Recommended Practices in Laser-Induced Fluorescence (LIF) Diagnostics for Electric Propulsion

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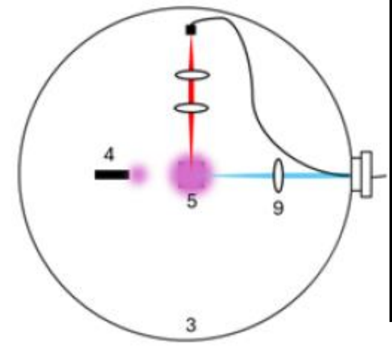

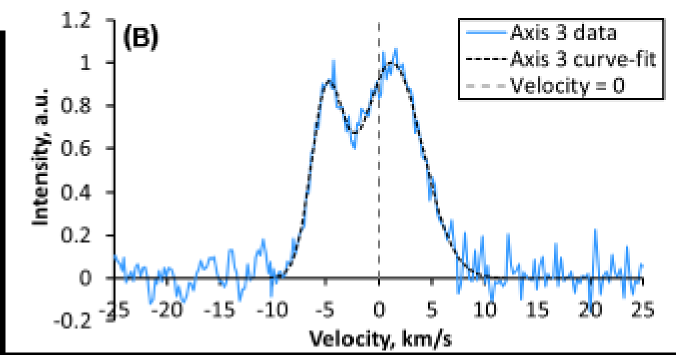

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Introduction

- In this year's refresh of the "Recommended Practices for Electric Propulsion Testing" papers originally published in 2016-2017, laser-induced fluorescence (LIF) is included for the first time.
- LIF is an active spectroscopic technique enabling **non-invasive, spatially resolved measurements**.
- **Single-photon absorption LIF** is good at measuring ion/atom velocity distributions (VDFs).

$$v_x = c\left(\frac{\lambda}{\lambda_0} - 1\right)$$

- **Two-photon absorption LIF (TALIF)** makes it possible to measure neutral densities.
- Both types of LIF measurements require moderately complex experimental setups and sophisticated data analysis methods

Motivation and Team

- This paper aims to provide a standardized set of LIF testing and analysis practices to improve accuracy of results, facilitate adoption of the diagnostic by new institutions, and maximize the benefits of LIF for electric thruster development and qualification.
- Collaboration between authors from **7 institutions**, drawing upon **>30 years of LIF research in EP** by the authors and numerous other researchers
- **171 citations**, referenced papers come from at least **14 countries**

Paper Outline

Jet Propulsion Laboratory
California Institute of Technology

Part I: Single Photon LIF

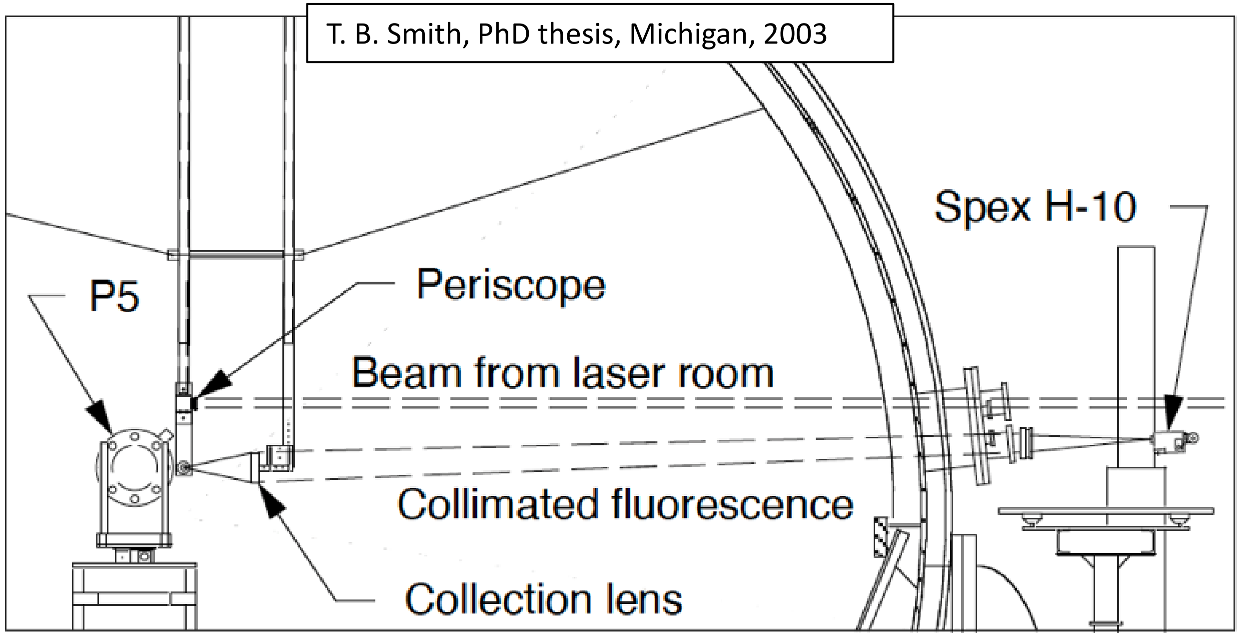
1. Introduction
2. Atomic Transitions for Single-Photon LIF
3. Hardware Setup for Single-Photon LIF
4. Analysis of Single-Photon LIF Data
5. Metastable versus Ground State Ion Velocities

Part II: Two-Photon Absorption LIF (TALIF)

6. Introduction
7. Theory
8. TALIF Experimental Setups
9. Measurement and Data Analysis
10. Recommended Practices for TALIF Measurements
11. Recent Developments and Related Techniques

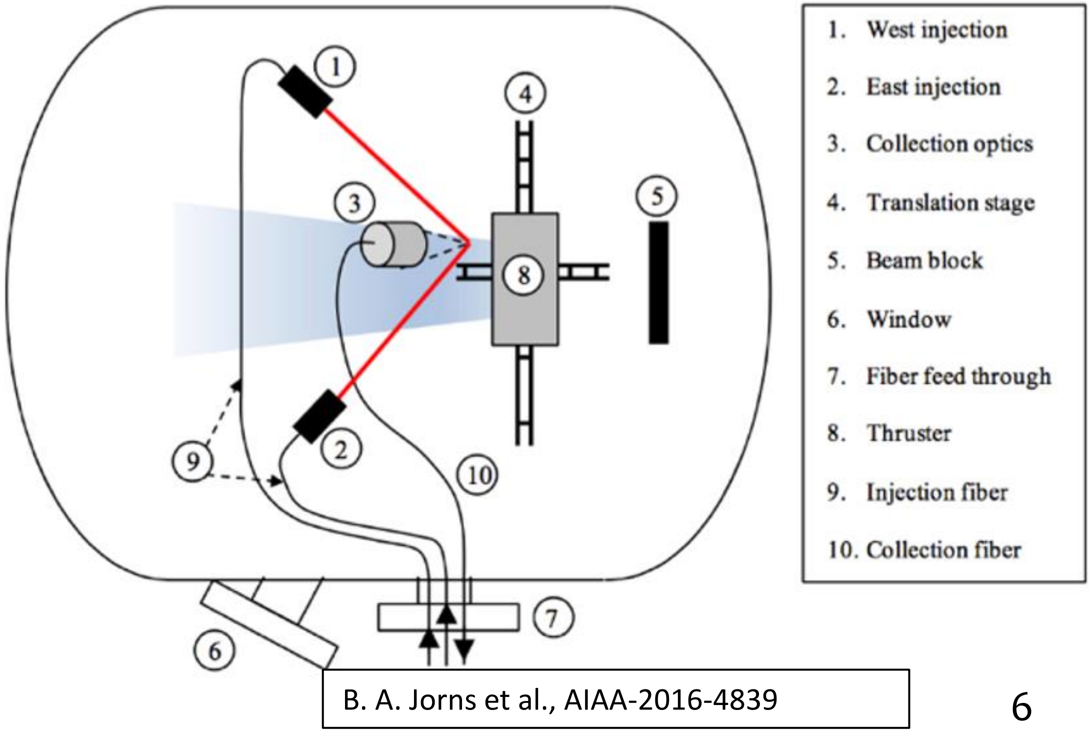
Single-Photon LIF Highlights

Optical Components and Layout



Free-space coupled scheme

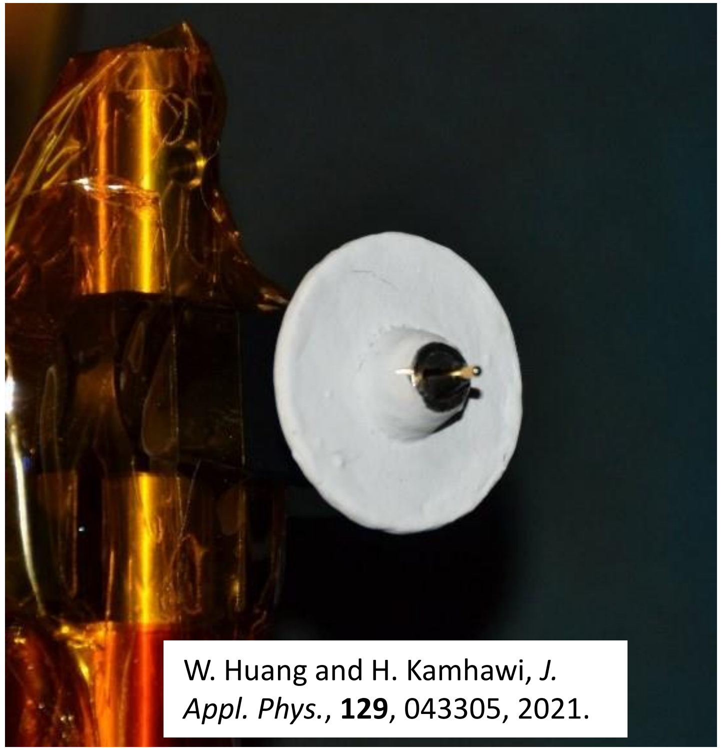
Fiber coupled scheme



Alignment and Position Referencing Techniques

- Most LIF setups leave the measurement volume location approximately fixed while **translating the thruster** to access different parts of the plume.

Alignment reference target →



W. Huang and H. Kamhawi, *J. Appl. Phys.*, **129**, 043305, 2021.

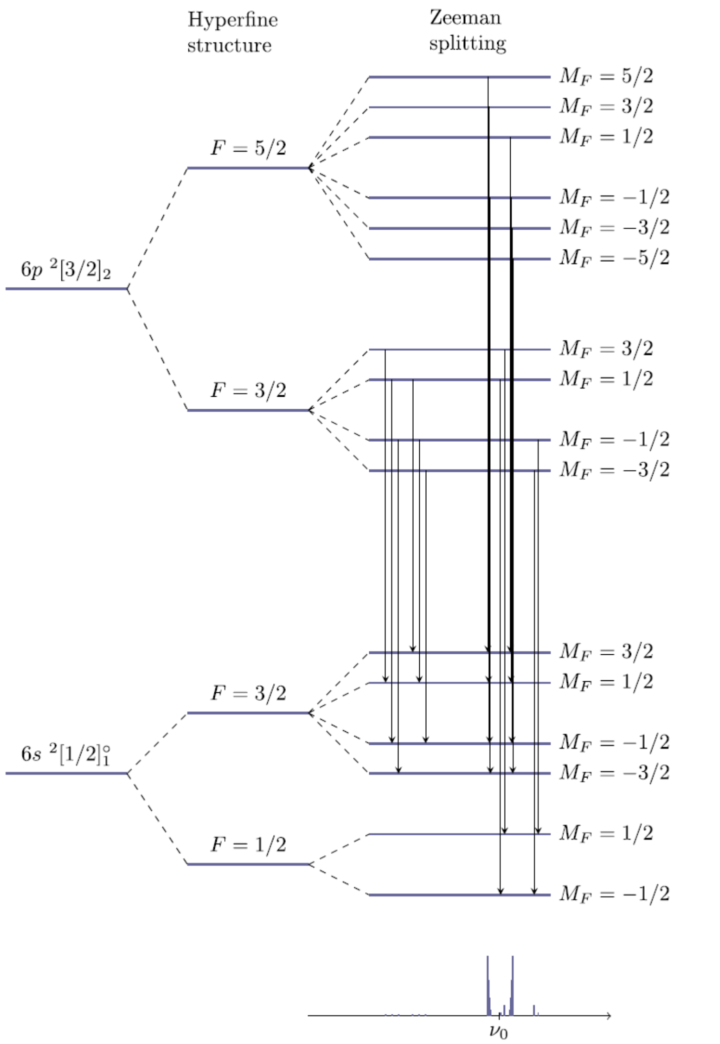
- **Visible laser-based alignment steps** are typically used to achieve the required mm-scale precision over distances of up to meters.

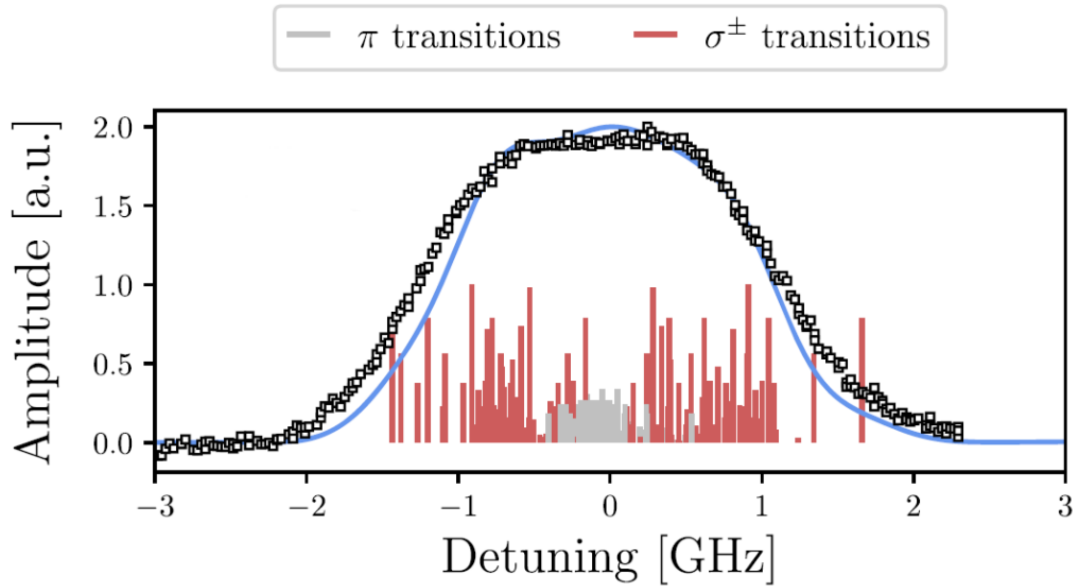
- **Thermal position drift** during testing often requires optics to be mounted on two-axis linear motion stages or pan/tilt motors to maintain alignment.

Hyperfine Structure and Zeeman Splitting

- Xenon has **9 isotopes** with slightly different transition wavelengths, of which two (^{129}Xe and ^{131}Xe) have additional **hyperfine splitting** due to nuclear spin interactions.
- **Zeeman splitting** leads to additional wavelength shifts in a B-field depending on the laser polarization with respect to $\boldsymbol{B}$.

^{129}Xe σ-transitions of Xe I 834.910 nm (A. E. Vinci, et al., *PSST*, **31**, 095007, 2022)





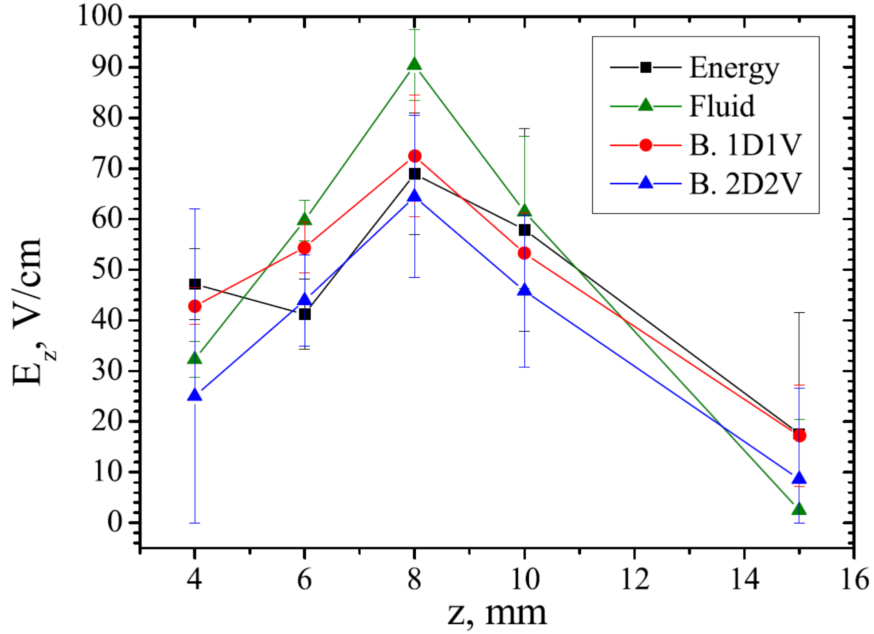
Modeled/measured Xe II 834.953 nm line shape in a helicon thruster (A. E. Vinci, et al., *PSST*, **31**, 095007, 2022)

Electric Field Calculations

- Calculation of the electric field vs. position from measured ion velocities is a valuable application of LIF in Hall thrusters.
- Simple **energy conservation method** gives acceptable results, especially if the most probable velocity or only the high-energy ion population is considered.

$$\frac{1}{2} m_i u_z^2 = e(\phi_0 - \phi) \quad \longrightarrow \quad E_z = \frac{m_i}{2e} \frac{d}{dz}(u_z^2)$$

Data from 200 W Hall thruster (J. Vaudolon and S. Mazouffre, *Phys. Plasmas*, **21**, 093505, 2014)



- **1D Boltzmann method** is recommended for a more accurate result, and it also yields the ionization rate, but its zero-collisionality assumption may not be valid in the presence of non-classical ion heating.

$$\boldsymbol{v} \cdot \boldsymbol{\nabla}_x f_i + \boldsymbol{a} \cdot \boldsymbol{\nabla}_x f_i = \nu_i f_0$$

TALIF Highlights

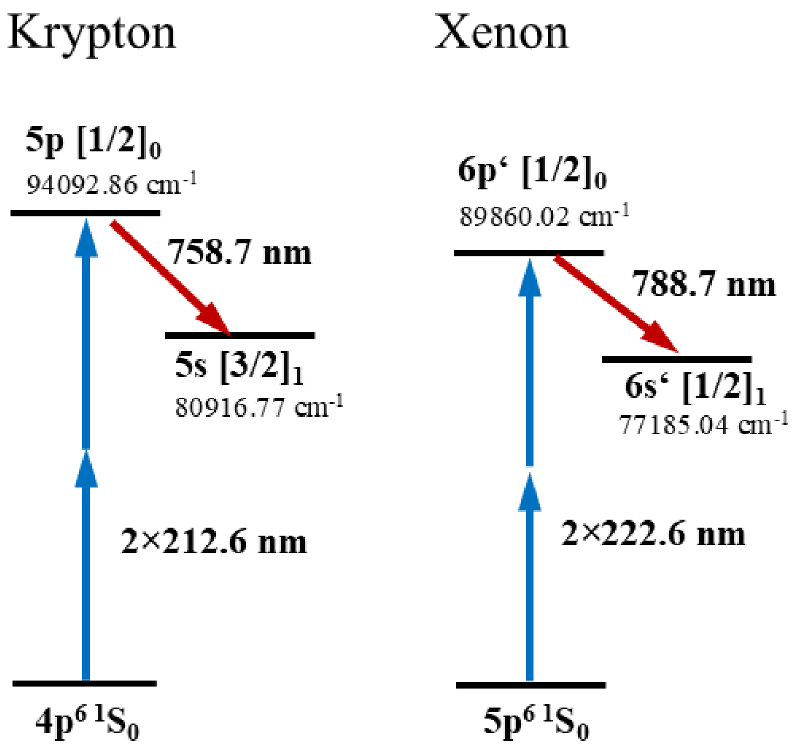
TALIF Introduction

- For noble gas propellants, single-photon LIF must target excited atomic states.
- TALIF can **directly target the ground state** of neutral Xe and Kr with two incident photons at 200-260 nm, enabling neutral density measurements.
  - Valuable for ion thrusters (CEX with neutrals is dominant source of erosion) and Hall thrusters (neutrals alter performance and affect transport, oscillations, and erosion).
  - Ion density measurements would require a VUV laser (<200 nm) or 3 photons—not yet demonstrated.
- Unsaturated TALIF has a signal strength that **scales with the square of the laser intensity**.
  - Requires a high-energy pulsed laser (usually <10 ns pulses) to get sufficient signal.

TALIF Schemes

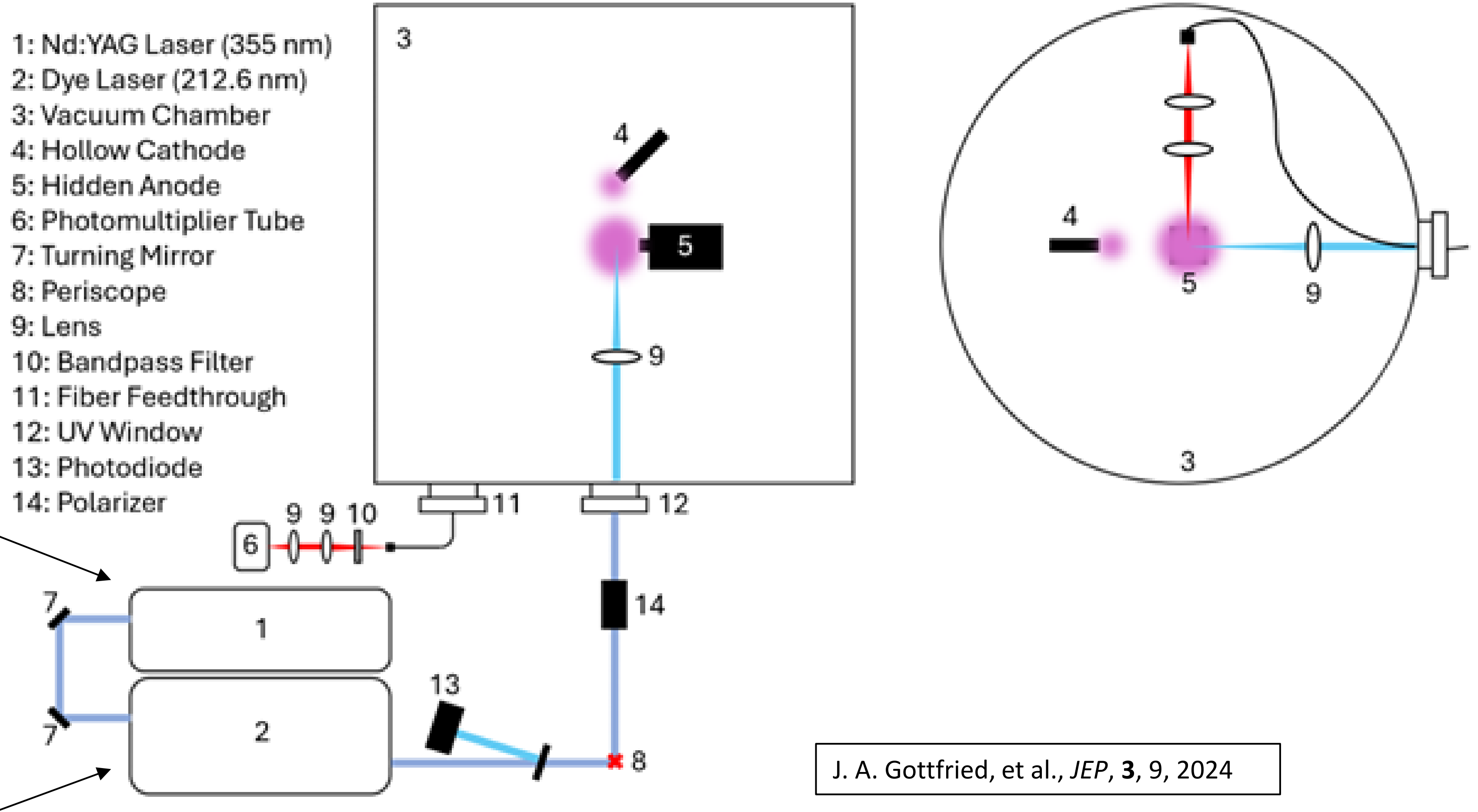
- Two-photon absorption selection rules require transitions between states of matching parity.
- An "efficient" TALIF scheme should have **relatively high two-photon absorption probability** (not much data available) and **high fluorescence transition rate** (good data for Xe I and Kr I).
- The paper lists 6 candidate schemes for xenon and 4 for krypton.

<u>Common TALIF schemes</u>



TALIF Experimental Hardware

Nd:YAG laser pumps a tunable dye laser or optical parametric oscillator (OPO)



TALIF beam is created by second harmonic generation crystals or frequency mixing of dye/OPO output

J. A. Gottfried, et al., *JEP*, **3**, 9, 2024

Some Recommended Practices for TALIF

- Use a narrow linewidth laser source if possible.
- Capture the fluorescence with a high f-number optic to maximize signal level.
- Measure the laser energy per pulse and plot signal vs. pulse energy.
- Focus the laser beam into the interaction region with focal length and beam waist suitable for high signal-to-noise ratio and good spatial resolution.
- Subtract background plasma emission from the detector signal.
- Check for all kind of drifts (laser wavelength and energy, boxcar offset, plasma self-emission, etc.).
- Use one of the absolute density calibration approaches described in the paper.

Summary and Next Steps

- The "Recommended Practices in LIF" paper is intended as a guide for the EP community when implementing a new LIF diagnostic, upgrading an existing setup, and/or performing data analysis.

- Following IEPC, this paper and others in the series will be updated and submitted to the peer-reviewed *Journal of Propulsion and Power*. Additional sections to be added:
  - Time-resolved (high-speed) techniques for single-photon LIF
  - Minimizing systematic uncertainty in velocity measurements
  - Velocity distribution broadening from oscillations, ionization, and collisions

- **We encourage feedback on the IEPC paper which could be incorporated into the final *JPP* version.**