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LASER DIAGNOSTICS FOR SPACECRAFT PROPULSION

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Outline

• Motivation

• Monopropellant thrusters
  – Diode Laser Absorption Spectroscopy (DLAS)
  – Wavelength Modulation Spectroscopy (WMS)

• Arcjets

• Hall thrusters/ion engines
  – Laser Induced Fluorescence (LIF)
  – Time resolved LIF Methods

• Recent results from Time-Synchronized LIF
  – Time-Sync Method
  – BHT-600 Results

• Summary

• References
Motivation

• Many satellite propulsion technologies were developed in the 1960s
  – Didn’t have the diagnostics to fully understand how/why they worked
  – Aging workforce causing us to lose knowledge of how the systems were made, recipes for materials, trade secrets, etc.
  – Now having to go back and characterize old systems to lay groundwork for advancements in technologies

• Tunable diode lasers developed in the 1960s
  – Diagnostic techniques have been developed alongside propulsion technologies
  – Simulation of space environment, rarefied gases – facility effects become important
  – Laser diagnostics non intrusive, can survive harsh environments of combustion, plasmas

• New methods of laser diagnostics
  – Provide insight into dynamics of thruster operation
  – Are linked to thruster performance metrics
  – Are critical to validating numerical simulations
Monopropellant Thrusters

**Operation**
- Monopropellant flows over catalyst bed to initiate exothermic decomposition
- Propellant is expanded and accelerated out of a nozzle
- Developed in 60s, having to now go back and figure out how they work

**Diagnostics**
- Destructive testing the current standard
  - Intrusive, post-test
  - Cut open thruster to examine catalyst
- Diode Laser Absorption Spectroscopy
  - Non-intrusive, in-situ measurements
  - Temperature, species concentrations
  - Wavelength Modulation Spectroscopy (WMS)
- Other methods such as FTIR, PLIF, emission spectroscopy on combustion/propellants, not on thrusters in operation

**Aerojet MR-106**
Propellant: Hydrazine
Thrust: 22 N       Isp: 235 sec
**Beer-Lambert Law**

\[ I_v(L) = I_v^0 \exp(-k_v L) \]

- \( I_v(L) \): Transmitted spectral intensity after traveling through a distance, \( L \), through the medium [W/cm\(^2\)s\(^{-1}\)]
- \( I_v^0 \): Initial spectral intensity of the laser per unit frequency [W/cm\(^2\)s\(^{-1}\)]
- \( k_v \): Spectral absorption coefficient [cm\(^{-1}\)]

**Ramp input to laser**
- Modulates intensity and wavelength (modulation frequency up to 1 MHz)
- Baseline fit + Beer-Lambert Law gives absorbance of spectral feature

**Species Identification**
- \( k_v \) can be related to number densities, partial pressures to detect concentrations of combustion products such as NH\(_3\)
- Presence of different species indicates catalyst health

**Temperature**
- FWHM of transition indicates temperature (if no pressure broadening)
- Ratio of two nearby transition intensities indicates temperature (pressure independent)
- Lowering temperature indicates degradation of catalyst
Wavelength Modulation Spectroscopy (WMS)

1f-normalized WMS-2f

- Diode laser modulated in wavelength and intensity via:
  - Current injection at frequency = 1f
  - Ramp voltage
- Detector output sent through two lock-in amplifiers
  - Reference frequencies = 1f and 2f
  - Comparison of 2f signal ("WMS-2f") to model of absorption feature indicates temperature and gas concentration

- Improved sensitivity and noise-rejection over direct absorption (2 to 100x better SNR)

- 2f signal is related to the original absorption feature by a mathematical transform

\[ I_v(L) = I_v^0 H_n(\bar{\nu})L \]

\[ H_n(\bar{\nu}) = \frac{2^{1-n}}{n!} \frac{d^n \alpha(\nu)}{d\nu^n} \bigg|_{\nu=F} \]

- \( H_v^n \) = nth Fourier component of modulated absorption coefficient (n=2 for WMS-2f)
- \( \alpha(\nu) \) = absorption coefficient (modeled by Gaussian, Lorentzian, Voigt)
- \( \nu \) = mean modulation frequency

- Normalization of 2f signal by 1f signal eliminates effects of laser intensity drift, scattering, etc.

\[ \frac{2f}{1f} = \frac{H_2}{i_0} = \frac{S(T) \cdot P \cdot x_i \cdot L}{i_0 \cdot \pi} \int_{-\pi}^{\pi} \phi(\bar{\nu}_{peak} + a \cos \theta) \cos 2a \delta \theta \]

- \( S(T) \) = Linestrength at temperature = T
- \( x_i \) = species concentration
- \( i_0 \) = incident laser intensity
- \( \phi \) = lineshape function (Gaussian, Lorentzian, Voigt)
- \( a \) = amplitude of frequency modulation
Arcjets

**Operation**
- Electrothermal thruster
- Heats a gaseous propellant (hydrazine, NH₃, H₂) via electrical arc
- Propellant is expanded and accelerated out of a nozzle similar to chemical thrusters

**Diagnostics**
- Laser Induced Fluorescence
  - Velocity, temperature measurements
  - Development of LIF techniques
    - Hydrogen plasma
- Raman spectroscopy

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Aerojet MR-510 Arcjet
Propellant: Hydrazine
Thrust: 250 mN  Isp: 585 sec

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Ion Engines & Hall Thrusters

**Operation**

Ion engines and Hall thrusters are electrostatic propulsion devices

**Ion Engines**
- Propellant is ionized via electron bombardment and then accelerated by high voltage grids
- Thrust, Isp, Propellant: Xenon

**Hall thrusters**
- Hall thrusters are gridless electrostatic thrusters
- Propellant ionized by electrons trapped in magnetic field
- Ions accelerated by an electric field between anode and electron cloud
- Thrust, Isp, Propellant: Xenon, Krypton

**Diagnostics**
- Laser Induced Fluorescence
  - Velocity, temperature measurements
- Diode Laser Absorption Spectroscopy
  - Metastable neutrals
Laser Induced Fluorescence

- Laser beam tuned across electronic transition in Xe ions
  - $5d[4]_{7/2} \rightarrow 6p[3]_{5/2}$ at 834.72 nm
- Ions spontaneously emit photons resulting in their relaxation from its excited state to a lower state (fluorescence)
  - $6s[2]_{3/2} \rightarrow 6p[3]_{5/2}$ at 541.92 nm

- Fluorescence excitation spectrum
  - Convolution of ion velocity distribution function (VDF), transition lineshape (inc. hfs, etc.)
  - Shape (broadening/shift) dominated by Doppler effect:
    \[
    \delta v_{12} = \frac{V}{c} v_{12}
    \]

![Diagram of Xe^+ transition levels](image)

Non-resonant fluorescence scheme

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Measurement of time-averaged velocity vectors
- Non-intrusive measurements in channel and near field plume
- High spatial resolution (~1mm)
- High spectral resolution can resolve multiple velocity populations
- Temporal resolution eliminated by need for long integration times (>100 ms)

Necessary to develop time-resolved LIF velocity measurements
- Resolve oscillatory behavior of thrusters
- Inform M&S for S/C interactions

CW diode lasers required to take time resolved LIF measurements
- Typical linewidth of pulsed laser is larger than desired
- CW Diode Laser: < 300 kHz
- Pulsed Nd:Yag Dye Laser: > 1.5 GHz
- Doppler width of transition: < 2 GHz

Laser Induced Fluorescence Velocimetry

Hargus, IEEE (2011)
Experimental Apparatus

- New Focus Vortex TLB-6917 tunable diode laser used to seed a TA-7600 VAMP tapered amplifier
  - 60 mW output power
  - Xenon ion (Xe II) transition at 834.72 nm probed \((5d[4]_{7/2} - 6p[3]_{5/2})\)
  - Non-resonant fluorescence collected at 541.92 nm \((6s[2]_{3/2} - 6p[3]_{5/2})\)

- Stationary xenon neutral (Xe I) reference
  - 9.03 GHz distant \(6p'[3/2]_1 - 8s'[3/2]_1\)

- Parallelized sample-hold method of time-synchronization
  - 6 time points taken simultaneously

- 9x improvement in data acquisition efficiency
  - Better signal-to-noise
  - Faster data acquisition
1. Take simultaneous measurements of AC discharge current, emission + fluorescence

2. AC current from the discharge is fed into a comparator to find zero point crossings (reference point for time = $t_0$)

3. Raw emission + fluorescence trace and comparator signal sent into sample-hold circuit (samples at $t_0$ trigger, holds value)

4. Sample-hold repeats at $t_0$ points along entire scan

5. Pass sample-held signal through lock-in amplifier

   Fluorescence excitation lineshape for $t_0$

6. Repeat for $t_1$, $t_2$, etc.

   Lineshapes for $t_0$, $t_1$, $t_2$
**BHT-600 Specifications**

- **BHT-600**
  - 600 W annular Hall thruster
  - Manufactured by Busek Co.
- **Tested in Chamber 6 at AFRL**
  - Background pressure $1.2 \times 10^{-5}$ Torr

**Nominal Operating Conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode Flow</td>
<td>2.45 mg/s Xe (20.5 sccm)</td>
</tr>
<tr>
<td>Cathode Flow</td>
<td>197 $\mu$g/s Xe (1.5 sccm)</td>
</tr>
<tr>
<td>Anode Potential</td>
<td>300 V</td>
</tr>
<tr>
<td>Anode Current</td>
<td>2.05 A</td>
</tr>
<tr>
<td>Magnet 1 Current</td>
<td>2.0 A</td>
</tr>
<tr>
<td>Magnet 2 Current</td>
<td>2.0 A</td>
</tr>
</tbody>
</table>

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Velocity and Intensity Trends

- Peak lineshape intensity
  - In phase with current
  - Intensity increases with growth of ion population
- Most probable ion velocity
  - 90° phase lag relative to current
  - Max velocity after point of peak ionization

Breathing mode cycle

Most probable ion velocity and peak lineshape intensities for IVDFs measured along centerline of discharge channel (R = 28 mm, Z = -2 mm)

Average of individual time-synchronized velocity distribution function matches well with measured time-averaged velocity distribution
Channel IVDFs

- Minimal radial variations in channel

- **Z = -8 mm (near anode)**
  - Slight negative velocity
  - Gradient-driven field reversal

- **Z = -6 mm**
  - Accelerating potential begins
  - Broader IVDFs

- **Z = -4 mm**
  - Significant broadening of IVDFs
  - Large temporal variations (5-13 km/s)
  - Spatial extent of propellant ionization and local potential drop fluctuate

- **Z = -2 mm, Z = 0 mm**
  - IVDFs narrow
  - More even acceleration in time
Near-Field Plume Measurements

- Time-sync axial IVDFs obtained throughout near-field plume
- Secondary ion velocity population
  - Appears near centerline of thruster
  - Low velocity dominates at current minimum
  - Primarily caused by geometric effects
  - Other causes:
    - Charge exchange collisions w/ neutrals
    - Residual ionization downstream of main potential drop

- Upcoming radial IVDF measurements
  - Elucidate fluctuations in plume divergence
  - Ion velocity vectors compared to numerical models in HPHall, emission data
Summary

• Laser diagnostic techniques have been developed alongside propulsion technologies

• Allow us to better understand propulsion technologies that were previously ‘black boxes’

• In-situ, time-resolved diagnostics are becoming more important for understanding spacecraft interactions, pushing towards predictive modeling & simulation efforts
Thank You!

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