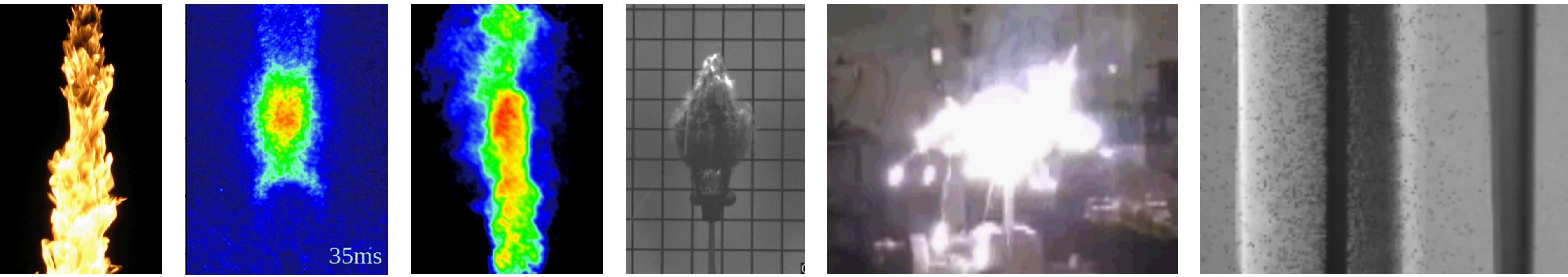
SAND2017-12992PE



Development and Application of Ultrafast Laser Diagnostics

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Dec 6th, 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Acknowledgements
- Previous work with Spectral Energies and AFRL
  - Radiation from sooting flames
  - Visualization of combustion species at 1 kHz
  - kHz-rate mixture fraction imaging
- Current projects at Sandia NL
  - Characterization of post-detonation fireballs
  - Temperature measurements in propellant fires
  - Understanding emission from high-temperature air in shock tube

Acknowledgements

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- Dr. James Gord

Sandia National Labs

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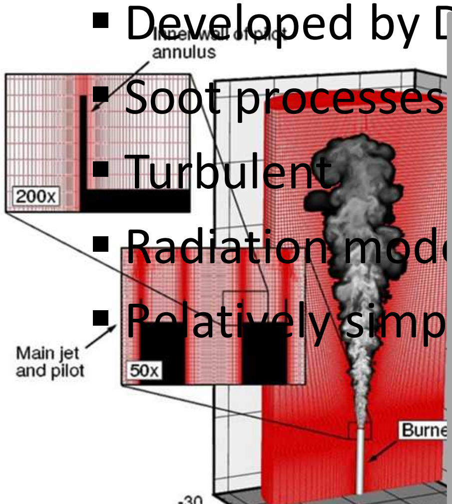
- Dr. Yi Chen
- Dr. Daniel Guildenbecher
- Dr. Kyle Lynch
- Dr. Justin W

Funding from Air Force Office of Scientific Research and Air Force Research Laboratory

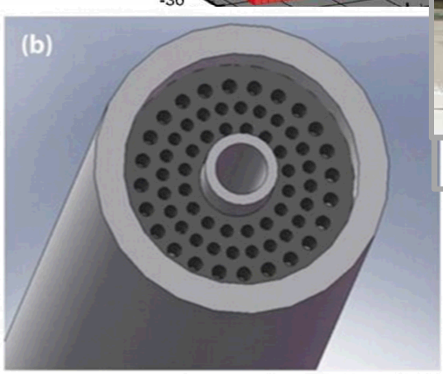
Radiation from Sooting Flames

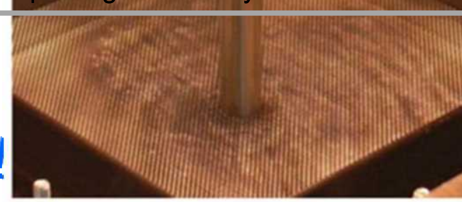
Canonical sooting flame

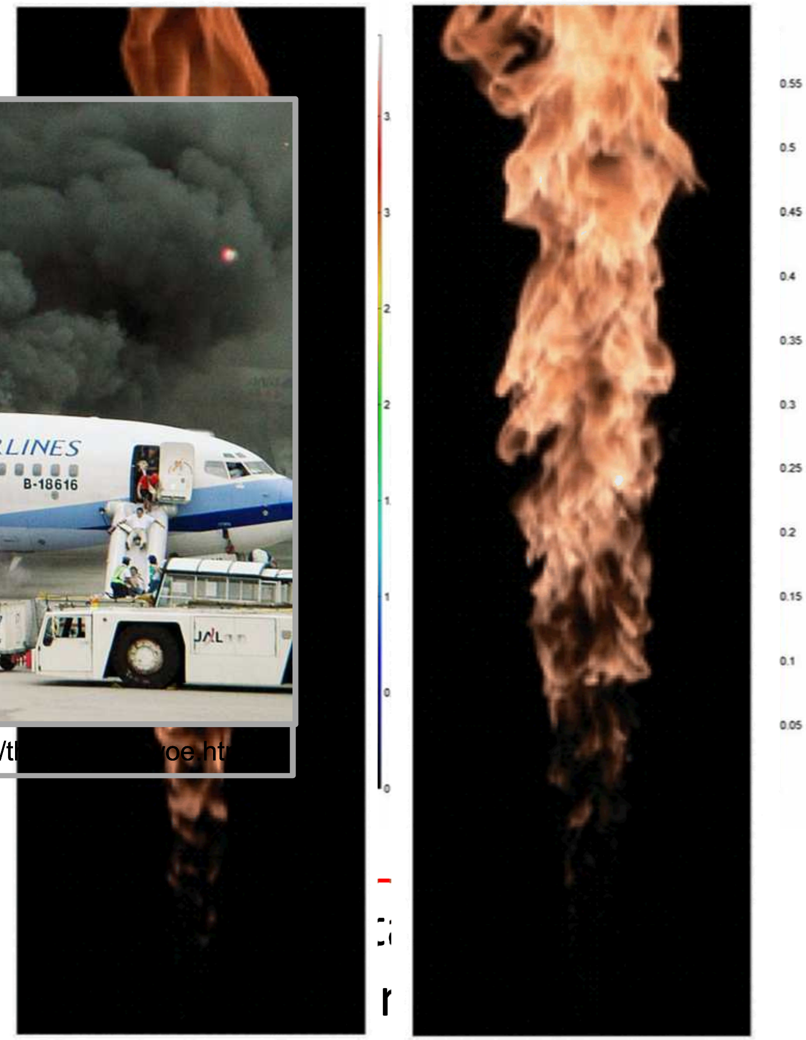
- Developed by D
- Soot processes
- Turbulent
- Radiation mod
- Relatively simp



http://blogs.mcclatchydc.com/china/2007/08/t







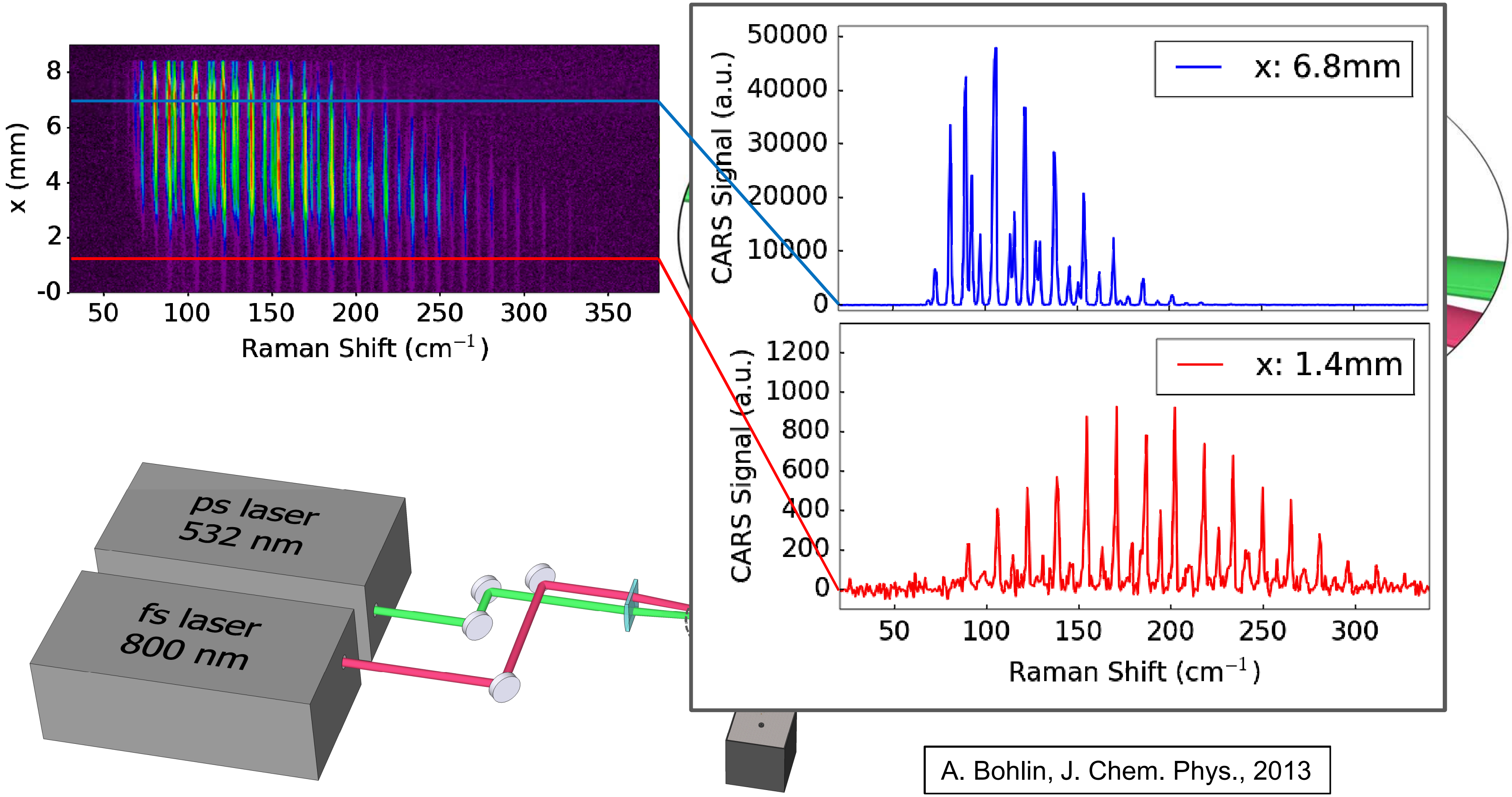
Re = 10,000 20,000

$$\frac{d\overline{I_\lambda}}{ds} = \overline{\mu_\lambda I_{\lambda,b}(T)} - \overline{\mu_\lambda I_\lambda}$$

J. Zhang, R. Sci. Instrum., 2011

Radiation from Sooting Flames

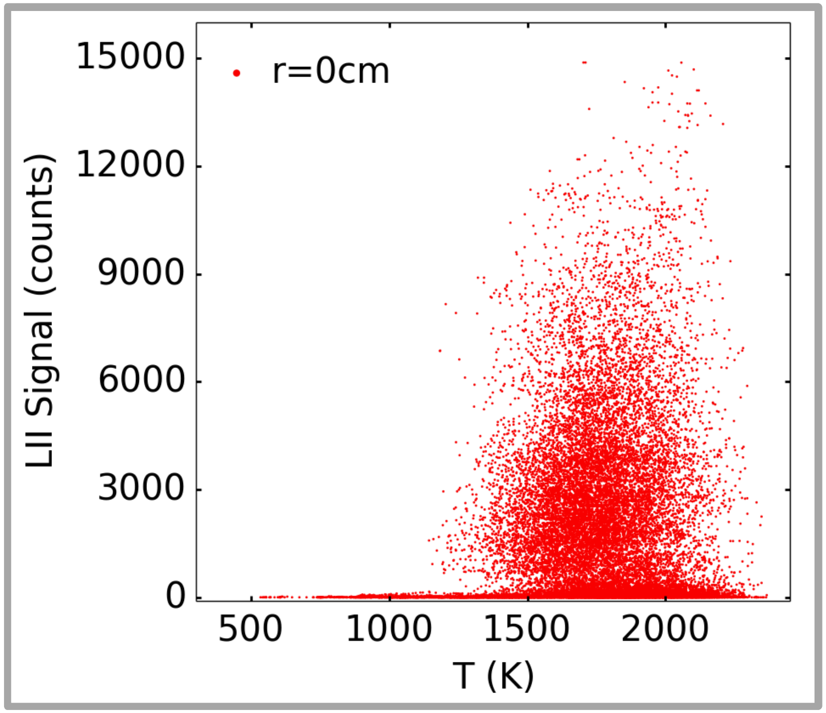
Application of CARS and LII for simultaneous measurements of temperature and soot volume fraction



A. Bohlin, J. Chem. Phys., 2013

Radiation from Sooting Flames

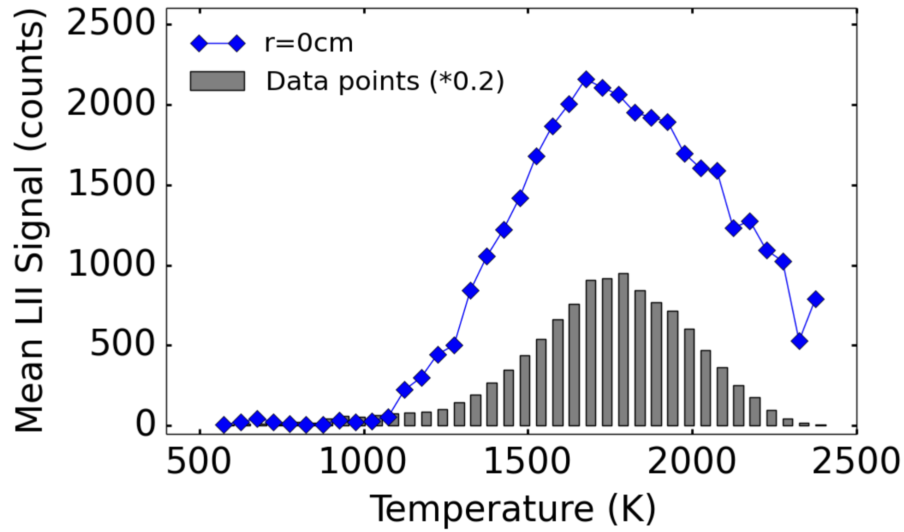
Application of CARS and LII for simultaneous measurements of temperature and soot volume fraction

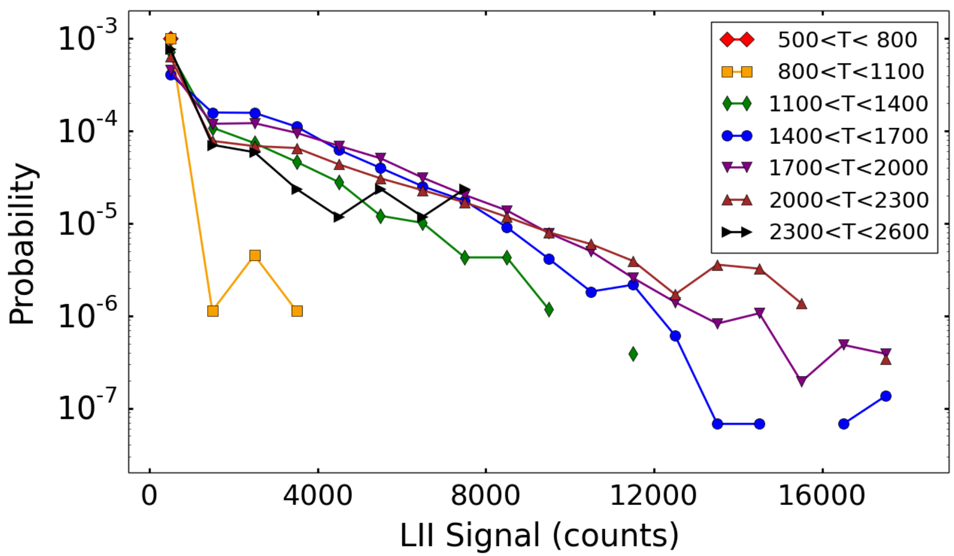


Radiation from Sooting Flames

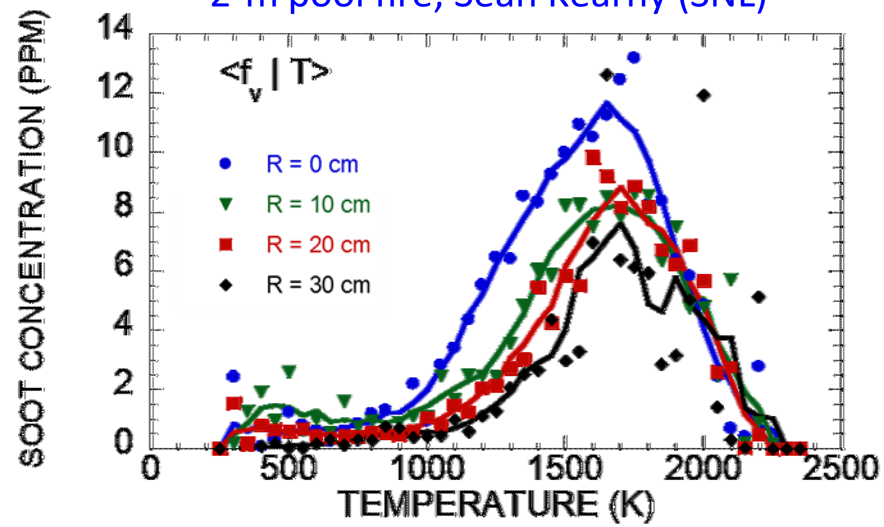
Joint statistics of soot, T:

- Conditional averages
- Comparison to 0D RCARS data from SNL pool fires
- Temperature-filtered PDF of soot





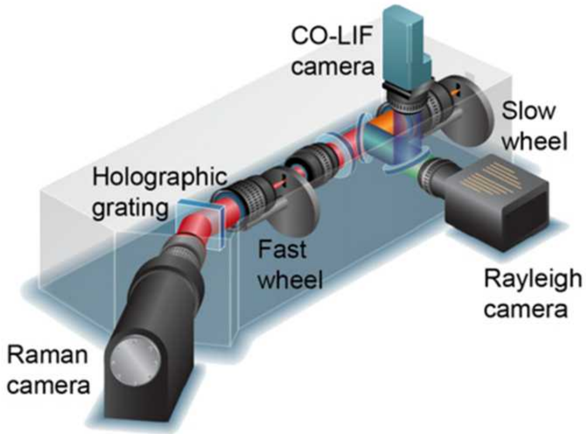
2-m pool fire; Sean Kearny (SNL)



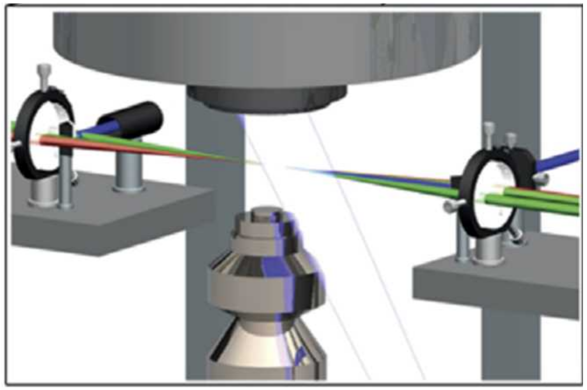
Carbon Monoxide Visualization

Carbon Monoxide (CO):
- Toxic
- Pollutant
- Indicator of incomplete combustion
- Key species in combustion chemistry

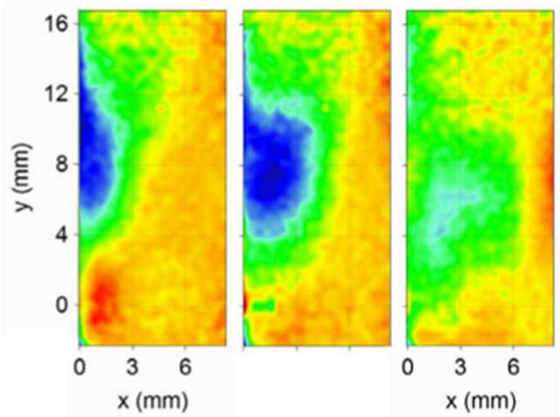
State-of-the-Art for CO Visualization:
- Two-photon CO (P)LIF
- Nd-YAG ns laser systems
- 10 Hz measurements
- Significant photolytic interferences



Barlow, Proc. Combust. Inst. **32**, 945 (2009)



Mann, Combust. Flame **161**, 2371 (2014)



Richardson, Combust. Flame **168**, 270 (2016)

Carbon Monoxide Visualization

Sandia National Laboratories

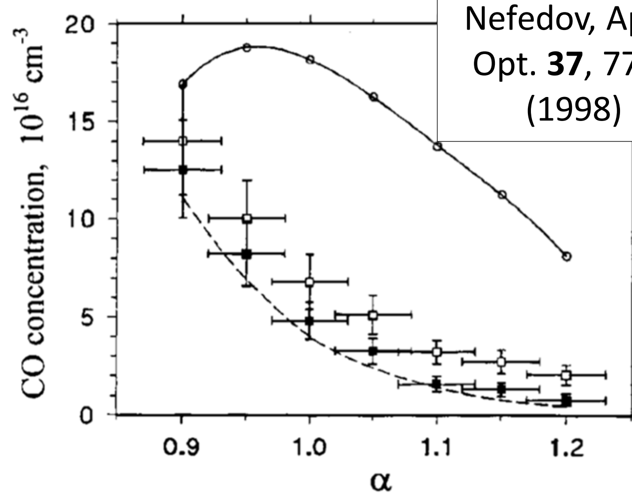
Proposed improvements:

- Amplified fs laser systems
- 1000 Hz measurements
- Reduced photolytic interferences

Photolytic Interferences:

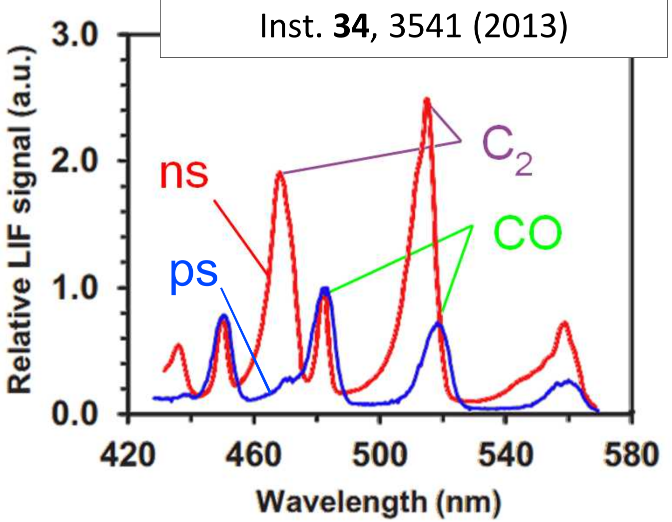
Perturbations to the flow or signal *caused by the laser*
(e.g. photodissociation, photoionization, stimulated emission)

Nefedov, Appl. Opt. **37**, 7729 (1998)

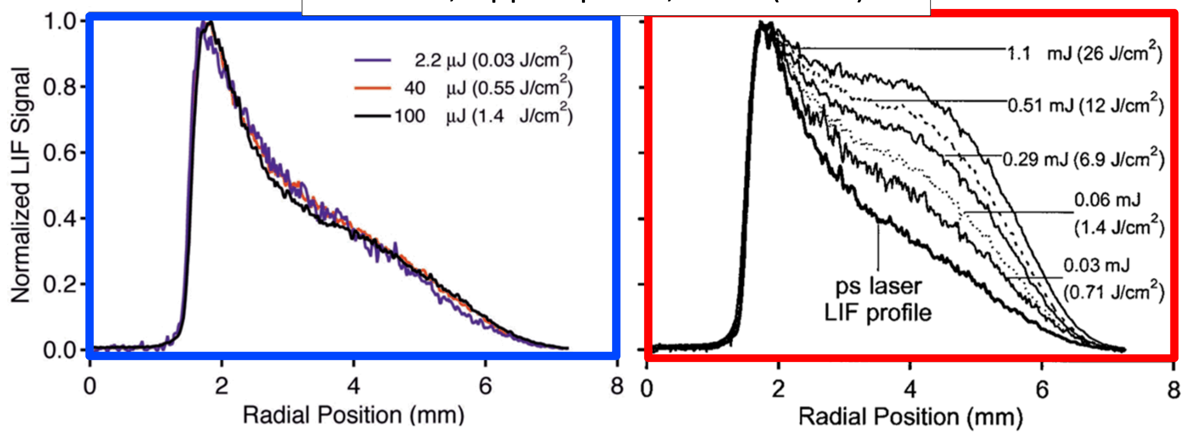


$$CO_2 + h\nu \rightarrow CO + O$$

Brackmann, Proc. Combust. Inst. **34**, 3541 (2013)



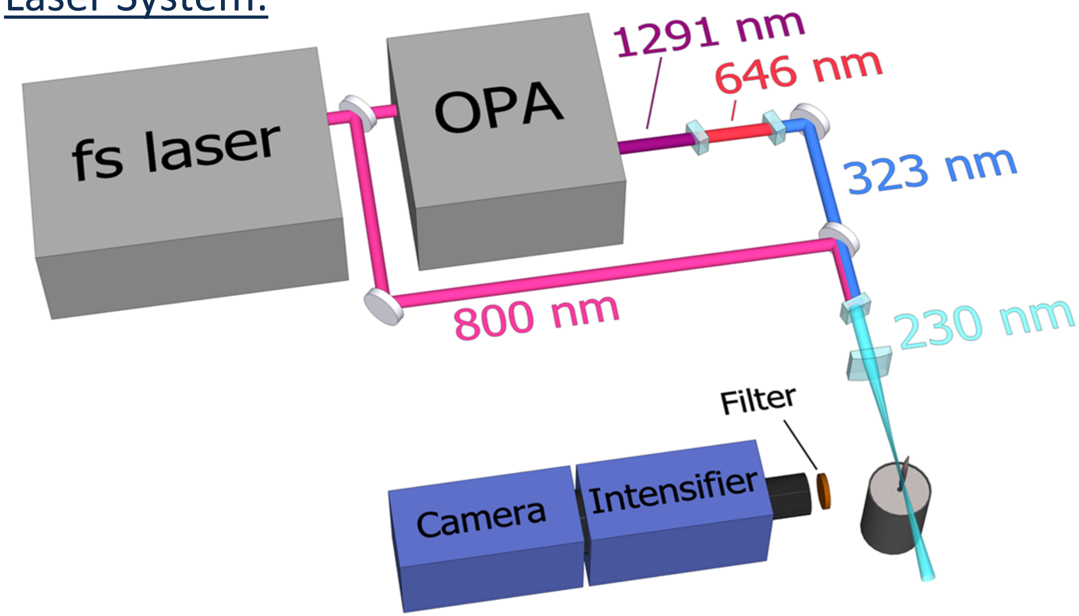
Frank, Appl. Opt. **43**, 2588 (2004)



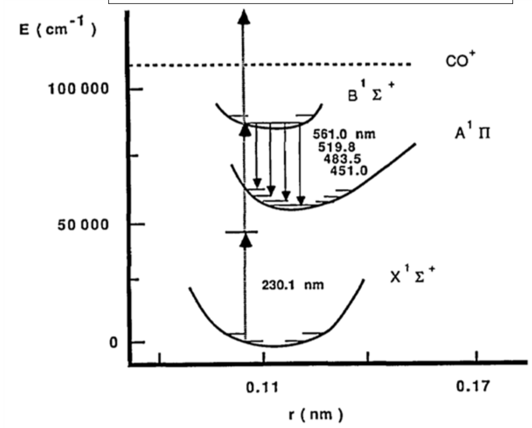
Carbon Monoxide Visualization

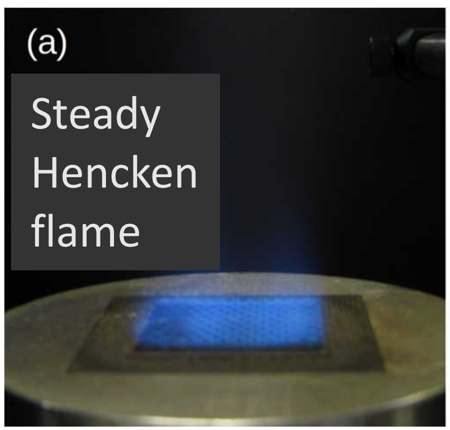
Sandia National Laboratories

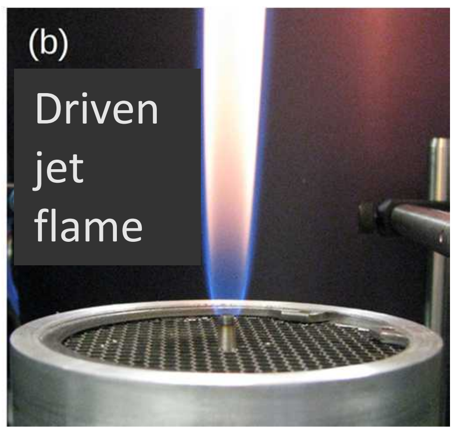
Laser System:

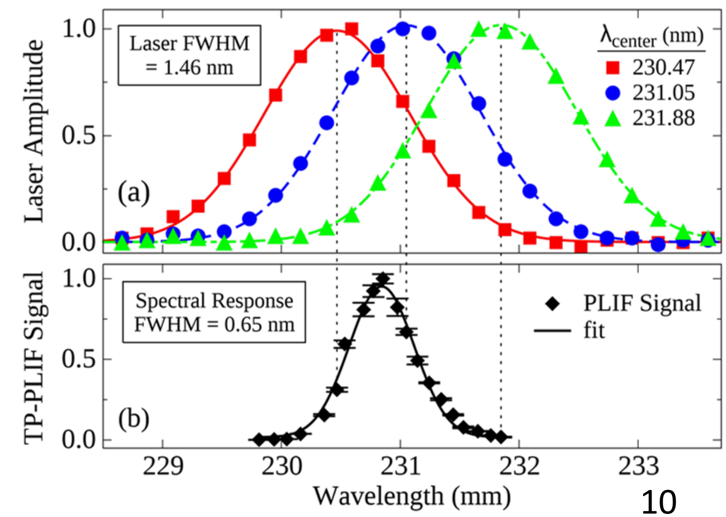


Haumman, Opt. Lett. **11**, 775 (1986)





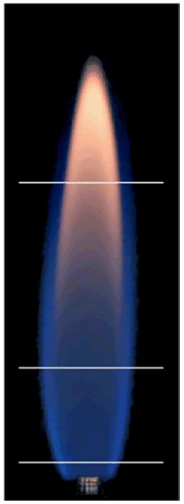


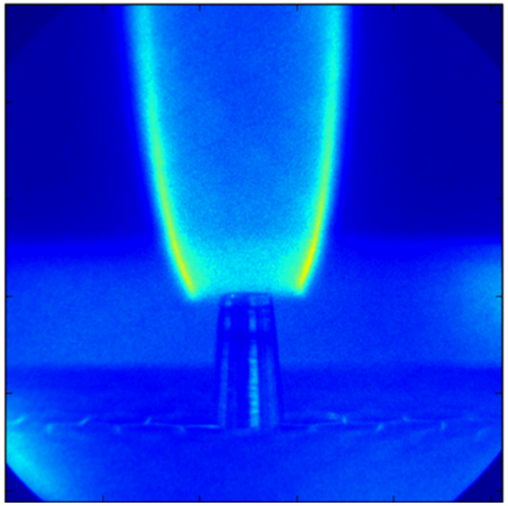


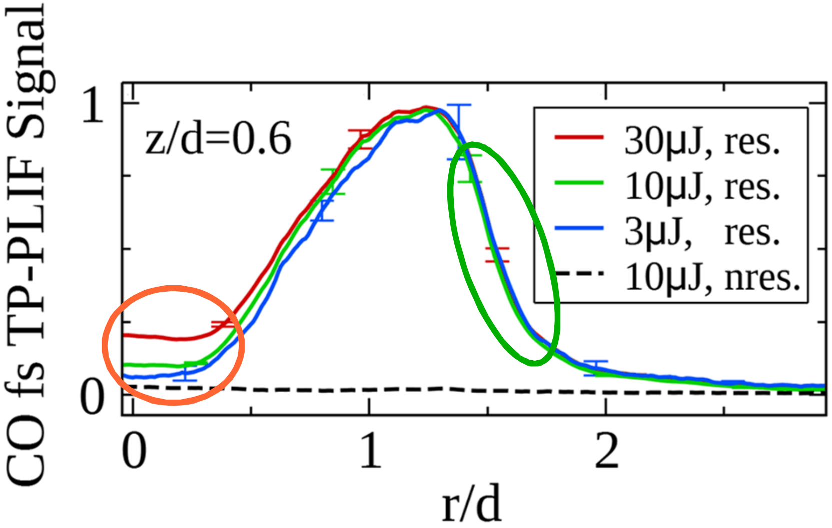
Carbon Monoxide Visualization

Jet Flame Data:

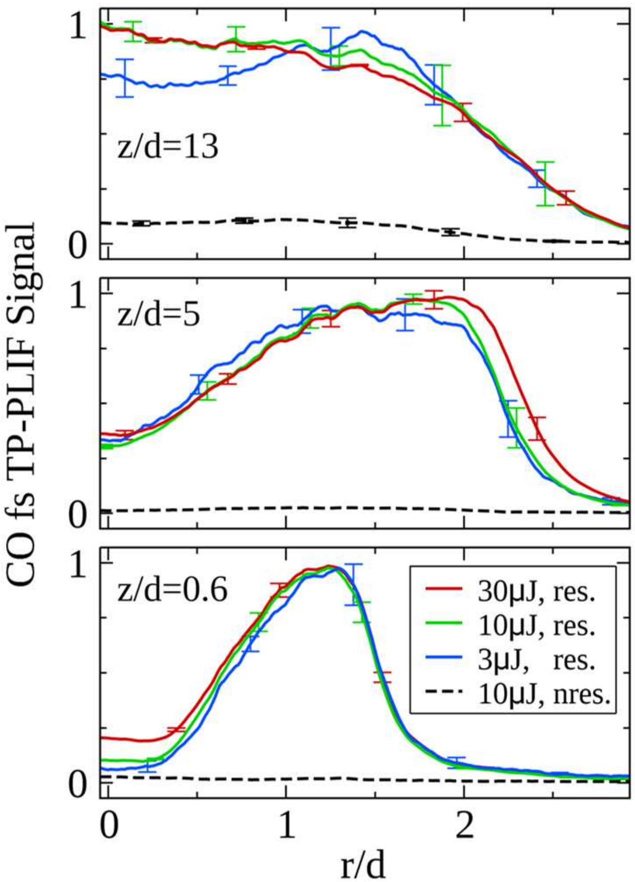
- Steady methane jet flame
- 10% CO_2 in coflow
- Average and σ from 10 sets of 200 single-laser-shot images
- Moving average of 10 applied to profiles

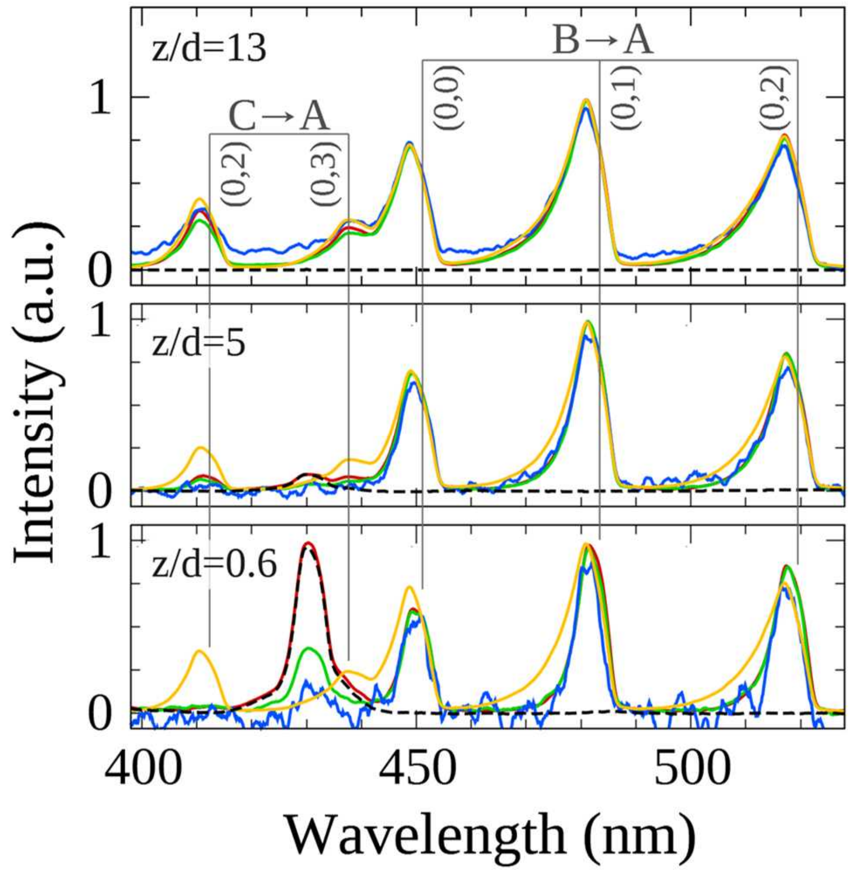


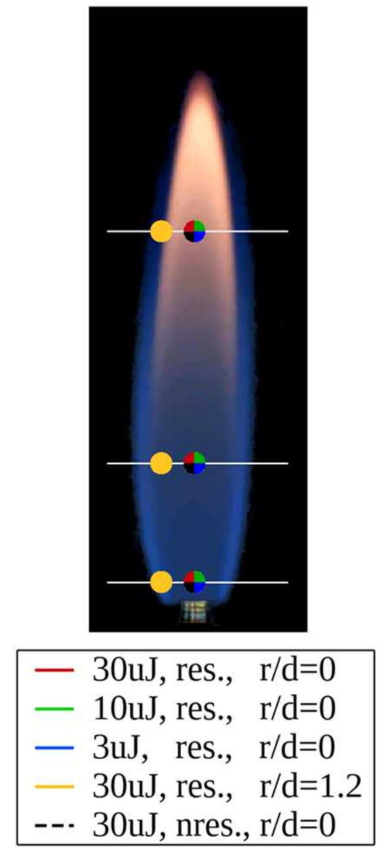




Carbon Monoxide Visualization





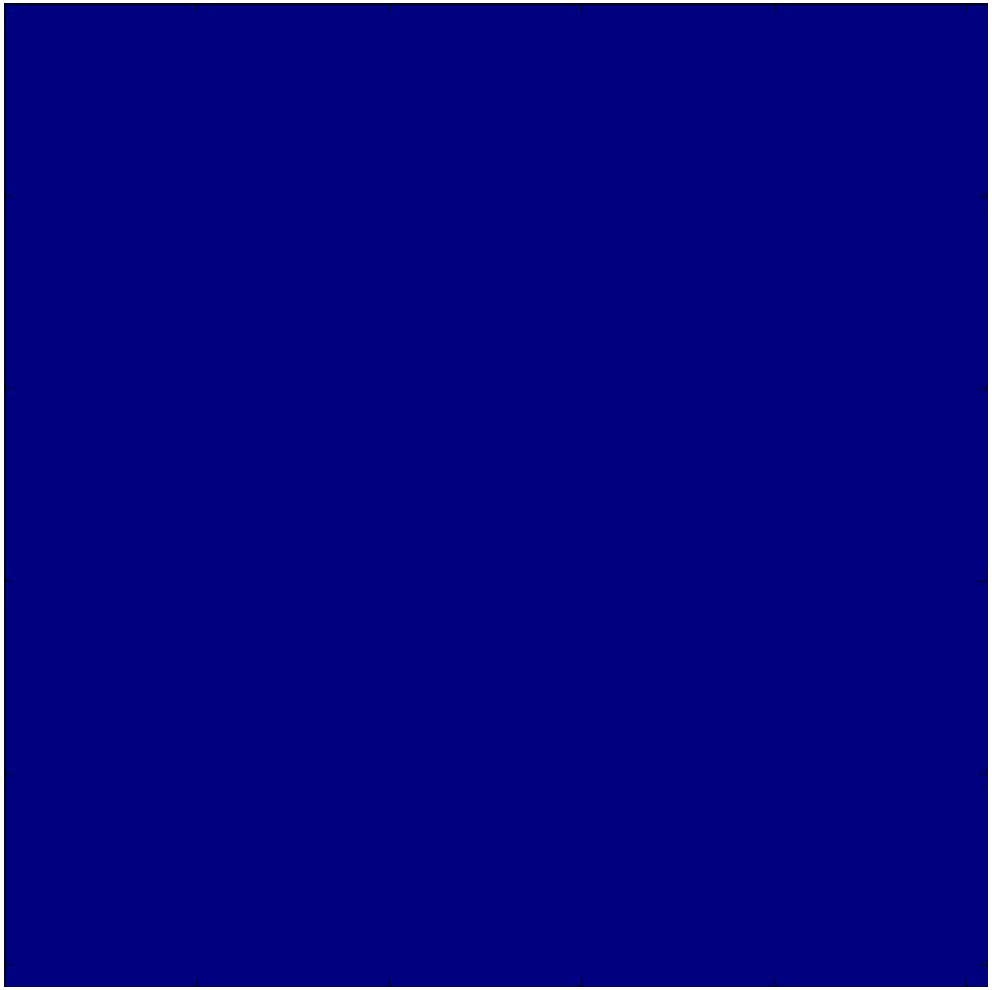


Richardson, et al., Opt. Lett. **42**, 875 (2017)

Carbon Monoxide Visualization

Driven jet flame:

- Nozzle ID = 2.2 mm
- Average jet (methane) velocity = 7.6 m/s
- Average air coflow velocity = 0.33 m/s
- Reynolds number ~ 1000
- Driven at 60 Hz using a piston device in fuel line
- Single-laser-shot images acquired at 1 kHz



Carbon Monoxide Visualization

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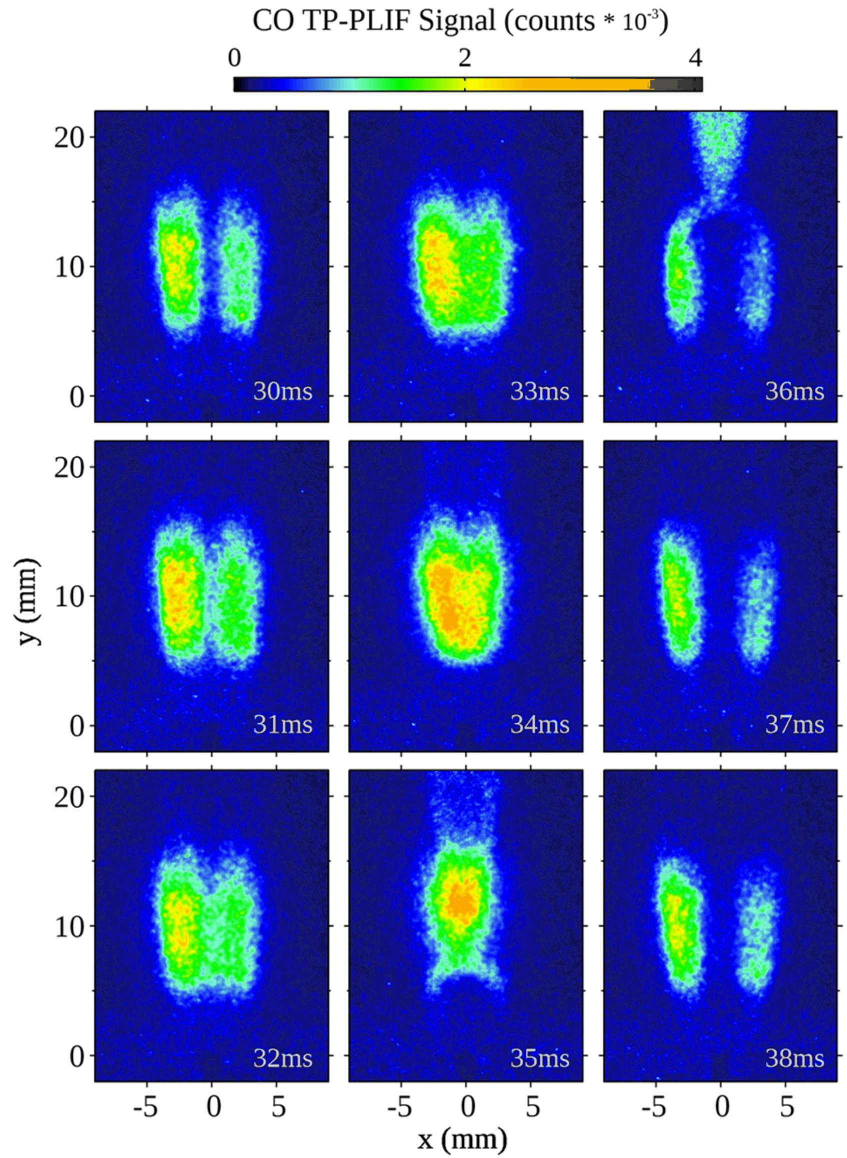
- Reynolds number ~ 1000
- Driven at 60 Hz using a piston device in fuel line
- Single-laser-shot images acquired at 1 kHz

CO fs TP-PLIF:

- Reduced or eliminated photolytic interferences
- 1 kHz CO visualizations



Mixture Fraction Measurements

Kr PLIF:

- Scalar imaging in:
  - supersonic flows
  - combustion
- Chemically inert
- Easy to seed
- Kr tagging velocimetry

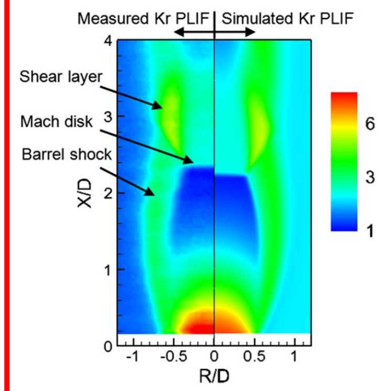
State-of-the-Art Kr PLIF:

ns laser systems

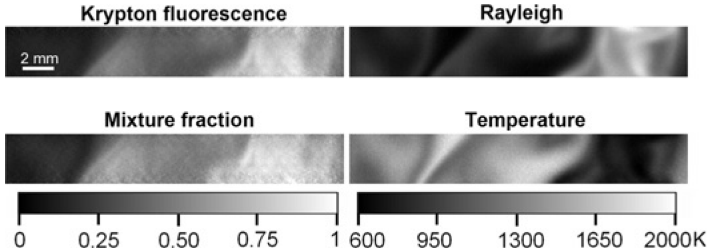
- 10 Hz measurements
- 214.7 nm excitation

fs laser systems

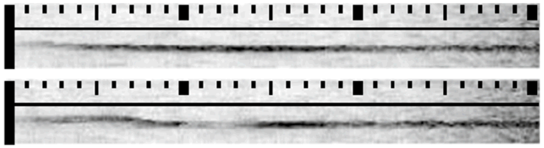
- 1 kHz measurements
- 204.1 nm excitation



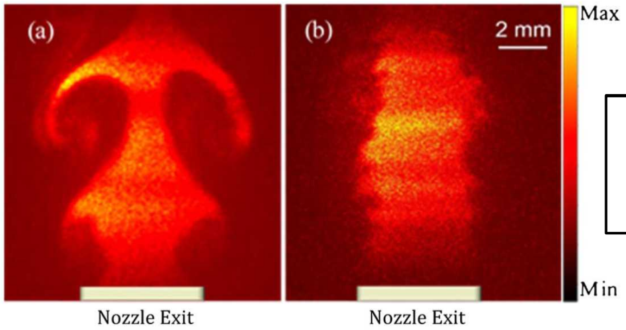
Narayanaswamy, et al., Opt. Lett. 36, 4185 (2011)



Hsu, et al., PCI 33, 759 (2011)



Zahradka, et al., Exp. Fluids 57, 62 (2016)



Wang, et al., Opt. Lett. 42, 711 (2017)

Mixture Fraction Measurements

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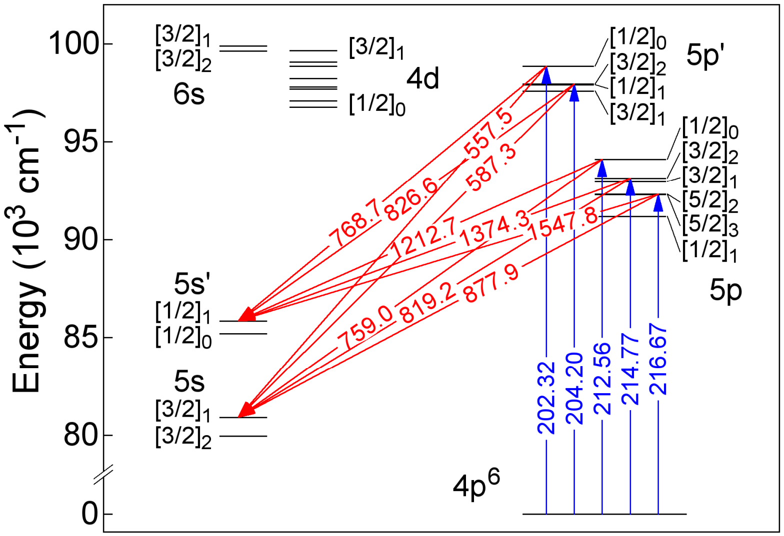
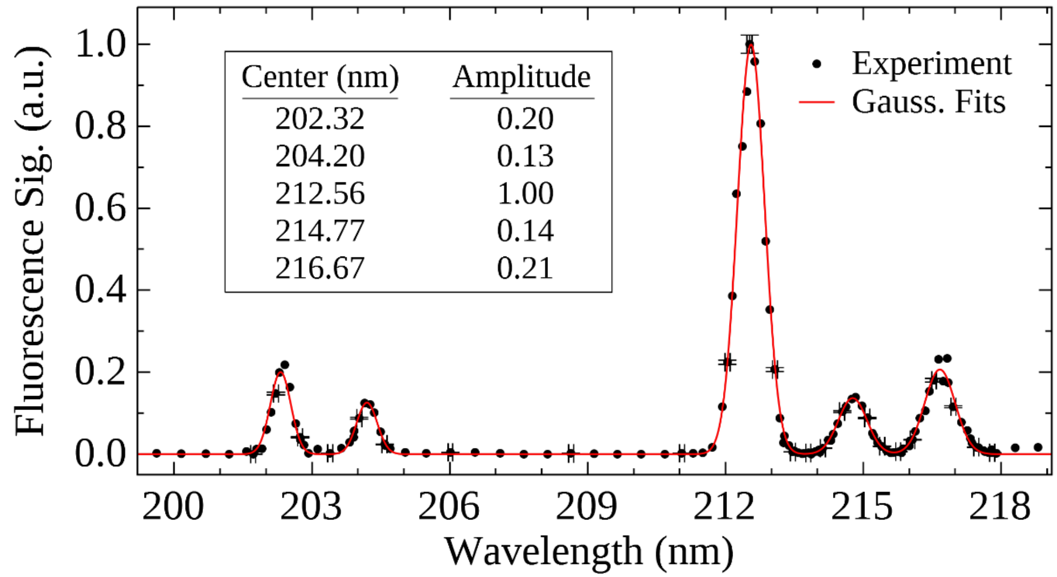
Excitation Scan:





- Excitation scan performed in gas cell with 5% Kr + 95% Ar at 1 bar
- Excitation with 212.56 nm leads to 7x improvement in signal
- Not attempted previously due to difficulty of scanning UV ns laser systems

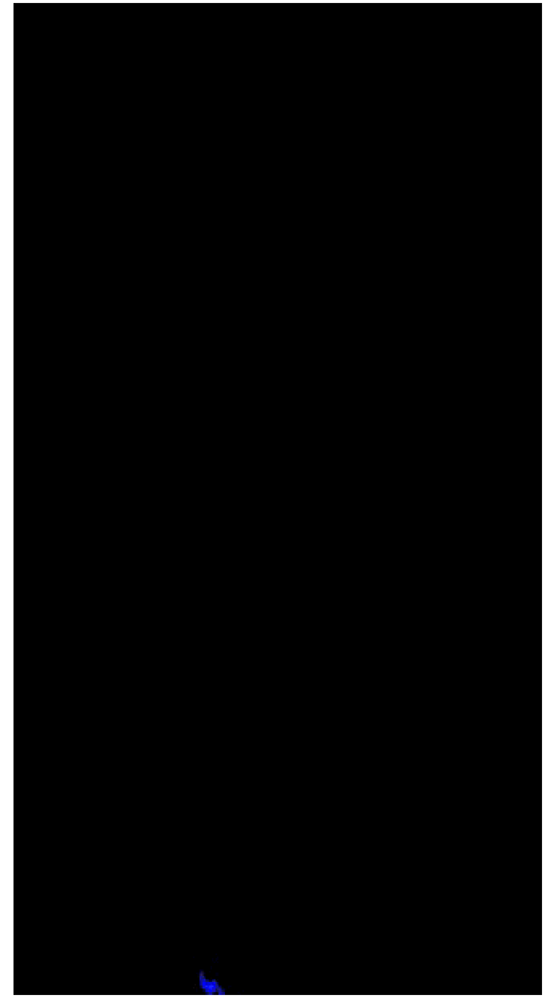
Mixture Fraction Measurements

Flow conditions:

- Flow from axisymmetric jet
- 20% Kr in N_2
- $Re_D = 1200$
- Flow perturbed using valve

Mixture fraction: the portion of the flow originating from the jet

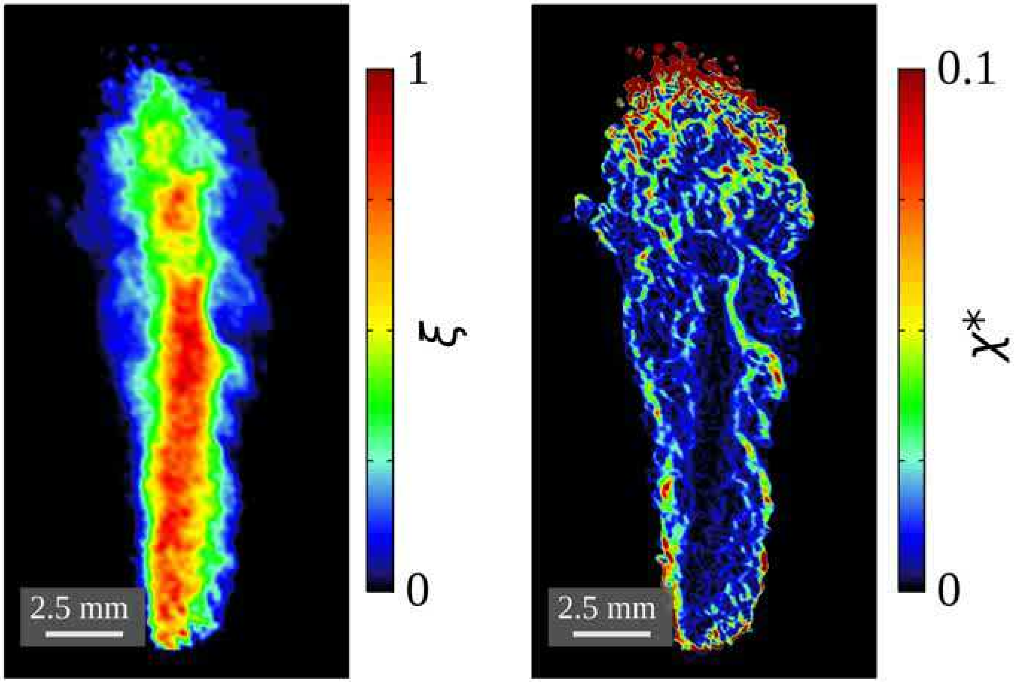
$$\xi(\boldsymbol{x}, t) = mjet/mtot$$



Mixture Fraction Measurements

Flow conditions:

- Axisymmetric jet
- 20% Kr in N_2
- $Re_D = 7750$



Richardson, et al.,
Opt. Lett. **42**, 3498 (2017)

Scalar dissipation rate: the rate at which variations in ξ are destroyed due to molecular mixing

$$\chi = 2D(\nabla\xi \cdot \nabla\xi)$$

$$\chi^* = \frac{\chi}{D(\langle\xi\rangle/\lambda_D)^2}$$

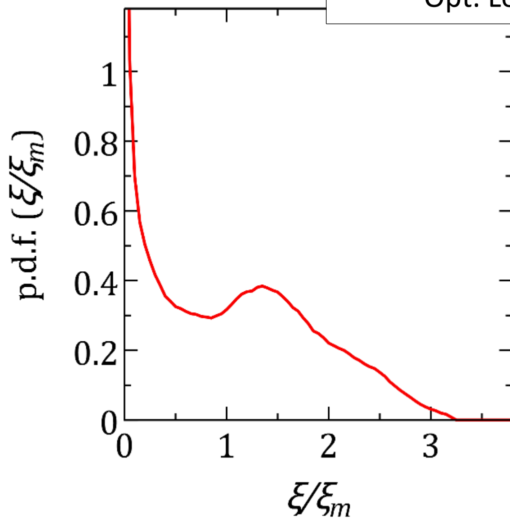
Mixture Fraction Measurements

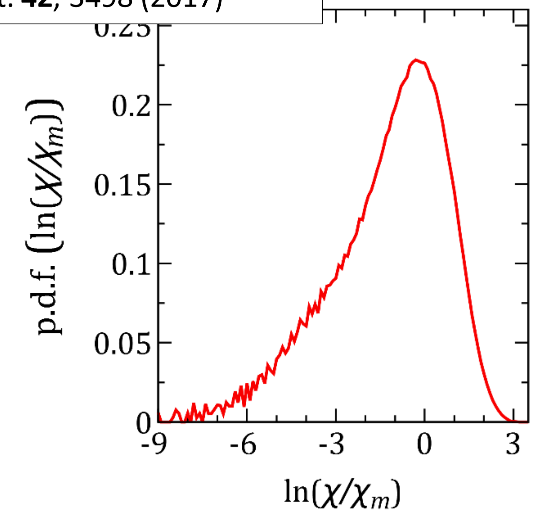
Sandia National Laboratories

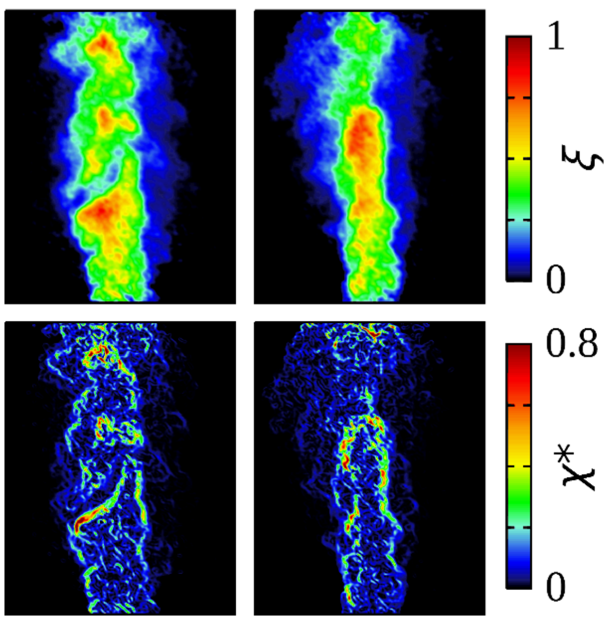
Mixing statistics comparison

- Compare Kr fs TALIF to Rayleigh imaging in free jet
- Similar probability density functions (p.d.f.)
- Joints statistical analysis

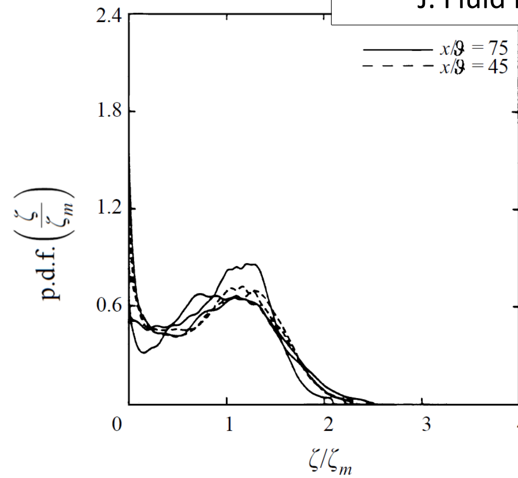
Richardson, et al., Opt. Lett. **42**, 3498 (2017)

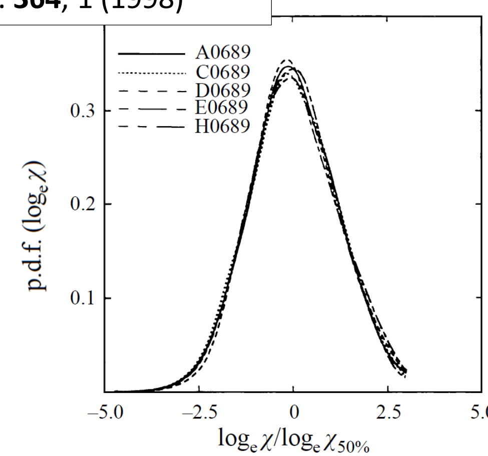




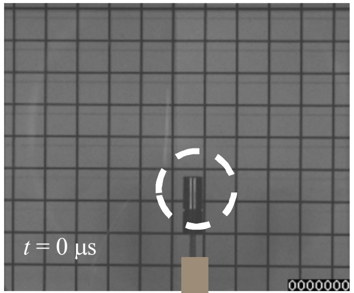


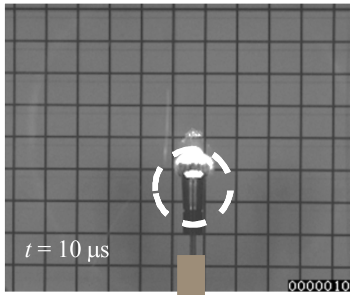
Buch and Dahm, J. Fluid Mech. **364**, 1 (1998)

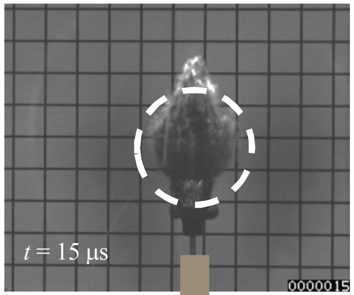


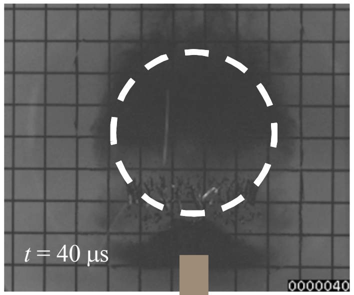


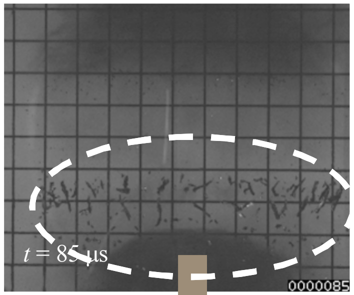
Post-Detonation Fireballs











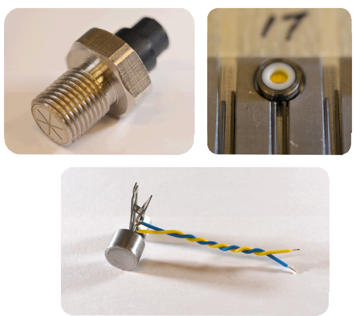
Commercial and custom devices for known boundary conditions

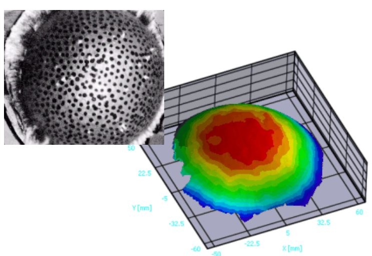
Case strain quantified at 5 MHz using DIC

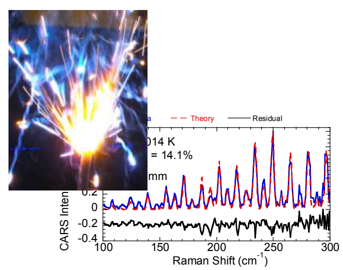
Fireball temperatures and major species concentration (O_2, N_2) using10 kHz CARS and PLIF

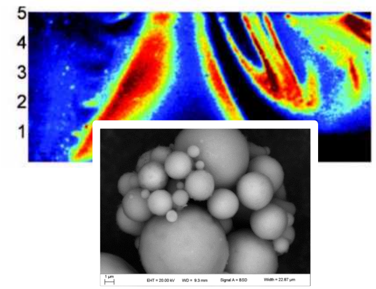
Soot structure and concentration using 50–100 kHz LII and in-situ sampling

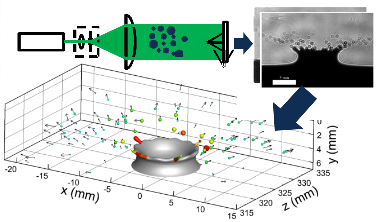
3D fragment tracking and sizing using 20 kHz DIH











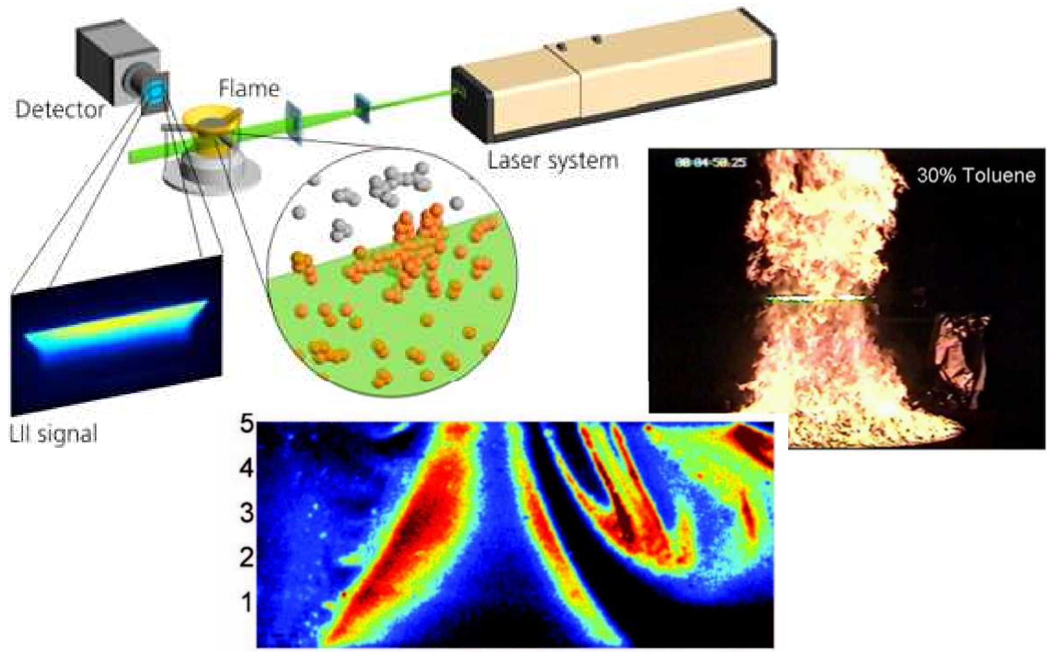
Detailed measurements at all stages in laboratory-scale explosions

Post-Detonation Fireballs

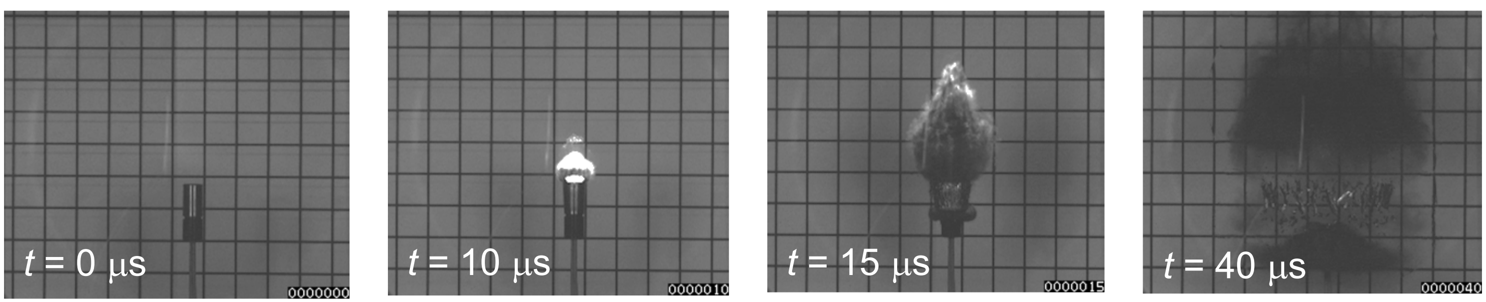
The combustion community has many advanced, *in-situ* diagnostics

- Laser Induced Incandescence (LII)
- Coherent Anti-Stokes Raman Scattering (CARS)
- Planar Laser Induced Fluorescence (PLIF)

This work will focus on applying kHz-rate diagnostics to in the post-detonation fireball region

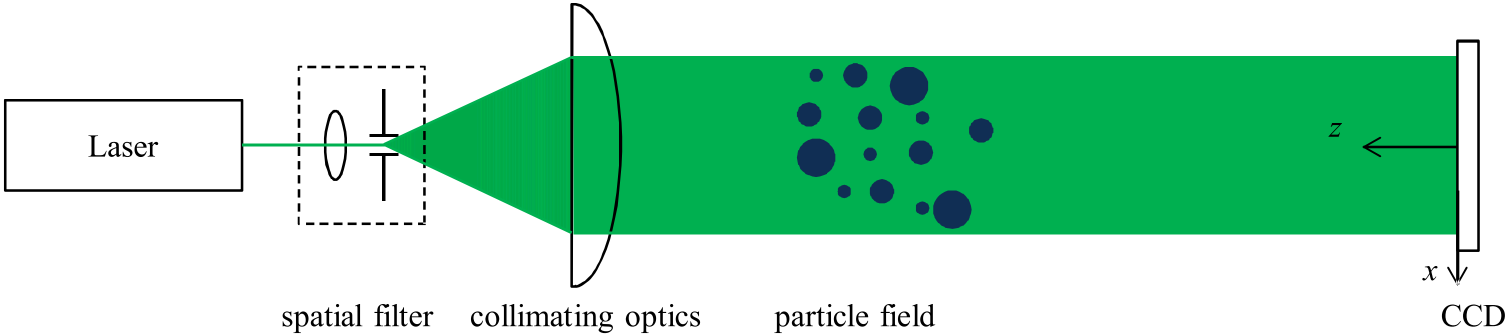


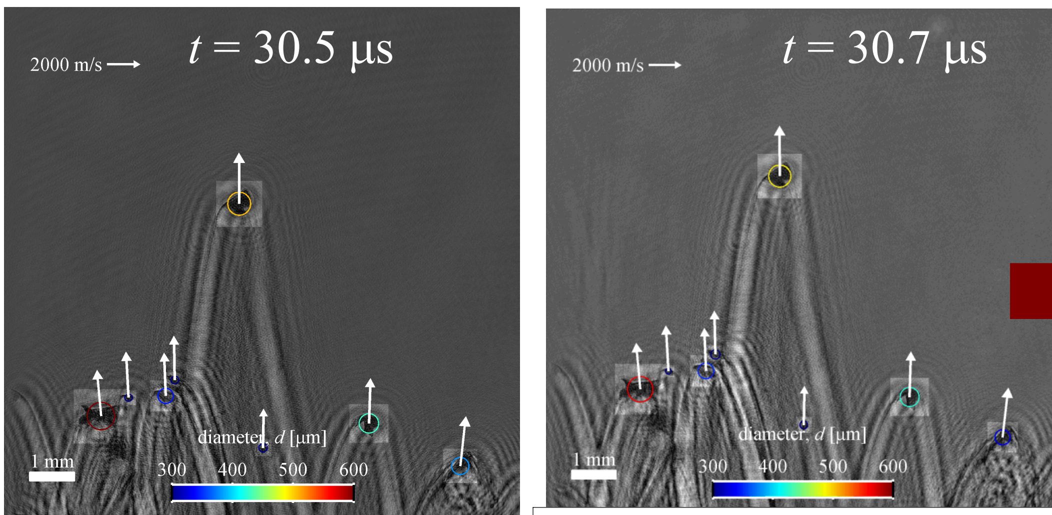
Pool Fire LII at Sandia

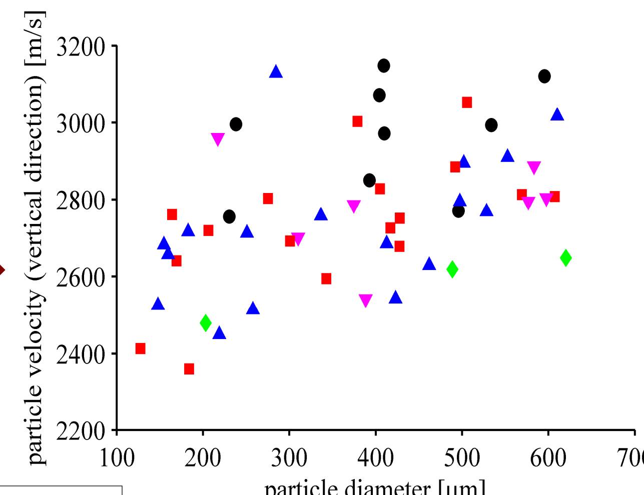


Post-Detonation Fireballs

Digital In-Line Holography:







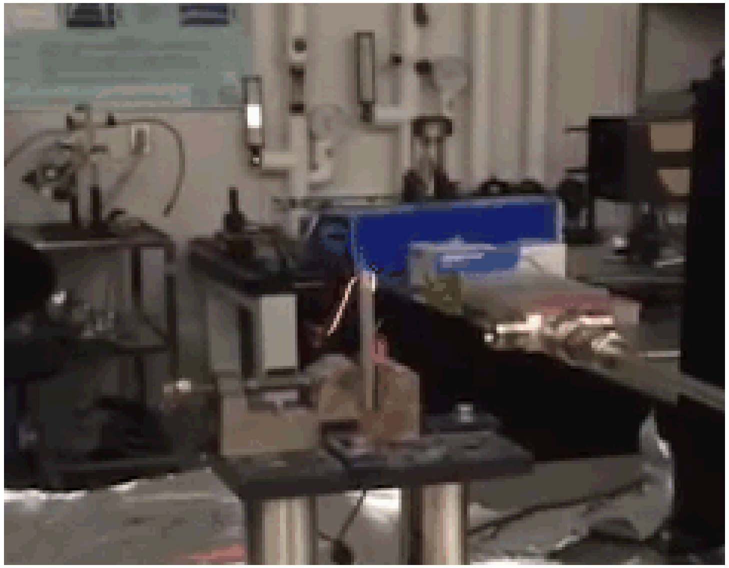
Yeager, et al., J. Appl. Phys. **122**, 035901 (2017)

Provides particle position, size, and velocity

Propellant Flames

http://www.cbsnews.com/news/rocket-crash-no-immediate-threat-to-station-but-cause-is-unknown/

Color video of burning propellant



Problem:

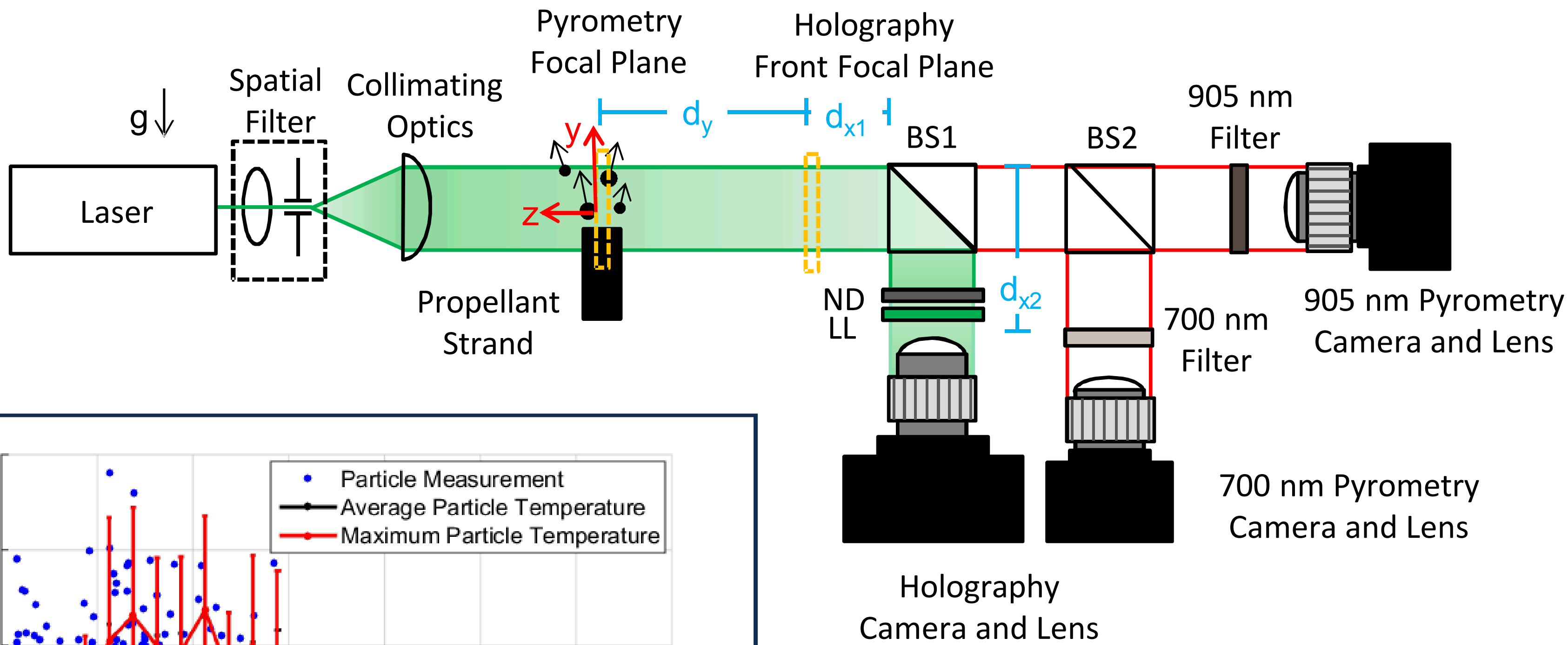
- Rocket failures can lead to propellant fires
- Aluminum agglomeration at the surface yields large reacting drops with high damage potential
- Threat prediction requires knowledge of flame characteristics

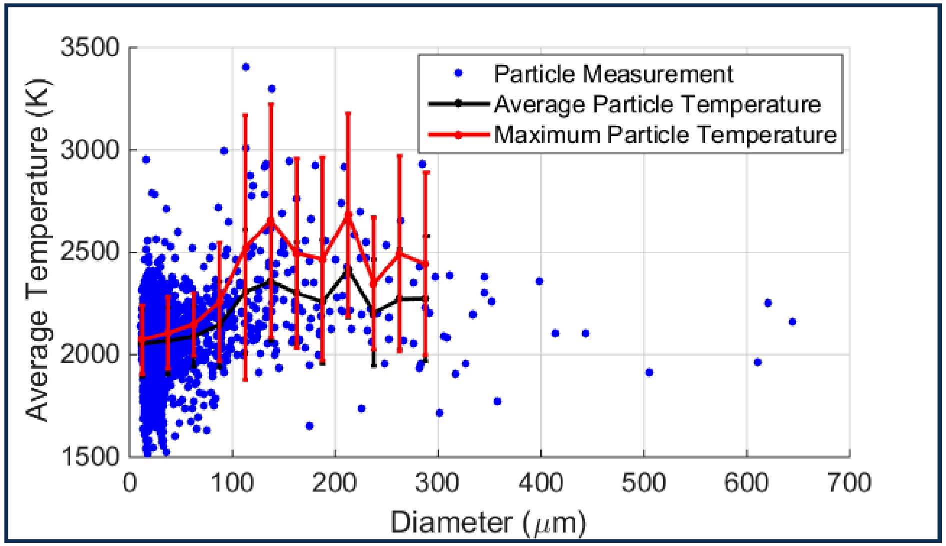
Goals:

- Measure particle size and temperature from real propellant burns
- Characterize gas-phase temperature and composition in plume
- Study scaling effects on propellant fires

Propellant Flames

Digital in-line holography and two-color pyrometry:



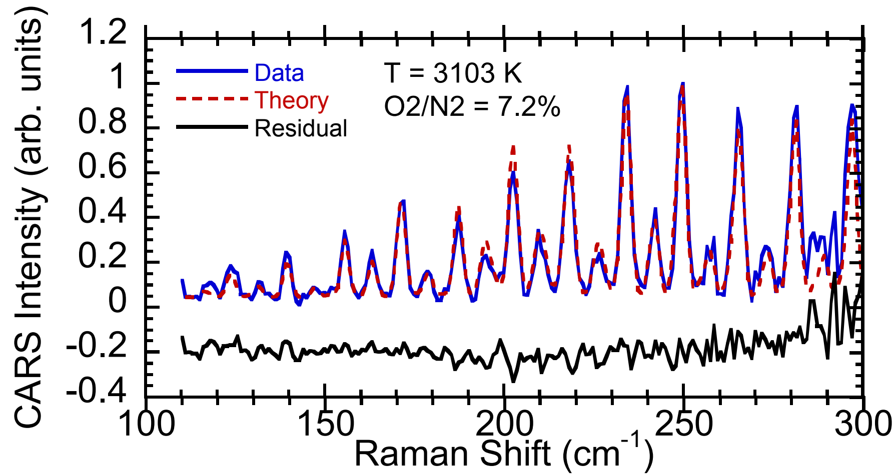


Chen, et al., Combust. Flame **182**, 225 (2017)

Propellant Flames

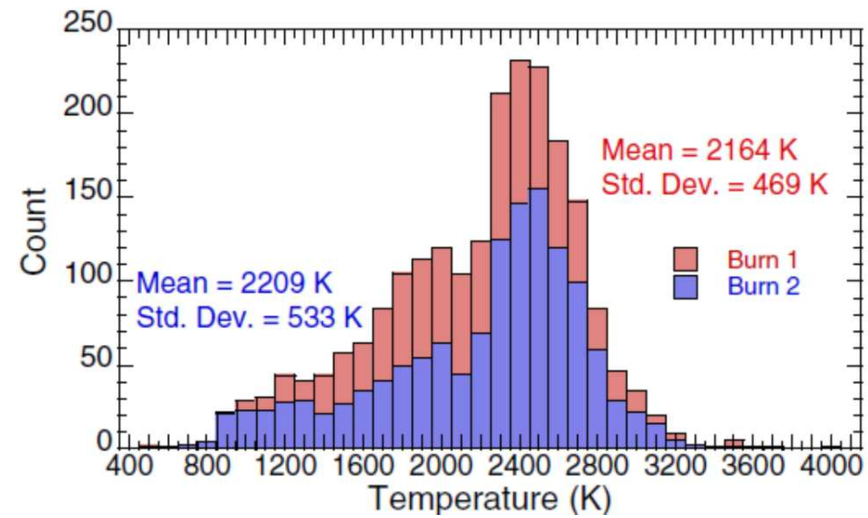
Previous research efforts:

- fs/ps rotational CARS
- Low (mJ) pulse energies reduces dielectric breakdown
- Time-delayed probe eliminates background signal



Future measurements

- Vibrational N_2 CARS for high temperature regions of plume
- H_2 CARS for temperature and concentration measurements
- 1D measurements for gradient statistics



Kearney and Guildenbecher, Appl. Optics, **55**, 4958 (2016)

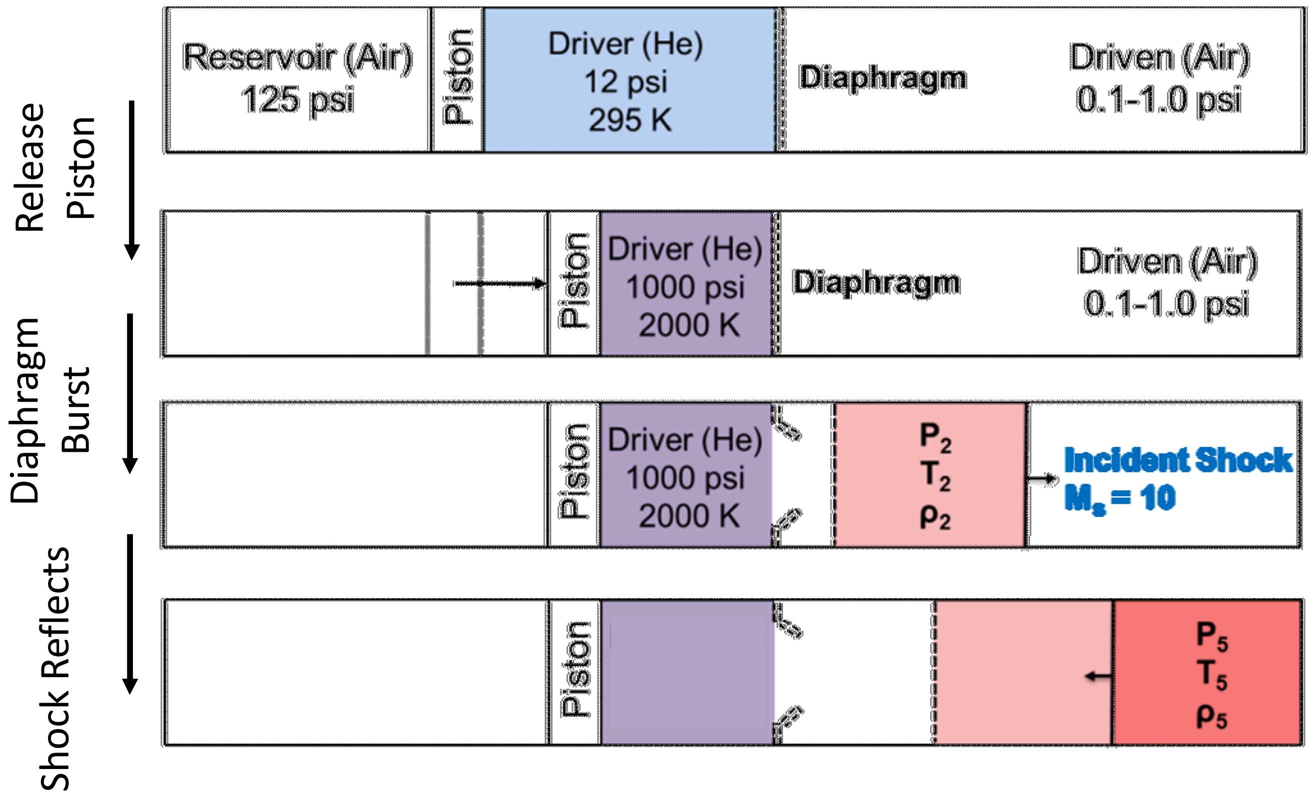
Shock Tube Diagnostics

A free-piston shock tube is being constructed which will have the capability to reach extreme temperatures and pressures

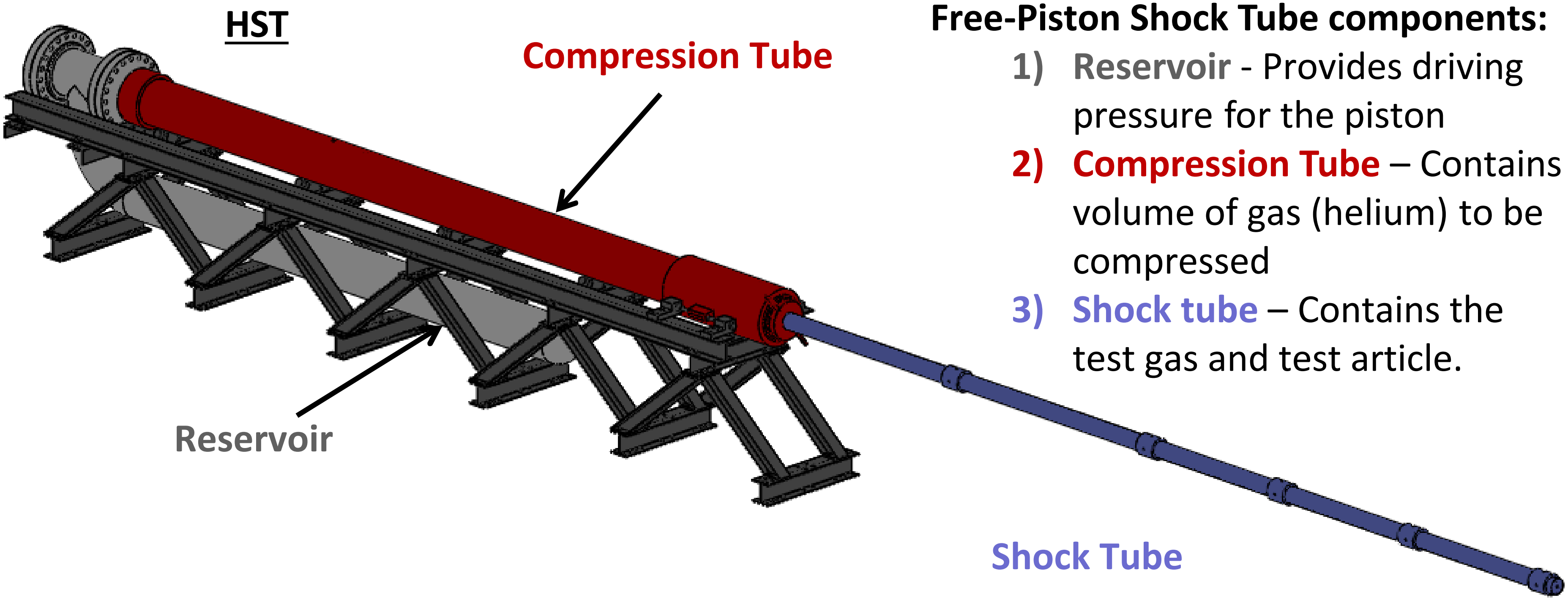
Operational principle: Secondary reservoir drives free-piston to compress helium to burst pressure, which **simultaneously heats the helium, further boosting driver performance.**

Produces ***much stronger shocks*** than a standard tube.

- T2 > 3000 K
- P2 > 50 bar



Shock Tube Diagnostics



Free-Piston Shock Tube components:

1) **Reservoir** - Provides driving pressure for the piston
2) **Compression Tube** – Contains volume of gas (helium) to be compressed
3) **Shock tube** – Contains the test gas and test article.

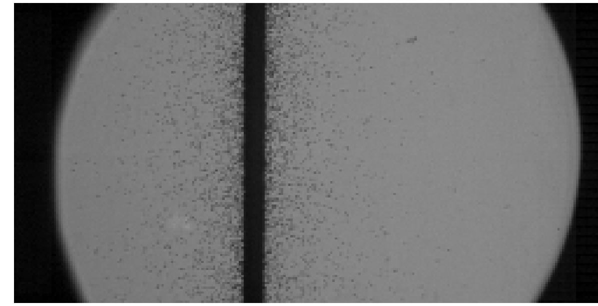
The High-Temperature Shock Tube (HST) will be used to study:

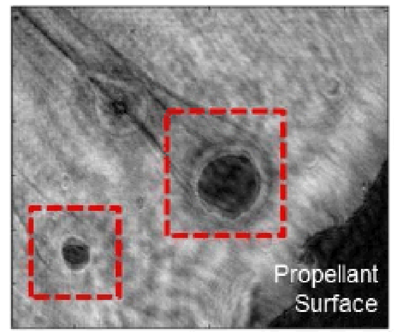
- Ignition of particles in a shocked flow
- Optical emission from high-temperature and high-pressure gasses

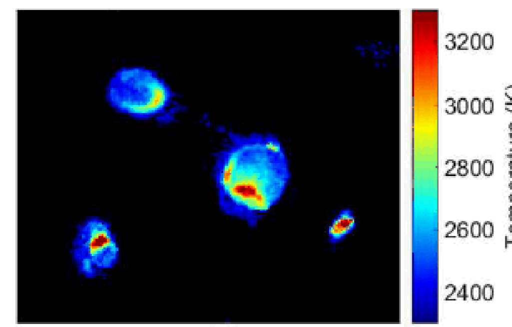
Shock Tube Diagnostics

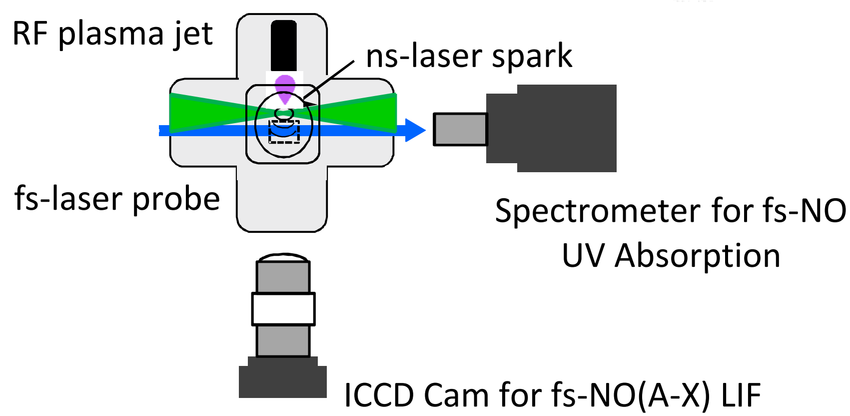
<u>**Measurement Diagnostics**</u>

- Begin with proven diagnostics:
  - Schlieren / Imaging
  - Pressure Sensors
  - Emissions spectroscopy
- Digital In-Line Holography (DIH) for particle morphology
- Imaging pyrometry for particle temperature
- Gas phase temperature measurements
  - Emissions Spectroscopy
  - Absorption Spectroscopy
  - Laser Induced Fluorescence (LIF)
  - Raman Spectroscopy
  - Coherent Anti-Stokes Raman Scattering (CARS)



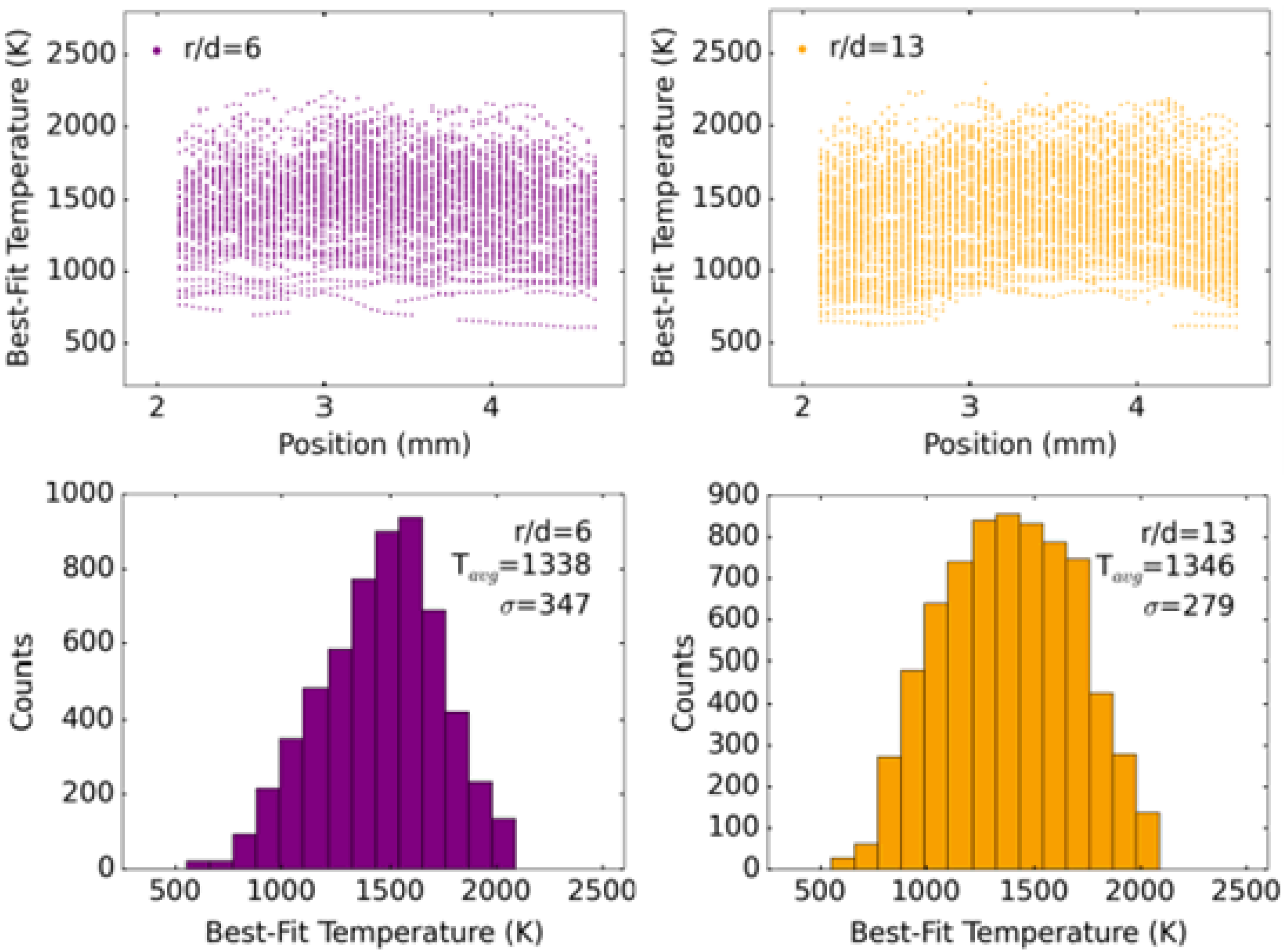


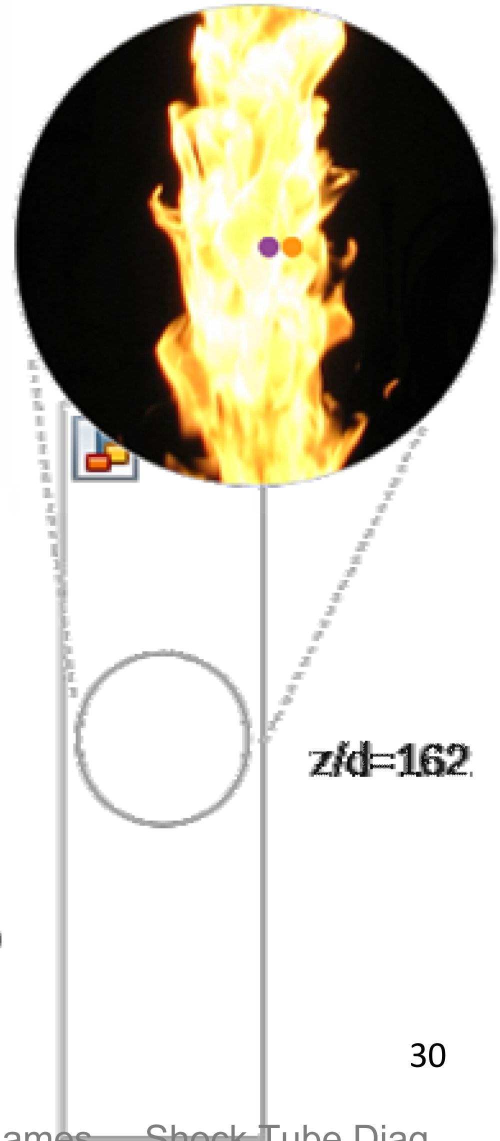




Backup Slides

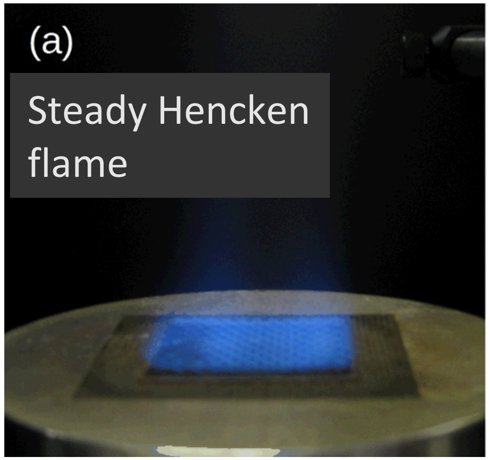
Results: Temperature Measurements



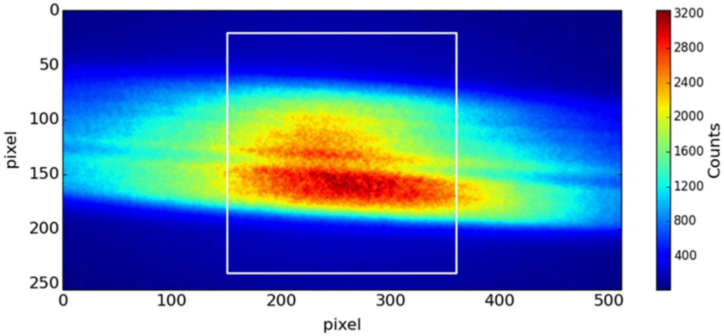


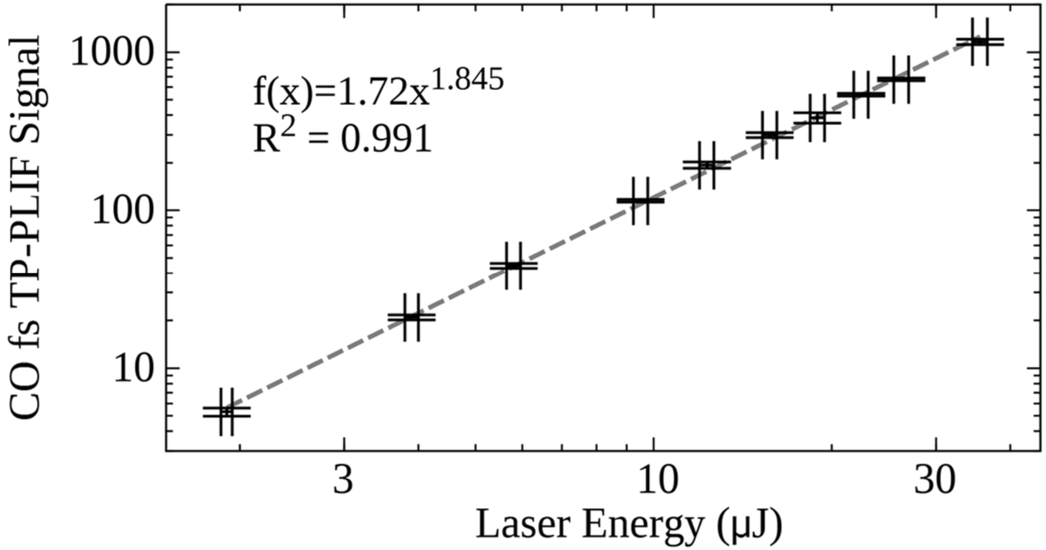
Power Dependence:

- Steady methane–air Hencken flame
- Equivalence ratio = 1.3
- CO concentration = 4.0%
- Adiabatic temperature = 1810 K
- Reflected ND filters to reduce energy
- Average and σ from 10 sets of 200 single-laser-shot images



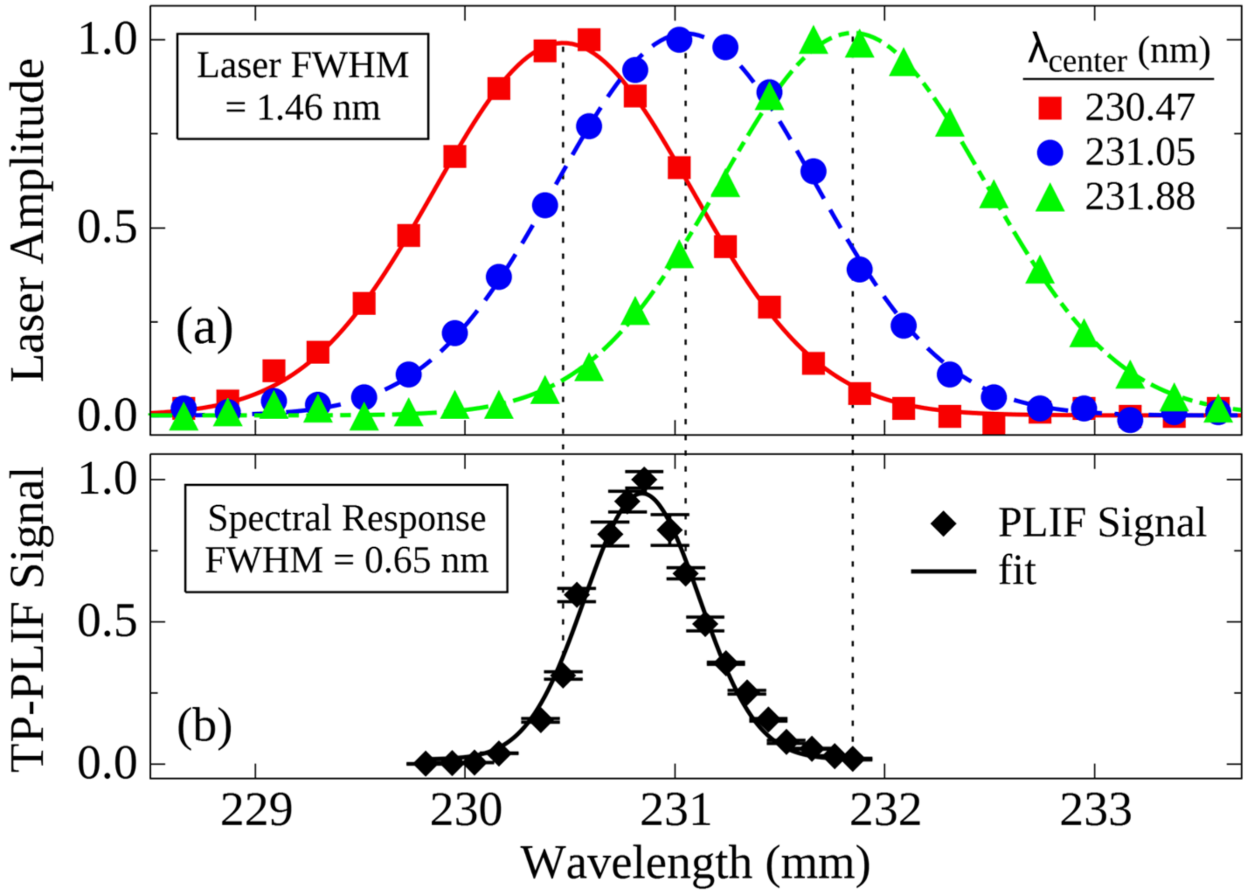
CO fs TP PLIF images from Steady Hencken flame





Spectral Dependence:

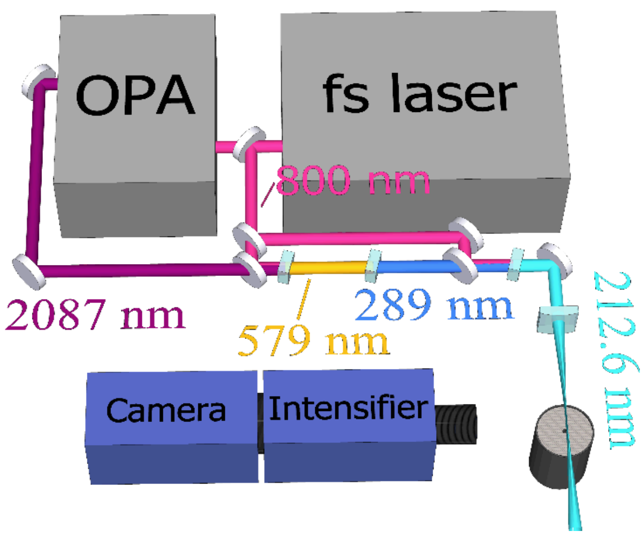
- Laser spectra recorded with fiber-coupled spectrometer
- Central excitation wavelength changed using OPA, harmonic generators and mixing crystal



Mixture Fraction Measurements

Proposed improvements

- Tunable fs laser system
- Excitation at 212.7nm
- 1000 Hz imaging
  - Mixture fraction
  - Scalar dissipation rate



Measurements performed in: