Iodine Plasma Species Measurements in a Hall Effect Thruster Plume

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14. ABSTRACT
The plasma plume from a 200 W Hall Effect Thruster fueled by iodine vapor was analyzed. The plasma source included a laboratory propellant feed system and a laboratory model Hall thruster powered by a breadboard power processing unit. The hollow cathode was fed with xenon. The distribution of iodine ions was measured with an ExB probe, an electrostatic analyzer (ESA), and a combined ESA/ExB probe. The distribution of xenon ions was also measured. Multiply charge species were detected with both iodine and xenon. Significant populations of diatomic iodine ions were also detected. The dimer fraction was found to vary with operating conditions and angular distance from the beam centroid. The greatest populations of high energy dimers were observed at lower discharge current, and at angles of 30-50 degrees from the beam centroid. At one operating condition, the high energy dimer fraction was approximately 20% by mass in this region. Significant dimer fractions could increase thrust to power by useful amounts at the cost of some overall efficiency.

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Iodine Plasma Species Measurements in a Hall Effect Thruster Plume


AIAA Paper 2013-XXXX

[1] Chief Scientist for Hall Thrusters, AIAA Associate Fellow
[2] Research Engineer, AIAA Member
Abstract

• The plasma plume from a 200 W Hall Effect Thruster fueled by iodine vapor was analyzed.
• The plasma source included a laboratory propellant feed system and a laboratory model Hall thruster powered by a breadboard power processing unit.
• The distribution of iodine ions was measured with an ExB probe, an electrostatic analyzer (ESA), and a combined ESA/ExB probe.
• Results:
  – Multiply charged species were detected
  – Significant populations of diatomic iodine ions were detected.
  – The dimer fraction was found to vary with operating conditions and angular distance from the beam centroid.
  – The greatest populations of high energy dimers were observed at lower discharge current, and at angles of 30-50 degrees from the beam centroid.
• Dimers could increase thrust to power by useful amounts at the cost of some overall efficiency.
Outline

• Background on Iodine Hall Thrusters
• Apparatus and Procedure
• Experimental Data
• Discussion and Implications
• Conclusions
HET Propellants at Busek

- **Magnesium**
  - High Isp

- **Zinc**
  - High Storage Density

- **Krypton**
  - Alternative Noble Gas

- **Iodine**
  - Replacement for Xe

- **Xenon**
  - SOTA Propellant

- **Bismuth**
  - High Thrust to Power
Iodine Propellant

- Iodine is an attractive alternative to Xe
  - Easy to ionize
  - Measured thrust, specific impulse, and anode efficiency similar to values obtained with Xe at similar operating conditions
  - Lower beam divergence than Xe
- High density
  - Stores at 2-3 times density of Xe
  - Modest heating to generate gas (sublimation)
- Low feed system pressure
  - Tank pressure is 1000 times lower than Xe
- Passive long term storage
  - I$_2$ stores in the solid phase
  - No temperature control for inactive system
- Low cost
  - Depends on market, purity
- Easy to pump in test facilities
  - High power ground demonstrations feasible

<table>
<thead>
<tr>
<th>Element</th>
<th>I</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Mass</td>
<td>126.9</td>
<td>131.3</td>
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<tr>
<td>Ionization Properties (monatomic)</td>
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<tr>
<td>First Ionization Potential (eV)</td>
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<td>Peak Cross Section (10$^{-16}$ cm$^2$)</td>
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<td>Storage and Handling Properties</td>
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<td>Storage density (gm/cm$^3$) near room temp.</td>
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<tr>
<td>Melting Point (°C)</td>
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<td>-112</td>
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<tr>
<td>Boiling Point at 10 Pa (°C)</td>
<td>9</td>
<td>-181</td>
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</table>

*$^*$14 Mpa, 50 C (NIST Database)
BHT-200 Flowing Iodine (2010)

• Apparatus
  – BHT-200 Thruster & cathode (flight models)
  – Breadboard PPU
  – Custom propellant feed system

• Procedures
  – Preheat thruster with Xe discharge
  – Measure thrust, plume current with I2 and Xe
  – Measure species (ExB, beam centroid, one condition)

• Results
  – Efficiency with I2 and Xe close at most conditions
    • Superior to Xe at highest power
  – At same voltage, thrust to power (T/P) usually slightly higher
    but Isp slightly lower with I2
  – Much lower tank pressure with I2
  – Plume divergence lower with I2
  – Dimers (I2\textsuperscript{+}) measured at beam centroid (a few %)
What is the Composition of the Iodine Plume?

- Iodine plasma discharge more complicated than Xe discharge
- What processes need to be included when modeling the discharge and plume?
- How might heavy species impact performance?

### Basic Xe physics

<table>
<thead>
<tr>
<th>Process</th>
<th>Equations</th>
</tr>
</thead>
</table>
| Elastic & Inelastic Scattering | $e + I \rightarrow 2e + I^+$  
|                             | $e + I \rightarrow 3e + I^{2+}$  
| Dissociation                | $e + I_2 \rightarrow 2e + I_2^+$  
|                             | $e + I_2 \rightarrow 3e + I_2^{2+}$  
| Electron Attachment        | $e + I \rightarrow I^-$  
| (Negative Ions)             | $e + I_2 \rightarrow I_2^-$  
|                             | $e + I_2 \rightarrow I^- + I$  
| Charge Transfer             | $I^+ + I^- \rightarrow I^+ + I$  
| Recombination               | $I_2^+ + I^- \rightarrow I_2^+ + I$  
|                             | $e + I^+ \rightarrow I$  

### Processes

- Elastic & Inelastic Scattering
- Dissociation
- Electron Attachment (Negative Ions)
- Charge Transfer
- Recombination

### Products

- $e$
- $I, I_2$
- $I^+, I_2^+, I^{2+}$
- $I, I_2^-$
Apparatus

• **System Hardware**
  – BHT-200 Thruster
    • Experimental version
    • Not identical to flight model
  – BHC-1500 Cathode
    • Flight design
  – BPU-600 PPU
    • Breadboard of flight model
  – Custom propellant feed system
    • Developed at Busek

• **Test Hardware**
  – Vacuum test facility (6’ diameter)
  – Faraday probe (MIT)
  – ESA, ExB, ESA/ExB Probes (Plasma Controls)
  – Rotary probe arm (about thruster exit plane)
Procedure

• Survey plume with Faraday probe
• Measure total species currents with ExB probe
• Measure energy distributions with ESA probe
• Measure high energy species with ESA/ExB probe
• Analyze data
Results - Plume Current

- Probe measures current density vs. angle
- Current vs. angle
  - Integrate \( j(\theta) \sin(\theta) \)
    \[
    I_b = 2\pi r^2 \int_0^{\pi/2} j(\theta) \sin(\theta) d\theta
    \]
- Axial momentum vs. angle (est.)
  - Integrate \( j(\theta)\sin(\theta)\cos(\theta) \)
  - Trig multiplier peaks at \( 45^\circ \)
    \[
    F_t = \frac{2\pi r^2 \int_0^{\pi/2} j(\theta) \sin(\theta) \cos(\theta) d\theta}{I_b}
    \]
- Significant momentum at \( \theta > 20^\circ \)
- Composition away from centroid matters

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Species Analysis (ESA/ExB)

- ExB probe measures current
- Species fractions are proportional to the area under the curve

Species fraction by current proportional to area under curve

[Graph showing measured current (A) plotted against set voltage (V), with peaks at $I^+$, $I_{2^+}$, and $I^{++}$]
Results - Iodine ExB

- ExB sweeps taken at a wide variety of operating conditions, angles
- $I_2^+$ signals clearly observed in many sweeps
- Issue: ExB sweeps do not resolve energy or momentum carried by species
  - Some or all of the dimers could be low energy

![Graph showing measured current vs. set voltage with $I^+$ and $I_2^+$ peaks at 250 V, 150 W]
Results - Iodine ESA

- ESA sweeps taken at same operating conditions, angles
- Energy distribution varies with position
  - Mostly low energy CEX in wings
- For effect of dimers on thrust, want to limit analysis to high energy populations
• Combined probe selects only high energy ions
  - At 250 V, 150 W, 30 degrees, >20% of the high energy beam by mass comes from dimers

<table>
<thead>
<tr>
<th>Angle (deg)</th>
<th>Species</th>
<th>Mass</th>
<th>Charge</th>
<th>f</th>
<th>g</th>
<th>h</th>
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<tr>
<td>0</td>
<td>I₂⁺</td>
<td>2</td>
<td>1</td>
<td>0.02</td>
<td>0.04</td>
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<tr>
<td>0</td>
<td>I⁺</td>
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<td>1</td>
<td>0.92</td>
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<td>0</td>
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<td>2</td>
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<td>0.03</td>
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<tr>
<td>0</td>
<td>I³⁺</td>
<td>1</td>
<td>3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>10</td>
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<td>0.04</td>
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<td>I⁺</td>
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<tr>
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<td>2</td>
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<td>0.05</td>
</tr>
<tr>
<td>10</td>
<td>I³⁺</td>
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<td>3</td>
<td>0.01</td>
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<td>0.00</td>
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<td>30</td>
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<td>0.12</td>
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<td>0.06</td>
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<tr>
<td>30</td>
<td>I³⁺</td>
<td>1</td>
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<td>0.00</td>
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<td>0.00</td>
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<tr>
<td>40</td>
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<td>1</td>
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<tr>
<td>40</td>
<td>I⁺</td>
<td>1</td>
<td>1</td>
<td>0.85</td>
<td>0.80</td>
<td>0.87</td>
</tr>
<tr>
<td>40</td>
<td>I²⁺</td>
<td>1</td>
<td>2</td>
<td>0.05</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>50</td>
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<td>0.20</td>
<td>0.11</td>
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<tr>
<td>50</td>
<td>I⁺</td>
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<td>1</td>
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<td>0.75</td>
<td>0.83</td>
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<tr>
<td>50</td>
<td>I²⁺</td>
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<td>2</td>
<td>0.11</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>60</td>
<td>I₂⁺</td>
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<td>1</td>
<td>0.08</td>
<td>0.17</td>
<td>0.09</td>
</tr>
<tr>
<td>60</td>
<td>I⁺</td>
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<td>1</td>
<td>0.80</td>
<td>0.78</td>
<td>0.85</td>
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<tr>
<td>60</td>
<td>I²⁺</td>
<td>1</td>
<td>2</td>
<td>0.12</td>
<td>0.06</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Species Fraction Definitions

- **Area A**: peak height \( x \) width @ half maximum
- **f**: current fractions
  - Collected by ExB
- **h**: number fractions
  - Factor out charge
  - \( I^{++} \) has twice as much
- **g**: mass fractions
  - Factor in mass
  - Dimers weigh twice as much

\[
\begin{align*}
    f_k &= \frac{A_k}{\sum_k A_k} \\
    h_k &= \frac{A_k / q_k}{\sum_k A_k / q_k} \\
    g_k &= \frac{A_k M_k / q_k}{\sum_k A_k M_k / q_k}
\end{align*}
\]
Results – High Energy Iodine Species

- Measured fraction of beam that is dimers can be very significant
  - Fraction by mass (function g) is 20% at some locations and operating conditions

![Populations by Mass at 250 V, 150 W](chart)
What Effect Might Dimers Have Upon Performance?

- **Thrust**
  - Thrust is sum of species
    \[ F = \sum_k \dot{m}_k <v_{k,z}>. \]
  - Ion voltage, mass, charge determine ion velocity
    \[ v = \sqrt{\frac{2q\Delta\Phi}{M}} \]

- **Specific Impulse**
  - Determined by thrust and mass flow

- **Efficiency**
  - Determined by thrust, mass flow, power

- **Thrust to power**
  - Determined by efficiency, specific impulse

- Can estimate effect of species distributions upon these parameters

\[ I_{sp} = \frac{F}{\dot{m}g_0} = \frac{\bar{v}}{g_0} \]

\[ \eta = \frac{F I_{sp} g_0}{P} = \frac{F^2}{2\dot{m}P} \]
Discussion - Efficiency Factor (Theory)

Efficiency factor (polydispersivity) with respect to a purely monatomic beam

\[ \eta_s \propto \frac{\left( \sum_k h_k M_k v_k \right)^2}{\sum_k h_k M_k \sum_k h_k q_k} \]

\[ \eta = \frac{F^2}{2mP} \]

The presence of multiple species does not mean the thruster will be inefficient (though there is an efficiency loss)

<table>
<thead>
<tr>
<th>( \eta_s )</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98</td>
<td>50% → 49%</td>
</tr>
<tr>
<td>0.94</td>
<td>50% → 47%</td>
</tr>
</tbody>
</table>

Starting point

Is not \( \eta_s = 1.0 \) (Xe++)

No dimers

No doubly charged
Discussion - Thrust to Power Factor (Theory)

\[
\frac{T}{P} \propto \frac{\sum_k h_k M_k v_k}{\sum_k h_k q_k}
\]

T/P factor is with respect to a purely monatomic beam

Dimers have the potential to increase T/P by a significant amount (but you need a lot to make a really big difference)

250 V, 150 W
80-90% I+
\(h I_2^+/I^{++} = 2/3\) to 3

No dimers

No doubly charged

(Varies with angle)
Results vary with Operating Conditions, Position

• Dimer fraction varies significantly with operating conditions.
  – Largest when the current is low and the discharge is rarified.
  – Highest fractions are observed at 250 V and 150 W, where I=0.6 A.
  – Relatively large, localized populations are also found at 0.71 and 0.8 A.

• Dimer fraction is larger off axis than in the center of the beam.
  – But momentum also peaks away from the centroid.

• Dimers are present in sufficient numbers to measurably increase T/P
Conclusions

• Iodine vapor has been shown to be an attractive replacement for Xe for typical missions (past work)
  – Thrusters characterized at power levels from 100 W to 10 kW
  – Measured thrust, specific impulse, and anode efficiency similar to values obtained with Xe at similar operating conditions
  – Beam divergence lower with iodine

• Plume of experimental BHT-200 measured with multiple instruments
  – Faraday probe → plume current
  – ExB probe → species populations across all energies
  – Electrostatic analyzer (ESA) → ion energies across all populations
  – ESA/ExB → species populations at selected energies and positions

• Results
  – Significant populations of molecular iodine present at some locations and operating conditions
  – Should be included in models of the discharge and plume
  – Populations large enough to measurably affect performance
  – Future work is required
Potential Applications for Iodine

- **Low power (200 W and similar)**
  - Compact, low mass propulsion system for small S/C
  - De-orbit systems

- **Medium power (1 to 5 kW)**
  - Geo-stationary satellites
    - GTO to GEO transfers
    - Station-keeping
  - Payload delivery systems based on ESPA or similar
  - Interplanetary probes
    - NASA Flagship, Frontier, Discovery class missions to Asteroids, comets, dwarf planets, outer planets

- **High power (10 kW and above)**
  - High power electric upper stages
  - NASA SEP demonstration
  - Missions to the moon, Mars, asteroids, supporting human exploration
Acknowledgements

- Species measurements were supported by the Air Force Research Laboratory (AFRL) under FA9300-10-C-2108
- Additional testing supported by the USAF, NASA, and ULA
Backup Slides

BHT-8000 Operating on Iodine
Hall Effect Thrusters (HETs)

- Form of electric propulsion used for in-space maneuvers
  - Simple
  - Efficient
  - High thrust density
  - Low cost
- Plasma is ionized in an electron-impact cascade and accelerated by an applied electric field
- Beam neutralized by a cathode
- Typical propellant is xenon
  - All known flight thrusters
- Many potential alternatives

**Axisymmetric Hall thruster**
History of Hall Effect Thrusters

• 1962  First Hall Effect Thrusters (US)
• 1963  First Soviet thrusters (Morozov, USSR)
• 1971  First HET in space (USSR, Meteor-18)
• 1982  SPT-100 and SPT-70 introduced (USSR)
• 1991  Soviet HETs reintroduced to West
• 1993  Busek begins Hall thruster development
        -- All US owned technology
• 1998  D-55 (USSR) launched on STEX (US)
• 2003  SMART-1 mission (ESA) beyond GEO
        -- French thruster based on Russian technology
• 2006  Busek BHT-200 launched on TacSat-2 (US)
        -- First US Hall thruster in Space
• 2010  Aerojet BPT-4000 launched on AEHF (US)
        -- Licensed Busek technology
• 2010  BHT-200 demonstrated on iodine propellant (US)
The Rocket Equation

- Station keeping (15 years) ~ 0.75 km/s
- Earth to Mars (low thrust transfer) ~ 6 km/s

\[ \frac{m_p}{m_0} = 1 - \exp\left[-\frac{\Delta V}{I_{sp} g_0}\right] \]
HET Propellant Selection

- Factors to consider
  - Performance (thrust, Isp, eff.)
  - Density
  - Condensability/vapor pressure
  - Reactivity
  - Toxicity
  - Cost
  - Spacecraft interactions potential
Iodine vs. Cryogenic Noble Gases

- Cryogenic Kr stores at ~2.4 g/cc
  - Density = 2.41 g/c at b.p. (wikipedia)
- Cryogenic Xe stores at ~2.9 g/cc
  - Density = 3.06 at b.p. (wikipedia)
- Iodine stores at up to 4.9 g/cc at room temperature
Facility Background Pressure

- Indicated pressure is several times lower when running with iodine.
- Sensitivity of pressure sensor to different gases is approximately proportional to ionization X-section at 150 eV.
- The ratio of I vs. I\textsubscript{2} neutrals is unknown at this time.
- What can we say? Iodine partial pressure is roughly 50%-90% of what is indicated with the sensor calibrated for Xe.
- Complicating matters is the presence of Xe (cathode) and other gases (N\textsubscript{2}, etc.)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Ionization Cross Section at 150 eV (Ang\textsuperscript{2})</th>
<th>Relative Sensitivity w.r.t. N\textsubscript{2}</th>
<th>Relative Sensitivity w.r.t. Xe</th>
<th>Reported Relative Sensitivity w.r.t. N\textsubscript{2}</th>
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<tbody>
<tr>
<td>N\textsubscript{2}</td>
<td>1.75</td>
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<td>Kr</td>
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<td>I</td>
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<td>4.85</td>
<td>1.94</td>
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### Iodine Performance (BHT-200)

- Nominal thruster operating condition is 250 V, 200 W
  - Slightly higher T/P, slightly lower Isp

<table>
<thead>
<tr>
<th>Gas</th>
<th>Flow Rate (mg/s)</th>
<th>Potential (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
<th>Thrust (mN)</th>
<th>T/P (mN/kW)</th>
<th>Anode Isp (s)</th>
<th>Anode Eff (-)</th>
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<tbody>
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Iodine Plume (BHT-1000)

- Plume current (Faraday probe)
- Iodine yields lower divergence than Xe
- Favorable point for Xe
  - 30 degrees encloses 86% of Xenon plume, 90% of Iodine plume
- Tank pressure always lower with iodine

![Graph showing current vs. angle for Iodine and Xenon plumes]

Xenon

Iodine 500 V, 2 A, I₂

Distribution A: Approved for public release; distribution is unlimited
Presented at 2012 JPC
A plume shield can greatly reduce the large angle plume

Plume Shield (BHT-1000)

**Current Density, 500V, 2A, Iodine, with and without Plume Shield**

- **iodine, p = 3.2e-5 torr**
- **iodine with plume shield, p = 2.7e-5 torr (Corrected for probe location)**

**Angular Position**

**Current Density [mA/cm²]**

- 1.0e+00
- 1.0e+01
- 1.0e+02
- 1.0e-02
- 1.0e-03

0 deg

View from overhead

Probe & Arm

Thruster

Plume Shield
High Power Iodine Testing (BHT-8000)

• Power levels up to 10.9 kW (600 V) demonstrated
• Chamber pressure below $5 \times 10^{-5}$ torr (corrected for iodine) with only diffusion pump & LN$_2$ shroud
• Performance similar to Xe
• Peak anode efficiency is 60-70%
• I$_2$ cathode also demonstrated
Iodine Hollow Cathode (2012)

- **Apparatus**
  - Feedback controlled $I_2$ feed system
  - Busek LaB$_6$ cathode

- **Key Results**
  - Discharge initiation on LaB$_6$
  - Over 1 hour of operation on iodine
  - Additional 1/2 hour with thruster flowing Xe
  - Current up to ~50 A into anode