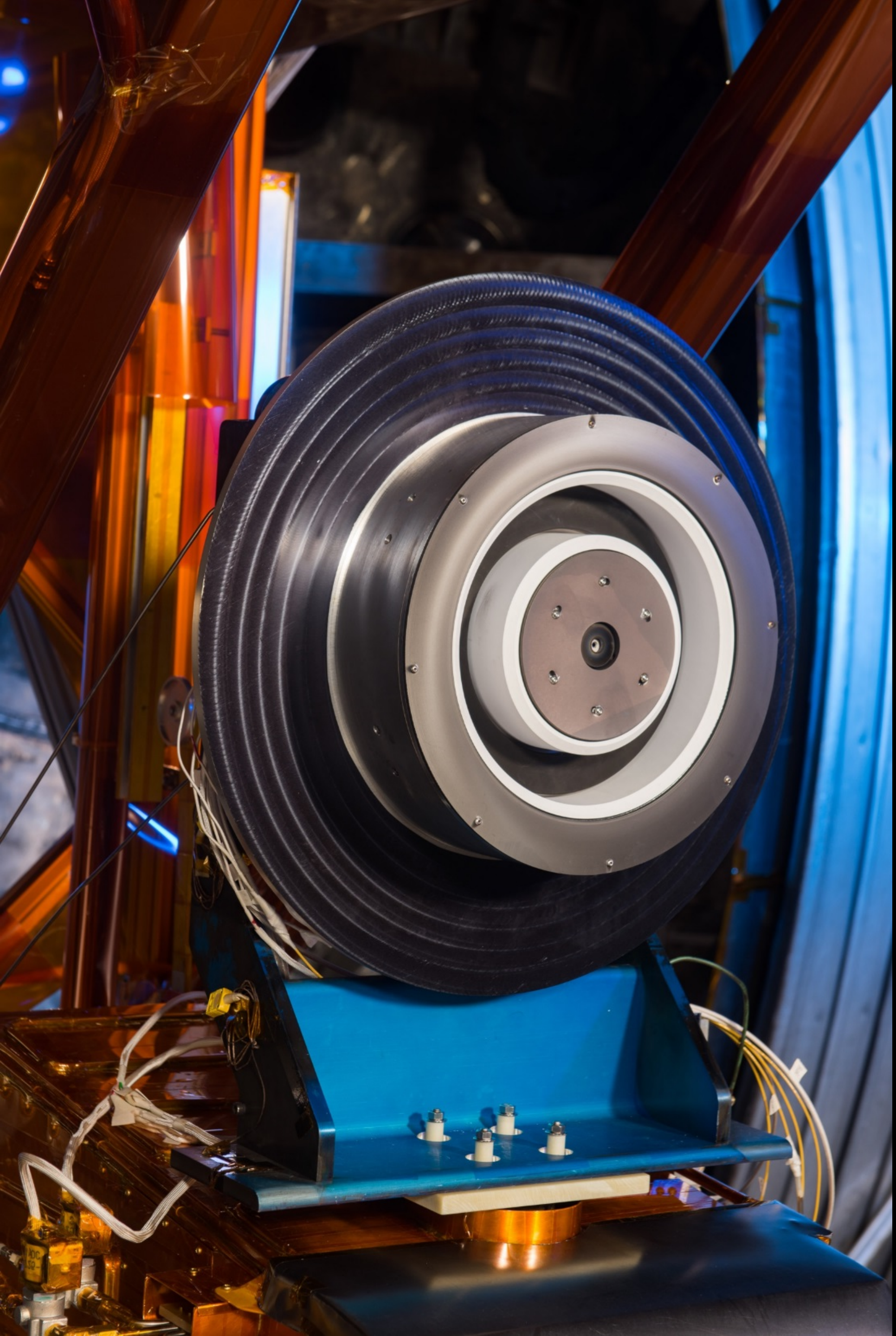

ELECTRIC PROPULSION AND THE GATEWAY:

SUSTAINABLE EXPLORATION OF CIS-LUNAR SPACE

Georgia Institute of Technology
Atlanta, GA
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Introduction: Moon to Mars

Space Policy Directive - 1

SPACE POLICY DIRECTIVE-1

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities.

Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations."

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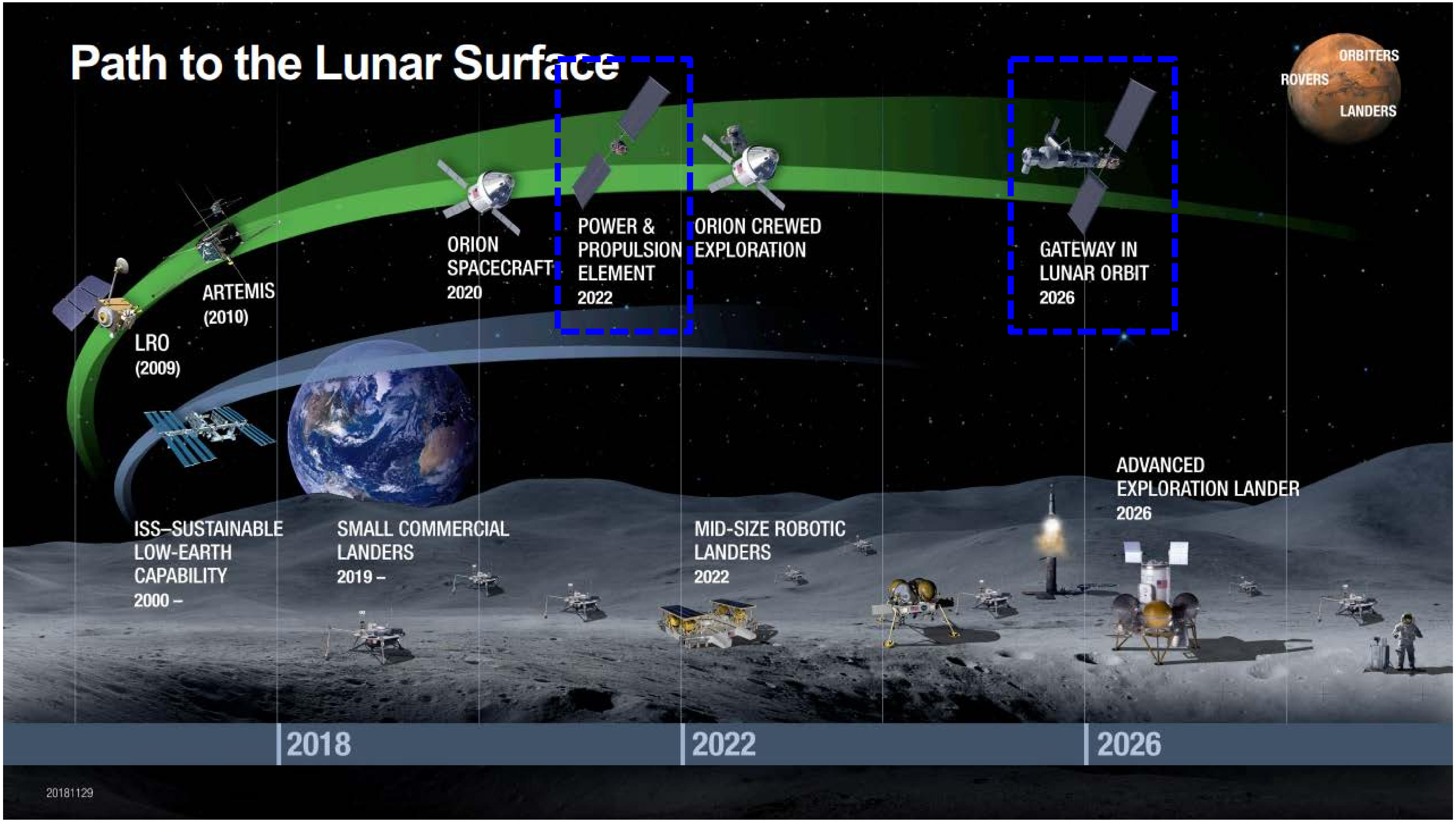
Path to the Lunar Surface



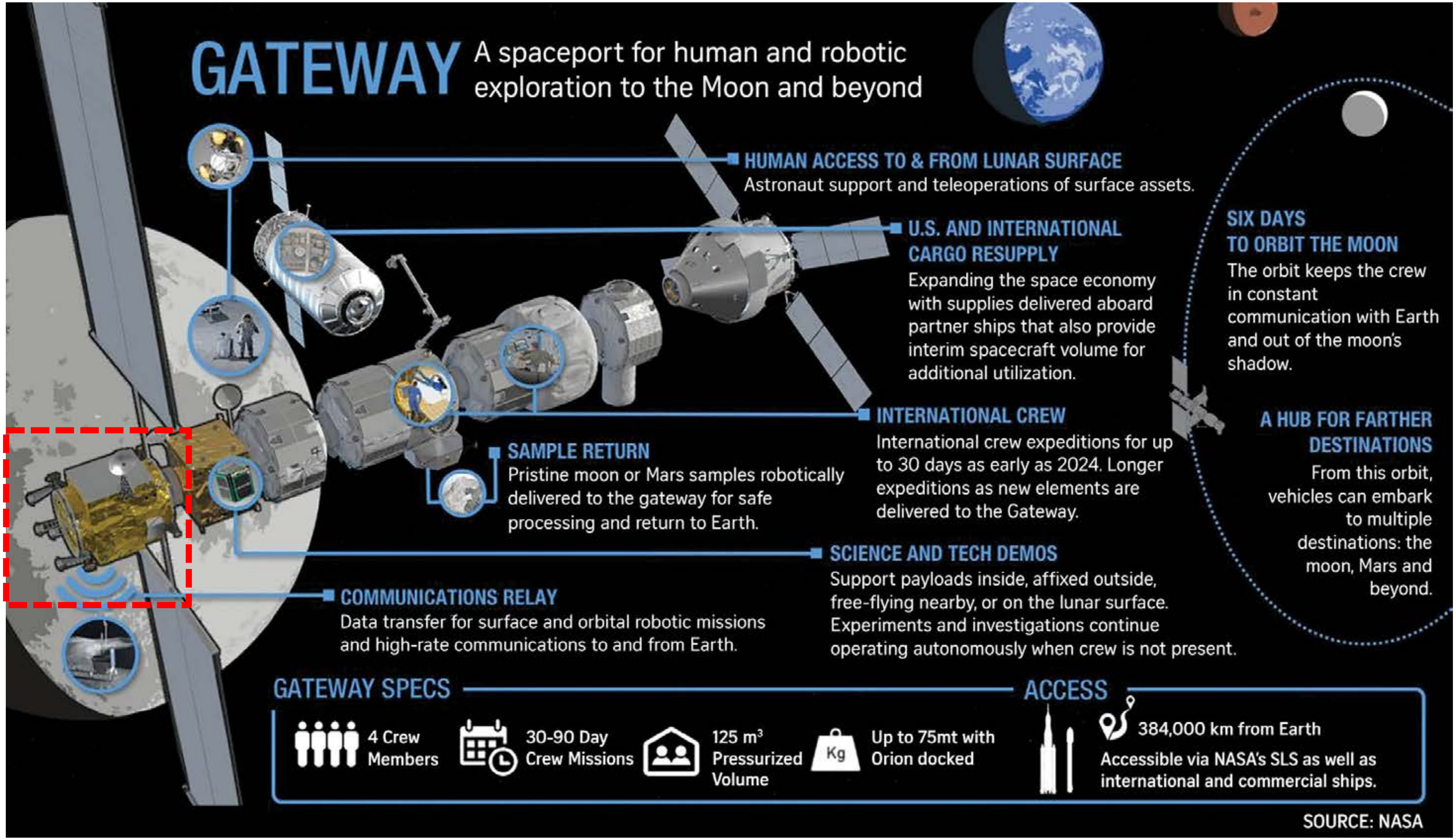
The Gateway: Objectives

Gateway Objectives

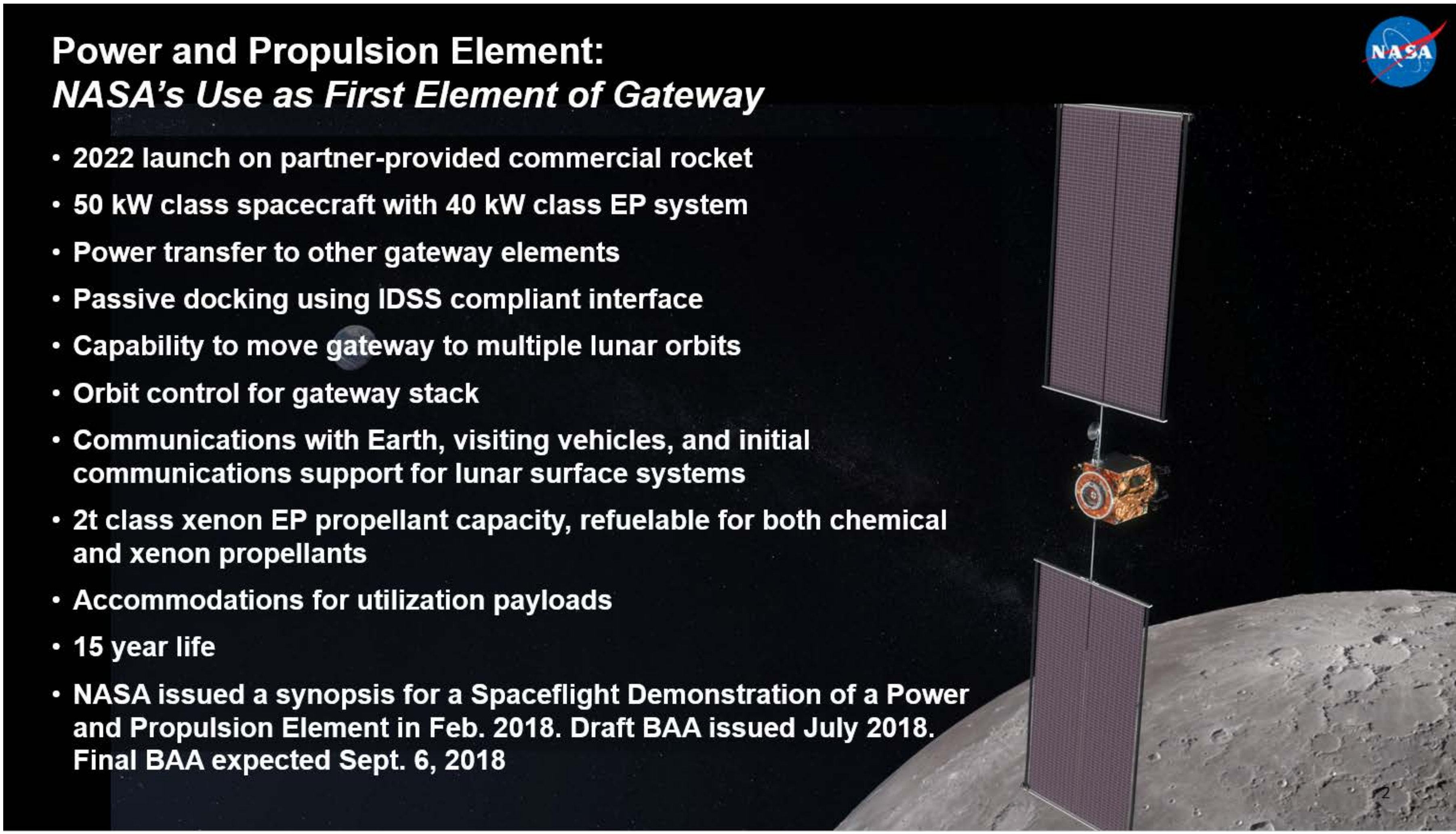
NASA shall establish a Gateway to enable a sustained presence around and on the Moon and to develop and deploy critical infrastructure required for operations on the lunar surface and at other deep space destinations.

- The Gateway shall be utilized to enable human crewed missions to cislunar space including capabilities that enable surface missions. (*Crewed Missions*)
- The Gateway shall provide capabilities to meet scientific requirements for lunar discovery and exploration, as well as other science objectives. (*Science Requirements*)
- The Gateway shall be utilized to enable, demonstrate and prove technologies that are enabling for Lunar missions and that feed forward to Mars as well as other deep space destinations. (*Proving Ground & Technology Demonstration*)
- NASA shall establish industry and international partnerships to develop and operate the Gateway. (*Partnerships*)

The Gateway: Configuration Concept

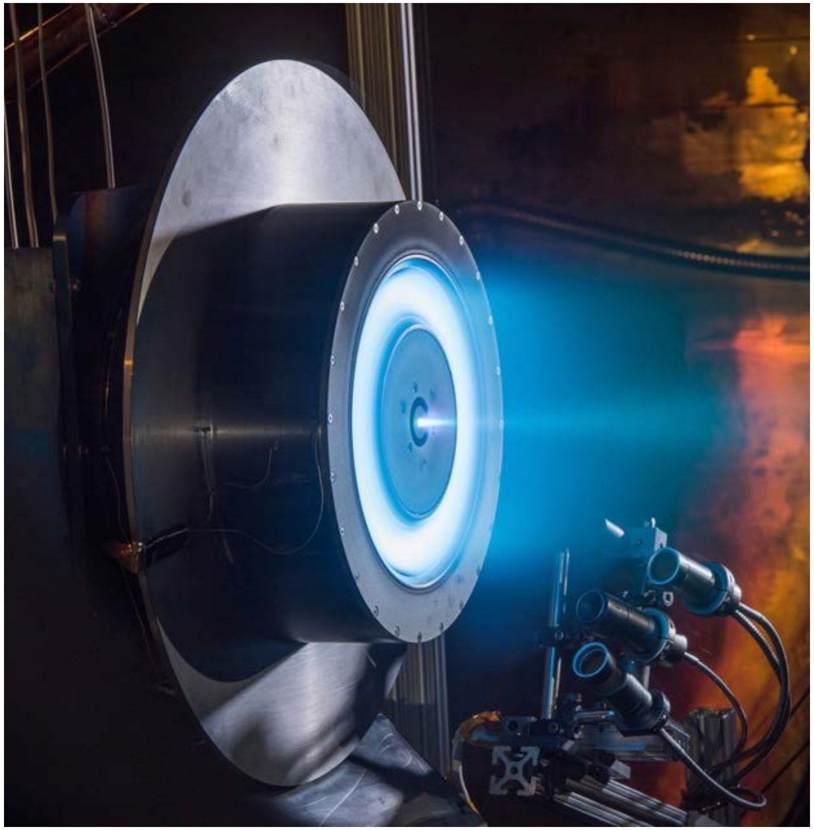


Power and Propulsion Element (PPE)



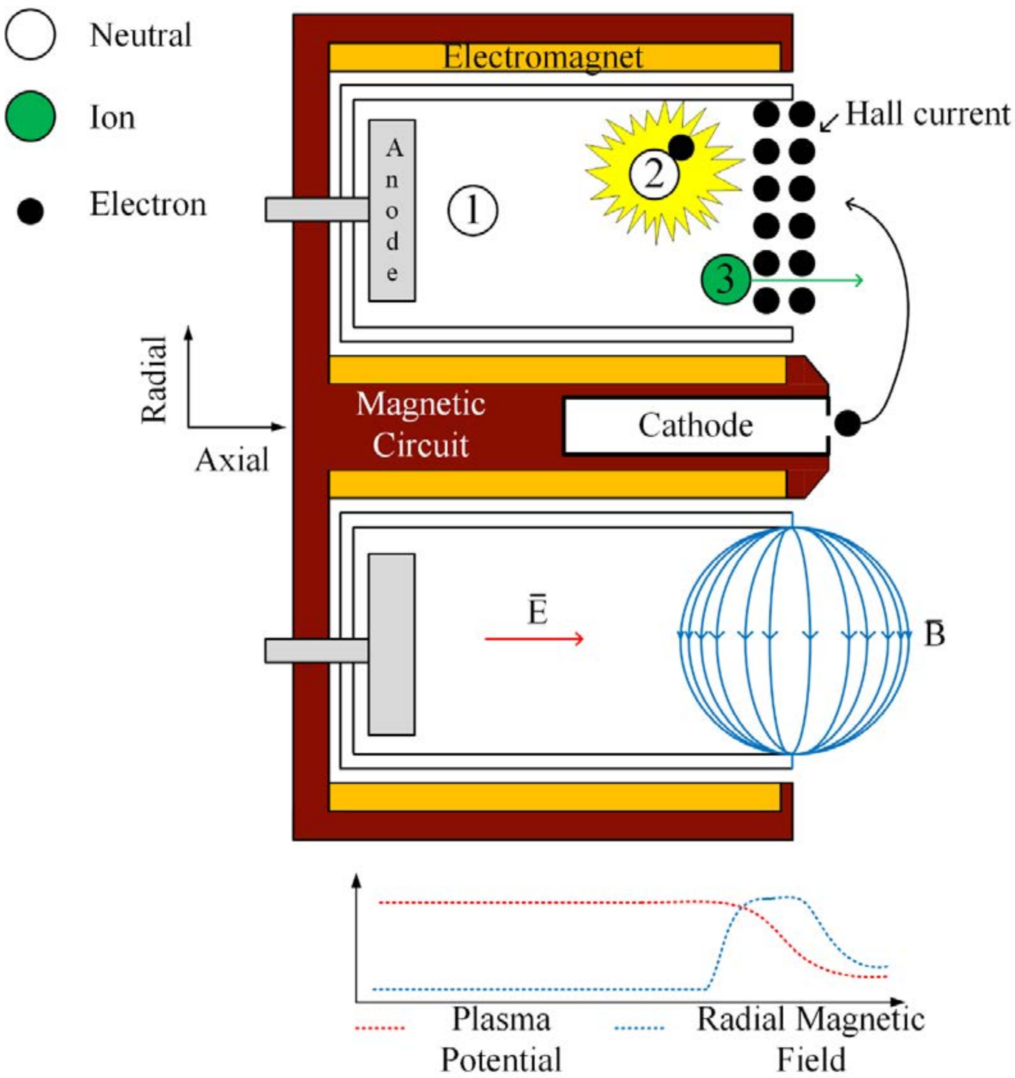
Why Electric Propulsion?

- Fuel (xenon) is storable, does not boil off, and can be resupplied
- Advanced EP provides the ability to move habitat systems to various orbits around the moon
  - Halo, Lagrangian, or other Earth-Moon orbits
- Analyses of in-space orbit transfers in the lunar vicinity shows a 5 to 15 fold savings in propellant with this system as compared to chemical-only systems with equivalent trip times
- Early use supports ensured extensibility to future Mars class transportation system
  - Also directly applicable to a wide range of robotic and human spaceflight missions



Hall Effect Thruster Overview

- Hall effect thrusters (HETs)
  - Electrostatic EP systems that offer:
    - High thrust efficiency
    - High thrust density
  - Theory of operation:
    - Cathode electrons trapped by perpendicular electric and magnetic fields (Hall current)
    - Propellant:
      1. Injected by anode
      2. Collisionally ionized by Hall current
      3. Ion accelerated by electric field to generate thrust



Advanced Electric Propulsion System (AEPS)

- Since 2012, NASA has been developing a 14-kW Hall thruster electric propulsion string that can serve as the building block for the high-power system on PPE
  - Result: Hall Effect Rocket with Magnetic Shielding (HERMeS) Technology Development Units (TDUs)
- Development work transitioned to Aerojet Rocketdyne via a competitive selection for the AEPS contract
  - Contract includes development and qualification of the entire EP string (thruster, power processing unit, xenon flow controller, and harnessing)

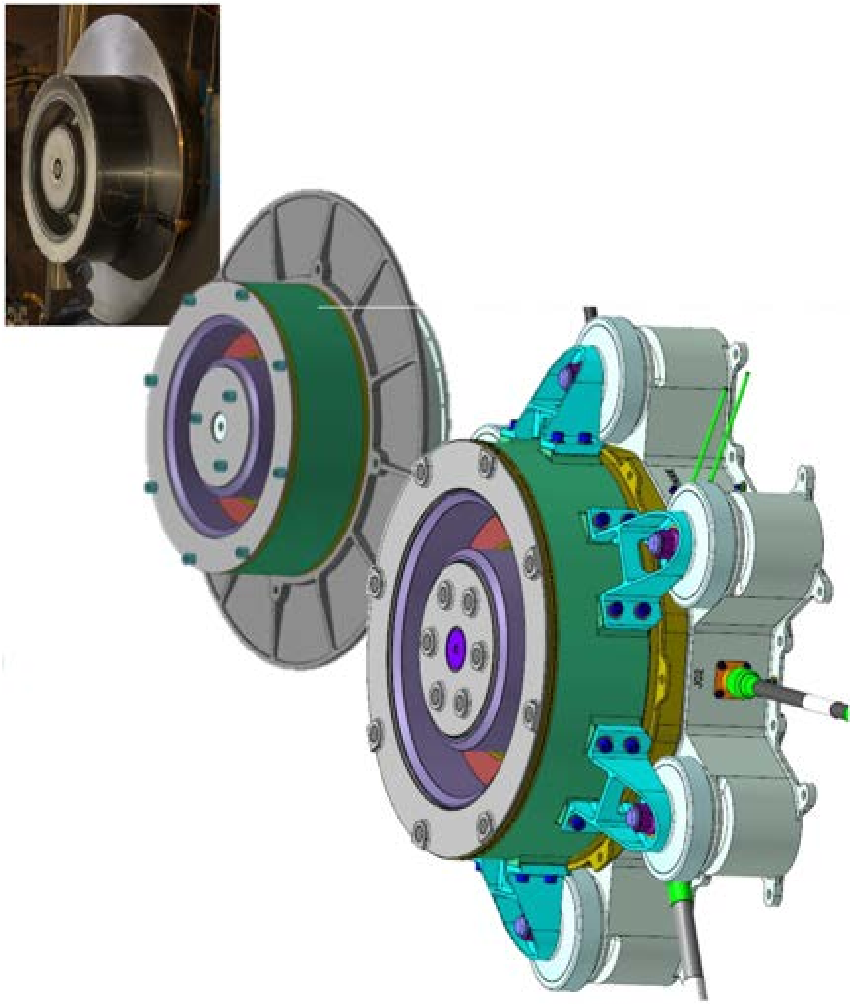
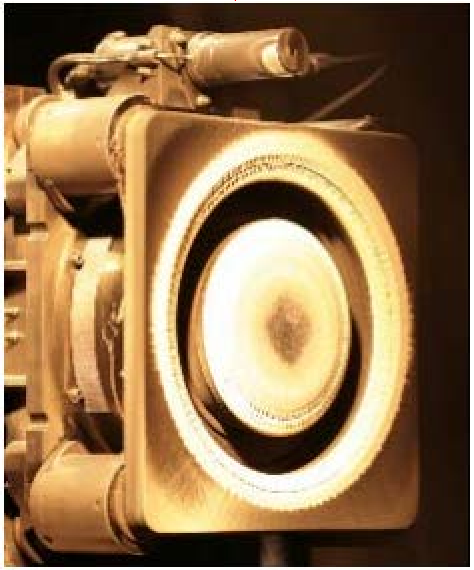


Image from GRC-E-DAA-TN45528

Comparison to State of the Art

Performance Parameter	State of the Art	AEPS
Thruster Input Power	4.5 kW	12.5 kW
Thrust	0.24 N	0.60 N
Specific Impulse	2040 sec	2000-2600 sec
Propellant Throughput	450 kg	1700 kg



Life limited by erosion of discharge channel

Image from NASA/TM 2006-214453

Magnetic shielding eliminates channel erosion

Life limited by erosion of inner/outer pole covers and keeper (lower rate)

Technology Development Activities at NASA

- NASA continues to support the AEPS development by leveraging in-house expertise, plasma modeling capability, and world-class test facilities
- NASA also executes AEPS and mission risk-reduction activities to support the AEPS development and mission applications
  - Activities include the performance of wear tests to inform service-life assessments for magnetically-shielded thrusters

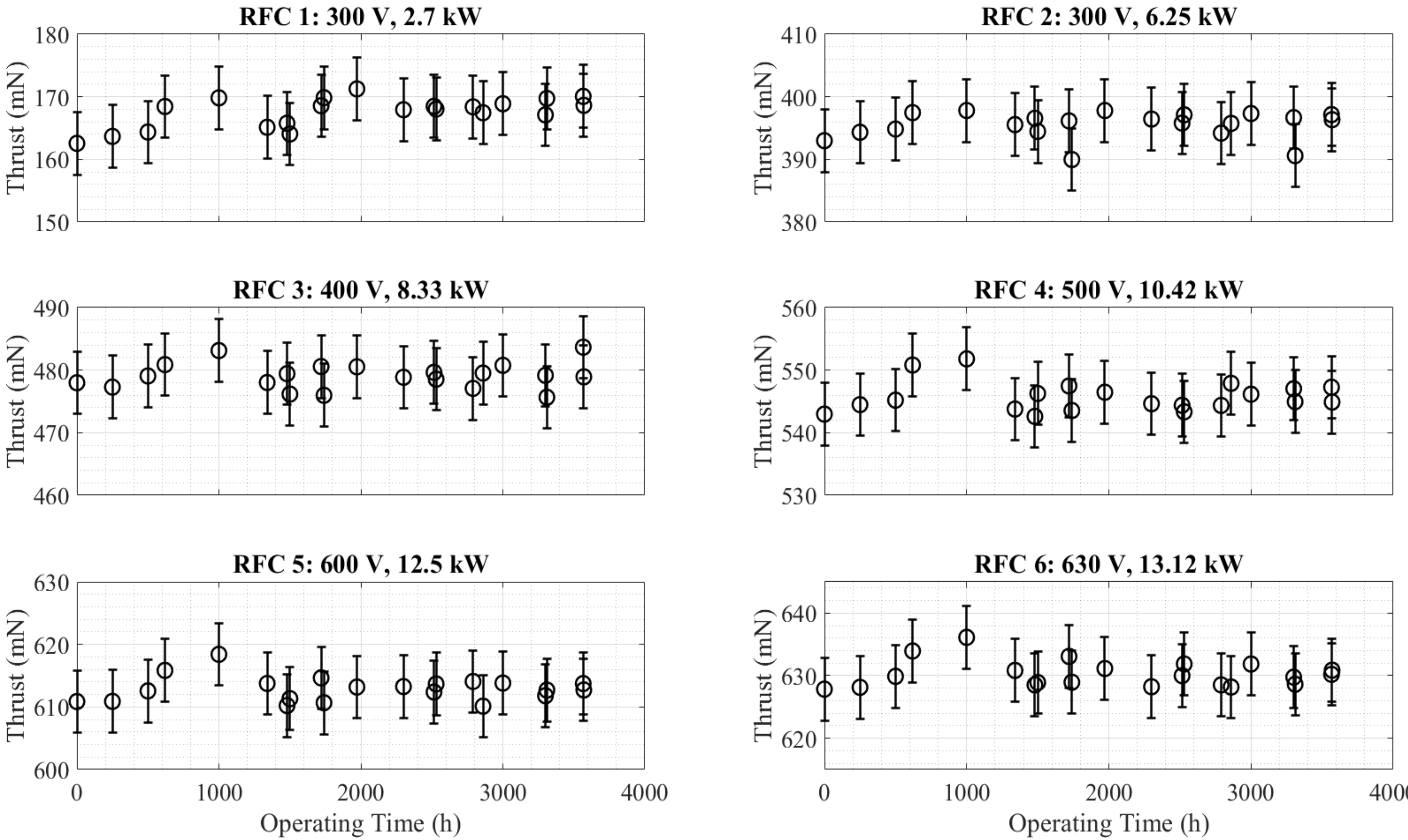
HERMeS Wear Tests

- 2016: TDU-1 Wear Test: AIAA 2016-5025
  - Goal: provide first quantitative insight into wear and performance trends over an extended period of thruster operation
  - 1700 h of operation at 600 V, 12.5 kW

- 2017: TDU-3 Short Duration Wear Test (SDWT): IEPC 2017-207
  - Goal: quantify the impact of operating condition on thruster life
  - 200 h segments (7x) each performed at a different operating condition

- 2017-2018: TDU-3 Long-Duration Wear Test (LDWT): AIAA 2018-4645
  - Goal: pathfinder test for the planned 23 kh AEPS life and qualification campaign
  - 3,570 h total operation split between 6 segments
    - 2 segments at 600 V, 12.5 kW
    - 3 segments at 300 V, 6.25 kW (impact of magnetic field on wear)
    - 1 segment at 3x nominal facility pressure (impact of background pressure on wear)

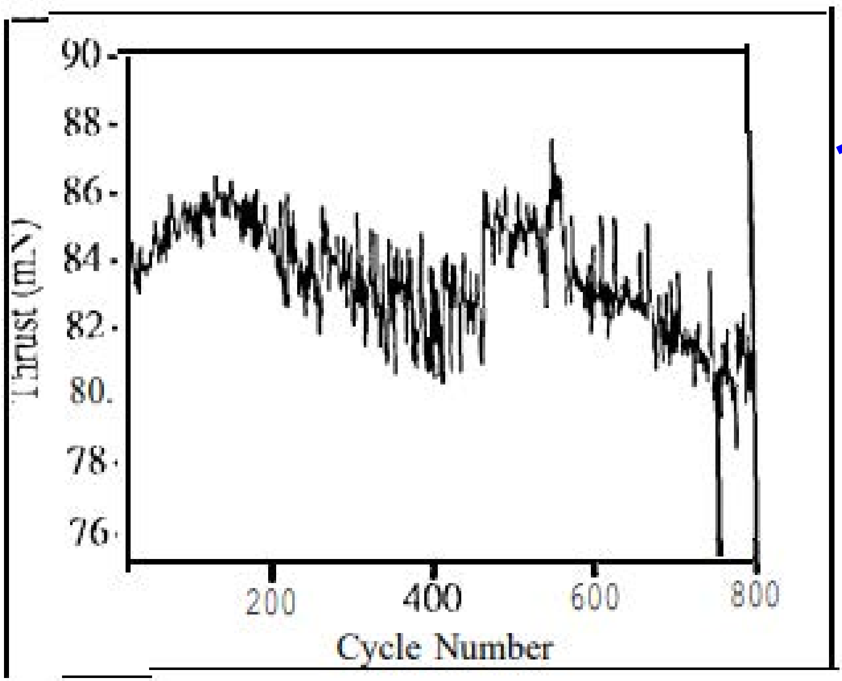
Key Findings: Performance



Performance and stability vary by less than the uncertainty during LDWT and when compared against previous TDU wear tests

Key Findings: Performance

SOA Hall Thruster



Images from NASA/TM:
20060039356
2006-214453

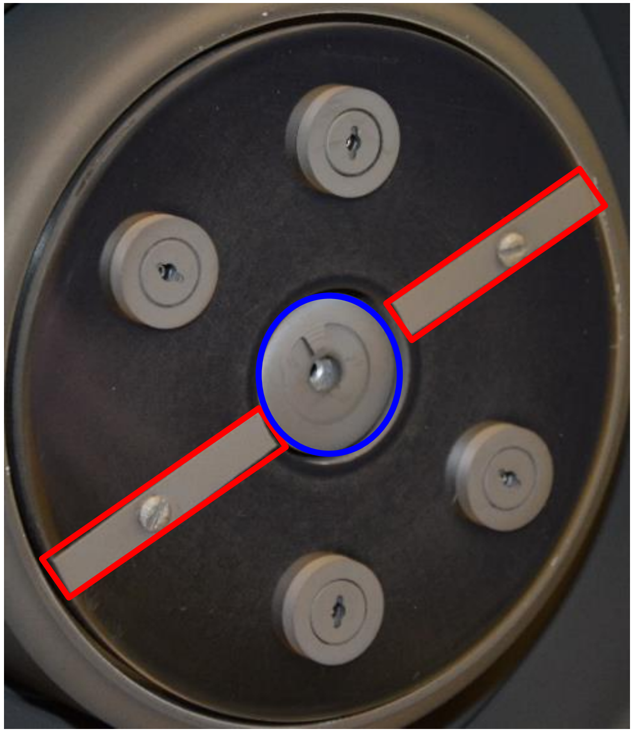
Thrust decrease of ~3% over first 500 h of operation caused by erosion of discharge channel

Constant performance of HERMeS over LDWT indicates effectiveness of magnetic shielding topology

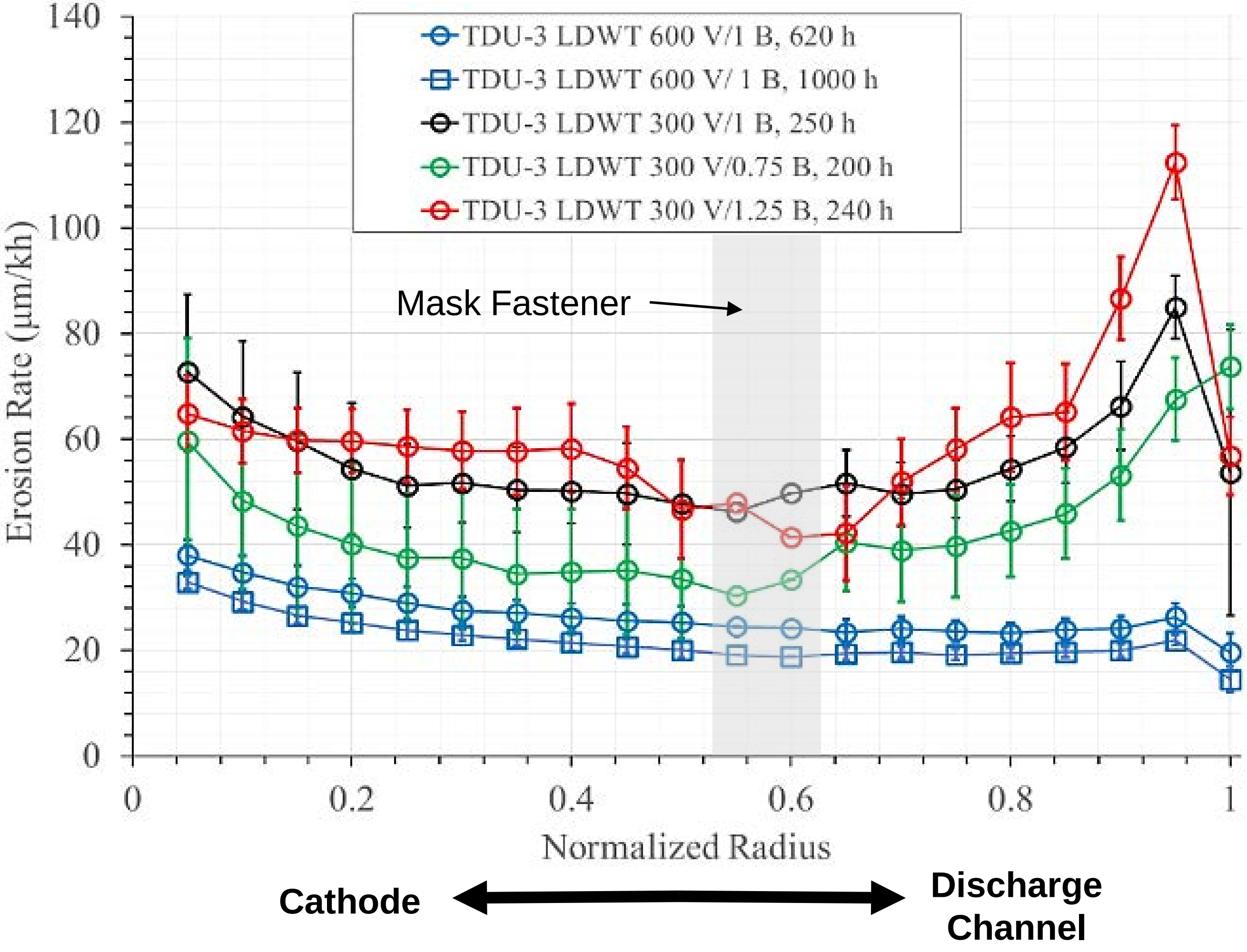
Experimental Apparatus: Wear Measurements

- Graphite IFPC, keeper, and OFPC modified to enable wear measurements
  - Components polished pre-test to maximize surface uniformity
  - Graphite masks installed to provide unexposed reference surfaces:
    - IFPC: two graphite strips covering approximately 95% of radius at 2 and 8 o'clock
    - Keeper: graphite ring with a tab protruding radially inward
    - OFPC: series of graphite strips covering approximately 95% of radius

- Erosion measurements made with a chromatic, white-light, non-contact profilometer
  - Data analyzed per ISO 5436-1 guidance for a type A1 step
  - Typical uncertainties ±2 µm accounting for:
    - Instrument error
    - Surface roughness
    - Non-flat surface geometry



Results: IFPC Wear



Key Observations:

1) The erosion rate varies with radius
   - 300 V strongly varying

Results: IFPC Wear

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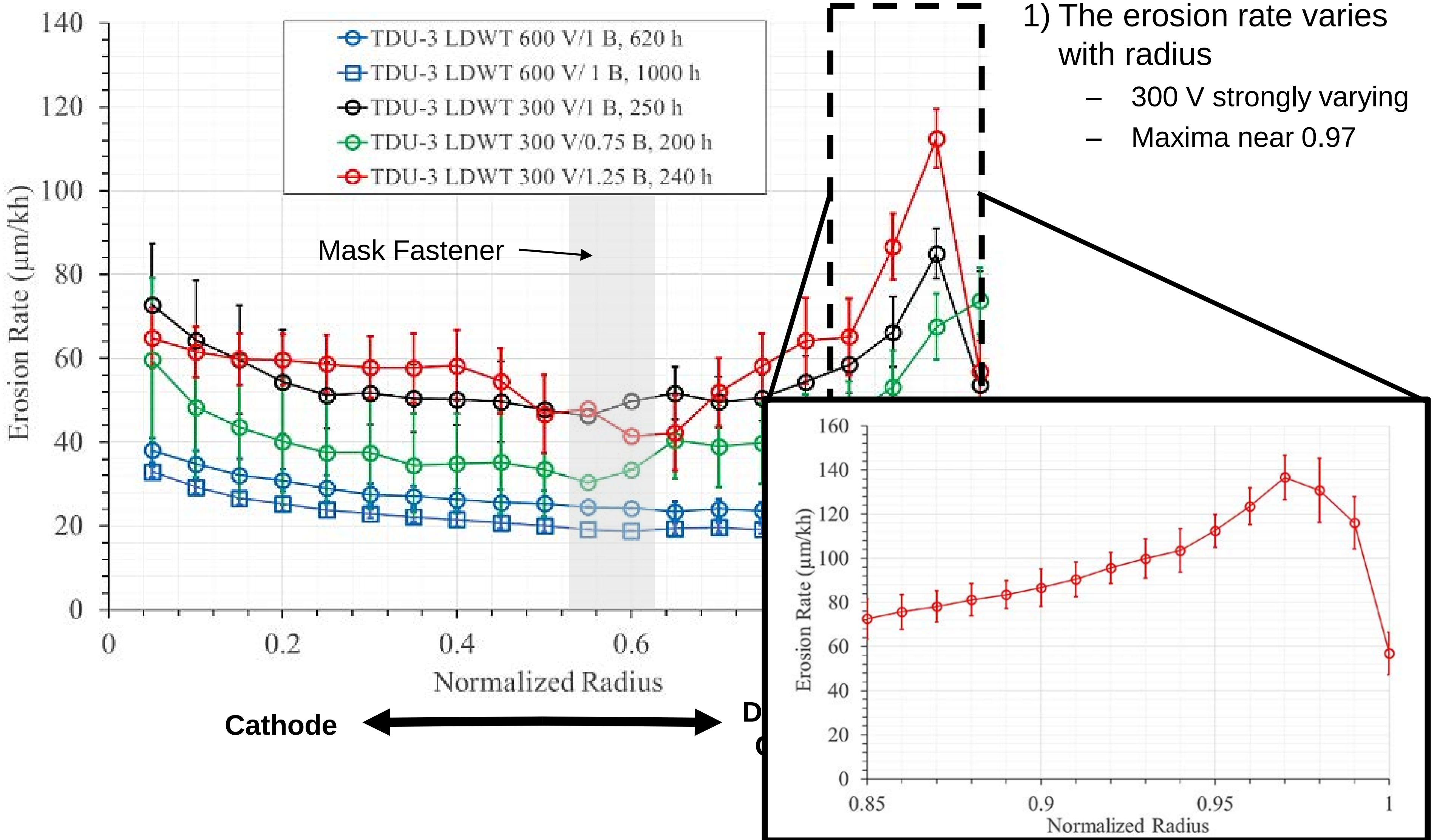
   - Maxima near 0.97



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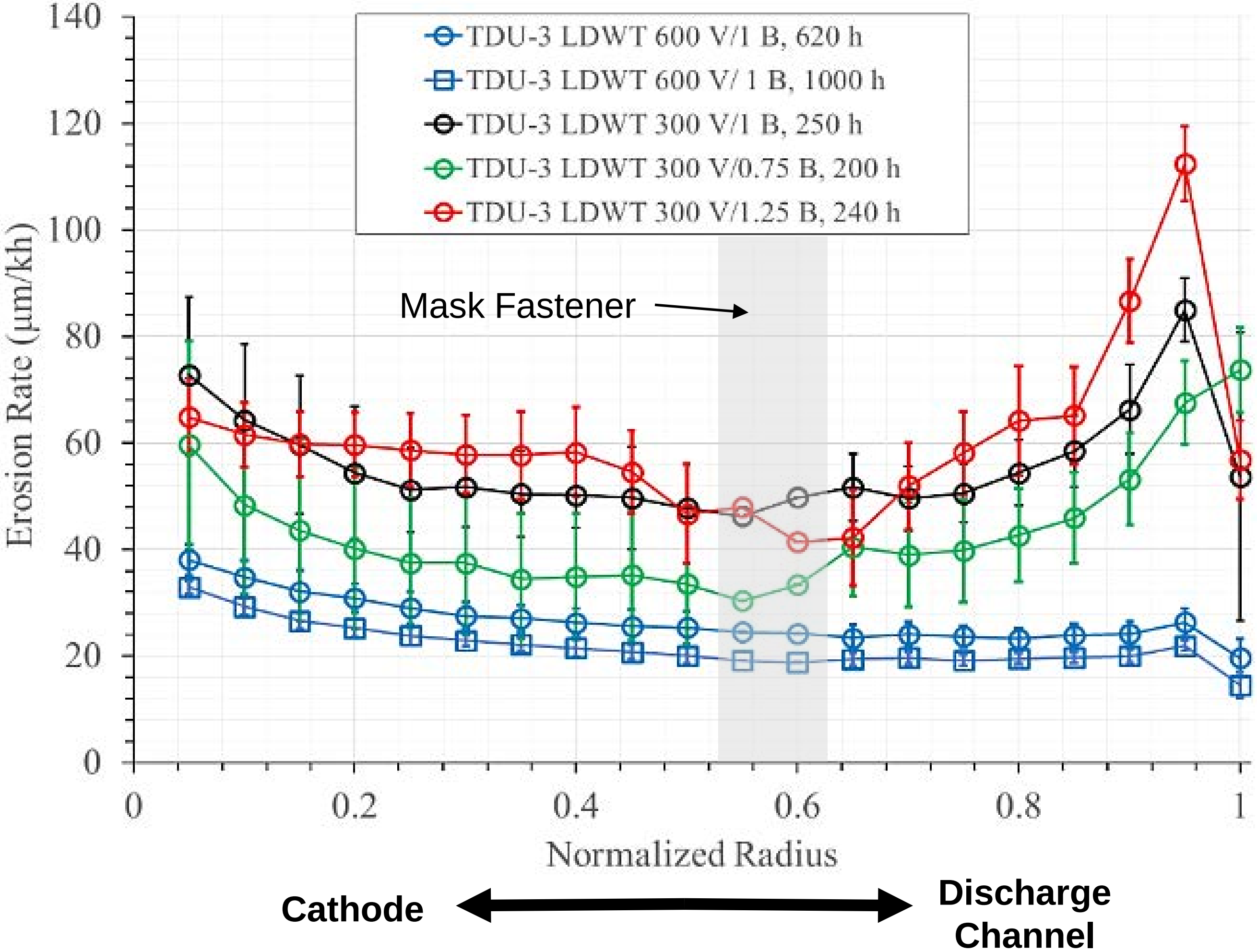
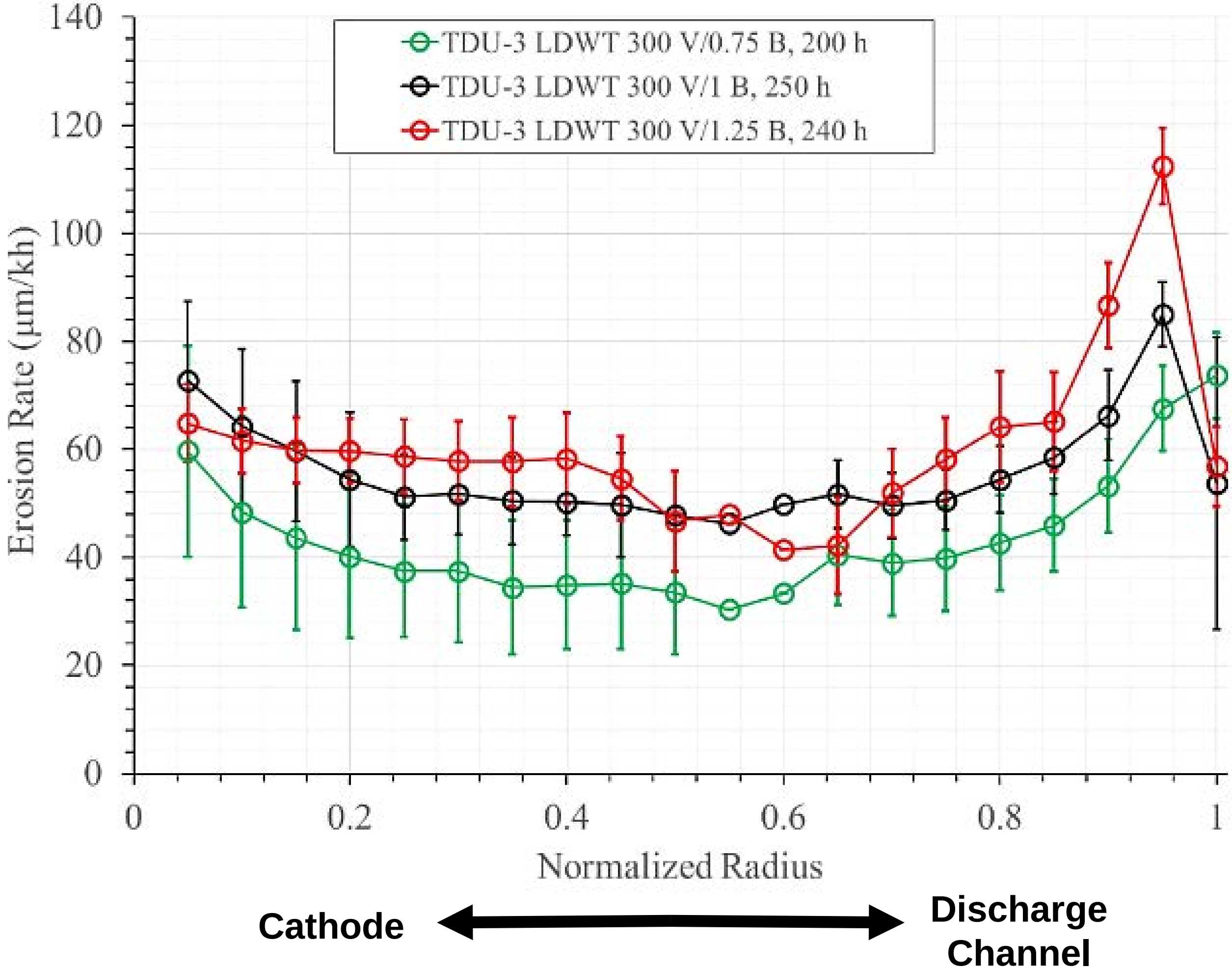


Key Observations:

1) The erosion rate varies with radius
   - 300 V strongly varying
   - Maxima near 0.97
2) The erosion rate at 600 V decreases with time
   - Consistent with TDU-1 wear test
3) The erosion rate at 600 V/1 B is 76% less than 300 V/1 B
   - Driven by axial shift in acceleration zone

Results: IFPC Wear



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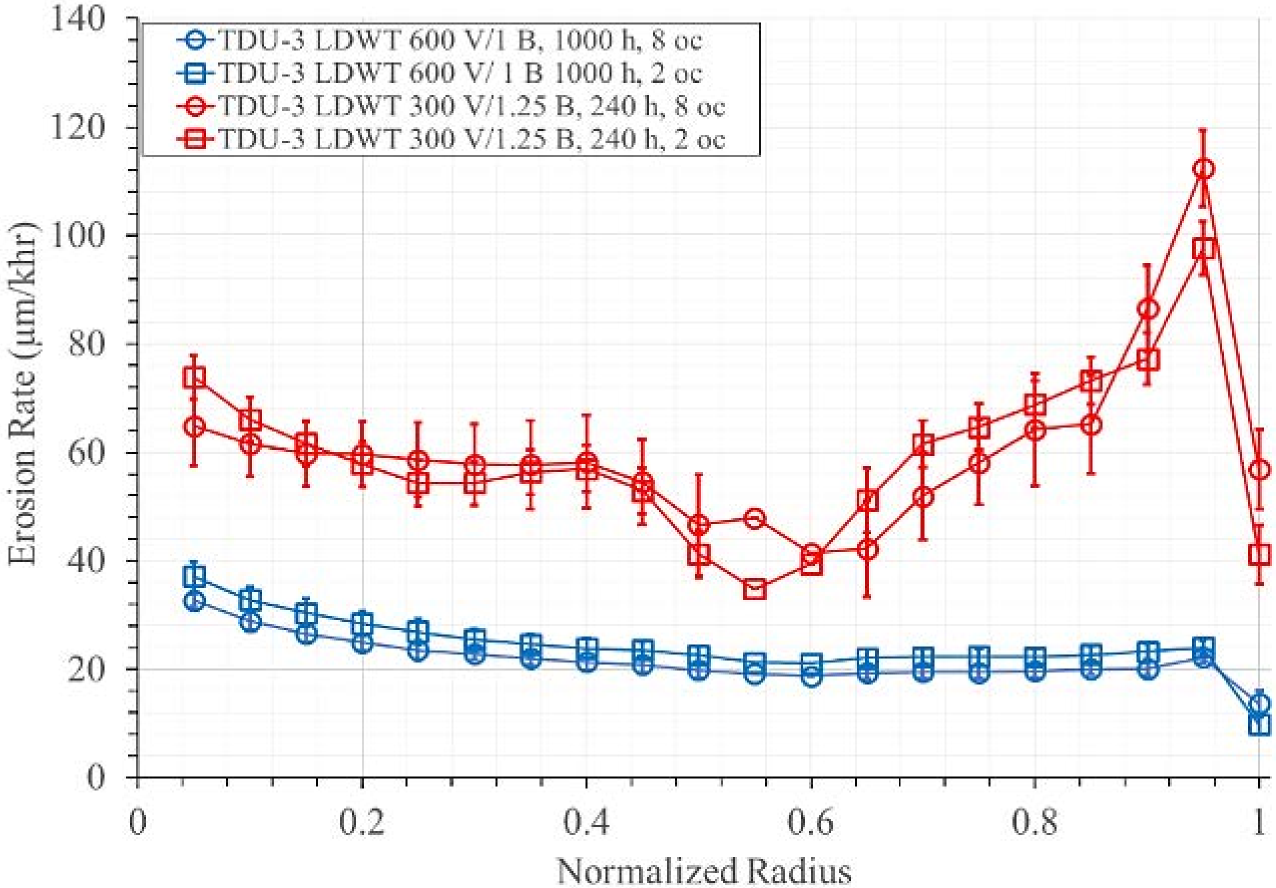
   - Cause not presently known

Results: IFPC Wear

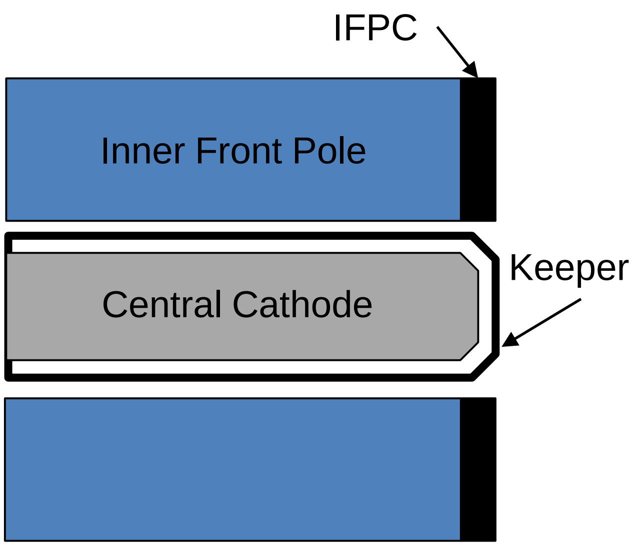


Cathode ⟷ **Discharge Channel**

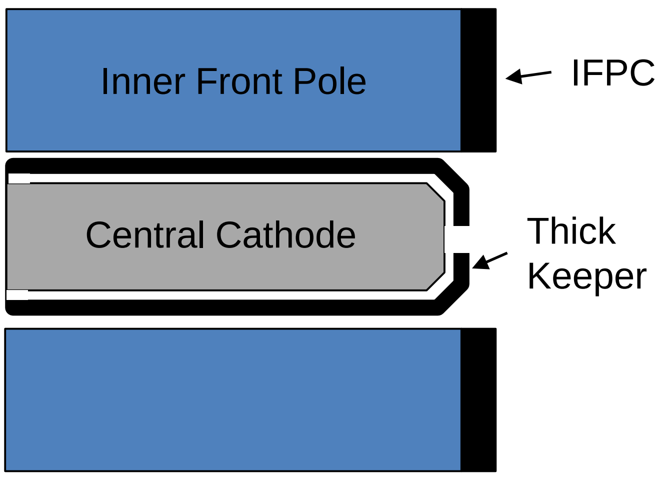
Key Observations:

1) The erosion rate varies with radius
   - 300 V strongly varying
   - Maxima near 0.97
2) The erosion rate at 600 V decreases with time
   - Consistent with TDU-1 wear test
3) The erosion rate at 600 V/1 B is 76% less than 300 V/1 B
   - Driven by axial shift in acceleration zone
4) At 300 V, the erosion rate increases with magnetic field strength
   - Cause not presently known
5) IFPC wear is azimuthally symmetric

- Keeper position and thickness changed relative to SDWT to try to mitigate elevated wear rates



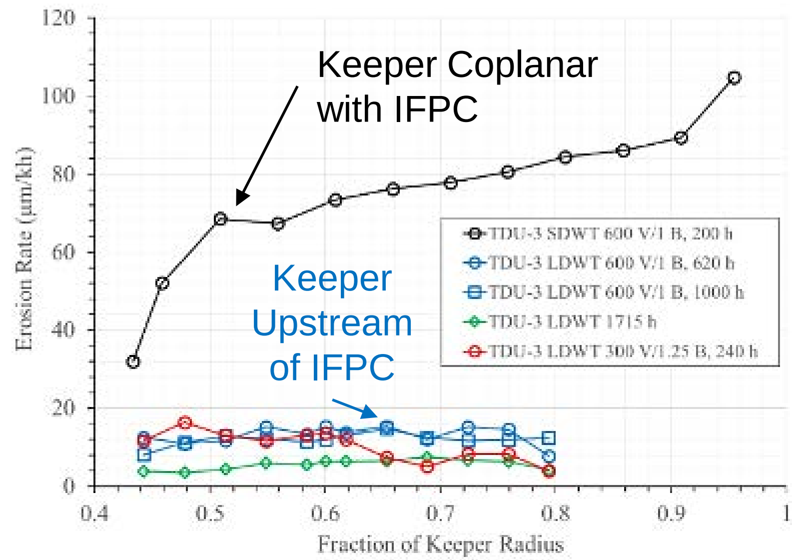
SDWT: Keeper Coplanar with IFPC



LDWT: Keeper Upstream of IFPC

Results: Keeper Wear

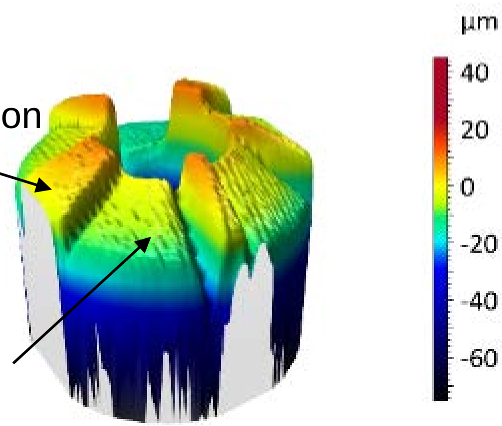
- Keeper position and thickness changed relative to SDWT to try to mitigate elevated wear rates
- Radially-averaged keeper erosion rates for operation at 600 V, 12.5 kW, nominal magnetic field:
  - SDWT: 80 µm/kh (Coplanar Keeper)
    - Rates increase near IFPC and decrease near orifice
  - LDWT: 13 µm/kh (Upstream Keeper)
    - No significant radial variation in erosion rates observed
- Trends qualitatively supported by 3D keeper surface maps



Orifice ⟷ **IFPC**

Masked Region

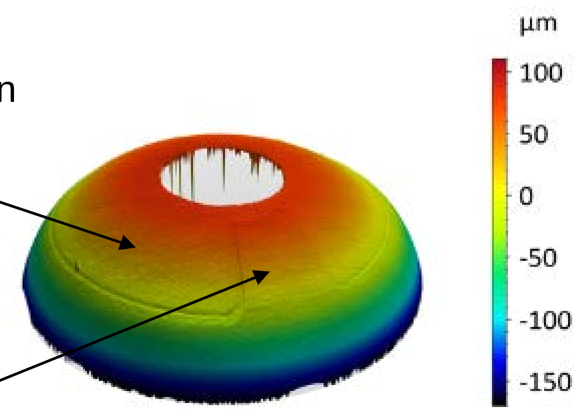
Eroded Region (~200 h)



SDWT: Keeper Coplanar with IFPC

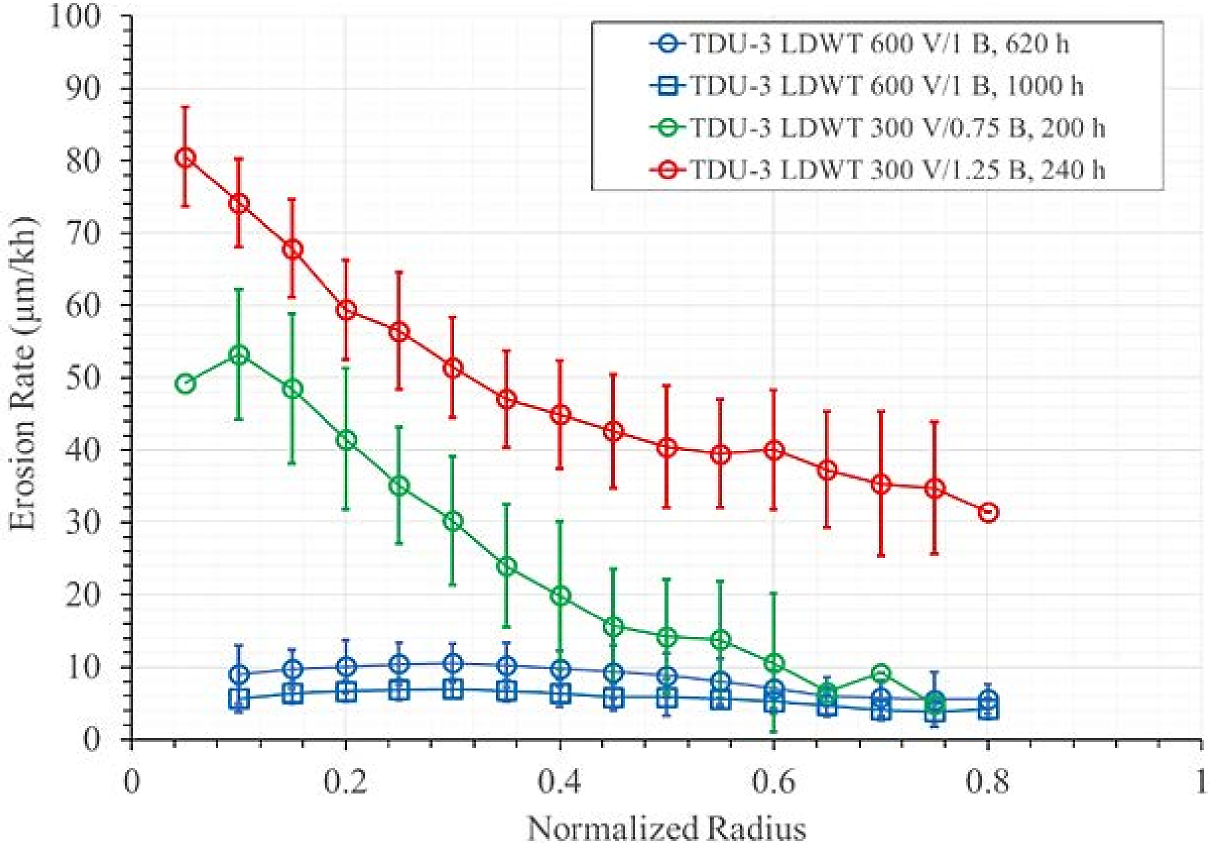
Eroded Region (1015 h)

Masked Region



LDWT: Keeper Upstream of IFPC

Results: OFPC Wear

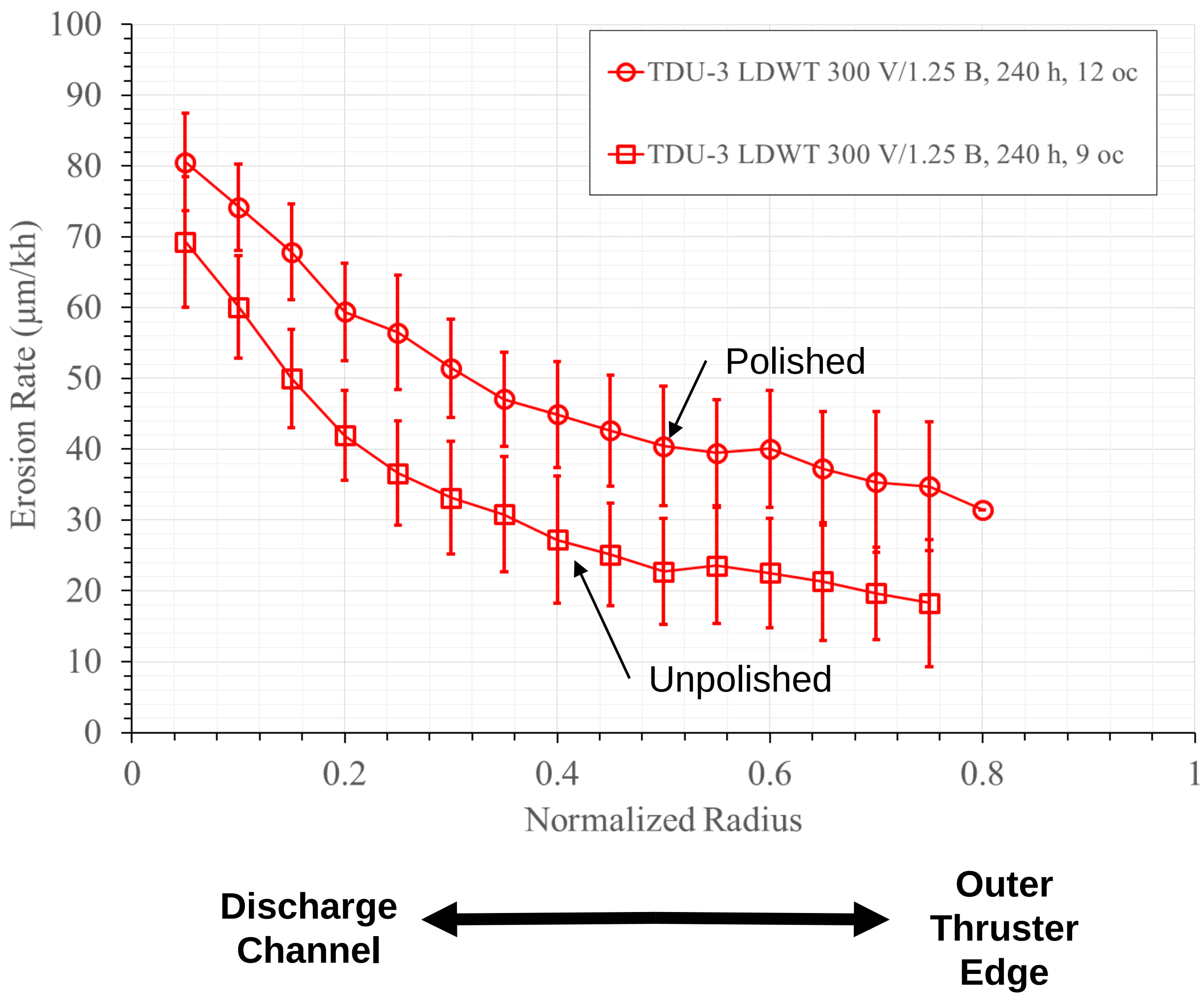


Discharge Channel ↔ **Outer Thruster Edge**

Key Observations:

1) The erosion rate varies with radius
   - Maxima near channel
2) The erosion rate at 600 V/1 B is 25% of 300 V/0.75 B
3) At 300 V, the erosion rate at 1.25 B is 1.4x higher than at 0.75 B

Results: OFPC Wear



Key Observations:

1) The erosion rate varies with radius
   - Maxima near channel
2) The erosion rate at 600 V/1 B is 25% of 300 V/0.75 B
3) At 300 V, the erosion rate at 1.25 B is 1.4x higher than at 0.75 B
4) OFPC wear appears azimuthally asymmetric
   - Pre-test surface finish different
   - Suggests possible link between surface finish and erosion rates

Results: OFPC Wear

Beginning of Test: Surface Polished
Higher Erosion Rates

End of Test: Surface Roughened
Lower Erosion Rates

Key Observations:

1) The erosion rate varies with radius
   – Maxima near channel
2) The erosion rate at 600 V/1 B is 25% of 300 V/0.75 B
3) At 300 V, the erosion rate at 1.25 B is 1.4x higher than at 0.75 B
4) OFPC wear appears azimuthally asymmetric
   – Pre-test surface finish different
   – Suggests possible link between surface finish and erosion rates
   – Link would also explain apparent time dependence of IFPC erosion rate

Conclusions

- NASA is committed to a sustainable return of humans to the Moon for long-term exploration and utilization
  - Gateway will enable this sustained cis-lunar presence and provide the capabilities necessary to develop and deploy critical infrastructure
  - The first element of the Gateway is planned to be the Power and Propulsion Element (PPE), which will launch in 2022 with a high-power solar electric propulsion system

- NASA is developing the requisite electric propulsion technologies under the Advanced Electric Propulsion Systems contract with Aerojet Rocketdyne
  - Risk-reduction activities including the performance of wear tests on TDU-level hardware have been completed
  - Engineering hardware fabrication is ongoing and development testing planned to start in 2019

Questions?