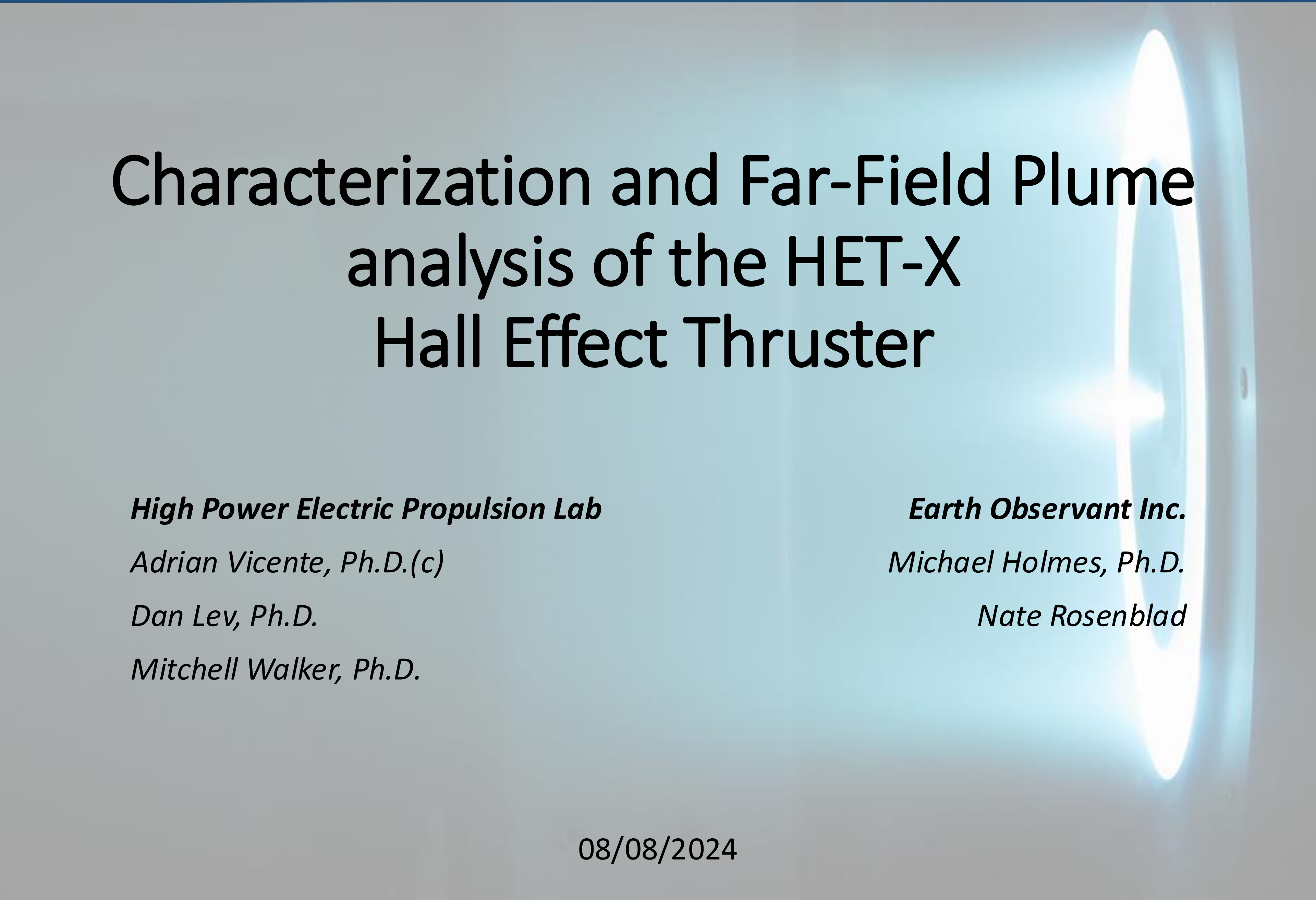

Characterization and Far-Field Plume analysis of the HET-X Hall Effect Thruster

High Power Electric Propulsion Lab

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Electric Propulsion

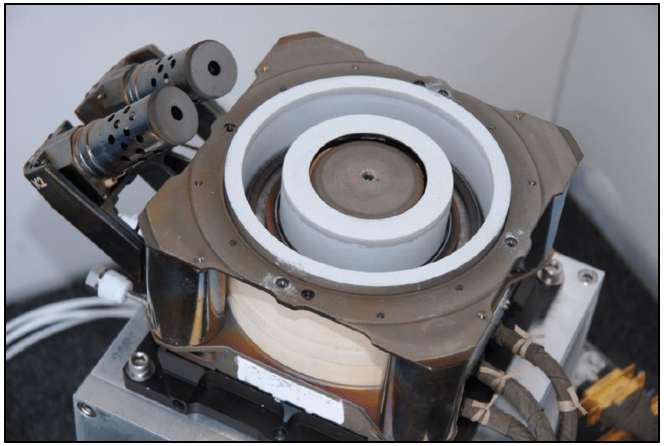
- Space **electric propulsion (EP)** is a branch of in-space propulsive technology. It encompasses any propulsion technology in which electrical power is used to increase the propellant exhaust velocity.
- EP serves as an attractive alternative to conventional chemical propulsion due to its **high specific impulse (I_{sp})** and **fuel efficiency**. By achieving higher exhaust velocities, an equivalent delta-V can be accomplished for a fraction of the propellant mass.
- Across both large spacecraft and SmallSat missions, EP is consistently favorable for long-duration and high delta-V missions.

Propulsion Category	Thruster	Specific Impulse (s)	Total Efficiency (%)
Chemical	Monopropellant	150 - 225	-
Chemical	Bipropellant	300 - 450	-
Electric	Arcjet	500 - 600	24 - 45
Electric	Hall Thruster	1500 - 3000	35 - 60
Electric	Ion Thruster	2500 - 6000	40 - 80

Electric thruster used for NASA's DART mission

Hall Effect Thruster

- A **Hall Effect Thruster (HET)** is an electrostatic thruster that uses crossed magnetic and electrostatic fields to ionize and accelerate its propellant.
- Compared to other EP technologies, HETs boast **greater thrust output** and **thrust efficiency at high power levels**.
- In the last decade alone, they have **successfully flown on thousands of spacecraft** in the private and public sectors. Research and development of HETs has expand their role to deep-space and VLEO applications.



OKB Fakel SPT-100, 1.35kW Thruster

Busek BHT-100, 100W Thruster

High Power Electric Propulsion Lab

- While reliable, HETs **remain poorly understood** and are thus **difficult to predictively model**.

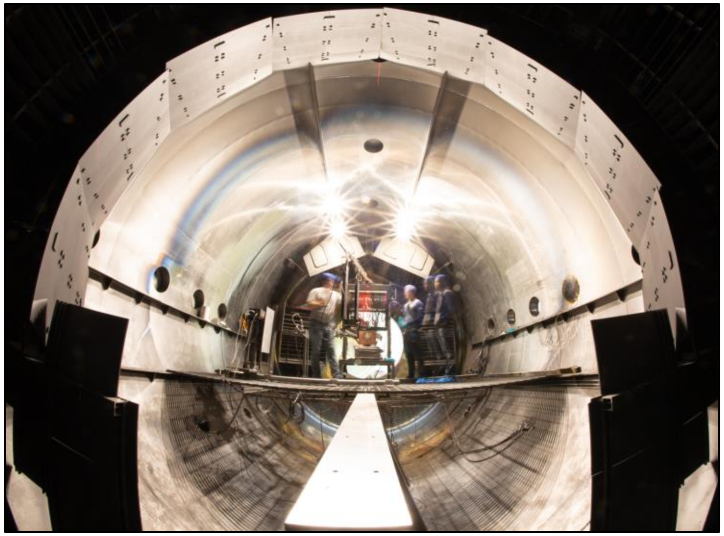
- HET development is **a largely empirical process** guided by heavily iterative design cycles. Highly specialized facilities are required for this.

- Georgia Tech's **High Power Electric Propulsion Lab (HPEPL)** focuses on the characterization of EP devices, plasma physics, and vacuum test facility effects on the performance of EP devices.

- VTF-2 Specifications:

Length:	9.0 m
Diameter:	4.2 m
Pumping speed:	350,000 L/s Xe

HPEPL, Vacuum Test Facility 2 Exterior



HPEPL, Vacuum Test Facility 2 Interior

Collaboration with EOI

- HPEPL entered collaboration with EOI Space in the development of their HET prototype: **HET-X**.
- HET-X operates at moderate-to-high operating power, has a small form factor, and is designed to operate on **various propellants**.

HET-X, Front View

HET-X experimental installation

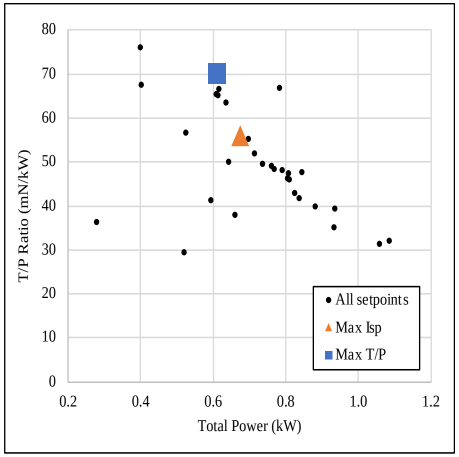
HET Design Cycle

- Comprehensive HET characterizations are generally performed in two phases.
- Phase 1: **Performance Survey**
  Thruster inputs are varied to determine the combinations that yield the desired performance.
- Phase 2: **Characterization**
  Detailed investigation of the ionization and acceleration mechanisms. Internal plasma phenomena are explored.

Phase 0
Thruster Design

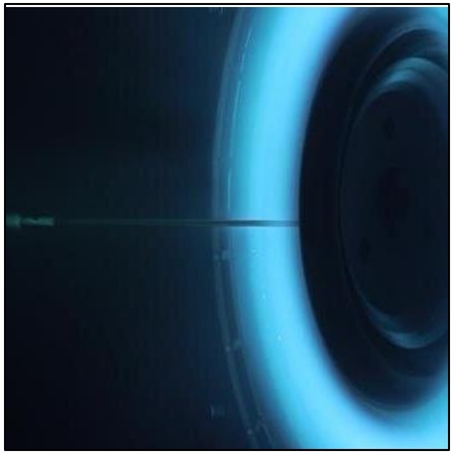
HET-X channel dimension adjustment

Phase 1
Performance Survey



HET-X Power vs. T/P Survey Plot

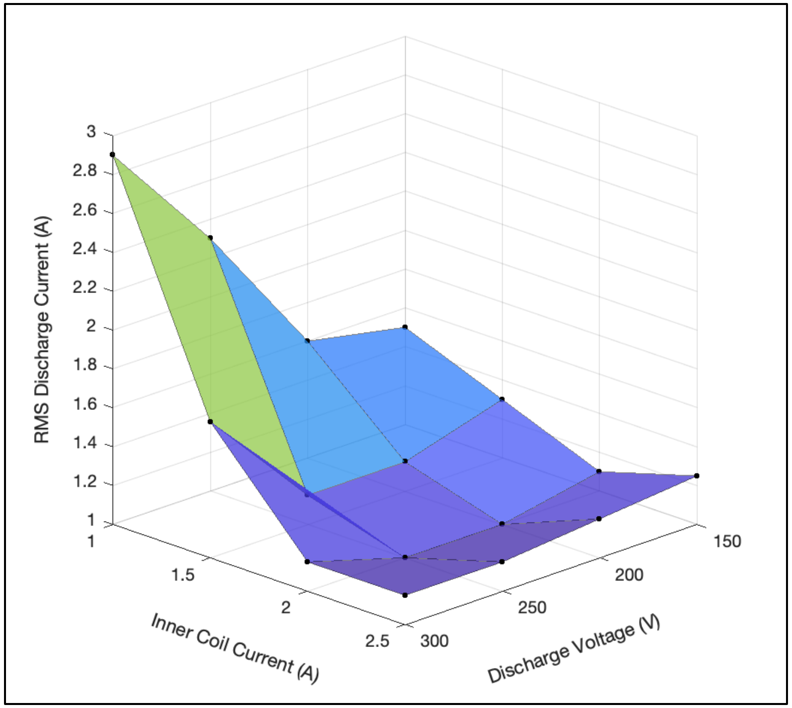
Phase 2
Plasma Characterization



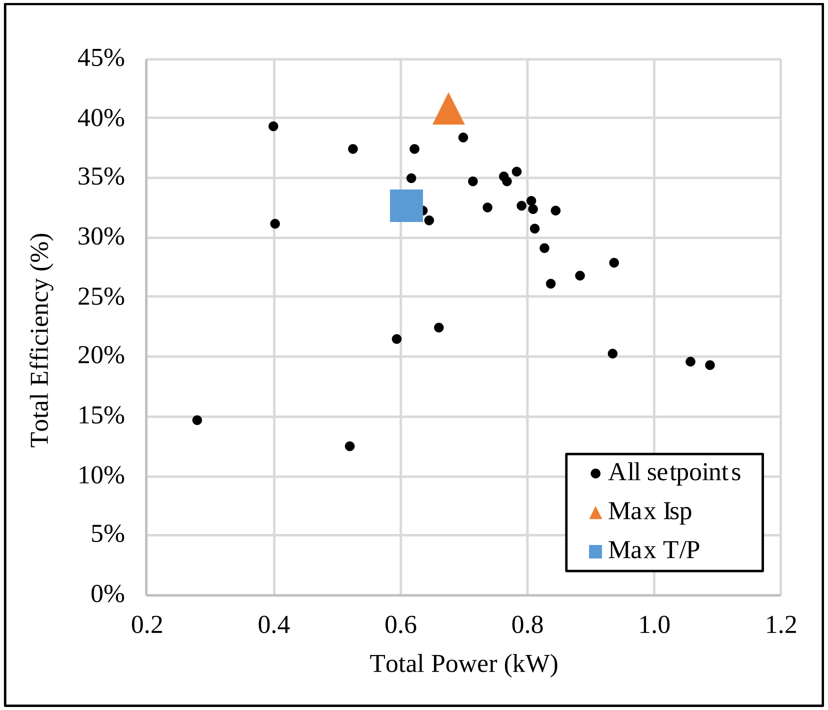
Plasma diagnostics employed on HET

Performance Survey

- The objective is to **obtain empirical performance trends** and **identify the optimal thruster inputs** for a desired configuration.
- The design space is greatly reduced by first generating an **IVB map**. After this, a detailed survey is performed in which all six thruster inputs are varied. Thrust, propellant flow, and power consumption are measured. Efficiency is computed.



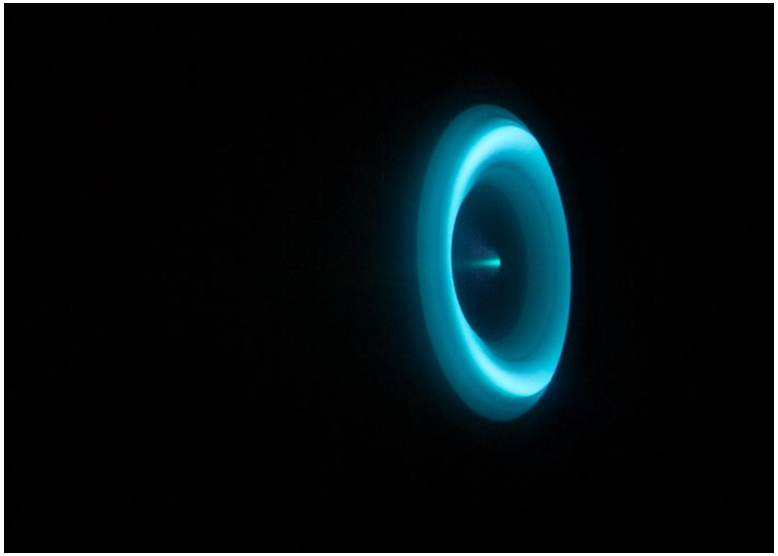
IVB Map, anode flowrate 1.5 mg/s



HET-X Setpoint Survey, η vs P

Optimized Configurations

- The performance survey identified two optimal thruster configurations: **Max. I_{SP}** and **Max. T/P Ratio.**



Operation of HET-X thruster prototype

Table 1. *HET-X Inputs for max I_{sp} and T/P configs.*

Configuration	Max. I_{sp}	Max. T/P
Discharge Voltage [V]	340	150
Discharge Current [A]	1.88	3.84
Inner Magnet Voltage [V]	10.26	10.44
Inner Magnet Current [A]	2.53	2.53
Outer Magnet Voltage [V]	4.39	4.81
Outer Magnet Current [A]	0.88	0.88
HC Keeper Voltage [V]	26	20
HC Keeper Current [A]	0.2	0.2
Total Power [W]	674	611
Cathode-to-Ground [V]	-15.5	-15.0
Anode Flow [Xe mg/s]	2.44	3.90
Cathode Flow [Xe mg/s]	0.29	0.97
Facility Pressure [Torr]	1.00E-06	2.20E-06

Phenomenological Model

From the Performance Survey… →

$$I_{sp} = \frac{T}{\dot{m}g} \qquad \eta = \frac{T^2}{2\dot{m}P}$$

From the Characterization... →

$$\eta = \eta_v \eta_d \eta_b \eta_m \eta_q$$

$$\eta_v = \frac{V_{RPA}}{V_D}$$

$$\eta_b = \frac{I_B}{I_D}$$

$$\eta_d = (\cos(\lambda))^2$$

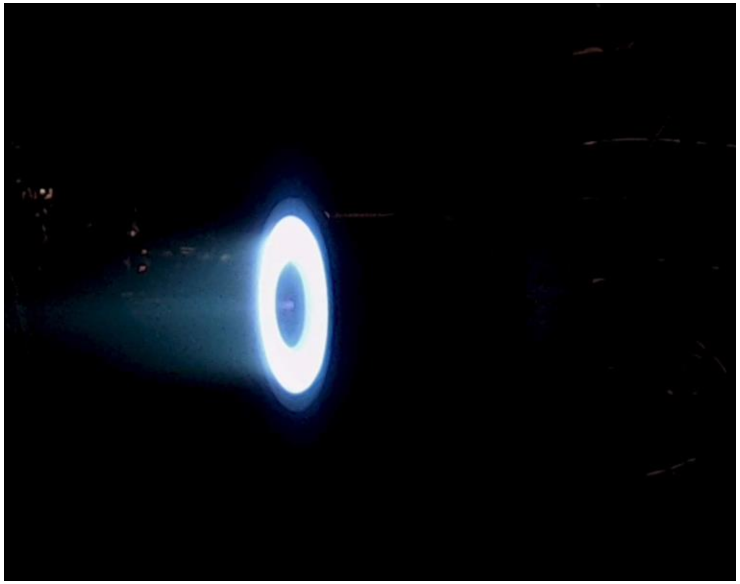
Far-Field Plasma Diagnostics

- **Traditional plasma diagnostic probes are invasive** and known to strongly perturb the discharge plasma of an HET.

- In HET characterization, plasma diagnostics must be **swept through the far-field plume** (~1m downstream).

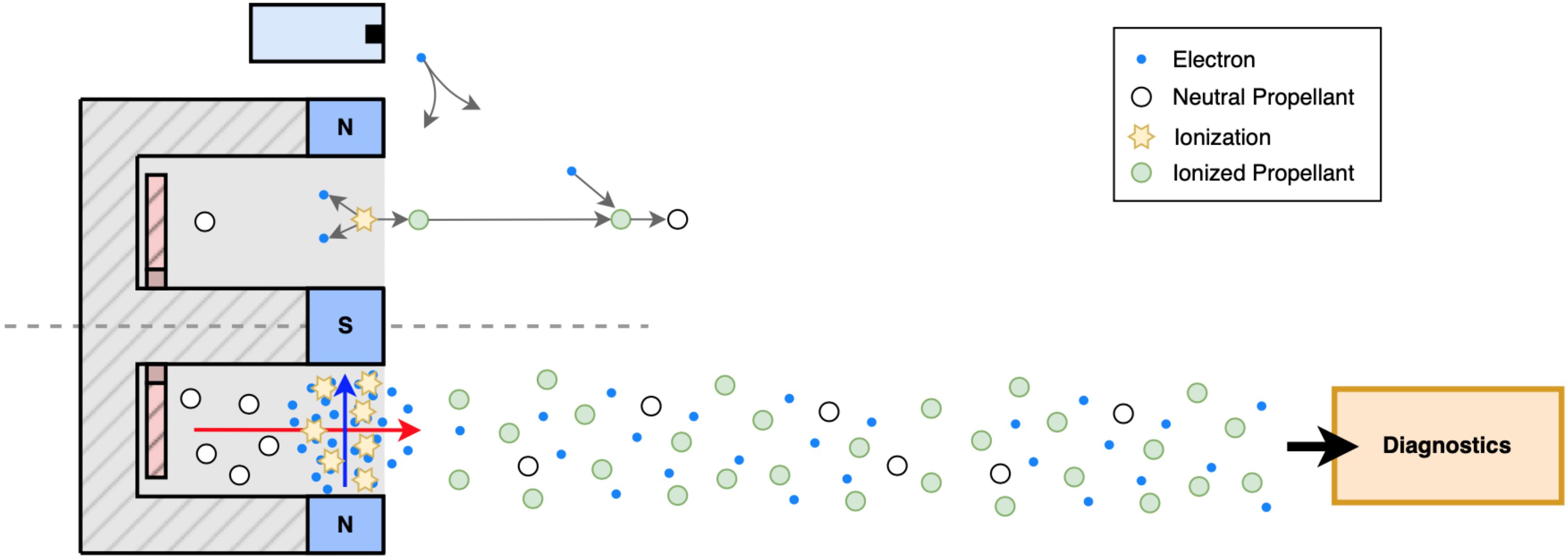
- The efficacy of internal ionization and acceleration processes must be **inferred from downstream measurements.**

Far-Field Probes (left) and HET-X thruster (right)



Hemispherical sweep footage

Far-Field Plume Diagram



- ● Electron
- ○ Neutral Propellant
- ✩ Ionization
- 🟢 Ionized Propellant

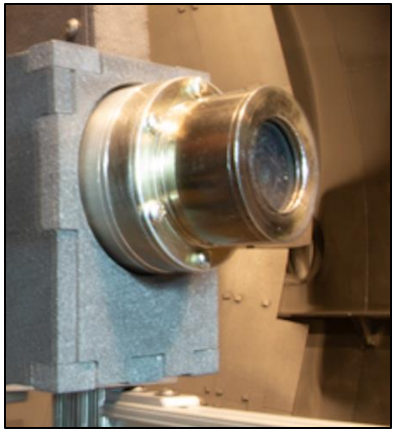
Characterization; Voltage Util. Eff.

- The **voltage utilization efficiency**, η_v , describes how much of the voltage provided by the discharge supply is effectively used to accelerate the ions.
- A **Retarding Potential Analyzer** (RPA) is comprised of several biased grids which decelerate incoming ions. This prove ascertains the ion energy distribution function.
- Voltage Utilization efficiency is defined as the most probable ion energy per charge divided by discharge voltage.

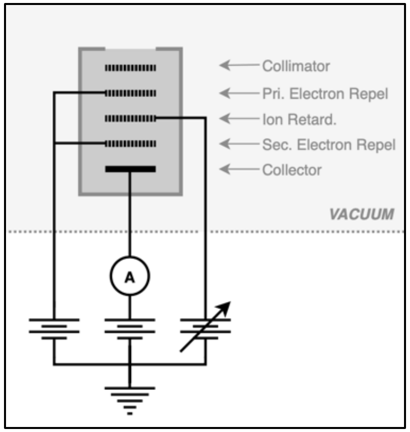
$$f(E_i/q_i) = -\left(\frac{m_i}{A_C q_i^2 e^2 n_i}\right)\frac{dI_C}{dV_3} \propto -\frac{dI_C}{dV_3}$$

$$V_{RPA} = V_3\left(-\frac{dI_C}{dV_3}\right)_{max}$$

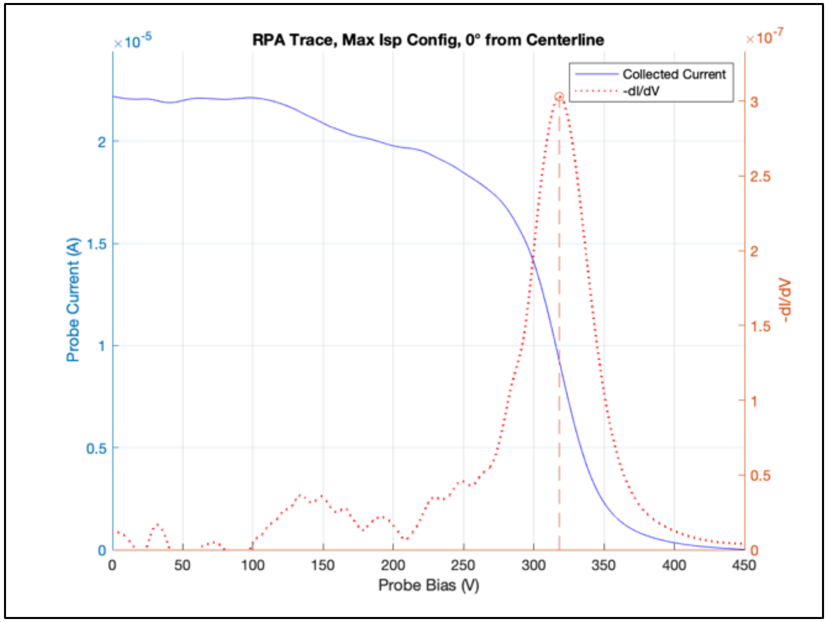
$$\eta_v = \frac{V_{RPA}}{V_D}$$



RPA Probe



RPA Electrical Schematic



RPA trace of Max I_{sp} config. at 0° from centerline

Characterization; Divergence & Current Eff.

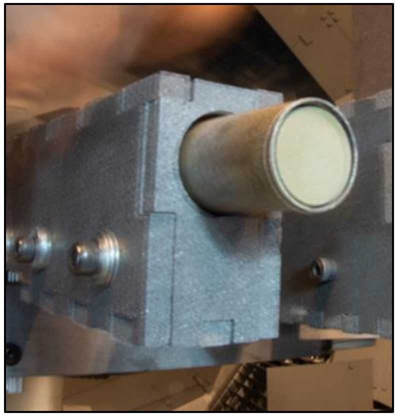
- The **divergence efficiency**, η_d , describes how much of the kinetic energy imparted to the ion is axial and thus produces thrust.
- The **current utilization efficiency,** η_b , describes how much of the discharge current is carried by ions instead of electrons.
- A **Faraday Probe** is employed to measure the ion current density profile of the HET.

$$I_B = 2\pi R^2 \int_0^{\pi/2} j[\theta] \frac{\kappa_D}{\kappa_A} \sin(\theta)\, d\theta$$

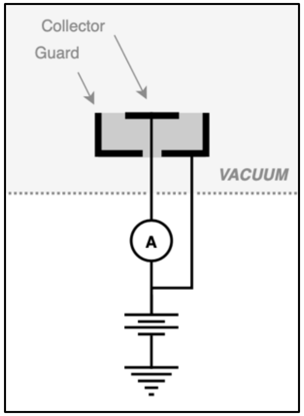
$$I_A = 2\pi R^2 \int_0^{\pi/2} j[\theta] \frac{\kappa_D}{\kappa_A} \cos(\alpha_A) \sin(\theta)\, d\theta$$

$$\lambda = \cos^{-1}(I_A/I_B)$$

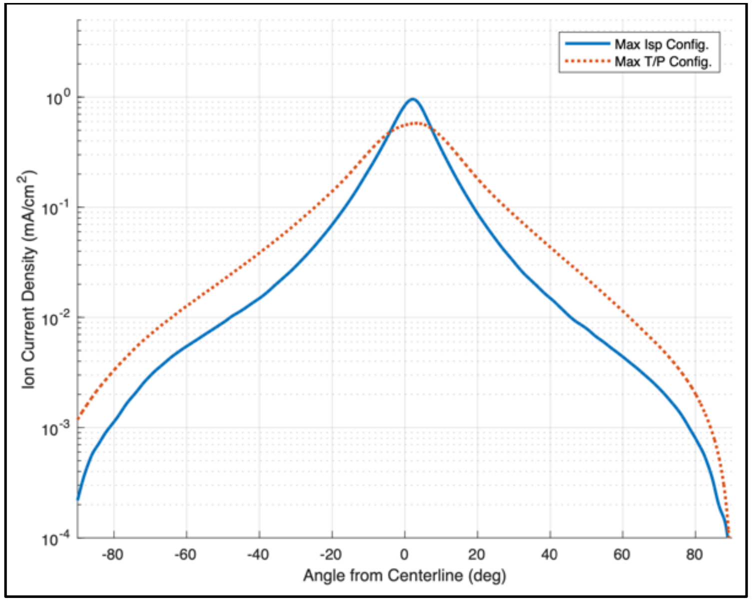
$$\eta_d = (\cos(\lambda))^2 \qquad \eta_b = \frac{I_B}{I_D}$$



Faraday Probe



Faraday Probe Elec. Schem.



Ion current density at 1.0 m from thruster face

Conclusions & Future Work

- **Divergence efficiency** was identified as a mode for improvement.
- The prototype has demonstrated performance characteristics that are **comparable to those of similar sub-kW HETs from other established developers.**
- This initial round of HET-X development was performed in 2022. Since then, several design iterations have passed to improve the efficiency and reliability.
- Subsequent research consisted of improving performance on various other gases to verify its **"propellant agnosticism."**

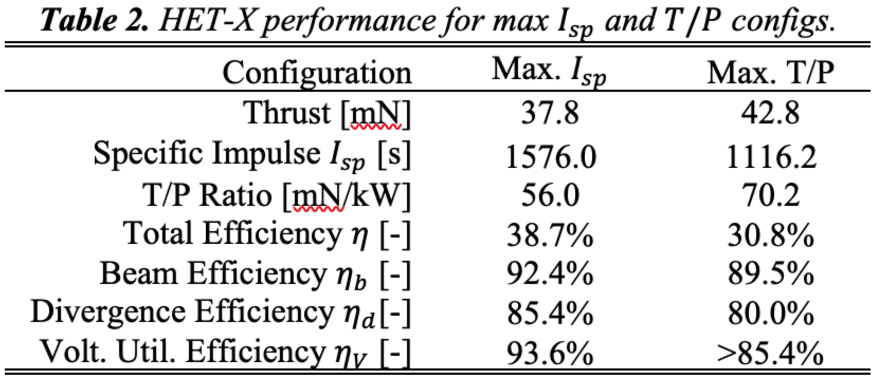


Table 2. *HET-X performance for max I_{sp} and T/P configs.*

Configuration	Max. I_{sp}	Max. T/P
Thrust [mN]	37.8	42.8
Specific Impulse I_{sp} [s]	1576.0	1116.2
T/P Ratio [mN/kW]	56.0	70.2
Total Efficiency η [-]	38.7%	30.8%
Beam Efficiency η_b [-]	92.4%	89.5%
Divergence Efficiency η_d[-]	85.4%	80.0%
Volt. Util. Efficiency η_V [-]	93.6%	>85.4%

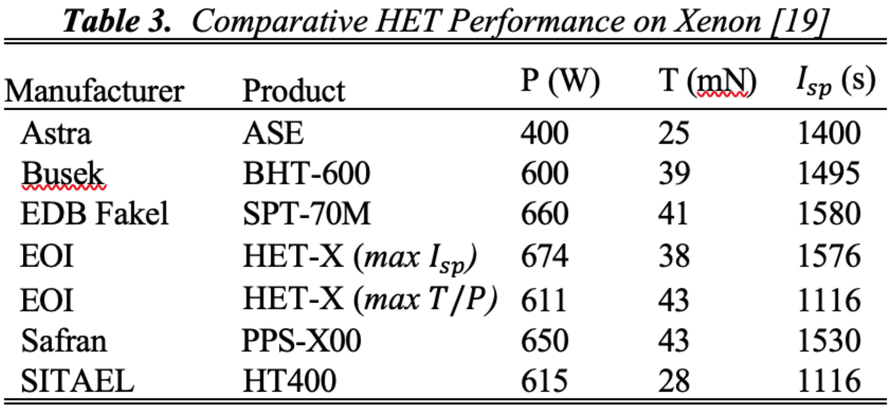


Table 3. *Comparative HET Performance on Xenon [19]*

Manufacturer	Product	P (W)	T (mN)	I_{sp} (s)
Astra	ASE	400	25	1400
Busek	BHT-600	600	39	1495
EDB Fakel	SPT-70M	660	41	1580
EOI	HET-X (*max I_{sp}*)	674	38	1576
EOI	HET-X (*max T/P*)	611	43	1116
Safran	PPS-X00	650	43	1530
SITAEL	HT400	615	28	1116

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