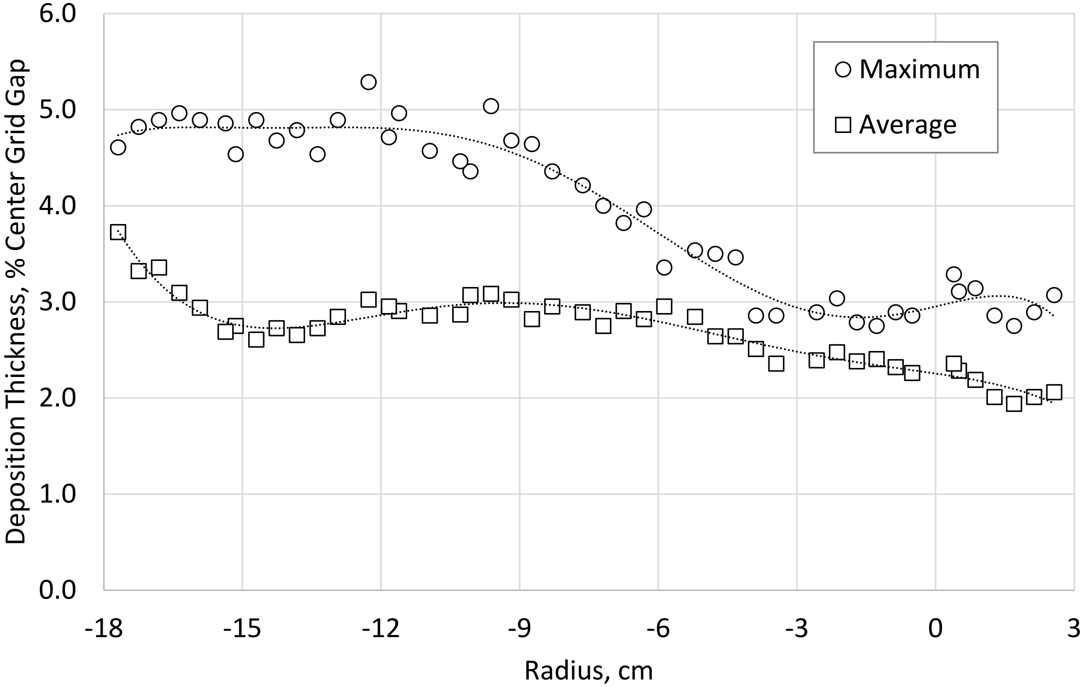
Screen Grid Downstream Deposition

- Downstream webbing deposition was small percentage of cold grid gap
- *Little evidence of deposition spalling*
- Deposition increased with increasing radius & was thickest closest to optics center
  - Due to non-uniform accelerator aperture wall erosion



Optics Center →

r = -9.2 cm

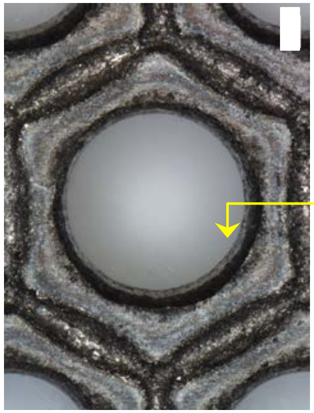


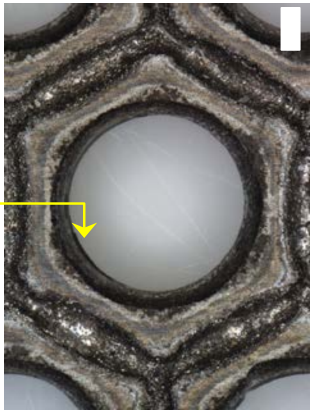
Accelerator Grid

Accelerator Grid Overall Condition

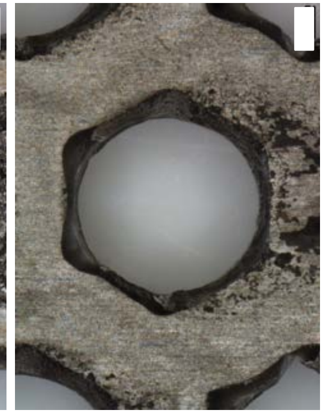
- Net carbon deposition was observed throughout most of grid perforated region
- Net carbon deposition expected within aperture walls
  - Removal rate of back-sputtered carbon decreases as aperture enlarges
- Net carbon deposition within pit & groove erosion pattern unexpected
  - Investigation revealed that erosion persisted until 36.5 kh (621 kg throughput)

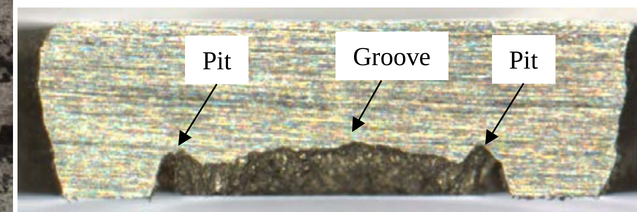
Accelerator Grid Downstream Erosion


r = 1.7 cm


r = 6.5 cm


r = 9.0 cm

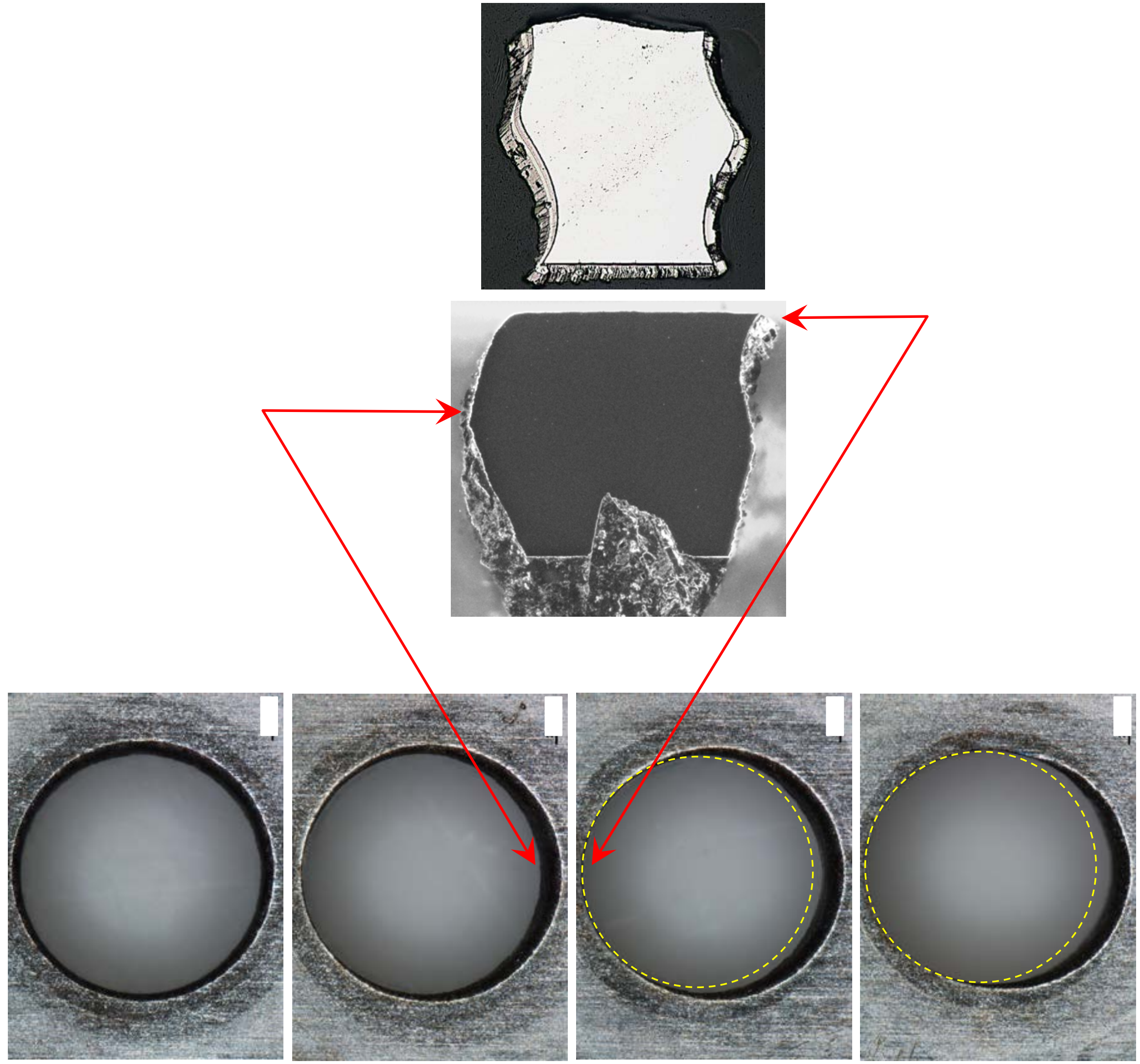

r = 17.6 cm



- Pit & groove erosion pattern
  - Evident and fades away at larger radii due to masking by back-sputtered carbon
  - Grooves that are deeper than pits
- Chamfering of downstream accelerator apertures evident
  - Measured with in situ diagnostics at three radial locations
  - Transitions to hexagonal star-shaped pattern at outer radii

Accelerator Grid Upstream Aperture Erosion

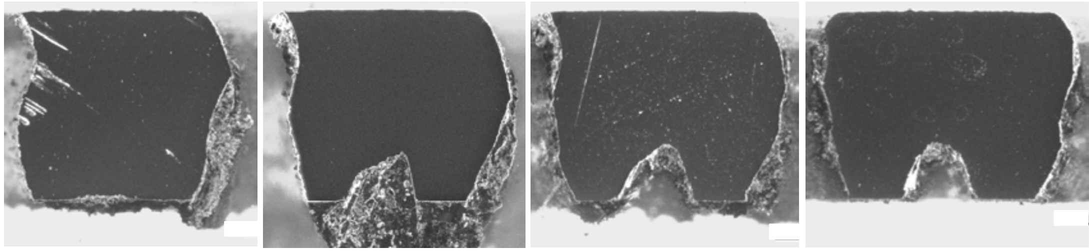
- Slight chamfering of upstream aperture is evident
- At larger radii, chamfering is preferentially towards grid outer radius
- Erosion is result of minor systemic aperture misalignment, leading to preferential erosion of surfaces closest to deflected beamlet
- This erosion likely caused:
  - Uneven deposition on screen aperture walls & upstream surfaces
  - Slightly more collimated beam profiles at EOL
- Resolution is straightforward - adjust aperture alignment during manufacture



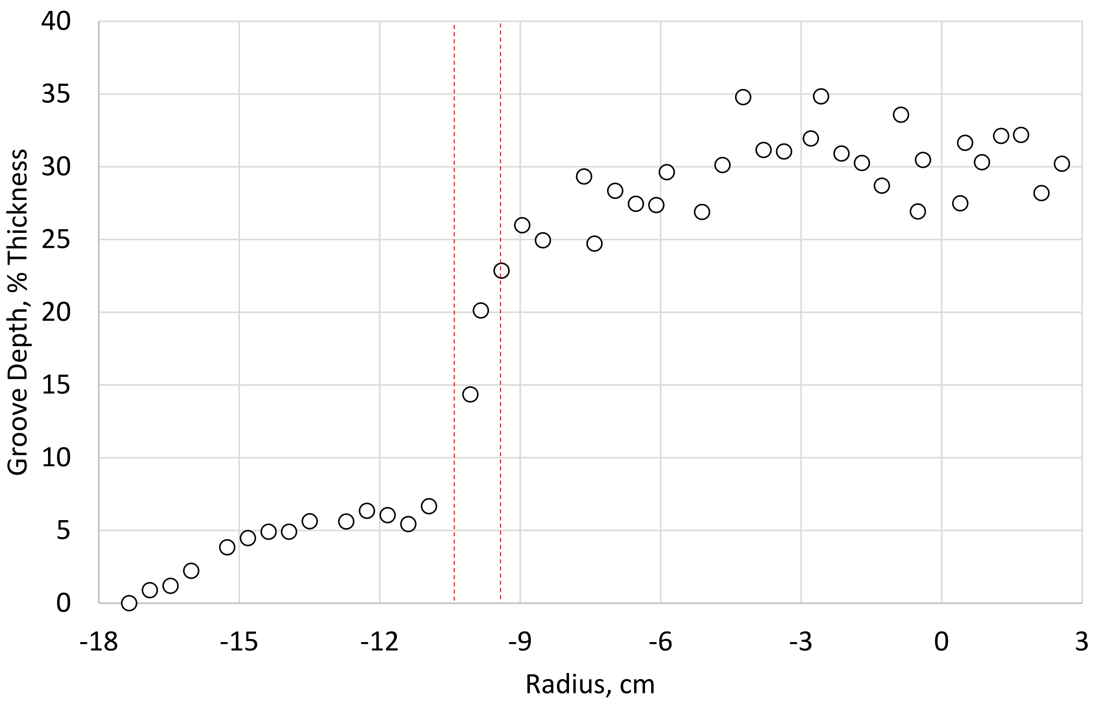
r = 1.7 cm | r = 6.5 cm | r = 9.0 cm | r = 15.4 cm

Accelerator Grid Pit & Groove Erosion

- Webbing cross-sectioned
  - Radius selected because along probe path & highest j_b
  - Photomicrographs show eroded pattern & deposition
- Groove depths were 27-35% of grid thickness within 6 cm radius, then decreased
  - Transition from net erosion to net deposition at full power appear consistent with post-test measurements
- Max groove depth was half that measured in situ diagnostics
  - Due to changes in reference plane locations
  - More recent measurements show groove depths as large as 45% thickness



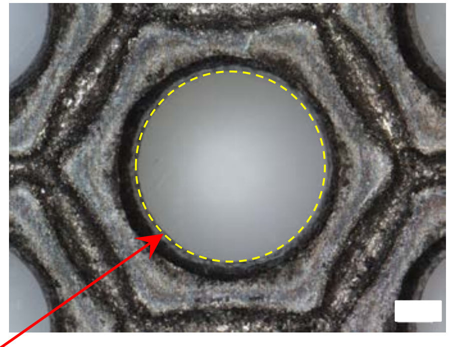
r = -16.0 cm r = -9.0 cm r = -4.7 cm r = 0.9 cm

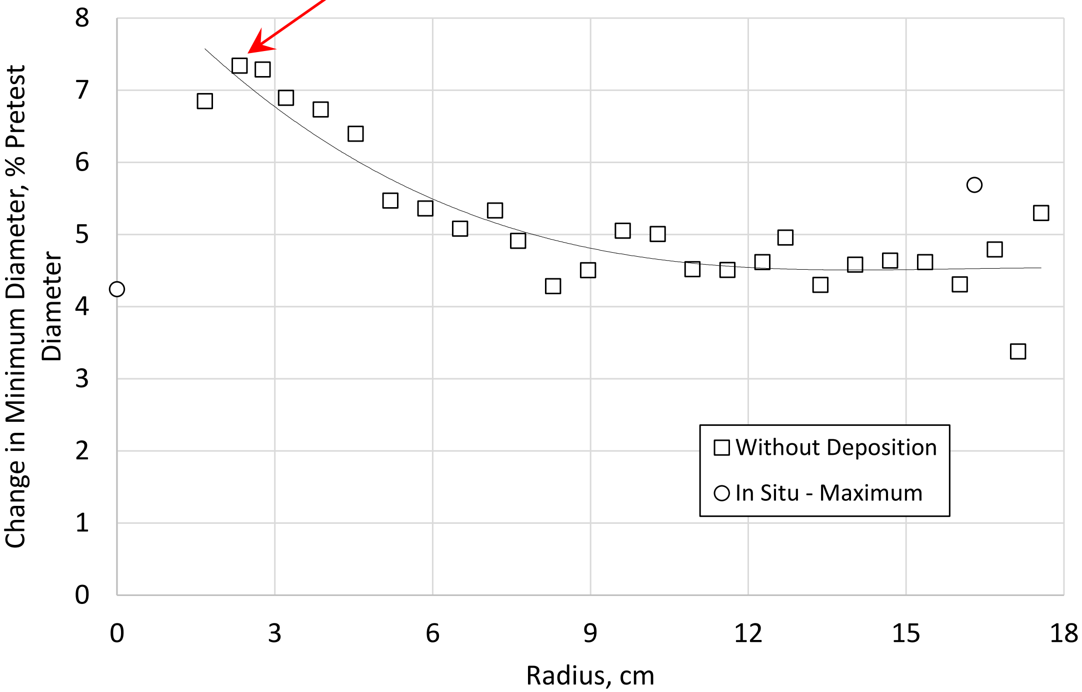


Accelerator Grid Aperture Enlargement

- Minimum aperture diameters without deposition increased by ~5-7% of pretest measurements
  - In situ measurements indicate that minimum diameter increases occurred during throttled power operation (13.0-29.2 kh)
- Smaller than NSTAR ELT changes, which was as large as 24% of pretest
  - In addition to different operating voltages, lower peak beam current density & 11% larger BOL diameter
- In situ measurements compared favorably with post-test
  - Within measurement uncertainties

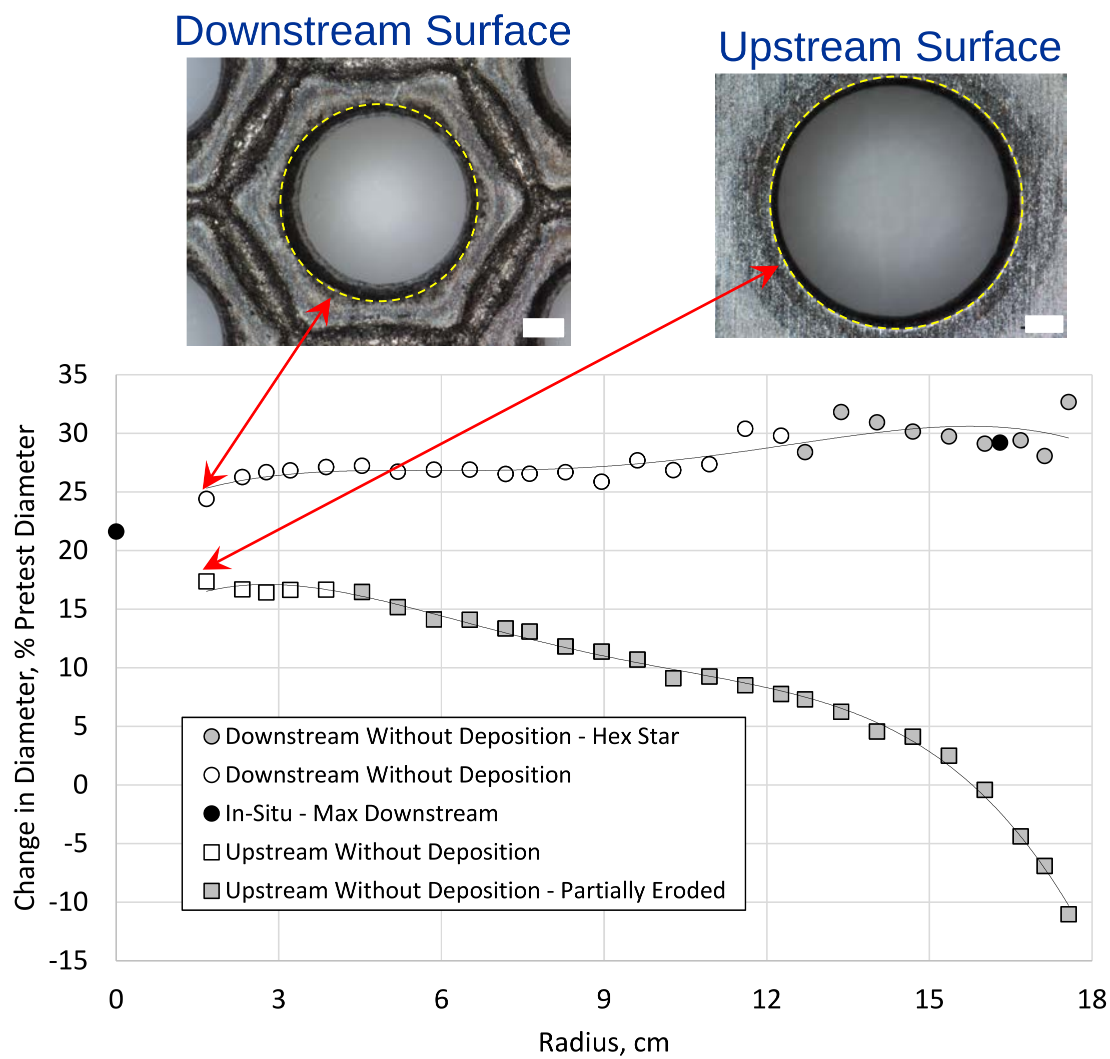
Downstream Surface





Accelerator Grid Aperture Erosion

- Downstream aperture diameters without deposition increased by 24-33% of pretest diameter
  - In situ measurements indicate that that increase occurred predominantly during 1st full power segment (up to 13 kh)
- *Grid geometric changes (36 cm, large diameter, & better tolerance control) reduced degree of erosion at larger radii*
- Upstream diameter increased by as much as 17% of pretest diameter
- Impact on ion optics performance requires further assessment
  - Affect perveance, electron backstreaming, & accelerator current



Summary

- Average change in cold grid gap was -7% of pretest center gap
  - Efforts to stabilize NEXT cold grid gap were largely successful
- Screen grid
  - Upstream erosion exhibited chamfered erosion pattern with minimum grid thickness at 86% of pretest thickness
    - Screen grid has substantial service life remaining
  - Deposition
    - Composed of grid material from accelerator aperture erosion & back-sputtered carbon
    - On aperture walls: Thicknesses up to 1.9% of nominal diameter
      - Average aperture diameter decreased by 2.2% from deposition
    - On downstream surfaces: Thicknesses up to 5% of center grid gap
    - Little evidence of spalling

Summary

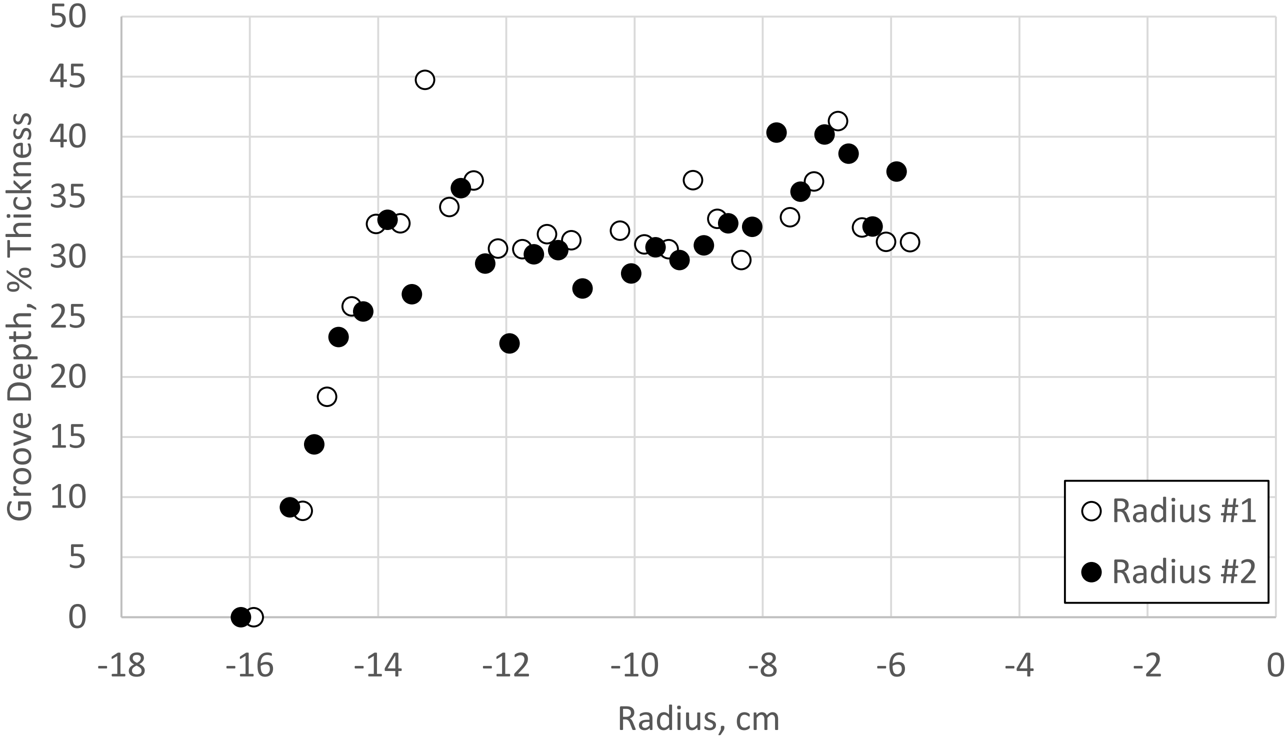
- Accelerator grid
  - Net carbon deposition within pit & groove erosion pattern
    - Investigation revealed that erosion persisted until 36.5 kh (621 kg throughput)
  - Downstream erosion
    - Groove depths deeper than pits
    - Groove depths were 27-35% of grid thickness for 6 cm radius, then decreased
  - Aperture erosion
    - Slight upstream aperture chamfering is evident and preferentially towards grid outer radius at larger radii
      - Erosion is result of minor systemic aperture misalignment that can be corrected
    - Minimum aperture diameters increased by ~5-7% of pretest measurements
    - Downstream aperture diameters increased by 24-33% of pretest diameter
    - Upstream diameter increased by as much as 17% of pretest diameter

Future Work

- Make additional measurements
- Complete correlation of inspections results with test data
  - Understand impact of back-sputtered carbon on test results
- Verify/update service life models

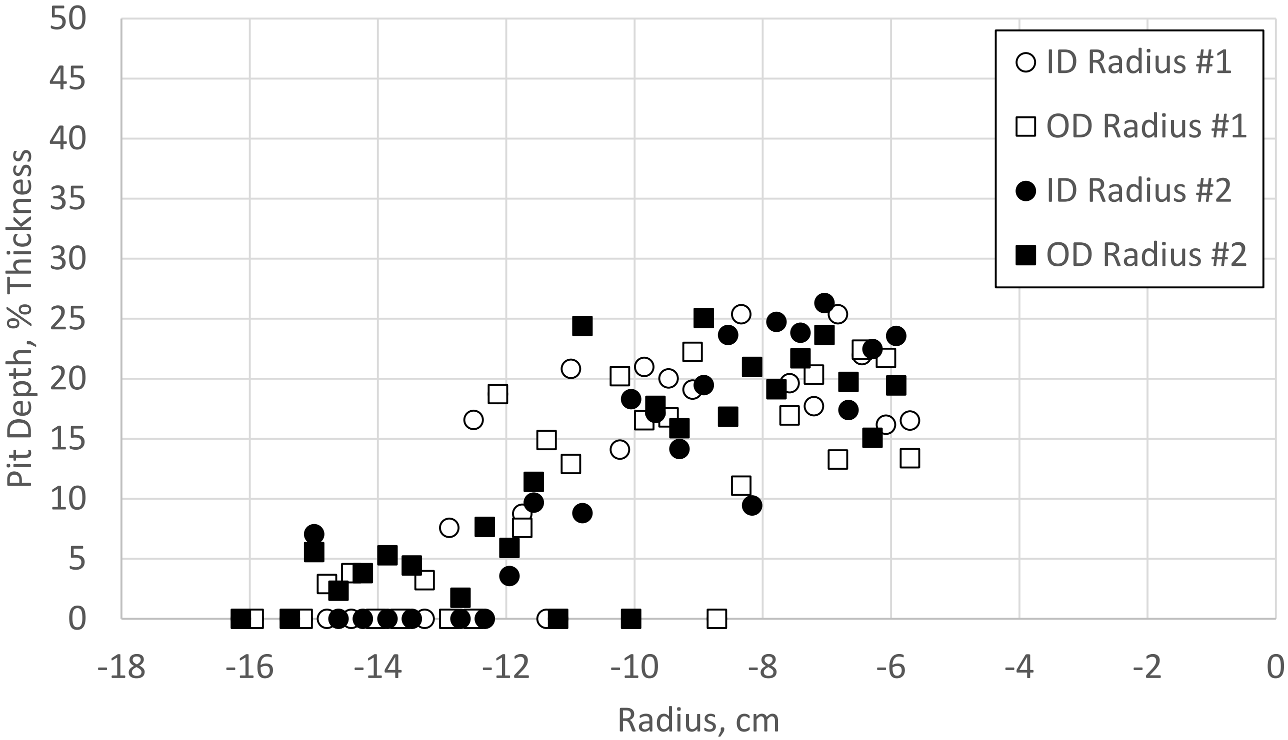
Backup

Recent Groove Measurements



- Groove depths as deep as 45% of grid thickness
- Transition from net erosion to net deposition at 14-16 cm

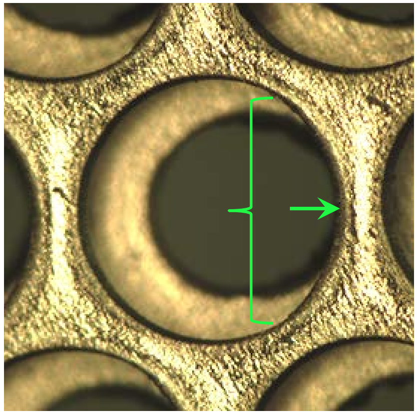
Pit Measurements



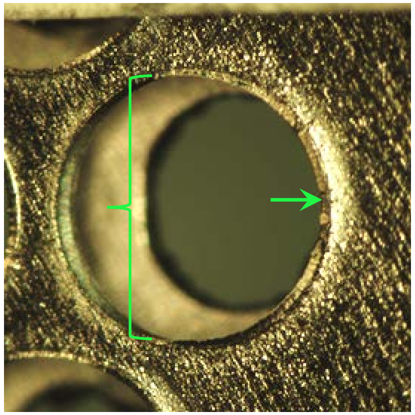
- Pit depths as deep as 27% of grid thickness
  - Less than groove depths

Screen Grid Deposition

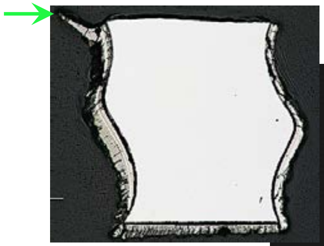
- Partial ring deposition
  - Non-uniformly distributed azimuthally
  - Center of ring aligned with outer radius
  - Coverage increased from 90° at mid-radius to 240° at r = 18 cm
  - Maximum protrusion into aperture was 4% of nominal diameter
- Backscatter electron image shows that ring predominantly formed during second full power segment (after 29 kh)
- Although cause unknown, likely a facility effect that only modestly reduced open area (~2.5%)



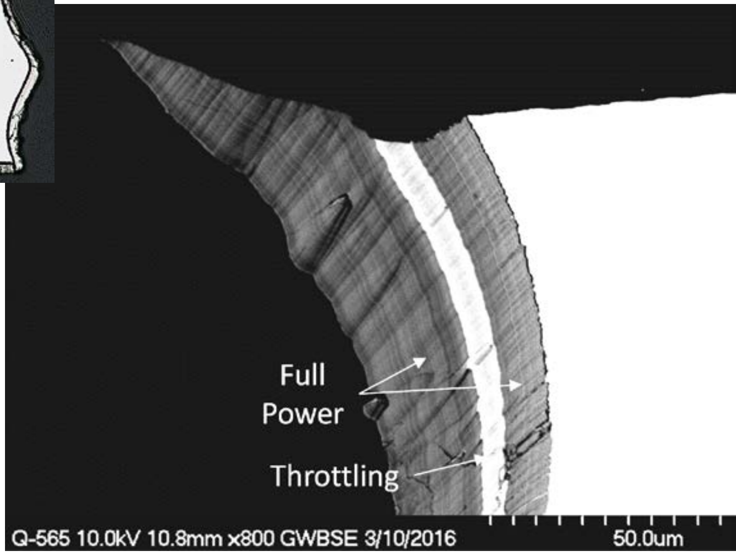
Upstream, r = 10.8 cm



Upstream, r = 18 cm

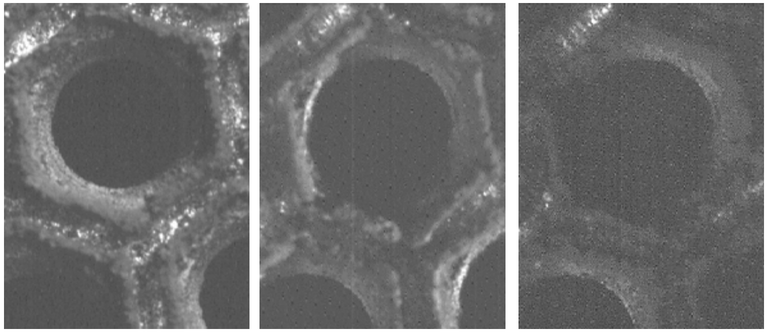


r = -13.4 cm

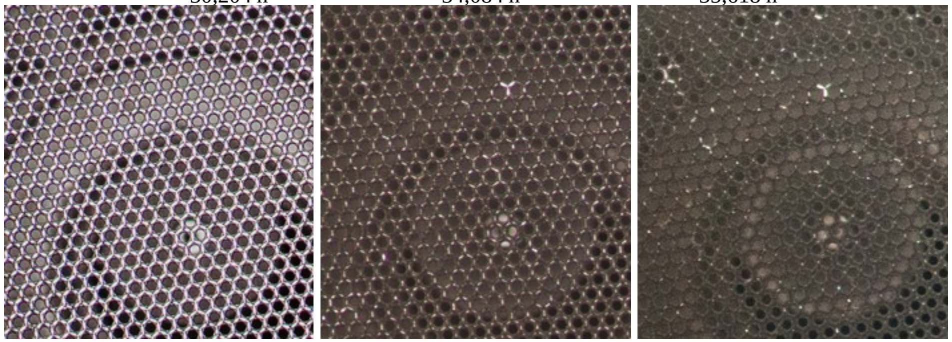


Accelerator Grid Net Deposition

- In situ images show net erosion evident 35.6 kh
  - Imaging system failed
- Long range images
  - Net erosion to 36.5 kh (621 kg throughput), but net deposition by 41.5 kh
  - 36.5 kh image shows changes have just begun to occur
- Root cause presently unknown
  - At 41.5 kh (2nd full power segment), annular net erosion pattern evident
  - Only known mechanism is redistribution of accelerator current



30,204 h 34,084 h 35,618 h



29,240 h 36,467 h 41,468 h

13,042 h 41,468 h

Grid Masses

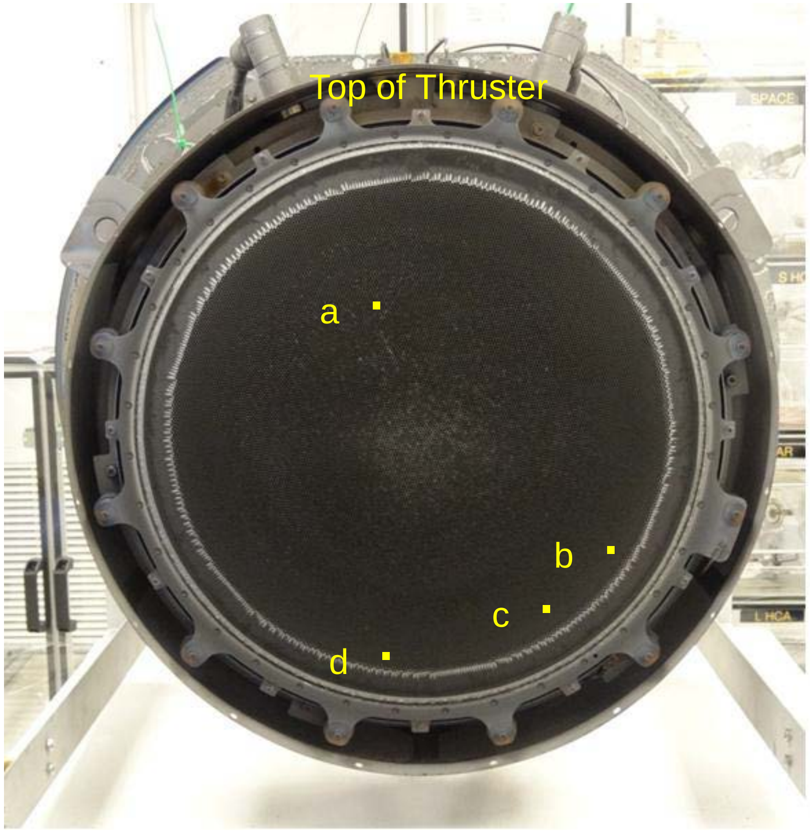
- Screen grid
  - Net mass loss of 0.8 gm
  - Deposition would have masked mass loss due to erosion
  - Based on erosion measurements, preliminary mass loss from erosion estimated to be 5.2 gm
    - Mass of deposition difficult to estimate
  - NSTAR ELT mass loss due to erosion was 3.2 gm
    - Difference due to longer duration & higher beam currents of LDT

- Accelerator grid
  - Net mass loss of 29.5 gm
  - Deposition mass was 12.4 gm based on measurement & analysis
  - Based on deposition mass, preliminary mass loss from erosion estimated to be 42 gm
    - Does not include deposition on unperforated region
  - NSTAR ELT mass loss due to erosion was 33.7 gm
    - Difference due to longer duration & higher beam currents of LDT

Accelerator Grid Rogue Holes

- Four rogue holes identified on accelerator grid during LDT

- Source of rogue holes (e.g. deposition on screen apertures) was not found



Accelerator Grid Aperture Enlargement

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  - In situ measurements indicate that minimum diameter increases occurred during throttled power operation (13.0-29.2 kh)
- Smaller than NSTAR changes, which was as large as 24% of pretest
  - In addition to different operating voltages, lower peak beam current density & 11% larger BOL diameter
- With deposition, diameters decreased due to back-sputtered carbon
  - In situ measurements detected minimum diameter decrease at 38-42 kh

Downstream Surface