Mass Utilization Scaling with Propellant Type on a Magnetically Shielded Hall Thruster

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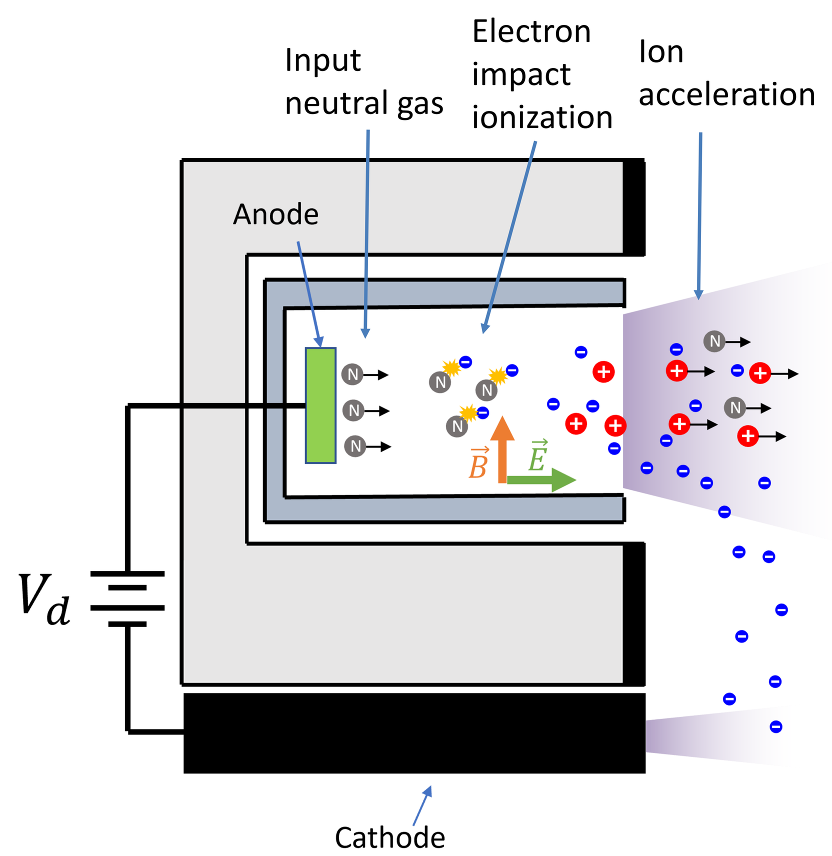
Introduction

- Hall thrusters electrostatically accelerate ions to produce thrust → overall device efficiency dependent on how well the input neutrals are ionized (**η_m**)
- Most Hall thrusters are optimized for xenon due to its large mass and ionization cross section → xenon cost is driving a growing interest in other propellants like krypton, argon, and nitrogen

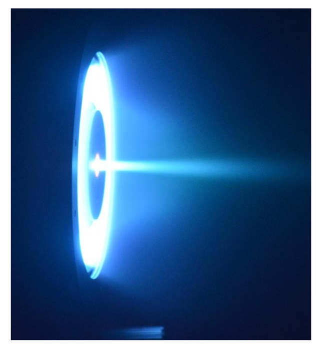


Key point: Mass utilization (η_m) for harder to ionize alternative gases (krypton, argon, nitrogen) is typically low, driving down overall performance [1-3].

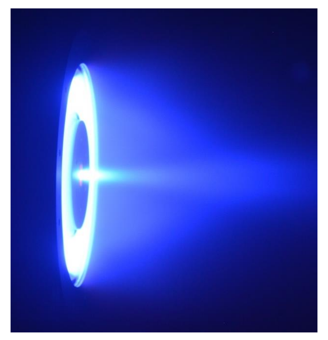
Goal: Develop a simple mass utilization model and validate it with experimental data on xenon[1], krypton[1], argon, and nitrogen.

Experimental Campaign

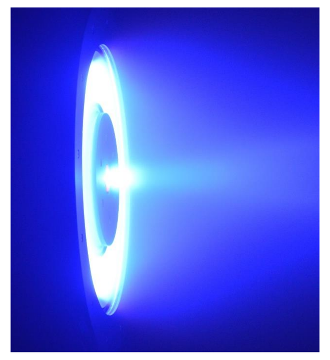
Xenon Operation [1]



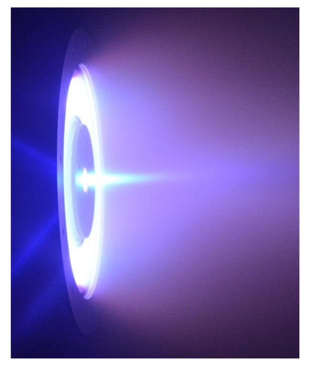
Krypton Operation [1]



Argon Operation



Nitrogen Operation



Test Article	H9
Facility	LVTF
Discharge Voltage (V)	200, 300 V
Propellants	Xenon, Krypton, Argon, Nitrogen
Diagnostics	Faraday, Langmuir, ExB

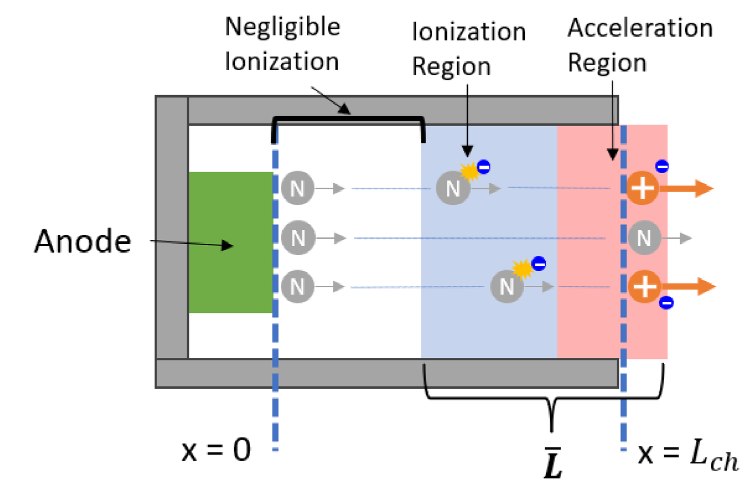
Inferring mass utilization η_m with far-field probes

$$\eta_m \equiv \frac{\dot{m}_i}{\dot{m}_a} = \frac{I_b}{\dot{m}_a}\sum \frac{\Omega_s m_s}{q_s}$$

Variable	Description	Probe/ Instrument
$\dot{m}$	Mass flow rate	Mass flow controller
I_b	Ion beam current	Faraday probe
Ω_s	Ion current fractions	ExB probe

0-D Mass Utilization Model

Hall thruster discharge channel



Mass utilization (η_m) Definition

$$\eta_m \equiv \frac{\dot{m}_i}{\dot{m}_a} = 1 - \boxed{\frac{n_n(\bar{L})}{n_n(0)}}$$

Need to estimate neutral density ratio

Variable	Description
$\dot{m}$	Mass flow rate
n	Density
k_{iz}	Ionization rate
T_e	Electron temperature
v_n	Neutral velocity
T_n	Neutral temperature
L_{ch}	Channel length
$\bar{L}$	Channel length relevant for ionization

1D steady state continuity equation

Electron impact ionization depletes neutrals

$$\underbrace{\cancel{\frac{dn_n}{dt}}}_{\text{Steady state}} + \frac{dn_n}{dx}v_n + \underbrace{\cancel{\frac{dv_n}{dx}}}_{\text{Constant neutral velocity (no expansion)}} n_n = -n_n n_e k_{iz}(T_e)$$

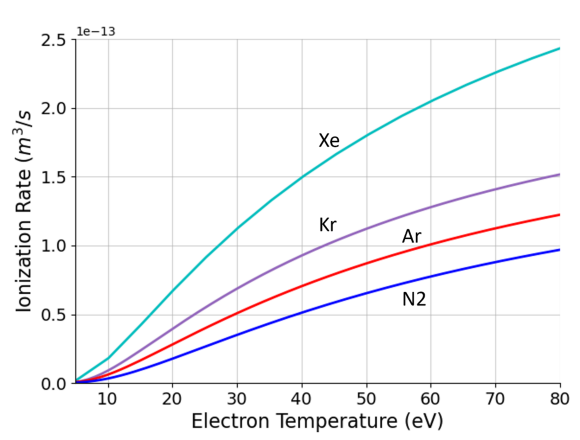
Integrate continuity equation along channel length

$$\frac{n_n(\bar{L})}{n_n(0)} = \exp\left(-\frac{\bar{L}}{\lambda_i}\right) \Rightarrow \boxed{\eta_m = 1 - \exp\left(-\frac{\bar{L}}{\lambda_i}\right)}$$

$$\lambda_i = \frac{v_n}{k_{iz} n_e}$$ *Ionization Mean Free path*

Estimating model parameters

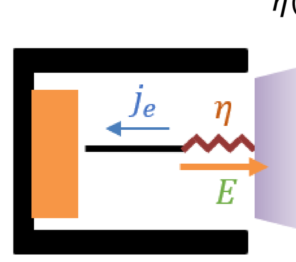
Ionization Rate: $k_{iz}(T_e)$



Assumption(s)
- Maxwellian electrons
- Electron temperature scales with discharge voltage 0.1 V_d[4]

Plasma Density: n_e

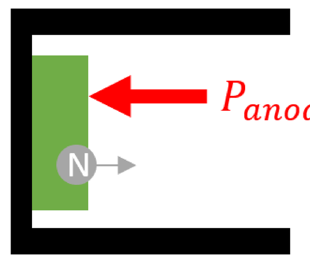
Ohms law $j_e = \frac{E}{\eta(n_e)}$



j_D: Discharge current density
V_D: Discharge Voltage
B: Magnetic Field

Assumption(s)
- Constant beam utilization, cathode coupling voltage, and width of acceleration region [1,5]
- Electron Collision Frequency is Bohm-like [6-7]
- Neglect pressure terms in ohms law

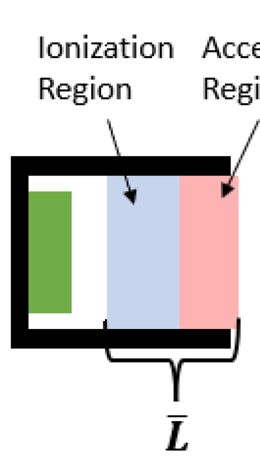
Neutral Velocity: v_n



$$v_n = \sqrt{k_b T_n / m_i}$$

Assumption(s)
- Neutrals thermalize with anode
- Anode temperature scales with discharge power and radiative heat transfer dominates

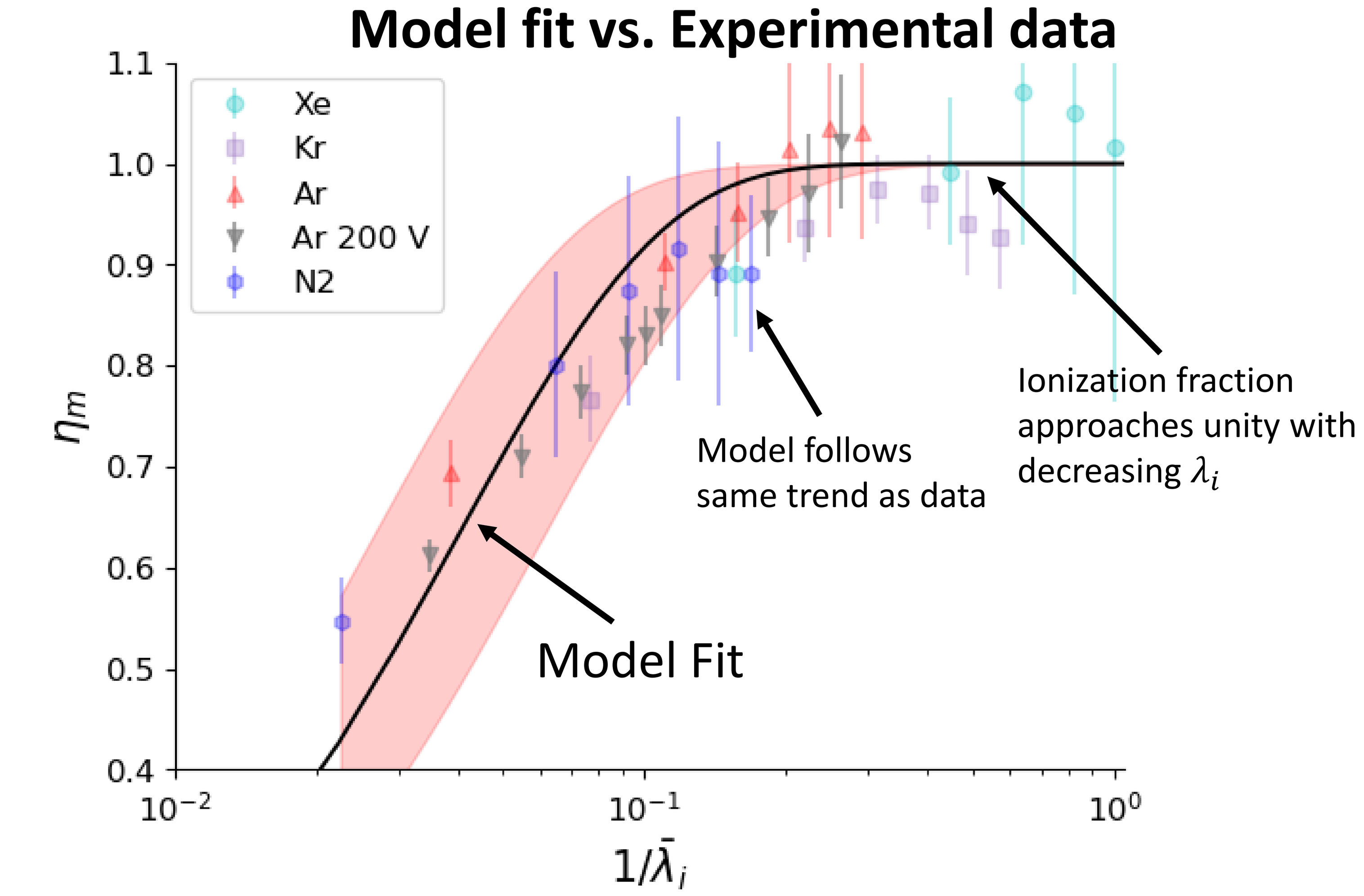
Characteristic length: $\bar{L}$



We learn $\bar{L}$ from experimental data

Results

Model fit vs. Experimental data



Key Takeaways

- The model captures all the data within experimental uncertainty
  - The data spans 4 gases across many disparate operating conditions
- Both the mass utilization data and model asymptote to unity (all propellant ionized) with decreasing λ_i
- The fit quality indicates we are capturing some of the underlying physics driving mass utilization

Summary

- We developed a model to predict Hall thruster ionization fraction as a function of both gas type and operating condition
- We generated a large experimental data set for model validation
- The model shows excellent agreement with the experimental data, corroborating our assumptions
- The validated model could assist with future thruster designs

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