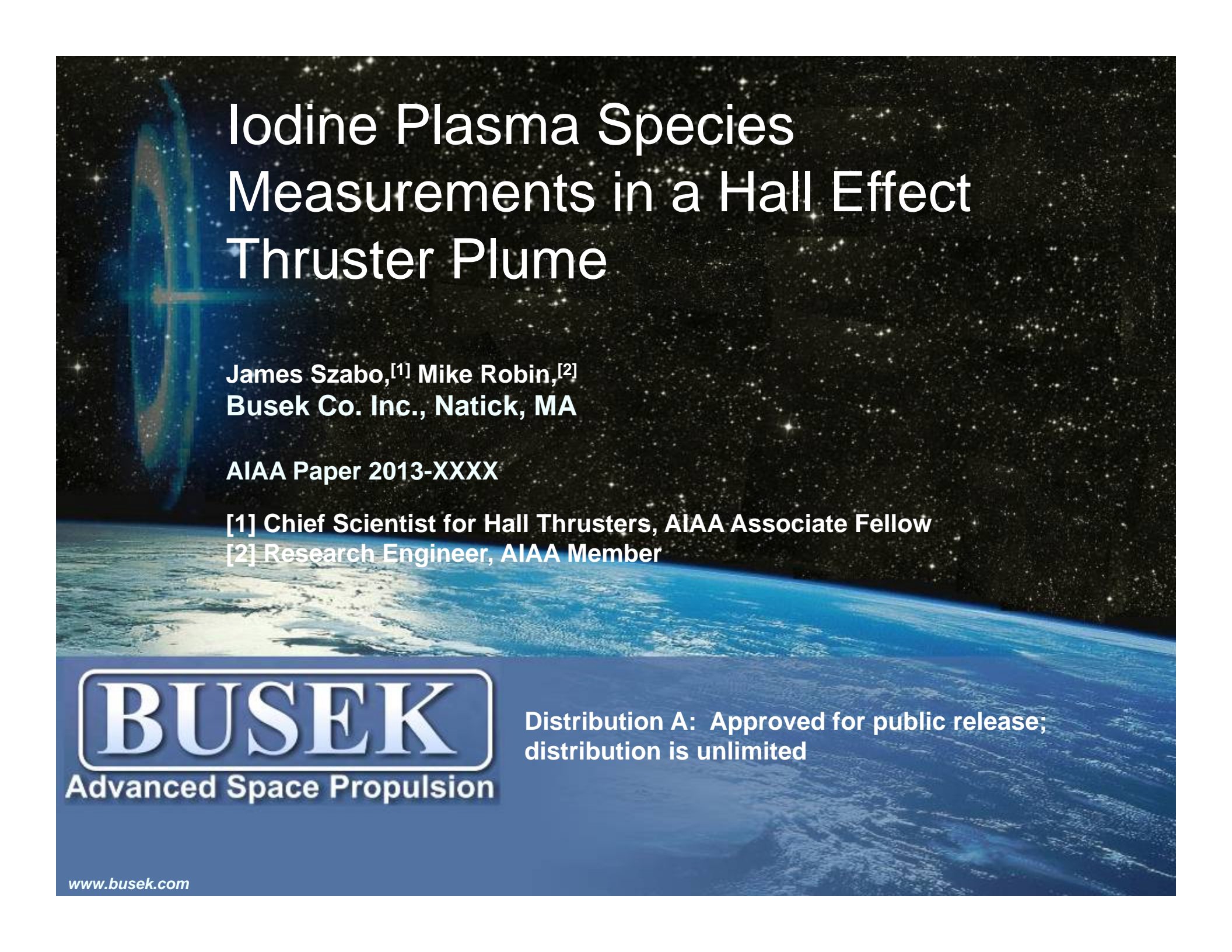


# REPORT DOCUMENTATION PAGE

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# Iodine Plasma Species Measurements in a Hall Effect Thruster Plume

James Szabo,<sup>[1]</sup> Mike Robin,<sup>[2]</sup>  
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AIAA Paper 2013-XXXX

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[2] Research Engineer, AIAA Member

**BUSEK**  
Advanced Space Propulsion

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# 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**

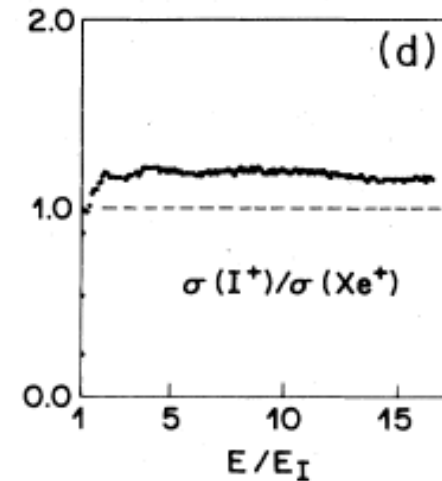


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# Iodine Propellant

- 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<sub>2</sub> 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

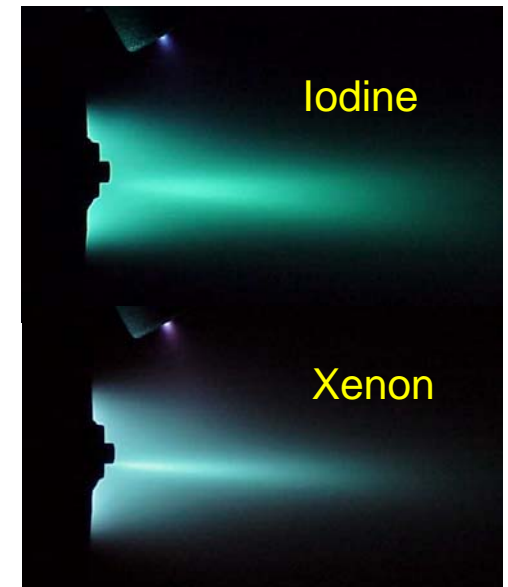
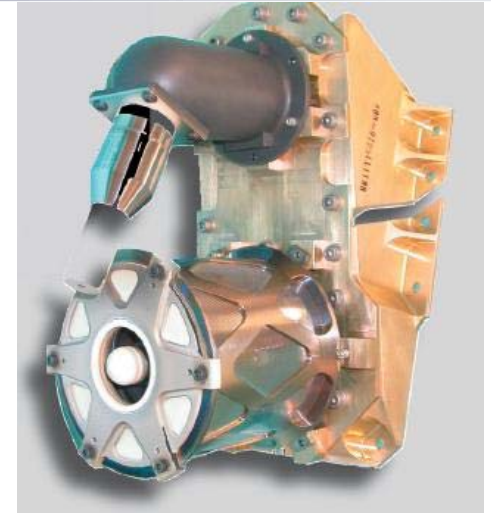
Relative size of ionization cross section



| Element   | I     | Xe    |
|---|-------|-------|
| <b>Atomic Mass</b>                                      | 126.9 | 131.3 |
| <b>Ionization Properties (monatomic)</b>                |       |       |
| First Ionization Potential (eV)                         | 10.5  | 12.1  |
| Peak Cross Section (10 <sup>-16</sup> cm <sup>2</sup> ) | 6.0   | 4.8   |
| <b>Storage and Handling Properties</b>                  |       |       |
| Storage density (gm/cm <sup>3</sup> ) near room temp.   | 4.9   | 1.6*  |
| Melting Point (°C)                                      | 113.7 | -112  |
| Boiling Point at 10 Pa (°C)                             | 9     | -181  |
| *14 Mpa, 50 C (NIST Database)                           |       |       |

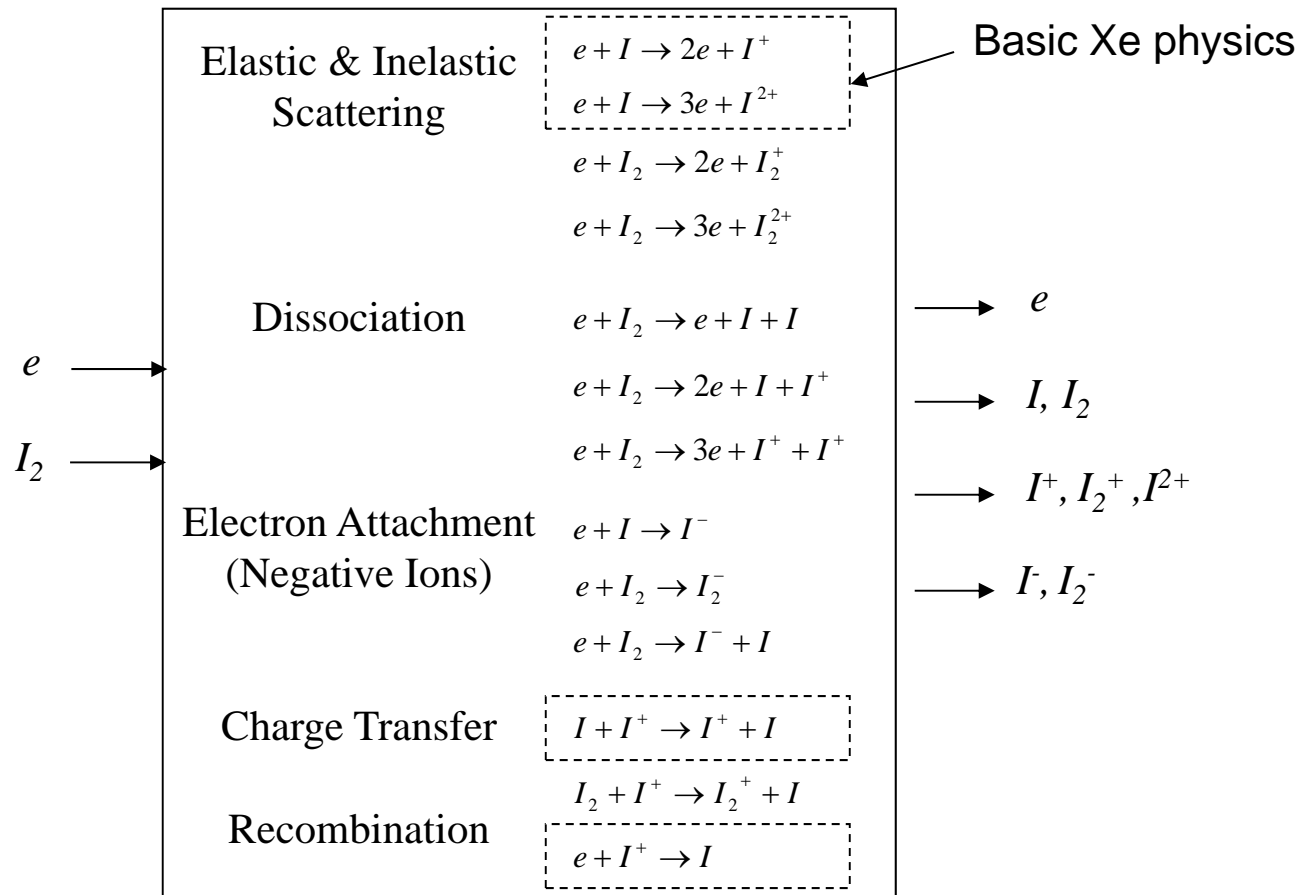
# BHT-200 Flowing Iodine (2010)

- Apparatus
  - BHT-200 Thruster & cathode (flight models)
  - Breadboard PPU
  - Custom propellant feed system
- Procedures
  - Preheat thruster with Xe discharge
  - Measure thrust, plume current with I<sub>2</sub> and Xe
  - Measure species (ExB, beam centroid, one condition)
- Results
  - Efficiency with I<sub>2</sub> 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 I<sub>2</sub>
  - Much lower tank pressure with I<sub>2</sub>
  - Plume divergence lower with I<sub>2</sub>
  - Dimers (I<sub>2</sub><sup>+</sup>) measured at beam centroid (a few %)



# What is the Composition of the Iodine Plume?

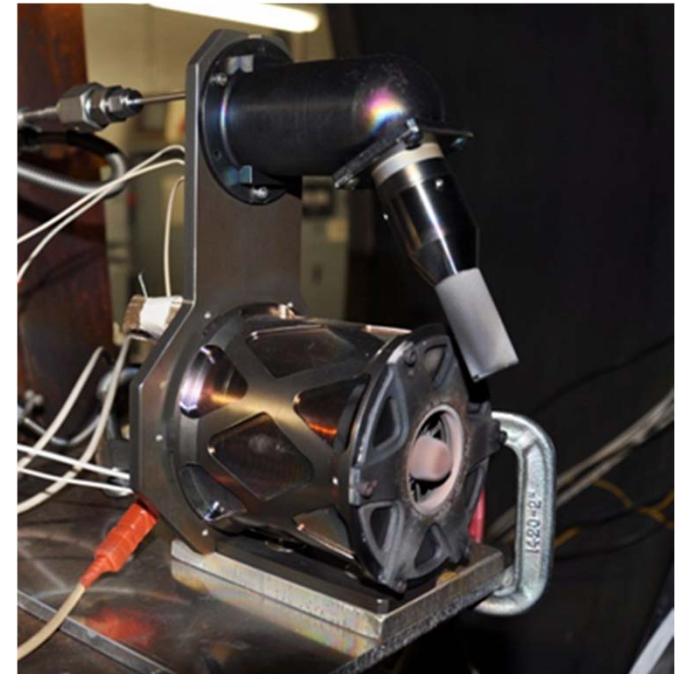
- Iodine plasma discharge more complicated than Xe discharge
- What processes need to be included when modeling the discharge and plume?
- How might heavy species impact performance?





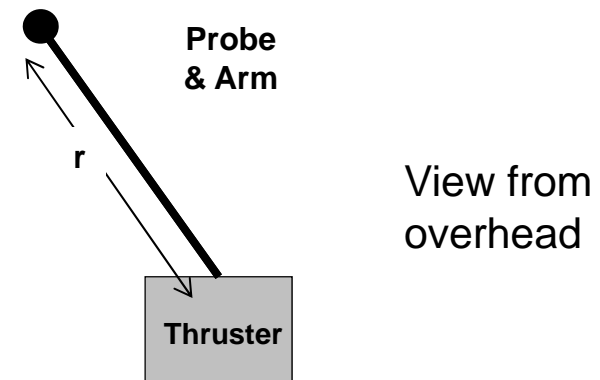
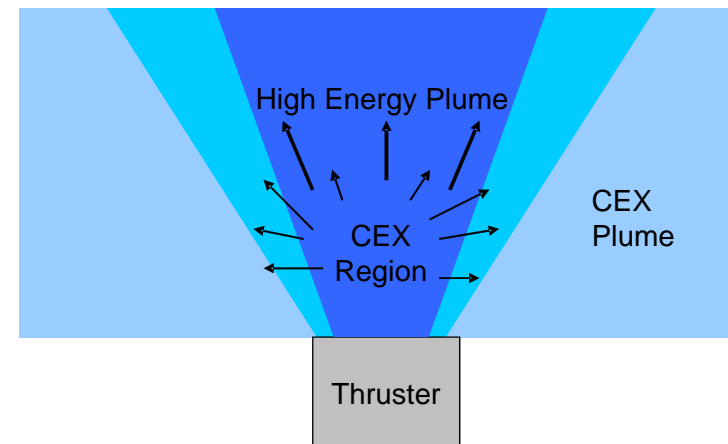
# Apparatus

- 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

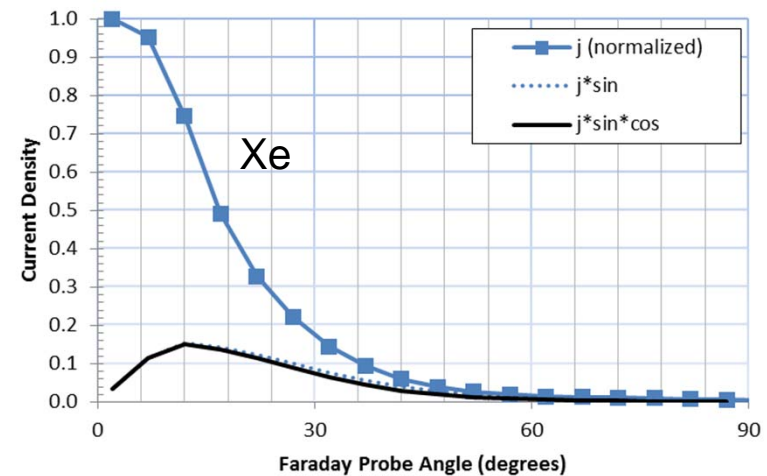
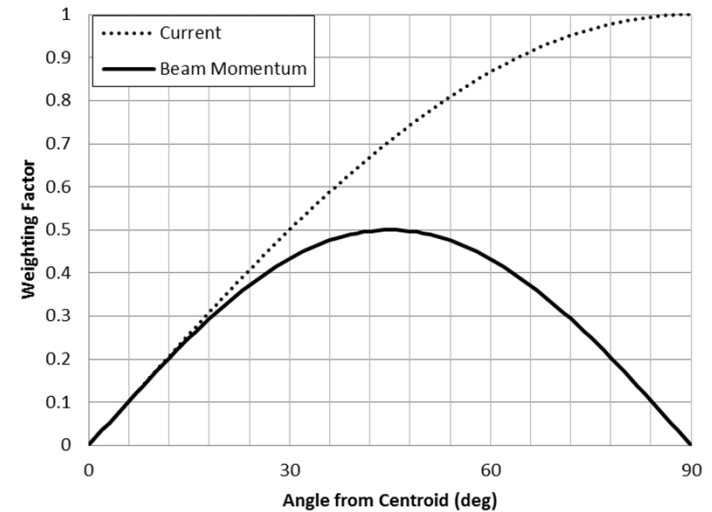
- Probe measures current density vs. angle
- Current vs. angle
  - Integrate  $j(\theta) \sin(\theta)$

$$I_b = 2\pi r^2 \int_0^{\pi/2} j(\theta) \sin(\theta) d\theta$$

- Axial momentum vs. angle (est.)
  - Integrate  $j(\theta) \sin(\theta) \cos(\theta)$
  - Trig multiplier peaks at  $45^\circ$

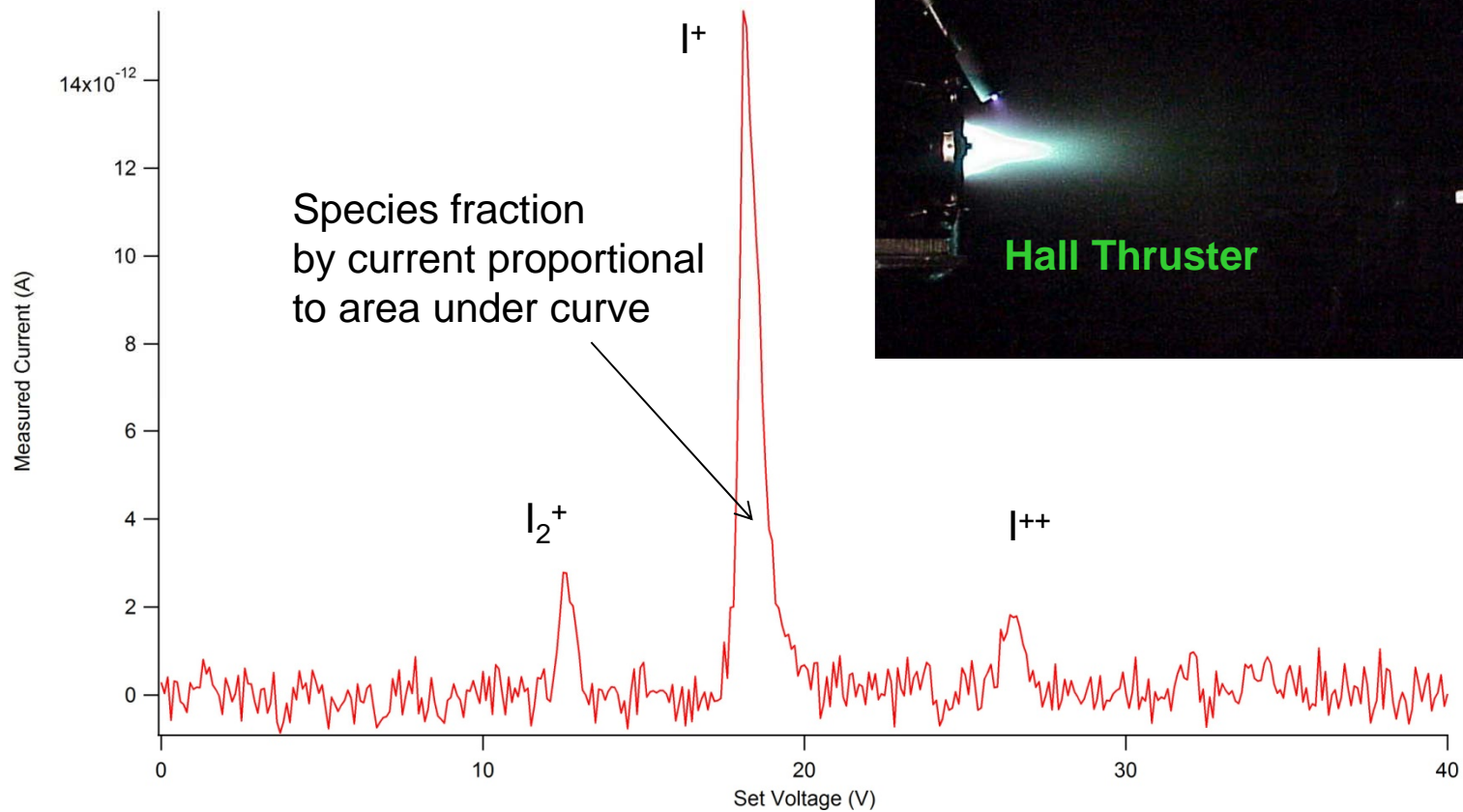
$$F_t = \frac{2\pi r^2 \int_0^{\pi/2} j(\theta) \sin(\theta) \cos(\theta) d\theta}{I_b}$$

- Significant momentum at  $\theta > 20^\circ$
- Composition away from centroid matters



# Species Analysis (ESA/ExB)

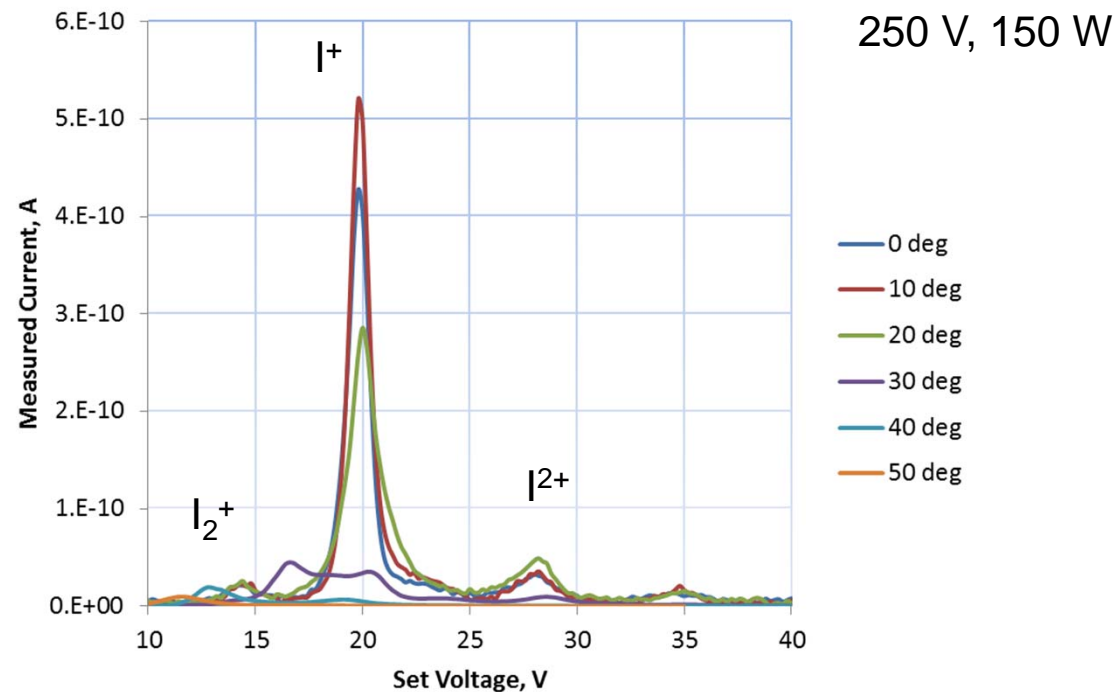
- ExB probe measures current
- Species fractions are proportional to the area under the curve





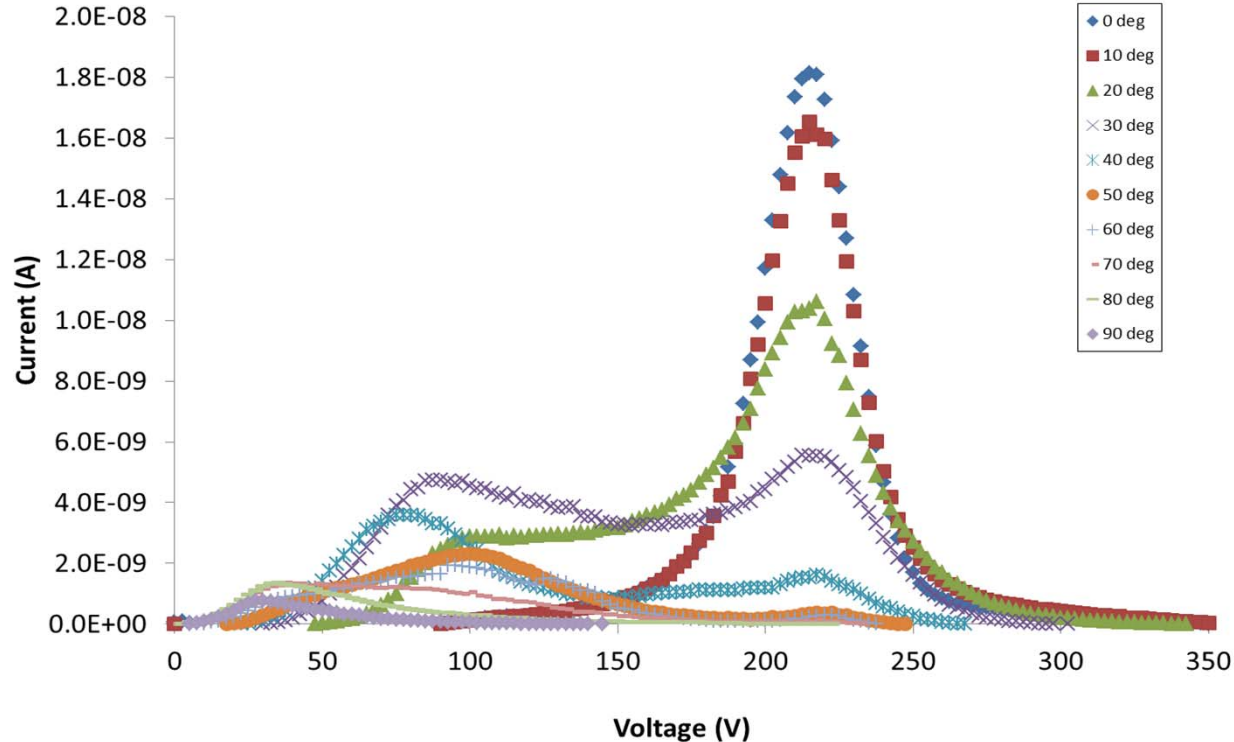
# Results - Iodine ExB

- 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



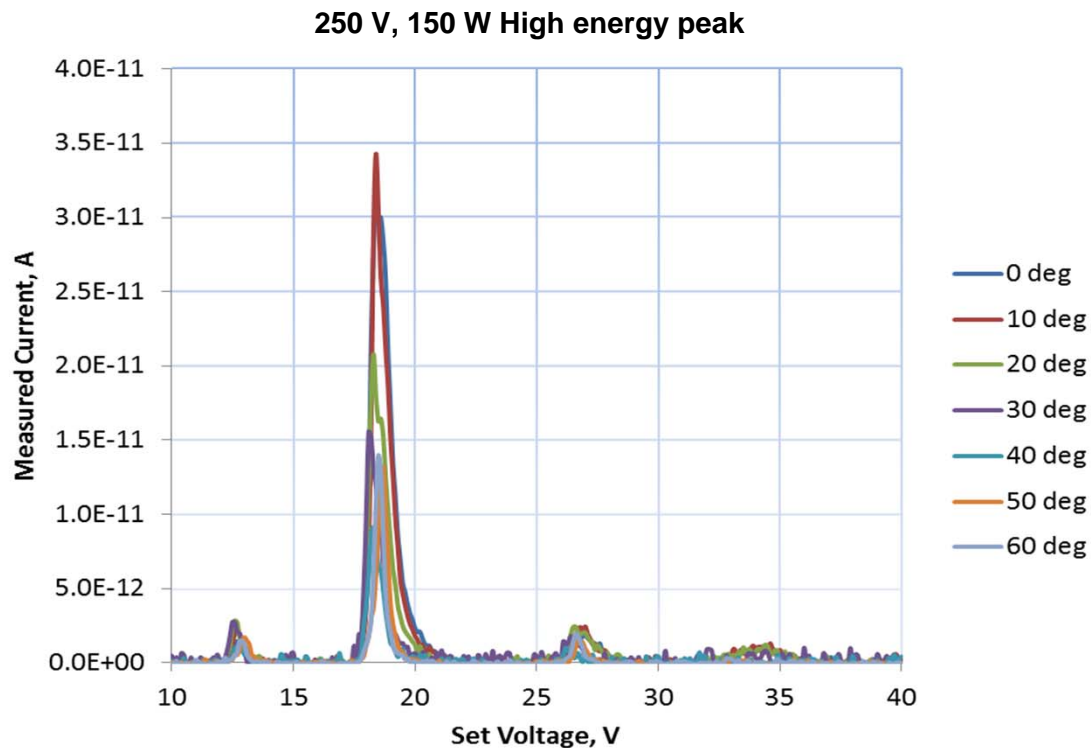
# Results - Iodine ESA

- 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



# Results – Iodine ESA/ExB

- 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



| Angle (deg) | Species                     | Mass | Charge | Current Mass Molar |      |      |
|-------------|-----------------------------|------|--------|--------------------|------|------|
|             |                             |      |        | f                  | g    | h    |
| 0           | I <sub>2</sub> <sup>+</sup> | 2    | 1      | 0.02               | 0.04 | 0.02 |
| 0           | I <sup>+</sup>              | 1    | 1      | 0.92               | 0.93 | 0.95 |
| 0           | I <sup>2+</sup>             | 1    | 2      | 0.05               | 0.03 | 0.03 |
| 0           | I <sup>3+</sup>             | 1    | 3      | 0.00               | 0.00 | 0.00 |
| 10          | I <sub>2</sub> <sup>+</sup> | 2    | 1      | 0.04               | 0.08 | 0.04 |
| 10          | I <sup>+</sup>              | 1    | 1      | 0.86               | 0.87 | 0.91 |
| 10          | I <sup>2+</sup>             | 1    | 2      | 0.09               | 0.05 | 0.05 |
| 10          | I <sup>3+</sup>             | 1    | 3      | 0.01               | 0.00 | 0.00 |
| 20          | I <sub>2</sub> <sup>+</sup> | 2    | 1      | 0.07               | 0.14 | 0.07 |
| 20          | I <sup>+</sup>              | 1    | 1      | 0.80               | 0.80 | 0.86 |
| 20          | I <sup>2+</sup>             | 1    | 2      | 0.13               | 0.07 | 0.07 |
| 20          | I <sup>3+</sup>             | 1    | 3      | 0.00               | 0.00 | 0.00 |
| 30          | I <sub>2</sub> <sup>+</sup> | 2    | 1      | 0.12               | 0.22 | 0.12 |
| 30          | I <sup>+</sup>              | 1    | 1      | 0.76               | 0.72 | 0.81 |
| 30          | I <sup>2+</sup>             | 1    | 2      | 0.12               | 0.06 | 0.06 |
| 30          | I <sup>3+</sup>             | 1    | 3      | 0.00               | 0.00 | 0.00 |
| 40          | I <sub>2</sub> <sup>+</sup> | 2    | 1      | 0.10               | 0.18 | 0.10 |
| 40          | I <sup>+</sup>              | 1    | 1      | 0.85               | 0.80 | 0.87 |
| 40          | I <sup>2+</sup>             | 1    | 2      | 0.05               | 0.02 | 0.03 |
| 50          | I <sub>2</sub> <sup>+</sup> | 2    | 1      | 0.11               | 0.20 | 0.11 |
| 50          | I <sup>+</sup>              | 1    | 1      | 0.79               | 0.75 | 0.83 |
| 50          | I <sup>2+</sup>             | 1    | 2      | 0.11               | 0.05 | 0.06 |
| 60          | I <sub>2</sub> <sup>+</sup> | 2    | 1      | 0.08               | 0.17 | 0.09 |
| 60          | I <sup>+</sup>              | 1    | 1      | 0.80               | 0.78 | 0.85 |
| 60          | I <sup>2+</sup>             | 1    | 2      | 0.12               | 0.06 | 0.06 |

# 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

$$f_k = \frac{A_k}{\sum_k A_k}$$

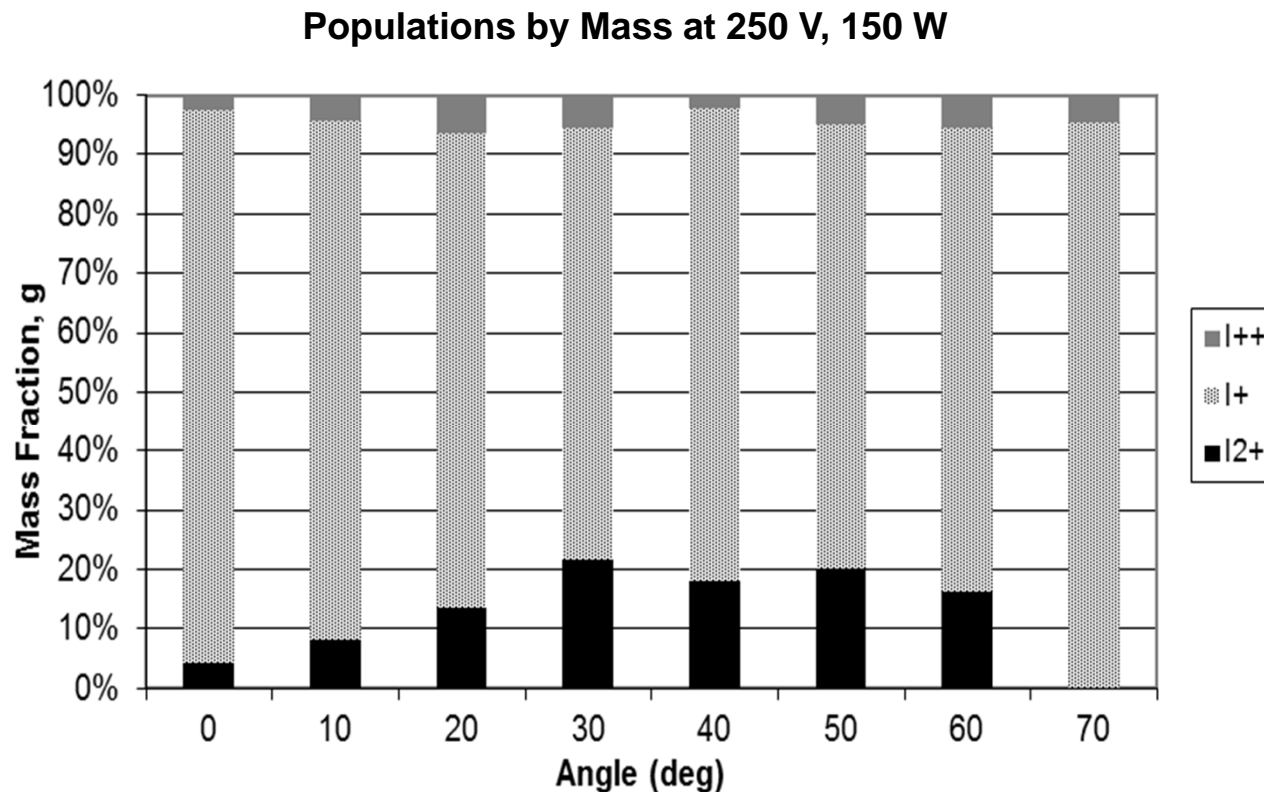
$$h_k = \frac{A_k / q_k}{\sum_k A_k / q_k}$$

$$g_k = \frac{A_k M_k / q_k}{\sum_k A_k M_k / q_k}$$



# 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



# What Effect Might Dimers Have Upon Performance?

- Thrust

- Thrust is sum of species

$$F = \sum_k \dot{m}_k \langle v_{k,z} \rangle.$$

- Ion voltage, mass, charge determine ion velocity

$$v = \sqrt{\frac{2q\Delta\Phi}{M}}$$

- Specific Impulse

- Determined by thrust and mass flow

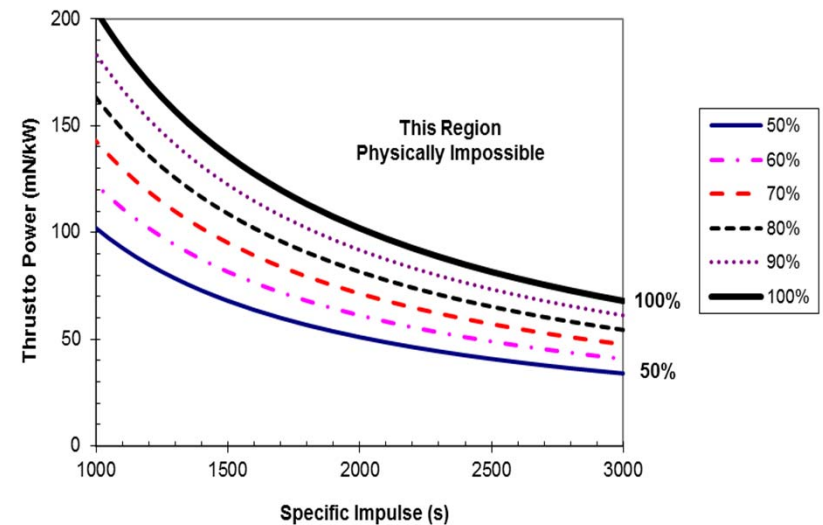
- Efficiency

- Determined by thrust, mass flow, power

- Thrust to power

- Determined by efficiency, specific impulse

- Can estimate effect of species distributions upon these parameters



$$I_{sp} = F / \dot{m}g_0 = \bar{v} / g_0$$

$$\eta = \frac{F}{P} \frac{I_{sp}g_0}{2} = \frac{F^2}{2\dot{m}P}$$

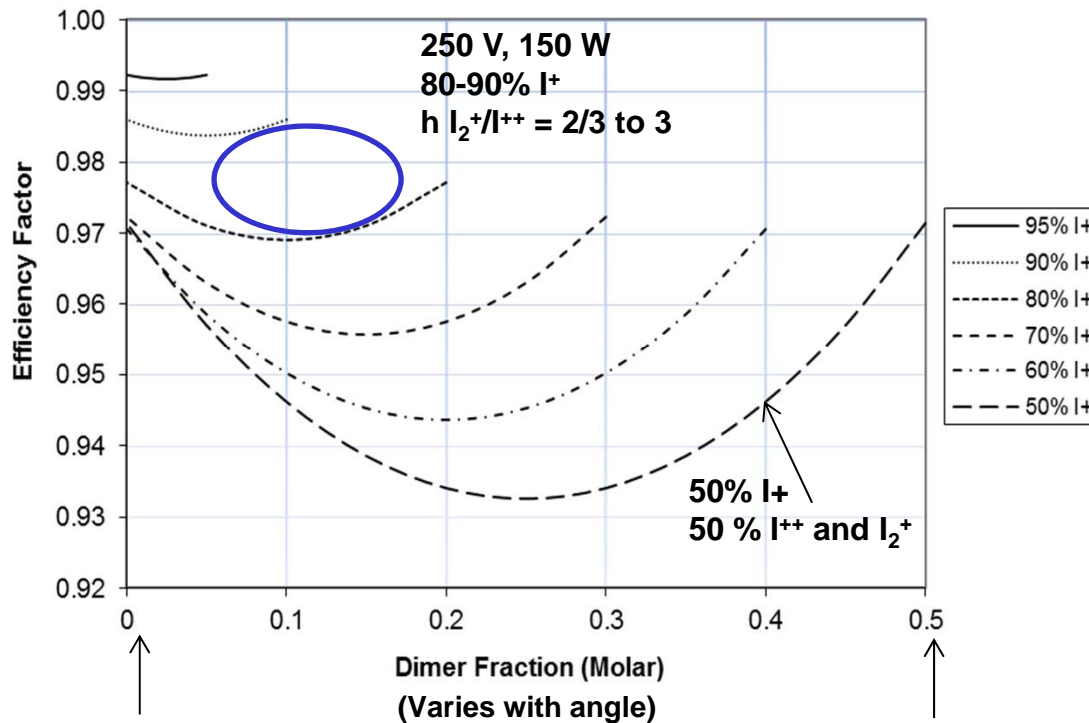
# Discussion - Efficiency Factor (Theory)

$$\eta_s \propto \frac{(\sum_k h_k M_k v_k)^2}{\sum_k h_k M_k \sum_k h_k q_k}$$

$$\eta = \frac{F^2}{2mP}$$

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

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



$\eta_s = 0.98$   
 $\eta = 50\% \rightarrow 49\%$

$\eta_s = 0.94$   
 $\eta = 50\% \rightarrow 47\%$

Starting point  
Is not  $\eta_s = 1.0$   
(Xe<sup>++</sup>)

No dimers

No doubly charged

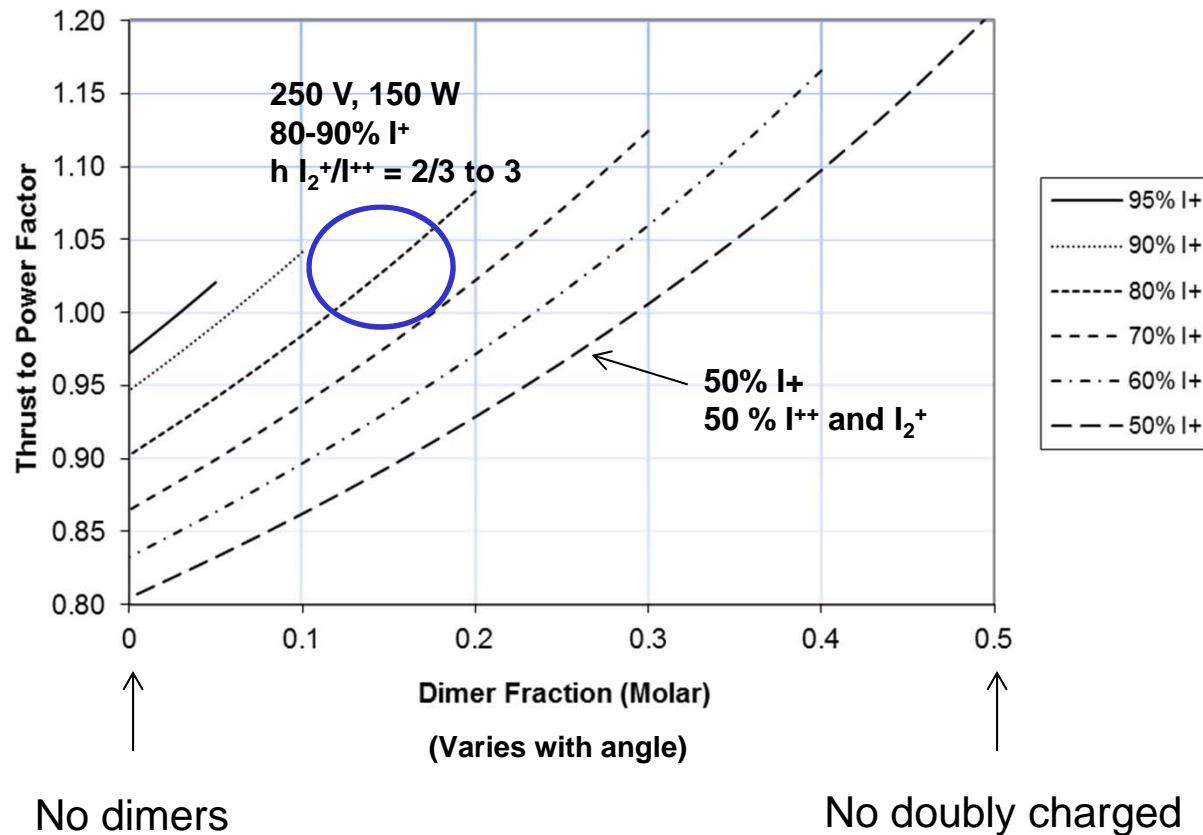
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# Discussion - Thrust to Power Factor (Theory)

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

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)





# 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

Current Fractions

| Angle [deg] | Species  | Discharge Conditions |      |      |      |      |      |      |     |
|-------------|----------|----------------------|------|------|------|------|------|------|-----|
|             |          | 150                  | 200  | 250  | 250  | 300  | 350  | 350  | [V] |
|             |          | 1.00                 | 1.00 | 0.60 | 0.80 | 0.80 | 0.71 | 1.00 | [A] |
|             |          | 150                  | 200  | 150  | 200  | 240  | 250  | 350  | [W] |
| 0           | $I_2^+$  |                      |      | 0.02 | 0.01 |      | 0.01 |      |     |
| 0           | $I^+$    | 0.53                 | 1.00 | 0.92 | 0.95 | 0.93 | 0.94 | 0.96 |     |
| 0           | $I^{2+}$ | 0.47                 | 0.00 | 0.05 | 0.04 | 0.07 | 0.05 | 0.04 |     |
| 0           | $I^{3+}$ |                      |      | 0.00 | 0.00 | 0.00 |      |      |     |
| 10          | $I_2^+$  |                      |      | 0.04 | 0.03 | 0.02 | 0.02 |      |     |
| 10          | $I^+$    | 0.98                 | 0.83 | 0.86 | 0.82 | 0.83 | 0.90 | 0.88 |     |
| 10          | $I^{2+}$ | 0.02                 | 0.14 | 0.09 | 0.08 | 0.11 | 0.08 | 0.12 |     |
| 10          | $I^{3+}$ |                      | 0.03 | 0.01 | 0.07 | 0.05 |      |      |     |
| 20          | $I_2^+$  |                      |      | 0.07 | 0.02 | 0.02 | 0.06 | 0.00 |     |
| 20          | $I^+$    | 0.99                 | 0.40 | 0.80 | 0.85 | 0.82 | 0.77 | 0.86 |     |
| 20          | $I^{2+}$ | 0.01                 | 0.60 | 0.13 | 0.13 | 0.15 | 0.18 | 0.13 |     |
| 20          | $I^{3+}$ |                      |      | 0.00 | 0.01 | 0.00 |      |      |     |
| 30          | $I_2^+$  |                      |      | 0.12 | 0.00 | 0.03 |      | 0.02 |     |
| 30          | $I^+$    | 1.00                 | 0.85 | 0.76 | 0.95 | 0.77 | 0.86 | 0.79 |     |
| 30          | $I^{2+}$ |                      | 0.15 | 0.12 | 0.00 | 0.18 | 0.14 | 0.19 |     |
| 30          | $I^{3+}$ |                      |      | 0.00 | 0.05 | 0.03 |      |      |     |
| 40          | $I_2^+$  |                      |      | 0.10 | 0.00 | 0.05 | 0.01 | 0.02 |     |
| 40          | $I^+$    | 1.00                 | 0.85 | 0.85 | 0.90 | 0.76 | 0.87 | 0.75 |     |
| 40          | $I^{2+}$ |                      | 0.15 | 0.05 | 0.10 | 0.19 | 0.13 | 0.23 |     |
| 50          | $I_2^+$  |                      |      | 0.11 | 0.00 | 0.04 | 0.01 | 0.00 |     |
| 50          | $I^+$    | 1.00                 | 1.00 | 0.79 | 0.91 | 0.82 | 0.90 | 0.84 |     |
| 50          | $I^{2+}$ |                      |      | 0.11 | 0.09 | 0.14 | 0.09 | 0.16 |     |
| 60          | $I_2^+$  |                      |      | 0.08 | 0.06 | 0.04 | 0.08 | 0.00 |     |
| 60          | $I^+$    |                      | 1.00 | 0.80 | 0.81 | 0.92 | 0.81 | 0.83 |     |
| 60          | $I^{2+}$ |                      |      | 0.12 | 0.13 | 0.04 | 0.12 | 0.17 |     |



# 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



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- Additional testing supported by the USAF, NASA, and ULA



BHT-8000 Operating on Iodine

# Backup Slides

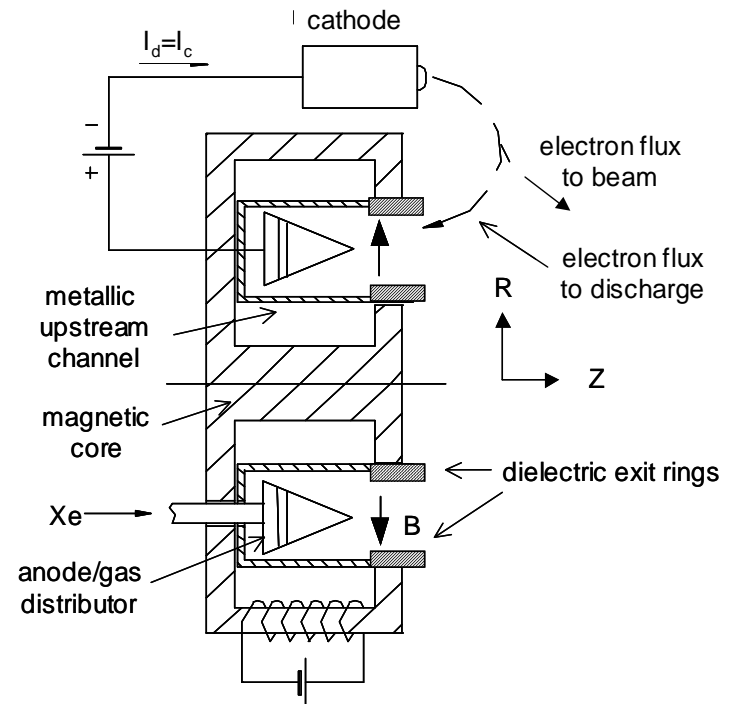
Distribution A: Approved for public release; distribution is unlimited

**BUSEK**  
Advanced Space Propulsion



# 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

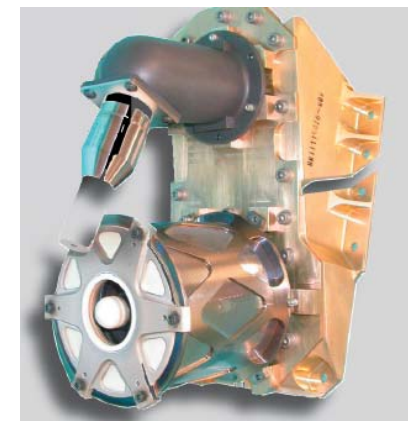
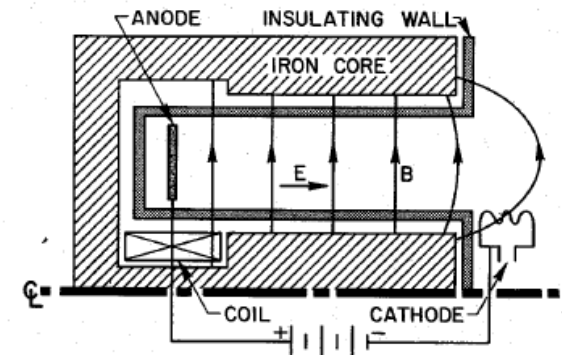


**Axisymmetric Hall thruster**

# 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)

Axisymmetric Hall thruster of United Aircraft Corporation (1962)



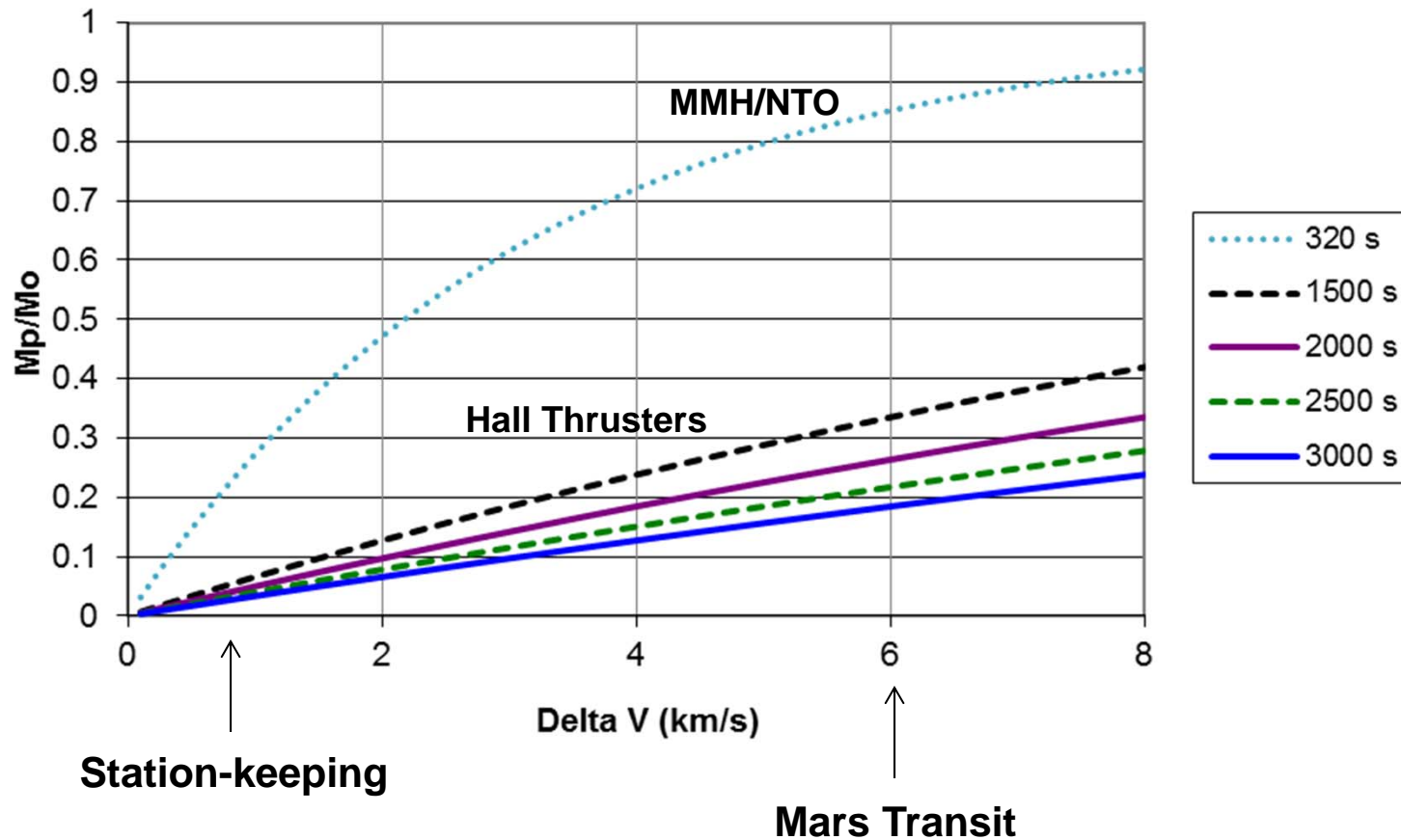
Busek BHT-200  
First US thruster in Space



# The Rocket Equation

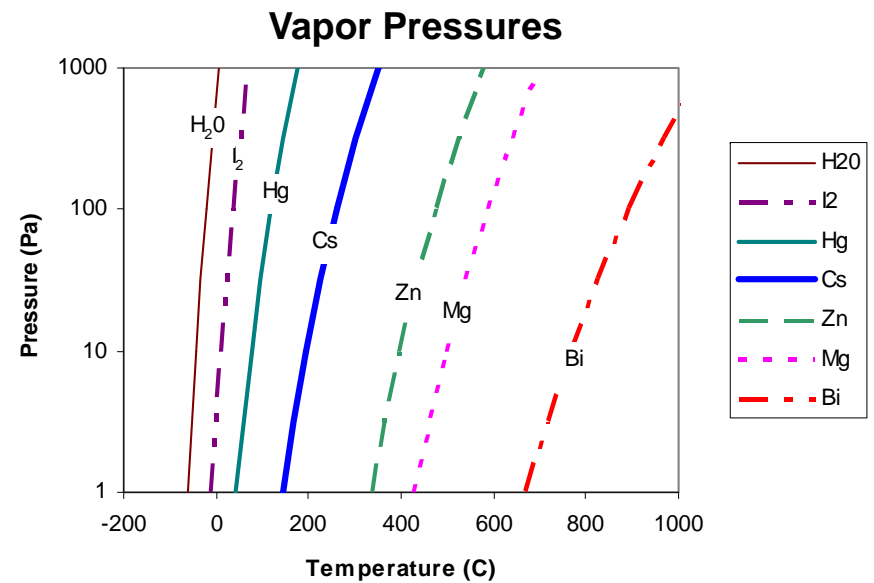
- Station keeping (15 years) ~ 0.75 km/s
- Earth to Mars (low thrust transfer) ~ 6 km/s

$$m_p / m_0 = 1 - \exp[-\Delta V / I_{sp} g_0]$$



# 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<sub>2</sub> *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<sub>2</sub>, etc.)

| Gas            | Ionization Cross Section at 150 eV (Ang <sup>2</sup> ) | Relative Sensitivity w.r.t. N <sub>2</sub> | Relative Sensitivity w.r.t. Xe | Reported Relative Sensitivity w.r.t. N <sub>2</sub> |
|----------------|--|--|--------------------------------|---|
| N <sub>2</sub> | 1.75   | 1.00                                       | 0.40                           |   |
| Kr             | 3.28   | 1.87                                       | 0.75                           | 1.7 - 1.9   |
| Xe             | 4.38   | 2.50                                       | 1.00                           | 2.2 - 2.9   |
| I              | 4.74   | 2.71                                       | 1.08                           |   |
| I <sub>2</sub> | 8.48   | 4.85                                       | 1.94                           | 5.4   |

# Iodine Performance (BHT-200)

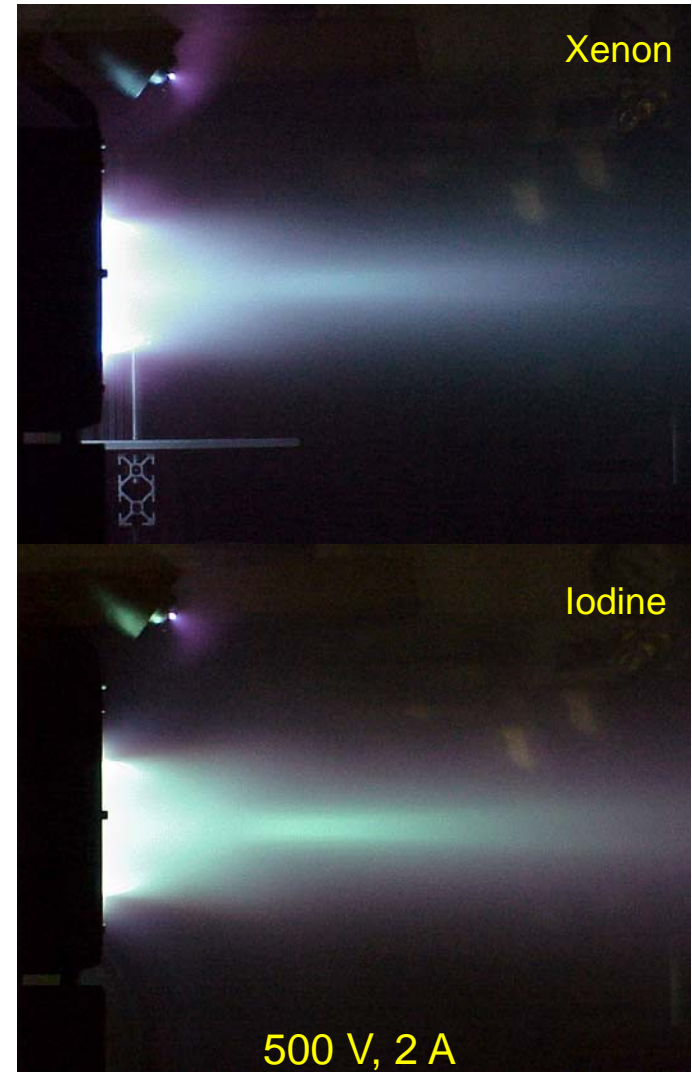
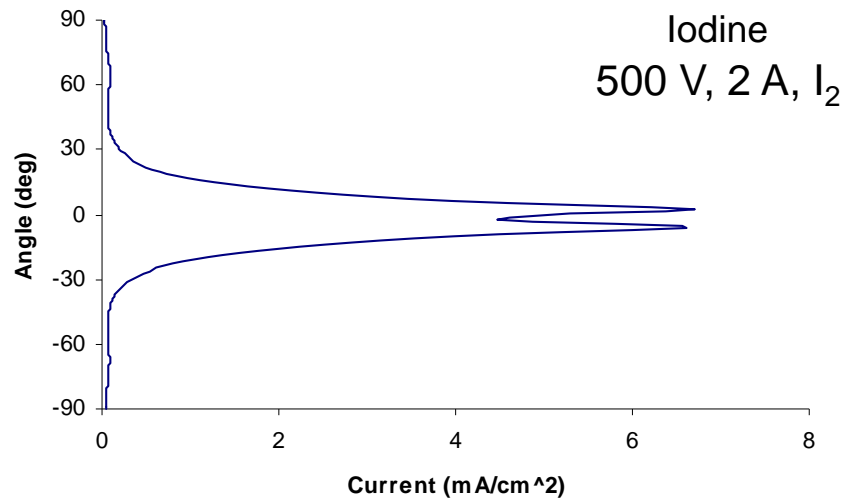
- Nominal thruster operating condition is 250 V, 200 W
  - Slightly higher T/P, slightly lower Isp

| Gas | Flow Rate<br>(mg/s) | Potential<br>(V) | Current<br>(A) | Power<br>(W) | Thrust<br>(mN) | T/P<br>(mN/kW) | Anode Isp<br>(s) | Anode Eff<br>(-) |
|-----|---------------------|------------------|----------------|--------------|----------------|----------------|------------------|------------------|
| I2  | 1.02                | 151              | 1.02           | 155          | 11.1           | 71             | 1110             | 0.39             |
| Xe  | 0.99                | 152              | 1.03           | 156          | 11.2           | 72             | 1151             | 0.41             |
| I2  | 1.02                | 202              | 1.05           | 211          | 14.3           | 68             | 1436             | 0.48             |
| Xe  | 0.99                | 202              | 1.01           | 203          | 13.5           | 67             | 1394             | 0.46             |
| I2  | 0.62                | 251              | 0.53           | 133          | 8.3            | 62             | 1350             | 0.41             |
| Xe  | 0.58                | 252              | 0.53           | 134          | 8.0            | 60             | 1409             | 0.41             |
| I2  | 0.82                | 251              | 0.74           | 187          | 12.1           | 65             | 1506             | 0.48             |
| Xe  | 0.78                | 252              | 0.76           | 193          | 11.9           | 62             | 1544             | 0.47             |
| I2  | 0.85                | 302              | 0.81           | 245          | 14.4           | 59             | 1738             | 0.50             |
| Xe  | 0.78                | 302              | 0.76           | 231          | 13.4           | 58             | 1750             | 0.50             |
| I2  | 1.02                | 353              | 1.04           | 368          | 20.0           | 54             | 1996             | 0.53             |
| Xe  | 1.04                | 353              | 1.13           | 400          | 19.4           | 48             | 1906             | 0.45             |

Szabo et al., "Performance Evaluation of an Iodine Vapor Hall Thruster", *AIAA Journal of Propulsion and Power*, Vol. 28, No. 4, July/August 2012.

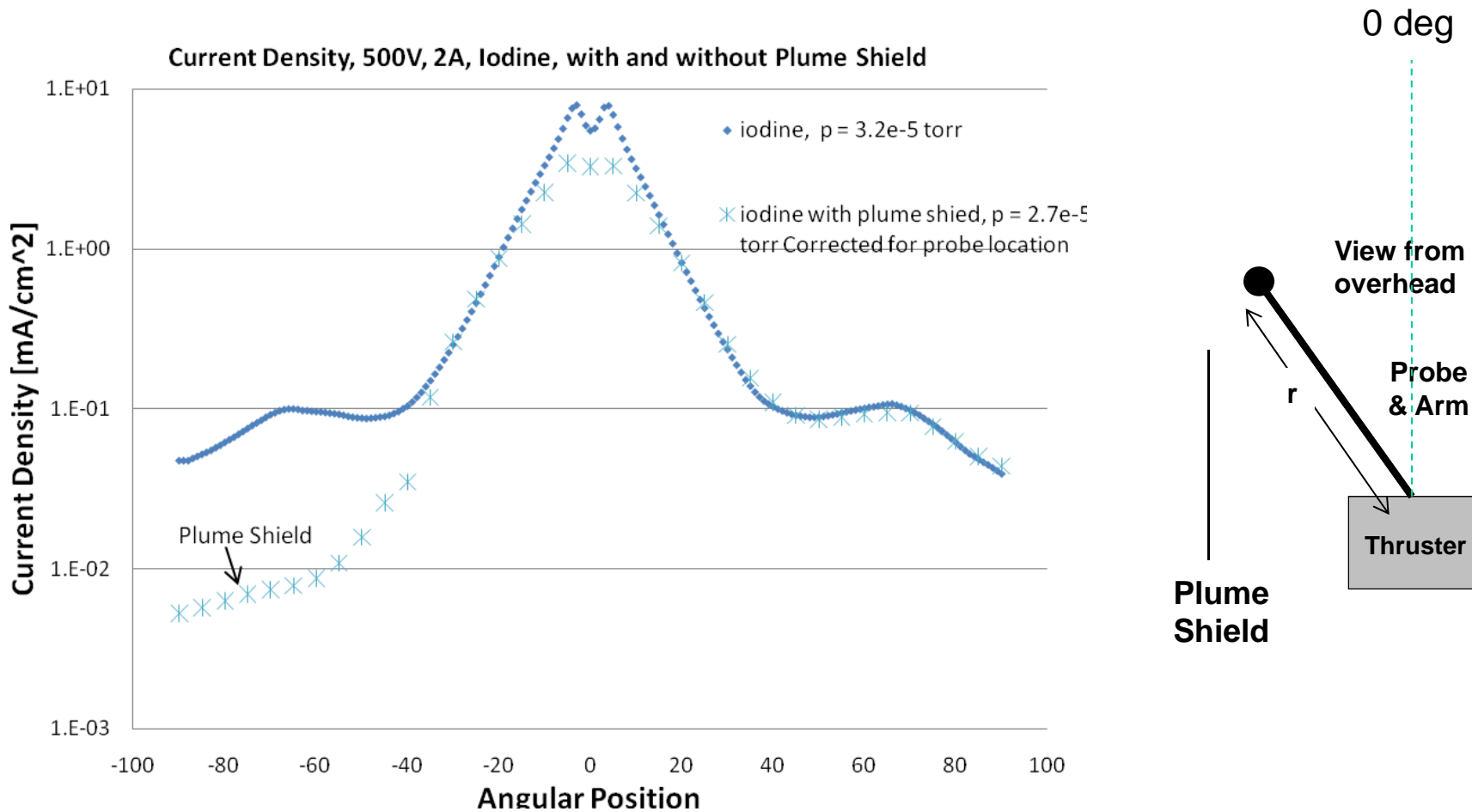
# Iodine Plume (BHT-1000)

- 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





# Plume Shield (BHT-1000)

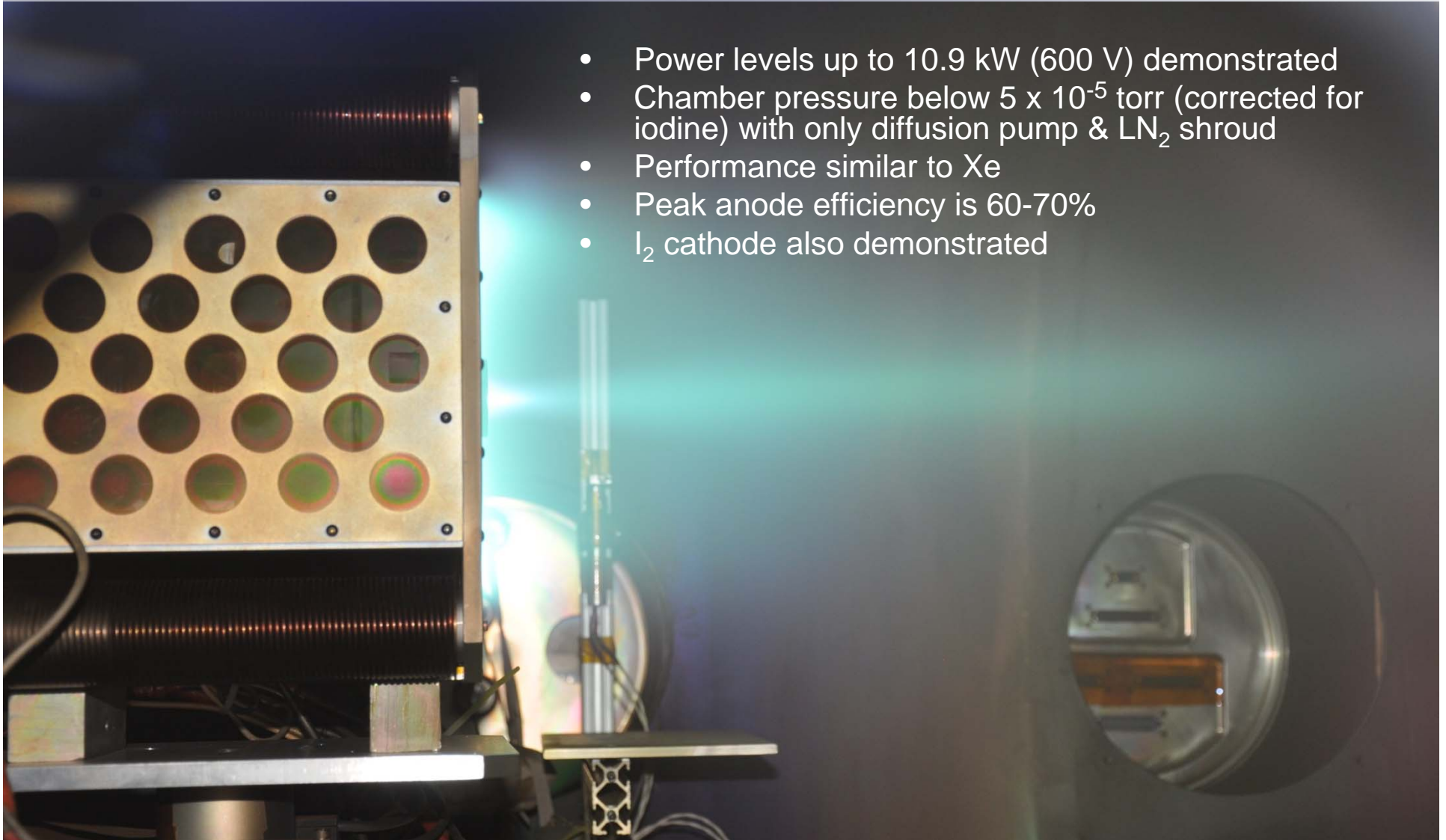


A plume shield can greatly reduce the large angle plume

Distribution A: Approved for public release; distribution is unlimited

# 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<sub>2</sub> shroud
- Performance similar to Xe
- Peak anode efficiency is 60-70%
- I<sub>2</sub> cathode also demonstrated



Distribution A: Approved for public release; distribution is unlimited



# 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  $\sim 50$  A into anode

