Comparison of NASA’s 30-cm Ion Thruster Capabilities with the Dawn Mission Requirements

July 11, 2006

John Brophy and Charles Garner
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
Dawn Mission and Flight System

- Dawn will launch in June-July, 2007
- The Ion Propulsion System (IPS) includes three 30-cm diameter ion thrusters operated one at a time
- The IPS must process ~395 kg of xenon
  - 132 kg per thruster if all three thrusters work
  - 198 kg per thruster if one fails at the beginning of the mission
Dawn Ion Thruster Status

**Status**

- Fabrication of all 3 Dawn Ion Thrusters is Complete
- All 3 thrusters have been tested for approximately 60 hours each
  - Pre-Vibe; Post-Vibe; Thermal-Vac & Final Functional
- All 3 thrusters are in storage at JPL
Thruster Throttle Range
112 Mission Levels; 16 Throttle Levels (TH)
Performance Parameters

Independent parameters:
1. Beam Supply Current, $J_B$
2. Beam Supply Voltage, $V_B$
3. Accel. Voltage, $V_A$
4. Neut. Keeper Current, $J_{NK}$
5. Main Xe Flow Rate

Dependent parameters:
1. Input Power, $P_T$
2. Thrust, $T$
3. Specific Impulse, $I_{sp}$
4. Thruster Efficiency, $\varepsilon_T$
5. Discharge Loss, $\varepsilon_B$
6. Discharge Current, $J_D$
7. Discharge Voltage, $V_D$
8. Accel. Current, $J_A$
9. Neut. Keeper Voltage, $V_{NK}$
10. Coupling Voltage, $V_C$
11. Double Ion Fraction, $J^{++}/J^+$
12. Beam Divergence, $F_T$
13. Beam Flatness, $f_B$
14. Electron-Backstreaming Voltage
15. Perveance limit
16. Thrust-vector Location
17. Neutralizer flow margin

Performance Equations

\[
P_T = J_B V_B + J_D V_D + J_{NK} V_{NK} + J_A V_A
\]

\[
T = \sqrt{\frac{2m_e}{e} \gamma (J_B - J_A) \sqrt{V_B}}
\]

\[
I_{sp} = \frac{T}{m_T g}
\]

\[
\varepsilon_T = \frac{T I_{sp} g}{2 P_T}
\]

\[
\varepsilon_B = \frac{J_D V_D}{J_B}
\]
• All three thrusters produce the required beginning-of-life (BOL) thrust

• No changes after vibe and thermal tests
- FT001 does not meet the discharge loss specification between mission levels 20 to 50
  - Two magnets in sideways
- No changes after vibe and thermal tests
- FT001 slightly exceeds the BOL discharge current specification
  - Two magnets in sideways
- No changes after vibe and thermal tests
Neutralizer Keeper Voltage

- All three thrusters meet the BOL neutralizer keeper voltage specification
- No significant changes after vibe and thermal tests
• All three thrusters meet the BOL perveance specification
• No significant changes after vibe and thermal tests
Centerline Double Ion Fraction

- All three thrusters exceed the specification for the BOL double ion fraction
- No significant changes after vibe and thermal tests
• All three thrusters exceed the electron-backstreaming voltage specification

• No significant changes after vibe and thermal tests
Thruster Life
Mission Specific Throttling
Mars Gravity Assist Trajectory

- The Dawn IPS must operate over an 8.5-year period
- At the beginning of the mission the solar array provides more power than the IPS can use so the PPU input is constant
- About 4 years into the mission the PPU input power decreases with the available solar array power
Electron-Backstreaming Data from the Extended Life Test (ELT)

- **EBS Limit (V)**
- **Run Time (hrs)**

The graph shows the electron-backstreaming data from the extended life test (ELT) with the accelleration supply capability indicated.

Key points:
- TH0
- TH5
- TH12
- TH15
- TH8
Electron-Backstreaming Model

- EBS model from J. Williams, D. Goebel, and P. Wilbur (AIAA-2003-4560)

- Requires knowledge of:
  - Beamlet current, $J_b$
  - Accel. Hole Diameter, $d_a$
  - Beam Plasma Potential, $V_{bp}$
  - Beamlet diameter, $d_b$
  - Electron Temperature, $T_e$
  - Grid Gap, $l_g$
  - Accel. Grid Thickness, $t_a$

- Must know the value of these parameters over the full throttle range

$$V_a = \frac{V_{sp} - \Delta V - V_{dp}B}{1 - B}$$

$$V_{sp} = V_{bp} + T_e \ln \left( \frac{2J_e}{J_b} \sqrt{\frac{V_{dp} - V_{bp}}{T_e}} \right) \left( \frac{\pi m_e}{m_i} \right)$$

$$\Delta V = \frac{J_b}{2\pi \varepsilon_0} \sqrt{\frac{m_i}{2e(V_{dp} - V_{sp})}} \left[ \frac{1}{2} - \ln \left( \frac{d_b}{d_a} \right) \right]$$

$$B = \frac{d_a}{2\pi l_e} \left[ 1 - \frac{2t_a}{d_a} \tan^{-1} \left( \frac{d_a}{2t_a} \right) \right] e^{\frac{t_a}{d_a}}$$

$$l_e = \sqrt{(l_g + t_s)^2 + \frac{d_s^2}{4}}$$
The maximum beamlet current has a significant effect on the EBS voltage and this effect increases as the accel. grid wears.

**Mathematical Representation:***

- EOL: $y = 613.6x + 55.66$
- BOL: $y = 459.75x + 32.092$

**Graphical Representation:**
- **Y-axis:** Calculated EBS Voltage (V)
- **X-axis:** Beamlet Current (mA)
- **Lines:**
  - Red line represents the EOL curve.
  - Blue line represents the BOL curve.

---

**Additional Text:**

- Effect of Beamlet Current
- at Full Power

---

**Footer:**

- Ion Propulsion System
- UCLA JPL Orbital
- Los Alamos
- DLR
- XE

---

**Page Number:** 17
Faraday Probe Data Analysis to Determine the Beamlet Current, $J_b$

Probe traces made symmetric by:
- Shifting the centerline to match the wings
- Averaging the resulting right and left sides

Visual Basic program determines the beamlet current profile necessary to result in the measured Faraday probe trace

The program accounts for the variation in beamlet divergence as a function of beamlet current based on the CEX2D code and the grid curvature
Example of Faraday Probe Data Analysis

- FP data from FT3 final functional at TH15
- Beamlet divergence angle vs beamlet current from CEX2D
- Results:
  - Measured: $J_B = 1.754$ A
  - Calculated: $J_B = 1.745$ A
  - Flatness Parameter: 0.42

![Graph showing Faraday Probe data analysis results](image)

- Calculated
- Measured

$y = 2.767E+02x^2 - 1.413E+02x + 2.558E+01$

$R^2 = 9.958E-01$

- $V_S = 1100$ V
- $V_A = -200$ V
- $I_g = 490$ microns

![Graph showing calculated beamlet currents](image)

- Calculated Beamlet Currents

- Relative Beamlet Current

![Graph showing grid radius vs beamlet current](image)

- Grid Radius (cm)
- Beamlet Current (mA)
• Life Demonstration Test (LDT) used an “EM” thruster

• Extended Life Test (ELT) used the DS1 Flight Spare thruster

• DS1 flew the NSTAR FT1 thruster

• Peak beamlet currents range from 0.27 mA to 0.30 mA
• Peak beamlet current range from 0.27 mA to 0.33 mA
• FT002 has the most peaked profile
• No significant changes after vibe and thermal tests
Maximum Beamlet Current

- FT002 exceeds the BOL peak beamlet current specification by 10% to 14% at the high-power end of the throttle range.
- No significant changes after vibe and thermal tests.

Dawn FT1 Maximum Beamlet Current

Dawn FT2 Maximum Beamlet Current

Dawn FT3 Peak Beamlet Current
• Erosion Geometry Based on the ELT Results
• Thee phases of erosion: Cusp removal; Cylindrical erosion; Chamfer erosion

Minimum hole diameter occurs at ~160 microns from the upstream surface at EOL.
Accelerator Grid from the ELT Showing the Erosion Geometry

- Pit Eroded Completely Through the Grid
- Accel. Grid Aperture
- Original Downstream Grid Surface
- Pits & Grooves Erosion

500 microns
Scaling Accel. Hole Wall Erosion Rates from the ELT Using the CEX2D Code

Total mass removed from the hole wall of the center hole:

\[ M_{TOTAL} = \dot{M}_{TH15}(T_1 + T_3 + T_5) + \dot{M}_{TH15}\left(\frac{\dot{M}_{TH8}}{M_{TH15}}\right)T_2 + \dot{M}_{TH15}\left(\frac{\dot{M}_{TH5}}{M_{TH15}}\right)T_6 + \dot{M}_{TH15}\left(\frac{\dot{M}_{TH0}}{M_{TH15}}\right)T_4 \]

ELT Segment Run times
\[ T_1 = 4.2 \text{ khrs at TH15} \]
\[ T_2 = 5.8 \text{ khrs at TH8} \]
\[ T_3 = 5.2 \text{ khrs at TH15} \]
\[ T_4 = 5.7 \text{ khrs at TH0} \]
\[ T_5 = 4.4 \text{ khrs at TH15} \]
\[ T_6 = 4.6 \text{ khrs at TH5} \]

Relative accel. hole wall erosion rates determined from the CEX2D code

Relative Accel. Hole Wall Erosion Rate

Throttle Level -- TH

y = -7.482E-05x^4 + 1.728E-03x^3 - 5.355E-03x^2 + 1.076E-03x + 1.145E-01
Change in Minimum Accel. Hole Diameter

**Ion Propulsion System**

- **BOL Spec.**
- **Model**
- **Cusp Erosion**
- **Cylindrical Erosion**
- **Chamfer Erosion**

**Measured from video tape images**

"Probably indicates that not all of the erosion is simply making the cylindrical hole walls uniformly larger in diameter as the model assumes."
EBS Model Prediction for a Fixed Hot Grid Gap

The graph shows the measured and calculated EBS limits over run time for different hot grid gaps. The x-axis represents run time in hours, ranging from 0 to 35000. The y-axis represents EBS limit in volts, ranging from 50 to 250. The graph includes data points for TH12, TH15, TH8, TH15, TH0, TH15, and TH5 hot grid gaps.
Required Grid Gap Variation Over the Throttle Range

- Nominal Cold Gap
- Fixed Value

Beam Current (A)

Relative Grid Gap
EBS Model Prediction
for a Variable Hot Grid Gap

Run Time (hrs)
EBS Limit (V)

Variable Grid Gap
Fixed Grid Thickness

TH12  TH15  TH8  TH15  TH0  TH15  TH5

Note: Wrong Slopes

Measured
Calculated

Dawn

Ion Propulsion System
EBS Model Prediction
for a Variable Hot Grid Gap and Accel. Grid Thinning
Probabilistic Failure Analysis

Input Parameter Distributions:

- Erosion rates uncertainty: +/-15%
- Flow rates uncertainty: +/-3%
- Beamlet current uncertainty: +/-10%
- Beamlet diameter uncertainty: +/-10%
- Hot grid gap uncertainty: +/-0.02 mm
- Minimum hole dia. after cusps removal uncertainty: +/-0.010 mm
- Minimum hole dia. at which chamfering starts uncertainty: +/-0.020 mm
- Pits & Grooves width uncertainty: 450 to 575 microns
- Beam plasma potential uncertainty: +/-5 V
- Electron temperature in the beam plasma uncertainty: +/-0.25 eV

Dawn Mission Trajectory

- PFA follows the thruster power use for a representative Dawn trajectory
Predicted Failure Distribution
Full Power Operation Only

Failure Distribution Due to Accelerator Grid Erosion

Most Probable Failure at 187 kg

Relative Probability vs. Total Xe Throughput (kg)
Predicted Failure Distribution

ELT Profile

EBS Failure Probability

- 50% failure probability

The ELT was suspended at 235 kg

<table>
<thead>
<tr>
<th>Level</th>
<th>(Khrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH12</td>
<td>0.43</td>
</tr>
<tr>
<td>TH15</td>
<td>4.20</td>
</tr>
<tr>
<td>TH8</td>
<td>5.80</td>
</tr>
<tr>
<td>TH15</td>
<td>5.20</td>
</tr>
<tr>
<td>TH0</td>
<td>5.70</td>
</tr>
<tr>
<td>TH15</td>
<td>4.40</td>
</tr>
<tr>
<td>TH5</td>
<td>Until failure</td>
</tr>
</tbody>
</table>

Total Xe Throughput (kg)
Predicted Failure Distribution
One Thruster for the Entire Dawn Mission

EBS Failure Probability

100% Probability of Failure
50% failure probability

Required throughput per thruster for one thruster

Total Xe Throughput (kg)
Predicted Failure Distribution

- **One Thruster**
  - 100% Probability of Failure

- **Two Thrusters**
  - Required throughput per thruster for two thrusters

- Required throughput per thruster for one thruster

Total Xe Throughput (kg):
- 100
- 150
- 200
- 250
- 300
- 350
- 400
- 450
Summary of PFA Results

• The PFA model predicts:
  – At full power NASA’s 30-cm thruster is most likely to fail after processing 187 kg of xenon
  – If the Extended Life Test (ELT) of the DS1 flight spare ion thruster had been continued it would most likely have processed about 300 kg of xenon before it failed – the test was suspended at 235 kg
  – A 100% probability of failure for Dawn if one thruster is used for the entire mission
  – A 2.6% probability of failure for each thruster if two thrusters are used for the entire mission (worst case mission requirement)
    • This is reduced to less than 1% wear-out failure risk for the mission if the second thruster is used to complete the mission in the event that the first one wears out
  – Zero probability of accelerator grid wearout failures if all three thrusters are used
Conclusions

- The Dawn ion thrusters meet all of the performance and life requirements for the Dawn mission
  - FT001 has two magnets in sideways in the middle magnet ring, but this has only a minor impact on the thruster performance

- Electron-backstreaming is the first wear-out failure mechanism for the Dawn ion thrusters – PFA Modeling Indicates
  - The mission cannot be completed with a single thruster
  - The probability for mission success based on accelerator grid wear is > 99% for the worst case thruster usage for nominal thruster beamlet profiles
  - FT002 has the most peaked beam profile which impacts the thruster’s throughput capability
    - PFA results indicate that this reduces the probability for mission success based on accelerator grid wear to 97% based on the worst case thruster usage
  - The wear-out probability is zero if all three thrusters are used during the mission