Accelerating Electric Propulsion Development for Planetary Science Missions with Optical Plasma Diagnostics

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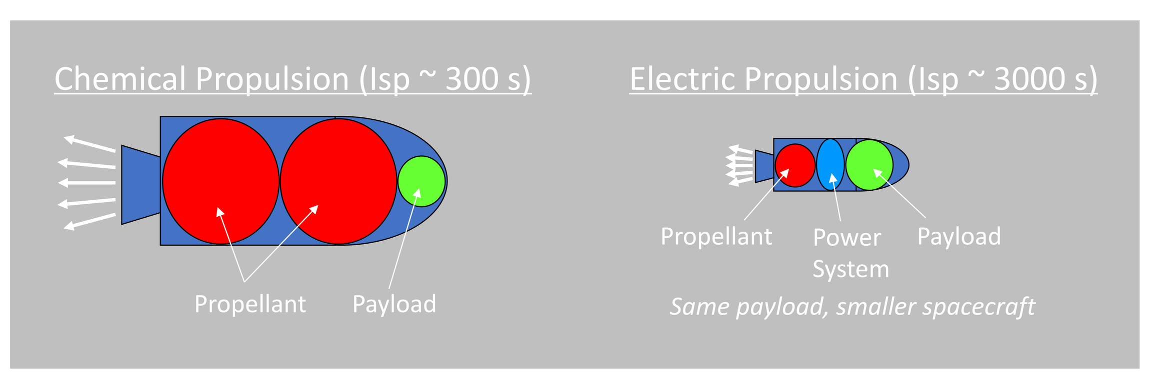
ABSTRACT: This NASA MOSAICS Seed Funding project establishes a research partnership between the University of Alaska Anchorage (UAA) and the NASA Jet Propulsion Laboratory (JPL) on the topic of electric propulsion (EP). With much higher specific impulse than chemical rockets, EP can dramatically lower mission costs, increase delivered scientific payload mass, and enable otherwise unattainable science goals to be achieved in applications such as sample returns and multi-body rendezvous missions. The research focuses on development of optical emission spectroscopy (OES) diagnostics for Hall thrusters. NASA's life qualification strategy for these thrusters utilizes a combination of laboratory wear testing and high-fidelity physics-based modeling, with validation of the models accomplished through comparisons with wear test results and detailed plasma measurements. At present, ion dynamics can be effectively diagnosed using laser-induced fluorescence (LIF), but no comparably mature capability exists for non-perturbing measurements of electron properties such as density and temperature. OES is a promising approach that uses a collisional-radiative (CR) model of atomic processes in the plasma to determine electron fluid properties from the wavelength and intensity of light spontaneously emitted by excited atoms and ions. This research addresses the remaining challenges for implementing OES in NASA's Hall thruster testing by advancing our understanding of the CR models' sensitivities and by validating the plasma properties derived from OES via comparisons with measurements made using Langmuir probes. To increase the sustainability and impact of the UAA research program, JPL's existing CR models for xenon plasmas will be extended to krypton and argon. These less expensive alternate propellants are of rapidly growing interest to NASA and the commercial EP sector and can enable higher specific impulse. Initial results in adapting the CR models and plans and designs for the plasma source and diagnostics are presented.

Introduction

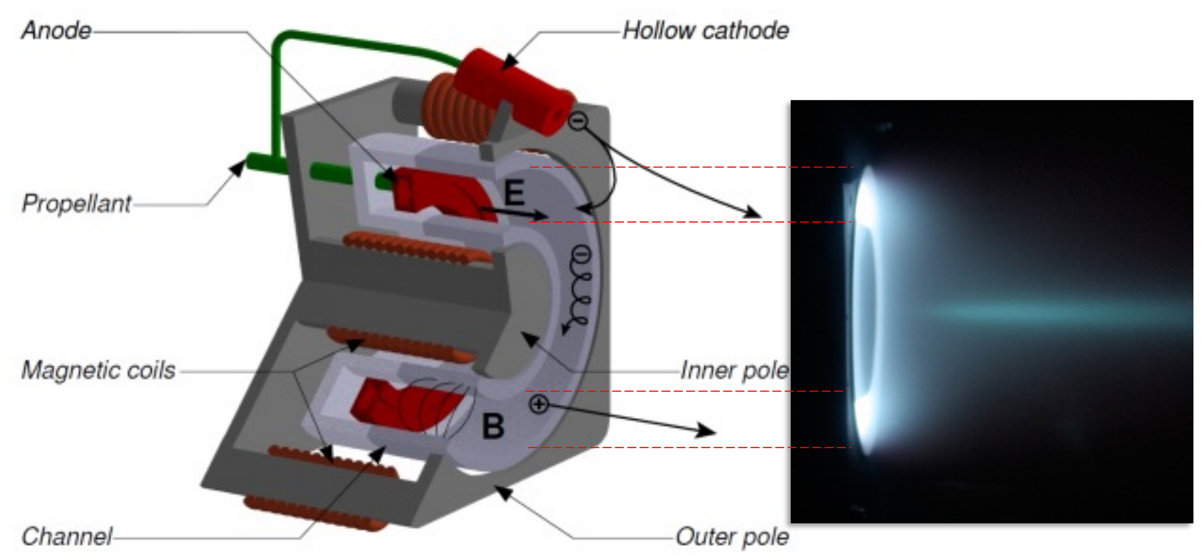
- Electric propulsion (EP) achieves high specific impulse (I_{sp}) compared to chemical rockets (1000 – 4200 s for state-of-the-art Hall thrusters and gridded ion thrusters running on xenon [1])
- The fraction of the initial spacecraft mass that must be propellant in order to enter an orbit requiring velocity change Δv depends exponentially on the exhaust velocity: $\frac{m_s}{m_{p0}+m_s} = \exp\left(-\frac{\Delta v}{v_{ex}}\right) \equiv \exp\left(-\frac{\Delta v}{I_{sp} g}\right)$
- High-I_{sp} thrusters provide valuable benefits for planetary science missions including higher scientific payload mass, launch window flexibility, elimination of critical events such as orbit insertion, and shorter flight times [2].



- EP can be enabling for sample return missions, such as the upcoming Mars Sample Return mission led by NASA, and for missions that go into orbit around multiple bodies, achieved for the first time when NASA's Dawn spacecraft visited Ceres and Vesta [3].
- Ongoing research in EP seeks to improve thruster performance, peak power, and lifetime, and to develop high-efficiency, long-life low-power thrusters for small satellite missions requiring large spacecraft Δv [1]. Life qualification by brute force long duration testing is costly, and building physical understanding through modeling is critical to reduce mission risk [4].
- Hall thruster operation in particular involves complex plasma physics in which electrons are transported across a confining magnetic field by gradient- and flow-driven wave instabilities [5] while the electric field enabled by restricted electron mobility accelerates unmagnetized ions to produce thrust.

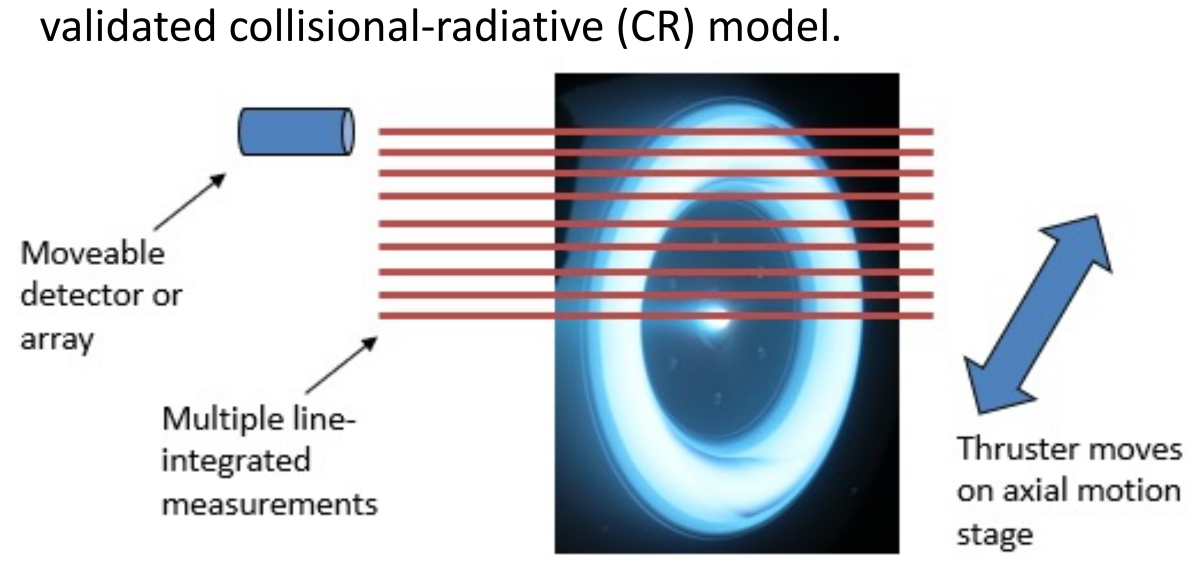
Hall Thruster Operation and Diagnostics

- The Hall thruster employs a cross-field discharge to generate plasma. The electric field perpendicular to the applied magnetic field electrostatically accelerates ions to high exhaust velocities v_{ex}, while the magnetized electrons have limited mobility to the anode.



1. Electrons from the cathode are trapped in an azimuthal drift by the applied electric (**E**) and magnetic fields (**B**).
2. Neutral propellant gas is <u>ionized</u> by electron bombardment.
3. Ions are <u>accelerated</u> by the electric field producing thrust.
4. Electrons from the cathode <u>neutralize</u> the ion beam.

- As mission-required thruster lifetimes increase and higher power thrusters are developed, plasma simulations are taking a central role in life qualification.
- To validate Hall thruster models, *non-invasive optical measurements* are an important diagnostic tool, since direct probe measurement can perturb the plasma [#]
- Laser-induced fluorescence (LIF) is used to measure ion and neutral velocities with high resolution…
- …and optical emission spectroscopy (OES) can measure electron properties (but is currently less mature and accurate as compared to LIF).
- OES measurements are relatively simple to set up, but deriving plasma properties such as electron temperature and density requires significant post-processing with a validated collisional-radiative (CR) model.



- The CR model predicts population densities of atomic energy levels (and theoretical emission spectra) as a function of T_e, n_e, n_n, etc.; observed OES data are compared to the CR model to yield corresponding values of the electron plasma parameters.
- So far, a xenon CR model exists [6], but models for other gases (e.g. argon, krypton) are needed as well.

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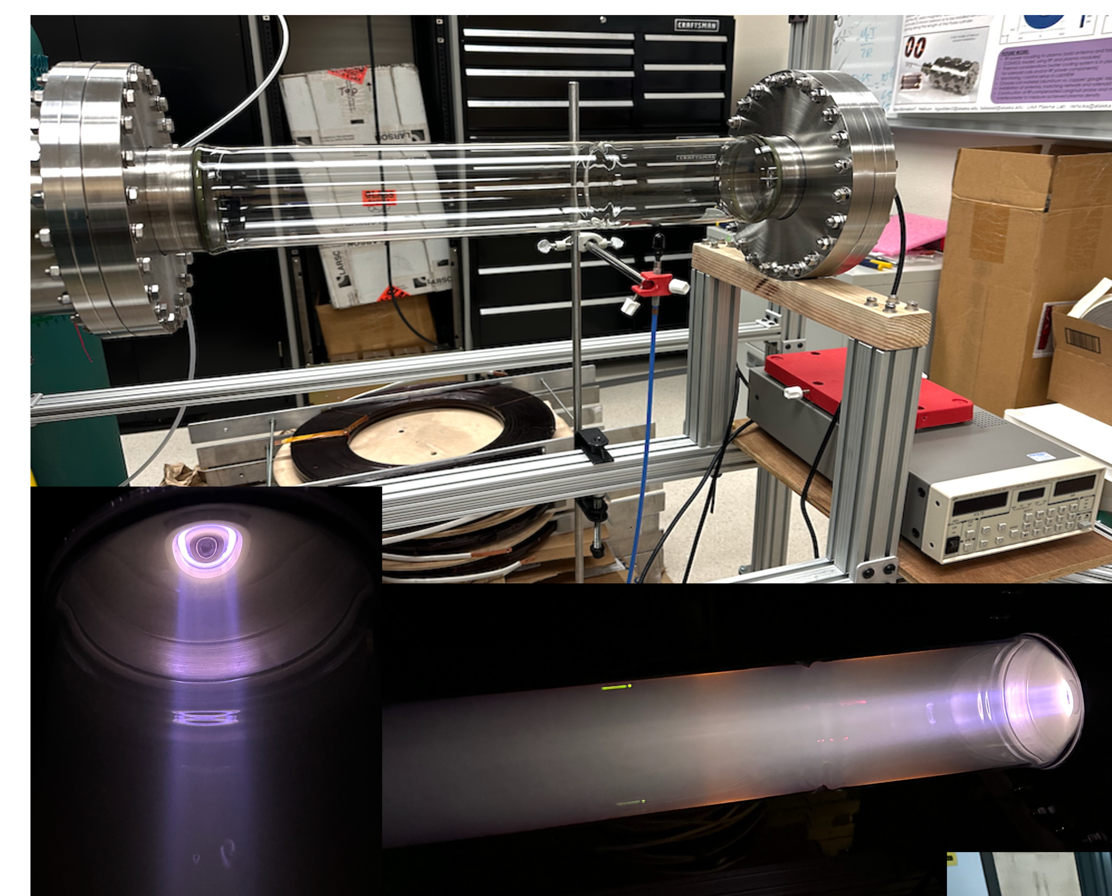
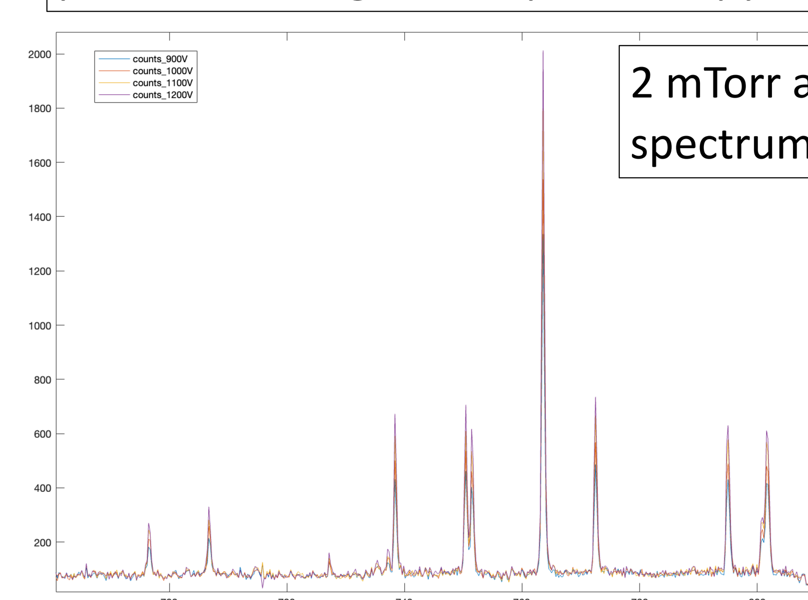
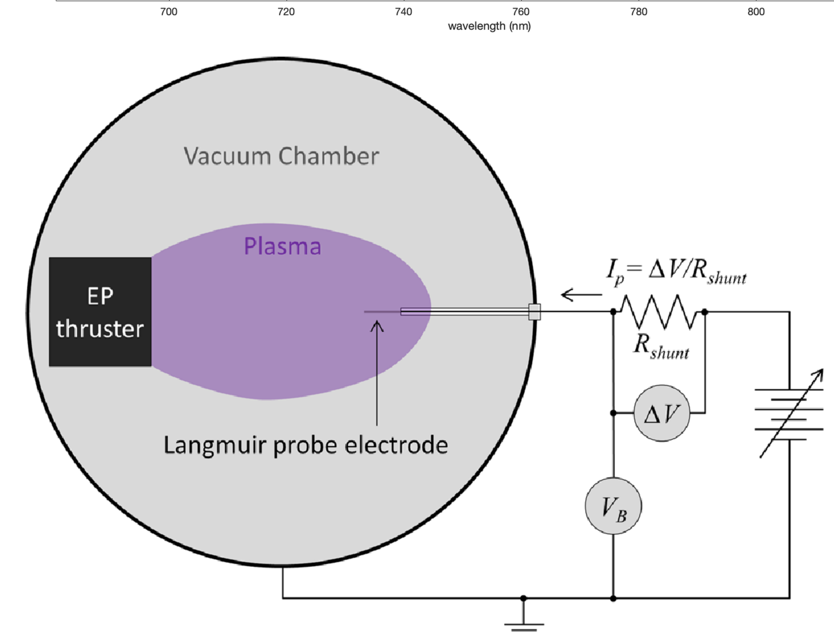
Target Plasma Development for Argon OES

- A testbed for generation of Hall thruster-like plasma in argon is being developed at UAA, so that OES measurements of relevant plasma conditions can be made. Argon is becoming more commonly used as a propellant, and this project will complement the existing and continuing work with xenon.
- A Pyrex tube (60 x 10 cm) is mounted to a stainless steel vacuum chamber, with sightlines and ports for plasma source and diagnostic apparatus.
- As a preliminary test, a DC discharge using an anode layer ion source was produced at 1 – 2 mTorr argon pressure, and spectra in the visible-UV range were acquired using an Ocean HDX spectrometer. Expected emission lines for argon were observed (e.g. in the 700 – 800 nm range), with good signal-to-noise.



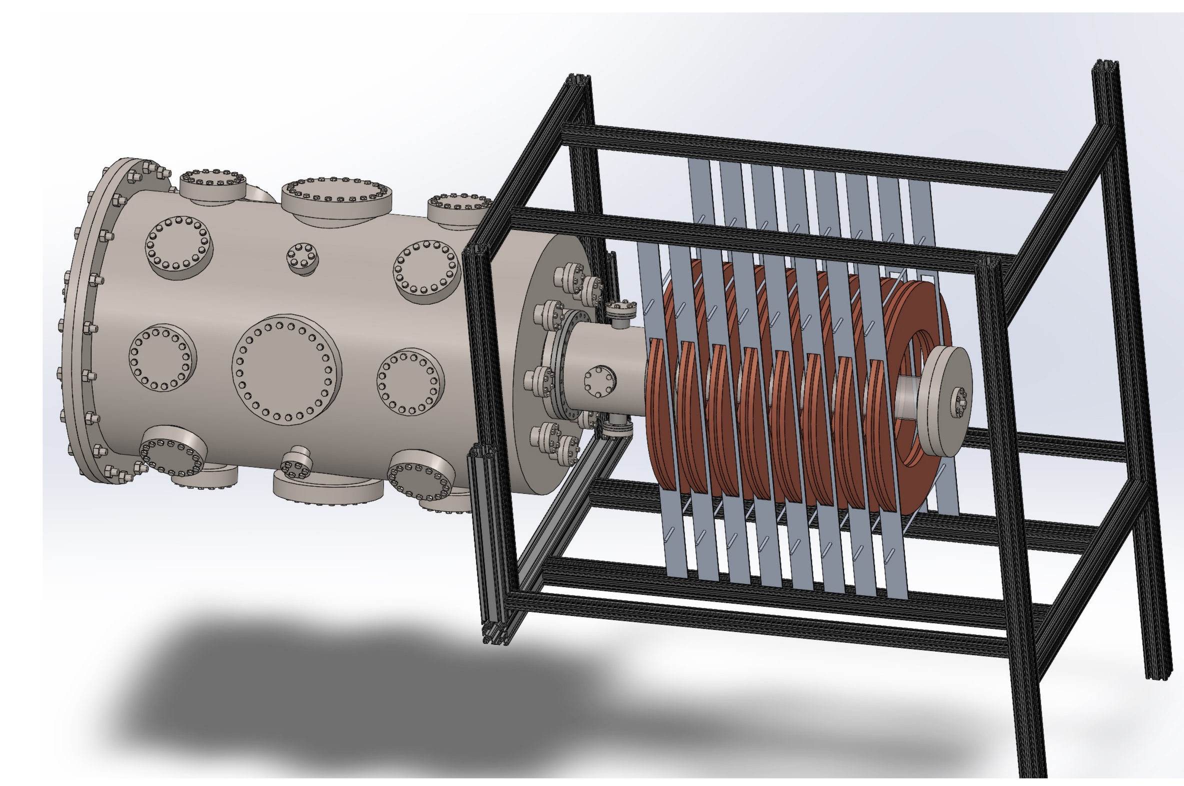
Experimental setup including anode layer ion source and optical fiber / lens for initial argon plasma discharges and spectroscopy.





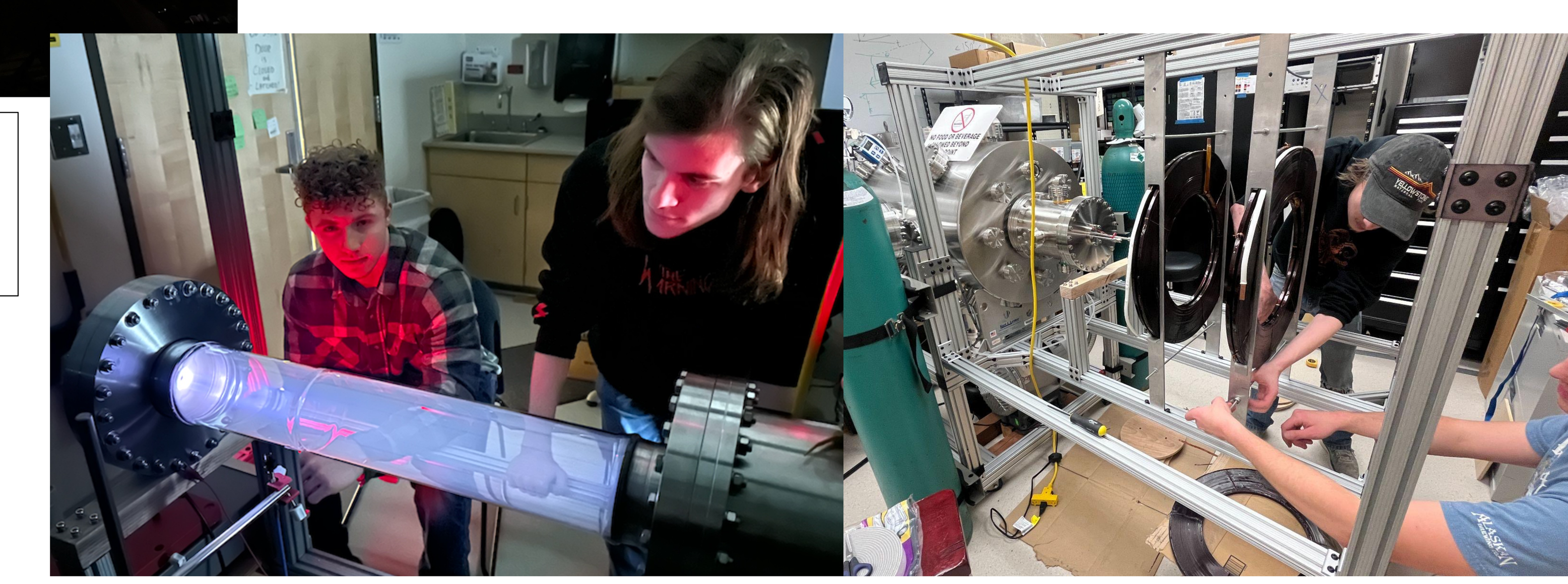
- The spectroscopy setup will be expanded to additional viewing chords and locations, as well as extended wavelength range into the infrared, and these data will be used to validate the argon CR model being developed in the UAA-JPL collaboration.
- An RF-compensated Langmuir probe [7] will be installed to make direct measurement of T_e and n_e, calibrating the OES data and argon CR model results.

- A radio frequency (RF) plasma source will be installed on the Pyrex tube to achieve higher-density discharges
- The experimental setup is being expanded to include a set of 16 magnetic coils, producing a 0.1 T axial field. This capability is needed e.g. to operate a high-density helicon mode plasma source.



Student Opportunities and Outreach

- The project provides hands-on experimental as well as computational physics research for participating undergraduate students in the UAA Plasma Lab.
- Summer internships at NASA-JPL will be available to a subset of students, to advance the research goals of the collaboration and provide further experience.
- The UAA-JPL collaboration is being presented to the UAA and Anchorage communities, including K-12 outreach, to encourage future students to participate.



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