High-Power Performance of a 100-kW class Nested Hall Thruster

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Many missions are enabled by multi-hundred kW EP systems

- **Earth orbit transfer**: 200 kW @ 1500 s: LEO to GEO transfer
- **Near-Earth asteroids**: 300 kW @ 1800 s: cargo tug
- **Phobos**: 300 kW @ 3000 s: cargo, 700 kW @ 1800 s: humans
- **Mars**: 600 kW @ 3000 s: cargo, 800 kW @ 3000 s: humans
NASA is funding three options for 100-kW class electric propulsion.
The XR-100 system features the X3, a nested Hall thruster developed at UM.
The XR-100 system
The XR-100 system

VF5 (GRC)

PLASMA & THERMAL MODELING (JPL)

X3 NHT (UM)

300 A LaB$_6$ CATHODE (JPL)

TESTING INFRASTRUCTURE (GRC)

XFC (AR)

100-kW PPU (AR)

Aerojet Rocketdyne

NASA

University of Michigan
Testing focused on thruster and facilities

- X3 NHT (UM)
- 300 A LaB₆ CATHODE (JPL)
- VF5 (GRC)
- TESTING INFRASTRUCTURE (GRC)
A Brief History of NASA High-Power Hall Thruster Development
Timeline of NASA high-power Hall thruster development

1999

**NASA-457M**
- 50 kW class
- Operated to 100 kW (850 V and 1000 V)
Timeline of NASA high-power Hall thruster development

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2003

NASA-400M
- 50 kW class
- High-$I_{sp}$ operation (via NASA-173M)
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2004/2012

NASA-457Mv2
- 50 kW class
- Improved efficiency over v1
# Timeline of NASA high-power Hall thruster development

<table>
<thead>
<tr>
<th>Year</th>
<th>Model</th>
<th>Class</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>NASA-457M</td>
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<tr>
<td>2005/2011</td>
<td>NASA-300M</td>
<td>20 kW class</td>
<td>Best efficiency yet (65-73% anode)</td>
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</table>
All this work (and lessons learned) fed directly into X3 design
Open questions about the X3 and NHTs

- Does the X3 provide expected performance?
- Are there cathode coupling issues?
- How do the channels interact with each other?
X3 Performance Results
Thruster was throttled through 47 unique conditions

<table>
<thead>
<tr>
<th></th>
<th>300 V</th>
<th>400 V</th>
<th>500 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>I+O</td>
<td>0.6 j_{ref}</td>
<td>0.6 j_{ref}</td>
<td>0.6 j_{ref}</td>
</tr>
<tr>
<td>M+O</td>
<td>1.0 j_{ref}</td>
<td>1.0 j_{ref}</td>
<td>1.0 j_{ref}</td>
</tr>
<tr>
<td>I+M+O</td>
<td>1.3 j_{ref}**</td>
<td>1.3 j_{ref}**</td>
<td></td>
</tr>
</tbody>
</table>

At each (V_{dr}, j) condition:

- Inner (I)
- Middle (M)
- Outer (O)
- I+O
- I+M
- I+O+M
- M+O
- I+M+O
Thrust versus power is linear for each discharge voltage.
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5.4 N at 400 V, 98 kW
Average T/P ratio compared to other high-power thrusters
Average T/P ratio compared to other high-power thrusters

![Graph showing the average T/P ratio compared to other high-power thrusters. The graph plots discharge voltage against average T/P ratio, with data points for NASA-457Mv1 and NASA-400M.](image-url)
Average T/P ratio compared to other high-power thrusters
Average T/P ratio compared to other high-power thrusters
Maximum anode efficiency compared to other thrusters
Maximum anode efficiency compared to other thrusters
Maximum anode efficiency compared to other thrusters

![Graph showing maximum anode efficiency vs. discharge voltage for different thrusters. The graph includes data for NASA-457Mv1, NASA-400M, and NASA-300M.](image-url)
Maximum anode efficiency compared to other thrusters
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Cathode to ground voltage varied between $-9$ and $-14$ V.
Open questions about the X3 and NHTs

- Does the X3 provide expected performance?
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- How do the channels interact with each other?
Thrust for I+M+O is not significantly higher than sum of individual channels
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X2 work showed 5—11% increase in multi-channel thrust
Oscillations changed between single- and multi-channel operation
Example PSD from multi-channel operation
Example PSD from multi-channel operation

Inner breathing at different frequency

PSD of $I_D$

Frequency, kHz

Inner, Middle, Outer
Example PSD from multi-channel operation

- Inner breathing at different frequency
- Higher-frequency peak decreases in frequency and broadens

![Graph showing PSD of I_D vs Frequency, kHz].

- Log scale for PSD: $10^1$ to $10^6$
- Frequency range: 20 kHz to 100 kHz
- Lines represent Inner, Middle, and Outer channels.
Example PSD from multi-channel operation

Inner breathing at different frequency

Higher-frequency peak decreases in frequency and broadens
Example PSD from multi-channel operation

Inner breathing at different frequency

Higher-frequency peak decreases in frequency and broadens

PSD of $I_D$

Frequency, kHz
Open questions about the X3 and NHTs

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The X3 is expanding the boundaries of Hall thruster operation

96 kW @ 3460 s

112 A

3.3 N
The X3 is expanding the boundaries of Hall thruster operation.

- 96 kW @ 3460 s ($\eta_t=0.58$)
  - 112 A
  - 3.3 N

- 102 kW @ 2400-2600 s ($\eta_t=0.63$)
  - 247 A
  - 5.4 N
The X3 is expanding the boundaries of Hall thruster operation

96 kW @ 3460 s ($\eta_t=0.58$)  
112 A  3.3 N

102 kW @ 2400-2600 s ($\eta_t=0.63$)  
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- Dan M. Goebel at JPL
- Sarah E. Cusson at UM
Questions?
Backup Slides
Anode specific impulse versus discharge power
Consistent except for low current density
Maximum anode $I_{sp}$ comparable to other high-power Hall thrusters