Factors Affecting the Efficiency of Krypton Hall Thrusters

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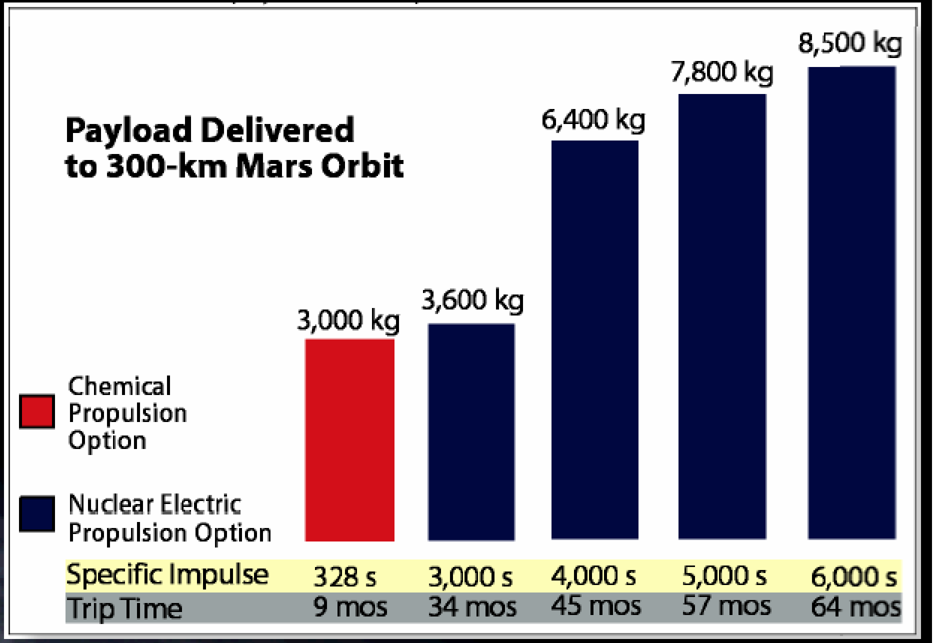
Payload Advantage – Mars

- Nuclear electric propulsion delivers greater payloads than chemical propulsion at the expense of trip time.
- Specific impulse of 4000 s balances trip time with delivered payload.
  - Typical specific impulse for ion thrusters
  - More than twice the typical specific impulse of xenon Hall thrusters
- Compared to ion thrusters, Hall thrusters offer benefits in terms of volume, Mass, and cost

The Question:
How can Hall thrusters achieve high-specific Impulse AND long Lifetime?

One (possible) answer:
Krypton Hall thruster



Krypton vs. Xenon

	Xenon	Krypton	Relative to xenon…
Molecular Weight (g/mol)	131.3	83.8	↑I_{sp}, ↓T, ↑Lifetime (@ Constant Voltage and density)
1st ionization potential (eV)	12.1	14.0	↓ Mass utilization efficiency, ↓Multiply-charged Ions (↑Lifetime)
Cost ($/L)	$4.50	$0.38	↓Qualification & On-orbit Costs ↑Availability, ↓Price Volatility
Density (@ 190 bar, 340 K, kg/m^3)	1.66	0.67	↑Storage tank mass/volume

In general,

Xe → high-η, high-T

Kr → high-I_{sp}, Long Life

The Krypton Efficiency Challenge

Efficient krypton operation requires increasing the propellant utilization, which is affected by several design variables.

↓ Wall losses	Channel Length	↑ Ionization
Optimum B shape	Channel Width	↓ Wall losses
↑ Lifetime	Current Density	↑ Ionization
↓ Wall losses	Discharge Voltage	↑ Ionization
↓ Wall losses	Axial width of B_R	↑ Ionization

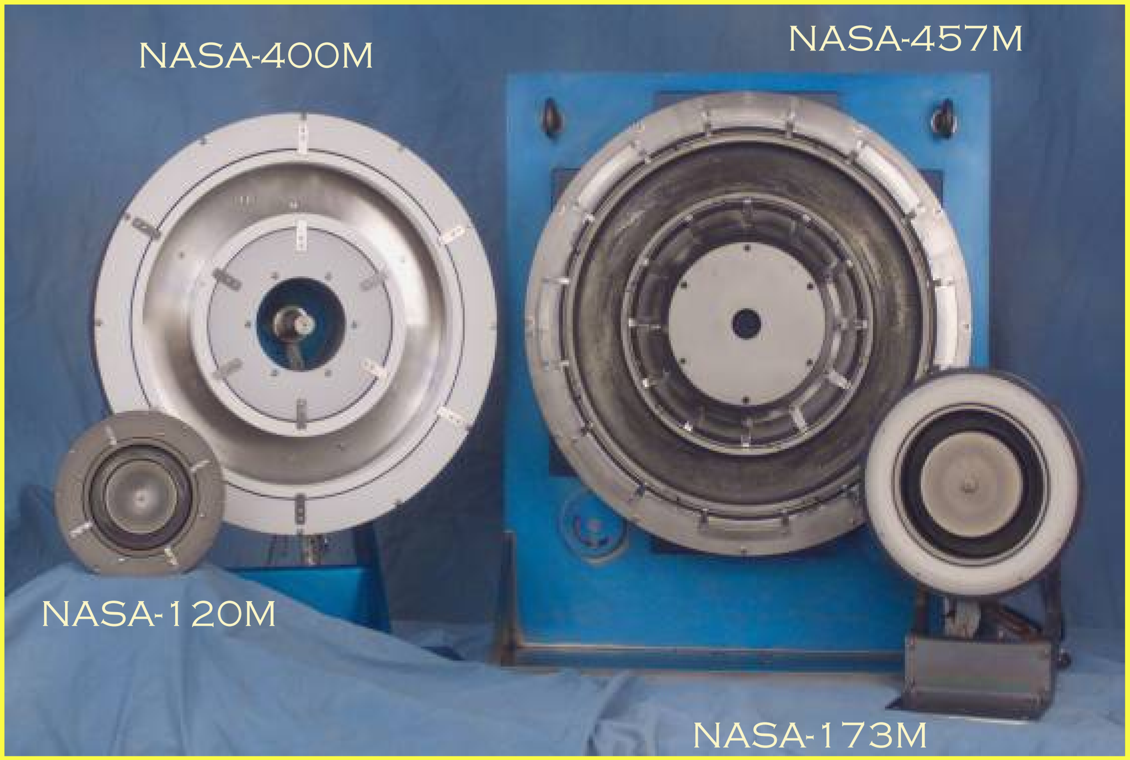
Performance
Thermal
Stability
Lifetime

The challenge is to achieve high-propellant utilization without sacrificing thermal margin, stability, and lifetime.

NASA's Hall Thrusters

GRC-developed Hall thrusters have demonstrated efficient operation over a wide range of conditions

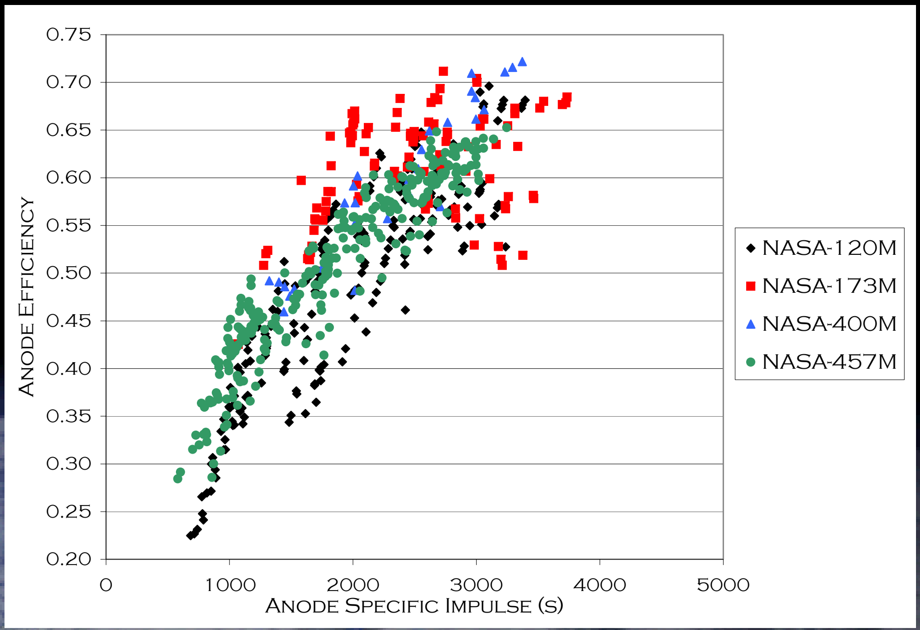
Power: 1-100 kW
Thrust: 0.1-3 N
I_{SP}: 1000-5000 s
Efficiency: 40-70%
Propellant: Xe, Kr



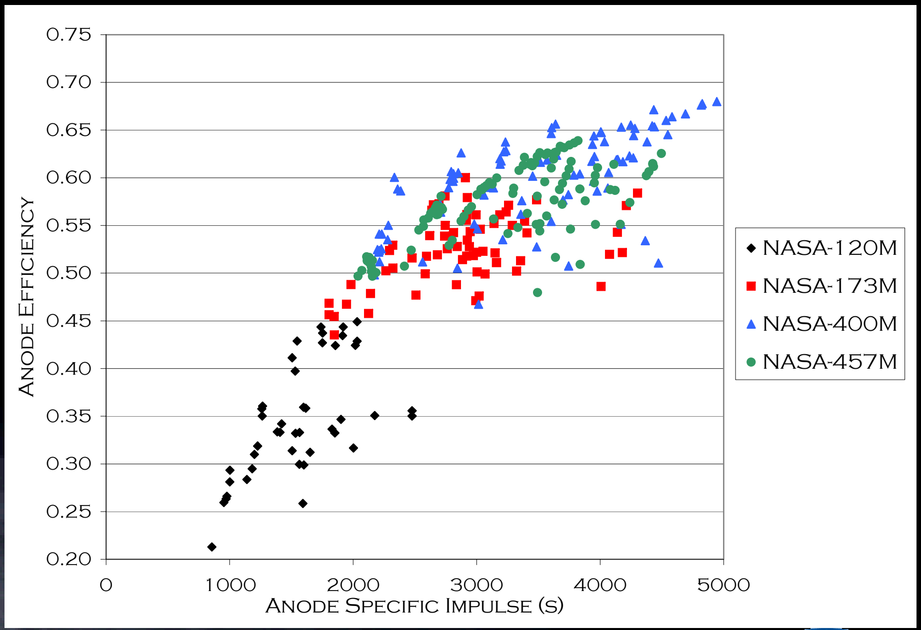
Performance – Xenon vs. Krypton

- At constant current density, efficiency increases with thruster size (power)
- Compared to xenon, krypton efficiency is typically 5-15% less
- Both trends are primarily due to differences in the mass utilization

Xenon



Krypton



Hall Thruster Efficiency

By accounting for the effects of a multiply-charged, partially-ionized plasma, Hall thruster efficiency can be expressed as a function of the charge-, voltage-, current-, and mass-utilization efficiencies.

Anode efficiency

$$\eta_a = \frac{T^2}{2\dot{m}_a P_d} = \eta_q \eta_v \eta_b \eta_m$$

Charge utilization efficiency

$$\eta_q = \frac{\left(\sum \Omega_i / \sqrt{Z_i} \right)^2}{\sum \Omega_i / Z_i}$$

Voltage utilization efficiency

$$\eta_v = \frac{V_a}{V_d} = 1 - \frac{V_l}{V_d}$$

Current utilization efficiency

$$\eta_b = \frac{I_b}{I_d}$$

Mass utilization efficiency

$$\eta_m = \frac{\dot{m}_b}{\dot{m}_a}$$

Hall Thruster Efficiency (2)

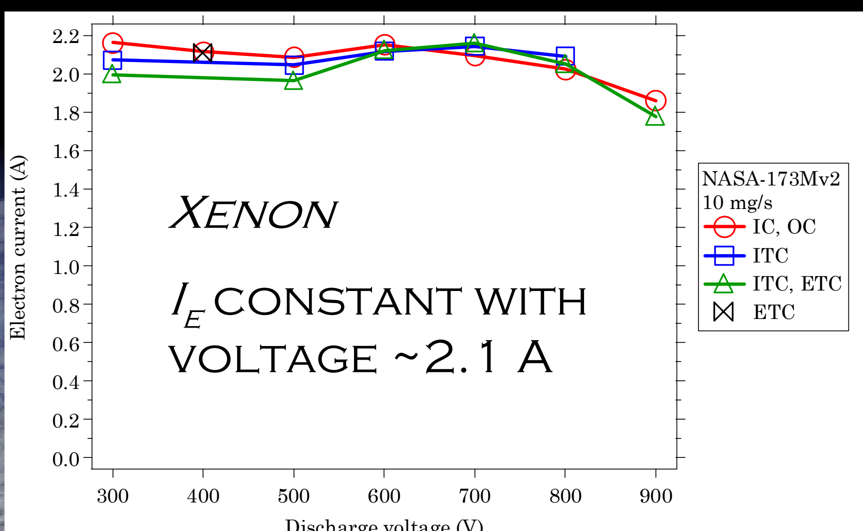
Electron current and utilization efficiencies can be computed if the following quantities are known:

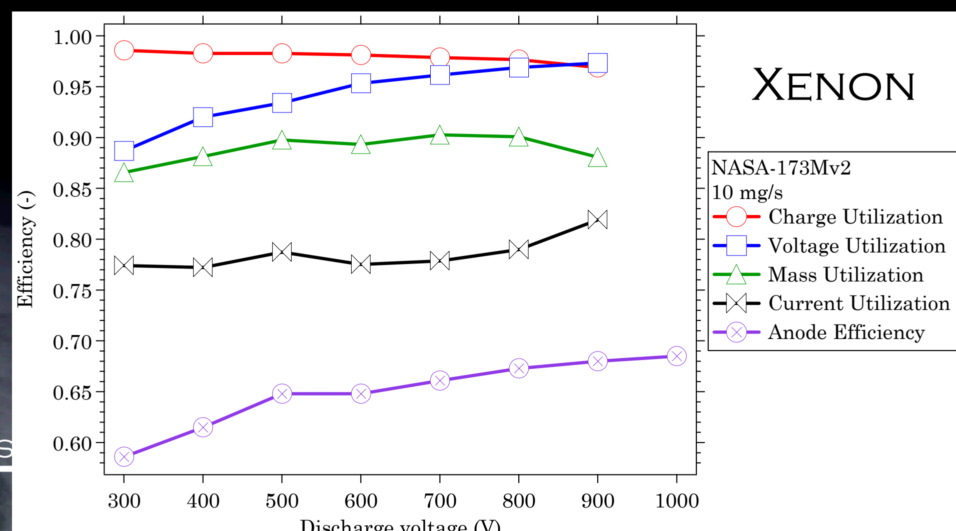
- ✓Anode efficiency – measured with thrust stand
- ✓Loss voltage – measured with RPA
- ✓Ion species fractions – measured with ExB probe

$$\eta_a = \underbrace{\left(1-\frac{V_l}{V_d}\right)}_{\eta_v}\underbrace{\left(1-\frac{I_e}{I_d}\right)^2\left(\sum\frac{\Omega_i}{\sqrt{Z_i}}\right)^2\frac{m_{xe}I_d}{\dot{m}_a e}}_{\eta_b\eta_m\eta_q}$$

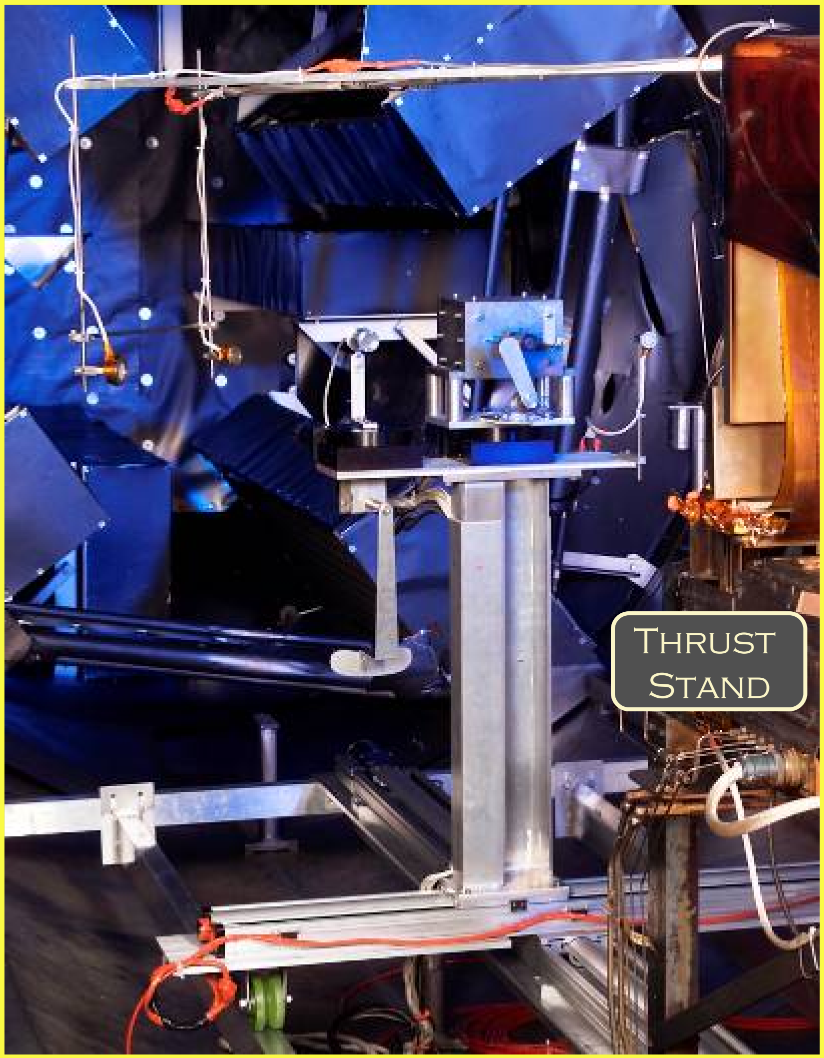
XENON

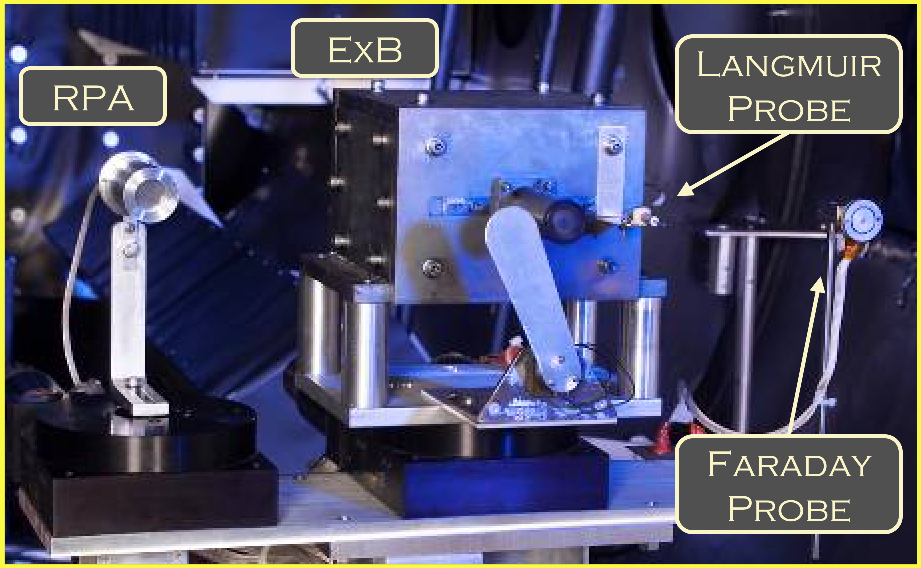
- Charge utilization = 98-99%
- Mass utilization = 86-90%
- Voltage utilization = 89-97%
- Current utilization = 77-81%





Plasma Diagnostics in Vacuum Facility 12





NASA-173Mv2 Operating Conditions

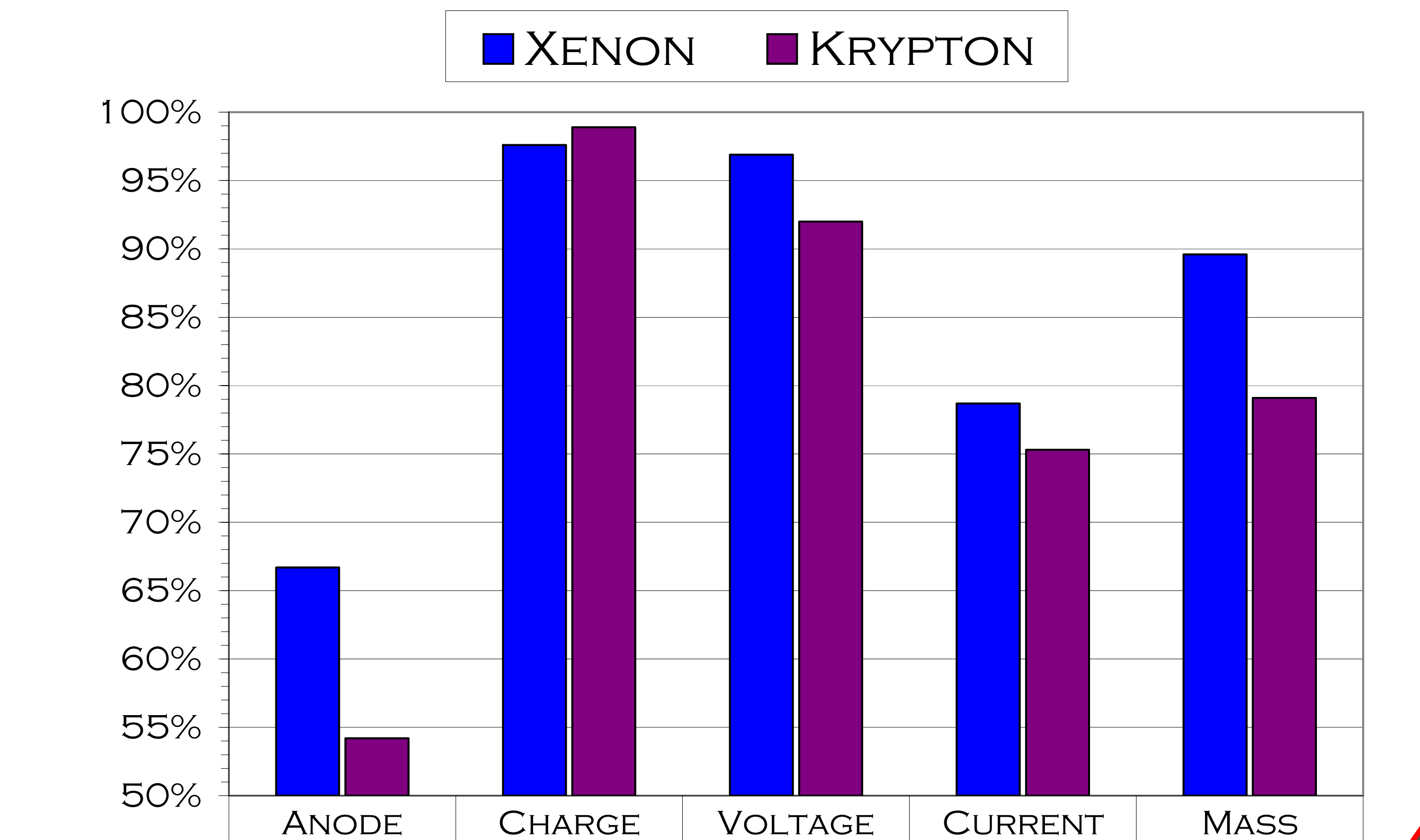
- NASA-173Mv2 Hall thruster
  - Magnetic circuit optimized for high-Isp
  - Designed for xenon
- Xenon conditions
  - 800 V, 9.84 A
  - 10 mg/s anode, 1 mg/s cathode
  - Thrust 324 mN
  - Anode Isp 3310 s (Total Isp = 3000 s)
  - Anode efficiency 66.7% (Total Efficiency= 59.6%)
- Krypton conditions
  - 800 V, 8.27 A
  - 6.4 mg/s anode, 0.64 mg/s cathode
  - Thrust 215 mN
  - Anode Isp 3410 s (Total Isp = 3100 s)
  - Anode efficiency 54.7% (Total Efficiency = 48.8%)

Constant Neutral density

NASA-173Mv2 – Xenon vs. Krypton

Vd = 800 V	Xenon	Krypton
Loss voltage (V)	25	64
Species Fractions (%)	88, 11, 1	96.1, 3.4, 0.5
Divergence Angle (degrees)	61°	67°
Breathing-Mode Frequency (kHz)	25	31
Oscillation Magnitude (% of I_D)	15	14
Electron Current (A)	2.09	2.04

NASA-173Mv2 – Xenon vs. Krypton Efficiencies



	Anode	Charge	Voltage	Current	Mass
Xenon	66.7%	97.6%	96.9%	78.7%	89.6%
Krypton	54.2%	98.9%	92.0%	75.3%	79.1%

VD = 800 V

10.5% decrease in Mass utilization

Conclusions

- The krypton-fueled Hall thruster offers the possibility of high-specific impulse and long lifetime
- NASA's series of Hall thrusters have demonstrated krypton efficiencies only 5-15% less than xenon
  - Larger thrusters have smaller differences in efficiency
- Plasma measurements have demonstrated that efficiency is reduced due to a decrease in mass utilization
- Current efforts are considering the implications of these results, and how design changes can be made to increase the efficiency of krypton Hall thrusters