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Integrity ★ Service ★ Excellence

68th Annual Gaseous Electronics Conference

LASER DIAGNOSTICS FOR SPACECRAFT PROPULSION

GEC15-2015-000599

Tuesday, October 13, 2015

Natalia MacDonald-Tenenbaum
In-Space Propulsion Branch
Air Force Research Laboratory
Edwards AFB, CA
natalia.macdonald@us.af.mil

DISTRIBUTION A: Approved for public release; distribution unlimited. AFTC/PA Clearance No. XXX
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

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**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

---

**Diode Laser Absorption Spectroscopy**

**Hydrazine Thruster**

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**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**
  \[
  I_v(L) = I_v^0 H_n(\nu)L
  \]
  \[
  H_n(\nu) = \frac{2^{1-n}}{n!} \frac{d^n\alpha(\nu)}{d\nu^n}
  \]
  - \(H_n(\nu)\) = 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.**
  \[
  \frac{2f}{1f} = \frac{H_2}{i_0^2} \cdot \frac{S(T) \cdot P \cdot x_i \cdot L}{i_0 \cdot \pi} \int_{-\pi}^{\pi} \phi(\nu_{peak} + a \cos \theta) \cos 2\theta d\theta
  \]
  - \(S(T)\) = 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

**Arc Column**
- Propellant
- Cathode
- Constrictor
- Anode

**Aerojet MR-510 Arcjet**
- Propellant: Hydrazine
- Thrust: 250 mN
- Isp: 585 sec
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
  - $5d[4]_{7/2} - 6p[3]_{5/2}$ at 834.72 nm
- Ions spontaneously emit photons resulting in their relaxation from its excited state to a lower state (fluorescence)
  - $6s[2]_{3/2} - 6p[3]_{5/2}$ 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:
    \[ \delta \nu_{12} = \frac{V}{c} \nu_{12} \]

\[ \nu = 0 \quad \lambda = \lambda_0 \]
\[ \nu \quad \lambda > \lambda_0 \]

Non-resonant fluorescence scheme
Laser Induced Fluorescence Velocimetry

- 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

Lineshape of the 834.68 nm Xe transition compared to widths of a pulsed laser and a CW laser. Hyperfine structure (HFS) shown as reference.
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)

• 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 = t₀).

3. Raw emission + fluorescence trace and comparator signal sent into sample-hold circuit (samples at t₀ trigger, holds value).

4. Sample-hold repeats at t₀ points along entire scan.

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

6. Repeat for t₁, t₂, etc.

Fluorescence excitation lineshape for t₀.

Lineshapes for t₀, t₁, t₂.
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

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<td>Cathode Flow</td>
<td>$197 \text{ \mu g/s Xe}$ (1.5 sccm)</td>
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<tr>
<td>Anode Potential</td>
<td>300 V</td>
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<tr>
<td>Anode Current</td>
<td>2.05 A</td>
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<tr>
<td>Magnet 1 Current</td>
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<tr>
<td>Magnet 2 Current</td>
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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

- $Z = -8 \text{ mm (near anode)}$
  - Slight negative velocity
  - Gradient-driven field reversal

- $Z = -6 \text{ mm}$
  - Accelerating potential begins
  - Broader IVDFs

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

- $Z = -2 \text{ mm}, Z = 0 \text{ mm}$
  - 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!

Dr. Bill Hargus – Air Force Research Laboratory

Chris Young, Dr. Andrea Lucca-Fabris, Prof. Mark Cappelli – Stanford University

Amanda Makowiecki, Torrey Hayden, Prof. Greg Rieker – U. of Colorado, Boulder