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

Scott J. Hall, Benjamin A. Jorns, and Alec D. Gallimore
University of Michigan

Hani Kamhawi, Thomas W. Haag, and Jonathan A. Mackey
NASA Glenn Research Center

James H. Gilland
Ohio Aerospace Institute

Peter Y. Peterson
Vantage Partners

Matthew J. Baird
Western Michigan University
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:

- VASIMR
- ELF
- XR-100
The XR-100 system features the X3, a nested Hall thruster developed at UM.
The XR-100 system
The XR-100 system

VF5 (GRC)

X3 NHT (UM)

PLASMA & THERMAL MODELING (JPL)

300 A LaB₆ CATHODE (JPL)

TESTING INFRASTRUCTURE (GRC)

XFC (AR)

100-kW PPU (AR)
Testing focused on thruster and facilities

VF5 (GRC)

X3 NHT (UM)

300 A LaB₆ CATHODE (JPL)

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

1999

**NASA-457M**
- 50 kW class
- Operated to 100 kW (850 V and 1000 V)

2003

**NASA-400M**
- 50 kW class
- High-$I_{sp}$ operation (via NASA-173M)
Timeline of NASA high-power Hall thruster development

1999
- **NASA-457M**
  - 50 kW class
  - Operated to 100 kW (850 V and 1000 V)

2003
- **NASA-400M**
  - 50 kW class
  - High-$I_{sp}$ operation (via NASA-173M)

2004/2012
- **NASA-457Mv2**
  - 50 kW class
  - Improved efficiency over v1
Timeline of NASA high-power Hall thruster development

1999

- NASA-457M
  - 50 kW class
  - Operated to 100 kW (850 V and 1000 V)

2003

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

2004/2012

- NASA-457Mv2
  - 50 kW class
  - Improved efficiency over v1

2005/2011

- NASA-300M
  - 20 kW class
  - Best efficiency yet (65-73% anode)
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>0.6 $j_{\text{ref}}$</td>
<td>0.6 $j_{\text{ref}}$</td>
<td>0.6 $j_{\text{ref}}$</td>
<td></td>
</tr>
<tr>
<td>1.0 $j_{\text{ref}}$</td>
<td>1.0 $j_{\text{ref}}$</td>
<td>1.0 $j_{\text{ref}}$</td>
<td></td>
</tr>
<tr>
<td>1.3 $j_{\text{ref}}$</td>
<td>1.3 $j_{\text{ref}}$</td>
<td>1.3 $j_{\text{ref}}$ **</td>
<td></td>
</tr>
</tbody>
</table>

At each $(V_d, j)$ condition:

- Inner (I)
- Middle (M)
- Outer (O)
- I+O
- I+M
- M+O
- I+M+O
Thrust versus power is linear for each discharge voltage.

![Graph showing linear relationship between thrust and discharge power for different voltages](image)
Thrust versus power is linear for each discharge voltage.

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
Average T/P ratio compared to other high-power thrusters
Average T/P ratio compared to other high-power thrusters

[Graph showing discharge voltage vs. average T/P ratio for different thrusters]
Maximum anode efficiency compared to other thrusters
Maximum anode efficiency compared to other thrusters
Maximum anode efficiency compared to other thrusters
Maximum anode efficiency compared to other thrusters
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?
Cathode to ground voltage varied between $-9$ and $-14$ V
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?
Thrust for I+M+O is not significantly higher than sum of individual channels.
Thrust for I+M+O is not significantly higher than sum of individual channels
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

PSD of $I_D$

Frequency, kHz

10^1

10^2

10^3

10^4

10^5

10^6

Inner

Middle

Outer
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 $I_0$

Frequency, kHz

10^6

10^5

10^4

10^3

10^2

10^1

20 40 60 80 100

Inner blue, Middle red, Outer black
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?
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

<table>
<thead>
<tr>
<th>Power</th>
<th>Current</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>96 kW @ 3460 s ($\eta_t=0.58$)</td>
<td>112 A</td>
<td>3.3 N</td>
</tr>
<tr>
<td>102 kW @ 2400-2600 s ($\eta_t=0.63$)</td>
<td>247 A</td>
<td>5.4 N</td>
</tr>
</tbody>
</table>
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
Acknowledgments

• NASA Space Technology Fellowship (NNX14AL67H)
• NASA Next Space Technologies for Exploration Partnerships (NNH16CP17C)
• At GRC: Eric Pencil, Luis Pinero, Wensheng Huang, Taylor Seablom, Chad Joppeck, Richard Senyitko, Jim Zakany, Nick Lalli, Jim Zologowski, Kevin Blake, Joshua Gibson, David Yendriga, Larry Hambly, George Jacynycz
• Dan M. Goebel at JPL
• Sarah E. Cusson at UM
Questions?
Backup Slides
Consistent except for low current density
Maximum anode $I_{sp}$ comparable to other high-power Hall thrusters