SAND2024-08183C

Sandia National Laboratories

Exceptional service in the national interest

Increased Spatial Coverage in Optical Diagnostics Using Glass Wedges

Daniel Richardson

Optica Sensing Congress

Laser Applications to Chemical, Security and Environmental Analysis (LACSEA)

July 15–19, 2024

SAND2024-08183C

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

U.S. DEPARTMENT OF ENERGY

NNSA

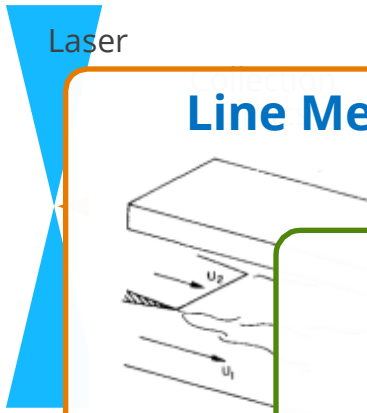
Introduction and Motivation

Push to expand dimensionality of optical diagnostics

Example: Laser induced fluorescence measurements

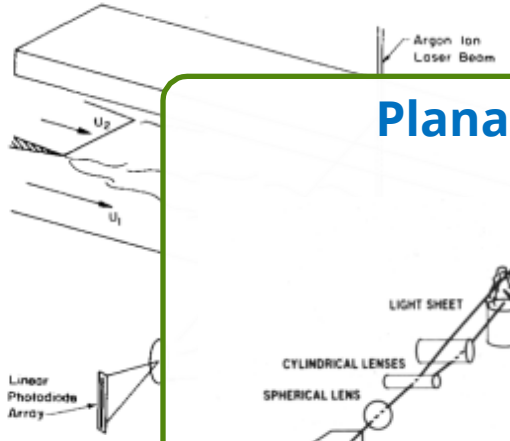
- Point → line → planar → volumetric

Point Measurements



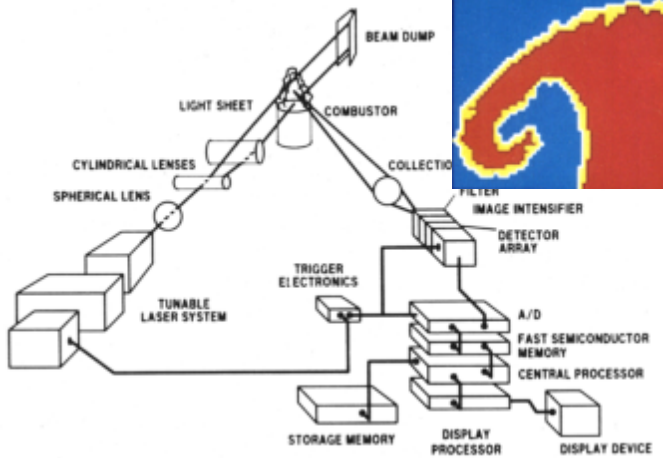
Kinsey

Line Measurements



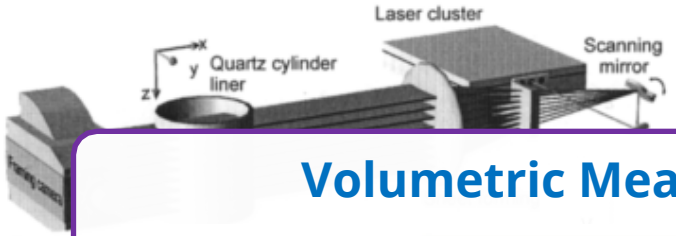
Koo

Planar Measurements

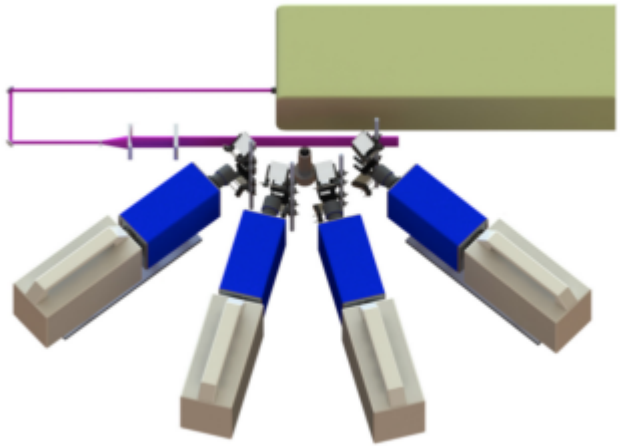


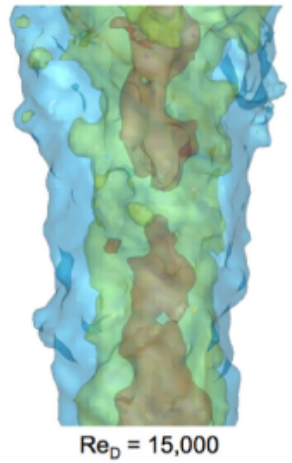
Cattolica, Proc. Combust. Inst. 1986
Hanson, J. Quant. Spectrosc. Radiant. Transfer 1988

Multi-Planar Measurements



Volumetric Measurements





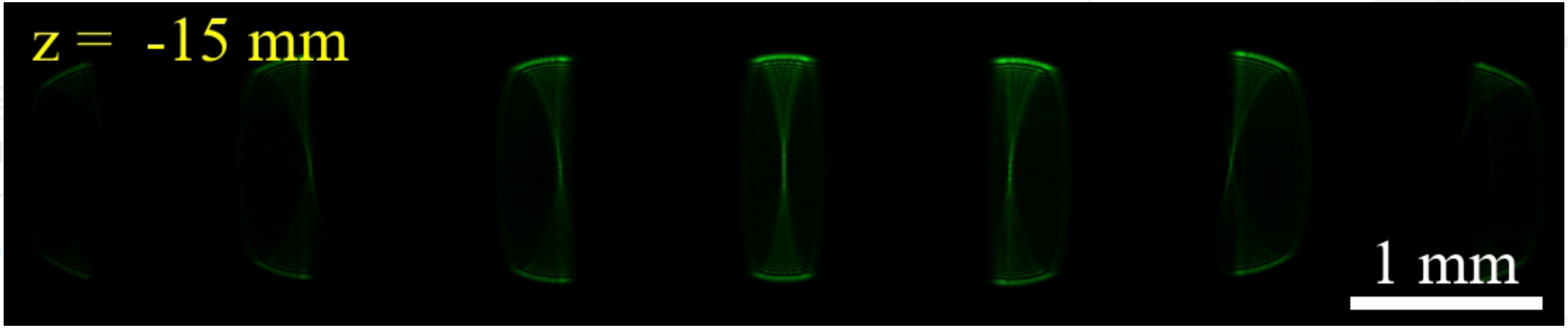
Halls, Opt. Express 2016

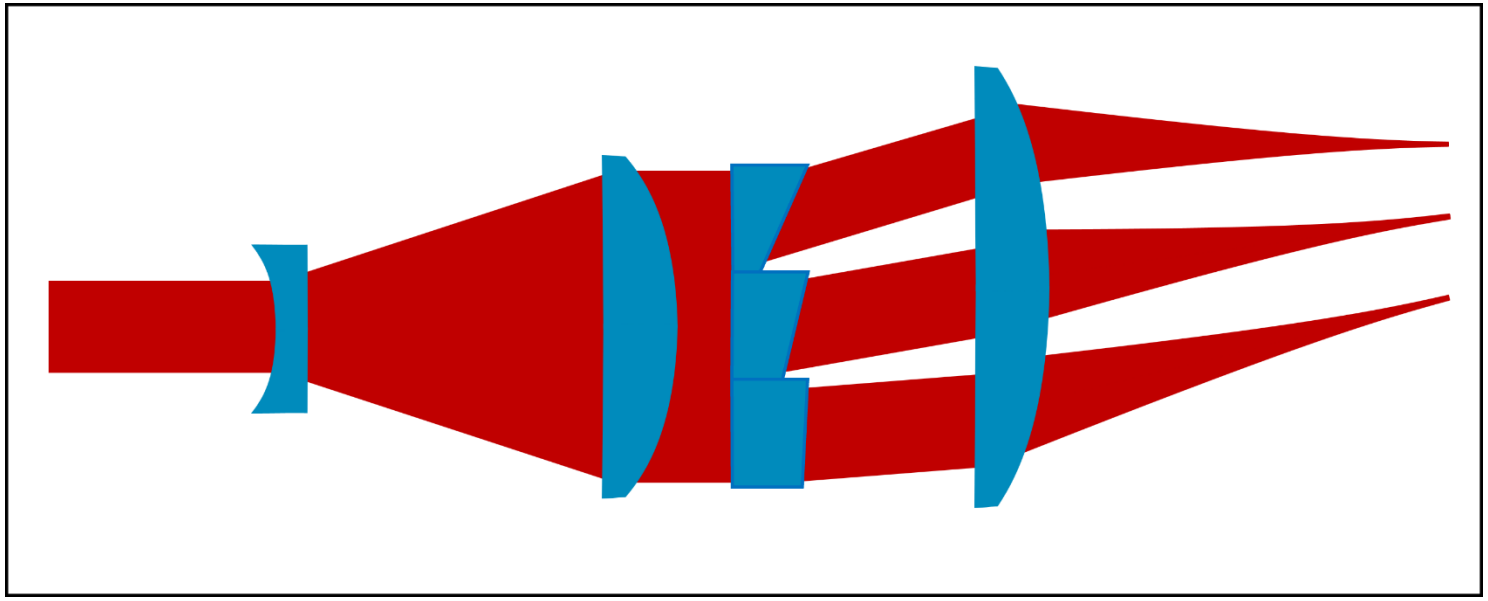
Previous Work: Tools for Multi-Dimensional Measurements

Goal: Develop optical tool(s) for multi-dimensional laser diagnostics with high-energy lasers

1. Use of glass wedges
   A. Principles and design
2. Applications
   A. Multi-spot tomographic laser tagging velocimetry
   B. Multi-line nitric oxide tagging velocimetry
   C. Multi-planar soot measurements

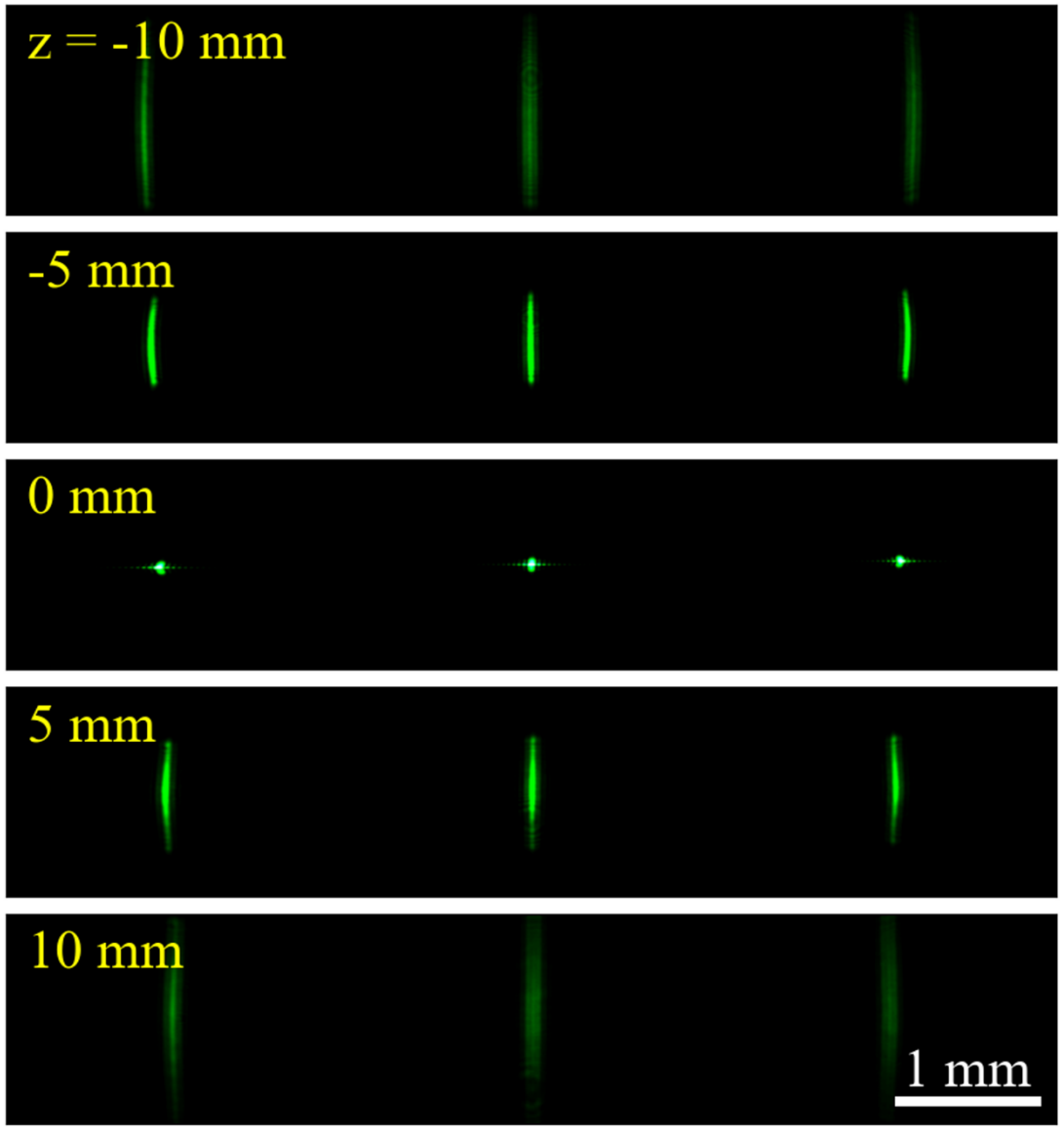
Glass Wedges: Basic Principles

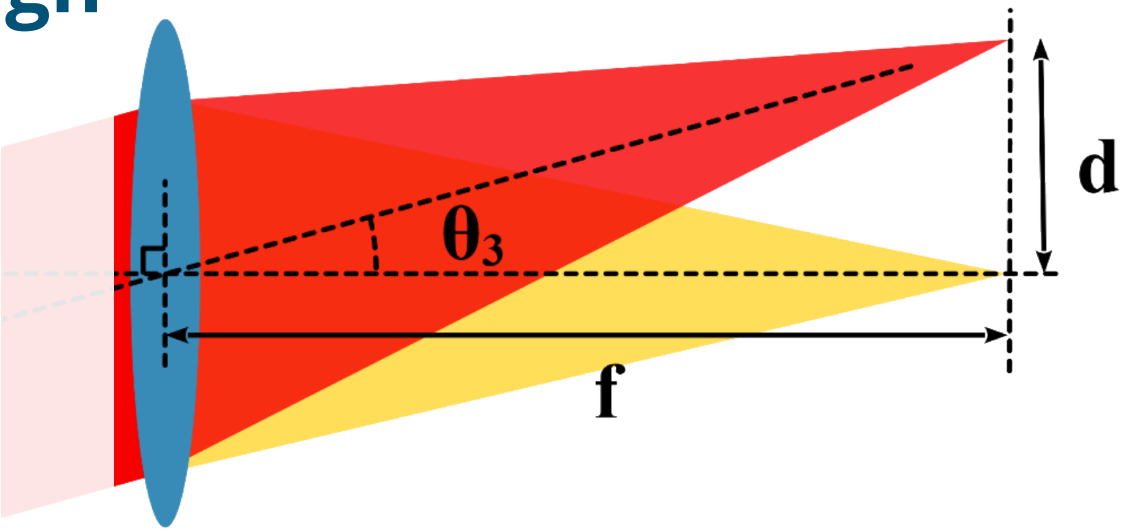




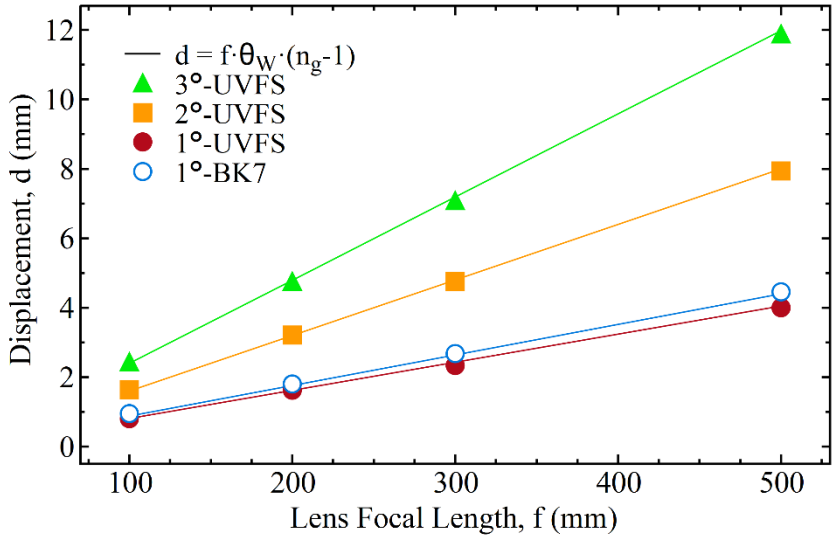
Richardson, Appl. Optics 2023

Glass Wedges: Array Design





$$d = f \cdot \theta_W \cdot (n_{glass} - 1)$$

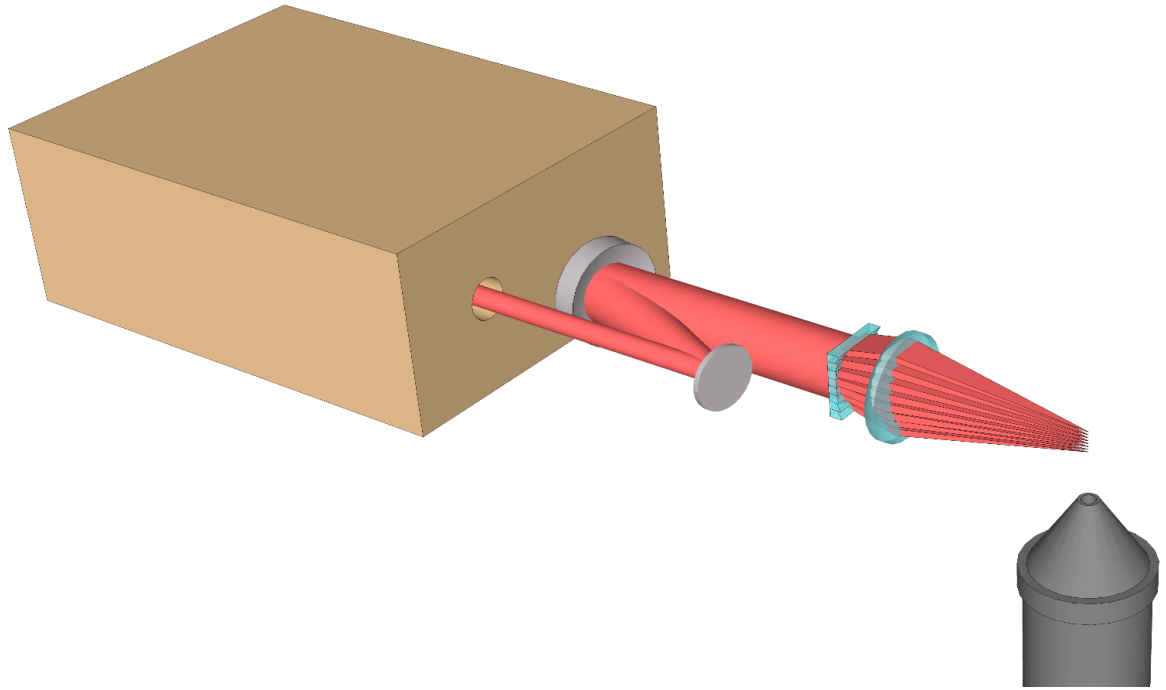


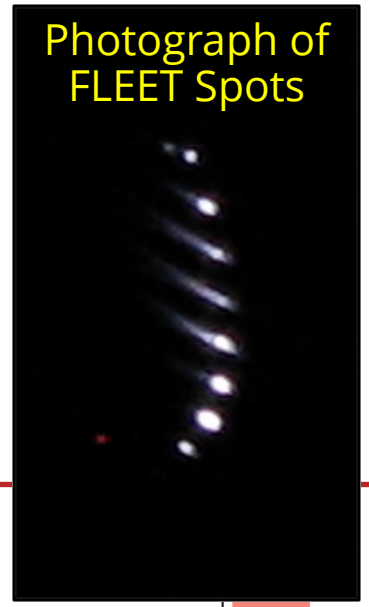
Applications: Glass Wedges for Multi-Dimensional Measurements

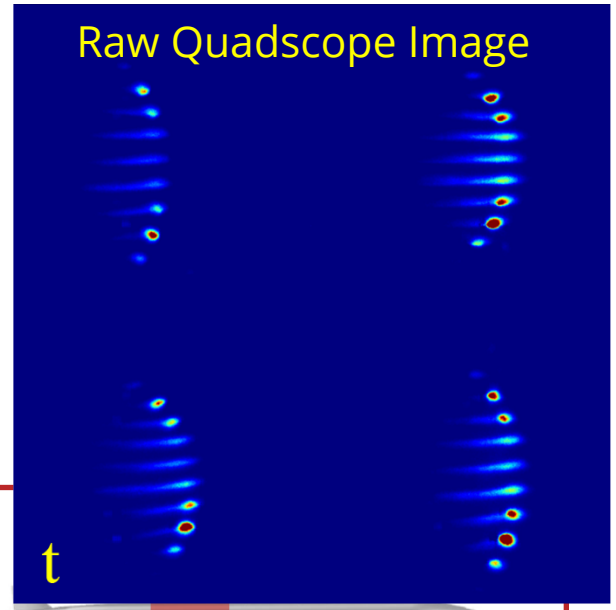
Application 1: Multi-Spot FLEET

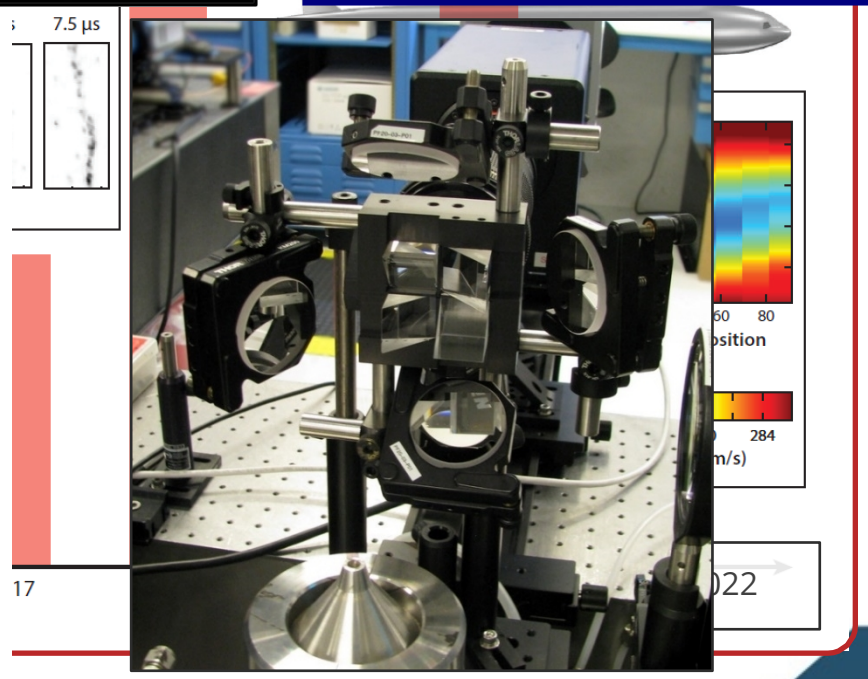
Femtosecond Laser Electronic Excitation Tagging (FLEET) Velocimetry

- Femtosecond (fs) laser used to dissociate N_2
- Fluorescence imaged at t and t+Δt (MTV)
- Typically done with a single laser line for one-dimensional, one-component velocimetry
- Wedge array used to create many (9) spots

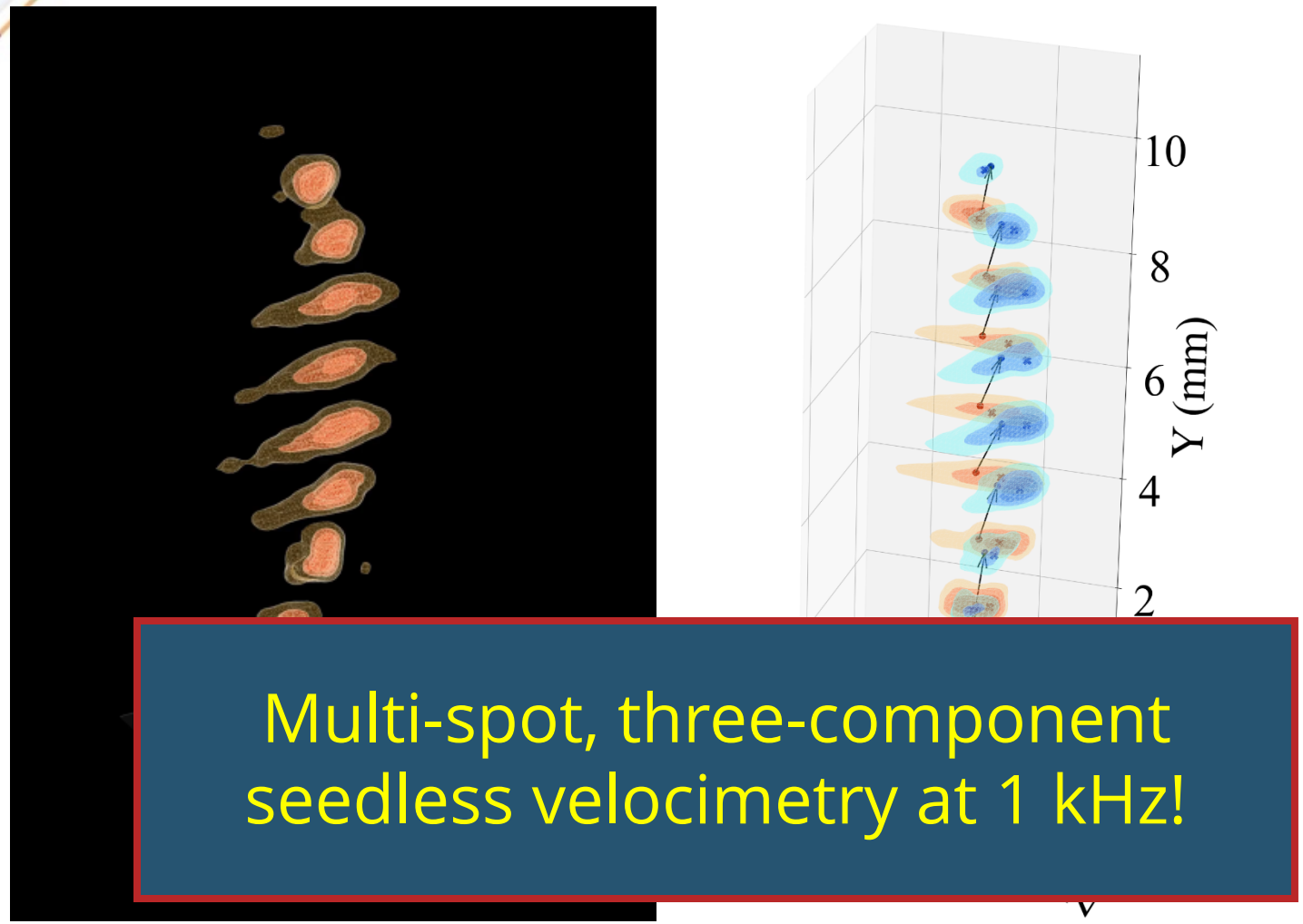


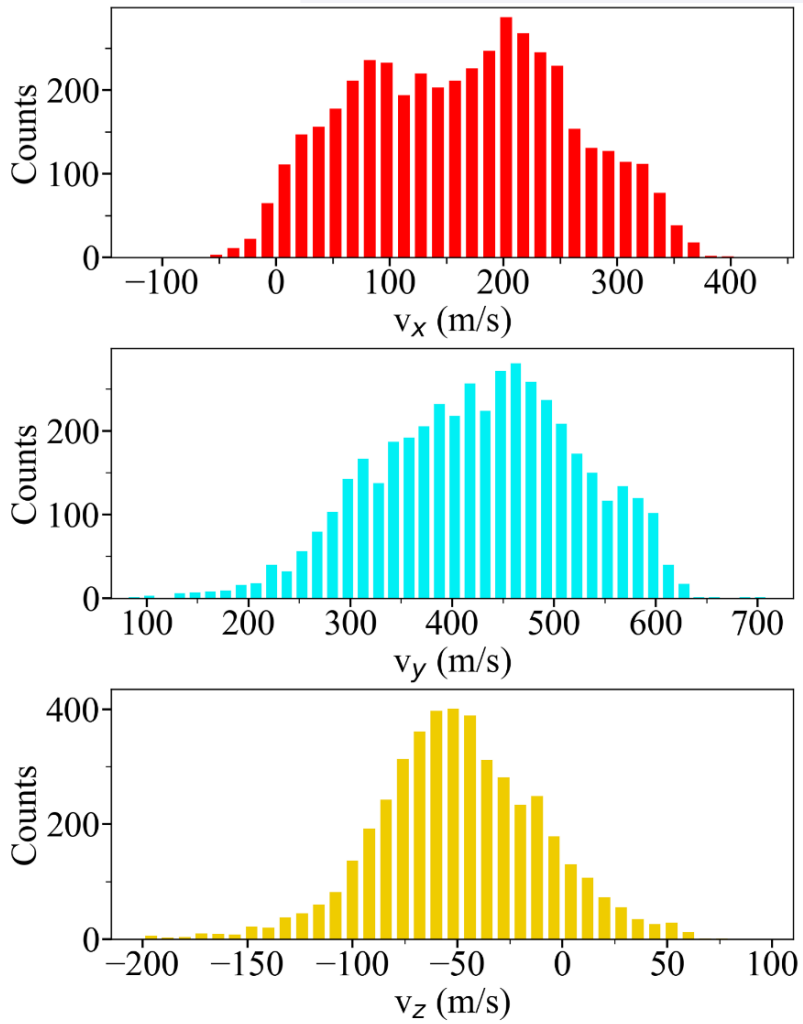






Application 1: Multi-Spot FLEET





Multi-spot, three-component seedless velocimetry at 1 kHz!

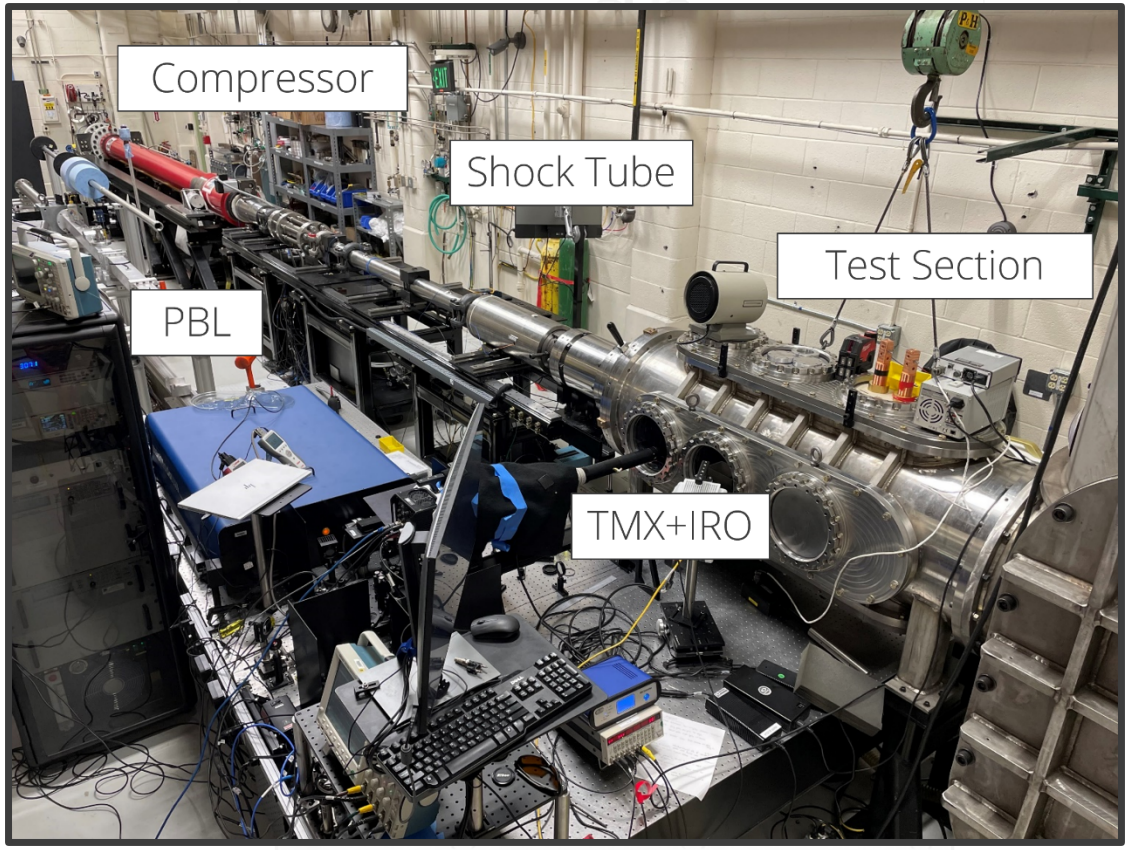
- Tomographic reconstructions calculated using quad-scope data
- Displacement of FLEET centroids tracked in time

Richardson, Opt. Lett 2024

Application 2: Multi-Line NO MTV

Nitric oxide (NO) molecular tagging velocimetry (MTV)

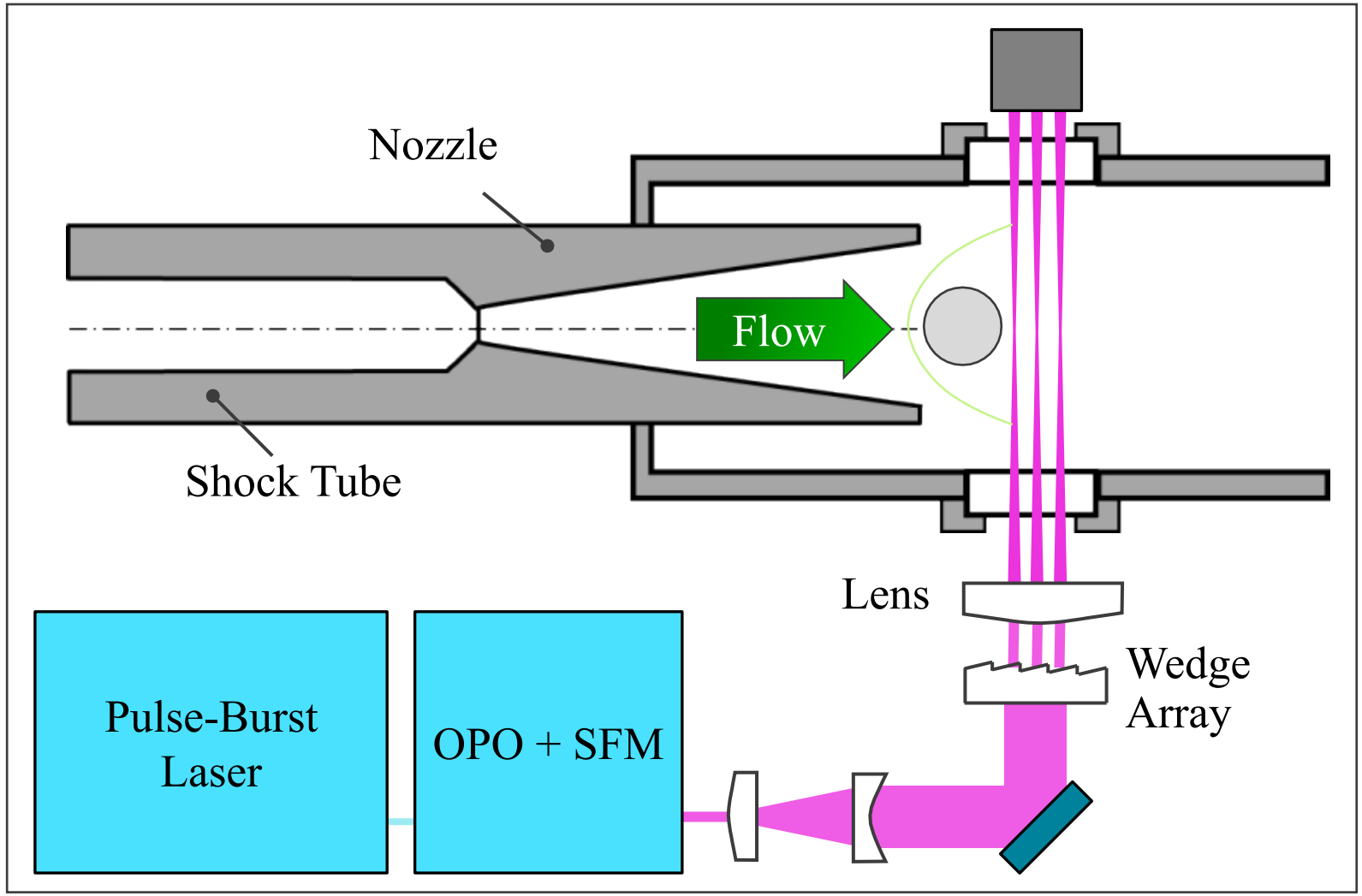
- NO naturally present in air if T > 2000 K
- UV laser pulse excites NO fluorescence
  - Fluorescence tracked for velocimetry
- Typically done with one laser line for one-dimensional, one-component velocimetry
- Measurements performed in high-enthalpy flows shock tunnel at 4-5 km/s
- Pulse-burst laser (PBL) used to acquire data during 1-ms shock tunnel run
- Wedge array used to write many (5) lines



Danehy, AIAA J. 2023

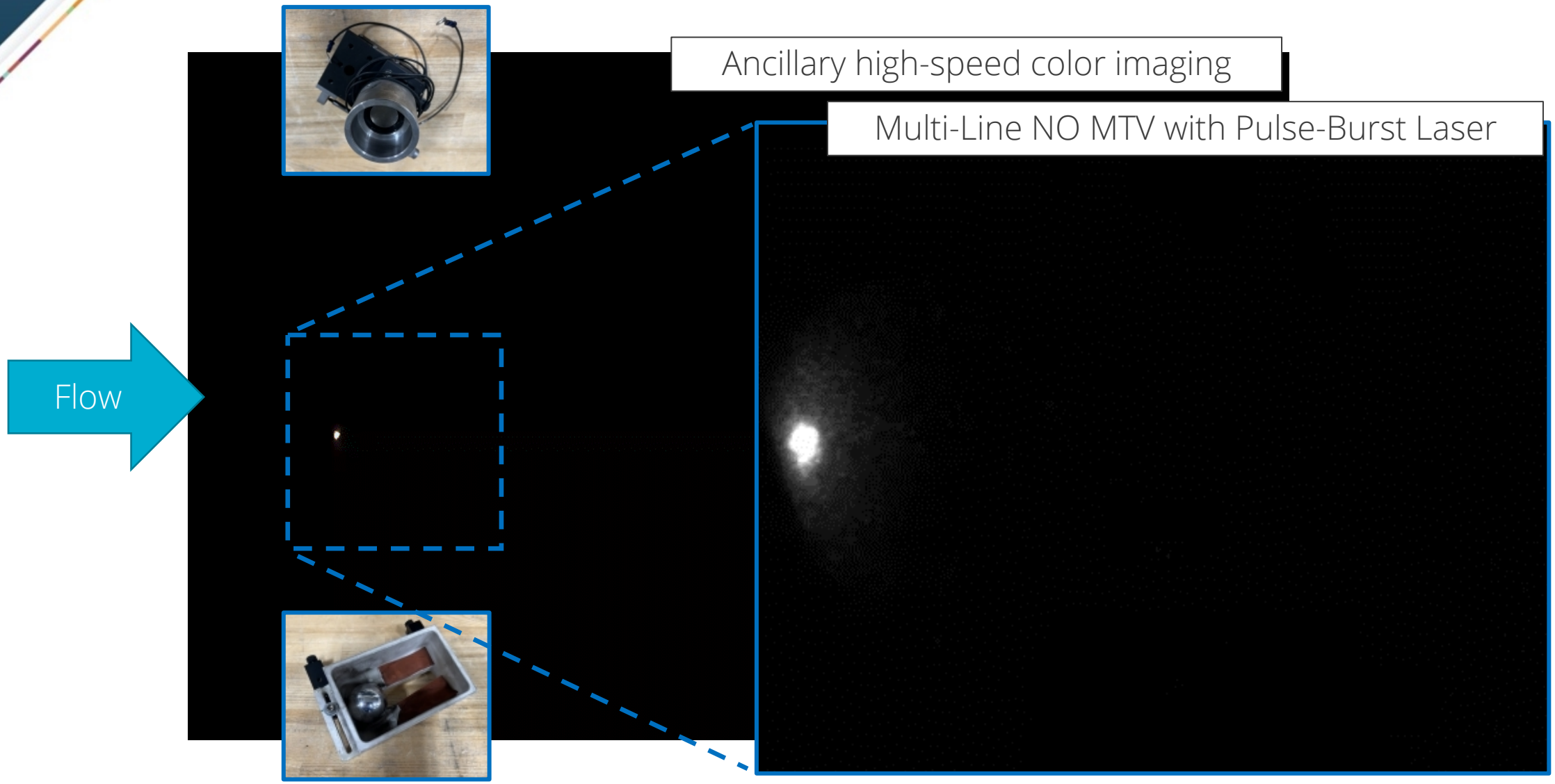
Work of Drs. Kyle Lynch, Elijah Jans, Kyle Daniel, and Sean Kearney!

Application 2: Multi-Line NO MTV



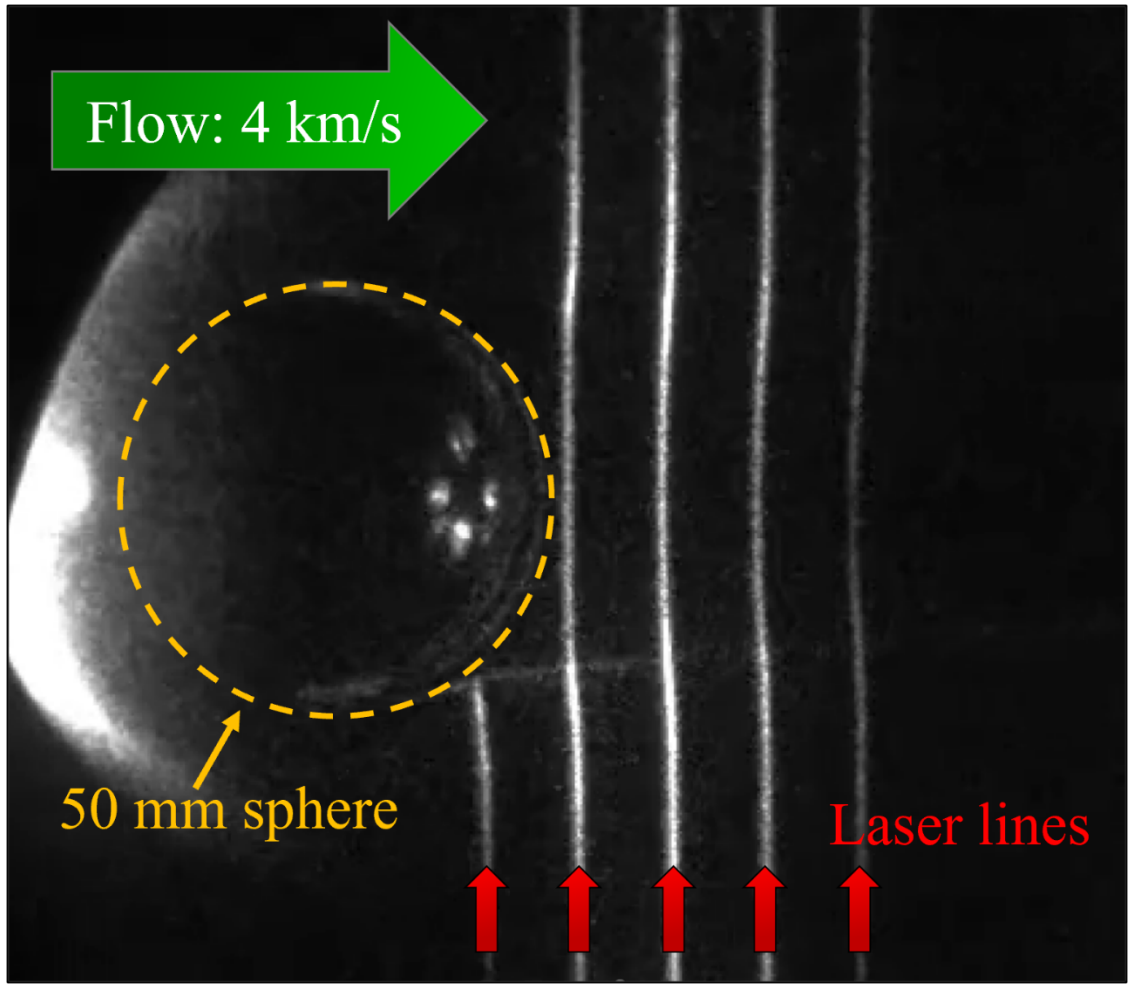
Work of Drs. Kyle Lynch, Elijah Jans, Kyle Daniel, and Sean Kearney!

Application 2: Multi-Line NO MTV

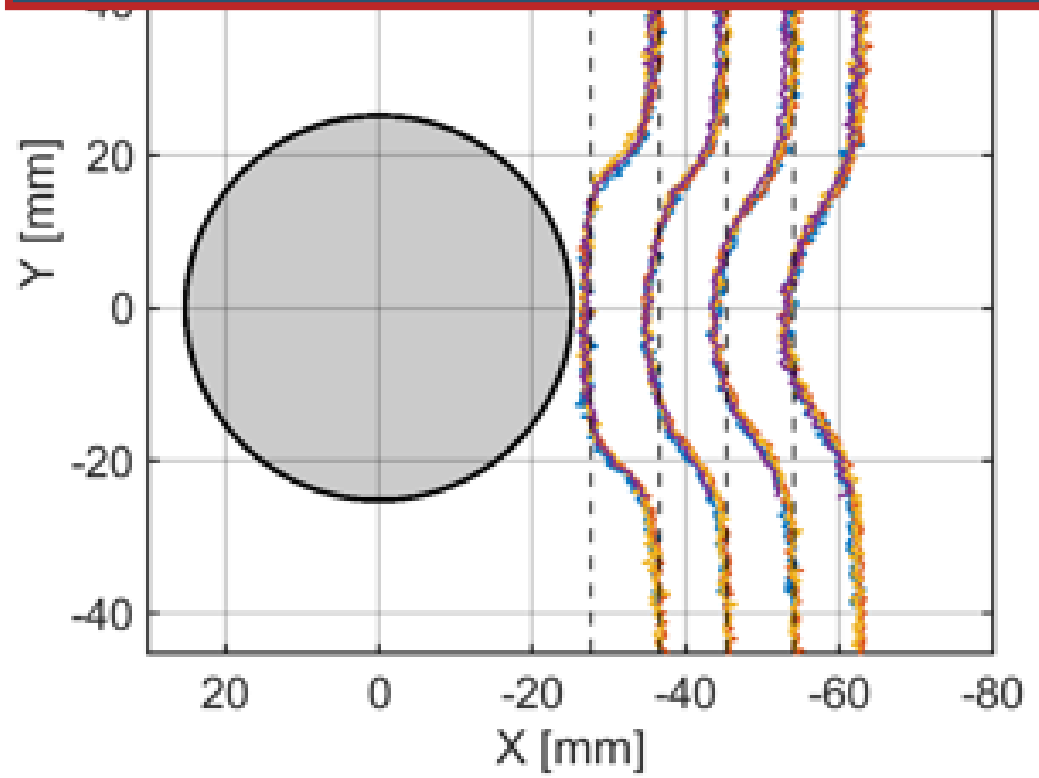


Work of Drs. Kyle Lynch, Elijah Jans, Kyle Daniel, and Sean Kearney!

Application 2: Multi-Line NO MTV



Multi-line NO MTV data with pulse-burst laser



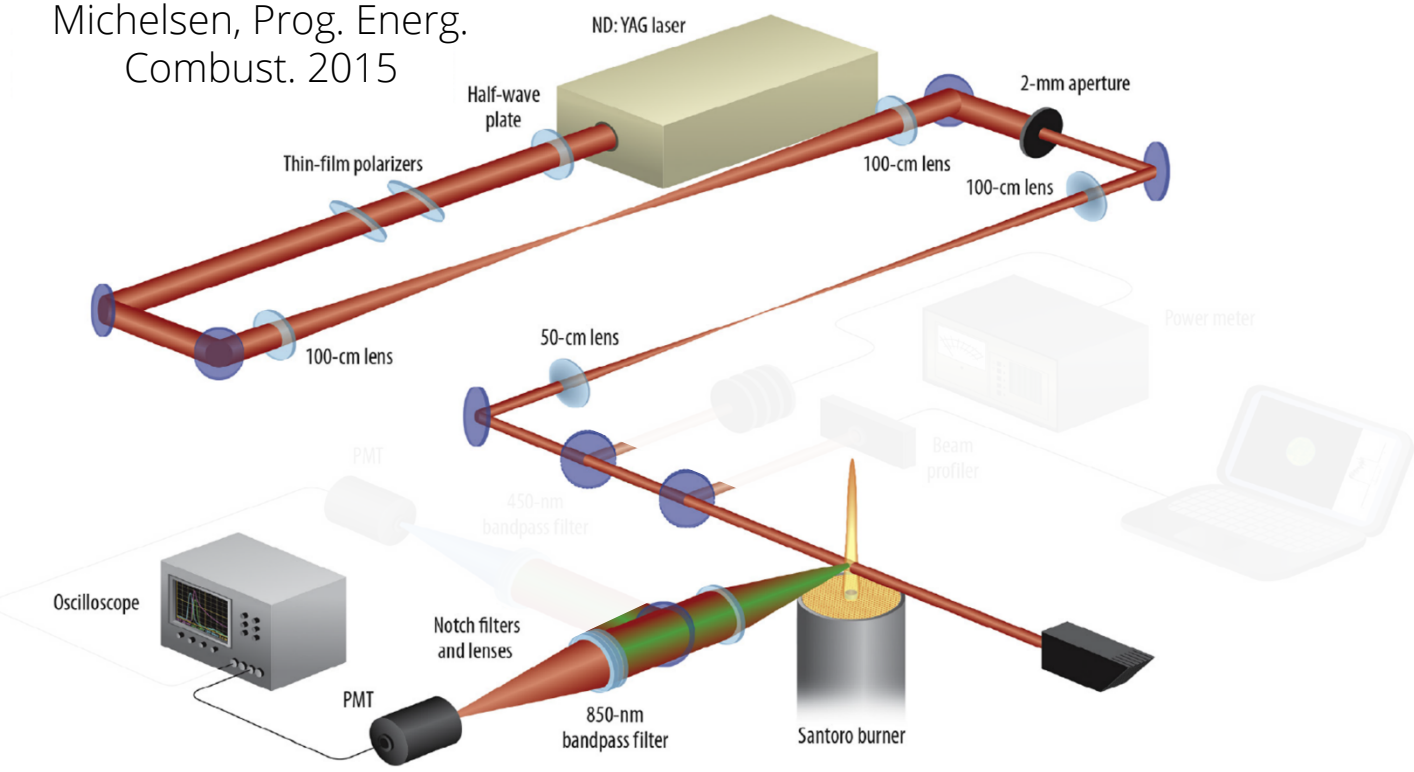
Work of Drs. Kyle Lynch, Elijah Jans, Kyle Daniel, and Sean Kearney!

Application 3: Multi-Planar LII

Laser-Induced incandescence (LII) for soot concentration measurements

- Soot absorbs laser energy and incandesces
- Typically done with one laser sheet for planar soot concentration measurements
- Can be used for quantitative soot measurements of:
  - Concentration
  - Primary soot particle size
- Use wedge array and structured illumination for multi-planar LII!

Michelsen, Prog. Energ. Combust. 2015



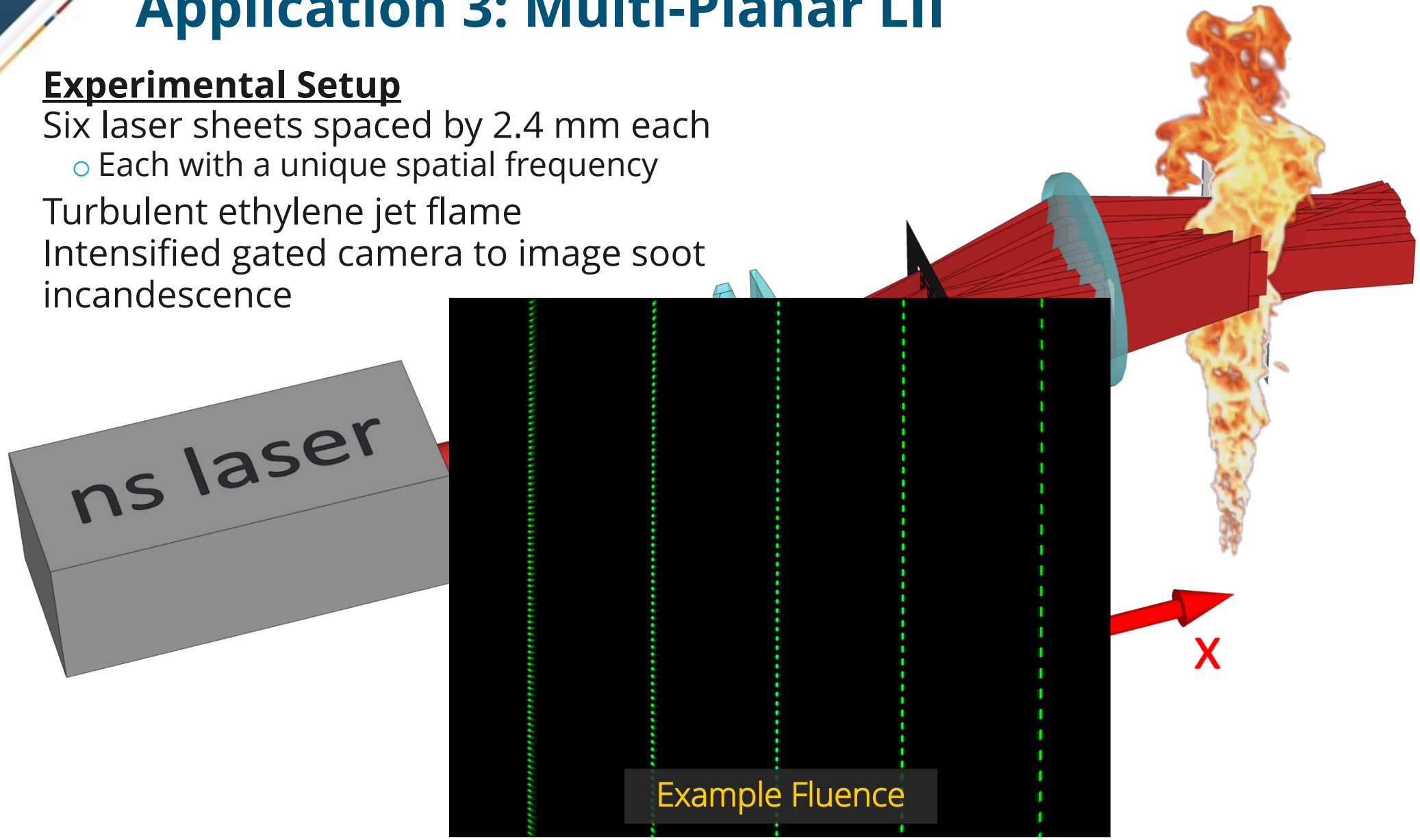
Application 3: Multi-Planar LII

Experimental Setup

Six laser sheets spaced by 2.4 mm each
- Each with a unique spatial frequency

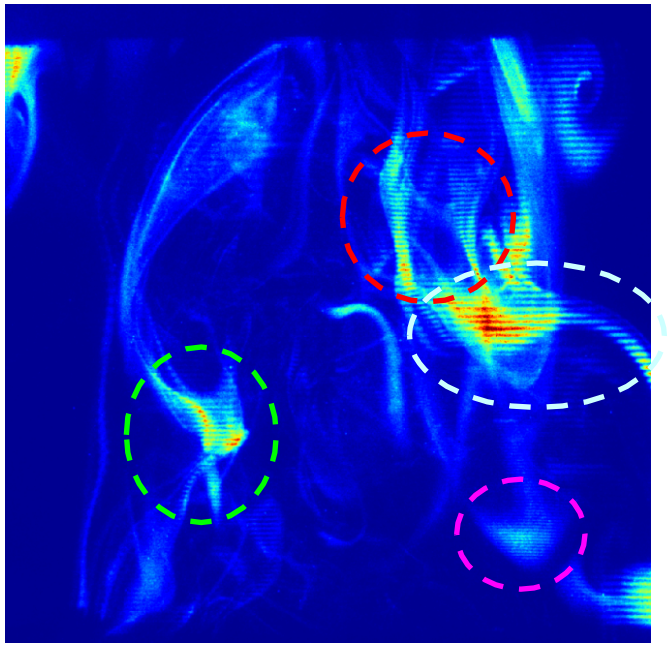
Turbulent ethylene jet flame

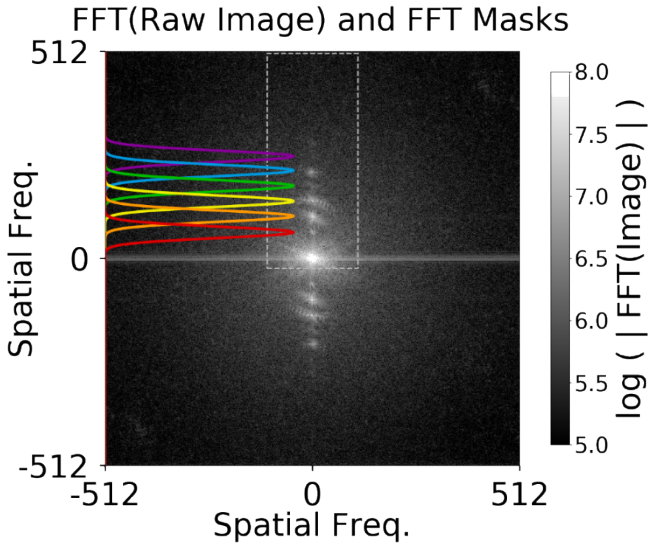
Intensified gated camera to image soot incandescence



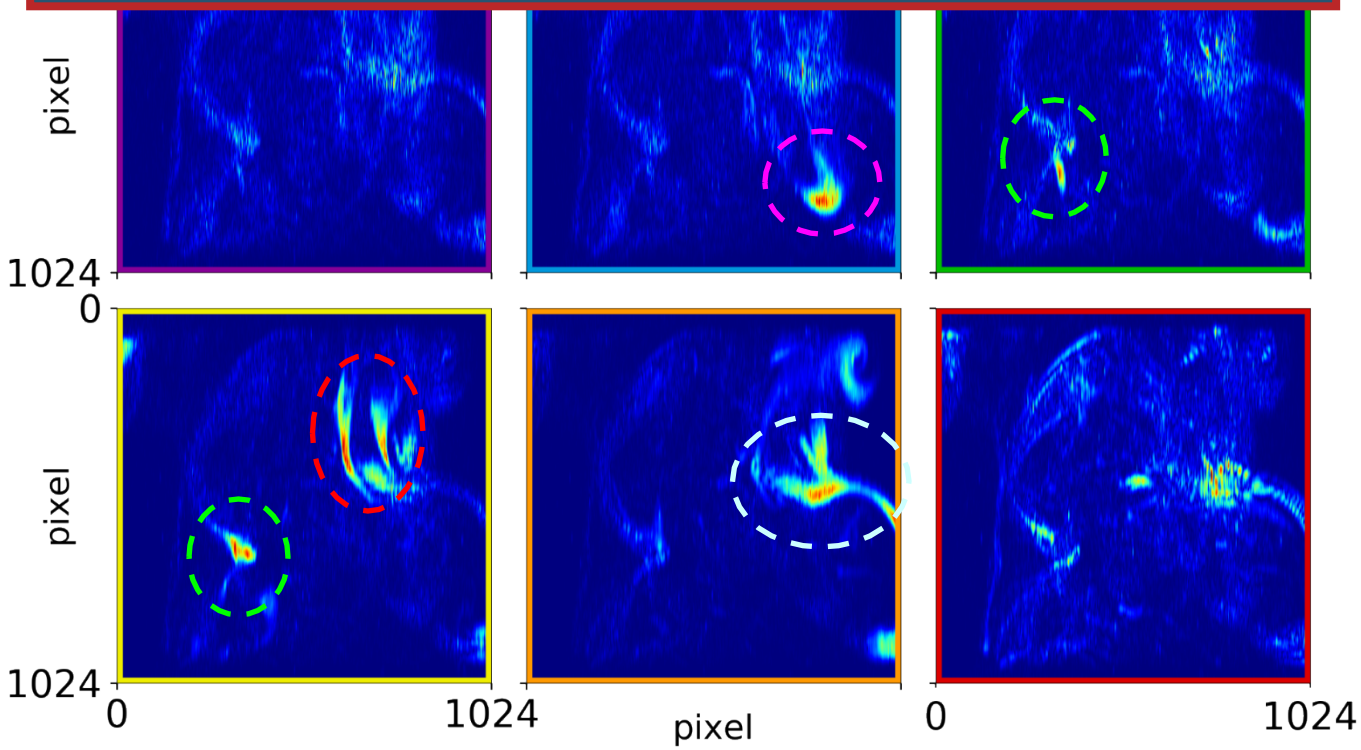
Burner Design: Zhang, et al., Rev. Sci. Instrum. 2011

Application 3: Multi-Planar LII





Single-laser, single-camera, multi-planar soot measurements!



Fourier-domain filtering done to isolate signal from each plane.

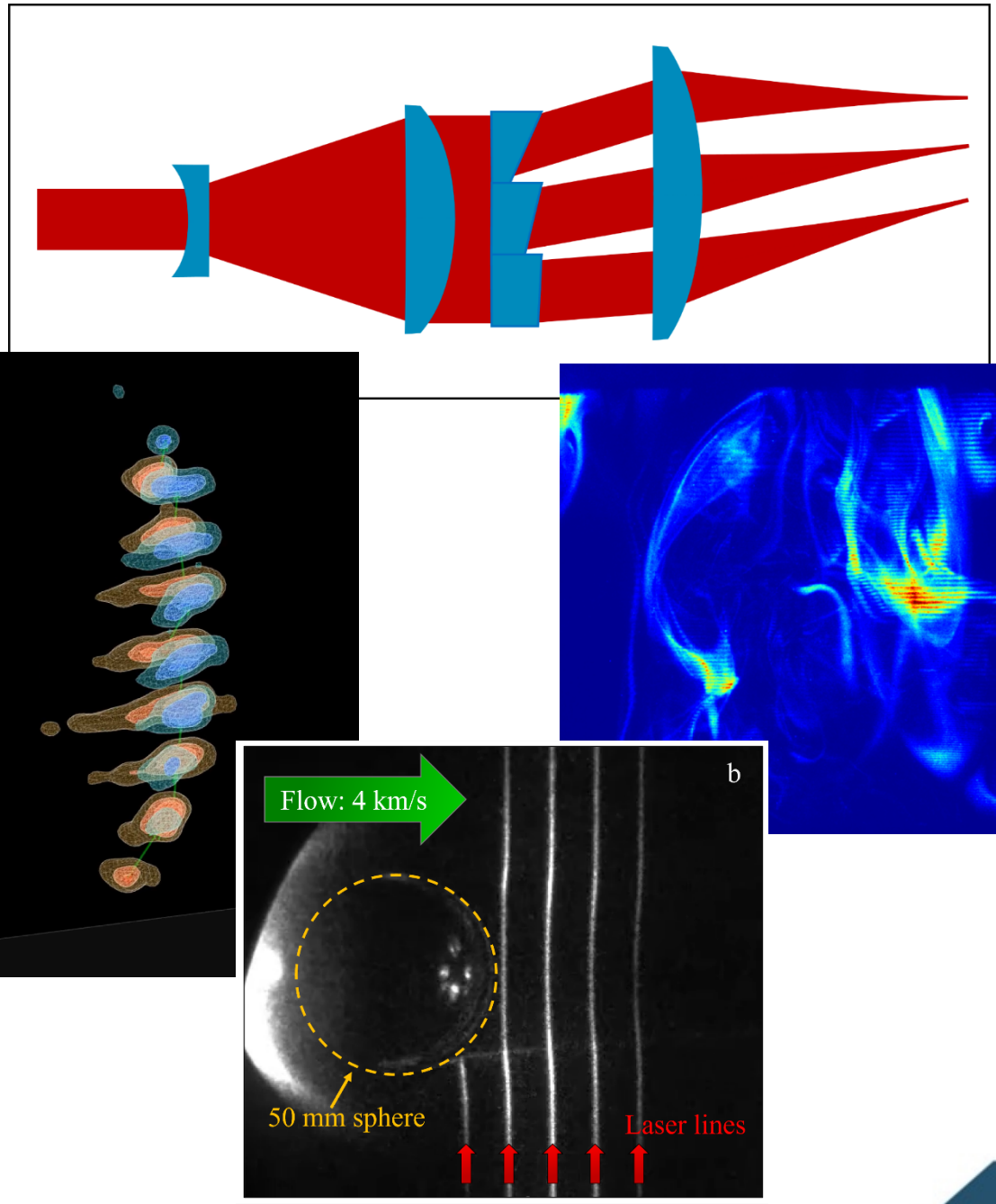
Conclusions

Glass Wedges

- Glass wedges used to create closely spaced focal points
- Can be used to form multiple points, lines, or planes of illumination
  - Simple optical setup
  - High transmission efficiency
  - Compatible with high-energy (fs, ns, pulse-burst) lasers

Applications Demonstrated

- Multi-point FLEET velocimetry
- Multi-line NO MTV
- Multi-planar LII

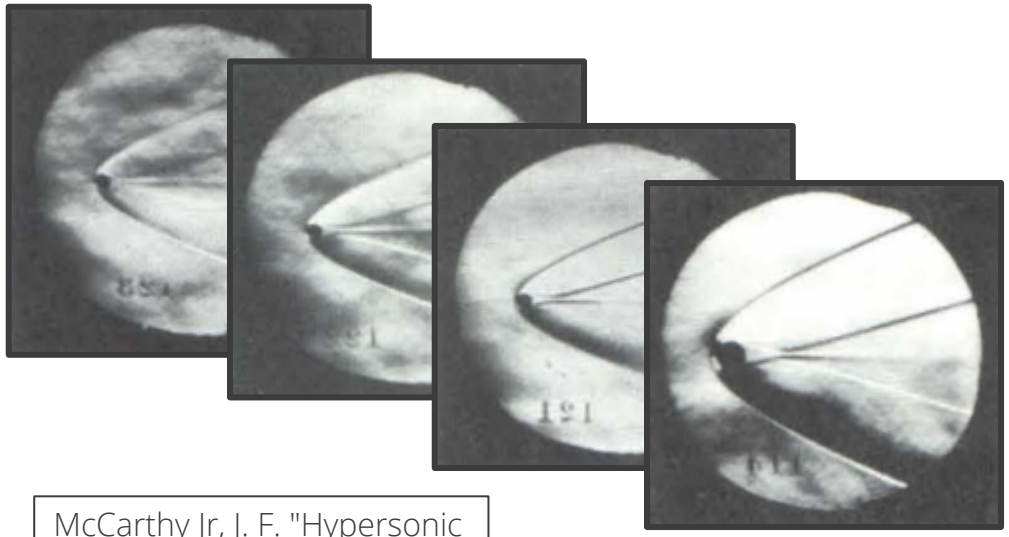


Thank you!

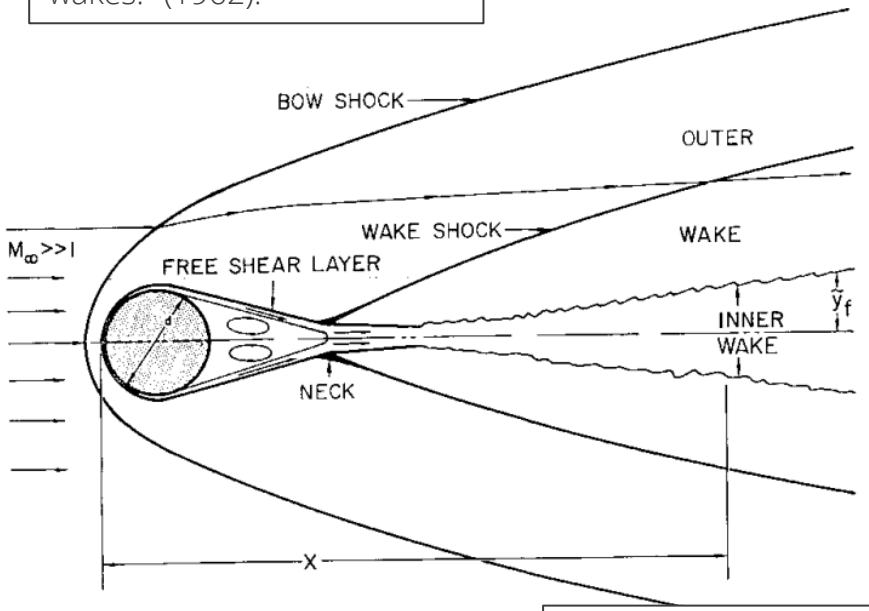
Backup Slides

background

- Hypersonic wake flows difficult to simulate, empirical models informed by visualizations
- Flow topology well-known from historical Schlieren, *little quantitative velocimetry data*
- It's a measurement challenge…
  - *High-speed, low-density,* precludes the use of particle velocimetry techniques
  - *Cannot use sting mounting,* requires free-flying models in shock tunnels or ballistic ranges
  - *Transient test facilities,* maximizing throughput requires burst-mode techniques



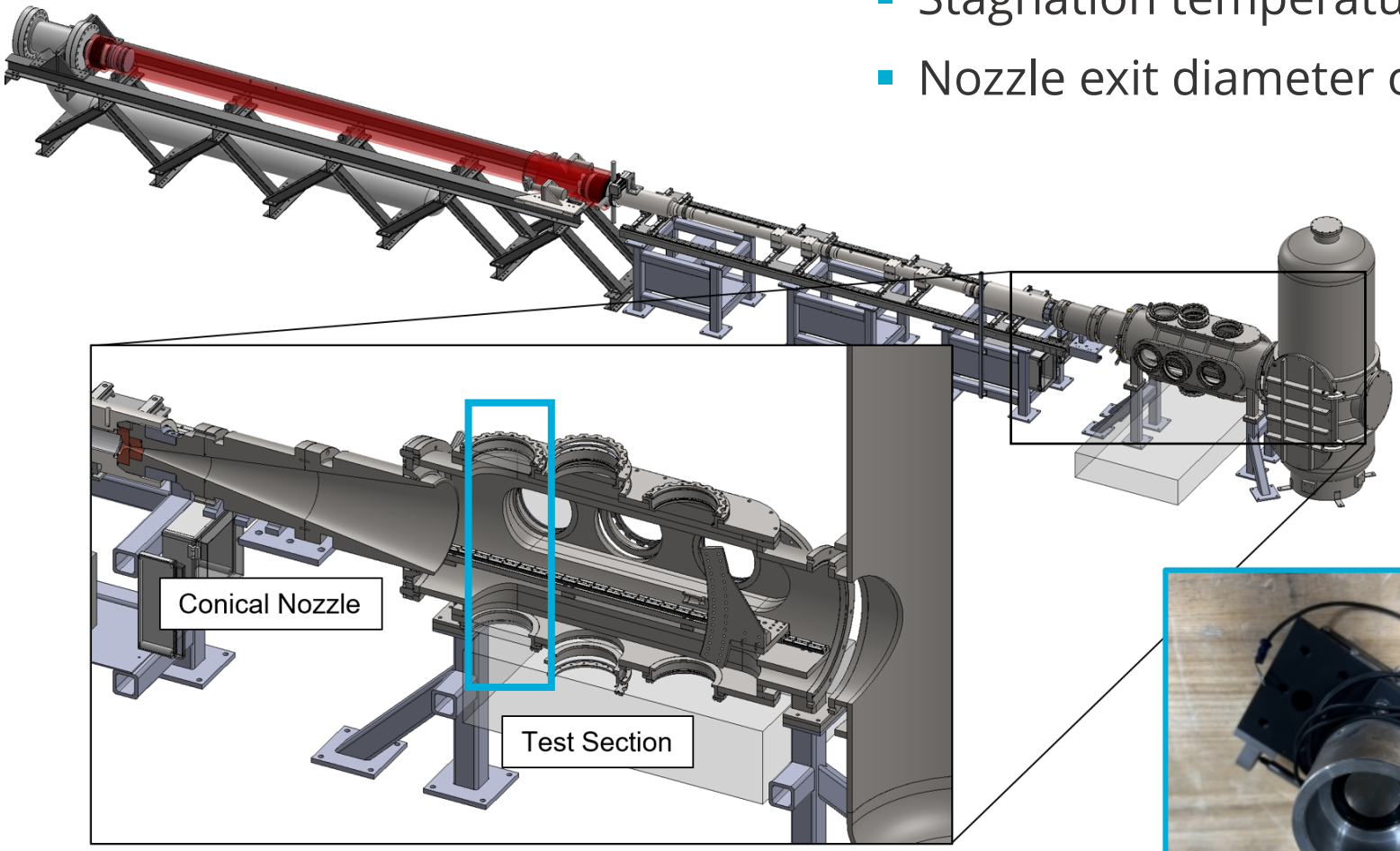
McCarthy Jr, J. F. "Hypersonic wakes." (1962).



Lees, L.. "Hypersonic wakes and trails." AIAA Journal (1964).

Facility and model

- Velocity 3 to 5 km/s (Mach 8-12) at 40 km (130 kft)
- Stagnation temperature 3700–8000 K
- Nozzle exit diameter of 36 cm (14 in)



- Flow durations 1-2 ms
- Allows ‘free-flight’ models, first demonstration application
- Electromagnet drops 2 in metal sphere into test section

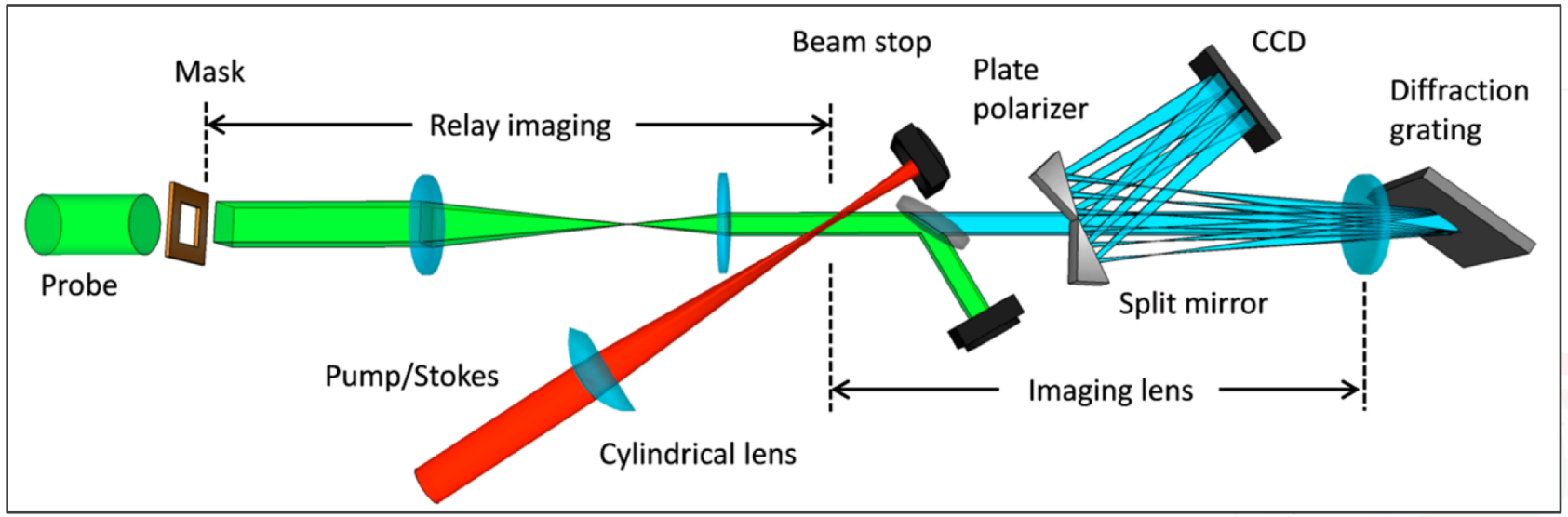
Electromagnet Holder

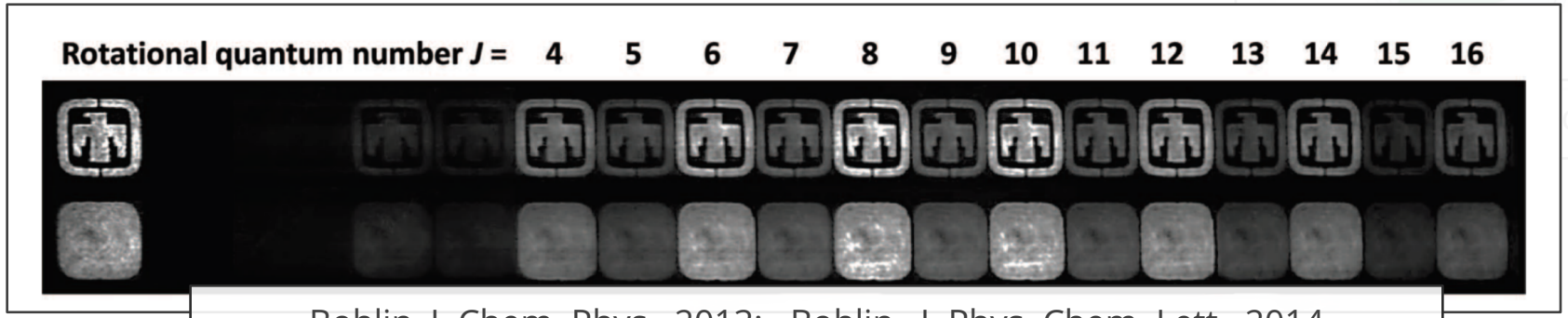
Catch with optical access

Application 4: Multi-Planar CARS Thermometry

Coherent Anti-Stokes Raman Scattering (CARS) Thermometry

- Broadband femtosecond (fs) pulse excites Raman coherence
- Narrowband picosecond (ps) pulse scattered to produce CARS signal
- Spectral analysis to extract quantitative temperatures



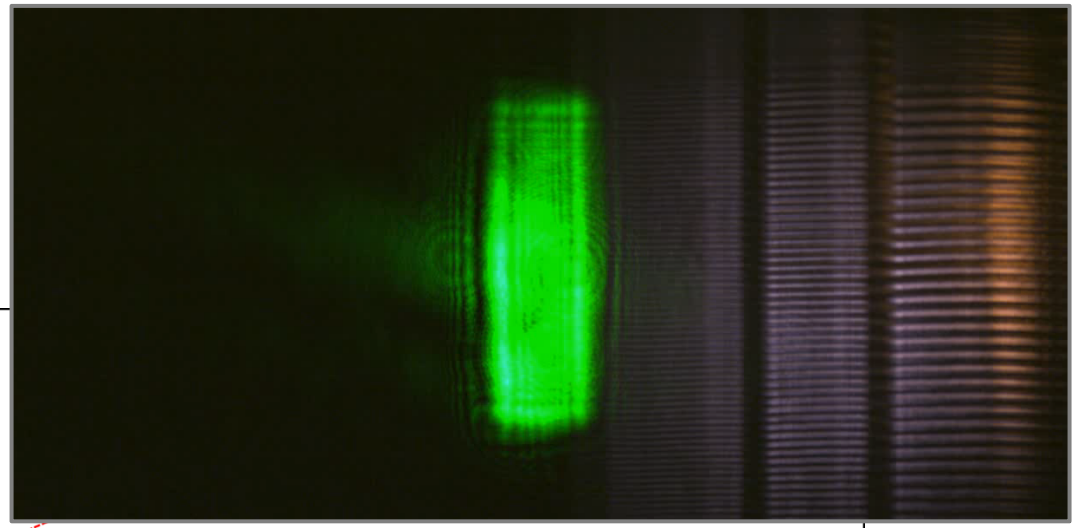


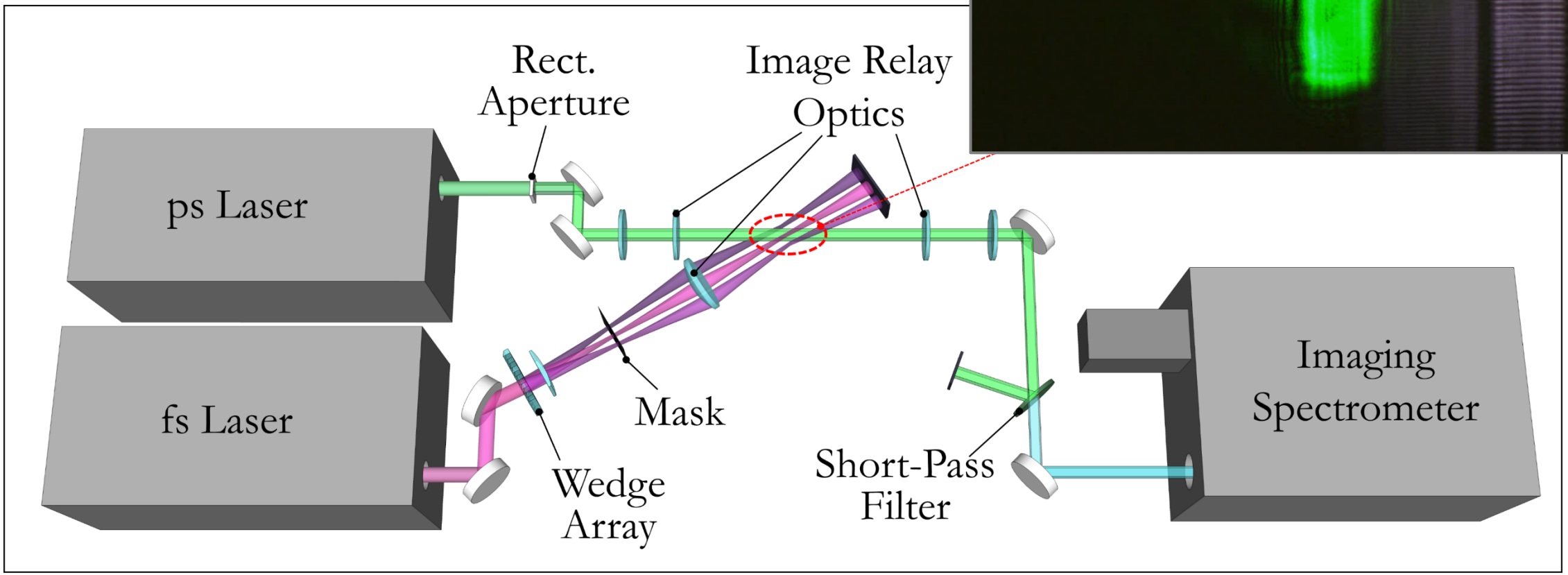
Bohlin, J. Chem. Phys., 2013; Bohlin, J. Phys. Chem. Lett., 2014

Application 4: Multi-Planar CARS Thermometry

- Use structured illumination and fs/ps CARS to perform multi-planar gas thermometry
- Incorporates wedge array, Fourier analysis, and spectroscopy from previous experiments

Beam Profiles at Crossing





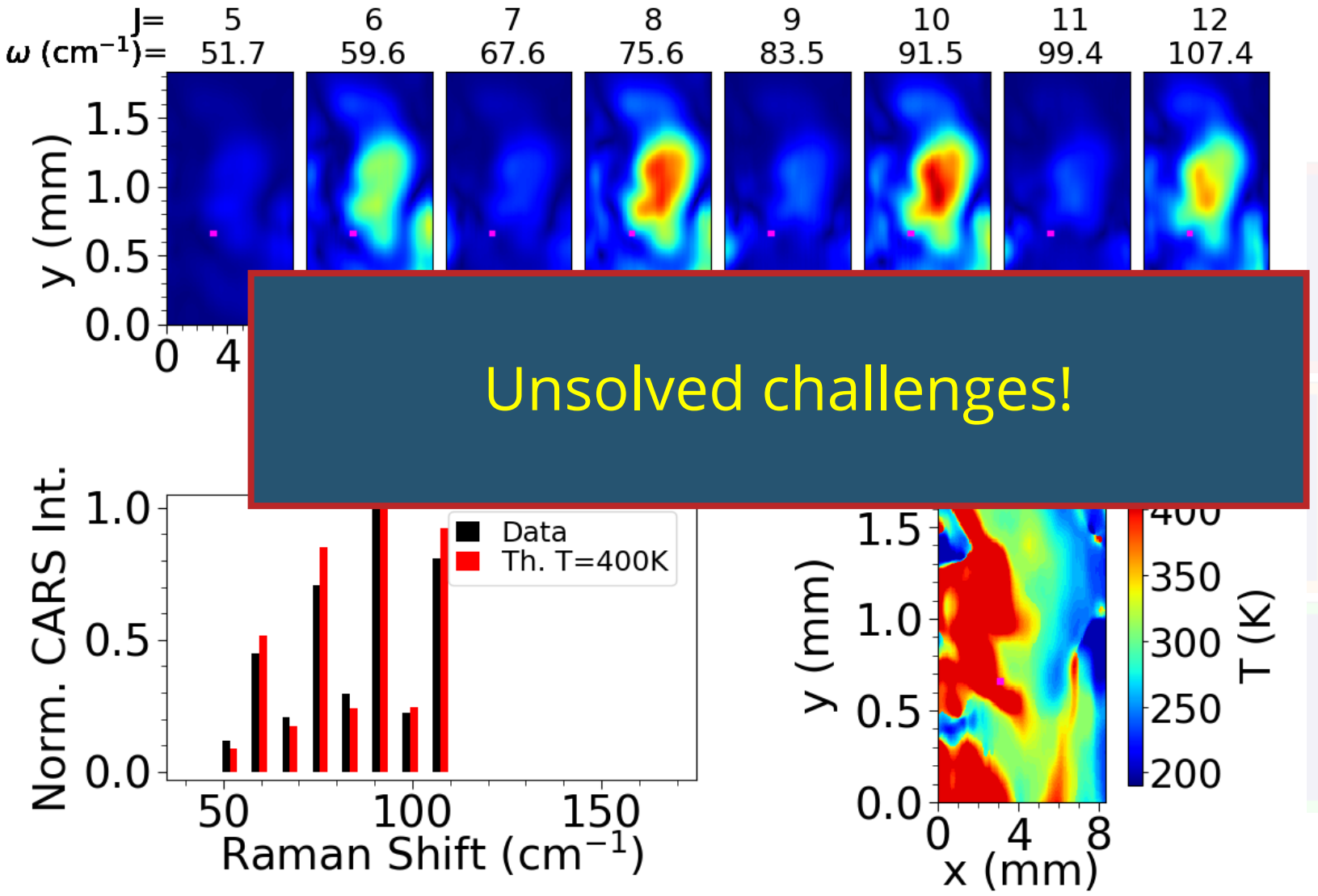
Application 4: Multi-Planar CARS Thermometry

Large variations in planar temperature results

- Interference from CARS signals from different planes

Possible Next Steps

- Minor changes to pump/Stokes delays to promote constructive interference
- Polarization approach
- Spatial differentiation



Unsolved challenges!